Interaction Point Backgrounds from the CLIC Post Collision Line

A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Engineering and Physical Sciences

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ABSTRACT OF THESIS submitted by Michael David Salt

for the Degree of Doctor of Philosophy and entitled

Interaction Point Backgrounds from the CLIC Post Collision Line. July 2012

The proposed CLIC accelerator is designed to collide electrons and positrons at a centre of mass energy of 3 TeV, and a luminosity of $5.9 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ at the interaction point (IP). Being a single-pass machine, luminosity must be maximised by minimising the beam spot size to the order of a few nanometres. The effects of the final focussing and the intense beam-beam effects lead to a high production cross section of beamstrahlung photons, and highly divergent outgoing beams, both spatially and in energy. Pair-production of the beamstrahlung photons leads to coherent pairs.

The proposed CLIC post-collision line must transport electrons, positrons and photons from the IP to their respective dumps with minimal losses and background contribution. It is favourable to separate the particle species for diagnostic purposes, and thus the proposed post-collision line contains vertically bending magnets to separate based on charge. This process introduces dispersion to the energetically divergent beam, requiring the vertical apertures of the accelerator components to increase with distance from the IP. Particles in the low energy extreme of the beam cannot realistically pass through the components, which must therefore be protected by carbon-based absorbers. Losses in these absorbers and in the various dumps of the accelerator lead to electromagnetic showering within the material, some of which may be directed onto the IP. Optimisation of the apertures and positions of these components is presented as original research in this thesis.

It is the purpose of this thesis to study the CLIC post-collision line, beam transport and the production and effects of secondary particles at the IP. Primarily, the backscattered photons are evaluated, with an introduction to the effect of neutrons. Photons incident on silicon detectors have the potential to produce false hits, and neutrons to degrade the detectors. The effect of losses on the accelerator components is studied and the survivability of these components discussed.
Declaration

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Dedication

For Smudge, for always listening yet never forcing advice upon me.
Publications


M. Salt, R. Appleby, D. Bailey, *Beam Dynamics using Graphical Processing Units*, EPAC 08, Genoa, Italy.


M. Salt, R. Appleby, K. Elsener, A. Ferrari, *Photon backgrounds at the CLIC interaction point due to losses in the post-collision extraction line*, PAC 09, Vancouver, Canada.


M. Salt, R. Appleby, A. Apyan, E. Elsener, A. Ferrari, E. Gschwendtner, *Background at the interaction point from the CLIC post-collision line*, WEPE020, IPAC 10, KEK, Japan.

Chapter 1

Introduction

The key goals of this thesis are to design the CLIC post-collision line, suitable for the transport of the remnants of the collided beam from the CLIC interaction point to the beam dumps and study the associated backgrounds. The requirements for the post-collision line are presented and a baseline design created through beam dynamics optimisation. Beyond beam dynamics simulation, the effects of particles lost in the post-collision line are presented, along with results from physics-in-matter simulation to study the effects of charged particle showers. This thesis presents these results and discuss the impact on detector backgrounds and to consider component lifetime effects in the post-collision line design.
CHAPTER 1. INTRODUCTION

1.1 Introduction to Particle Accelerators

Any device that increases the kinetic energy of a charged particle may be described as a particle accelerator. Early accelerators were electrostatic devices, using a static electric field to accelerate charged particles. It is from these accelerators that the concept of an electron Volt is derived; one electron Volt is the kinetic energy gain of a particle possessing $1.602 \times 10^{-19}$ Coulombs of charge traversing a field of one Volt. Electrostatic accelerators are restricted by the maximum sustainable terminal voltage limited by breakdown, which occurs at approximately 10 MV [1]. To accelerate charged particles beyond this limit of a few 10 MeV, it is necessary to use a non-static accelerating field. In these accelerators, the particle passes through multiple gaps, or multiple times through the same gap, and is synchronised with the electric field such that it always receives an accelerating electrical field. Using radio-frequency acceleration schemes, the current high-energy limit is at 8 TeV [2].

In this chapter, a general introduction to particle accelerators is given. The application to high-energy physics is presented, and the rationale for the CLIC accelerator discussed. This is summarised with an overview of the research undertaken in the course of producing this thesis.

1.2 Applications of Particle Accelerators

The application of an accelerated beam of particles may be found in scientific research, industry and medicine. These accelerators vary greatly in their size, cost and type and
the applications are reviewed in this section.

1.2.1 Nuclear Research

In nuclear physics research, particle accelerators are required to accelerate atomic nuclei to a few tens of MeV. Due to their simplicity and cost effectiveness, electrostatic accelerators are frequently specified for this research. By colliding the beam with a target, nuclear researchers can use various detectors to study the nuclear properties, for example the discovery of superdeformed nuclei at the Daresbury Nuclear Structure Facility [4]. This discovery was powered by the 20 MW tandem van der Graaf accelerator housed in the 70 m tower shown in Figure 1.1. Accelerated beams also permit the production of beams of radioactive particles through collision with a target [5]. This is of particular importance to study isotopes far out of the valley of nuclear stability since these are usually short-lived. Beams of protons, neutrons or muons may be used to probe the nuclei of atoms within a target material [6].

1.2.2 Medical Applications

Accelerators are currently in use in medicine as a form of treatment for cancer. In conventional radiotherapy techniques, cancerous cells are exposed to X-ray radiation produced from accelerator generated $e^-$ interacting with a target via the Bremmstrahlung process [7]. If the cancer exists deep within the body, healthy tissue between the radiation source and the cancer are also damaged. In particle accelerator based hadron
therapy, a beam of protons or carbon ions are used [8]. The energy of the incident beam is tuned such that the majority of the energy is dissipated at a desired tissue depth, as described by the Bragg peak. This significantly reduces the damage to the tissue both in front and behind the area to be treated.

In diagnostic medicine, metastable isotopes are used in procedures such as bone scans and cardiac perfusion studies [9]. At present, these isotopes are produced by just a few nuclear reactors globally and accelerator-based techniques have low yield. Research is ongoing into improving the efficiency of the manufacture of $^{99}$Mo using accelerator-based techniques.

### 1.2.3 Light Sources

A consequence of bending a charged particle beam by the action of a perpendicular magnetic field is the emission of synchrotron radiation [10]. First considered to be a
parasitic loss of beam energy, it was discovered that this radiation had a highly desirable X-ray spectrum. Dedicated light sources were built as a result to probe matter at both the atomic and subatomic level, bending the beam around a closed circuit to produce light. Dedicated sources often use magnetic insertion devices known as wigglers or undulators. These devices pass the beam through a rapidly varying magnetic field to stimulate synchrotron emission. Light sources have been used to study subjects such as proteins, microelectronics, foodstuffs and microbiology [11].

An evolution of light sources is the Free Electron Laser (FEL). By passing an electron beam through a periodic magnetic field acting transversely on the beam, coherent radiation is produced that may have excellent time resolution [12].

1.2.4 Production of Other Particle Beams

Where high energy is not the primary concern, fixed-target experiments are used. Since the target area is large, beam stability is less of an issue to achieve high luminosity. Fixed target experiments such as ISIS at the Rutherford Appleton Laboratory [6] may be used to generate neutrons and also muons to probe matter, much like photons do in light sources.

1.3 High Energy Physics

The largest and most powerful particle accelerators are designed for the study of high energy particle physics. Due to the laws of the conservation of momentum and energy,
the majority of modern high-energy accelerators are of the colliding beam type rather than the fixed target type. This is because in a fixed target experiment, much of the available energy is wasted in the transfer of momentum to the particles in the target. The centre-of-mass energy in GeV ($E^*$) available for the production of new particles is given as

$$E^* = \sqrt{2E_i \times m}$$

for a fixed target machine and

$$E^* = 2E_i$$

for colliding beams where $E_i$ is the incident particle energy and $m$ is the mass of the colliding particles, both defined in eV. Colliding beams are energetically favourable for generating new physics where $2E_i > m$ because more energy is available in colliding beam machines to make new particles. The beams collide at designated positions known as the interaction point (IP) where the kinetic energy of the incident beams generate various particle species. The IP consists of a detector to confirm their presence and to measure their properties. It is typical for these particles to be particularly short-lived, and thus the detectors can infer their presence due to the detection of their decay products. Sophisticated computational methods are required to reconstruct the decay data to confirm the mass of the particle.

The two key parameters of a particle accelerator are the particle energy and the luminosity, which we shall now discuss in turn.
CHAPTER 1. INTRODUCTION

1.3.1 Energy and Luminosity

The Standard Model [13] has proved to be a largely successful theory of particle physics within the energy limits of current accelerator technology. The Standard Model describes the fundamental building blocks of matter, and the particle exchanges between them that form the mechanism of particle interactions. The building blocks are described as fermions, which are subdivided into leptons (electron, positron, muon, anti-muon, tau and anti-tau), quarks (up, down, strange, charm, bottom, top) and their respective anti-particles. Interactions between particles work through the exchange of bosons, such as the photon for electromagnetic interactions, $W^-$, $W^+$ and $Z$ for the Weak interaction and gluons for the Strong interaction. In order to probe the standard model beyond what is currently known, it is necessary to build machines with a greater centre of mass energy to produce massive undiscovered particles. The current maximum energy from a fully operational machine is at the Large Hadron Collider (LHC) [14], which has been designed for a centre of mass energy of 14 TeV but is currently operational with 8 TeV. In circular hadron colliders, the energy is limited by the maximum size of the ring and the strength of the dipole magnets that bend the beam. Hadron colliders are typically circular since this permits the beam to pass through the accelerating cavities multiple times, reducing the number of radiofrequency cavities and klystrons required to power them. A linear hadron collider would be prohibitive since it would require a tunnel of approximately 100 km in length to achieve 7 TeV collisions (assuming maximum accelerating gradient of 100 MV/m [16] and half the
The luminosity of a particle accelerator is important for physics discoveries since it is related to the number of events observed as

\[ N = \mathcal{L}\sigma T \]  

where \( N \) is the number of events, \( \mathcal{L} \) is the luminosity, \( \sigma \) is the cross section of the event of interest and \( T \) is the time for which the experiment is run. Increased luminosity proportionally increases the number of events observed. Natural cosmic rays produce events of significantly higher energy than any man-made particle accelerator would be capable of and, in theory, a detector could detect these events without requiring a particle accelerator. The limiting factor is luminosity; cosmic ray events are rare and distributed throughout the volume of the atmosphere, so the luminosity is low. In a colliding beam accelerator, the luminosity may be given as [17]

\[ L = H_d f \frac{N_1 N_2 n_b}{A} \]  

where \( f \) is the bunch crossing frequency, \( N_1, N_2 \) are the number of particles in each bunch, \( n_b \) is the number of bunches per bunch train, \( A \) is the transverse beam-beam cross section and \( H_d \) is the beam-pinch factor, which is the focussing effect experienced by a particle as it passes through the magnetic field of the opposing beam [18].
Figure 1.2: Beam Emittance and Phase Space Ellipse. The relationship between the particle horizontal position and its horizontal motion traces out an ellipse in $(x, p_x)$ phase space. The emittance ($\epsilon$) of the beam is the area of the phase space ellipse divided by $\pi$.

particles per bunch and decreasing the cross sectional area of the beam. The repetition rate and number of particles per bunch are limited by beam loading effects in the accelerating cavities [19], where the bunch projects an image current on the cavity which distorts the field seen by subsequent bunches leading to beam blow up and particle loss.

Figure 1.2 shows the motion of a particle in horizontal phase space where the area of the phase space ellipse divided by $\pi$ describes the emittance of the beam. In a conservative system, the emittance is intrinsic to the beam [20] and can only be minimised through injector gun design, and non-conservative systems such as acceleration and damping. Damping is achieved through the deliberate stimulation of Bremsstrahlung,
synchrotron radiation or other emission, which due to the loss of beam energy is thus non-conservative and may be used to reduce the emittance. Since the transverse beam size increases with emittance and the beta function at the IP, it is important that these values are minimised. The beta function is determined by the magnetic properties of the accelerator, and thus the final focussing system of an accelerator is designed to provide a minimum beta value at the IP in both vertical and horizontal planes. Due to the presence of the detector, a length of accelerator with no focussing elements is required, and so the mini-$\beta$ principle is needed [21]. Figure 1.3 shows the optics for a typical mini-$\beta$ insertion, requiring a minimum of eight individually powered magnets to achieve matching to the solution. The strong magnetic focussing fields of the mini-$\beta$ insertion acting on the charged beam stimulates synchrotron radiation production [10], which leads to photon emission.

Another factor in achieving maximum luminosity is to ensure that the beams collide on the same collision axis. Partial misalignment of the beams relative to each other leads to a reduction in the luminosity since a proportion of the particles do not pass through the opposing beam. To prevent such luminosity loss, the final focussing must be capable of delivering beams with high transverse stability.

1.3.2 Hadron Colliders

In a hadron collider, the particles which are usually accelerated and subsequently collided are either protons or antiprotons. In proton-antiproton colliders, the quarks and antiquark constituents of the protons annihilate. The proton possesses sea quarks [22]
in addition to valence quarks, and the kinetic energy distribution between these quarks becomes variable. A consequence of this is that the energy available for the production of new particles is certainly less than that of the parent hadrons. As a result, hadron colliders produce new particles over a broad section of the collision energy, depending which quarks interact, meaning that the collision energy is not known and must be reconstructed. An advantage of proton-antiproton colliders are that the beam can travel in the same magnetic region in a circular machine since their opposite charge permits transport in opposite directions as was used at the Tevatron [15].

In the Large Hadron Collider (LHC) [14], protons are collided with protons with a design centre of mass energy $= 14$ TeV (currently 8 TeV). Antiprotons are difficult to produce [23], and as such limit the maximum number of particles per bunch and thus the luminosity. The LHC is built in the tunnel of the Large Electron Positron
(LEP) collider [24], with a circumference of 27 km using dipole magnets with a design
strength of 8.3 Tesla [25].

Due to the broadness of the interacting centre of mass energy, and the relative
ease of achieving high energy compared to lepton machines, hadron colliders are often
referred to as 'discovery machines' [26]; finding new physics to be further studied.
A hadron collision event is usually more difficult to reconstruct because of various
backgrounds, including non-interacting quarks. In order to study new physics at a
more precise level, a cleaner interaction environment is required. Lepton-antilepton
colliders can provide this.

1.3.3 Lepton Colliders

In a lepton collider, the particle species accelerated are usually electrons and positrons.
Whereas hadrons are composite particles, made up of quarks, leptons are fundamental,
point-like particles. As a result, when these particles collide they annihilate completely,
and the full kinetic energy of collision is available for the production of new physics.
Since the spread in kinetic energy is usually small, this equates to a narrow energy
spectrum for the centre-of-mass energy. It is typical for a hadron machine to make a
discovery, and then a lepton machine tuned to explore in this energy region. Another
advantage of complete annihilation is that there is no debris resulting from spectator
quarks, resulting in a cleaner IP environment with lower backgrounds.

The highest energy lepton collider to have ever existed is the Large Electron Positron
(LEP) Collider [24] with a centre of mass energy eventually exceeding 200 GeV. LEP
was also a circular collider, residing in the tunnel that is now occupied by the LHC. Beyond this energy, power losses due to synchrotron radiation become unmanageable in a circular collider since loss scales as a factor of $\gamma^4$. The instantaneous power emitted, $P$, is given by the equation

$$P = \frac{2}{3} e^2 c \frac{\beta^4 \gamma^4}{\rho^2},$$

(1.5)

where $e$ is elementary charge, $\varepsilon_0$ is the permittivity of a vacuum and $\rho$ is the effective radius of the collider. $\beta$ and $\gamma$ are defined from the particle velocity $v$ and the speed of light $c$ as

$$\beta = \frac{v}{c}$$

(1.6)

and

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}.$$  

(1.7)

The beam power loss effects may be mitigated by increasing the radius of the collider ($\rho$), but this would require considerable expense for the required civil engineering to build such a tunnel to contain it. As a result, the next generation of electron-positron colliders are proposed to be linear.
### Chapter 1. Introduction

#### 1.1 The International Linear Collider

The International Linear Collider (ILC) [27] is one proposed solution for the next generation of linear colliders. It is designed to accelerate electrons and positrons to a centre of mass energy of 500 GeV over a distance of 31 km using 16,000 superconducting niobium cavities operating at an accelerating gradient of 31.5 MV/m. The option will exist to upgrade this to a centre of mass energy of 1 TeV later in its operation.

#### 1.4 The Compact Linear Collider

The Compact Linear Collider (CLIC) [28] is an alternative proposal to the ILC to supplement the physics discoveries at the LHC. The LHC explores the TeV energy range, and the first discoveries will indicate more precisely the energy range required of its partnering lepton collider.

---

**Table 1.1: A comparison of the ILC and CLIC**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ILC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Centre-of-Mass Energy (TeV)</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Accelerating Cavity Type</td>
<td>Superconducting</td>
<td>Normal conducting</td>
</tr>
<tr>
<td>Maximum Accelerating Gradient (MV/m)</td>
<td>31.5</td>
<td>100</td>
</tr>
</tbody>
</table>

---
Figure 1.4: General layout of the proposed CLIC two-beam acceleration scheme [28]. The upper half of the diagram shows the generation of the electron drive beam using two 1 km drive-beam accelerators and combiner rings to shape the pulses as required by the accelerating cavities. The lower half of the diagram shows the main beam generation, including damping rings to reduce the emittance before being injected into the main accelerator and then into the Beam Delivery System for collision at the IP. The 20 mrad crossing angle permits the beams to exit the IP without colliding with the next incoming beam. Exiting beams are directed into the post-collision line for transport to their appropriate dumps.

1.4.1 Physics at CLIC

The Standard Model has been particularly successful in explaining and predicting physics in the 100 GeV region. A key element of physics not described by the Standard Model is the origin of mass. It is postulated that particle mass originates from the interaction with the Higgs field, with the Higgs boson as an observable consequence [29]. Early indications at the LHC suggest a Higgs-like particle with a mass of 126.5 GeV at a local significance of 5.0 $\sigma$ [30]. To complement these indications, a precision lepton collider in the TeV regime is required to probe the details of the Higgs boson and its
variants.

Beyond the Standard Model, CLIC is expected to explore the possibility of extra dimensions, supersymmetry and the origins of dark matter. This requires a linear collider in the TeV regime with luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ [31].

