Radiation studies of the ATLAS beam induced backgrounds and the future upgrades
Studies for Run-1, Run-2 and upgrades for Phase-II

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Στον πατέρα μου, που έφυγε νωρίς...
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Abstract

In this thesis, results of dedicated Monte Carlo simulations of beam–induced background (BIB) in the ATLAS experiment at the Large Hadron Collider (LHC) are presented and compared with data recorded in 2012 and in dedicated loss map tests performed in 2015. Methods of reconstructing the BIB signals in the ATLAS detector, developed and implemented in the simulation chain, based on the FLUKA Monte Carlo simulation package, are described. The simulations reveal information about features that are not experimentally accessible, like correlations between backgrounds and the distributions of proton impacts on the collimators and contributing beam–gas events in the vicinity of the experiment. The level of agreement between simulation results and BIB measurements demonstrates that a good understanding of the origin of BIB has been reached. The results provide vital information about the dependence between background and collimator settings, which is of central importance when optimizing the LHC optics for maximum peak luminosity. The radiation environment in the region of the High-Granularity Timing Detector (HGTD) for the Phase-II ATLAS upgrades has been studied. These studies provided vital input for the radiation hardness qualification of the HGTD electronics and sensors and for the design of the new End-Cap moderator.
Περίληψη (Εκτεταμένη)

Στη διατριβή αυτή παρουσιάζονται αποτελέσματα από εξειδικευμένες προσομοιώσεις Μοντε Κάρλο (Monte Carlo) για το υπόστρωμα που προκαλείται από τη δέσμη (Beam Induced Background-BIB) στο πείραμα ATLAS του Μεγάλου Αδρονικού Επιταχυντή (Large Hadron Collider, LHC). Τα αποτελέσματα αυτά συγκρίνονται με δεδομένα του 2012 και με δεδομένα από ειδικά τεστ (loss map tests) του 2015. Επιπλέον παρουσιάζονται μελέτες σχετικά με τα αναμενόμενα επίπεδα ακτινοβολίας για τις μελλοντικές αναβαθμίσεις του ανιχνευτή ATLAS, ιδιαίτερα ως προς τον ανιχνευτή High Granularity Timing Detector (HGTD).

Ο επιταχυντής LHC λειτουργεί με ενέργεια σύγκρουσης 13 TeV, ενώ η αναβάθμιση του για τη τρίτη φάση (Run-3) λειτουργείται τον καθός και για τη φάση υψηλής φωτεινότητας (HL-LHC) συνεχίζεται. Η εξαρτημένη απόδοση του επιταχυντή καθός και των πειραμάτων/ανιχνευτών επέτρεψε στα πειράματα να καταγράψουν πληθώρα δεδομένων, εμβαθύνοντας την κατανόηση του καθιερωμένου προτύπου (Standard Model).

Ένας από τους βασικούς παράγοντες που πρέπει να λαμβάνεται υπόψη, ιδιαίτερα όταν η λειτουργία του επιταχυντή γίνεται με υψηλότερη φωτεινότητα (luminosity), είναι το υπόστρωμα που προκαλείται από τα σωματίδια της δέσμης (Beam Induced Background - BIB). Οι δύο κύριες πηγές αυτού του υποστρώματος είναι οι αλληλεπιδράσεις πρωτονίων με το εναπομένο αέριο στον σωλήνα δέσμης (σκέδαση δέσμης - αερίου) ή με άλλα εξαρτήματα της όλης μηχανής, όπως οι κατευθυντήρες δέσμης (collimators).

Το BIB μπορεί να επηρεάσει την ασφάλεια των πειραμάτων αλλά και να μειώσει την ποιότητα των πειραματικών μετρήσεων. Είναι προβληματικό για διάφορους λόγους, ιδιαίτερα λόγω του γεγονότος ότι τα σωματίδια που το αποτελούν ταξιδεύουν σχεδόν παράλληλα με τη γραμμή δέσμης, δημιουργώντας επιμήκειες καταιγίδες που μπορούν να αποθέσουν μεγάλες ποσότητες ενέργειας με την απόδοση τους στη λήψη δεδομένων. Επιπλέον, το BIB περιπλέκει την ανάλυση της φυσικής καθός μπορεί να εναποθέσει μεγάλες ποσότητες ενέργειας στις θερμιδόμετρα (calorimeters), οι οποίες μπορούν να ανακατασκευαστούν ως fake-jets, που οδηγούν σε χαμένη ενέργεια σε αναθηματικες διεργασίες. Ειδικά στις αναζητήσεις για ορισμένες εξωτικές διεργασίες φυσικής, τα fake-jets αντιπροσωπεύουν ένα μη ανεξαρτήτως υπόβαθρο που πρέπει να ελεγχθεί και να αφαιρεθεί.
Προηγούμενοι επιταχυντές, συμπεριλαμβανομένων των Tevatron και HERA, παρέχουν πολύτιμη εμπειρία στην αντιμετώπιση του BIB. Οι πρώτες προσομοιώσεις για την κατανόηση του BIB στον LHC παρουσιάστηκαν πριν από περισσότερα από 20 χρόνια και εξελίσσονταν παράλληλα με την εξέλιξη του σχεδιασμού του επιταχυντή, οδηγώντας σε λεπτομερέστερη και καλύτερη κατανόηση.

Σε αυτή τη διατριβή παρουσιάζεται η ανάπτυξη ενός πλαισίου προσομοίωσης Monte Carlo βασισμένο στο Fluka για τη μελέτη του BIB και τα αποτελέσματα από τις προσομοιώσεις συγκρίνονται με μετρήσεις αλληλεπιδράσεων δέσμες – αερίου στον επιταχυντή κατά τη διάρκεια του 2012. Τα αποτελέσματα των προσομοιώσεων συμφωνούν με τους σκανδαλισμούς από BIB στους ανιχνευτές κατάστασης δέσμης (BCM) αλλά και με τα fake jets που εμφανίζονται στα δεδομένα. Οι αποκλίσεις είναι κατανοητές με βάση την αβεβαιότητα της υπολειπόμενης πίεσης αερίου εντός του σωλήνα δέσμης. Οι προσομοιώσεις αναπαράγουν επιτυχώς την κατανομή χρόνου των σημείων αλληλεπιδράσεων (hits) στον ανιχνευτή BCM αλλά και αυτήν των fake jets. Επιπλέον, το προσομοιωμένο φάσμα ενεργειών στον επιταχυντή του ATLAS ταιριάζει με την ανακατασκευασμένη γεγονότα στην κατανομή των fake jets και τις χαρακτηριστικές κορυφές στον οριζόντιο επίπεδο. Επιπλέον οι προσομοιώσεις αποκαλύπτουν πληροφορίες που δεν μπορούν να ανακτηθούν από τις αναλύσεις των δεδομένων: το υπόβαθρο στους ανιχνευτές BCM προέρχεται κυρίως από περιοχή όπου βρίσκονται οι inner triplet μαγνήτες (<55μ) ενώ η πλειονότητα των BIB fake jets έχουν προέλευση περίπου 150μ από το κέντρο του ATLAS.

Το καλό επίπεδο συμφωνίας που βρέθηκε σε αυτή τη διατριβή επιβεβαιώνει την καλή κατανόηση των πηγών και της δυναμικής του υποβάθρου της δέσμης. Επιπλέον, δείχνει τη δύναμη των εργαλείων προσομοίωσης που έχουν αναπτυχθεί, τα οποία μπορούν να εκτελέσουν πολύπλοκες προσομοιώσεις του αντιπροσωπεύουν μια σειρά δυναμικών φαινομένων της δέσμης, παρακολούθηση των δευτερογενών σωματιδίων από αλληλεπιδράσεις δέσμης – σωματιδίων σε μεγάλες αποστάσεις μέσω των μαγνητών του επιταχυντή και του ανιχνευτή ATLAS, και τέλος επιτρέπει τη μοντελοποίηση των ανακατασκευασμένων γεγονότων του υποβάθρου δέσμης (BIB) στο ATLAS.

Μια άλλη πηγή του BIB είναι οι αδρονικοί και ηλεκτρομαγνητικοί καταιγισμοί από απώλειες πρωτονίων σε collimators λόγω του καθαρισμού των - εκτός της κύριας δέσμης – περιβάλλοντων σωματιδίων (beam–halo particles). Σε αυτή τη διατριβή παρουσιάζονται οι πρώτες μεμονωμένες μετρήσεις του beam–halo υποβάθρου στο πείραμα ATLAS. Τα αποτελέσματα βασίζονται σε ειδικές loss map δοκιμές κατά τις οποίες οι απώλειες δέσμης προκαλούνται στους πρωτεύοντες collimators. Τα αποτελέσματα δείχνουν σαφή συσχέτιση μεταξύ των πειραματικών υποβάθρων και τη ρύθμιση των tertiary collimators (TCTs). Επιπλέον φαίνεται ότι κατά τη διάρκεια λειτουργίας του επιταχυντή, το beam–halo συμβάλλει στο συνολικό υποβάθρο που προκαλείται από
τη δέσμη σε επίπεδο 1% ή και λιγότερο, επιβεβαιώνοντας έτσι την εγκυρότητα προηγούμενων προσομοιώσεων.

Επιπλέον, στη διατριβή αυτή παρουσιάζονται ειδικές προσομοιώσεις του beam–halo και τα αποτελέσματα συγκρίνονταν με τις πειραματικές μετρήσεις. Τα αποτελέσματα της προσομοίωσης κανονικοποιούνταν με την απώλεια έντασης δέσμης, η οποία κατά τη διάρκεια των μετρήσεων οφείλεται σχεδόν εξ ολοκλήρου στους TCP collimators. Λαμβάνοντας υπόψη τις συστηματικές αβεβαιότητες, ειδικές πειραματικές αποτελέσματα του μηχανήματος που δεν λαμβάνονταν υπόψη στις προσομοιώσεις, επιτεύχθηκε μια καλή ποσοτική συμφωνία με το μετρούμενο υπόβαθρο και αναπαράθηκαν με ακρίβεια χαρακτηριστικά όπως η εγκάρσια ορμή και οι αζιμουθιακές κατανομές των fake jets.

Θα πρέπει να σημειωθεί ότι για όλες τις ρεαλιστικές ρυθμίσεις των TCT collimators, οι οποίες σέβονται την ιεραρχία του πολλαπλών σταδίων συστήματος των collimators, το υπόβαθρο beam–halo είναι κατά και περιορισμό στο άνοιγμα των TCT. Αυτό το αποτέλεσμα έχει σημαντικές επιπτώσεις για οποιαδήποτε μελλοντική βελτιστοποίηση της απόδοσης του LHC, συμπεριλαμβανομένης της αναβάθμισης υψηλής ϕωτεινότητας της μηχανής.

Τα αποτελέσματα παρέχουν ζωτικές πληροφορίες σχετικά με την εξάρτηση του υποβάθρου με τις ρυθμίσεις των collimators. Η εξάρτηση αυτή έχει κεντρική σημασία κατά τη βελτιστοποίηση του επιταχυντή για μέγιστη φωτεινότητα. Τα αποτελέσματα δείχνουν πως το υπόβαθρο beam–halo, στον επιταχυντή και στο πείραμα ATLAS, είναι καλά κατανοητό και δεν περιορίζει την παρούσα λειτουργική απόδοση του επιταχυντή αλλά ούτε φαίνεται να αποτελεί περιοριστικό παράγοντα βελτιστοποίησης απόδοσης στο άμεσο μέλλον.

Οι μελέτες προσομοίωσης δείχνουν ότι οι αλληλεπιδράσεις δέσμης – αερίου που συμβάλλουν στο υπόβαθρο του ATLAS λαμβάνουν χώρα σε απόσταση <500μ από το σημείο συγκρούσεων του πειράματος. Αυτό διερευνήθηκε περαιτέρω μέσω μιας σειράς ειδικών δοκιμών που πραγματοποιήθηκαν κατά τη διάρκεια της Run-2 του LHC. Αυτές οι δοκιμές περιελάμβαναν τοπική έγχυση μικρών ποσοτήτων αερίου για την εκατομμύριση της ευαισθησίας σε γεγονότα δέσμης – αερίου ως συνάρτηση της απόστασης από το πείραμα. Η ανάλυση αυτών των δεδομένων βρίσκεται σε εξέλιξη και τα αποτελέσματα θα μπορούσαν να επικυρώσουν τις ακριβείς περιοχές όπου η βελτιστοποίηση κενού έχει τη μεγαλύτερη επίδραση στο υποβάθρο.

Τέλος, κατά τη διάρκεια αυτής της εργασίας, πραγματοποιήθηκαν μελέτες σχετικά με τα αναμενόμενα επίπεδα ακτινοβολίας στο HGTD για τις αναβαθμίσεις της Phase-II του ATLAS, αποτελώντας μια σημαντική συνεισφορά για το σχεδιασμό του ανθεκτικού αισθητήρα καθώς στον προσδιορισμό της αντοχής στην ακτινοβολία (radiation hardnness) των αισθητήρων και των ηλεκτρονικών, δεδομένου ότι είναι απαραίτητο ο ανιχνευτής να αντέξει τα επίπεδα ακτινοβολίας σε όλες τις λειτουργίες κατά
τη διάρκεια της HL-LHC φάσης. Επιπλέον, αυτές οι προσομοιώσεις αποκάλυψαν πληροφορίες σχετικά με τη φύση του μεταγενέστερου επιπέδου ακτινοβολίας (afterglow) στο HGTD που οφείλεται κυρίως σε θερμικά νετρόνια και αργά (ή σταματημένα) μιόνια.

Οι περισσότερες πτυχές του BIB και του περιβάλλοντος ακτινοβολίας στο πείραμα AT-LAS περιγράφονται στις δημοσιεύσεις αυτής της διατριβής (Δημοσίευση-1, Δημοσίευση-2, Δημοσίευση-3, Δημοσίευση-4), οι οποίες και παρατίθενται στα αντίστοιχα παραρτήματα. Το κείμενο πριν από τα παραρτήματα προορίζεται να δώσει μια γενική ανασκόπηση των τεχνικών προσομοίωσης, της φυσικής ακτινοβολίας αλλά και πρόσθετες πληροφορίες για τα αποτελέσματα που παρουσιάζονται στις δημοσιεύσεις.
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Chapter 1

Introduction

The LHC operated at a c.m.s collision energy of 13 TeV while the machine and detector upgrades for Run-3 and the high-luminosity phase (HL-LHC) are ongoing. The excellent performance of the machine and the detectors allowed the LHC experiments to record a wealth of experimental data deepening our understanding of the Standard Model and extending the research to physics beyond the Standard Model.

One of the key factors to consider when moving towards higher luminosities at the LHC is the beam induced background (BIB). The two main sources of BIB at the LHC are proton interactions with residual gas in the beam pipe (beam–gas scattering) or with other machine components like collimators. BIB can impact the experimental conditions, reducing the quality of experimental triggers and track reconstruction as well as the safety of the experiments.

BIB can be problematic for a number of reasons, particularly due to the fact that BIB particles travel almost parallel to the beam line, creating elongated clusters that can deposit large amounts of energy directly on the innermost tracking detectors; impacting their data-taking performance or even damage them. Furthermore, BIB complicates physics analysis. Muons, originating from the pion and kaon decays resulting from the hadronic showers that the beam loss creates, can deposit large amounts of energy in the calorimeters through radiative processes which can be reconstructed as fake jets leading to missing transverse momentum if overlaid with a collision event. Especially in searches for some exotic physics processes [1–4], fake jets represent a non-negligible background that must be well controlled and subtracted.

In light of the upcoming ATLAS upgrades, an in-depth understanding of the sources and nature of BIB is crucial for improving the detector performance and boosting future searches. This task calls for a combination of measurements and simulations. The main purpose of this thesis is the validation of the latter.
Previous colliders, including Tevatron and HERA [5–7], offered valuable lessons and experience in dealing with BIB while operating a high-energy proton collider. The first simulations for understanding the BIB at the LHC were presented more than 20 years ago [8] and were frequently updated with the evolution of the machine design thus allowing for a more detailed understanding [9–11]. In this work, the development of a Monte Carlo simulation framework based on FLUKA for studying the BIB is presented and results from the simulations are compared with measurements of inelastic beam–gas interactions from the 2012 LHC run [12].

Another source of BIB are the hadronic and electromagnetic showers from proton losses on collimators due to beam–halo cleaning. During this thesis, the first isolated LHC measurements of this type of background to the experiments are presented. These measurements have been taken during dedicated loss map tests in 2015 and the results are analysed and compared with simulations.

Finally, studies on expected radiation levels in the HGTD for the ATLAS Phase-II upgrades have been performed during this work, forming a significant input for the design of the detector, since the characterisation of the radiation environment has an important role in the life expectancy of sensors and electronics.

Most aspects of the BIB and the radiation environment at the ATLAS experiment are described in the publications of this thesis [Publication-1, Publication-2, Publication-3, Publication-4]. This introductory paper is intended to give a general review of the simulation techniques, of radiation and beam background physics and additional information on the results presented in the publications. Chapters 2 and 3 provide a description of the LHC and ATLAS respectively. A short introduction of the FLUKA Monte Carlo framework is given in Chapter 4 and a description of the BIB with their monitoring methods by ATLAS in Chapter 5. Chapters 6 and 7 are complementary to the Publications 1 and 2, respectively, and Chapter 8 to Publications 3 and 4.
Chapter 2

The Large Hadron Collider (LHC) Accelerator

The Large Hadron Collider (LHC) [13] [14], located at the French-Swiss border near Geneva, Switzerland, consists of a 27-kilometre underground ring of superconducting magnets and is the world’s largest and most powerful accelerator. It is designed to accelerate and collide mainly protons at a centre of mass energy of 14 TeV at four interaction points (IPs) inside experimental detectors, which correspond to the four main experiments ALICE [15], ATLAS [16], CMS [17] and LHCb [18]. The LHC gives the opportunity to physicists to answer questions about the Standard-Model and measure the Higgs boson’s properties, as well as to search for new particles and verify theories beyond the Standard-Model, exploring the present frontier of high energy physics.

In this chapter, a short introduction of the importance of the luminosity which is crucial for the reach of physic searches and defines the machine performance is given in Section 2.1. Section 2.2 describes the CERN accelerator chain from the generation of the protons till their injection into the LHC. A short description of the LHC general layout is given in Section 2.5. Section 2.6 describes the ATLAS interaction region. The LHC beam vacuum system is presented in Section 2.7 while the beam cleaning system of the LHC is described in Section 2.8. Sections 2.7 and 2.8 are described in detail since they are most relevant for the studies of beam backgrounds.

2.1 Luminosity and crossing angle

An important parameter for the design of the LHC as well as for any other accelerator is the rate of the detected events in the experiments for the search of physics processes. The likelihood of these processes is expressed by a cross-section $\sigma$. The standard unit of the cross-section in nuclear & high energy physics is the barn ($10^{-24}$ cm$^2$). Since the LHC experiments are searching for rare physics
The Large Hadron Collider (LHC) Accelerator

events against a background from processes with larger cross-sections, high statistics (i.e. high number of events) is needed for the measurements in order to distinguish the signal from the background. The number of the produced events in the experiments of a certain physics process \( pp \to X \) is given by:

\[
R_{pp \to X}(t) = \mathcal{L}(t) \times \sigma_{pp \to X}
\]

where \( \sigma_{pp \to X} \) is the production cross-section and \( \mathcal{L}(t) \) is the luminosity. The latter is also referred to as \textit{instantaneous luminosity} and is usually expressed in units \( \text{cm}^{-2}\text{s}^{-1} \), defined as the process-independent proportionality factor between the rate \( R_{pp \to X}(t) \) and its production cross-section \( \sigma_{pp \to X} \). Its precise knowledge is important since for many cross-sections measurements the uncertainty on the luminosity dominates the final result. For example, in order to study of the Higgs Boson’s properties, the cleanest channel is where the Higgs boson decays into four leptons:

\[
H \to ZZ \to 4l
\]

The cross-section for this process is the product of the Higgs cross-section, \( \sigma(pp \to h) \), shown in Figure 2.1a, the branching ratio to ZZ, \( BR(h \to zz) \), shown in Figure 2.1b and the branching ratio squared of \( z \to ll \), \( BR(z \to ll) \). For \( m_h=125 \text{ GeV} \) \( \sigma(pp) \sim 20 \text{ pb} \) as seen in Figure 2.1a, and \( BR(h \to zz) \) is 0.02 from Figure 2.1b. The leptonic \( BR \) of the Z boson was measured at LEP to be 0.09. This gives a total cross-section of \( \sim 2 \text{ fb} \):

\[
\sigma(pp \to h \to zz \to 4l) = \sigma(pp \to h) \times BR(h \to zz) \times BR(z \to ll)^2 = \sim 2 \text{ fb}
\]

In order to collect sufficient statistics of such events, several \( \text{fb}^{-1} \) of data need to be recorded in order to observe a few events.

**Figure 2.1** Standard Model Higgs boson production cross sections (a) and Higgs boson decay branching ratios (b). Figures from [19].
2.1 Luminosity and crossing angle

In particle colliders, the luminosity is given by:

\[ \mathcal{L} = \gamma \frac{n_b N_b^2 f_{\text{rev}}}{4\pi \beta^* \epsilon_n} F \]  

(2.2)

where \( \gamma \) is the relativistic gamma factor, \( N_b \) is the number of particles per bunch, \( n_b \) is the number of bunches per beam, \( f_{\text{rev}} \) is the revolution frequency, \( \beta^* \) is the beta function at the Interaction Point (IP), \( \epsilon_n \) is the normalised transverse beam emittance and \( F \) is the geometric luminosity reduction factor. The area of the beam spot at the IP is defined by the product of \( \beta^* \) and \( \epsilon_n \) of Equation 2.2. The beam emittance \( \epsilon \) defines the average spread of particle coordinates in position-and-momentum phase space, while the transverse emittance \( \epsilon_n \) is defined as:

\[ \epsilon_n = \frac{\nu}{c} \gamma \epsilon \]  

(2.3)

where \( \gamma \) is the relativistic \( \gamma \).

In the LHC, since the colliding beams travel in the same beam-pipe in the interaction regions, the crossing angle between the two beams, as illustrated in Fig 2.2, was introduced in order to restrict collisions only to the IP and to avoid unwanted parasitic collisions at other positions in the ring. The crossing angle has to be optimised to provide the necessary separation between the two beams and at the same time has to be kept small enough for minimising the reduction of the luminosity. The geometric factor \( F \), seen in Equation 2.2, is due to the crossing angle and is expressed as:

\[ F = \frac{1}{\sqrt{1 + \left( \frac{\theta_c \sigma}{2\sigma_c} \right)^2}} \]  

(2.4)

where \( \theta_c \) is the crossing angle, \( \sigma_c \) is the longitudinal r.m.s. size of the bunches and \( \sigma \) is the transverse r.m.s. size of the bunches.
The normalised emittance, in contrast to the beam emittance, is preserved during acceleration since it does not change as a function of energy; thus it can track beam degradation if the particles are accelerated. The beta function $\beta$ defines the beam size i.e. the maximum amplitude a single particle trajectory can reach at a given position in the ring and it is determined by the focusing properties of the lattice following the periodicity of the machine. Assuming that the beam has a Gaussian shape in the transverse direction, the beta function is related to the transverse beam size by:

$$\sigma(s) = \sqrt{\epsilon \times \beta(s)} \quad (2.5)$$

where $s$ is the location along the nominal beam trajectory, $\sigma(s)$ is the width of this Gaussian and $\epsilon$ is the beam emittance $^1$. The value of $\beta(s)$ at an interaction point is referred to as beta star $\beta^*$ and the evolution of the beta function around the minimum point is given by:

$$\beta(s) = \beta^* + \frac{z^2}{\beta^*} \quad (2.6)$$

where $z$ is the distance along the nominal beam direction from the IP.

As seen from Equation 2.2, there are three ways to achieve a higher luminosity: by increasing the number of particles in each bunch ($N_b$), by increasing the number of bunches that are contained in each beam ($n_b$) and by shrinking the size of the bunch at the collision point, which is related to the $\beta^*$ and $\epsilon$, since the product of these two terms gives the area of the beam spot at the IP.

The number of collected physics events is determined by the recorded integrated luminosity $L_{int}$, which depends on the variation of the instantaneous $L$, the fill duration and the machine and experiment availability. The delivered integrated luminosity refers to the integrated luminosity which the machine has delivered to an experiment. Figure 2.3 shows the delivered integrated luminosity to the ATLAS experiment through all the operational years.

The LHC design luminosity is $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ which leads to around $8 \times 10^8$ inelastic proton-proton interactions. The LHC started its first physics run in 2009 which ended in 2012. During this run, an energy of 4 TeV per proton was achieved and $\sim$30fb$^{-1}$ of data were collected by ATLAS. Then, the machine was shut down for an upgrade period of two years and restarted for its’ second operational period till 2018, achieving a new record energy of 6.5 TeV per proton and an instantaneous luminosity of a factor of 2 above its’ design value. A summary of the main LHC design parameters, as well as those during 2012, 2015 and 2016 operations, are listed in Table 2.1.

---

$^1\epsilon$ is the non normalised emittance
2.2 The CERN accelerator chain

In this section, a description of how the protons are generated, accelerated and finally brought into collision is given.

At first, hydrogen nuclei (protons) are stripped from their electrons by an electric field with an energy of 100 keV. These protons, before being injected to the LHC, have to be accelerated by a
complex of different machines, each of which increase the protons energy typically by a factor of 10-20.

From the initial energy of 100 keV, the produced protons are first accelerated to 750 keV and then they are injected to Linac2, which rises their energy to 50 MeV, i.e. to 1/3 of the speed of light. During this phase, the protons are formed into beam bunches by the radio-frequency quadrupoles (RFQ).

Then the beam is injected to the Proton Synchrotron Booster (PSB), where the circulating protons are reaching an energy of 1.4 GeV. Since PSB consists of four identical rings, it accelerates four bunches in parallel per ring in one cycle.

From the PSB, the protons are injected into the Proton Synchrotron (PS) in a two step procedure; at first, one bunch (1\textsuperscript{st} batch) from one of the four PSB beam-pipes is injected followed by two more bunches (2\textsuperscript{nd} batch) with a time difference of 1.2 s. This procedure is repeated twice, leading to a total number of six bunches being injected in the PS RF harmonic 7\textsuperscript{2}. The additional empty bucket is important for the PS and SPS kickers rise times. Afterwards, and still at the injection energy of 1.4 GeV, the triple splitting of the bunches is performed providing a total number of 18 consecutive bunches. The beam is then accelerated up to 25 GeV and and then each bunch is split twice into two, resulting to a total number of 72 bunches spaced by 25 ns. This bunch scheme is the nominal, used during the Run-2 until mid 2016. In order to reduce the emittance, a new more complicated beam scheme, the Batch Compression Merging and Splitting scheme (BCMS), was used later in Run-2. Figure 2.4 illustrates the nominal and the BCMS filling schemes.

The next step is the Super Proton Synchrotron (SPS), which is a 6.9 km long circular accelerator, where the beam is accelerated to the LHC injection energy of 450 GeV. The SPS is filled with either two, three or at maximum four batches of 72 bunches with the nominal filling scheme. In order to fill the LHC, this process is repeated 12 times per ring.

In the LHC the protons reach their nominal collision energy after \(\sim 20\) minutes of circulation, accelerated by the LHC Radio Frequency (RF) system. During Run-1, the LHC accelerated protons up to an energy of 3.5 and 4 TeV, while in Run-2 this energy has been increased to 6.5 TeV.

<table>
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<tr>
<th>Accelerator</th>
<th>Injection Energy</th>
<th>Extraction Energy</th>
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<tr>
<td>Linac2</td>
<td>750.0 keV</td>
<td>50.0 MeV</td>
</tr>
<tr>
<td>PSB</td>
<td>50.0 MeV</td>
<td>1.4 GeV</td>
</tr>
<tr>
<td>PS</td>
<td>1.4 GeV</td>
<td>25.0 GeV</td>
</tr>
<tr>
<td>SPS</td>
<td>25.0 GeV</td>
<td>450.0 GeV</td>
</tr>
</tbody>
</table>

\(\textsuperscript{2}\)Harmonic H is an integer multiple of the revolution frequency
2.2 The CERN accelerator chain

Figure 2.4 Nominal PS filling scheme (a), as described in the text, and BCMS PS filling scheme (b) where even lower emittances have been achieved.
The Large Hadron Collider (LHC) Accelerator

**Figure 2.5** A detailed overview of the CERN accelerator complex. The LHC ring has four Interaction Points (IPs) where the collisions take place, represented by yellow points. Figure from [21].

A detailed layout of this accelerator complex can be found in Figure 2.5 and a summarised table with the Injection and Extraction energies of the accelerators in Table 2.2.

### 2.3 The LHC machine cycle

The LHC operation cycle is organised in a series of phases called *beam modes*.

At the beginning, during the *Setup* phase, the LHC is prepared to accept the two beams from the injector complex. Afterwards, the energy of the two beams is ramped-up during the *Ramp* phase until the achievement of the targeted energy. When the beams are ramped, actions for preparing for the next phase are performed during the *Flattop* phase, and squeezed afterwards (*Squeeze* phase) at the interaction points to a smaller $\beta^*$. In the squeeze phase, the $\beta^*$ is reduced in order to achieve the maximum luminosity. At the end of the squeeze stage, the two beams are adjusted to achieve collisions during the *Adjust* phase. Once the luminosities have been optimised in all experiments, the operators declare *Stable Beams* and experiments can start the data taking. The LHC brings the proton bunches into collisions during the Stable phase for 10-20h. At the end of the run, the two beams are *Dumped* and the *Ramp-Down* stage starts, during which the magnet currents are brought back to
2.4 The LHC filling scheme

The 400.79 MHz LHC RF frequency and the revolution time of 88.9244 $\mu$s form 35640 RF-buckets around the machine that can be filled with bunches. Since the bunches are spaced by 25 ns (40 MHz) during the nominal LHC filling scheme, only 3564 slots are available.

The LHC is designed to run with different filling schemes and bunch spacings. During the 2012 Run-1, every 20$^{th}$ bucket was filled, leading to a bunch spacing of 20 ns and up to 1380 slots to be filled. In order to distinguish the available slot, a unique Bunch Crossing IDentifier (BCID)\(^3\) number is given to them, with the numbered 1 being the first BCID after the abort gap of 3$\mu$s\(^4\).

At high luminosities multiple interactions can contribute to the detector signals associated with a single bunch-crossing. These effects are referred to as pile-up. The mean number $\mu$ of interactions per crossing corresponds to the mean of the poisson distribution of the number of interactions per crossing calculated for each bunch and it is calculated from the instantaneous per bunch luminosity as:

$$\mu = \mathcal{L}_{\text{bunch}} \times \sigma_{\text{inel}} / f_r$$

where $\mathcal{L}_{\text{bunch}}$ is the per bunch instantaneous luminosity, $\sigma_{\text{inel}}$ is the inelastic cross section and $f_r$ is the LHC revolution frequency. For 13 TeV collisions with a $\sigma_{\text{inel}}$ of 80 mb the mean $\mu$ value is 36.1. A detailed description of the LHC filling scheme can be found at Reference [23].

---

\(^3\)The BCID is an ATLAS concept; the LHC refers to them as slots

\(^4\)The abort gap allows a safe abort of the beams
2.5 The LHC general layout

The LHC is segmented in eight Long Straight Sections (LSSs) and eight arcs, as presented in Figure 2.7. Each straight section is approximately 528 m long and can serve as an experimental or utility insertion [13]. The interaction regions (IRs) are located in the middle of each LSS. There are four experimental IRs which host the four LHC detectors. IR1 and IR5, located in diametrically opposite LSSs, host ATLAS and CMS, respectively, that search mainly for new physics, explore the Higgs sector and measure standard model processes. The ALICE detector, which mainly studies the quark–gluon plasma and physics of heavy ions, is located in IR2 and the LHCb detector, where asymmetries between matter and antimatter are hunted, is found in IR8. IR2 and IR8 include the injection systems for beam-1 and beam-2, respectively, through the transfer lines TI2 and TI8. In IR4, there are two independent RF systems (one for each beam) that accelerate the two beams. IR3 and IR7 house the momentum and betatron cleaning systems of both beams, respectively, and finally, IR6 hosts the beam abort system, which safely extracts the two beams into the beam dump. In order to cancel the horizontal dispersion due to the spread of energy within the proton beam, special strings of magnets (dispersion suppressors DSL and DSR) have been installed between the straight sections and the regular arcs.

Figure 2.7 The general layout of the LHC. Beam-1 circulated clockwise while Beam-2 circulated anticlockwise. Figure adapted from [13].
2.6 The interaction region of ATLAS (IR1)

A detailed layout of the ATLAS interaction region (IR1) is shown in Figure 2.8. The first element that the beams traverse while exiting the ATLAS cavern are the Target Secondary Absorber (TAS) absorbers, located at $|z|=|19–20.8|$ m from the IP. They protect the following magnets against the heat load from particles leaving IP (collision debris). These absorbers are 1.8 m copper blocks and have an aperture of $r=1.7$ cm. In order to reduce the radiation levels in the ATLAS experimental cavern, a massive shielding of steel surrounds the TAS. The final focus of the two beams is performed by the Inner Triplets at $|z|=|23–54|$ m on both sides of the Interaction Point (IP) at $z=0$. The inner triplets are strings of four matching low–beta focusing quadrupole magnets. The beam trajectories are separated at $|z|\approx70$ m inside the separation dipoles D1 and are recombined in dipoles D2 at $|z|\approx160$ m, which bring the two beams into parallel trajectories at a distance of 194 mm from each other. A Target Absorber Neutral (TAN) absorber, located between the D1 and D2, protects the machine elements from neutral particles emerging form the IP and the inner triplet from beam backgrounds generated in the LHC tunnel. The two rings share the same vacuum chamber from the IP up to the separation dipole D1. The sections after D1 consist of magnets with separate beam-pipes for each ring.

2.7 The LHC beam vacuum system

The requirements for the design of the LHC beam vacuum system are tight [13, 14]. Collisions between the beam protons and gas molecules inside the accelerator beam-pipe have to be avoided, since they impact the beam lifetime and they produce particle showers that increase the background into the particle detectors. Thus, a sophisticated beam vacuum system [24, 25] has to be designed, both for the cryogenic 24 kms of arc section and for the $\approx3$ km of straight sections with room temperature, allowing the beam to travel in a vacuum as empty as interstellar space. The LHC vacuum system has been designed to deal with static (no beam) and dynamic (ion, electron and photon induced outgassing due to presence of beam) sources of gases.
At the cryogenic temperature of 1.9 K the conditions for such a vacuum system are expressed as gas densities normalised to hydrogen in terms of hadronic interaction length. These equivalent hydrogen gas densities have to remain below $10^{15}$ H$_2$ m$^{-3}$ in order to provide a beam lifetime of 100 hours. In the interaction regions the requirements are even tighter since these densities must remain below $10^{13}$ H$_2$ m$^{-3}$, whereas for the straight sections with room temperature the pressure inside the beam-pipe should remain between $10^{-11}$ and $10^{-10}$ mbar H$_2$ equivalent.

The static pressure in the LHC is below $10^{-11}$ mbar. However, during proton beam operation, the LHC vacuum system is subjected to molecular desorption induced by electron, ion and photon bombardment. These effects produce a dynamic pressure which is observed during a normal LHC fill. Electron bombardment originates from the build-up of an electron cloud inside the vacuum chamber, as discussed in the next Section; ion bombardment arises from the residual gas ionization by the beam; and photon bombardment arises from the synchrotron radiation produced in dipoles (and in quadrupoles by bending in the magnets).

### 2.7.1 Vacuum chamber and heat loads

![Diagram of LHC beam screen](image)

**Figure 2.9** The LHC beam screen. Figure from [13].

The emitted synchrotron radiation is one of the main factors for the design of the LHC vacuum system, since it generates a heat load of 0.2 W/m per beam at the nominal beam energy of 7 TeV. In order to reduce this heat load from reaching the cryogenic systems of the accelerator, a *beam screen* [26], shown in Figure 2.9, has been installed inside the magnet cold-bore in all the cryogenic parts of the accelerator that provides a shielding to the cold wall of the helium vessel from impinging radiation and lost particles. It is made of a low-permeability stainless steel strip and a high conductive layer of copper with a thickness of 0.05 mm covers it’s inner wall for better electric conductivity.
2.7 The LHC beam vacuum system

Keeping the electric impedance as low as possible. The beam screen is cooled by two 0.53 mm thick stainless steel tubes.

When the synchrotron radiation hits the beam screen walls, photoelectrons are generated by the atoms of the surfaces that remain trapped on the surface of the walls. These photoelectrons are accelerated by the proton bunch onto the opposite wall producing secondary electrons, which then are accelerated by the beam’s electrical field ultimately building up to an electron cloud. The formed electron cloud can be dense enough to destabilise the beam and at the same time can deposit significant power into the cold bore through the pumping slots and rise the vacuum pressure. The electron cloud is a threshold phenomenon that depends on the bunch population and on the number of bunches in the train. The latter causes a build-up of the electron cloud. In addition, it is highly dependant on the Secondary Electron Yield (SEY) $\delta$ and the bunch spacing, since low energy electrons surviving the gaps between the bunch trains enhance it, and is attenuated by the spacing between bunches and bunch trains. Figure 2.10 illustrates the electron cloud build-up mechanism inside the LHC beam pipe walls. In order to minimise this effect, the so-called beam scrubbing (conditioning) technique is used, during which gradually increased number of proton bunches at injection energy are used. These bunches release the trapped gas molecules from the metal and reduce the rate of production of electrons on the walls of the pipe.

A non-negligible heat load in the LHC is due to the beam losses due to nuclear scattering of protons on residual gas and constitutes the only contribution to the total heat load that cannot be reduced by the beam screen.

Some protons from elastic collisions can be intercepted by the beam cleaning, but most of these collision products have enough energy to escape the vacuum chamber and generate particle showers that deposit their energy in the cryogenic coils of the magnets. These heat losses are proportional to the density of the gas that exists inside the beam-pipe and define additional limits of the gas density.
2.7.2 Cryopumping

In the cryogenic sections of the LHC the vacuum is produced and maintained by taking profit of a procedure called cryopumping, when the gases condense and stick to the cold surfaces thanks to interactions between gas particles without requiring chemical bonds, since the forces that are involved are relatively weak. Such cryopumping is effective for all gasses, including noble gasses with sufficiently low temperatures. In addition, the perforations in the beam screen exist to allow the gas to flow to the cold bore where it condenses (out of reach of synchrotron radiation).