### 1.4.2 Injection and Positron Production

To achieve sufficient luminosity at CLIC, it is essential that the beam sizes at the IP are sufficiently small. At the IP, the transverse beam size is dependent upon the product of the magnetic beta function ($\beta_x$, to be discussed more in Chapter 3) and the transverse emittance ($\epsilon_x$) as in Equation 1.8.

$$x = \sqrt{\epsilon_x \beta_x}$$  \hspace{1cm} (1.8)

The initial beam production has a major influence on the emittance of the beam, and thus careful design is required. Beam production is shown in the lower half of Figure 1.4. In the current baseline design for the injection complex [32], electron generation is produced by a high-voltage DC photo injector with the time-structure controlled by a laser to provide 312 bunches per train with a repetition rate of 50 Hz. The electron beam will be 80% polarised for physics reasons such as supersymmetry studies [33]. From the photo injector, the beam is accelerated to a kinetic energy of 2.2 GeV in linear accelerators before entering the damping rings. Positrons are generated from an unpolarised electron gun. The electrons are accelerated to 5 GeV and collided with a set of two targets to generate the positrons. The time structure of the positrons are
matched to that of the first accelerating structure by an Adiabatic Matching Device (AMD), which uses a high-strength magnetic field to capture positrons from their interaction with the target. The first accelerator structure raises the energy to 200 MeV, then another to 2.86 GeV before passing positrons into an acceleration and damping ring system symmetrical to the electron system.

1.4.3 Emittance Damping

The emittance of the beam is characterised at the injection gun or target and according to Liouville’s Theorem, cannot be changed in a conservative system [20]. In electron and positron accelerators, it is possible to use a non-conservative characteristic to minimise beam emittance: synchrotron radiation. The beam is passed through multiple turns of the damping rings to stimulate photon emission, where the emitted photon power is proportional to the kinetic energy of the particle and thus damps the emittance in all planes. Radiofrequency acceleration is used to replace the energy lost to synchrotron radiation, and coupling between the longitudinal and transverse emittance due to dipole and quadrupole magnets damps the transverse oscillations, reducing the beam emittance as much as possible within the timing constraints [35]. Since the beam spot size at the IP is a product of the beta function and emittance, this ultimately reduces the beam spot size at the IP. To preserve the emittance, it is necessary to manage the following effects [36]:

- Synchrotron radiation
- Collective effects
CHAPTER 1. INTRODUCTION

– Space charge
– Wakefields
• Residual Gas scattering
• Accelerator errors
  – Field errors
  – Magnet alignment errors.

Synchrotron radiation causes energy to be lost from the beam, making it a non-conservative system. This may be used deliberately to reduce emittance in damping rings, but has the potential to increase the emittance too. Where beams are not ultra-relativistic, the Coulomb repulsion of like-charge particles can lead to emittance growth. Wakefields are the image charges that the beam creates in the vacuum vessel walls, cavities and collimators that can influence particles later in the bunch to lead to emittance growth. The charged particles are assumed to travel in a vacuum, however collision with residual gas in the vacuum chamber can lead to particle loss. Finally, errors in the accelerator components can lead to non-conservative distortion of the beam.

1.4.4 Two-Beam Acceleration

The main linear accelerating sections are required to be 24 km in length to accelerate the beam to 1.5 TeV at a maximum gradient of $100 \text{ MV m}^{-1}$. Theoretically, this would mean that the accelerator would only be 15 km long, but some of the length must be devoted to beam focusing and also for the beam delivery system (2.75 km long). Conventionally, the accelerating structures would be driven by klystron generators. In an accelerator that is 24 km in length, many thousands of klystrons would be required.
Figure 1.5: Two beam acceleration. The 1 GHz, 100 A drive beam is decelerated in the power extraction structures to provide radio-frequency (RF) power to the main accelerating structures at 12 GHz.

This presents several reliability and maintenance issues since the klystrons would be distributed along the accelerator length [37]. The solution is a two-beam acceleration scheme (Figure 1.5), one in which a lower energy, high current beam drives a higher-energy, low current beam in the main Linear Accelerator (LINAC). The high-current drive beam is generated by fewer klystrons distributed over a smaller service area than powering the cavities directly.

1.4.5 Drive Beam and Power Extraction Structures

The drive beam is generated using a 1 km long linear accelerator (LINAC) facility driven by 326 klystrons per beam (both positron and electron lines are driven by an electron beam) [34]. The LINAC, operating at a frequency of 1 GHz accelerates the beam to 2.38 GeV with a current of 4.21 A. The drive beam profile is generated by combining pulses from the LINAC in two combining rings to give pulses of 240 ns every 5.8 µs. The beam is then directed along the service tunnel to be distributed along the main LINAC length to the power extraction structures (PETs). Each side
of the main LINAC is powered by decelerating the drive beam in twenty-four 878 m decelerating sections. The power extracted from decelerating the beam is passed via couplers to the main LINAC.

1.4.6 Main Accelerating Structures

In order to maintain a reasonable site length, it is desirable that the accelerating cavities must be capable of sustaining $100 \text{ MV m}^{-1}$ accelerating gradient. At these levels, the possibility for electrical breakdown exists, and thus a high-frequency power source is desired. Originally, the CLIC specification was for a 30 GHz oscillating frequency but further optimisation studies revealed that approximately 12 GHz would be a more realistic solution [38]. This is due to the machining tolerances of the cavities, where the 30 GHz wavelength is approximately equal to the surface imperfections of the cavity; leading to electrical breakdown [3].

At these frequencies, the cavity iris dimensions are small and very close to the beam. In the loaded condition, the beam can act upon the cavity generating an electrical field within the cavity. This leads to a phenomenon known as ’wakefield’ [39]. An induced wakefield caused by the head of the bunch can interact with the tail of the bunch or subsequent bunches, leading to emittance dilution and beam break up. Due to the intrinsically resonant nature of these cavities, wakefields can build up along lengths of accelerator. In order to suppress wakefield effects, these unwanted resonances must be damped using dielectric materials [40]. Alternatively, detuning the cavities by varying the cell-to-cell parameters permits the wakefield to be extracted through manifolds to
be absorbed remotely [39].

1.4.7 Beam Delivery System

The beam delivery system must deliver the beams to the IP with nanometre precision in order to deliver the luminosity requirements of the specification given in Table 1.2 [41]. Due to the size of the detector, the accelerator must rely on quadrupole magnets 3.5 m from the IP to generate the low small spot size required for high luminosity [42]. The final focusing quadrupole must have high structural and electrical stability and to maintain such precision, feedback systems are required to counteract misalignments generated by vibration and electromagnetic interferences.

Table 1.2: Incoming beam parameters at CLIC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>$E_{cm}$</td>
<td>3 TeV</td>
</tr>
<tr>
<td>Acceleration frequency</td>
<td>$f_{RF}$</td>
<td>12 GHz</td>
</tr>
<tr>
<td>Acceleration gradient</td>
<td>$g_{ACC}$</td>
<td>100 MV/m</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$N_b$</td>
<td>$3.72 \cdot 10^9$</td>
</tr>
<tr>
<td>Bunches per RF pulse</td>
<td>$n$</td>
<td>312</td>
</tr>
<tr>
<td>Bunch-bunch spacing</td>
<td>$\Delta t_b$</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>$f$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Primary beam power</td>
<td>$P_b$</td>
<td>14 MW</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>$(\beta \gamma)\epsilon_x$</td>
<td>660 nm.rad</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>$(\beta \gamma)\epsilon_y$</td>
<td>20 nm.rad</td>
</tr>
<tr>
<td>Horizontal rms beam size</td>
<td>$\sigma_x^*$</td>
<td>40 nm</td>
</tr>
<tr>
<td>Vertical rms beam size</td>
<td>$\sigma_y^*$</td>
<td>1 nm</td>
</tr>
<tr>
<td>Rms bunch length</td>
<td>$\sigma_z^*$</td>
<td>45 $\mu$m</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$L$</td>
<td>$5.9 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Beamstrahlung</td>
<td>$\delta_B$</td>
<td>29%</td>
</tr>
</tbody>
</table>

Optimisation studies have revealed that flat beams are required at CLIC since minimising the horizontal beam size induces further beam-beam effects, inflicting a net
CHAPTER 1. INTRODUCTION

Figure 1.6: Crossing Angle Scheme without (left) and with (right) Crab Correction. Blue represents the electron bunch, orange the positron bunch.

degradation of the luminosity [43]. It is the beam-beam effects, not the machine optics that ultimately determines the luminosity. Consequently, it is these effects that lead to the challenging nature of the post-collision line.

To allow the spent beams to be extracted, and to avoid unwanted parasitic collisions, the accelerator employs a crossing angle of 20 mrad [44]. If the beams were to remain aligned along the axis of travel, this would seriously reduce luminosity compared to a zero crossing angle. To maximise the possible luminosity where a crossing angle exists, crab cavities are employed to deflect the head and tail of the beam such that the bunch axes are aligned as in Figure 1.6.

Finally, the Beam Delivery System must include a system of collimators to remove any beam halo. Halo can interact with components of the beam delivery system resulting in unwanted background events and component activation [45].

1.4.8 IP

The detector at CLIC will be a general purpose detector, positioned symmetrically over the IP. Since CLIC is a precision machine, high vertexing and tracking precision
is required of the detector [46]. Accurate particle identification with precise spatial and momentum measurement requires highly sensitive semi-conductor based detectors. Being so sensitive, these devices will be susceptible to registering false hits from photon background and damage from neutrons. As a result, both the Final Focussing System (FFS) and post-collision line must be optimised for low-background conditions.

The IP itself will contain a general purpose detector based on the Silicon Detector (SiD) and (International Linear Detector) ILD designs [47]. Typical of general detectors, the inner portion will contain silicon-based vertex detectors. It is in this region that the detector is most sensitive to false hits due to backscattered photon background, or detector damage due to neutrons. Due to the high luminosity conditions at CLIC, beam-beam interactions are significantly greater than the ILC or LHC. The beam-beam effect is discussed in greater detail in Chapter 3.

1.4.9 Beyond the IP

After the collision of the beams, the high-energy particles and their beam-beam products must be transported to a dump for disposal. The part of the accelerator that handles these particles is the post-collision line and the requirements at CLIC represent a unique challenge in its design. It is the purpose of this thesis to design a post-collision line, and to demonstrate through simulation that the design is suitably appropriate for CLIC. This design will be presented in Chapter 3, with a detailed study of its particle background contribution presented in Chapters 5 and 6.
CHAPTER 1. INTRODUCTION

1.5 Overview of Thesis

In this thesis a post-collision line suitable for use at CLIC is designed and presented. Computational modelling techniques are introduced for both beam dynamics and physics in matter simulation before a study of the losses and backgrounds are presented. Finally, the post-collision line performance will be reviewed in terms of the initial requirements.

1.5.1 Computational Beam Dynamics

The goal of Chapter 2 is to explain the methods used to track particles through an accelerator. The matrix-vector techniques used to model the motion of a particle in simulation are introduced, including the mapping system used. This review chapter is intended to introduce the tools used in Chapter 3.

1.5.2 The CLIC Post-Collision Line

In Chapter 3, the goal is to design the post-collision line and explain how it solves the issues associated with the unique requirements at CLIC. This will cover considerations with regard to losses, physical space, minimising backgrounds and the application of instrumentation.
1.5.3 Physics in Matter and Simulation Validation

The goal of Chapter 4 is to present a general review of the physics-in-matter simulation techniques used in this thesis to generate the key background results. The aim of this chapter is to demonstrate the toolkits and methods that are used to obtain the results for the background study of the post-collision line, including the use of distributed computing to ensure sufficient statistics for modelling. A verification of published data is included to indicate the suitability of these tools for the study of backgrounds at CLIC.

1.5.4 Photon Backgrounds at the CLIC Post Collision Line

The goal of Chapter 5 is to present a comprehensive study of the electromagnetic backgrounds arising from particle loss in the CLIC post-collision line. The likely locations of secondary particle generation are proposed, and the simulation results presented. In addition to a general overview of the electromagnetic radiation background, the major goals of this chapter are to determine whether the magnets are over-exposed to energy losses where secondary particle production is considered, and to determine if the post-collision line will contribute significant backgrounds to the IP. The IP photon flux arising from the post-collision line will be compared to other estimated backgrounds to assess the performance of the post-collision line presented in Chapter 3.
1.5.5 Neutron Backgrounds at the CLIC Post Collision Line

The goal of Chapter 6 is to simulate the neutrons generated in the post-collision line. Neutrons can be particularly damaging to detectors, and so the aim of this chapter is to analyse the neutron flux incident on the detector and present the 1 MeV equivalent flux. An estimate will be made for the impact of the neutron background on the detector as a performance indicator of the post-collision line to suppress background.

1.5.6 Summary

In summary, the key areas of new research presented in this thesis are:

- To design a post-collision line optimised for CLIC, and provide evidence of its suitability through beam dynamics simulation.

- To consider the physics of particles travelling through the materials of the post-collision line using simulation to determine its suitability when considering secondary particle production.

- To consider the effect of backgrounds generated by the post-collision line on the IP.
Chapter 2

Computational Beam Dynamics

2.1 Overview

The aim of this chapter is to present basic beam dynamics theory, and introduce the concept of the transport map and its matrix representation. The purpose of this chapter is to introduce the methods that are used to generate the results in Chapter 3. Particle accelerator design usually starts with an analytical method, which then requires simulation to assess the performance of the machine for realistic beams, and for computing the dynamic aperture in the presence of lattice errors. In order to model the beam dynamics in a particle accelerator, it is necessary to model the system computationally. There exist many varied methods to simulate an accelerator, but computational beam dynamics may broadly be divided into two types: optics, and single particle tracking.
2.1.1 Optics

Optics is the study of the general beam behaviour as a result of the magnetic, electrostatic and radio-frequency elements in the beam line. In linear optics, the accelerator may be characterised by the Twiss parameters of alpha ($\alpha$), beta ($\beta$) and gamma ($\gamma$). It is possible to evolve the optical functions through the accelerator to define a specific length or a full turn in a circular machine. Optics functions allow for calculation of the beam size at any point in the machine should the beam emittance be known. The values of $\alpha$, $\beta$ and $\gamma$ are related by the following equations [48],

$$\alpha(s) = -\frac{1}{2} \beta'(s)$$  \hspace{1cm} (2.1)

and

$$\gamma(s) [m^{-1}] = \frac{1 + (\alpha(s))^2}{\beta(s) [m]}$$  \hspace{1cm} (2.2)

where $s$ is the longitudinal distance along the accelerator.

The Beta Function

The $\beta$ function is given by the focusing properties of the lattice. The value of $\beta$ and $\beta'$ are defined by the value of $\alpha$ and $\gamma$ and are characterised by the focusing elements of the lattice [49]. The function, $\beta(s)$ determines the extent of the outer beam envelope ($\sigma$) at any point in the accelerator by the equations [20],
\[
\sigma_x(s) \, [m] = \sqrt{\beta_x(s) \, [m] \, \epsilon_x \, [m \, \text{rad}]} \tag{2.3}
\]
and
\[
\sigma_y(s) \, [m] = \sqrt{\beta_y(s) \, [m] \, \epsilon_y \, [m \, \text{rad}]} , \tag{2.4}
\]
where \(\sigma_x, \sigma_y\) are the horizontal and vertical beam sizes and \(\epsilon_x, \epsilon_y\) are the horizontal and transverse beam emittances. The motion of a single particle horizontally as a function of \(s \, (x(s))\) is given as
\[
x(s) = \sqrt{\epsilon \beta} \cos(\Psi(s) + \phi), \tag{2.5}
\]
where \(\epsilon\) and \(\phi\) are integration constants determined by the initial conditions and the phase advance is given by
\[
\Psi(s) = \int_0^s \frac{ds'}{\beta(s')} . \tag{2.6}
\]

**Dispersion**

Where a beam is bent using dipole magnetic fields, the radius of curvature of an individual particle (\(\rho\)) is related to the magnetic field strength (\(B\)), and the particle momentum (\(p\)) by the beam rigidity equation [50],
\[
B \, [T] \, \rho \, [m] = \frac{p \, [kg \, m \, s^{-2}]}{e \, [C]} , \tag{2.7}
\]
CHAPTER 2. COMPUTATIONAL BEAM DYNAMICS

where $B \rho$ is the beam rigidity and $e$ is the elementary charge constant ($1.602 \times 10^{-19} \text{ C}$).

Rearranging Equation 2.7 gives

$$\rho [\text{m}] = \frac{p [\text{kg m s}^{-2}]}{B [\text{T}] \times e [\text{C}]},$$  \hspace{1cm} (2.8)

which demonstrates that the bending radius is a function of the particle momentum for fixed $B$. The dispersion is defined as the closed orbit distortion for an off-momentum particle, and is described as the function $D(s)$, which is dependent upon the position in the lattice. The (horizontal) displacement of an off-momentum particle relative to the ideal particle is given as $(x_D)$, which at any point of the accelerator may be found from the equation,

$$x_D [\text{m}] = D_x(s) [\text{m}] \frac{\Delta p}{p}, $$  \hspace{1cm} (2.9)

where $\Delta p/p$ is the relative momentum variation compared to the ideal reference particle.

Figure 2.1 shows the effects of dispersion since the transverse position of the particle is a function of its momentum relative to the ideal particle. In the first of the dipole magnets, due to the lower beam rigidity of the low energy particle, the trajectory is more strongly curved than that for the high energy particle. Since the second dipole magnet has an equal but opposite field to the first magnet, particles of all energies (that have remained in the apertures) are curved such that they are parallel. Since the transverse position is related to the particle momentum, the momentum may be inferred
Figure 2.1: Dispersion effects in a magnetic chicane.

from measuring the transverse location of the particle. This is particularly important to consider in post-collision lines where the energy distribution of the emerging beams will be disturbed by the action of beam collision at the IP.

### 2.1.2 Single Particle Tracking

Where the behaviour of individual particles is important, single-particle tracking is required. Instances where this is likely to be important are where there are large non-linear components to the accelerator, or where particle loss may lead to damage or background contribution. In single particle tracking, the phase-space coordinate of a particle may be given by the vector notation,

\[
X = \begin{pmatrix} x \\ p_x \\ y \\ p_y \\ \tau \\ p_t \end{pmatrix}
\] (2.10)
where we define

\[ x = \text{transverse horizontal position}, \]
\[ p_x = \text{transverse horizontal momentum}, \]
\[ y = \text{transverse vertical position}, \]
\[ p_y = \text{transverse vertical momentum}, \]
\[ \tau = \text{time of flight relative to ideal reference particle}, \]
\[ p_t = \frac{\Delta E}{p_s c}, \text{ and } p_s \text{ is the longitudinal momentum and} \]
\[ \Delta E \text{ is the energy difference to the ideal particle}. \]

These values are given relative to an ideal reference particle that passes through the magnetic elements at their functional centre, and has energy identical to the design energy. The orientation of the co-ordinate system is shown in Figure 2.2, with the transverse \( x \) and \( y \) dimensions moving with the ideal reference particles as it travels along \( s \).