There are three different mechanisms that describe the cryopumping [28]: cryocondensation, cryosorption and cryotrapping. Cryocondensation is the process during which gas particles are condensed onto a cold surface by attaching them to gas particles already attached to the surface. In order for this phenomena to take place, the temperature of the surfaces of the beam chambers must be low enough to keep the saturation pressure below the desired vacuum pressure. Cryosorption is the physical adsorption process under vacuum conditions and low temperatures, during which the gas particles that are hitting a sufficiently cold surface become attached by weak intermolecular forces leading to higher concentrations of the gas particles on the surface than in the gas phase. During cryotrapping, two or more gases are pumped that are not condensable at the prevailing temperatures and pressure conditions [28].

2.7.3 Bake-out and NEG activation

In order to maintain the design pressure in the room-temperature sections of the LHC, the inner surfaces of the vacuum chambers are coated with Non-Evaporable Getter (NEG) [29, 30] material made of TiZrV with a thickness of \( \sim 1 \mu m \), leading to large pumping speeds, low SEY and desorption yields. The coated surfaces act as pumps instead of sources of gas. Getters fix gas molecules on their surfaces by chemical reactions due to the nature of the material they are made of. In order to avoid the progressive decrease of their pumping capacity, since the amount of gas deposit on the NEGs increases due to pumping, NEGs are heated in order to diffuse the molecules from the surface into the bulk. Before the installation of the NEGs, the vacuum chambers are baked and the NEGs are activated at 230°C for a duration of 24 h [13]. This activation process is crucial for the effectiveness of the getters, since when heated the surface oxides are dissolved in the bulk material. The NEGs can remove all residual gases except methane and noble gases. The latter are removed by 780 ion pumps distributed along the entire ring.

In addition to the NEG activation process, the quality of the vacuum is improved by a procedure called “bake-out” [14], during which the vacuum chambers are heated from the outside. In order to keep the vacuum at the desire pressures, the bake-out procedure has to be performed at regular intervals, taking into account the NEG activation in order for them to be kept unsaturated.
2.7.4 Residual gas distribution in the beam-pipe

The rate of beam–gas interactions is proportional to the residual gas pressure in the beam pipe and to the beam intensity. The latter is a property of the beams and is measured by the LHC with percent-level accuracy. On the other hand, the pressure as well as the molecular composition of the residual gas varies as a function of position around the accelerator.

After pumping down of the LHC beam vacuum, a small amount of gas remains stuck on the beam-pipe surface. The rate of outgasing depends on the intensity of the radiation, thus the dynamical pressure depends on beam intensity and energy. The residual gas consists of $\text{H}_2$, $\text{CH}_4$, $\text{CO}_2$ and $\text{CO}$, and their relative fractions depend on local temperature, radiation load and surface characteristics of the beam pipe.

Almost all room-temperature sectors of the LHC beam-pipe are coated with a non-evaporable getter material that provides distributed pumping along the beam line for all common gases except $\text{CH}_4$. Therefore, methane is the dominant gas species in room-temperature sections, including the D1 dipole. Inside cryogenic magnets where the cold bore is at 1.9 K, notably those of the inner triplet and the LHC arc, the dominant gas is $\text{H}_2$ since all gases except hydrogen stick relatively firmly on the surface. The magnets in the LSS, from D2 to the arc, are operated at 4.5 K. At this temperature all gases are more easily desorbed and here $\text{CO}_2$ is the most abundant gas species. Vacuum pumps produce local minima in the pressure and corresponding gradients, which result in gas diffusion from sections with higher pressure towards the pumps.

During the beam operation, the rate of out-gasing slowly decreases since the gas inside the beam-pipe is desorbed by synchrotron radiation and particles hitting the pipe walls. The amount of gas present on the beam-pipe walls depends on the surface condition of the beam-pipe which depends on the past operation (beam scrubbing). Each electron hitting the chamber walls can release gas molecules as well. Coatings with low secondary electron yield and/or surface conditioning techniques (bake–out where possible and beam-scrubbing in the cold sections) are used to reduce the secondary emission and reduce the effect.

2.7.5 Vacuum instrumentation around IR1

Penning and ionisation gauges are used for measuring the pressure in IR1 at different locations along the beam pipe, as described in Table 2.3, with a sensitivity down to $10^{-11}$ mbar. It is only possible to have a discrete number of pressure measurements from gauges along the circumference of the ring and only in the warm sections. These gauges measure the total pressure at their location since they cannot distinguish the gas species. In order to get partial pressures of the different gases along the ring, simulations must be employed, based on theoretical models and laboratory measurements of desorption rates and gas composition [31], together with the pressure measurements.
The Large Hadron Collider (LHC) Accelerator

Table 2.3 Location, name and type of the gauges in IR1 for beam-1. The VGI stands for ionisation gauges and VGPB for penning gauges. “B” stands for blue beam (beam-1) and “X” for common (crossed) beam-pipe. L stands for left and R for right.

<table>
<thead>
<tr>
<th>Location [m]</th>
<th>Vacuum Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>VGPB.220.1L1.X</td>
</tr>
<tr>
<td>22</td>
<td>VGI.220.1L1.X</td>
</tr>
<tr>
<td>22.18</td>
<td>VGPB.222.1L1.X</td>
</tr>
<tr>
<td>58.635</td>
<td>VGPB.7.4L1.X</td>
</tr>
<tr>
<td>58.884</td>
<td>VGPB.9.4L1.X</td>
</tr>
<tr>
<td>120.775</td>
<td>VGI.628.4L1.X</td>
</tr>
<tr>
<td>151.493</td>
<td>VGPB.935.4L1.B</td>
</tr>
<tr>
<td>151.732</td>
<td>VGPB.938.4L1.B</td>
</tr>
<tr>
<td>172.886</td>
<td>VGPB.2.5L1.B</td>
</tr>
<tr>
<td>173.125</td>
<td>VGPB.4.5L1.B</td>
</tr>
<tr>
<td>177.846</td>
<td>VGI.52.5L1.B</td>
</tr>
<tr>
<td>192.242</td>
<td>VGPB.196.5L1.B</td>
</tr>
<tr>
<td>192.481</td>
<td>VGPB.198.5L1.B</td>
</tr>
<tr>
<td>201.106</td>
<td>VGPB.2.6L1.B</td>
</tr>
<tr>
<td>201.355</td>
<td>VGPB.4.6L1.B</td>
</tr>
<tr>
<td>209.406</td>
<td>VGI.85.6L1.B</td>
</tr>
<tr>
<td>224.142</td>
<td>VGPB.232.6L1.B</td>
</tr>
<tr>
<td>224.381</td>
<td>VGPB.235.6L1.B</td>
</tr>
<tr>
<td>233.006</td>
<td>VGPB.2.7L1.B</td>
</tr>
<tr>
<td>233.255</td>
<td>VGPB.4.7L1.B</td>
</tr>
<tr>
<td>246.25</td>
<td>VGI.134.7L1.B</td>
</tr>
<tr>
<td>256.172</td>
<td>VGPB.234.7L1.B</td>
</tr>
</tbody>
</table>

2.8 Beam Cleaning

As the protons circulate in the LHC, a halo of particles slowly builds up around the core of the beam due to various dynamic processes and small perturbations of the magnetic field. If this is left uncontrolled, these particles can eventually hit the wall of the vacuum chamber producing unwanted background in the detectors and magnet systems, affecting their performance and operation. For example, a local loss of $4 \times 10^7$ protons inside a superconducting magnet would induce an energy of about 30 mJ/cm$^3$ per second, which is enough to cause a quench of the magnet. Thus, it is necessary to clean this beam–halo and this is achieved using a sophisticated multi-stage system of collimators installed in the insertion regions IR3 and IR7 [32–37]. In IR3, particles with a large momentum offset due to synchrotron radiation are intercepted whereas the collimators in IR7 intercept particles with a large betatron oscillation amplitude.
The collimation system of the LHC is a three-stage system composed of a series of movable two-sided collimators, as illustrated in Figure 2.11. At the first stage, the primary halo is intercepted by the primary collimators (TCPs). The jaws of the TCPs, made of carbon fibre composite (CFC), are inserted close to the beam with an aperture adjusted according to the energy of the beam, machine optics and operational mode. This aperture is equal or larger to the dynamic beam-size, thus the stable beam particles will not be intercepted.

Due to the large LHC beam energies and often short effective distance traversed inside the collimator material, many protons hitting the TCPs are not stopped through inelastic interactions but scatter out again, forming the so-called secondary halo. These protons have received small kicks in angle and energy from multiple Coulomb scattering and ionization, and could in addition have received large kicks caused by elastic or single diffractive scattering. In addition to this, hadronic showers can be generated by inelastic processes in the collimators. Since both the escaping shower as well as the secondary halo have enough energy to cause a quench, secondary collimators (TCSs) made of tungsten alloy (CFC) and absorbers (TCLs) have been installed downstream of the TCPs in order to intercept these contributions.

The secondary particles generated by interactions inside the TCSs and form the tertiary halo are captured by active absorbers and by tertiary collimators (TCTs). Both made CFC and are installed downstream of the TCSs and close to the experimental areas, respectively. The choice of CFC for the primary and the secondary collimators was made in order to ensure high robustness [37], since they intercept large beam losses, while the choice of W alloy for the absorbers and the TCTs was made in order to ensure that they will be able to stop as much as possible of the incoming energy. The positions of the collimators around the ring and a list of collimator types with a description of their functionality is given in Figure 2.12 and Table 2.4, respectively.

**Figure 2.11** Schematic illustration of the three-stage LHC collimation system.
Figure 2.12 Layout of the LHC, showing the collimator locations around the ring. Figure from [37].
2.8 Beam Cleaning

Table 2.4 List of movable LHC collimators for Run-2. CFC, carbon fibre composite; H, horizontal; S, skew; V, vertical. Table from [37].

<table>
<thead>
<tr>
<th>Functional type</th>
<th>Name</th>
<th>Plane</th>
<th>Number</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary IR3</td>
<td>TCP</td>
<td>H</td>
<td>2</td>
<td>CFC</td>
</tr>
<tr>
<td>Secondary IR3</td>
<td>TCSG</td>
<td>H</td>
<td>8</td>
<td>CFC</td>
</tr>
<tr>
<td>Absorbers IR3</td>
<td>TCLA</td>
<td>H,V</td>
<td>8</td>
<td>W alloy</td>
</tr>
<tr>
<td>Primary IR7</td>
<td>TCP</td>
<td>H,V,S</td>
<td>6</td>
<td>CFC</td>
</tr>
<tr>
<td>Secondary IR7</td>
<td>TCSG</td>
<td>H,V,S</td>
<td>22</td>
<td>CFC</td>
</tr>
<tr>
<td>Absorbers IR7</td>
<td>TCLA</td>
<td>H,V</td>
<td>10</td>
<td>W alloy</td>
</tr>
<tr>
<td>Tertiary IR1/2/5/8</td>
<td>TCTP</td>
<td>H,V</td>
<td>16</td>
<td>W</td>
</tr>
<tr>
<td>Physics debris absorber</td>
<td>TCL</td>
<td>H</td>
<td>12</td>
<td>Cu/W alloy</td>
</tr>
<tr>
<td>Dump protection</td>
<td>TCSP</td>
<td>H</td>
<td>2</td>
<td>CFC</td>
</tr>
<tr>
<td></td>
<td>TCDQ</td>
<td>H</td>
<td>2</td>
<td>C</td>
</tr>
<tr>
<td>Injection protection (lines)</td>
<td>TCDI</td>
<td>H,V</td>
<td>13</td>
<td>CFC</td>
</tr>
<tr>
<td>Injection protection (ring)</td>
<td>TDI</td>
<td>V</td>
<td>2</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>TCLI</td>
<td>V</td>
<td>4</td>
<td>CFC</td>
</tr>
<tr>
<td></td>
<td>TCDD</td>
<td>V</td>
<td>1</td>
<td>CFC</td>
</tr>
</tbody>
</table>

2.8.1 Collimation performance

The cleaning performance of a collimation system is defined as the fraction of halo particles intercepted by the system over the total lost from the beam. In a perfect machine the collimation system should provide 100% efficiency and no losses would end up in sensitive equipment. Since this is impossible in real systems, the cleaning inefficiency, $\eta_c$, has been introduced, defined as the relative fraction of the beam losses compared with what is intercepted and safely disposed of by the collimators.
Chapter 3

ATLAS Detector

The ATLAS experiment[16] is one of the four LHC experiments and, besides the CMS experiment, the other of the two general-purpose detectors optimised to study proton-proton collisions at the highest available energies. The detector, schematically presented in Figure 3.1, is 44 m long and 25 m high, has a cylindrical shape and weighs about 7000 tonnes.

ATLAS is composed of a number of different sub-detectors. The inner detector (ID), sub-divided into a silicon pixel (PIX), a silicon strip (SCT) and a transition radiation tracker (TRT), measures the trajectories of charged particles. It is embedded inside a solenoid, which produces a 2 T magnetic field along the $z$-axis, such that the tracks of charged particles are curved allowing their momentum to be determined. The solenoid is surrounded by calorimeters, that measure the energies of charged and neutral particles, and a muon spectrometer, that tracks the trajectories of muons travelling through a toroidal magnetic configuration.

In this chapter the technologies and performance of the detector are briefly summarised. A full description of the detector can be found in Reference [16].

3.1 Axes definitions and conventions

In the right-handed ATLAS coordinate system, with its origin at the nominal IP, the azimuthal angle $\phi$ is measured with respect to the $x$-axis, which points towards the centre of the LHC ring, covering the range $\phi \in [-\pi, \pi]$. Thus, the positive $x$-axis has an azimuthal angle $\phi = 0$ whereas the positive $y$-axis has an azimuthal angle $\phi = \pi/2$. Side A of ATLAS is defined as the side of the incoming, clockwise, LHC beam-1 while the side of the incoming beam-2 is labelled C, as illustrated in Figure 2.7. The $z$-axis in the ATLAS coordinate system points from C to A, i.e. along the beam-2 direction. The polar angle $\theta$ is measured from the positive $z$-axis and covers the range $\theta \in [0, \pi]$. 
For describing the angle of a particle relative to the beam axis the pseudorapidity $\eta$ is often used instead of the polar angle, since the difference in the $\eta$ between two massless particles is Lorenz invariant under a boost along the $z$ axis. The pseudorapidity is defined as:

$$\eta \equiv -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \quad (3.1)$$

When the polar angle approaches zero, the pseudorapidity tends to infinity, and particles with these high pseudorapidity values usually do not deposit energy in active areas of the detector, since they travel close to the beam axis and therefore they escape through the TAS aperture.

### 3.2 The ATLAS Magnet System

A magnetic field is required in order to bend a charged particle such that their momentum can be determined from the reconstructed track’s curvature, as:

$$P = 3QBR \quad (3.2)$$

where $P$ is the momentum expressed in MeV/c, $B$ is the magnetic field expressed in T, $Q$ is the charge of the particle expressed in multiples of the electron charge and $R$ is the radius expressed in cm.

The magnetic field of ATLAS [38] is produced by four large superconducting magnets:
3.2 The ATLAS Magnet System

- one central Solenoid
- one Barrel Toroid
- two End-Cap Toroids

The schematic location of these are shown in Figure 3.2.

![ATLAS Magnet System Diagram](image)

Figure 3.2 A schematic layout of the ATLAS magnet system. Figure from Reference [39].

The coil of the central solenoid has a length of 5.8 m and inner and outer diameters of 2.46 m and 2.56 m, respectively. It is located inside the calorimetry systems, integrated into the cryostat of the barrel liquid argon calorimeter (LAr), and surrounds the ID. Since particles produced by proton-proton collisions passing through matter, it is desirable to minimise the energy loss of particles in front of calorimeters by keeping the amount of material to a minimum; thus Al-stabilised NbTi for the coil and the cryostat has been used\(^1\).

The three toroids are located outside the calorimeters and produce the magnetic field for the muon spectrometer. The Barrel Toroid, which covers the central region, consists of eight superconducting coils and produces a magnetic field of 0.5 T. It weights approximately 830 tonnes, measures 25.3 m in length and has inner and the outer diameter of 9.4 m and 20.1 m, respectively. The end-cap toroid consists of eight flat squared coils and eight keystone wedges, producing a magnetic field of 1.5 T. The overall size of the end-cap toroid is 5 m in length with an outer radius of 5.35 m.

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\(^1\)The use of these light materials results in 2.5 radiation lengths of material, before the calorimeters in the central region including the beam-pipe, inner detector tracker and solenoids.
### 3.3 The Inner Detector

The ATLAS Inner Detector (ID) \([40, 41]\) is surrounding the beam-pipe, so it is the first part of ATLAS that sees the products from the proton-proton collisions. It measures the position, the momentum and the sign of electrically-charged particles. The ID is divided in three different sub-detectors:

- the pixel detector
- the silicon microstrip detector (SCT)
- the transition radiation tracker (TRT)

Figure 3.3 schematically presents the \(z\) length and the radii of the various layers of the inner detector. A detailed description of the three sub-detectors is given in the following sections.

#### Figure 3.3 \(z\) length and the radii of the various layers of the inner detector. Figure from Reference [16].

#### 3.3.1 The Pixel Detector

The pixel detector \([16, 40]\) consists of three barrel layers at average radii of 50.5 mm, 88.5 mm and 122.5 mm, and three end-cap disks on each side between 495 and 650 mm in \(z\), which host in total 1744 identical pixel modules. A pixel module has the dimension of \(24.4 \times 63.4 \text{ mm}^2\), is approximately 250 \(\mu\text{m}\) thick and is read out by 16 identical front-end electronics chips, each with 2880 electronics
channels. This leads to $\sim 46000$ pixels per module and a total number of 80 million read-out channels. Most pixels have a size of $50 \times 400 \mu m^2$ and yield, aided by charge sharing among neighbouring pixels, a resolution of $10 \mu m$ in the lateral $r - \phi$ plane and $115 \mu m$ in the longitudinal $z$ plane. The detector covers up to $|\eta|=2.5$ and the layout of the layers is designed in such a way that each track provides at least three measurement points.

### 3.3.1 The Insertable B-Layer

For LHC Run-2, a new detector was installed between the beam-pipe and the Pixel detector of ATLAS. This Insertable B-Layer (IBL) [42] lies between $r = 31$ mm and $r = 40$ mm. The primary purpose of this new detector is to maintain the performance of the Pixel Detector with increasing luminosity, since the tracking efficiency of the Pixel’s innermost layer would degrade. In addition, it improves the tracking efficiency with respect to the original layout of the Pixel detector by increasing the accuracy of the impact parameter determination for each track. Thus, vertexing and b-tagging performance are improved. The IBL is composed of a barrel layer of 14 tilted staves with 32 modules each. Every module has an array of $80 \times 336$ pixels with a pixel size of $250 \times 50 \mu m^2$. The detector covers up to $|\eta|=3.0$.

### 3.3.2 The Semiconductor Tracker Detector (SCT)

The SCT [16, 40] is located outside the Pixel detector. The difference with the Pixel detector is that instead of pixels the SCT uses silicon strips. It is divided into four cylindrical barrel layers with their axes parallel to the beam direction that provide the tracking in the central region and into nine end-cap disks on each side which extend the tracking up to $|\eta|=2.5$. The four barrel layers consist of a total of 2012 modules of silicon-strips, with a pitch of $80 \mu m$, arranged with a small stereo angle of 40 mrad. Due to this angle, the modules have a resolution of $960 \mu m$ in $z$ and $17 \mu m$ in $r$. The end-cap modules, 1976 in total, are similarly structured in layers in $z$, with the strips placed in each layer with a small stereo angle of 20 mrad to provide a 2D position measurement for each layer. The layout of the detector is designed in such a way that each track has to traverse at least four layers anywhere in the acceptance region [43].

### 3.3.3 The Transition Radiation Tracker Detector (TRT)

The TRT [44] [45] is a drift tube detector that surrounds the SCT. It makes use of the electromagnetic radiation (transition radiation) for complementary electron identification emitted when a charged particle passes from one material to another with different optical properties. The detector has three major modular components: one barrel and two end-caps. The barrel consists of three layers of 32 modules each and has a total number of about 5000 straw tubes (gaseous detector), covering a
pseudorapidity range of $|\eta|<1$. Each straw tube has a diameter of 4 mm, a total length of 144 cm and is aligned parallel to the beam axis. Gold-plated tungsten anode wires of 0.03 mm diameter are located at the center of the straws which are filled with a Xe-CO$_2$-O$_2$ gas mixture. In the end-caps there are about 320000 straws arranged in 18 units per side called wheels, covering a pseudorapidity range of $1<|\eta|<2$. The charged particle ionises the gas mixture resulting in an electron shower towards the central wire of the straw (anode). The time taken by this process is used to measure the distance between the particle trajectory and the anode. The detector provides approximately 30 $r$-$\phi$ measurements per track with an accuracy of 130 $\mu$m due to high dead time.

### 3.4 Calorimeters

The ATLAS calorimeter system [16, 46] schematically presented in Figure 3.4, is located outside of the solenoids and consists of an electromagnetic and a hadronic calorimeter system. These cover pseudorapidities up to $|\eta|=4.9$. Two different technologies are used in the different calorimeters; liquid-argon scintillator (LAr) and plastic scintillator tiles (Tile) with various absorber materials. The granularity of each of the sub-detectors is given in Table 3.1

![Figure 3.4](image.png)

**Figure 3.4** The calorimeter system of ATLAS, where the position of the electromagnetic and hadronic components is indicated. Figure from Reference [16].

The electromagnetic calorimeter system (ECAL) consists of a barrel (EMB) and two end-cap calorimeters (EMEC), covering a pseudorapidity range of $|\eta|<1.475$ and $1.375<|\eta|<3.2$ respectively. In the barrel electrodes and lead plates are arranged in an accordion geometry, as shown in
Table 3.1  Granularity of the calorimeter sub-detectors. Table adapted from [16]. For the LAr hadronic end-caps the granularity grows with increasing $\eta$. The FCal consists of cells in the $x$–$y$ plane, thus the varying cell sizes in the $\eta$–$\phi$ projection.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Granularity $\Delta \eta \times \Delta \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM calorimeter</td>
<td></td>
</tr>
<tr>
<td>Barrel</td>
<td>0.025/8 – 0.075 $\times$ 0.025</td>
</tr>
<tr>
<td>Endcap</td>
<td>0.025/8 – 0.075 $\times$ 0.025</td>
</tr>
<tr>
<td>LAr hadronic end-cap</td>
<td>0.1 – 0.2 $\times$ 0.1 – 0.2</td>
</tr>
<tr>
<td>FCal</td>
<td>3.0 – 5.4 $\times$ 2.6 – 4.7</td>
</tr>
<tr>
<td>Scintillator tile</td>
<td></td>
</tr>
<tr>
<td>Barrel</td>
<td>0.1 – 0.2 $\times$ 0.1</td>
</tr>
<tr>
<td>End-cap</td>
<td>0.1 – 0.2 $\times$ 0.1</td>
</tr>
</tbody>
</table>

Figure 3.5. The ECAL provides uniform response across $\eta$ and $\phi$, independent of the shower depth. Liquid-argon is used as the active detector medium and lead as the absorber. Both the barrel and the end-caps are segmented longitudinally, along the shower axis, in three layers providing accurate energy and direction measurements for electrons and photons. The fine $|\eta|$ granularity in the 1st layer of the barrel additionally allows for photon showers to be pointed back to the original vertex, improving their transverse momentum resolution. The pseudorapidity coverage of the EM system is extended up to $|\eta| < 4.9$ by the first layer of the forward calorimeter (FCAL), which is designed for electromagnetic measurements and uses liquid-argon as the active material and copper as absorber.

The hadronic calorimeter system consists of the tile calorimeter, the hadronic end-cap calorimeter (HEC) and the 2nd and 3rd layers of the forward calorimeter (FCAL). The tile calorimeter is segmented into one central barrel (Tile barrel) and two extended barrels (Tile extended barrels), both using steel as the absorber medium, covering a pseudorapidity range of $0 < |\eta| < 1.7$. The pseudorapidity coverage of the hadronic calorimeter system is extended up to $|\eta| < 3.2$ by the HEC, which is a copper/liquid-argon detector, and up to $|\eta| < 4.9$ by the FCAL, which use tungsten as absorber. This results in a denser calorimeter with smaller lateral shower size, allowing the separation of close-by jets.

### 3.5 The Muon Spectrometer

The muon spectrometer [16, 47], illustrated in Figure 3.6, is the outermost component of the ATLAS detector, designed to provide a trigger at $|\eta| < 2.4$ and a momentum resolution of 10% for 1 TeV muons exiting the calorimeters at $|\eta| < 2.7$. It covers the space between approximately 4.5 m and 11 m in radius and 0 m and 23 m longitudinally on both sides of the IP.
Figure 3.5 Schematic diagram of the accordion and cell structure of the EM calorimeter. Illustrated are the different cell sizes as well as the trigger tower structure where cells within the tower are summed. Figure from Reference [16].

The magnetic deflection of the muon tracks by the magnetic field of ATLAS is the principle of the operation of this detector; at the region of $|\eta| < 1.4$ the magnetic bending is achieved by the large barrel toroid and in the region of $1.6 < |\eta| < 2.7$ the muon tracks are bent by the two end-cap magnets. At the transition region, $1.4 < |\eta| < 1.6$, the combination of both fields provide the magnetic deflection. The chamber layers, measure the bending in the toroidal field to provide a stand-alone momentum determination and ultimately the track is matched to the tracks of the ID to further improve the resolution.

The spectrometer consists of 4000 individual trigger and high-precision tracking chambers, integrated in four different technologies. Monitored Drift Tube chambers (MDTs) that provide the precision functionality and Resistive Plate Chambers (RPC) that contribute to the triggering are located between and around the eight coils of the superconducting barrel toroid magnet. They are arranged in three concentric cylindrical layers around the beam axis at radii of 5 m (inner), 7.5 m (middle), and 10 m (outer). Cathode Strip Chambers (CSC), Thin Gap Chambers (TGC) and MDTs provide the precision measurements and triggering in the end-cap region. In the forward regions, the muon chambers form wheels that are perpendicularly to the beam axis at distances of $|z| = 7.4$ m, 12.8 m, 14 m and 21.5 m from the IP. A cross section of the muon system is schematically presented in Figure 3.6.
3.5 The Muon Spectrometer

The MDTs provide momentum measurements covering the pseudorapidity range $|\eta| < 2.7$. They consist of several layers of drift tubes, filled with a gas mixture of argon and carbon monoxide. When a muon passes through the gas, it ionizes the atoms and released electrons that drift in the electrical field towards the central wire. This results in an electrical current on the wire which is used to measure the arrival time of these electrons, from which the initial position of the ionization is deduced.

The spectrometer can measure the momenta of the muons from as low as $\approx 3$ GeV at the IP up to the highest energies, where the 3 GeV lower limit come mainly from the energy loss of the muon in the calorimeters. In the forward regions, where particle rates are high, the tracking is provided by cathode strip chambers (CSCs). CSCs are multi-wire proportional chambers with segmented cathode readout and have a finer granularity and better time resolution compared to the MDTs. The CSCs provide coordinate measurements covering a pseudorapidity range of $2 < |\eta| < 2.7$ and in addition they have good enough time resolution to identify the bunch crossing which the muon originated from.

The RPCs in the barrel region and the TGCs in the end-caps provide a fast muon trigger that delivers tracking information in the bending, $\eta$, and in the non-bending, $\phi$, plane and time information which is sufficient for the bunch crossing identification. The RPCs and the TGCs cover a pseudorapidity range $|\eta| < 1.05$ and $1.05 < |\eta| < 2.4$, respectively.

![Figure 3.6 Schematic cross-section of the the ATLAS muon detectors. Figure from Reference [39].](image)
3.6 Trigger System

The trigger system in ATLAS [16, 48] consists of three different levels, referred to as Level-1 (L1), Level-2 (L2) and Event Filter (EF). A schematic layout of this trigger system is shown in Figure 3.7, where the above mentioned three level structure, including all the increasing levels of information used in the reconstruction, is presented.

In the ATLAS L1 trigger, the BCIDs are arranged into Bunch Groups (BGs) according to their different characteristics, of which those relevant for this work are:

- **Paired or colliding**: bunch pairs collided in both ATLAS and CMS
- **Unpaired**: bunches that do not collide at the IPs of ATLAS and CMS
- **Unpaired isolated**: bunches of one beam when there is no other bunch in the other beam within t=150 ns
- **Unpaired non-isolated**: bunches in only one LHC beam with a nearby bunch, within three BCIDs in the other beam
- **Empty**: a BCID without a proton bunch.
The L1 is a low level, hardware based, trigger whereas the other two are software based. The L2 and EF are collectively known as the High-Level Trigger (HLT). Until Run-2, the two software based triggers were merged in one. During the selection process, at each trigger level, more criteria are applied to reduce the output rate.

The L1 trigger fires on high transverse-momentum muons, electrons, photons, jets and \( \tau \)-leptons decaying into hadrons, as well as large missing and total transverse energy [49]. It uses only a limited amount of information from a subset of the detector in order to decide if an event should be accepted or not. The information collected by the muon spectrometers is used to trigger on high transverse-momentum muons, while all the calorimeter sub-systems using a reduced granularity are used for the identification process of high transverse momentum electrons, photons, jets and large amounts of missing energy. These decisions are made within 2.5\( \mu \)s and the event rate is reduced from 20 MHz to about 75 kHz in Run-1 and from 40 MHz to \( \sim 40 \) kHz in Run-2.

For each event with interesting features, the L1 trigger defines one or more Regions-Of-Interest (RoI), providing the geometrical coordinates in \( \eta \) and \( \phi \) of these regions. In addition to the geometrical coordinates, RoIs provide all the available detector information for the type of the recorded signatures as well as the criteria passed. This information constitutes the input to the L2 trigger which uses full detector granularity and precision for it’s decisions and has a latency of \( \sim 40 \) ms [49]. The L2 is focused only on the RoIs identified by the L1 and the total event rate is reduced to \( \sim 2 \) kHz.

The final trigger level is the EF, which reduces the output rate to \( \sim 200 \) Hz and has a latency of \( \sim 4 \) s. Off-line reconstruction algorithms are used by the trigger only in the RoIs that have been accepted by the L2 trigger. In order to refine the selection criteria, these algorithms use the full precision and granularity of the calorimeter and muon chamber data, as well as data from the inner detector. Thus, the particle identification is improved by the ID reconstruction and the threshold cuts are enhanced by the better information on the energy deposition. Events accepted by the EF trigger are written to storage.

For some objects, since the rate of their production is too high to be recorded by the triggers, only a fraction of the selected events are recorded. This is known as pre-scaling trigger and the pre-scale is defined as the inverse of the fraction of the events to be recorded [49].

### 3.7 Reconstruction of physics objects

The ATLAS detector is designed for a wide physics program and is able to reconstruct electrons, muons, photons, taus, hadronic jets and missing transverse energy (\( E_T^{\text{miss}} \)). The latter is the negative sum of transverse momenta of all observed particles which should represent the inferred transverse momenta of any non-interacting particles. This thesis uses jets for the analyses, thus a description for the reconstruction of these objects, only, is given below.
3.7.1 Jet Reconstruction

Jets are energetic sprays of particles produced in proton-proton collisions via the fragmentation of quarks and gluons and the subsequent hadronisation of the shower. These particles hit the calorimeters where they develop showers and deposit their energy in the calorimeter cells, as schematically presented in Figure 3.8. Since the calorimeters have a high granularity (see Table 3.1), the energy is distributed across many cells in both the lateral and longitudinal directions with respect to the jet axis. A sophisticated algorithm for forming groups of cells (clusters) from each physics object is implemented in the reconstruction software. The inputs to the jet reconstruction [50, 51] can be either topological calorimeter clusters (topo-clusters), which are groups of calorimeter cells or grid elements built directly from calorimeter cells forming calorimeter towers. These towers are formed from the sum of energy of cells in all longitudinal layers to the jet axis within a given grid element.

For the topo-cluster algorithm, if a calorimeter cell has a signal-to-noise ratio $S/N > 4$, it forms a seed cell to the topo-cluster algorithm. The noise includes both the electronic noise for the cell and the expected fluctuations in the cell energy due to pile-up. This is shown in Figures 3.9a, 3.9b, where the energy-equivalent cell noise on the electromagnetic (EM) scale in the ATLAS calorimeters as function of $|\eta|$ for the 2010 and 2012 pile-up conditions is presented.

The neighbours of the initial seed cells with a signal-to-noise ratio $S/N \geq 2$ are added to the cluster. This is done iteratively until no further cells with $S/N \geq 2$ are touching the cluster. Finally an additional layer of neighbouring cells are added to complete the cluster formation process. For separating the showers from different close-by particles, a cluster splitting is performed by looking for multiple energy maxima within a cluster. An energy maximum is defined by a cell having more than 500 MeV of energy with at least four neighbouring cells and no neighbours with larger energies. The cluster is then split between the maxima in all three spatial dimensions.
3.7 Reconstruction of physics objects

Figure 3.9 Energy-equivalent cell noise in the ATLAS calorimeters on the electromagnetic (EM) scale as a function of the direction $|\eta|$ in the detector for the 2010 configuration with $\mu = 0$ (refers to the configuration of the calorimeter and was set to only the electronic noise) assuming no contributions from pile-up (a) and the 2012 configuration with $\mu = 30$. The various colours indicate the noise in the pre-sampler (PS) and the three layers of the LAr EM calorimeter, the three layers of the Tile calorimeter, the four layers of the (HEC) calorimeter, and the three modules of the FCal. Figure from [50].

The energy of the topo-cluster is equal to the energy sum of all the included calorimeter cells. The direction of the reconstructed topo-clusters with respect to the centre of the detector is calculated from the energy weighted averages of the pseudorapidities and azimuthal angles of the constituent cells [50]. These topo-clusters are combined into jets using the anti-$k_t$ algorithm [53]. The distance parameter for the algorithm is usually $R=0.4$ and a required jet $p_T$ threshold of $p_T^{jet}=7$ GeV is set in the reconstruction process. This algorithm is designed to form circular jets in the $\eta - \phi$ space with radius approximately equal to the chosen value of the parameter $R$. This algorithm is a sequential combination algorithm which combines topo-clusters nearby in $\eta - \phi$ space with a distance parameter which prevents combinations of pairs at large distances. The topo-cluster centroid is defined by the energy weighted position of the constituent cells. The direction is then formed from the vector between this centroid and the center of the detector. The jet is then built from these massless vectors. During the calibration sequence there are small corrections to the jet direction to account for lower response regions of the calorimeter and the primary vertex $z$ position such that the jet points back to the primary vertex rather than the center of the detector. If there is no primary vertex the jet points back to $(z,y,x) = (0,0,0)$.

The energy deposits in the calorimeter cells can be either of electromagnetic or hadronic nature, giving different responses in the calorimeter. The calorimeters are calibrated to electromagnetic objects referred to as the EM-scale. The response to hadronic showers is lower than that to electromagnetic ones, primarily due to energy lost into nuclear effects, like binding energy and neutron emission. The jet energy scale corrections [54, 55], which are multiplicative factors dependent on $E$ and $\eta$ of the
jet, restore the calibration of the jet to a jet built using the same algorithm from true particles. The calibration is then refined using the energy fraction in different layers of the calorimeter and tracking information. Finally the jets in data are corrected based on a series of in situ measurements; The forward jet energy scale is corrected based on the balance between forward and central jets; Central jets are calibrated using the balance between well known objects and the jet momenta in the transverse plane. Such reference objects include photons, and Z bosons decaying to leptons. The highest energy jets are calibrated in multijet events by measuring their balance against systems consisting of, better known, lower momenta jets.

3.8 Experimental area and Shielding

In order to minimise the high radiation levels in the experimental area a multilayer shielding has been installed in ATLAS. The purpose of such shielding is to reduce, to a manageable level, the background seen by the detectors as well as to protect the persons that are working in the nearby service cavern.

Particles hitting the beam-pipe, the forwards calorimeter and the TAS absorber generate hadronic showers that can cause problems such as radiation damage in the electronics of the various detectors, high background signals and activation of certain detector elements. Especially the ATLAS muon system, based on an air-core toroid, is vulnerable to photon and charged particle background in the cavern. In order to absorb the energetic particles in the hadronic and electromagnetic cascades the use of dense materials is required for the shielding’s innermost layer (close to the beam-pipe). This first layer should have a sufficient depth such that most of the deposited energy will be contained in it. However, this first layer does not provide sufficient shielding against neutrons and associated photons. Thus, a second layer made of polyethylene is used to reduce the energy of neutrons that escaped from the first layer. The polyethylene is doped with boron in order to capture the low energy neutrons. A third layer, which consists of Lead or Steel is used in order to absorb the photons created in the neutron capture process. Figure 3.10 illustrates the location of different parts of the shielding in the ATLAS experimental area.

The main purpose of the JF shielding is to protect the muon chambers and the muon Small Wheel from showers induced by particles hitting the beam-pipe, the TAS and the calorimeters. It consists of two parts, both of which are made of cast ductile iron surrounded by a 5 cm layer of polyethylene doped with boron. A 3 cm layer of steel plates surrounds the polyethylene layer. The design of the forward shielding follows the philosophy described in the previous paragraph: the ductile iron suppress the hadronic cascades and has a carbon content sufficient to fill up the energy ranges where pure Fe is transparent for neutrons, while the polyethylene layer slows down the neutrons due to the presence of hydrogen, absorbs the thermal neutrons due to the presence of boron and provides

\(^3\)True particles are defined as those with life-time longer that 30 ps excluding muons and neutrinos
additional safety against any remaining transparency. The steel plates stop the photons that are generated by the absorption of the neutrons.

The disk shielding (JD) supports the muon chambers in the first forward muon station. It shields these chambers from background radiation created by interactions in the beam-pipe and forward calorimeter and serves as return yoke for the magnetic field of the solenoid magnet.

The nose shielding (TX1S) has two roles: it supports the TAS and protects ATLAS from the showers created in the TAS. Its main part is a cylindrical mono-bloc made of cast iron that weighs 117 tones and has an outer diameter of 295 cm. A tube made of concrete with an inner diameter of 257 cm supports the cylindrical mono-bloc. In addition, six heavy washers made of iron surround the mono-bloc and the tube.

The moderator shielding (JM) is made of polyethylene doped with boron carbide (B₄C). It consists of two main parts on each side of ATLAS: a disk of 2 m diameter that weights 90 kg and is located in front of the end-cap liquid argon calorimeters and a tube with a plug of 52 kg in total that are placed in front of the forward calorimeters. In addition, a 2 mm layer of aluminium covers both the disk and the tube/plug.

**Figure 3.10** The ATLAS forward radiation shielding, as described in the φ symmetric Fluka geometry. The dimensions are measured in cm: horizontally (z) from the IP and vertically (r) from the centre of the beam-pipe.
The toroid shielding (JT) consists of two main parts: the JTT and the JTV. The JTT surrounds the beam-pipe while the JTV is located inside the endcap toroid cryostat. The purpose of this shielding is to moderate the neutron radiation and stop the low-energy neutrons by absorption in boron. All the photons that will be created due to the boron absorption will be stopped by the end-cap cryostat.
Chapter 4

The FLUKA Monte Carlo simulation framework

The studies for understanding the nature and the origin of the beam backgrounds and their effect on physics analyses, as well as the radiation studies for any detector upgrades, require complex Monte Carlo (MC) codes. The MC code that has been used for this thesis is FLUKA.

FLUKA [60–62] is a fully integrated, well benchmarked, framework to simulate the interactions and transport of particles through matter. The physics models that are implemented in the package give the ability to simulate a series of applications such as target design, proton and electron accelerator shielding, activation and dosimetry, calorimetry, cosmic ray studies as well as radiotherapy.

A detailed description of the particle interactions with matter and of the FLUKA capabilities, physics models and different settings can be found at References [60] and [62], respectively. A very short summary of the physics and the models that are implemented in FLUKA is given in Sections 4.1 and 4.2, where the basics of the hadronic and electromagnetic interactions are presented as well. Section 4.3 describes the neutron transport in FLUKA with emphasis on neutrons below 20 MeV and Section 4.4 presents in detail the simulation settings and tunes that have been used for the simulations of this thesis. A description of the Combinatorial Geometry package of FLUKA is given in Section 4.5 and the description of the ATLAS magnetic field as implemented in FLUKA is presented in Section 4.6 In Section 4.7, results of studies that have been performed in order to quantify the effect of the presence of the magnetic field and the number of regions on the tracking speed are presented.

4.1 Hadronic interactions

The main types of hadronic interactions are the elastic and the inelastic ones. During the elastic interactions, part of the projectile’s energy is transferred to the target, while the target and the projectile
are deflected in opposite directions in the Centre–of–Mass system with no change in their energy. The internal structure of the projectile does not change and no new particles are generated. On the contrary, during inelastic collisions, part of the kinetic energy is changed to some other form of energy, new particles are produced and/or the internal structure of the projectile is changed (e.g. the nucleus is excited). A specific non-elastic reaction has usually an energy threshold below which it cannot occur (the exception being neutron capture).

The complex process of an inelastic collision between a high energy hadron and a target-nucleus can be described by three stages in regards of time, energy and type of particles involved. At a first stage, with the amount of available center of mass energy being above several GeV, the interactions occur at parton (quark) level. Fragmentation of the stressed gluon strings leads to hadronization to final states.

During the second stage, at a longer time scale and at lower energies (from few MeV to a few GeV), the interactions occur at the nucleon level. The target’s nucleons hit by the projectile are either ejected out of the target or knock in their turn neighbouring nucleons causing a cascade of collisions within the nucleus (intranuclear cascade) ending up in the residual target at an excited state far from the stability valley. Since these pre-equilibrium processes occur at medium energy ranges, not high enough to be easily parametrized by high energy models but neither low enough to belong to the nuclear field, it was not until recently that algorithms have started to produce acceptable results.

The third stage is characterized by the evaporation process during which particles, mostly neutrons, evaporate from the residual target in it’s struggle to reorder and reach an equilibrium state and the valley of stability. Competing mechanisms to the evaporation are fission or multi-fragmentation, which, however, require energies of the order of at least some MeV per nucleon or quite heavy nuclei. The radioactive decay of the residual nucleus is not included in any simulation code since it occurs within time-scales that may reach even millions of years.

In FLUKA, the hadron nucleus (h-A) and nucleus-nucleus (A-A) nuclear reactions are treated by different event generators depending on the energy range of the reaction:

**h-A reactions** The PEANUT (Pre-Equilibrium Approach to NUclear Thermalization) package is used for energies up to 3-5 GeV. It includes detailed Generalized IntraNuclear Cascade (GINC) models. At high energies the Gribov-Glauber (GG) multiple collision mechanism applies, which is included in the PEANUT package, providing reliable results up to several tens of TeV. The number of hadron-nucleon interactions is sampled from GG theory and each interaction is simulated based on the dual parton model.

**A-A reactions** The Boltzmann Master Equation model (BME) is used for energies below 125 MeV/A and the Relativistic Quantum Molecular Dynamics Model (RQMD) is employed for energies between 125 MeV/A and 5 GeV/A. Above 5 GeV/A, the Monte Carlo event generator DPMJET-III, which is based of the Dual Parton Model (DMP) is called, allowing the simulation of hadron-
hadron, hadron-nucleus, nucleus-nucleus, photon-hadron, photon-photon and photon-nucleus interactions from a few GeV up to the highest cosmic ray energies [63, 64]. All the implemented modules are followed by the equilibrium processes, i.e. evaporation, fission, Fermi break-up, gamma de-excitation, and photo-nuclear interactions.

\section*{4.2 Particle transport and interactions of particles with matter}

Particle transport is fundamentally a ray-tracing problem which, in theory, can be solved analytically through the transport equation. However, the analytical solution can be applied only for restricted geometries and interaction models since the large number of interactions in high energy particle showers excludes any analytical method. Thus, the Monte Carlo method is employed for solving all particle transport problems, where the solution to the transport equation is obtained by sampling interactions from the appropriate probability distributions while stepping along the trajectory of each particle [65].

In FLUKA, the transport of the electromagnetic cascade is performed by the EMF package which is adapted from EGS4 [66]. Pair production and bremsstrahlung are treated by sampling from the proper double differential energy-angular distributions, which improves the common practice of using average angles. In a similar way the three-dimensional shape of the electromagnetic cascades is reproduced in detail by a rigorous sampling of correlated energy and angles in decay, scattering and multiple Coulomb scattering. In addition, since photons and electrons may undergo photo-nuclear and electro-nuclear reactions, respectively, the electro-magnetic and hadronic showers are fully coupled.

\subsection*{4.2.1 Cross-section and mean free path}

The collision probability of an incident particle with an atom or nucleus is quantified by a cross-section which depends on the projectile energy \(E\), the atomic number of the atom \(Z\) and the mass number \(A\). For energetic hadrons and heavy nuclei a uniform density assumption can be used to approximate the inelastic cross section as:

\[
\sigma(A) = \pi r_o^2 A^{2/3}
\]  

(4.1)

where \(r_o \sim 1.1 \text{ fm}\).

For a particle that transverses a material, the mean free path, i.e. the average distance travelled between two successive collisions, is given by:

\[
\lambda = \frac{A}{\rho N_A \sigma}
\]  

(4.2)

where \(N_A\) is the Avogadro constant and \(\rho\) the material density.
The inverse of the mean free path is referred to as the macroscopic cross-section $\Sigma$ which is usually expressed in cm$^{-1}$.

### 4.2.2 Ionization energy loss

The mean energy loss of a charged particle due to small momentum transfers to atomic and free electrons is described by the Bethe-Bloch formula:

$$-\frac{dE}{dx} = 2\pi N_a e^2 m_e c^2 \rho \frac{Z}{A} \frac{Z}{A} \left( \ln \left( \frac{2m_e \gamma^2 v^2 W_{\text{max}}}{I^2} \right) - 2\beta^2 - \delta - 2 \frac{C}{Z} \right)$$

where:

- $N_a$ is the Avogadro’s number $6.022 \times 10^{23}$ mol$^{-1}$,
- $r_e$ is the electron radius $2.817 \times 10^{-13}$ cm,
- $m_e$ is the electron mass,
- $\rho$ is the density of the absorbing material,
- $Z$ is the atomic number of the absorbing material,
- $A$ is the atomic weight of the absorbing material,
- $z$ is the charge of incident particle in units of $e$,
- $\beta$ is the incident particle’s $v/c$,
- $\gamma$ equals with $1/\sqrt{1-\beta^2}$,
- $W_{\text{max}}$ is the maximum energy transfer in a single collision,
- $I$ is the mean excitation potential,
- $\delta$ is the density correction (correction to the far interactions of the particle’s electric field with the matter) and
- $C$ is the shell correction due to screening effects.

For small values of $\beta \gamma$, the energy loss decreases as $1/\beta^2$ and reaches a minimum value at $\beta \gamma \sim 3$. The relativistic particles with mean energy loss rates close to the minimum, are referred as Minimum Ionizing Particles. The ionization energy loss increases logarithmically towards higher energies. Below $\beta \gamma \sim 2$ it increases rapidly with decreasing energy.
4.2.3 Energy loss processes of photons, $e^+ e^−$ and the radiation length, $X_0$

Figure 4.1 shows the energy loss processes of photons and electrons as function of their energy.

![Figure 4.1](image)

Figure 4.1 Photon total cross sections as a function of energy in lead, showing the contributions of different processes (a) and, fractional energy loss per radiation length in lead as a function of electron or positron energy (b). Both Figures from [67]

Various processes contribute to the absorption and scattering of photons in matter, as shown in Figure 4.1a. At low photon energies, the photoelectric effect dominates, although Compton scattering, Rayleigh scattering, and photo-nuclear absorption also contribute. At intermediate energies, in a very narrow range only, the dominant process is the Compton scattering. At the energy of 1.022 MeV, which is the combined rest energy of an electron and a positron, the $e^− e^+$ pair production channel opens. Pair production is the main absorption process of photons at higher energies ($>\sim 5$ MeV) and the photon process in electromagnetic cascades.

Electrons and positrons, in addition to the ionization, experience radiative energy losses; while at low energies they primarily lose energy by ionization and other processes, such as $e^\pm$ annihilation, Möller and Bhabha scattering, at high energies Bremsstrahlung is the dominant process for energy loss, as shown in Figure 4.1b. The energy at which the ionisation loss rate equals the bremsstrahlung rate is defined as critical energy $E_{\text{crit}}$.

The mean distance over which an electron loses all but $1/e$ of its energy by bremsstrahlung is defined as the radiation length $X_0$ given, as an approximate fit accurate to few percent, by:

$$X_0 = \frac{A\,716.4\,\text{gcm}^{-2}}{Z(Z+1)\ln(287/\sqrt{Z})}$$

(4.4)

where $A$ is the atomic mass and $Z$ the atomic number of the material.
4.2.4 Radiative energy loss of muons

For muons, because of the higher mass, the $E_{\text{crit}}$ is significantly higher than for $e^{\pm}$ but the basic radiative processes are the same. Their relative importance depends on the muon energy, as seen in Figure 4.2. Muons can experience point-like interactions already below this $E_{\text{crit}}$, resulting in large amounts of energy being deposited in electromagnetic cascades, thus they play a significant role in the observed background rates in ATLAS.
peak that is observed can be due to different implementations of the theory between FLUKA and MARS15.

Figure 4.4 Probability of muons with various energies to create a local energy deposition cluster above the energy indicated on the horizontal axis. The results are normalised to the muon traversing 1 metre of iron.

In addition, the probability of muons of different energies to generate energy deposition clusters have been studied. Figure 4.4 shows the probabilities, as a function of threshold, for muons of various energies to create an energy deposition cluster as a function of cluster energy. Energy depositions up to the initial muon energy are possible, although the probabilities to deposit almost the full energy are around $10^{-5} \text{ m}^{-1}$. For a muon with an energy above 300 GeV the probability to deposit few tens of GeV is around 1% per metre of iron traversed.

### 4.3 Neutron transport

The transport of neutrons in FLUKA is divided into two different approaches depending on the neutron energy:

- Neutrons above 20 MeV are treated by FLUKA as any other particle and are handled by the implemented nuclear models.
- For neutrons below 20 MeV, a multi-group algorithm is used which makes use of dedicated neutron cross section data sets.
In the multi-group transport approach for neutrons below 20MeV, the cross sections are converted to energy groups like histograms. Each group $i$ contains the “averaged” $\sigma_i$, which is defined as:

$$\langle \sigma_i \rangle = \frac{\int_{E_{i,low}}^{E_{i,high}} \sigma(E) \Phi(E) dE}{\int_{E_{i,low}}^{E_{i,high}} \Phi(E) dE}$$

where $\sigma(E)$ is the actual cross section at energy $E$ and $\Phi$ the neutron spectrum to be used as a weighting function. Since $\Phi(E)$ is a priori unknown, experimental knowledge of average fluences is used to derive the group cross sections. The experimental cross sections themselves are subject to uncertainties of the spectrum unfolding, or are not valid for a particular material used in the simulation. If the cross sections are wrong, nothing helps, but the error due to material/spectrum differences can be reduced by a larger number of groups. A down-scattering matrix describes the group-to-group transfer probabilities for the simulations of the elastic and inelastic reactions and the polar scattering angle is usually sampled from discrete values. The latter are obtained from Legendre expansions of the differential cross sections.

Other neutron transport codes use point-wise transport, where the cross section is followed precisely. This approach can be CPU time and memory consuming in comparison to the group approach that is fast and gives good results for most applications. While point cross-sections avoid the problems of spectrum mismatch, the experimental determination of these cross sections remains subject to uncertainties in the unfolding of the spectrum used in the cross-section measurement.

The cross section library for low energy neutrons consists of 260 different energy groups, with approximately equal logarithmic width, 31 of which are in the thermal energy region. More than 250 different materials are contained in this library which is based on the recent evaluated nuclear data files ENDF, JENDL and JEFF. The selection of these materials was made taking into account their interest in physics, accelerator and dosimetry applications and they are available for two different temperatures: 87 K and 296 K.

Photon generation by low energy neutrons is done by FLUKA in the same multi-group scheme using 42 different gamma energy groups, covering an energy range between 1 keV and 50 MeV. A down-scattering matrix provides the probability, for a neutron in a given energy group, to generate a photon in any of the 42 gamma energy groups. In all cases, the generated photons are transported in the same way as all other photons in FLUKA.

### 4.4 Simulation settings

For the results that will be presented in the next chapters, the accuracy of FLUKA simulations was controlled by a series of different settings, allowing the best possible accuracy in tracking within a reasonable CPU time, as listed below:
• A detailed transport of electrons, positrons and photons, involving the simulation of electromagnetic cascades, including:
  – Rayleigh scattering and inelastic form factor corrections to Compton scattering and Compton profiles
  – Detailed photoelectric edge treatment and fluorescence photons
• 100 keV particle transport threshold except neutrons which are transported down to thermal energy
• Low-energy neutron transport between 20 MeV and thermal energies
• $\delta$-ray production with a lower production threshold of 100 keV
• Restricted ionisation fluctuations for hadrons, muons and electromagnetic particles below the $\delta$-ray threshold
• Pair production by heavy particles with explicit production of the $e^\pm$ pair
• Heavy particle bremsstrahlung with explicit photon production above 300 keV
• Muon photo-nuclear interactions with explicit generation of secondaries
• Transport of heavy fragments
• Tabulation ratio of 1.04 for hadron and muon $dp/dx$. In addition, a fraction of 0.05 kinetic energy to be lost in each step.

The simulations that have been performed for the purposes of this thesis, both for the beam background studies and the upgrades, the transport threshold for photons was set to 30 keV. However, a higher energy threshold was used in some regions (i.e. forward shielding) in order to reduce the CPU time. Moreover, the pair production and bremsstrahlung by high-energy muons, charged hadrons and light ions was enabled with a kinetic energy threshold of 300 keV for electrons and positrons and 100 keV for gammas. In addition, the muon pair production through the process $\gamma \rightarrow \mu^+\mu^-$ was activated.

4.5 Geometry description

FLUKA relies on a Combinatorial Geometry (CG) package from the neutron and $\gamma$-ray transport code MORSE [69]. This package has been enriched with additional bodies and new capabilities, allowing the user to build complex geometry layouts.
The FLUKA Monte Carlo simulation framework

Figure 4.5 Three bodies (left), zone (middle) and region (right) definition obtained by boolean operations If a body appears in a zone description preceded by a + operator then the zone that is described is wholly contained inside the body. On the contrary, if a body that appears in a zone description is preceded by a − operator, then the zone is wholly outside of the body.

In order to describe the geometry space, FLUKA uses bodies, zones and regions. The bodies are analytic geometric shapes that divide the space into two parts: the inside and the outside of the body. Based on the specified bodies, the zones are defined as combinations of bodies obtained by the Boolean operations union, intersection and subtraction between the bodies, whereas the regions are defined by unions of different zones. The regions are portions of space having homogeneous properties and material composition, typically representing the actual components of a given space. Figure 4.5 shows some examples of how zones and regions can be defined based on simple bodies.

In the original CG package, the bodies were finite portions of space completely delimited by surfaces of first or second degree, such as planes or quadrics. This CG has been extended by including infinite cylinders and infinite planes. These new bodies are less error-prone allowing the tracking of particles to be performed faster and in a more accurate way, since unnecessary boundary intersection calculations are avoided when the particle step is shorter than the distance to the boundary.

FLUKA provides the ability to describe repetitive geometry structures with the use of the lattice capability. Such use avoids the repetition of the same bodies, zones and regions in different positions and allows the implementation of any analytical symmetry like rotation, translation and reflection, as well as their combination between the prototype structure and its replica. When the lattice option is enabled, the tracking proceeds in two different systems: the “real” one and that of the basic symmetry unit. The positions and the directions of each particle are swapped from their real values to their symmetric ones, in order to perform the physical transport in the regions and materials that form the prototype geometrical structure, and are then swapped back again to the real world.

The implementation of the ATLAS geometry in FLUKA started initially in 1991, is constantly under development and available in four different versions:

- Run-1 geometry for the LHC start-up (frozen)
- Run-2 geometry with the Insertable B-Layer implemented (frozen)
- Run-3 Geometry (constantly developed)
4.6 Magnetic fields and the ATLAS Magnetic field in FLUKA

The ATLAS FLUKA provides the ability to use arbitrarily complex magnetic fields. During the propagation in a magnetic field, the true trajectory of a charged particle is approximated by linear steps, as illustrated in Figure 4.7 and a correction of the correct curved path length is applied for calculating the energy loss and the interaction probability. The end point of the step will always fall in the true path of the particle but not exactly on the region boundary. Due to this, the particle transport is performed by iterations until a given accuracy when the region boundary will be crossed. The user is able to tune the tracking accuracy by defining the maximum angle $\alpha$ subtended by a single step from the origin of the curved path and the maximum permissible error $\varepsilon$ in geometry intersections. In case either one or both of $\alpha$ and $\varepsilon$ will be too large, geometry regions can be missed during tracking, and if they will be too small, the CPU time will be significantly increased. FLUKA accounts for the precession of the multiple coulomb scattering final direction around the particle direction, the precession of a

---

Figure 4.6 Cross-section of the ATLAS geometry as implemented in FLUKA. Only one quadrant of the geometry is illustrated since the geometry is mirrored in longitudinal $-z$ and is symmetric in azimuth $\phi$.

- Phase-II geometry for the ATLAS future upgrades (constantly developed) with the Inner Tracker (ITk) and the High Granularity Timing Detector (HGTD) implemented

Due to the ATLAS symmetry, the geometry of the whole detector is described only in $+z$ in FLUKA, and a lattice routine has been implemented to reflect the geometry to $-z$. A cross section of the ATLAS FLUKA geometry is presented in Figure 4.6, where only one quadrant is illustrated since the geometry is mirrored in longitudinal $-z$ and is symmetric in azimuth $\phi$.

4.6 Magnetic fields and the ATLAS Magnetic field in FLUKA

Parts of the ATLAS cavern are described separately in $\pm z$ due to lack of symmetry.
The FLUKA Monte Carlo simulation framework

Figure 4.7 Approximation mechanism of the true trajectory (blue) of a charged particle in FLUKA using linear steps (red). $\alpha$ is the maximum angle and $\varepsilon$ the maximum permissible intersection error.

possible particle polarization around it’s direction of motion (mostly for muons), and the decrease of the particle momentum due to energy losses along a given step - hence the corresponding decrease of its curvature radius. The latter avoids for building up excessive tracking inaccuracies or using very small steps in tracking.

Figure 4.8 Comparison of the new (right) versus the old (left) magnetic field implemented in FLUKA

The implementation of the ATLAS magnetic field in FLUKA can be achieved by a user defined routine. This routine reads the $B_r$, $B_\phi$ and $B_z$ components of a 2D field map in a $(r \times z) = (10 \times 10)$ cm mesh between $\pm 24$ m in $z$ and $0 - 13.3$ m in $r$ and returns field components based on the current position and region of each particle. Figure 4.8 presents the comparison of the old magnetic field that was used and the new one which was implemented for the purposes of this thesis.
Due to the presence of the magnetic field in the ATLAS simulations, the maximum step size on a region-by-region basis for the transport of all charged particles had to be optimised. A minimum value of $100 \mu$m boundary crossing accuracy was set for all regions, ensuring that the location of the boundary will be found with an uncertainty of the set value. The maximum step-size was set to 10 cm and to 2 cm for some regions where the step-length had to be kept as low as possible without a severe CPU penalty.

### 4.7 Tracking speed

The large amount of regions in the ATLAS geometry as well as the presence of the magnetic field might have a significant effect on the CPU time that is required for the simulations. Thus, a series of simplified tests with four different geometries has been performed in order to determine the effect of the number of disconnected regions inside a bigger one on the magnetic field tracking speed.

![Geometries used in the tracking speed tests](Image)

Figure 4.9 schematically presents the four simplified geometry layouts that have been used for these tests. There is only one region, from $\pm 40 \text{ cm}$ in $x$ and $y$ and from $\pm 200 \text{ cm}$ in $z$ in GEOMETRY-1, while in GEOMETRY-2 one more region has been inserted inside the main region. In order to increase the amount of regions in the tests, 13 and 26 square regions of $20 \text{ cm}$ length each have been inserted in GEOMETRY-3 and GEOMETRY-4, respectively.

$10^8 \mu^+$ with an energy of 100 GeV have been sent through the four defined geometries. Different starting conditions for the beam and different maximum step-size values have been set for each test.
The beam position was set at $(x, y) = (0, 0)$ cm for Test-1 and Test-2 and at $(x, y) = (0, -25)$ cm for Test-3 and Test-4. The maximum step-size was set to 10 cm for Test-1 and Test-3 and to 1 cm for Test-2 and Test-4.

All the regions have been assigned with AIR as material with a density of $1 \times 10^{-7}$ g/cm$^{-3}$ and an energy threshold of 10 GeV for electrons, positrons and photons has been set. In all tests, the ATLAS magnetic field has been activated and the direction of the beam was positive.

Table 4.1 Average CPU time per primary event ratio between the different tracking speed tests and the base one (Test-1 - Geometry-1)

<table>
<thead>
<tr>
<th>Beam Position (X,Y) (cm)</th>
<th>Max Step-size (cm)</th>
<th>Geometry 1</th>
<th>Geometry 2</th>
<th>Geometry 3</th>
<th>Geometry 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test-1</td>
<td>(0.0,0.0)</td>
<td>10</td>
<td>1.02</td>
<td>1.11</td>
<td>1.19</td>
</tr>
<tr>
<td>Test-2</td>
<td>(0.0,0.0)</td>
<td>1</td>
<td>2.97</td>
<td>3</td>
<td>3.39</td>
</tr>
<tr>
<td>Test-3</td>
<td>(0.0,-25.0)</td>
<td>10</td>
<td>1</td>
<td>1.25</td>
<td>2.2</td>
</tr>
<tr>
<td>Test-4</td>
<td>(0.0,-25.0)</td>
<td>1</td>
<td>2.97</td>
<td>3.89</td>
<td>4.93</td>
</tr>
</tbody>
</table>

In total 16 different tests have been performed and the results are summarised in Table 4.1, where the average CPU time per primary event ratio between the different tracking speed tests and the base one is indicated. It can be seen that the number of possible regions in the geometry set-up plays a significant role in the FLUKA tracking speed. Especially in Test-2, the CPU time increases despite the number of boundaries actually crossed is the same in all geometries. Due to these results, and in order to keep the tracking speed at the lowest possible values in the ATLAS simulations, significant care has been taken in the design of new components by tuning the minimum number of possible regions that can be entered from the region where the particle is, i.e. the number of boundaries that can be crossed on the next step.
Chapter 5

Beam–induced backgrounds

The data produced by ATLAS contain not only the signals from the collisions but also an unwanted background from non-collision sources. Aside of detector and electronics noise, the latter are divided into two categories, according to the origin: beam–induced (BIB) coming from the machine and cosmic rays (CRB) [70, 12]. The rate of both BIB and CRB is low compared to the intense background generated from $p - p$ collisions, but understanding and minimising the effect of these components is important for an efficient data analysis, for detector performance and, especially, some rare physics searches, like those for long lived particles [71–73].

The BIB originate from three different beam loss processes, which are illustrated in Figure 5.1 and listed below.

- Inelastic beam–gas events in the LSS or the adjacent arc (1)
- Beam losses on the TCTs (2)
- Elastic beam–gas scattering around the ring (3)

The contribution to the experimental background from BIB in described in Sections 5.1 and 5.2. A short description of the CRB and the formation of the ghost charge is given in Sections 5.3 and 5.4, respectively. Section 5.5 presents the systems and the methods that are used by ATLAS for monitoring these backgrounds.

5.1 Inelastic beam–gas events

The dominant source of BIB in ATLAS is constituted by proton interactions with residual gas inside the beam-pipe, within ±500 m from the IP[8]. Hadronic and electromagnetic showers, but in particular high energy muons, produced by these interactions, can enter ATLAS and be detected by the BIB monitoring system.
Figure 5.1 Schematic illustration of the three different sources of BIB. The cleaning insertions are several kilometres away from ATLAS and the elastic beam–gas events are distributed around the entire accelerator ring. The BIB reaching ATLAS originates from halo and elastically scattered proton losses on the TCT or from close-by inelastic beam–gas collisions.

Particles generated from beam–gas interactions close to the beam-line can pass through the TAS aperture\(^1\) due to their small angle with respect to the beam-line and hit the Pixel detectors close to the interaction point. Thus large longitudinal energy deposition clusters can be generated in the detector that will increase it’s occupancy and affect the track reconstruction by introducing false clusters.

High energy muons are not affected by the shielding materials, so many of them reach and penetrate ATLAS and some will deposit large amounts of energy in the calorimeters via radiative energy losses. These depositions can be wrongly reconstructed as jets and enter the physics analyses which rely on measurements of the missing transverse energy \(E_T^{\text{miss}}\) and on jets which are not associated to tracks in the ID.

5.2 Tertiary halo losses on the TCTs and elastic beam–gas events

Beam halo, which is continuously repopulated by scattering of particles from the beam, is intercepted by the multi-step cleaning system of the LHC [74], as described in Section 2.8. Protons that escape the primary cleaning insertions in IR3 and IR7 are intercepted by the tertiary collimators (TCT), located at distances of \(z\approx 150\) m from each experimental IP. These losses on the TCTs, which depend on the leakage from the primary collimators, can create hadronic showers and high energy muons. These contributions can propagate all the way to the IP depositing energy in the calorimeters and in the Pixel detector, resulting in the same problems of increased occupancy and false track reconstruction and jet identification, as in the case of the inelastic beam–gas scattering described before.

\(^1\approx 94\%\) of the measured background rate by the BCMs are due to particles that are passing through the TAS
Protons impinging on the TCTs can also originate from elastic beam–gas interactions, which deflect protons out of the beam, around the whole accelerator ring. Unfortunately it is difficult to distinguish the elastic beam–gas scattering contributions from the tertiary halo. Since the primary halo is populated by many processes, one of them being small-angle elastic beam–gas scattering. The events that could be considered as contributions from elastic scattering are those which have large enough momentum transfer to kick the protons beyond the betatron amplitude at which the primary collimators cut into the beam.

The intensity of the beam–halo background depends on the beam conditions and the machine configuration, especially the collimator settings. In general, the beam–halo background is reduced when the tertiary halo is minimized, by setting up tight apertures in the upstream collimators. However, the beam–halo depends on the beam optics, in particular the dispersion and the betatron phase advances between IR7 and the TCT. For fixed collimation and optics settings, the beam–halo background is proportional to the instantaneous loss rate of halo protons on the TCPs.

Dedicated tests during 2015 and 2016 have shown that in normal physics conditions, losses on the TCTs are minor contributions (of the order of 1%) to the total background seen in ATLAS. These tests are presented in the Publication-2.

### 5.3 Cosmic rays

![Figure 5.2](image-url)  
**Figure 5.2** Distributions of the leading jet transverse momentum in the fake jet samples obtained from the colliding bunches and the dedicated CRB data during 2012. The ratio indicates the fraction of CRB in the NCB sample. Figure from [12].
The CRB is entirely due to high-energy muons. These muons can penetrate the 60 m thick overburden and reach the experiment, creating fake jets in the calorimeters by radiative energy losses and thereby introducing backgrounds to physics searches [12]. The CRB are uniform in time and independent of beam, i.e. scale with wall-clock time and not beam intensity passing through ATLAS. Figure 5.2 compares the rates of CRB and BIB induced fake jets using data from 2012. It can be seen that the BIB is the dominant source of background and therefore the focus on this thesis is only on that.

5.4 Ghost charge

The ghost charge [12] is formed by all protons outside the RF buckets housing nominally filled bunches. Two mechanisms are responsible for ghost bunch formation:

- The first one takes place in the LHC injectors. A characteristic example are the ghost bunches formed in the Proton Synchrotron (PS) while creating the proton bunches for the LHC. As the proton bunches are injected in the PS from the booster (PSB), the multiple splitting scheme applies that splits single PSB bunches into six separated by 50 ns. This means that any protons injected from PSB that fail to fall into the PS bucket could be captured in an otherwise empty bucket generating further splitting, thus ghost bunches with a time space of 50 ns. In this case, six ghost bunches with a 50 ns spacing will be formed. The same mechanism applies during the injection from the PS to SPS leading to the generation of ghost bunches with distance of 5 ns.

- The second mechanism is related to de-bunching in the LHC. During the LHC fills, due to the momentum distribution of the proton bunch, a certain fraction of the protons could get large-enough momentum and leave the initial bucket [75]. The de-bunched protons drift in the LHC for fairly long time period of tens of minutes and, as a result, complete more turns compared to the bucket from which they originated before being intercepted by the beam cleaning [75, 76], thus ghost charge is distributed rather uniformly around the ring. The de-bunched charge might be re-captured by the RF forming ghost bunches around the LHC retaining an imprint of the bucket structure.

5.5 Background monitoring methods in ATLAS

During each LHC fill ATLAS data-taking is subdivided into Luminosity Blocks (LB), typically 60 s in duration but some can be as short as 10 s. While recorded events carry an exact time-stamp, trigger rates and luminosity data are recorded only as averages over a LB. This definition of an LB is motivated by the assumption that beam conditions do not change over a 1 minute time-scale.

---

2 If the charge is in any of the 9 RF buckets in the same BCID as a filled bunch, then it is referred as satellite bunch
The trigger timing is centred such that the collision time $t = 0$ of two filled bunches falls into the middle of the BCID. In the L1 trigger decision, ATLAS arranges the BCIDs into various Bunch Groups (BG) according to their characteristics. Two of these groups, the unpaired isolated and the unpaired non-isolated are significant for the studies of the beam backgrounds.

During the LHC Run-1 and Run-2 the rates of the beam backgrounds were mainly derived from two detector systems: the Beam Conditions Monitors (BCM), which was the primary detector that was used for monitoring the beam backgrounds and the calorimeters, which measure the rate and energy of the formed fake jets.

### 5.5.1 Beam Conditions Monitors - BCM

The BCM detector [77] consists of two stations with four small modules, each positioned at $z = 184$ cm on both sides of the IP. These four modules are arranged in a cross with two modules in the horizontal and two in the vertical plane at a mean radius of 5.5 cm ($|\eta| \approx 4.2$) from the beam-line. Each module is equipped with two back-to-back diamond sensors with an active area of $8 \times 8$ mm$^2$ and a thickness of 0.5 mm, designed to tolerate doses up to 500 kGy and in excess of $10^{15}$ charged particles per cm$^2$ over the lifetime of the experiment.

Hits in the BCM modules are counted above a threshold of 250 keV, a value that corresponds to roughly 1/3 of a minimum ionising particle energy deposition in 1 mm of diamond. Particles from beam losses reach the upstream detectors 6.1 ns before the nominal collision time, i.e. the passage of the bunch at the IP at $t = 0$, and produce early hits. Both, beam background and collision products from the IP, produce in-time hits in the downstream detectors at $t = 6.1$ ns. Due to this build-in direction requirement the BCM trigger is able to distinguish the beam from which the background originates.

The time resolution of the BCM is of the order of 0.5 ns. In the readout the duration of 25 ns of each BCID is subdivided in 64 bins with a 390.625 ps width each. These bins are aligned such that the nominal collision time falls into bin 27. For each recorded event the whole 64-bin vector is stored for off-line analysis, allowing the determination of the exact arrival time and duration of each recorded signal.

Two L1 triggers were provided by the BCM detector during the LHC Run-1 and four during Run-2: L1\_BCM\_AC\_CA and L1\_BCM\_Wide for Run-1 and BCM\_AC,BCM\_CA, L1\_BCM\_AC\_CA and BCM\_Wide for Run-2. The latter is a trigger that selects collision events with the requirement that a coincidence of hits will exist on both stations, while the other triggers are a background-like "coincidence" triggers, illustrated in Figure 5.3. This BCM background trigger is provided by an early and an in-time hit on the upstream and downstream sides, respectively. Since the two stations are placed symmetrically with respect to the IP, the particles generated by beam-background events hit these stations with a time difference of $\Delta t = 2z/c$. The nominal time windows of the background trigger are 5.46 ns
wide around the expected arrival, which is defined as \( t = +6.25 \pm 2.73 \) ns for the early window and \( t = -6.25 \pm 2.73 \) ns for the in-time window, where \( t = 0 \) is the IP-passage of the bunch.

Figure 5.3 Illustration of the BCM background trigger signature for beam-1. The red dotted line represents the track from one event hitting the upstream and downstream BCM modules. For beam-1 the early hit is on side A and the in-time hit on side C. For beam-2 the direction is reversed. The trigger can be fired also by two separate tracks, the only requirement being that both time windows have a hit.

Previous dedicated studies [70] have shown that there is a correlation between the beam background observed by the BCM detector and the residual gas pressure read by the gauges at 22 m the IP. Figure 5.4 presents this correlation between the pressure at 22 m and the observed background.

Figure 5.4 Correlation between pressure read by the gauge at 22 m from the IP and BCM background rate. Each dot represents one LB. Figure from [70].
5.5.2 Fake jets

High energy muons, with energies up to the TeV range, generated by beam–gas interactions and by scattering of the beam halo protons at limiting apertures of the LHC, can enter the ATLAS calorimeters and deposit large amounts of energy via radiative losses. These energy deposits can be reconstructed as fake jets, as illustrated in Figure 5.5.

![Figure 5.5 ATLAS event display of muon reconstructed as fake jet.](image)

All the ATLAS calorimeters, described in Section 3.4 have a nanosecond time resolution and contribute to a low-$p_T$ jet trigger. This trigger is used to select fake jet candidates in unpaired bunches and is calibrated at approximately by the electromagnetic energy scale. The trigger is applied at $|\eta| < 3.0$ and with reduced efficiency up to $|\eta| = 3.2$. Depending on the LHC run, a different energy threshold has been applied for the trigger; for the LHC Run-1 a threshold of 10 GeV was set and the L1 trigger item was defined as L1_J10, whereas for the LHC Run-2 this threshold was raised to 12 GeV with the trigger named as L1_J12.

The fake jets have a very different topology from collision jets: they do not point to the IP and are almost entirely of electromagnetic nature with very little hadronic activity. The BIB muons that generate fake jets travel parallel to the beam-pipe forming different cluster shapes from those coming from $pp$ collisions; the particle shower in the calorimeters is mainly developing along the $z$ direction of the BIB muon compared to the one from collisions which develops in a direction pointing from the IP.

The offset in arrival time, at a given $z$ location, between the proton bunch and a beam background muon originating from that bunch, is negligible. Therefore, when the beam background muon reaches an upstream point $P(r, z)$ in the calorimeter, the proton bunch still has to cover a distance $|z|$ to reach
the IP and then the produced secondary particles have to travel a distance \( s = \sqrt{r^2 + z^2} \) to reach \( P \), as illustrated in Figure 5.6. For a downstream \( P \) the expression for \( s \) is the same, but in this case the muon has to cover the additional distance \( |z| \). The calorimeter timing is such that for each point \( P \) the arrival time of a secondary particle produced in collisions at the IP is 0. Thus the relative time \( \Delta t \) of a beam background muon at \( P \) is given by:

\[
\Delta t = -\left(\sqrt{r^2 + z^2} \pm |z|\right)/c
\]  

(5.1)

where \( c \) is the speed of light and \( +|z| \) and \( -|z| \) correspond to the upstream and downstream sides respectively. Equation 5.1 shows that fake jets due to BIB always arrive early, i.e. have \( \Delta t < 0 \).

Figure 5.6 Schematic illustration of reconstructed arrival time of beam background muons compared to collision jets in the calorimeter regions. The two grey boxes represent two different calorimeters and the red solid line represents \( t = 0 \), corrected for the time of flight of particles coming from the IP.

It is possible to distinguish the jets formed by collision products from the fake jets formed by BIB particles based on the shape of the formed clusters. This is performed by considering the ratio of the standard deviations of the longitudinal, \( z \), and radial, \( r \), positions of the cells contained within a formed cluster, given by:

\[
\frac{\sigma_r}{\sigma_z} = \frac{\sum (r_{cell} - r_{clus})^2}{\sum (z_{cell} - z_{clus})^2}
\]  

(5.2)

where \( z_{cell}, r_{cell} \) and \( z_{clus}, r_{clus} \) are the positions of cells and clusters, respectively. In order to suppress the noise of the calorimeters 3.7, only the cells with an energy deposition above 100 MeV and a well-measured time are considered in Equation 5.2. Figure 5.7 shows the comparison of the ratio of the standard deviation of \( r \) and \( z \) position of the cells contained within a cluster in unpaired bunches and simulated collision events. As seen by comparing the two histograms, a cut on \( \sigma_r/\sigma_z < 0.15 \) can be applied to improve the rejection of the BIB background. However, this is still not sufficient for
distinguishing clusters between background and collision events, since non-negligible fraction of the latter will sometimes satisfy the $\sigma_r/\sigma_z$ cut. Therefore, this cut alone is insufficient for the physics analyses and further selection criteria on other variables need to be applied in addition.