### 2.2 Transfer Maps

To model the behaviour of a magnetic element acting upon the beam, the component or the combination of the components may be expressed as a transfer map. To a first-
order approximation, the motion may be modelled as a matrix-vector operation per magnetic element. The $6 \times 6$ matrix used to represent a magnetic element is known as an 'R-matrix'. An example linear matrix-vector operation for a drift space of length $L$ is

$$X = \begin{pmatrix}
1 & L & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & L & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & \frac{L}{\beta_s \gamma_s} \\
0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix} \times X^0, \quad (2.11)$$

where $\beta_s$ and $\gamma_s$ are defined from the particle velocity ($v$) and speed of light ($c$) as

$$\beta_s = \frac{v \ [ms^{-1}]}{c \ [ms^{-1}]} \quad (2.12)$$

and

$$\gamma_s = \sqrt{\frac{1}{1 - \beta_s^2}} \quad (2.13)$$

Performing the matrix algebra, the result for a drift map acting upon the phase-space vector is hence
\[
x = x_0 + Lp_{x0} \\
p_x = p_{x0} \\
x = y_0 + Lp_{y0} \\
p_y = p_{y0} \\
\tau = \tau_0 + \frac{L}{\beta_y^2 \gamma^2} p_{\tau0} \\
p_t = p_{t0}
\]

(2.14)

where the momentum in three dimensions \((p_x, p_y \text{ and } p_t)\) remains constant since there are no external forces acting upon the particle in the drift space. For small values of \(p_x \text{ and } p_y\), these are approximately equal to the angle of the direction of motion, which is why the terms \(Lp_{x0} \text{ and } Lp_{y0}\) appear in the mapping of \(x \text{ and } y\) respectively. The final state particle 6-vector at the exit of a particular magnetic element as a function of the initial values at entry may be modelled using a Taylor expansion. This consists of the R-matrix with the addition of second-order \(T_{ijk}\) terms,

\[
X_i = \sum_{j=1}^{6} R_{ij} X^0_j + \sum_{j=1}^{6} \sum_{k=1}^{6} T_{ijk} X^0_j X^0_k,
\]

(2.15)

where \(T_{ijk}\) are the second-order terms defined in [53] and \(i, j \text{ and } k\) represent the values, \(x = 1, p_x = 2, y = 3, p_y = 4, \tau = 5 \text{ and } p_t = 6\). The \(T_{ijk}\) terms are most important for large values of \(x, p_x, y, p_y, \tau \text{ and } p_t\).

The TRANSPORT [51] system assumes that the charged particles are sufficiently relativistic such that inter-particle Coulomb effects may be neglected. It is also assumed that deviations in position and momentum of a particle relative to the reference particle
are small for the truncation of the Taylor expansion to be valid.

The transport maps originate from the solution to the equations of motion of charged particles in a magnetic field. In drift spaces, there is no magnetic field, and so the particle will continue with its initial momentum vector. A dipole magnet has a constant magnetic field in one direction and a quadrupole has a magnetic field that is linear in both horizontal and vertical directions. In reality, magnets do not create a perfect magnetic field due to finite extent of the magnet material defining the poles and machining imperfections, but the ideal case is assumed in the transfer map presented in this thesis.

### 2.2.1 Examples of Accelerator Components in R-Matrix Form

Drift sections, bending magnet and quadrupole magnet behaviour is predominantly linear in nature for small deviations from the ideal particle trajectory, and so the beam behaviour is mostly described by the R-matrices. A drift section is a length of accelerator where there are no magnetic elements acting on the beam. Bending magnets may be divided into two main classes, rectangular-bends (rbends) and sector-bends (sbends), of which the differences are given later in Section 2.2.1. Quadrupole magnets are divided into two types, focussing and defocussing. A quadrupole can only focus in one plane at a time, leading to a defocussing effect in the vertical dimension when a focussing effect is applied to the horizontal dimension and vice-versa due to the shape of the quadrupole field and Maxwell’s equations [52].
Drift

In a drift space, there are no external forces acting upon the particles in motion. For this reason, the momentum of the particle will remain constant. The only terms which will be affected are those of the particle position, as a function of the momentum. The $R_{ij}$ matrix for this motion is

$$
\begin{pmatrix}
  x \\
  p_x \\
  y \\
  p_y \\
  \tau \\
  p_t \\
\end{pmatrix} = \begin{pmatrix}
  1 & L & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 & 0 & 0 \\
  0 & 0 & 1 & L & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 & 0 \\
  0 & 0 & 0 & 0 & 1 & \frac{L}{\beta_s \gamma_s} \\
  0 & 0 & 0 & 0 & 0 & 1 \\
\end{pmatrix} \times \begin{pmatrix}
  x^0 \\
  p_x^0 \\
  y^0 \\
  p_y^0 \\
  \tau^0 \\
  p_t^0 \\
\end{pmatrix},
$$

(2.16)

where $\beta_s$ and $\gamma_s$ are defined previously in Equations 2.12 and 2.13. The transport maps are based on a co-moving co-ordinate system, with the origin centred about an ideal reference particle that passes through the magnetic centre of every element as shown in Figure 2.2.

Sbend/Rbend

The dipole magnet is modelled by three matrices, one dipole matrix sandwiched between an entrance and exit matrix, each representing edge-focussing effects. Edge focussing effects are caused by two mechanisms. One is that the particle may be far from the lateral magnetic centre (assuming horizontal bending magnet) and therefore may traverse a different path length to the ideal particle, and thus experience the magnetic effects over a different length. Also, at the edges, the flux lines extend beyond the magnet face, leading to curved fields, and a vertical dependence for a horizontal
Figure 2.3: Edge focussing at the entrance and exit of dipole magnets. The curvature of the magnetic field outside the magnet aperture leads to an additional dependency depending of the offset of the particle from the centre of the magnet aperture.

bend since the field is not tangential to the particle as shown in Figure 2.3. The edge focussing effects at both the entrance and exit are modelled by [51]

\[
\begin{pmatrix}
  x \\
  p_x \\
  y \\
  p_y \\
  \tau \\
  p_t
\end{pmatrix} = 
\begin{pmatrix}
  1 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 1 & 0 & 0 & 0 \\
  0 & 0 & -h \tan \psi_t & 1 & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 & 0 \\
  0 & 0 & 0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
  x^0 \\
  p_x^0 \\
  y^0 \\
  p_y^0 \\
  \tau^0 \\
  p_t^0
\end{pmatrix},
\]

(2.17)

where \( \psi \) is the pole face rotation, as defined in Figure 2.4. For the body of the dipole, the value of \( k_x \) and \( k_y \) is defined as

\[
k_x = \sqrt{K_1 + \left( \frac{\theta}{L} \right)^2}
\]

(2.18)

and

\[
k_y = \sqrt{-K_1},
\]

(2.19)

where \( K_1 \) is the quadrupole co-efficient of the combined function component of the dipole and \( \theta \) is the bending angle. Since it is possible that either \( k_x \) or \( k_y \) could be
imaginary, the solution requires the trigonometric identities

$$\cos(kL) \equiv \cosh(ikl) \quad (2.20)$$

and

$$\frac{\sin(kL)}{kL} \equiv \frac{\sinh(ikL)}{ik} \quad (2.21)$$

to resolve the terms to real numbers to be used to populate the R-matrix. The dipole
R-matrix is given as
\[
\begin{pmatrix}
\cos(k_Lx) & \sin(k_Lx) & 0 & 0 & 0 & \frac{h}{\beta_s} \times \frac{1-\cos(k_Lx)}{k_s^2} \\
-k_L \sin(k_Lx) & \cos(k_Lx) & 0 & 0 & 0 & \frac{h}{\beta_s} \times \frac{\sin(k_Lx)}{k_s} \\
0 & 0 & \cos(k_Lx) & \frac{\sin(k_Lx)}{k_s} & 0 & 0 \\
0 & 0 & -k_L \sin(k_Lx) & \cos(k_Lx) & 0 & 0 \\
-\frac{h}{\beta_s} \times \frac{\sin(k_Lx)}{k_s} & -\frac{h}{\beta_s} \times \frac{1-\cos(k_Lx)}{k_s^2} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & \frac{L_{yy}^2}{\beta_s^2 \gamma_s^2} - \frac{h^2_{yy}^2}{\beta_s^2 \gamma_s^2} \frac{k_s^2}{k_s^2} \\
\end{pmatrix}
\]
\[(2.22)\]

In the dipole R-matrix, it is clear that the values of \(x\) and \(x'\) are coupled by the focussing terms, as are \(y\) and \(y'\). Since this is a horizontally bending dipole magnet, the values of \(x\) and \(x'\) are also a function of \(p_t\), coupled by the terms in the top right of the matrix. These terms represent the action of dispersion; the energy dependency of the horizontal motion.

**Quadrupole**

The quadrupole has focussing terms defined as
\[
k_s^2 = K_1 = -k_y^2 = -\frac{1}{B_0} \frac{\partial B_y}{\partial x},
\]
where \(K_1\) is the quadrupole coefficient, \(B_0\) is the beam rigidity as defined in Equation 2.7 and \(\frac{\partial B_y}{\partial x}\) is the field gradient. The quadrupole representation in \(R_{ij}\) form is given by
\[
\begin{pmatrix}
\begin{array}{cccccc}
x \\
p_s \\
y \\
p_y \\
\tau \\
p_t \\
\end{array}
\end{pmatrix}
= \begin{pmatrix}
\cos(k_Lx) & \sin(k_Lx) & 0 & 0 & 0 & 0 \\
-k_L \sin(k_Lx) & \cos(k_Lx) & 0 & 0 & 0 & 0 \\
0 & 0 & \cos(k_Lx) & \frac{\sin(k_Lx)}{k_s} & 0 & 0 \\
0 & 0 & -k_L \sin(k_Lx) & \cos(k_Lx) & 0 & 0 \\
-\frac{h}{\beta_s} \times \frac{\sin(k_Lx)}{k_s} & -\frac{h}{\beta_s} \times \frac{1-\cos(k_Lx)}{k_s^2} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & \frac{L_{yy}^2}{\beta_s^2 \gamma_s^2} - \frac{h^2_{yy}^2}{\beta_s^2 \gamma_s^2} \frac{k_s^2}{k_s^2} \\
\end{pmatrix}
\times
\begin{pmatrix}
x^0 \\
p_s^0 \\
y^0 \\
p_y^0 \\
\tau^0 \\
p_t^0 \\
\end{pmatrix}
\]
\[(2.24)\]
Notice that because \( k_x^2 = -k_y^2 \), the quadrupole will always focus in one transverse dimension whilst defocussing in the other.

**Sextupole**

To first-order, the sextupole is identical to Equation 2.16 \( R_{ij} \) for a drift. Second order terms are the important components of the sextupole due to their non-linear action on the beam. The complete TRANSPORT map to second order for a sextupole field strength, \( K_2 \), in a thick sextupole is defined as \[53\]

\[
x_2 = x_1 + L \left( 1 - \frac{p_{t1}}{\beta_s} \right) p_{x1} - K_2 \left( \frac{L^2}{4} (x_1^2 - y_1^2) + \frac{L^3}{12} (x_1 p_{x1} - y_1 p_{y1}) + \frac{L^4}{24} (p_{x1}^2 - p_{y1}^2) \right) - \frac{L}{2 \beta_s} p_{x1} p_{t1}
\]

\[
p_{z2} = p_{x1} - K_2 \left( \frac{L^2}{2} (x_1^2 - y_1^2) + \frac{L^2}{4} (x_1 p_{x1} - y_1 p_{y1}) + \frac{L^3}{6} (p_{x1}^2 - p_{y1}^2) \right)
\]

\[
y_2 = y_1 + L \left( 1 - \frac{p_{t1}}{\beta_s} \right) p_{y1} + K_2 \left( \frac{L^2}{4} x_1 y_1 + \frac{L^3}{12} (x_1 p_{y1} + y_1 p_{x1}) + \frac{L^4}{24} p_{x1} p_{y1} \right) - \frac{L}{2 \beta_s} p_{y1} p_{t1}
\]

\[
p_{z2} = p_{y1} + K_2 \left( \frac{L}{2} x_1 y_1 + \frac{L^2}{4} (x_1 p_{y1} + y_1 p_{x1}) + \frac{L^3}{6} p_{x1} p_{y1} \right)
\]

\[
\tau_2 = \tau_1 + \frac{L}{\beta_s^2 y_1^2} p_{t1} - \frac{L}{2 \beta_s} \left( p_{x1}^2 + p_{y1}^2 + \frac{3 p_{t1}^2}{\beta_s^2 y_1^2} \right)
\]

\[
p_{z2} = p_{t1}
\]

\[ (2.25) \]
The magnetic field strength increases as a function of $x^2$ for an upright sextupole, rather than being proportional to $x$ as in quadrupoles. Sextupoles are used, amongst other applications to correct chromatic aberration caused by off-energy particles passing through quadrupoles.

### 2.2.2 Combining Matrices

The net effect of the transfer maps can be modelled by concatenating the matrices:

$$M_{\text{total}} = M_n \times \ldots \times M_2 \times M_1$$  \hspace{1cm} (2.26)

where $M_{\text{total}}$ is the overall matrix and $M_{1,\ldots,n}$ are the magnetic elements in order with 1 being the first and $n$ the last as shown in Figure 2.5. For circular machines, a single matrix can be calculated to define a complete turn to first order, known as a one-turn map.

### 2.3 Rationale for using Beam Dynamics Codes

Beam dynamics codes are only an approximation to the real motion of particles in an accelerator, and in the instance of the transfer maps presented in this thesis, only
works for small variations from the ideal particle motion. Beam dynamics codes do not consider the additional physics involved where a particle is lost to the walls of the vacuum containment vessel. By simplifying the physics involved however, the user may track large numbers of particles to provide high statistics to assess the evolution of the beam shape and the potential locations for particle loss with a moderate amount of computing power.

In Chapter 3, beam dynamics simulation will be required to assess the performance of a CLIC post-collision line using realistic beams. Post-collision lines represent a unique challenge since the collision of particles at the IP can lead to a spread in energy of the emerging beams. The choice of simulation software used will be determined on its ability to accurately model dispersion and chromaticity across a wide range of energy. For this reason, it is necessary to compute particle trajectories using the second-order matrix formalism presented in this chapter, but to all orders in energy. The beam dynamics program DIMAD [54] provides such functionality through the use of the chromaticity precision option, which is reason it was chosen for the post-collision line optimisation procedure presented in Chapter 3.
Chapter 3

The CLIC Post-Collision Line

The goal of this chapter is to design and present the CLIC post-collision line, the design challenges and the features of the design that overcame them. Beam-beam effects are introduced, and the computational tools used to simulate them, along with the various components required for the design and their purpose explained. A key feature of the design is the beam loss optimisation, which required simulation of the post-collision line, and the optimisation of various parameters. Through this optimisation, the design goals are shown to be satisfied. The electron-positron beams at CLIC will collide at a centre of mass energy of 3 TeV with a luminosity of $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ (within 1% of energy) [59]. Under these collision conditions, beam-beam effects will be large, with high production rates of beamstrahlung photons, coherent pairs, radiative Bhabha and incoherent pairs. The CLIC accelerator is designed with a crossing angle of 20 mrad to permit the outgoing beams to clear the incoming beam lines [59]. These outgoing beams are handled by the CLIC post-collision line, which was published in [60].
3.1 Design Constraints

The design requirements for the CLIC post-collision line must satisfy four key constraints which are detailed in this section:

- Transport of the 1.5 TeV nominal non-colliding beams.
- Minimisation of power losses when transporting the products of colliding beams.
- Separation of photons and charged beams.
- Spatial clearance constraints

We shall now consider them one by one in greater detail.

3.1.1 Transport of the 1.5 TeV Nominal Noncolliding Beams

In the event of non-colliding beams, the post-collision line must be able to transport the beam to the dump whilst the product of the beam size \((\sigma_x, \sigma_y)\) must be allowed to expand to 1 mm\(^2\) to prevent damage to the beam windows [60]. This favours a longer post-collision line since the beam size will grow naturally in drift space. This drift space may also include sweeping magnets and spoilers to generate additional beam size growth if required.
3.1.2 Minimisation of Power Losses when Transporting the Products of Colliding Beams

Under normal operation, the post-collision line must transport all particles produced during collision with minimal losses, the thresholds of which will be defined later. The interaction of the magnetic fields of opposing beams passing through each other generates beam-beam effects [18]. Under the influence of the magnetic field of the opposing beam, the change in particle momentum leads to the stimulation of synchrotron radiation, which is known as 'beamstrahlung' in this context of production. Beamstrahlung photons continue to be influenced by the opposing beam such that a proportion will undergo pair-production, producing an $e^-e^+$ pair. The pairs originating from this process are known as 'coherent pairs'. Strong beam-beam effects at the interaction point of CLIC lead to an emittance growth for the outgoing beams (disrupted beams) as well as the production of beamstrahlung photons and $e^-e^+$ coherent pairs. Magnets used in the post-collision line will be susceptible to damage due to beam losses affecting their service lifetime. The expected magnet lifetime is

$$\text{magnet lifetime [s]} = \frac{\text{dose limit [J kg}^{-1}]\text{]}{\text{dose rate [J kg}^{-1}\text{s}^{-1}]},$$

(3.1)

where the dose limit for a typical normal conducting copper coil magnet is $10^7$ Gy [62], at which point the coil insulation is expected to break down leading to short circuit induced failure. Where the losses are non-uniform along the length of the magnet, the concept of power losses per metre is useful. The dose rate as a function of power loss
per metre is given as

\[
\text{dose rate } [\text{J kg}^{-1} \text{s}^{-1}] = \frac{\text{power loss per metre } [\text{J s}^{-1} \text{ m}^{-1}]}{\text{mass per metre } [\text{kg m}^{-1}]}, \tag{3.2}
\]

where the mass per metre is calculated to be approximately 7,000 kg m\(^{-1}\) for the magnets proposed in the post-collision line design presented later in this chapter. Substituting Equation 3.2 into Equation 3.1 gives the maximum permitted power loss per metre

\[
\text{power loss per metre } [\text{J s}^{-1} \text{ m}^{-1}] = \text{dose limit } [\text{J kg}^{-1}] \times \frac{\text{mass per metre } [\text{kg m}^{-1}]}{\text{magnet lifetime } [\text{s}]} \tag{3.3}
\]

At the high energy frontier of particle physics, the last two machines to be decommissioned are the Large Electron-Positron Collider [24] and the Tevatron [61], with service lifetimes of 11 years and 26 years respectively. Taking an average of these lifetimes, an estimated service lifetime of CLIC would be approximately 20 years. Since the post-collision cavern will contain the beam dumps, access to service personnel will be restricted due to radiation levels in the cavern. For this reason, the post-collision line should be designed with a magnet lifetime exceeding 20 years to prevent the requirement for magnet servicing. To achieve this lifetime, assuming a magnet mass per metre of 7,000 kg m\(^{-1}\) and a dose limit of 10\(^7\) Gy, Equation 3.3 gives a maximum power loss per metre of approximately 100 Wm\(^{-1}\). This was taken to be a design constraint in the optimisation procedure. It is also desirable to minimise losses since these will generate
secondary particles through Bremsstrahlung, pair production and Compton scattering. Figure 3.1 shows some of the mechanisms of secondary particle production, which includes the possibility of a particles being backscattered towards the IP. The impact of these secondary particles is discussed later in Chapters 5 and 6.