![Figure 5.7](image)

**Figure 5.7** Ratio of the standard deviation of $r$ and $z$ position of the cells contained within a cluster in unpaired bunches (solid) and simulated collision events (dashed). Figure from [70].

Fake jets have more characteristics that can be used to separate them from the collision jets. The energy deposits of a BIB muon are mostly contained in one single layer of the barrel calorimeter and, in addition, no tracks exist that connect the measured calorimeter signals with the primary vertex. Thus, based on these non-collision background characteristics, two variables have been defined for an efficient jet cleaning: the charged particle fraction $f_{ch}$ and the maximum energy fraction in the calorimeters $f_{max}$. The $f_{ch}$ is defined as the fraction of the total transverse momentum of a jet due to tracks with a $p_T > 500$ MeV. This selection is not applicable to all analyses, in particular to long lived particle searches. Figure 5.8 shows the distribution of the ratio $f_{ch}/f_{max}$ for leading jets in the events from colliding bunches triggered by the $E_T^{miss}$ trigger with an offline requirement of $E_T^{miss} > 160$ GeV. The black points present the measured data, while the green and red histograms are the Standard Model expectation from the $W \rightarrow l\nu + jets$ and $Z \rightarrow \nu\nu + jets$ electroweak processes, respectively. These distributions suggest that a cut off with value of $f_{ch}/f_{max} > 0.1$ constitutes an efficient method for cleaning selection.3

For all the analyses that are presented on this thesis the data from periods affected by calorimeter noise bursts, i.e. periods where high number of channels had bad quality factor, are excluded.

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3Such cut cannot be applied to long lived particles since it would risk to throw away the signal too.
Figure 5.8 Distribution of the ratio $f_{ch}/f_{max}$ for leading jets in the events from colliding bunches triggered by the $E_T^{\text{miss}}$ trigger with an offline requirement of $E_T^{\text{miss}} > 160$ GeV. Figure from [70].
Chapter 6

Simulations of beam–gas inelastic interactions and comparison with 2012 data

Since the ATLAS recorded data do not provide information about the origin of BIB, extensive and detailed Monte Carlo simulations are required in order to reveal all the needed information about their nature and their characteristics. For these purposes, dedicated simulation tools needed to be developed for the study of the beam backgrounds and for the trigger emulation implemented in the simulations. This Chapter describes the simulation methods that were implemented during this thesis, explaining the developed simulation chain, based on FLUKA and the methods that have been implemented for emulating the trigger signatures and analysing the simulation results. In addition, in order to test the simulation framework and the new features, a comparison between the simulation results and the data is necessary. The simulation results studying the background generated by inelastic beam–gas scattering are compared with ATLAS data from 2012 during the LHC fill 2736. Through these comparisons, the origins of the BIB leading to different observables in the ATLAS detectors were analysed. The results presented in Publication-1 constitute the first time that BIB simulations are compared with LHC data at quantitative level.

Section 6.1 describes in detail the entire simulation chain for the study of BIB. The pressure map profile and the procedure for including it in the simulation chain for emulating the contribution of the inelastic beam–gas events is described in Section 6.1.2. Since the simulation framework does not include the ATLAS digitisation and reconstruction software, new algorithms had to be developed in order to emulate the trigger signatures in the simulations. These new algorithms are presented in in Subsections 6.2 and 6.3.
6.1 Multi-step Simulation Framework for the study of Beam Backgrounds

For simulating and studying the beam–gas inelastic contribution of BIB, a multi-step simulation framework had to be developed. This framework, illustrated in Figure 6.1 is divided in two main parts:

6.1.1 The Accelerator simulations

The accelerator simulations, which forms the first phase of the framework, provides the basic input to the simulations performed for the purposes of this thesis and is described in detail in [78].

During this step, beam–gas events were generated as inelastic $p - N_2$ interactions and sampled with a uniform distribution in a $z$-range from 22.6 m to 546.6 m. The FLUKA code with the PEANUT...
hadronic event generator was used for the generation of these events and nitrogen as the gas since it represents a good average of the atomic composition of the residual gas in the beam vacuum [11], as will be described in Section 6.1.2. It should be emphasized that, in the final normalisation, the number of interactions is always determined from the true gas composition, so the only approximation is in assuming the production of secondary particles to be the same on average. The use of a generic gas species and a uniform distribution (i.e. no pressure profile is applied at this stage) has the advantage that the same simulation results can be used with different pressure distributions, provided that the coordinate of the original proton interaction is stored in the event information.

The proton beam hitting the nitrogen molecules was set up in a way to include the beam size, as well as the crossing angle in the vertical plane. Since the beam size can be very large inside the inner-triplets, beam–gas interactions may occur outside of the central beam trajectory and affect the azimuthal distribution of particles that have reached the interface plane.

For a complete description of the background, especially for emulating the BCM trigger that requires low hit threshold, a low energy cut is needed for particle transport and production. Since particle transport down to low energies is very time consuming, the transport cut-off used in this first step of the simulations was 20 MeV, resulting to a total number of $10^6$ simulated inelastic events. This energy transport cut-off was chosen in order to stay above the low-energy nuclear reactions regime, which are the source of a large numbers of low-energy particles. These low-energy particles are insignificant for the BIB studies since most of them never reach the interface plane but are absorbed locally and their simulation is expensive in terms of CPU time in regions that are of no interest. Since $10^6$ events do not provide enough statistics for the fake jet studies, a second simulation was performed with a higher transport cut–off of 20 GeV, based on 300 million $p - N_2$ interactions. This high cut-off corresponds to the energy needed to create a fake jet with sufficient transverse momentum to fire the jet trigger.

### 6.1.2 Residual gas distribution in the beam-pipe

The pressure distribution is a crucial input for the inelastic beam–gas simulations, since it defines the absolute scale for the simulated rates. It varies from fill to fill and is non-uniform along the circumference of the ring. In the absence of beam, the static pressure\(^1\) is very low in the warm sections of the LHC and almost zero in the cold sections due to the cryo-pumping effect, explained in Section 2.7.

The state of the surface conditioning, at any given time, is estimated empirically based on prior experience and the beam operation history. The local characteristics and temperature of the beam pipe, the local pumping speeds, the beam intensity and the estimated effects of the beam-conditioning history contribute to the uncertainties of the simulated results. The total uncertainty in the local

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\(^1\)The static pressure is referred to the pressure in the beam-pipe in the absence of beam
Simulations of beam–gas inelastic interactions and comparison with 2012 data

pressure due to these parameters, is estimated to be a factor of \( \sim 2-3 \), dominated by the state of surface conditioning. Since both the surface characteristics and the intensity of radiation vary as a function of position, this uncertainty varies accordingly. This means that the simulated pressure can be underestimated in some regions and overestimated in others.

For the purposes of this thesis, a simulated pressure map was created by the LHC Vacuum Group using the VASCO (VACuum Stability COde) \cite{79} code. This pressure map was generated for LHC fill 2736, which was selected jointly by the LHC Vacuum Group and by ATLAS & CMS, since it represents the typical beam conditions of 2012.

The simulated pressure map generated is based on a vacuum model that takes into account a series of parameters that affect the residual gas density. These are the ion, electron and photon-stimulated gas desorption, the molecular diffusion along the beam chamber and the gas pumping distribution along the beam pipe. The model utilises parameters such as the induced gas desorption and photoelectron yields that depend on the wall conditioning and beam scrubbing as well as the pumping stations. Additional model parameters are the temperature and the geometry (cylindrical) of the beam pipe, the distributed pumping on the walls and the sticking coefficients. The vacuum model takes into account the four different gas species and provides the densities of those at given locations up to \( \sim 280 \) m from the IP, calculated by the differential equations described in \cite{79, 80}.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Gauge sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)</td>
<td>2.4</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>0.7</td>
</tr>
<tr>
<td>CO</td>
<td>0.95</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The densities for each gas species provided by VASCO are presented as molecules per unit volume and the simulations can be compared with the measurements by the gauges. Figure 6.2a shows the simulated total and partial densities as a function of \( z \).

The total N\(_2\) equivalent pressure at room temperature can be derived from these densities by:

\[
P_{\text{Neq}} = \sum_i \frac{T \times k_B \times \rho_i}{s_i}
\]

where \( i \) runs over H\(_2\), CH\(_4\), CO and CO\(_2\), \( T \) is the room temperature, \( k_B \) is the Boltzmann’s constant, \( \rho_i \) is the partial density of the gas at a given location and \( s_i \) is the gauge sensitivity with regard to N\(_2\), as shown in Table 6.1. Figure 6.2b shows the total and the partial nitrogen equivalent gas pressures of the residual gas species in the LHC beam vacuum as a function of \( z \) as well as the comparison of the total with the measurements by the gauges.
6.1 Multi-step Simulation Framework for the study of Beam Backgrounds

The simulated densities are $\sim$10 orders of magnitude lower than those at standard temperature and pressure conditions (STP)\(^2\) resulting in an average proton mean free path of the order of $10^{10}$ km. Thus, and considering the 27 km LHC circumference and the revolution frequency of 11245 Hz, the average lifetime of a proton before having a beam–gas interaction is 100 h.

Although H\(_2\) is most abundant in the cold 1.9 K sections, the interaction rate is dominated by the other gas species, especially in the LSS, due to their much larger interaction cross-sections. Therefore, Nitrogen (N\(_2\)) represents a good average of the atomic composition of the residual gas in the beam pipe.

Table 6.2 Densities, collision lengths and inelastic cross sections of beam protons for the residual gas molecules. The collision lengths are obtained from FLUKA and the cross sections are derived from these.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Density ([g/m^3 \text{ at STP}])</th>
<th>Collision lengths ([m \text{ at STP}]) for 4.0 TeV proton</th>
<th>Cross section ([\text{barn at STP}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)</td>
<td>89.9</td>
<td>4830</td>
<td>0.077</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>716</td>
<td>900</td>
<td>0.412</td>
</tr>
<tr>
<td>CO</td>
<td>1250</td>
<td>645</td>
<td>0.577</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>1970</td>
<td>415</td>
<td>0.894</td>
</tr>
</tbody>
</table>

\(^2\)STP is defined as a temperature of 273.15 K (0\(^\circ\)C, 32\(^\circ\)F) and an absolute pressure of exactly 105 Pa (100 kPa, 1 bar).
The pressure profile can be converted into the probability of a proton to experience an inelastic beam–gas interaction over a short distance $x$, since the interaction probability is given by:

$$ P = x/\lambda $$

(6.2)

where $\lambda$ ($\lambda \gg x$) is the scattering length at the residual gas density. The total $\lambda$ at a given location is calculated by:

$$ \frac{1}{\lambda_{\text{Total}}} = \sum_i \frac{\rho_i \times N_A \times \sigma_i}{M} $$

(6.3)

where $i$ runs over $\text{H}_2$, $\text{CH}_4$, CO and $\text{CO}_2$, $N_A$ is the Avogadro number, $M$ the molar mass, $\rho$ the density of the gas and $\sigma$ the cross section for p-Gas scattering as given in Table 6.2. Figure 6.3a presents the fraction of all the simulated inelastic beam–gas interactions that take place on the indicated molecule, while Figure 6.3b shows the rate of these beam–gas interactions per indicated molecule.

The NEG technology used in the warm sections of the beam-pipe efficiently pumps all gas species except $\text{CH}_4$. In addition, the most abundant gas species in the LHC cold arc ($T=1.9$ K at $z > \sim 270$ m) is $\text{H}_2$. But since $\text{H}_2$ has a much smaller inelastic cross section for the LHC beam protons than the other gases, most of the interactions happen with the heavier molecules in the 1.9 K cold sections but not in the warm ones. Figure 6.3a shows, as expected, that the warm sections are dominated by interactions on $\text{CH}_4$, while interactions on $\text{CO}_2$ dominate within 4.5 K magnets.
6.1 Multi-step Simulation Framework for the study of Beam Backgrounds

Figure 6.4 Probability of the generated events to reach the interface plane. The blue histogram represents the initial uniform distribution with which the events have been generated, while the red histogram shows the fraction of the beam–gas events that reach the interface plane. The histograms are prior to any pressure normalisation.

6.1.3 Pressure normalisation

The probability \( P(z) \) of secondary particles produced in a beam–gas event to reach the ATLAS experimental area depends on the location of the event, due to the magnet string and material to be traversed. Especially for large \( z \), a significant fraction of the generated beam–gas events have no particles reaching the interface plane, i.e. \( P(z) \to 0 \) when \( z \to \infty \), since the particles from the cascades due to beam–gas interactions have been absorbed by interacting with the various machine elements. This means that the interface file misses a non-significant number of the events generated during the first simulation step. The red histogram in Figure 6.4 shows the probability of the secondaries of the generated events to reach the interface plane. Almost all the close-by beam–gas events, i.e. with \( z < 130 \text{ m} \), have secondaries that reach the ATLAS cavern, while less that 5% of the events at \( z > 280 \text{ m} \) give contribution at 22.6 m.

Since the initial beam–gas events were generated with a uniform distribution, “empty” events have been added to the interface file in order to restore the originally generated uniform distribution of \( z \)-origins for the events. Empty events are events with no secondaries, i.e. a unique id has been attached to them but no transport will be performed by FLUKA. These empty events are crucial for the normalisation of the beam–gas events inside the ATLAS cavern, since through this procedure the
proper particle statistical weights are restored and maintained in the future FLUKA simulations. The number of these empty events is determined, as a function of $z$ from: $N(\Delta z)(1 - P(z))$, where $N(\Delta z)$ is the number of generated events in a bin of width $\Delta z$. The difference between the blue and the red histogram in Figure 6.4 represents the number of empty events.

Afterwards, the events are selected from this uniformised file by sampling according to the inelastic interaction probability obtained from the pressure profile and shown in Figure 6.5. The solid histogram in Figure 6.5 shows the rate of the $p - N_2$ interactions as a function of $z$. This distribution is obtained from the equivalent $N_2$ density. This equivalent density is defined in an entirely different way through the inelastic cross section, as opposed to relative gauge sensitivity, and is derived from the partial densities of all residual gas species at the location $z$, weighted by the ratio between inelastic proton-molecule ($\sigma_i$) to $p - N_2$ ($\sigma_{N_2}$) cross-sections:

$$
\rho_{N_2}(z) = \sum_i \frac{\rho_i(z) \sigma_i}{\sigma_{N_2}}
$$

(6.4)

where $i$ runs over H$_2$, CH$_4$, CO and CO$_2$.

The prominent peaks between $z \approx 150$ m and $z \approx 270$ m correspond to the TCT, the D2 dipole ($T = 4.5$ K), Q4–Q6 quadrupoles ($T = 4.5$ K) and cold-warm transitions at the exit of the arc. The pressure in the LHC cold arc ($T = 1.9$ K), starting at $\sim 270$ m, is assumed constant in the simulations.
The dotted histogram in Figure 6.5 shows, as a function of \( z \), the rate of those events for which at least one particle with kinetic energy \( E > 20 \text{ MeV} \) has reached the interface plane. A comparison of the two histograms in Figure 6.5 reveals that practically all close-by events give contributions, while less than \( \sim 5\% \) of events with a location \( z > 270 \text{ m} \) result in particles at the interface plane. On the contrary, all the events generated within \( 22.6 < z \leq 150 \text{ m} \) give contributions to the interface plane.

In order to account for beam–gas events between the IP and the interface plane, \( p - N_2 \) events were generated separately in \( z = [0–22.6] \text{ m} \) with a \( z \)-distribution sampled directly from the inelastic interaction probability in that region, i.e. left of the dashed line in Figure 6.5. The \textsc{peanut} event generator of \textsc{fluka} was used in order to generate 4\ TeV protons interactions with Nitrogen, taking into account both the beam-size and the crossing angle.

Since the normalisation with the inelastic interaction probability is derived from the simulated pressure map, the uncertainty of the vacuum simulations, which is a factor of \( \sim 2–3 \), propagates into it.

### 6.1.4 The ATLAS simulations

During the second step of the simulation framework, the ATLAS simulations, the tracks of the beam–gas events that have reached the interface plane, as well as those those generated at \( z < 22.6 \text{ m} \), were transported through the ATLAS cavern and detector using a dedicated geometry model of that region, as described in Chapter 4. The propagation and showering of the particles through ATLAS is simulated with \textsc{fluka}. \textsc{fluka} provides the full simulation of hadronic and electromagnetic shower through accurate models, as well as a detailed transport of muons through matter with complete modelling of all energy loss processes and explicit production of secondary particles in radiative events. The advantage of \textsc{fluka} is that it is much more lightweight and faster compared to the full ATLAS simulation \[81\] based on \textsc{geant4}\[82\]. The downside of choosing \textsc{fluka} is that the exact detector response, including digitisation and object reconstruction, cannot be done at a level comparable to what is done for real data. Thus, in order to emulate the fake jets and the BCM background trigger signatures, custom scoring and reconstruction algorithms have been implemented in \textsc{fluka} and in the post-processing of the simulation output. A detailed description of the BCM trigger emulation and the simulation of fake jets is given in the following Section 6.2 and Section 6.3, respectively.

### 6.2 BCM Trigger Emulation

The BCM detector has been described in \textsc{fluka} by implementing a detailed geometry, including both the sensitive area and the services on both sides of the IP. In the simulations, during transport, each charged particle with an energy above 250 keV that enters the sensitive area of the BCM modules
Simulations of beam–gas inelastic interactions and comparison with 2012 data

Figure 6.6 BCM total cumulative multiplicity of hits (a) and multiplicity of modules hit (b) per side, i.e. 4 modules. The histograms show, as a function of N the probability to have at least N hits (left) or at least N modules with a hit (right).

is considered as a hit. The identifier of the BCM module that the particle enters, along with the event id, the kinetic energy of the particle and the arrival time on the BCM module are recorded in a separate file which is used for post-processing the simulation results in order to emulate the BCM trigger. Each of these hits result in a dead-time of the affected BCM module, the length of which depends on the energy, but is typically 10-20 ns. Thus, for simplicity, only the first hit in each BCM module, in a ±12.5 ns wide window around $t = 0$, is considered in the analysis of the results, both in the simulations and the data. The total multiplicity of hits recorded during the simulations and the multiplicity of modules hit is presented in Figure 6.6a and Figure 6.6b, respectively. The latter is actually the total multiplicity of hits with the requirement of max 1 hit/module/BCID.

In order to include all the relevant tracks that could generate hits in the BCM detector, the transport cut-off for the ATLAS simulations was set to 100 keV. In addition, all the neutrons are transported to thermal energies, such that the capture by nuclei with associated photon emission is simulated as well. There is a difference in the transport cut-off between the LHC simulations (20 MeV) and the ATLAS simulations (100 keV). This difference is justified since the only direct path from the interface plane to the BCM modules is through the small aperture of TAS, as seen from Figure 6.7. The presence of TAS results to a very low probability for particles crossing the interface plane to directly reach the BCM modules, i.e. giving a hit without showering. Even those that pass through the TAS aperture have to cross the beam pipe at very shallow angle and are likely to interact. All the rest of the particles that have reached the interface plane will shower in the ATLAS shielding generating lower energy secondaries. A sensitivity study has been performed in order to quantify the effect of the transport cut-off in the LHC simulations where an energy cut-off of 30 MeV, 40 MeV and 50 MeV has been applied when loading the particles at the interface plane. and the results showed that there was no impact on the BCM rate.

The energy spectra of all hits in the BCM modules as well as the probability for hits to be below a certain threshold is presented in Figure 6.8. As seen from Figure 6.8, only a small fraction of hits,
6.2 BCM Trigger Emulation

Figure 6.7 Geometry of the TAS region and shielding as implemented in FLUKA.

Figure 6.8 Energy spectrum of hits in the BCM modules 6.8a and probability of hits to be below a set threshold 6.8b.

∼9%, have energies between 100 keV and 1 MeV. However, since several modules are hit on one side in many events, the probability of having hits only in this range in the four modules is $P = 0.09^x$, where $x$ is the average hit multiplicity per side in events with at least one hit per side. Thus, going from a 100 keV threshold to 1 MeV should decrease the BCM trigger rate by less than 9%, since $x > 1$ by construction.
Simulations of beam–gas inelastic interactions and comparison with 2012 data

![Figure 6.9](image)

Figure 6.9 Hit rate of the BCM as a function of threshold, relative to a threshold of 100 keV. The blue dotted line represents the BCM signal threshold of 250 keV, whereas the red dotted line the mean energy deposition of a minimum ionising particle (mip) at 90 degrees of ∼610 keV.

Indeed, as seen in Figure 6.9 where the BCM rate is presented as a function of energy threshold, the rate decreases by less than 3%, between 100 keV and 1 MeV, confirming that the systematic uncertainty due to the exact choice of hit threshold in the BCM is negligible, with respect to the 250 keV signal threshold of the BCM detector.

6.2.1 BCM rates and time distribution

As described in Section 6.1.1, the simulations are based on $p - N_2$ events while in the inner triplet the beam–gas interactions are dominated (∼90%) by $p - H_2$ scattering. In order to estimate the possible dependence of the background rate on the target nuclide, new simulations have been performed for the less CPU-intensive simulations at $z < 22.6$ m. during which $H_2$ was used as the target nuclide. The result of this study is presented in Figure 6.10, where the rates between H and $N_2$ as target nuclides are compared. By using H, the rate was found to decrease only by about 15%. Thus, it can be assumed that the use of $p - N_2$ events overestimates the BCM trigger by 15%, assuming a similar reduction for the inner-triplet region, where most of the BCM background originates from.

Moreover, the simulations reveal information about the origin of the background that is responsible of the production of the tail presented in Figure 9 of Publication-1. This tail is mainly produced by low energy delayed particles close to the IP, i.e. with an origin < 80 m, as indicated in Figure 6.11. The fact that a tail of similar height, with respect to the peak, is seen in both simulated distributions ($z < 22.6$ m and total) indicates that the delayed particles are due to locally produced afterglow. This is not surprising, since several processes could possible contribute to the afterglow, such as neutron...
6.2 BCM Trigger Emulation

Figure 6.10 BCM trigger rate as a function of the distance of the BG event between H (red squares) and \( \text{N}_2 \) (blue circles) as target nuclides.

Figure 6.11 Distribution of energy versus time (a) and origin versus time (b) of BCM hits for events with an origin > 22.6 m

capture followed by photon emission, de-excitation of residual nuclei after high-energy collisions and albedo from downstream calorimeters. For identifying the contributors to the tail, new simulations have been employed, using 5000 beam–gas events with \( z < 22.6 \) m, where the low-energy neutron physics, the gamma emission from nuclear de-excitation and the magnetic field of ATLAS have
Simulations of beam–gas inelastic interactions and comparison with 2012 data

Figure 6.12 Distribution of energy versus time (a) and origin versus time (b) of BCM hits for events with an origin < 22.6 m, when the magnetic field is switched-off. The pressure distribution and probability to hit the BCM is folded in both figures.

been switched-off. No difference to the BCM simulated rate or to the time distribution tail have been observed by disabling either the low-energy neutrons or the gamma de-excitation process. On the contrary, by switching-off the ATLAS magnetic field, the tail observed in the time distribution caused by delayed particles with \( t > -3 \) ns disappeared. This is an indication that the tail is almost entirely due to low energy curling particles, and not from nuclear de-excitation process, as seen in Fig 6.12a and 6.12b, where the time-energy and time-origin distributions of all BCM hits during the simulations where the magnetic field was switched-off are illustrated. The tail is underestimated in simulations in comparison to the data probably due to the fact that there is more material in the geometry model used in FLUKA that causes the looping particles to have a shorter range that in reality.

6.3 Characteristics and distribution of high energy muons at the Interface Plane

High energy muons are the main cause for the generation of fake jets. Practically all of these muons have trajectories parallel to the beam-axis. This is shown in Figure 6.13, where the direction cosine along \( z \) of muons that reached the interface plane within \( r = [1.4–3.9] \) m is illustrated.

The \( x–y \) distribution of muons with energy \( E > 20 \) GeV reaching the interface plane at \( z = 22.6 \) m is presented in Figure 10 of Publication-1, where the tunnel geometry, with a radius of 2.2 m and the floor at \( y = -1.1 \) m, is reflected as a relatively sharp edge in the simulated muon flux. The spread in the horizontal plane of the distribution of muons has some hot spots, suggesting that the LHC lattice acts as a spectrometer. In order to study this effect, the \( x \)-coordinates of the muons at the interface plane,
in a narrow band of \( y = \pm 15 \text{ cm} \), have been plotted for two \( z \)-ranges of the initial beam–gas event. The first range between \([90–150] \text{ m}\) corresponds to the region between the D1 and D2 magnets. In this case, D1 is the only dipole traversed by particles staying close to the beam-line. Particles from the \([165–270] \text{ m}\) range can traverse both D2 and D1, unless they get deflected enough by D2 to bypass D1. Since the bending of these two magnets is in opposite directions, the effect is that particles experiencing only the deflection by D1 or D2 fall on negative and positive \( x \), respectively while particles passing both magnets get smeared over \( x \).

Figures 6.14 and 6.15 show the horizontal distributions at the interface plane, due to bending in D1 and D2 magnets, of negative and positive muons, respectively. In can be seen, from Figure 6.14, that at low muon energies the \( x \)-coordinates are smeared over a rather large area. This is mainly caused by other effects, like the quadrupole fields and scattering in material traversed. For energies above 100 GeV, a clear peak at \( x \approx 80 \text{ cm} \) appears for the muons in the \([90–150] \text{ m}\) range. For higher energies this peak remains, but gets narrower and moves to smaller \( x \). This behaviour is consistent with a spectrometer effect by the D1 magnet. On the contrary, for the \([165–270] \text{ m}\) range, the picture is more complicated since a prominent and narrow peak appears only at the highest energy. At lower energies, between 300–1000 GeV, peaks can be seen, but they are more smeared, indicating that other deflections (e.g. by D1) take place on the way to the interface plane. The fact that the total rates from the 165-270 m range are lower than for the 90–150 m range is due to the fact that less muons reach the

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*Figure 6.13* Direction cosine along \( z \) of muons within \( r = [1.4–3.9] \text{ m} \) at the interface plane.
interface plane from the larger distance. A comparison of Figure 6.14 and 6.15 verifies that positive and negative muons are deflected to opposite sides, as is expected from a spectrometer.

Figure 6.14 Horizontal distribution of negative muons at the interface plane due to bending in D1 and D2 magnets. The red histogram shows the muons from events in the region between D1 and D2, which experience only the bending of D1. The blue histogram shows the muons originating from events beyond D2, which experience the bending by both magnets.
Figure 6.15 Horizontal distribution of positive muons at the interface plane due to bending in D1 and D2 magnets. The red histogram shows the muons from events in the region between D1 and D2, which experience only the bending of D1. The blue histogram shows the muons originating from events beyond D2, which experience the bending by both magnets.
6.4 Fake Jets Emulation

Since high energy muons are relatively rare, the interface file that has to be used for studying the fake jets is the one with the 20 GeV transport cut-off, providing higher statistics to the simulation results. While the full 20 MeV file can easily be handled by FLUKA, in terms of computational time, the 20 GeV file requires a lot of CPU power. Thus, in order to reduce the computational effort, a derived file (“20 GeVμ”) has been produced from the 20 GeV file by selecting only the events that have muons. In addition, for increasing the statistics of the simulations, all the events in this new generated file were used twice with a different initial random seed assigned to them. Figure 6.16 shows the probability of a muon that is used more than once to generate a fake jet. The probability of getting twice a jet with $p_T > 16$ GeV is $\sim 10\%$ while for $p_T > 100$ GeV the “double counting” is at a level of 0.5%. It should be emphasized that even if the jets will come from the same muon, they will be at different $z$ and have different $p_T$, sampling the probability of jet types created by such muons, i.e. the jet is not a clone of the other even if the muon is. The propagation and showering of the particles in ATLAS is simulated with a 100 keV transport cut-off, while neutrons are transported to thermal energies for simulating the capture by nuclei with the associated photon emission, as in the case of the 20 MeV file for the study of the BCM rates.

Since FLUKA is not part of the standard ATLAS simulation software, it doesn’t profit of the sophisticated and thoroughly developed jet reconstruction tools that exist in the Athena software. Instead of these tools, new algorithms had to be developed for assessing the fake jet rates in the FLUKA simulations; the local energy depositions are recorded during transport, event by event, in the different calorimeter regions of the ATLAS detector, using a custom scoring with variable ($\delta r, \delta z$) bin sizes, as described Table 6.3. Except for the small high-\(\eta\) end-cap regions, the bins are roughly 40 cm wide in $z$. 

![Figure 6.16 Multiplicity of the same high energy muon to generate more than one jet with $p_T > 16$ GeV (left) and $p_T > 100$ GeV (right).](image-url)
Table 6.3 Ranges of calorimeters and bin sizes ($\delta r, \delta z$) in mm as implemented in the ATLAS FLUKA Geometry. An azimuthal binning of 36 bins of 10 degrees each has been applied to all the calorimeters. The end-caps at the negative ('-') side of ATLAS are mirror images of the positive ('+') ones.

<table>
<thead>
<tr>
<th>Calorimeter</th>
<th>$r_{\text{min}}$</th>
<th>$r_{\text{max}}$</th>
<th>$z_{\text{min}}$</th>
<th>$z_{\text{max}}$</th>
<th>$\delta r$</th>
<th>$\delta z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel LAr</td>
<td>1471</td>
<td>2009</td>
<td>-3172</td>
<td>3172</td>
<td>107.6</td>
<td>396.5</td>
</tr>
<tr>
<td>Barrel Tile</td>
<td>2285</td>
<td>3885</td>
<td>-6000</td>
<td>6000</td>
<td>160.0</td>
<td>400.0</td>
</tr>
<tr>
<td>Endcap1 (+)</td>
<td>475</td>
<td>2075</td>
<td>3670</td>
<td>6120</td>
<td>160.0</td>
<td>408.3</td>
</tr>
<tr>
<td>Endcap2 (+)</td>
<td>300</td>
<td>475</td>
<td>3670</td>
<td>4650</td>
<td>87.5</td>
<td>490.0</td>
</tr>
</tbody>
</table>

After the transport of each event, the energy depositions are analysed for identifying the generated clusters, which are formed by summing the energy depositions of $3 \times 3 \times 3 = 27(r, \phi, z)$-bins centred around the maximum deposition bin. In the barrel calorimeters this clustering produces jets with angular dimensions comparable to those of the ATLAS jet-reconstruction algorithm. Starting with the highest deposited energy in any bin, each deposition is used only once. A transverse energy threshold of 10 GeV is defined, and, if the cluster energy is large enough to exceed this value, then this cluster is counted as a fake jet. The energy in the bins included in a cluster is set to 0 and the procedure is repeated by finding the maximum of the remaining bins. The process ends when no clusters above the set $p_T$ threshold are found. The position of the fake jet is determined by the energy-weighted average of the bins considered and the jet time is defined as an energy weighted time of the individual depositions.

In order to avoid small energy depositions with large time delay that could influence the average time of the jet, i.e. as those from thermal neutron capture, all depositions at times larger than 50 ns have been excluded during the FLUKA transport. This exclusion is consistent with the jet reconstruction methods used for the ATLAS data analyses, since the latter take into account only depositions in a narrow time window.

For assessing the systematic uncertainty due to the energy spread, sums over more bins were explored and it was found that an extension of the sum in $r$ and $\phi$ adds practically no energy to the cluster. In $z$, however, a wider binning results in a larger energy sum. Thus, it makes sense to also study a $3 \times 3 \times 5$ and $3 \times 3 \times 7$ binning, i.e. clusters narrow in $r$ and $\phi$, but long in $z$-direction. In all cases the center of the cluster is interpolated from the energy-weighted single-bin positions. Table 6.4 compares the simulated fake jet rates found with the various sums. The last column shows the result if $n_z \times 0.5$ GeV ($n_z = \text{number of } z\text{-bins}$) have been subtracted in order to remove the $dE/dx$ of the passing muon. The results indicate that the energy is well contained in 3 radial and 3 azimuthal bins, but more jets are found if the $z$-length in the clusters is increased.

It should be noted that by this method of simply summing a fixed number of bins around the maximum, the continuous energy loss of the passing muon is included in the cluster energy. For a
Table 6.4 Simulated rates of fake jets for various binnings over which to sum the energy.

<table>
<thead>
<tr>
<th>Symmetric bins</th>
<th>Rate</th>
<th>Elongated bins</th>
<th>Rate</th>
<th>Muon dE/dx subtracted</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binning</td>
<td></td>
<td>Binning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3x3x3</td>
<td>0.00216</td>
<td></td>
<td></td>
<td>3x3x3 no-µ</td>
<td>0.00191</td>
</tr>
<tr>
<td>5x5x5</td>
<td>0.00242</td>
<td>3x3x5</td>
<td>0.00242</td>
<td>3x3x5 no-µ</td>
<td>0.00196</td>
</tr>
<tr>
<td>7x7x7</td>
<td>0.00264</td>
<td>3x3x7</td>
<td>0.00264</td>
<td>3x3x7 no-µ</td>
<td>0.00199</td>
</tr>
</tbody>
</table>

40 cm bin this amount to an average of about 0.5 GeV, i.e. a non-negligible 3–4 GeV for 7 bins. Even though it is correct to account for this energy in the centre of the cluster, it is less obvious for the sums over larger areas. In particular, since the intention is to compare the simulations with data, where the latter is reconstructed with the official ATLAS software, the goal is to reproduce as closely as possible the jet reconstruction of ATLAS data. The cell size used by the ATLAS reconstruction is 0.025 in $\eta$. At a radius of 1.5 m in the Barrel LAr this corresponds to a $\Delta z$ -width between 4–8 cm, i.e. 10–20% of the bin width used in the FLUKA simulations. For such a narrow bin the average energy loss of a muon is 50–100 MeV, while the noise cut-off used in the ATLAS jet reconstruction is close to 200 MeV per cell. This means that only upward fluctuations of the continuous muon loss will be considered and included in the jet energy if closer than 0.4 in $\eta \times \phi$ to the deposition from the large radiative loss.

6.4.1 Fake jet rates

Figure 6.17 $p_T$ (left) and angular distributions (right) of fakes-jets using with the EM (blue histograms) and the LC (red histograms) jet calibrations

As discussed in Chapter 5, the fake jets have a very different topology from collision jets. The standard ATLAS jet reconstruction includes a jet energy scale calibration, which takes into account the hadronic fraction in jets and the reduced calorimeter response to it. These jet calibrations are tuned for average jets emerging from the IP, while the fake jets from BIB are mostly due to muon
bremsstrahlung or $e^+e^-$ pair production. This means that instead of pointing to the IP, they are elongated along $z$ and almost entirely of electromagnetic nature. Therefore the standard jet calibration (LC) is not applicable for the comparisons between the simulation results and the data. Thus, the simulation results are compared with jet data calibrated to the electromagnetic (EM) energy scale rather than with fully calibrated jets. Figure 6.17 shows the $p_T$ and angular distributions of fakes-jets using the EM and the LC jet calibrations. While no difference is visible in the angular distributions, a shift of $\sim 14$ GeV towards higher momenta is observed in the $p_T$ distribution of the LC calibration, which is due to the hadronic response corrections.

Figure 6.18 “Banana” signatures in the $\eta$-time plane of the simulated fake jets

The curvature of the energy clusters shape depends on the radial position in the calorimeter. Figure 6.18 shows the “banana” signatures in the $\eta$-time plane of the simulated fake jets while
Figure 6.19 presents the radial position of the clusters in the four different calorimeters. At higher $|\eta|$ on the downstream side these two bananas merge and the fake jet times approach $\Delta t = 0$. In the downstream end-cap, almost all the generated clusters are in-time with the collision jets, while in the upstream end-cap all entries fall outside the trigger window. These clusters are caused by upstream fake jets associated with the following bunch which arrives 50 ns later.
Chapter 7

Tertiary halo simulations

The first set of beam background measurements from the 2012 high-$\beta^*$ LHC fills revealed that sufficiently large beam losses in the cleaning insertions can be seen as higher background in the ATLAS detectors [12]. The analysis of data demonstrated a correlation between the magnitude of these backgrounds and the bunch intensity loss. This preliminary result motivated a new study to investigate the possibility of similar correlations in normal optics in the case of clean beam conditions and large losses.

Such clean conditions are provided by loss map measurements which are regularly performed at the LHC to validate the beam halo cleaning of the collimation system. Their particular advantage is that they are performed in well controlled conditions and in a clean environment. The data that is used in this study come from a loss-map fill that took place in 2015, during which the standard optics for physics of that year with $\beta^*$=80 cm and a half crossing angle of -145$\mu$rad have been used, and a more dedicated test in the same year with $\beta^*$=40 cm and zero crossing angle [83]. In both cases the energy of the proton beams was 6.5 TeV.

The results, thoroughly presented in Publication-2, revealed that the halo related component of the beam background decreases exponentially when the aperture of the tertiary collimators increases and that the halo losses contribute at most 2% to the background seen by the BCM trigger during typical Run 2 operating conditions. In addition, it is demonstrated that in halo-related background events, there is practically no correlation between background-like signals in the Beam Conditions Monitor and fake jets seen in the ATLAS calorimeters. Comparing the data with dedicated FLUKA Monte Carlo simulations revealed an excellent agreement for several observables, in particular the background rates per unit of beam-intensity loss and the transverse-momentum and azimuthal distributions of fake jets.

In the next sections, a description of the simulation chain used for this study, as illustrated in Figure 7.1, is given. The analysis of the data and details about the comparison between data and simulation results are presented in Publication-2. Section 7.1 describes in detail the steps of the
simulation framework for the study of beam losses, while a simulation study of sample-to-sample correlations between BCM triggers and fake jets is given in Section 7.2.

### 7.1 Multi-step Simulation Framework for the study of the TCT losses

Table 7.1 Loss fraction, with respect to the total halo-related loss, on the TCT for TCT settings of 8.8 $\sigma$ (at $\beta^*=40$ cm) and 13.7 $\sigma$ (at $\beta^*=80$ cm), as obtained from the SIXTRACK simulations [78].

<table>
<thead>
<tr>
<th>Beam</th>
<th>TCT at 8.8 $\sigma$</th>
<th>TCT at 13.7 $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$3.6\times10^{-4}$</td>
<td>$1.1\times10^{-5}$</td>
</tr>
<tr>
<td>2</td>
<td>$1.4\times10^{-4}$</td>
<td>$1.4\times10^{-5}$</td>
</tr>
</tbody>
</table>

Like for beam–gas induced BIB, the background in ATLAS has been estimated by Monte Carlo simulations for which the input is obtained from beam loss simulations in the LHC [78]. For beam halo losses these MC simulations proceed in three steps. In the first step particles scattered on the TCP jaws are transported with the SIXTRACK code [84] until they are lost on the TCTs, where their impact points are recorded. The fraction of protons lost on the IR1 TCTs, with respect to the total halo-related loss, is estimated from the SIXTRACK simulations and the obtained fractions are given in Table 7.1 for the two beams and $\beta^*$ settings. The SIXTRACK simulations are done for a "perfect" machine but it should be noted that including realistic imperfections of the machine elements and their alignment can increase the losses on the TCTs by a factor of 2-3 [74].