### 3.1.3 Separation of Photons and Charged Beams

It is desirable to include luminosity monitoring within the post-collision line to provide diagnostic feedback for the final focus system. The number of coherent pairs and beamstrahlung photons is dependent on the luminosity, and so identifying these particles is an important constraint of the post-collision line. To provide such distinction, it is necessary to separate the beams with different charge characteristics so they can...
be identified by their position in the post-collision line. By introducing dispersion, charged beams may be separated from the neutral photons and from particles within the beam possessing an opposite charge to the main beam. Dispersion will also order the particles spatially by energy which may be used to evaluate the energy profile and thus provide quality of collision feedback.

### 3.1.4 Spatial Clearance Constraints

The post-collision design must consider the actual space within which it can physically occupy, as shown in Figure 3.2. The first constraint to consider is the clearance between the incoming beam line and the post-collision line. If it is assumed that the maximum lateral incoming beam-line clearance that the post-collision line may occupy is half of the crossing angle, the dependency on the distance from the IP may be given as:

\[
 w [\text{m}] = s [\text{m}] \times \frac{1}{2} \theta [\text{rad}],
\]

for small angles of \( \theta \) where \( w \) is the lateral clearance from the incoming beam-line, \( s \) is the distance from the IP and \( \theta \) is the crossing angle, which is 20 mrad for CLIC under 3.0 TeV operation. Due to this restriction, it is desirable to separate the beams in the vertical direction to avoid violating the incoming beam-line clearance. Positioning components further from the IP provides more lateral clearance, but must have larger apertures to account for the expanding beam. Another important consideration is the space between components along the post-collision line. The face clearance is no less
Figure 3.2: Plan view of the I.P. showing the physical constraints on the size and position of the post-collision line components. The crossing angle is 20 mrad for CLIC and the proposed minimum face clearance is 1 m [65]. The maximum extent of the detector is 7086 mm [47] and so to ensure the post-collision line components do not have to be integrated into the detector the IP clearance must be 7086 mm as a minimum.

than 1 m to allow for magnet coil returns and connections for cooling and power [65].

### 3.2 Simulating Beam-Beam effects using GUINEA-PIG

In order to simulate the performance of the post-collision line, it is necessary to generate the particles to be transported. The beam-beam simulator GUINEA-PIG [66] is
used to generate the input particles for the post-collision line simulations. GUINEA-PIG uses a specific input file to define the accelerator and beam characteristics by multiple parameters such as number of particles per bunch and transverse beam sizes at the IP. By replacing the incoming beam particles with a smaller number of macro-particles, GUINEA-PIG divides these into time slices and solves the Poisson equation [67] for each cell,

\[
\frac{\Phi_{i+1,j} - 2\Phi_{i,j} + \Phi_{i-1,j}}{(\Delta x)^2} + \frac{\Phi_{i,j+1} - 2\Phi_{i,j} + \Phi_{i,j-1}}{(\Delta y)^2} = -\frac{4\pi \epsilon_0 Q_{i,j}}{\Delta x \Delta y \Delta z},
\]

where \(\Delta x\), \(\Delta y\) and \(\Delta z\) are the dimensions of the cell and \(Q_{i,j}\) is the total charge within the cell. The indices \(i\) and \(j\) represent the cell number of the cell and its opposing cell respectively. By solving Poisson’s equation, the electric field potential (\(\Phi\)) seen by a particle due to the pinch effect [69] can be calculated and its motion predicted. The pinch effect is a focussing effect caused in ultra relativistic particles where the electric and magnetic fields are almost transverse to the direction of motion. If a particle has the opposite charge to the bunch, both the magnetic and electric forces will focus it to the centre of the bunch, whereas particles having the same charge will be bent away from the bunch centre.

In single-pass machines, particularly CLIC, these beam-beam induced electric fields are particularly strong, leading to deflection of the outgoing beams and causing beam blow-up. The change in momentum due to the pinch effect leads to Bremsstrahlung photon emission known as beamstrahlung when originating from this process. Within the magnetic field of the opposing beam, these photons can pair-produce, and these
pairs can interact yet further with the beam, producing a transverse asymmetry between those coherently produced pairs of the same and opposite charge to the main beam. For convenience, the coherently produced $e^-/e^+$ of the same charge as the main beam will be referred to as ’cohplus’, and those with an opposite charge as ’cohminus’. The particles that were originally in the main beam, but have had their energy and angular distributions disrupted by the beam-beam effects, will be known as the disrupted beam. In reality, the disrupted and cohplus beams would be indistinguishable, since they are the same particle species and have the same charge.

GUINEA-PIG produces many output files; however, the important data for the post-collision simulations are that of the disrupted beam, coherent pairs and beamstrahlung photons since these are most abundant in the post-collision line compared to other particles. For the purpose of DIMAD simulations, these output files must be converted before use. In order to generate these files, 10 runs of GUINEA-PIG were run on 10 different machines, each run with a unique random seed and with parameters defined in Appendix A. The output files were combined to give the equivalent output of 1% of the particles in a single bunch, which was estimated to be sufficient for the simulations presented in this thesis.

3.3 Beam-beam effects

At CLIC, the two opposing beams collide with a spot size of just a few nanometres, leading to a large charge density [59]. The change in particle momentum by this fo-
cussing effect leads to the angular distribution as shown in Figure 3.3 (double-peaked transversely since the incident beams have $\sigma_x << \sigma_y$ to minimise beamstrahlung yet maximise luminosity [43]) and the emission of photons through the synchrotron radiation mechanism. These emitted photons are known as beamstrahlung photons, and their emission spectrum is responsible for the spread in energy of the disrupted beam, as shown in Figure 3.4. The energy distribution is strongly peaked at 1500 GeV, which indicates that most beam particles pass through the IP having lost very little energy. However, many particles exist with energy between 20 GeV and 1500 GeV which must be considered in the post-collision line design. In the strong magnetic field of the opposing beam, these photons can undergo pair production, generating coherent pairs. The magnitude of these effects is measured by the beam-beam interaction and beamstrahlung photon emission parameter ($\Upsilon$), which is used to compare different beam-beam regimes and is defined as

$$\Upsilon = \frac{5}{6} \frac{\gamma r_e^2 N_b}{\alpha \sigma_x^2 \sigma_y^2 (1 + \frac{\sigma_z^2}{\sigma_y^2})},$$

(3.6)

where $\alpha = 1/137$ (fine structure constant), $r_e = 2.82 \times 10^{-15}$ m (classical electron radius), $\sigma_x^2, \sigma_y^2, \sigma_z^2$ are the Gaussian beam size in three dimensions and $N_b$ is the number of particles per bunch [70]. At CLIC, $\Upsilon \approx 5.4$, compared with only 0.046 at the ILC. The enhanced beam-beam effects generate more beamstrahlung photons and coherent pairs requiring a post-collision line that differs from a design that would satisfy the requirements at the ILC [68]. The energy spectrum of the emerging beam will be broader for larger values of $\Upsilon$ since more beam particles will lose energy to the beamstrahlung...
Table 3.1: CLIC incoming beam parameters as used in GUINEA-PIG [66] beam-beam simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>1500 GeV</td>
</tr>
<tr>
<td>$\beta_x$</td>
<td>8.0 mm</td>
</tr>
<tr>
<td>$\beta_y$</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>$\epsilon_x$</td>
<td>$0.66 \times 10^{-6}$ m.rad</td>
</tr>
<tr>
<td>$\epsilon_y$</td>
<td>$0.03 \times 10^{-6}$ m.rad</td>
</tr>
</tbody>
</table>

process. The high interaction parameter at CLIC is responsible for the plateau seen in Figure 3.4 since the particles in this region have lost energy to the emission of beamstrahlung photons.

When coherent pairs are produced, one has the same charge as the disrupted beam exiting the detector, whilst the other has the opposite charge. Having an opposite charge to the disrupted beam, these particles undergo a further transverse emittance dilution due to the beam-beam effects. Being divergent in both space and energy, these particles in particular require the post-collision line to have large bandwidth in energy. To achieve this bandwidth requires large apertures and magnets that do not over-focus (chromaticity bandwidth) or over-bend (dispersion bandwidth) the low-energy particles such that they collide with the vacuum containment walls. At 3 TeV operation, the author’s GUINEA-PIG simulations generate 2.5 beamstrahlung photons and 0.215 coherent pairs per incident beam particle. Coherent pairs are produced by pair-production due to beamstrahlung photons interacting with the magnetic field of the opposing beam [18].
Figure 3.3: Horizontal and vertical angular distributions of the CLIC disrupted beam, obtained with GUINEA-PIG [66] using Gaussian incoming beams as given in Table 3.1 and using $7.44 \times 10^6$ incident particles normalised to the equivalent of one bunch ($3.72 \times 10^9$ incident particles).

The angular distribution of the beamstrahlung photons emerging from the IP are presented in Figure 3.5. Being uncharged particles, the photons do not experience the same beam-beam effects as the charged beam. As a result, the horizontal angular divergence of the photon cone is narrower than that for the disrupted beam. In Figure 3.6, the coherent pairs resulting from pair-production of the beamstrahlung photons are shown. The particles of the opposite charge to the main beam (the cohminus particles) are subjected to an additional vertical kick due to charge-specific beam-beam effects compared to the cohplus particles. Since the energy distribution of pair-production is not a function of charge, cohminus and cohplus beams have the same energy spectrum,
Figure 3.4: Energy spectrum of the CLIC disrupted beam (parameters as in Figure 3.3). as shown in Figure 3.7 and so it is the difference in the angular distribution that will require larger acceptance for the cohminus beam than the cohplus beam.

Incoherent pairs are $e^-e^+$ pairs that are not produced from a single beamstrahlung photon, as is the case for coherent pairs. In addition to the coherent pairs, incoherent pairs will also be produced via the Breit-Wheeler ($\gamma\gamma \rightarrow e^+e^-$), Bethe-Heitler ($e\gamma \rightarrow ee^+e^-$) and Landau-Lifshitz ($ee \rightarrow eee^+e^-$) processes [71]. However, the author’s GUINEA-PIG simulations reveal that these pairs are typically created with a large angle relative to the outgoing beams, so are unlikely to enter the post-collision line. The total energy carried away by the incoherent pairs is 5 mJ per bunch crossing, which corresponds to a total power of 78 W. Hence in the following, their impact is neglected.

Another source of energy loss for the incoming beams is radiative Bhabha scatter-
Figure 3.5: Horizontal and vertical angular distributions of the beamstrahlung photons (parameters as in Figure 3.3).

The process is given by \( e^+ e^- \rightarrow e^+ e^- \gamma \), where the exchange of a virtual photon may induce the emission of a real photon by one incoming electron or positron. At CLIC, one expects \( 5 \times 10^5 \) radiative Bhabhas per outgoing bunch. Their energy spectrum is shown in Fig. 3.8. In contrast with those coming from the incoherent pairs, the electrons and positrons produced by this process may carry up to 100\% of the primary beam energy per particle. Even if they only carry a tiny fraction of the outgoing beam power (about 1 kW out of 14 MW), the low-energy tail of the radiative Bhabhas may lead to small losses along the post-collision line.
Figure 3.6: Horizontal and vertical angular distributions of the particles of the $e^+e^-$ coherent pairs with the same charge as the CLIC disrupted beam (Cohplus) and with the opposite charge (Cohminus) (parameters as in Figure 3.3).

Table 3.2: Outgoing beam power of the charged beam-beam products at CLIC. It is clear that the disrupted beam and charged particles produced by the coherent process are dominant, and thus these are the particles studied in the beam dynamics simulation.

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>Power [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>disrupted</td>
<td>9.76</td>
</tr>
<tr>
<td>cohplus</td>
<td>0.177</td>
</tr>
<tr>
<td>cohminus</td>
<td>0.177</td>
</tr>
<tr>
<td>radiative Bhabha</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>incoherent pairs</td>
<td>0.000078</td>
</tr>
</tbody>
</table>
Figure 3.7: Energy spectrum of the particles of the $e^+e^-$ coherent pairs with the same charge as the disrupted beam (Cohplus) and with the opposite charge (Cohminus) (parameters as in Figure 3.3). It is clear that energy distribution is not charge dependent since the distributions are almost identical.
CHAPTER 3. THE CLIC POST-COLLISION LINE

Figure 3.8: Relative energy spectrum of the electrons and positrons coming from radiative Bhabha scattering (full line) and from the incoherent pair production (dashed line). This plot shows the number of particles per bunch crossing.
3.4 General Layout

In the International Linear Collider, the proposed post-collision line for the 14 mrad crossing angle consists of a quadrupole quadruplet, followed by a vertical magnetic chicane [72]. Beam-beam effects at CLIC lead to a significantly greater proportion of lower-energy particles than at the ILC due to the higher interaction parameter ($\Upsilon$). These low-energy particles would result in unacceptable losses in the quadrupoles due to chromaticity (over-focussing of low-energy tail), which is addressed by the post-collision line presented here by the author by eliminating quadrupoles from the design. The absolute minimum design would be a simple drift section without any dipole magnets. However, under this scheme, the charged particles and the beamstrahlung photons would be difficult to distinguish. By providing a separation scheme, the vertical transverse position indicates both the charge or the particle, and the momentum per charge, useful for determining the particle energy. The separation is in the vertical direction to clear the incoming beam line, with the main beam and like sign charged particles being bent downwards, perpendicular to the plane of the crossing angle. The cohminus beam and low-energy tail would then be absorbed by an intermediate dump so that the number of cohminus particles may be monitored, and the low-energy tail of the disrupted and cohplus beams is not lost in the c-type magnets due to dispersion. The remaining beam and beamstrahlung photons are passed through four dipole magnets (4.0 m, -0.8 T) intended to bend the charged beam upwards so that it is parallel to the beamstrahlung photons. The beam and photons would then travel in the same
vacuum vessel to the main water-based dump 315 m from the IP. This proposal takes into account physical clearance issues, such as sufficient face clearance (Figure 3.2) between the magnets and masks (1.0 m minimum) to allow space for the magnet coil returns. It is desirable to separate the beams far from the IP such that the post-collision line is outside the detector, and the first loss location and potential source of background (from the processes in Figure 3.1) is further from the IP and therefore less likely to contribute to IP backgrounds. In order to reduce the photon and neutron background contribution at the IP, the main dump is located 315 m away, allowing space for instrumentation, or beam sweeping apparatus to minimise the impact of non-colliding beams on the main dump.

The post-collision line in relation to the IP is schematically represented in plan view form in Figure 3.9. The horizontal 20 mrad crossing angle provides a means for extracting the beam-beam products after collision. However, the lateral space between the post-collision line and the incoming beam line is restricted and thus it is important to ensure the post collision line is as narrow in the horizontal direction as possible. Since it is a requirement to separate the spent beams for particle identification and luminosity monitoring, the horizontal constraints dictate that this separation must be in vertical direction, as is shown in the side view of Figure 3.10. Following Figure 3.10 from left to right, the beam encounters five vertically bending window-frame magnets to separate the charged beams from the beamstrahlung photons. The cross-sectional view of these magnets is shown in Figure 3.9, so chosen because a window-frame magnet is narrower than a c-type magnet because the returning flux has two return
paths. Continuing along Figure 3.10, the beam passes through an intermediate dump which is designed to absorb all particles with an opposite charge to the main beam (to be monitored as a luminosity indicator), and the low energy tail of the particles with the same charge as the disrupted beam. Beyond this, the beamstrahlung photons and disrupted beam pass through four c-type magnets which act to bend the charged beam upwards to bring it parallel to the beamstrahlung photons. Both beams then travel in a common beam pipe to the dump. The proposed dump is of a pressurised water type, 10 m in length based on the ILC design [73]. The individual components are now discussed in more detail.
Figure 3.9: Schematic (not to scale) plan view of the CLIC post-collision line in relation to the incoming beam lines.
Figure 3.10: Schematic (not to scale) side view of the CLIC post-collision line. The vertical bending section to the far left of the diagram is the window-frame magnets. The dump for the wrong-sign charged particles is also known as the intermediate dump, and is carbon-based. The vertically bending section to the right of the intermediate dump is comprised of c-type magnets so that beamstrahlung photons may pass through the gap between the coils. Finally, 315 m from the IP is a water-based dump. This shows the post-collision line for the electron beam; the positron beam line will have electrons bending upwards and positrons passing through to the main dump.
3.4.1 Window-Frame separation magnets

To minimise losses in the magnets, 90 cm collimators are placed between the magnets to absorb low-energy charged particles lost due to dispersion as in Figure 3.10. Initial designs positioned the first magnet at 30 m from the IP to give sufficient clearance from the detector and incoming beam lines, with 4 m separation between the magnets, giving 1.55 m face clearance. To avoid excessive dispersion-induced beam blow up, the magnet strength is set to 0.8 T to minimise dispersion, shown in Figure 3.11, and thus minimise the loss of low-energy particles. The reason that the first magnet was split into a 50 cm section and 3.5 m section is discussed later in the chapter under the loss computation section.

In Figure 3.11, the optics for the post-collision line are presented. The influence of the magnetic chicane is evident in the vertical dispersion, $D_y$, which is increased to 120 mm by the action of the window frame and c-type magnets. The horizontal dispersion, $D_x$ is not due to the action of the post-collision line magnets but is a product of the beam-beam effects experienced by the beam under the magnetic influence of the opposing beam. The $\beta_y$ function increases sharply along the post-collision line, which serves to maximise the beam size at the main dump, reducing its intensity.

The limiting factors to the window-frame magnets are the current density, aperture size, maximum permissible losses and maximum physical size dictated by the transverse space required for the incoming beam line. All of these parameters were considered when designing this section of the post-collision line, and the parameters
CHAPTER 3. THE CLIC POST-COLLISION LINE

Figure 3.11: Optical functions of the CLIC post-collision line.

presented in Table 3.3.

3.4.2 Intermediate Dump

The 6 m long intermediate dump is located between 67 m from the IP and 73 m, and is shown schematically in Figure 3.13. At the entrance to the dump, the same-charge, opposite-charge and beamstrahlung photons are separated due to the preceding window-frame magnets, with the separation direction and the spatial energy ordering shown in Figure 3.10. The coherently produced \( e^-/e^+ \) of the same sign as the disrupted
beam are virtually indistinguishable from the main beam. Conversely, coherently produced $e^-/e^+$ of opposite charge to the main beam are easily identified due to their vertical position induced by the bending region. In the upper half of the intermediate dump, losses are exclusively of this species. By adding instrumentation to the top half of the dump, the number of coherent pairs can be measured, inferring the quality of collisions at the IP [60].

The conceptual design for the intermediate dump is one of a carbon-based absorber with water-cooled aluminium plates [65]. The aperture is variable along the length of
Table 3.3: Main properties of the window frame magnets that are installed at the beginning of the CLIC post-collision line as presented in [60] where \( s \) is distance from the IP, \( X_{\text{pipe}} \) is the full transverse aperture of the beam pipe, \( X_{\text{pipe}} \) is the full vertical aperture of the beam pipe, \( g, h \) and \( d + g/2 \) are defined in Figure 3.12 and \( nI \) is the product of the number of turns and the current. The parameters are the result of the updated design that was produced from the optimisation procedure detailed in Section 3.5. Each magnet has a field strength of 0.8 T.

<table>
<thead>
<tr>
<th>Magnet Name</th>
<th>( s_{\text{start}} ) (m)</th>
<th>( X_{\text{pipe}} ) (cm)</th>
<th>( Y_{\text{pipe}} ) (cm)</th>
<th>( g ) (cm)</th>
<th>( h ) (cm)</th>
<th>( nI ) (kA.turns)</th>
<th>( d + g/2 ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mag1a</td>
<td>27.5</td>
<td>20</td>
<td>44.0</td>
<td>22.2</td>
<td>57.7</td>
<td>141.3</td>
<td>24.7</td>
</tr>
<tr>
<td>Mag1b</td>
<td>30.5</td>
<td>20</td>
<td>44.0</td>
<td>22.2</td>
<td>57.7</td>
<td>141.3</td>
<td>24.7</td>
</tr>
<tr>
<td>Mag2</td>
<td>38.0</td>
<td>27</td>
<td>70.2</td>
<td>29.6</td>
<td>83.9</td>
<td>188.4</td>
<td>34.6</td>
</tr>
<tr>
<td>Mag3</td>
<td>46.0</td>
<td>34</td>
<td>102.0</td>
<td>37.0</td>
<td>115.7</td>
<td>235.5</td>
<td>45.7</td>
</tr>
<tr>
<td>Mag4</td>
<td>54.0</td>
<td>41</td>
<td>139.4</td>
<td>44.4</td>
<td>153.1</td>
<td>282.6</td>
<td>58.2</td>
</tr>
</tbody>
</table>

the dump, with asymmetric vertical clearances to capture all of the opposite-charge \( e^-/e^+ \), but permit the majority of the beamstrahlung photons and same-charge \( e^-/e^+ \) to pass through. The aperture of the lower half of the dump is designed to capture all same-sign \( e^-/e^+ \) with an energy less than 14% of the nominal 1.5 TeV since these will have a large dispersion induced angle and would otherwise be lost in the body of the magnets following the intermediate dump.

### 3.4.3 C-type Magnets

Beamstrahlung photons and \( e^-/e^+ \) with at least 14% of the nominal beam energy pass through the exit of the intermediate dump at 73 m from the IP and are directed onto the C-type magnets (Figure 3.14), which are tilted 90 degrees compared to a conventional C-type magnet to provide vertical bending. The first of these magnets is located 2 m downstream of the intermediate dump exit. Each of these magnets is 4 m long,
with a 4 m separation between them. Due to the less stringent aperture restrictions in the preceding dump, losses in the C-type magnets are expected to be negligible, so masks are not required between them. The purpose of these magnets is to rapidly reduce $D'_y$ to zero, so that the beam may be transported in parallel with the beamstrahlung photons towards a common dump. Due to synchrotron radiation losses in the downward-bending region, the field strength of the upward-bending region is reduced to 0.784 T (compared to 0.8 T for the downward-bending magnets) to ensure that the charged beam remains parallel to the beamstrahlung photons.

### 3.4.4 Main Dump

Any attempt to physically separate the charged beam from the beamstrahlung photons (see Figure 3.10) would result in damaged separator material due to synchrotron radiation from the downward-bending region. Therefore, both the beamstrahlung photons and the charged beam must be transported in parallel along a common vacuum pipe.
Figure 3.14: Cross section of a C-type magnet, with the relevant parameters to be considered for its design, where \( g = 45 \text{ cm} \), \( h = 75 \text{ cm} \) and \( d = 46 \text{ cm} \). The disrupted beam passes between the poles, while uncharged beamstrahlung photons travel between the upper coils where the field quality is irrelevant (taken from [60]).

to a common dump. Due to dispersive effects acting on the energy distribution of the charged beam, the vacuum chamber must have top-bottom asymmetry to contain both the photons and the charged beam. From the final magnet, the beams travel for 210 m passing through the vacuum exit window, through the dump entrance window and into the dump itself. The section in between the two windows is at atmospheric pressure and so the windows must withstand the pressure differences. The dump is a pressurised water type as proposed for the ILC at a pressure of 10 bar to raise the boiling point of the water to minimise localised boiling effects [80]. It is 10 m in length and 1.8 m in diameter with a 30 cm diameter titanium alloy entrance window. The water is in constant motion to minimise localised boiling effects as subsequent bunch trains strike
the water [73]. The dump entrance window is proposed to be 20 mm thick titanium alloy [65].

3.4.5 Instrumentation

An important design constraint for the post-collision line is that it should provide feedback on the luminosity of the collider. Possible methods are:

Tail Monitors

In the magnet protection masks, the presence of losses due to the bending effects of the window-frame magnets is an indication of the presence of very low energy particles in the spent beam resulting from an increased beamstrahlung parameter (Equation 3.6). By embedding PIN diodes [74] into the body of the magnet protection masks, the loss of particles in the low-energy tail may be used to infer the luminosity of the collisions.

Monitoring of Coherent Pairs

The particles produced from coherent processes with the same charge as the disrupted beam are indistinguishable from the main beam. The cohminus particles however are separated from the spent beam and thus easily identified at the point they are absorbed by the main dump and, due to the effects shown in Figure 3.10, the cohminus particles are spatially ordered by energy in the vertical dimension. By implementing a drift chamber with horizontal wires to detect the vertical position of the losses in the dump, the coherent particle energy distribution may be reconstructed, inferring the quality of
the collisions at the IP and providing feedback.

**Beamstrahlung Detectors**

Since the beamstrahlung photons are separated from the charged beam, it is possible to detect these and infer the beamstrahlung parameter and thus the luminosity. Figure 3.15 schematically demonstrates the use of a Cerenkov detector to monitor muons from the exit of the main dump [75]. Both the main beam and beamstrahlung photons will produce muons through the pair-production process, but since these beams are separated by over 120 mm, the source of the muons can be distinguished by their vertical position. As the muons pass through the gas, photons will be emitted due to the Cerenkov process, which are reflected by a mirror to a photo-multiplier tube. By keeping the tube offset to the dump exit, it is hoped to avoid damage from the secondary particles emerging potentially emerging from the dump exit.

![Figure 3.15: Cerenkov beamstrahlung detector at the main dump exit to detect the muons produced by the beamstrahlung photons. The vertical offset between the disrupted beam and beamstrahlung photons due to the magnetic chicane permits muon identification from the vertical location.](image-url)
Beam Dump Thermometry

Due to the spatial ordering of particles by energy as shown in Figure 3.10, the vertical position of particle absorption in the main dump can be used to estimate the energy distribution of the spent beam. The temperature of the dump at different vertical positions could be monitored using laser interferometry providing the turbulence of the water and bunch deposition shockwave did not interfere with the apparatus [76]. The schematic layout of this detector is shown in Figure 3.16 which would require a window at the side of the dump, with a mirror within the dump itself.

![Schematic layout of the interferometric thermometer](image)

Figure 3.16: Schematic layout of the interferometric thermometer proposed to measure temperature variations following energy deposition by the disrupted beam in the water dump.
3.5 Beam Loss Optimisation

Beam losses within the post-collision line must be controlled for two key reasons. The first is due to potential damage and ageing effects caused to components affecting their function and making them too active to be easily serviced. The second reason is to minimise IP background contributions from losses in the post-collision line, which will be discussed in Chapter 4. For the latter reason, losses further from the IP are favoured, and thus the post-collision line apertures must be optimised for this. This section presents original work submitted to the post-collision line design effort [60]. The optimisation procedure described here was necessary to ensure that the original constraints were satisfied.

3.5.1 Beam Loss Optimisation Constraints

The first major constraint is a dimensional constraint. The post-collision line must not protrude into the incoming beam lines, and there must be sufficient space between the elements for ancillary equipment, which is given by Equation 3.4. The post-collision line separates the charged particles and beamstrahlung photons vertically for the reason of clearing the incoming beam lines. Nevertheless, the magnets still require space in the horizontal plane for the iron flux return of their window-frame magnets. A field strength of 0.8 T is required to provide $3 \sigma_y$ separation between the disrupted beam and beamstrahlung photons so that the photons and charged beam will be distinct to instrumentation placed behind the main dump. A reasonable maximum for coil current
density in copper is 10 A/mm$^2$, beyond which superconducting magnets become more appropriate [77]. The horizontal size of the coil is defined by the width of the magnet gap, which is the horizontal beam pipe aperture size plus the thickness of the beam pipe. To prevent collapse of the beam pipe, the wall thickness is set to 5 mm vertically (vacuum vessel is 1.404 m × 0.444 m at the final window-frame magnet, requiring thick walls to prevent collapse), and horizontally the thickness is proportional to that of the vertical, with the ratio given by the vertical aperture size ($X_{pipe}$) divided by the horizontal aperture size $Y_{pipe}$. Therefore, the magnet horizontal aperture size ($g$) can be expressed as [60]

$$g[cm] = X_{pipe} + 2T_x = X_{pipe} + 1cm \times \frac{Y_{pipe}}{X_{pipe}},$$

(3.7)

where $T_x$ is the beam pipe thickness in the horizontal dimension. The yoke flux return extent in the horizontal direction must be known for clearance calculation. Assuming a maximum field strength in low-silicon steel of $B_{max} = 1.7$ T [78], then this constrains the horizontal thickness of the iron to be

$$d \geq h \times \frac{B}{2B_{max}},$$

(3.8)

where $B$ is the required magnetic field strength in Tesla and $g$, $h$ are defined in Figure 3.12. From this information the vertical size of the coil ($Y_{coil}$) is

$$Y_{coil} = \frac{Bg}{\mu_0} \times \frac{1}{JX_{coil}} = 12.7 cm,$$

(3.9)
and the value $h$, which is the vertical aperture size plus $Y_{coil}$ is

$$h[\text{cm}] = Y_{pipe} + Y_{coil} + 2T_y = Y_{pipe} + 13.7 \text{ cm},$$  \hspace{1cm} (3.10)

where $X_{coil}$ and $Y_{coil}$ are the horizontal and vertical coil sizes respectively ( $g = X_{coil}$ in these magnets). The half-width of the magnet is given as $d + g/2$. This value must be less than the clearance required for the incoming beam line, which is defined by the crossing angle. During the optimisation procedure, any alteration to the magnet apertures or field strength results in a recalculation of the horizontal magnet size to check for incoming beam-line clearance. All the magnets clear the incoming beam line by a minimum of 30.3 cm in the current configuration, though this is reduced to 26.5 cm for 18.6 mrad [79] operation since

$$x[\text{m}] \approx \frac{1}{2} \phi[\text{rad}] \times s[\text{m}]$$  \hspace{1cm} (3.11)

for small angles of $\phi$ where $x$ is the transverse space, $s$ is the distance along the line from the IP and $\phi$ is the crossing angle, as shown in Figure 3.2. The vertical extent of the magnets requires little consideration since these clear the tunnel height restrictions.

Beam loss optimisation requires the use of simulation to determine the losses of a particular configuration. Magnet losses are to remain below 100 W/m to prevent damage, as indicated earlier in Section 3.1.2. Graphite-based magnet protection masks can absorb several kW of power each [64], but losses in these are likely to produce IP background through Bremsstrahlung, favouring losses later in the post-collision line.
CHAPTER 3. THE CLIC POST-COLLISION LINE

These were taken as constraints for the optimisation procedure.

3.5.2 Beam Loss Optimisation Simulation

The first estimate of post-collision line performance was computed using the program DIMAD [54], a matrix-based second-order tracking code, with the option to track for all orders in the Taylor series for energy deviation. This is an important feature since the energy distribution of the outgoing particles is particularly susceptible to the beam-beam effects, which are strong at CLIC, so there exists a long energy tail. DIMAD uses a hard collimation model, scoring lost particles at their point of loss and discontinuing transportation for that particle. The post-collision line and its apertures are defined using files as given in Appendix B. DIMAD employs a co-moving frame of reference for the particles, and thus small misalignments must be defined for the window-frame magnets since these are centred on the beamstrahlung photon axis, not on the ideal particle axis as DIMAD assumes by default. Power losses (in Watts) are estimated using:

\[
P_{\text{loss}} = 1.602 \times 10^{-10} \frac{N_b n_f}{N_{\text{tracks}}} N_{\text{loss}} \sum_{i=1}^{N_{\text{loss}}} E_i
\]  

(3.12)

where \(E_i\) is the energy of the lost particle \(i\) in GeV, \(N_{\text{tracks}}\) and \(N_{\text{loss}}\) are the number of particles tracked and lost respectively, \(N_b\) is the number of particles per bunch, \(n\), the number of bunches per bunch train, and \(f\) the number of bunch trains per second. The elementary charge constant is used to convert between GeV and J.
The loss optimisation procedure was an iterative process following these steps:

- Run DIMAD simulation for cohplus and disrupted beams using the geometry described in Appendix B, which includes apertures defined as the lower aperture size where an asymmetry exists.

- Run DIMAD simulation for cohminus beam using a modified lattice to account for particle being of opposite charge to the disrupted and cohplus beams, and run only to the intermediate dump. This included inverting of the dipole fields, inverting the misalignments and using the upper asymmetric aperture restrictions.

- Sum over the particle energy losses per element and check if this is within the constraints.

- Modify the collimator aperture dimensions to achieve losses as far from the IP as possible whilst remaining within the constraints and repeat.

Losses are tuned using a trial and improvement method such that losses are mainly present in the dumps and magnet protection masks. Earlier in the design process, the post-collision line consisted of four 4 m window frame magnets. The apertures of the magnets are tuned such that losses in each magnet were below 400 W. Due to dispersion effects, it was suspected that the distribution of losses along the magnet length was not homogeneous, and that losses would be greater at the end of the magnet. Preliminary investigation revealed the losses to exceed 100 W/m towards the end of the first magnet, requiring an optimisation and redesign. The cause of this excessive loss
Table 3.4: CLIC post-collision line power losses into magnets after optimisation with DIMAD where $s$ is the distance from the IP and $l$ is the length of the magnet.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>$s$ [m]</th>
<th>$l$ [m]</th>
<th>Disrupted [Wm$^{-1}$]</th>
<th>Cohplus [Wm$^{-1}$]</th>
<th>Cohminus [Wm$^{-1}$]</th>
<th>Total [Wm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>27.5</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>4.4</td>
<td>4.4</td>
</tr>
<tr>
<td>1b</td>
<td>30.5</td>
<td>3.5</td>
<td>14.7</td>
<td>13.8</td>
<td>61.4</td>
<td>89.9</td>
</tr>
<tr>
<td>2</td>
<td>38.0</td>
<td>4.0</td>
<td>3.8</td>
<td>1.0</td>
<td>42.6</td>
<td>47.4</td>
</tr>
<tr>
<td>3</td>
<td>46.0</td>
<td>4.0</td>
<td>6.6</td>
<td>1.5</td>
<td>33.3</td>
<td>41.4</td>
</tr>
<tr>
<td>4</td>
<td>54.0</td>
<td>4.0</td>
<td>11.8</td>
<td>2.2</td>
<td>18.7</td>
<td>32.7</td>
</tr>
<tr>
<td>5</td>
<td>77.0</td>
<td>4.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>85.0</td>
<td>4.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>93.0</td>
<td>4.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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</tr>
<tr>
<td>8</td>
<td>101.0</td>
<td>4.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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</tr>
</tbody>
</table>

was traced to highly divergent opposite-sign particles with particularly low energy.

The optimisation procedure was modified to treat the magnets as 8 distinct magnets, including a recalculation of the misalignments so that the losses per 0.5 m of magnet could be studied. Aperture size optimisation proved fruitless since too many losses occurred close to the IP whilst keeping the magnet losses acceptable. It was realised that a small dispersion was required and a mask to remove these problematic particles.

For this reason, magnet 1 was split into two magnets, with the optimum being a 0.8 T, 0.5 m magnet (magnet1a), a 0.5 m magnet protection mask and a 0.8 T, 3.5 m magnet (magnet1b), as shown in Figure 3.10. Further optimisations involved asymmetrical apertures in the magnet protection masks to compensate for the higher divergence of the oppositely-charged particles, caused by the beam-beam effects. The total losses on the magnets are shown in Table 3.4 showing an average loss over the length the magnets to be within the 100 W/m design constraint.
3.5.3 Beam Losses

Radiative Bhabhas, where the exchange of a virtual photon between \( e^-e^+ \) to induce an actual photon (\( e^-e^+ \rightarrow e^-e^+\gamma \)), has a total power loss of 22 W in the post-collision line [60], and therefore is considered insignificant in this calculation. Similarly, photon losses in the post-collision line are approximately 100 W, so their losses will only be considered at the main dump into which they are incident. Therefore, the only beams which require consideration for loss calculation are the disrupted beam and the coherent pairs. Due to the separation scheme, the disrupted beam and coherently produced \( e^-e^+ \) of the same charge as the disrupted beam are directed downwards, and thus the losses will be on the lower apertures. Charged particles of the opposite charge to the disrupted beam are directed upward, and thus are lost on the upper apertures. This permits the ability to independently reduce the lower and upper apertures to tune same-charge and opposite-charge losses respectively. Figure 3.17 shows the aperture profiles of the post-collision line and their distance from the IP. The actual power losses are presented in Table 3.5

Losses close to the IP should be avoided since electromagnetic showering of the lost particles in the masks can lead to backscattered photons incident on the IP. Of particular concern is the loss of 0.98 kW on the first magnet protection mask (Mask 1a1b in Table 3.5), which is situated between 28.5 and 29.0 m from the IP, and has direct line-of-sight to it, this meaning that the photon can travel between the mask and the IP
without having to scatter. However, a loss of approximately 1 kW at this distance is considered preferable to the main dump at 315 m having a line-of-sight with 10 MW of losses (calculated from the particles per bunch, the number of bunches per train and the repetition rate given in [59]) since these upstream components will provide shielding against the flux from the dump. Subsequent collimator jaws and much of the intermediate dump are all shielded from the IP by the magnets and the first mask, and thus there is no line of sight. The only possible source of backscattering from lost particles is the upper aperture in the intermediate dump where the most high energy opposite-charge particles are lost. Since 170 kW of cohminus particles are lost in this region, this will be an important area of study in Chapters 5 and 6 to determine any
Table 3.5: Power losses for the disrupted beam and for the coherent pairs into the collimators and the intermediate dump from DIMAD [54] simulation.