In the second step, the interactions of the 6.5 TeV protons with the collimator material were simulated with FLUKA at the recorded impact points in the TCT. Subsequently the produced particles were transported with FLUKA to the interface plane at $z = 22.6$ m from the IP. Files of particles reaching the interface plane were produced with 20 MeV and 20 GeV transport cut-offs. The latter is based on about 287 million protons lost on the TCT per beam.

Figure 7.1 Flowchart of the three-step process for the simulation of TCT losses. The trigger emulation, clustering and rate analysis are performed on the custom FLUKA output.
During the third step, the particles are picked up at the interface plane and transported through the experimental area and the detector using FLUKA, as described in detail in Chapter 6, using the same reconstruction algorithms for the BCM trigger emulation and the fake jets. While the entire 20 MeV files could easily be treated in the ATLAS simulation, this turned out to be very CPU-intensive for the entire 20 GeV files. Therefore only 25 % (68.1 million events) of the latter were simulated to serve as consistency check and a further selection was made by considering from the 20 GeV files only events which had muons.

Like in Chapter 6, the transport threshold of 100 keV was used for both types of files. Since a sizeable amount of material is present between the interface plane and the BCM or calorimeters, it is practically excluded that any particles with energy less than 20 MeV at the interface plane could directly reach the detectors used in this study. In particular, the TAS absorber, seals the tunnel entry, and the only direct passage is in its center where a hole of 34 mm diameter is left for the beam.

![Image](image-url)

**Figure 7.2** Radial distributions of charged hadrons (a), photons (b) and electrons/positrons crossing the interface plane close to the beam line, as simulated with FLUKA for beam–halo losses on the TCTs assuming the 2015 machine optics with $\beta^* = 80$ cm. The solid histograms show the totals in two energy ranges, while the dotted ones correspond to particles which, using a straight extrapolation of the trajectory, pass the TAS aperture but cross the beam-pipe wall upstream of the BCM detector. The histograms are normalized per radial unit in order to give a better impression of the number of particles at any given radius.
Figure 7.2 shows the distribution of charged hadrons, photons and electrons/positrons at the interface plane. The contribution of those particles for which a trajectory projection passes the TAS aperture, but exceeds the 23.5 mm radius of the beam pipe before the first BCM station, is shown separately. From the particles that are passing the TAS aperture, a contribution of 40% of the simulated BCM triggers is coming from muons and a 25% is due to photons. The simulations suggest that about 2/3 of the background seen by the BCM is due to particles not interacting with the TAS, but showering on the beam pipe inside ATLAS, as described in Publication-2. Furthermore, all charged hadrons passing the TAS and leading to BCM triggers in the simulations have energies above 100 GeV and a majority even several TeV. These are exactly the expected characteristics of particles scattered back into the beam vacuum from events at very shallow depth, i.e. within a few tens of µm of the TCT inner bore surface.

During this study, the impact depth \(d\) of the inelastic interactions inside the TCT jaws as well as the correlation between this impact and the BCM/fake jet rates for beam-1 were thoroughly studied and the results are presented and discussed in Publication-2. Figure 7.3 complements this discussion by presenting the corresponding rates for beam-2.

### 7.2 Simulation study of sample-to-sample correlations

Based on the hypothesis that fake jets are created by rare radiative loss events of high energy muons, it should also be possible to increase the fake jet statistics obtained from the 20 MeV file by simulating the same file repeatedly with different random seeds. During this study, the input file was simulated 20 different times (each simulation forms a different sample). Since more than 99% of fake jets are associated to a \(>20\) GeV muon, only events including such a muon were considered.

In order to check if there are any undesired correlations, i.e. some events are much more likely to give a fake jet than others, a highly simplified toy model was constructed that uses the same probability for all events. Thus, if the results of the toy model are matching the ones from the simulations, it can be assumed that no muons are significantly more probable to generate a fake jet, than others. This model takes as input the average number \(N=773.2\) and standard deviation \(S=21.6\) of fake jets in the 20 simulated samples. Then \(N\) (varied by \(S\)) cases are sampled from a uniform distribution among \(M\) events, where \(M\) is a parameter to be fitted and can be interpreted as the number of events that are capable of producing a fake jet.

Two quantities are derived from the simulation samples and the toy model:

- the cumulative distribution of different events having produced a fake jet. The value of \(M\) is fitted by requiring that the cumulative value after 20 samples obtained from the toy model matches that of the simulation samples.
- the event multiplicity, i.e. how often a given event appears in the 20 samples.
The comparison of the toy model and the fake jets obtained from the simulations are shown in Figure 7.4. In Figure 7.4a it can be seen that the shape of the cumulative distribution from the toy model matches very well the simulations and also the multiplicity distributions i.e. in how many samples a given jet appears, shown in Figure 7.4b are very similar. These good agreements confirm that any event has only a small probability to produce a fake jet and it is possible to increase the size of the simulated sample by re-using the same events multiple times.

For fake jet studies such a sample re-use is not needed, since the 20 GeV file covers all fake jet production and provides a much larger number of events. The multiple simulation of the 20 MeV files would be interesting only if it would provide a means to study the correlations between fake jet and BCM events. A test of this is provided by re-doing the same comparison with the toy model, after adjusting the input parameters for fake jets in BCM triggered events seen in the simulations, i.e. the average number $N=57.7$ and standard deviation $S=3.9$ of events that have a BCM trigger and a fake jet. The comparison is shown in Figure 7.5, where it can be seen that the shapes of the cumulative distribution deviate significantly and the multiplicity distribution show no similarity at all. In particular, the simulations show a tail to very large multiplicities, which indicate that there are events which tend to systematically produce fake jets in each simulation sample. The conclusion is that the BCM triggers are not randomly distributed among the events and the fake jet vs BCM correlations cannot be extracted from the simulations using the same sample multiple times. In addition, some events selected by the BCM trigger have topologies that increase the probability of observing also a fake jet, but the nature of it is quite unclear.
Figure 7.3 Distribution of the transverse depth of the inelastic interactions inside the jaws of the TCTs in B1 (upper row) and B2 (lower row) at $\beta^* = 40$ cm and $\beta^* = 80$ cm for a superposition of horizontal and vertical losses in IR7. The left plots show the distribution of all impacts. The middle and right plots show only those impacts that have resulted in a BCM background signature or a fake jet, respectively.
7.2 Simulation study of sample-to-sample correlations

Figure 7.4 Cumulative number of different jets per number of samples and multiplicity distribution of samples between the simulated samples of fake jet rates and the toy model

Figure 7.5 Cumulative number of different BCM triggers per number of samples and multiplicity distribution of samples between the simulated samples of BCM rates and the toy model
Chapter 8

Radiation Studies for the ATLAS Phase-II Upgrade Detector

The LHC has performed remarkably so far by exceeding its target design parameters in terms of peak luminosity. However, its peak annual integrated luminosity is not expected to go much beyond 100 fb$^{-1}$. At this rate, significantly increasing the available number of collisions to improve the precision of physics measurements and the sensitivity of searches will take several decades. It is therefore necessary to increase the instantaneous luminosity to accumulate collisions at a much faster rate. The high-luminosity phase of the LHC (HL-LHC) [85] aims to increase the instantaneous luminosity by a factor 3 to 4. In section 8.1 a short summary of the major upgrades for the LHC, towards HL-LHC and for the corresponding ATLAS Phase-II upgrades is given. One component of the upgrades is the High-Granularity Timing Detector (HGTD). Section 8.2 describes the future ATLAS HGTD and 8.4 presents the afterglow studies for the detector. The increased collision rate foreseen for the HL-LHC, while essential for the LHC physics programme, comes with a significantly higher rate of radiation in the detector. This represents a major challenge to the detector systems that are part of the Phase-II ATLAS detector. Radiation studies are therefore necessary to understand the radiation profile within ATLAS and identify the expected levels of radiation sustained by the detector components, including the HGTD. The quantities that characterise the radiation environment as well as the studies for the radiation background and the design of the end-cap moderator for the HGTD detector are described in Publications 3 and 4.

8.1 The HL-LHC and the ATLAS Phase-II upgrades

After the first long shut-down, between years 2013 and 2014 (LS1), the LHC collision energy was increased from 8 TeV to 13 TeV, the bunch spacing was reduced from 50 ns to 25 ns allowing the number of bunches per beam to be increased from 1380 to 2808, and the instantaneous luminosity ex-
ceeded the nominal value of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ during most of Run-2. Concerning the ATLAS experiment, the IBL was installed in the heart of the inner detector (see Section 3.3.1.1 in Chapter 3) providing an additional precision tracking layer and the pixel detector was fully recommissioned including this additional hardware.

After the new long shut-down during the years 2019-2021 (LS2), the LHC is expected to double the peak luminosity, reaching $\mathcal{L} = 2\times3\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ with the design collision energy of 14 TeV and bunch spacing of 25 ns. This will be achieved by integrating the Linac4 into the LHC injector chain, reducing the beam emittance by increasing the energy of the PS Booster and upgrading the LHC collimation system. For the ATLAS experiment, the main upgrades that will take place are in the trigger system of the muon spectrometer and the calorimeters, in order to cope with the high luminosities that will be achieved (Phase-I Upgrade), and the installation of the New Small Wheel (NSW) [86] which involves the replacement of the innermost sections of the ATLAS end-cap muon-detection system.

With these upgrades the LHC will deliver a total integrated luminosity of $\sim 300\text{fb}^{-1}$ in a three-year operation till the end of 2024. But by that time, both the accelerator and the experiments will face the degradation of their components due to ageing and accumulated radiation damage. Thus, a new long shut-down is planned (LS3), from 2025 until mid 2026, during which a series of major upgrades will take place, both for the machine and for the experiments. This phase will be the final step towards the High Luminosity LHC (HL-LHC), aiming at a peak instantaneous luminosity of $7.5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ with up to 200 interactions per beam crossing every 25 ns. A total integrated luminosity of $\sim 4000\text{fb}^{-1}$ in approximately 12 years of operation. This will be achieved by a series of major changes in the elements of the accelerator, including the replacement of the inner triplet magnets, the installation of a new cryogenics plant, a new optimised collimation system and a re-optimisation of the collision optics by using dedicated crab cavities. During LS3, ATLAS will enter in the Phase-II Upgrade state, where major changes will take place in order to cope with the high-radiation environment, the new higher data rates and the large increase in the number of collisions per bunch-crossing.

The above described operation and upgrade plan is illustrated in Figure 8.1, where the three long shut-downs are presented by dedicated time slots.

### 8.2 The High Granularity Timing Detector (HGTD)

One of the main challenges during the HL-LHC period is the pile-up suppression, assuming that the interactions would be spread over about 50 mm RMS along the beam axis. This will lead to the production of an average of 1.6 collisions per mm for a pile-up of $\mu=200$, causing tracking problems in the forward regions of ATLAS. In order to provide timing information to aid in the proper assignment of a collision vertex to each particle a new detector, the HGTD, has been approved by ATLAS.
This new HGTD detector [88] is a silicon detector, schematically presented in Figure 8.2, that will be located in front of the LAr end-cap cryostats at about $z = \pm 3.5$ m and is designed to cover a pseudorapidity range between 2.4 and 4.0. Due to the pad size of $1.3 \times 1.3$ mm$^2$ and the time resolution of 30 ps for minimum-ionizing particles, a value which is much smaller compared to collision spread of 180 ps RMS, this detector is expected to be able to increase the pile-up mitigation capabilities in the end-caps and forward regions of ATLAS, improving the reconstruction of many physics objects such as jets, leptons and missing transverse momentum.

The space that is allocated for the installation of the HGTD is limited due to its position between the ITk and the end-cap calorimeters. In order to ensure sufficient clearance to the beam-line instrumentation, the inner radius will be 11 cm while the outer radius is 110 cm. This provides enough space for routing of services and the off-detector electronics. Table 8.1 gives a summary of all the main parameters of the HGTD.

8.3 Radiation background in the HGTD region

The HGTD will replace the present MBTS & the end-cap moderator, placed next to the end-cap calorimeter; a position that will increase the radiation damage to the detector and to the ITk as well due to the high neutron albedo from the ECT. This thesis focuses on determining the radiation levels based on FLUKA simulations and on designing an appropriate shielding that will reduce the neutron component of the Si1MeVneq fluence. The aim is to maintain the fluence levels in the ITk at the
Table 8.1 Main parameters of the HGTD detector. Values from [88].

<table>
<thead>
<tr>
<th>Detector Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo-rapidity coverage</td>
<td>$2.4 &lt;</td>
</tr>
<tr>
<td>Thickness in $z$</td>
<td>75 mm (+50 mm moderator)</td>
</tr>
<tr>
<td>Position of active layers in $z$</td>
<td>$\pm 3.5$ m</td>
</tr>
<tr>
<td>Radial extension (active area)</td>
<td>110–1000 mm (120 mm–640 mm)</td>
</tr>
<tr>
<td>Pad size</td>
<td>1.3 mm $\times$ 1.3 mm</td>
</tr>
<tr>
<td>Active sensor thickness</td>
<td>50 $\mu$m</td>
</tr>
<tr>
<td>Number of channels</td>
<td>3.6 M</td>
</tr>
<tr>
<td>Active area</td>
<td>6.4 m$^2$</td>
</tr>
<tr>
<td>Module size</td>
<td>30 $\times$ 15 pads (4 cm $\times$ 2 cm)</td>
</tr>
<tr>
<td>Modules</td>
<td>8032</td>
</tr>
</tbody>
</table>

initial/original values and reduce as much as possible the A detailed description of these studies in given in Publications 3 and 4.
8.4 Afterglow in the HGTD detector

One of the motivations for the HGTD is to provide a luminosity measurement that is independent from the current luminosity detectors. The HGTD is affected by three distinct background contributions to the luminosity signal: single-beam backgrounds, instrumental noise, and afterglow, in order of increasing importance. For a given bunch pattern, the afterglow level is observed – in other luminosity detectors operated during Run-2 – to be proportional to the luminosity in the preceding colliding bunches. Dedicated FLUKA simulations have been performed in order to identify the nature\textsuperscript{1} of the afterglow that contributes to the occupancy and the dose and help to its reduction using timing information.

The simulation of the afterglow measured by the HGTD detector is performed as follows: as particle hits are considered all the particles entering the silicon layer and their time coordinate ($t$) is recorded. Figure 8.3 shows the Time of Flight (ToF) of particles in the simulations. The protons arrive first within $\approx 12$ ns from the collisions, which is the ToF from the IP to $z \sim 3.5$ m and $r < 20$ cm, the pions as well as the muons are a bit more spread out since they are lighter, while the $e^+e^-$ give a big bump in the ms range. For neutrons and photons a long tail is observed that reaches times up to ms.

Figure 8.4a shows that all the particles arriving at the HGTD have a delay larger than 10 ns ToF. The $e^+e^-$ are characterised by a long tail at $> 1 \mu$s, but there is also a clear shoulder in this tail at 1–10 $\mu$s. Figure 8.4b reveals that the total contribution of particles with $E < 100$ keV is at 1% level

\textsuperscript{1}i.e. particle types, ToF and physics processes they originate from
Relative ToF tail by particle type (a), energy (b) and direction (c). The histograms are integrated over the full HGTD radial range and show which fraction of all hits correspond to the given particle type/energy/direction and a ToF larger than the value on the time-axis. For (c) the solid histograms represent the particles coming from the IP, while the dotted ones the particles arriving from the ECAL side.

while the large ToF entries are all due to particles with E<100 MeV. In order to identify the origin of the particles that contribute to the long tail, i.e. if they are originating from proton–proton collisions at the IP or they are backscattered from the calorimeters, simulations have been performed where the direction of the hits in the HGTD detector was recorded. Looking at the direction of particles entering HGTD in Figure 8.4c, most of the particles at higher energies are coming from the IP but the shoulder and the tails are equally arriving from both sides.

There are two sources that contribute to the large ToF of e+e− that is seen in the HGTD:

- **slow neutrons** that generate the long tail between few µs and few ms. A thermal neutron has a speed of 2.2 m/ms, i.e. it takes “forever” to cross the ITk volume, but is likely absorbed much faster, and the
thermal neutron capture is usually associated with photons emission, typically with an energy of a few MeV, e.g. 2.2 MeV from hydrogen. These photons can have normal EM interactions and produce $e^+e^-$ which carry the long ToF of the original neutron. Figures 8.5a and 8.5b show the relative ToF tail by particle type and by energy, respectively, obtained by dedicated simulations during which slow neutrons, i.e. $<20$ MeV have been suppressed. It can be seen that by discarding the slow neutrons the long tail disappears, but contributions by $e^+e^-$ with a delay up to $10\mu$s still remain. In addition the remaining “shoulder” includes particles with an energy $>10$ MeV, while from nuclear de-excitation a maximum energy of $\sim10$ MeV is expected.
stopped muons that generate the “shoulder” up to 10µs. A muon with sufficiently low energy can range out in the inner detector’s material - especially when looping in the solenoid field. A stopped muon will just rest for a mean time of 2 µs until it decays into an electron with up to 60 MeV of energy. These electrons from stopped muon decay form the hump in the ToF distribution, that extends up to ∼10 µs. Figures 8.6a and 8.6b show the relative ToF tail by particle type and by energy, respectively, obtained by dedicated simulations during which muons have been discarded while the low energy neutrons have been included. By discarding the muons, the “shoulder” as well as large-ToF particles with an energy >10 MeV disappear and only a smooth (long) tail remains.

Figure 8.7 Comparison of the total ionising dose in HGTD as a function of ToF between simulations where neutrons below 0.5 eV were included (black points) and discarded (red points).

In addition, a new simulation was performed during which the neutrons below 0.5 eV were killed. This energy corresponds to a velocity of 10 m/ms, as opposed to 2.2 m/ms for thermal neutrons. The results of this study are presented in Figure 8.7, where the extent of the neutron tail is noticeably reduced. This suggests that the cut-off of the tail at ∼10 ms arises from the ID dimension (few m) and the thermal velocity (2.2 m/ms), thus it gets cut with some correlation between the velocity of the neutrons and the length of the tail. The afterglow tail between few µs and few ms is due to (epi)thermal neutrons.
Chapter 9

Summary

During this thesis, new methods for extracting beam–induced background (BIB) fake jets and BIB-like BCM trigger signatures in the simulations and in the post-processing of the results have been developed. The simulation results have been compared with measurements of BIB in ATLAS during 2012 proton–proton operation and it is shown that the results agree within a factor of two with the BCM BIB and fake jet rates seen in the data. This factor is in agreement with the uncertainty of the residual gas pressure inside the beam pipe. The simulations reproduce successfully the time distribution of hits in the BCM detector and the one of fake jets in the pseudorapidity-time plane. Moreover, the simulated spectrum of energy depositions in the ATLAS calorimeters nicely matches the reconstructed transverse momentum of fake jets. The simulations also reproduce the azimuthal distribution of fake jets with the characteristic peaks at the horizontal plane. The simulations reveal also information that cannot be retrieved by the analyses of the data; the background at the BCM detectors mainly originates from the inner triplet region \( z < 55 \text{ m} \) while the majority of fake jets induced by beam–gas interactions have an origin at a distance of \( z \approx 150 \text{ m} \) from the IP.

The good level of agreement found in this work, testifies that a good understanding of beam background sources and dynamics has been achieved. Furthermore, it illustrates the power of the simulations tools that have been developed which can perform complex simulations accounting for a number of dynamic beam effects, transport of the beam–gas secondaries over long distances through the LHC magnets and eventually the ATLAS detector, and finally the modelling of the reconstructed background signatures in ATLAS.

In addition, the first isolated measurements of beam–halo background in the LHC experiments have been presented. Results are based on dedicated loss-map tests where low-intensity beams have been excited in order to induce beam losses on the primary collimators. The results demonstrate a clear correlation between the experimental backgrounds and the setting of the tertiary collimators (TCTs). Furthermore, it is shown that during the LHC physics runs, the beam halo contributes to
the total beam–induced background at the level of a percent or less thus confirming the validity of previous simulations.

Moreover, dedicated simulations of the halo-related background have been presented, demonstrating good agreement with the experimental data. The simulation results are normalized with the bunch intensity loss, which during the loss-map test is almost entirely due to losses on the TCPs. Taking into account systematic uncertainties, in particular possible machine imperfections which are not considered in the simulations, a good quantitative agreement with the measured background was obtained and features like transverse momentum and azimuthal distributions of fake jets were accurately reproduced. It should be noted that these cross-checks offer information about features that are not experimentally accessible, like correlations between backgrounds and the distributions of proton impacts on the collimators. The results provide vital information about the dependence between background and collimator settings, which is of central importance when optimizing the LHC optics for maximum peak luminosity. These results demonstrate that the beam–halo background at the LHC experiments is well understood and is not limiting the present operational performance of the LHC, nor does it seem to be a limiting factor of performance optimization in the foreseeable future.

It should be noted that for all realistic TCT settings - that respect the hierarchy of the multi-stage collimation system - the beam–halo background is almost negligible and does not impose a constraint on the TCT aperture. This result has significant implications for any future optimization of the LHC performance including the high-luminosity upgrade of the machine.

The simulation studies indicate that the beam–gas interactions contributing to the ATLAS backgrounds take place within a distance of $\sim$500 m from the IP of the experiment. This was further explored through a series of dedicated tests that took place during Run 2 of the LHC. These tests included local injection of small amounts of gas to determine the sensitivity to beam–gas events as a function of distance from the experiment. Analysis of these data is ongoing and the results could validate the exact regions where vacuum optimization has the largest impact on the background.

Finally, FLUKA simulation studies have been performed in order to characterise the radiation environment of the future HGTD detector of ATLAS. These studies had a strong contribution to the final design of the new moderator that protects the HGTD as well as to the determination of the radiation hardness of the sensors and the electronics, since it is essential that the detector can withstand the radiation levels throughout the HL-LHC operations. Moreover, these simulations revealed information about the nature of the afterglow seen by the HGTD, which is mainly due to thermal neutrons and slow (or stopped) muons.


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Publication-1

Published in Journal of Instrumentation, Volume 13, December 2018
Comparison between simulated and observed LHC beam backgrounds in the ATLAS experiment at $E_{\text{beam}} = 4$ TeV

The ATLAS collaboration

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ABSTRACT: Results of dedicated Monte Carlo simulations of beam-induced background (BIB) in the ATLAS experiment at the Large Hadron Collider (LHC) are presented and compared with data recorded in 2012. During normal physics operation this background arises mainly from scattering of the 4 TeV protons on residual gas in the beam pipe. Methods of reconstructing the BIB signals in the ATLAS detector, developed and implemented in the simulation chain based on the FLUKA Monte Carlo simulation package, are described. The interaction rates are determined from the residual gas pressure distribution in the LHC ring in order to set an absolute scale on the predicted rates of BIB so that they can be compared quantitatively with data. Through these comparisons the origins of the BIB leading to different observables in the ATLAS detectors are analysed. The level of agreement between simulation results and BIB measurements by ATLAS in 2012 demonstrates that a good understanding of the origin of BIB has been reached.

KEYWORDS: Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Radiation calculations; Simulation methods and programs

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1 Introduction

Proton losses in the Large Hadron Collider (LHC) ring upstream of the ATLAS experiment [1], due to interactions with either residual gas in the beam pipe (beam-gas scattering) or with machine elements such as collimators, result in beam-induced background (BIB). Although the rates are negligible compared to particle debris from almost $10^9$ proton-proton ($pp$) collisions per second, BIB has particular features that render it potentially problematic: it is characterised by particles almost parallel to the beam line, which can produce elongated clusters with large energy deposition in the innermost tracking detectors based on silicon pixel technology. At high rates, these abnormally large clusters can affect data-taking efficiency [2]. Furthermore, a potential background for physics analyses arises from high-energy muons, originating mostly from pion and kaon decay in the hadronic showers induced by beam losses. These muons can deposit large amounts of energy in calorimeters through radiative processes. Such energy depositions, which are not associated with a hard scattering at the interaction point (IP), can be reconstructed as fake jets leading to...
Table 1. LHC parameters during operation as a pp collider in the second half of 2012. The parameter $\beta^*$ refers to the value of the optical $\beta$-function at the collision point.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [TeV]</td>
<td>4.0</td>
</tr>
<tr>
<td>Protons per bunch [$10^{11}$]</td>
<td>$\sim$1.5</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>1374</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>50</td>
</tr>
<tr>
<td>Vertical crossing angle in IR1 [$\mu$rad]</td>
<td>145.0</td>
</tr>
<tr>
<td>$\beta^*$ in IR1 [m]</td>
<td>0.6</td>
</tr>
</tbody>
</table>

missing transverse momentum if overlaid with a collision event. Especially in searches for some exotic physics processes [3–6], fake jets represent a non-negligible background that must be well controlled and subtracted.

Although BIB has had no detrimental effects on ATLAS operation so far, the continuous striving for better LHC luminosity performance might change this situation in the future. A thorough understanding of the sources and nature of BIB, which is crucial when planning upgrades to the LHC, can only be achieved by a combination of measurements and simulations. A validation of the latter is the main purpose of this work.

A lot of experience with BIB was gained at the Tevatron and HERA colliders [7–9]. The first simulation predictions for BIB at the LHC were presented more than 20 years ago [10] and have been refined several times thereafter [11–14]. Throughout the LHC operation, BIB is routinely monitored and analysed by ATLAS [15, 16]. In this paper, comparisons between detailed simulations using the Fluka Monte Carlo (MC) simulation package [17, 18] and measurements [16] of BIB during the 2012 LHC run, with a proton beam energy of 4 TeV, are presented.

2 The LHC accelerator and the ATLAS experiment

The LHC accelerator and the ATLAS experiment are described in detail in refs. [19] and [1] respectively. Only a summary, focused on aspects relevant to the studies and simulations of BIB, is given here.

2.1 The LHC

The LHC, shown schematically in figure 1, consists of eight arcs that are joined by long straight sections (LSSs) of 500 m length. In the middle of each LSS there is an interaction region (IR); the ATLAS experiment is situated in IR1. The LHC beam-cleaning equipment is located in IR3 and IR7, for momentum and betatron cleaning respectively. The principal performance parameters of LHC operation in 2012 are listed in table 1.

A schematic layout of IR1, up to 165 m from the interaction point (IP, at $z = 0$), is shown in figure 2, where the separation of the two counter-rotating beams is illustrated. Copper absorbers
Figure 1. The general layout of the LHC [19], showing the eight interaction regions. The counter-circulating beams are shown schematically, i.e. their separation is not to scale. The ATLAS convention of labelling sides by ‘A’ and ‘C’ is indicated. The figure is adapted from ref. [20].

(TAS), which protect the superconducting inner triplets from collision debris, are located between \(|z| = 19\) m and \(|z| = 20.8\) m and have an aperture of \(r = 17\) mm. The final focus is provided by the quadrupoles of the inner triplets on each side of the IP, between \(|z| = 23\) m and \(|z| = 54\) m. The beam trajectories are separated at \(|z| \approx 70\) m inside the separation dipoles D1 and recombined in dipoles D2 at \(|z| \approx 160\) m, which bring the two beams into parallel trajectories at a distance of 194 mm from each other. The dipole D2 is superconducting and is protected by the neutral particle absorber (TAN), which intercepts energetic neutrons and photons emitted from the IP at very small angles.

The 400.79 MHz frequency of the LHC radio-frequency (RF) system and the revolution time of 88.9244 \(\mu s\) form 35640 buckets that can be filled with particles. In the 2012 LHC run, every 20\(^{th}\) bucket was filled giving a bunch spacing of 50 ns. In order to facilitate monitoring of BIB, a few (typically six per beam in 2012) unpaired bunches are included in each LHC bunch pattern. Having no counterpart in the other beam to collide with, these bunches provide the LHC experiments with a rather clean measurement of BIB.

2.2 The ATLAS experiment

The ATLAS experiment is one of the two general-purpose detectors at the LHC. With a length of 46 m and a diameter of 25 m, it is optimised to study proton-proton collisions at the highest available energies and luminosities.
Figure 2. Layout of the IR1 region showing the $z$-location of LHC beam-line elements and schematic beam trajectories. The $x$-coordinates refer only to the positions of the beams, not to the beam-line elements. The beams are separated by the D1 magnet and recombined into parallel trajectories by the D2 magnet. The tertiary collimator (TCT) is only on the incoming beam, just before the neutral particle absorber (TAN). The sense of focusing of the four triplet elements is indicated by the colour of the boxes (red = vertical, blue = horizontal) for the incoming beam. The interface plane is explained in section 5.

In this study, the right-handed ATLAS coordinate system is used. The origin is at the nominal IP and the azimuthal angle $\phi$ is measured relative to the $x$-axis, which points towards the centre of the LHC ring. Side A of ATLAS is defined as the side of the incoming, clockwise, LHC beam-1 while the side of the incoming beam-2 is labelled C, as illustrated in figure 1. The $z$-axis points from C to A, i.e. along the beam-2 direction. The pseudorapidity is given by $\eta = -\ln \tan(\theta/2)$, where $\theta$ is the polar angle relative to the $z$-axis. The transverse momentum is defined as $p_T = p \sin \theta$, where $p$ is obtained from the energy deposits in the calorimeters, assuming them to be massless.

ATLAS includes a dedicated beam conditions monitor (BCM) [21] for beam background measurements. The BCM consists of four small diamond modules on each side of the IP, at $z = \pm 1.84$ m, at a mean radial distance of $r = 55$ mm ($|\eta| \approx 4.2$) from the beam line. The modules are arranged in a cross: two in the horizontal and two in the vertical plane. Each module has two back-to-back sensors with an active area of $8 \times 8$ mm$^2$ and a total thickness of 1 mm.

The inner detector [22] is subdivided into a pixel detector immediately outside the beam pipe, a silicon-strip tracker and an outer transition-radiation tracker. These are inside a solenoid, which produces a 2 T magnetic field along the $z$-axis. The inner detector is used to determine the momentum of charged particles in the pseudorapidity range $|\eta| < 2.5$.

The calorimeter system, which measures the energy of the particles, includes a high-granularity liquid-argon (LAr) electromagnetic barrel calorimeter with lead as absorber; it has a half-length of $\sim 3$ m and extends radially from $r = 1.5$ m to 2.0 m, thus covering pseudorapidities up to $|\eta| = 1.5$. Between $r = 2.3$ m and 4.3 m a scintillator-tile hadronic barrel calorimeter (Tile) with steel as absorber and $\sim 6$ m half-length covers pseudorapidities up to $|\eta| = 1.7$. The calorimeter system is extended, up to $|\eta| = 3.2$, by electromagnetic and hadronic endcaps based on LAr technology. These have lengths, along $z$, of 0.6 m and 1.8 m respectively.
The calorimeters are surrounded by a muon spectrometer based on three large air-core superconducting toroidal magnets with eight coils each: one barrel toroid and two endcap toroids positioned inside the barrel at the ends of the central solenoid.

### 3 Beam-induced background

Beam induced background originates from three different beam-loss processes, which are illustrated in figure 3 and detailed below.

Inelastic proton interactions with residual gas inside the beam pipe (labelled 1 in figure 3), in the vicinity of the IP, constitute the dominant source of BIB in ATLAS. Hadronic and electromagnetic showers, but in particular high-energy muons produced by these interactions, can enter ATLAS and be detected by the BIB monitoring system. It was shown in previous studies [10] that inelastic beam-gas collisions up to distances of $\sim 500$ m from the IP contribute to the background.

A small fraction of BIB arises from beam halo, which is continuously repopulated by scattering of particles from the beam due to various processes such as elastic collisions at the experiments and with residual gas, noise on the RF system and feedback, intrabeam scattering, resonances and instabilities. The superconducting magnets of the LHC require very efficient halo-cleaning, which is realised by a multi-step cleaning system [23]. The primary and secondary collimators of the cleaning insertions in IR3 and IR7 intercept most of the off-momentum and betatron halo. A small fraction of the protons escape these insertions and constitute the tertiary halo (labelled 2 in figure 3) which is intercepted by the tertiary collimators (TCTs), located at distances of $z \approx 150$ m from each experimental IP. Protons impinging on the TCTs can also originate from elastic beam-gas interactions (labelled 3 in figure 3), which deflect protons out of the beam, around the whole accelerator ring. The losses on the TCTs create showers, which can propagate all the way to the IP. Dedicated tests [24] during 2015 and 2016 showed that, in normal physics conditions, total losses

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Figure 3. Schematic illustration of the three sources of BIB reaching ATLAS: (1) nearby inelastic beam-gas collisions, (2) tertiary beam halo losses on the TCT and (3) protons deflected by elastic beam-gas collisions and hitting the TCT. The cleaning insertions are 6.7 km away from ATLAS and the elastic beam-gas events are distributed around the entire accelerator ring. The distance from the beam to the collimators is a few millimetres.
on the TCTs contribute of the order of only 1% to the total BIB seen in ATLAS. Thus they are not considered in this paper.

The rate of beam-gas interactions is proportional to the residual gas pressure and the beam intensity. The latter is a property of the beams and is measured by the LHC with percent-level accuracy, but the pressure and molecular composition of the residual gas varies as a function of position around the accelerator. After pumping down of the LHC beam vacuum, a small amount of gas remains stuck on the beam-pipe surface. These gas molecules can be desorbed by synchrotron radiation or charged particles hitting the beam-pipe walls. The rate of outgassing depends on the intensity of the radiation and therefore the dynamical pressure depends on beam intensity and energy. In addition, the surface characteristics and temperature have a large influence on the residual pressure. The residual gas consists of H\textsubscript{2}, CH\textsubscript{4}, CO\textsubscript{2} and CO. Their relative fractions depend on local temperature, radiation load and surface characteristics of the beam pipe. In cryogenic sectors the gas condenses on the cold walls, but is relatively easily released by irradiation. Almost all room-temperature sectors of the LHC beam pipe are coated with a non-evaporable getter material [25], which provides distributed pumping along the beam line for all common gases except CH\textsubscript{4}. Therefore, methane is the dominant gas species in room-temperature sections, including the D1 dipole. Inside cryogenic magnets where the cold bore is at 1.9 K, notably those of the inner triplet and the LHC arc, all gases except hydrogen stick relatively firmly on the surface, so the dominant gas is H\textsubscript{2}. The magnets in the LSS, from D2 to the arc, are operated at 4.5 K. At this temperature all gases are more easily desorbed and here CO\textsubscript{2} is the most abundant gas species. Vacuum pumps produce local minima in the pressure and corresponding gradients which result in gas diffusion from sections with higher pressure towards the pumps.

The room-temperature sections of the LHC are equipped with vacuum gauges, but between these measurement points the pressure has to be obtained from simulations. The simulation models are based on theory and laboratory measurements of desorption rates and gas composition [26]. The amount of gas on the surfaces depends on the beam-conditioning history: when gas is desorbed and pumped out during beam operation the rate of outgassing slowly goes down. The state of surface conditioning, at any given time, has to be empirically estimated based on prior experience. Thus, the simulations depend on the local characteristics and temperature of the beam pipe, local pumping speeds, beam intensity and the estimated effects of the beam-conditioning history. The overall uncertainty in the local pressure due to knowledge of these parameters, especially of the state of surface conditioning, is estimated to be a factor of \( \sim 3 \). Since both the surface characteristics and the intensity of radiation vary as a function of position, this uncertainty is not a global scale factor of the entire pressure distribution; it is possible that the pressure is underestimated in some regions and overestimated in others.

4 Background monitoring methods

The rates of BIB are measured by the BCM and the calorimeters, which are described in section 2.2. They both provide low-level trigger signals which can be used for real-time background monitoring, and also record the data for detailed offline analysis. Only the unpaired bunches are used for monitoring and analysis of BIB. For inelastic beam-gas background these can be assumed to be perfectly representative of colliding bunches.
Figure 4. Illustration of the BCM background trigger signature for beam-1. The dotted line represents the trajectory of one particle hitting the upstream and downstream BCM modules. For beam-1 the early hit is on side A and the in-time hit on side C. For beam-2 the direction is reversed. The trigger can also be fired by two different particles, the only requirement being that any of the four modules on one side of the IP has an early hit and any of those on the opposite side has an in-time hit.

4.1 BCM background rates

Hits in the BCM modules are counted above a threshold of 250 keV, which corresponds to roughly 40% of the energy deposition of a minimum-ionising particle in 1 mm of diamond. Particles from beam losses reach upstream BCM detectors 6.1 ns before the nominal collision time, i.e. the passage of the bunch at the IP at $t = 0$, and produce early hits. Both the BIB and collision products from the IP produce in-time hits in the downstream detectors at $t = \pm 6.1$ ns.

A BCM background trigger signature, illustrated in figure 4, consists of an early hit in any module on the upstream side and an in-time hit in any module on the downstream side. The time windows of the background trigger are 5.46 ns wide and nominally centred at $t = \pm 6.25$ ns. The BCM has sub-nanosecond time resolution and the nominal centre of the trigger window is aligned with the LHC collision time to an accuracy better than 2 ns.

Due to the built-in direction requirement, the BCM background trigger is able to distinguish which beam the background originates from. In 2012 a single BCM background trigger, which fired on events in either direction, was used to collect events for the offline analysis.

4.2 Fake jets in calorimeters

The barrel and endcap calorimeters have nanosecond time resolution and contribute to a jet trigger with a $p_T$ threshold of 10 GeV at the electromagnetic scale, which is used to select fake-jet candidates induced by BIB in unpaired bunches. The jets are reconstructed with the anti-$k_t$ jet algorithm [27] with radius parameter $R = 0.4$ using the FastJet software package [28]. The inputs to this algorithm are topologically connected clusters of calorimeter cells [29], seeded by cells with an energy at least four standard deviations above the measured noise. These topological clusters are calibrated at the electromagnetic scale. The reconstructed jets are corrected for contributions from additional $pp$ interactions in the same and neighbouring bunch crossings as described in ref. [29]. In order to suppress instrumental backgrounds, standard data-quality requirements are imposed [30]. Data from periods affected by calorimeter noise bursts are excluded from the analysis.


5 Simulation framework

The simulation of the inelastic beam-gas events was performed with FLUKA using a two-step approach — a method first introduced in ref. [10] and illustrated in figure 5. The advantage of dividing the simulation into accelerator- and detector-specific parts is that it leaves more flexibility in the choice of simulation tools. This approach also saves computational resources since the results of the first step, simulation of particle transport and showering in the accelerator structures, can be used for several studies of the impact on the ATLAS detector.

The first step is discussed in detail in ref. [31]: beam-gas events with a uniform distribution in a z-range from 22.6 m to 546.6 m were generated with FLUKA as inelastic p-N\textsubscript{2} interactions. Although the residual gas composition varies along the ring and H\textsubscript{2} is most abundant in 1.9 K sections, the much larger interaction cross-sections of the other gas species cause them to dominate the interaction rate, especially in the LSS. Nitrogen is therefore considered to represent a good average of the atomic composition of the residual gas [14]. Using a generic gas species and a uniform distribution of events has the advantage that the same simulation results can be used with different pressure distributions. Unlike most previous studies [10–13], all simulations in this work were performed without any Monte Carlo variance reduction techniques, in order to preserve correlations within individual events. This is a prerequisite for reconstructing the trigger signatures. In the first simulation step, the secondaries produced in the beam-gas interactions are transported to a virtual interface plane at $z = 22.6$ m upstream of the IP. The choice of this z-location is motivated by the fact that it is on the IP-side of the closest inner-triplet magnet. Thus it naturally separates the experimental area, where a detailed FLUKA geometry of the ATLAS detector is available, from the LHC accelerator with its own geometry and magnetic field modelling. For all particles reaching this plane the positions, four-momenta and times of flight are recorded and serve as input to subsequent

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Variance reduction refers to favouring some regions of phase space at the cost of others in order to achieve faster convergence of the estimates in the favoured regions. While significantly reducing the computational effort, the disadvantage of these methods is that they do not preserve correlations within events.
detector simulations. For a complete description of the background, especially in the BCM with its low hit threshold, particles have to be transported down to low energies to ensure that all potential hits are simulated. Since this is very CPU-intensive, only six million inelastic events were simulated, transporting particles down to a kinetic energy of 20 MeV. This value of 20 MeV is chosen in order to stay above low-energy nuclear reactions which are the source of a large number of low-energy particles. Such particles are absorbed locally but, due to their abundance, their simulation is costly in terms of CPU time. Six million events are not enough for the fake-jet studies, so a second sample of 300 million \( p-N_2 \) interactions was generated with a threshold of 20 GeV. This 20 GeV threshold corresponds to the minimum energy of the muon needed to create a fake jet with sufficient transverse momentum to fire the jet trigger used in this study.

The rate of \( p-N_2 \) interactions as a function of \( z \), shown by the solid histogram in figure 6, is obtained from an equivalent \( N_2 \) density distribution of the residual gas, \( \rho_{N_2}(z) \). The partial densities \( (\rho_i) \) of all residual gas species at the location \( z \) are taken from the simulated pressure distribution and weighted by the ratio of inelastic proton-molecule \( (\sigma_i) \) to \( p-N_2 \) \( (\sigma_{N_2}) \) cross-sections:

\[
\rho_{N_2}(z) = \sum_i \rho_i(z) \cdot \frac{\sigma_i}{\sigma_{N_2}}, \tag{5.1}
\]

where \( i \) runs over \( \text{H}_2 \), \( \text{CH}_4 \), CO and \( \text{CO}_2 \). The absolute normalisation of all simulated rates in this paper is fixed by the interaction rates shown in figure 6. Since these are derived from the pressure distribution, they are subjected to the uncertainty in the pressure simulations, discussed in section 3.

The events used as input to the ATLAS simulations are sampled according to their \( z \)-coordinate, using the rate distribution of inelastic interactions, shown in figure 6. The dotted histogram in figure 6 shows, as a function of \( z \), the rate of those events for which at least one particle has reached the interface plane. A comparison of the two histograms in figure 6 reveals that practically all events produced at \( z \lesssim 150 \) m give contributions, while only \( \sim 1\% \) of events with \( z > 300 \) m result in particles at the interface plane.

In order to account for beam-gas events between the IP and the interface plane, \( p-N_2 \) events were generated separately for \( z < 22.6 \) m with a \( z \)-distribution sampled directly from the inelastic interaction probability in that region, i.e. left of the dashed vertical line in figure 6.

The particles at the interface plane, as well as those generated at \( z < 22.6 \) m, were transported through the ATLAS experimental area and detector using a dedicated FLUKA geometry model [32]. The magnetic fields produced by the ATLAS magnets were implemented as two-dimensional maps covering the entire detector radius and extending in \( z \) up to the interface plane. The propagation and showering of the particles through ATLAS was simulated with FLUKA, which provides accurate simulation of all relevant physics processes. Besides full simulation of hadronic and electromagnetic showers, FLUKA provides detailed transport of muons through matter with complete modelling of all energy loss processes and explicit production of secondary particles in radiative events. Compared to the full ATLAS simulation [33] based on GEANT 4 [34], the disadvantage of choosing FLUKA is that an exact modelling of the detector response is not available. In particular, digitisation and reconstruction of e.g. tracks and jets cannot be performed in FLUKA simulations with a level of...
Figure 6. Inelastic beam-gas interaction rate of beam-1 in IR1 as a function of distance from the IP at the start of data-taking in LHC fill 2736. The beam moves towards negative \( z \), i.e. from right to left in the figure. The total rate (solid blue histogram) reflects the residual gas pressure. The dotted histogram shows the rate of interactions which contribute at least one particle with kinetic energy \( E > 20 \text{ MeV} \) at the interface plane at \( z = 22.6 \text{ m} \). The prominent peaks between \( z \approx 150 \text{ m} \) and \( z \approx 270 \text{ m} \) correspond to the positions of the TCT, the D2 dipole (\( T = 4.5 \text{ K} \)), Q4–Q6 quadrupoles (\( T = 4.5 \text{ K} \)) and cold-warm transitions at the exit of the arc. The pressure in the LHC cold arc (\( T = 1.9 \text{ K} \)), starting at \( \sim 270 \text{ m} \), is assumed constant. The small inset shows the interaction rate on the IP side of the interface plane in more detail.

detail comparable to real data. Dedicated algorithms were incorporated in the \textsc{Fluka} simulation in order to record quantities of interest, namely energy depositions and detector hits, on an event basis. The rates of fake jets and events with the BCM background trigger signature were estimated using custom reconstruction algorithms during the post-processing of the simulation output.

The geometry of the BCM detector was modelled, including both the sensitive detector and the services. The transport threshold in the ATLAS simulations was set to 100 keV, so that all particles able to generate hits in the BCM detector were included in the simulations. Neutrons were always transported to thermal energies and their capture by nuclei, with associated photon emission, was simulated.

Due to the 20 MeV transport threshold the LHC simulations do not include particles down to 100 keV. This has no significant influence on the results, since particles starting from the interface plane will not reach the BCM directly: most of them are intercepted by the TAS. Those which pass through its small central aperture have to traverse the beam-pipe wall at a very shallow angle, which implies a high probability for an inelastic interaction. This was verified by checking that the BCM trigger rates as a function of the \( z \)-coordinate of the origin of the event, as obtained from the “fully
Table 2. Radial and longitudinal extent of the ATLAS calorimeter regions and bin sizes ($\delta r$, $\delta z$) as implemented in the FLUKA geometry. An azimuthal binning of 36 bins of 10 degrees each is used in all calorimeter regions. The endcaps at the negative (‘−’) side of ATLAS are mirror images of the positive (‘+’) ones.

<table>
<thead>
<tr>
<th>Calorimeter</th>
<th>$r_{\text{min}}$ [mm]</th>
<th>$r_{\text{max}}$ [mm]</th>
<th>$z_{\text{min}}$ [mm]</th>
<th>$z_{\text{max}}$ [mm]</th>
<th>$\delta r$ [mm]</th>
<th>$\delta z$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel LAr</td>
<td>1471</td>
<td>2009</td>
<td>−3172</td>
<td>3172</td>
<td>107.6</td>
<td>396.5</td>
</tr>
<tr>
<td>Barrel Tile</td>
<td>2285</td>
<td>3885</td>
<td>−6000</td>
<td>6000</td>
<td>160.0</td>
<td>400.0</td>
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<tr>
<td>Endcap1 (+)</td>
<td>475</td>
<td>2075</td>
<td>3670</td>
<td>6120</td>
<td>160.0</td>
<td>408.3</td>
</tr>
<tr>
<td>Endcap2 (+)</td>
<td>300</td>
<td>475</td>
<td>3670</td>
<td>4650</td>
<td>87.5</td>
<td>490.0</td>
</tr>
</tbody>
</table>

Figure 7. The $r$-$z$ projection of the average fractional energy distribution, found in the FLUKA simulations for jets with $p_T > 16$ GeV in the barrel LAr calorimeter. The beam direction is from right to left in the plot. The values are summed over seven bins in azimuth, centred at the maximum, and normalised such that for each event the maximum bin is 1.0. Before averaging over all events, they are aligned such that the largest deposition is at the centre of the plot. The $r$ and $z$ bin numbers shown in the plot are relative to the centre. The dashed box indicates the $3\times3$ $r$-$z$ bins used for determining the jet energy (summed over azimuthal bins).

100 keV simulation of events on the IP side of the interface plane, join smoothly with the rates from the “mixed 20 MeV & 100 keV” simulation of events beyond $z = 22.6$ m. In the simulations the threshold of a BCM module is accounted for by considering as a hit each charged particle with a kinetic energy above 250 keV, entering the sensitive area of a BCM module. This simplification is motivated by the fact that a particle deposits in the module at least the minimum-ionising equivalent or its total kinetic energy, whichever is smaller. The sensitivity of the results to the choice of threshold was evaluated by varying it between 100 keV and 1 MeV. The simulated BCM trigger rate was affected by only a few percent. The arrival time and the identifier of the module entered are used to reconstruct the BCM background triggers from the recorded data and simulation output. Each hit results in a dead time of the affected BCM module, the duration of which depends on the energy but is typically 10–20 ns. For simplicity only the first hit in each BCM module, in a $\pm 12.5$ ns window around $t = 0$, is considered, both in the simulations and the data.
Since fake jets are mainly produced by radiative energy losses of high-energy muons, the computational effort was significantly reduced by selecting only muons from the sample with a 20 GeV threshold. The propagation and showering in ATLAS was simulated with a 100 keV transport threshold. The fake-jet rates are estimated by recording, event by event, the local energy depositions in the different calorimeter regions which are described in Table 2. After the simulation of each event, the energy depositions are analysed.

Since Fluka is not part of the standard ATLAS simulation software, it does not benefit from the sophisticated ATLAS jet-reconstruction tools. Instead, a much simplified algorithm is used to assess the fake-jet rate in the simulations. A cluster is formed by summing the energy depositions in $3 \times 3 \times 3 = 27 (r, \phi, z)$-bins, centred around the maximum deposition. In the barrel calorimeters this clustering produces jets with angular dimensions comparable to those of the ATLAS jet-reconstruction algorithm. Each deposition is used only once, starting with the highest in any bin. If the cluster energy is large enough to exceed the 10 GeV transverse-energy threshold, the cluster is counted as a fake jet. The position of the fake jet is determined from the energy-weighted average of the bins considered. Likewise the jet time is determined from the energy-weighted time of the individual depositions. Depositions at times larger than 50 ns are excluded in order to prevent small depositions with very large delay, e.g. from thermal neutron capture, to influence the average time. This procedure is fully consistent with the reconstruction of jet time in ATLAS data, which also takes into account only depositions in a narrow time window.

In order to assess the systematic uncertainty due to the energy spread, sums over more bins were explored and it was found that an extension of the sum in $r$ and $\phi$ adds almost no energy to the cluster. In $z$, however, taking the sum over more bins results in a larger cluster energy. Figure 7 shows the $r$-$z$ projection of the average energy fraction in the different bins around the maximum. The energy is well contained in the central $3 \times 3$ bins. The continuous energy loss of the passing muon, about 1 GeV per metre in the calorimeters, is reflected as a row of almost constant values for $r$-bin = 0 and $|z|$-bin > 1 in figure 7. A wider summing range in $z$ mostly adds this ionisation energy loss of the muon, which would be a non-negligible contribution to the lowest jet energies considered in this study. The average energy lost by the muon, however, is below the threshold of the ATLAS jet reconstruction, so in data only upward fluctuations of the muon energy loss are likely to be combined into the jet, if they happen close enough to the large radiative loss. Therefore an energy sum over $3 \times 3 \times 3$ bins is considered a good approximation to the reconstruction algorithm applied to the data.

6 Comparison with data

The principal objective of this work is to validate, through comparisons with data, the simulation methods described in section 5. For this purpose, events collected with the BCM background and low-$p_T$ jet triggers during 2012 are analysed. The vacuum simulations assume the beam conditions at the start of LHC fill 2736, which correspond to the parameters listed in Table 1 and are typical of the operation in the second half of 2012. Only fills with the same bunch pattern as in fill 2736 are considered in the analysis. Data affected by more than 20% trigger dead time are rejected and a dead-time correction is applied to the remaining data. In order to remove the effect of the beam intensity, which decreases in the course of a fill, all results are normalised to $10^{11}$ protons. However,
since the residual gas pressure follows the decrease of beam intensity over a LHC fill, fill-averaged beam-gas rates are lower than those at the start of a fill.

### 6.1 BCM background

In figure 8 the BCM background rates during the first ten minutes of data-taking are shown for all LHC fills included in the analysis. The direction information provided by the BCM is used to reject events in the direction opposite to the unpaired bunches, which are used for the background measurement. Such wrong-direction signals can arise either from ghost charge in the opposite beam or from accidental background signatures involving hits from afterglow [16]. Although the data are selected such that they should correspond to the same beam conditions, a significant fill-to-fill variation and slightly increasing trend over the year can be seen. The BCM background from beam-1 is found to be systematically higher than from beam-2. The relative difference, averaged over all the data in figure 8, is 28%. Since the simulations make no distinction between the two beams, they are compared with the average. Although, at ±14%, the difference between the beams is small compared to the fill-to-fill variation, it is included in the variation in the data quoted in table 3.

Table 3 compares the simulated BCM beam background rates with the start-of-fill and the fill-averaged data taken in 2012. The simulated rate of $1.2 \text{Hz}/10^{11}$ protons is almost twice the measured start-of-fill value. Figure 8 shows separately the observed BCM background rate in fill 2736, for which the pressure simulations are performed. With a rate of $0.72 \text{Hz}/10^{11}$ protons it falls close to the upper edge of the fill-to-fill variation and thus closer to the simulated value than the 2012 average shown in table 3.

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4 Ghost charge is formed by beam protons that have escaped their initial RF-bucket and been recaptured in nominally empty buckets.
Table 3. Simulated BCM background rates compared with ATLAS data. The rates correspond to events giving, in the BCM, a background signature that is consistent with the direction of the unpaired bunch. The simulations correspond to the start of data-taking, while the last two columns illustrate the difference in background between averaging over the first ten minutes of data-taking in each fill and averaging over entire fills. For the data, the uncertainty in the average corresponds to one standard deviation of the mean of all fills. For the simulations it indicates the statistical uncertainty. The fill-to-fill variation includes the difference between beam-1 and beam-2. The last row indicates the possible range of the simulated rate, due to the estimated uncertainty of the pressure simulation, discussed in section 3.

<table>
<thead>
<tr>
<th></th>
<th>MC simulation [0–546.6 m]</th>
<th>Data Fill Start</th>
<th>Data All Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average rate [Hz/10^{11} protons]</td>
<td>1.2</td>
<td>0.642</td>
<td>0.463</td>
</tr>
<tr>
<td>Uncertainty in average rate</td>
<td>0.4%</td>
<td>2.0%</td>
<td>2.3%</td>
</tr>
<tr>
<td>Fill-to-fill rate variation</td>
<td>—</td>
<td>27%</td>
<td>34%</td>
</tr>
<tr>
<td>Pressure uncertainty [Hz/10^{11} protons]</td>
<td>0.4–3.6</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

In the inner triplet, \( p-H_2 \) scattering contributes about 90% of the beam-gas interactions, while the simulations are based on \( p-N_2 \) events. Equation (5.1) ensures that the correct number of beam-gas collisions is generated in the simulations, but it does not account for differences in the collision dynamics, especially the multiplicity of produced secondaries. In order to estimate the possible dependence of the background rate on the target nuclide, the less CPU-intensive simulations at \( z < 22.6 \) m were repeated with \( p-H_2 \) events. The rate was found to decrease by about 15%. Assuming a similar reduction for the inner-triplet region, where most of the BCM background originates from (see section 7), the use of proton-\( N_2 \) events overestimates the BCM trigger rate by up to 15%.

Even after accounting for this correction, the observed difference between simulation and data is larger than the fill-to-fill variation, but remains well within the estimated uncertainty range of the simulation, which is dominated by knowledge of the pressure distribution.

In figure 9 the distribution of particle arrival times at the BCM modules in the simulation is compared with data. The histograms represent the time distribution of hits in upstream BCM modules for events which give the BCM background signature in beam-1 unpaired bunches. The plain Fluka simulations yield a very narrow time distribution with a vertical rising edge. In the analysis, this is smeared by the 0.25 ns time fluctuation due to the LHC bunch length of 75 mm. A larger broadening effect comes from the instrumental resolution and time alignment of the BCM. In order to account for these, the rising edge of the simulated time distribution is fitted to that in data with the time alignment and time resolution as free parameters. Values of \(-1.0 \) ns and 0.55 ns are found for these parameters respectively. The fit yields an uncertainty of about 10% in both parameters. The observed time shift is well within the 2 ns alignment tolerance specified for the BCM. The fitted time resolution is about 30% better than that found in test-beams [21]. However, it agrees, within its 10% uncertainty, with the resolution derived from in-situ monitoring of the time difference between hits in upstream and downstream modules in collision events recorded by the BCM detector.

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The centre of the bunch passes the IP at \( t = 0 \), but the background event can originate from any proton within the bunch.
Figure 9. Comparison of the time distribution of BCM hits in ATLAS unpaired-bunch data (blue histogram) with FLUKA simulation (red circles). The bunch passes the IP at $t = 0$ ns. The histograms show the early hits per upstream BCM module for events which have fired the BCM beam-background trigger in the beam-1 direction. The black open squares show the contribution from beam-gas events within the ATLAS experimental area $z < 22.6$ m, while the red solid circles show the total, i.e. $z < 546.6$ m. The errors shown on the simulation are statistical only. The blue band indicates the fill-to-fill and module-to-module variation of the data and the error bars show the uncertainty in the mean value. The lower panel shows the ratio of simulation to data, taken between the red circles and the blue histogram. Only data from the first ten minutes of ATLAS data-taking in each LHC fill are considered.

The data shown in figure 9 are extracted from the events recorded during the first ten minutes of each LHC fill. A determination of the fill-to-fill variation for each bin is not feasible since, especially in the tail region, the very low counting rate causes many bins to have zero counts for a single fill. If, however, the shape of the distribution is assumed to be invariant between fills, the fill-to-fill variation of each bin can be taken as 27%, which is the value given in table 3 for the total rate. The blue band shown around the data in figure 9 illustrates this fill-to-fill variation, but takes also into account the total counting statistics in each bin. The uncertainty in the mean value in each bin is determined from the data in all fills and shown by the smaller error bars on the data. For the simulations, only the statistical uncertainties are shown. The error bars on the ratio of simulation to data are based on the statistical uncertainties only. If the shape of the distribution is correctly reproduced by the
Figure 10. Simulated $x$-$y$ distribution of muons with energy $E > 20$ GeV entering the ATLAS experimental area at $z = 22.6$ m. The beam passes at $(x, y) = (0, 0)$. The plot is based on ref. [31] and constitutes the input to the study described in this paper. The rate corresponds to the pressure conditions at the start of fill 2736.

simulation, the ratio should be a constant. However, since the simulations correspond to a particular fill, this constant can deviate from unity by the amount of the fill-to-fill variation. The allowed range ($1\sigma$), ignoring the uncertainty arising from the pressure distribution, is indicated by the blue band.

The ratio shown in figure 9 indicates that the peak is overestimated by the simulations, while the tail at positive times is underestimated, i.e. the peak-to-tail ratio is larger in the simulations than in data and, consequently, the falling slope is slightly steeper. The open squares in figure 9 show that the events within the ATLAS experimental area contribute only 20% to the total hit rate but the shape, especially the peak-to-tail ratio, is similar to that of the total rate. If the tail were due to delayed arrival of some particles from distant events, i.e. due to a dependence between time spread and distance to the event, then it should not appear for the beam-gas events at $z < 22.6$ m. The fact that a tail of similar height, relative to the peak, is seen in both distributions indicates that the delayed particles are due to a local effect. The simulated hits in the tail are found to be caused by particles with a kinetic energy below $\sim 10$ MeV and if the solenoidal field is turned off in the simulations, the tail is suppressed. These findings indicate that the tail is due to low-energy particles looping in the magnetic field and accumulating a delay due to the longer path along the helix. Since such low-energy particles have a short range in matter already a slightly too large amount of material in the simulation geometry, with respect to reality, is sufficient to explain the observed underestimation.

6.2 Fake-jet background

Most of the fake jets are produced by radiative energy losses of high-energy muons in the calorimeters. Such fake jets have a very different topology from collision jets: they do not point to the
IP and are almost entirely of electromagnetic nature with very little hadronic activity. Therefore
the simulation results are compared with jet data calibrated to the electromagnetic energy scale rather than with fully calibrated jets, which are corrected for the non-compensating response of the calorimeter to hadrons. Possible jets from collisions of the protons in the unpaired bunch with ghost charge in the other beam are removed by rejecting events for which a primary vertex has been reconstructed from the tracks measured by the inner detector. Only the highest-$p_T$ jet in each event is included in the analysis. In the endcap calorimeters, hadronic showers can contribute to the fake jets. Since only muons are considered in the simulations, the analysis is restricted to $|\eta| < 1.5$, i.e. the barrel calorimeters. These are at large radii and shadowed by other detector elements so hadronic showers from the beam line cannot reach them.

Figure 10 shows the $x$-$y$ distribution of muons with energy $E > 20$ GeV reaching the interface plane. This distribution reflects the geometry of the LHC tunnel, and also the effect of some beam-line magnets. The tunnel’s radius of 2.2 m and the floor at $y = -1.1$ m produce a relatively sharp edge in the muon flux. The higher rate seen on the inside of the ring at $y \approx \pm 1$ m, between $x \approx 1.5$ m and $x \approx 2.5$ m, is due to the offset of the beam line relative to the centre of the tunnel, leaving more free space for pions and kaons to decay into muons on the inside of the ring. The “hot spots” seen around $x \approx \pm 0.8$ m are mainly due to bending of the off-momentum muons by the D1 and D2 dipoles of the LSS. The vertical spread at $x = 0$ is probably due to bending in the quadrupoles of the inner triplet, although the crossing angle might also have some influence on this.

In table 4 the rates of simulated fake jets, created by the muons shown in figure 10, are compared with the data from all relevant fills in 2012. Systematic uncertainties may arise from the jet reconstruction used in the simulations. The studies described in section 5 show that increasing the extent over which the jet energy is integrated in the simulations from $3 \times 3 \times 3$ bins to a very wide $7 \times 7 \times 7$ bins increases the jet rate by 20%. However, since this increase is due to including the ionisation energy loss of the passing muon, it does not seem justified to consider it as a systematic uncertainty, but rather an upper limit thereof. Thus the uncertainty from the jet reconstruction algorithm is considered negligible compared with the uncertainty from the pressure distribution. The latter is estimated to be a factor of three, which means that the high level of agreement between simulations and data, seen in table 4, must be largely fortuitous.

The offset in arrival time, at given $z$, between the proton bunch and a beam background muon originating from that bunch, is negligible. Therefore, when the beam background muon reaches an upstream point $P(r, z)$ in the calorimeter, the proton bunch still has to cover a distance $|z|$ to reach the IP and then the produced secondary particles have to travel a distance $s = \sqrt{r^2 + z^2}$ to reach $P$, as illustrated in figure 11. For a downstream $P$ the expression for $s$ is the same, but in this case the muon has to cover the additional distance $|z|$. The calorimeter timing is such that for each point $P$ the arrival time of a secondary particle produced in collisions at the IP is 0. Thus the relative time $\Delta t$ of a beam background muon at $P$ is given by

$$\Delta t = -\left(\sqrt{r^2 + z^2} \pm |z|\right)/c$$

(6.1)

where $c$ is the speed of light and $+|z|$ and $-|z|$ correspond to the upstream and downstream sides respectively. Equation (6.1) shows that fake jets due to BIB always arrive early, i.e. have $\Delta t < 0$. A characteristic banana shape is seen in the $\eta$-$\Delta t$ plane, shown in figure 12; this arises from the definition of $\eta$ and the dependence of jet time on $z$ and $r$. 

\[ \text{Figure 11}\]
Table 4. Simulated fake-jet rates compared with ATLAS data. Only jets with $p_T > 16$ GeV and $|\eta| < 1.5$ are considered. The simulations correspond to the start of data-taking, while the last two columns illustrate the difference in background between averaging over the first ten minutes of data-taking in each fill and averaging over entire fills. For the data, the uncertainty in the average corresponds to one standard deviation of the mean of all fills. For the simulations it indicates the statistical uncertainty. The fill-to-fill variation includes the difference between beam-1 and beam-2. The last row indicates the possible range of the simulated rate, due to the estimated uncertainty of the pressure simulation, discussed in section 3.

<table>
<thead>
<tr>
<th></th>
<th>MC simulation [0–546.6] m</th>
<th>Data Fill Start</th>
<th>Data All Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average rate [Hz/10^{11} protons]</td>
<td>0.0053</td>
<td>0.0046</td>
<td>0.0037</td>
</tr>
<tr>
<td>Uncertainty in average rate</td>
<td>1.0%</td>
<td>3.4%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Fill-to-fill rate variation</td>
<td>—</td>
<td>56%</td>
<td>39%</td>
</tr>
<tr>
<td>Pressure uncertainty [Hz/10^{11} protons]</td>
<td>0.002–0.015</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 11. Schematic illustration of reconstructed arrival time of beam background muons compared with collision jets in the calorimeter regions. The two grey boxes represent two different calorimeters and the red solid line represents $t = 0$, corrected for the time of flight of particles coming from the IP.

The number of fake-jet counts in the data is low. To maximise the amount of data when studying distributions of fake jets, in the following plots data from entire fills are used while the simulations correspond to the higher rate at the start of a fill. In order to compensate for this, the MC results have been scaled by the ratio of “All Fill” to “Fill Start” values given in table 4.

Figure 12 compares the distribution in the $\eta$-$\Delta t$ plane of fake jets seen in ATLAS data with the simulated rate of energy deposition clusters having $p_T > 16$ GeV. The pedestal, i.e. entries outside the banana area, seen in figure 12a is mostly due to beam-gas and off-momentum halo background from ghost charge [16], a contribution that is not included in the simulations. A time-smearing due to the LHC bunch length has been applied to the simulated jet times. The instrumental time resolution

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The data in the $\eta$-$\Delta t$ plot are restricted to LHC fills prior to 3rd August when the LHC made chromaticity changes which caused a significant increase of ghost charge [16].
Figure 12. (a) Fake-jet counts in unpaired bunches in the pseudorapidity-time ($\eta$-$\Delta t$) plane for beam-1 in ATLAS data and (b) the simulated rate of energy deposition clusters with $p_T > 16$ GeV in the $\eta$-$\Delta t$ plane. The width of the bins is 1 ns in time and 0.1 units in $\eta$. The FLUKA simulations, which correspond to the start-of-fill conditions, have been scaled by the ratio of the total “All Fill” to “Fill Start” rates, shown in table 3.

of the calorimeters depends on $\eta$ and the calorimeter cell energy. For figure 12b the instrumental resolution was determined by fitting the width of the downstream tail of the banana shape in simulation, between $\eta = -3$ and $\eta = -2$, to the data. The fitted value of 0.5 ns is consistent with the range of resolutions measured for the ATLAS calorimeters. The dashed horizontal lines indicate the jet-trigger time window of $\pm 12.5$ ns. Entries falling outside these lines are not seen in data, unless the event was selected by another trigger or has a sufficiently energetic subleading jet within the trigger window. The position and curvature of the banana pattern within the trigger window is well reproduced by the simulations, which indicates that the jet times are correctly simulated.

The curvature of the banana shape depends on the radial position in the calorimeter: as indicated by eq. (6.1) and figure 11, fake jets at $P_2$ will have a larger time advance than those at $P_1$ due to the difference in radial position. In figure 12, two banana shapes with slightly different curvature can be distinguished. The upper and lower tails correspond to fake jets in the LAr and Tile calorimeters respectively. At higher $|\eta|$ on the downstream side the bananas merge and the fake-jet times approach $\Delta t = 0$, although a small negative offset remains due to the dependence on $r$ in eq. (6.1). Very early fake jets, with $\Delta t < -20$ ns, are seen in the simulations. These are all in the upstream part of the barrel Tile calorimeter or the upstream endcaps. Falling outside the trigger window, they are not seen in the data. However, a minor concentration of jets at $\eta \approx 2$ and $\Delta t \approx 10$ ns can be distinguished in figure 12a. It is caused by upstream fake jets associated with the following bunch, which arrives 50 ns later. These jets are reproduced by the simulations and are seen at the same $\eta$ but at $\Delta t \approx -40$ ns in figure 12b.

Figure 13 compares transverse-momentum and azimuthal-angle distributions of the simulated fake jets with data. For these comparisons, jets within the banana area are extracted from data in order to minimise the contribution from the pedestal. As in the case of figure 9, the low count rates
Figure 13. Distributions of (a) transverse momentum $p_T$ and (b) azimuthal angle $\phi$ of fake jets with pseudorapidity $|\eta| < 1.5$ in data (blue histogram) compared with those of energy deposition clusters from FLUKA beam-gas simulations in the same $\eta$ range (red circles). The $p_T$ spectrum indicates that the ATLAS jet trigger reaches full efficiency only around 15 GeV. Therefore an additional requirement of $p_T > 16$ GeV is applied to events in the azimuthal-angle distribution. The errors shown on the simulation results are statistical only. The blue band indicates the fill-to-fill variation of the data, while the small blue error bars show the uncertainty in the mean of all fills. Data from entire fills have been used in order to minimise statistical uncertainties. The simulations, which correspond to the start-of-fill conditions have been scaled by the ratio of the total “All Fill” to “Fill Start” rates, shown in table 3.

prevent an estimation of the fill-to-fill variation in individual bins. The same approach as described for figure 9 is adopted, i.e. the blue band shows the fill-to-fill variation determined from the total rates and the small error bars show the uncertainty in the mean value in each bin.

The transverse-momentum distribution of the simulated fake jets, shown in figure 13a, continues on a rising slope below $\sim 15$ GeV, while the data dip down. This is due to the jet trigger, used to select the data, which reaches full efficiency only above $\sim 15$ GeV. When full trigger efficiency is reached, the simulations agree well with the data up to $p_T \approx 50$ GeV, but towards higher transverse momenta the simulation tends to overestimate the data.

In figure 13b an additional requirement of $p_T > 16$ GeV is applied in order to select events above the trigger efficiency turn-on. The azimuthal distribution of fake jets from BIB is well reproduced at a qualitative level. The characteristic peaks at $\pm \pi$ and 0 are mainly due to the bending in the horizontal plane that occurs in the D1 and D2 dipoles and the LHC arc [15]. The lower rate at $-\pi/2$ compared to $\pi/2$ is due to the tunnel floor reducing the muon flux, as seen from the contours in figure 10. A tendency of the simulation to overestimate the data between $\phi = -1$ and $\phi = \pi/2$ and to underestimate around $\phi = -\pi/2$ is seen. A comparison with figure 10 suggests that these effects might be related to the tunnel geometry: the simulations underestimate at $-y$, where the
tunnel floor reduces the free drift space for pion and kaon decay, and overestimate around $+x$ where the horizontal offset provides extra space. Such differences could arise, for instance, if the $z$-distribution of the beam-gas events is not correct. A wrong $z$-distribution could change the impact of the reduced, or increased, free drift space. Another possibility is an inaccurate description of material around the beam line, which would affect the free drift space available. Forthcoming background measurements, with artificially introduced local pressure bumps, may shed some light on this. Cosmic-ray muons, which can also produce fake jets, are included in the data but not in the simulation. Studies reported in ref. [16] indicate that the fake-jet rate at low $p_T$ arising from cosmic-ray muons is less than 10% of the total rate due to BIB. The radiative energy losses are point-like processes and since the flux of cosmic muons is uniform in space and time, the rate of fake jets produced by them should be independent of $\phi$. However, due to the significant variation of the rate as a function of $\phi$, a visible contribution from cosmic-ray induced fake jets cannot be entirely excluded around $\phi = -\pi/2$, where the rates are lowest.

Although the differences in the shapes of the distributions shown in figure 13 are not understood, the agreement can be considered good, given the complexity of the entire simulation chain. The large systematic uncertainty due to limited knowledge of the residual gas pressure distribution is the most likely cause of the differences seen, although more detailed studies with localised and well-controlled pressure bumps will be needed to verify this.

7 Origin of backgrounds

Knowledge of the $z$-coordinate of the origin of each simulated event provides information beyond that which can be extracted from the data. Figure 14 shows the distribution of the origins of the simulated events that give a BCM background trigger signature or generate a fake jet in the barrel calorimeters. The black histogram, which shows the $z$-distribution of the generated events, reflects the residual gas distribution in the beam pipe and is equivalent to figure 6. Most of the events with a BCM background trigger signature originate from the inner-triplet region ($z \approx 22–55$ m) with a small contribution from $z \approx 150$ m, where the tertiary collimator causes a local pressure bump. This result is consistent with the observations made in the data, that the BCM background trigger rate correlates with the residual gas pressure measured by vacuum gauges at $z = 22$ m [16]. The fake jets, on the contrary, originate predominantly from more distant beam losses with pronounced spikes at the locations of the 4.5 K magnets. According to the simulations, about 10% of fake-jet events are associated with beam-gas events in the LHC arc ($z > 270$ m), but this fraction depends strongly on the relative pressure in 4.5 K and 1.9 K sections. The lower plot in figure 14 shows the cumulative distributions corresponding to the histograms in the upper plot. These highlight that practically all BCM background events originate from $z < 60$ m while only $\sim 1\%$ of fake-jet events are associated with beam-gas collisions in that $z$-range. Since the simulations disfavour any significant correlation between BCM background and fake jets in the barrel calorimeters, they suggest that BCM and fake-jet rates, seen in the data, can be used to disentangle backgrounds originating from different regions in $z$. As discussed before, the residual gas pressure depends on local properties of the beam pipe, such as material and temperature, and also on the radiation intensity. Therefore the pressure in different $z$-regions, as well as its uncertainties, can be considered to be uncorrelated. In particular, the prediction of BCM background, which originates predominantly from the inner triplet, depends on the accuracy of the pressure simulations within 1.9 K magnets. Most of the fake
jets originate from the beam-gas events within 4.5 K magnets where the desorption characteristics and, therefore, the gas composition, are different. Thus it is not surprising to find, in tables 3 and 4, better agreement in one observable than in the other.
8 Conclusion

Beam-induced background measurements in ATLAS during the 2012 LHC run with 4 TeV proton beams are compared with dedicated FLUKA Monte Carlo simulations of the background due to inelastic beam-gas interactions. Methods of extracting fake jets and BCM trigger signatures from a FLUKA simulation were developed and applied during simulations and the post-processing of the results, i.e. reconstruction of the background signatures. The simulations, performed using a two-step method, agree within a factor of two with the rate of background trigger signatures in the BCM detector and the fake-jet rates observed in the ATLAS data. This is well within the uncertainty in the residual gas pressure in the beam pipe.

Simulations reproduce rather well the shape of the time distribution of hits in the BCM as well as that of the fake jets in the pseudorapidity-time plane. The simulated spectrum of energy depositions in the calorimeters agrees with the spectrum of reconstructed transverse momenta of the observed fake jets although there is an indication of an overestimate towards higher $p_T$. In the azimuthal distribution of the fake jets, the characteristic peaks in the horizontal plane are reproduced by the simulations, but differences are seen in some details of the structure in azimuthal angle. These might be related either to inaccuracies in the pressure distribution or incomplete modelling of material close to the beam line.

The simulations indicate that background seen by the BCM originates mainly from the inner triplet region ($z < 55 \text{ m}$) while the majority of fake jets induced by beam-gas interactions have an origin at a distance of $z \gtrsim 150 \text{ m}$ from the interaction point.

The level of agreement between the simulations and measurement demonstrates the good understanding of beam background that has been reached in the ATLAS experiment. It also illustrates the capability of the various simulation tools to reproduce the beam background through a complex chain involving simulation of the residual gas pressure distribution, taking into account various dynamic effects from the beam, transport of the beam-gas secondaries over long distances in the LHC magnet lattice and through the ATLAS detector, and finally the modelling of the reconstructed background signatures in ATLAS.

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Collimation-induced experimental background studies at the CERN Large Hadron Collider

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The data produced at the particle physics experiments at the Large Hadron Collider (LHC) contain not only the signals from the collisions, but also a background component from proton losses around the accelerator. Understanding, identifying and possibly mitigating this machine-induced background is essential for an efficient data taking, especially for some new physics searches. Among the sources of background are hadronic and electromagnetic showers from proton losses on nearby collimators due to beam-halo cleaning. In this article, the first dedicated LHC measurements of this type of background are presented. Controlled losses of a low-intensity beam on collimators were induced, while monitoring the backgrounds in the ATLAS detector. The results show a clear correlation between the experimental backgrounds and the setting of the tertiary collimators (TCTs). Furthermore, the results are used to show that during normal LHC physics operation the beam halo contributes to the total beam-induced background at the level of a percent or less. A second measurement, where the collimator positions are tightened during physics operation, confirms this finding by setting a limit of about 10% to the contribution from all losses on the TCTs, i.e. the sum of beam halo and elastic beam-gas scattering around the ring. Dedicated simulations of the halo-related background are presented and good agreement with data is demonstrated. These simulations provide information about features that are not experimentally accessible, like correlations between backgrounds and the distributions of proton impacts on the collimators. The results provide vital information about the dependence between background and collimator settings, which is of central importance when optimizing the LHC optics for maximum peak luminosity.

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I. INTRODUCTION

The Large Hadron Collider (LHC) [1,2] is a 27 km synchrotron, designed to collide two counterrotating beams of, up to, 7 TeV protons or heavy ions of equivalent magnetic rigidity, inside four experimental detectors. The experiments are located at interaction regions (IRs) in four out of the eight straight sections of the ring. The geometry of the LHC is schematically illustrated in Fig. 1.