<table>
<thead>
<tr>
<th>Element Name</th>
<th>Half-Aperture Limitation</th>
<th>Main beam</th>
<th>Cohplus</th>
<th>Cohminus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mask1a1b</td>
<td>Y = 6.6 cm</td>
<td>0</td>
<td>0</td>
<td>0.98</td>
</tr>
<tr>
<td>Mask12</td>
<td>Y = 12.8 cm</td>
<td>0.47</td>
<td>0.47</td>
<td>3.05</td>
</tr>
<tr>
<td>Mask23</td>
<td>Y = 28.5 cm</td>
<td>2.23</td>
<td>1.78</td>
<td>0.66</td>
</tr>
<tr>
<td>Mask34</td>
<td>Y = 46.3 cm</td>
<td>4.21</td>
<td>2.72</td>
<td>1.89</td>
</tr>
<tr>
<td>Intermediate Dump</td>
<td>Y = 54.4 cm</td>
<td>96.2</td>
<td>35.2</td>
<td>170.1</td>
</tr>
</tbody>
</table>

background contribution. The DIMAD simulations did not predict any losses in the C-type magnets, with all remaining particles being incident on the main dump. There is no line of sight between the spot where the charged beams are incident and the IP. Due to the nature of photons, the beamstrahlung photon spot on the dump does have such a line-of-sight and thus any secondary particles produced could backscatter towards the IP. Should further shielding be required, a mask may be placed in the dispersion-free region upstream of the first magnet (Magnet1a), with the aperture tuned to generate no losses, but provide shielding against backscattered photons.

3.5.4 Beam Profiles on the Main Dump

A base design for the CLIC dump is a pressurised water-based dump as proposed for the ILC [80]. In order to assess the performance of the dump, and to provide feedback for improvements, it is necessary to track the beams to give a profile at the dump. Due to the magnetic chicane of the CLIC post-collision line, the beamstrahlung photons and the disrupted beam are separated, permitting the use of independent instrumentation for these beams, and thus collision quality feedback. This is evident in Figure 3.18 with the
peaks between the disrupted beam and beamstrahlung photons separated by 0.121 m at 315 m from the IP. The horizontal beam profile is largely symmetric, as shown in Figure 3.19 but quite broad in width, requiring a vacuum exit window and dump entrance window to be wide to accommodate most of the beam. Both the disrupted and cohplus beams have retained a similar profile to that emerging from the IP.

The length of the extraction line, coupled with the dispersion induced in the magnetic chicane allows the beam to blow up before it reaches the main dump, as in Fig-

Figure 3.18: Vertical beam profile on the dump entrance window resulting from DI-
MAD tracking simulation. The profile is observed 315 m from the IP.
Figure 3.19: Horizontal beam profile on the dump entrance window resulting from DIMAD tracking simulation.

Figure 3.20. In this figure, the photon deposition is the area of high intensity centred on $y = 0$, whereas the charged beam centre is more than 120mm offset. Due to this offset, the beamstrahlung and charged beam profiles should be distinguishable to any instrumentation attached to the main dump, such as beam dump thermometry and Cerenkov detectors described earlier in the chapter. Finite element analysis of the vacuum exit window has shown that it will withstand the pressure difference between the atmosphere and vacuum under nominal beam conditions (colliding beams), as demonstrated in [60]. However, in order to capture the full beam incident on the dump, the vacuum exit window and dump entrance window will have to be large, approximately the same dimensions as the dump itself (1.8 m in diameter). Also, under non-colliding conditions, the lack of beam-beam effects leading to the divergent and dispersive beam-blow
Figure 3.20: Energy deposition profile at the main dump entrance, normalised to the number of particles in one bunch crossing (BX).

up leads to a very intense energy deposition.

3.5.5 Overview of the Optimised Design Parameters

As a result of the simulation and optimisation work presented in this thesis, the post-collision line is summarised in Table 3.6 where $s$ is the distance from the IP, $l$ is the element length, $x$ is the horizontal aperture width, $y_{up}$ is the upper aperture restriction, $y_{down}$ is the lower aperture restriction and $w$ is the total half-width of the element. All the magnets clear the incoming beam line apart from the magnet between 54.0 m and 58.0 m. At the entrance to this magnet, there is a 42 mm overlap, and a 2 mm overlap at the exit. If this were to interfere with the incoming beam line, the flux return thickness could be reduced by 42 mm since this represents only an 11.7% increase in the required
maximal field strength.

The magnet aperture sizes in Table 3.6 resulting from the optimisation give an indication of the typical beam sizes expected at each point. At the start of the magnetic chicane, 27.5 m from the IP, a vertical aperture of 440 mm is sufficient to contain the beam, whereas this must increase to 1394 mm to contain the beam at 54.0 m from the IP. This is a direct consequence of the energy spread of the beam under the action of dispersion. By optimisation of the magnet protection mask apertures, it has been possible to manage the losses of the particles in the low-energy tail such that the magnets are exposed to no more than 100 W m\(^{-1}\) along their length as shown in Table 3.4. Using the magnet aging analysis in Section 3.1.2, this should result in a magnet lifetime exceeding 20 years, which is the expected lifetime of a high-energy collider.

In Table 3.5, the total power losses on each mask increase with distance from the IP. This is favourable since each subsequent mask is shielded from the IP by the previous mask, reducing the likelihood of backscattered particles from the post-collision line contributing to backgrounds at the IP. In particular, the first magnet protection mask is subject to losses of less than 1 kW, which is important since this has a direct line of sight to the IP. Due to the small aperture of this mask, it also shields the IP from losses further in the post-collision line, and this aperture is only possible due to the splitting of the first magnet into the 0.5 m and 3.5 m sections.

The intermediate dump has a total loss of 301.5 kW, but this is 67 m from the IP and any background generated is shielded by the magnet protection masks.
Table 3.6: CLIC Post Collision Line Key Parameters.

<table>
<thead>
<tr>
<th>Type</th>
<th>s[m]</th>
<th>l[m]</th>
<th>x[m]</th>
<th>y_{up}[m]</th>
<th>y_{down}[m]</th>
<th>w[m]</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>0.00</td>
<td>27.50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Magnet</td>
<td>27.50</td>
<td>0.50</td>
<td>0.200</td>
<td>0.440</td>
<td>0.440</td>
<td>0.247</td>
<td>0.8T window-frame</td>
</tr>
<tr>
<td>Drift</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>0.200</td>
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<td>magnet protection mask</td>
</tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>Magnet</td>
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<td>3.50</td>
<td>0.200</td>
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<td>-</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>0.702</td>
<td>0.346</td>
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</tr>
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<td>-</td>
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<tr>
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<td>-</td>
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</tr>
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</tr>
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<td>-</td>
<td>-</td>
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<td>-</td>
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<td>-</td>
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<td>-</td>
</tr>
<tr>
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<td>0.400</td>
<td>0.120</td>
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<td>0.749</td>
<td>0.784T C-type</td>
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<td>-</td>
</tr>
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<td>-</td>
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<td>-</td>
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<td>-</td>
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<td>main dump</td>
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</table>
3.6 Conclusion

In presenting the post-collision line, four distinct goals were presented. The post-collision line provides a mechanism to transport charged beams and the beamstrahlung photons to the appropriate dumps. The non-colliding beams will follow the path of the most energetic particles in the colliding beams, so these can also be transported. The losses within the masks are limited to a few kW and in the magnets to less than 100 W/m. Finally, the scheme of splitting the beam permits the evaluation of each beam individually, using dedicated detectors. If the beams were not to be split, distinguishing coherent pairs, the disrupted beam and beamstrahlung photons would be considerably more difficult. Figure 3.20 shows that the beamstrahlung photons and disrupted beam have two distinct peaks which will allow instrumentation behind the dump to distinguish between these. Beamstrahlung photons provide valuable information about the quality of the collisions. The post-collision line presented here also includes suggestions for monitoring the various particle types to act as an indicator of the luminosity at the IP.

From this thesis, the key contribution to the CLIC post-collision line is the beam-loss optimisation. This study considered a non-uniform distribution of the losses in the magnets due to dispersion. Through beam-dynamics simulation, the magnet and protection mask properties were optimised within the constraints of the post-collision line environment. The resulting design satisfied the maximum permissible loss restriction on the magnets of 100 Wm$^{-1}$, which means under these conditions, the magnets
are expected to have a useful lifetime exceeding 20 years according to the analysis in Section 3.1.2.

Losses are also optimised to be as far from the IP as possible, and with consideration to minimising the line of sight between loss locations and the IP. Summing over all the power losses in Table 3.4 and Table 3.5, it is found that only 322 kW of the beam is lost between the IP and the main dump. The main dump absorbs approximately 10 MW of charged beam power, which means that over 96% of the beam is lost more than 315 m from the IP, which should serve to reduce the IP background contribution of the post-collision line.
Chapter 4

Physics in Matter and Simulation

Validation

In Chapter 3, losses were calculated as being the point at which the particle motion exceeded the aperture restrictions, and these particles were considered to be lost. However, those particles that are lost simply do not disappear. Having collided with material, these particles interact with that matter, dissipating energy as heat and secondary particles. Since these secondary particles may be directed towards the IP, they are capable of contributing to detector backgrounds and causing radiation damage to post-collision line components.

In this chapter, one of the aims is to present the relevant physical processes associated with the CLIC post-collision lines, and the tools used to simulate them. In order to obtain the main results of this thesis, it was necessary to develop a detailed model of the post-collision line. This chapter will present the processes required to gener-
ate the model, to run the simulations and to extend those simulations onto distributed computing to maximise the statistics, and minimise the associated statistical error. The results generated from these simulations will be used to estimate the magnet lifetime, the potential for false hits in the detector and detector damage estimates.


At the CLIC post-collision line, losses will be dominated by electrons and positrons interacting within its elements; therefore losses associated with high-energy electromagnetic physics are considered to be most important when considering backgrounds in the post-collision line.

4.1.1 Electromagnetic Cascade

Where a high-energy (>10 GeV) electron or positron is incident on material, the interaction is dominated by electromagnetic cascading [81] as in Figure 4.1 where an incident electron triggers an electromagnetic shower in matter. Due to interactions with the atoms within the material, Bremsstrahlung photon emission is stimulated from the incident $e^-/e^+$ being decelerated, producing a less energetic outgoing particle and a photon. In the high-energy regime, this photon will possess sufficient energy ($2 \times 511$ keV) to pair-produce under the influence of the nuclear and electric fields shown in Figure 4.2, resulting in an $e^-e^+$ pair, which will undergo subsequent
Bremsstrahlung processes. This process will continue until the photon energy is below the threshold for pair-production, forming an electromagnetic shower as shown in Figure 4.1. This is a particularly important process when considering backgrounds since a single high-energy incident $e^-/e^+$ can generate many photons, which combined with scattering processes can lead to photons being directed towards the IP. In Figure 4.3, a schematic of the backscattered photon process is shown. The incident electron is slowed by the atoms in the material, emitting a Bremsstrahlung photon and deflecting its current course due to conservation of momentum. The electron scatters twice under the influence of the Coulomb force presented by the electrons of atomic nuclei before emitting another Bremsstrahlung photon. In this particular example, the produced photon is produced in the opposite direction to the incident particle and is therefore backscattered.
Figure 4.2: Cross sections for photons in lead as a function of photon energy (taken from [86]) where $\sigma_{p.e.}$ is the photoelectric effect cross section, $\kappa_{nuc}$ is the pair production cross-section due to the nuclear field, $\kappa_e$ is the pair production cross section due to the electric field and $\sigma_{g.d.r.}$ is the cross-section for photonuclear interactions.

Figure 4.3: Electromagnetic scattering processes in graphite leading to the backscattering of photons which may contribute to IP backgrounds.
4.1.2 Multiple Scattering

Once electromagnetic cascading subsides at lower energy, multiple scattering from atoms within a material permits large deflection angles of photons and $e^-/e^+$, some of which may be incident on the IP. These deflections are caused by Coulomb forces of the atoms in the material acting upon the $e^-/e^+$, as in Figure 4.4.

4.1.3 Compton Scattering

When a low-energy photon collides with an atomic electron in a material, it transfers some of its energy to the electron and is deflected as in Figure 4.5. This deflection can lead to backscattered photons. In graphite, the Compton scattering cross-section is maximised at approximately 20 keV, as shown in Figure 4.6.
Figure 4.5: Compton scattering of lower energy photons in matter.

Figure 4.6: Cross sections in carbon as a function of photon energy (taken from [86]) where $\sigma_{p.e.}$ is the photoelectric effect cross section, $\kappa_{nuc}$ is the pair production cross-section due to the nuclear field and $\kappa_e$ is the pair production cross section due to the electric field.
4.1.4 Photo-nuclear Interaction

The photons produced in the electromagnetic cascade may interact with the nuclei of atoms within the material via the photo-nuclear interaction, the cross-section of which is proportional to the mass number [82]. The nucleus of the atom may disintegrate via the Giant Dipole Resonance (GDR) [83] to produce neutrons. An example of GDR cross section dependency on the energy of the incident photon is shown at the bottom of Figure 4.2.

4.1.5 Electronuclear Interaction

Electronuclear reactions are dominated by the one-photon exchange reaction and as such may be treated very much like a photo-nuclear reaction [82].

4.1.6 Bethe-Bloch Stopping Power

The Bethe-Bloch stopping power \(-\frac{dE}{dx}\) gives the mean rate of energy loss by a particle incident on material [84]. However, this is more suitable for heavier charged particles such as muons rather than electrons and positrons so will not be considered for the electromagnetic background study of CLIC. Rather than considering the stopping power, it is more useful to consider the energy deposited in the magnets of the post-collision line since this will allow an estimate to be made for the expected magnet lifetime.
4.2 Kerma

A useful concept to consider where a particle is incident on matter is that of Kinetic Energy Release per unit MAss (KERMA) [85]. Photons generated in electromagnetic showering transfer energy to charged particles via the photoelectric effect, Compton effect and pair-production. Since much of the incident energy is likely to exist as photons during electromagnetic showering, the total energy incident on the material, divided by the material mass will be approximately equal to the kerma. Since some particles may escape the material, carrying energy away with them, the kerma of the material will be higher than the absorbed dose. In the simulations of Chapter 3, the full energy of the lost particle was assumed to be lost to the body of the magnet, which would be the Kerma value. In reality, some particles are emitted from the body of the material carrying away kinetic energy and thus reducing the actual energy absorbed by the component. In order to understand where the energy is deposited, it is necessary to simulate the post-collision line with codes that can simulate the physics in matter.

4.3 Physics in Matter Simulation

In order to verify the effectiveness of the post-collision line design, it is necessary to simulate the performance with regard to beam loss interaction with its components. Beam dynamics studies using DIMAD were able to provide an estimate of power losses in various components using a collimation model where the full energy of the lost particle was deposited in that component. In reality, the particle loses energy through
a wide variety of mechanisms, and thus the actual energy deposited may be lower
due to emission of other particles. Consequently, these secondary particles may cause
damage to other components of the post-collision line and also backscattered particles
will contribute to detector backgrounds at the IP. It is therefore necessary to simulate
the extraction line with models that take account of these secondary particles to provide
background estimates.

4.3.1 The GEANT4 Toolkit

The GEANT4 Toolkit [87] is a general physics-through-matter simulation package
used in various applications such as medicine, nuclear physics, accelerator physics
and detector physics and was chosen to simulate the work presented in this thesis be-
cause of its toolkit extension BDSIM [56]. Being a toolkit rather than an application,
it permits the user a large degree of customisation in their simulations. Very little is
assumed by default, thus the user must have a general understanding of the underly-
ing physics required of their model in order to generate an accurate simulation. A
GEANT4 simulation is constructed of three key components [88], as listed below:

Primary Event Generator

The initial incident particles are generated using this component. The user can define
a particle beam by defining a G4ParticleGun and positioning it within the simulation.
A set of starting points can be generated within GEANT4 using a random number
generator, or can be read from an external file. The energy and particle type must
also be defined, the latter of which must also be included in the physics lists since no particles are included by default.

**Physics List**

It is in this component that the user can stipulate much customisation of the simulation. All particles to be used must be defined, and all physical processes required must be included, including basic transportation of particles. It is at the decision of the user to define which processes and particles are important to the simulation, and which to discard to reduce unnecessary processing.

**Spatial Model Construction**

The actual physical objects with which the particles will interact are produced in this component of GEANT4. The toolkit is provided with a wide array of Boolean solid shapes with which to construct the model required. Many parameters of these shapes can be customised, including the spatial position and orientation relative to other components. More complicated geometries can be created by combining geometries, or by extrusion of one solid from another. Materials can be defined generally using various parameters, or the user can select more common materials from within GEANT4 itself.

In order to extract data from the simulation, the user must define sections of the physical model that will score hits and record to a data file. This is implemented using a G4SensitiveDetector geometry.
4.3.2 GEANT4: How it Works

In GEANT4, an event is modelled as a collection of tracks. Particles are ‘transported’ rather than particle motion being an assumed default [89], with each track being made up of many smaller steps. Before a particle is transported, the step length must be decided. This is taken as the shortest length proposed by each of the processes. The probability of a particular process not interacting within length $L$ whilst passing through material is given by

$$P(L) = \exp\left(-\int_0^L \frac{dL}{\lambda(L)}\right) = \eta,$$  \hspace{1cm} (4.1)

where $\lambda$ is the mean free path of the process (taken to be constant in each material/step) and $\eta$ is a random number between 0.0 and 1.0. For an interaction with material, the length of a process is determined as

$$L = \frac{-\ln\eta}{\rho \sum_i x_i \sigma_i m_i},$$  \hspace{1cm} (4.2)

where $\rho$ is the density of the material, $m_i$ is the mass of the isotope, $x_i$ is the mass fraction and $\sigma_i$ is the cross section for that process for the isotope. Clearly, this random process is weighted such that higher cross-section processes are more likely to propose a shorter step length than processes with lower cross section. The distance to the next material boundary may also be proposed as the step length. The particle is then transported the distance of the smallest proposed step, with processes such as multiple scattering taking place along the step. Where the next vertex is reached, the process
Bremsstrahlung and ionisation processes propose step lengths

Step length proposed by Bremsstrahlung is the shortest

At Rest

Transportation and Multiple Scattering

Along Step

Bremsstrahlung process applied

Post Step

Step Length

Figure 4.7: GEANT4 stepping process example (based on [89]). At rest, each process proposes a cross-section, which is put into Equation 4.1 to determine a step length. In the example shown, the Bremsstrahlung process proposes the shortest step and this is taken as the next step. Along the step, the transportation and multiple scattering processes are applied. When the particle arrives at the end of the step, the Bremsstrahlung process takes place, leading to a deflection of the incident particle and a new photon being added to the stack for tracking. If the proposed step length is shorter than that defined by the user, the track ceases, with the energy being recorded as lost at that location.

that proposed the shortest step is applied. If this process produces new particles, these are added to the stack of tracks to be processed. Tracking ceases when the proposed step length is below that user specified minimum step length, with the energy being deposited at that location. The process is shown diagramatically in Figure 4.7.