At the nominal luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ the LHC produces about $8 \times 10^8$ inelastic proton-proton collisions per second at the low-$\beta^*$ [4] interaction points (IPs) inside the ATLAS [5] and CMS [6] detectors. Only a small fraction of these events include interesting physics processes, the remainder constituting the dominant experimental background. Backgrounds with much lower intensity, but very different characteristics, arise from losses of beam protons in the vicinity of the experiments [7]. The collisions of protons with residual gas molecules or machine elements induce particle showers which can reach the detectors and constitute machine-induced backgrounds [8–16]. Since the LHC detectors are optimized to efficiently detect and measure particles emerging from collisions at the IP, they have, in their central regions, high granularity in the longitudinal ($z$) and the azimuthal ($\phi$) direction. The particle tracks originating from beam losses are usually almost parallel to the beam and, unlike particles from the IP, can traverse a large number of detector cells along $z$. This can result in high occupancy and thereby degrade the data-taking efficiency. High-energy muons are a particularly important component of the machine-induced background, since they can lose a major fraction of their energy by radiative processes in the calorimeters of the detectors. If such losses are large enough they can get reconstructed as jets, which are important objects in most

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physics analyses. Such erroneously reconstructed jets are referred to as fake jets. If overlaid with a collision event, they can lead to missing transverse energy which might be confused with some signatures of rare new physics [17–20]. Therefore a good understanding and minimization of machine-induced backgrounds is among the requirements to reach optimal experimental conditions.

Machine-induced backgrounds arise from three conceptually different sources: (i) inelastic collisions of the beam protons with residual gas in the LHC beam vacuum; (ii) beam-halo losses on limiting apertures close to the experiment; and (iii) elastic beam-gas scattering around the accelerator, out of which a fraction results in protons lost on apertures close to the experiment. Operational experience with the LHC, so far, suggests that inelastic beam-gas interactions constitute the dominant source of machine-induced backgrounds [21,22]. This article, however, focuses on a first quantitative measurement of the halo-related background component during 6.5 TeV proton operation. Such a study must be done under dedicated beam conditions in order to have well-defined beam-halo losses and minimize the effect of other background components.

The beam halo is constantly populated by various processes, like elastic collisions at the experiments and with residual gas, noise in the rf system and the feedback, intrabeam scattering, resonances and instabilities. For this study beam-loss measurements under special conditions described in Ref. [23] are combined with ATLAS data, published in Ref. [24]. The LHC beam cleaning system is described in Sec. II and the measurement procedure in Sec. III. The results, discussed in Sec. IV, are used in Sec. V to make a quantitative assessment of the magnitude of beam-halo background during physics operation, which in turn provides important inputs for decisions on the future machine configuration. A second experimental test, aimed to set a rough limit on the background from elastic beam-gas scattering, is described in Sec. VI. Finally, the measured backgrounds are compared with simulations in Sec. VII.

All abbreviations used in the text are summarized in the Appendix.

II. LHC BEAM CLEANING

The collimators of the betatron cleaning insertion in interaction region 7 (IR7) form the backbone of the multistage LHC collimation system [25–30]. All transverse halo particles with high betatron amplitudes should first hit a primary collimator (TCP) in IR7, installed in the horizontal, vertical, and skew planes. Most protons that scatter out of the TCPs are intercepted by secondary collimators (TCSGs) and other collimator families at larger openings. Particles leaking out of the TCSGs constitute tertiary halo, which eventually could end up on the active absorbers (TCLA) in IR7 or the tertiary collimators (TCTs) 150 m upstream of the experiments. A similar cleaning hierarchy consisting of TCP, TCSGs, and TCLAs is installed for momentum cleaning in IR3, and special protection collimators (TCDQ and TCSP) are installed in IR6 to protect the machine in case of beam extraction failures. The TCPs and TCSGs are 0.6 and 1 m long, respectively. Both are made of carbon fiber composite, while the 1 m long TCTs and TCLAs are made of tungsten. All these collimators consist of two movable parallel jaws with the beam passing between them.

Each TCT assembly includes one horizontal (TCTH) and one vertical (TCTV) set of jaws. Their primary role is to protect the magnets of the final focusing system but they also intercept the tertiary halo and some of the showers from upstream beam-gas interactions. When halo particles interact with the material of a TCT, hadronic and electromagnetic showers are induced and some secondary particles leak through or scatter out of the TCT. Most of them are stopped in downstream magnetic elements or shielding, but a small fraction reaches the experiments.

This study is focused on background in the ATLAS experiment due to beam protons lost in IR7. It is evident from Fig. 1 that this creates an asymmetry between the clockwise B1 and counterclockwise B2: while the distance for B1 is only two octants, B2 has to travel six octants with several tight apertures (IR6, IR5 and IR3) along its path.

The intensity of the beam-halo background depends on the beam conditions and the machine configuration, in particular the collimator settings. In general the beam-halo background is reduced if the upstream collimators are set at tight apertures such that the tertiary halo is minimized.

FIG. 1. The schematic layout of the LHC showing the eight insertions of which four house experiments. Of particular importance for this study is the betatron cleaning in IR7. The two counterrotating beams are shown schematically, i.e. their actual separation of 194 mm in the arcs is not to scale. This figure was adapted from Ref. [3].
It can, however, also depend on the beam optics, in particular the dispersion and the betatron phase advances between IR7 and the TCT. For fixed collimation and optics settings, the beam-halo background is directly proportional to the instantaneous loss rate of halo protons on the TCPs.

Beam-halo backgrounds at the LHC have been studied in simulations during the design stage for the nominal 7 TeV configuration [7–15] and later for the first LHC run at 3.5–4 TeV [16,31] and for the foreseen LHC luminosity upgrade [31–33]. Measurements of machine-induced backgrounds have been reported by ATLAS [21,22], but it is difficult to disentangle the various background contributions during standard physics operation, when all sources are superimposed. However, data recorded during a short special physics run in 2012 with low intensity and high β∗ revealed that sufficiently large beam losses in the cleaning insertions can be seen as increased backgrounds in ATLAS [22]. This suggested that a direct measurement of the beam-halo related background, with normal low-β∗ optics, might be feasible under some special conditions.

Even though there is strong evidence [21,22] that the machine-induced backgrounds are dominated by beam-gas collisions, a quantification of the beam-halo component is important for optimization of the LHC performance. Since the beam-halo background is expected to increase with tighter TCT gaps, there could be a lower limit on the TCT setting below which the background is not deemed acceptable. This in turn limits the normalized aperture that can be protected in the superconducting quadrupole magnets of the final focusing system. Therefore the amount of beam-halo background, and how much of it is acceptable, imposes constraints on the allowed β∗ and hence also on the achievable peak luminosity [3,34].

III. MEASUREMENT PROCEDURE IN LOSS-MAP TESTS

Before high-intensity beams are allowed in the LHC, the protection and cleaning performance of the collimation system must be qualified. This is done in dedicated loss-map measurements [29,35–38], where controlled beam losses are provoked on a safe beam of low intensity, while recording the loss pattern around the LHC using beam loss monitors (BLMs) [39,40]. The BLMs are ionization chambers, attached to, e.g., magnets and collimators. Almost 4000 BLMs are installed around the LHC and, for all analyses presented in this article, the integrated signal over 1.3 s recorded at 1 Hz [41] is used. Any individual BLM measures the time distribution of losses at its location, but since shower development in the machine elements, and the location of the BLMs with respect to these elements, differ, two BLMs cannot be directly compared to determine the ratio of losses on two different accelerator elements. The ratio between signals from any two BLMs, however, can be used to determine how loss patterns change as a function of time or collimator settings.

Losses, either in the horizontal or vertical plane, are provoked on individual bunches by applying a white-noise excitation with the transverse damper (ADT) [42] system. During the ADT excitation, with a typical duration of a few seconds, a large fraction of the affected bunch is lost on the TCP associated to the plane of excitation. The loss rates reach values of the order of 1010 Hz per bunch. In these conditions it is expected that the signals seen by the experiments are dominated by the showers from the TCT impacts, caused by the leakage out of IR7. Thus the loss maps provide a very clean environment for studying the beam-halo component of the background.

Normally, the loss-map measurements are performed in the accelerator while experiments are in the idle state. The new feature of the present study is that the ATLAS experiment was partially turned on in order to record background data [24] during the loss-map tests. The principal background monitoring methods used by ATLAS are based on a dedicated beam condition monitor (BCM) [43] to measure near-beam backgrounds and a monitoring of fake-jet rates in the calorimeters. Both of these methods rely on the availability of a few noncolliding bunches in the LHC bunch pattern. Most of the bunches used in the loss-map measurements are of this type, i.e. do not have a partner in the other beam to collide with at the ATLAS IP.

The BCM detector, with subnanosecond time resolution, consists of four diamond modules on each side of the IP. Two modules are in the vertical and two in the horizontal plane at a mean radius of 5.5 cm from the beam line and at a distance |z| = 184 cm from the IP. The BCM background trigger is based on the assumption that the background arrives in time with the proton bunch. A background count is provided if any module on one side has an early hit while any module on the other side has an in-time hit during the same bunch passage.

The ATLAS calorimeter system consists of several subdetectors. In the central barrel part they extend from a radius r = 1.5 m to r = 4.3 m and have a length of ±3 m (electromagnetic) and ±6 m (hadronic). The end cap calorimeters extend the coverage to almost 4π around the IP [5]. The fake-jet monitoring is based on a single jet trigger with a low transverse momentum (pT) threshold of 12 GeV. For the analysis presented in Ref. [24], which also describes in detail the cuts applied to this trigger, the events recorded were analyzed in order to extract the exact time, apparent pT and position of each fake jet.

The BCM is designed to probe showers developing just outside of the beam pipe and is therefore most sensitive to local losses, although simulations indicate that it maintains some sensitivity at least up to the TCT location [44]. The fake jets in the calorimeters, especially the barrel part, are almost exclusively due to radiative energy losses of high-energy muons. Besides cosmic rays, these muons originate from beam losses far upstream. Since muons produced in
interactions of 6.5 TeV protons have a strong forward boost, they will not reach the radii of the barrel calorimeters \((r > 150 \text{ cm})\) unless they are produced at a large distance or deflected by the magnets of the LHC lattice. In this study the background originates from the TCT at \(|z| \approx 150 \text{ m}\) and the only dipole magnet traversed is the separation dipole D1, which extends from \(|z| = 59\) to \(|z| = 83 \text{ m}\) and has a field of 1.2 T.

Qualification loss-map tests in the LHC on two occasions were used for the measurements reported here. The first set of data was obtained during a test which took place on July 4, 2015, using the standard optics for physics of that year with \(\beta^*=80 \text{ cm}\) and a half crossing angle of \(-145 \mu\text{rad}\). A more extensive dataset was collected during a dedicated test on August 28, 2015, at \(\beta^*=40 \text{ cm}\) and zero crossing angle. In both cases the energy of the proton beams was 6.5 TeV.

During the \(\beta^*=80 \text{ cm}\) test, all collimators were kept at their standard physics operation settings, shown in Table I. Four pilot bunches, of \(10^{10}\) protons each, and two nominal bunches, of around \(10^{11}\) protons per bunch, were injected in each ring in order to have a filling scheme with nominal bunches colliding at all IRs [45]. All pilot bunches, but only one nominal bunch per beam, were noncolliding in ATLAS and could be used for the background measurement. Loss maps were performed by exciting sequentially bunches in B1 and B2 in either the horizontal or the vertical planes. Each bunch was used only in one plane.

During the \(\beta^*=40 \text{ cm}\) test, the openings of all TCTs simultaneously were varied between 7.8\(\sigma\) and 10.3\(\sigma\) in steps of 0.5\(\sigma\) [46], while keeping the rest of the collimators at constant openings as shown in the middle column of Table I. At each TCT setting, a set of the four standard loss maps was performed (both beams and both planes), which allows studying the dependence of background on the TCT setting.

For the test at \(\beta^*=40 \text{ cm}\), one nominal and 15 pilot bunches were injected into each LHC ring. Because the total intensity in loss-map tests is limited by machine protection, subdividing the beam into a large number of pilot bunches allowed performing measurements at different TCT settings within the same fill. In order to create losses over a longer time period for increased resolution, the nominal bunches were also excited. These excitations were done at a TCT setting of 8.8\(\sigma\) in the vertical and horizontal plane for B1 and B2, respectively.

### IV. Measurement Results of Loss-Map Tests

A typical loss distribution, around the LHC ring, resulting from an ADT excitation at \(\beta^*=40 \text{ cm}\) with the TCTs at 8.8\(\sigma\) is shown in Fig. 2. The main loss locations are found on the primary collimators in IR7, and the loss levels then decrease on downstream collimators in IR7. The losses on the TCTs, seen as black spikes in IR1 and IR5, are about 3 orders of magnitude below those in IR7.

The BLM signal at the TCPs in IR7 is very well resolved, being several orders of magnitude above the background noise. For monitors with lower signals the subtraction of pedestal noise of the electronics is mandatory, in particular for some monitors that constantly show higher rates than others. In order to remove the pedestal noise the count rate of each BLM is averaged over a period shortly before the start of the loss-map test, i.e. in absence of any excitation.

![Beam loss distribution around the LHC, measured with the BLMs using a 1.3 s integration time](image)

**Fig. 2.** Beam loss distribution around the LHC, measured with the BLMs using a 1.3 s integration time. The initial loss is provoked by a white-noise excitation of the ADT in the vertical plane of B1 at 6.5 TeV beam energy and \(\beta^*=40 \text{ cm}\). The TCTs were positioned at 8.8\(\sigma\) and the rest of the collimator settings are shown in Table I. The background noise of the electronics, taken as the BLM signals without any excitation, has been subtracted. The color indicates if the monitor is attached to a cold machine element (blue), a warm machine element (red), or a collimator (black).

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**TABLE I.** Collimator half gaps used during the tests described in this article, given in units of beam standard deviation \(\sigma\), assuming the nominal \(\beta\)-function and a normalized emittance of 3.5 \(\mu\text{m}\). The settings at \(\beta^*=80 \text{ cm}\) are the standard settings during physics operation in 2015, which were also used during the loss-map tests. At \(\beta^*=40 \text{ cm}\) the settings used in the 2015 loss-map test and the 2016 operational settings are both shown. The latter were used during the TCT closure test, discussed in Sec. VI.

<table>
<thead>
<tr>
<th>Collimator family</th>
<th>(\beta^*=80 \text{ cm})</th>
<th>(\beta^*=40 \text{ cm}) (loss maps)</th>
<th>(\beta^*=40 \text{ cm}) (2016 operation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP IR7</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>TCSG IR7</td>
<td>8.0</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>TCLA IR7</td>
<td>14.0</td>
<td>14.0</td>
<td>11.0</td>
</tr>
<tr>
<td>TCP IR3</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>TCSG IR3</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
</tr>
<tr>
<td>TCLA IR3</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>TCT IR1,5</td>
<td>13.7</td>
<td>7.8–10.3</td>
<td>9.0</td>
</tr>
<tr>
<td>TCSP IR6</td>
<td>9.1</td>
<td>8.6</td>
<td>8.3</td>
</tr>
<tr>
<td>TCDQ IR6</td>
<td>9.1</td>
<td>8.6</td>
<td>8.3</td>
</tr>
</tbody>
</table>
and subtracted from the BLM measurement during the excitation. Figure 3(a) shows a typical example of measured BLM signals at the TCP in IR7 in a period when eight consecutive excitations with increasing amplitude were performed on a nominal bunch. The loss is measured by a BLM called TCP.A, which is placed about 6 m downstream of the vertical TCP and 4 m downstream of the horizontal one. Therefore it intercepts the showers due to both, horizontal and vertical, excitations, all of which are reflected as clearly identifiable bumps in the BLM data. The bump limits, shown as shaded vertical bands, are determined from the rising and falling edges. Figure 3(b) shows the loss measurements at IR1 TCTs, where the sum of two BLMs, associated to the TCTH and TCTV are used. For the smaller losses, at the left in the plot, the bumps are barely distinguishable from the background. The signal is extracted as a sum between the bump limits, determined from the TCP.A BLM data. The pedestal, fitted in an excitation-free area, is subtracted. Figure 3(c) shows the BCM background measured by ATLAS. Like for the TCT BLMs, the signal is taken as the sum over the shaded areas after subtracting the pedestal. The coarse resolution arises from the fact that the intensities of individual bunches were logged only once per minute. Nevertheless, it can be seen that the amount of intensity loss correlates with the size of the loss bump at the TCPs.

Figure 4 shows, as a function of the TCT opening for the various excitations during the test, the sum of the signals and subtracted from the BLM measurement during the excitation.

Figure 3(a) shows a typical example of measured BLM signals at the TCP in IR7 in a period when eight consecutive excitations with increasing amplitude were performed on a nominal bunch. The loss is measured by a BLM called TCP.A, which is placed about 6 m downstream of the vertical TCP and 4 m downstream of the horizontal one. Therefore it intercepts the showers due to both, horizontal and vertical, excitations, all of which are reflected as clearly identifiable bumps in the BLM data. The bump limits, shown as shaded vertical bands, are determined from the rising and falling edges. Figure 3(b) shows the loss measurements at IR1 TCTs, where the sum of two BLMs, associated to the TCTH and TCTV are used. For the smaller losses, at the left in the plot, the bumps are barely distinguishable from the background. The signal is extracted as a sum between the bump limits, determined from the TCP.A BLM data. The pedestal, fitted in an excitation-free area, is subtracted. Figure 3(c) shows the BCM background measured by ATLAS. Like for the TCT BLMs, the signal is taken as the sum over the shaded areas after subtracting the pedestal. As the excitation strength increases, and the loss rate on the TCP goes up, the TCT BLM and the ATLAS BCM eventually reach signals up to 2 orders of magnitude above the pedestal, which for the BCM is mostly due to beam-gas interactions. A sum over the pedestal indicates that the BCM measures a beam-gas background at the level of less than 0.5 Hz per nominal bunch. It is therefore clear that during the stronger excitations, both the TCT BLM signals and BCM background are fully dominated by the beam-halo losses and all other background sources are negligible. Figure 3(d) shows the intensity of the excited bunch as a function of time. The coarse resolution arises from the fact that the intensities of individual bunches were logged only once per minute. Nevertheless, it can be seen that the amount of intensity loss correlates with the size of the loss bump at the TCPs.

Figure 4 shows, as a function of the TCT opening for the various excitations during the test, the sum of the signals...
from the BLMs associated to the horizontal and vertical TCTs of IR1 normalized by the measurement of the TCP.A BLM. For a given plane, the latter is proportional to the amount of beam lost, which can vary by a significant factor between excitations. The ratio between the TCT BLM signals and the TCP.A BLM, however, is proportional to the fraction of halo leaking from IR7 to the IR1 TCTs and any dependence on excitation strength and original amount of beam lost should be removed. The small spread between the points for the same excitation plane and at the same TCT setting supports this assumption.

The error bars in Fig. 4 have been estimated by calculating the TCT/TCP ratio for each 1 s time bin during the excitation separately and determining the average and its rms from these per-bin ratios. This method covers uncertainties from counting statistics and other effects that might alter the ratio during the peak. However, it does not account for systematic uncertainties like a possible dependence of the BLM response on impact distribution or possible changes, like orbit drifts, that occur between different excitations.

Results are presented for both beams and planes and for both the $\beta'/C_3 = 40$ cm and $\beta'/C_3 = 80$ cm tests. As expected, the TCT losses increase strongly with decreasing opening. If the TCT opening is wider a larger number of protons will miss it and be intercepted in IR7 or in other IRs on the next turn. The lines shown in Fig. 4 indicate that, to a good approximation, the ratio, as a function of TCT opening, can be fitted with an exponential, which indicates that the transverse halo distribution falls off exponentially with increasing amplitude. The points at $\beta'/C_3 = 80$ cm do not exactly match the fit, but this can be explained by the different optics and slightly different collimator settings in IR6 and IR7, as detailed in Table I.

![Graphs showing TCT/TCP ratio for varying TCT settings and excitation strengths.](image-url)

**FIG. 5.** Ratio between background rates measured by ATLAS and the signal from the TCP BLMs in IR7 for losses provoked on B1 (left) and B2 (right) in the horizontal (top) and vertical (bottom) planes. The red symbols correspond to the $\beta'/C_3 = 40$ cm test with TCT settings varied from 7.8 to 10.3\(\sigma\). The blue points at 13.7\(\sigma\) correspond to the $\beta'/C_3 = 80$ cm test. When several measurements fall on the same TCT setting, the points are slightly shifted in the plot in order to separate their error bars. The lines show exponential fits to the $\beta'/C_3 = 40$ cm points, of the form $Ce^{\eta\Delta}$, where $A$ is the TCT aperture. The ATLAS data are taken from Ref. [24].

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Since the halo-related background in the experiments is assumed to originate from losses on the TCTs, the ratio between the ATLAS background measurement and the loss rate on the TCTs should be constant. In Ref. [24] it is shown that, within the uncertainties, this is the case for the $\beta' = 40 \text{ cm}$ data, while the $\beta' = 80 \text{ cm}$ data shows some deviation, presumably due to the different optics at the IP. Consequently the ratio between the ATLAS background and the TCPA BLM signal, as a function of the TCT setting, should be fitted by an exponential. Figure 5 shows these ratios for both, BCM and fake-jet backgrounds, during excitations in the two planes and for both beams. Although the data points have a slightly larger spread than in Fig. 4, the correlation between the aperture of the TCTs and the measured background is clearly evident for both, the BCM and the fake jets. The $\beta' = 40 \text{ cm}$ data are well fitted by exponentials. The slopes ($s$) of these fits are very similar to those in Fig. 4, which is consistent with the hypothesis that the background seen in the experiments is proportional to the rate of protons hitting the TCTs. The extrapolation of the fits to the $\beta' = 80 \text{ cm}$ data points reveals that for B1 the agreement is rather good, although with a slight tendency for the fits to overshoot. For B2 the opposite is found, i.e. in both planes and both background observables the fits undershoot the data.

Since the BLM measurement is a running sum over 1.3 s with 1 Hz sampling frequency, it is not perfectly aligned with the ATLAS background data. Therefore the method of estimating the uncertainties from the bin-to-bin variation of the ratio is not applicable. Figure 3, however, shows that the signal in the TCPA BLM is very clear with correspondingly small uncertainties so that the dominant uncertainty in the ratio must arise from the ATLAS background measurement. This motivates to take the counting statistics of the ATLAS measurement as the total uncertainty, shown as error bars in Fig. 5.

The background data can also be normalized by the number of protons lost on the TCTs instead of the TCP BLM signal. The intensity of each individual bunch is measured by the beam current transformer (BCT) and logged once per minute. Since the drop in intensity during the loss-map tests is almost entirely due to the excitation-induced losses in IR7 (see Fig. 3), it can be assumed that all protons lost from the beam hit in a TCT on IR7. The numbers of background counts per proton lost on the TCP are summarized in Table II for the two most important configurations, namely the 2015 operational scenario with $\beta' = 80 \text{ cm}$ and a $13.7 \sigma$ TCT setting, and $\beta' = 40 \text{ cm}$ with a $8.8 \sigma$ TCT, which is closest to 2016 operation. These were also the configurations where nominal bunches were used for the loss maps. In order to maximize the background signals in the experiments the larger intensity of these nominal bunches was fully utilized by prolonged excitations on each of them.

The BCM counts per lost proton are a factor 5–10 higher than the fake-jet counts. This is not surprising, since these two background observables are based on totally different physics. While the BCM records any charged particle passing through its small sensors close to the beam line, the fake jets are created by high energy muons experiencing a large, and thus rare, radiative energy loss anywhere in the calorimeters.

**V. QUANTITATIVE ESTIMATES OF BEAM-HALO BACKGROUND IN PHYSICS OPERATION**

The loss-map measurements presented in Fig. 5 and Table II provide clean estimates of the amount of background seen by the experiments as a function of the beam losses on the TCPs. These results can be used to estimate the background rates in ATLAS during standard physics operation, by scaling them to the corresponding loss rate on the TCPs. The latter can be estimated for standard operation in 2015 and 2016 either from the bunch intensity data measured by the BCT or from the TCP BLM signals.

Neither of these two methods can provide a clean and direct measurement of the halo-related loss rate. The BCT measures the bunch intensity at percent level accuracy, but this measurement includes all loss processes. In the loss-map tests, when the excitation is turned on, all other processes are negligible compared to the halo losses. In a normal physics fill this is not the case. A large fraction of the beam intensity is lost due to luminosity production at the experiments while halo losses and beam-gas interactions are, at most, at the same level. During 2015 each bunch-bunch encounter in ATLAS resulted in 13.5 inelastic proton-proton collisions, averaged over all data taking. With a similar number for CMS and a revolution frequency of 11245 Hz, each bunch lost, on average, about $3 \times 10^5$ protons per second due to luminosity. This luminosity component has to be subtracted from the total intensity loss measured by the BCT. Protons scattered elastically at the IP remain in the machine aperture. These and the remaining signals in the experiments the larger intensity of these nominal bunches was fully utilized by prolonged excitations on each of them.
noncollisional losses are conservatively assumed to all hit the IR7 TCPs. This results in an overestimation, since the losses from inelastic beam-gas scattering occur around the entire ring and only a small amount of affected protons reach the collimators [16].

The signals of the TCP BLMs are proportional to local losses in IR7, however, they do not directly measure the number of lost protons, but rather the intensity of produced particle showers. The BLM measurement is also subject to a cross-talk effect: a shower generated by the loss on one TCP generates a signal also on BLMs associated to other downstream collimators. Therefore, to disentangle the losses between the different TCPs and to reconstruct the number of lost protons, a method described in Ref. [47] is used: the BLM signals are first recorded during loss maps with known excitation plane and intensity loss. The obtained results are then used to construct a matrix with the response of each BLM from each type of loss. The initial losses for any given BLM pattern can then be found through a single-value decomposition using the BLM response matrix. The total rate is estimated as the sum of horizontal and vertical losses.

Earlier studies have shown that the noncollisional loss rate is significantly higher during the first hour than later in the fill [48,49]. This suggests that the effective beam-halo background rates could evolve in the course of a long physics fill. Therefore, with both analysis methods, the average loss rates over two different time intervals are considered: the first hour of collisions, and the fifth hour.

The results are shown in Fig. 6 for all LHC physics fills which reached 5 h of length and the mean values over the years are presented in Table III.

As can be seen from Table III, there are significant differences between the two beams, the two years, and the two time windows within a fill. In 2016, the noncollisional losses are, on average, about a factor 5–10 lower in the fifth hour than in the first hour. Another striking feature is that in 2016 the losses in B1 during the first hour are about a factor of 2 higher than in B2. In 2015, the differences between the beams and the time windows are much smaller. The reason for the differences are not known in detail, but they could be related to imperfections on the feedback system or the magnetic lattice.

As detailed above, the BCT method provides a very accurate measurement of the total noncollisional losses, but it is not possible to determine exactly how large a fraction of these losses comes from impacts on the TCPs. For the BLM method, uncertainties come from possible differences in impact distribution between the losses at any given moment and the reference measurement where the BLM response matrix was constructed. By construction, in particular due to not subtracting the inelastic beam-gas contribution from the intensity loss, the BCT estimates should be higher. Table III, however, shows that differences are in both directions, but in all cases the methods agree.
TABLE III. Average beam loss rates, as obtained from the BLM and BCT data shown in Fig. 6, during physics operation in 2015 and 2016. Rates are given in units of protons/s/bunch for the first and fifth hour of collisions.

<table>
<thead>
<tr>
<th>Time window</th>
<th>2015, B1</th>
<th>2016, B1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st hour</td>
<td>BCT</td>
<td>BLM</td>
</tr>
<tr>
<td></td>
<td>$3.6 \times 10^5$</td>
<td>$2.6 \times 10^5$</td>
</tr>
<tr>
<td>5th hour</td>
<td>$1.1 \times 10^5$</td>
<td>$0.7 \times 10^5$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Time window</th>
<th>2015, B2</th>
<th>2016, B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st hour</td>
<td>BCT</td>
<td>BLM</td>
</tr>
<tr>
<td></td>
<td>$2.9 \times 10^5$</td>
<td>$3.0 \times 10^5$</td>
</tr>
<tr>
<td>5th hour</td>
<td>$1.0 \times 10^5$</td>
<td>$1.5 \times 10^5$</td>
</tr>
</tbody>
</table>

within 50%. In view of the uncertainties involved, this can be considered a good agreement.

Using the calculated beam-loss rates and the background observed per lost proton on the TCPs, given in Table II, it is possible to estimate the absolute halo-related background rates in ATLAS during physics runs. In order to obtain an upper estimate, the loss rates from the BCT during the first hour of physics are used. The results for the BCM background and the fake jets are presented in Table IV, for both beams and years. The estimated halo contribution to the BCM background reaches up to 50 mHz/bunch at $\beta^* = 40$ cm, but amounts to only a few mHz/bunch at $\beta^* = 80$ cm. The total BCM background rates in ATLAS during 2015 ($\beta^* = 80$ cm) operation are reported to be 3–5 Hz per bunch [24], which implies that the halo-related contribution is at the per-mil level. For the fake jets, Table IV indicates a beam-average rate of 0.3 mHz/bunch at $\beta^* = 80$ cm. A corresponding measurement by ATLAS for 2015 operation is not available, but Ref. [24] implies that this would be less than a percent of the total. In 2016, with a tighter TCT setting, the relative importance of the halo-related contribution increases, but still remains at a negligible level of about 1%. If, instead of the first hour BCT results, the fifth hour BLM results would be used, the obtained rates would be lower by up to a factor of 7.

TABLE IV. Estimated background count rates in ATLAS during physics operation in Hz/bunch, calculated as the product of the average loss rates on the TCPs during standard operation (taken from the BCT measurement for the first hour in Table III) and the background counts measured per proton lost on the TCP (Table II).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>2015, $\beta^* = 80$ cm</th>
<th>2016, $\beta^* = 40$ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B1</td>
<td>B2</td>
</tr>
<tr>
<td>BCM</td>
<td>$1.9 \times 10^{-3}$</td>
<td>$2.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>Fake jets</td>
<td>$1.9 \times 10^{-4}$</td>
<td>$3.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The preceding discussion highlights that the total uncertainty of the calculated background rates in Table IV is rather large. The uncertainty of the transfer function from the TCP losses to the ATLAS background is dominated by the counting statistics in the loss-map test and amounts to only a few percent. The dominant uncertainty, however, comes from the loss rate determination in a physics fill. The differences between the two independent methods, of up to 50%, give a rough estimate on this uncertainty. The estimates in Table IV are already constructed as upper values in this respect. In addition, any differences in loss distribution on the TCPs in physics fills, compared to the loss-map measurements, could influence the result. Even if a combined uncertainty of a factor 2 would be assumed on these conservative estimates, the beam halo remains a negligible contribution to the total background also during the first hour of physics operation for both studied years.

The exponential fits in Fig. 5 indicate an average slope of $s = -0.5$. This implies that if the TCT is closed by one nominal $\sigma$, while all other settings remain the same, the halo-related component of the background increases by 60%. However, for it to reach 10% of the total beam background, it would need to increase by a factor of about 10. A simple extrapolation of the fits shows that such a tenfold increase would require a TCT aperture of about 4.5$\sigma$. Obviously this extrapolation is not realistic, since such a setting would violate the collimation hierarchy, i.e. the TCTs would become primary collimators. In reality the TCTs can never be operated at a tighter setting in $\sigma$ than the TCSGs in IR7, which were at 7.5$\sigma$ in 2016. These considerations lead to the conclusion that beam-halo backgrounds in the experiments do not impose a limit on reducing the TCT aperture, as long as the TCT respects its role in the multistage cleaning hierarchy.

VI. TOTAL BACKGROUND FROM LOSSES ON THE TCT IN PHYSICS OPERATION

The results of Sec. V show that beam halo contributes by a negligible amount to the total machine-induced background in the experiments. The loss-map tests, however, do not probe the rate of protons ending up on the TCT as a result of elastic beam-gas scattering. In order to further quantify the effect of the TCT setting on the background, assessing the contributions from both beam halo and elastic beam-gas scattering, another experimental test was done by slightly reducing the TCT aperture in a normal physics fill.

The test was done on October 18, 2016, at the end of a 6.5 TeV physics fill with $\beta^* = 40$ cm, 2200 nominal bunches per beam, and the collimator settings in the rightmost column of Table I. The transverse emittances were in the range 2–2.5 $\mu$m and at the time of the test the average bunch intensity was around $8 \times 10^{10}$ protons. The total beam intensity ensured a representative dynamic pressure of the residual gas in the beam vacuum.
Around 14 h after the beams were first brought into collision, the aperture of the vertical TCTs in IR1 and IR5 was reduced. Machine protection considerations, in particular the risk of asynchronous beam dumps, prevented a movement of the horizontal TCTs and imposed a limit of 400 μm on the vertical movement. This corresponds to a reduction of the aperture from the nominal σ to about 8.4σ. Both jaws of each vertical TCT were moved symmetrically in order to stay centered around the beam. The machine was then left with these tighter TCT settings for about 1.5 h, while monitoring the experimental backgrounds. After this time, the TCTs were retracted again to the standard physics settings. The settings of the other collimators, which were not changed during this test, can be found in the last column of Table I.

The BCM backgrounds observed by ATLAS during this test [24] are shown in Fig. 7. No changes in measured background rates are visible during the time interval, shaded in gray, when the TCTs were tighter. The background evolution of both beams was fitted by a second-order polynomial, using the data before and after the period of reduced TCT aperture. It is shown in Ref. [24] that an increase of more than 1%–2% of the background, averaged over the shaded area, could be resolved as a shift with respect to a corresponding time average over the fit. The results of Sec. IV suggest that a reduction of the TCT aperture by 0.6σ would increase the halo-related background by about 30%. However, since only the horizontal TCT was moved, the effect is probably only half of this. Even at 15% the effect still is a factor of 10 larger than the sensitivity of the test, if all the observed background would originate from losses on the TCTs. Assuming that the protons from elastic beam-gas scattering have a similar betatron amplitude distribution as tertiary halo, this sets an upper limit of about 10% to the relative background contribution from proton losses on the TCT. This test, by itself, cannot distinguish between elastic protons and tertiary halo, but since the latter is estimated from the loss map test to be less than a percent, the 10% can be considered as an upper limit to the elastic scattering contribution.

The sensitivity of this test could be improved by closing also the horizontal TCT, and possibly by a larger amount, in order to increase the losses. But in order to do this in physics conditions a corresponding machine protection qualification is required.

VII. COMPARISON WITH SIMULATIONS

Since the measurements described in Sec. IV relate proton losses and experimental background with unprecedentedly small uncertainties, they provide excellent data to compare with beam-background simulations. The latter follow a three-step approach, first proposed in Ref. [7], which conveniently divides the task into accelerator and detector parts such that the most appropriate simulation tools can be used for both. The accelerator simulations, which consist of first tracking the beam halo from the TCP to the TCT and then transporting the particle showers from the TCT to a virtual interface plane between the machine and the experiment are described in detail in Refs. [16,31]. The positions, four-momenta and types of particles crossing the interface plane serve as input for the detector simulations.

A. Tracking simulations in LHC lattice

In the first step of the accelerator simulations, the six-dimensional multitrack code SIXTRACK [29,51–54] is used. It does a thin-lens element-by-element tracking through the magnetic lattice and when a proton encounters a collimator, a built-in scattering routine is invoked to simulate the proton-matter interactions. The tracking continues if the proton scatters back into the beam vacuum. The same simulation setup as in Ref. [29] is used. The starting conditions are halo protons with amplitudes large enough to hit a TCP. The diffusion of protons from the beam core [55] is not modeled, in order to keep the computing time feasible. At least 6 × 10⁶ halo protons per configuration are tracked for 200 turns.

A proton is considered to be lost either when it undergoes an inelastic interaction inside a collimator or if it hits the aperture of any other element. The tracking in a collimator stops at the position of the inelastic interaction and no secondary particles are generated. The exception is single diffractive events, where the beam proton survives
and is tracked further. The SIXTRACK simulation output consists of the proton coordinates at all loss locations.

Figure 8 shows a typical result of the SIXTRACK-simulated losses around the ring, using the same settings as those used for the studies in Fig. 2. Like in similar studies at 3.5 TeV [29] a good qualitative agreement between SIXTRACK results and BLM measurements is seen. Quantitatively, the loss distributions shown in Figs. 2 and 8 are not strictly comparable, since the simulation shows only the loss positions of primary beam protons, while the BLM signals are produced by the showers which are created by the proton impacts. These distribute the energy loss over a larger distance, depending on the local geometry.

Figure 8 shows vertical losses of B1 at $\beta^* = 40$ cm, but similar simulations have been performed for all cases relevant to this study. The obtained fractions of total simulated losses that end up on the TCTs in Table V. These provide the normalization factors, i.e. are used to express the simulated background per proton lost on the TCP. The results at $\beta^* = 40$ cm correspond to what might be intuitively expected: the TCT losses are larger in B1, for which the path from IR7 to IR1 is shorter than for B2 and where fewer collimators are passed. This is not the case at $\beta^* = 80$ cm, where the contributions from both beams are roughly equal due to differences in the phase advance between the IR7 TCSGs, the IR1 TCTs and other collimators in between: halo might pass a tight collimator at a location where betatron oscillations have a small transverse offset and be intercepted on a wider aperture at a position where the offset it large. For both beams, however, the TCT loss fraction is by about an order of magnitude larger at $\beta^* = 40$ cm than at $\beta^* = 80$ cm. This difference arises from the much smaller TCT opening of 8.8$\sigma$ at $\beta^* = 40$ cm as opposed to 13.7$\sigma$ at $\beta^* = 80$ cm.

Even though the SIXTRACK results cannot be compared with the data in absolute terms, it is interesting to compare the ratio of TCT hits between different machine configurations with the ratio of measured background. Such comparisons, shown in Table VI, assume implicitly that the background rate is directly proportional to the TCT hit rate, so that unknown factors, in particular the number of observed background events per TCT hit, cancel out. This proportionality can, however, be violated by a dependence between impact depth and background production. In particular, deeper TCT impacts can be assumed to result in less shower leakage and hence lower background per TCT hit.

The measured values in Table VI indicate that the B1/B2 background ratio is about 2 at $\beta^* = 40$ cm, while it is around 0.5 at $\beta^* = 80$ cm. These observations agree with the SIXTRACK ratios which are derived from Table V. Consequently the measured $\beta^* = 40$ cm/$\beta^* = 80$ cm is about 4 times larger for B1 than for B2. The fact that

### Table V. SIXTRACK predictions of the fraction of total losses that end up on the TCTs in IR1 for the machine configurations during the loss-map tests of this study: $\beta^* = 40$ cm with TCTs at 13.7$\sigma$ as in 2015 operation, and $\beta^* = 80$ cm with TCTs at 8.8$\sigma$, where the latter is also close to the 2016 configuration for physics operation. The presented values are the ratio of total losses on the horizontal and vertical TCTs with respect to all halo related losses around the machine.

<table>
<thead>
<tr>
<th>Beam</th>
<th>$\beta^* = 40$ cm</th>
<th>$\beta^* = 80$ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>$3.6 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>B2</td>
<td>$1.4 \times 10^{-4}$</td>
<td>$1.4 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

### Table VI. Ratios of measured background counts per TCP hit between various configurations, calculated from Table II, shown together with the corresponding ratios of simulated hits on the TCTs, taken from Table V. The average background over horizontal and vertical losses is considered. For the simulations, the sum of hits on the horizontal and vertical TCTs is used. For $\beta^* = 40$ cm the TCT setting of 8.8$\sigma$ is considered, which is closest to the 2016 operational configuration.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Measured BCM</th>
<th>Measured fake jets</th>
<th>Simulated TCT impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1/beam 2, $\beta^* = 40$ cm</td>
<td>$1.66 \pm 0.04$</td>
<td>$1.9 \pm 0.1$</td>
<td>2.6</td>
</tr>
<tr>
<td>Beam 1/beam 2, $\beta^* = 80$ cm</td>
<td>$0.55 \pm 0.03$</td>
<td>$0.45 \pm 0.07$</td>
<td>0.71</td>
</tr>
<tr>
<td>($\beta^* = 40$ cm)/($\beta^* = 80$ cm), beam 1</td>
<td>$19.8 \pm 0.9$</td>
<td>$35 \pm 5$</td>
<td>32.5</td>
</tr>
<tr>
<td>($\beta^* = 40$ cm)/($\beta^* = 80$ cm), beam 2</td>
<td>$6.6 \pm 0.2$</td>
<td>$8.4 \pm 0.8$</td>
<td>9.9</td>
</tr>
</tbody>
</table>
background measurements and SIXTRACK agree on this asymmetry between the beams is a strong indication that the effects of different machine configurations are well modeled in the simulations.

Overall, the fake-jet ratios agree better with the simulations than the BCM ratios, especially for B1. This suggests that the assumption of direct proportionality between impact rate on the TCT and observed background is to some extent violated for the BCM background. Being very close to the beam line, the BCM is likely to be more sensitive to the proton impact distribution on the TCT, and in particular the number of impacts close to the TCT surface. Because the fake jets are dominated by high-energy muons at large radii, the TCT impact distribution is expected to be less important.

Despite the discrepancies, the overall agreement between simulation and measurement in Table VI is rather good and in all cases within a factor 2. This suggests that the fractional losses on the TCTs from SIXTRACK alone can be used to estimate, within a factor of a few, the beam-halo background in a future machine configuration if it is known in the present configuration. This method could be a relatively easy way to estimate whether the beam-halo background in a future, untested, configuration risks to become significant.

B. TCT shower simulation

The second simulation step is the shower propagation from the TCTs to the experiment, using the particle physics Monte Carlo simulation code FLUKA [56,57] as described in Refs. [16,31]. The FLUKA simulations use as starting conditions the TCT impacts from SIXTRACK to generate inelastic interactions, averaged over horizontal and vertical losses, from which the particle showers are propagated through the accelerator structures to a virtual interface plane, next to the experiment. This plane is defined to be between the quadrupole triplet, providing the final focus at the IP, and a fixed absorber (TAS), which is installed to protect the superconducting magnets from collision debris from the IP. This location, at 22.6 m from the IP, forms a natural boundary between the accelerator geometry model and that of the ATLAS experimental area.

A detailed 3D geometry of the about 130 m-long region between the interface plane and the TCTs, as implemented in FLUKA, is shown in Fig. 9. It includes the magnetic fields in the lattice between the TCT and the experiment. Because of symmetry, only one side of the experiment is implemented and used for the simulation of both beams. Contrary to most previous studies [7,14,15], no variance reduction was applied so that all correlations within an event are preserved. The FLUKA simulations were done for both beams and $\beta^*$ settings.

Since the two background measurements by ATLAS are sensitive to very different radiation components, two sets of FLUKA simulations were performed. For the BCM studies, where low-energy particles are important, a 20 MeV cutoff was used to produce a sample of $5 \times 10^6$ events. The fake jets are almost exclusively due to radiative energy losses of high-energy muons in the ATLAS calorimeters. In order to produce a sufficient number of the relatively rare events with large energy loss, another sample of $3 \times 10^8$ simulated events was produced, using a 20 GeV transport cutoff. This value is chosen since the single-jet trigger with 12 GeV threshold, used to select fake jets from the data, reaches full efficiency around 20 GeV [24].

Examples of simulated particle distributions at the interface plane are shown in Figs. 10 and 11. Figure 10
shows the distribution of high-energy muons, which are susceptible to produce fake jets in the ATLAS calorimeters. The azimuthal structure of the incident muon flux, especially the maxima in the horizontal and vertical planes, is due to bending of the muon trajectory in the D1 dipole and the focusing quadrupoles of the inner triplet. During the FLUKA transport from the interface plane to the calorimeters the muons will spread out due to scattering, energy loss and bending in the forward toroid magnet of ATLAS. Figure 11 shows the distribution of charged hadrons at the interface plane. The contribution of those particles for which a trajectory projection passes the \( r = 17 \) mm aperture of the TAS, but exceeds the 23.5 mm radius of the beam pipe before the first BCM station, is shown separately. Their particular relevance will be discussed in the next section.

C. ATLAS detector simulation

The third simulation step is the transport of the particles from the interface plane through ATLAS, while recording quantities that are needed to reconstruct the background observables. Also for these simulations, described in full detail in Ref. [24], FLUKA is used. The transport threshold is set to 100 keV in order to include all particles possibly giving hits in the BCM, which records a hit when the deposited energy exceeds \( \sim 250 \) keV. This is about 1/3 of the average energy loss of a minimum ionizing particle traversing the 1 mm-thick diamond module at normal angle of incidence. Charged particles with an energy just exceeding 250 keV will stop in the module, depositing all of their energy.

In order to reconstruct the BCM trigger signature, the times of all hits must be known with respect to the bunch passage at the IP. In the simulations, the time of flight is set to 0 at the impact point in the TCT and then rigorously propagated through the shower simulations. Analogous to the real data, a BCM background count is formed when an upstream and a downstream module have a hit in their corresponding trigger time windows, within the same event [24]. The time spread caused by the LHC bunch length of 7.5 cm is accounted for by smearing the time of each event correspondingly. In addition, each BCM hit is smeared by 600 ps in order to model the instrumental time resolution of the BCM modules [24]. To match the threshold of the BCM modules in the simulations, particles with \( E > 250 \) keV entering a BCM module were counted as hits.

Since FLUKA simulations are not compatible with full ATLAS data reconstruction, a customized and simplified method to estimate the rate of fake jets is developed in Refs. [24,44]: the energy deposited in an \((r, \phi, z)\) binning covering the calorimeters is analyzed for each event and energy deposition clusters exceeding \( p_T = 12 \) GeV/c are recorded as fake jets. To allow for the full turn-on of the ATLAS jet trigger, the simulated fake-jet rates are compared with data only above \( p_T = 20 \) GeV/c [24].

The results of the complete simulation chain, from the impacts on the TCPs to the simulated background rates in ATLAS, are compared with the ATLAS measurements in Table VII. These results are taken from Ref. [24], but the simulated rates have been rescaled to correspond to the most recent SIXTRACK simulations. In all cases the rates are normalized to one proton lost on the TCPs by using the TCT loss fractions in Table V, which correspond to the configuration during the loss-map tests. For B1 at \( \beta^* = 80 \) cm the simulations and measurements are in very good agreement, while an underestimation by a factor of \( \sim 2 \) is found for the B2 simulations. At \( \beta^* = 40 \) cm the agreement is not as good for B1, where the simulated rates are more than a factor of 3 below the measurements. Even the largest ratio of \( \sim 3.5 \), however, can still be considered a good agreement, when considering the complexity of the three-step simulation chain and the fact that the simulated losses around the ring span over many orders of magnitude. In particular, the SIXTRACK simulations assume a perfect LHC geometry and optics, while it has been shown that realistic imperfections can increase the rates on the TCT by a factor of 2–3 [29]. The B2 rates, and those for B1 at \( \beta^* = 80 \) cm, are consistent within this uncertainty but for the B1 rates at \( \beta^* = 40 \) cm the agreement is slightly outside this estimated error margin.

In order to further investigate the largest discrepancy, found in B1 at \( \beta^* = 40 \) cm, the dependence on the TCT impact distribution was studied. While the distribution of the transverse depth \( (d) \) of the inelastic interactions inside...
TABLE VII. Comparison of measured background rates with simulations, normalized to the number of protons lost from the bunch. The data for the BCM background are the same as in Table II. The errors are statistical only. The ATLAS data and simulations are taken from Ref. [24], but the simulation results have been rescaled to the most recent SIXTRACK results in Table V.

<table>
<thead>
<tr>
<th>Background observable</th>
<th>Beam</th>
<th>Data</th>
<th>Simulation</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCM background</td>
<td>1</td>
<td>(5.2 ± 0.2) × 10^{-9}</td>
<td>(5.4 ± 0.1) × 10^{-9}</td>
<td>0.97 ± 0.04</td>
</tr>
<tr>
<td>Fake jets (&gt;20 GeV)</td>
<td>1</td>
<td>(2.5 ± 0.4) × 10^{-10}</td>
<td>(2.43 ± 0.04) × 10^{-10}</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>BCM background</td>
<td>2</td>
<td>(9.4 ± 0.3) × 10^{-9}</td>
<td>(4.5 ± 0.1) × 10^{-9}</td>
<td>2.09 ± 0.09</td>
</tr>
<tr>
<td>Fake jets (&gt;20 GeV)</td>
<td>2</td>
<td>(5.4 ± 0.7) × 10^{-10}</td>
<td>(2.33 ± 0.05) × 10^{-10}</td>
<td>2.3 ± 0.3</td>
</tr>
</tbody>
</table>

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021004-14

the TCT jaws, obtained from the SIXTRACK simulations, is very similar at $\beta^\tau = 40$ cm and $\beta^\tau = 80$ cm for B2, a significant difference is seen for B1. This is shown in the leftmost plot in Fig. 12. Table VIII lists, for each configuration, the fraction of very shallow impact depths, i.e. those corresponding to the leftmost bin in Fig. 12. At $\beta^\tau = 80$ cm, for B1, most impacts are at rather shallow depth, and 35% have $d < 50 \mu m$, while at $\beta^\tau = 40$ cm there is only a minor excess of 5.8% at $d < 50 \mu m$, followed by a long, almost flat, tail. This suggests that a larger fraction of the showers will leak back into the beam line at $\beta^\tau = 80$ cm. The middle plot in Fig. 12 shows that the BCM background events, reconstructed in the complete FLUKA simulation, originate indeed from very shallow impacts—about 90%–97% of them are due to protons lost at $d < 50 \mu m$. For fake jets, on the other hand, typically 50% come from impacts at $d > 50 \mu m$, as can be seen from the rightmost plot. Hence, a possible explanation as to why the agreement between simulations and measurement is not as good for B1 at $\beta^\tau = 40$ cm as in the other cases, could be an inaccuracy of the simulated impact depth $d$. This could possibly be due to ignoring the effect of imperfections in the simulations. Imperfections are

![Figure 12](image-url)

FIG. 12. Distribution of the transverse depth of the inelastic interactions inside the jaws of the TCTs in B1 at $\beta^\tau = 40$ cm and $\beta^\tau = 80$ cm for a superposition of horizontal and vertical losses in IR7. The probabilities, obtained from the simulations, are averaged over 50 $\mu m$ wide bins. The TCT apertures are 8.8$\sigma$ and 13.7$\sigma$ at $\beta^\tau = 40$ cm and $\beta^\tau = 80$ cm, respectively. The hits in the horizontal and vertical TCTs are summed. The left plots show the distribution of all impacts. The middle and right plots show only those impacts that have resulted in a BCM background signature or a fake jet, respectively.
known to affect the results by up to a factor of 3 [29] and their effect should be studied for both B1 and B2.

In this context it is interesting to return to the particles passing the TAS aperture, shown by the dotted lines in Fig. 11. The FLUKA results reveal that these particles give 40% of the simulated BCM triggers. Further 25% are due to photons passing the TAS aperture. Thus the simulations suggest that about 2/3 of the background seen by the BCM is due to particles not interacting with the TAS, but showering on the beam pipe inside ATLAS. Furthermore, all charged hadrons passing the TAS and leading to BCM triggers in the simulations have energies above 100 GeV and a majority even several TeV. These are exactly the expected characteristics of particles scattered back into the beam vacuum from events at very shallow depth. This finding also provides justification for the 20 MeV cutoff used in the LHC simulations, although the BCM has some sensitivity to particles with much lower energies. In fact, the simulated BCM background rate would be reduced by only 8% even if the sample with 20 GeV transport cutoff were used [24].

Figure 13 compares the shapes of simulated and measured distributions of the fake jets at $\beta^r = 40$ cm for B1. It is assumed that the shapes of the distributions are independent of the rate or impact depth distribution on the TCT.

In order to focus the comparison on the shapes only, the simulation results have been scaled to the data by using the ratios of data to simulations given in Table VII. The agreement on an absolute scale can be appreciated from Table VII. The upper plot compares the distributions in apparent transverse momentum, $p_T$. The effect of the ATLAS jet trigger turn-on is visible below 20 GeV, where the data drops down, while the simulated rate continues to rise towards lower transverse momenta. The bottom plot shows the distributions in azimuthal angle $\phi$, defined with respect to the horizontal axis, which points towards the center of the LHC ring. The highest fake-jets rates are found around $\phi = 0$ and $\phi = \pi$, i.e. in the horizontal plane. These maxima are caused by muons of opposite charge being separated and swept out in opposite directions by the separation dipole D1 between the TCT and the experiment [16]. The minor peaks at $\pm \pi/2$ are due to bending in the quadrupoles of the inner triplet, providing the final focus at the IP. The simulation results reproduce the shapes of both distributions within statistical uncertainties.

**VIII. CONCLUSIONS**

The first isolated measurements of beam-halo background in the experimental detectors at the LHC have been presented. The results are based on dedicated loss-map tests where low-intensity beams have been excited in order to induce beam losses on the primary TCP collimators. A small fraction of the protons leaks to the tertiary TCT collimators in front of the experiments and induces showers which are detected as machine-induced background. In these particular tests, the ATLAS experiment was recording background data, contrary to the routinely performed loss maps at the LHC. With the low beam intensity, but artificially provoked
short and intense loss spikes, the showers from the TCTs were the by far dominating source of background in the experiments. The results show that both the measured losses on the TCTs, as well as the observed background in ATLAS, as a function of the TCT aperture, can be fitted with a simple exponential.

The pure halo-related backgrounds measured in these tests are scaled to typical loss rates on the TCPs during standard operation, which, from two independent analyses, were found to be a few $10^5$ protons per second per bunch during the first hour of collisions. The fraction of background coming from beam halo was estimated to be at the per-mil level of the total background in 2015 and at the percent level in 2016. This confirms the indication obtained in previous studies [21,22] that the machine-induced background in the ATLAS experiment is dominated by local inelastic beam-gas interactions. A second test, in which the apertures of the vertical TCTs were slightly reduced during a high-intensity physics fill, supports this hypothesis, as no visible change in background was observed. This shows also that the background from elastic beam-gas scattering sending protons on the TCTs is negligible. The simulation studies presented in Ref. [44] indicate that the beam-gas interactions, which contribute to the background in ATLAS, take place within ~500 m of the experiment. Dedicated studies, injecting small amounts of gas locally into the beam vacuum, were undertaken during LHC run 2 in order to experimentally determine the sensitivity to beam-gas events as a function of distance from the experiment. The analysis of the data recorded during these tests is ongoing and is expected to provide verification for the regions where vacuum optimization has the largest impact on the background.

The results were used to estimate the effect on background from smaller TCT apertures. For all realistic TCT settings, which respect the hierarchy of the multistage collimation system, the beam-halo background is so small that it does not impose a constraint on the TCT aperture. This result has significant implications for the future optimization of the performance of the LHC, as well as the future high-luminosity LHC [58], since the TCT setting is directly connected to the aperture that can be protected and hence the achievable $\beta^*$. A tighter TCT allows reducing $\beta^*$, which results in a corresponding increase in luminosity. The fact that the TCT setting is not constrained by beam-halo background does, however, not mean that it can be arbitrarily tight. Other constraints from protection of the triplet magnets and the TCT itself, in particular during accidental losses, are the present limitation at the LHC for further reductions of $\beta^*$ [34,59], although they have been relaxed through the use of a specially matched optics [3].

The measurements have been compared with detailed three-step simulations. The first simulation step consists of tracking halo protons, with the SIXTRACK code, to estimate the impacts on the TCTs. In the second step FLUKA is used to generate inelastic interactions of protons in the TCT material and transporting the particle showers to a virtual interface plane close to the experiment. In the third and final step the particles recorded at the interface plane are transported with FLUKA through the ATLAS geometry and hit rates and energy depositions are recorded event by event. The simulation results are normalized with the bunch intensity loss, which during the loss-map test are almost entirely due to losses on the TCPs. Taking into account systematic uncertainties, in particular possible machine imperfections which are not considered in the simulations, a good quantitative agreement with the measured background is obtained. Features like transverse momentum and azimuthal distributions of fake jets are accurately reproduced.

Furthermore, it is shown that if the background is known for one configuration, SIXTRACK simulations of the transfer from the TCPs to the TCTs could be used to predict the background for other configurations of TCT settings and optics, with an accuracy of about a factor of a few, as long as the TCT impact distribution does not change significantly.

These results demonstrate that the beam-halo background at the LHC experiments is well understood and that it is not in any way limiting the present operational performance of the LHC, nor does it seem to be a limiting factor of performance optimization in the foreseeable future.

**APPENDIX: ABBREVIATIONS**

We summarize, in alphabetical order, all abbreviations used throughout the paper: ADT—transverse damper, used also to excite the beam to provoke losses; ATLAS—a general-purpose particle detector experiment located in IR1 of the LHC; B1, B2—the two counterrotating beams in the LHC; BCM—beam condition monitor, detector used to measure near-beam backgrounds in ATLAS; BCT—beam current transformer, used to measure beam intensity; BLM—beam loss monitor; CMS—a general-purpose particle detector experiment located in IR5 of the LHC; IP—interaction point; IR—insertion region [the LHC has eight IRs (see Fig. 1)]; LHC—large hadron collider [1,2]; TAD—transverse damper, used for beam dump protection in IR6; TCLA—active absorber located in IR7 or IR3; TCP—primary collimator located in IR7 or IR3; TCSG—secondary collimator located in IR7 or IR3; TCS—secondary collimator used for beam dump protection in IR6; TCT—tertiary collimator located in the experimental insertions; and TCTH, TCTV—horizontal (H) or vertical (V) tertiary collimator located in the experimental insertions.

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[4] $\beta^*$ is the optical $\beta$-function at the IP.


[24] ATLAS Collaboration, Beam backgrounds in the ATLAS detector during LHC loss-map tests at $\beta^* = 40$ cm and $\beta^x = 80$ cm at $E_{beam} = 6.5$ TeV, ATLAS PUB Note ATL-DAPR-PUB-2017-001, 2017.


[33] R. Kwee-Hinzmann, R. Bruce, F. Cerutti, L. S. Esposito, S. M. Gibson, and A. Lechner, Beam induced background studies in IR1 with the new HL-LHC layout, in Proceedings of the 6th International Particle Accelerator


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[40] The recorded value is the largest running sum anywhere in the 1 s interval.


[44] Since this background test was done in parallel with a standard qualification test, it was necessary to achieve the standard orbit, which requires collisions.

[45] The collimator settings are usually expressed as the half gap in units of the local betatron beam size $\sigma$, assuming a nominal normalized emittance of $3.5 \mu m$.


Publication-3

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3 Radiation levels

The expected radiation levels in the HGTD detector are an important parameter in the life expectancy of sensors and electronics. The radiation exposure can be reduced by an optimised detector design and appropriate shielding. With the introduction of a new detector system it is also important to verify that there are no adverse effects for other detectors. In the case of the HGTD, the potentially affected neighbouring system is the ITk. The extensive Monte Carlo simulation studies of the radiation environment, required for the layout optimisation, are performed using the FLUKA [9, 10] code. The results are scaled to an integrated luminosity of 4000 fb$^{-1}$.

The radiation environment is usually characterised by three quantities:

- **Non-ionising energy loss (NIEL)**, causing displacement damage in silicon detectors, which leads to increased leakage current, lower charge collection efficiency and changes of effective doping concentration. NIEL is usually given as the 1 MeV neutron equivalent fluence in silicon ($\text{Si1MeV}_{n\text{eq}}$), which expresses the fluence of a broad spectrum of particles as if they all would be 1 MeV neutrons [2, 11]. The exact NIEL of 1 MeV neutrons is difficult to assess experimentally, but has been defined to be 95 MeV mb. In the simulations the $\text{Si1MeV}_{n\text{eq}}$ fluence is obtained by weighting the fluence of a particle at a given energy by the ratio of its actual NIEL and 95 MeV mb. For high-energy hadrons, for instance, the NIEL is only around 50 MeV mb. It should be noted that the $\text{Si1MeV}_{n\text{eq}}$ fluence defined this way is valid only for silicon. Furthermore, while it is rather accurate for leakage current increase, changes of the effective doping concentration are found to exhibit additional particle type dependence [2].

- **Total ionising dose (TID)**, which is usually not significant for sensors, but affects some types of electronics. The degradation mostly results from charge trapping in oxide layers which leads to threshold voltage shifts and leakage current increase. MOS technologies are particularly sensitive to TID effects, while modern deep sub-micron devices usually are less affected.

- **High-energy hadron flux**, usually taken above a threshold of 20 MeV. This quantity is significant to estimate the rate of Single Event Upsets (SEU) in electronics. SEUs are caused by the very large ionisation loss of heavy nuclear fragments which are produced in collisions of high-energy hadrons with the nuclei in an electronics chip. The 20 MeV threshold is motivated by the fact that nuclear reactions start to produce sufficiently energetic fragments only above that energy [12]. The occurrence of SEU is statistical and normally has no dependence on cumulative fluence. The SEU sensitivity varies by orders of magnitude, depending on the properties of the chip, in particular the feature size, but also the architecture. In practice each potentially critical chip should be SEU qualified in a proton beam.

In the first proposals the HGTD was planned to replace the MBTS detectors and a borated polyethylene layer in the endcap region, which together constitute a 50 mm thick neutron moderator. Since the role of this moderator is to protect the inner detector from neutron albedo, its removal is bound to increase the radiation exposure of the future ITk.

For the HGTD and shielding optimisation the moderator configuration of run 2, i.e. no HGTD and 50 mm moderator covering the entire endcap calorimeter surface, is taken as the reference.

In the region where the HGTD is to be installed, the total ionising dose and the high-energy hadron fluence are practically irreducible since a suppression of these components would require thick and heavy shielding, which is not compatible with the ATLAS design and physics requirements of the HGTD. The
neutron component in the Si1MeV_{neq} fluence, however, can be reduced by moderators. With respect to silicon damage the role of a moderator is to lower the energy of neutrons below 100 keV, where their damaging potential is significantly reduced. Since the largest average energy loss is obtained when neutrons scatter on hydrogen the most efficient moderator is provided by polyethylene (PE). With a chemical composition (CH\textsubscript{2})\textsubscript{n} and a density just below 1 g/cm\textsuperscript{3} it is the material with highest hydrogen density. Boron can be added to capture thermal neutrons. While the boron has no influence on the Si1MeV_{neq} fluence, removing the thermal neutrons can reduce activation of materials and possibly SEU\textsuperscript{3}. Thus borated polyethylene (BPE) with a 5\% boron content (natural isotopic composition) and a density of 1.0 g/cm\textsuperscript{2} is used as moderator.

In the FLUKA simulation the HGTD detector is described as a stack of azimuthally symmetric disks with 70 cm outer radius and a r = 11 cm hole in middle. Along the z-axis a detailed structure, representing the different materials and sensitive layers of the HGTD, is implemented. The z-location depends on the configuration studied, in particular the relative order of the HGTD and the moderator. The fluences of various particles, the Si1MeV_{neq} fluence and the TID are recorded in a r−z binning with 2 × 2 cm\textsuperscript{2} bin size, averaged over azimuth. In addition these quantities are recorded separately inside each sensor and chip layer of the HGTD. The later provide more accurate estimates of the fluence and dose which the detectors and electronics are exposed to.

In the ITk the outermost ITk Strip disk, located at z = 3 m, is most affected by changes in the moderator configuration. The fluences in this region are presented as the average from z = 296–300 cm. Figure 36 shows, for the run 2 moderator configuration (baseline, i.e. no HGTD), the iso-fluence contour that goes through the lowest edge of the outermost disk. The fluence in an annular ring, r = 38–44 cm and z = 296–300 cm, corresponding to that most exposed edge, is used to quantify the impact of various HGTD and moderator configurations on the ITk.

Figure 36: Isofluence contour for the baseline solution, i.e. with 50 mm moderator over the entire endcap and no HGTD. The contour traces the fluence seen at the most exposed edge (z=300 cm, r=40 cm) of the ITk Strip detector.

The target level of Si1MeV_{neq} fluence in the ITk is set by the run 2 moderator configuration without an HGTD, shown in Figure 37(a). In order to study the impact of the HGTD and of the moderator on the ITk radiation levels three concepts are considered:

\textsuperscript{3} Many electronics chips contain boron dopants and upon neutron capture a boron-10 nucleus decays into an α-particle and a lithium fragment. In very sensitive chips these might have a large enough energy loss to cause an upset.
1. Replacement of the moderator at \( r < 80 \) cm by the HGTD, shown in Figure 37(b). In this configuration the HGTD occupies \( r = 70–110 \) cm and the range \( r = 70–80 \) cm is left for services, but modelled as air in the simulations. This configuration is referred to a plain HGTD.

2. The same as above, but a BPE layer added between the HGTD and the ITk (Figure 37(c)). This moderator extends from \( r = 11 \) cm to \( r = 85 \) cm and reduces the \( z \)-space available for the ITk.

3. The moderator placed on the endcap and the HGTD mounted in the IP side of it, i.e. between the ITk and the moderator (Figure 37(d)).

Figure 37: Different moderator configurations explored during the optimisation. The baseline without the HGTD and a run 2 like moderator configuration (a). The plain HGTD, where the HGTD replaces the run 2 moderator at \( r < 80 \) cm (b). The HGTD fixed on the endcap, but covered with a moderator layer (c). For option (c) the thickness of the moderator layer is varied from 0 to 10 cm in order to find an optimal balance between space consumption and Si1MeV
\( n_{eq} \) fluence reduction. In configuration (d) the HGTD is placed on the ITk side of the moderator. For this configuration the moderator thickness at \( r > 70 \) cm has been varied in order to create space for services. The geometry shown in (d) is referred to as optimised layout.

In the last option, any neutrons from the HGTD material could increase the radiation levels in the ITk. But since the HGTD consists of light materials, very similar to the ITk itself, no significant adverse effect are expected. The advantage of placing the HGTD on the ITk side of the moderator becomes evident from Figure 38 which shows that up to a factor 2.5 reduction of the Si1MeV\( n_{eq} \) fluence is obtained in the fourth HGTD silicon layer.

Several minor modifications of the last two concepts were investigated in order to arrive at an optimal configuration taking into account requirements from service routing and available space. Figure 37(d) shows the final result and is referred to as optimised layout. This choice is based on the results to be presented hereafter.

As indicated before, the Si1MeV\( n_{eq} \) fluence has contributions from neutrons, charged hadrons and, to a much lesser degree, from other particles. At small radii the charged hadrons dominate, while the neutron albedo increases towards the endcaps. Therefore the radius at which the two contributions are equal
Figure 38: Comparison of the Si1MeV$_{eq}$ fluence on the fourth HGTD sensor layer for the ‘plain HGTD’ and ‘optimised layout’. In the first case there is no moderator between the calorimeter and the HGTD, while in the second the HGTD is protected by 50 mm BPE.
depends on $z$. Figure 39 shows the Si1MeV$_{\text{eq}}$ fluence subdivided into the neutron and "other" components at four $z$-locations. The moderators covering the endcap have almost no effect on the Si1MeV$_{\text{eq}}$ fluences in the central parts of the ITk. At larger $z$, where the highest Si1MeV$_{\text{eq}}$ fluences are observed, the effect of the moderators is more significant. Their absence would increase the total Si1MeV$_{\text{eq}}$ fluence by $\sim$50% at the end of the ITk and even more in the HGTD itself.

Figure 39 verifies that only the neutron component of the Si1MeV$_{\text{eq}}$ fluence is affected by adding moderators. Even the neutron component, however, cannot be totally suppressed by moderators. Figure 40 illustrates that for neutron energies above $\sim$10 MeV, the moderation efficiency is very low. Below 100 keV the neutron damage in silicon is practically negligible, so a reduction in that part of the spectrum has little influence on the Si1MeV$_{\text{eq}}$ fluence. This leaves the energy range between 100 keV and 10 MeV where the moderators are actually effective.

Figures 39 and 40 imply that the Si1MeV$_{\text{eq}}$ fluence consists of a neutron component that can be reduced by moderators and a constant$^4$.

Figure 41 shows the Si1MeV$_{\text{eq}}$ fluence when the thickness of the moderator between ITk and HGTD is varied from 0 to 100 mm. The results are given relative to the baseline, indicated by the horizontal line. This target level is reached with a thickness of 50 mm which means that the shielding performance is restored if the moderator, removed in order to place the HGTD, is re-introduced. Increasing the moderator thickness beyond 50 mm brings no significant further reduction of the Si1MeV$_{\text{eq}}$ fluence. The slope of the fit is 0.285 cm$^{-1}$, which would imply that 5 cm of moderator should reduce the Si1MeV$_{\text{eq}}$ fluence by a factor of 4.2. But the significant constant term causes the real effect to be only a factor 1.4.

Inverting the order of the moderator and HGTD provides protection to the HGTD without increasing the Si1MeV$_{\text{eq}}$ fluence in the ITk by any significant amount. In Figure 41 three variations of such a configuration are included:

1. A BPE layer with constant 50 mm thickness over the full radial range of the endcap
2. A 50 mm BPE layer, restricted to $r < 70$ cm in order to leave space for services at larger radii
3. A 50 mm BPE layer at $r < 90$ cm, continued with a 20 mm thick layer to the outer radius of the endcap

While the Si1MeV$_{\text{eq}}$ fluences in the second option remain clearly above the target level, the first and third provide adequate shielding. All of these configurations reduce the Si1MeV$_{\text{eq}}$ fluence in the HGTD significantly. The advantage of the third option is that it leaves sufficient space for service routing, therefore it is adopted as the preferred design (optimised layout).

The three quantities to characterise the radiation environment in the first and fourth layer of the HGTD are summarised in Figure 42 for the optimised layout. For the assumed integrated luminosity of 4000 fb$^{-1}$ the Si1MeV$_{\text{eq}}$ fluence reaches up to $6 \times 10^{15}$ n$_{\text{eq}}$/cm$^2$ and the maximum TID is 4 MGy. The high-energy hadron fluence of $4 \times 10^{15}$ n$_{\text{eq}}$/cm$^2$ per 4000 fb$^{-1}$ translates into an instantaneous flux of $5 \times 10^7$ n$_{\text{eq}}$/cm$^2$·s at a luminosity of $5 \times 10^{34}$ cm$^{-2}$·s$^{-1}$. The SEU cross-section of electronics has a wide architecture-dependent variation, but for a rather typical value of $10^{-14}$ cm$^2$ per bit, this would imply an upset every 6 hours, on average, for any SEU sensitive bit. A safety margin of a factor 1.5 should be applied to all the values above to cover for systematic uncertainties of the simulations, in particular due to approximations in the geometry description. Additional safety factors to account for the impact on the electronics are applied, as discussed in Section 5.

$^4$ Constant with respect to moderator configuration, but not spatial position.
Figure 39: Division of Si1MeV$_{\text{n}}$ fluence into neutron and "other" components as a function of radius at four different z-locations. The values for two different moderator configurations are compared. The 'plain HGTD' corresponds to Figure 37(b) while the 'optimised layout' refers to Figure 37(d). At $z=0$ (a) and at the end of the ITk strip barrel (b) the moderators have practically no effect and the cross-over of neutrons and other particles is at about $r=30$ cm. The effect of the moderators becomes more evident at the outermost ITk endcap disk (c) and in the HGTD itself (d). In (c) the 'hot spot' radial range is indicated by the shade. In (d) the shade shows the radial range of the HGTD. As can be seen from Figures 37(b) and 37(d), the $z$-range plotted in (d) corresponds to the fluence in air next to the HGTD & moderator for the 'plain HGTD' layout, but for the 'optimised layout' the histogram, in the $r=11–70$cm range, shows the average fluence in the HGTD.
Figure 40: Neutron spectra averaged over the fourth silicon layer of the HGTD. The upper curve shows the spectrum when the HGTD is not protected by a moderator. The lower corresponds to 50 mm moderator between the endcap and the HGTD. The fluctuations between 1 keV and 10 MeV are due to resonances. The uncertainties are of the order of 5 %.

Figure 41: Si1MeV_{\text{eq}} fluence in the hottest spot of the outermost ITk Strip disk relative to the baseline without a HGTD. The horizontal line, showing the baseline configuration with 50 mm moderator and no HGTD, is considered the target level for the shielding optimisation. The solid blue circles and the fit show the reduction as a function of the moderator thickness between the ITk and the HGTD. The other symbols at 50 mm thickness correspond to configurations in which the HGTD is on the ITk side of the moderator. They differ only in terms of moderator thickness at r > 70 cm.
Figure 42: Si1MeV$_{\text{n}_{eq}}$ fluence (a), total ionising dose (b) and hadron fluence above 20 MeV (c) in the first and fourth detector layers of the HGTD. The pseudorapidity ($\eta$) range shown on the top of each plot corresponds to the $z$-location of Layer-4.

For comparable geometries the FLUKA results were found to agree within 30% with earlier work using the GCALOR simulation package.
2.4 Radiation hardness

One of the most important parameters of the HGTD will be the radiation hardness of the sensors and electronics. Since the HGTD will be installed with a pseudo-rapidity coverage of $2.4 < |\eta| < 4.0$, it is essential that the detector can withstand the radiation levels throughout the HL-LHC operations. The neutron-equivalent fluence at a radius of 120 mm, is expected to reach $5.6 \times 10^{15} \text{n}_{eq} \text{cm}^{-2}$ and the total ionising dose (TID) about $3.3 \text{ MGy}$ as shown in Figure 2.14. To account for uncertainties in the simulation, a safety factor of 1.5 is applied to both estimates. An additional factor of 1.5 is applied to the TID due to uncertainties in the behaviour of the electronics after irradiation, primarily for low-doses-rate effects, which have not been fully qualified as of today. This leads to a total safety factor of 1.5 for the sensors that are most sensitive to the particle fluence, and 2.25 for the electronics which are more sensitive to the TID. After applying these, the detector would need to withstand $8.3 \times 10^{15} \text{n}_{eq} \text{cm}^{-2}$ and 7.5 MGy.

To achieve sufficient performance of the sensors and ASICs, the detector layout has been designed considering a replacement scenario during the HL-LHC. Through an intensive R&D campaign described further in Chapter 5 and Chapter 6, a minimum charge of 4 fC is required to obtain a high efficiency signal. This can be achieved up to a radiation damage of $2.5 \times 10^{15} \text{n}_{eq} \text{cm}^{-2}$ and 2.0 MGy. As a result, the sensors and electronics within the lowest-radius ($r < 230 \text{ mm}$) will be replaced after each 1000 fb$^{-1}$ and the sensors and ASICs within $230 \text{ mm} < r < 470 \text{ mm}$ should be replaced at half of the data-taking (2000fb$^{-1}$) during the HL-LHC program. This corresponds to about 52% of the sensors and ASICs which will need to be replaced. The maximum fluence and total ionising dose as a function of the radial position including the replacement of the rings can be found in Figure 2.15. In the resulting three-ring layout, the maximal TID and fluence, using the Fluka estimations of September 2019, does not exceed 2 MGy and $2.5 \times 10^{15} \text{neq/cm}^2$. In the inner ring the total Si 1MeV neq has a similar contribution from neutrons and charged particles while in the middle and outer rings the dominant effect comes from neutrons.

The exact radial transition between the three rings will be tuned for the final detector layout, once the FLUKA simulations will be updated with the final ITk layout, and the radiation hardness of the final sensors and ASICs are re-evaluated.

More details can be found in Chapter 5 to Chapter 6. The expected proton, neutron, and pion energy spectra in the HGTD front and rear layer after 4000 fb$^{-1}$ are shown in Figure A.1, Figure A.2, and Figure A.3.
2 Detector Requirements and Layout

Figure 2.13: Time resolution per hit (left) and per track (right) within HGTD acceptance as a function of the radius. The time resolution is shown for various integrated luminosities. The time resolution is improved at higher luminosities corresponding to the replacements of inner-most rings during the lifetime of the detector.

Figure 2.14: Expected nominal Si1MeV$_{\text{eq}}$ fluence and ionising dose as functions of the radius in the outermost sensor layer of the HGTD for 4000 fb$^{-1}$, i.e. before including safety factors. The contribution from charged hadrons is included in 'Others'. These estimations used Fluka simulations using ATLAS Fluka geometry 3.1Q7 (from December 2019).

(a) Nominal Si1MeV$_{\text{eq}}$ fluence for HL-LHC. (b) Nominal ionising dose for HL-LHC.
2.4 Radiation hardness

(a) Si1MeV_{eq} fluence for HL-LHC with scale factor applied and considering ring replacements.

(b) Ionising dose for HL-LHC with scale factor applied and considering ring replacements.

Figure 2.15: Expected Si1MeV_{eq} radiation levels in HGTD, using Fluka simulations, as a function of the radius considering a replacement of the inner ring every 1000 fb^{-1} and the middle ring replaced at 2000 fb^{-1}. For the radiation levels, the particle type is included and the contribution from charged hadrons is included in ‘Others’. These curves included a safety factor (SF) of 1.5 to account for simulation uncertainty. An additional safety factor of 1.5 is applied to the TID to account for low dose-rate effects on the electronics, leading to a safety factor of 2.25.