4.3.3 The BDSIM Toolkit

Beam Delivery Simulator (BDSIM) [56] provides a front-end toolkit to GEANT4 for accelerator simulation. BDSIM was chosen since preliminary work on the post-
collision line already existed in this format. BDSIM uses a six-dimension phase space coordinate system similar to that presented in Chapter 2 which is convenient to compare to the DIMAD simulations in Chapter 3. BDSIM also offers a tracking only mode which ignores physics in matter simulation for fast beam dynamics tracking, which is particularly useful when optimising, requiring a rapid simulation time. BDSIM permits the use of GEANT4 in a more application-based manner, more similar in operation to major accelerator codes such as MAD and DIMAD than using GEANT4 directly.

The input file of BDSIM is usually given the suffix '.gmad' since it is interpreted using the geometry-MAD (GMAD) parser [56]. Within this file, the user stipulates the beam (either internally using a parameterised beam or externally from file), the geometry and required output. The lattice is constructed using the 'line' concept from MAD and other accelerator codes based on the Extended Standard Input Format (XSIF) [55]. BDSIM provides several grouped standard physics lists for the convenience. Output is generated using samplers, which may be attached to markers in the lattice. The user may choose from ASCII output or, for convenient processing with the ROOT Data Analysis Framework, ROOT output [93].

When BDSIM is initiated, the lattice is interpreted as a GEANT4 geometry and constructed in memory, including sensitive detectors with almost zero thickness to act as the sampler planes. The physics lists are constructed based on the group chosen by the user. The beam is generated from a G4ParticleGun object and the simulation commences. Data is output at each sampler plane in the format requested at the input file. A sample input file is given to simulate a 1500 GeV electron passing through a F0D0 cell:
option, beampipeRadius = 10*cm,
  beampipeThickness = 0.1*cm,
  thresholdCutCharged = 10*KeV,
  thresholdCutPhotons = 10*KeV,
  ngenerate = 1,
  physicsList = "em_standard";

qf: quadrupole, l=0.5*m, k1=0.05*m^2;
  d1: drift, l=0.5*m;
qd: quadrupole, l=0.5*m, k1=-0.05*m^2;
  d2: drift, l=0.5*m;
  mk: marker;
f0d0: line=(qf,d1,qd,d2,mk)

use, period=f0d0
beam, particle="e-",
  energy=1500*GeV,
  distrType="E[GeV]:x[mum]:y[mum]:z[m]:xp[rad]:yp[rad]",
  distrFile="myinputbeam.dat";
sample, range=mk;

In the example file, the default beam pipe radius and thickness are defined as 10 cm and 0.1 cm respectively. The kinetic energy cutoff thresholds for both charged particles and photons is set to 10 keV. Only a single particle is in the simulation (ngenerate=1) and the physics processes contained within the group "em_standard" are to be used. The accelerator components and the line are defined, including the 'use' command to indicate which beamline should be used, followed by the beam which is an electron beam with a nominal energy of 1500 GeV. The energy, position and angles of the incident particles are read from file. Finally, the command sample, range=mk defines a plane through which the particle properties can be sampled.
Mokka

Due to the specialised nature of some of the components in the post-collision line, the standard geometries generated in BDSIM from the XSIF input would be unrepresentative of the actual components used. In this instance, it is necessary to access the GEANT4 geometries more directly to generate these custom components. For this, BDSIM provides the Mokka [90] geometry description language (GDL). Mokka uses SQL style databases to assemble more complex geometries, which can be inserted into an XSIF style lattice in the same way that more standard components are. This is a convenient method for accelerator physicists to add customised geometries into the lattice.

Mokka uses the concept of Structured Query Language (SQL) tables with which to generate the geometry. In BDSIM v0.5 many of the GEANT4 geometries are available to the user. Of particular importance to this study is the G4EllipticalTube, which was used to construct the beam pipes and magnet protection masks in the model. The user must first generate a table template to include the parameters to be used (size, position, material etc.). Then the user must insert values into these tables to generate the geometries. Using the inheritance parameters, a shape can be inserted into another shape such that the volume is actually extruded rather than added. This is a Boolean subtraction method, and has been used extensively in this study to generate the specialised masks, beam pipes, magnets and dumps. The method is shown in the example to produce Figure 4.8:
CREATE TABLE B1_BOX (  
PARENTNAME VARCHAR(32),  
INHERITSTYLE VARCHAR(32),  
RED DOUBLE(10,3),  
GREEN DOUBLE(10,3),  
BLUE DOUBLE(10,3),  
VISATT VARCHAR(32),  
POSX DOUBLE(10,3),  
POSY DOUBLE(10,3),  
POSZ DOUBLE(10,3),  
LENGTHX DOUBLE(10,3),  
LENGTHY DOUBLE(10,3),  
LENGTHZ DOUBLE(10,3),  
MATERIAL VARCHAR(32),  
NAME VARCHAR(32)  
);  

CREATE TABLE E1_ELLIPTICALTUBE (  
PARENTNAME VARCHAR(32),  
INHERITSTYLE VARCHAR(32),  
RED DOUBLE(10,3),  
GREEN DOUBLE(10,3),  
BLUE DOUBLE(10,3),  
VISATT VARCHAR(32),  
POSX DOUBLE(10,3),  
POSY DOUBLE(10,3),  
POSZ DOUBLE(10,3),  
LENGTHX DOUBLE(10,3),  
LENGTHY DOUBLE(10,3),  
LENGTHZ DOUBLE(10,3),  
MATERIAL VARCHAR(32),  
NAME VARCHAR(32)  
);  

INSERT INTO B1_BOX VALUES ("", "", 0.0, 0.5, 1.0, "S"  
,0.0,0.0,500.0,1000.0,1000.0,1000.0,"Graphite","MASK1");  
INSERT INTO E1_ELLIPTICALTUBE VALUES ("MASK1","SUBTRACT"  
,0.0,0.0,0.0,"I".0.0,0.0,0.0,500.0,750.0,1001.0  
,"Vacuum","MASK1_APER");
Figure 4.8: Boolean subtraction of a G4EllipticalTube from a G4Box in Mokka.

where PARENTNAME is the name of the object the current object inherits from, INHERITSTYLE is the inheritance style (which is SUBTRACT for a boolean subtraction), RED, GREEN, BLUE, VISATT are visual attributes of the object, POSX, POSY, POSZ are the positions relative to the parent object, LENGTHX, LENGTHY, LENGTHZ are the size of the object, MATERIAL is one of the material names provided in the BDSIM toolkit and NAME is the name to assign to the current object. Objects are added by inserting into these tables, the type of object defined by the table name suffix ("BOX defines a G4Box for example).
4.4 Physics-in-Matter Simulation Tools for CLIC

BDSIM utilises a co-moving co-ordinate system for the convenience of the accelerator physicist when using standard XSIF input. However, when magnetic elements are used via the Mokka interface, the co-ordinate system remains in the laboratory frame, as shown in Figure 4.9. Care must be ensured that the components are aligned to a common co-ordinate system to avoid misalignments caused by the difference in the co-ordinate systems used.

4.4.1 Input Files

The three major input files required for the post-collision line simulation are the GMAD parser input, the SQL lists and the SQL databases.
Figure 4.10: Co-ordinate origin in Mokka under BDSIM. By default the element is centred on the starting point of the element, causing the Mokka object to overlap the preceding components of the beamline. By introducing an offset equal to half the component length, the object is positioned in the desired location (shown by the grey dashed line).

**GMAD Parser Input**

In the GMAD input file, the elements to be used are predefined in the usual XSIF manner before use. Any Mokka elements are defined in the following way;

```plaintext
COMPONENTNAME:element,geometry="mokka:SQLLISTNAME.sql,"
```

```plaintext
l=COMPONENTLENGTH*m;
```

The majority of the 315 m post-collision line is defined by Mokka elements. In total, there are 24 markers in the lattice attached to the entrance and exit faces of all elements shown in Figure 3.10. It is important to note that the Mokka reference co-ordinate system is centred transversely on the beam at the start of the element as defined in the input file. To prevent the Mokka object from overlapping the preceding element, it is necessary to introduce an offset along the beam axis as shown in Figure 4.10.
4.4.2 BDSIM Physics Lists

BDSIM provides grouped standard physics lists rather than allowing the user to specify each individual physics process that they would like to include [91]. For the photon background study in Chapter 5, the physics list 'em_standard' was used. This contains the following GEANT4 physics processes, listed by the particle they are applicable to:

- gamma
  - G4PhotoElectricEffect (the photo-electric effect)
  - G4ComptonScattering (Compton scattering)
  - G4GammaConversion (pair production)
- electron or positron
  - G4MultipleScattering (scattering from atomic electrons)
  - G4eIonisation (ionisation)
  - G4eBremsstrahlung (Bremsstrahlung of electrons and positrons)
  - G4Cerenkov (Cerenkov radiation)
  - G4eplusAnnihilation (for positrons only - annihilation with atomic electrons)
- all other charged particles (except geantino)
  - G4MultipleScattering (scattering from atomic electrons)
  - G4hIonisation (ionisation)
  - G4Cerenkov (Cerenkov radiation)

For the physics list 'hadronic_standard', as used in Chapter 6, the following processes are included in addition to those defined for 'em_standard':

- G4PhotoNuclearProcess (photo-nuclear process)
- G4ElectronNuclearProcess (electron-nuclear process)
- G4PositronNuclearProcess (positron-nuclear process)
- G4ElectroNuclearReaction (reaction of atomic nucleus to incident electron-nuclear or positron-nuclear process)
4.4.3 Running BDSIM

BDSIM is used as an Application, called in the usual UNIX manner:

```
bdsim --file=postcollision.gmad --batch --output=root
```

where `--batch` disables visualisation, and `--output=root` produces root ntuple output rather than the default ASCII.

4.4.4 BDSIM Output

If the ASCII output option is used, BDSIM outputs the Particle Data Group (PDG) ID number [92], Energy, \(x, y, z, x'\) and \(y'\) of the particle. If ROOT [93] output is requested, ROOT data structures are produce from which further information may be extracted such as the weight (useful for biasing operations), and the point of last scatter \((x_0, y_0, z_0)\). Once a ROOT analysing script is written, analysis is considerably faster than an equivalent analysis using the ASCII output.

4.4.5 Visualisation in GEANT4 and BDSIM

Visualisation provides a valuable diagnostic tool for geometrical issues. The SQL databases used to generate the geometries are text-based, and thus errors are difficult
Figure 4.11: Wire frame BDSIM and Mokka model of a 30 GeV electron incident on twenty radiation lengths of iron. The cylindrical incoming beam pipe is shown for clarity.

to diagnose without visual confirmation.

GEANT4 and subsequently BDSIM offer a variety of methods to generate visualisation, the choice governed by the preferences of the user. The post-collision line study uses the DAWN [94] rendering system for this purpose. Visual attributes are controlled in both GEANT4 and BDSIM by the \texttt{vis.mac} file. In order to use visualisation in BDSIM, the \texttt{--batch} option should be omitted when the simulation is initiated. This produces a \texttt{.prim} file that can be manipulated using DAWN to produce images as in Figure 4.8.
4.5 Validation of GEANT4, BDSIM and Mokka

In order to verify the simulation model used for Chapter 5, the passage of a 30 GeV electron through iron was modelled to produce the fractional energy loss per radiation length. This validation is essential to ensure that the tools correctly interpret the model to be simulated. The validation also confirms if the user chosen parameters are suitable for the required simulation, including the kinetic energy cuts which were set to 10 keV for both photons and charged particles. The model was built in Mokka using twenty iron blocks, each 2×2 m in the transverse plane, centred on the incoming electron and with a thickness equal to one radiation length (t) as shown in Figure 4.11. Between each iron block is a sampler to determine the energy lost, and the number of particles passing through that plane.

In the calculation, the BDSIM physics list ‘em_standard’ is used and one hundred 30 GeV electrons are incident on the iron. The results are normalised to a single electron. The thickness (z) of each iron block in centimetres is given by

\[ z \, [cm] = \frac{X_0 \, [g \, cm^{-2}]}{\rho \, [g \, cm^{-3}]} \],

(4.3)

where \( X_0 \) is the radiation length normalised to density and \( \rho \) is the density. Iron has a radiation length of 13.84 g cm\(^{-2}\) and a density of 7.874 g cm\(^{-3}\) [95], requiring each block to be 1.76 cm thick to represent one radiation length (t). The results of the simulation are given in Figures 4.12 - 4.14, with an EGS4 [96] result shown in Figure 4.15 for comparison.
Figure 4.12: Number of electrons with energy $\geq 1.5$ MeV as a function of radiation length for a single 30 GeV electron incident on iron as simulated using BDSIM and Mokka.

Figure 4.12 represents the number of electrons at a particular radiation length of material, and should be compared to the circles in Figure 4.15. The shape of the distribution obtained from the BDSIM simulation is the same, and the peak number of electrons is to be found at six radiation lengths, which is consistent with the results obtained for EGS4.

The BDSIM simulation of the number of photons as a function of radiation length shown in Figure 4.13 is consistent with that obtained with EGS4, shown as squares in Figure 4.15. For photons, the peak number appears at eight radiation lengths in both simulation, which is two radiation lengths deeper than that for electrons, which indicates that between six and eight radiation lengths, many photons are produced with an energy less than 1.022 MeV and thus possess insufficient energy to pair produce and generate more electrons.
In Figure 4.14 the peak rate of energy loss is found at seven radiation lengths of material, which is consistent with the histogram shown in Figure 4.15 from the EGS4 data. Since the BDSIM simulation faithfully reproduces the data from the Particle Data Group Review [97], we can be confident that the use of the BDSIM 'em_standard' physics list is satisfactory for simulation of electromagnetic backgrounds in the post-collision line.

From the validation of these results, it is also possible to conclude that the Mokka interpretation of the model works as expected under BDSIM. This is an important verification to make to ensure that the co-ordinate system used in Mokka is appropriately applied to the BDSIM model, and then subsequently to the underlying GEANT4 physics simulation.

Since the tools have proved to be reliable in reproducing published data, they may
Figure 4.14: Fractional energy loss as a function of radiation length for a single 30 GeV electron incident on iron as simulated using BDSIM and Mokka.

now be used to study the background effects of secondary particle production in the CLIC post-collision line. The results of these simulation will be presented in Chapters 5 and 6.
Figure 4.15: An EGS4 simulation of a 30 GeV electron induced cascade in iron (taken from [97]). The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at $X_0/2$ intervals (scale on right) and the squares the number of photons with $E \geq 1.5$ MeV crossing the planes (scaled down to have same area as the electron distribution).
4.6 Physics in Matter on the GRID

Due to the relatively rare nature of backscattered particles, it is necessary to have very good forward statistics to generate acceptable backward statistics. For this reason, it is necessary to use distributed computing to accomplish results. The GRID [98] is a multi-national collaboration of computing resources, which provides these required resources.

4.6.1 Packaging BDSIM for use on the GRID

BDSIM must be packaged to run in a virtual environment to work on the GRID. In addition to the binary file, the user must include ‘libCLHEP-2.0.3.5.so’, ‘libgmad.so’ and, for successful ROOT output, both the /root/lib and /root/etc directories. The non-data input files are placed into the same directory and the whole directory is packaged to be sent as a tarball (‘sabdsim.tar.gz’ in Figure 4.16). The input data files are split into multiple files with numerical identifiers.

4.6.2 Running BDSIM on the GRID

Executing the BDSIM simulation is accomplished using several scripts written in C++. A script is written that sequentially submits jobs to the GRID, producing the files in Figure 4.16 with the appropriate data file reference for each job. As part of the submission step, another script is called which generates a different Job Description Language (JDL) [99] for each submission to copy a different data set to each job. The
GLITE [100] method to submit a job is:

```
glite-wms-job-submit -d $USER -o
jobid_270111_cohplus_neutron_1_500
--config autowms.conf -r ce01.tier2.hep.manchester.ac.uk:2119/
jobmanager-lcgpbs-long bdsim-run.jdl
```

where `-d` specifies the delegated proxy to be used, `-o` appends the job identifiers to a file, `--config autowms.conf` specifies the configuration and `-r` specifies a particular endpoint. The file `bdsim-run.jdl` is the JDL file that controls input and output of the job. Another file, `standalonebdsim.sh` controls the specific steps within the
job, including calibration of the environment variables, unpacking of the BDSIM tar-ball and executing the simulation. The files copied between the local machine and the GRID are detailed in Figure 4.17.

4.6.3 Obtaining BDSIM Output from the GRID

Output from the jobs can be obtained using the file generated via the -o option during submission. The command to retrieve the job output is:
glite-wms-job-output --dir /tmp/ jobid_270111_cohplus_neutron_1.500

where --dir specifies a non-default directory to store the result. The results are combined using a ROOT script which iterates over all jobs using the file generated by the -o option during submission. The ROOT script can then be modified to generate an array of results.
4.7 Conclusions

The aims of this chapter were to present the physics involved in the CLIC post-collision line and the tools used to simulate them. In this chapter, GEANT4 and BDSIM were proposed as the tools to model the backgrounds. The tools used to generate the model have also been presented, and a detailed description of obtaining results shown. Critically, the simulation tools have been successfully validated against published results, permitting confidence in their application to the background study of the post-collision line. Finally, the distributed computing techniques developed for this thesis have been demonstrated, permitting the production of high-statistics modelling for the photon and neutron backgrounds presented in the Chapters 5 and 6.
Chapter 5

Photon Background in the Post-Collision Line

A key performance criterion for the CLIC post-collision line is the management of photon backgrounds. This is of particular importance to assess the effect of secondary particles incident on the detector such as false hits (hits generated from backgrounds rather than genuine collisions), silicon damage and practical issues such as machine access and longevity of active components in the background environment. The focus of this investigation will be to consider the effect of detector backgrounds caused by photons backscattered from the post-collision line and to calculate the losses on the magnets to determine the aging effects. These results will be compared to backgrounds from incoherent pair production at the IP, since these occur within the detector volume, acting as a reference point for the IP impact of backscattered particles from the post-collision line.
In this chapter, the potential sources of backscattered particles are identified, and their magnitude of contribution estimated by simulation using the GEANT4 simulation tool framework under BDSIM as described in Chapter 4. The results of simulation are presented and evaluated, indicating their significance to the backgrounds, magnet aging and other effects at CLIC. Both the flux and its time structure at the IP will be presented and the impact of these on the detector discussed. Finally, an assessment will be made on whether the photon background arising from the post-collision line is acceptable using the present design, or whether modification to the line is required to achieve this.

To summarise, key goals of this chapter are

- To present the results of the photons generated at the main sources of production: the intermediate and main dumps.

- To calculate the photon flux received at the detector region.

- To calculate the time structure of the backscattered photons and determine the possibility for false hits.

- To recalculate the energy losses in the magnets considering the effect of secondary particles escaping the masks and dumps with consideration to magnet aging and expected service lifetime.

The extent to which these goals are met will be assessed in the conclusion to the chapter. The photons are analysed at five regions of interest, which are shown in Figure 5.1.
Region of interest A is where the IP background contribution will be calculated, since it lies outside the inner structures of the detector. Region of interest B will focus on the photons travelling backwards from the intermediate dump, which lies only 67 m from the IP. Region of interest C is concerned with the photons travelling forward from the intermediate dump at 73 m from the IP and will be used to assess the performance of the intermediate dump for the absorption of the cohminus beam. Region of interest D focuses on the backscattered photons from the main dump, to give a feel for the number of photons that would be directed towards the IP in a design with no magnetic chicane. Finally, region of interest E will show the forward photons that are not fully absorbed by the dump, and are therefore incident on anything we wish to place behind the dump.

### 5.1 The Interaction Point

The interaction point (IP) is the point at which the two beams collide, and must be surrounded by a detector to measure the properties of the collisions. The IP design is not yet fixed, and thus some generalisations are required for this simulation. It can be safely assumed that the vertex detectors at the centre of the detector will be silicon-based, which due to the photoelectric effect is particularly sensitive to photon backgrounds. The purpose of the vertex detectors is to accurately detect the position and timing of an event vertex, so it must be positioned as close to the beams as possible whilst retaining a sufficient aperture to allow the beams to pass through. Since the exact
design of the regions before and after the IP (the forward regions) is not yet fixed, photon background fluxes will be quoted through a plane at 3.35m from the IP, which is designated as Region A in Figure 5.1. This position is outside of the BeamCal [102] of the detector, and so the flux will be further attenuated by the beam calorimeter (BeamCal) and luminosity calorimeter (Lumical) before hitting the vertex detectors. The purpose of Lumical is to monitor low-angle Bhabha scattering events, whereas the Beamcal monitors beamstrahlung photons, both of which provide fast feedback of the luminosity [102]. Due to the angle of trajectory required for backscattered photons to reach the IP, hits in the detector barrel will be unlikely since these are parallel to
the direction of photon travel, indicated by the red arrow in Figure 5.1. Any photon hits are more likely to be detected in the silicon detectors perpendicular to the incident photons, with many photons passing through the centre of the detector entirely and into the incoming beamlines. Since all silicon-based detectors will be within 1m of the beam axis, the fluxes in this chapter are quoted through a 2m x 2m plane centred on the beam axis.

At the IP, the time structure of the backscattered signal is important to consider. Backscattered photons that coincide with the collision of bunches at the IP will be particularly difficult to disentangle from genuine data. Much of particle physics analysis is based upon detecting a signal of significance amongst considerable background conditions. By minimising backgrounds at the IP, these signals are clearer.

5.1.1 Backscattered Photon Origins

Wherever beam losses occur, photons are generated through electromagnetic cascading. In this subsection, the sources of these photons are presented and discussed. For the purpose of this analysis, 'backscattered' refers to any particle travelling in the direction of the IP, and 'forward' is travel in the direction of the main dump and beyond. The product of the radiation length and density ($X_0$) of photons and electrons interacting in matter may be approximated using the Dahl method [81],

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

(5.1)
where A is atomic number and Z is the atomic mass number, accurate to within 2.5% for all elements except helium. The radiation length is the mean distance over which an electron loses energy through Bremsstrahlung such that only 1/e remains. It is also \( \frac{7}{9} \) of the mean distance a photon will travel before pair producing [81]. As a result, the electromagnetic shower development will depend on this factor. Clearly, higher Z materials will lead to a shorter radiation length.

**First Magnet-Protection Mask**

The vertically bending magnets create a large dispersion, which leads to a large vertical displacement of the beam for low energy particles. Charged particles in the low-energy tail of the beam would lead to unacceptably large energy deposits in magnets. Large deposits of energetic particles eventually leads to degradation of the insulation of the magnet coils, limiting their mean time before failure [62]. Being a highly active area of the accelerator, accessibility to the magnets will be restricted, and so a long service life is favourable. To maximise longevity, the magnets are protected by carbon-based absorbers with elliptical apertures to manage these deposits, with all except the very first mask having a longer vertical axis. The apertures are elliptical to minimise the losses in the elliptical beam pipe of the window-frame magnets described in Chapter 3. Lost electrons/positrons predominantly generate photons through electromagnetic cascading. Due to the close proximity to the IP, and the lack of upstream shielding elements, the first mask (Mask1a1b of Figure 5.1) can potentially provide a significant proportion of the background registered at the IP. To provide protection to Magnet1b, the aperture
of the first mask is smaller than the aperture in Magnet1a, and the points at which most losses occur on this mask have a direct line-of-sight to the IP as shown in Figure 5.2.

![Diagram](image-url)

**Figure 5.2:** Region of the first magnet protection mask with a direct line of sight to the IP. The diagram on the left shows the vertical magnet aperture (B) and the vertical magnet protection mask aperture (A). The diagram shows their relative position in three dimensions, with the interconnecting beam pipe removed to display the reduced aperture of the mask.

**Intermediate Dump**

The entire cohminus beam is lost in the intermediate dump, as well as those charged particles with energy less than 14% of the nominal beam energy due to dispersion (see Figure 3.10) and according to the DIMAD simulations in Chapter 3. With losses of the order 300 kW (from Table 3.5), secondary particle generation is expected to be particularly high for this region. The distance from the IP, and the shielding effect
of the other elements upstream should provide some attenuation of the photon flux, thus restricting background photon contributions at the IP. It is also the purpose of the intermediate dump to absorb low-energy particles that would otherwise be lost in the body of the c-type magnets. The intermediate dump reduces losses in the c-type magnets to a negligible level according to the simulations presented in Chapter 3. Considering the possibility of leakage of secondary particles from the intermediate dump, it may be that some of the energy will escape the dump and be deposited in the c-type magnets. This study will determine if these losses are acceptable in the c-type magnets in terms of the magnet lifetime.

Main Dump

The main dump, being situated at 315 m from the IP was expected to be too far from the CLIC experiment to contribute significantly to photon backgrounds due to angular constraints. The solid angle $\Omega$ for a target in an axially symmetric system is defined as

$$\Omega \text{ [sr]} = \frac{r^2 \text{ [m]}^2}{s^2 \text{ [m]}^2}, \quad (5.2)$$

where $r << s$, $r$ is the radial extent of the silicon vertex detector and $s$ is the distance between the source of the backscattered particles and the silicon vertex detector as shown in Figure 5.3.

The solid angle of the IP as seen from the main dump is small (calculated to be approximately $1.0 \times 10^{-5}$ sr), but does have a line of sight as indicated in Figure 5.1. In the main dump, the region of interest are the photons from the back, 325 m from
the IP (region of interest E in Figure 5.1), where these can be monitored for diagnostic purposes [60]. Through the use of the magnetic chicane, it is possible to differentiate between the showers originating from the beamstrahlung photons and the charged beam since they are lost at different locations vertically. Since the beamstrahlung photon intensity is an indicator of luminosity, monitoring these photons can provide active feedback to the final focusing system to improve collision quality. Since component activation will restrict human access to the dump in the event of component failure, the design must be reliable to avoid the need for such access.
5.2 Results of Photon Simulation

In this section, a detailed analysis of the photons at their points of origin will be presented with analysis of the plots and an analysis of their potential effects. The goal of this section is to understand the sources from which the photon background originates.

Section 5.2.1 will consider the farthest point from the IP, 325 m away at the exit of the main dump (Region E in Figure 5.1), looking at forward photons. Section 5.2.1 covers the entrance of the main dump, 315 m from the IP (Region D in Figure 5.1), looking at the photons heading in the backward direction, towards the IP. At 73 m from the IP is the intermediate dump exit (Region C in Figure 5.1) from which the forward photons will be analysed in Section 5.2.2. Finally, Section 5.2.2 analyses the backscattered photons from the front entrance face of the intermediate dump, 67 m from the IP (Region B in Figure 5.1). The cuts for photons and charged particle events were set to 10 keV for these simulations to capture the low energy detail since these can contribute to false hits in the detector. This was also verified as a sensible value in the validation of Section 4.5.

In all the electromagnetic background simulations, the results are based on the simulation of 73,000 incident disrupted beam electrons, 66,000 cohplus electrons and 62,825 cohminus positrons. These results are then normalised to the equivalent values per bunch crossing. The statistical uncertainty ($\sigma$) of any calculated flux or individual bin will follow the form
\[ \sigma = \frac{\sqrt{N}}{N}, \]  

(5.3)

where \( N \) is the number of particles observed.

### 5.2.1 Main Dump Photons

The main dump will be the most significant source of photons since most of the approximately 10 MW of disrupted beam energy is deposited within it.
Figure 5.4: Forward photon density per bunch crossing from the disrupted beam at the exit of the main dump, 325 m from the IP showing the results for the disrupted beam (top), cohplus beam (left) and cohminus beam (right). In the plot for the disrupted beam, the distribution is quite symmetric compared with the cohplus beam which is distorted in the $-y$ direction. The photons from the cohplus beam are the result of secondary particles leaking from the back of intermediate dump and continuing along the tunnel towards the main dump.
Forward Photons from the Main Dump Exit

The plots in Figure 5.4 are of the forward photon density from the main dump exit, 325 m from the IP (Region E in Figure 5.1). The density is defined as the number of photons per cm$^2$ per bunch crossing. It is apparent that that the photon profile is quite different for the three beam species, with the disrupted beam having a rounded distribution compared to the elongated distribution of the cohplus beam and the more scattered distribution of the cohminus beam. The most distinctive signature is that of the cohminus beam. These photons have a vertical offset of approximately 0.8 m relative to the beamstrahlung photon axis. None of the cohminus beam should pass beyond the intermediate dump since particles of this charge are absorbed by the upper part of dump’s absorber material. From this, it can be concluded that the photons observed at the main dump, originating from the cohminus beam are actually a product of the secondary particles that have escaped the exit of the intermediate dump.

The disrupted beam has a near-circular photon density distribution, reflecting the fact that most of the particles carry the nominal energy, and so the transverse vertical distribution under the influence of the magnetic chicane is approximately symmetrical. For the photons from the cohplus beam, the vertical beam spread is much more pronounced suggesting that this beam has a larger energy spread, which has translated into a vertical spatial divergence due to the action of the magnetic chicane. Since the vertical distribution at the dump is distinct between photons from the disrupted beam and cohplus beams, the possibility exists for beam dump thermometry to reconstruct
the relative number of cohplus particles that were within the beams, which may be used to estimate the luminosity and provide feedback on this.

The presence of photons originating from the cohminus beam in Figure 5.4 suggests an inadequacy in the performance of the intermediate dump to absorb the particles of opposite charge to the incident beam, which has two major implications: one is that any instrumentation used within the intermediate dump to monitor the quality of the collision must be calibrated to allow for the energy that was not fully absorbed by the intermediate dump. The other is that the c-type magnets will be exposed to this leaking flux, and thus will experience greater energy deposits than the hard collimation model used in the earlier DIMAD simulations would suggest.

A further implication of the results presented in Figure 5.4 is that it defines the degree of radiation hardness required of any instrumentation placed behind the dump to monitor beamstrahlung photons (another method of measuring collision quality). In certain regions, the instrumentation must be tolerant to a flux in excess of $10^9$ photons per cm$^2$ per bunch crossing, which is more than $1.6 \times 10^{13}$ photons cm$^{-2}$s$^{-1}$, which is clearly large, particularly when considering the power density. The average energy of the photons generated by the absorption of the disrupted beam by the dump is 3.2 GeV. In this region, the power per cm$^2$ is 8.2 kW, which is almost certainly too high for any detector to survive directly without a cooling system. For this reason, the post-collision line favours indirect detectors to monitor the photon flux emerging from the exit of the main dump.
Backscattered Photons from the Main Dump Entrance

Figure 5.5: Angular limits of a backscattered photon from the main dump to the IP. Assuming that the silicon detectors are within a radius of 1 m, $\alpha \approx 3.2 \times 10^{-3}$ radians. The red arrow indicates a backscattered photon incident on the detector silicon where the green arrow is excluded due to its larger angle.

When considering the backscattered particles incident on the IP, it is useful to consider the range of angles that a backscattered particle must be within to have a trajectory with the potential to strike the IP. In Figure 5.5, the size of the silicon vertex detector is assumed to lie within 1 m of the beam axis. Any particles with a trajectory outside the 1 m boundary, such as that indicated with the red arrow, will not hit the silicon detectors and are therefore excluded from any IP flux estimates. The angular envelope is given by

$$\alpha \text{ [rad]} = \frac{r \text{ [m]}}{s \text{ [m]}},$$

(5.4)

where $r \ll s$, $r$ is the radius of the target area and $s$ is the distance between the source of backscattered particles and the target.

The angular distribution of the photons backscattered from the main dump towards
the direction of the IP are presented in Figure 5.6 and 5.7, which represent the photons observed at Region D of Figure 5.1. At 315 m from the IP, the main dump is estimated to be a large source of electromagnetic background due to the dissipation of approximately 10 MW of disrupted beam power.
Figure 5.6: Backscattered horizontal angular distribution of photons from the entrance to the main dump, 315 m from the IP. The photons originating from the disrupted beam, cohplus and cohminus are shown at the top, left and right respectively. The value $p_x/p$ is the momentum in the x direction divided by the total photon momentum, making it a dimensionless value. At small values however, $p_x/p$ is approximately equal to the angle of the particle trajectory in radians. The region of interest is between $\pm 3.2 \times 10^{-3}$ radians since the silicon detectors of the IP exist within this angle.
CHAPTER 5. PHOTON BACKGROUND IN THE POST-COLLISION LINE

The horizontal $p_x/p$ distribution of the photons shown in Figure 5.6 is symmetric, which is to be expected since the post-collision line possesses left-right symmetry in its design. The plots have almost flat distributions in the region where $p_x/p$ lies between $\pm 0.2$. The value $p_x/p$ is dimensionless, but at small values may be considered to be the angle in radians relative to the beamstrahlung photon axis, and therefore the direction of travel in relation to the IP position. Figure 5.5 shows the angular constraints dictating which angles of backscattered photons from the dump will be incident on the region of silicon detectors at the IP. The magnets and intermediate dump have been removed from this diagram for clarity, but in reality would further restrict the line of sight between the dump and the IP, attenuating the photon flux. The number of photons originating from the disrupted beam are an order of magnitude greater than that of the photons originating from the cohplus and cohminus beams, making it the dominant source of background. In the horizontal angular region of the IP, between $\pm 3.2 \times 10^{-3}$ radians, the flux is approximately $2.4 \times 10^9$ photons per 0.01 radians per bunch crossing, which equates to $1.5 \times 10^9$ photons per bunch crossing with a horizontal angle incident on the IP. As part of the optimisation of the post-collision line, the main dump was moved from its position at 150 m from the IP to 315 m to allow for more beam blow up before striking the dump. At 150 m compared with the current baseline of 315 m, this would have meant an increased angular constraint of $\pm 6.72 \times 10^{-3}$ radians and that $3.2 \times 10^9$ photons per bunch crossing would be within the horizontal angular range required to be incident on the silicon vertex detector. Compared to the value of $1.5 \times 10^9$ expected for the dump at 315 m from the IP, the longer post-collision line is
more favourable by a factor of 2.1.
Figure 5.7: Backscattered vertical angular distribution of photons from the entrance to the main dump, 315 m from the IP. The photons originating from the disrupted beam, cohplus and cohminus are shown at the top, left and right respectively. The value $p_x/p$ is the momentum in the x direction divided by the total photon momentum, making it a dimensionless value. At small values however, $p_x/p$ is approximately equal to the angle of the particle trajectory in radians. The region of interest is between $\pm 3.2 \times 10^{-3}$ radians since the silicon detectors of the IP exist within this angle.
The vertical angular distribution of the backscattered photons are presented in Figure 5.7. Using the angular arguments described in Figure 5.5 as were used for the horizontal angular distribution, the estimated flux at the IP is reduced. Using the angular arguments presented for Figure 5.6, and assuming the disrupted beam to be dominant, \(0.9 \times 10^9\) photons per bunch crossing are estimated to have a vertical direction vector in the region of the silicon vertex detector.

### 5.2.2 Intermediate Dump Photons

The intermediate dump lies between Regions B and C in Figure 5.1 and is the second most significant position of particle loss. For this reason, it is a considerable contributor of secondary particles. Being that its entrance is only 67 m from the IP, backscattered photons from the intermediate dump have a significantly greater chance of hitting the IP than from the main dump which is a further 242 m from the IP. The increase is probability is due to two key factors, one is that it is not shielded by itself or the c-type magnets which the main dump is, and the other is that the angle of incidence is \(1.49 \times 10^{-2}\) radians from the beamstrahlung photon axis rather than only \(3.20 \times 10^{-3}\) radians for the main dump using the angular calculation detailed in Figure 5.5.
Figure 5.8: Photon energy density in GeV cm$^{-2}$ per bunch crossing from the exit of the intermediate dump, 73 m from the IP. The results of the disrupted beam is shown at the top with the cohplus and cohminus beam results at the right and left respectively. In the plots, the asymmetric aperture of the intermediate dump is evident. Being that the disrupted and cohplus beams are bent downwards, towards $-y$ by the window-frame magnets, the photons escaping the exit are to be found concentrated at the bottom of the aperture, indicated by the red region. For the cohminus beam, the opposite is true.
Forward Photons from the Intermediate Dump Exit

The hard collimation model is suitable for fast optimisation of a design since simulating the physics processes in matter is computationally expensive. Initial beam loss studies in Section 3.5.2 indicated that the losses within the c-type magnets should be negligible. The study in Chapter 3 assumed all beam loss energy to be deposited at the point where its transverse position exceeding the aperture limits. In reality, this is not true and the energy of lost particles generates secondary particles and these secondary particles can exit the beam line element they were produced in and deposit energy in neighbouring elements. In these simulations, losses were detected in the c-type magnets, which are presented later in this chapter. Since the initial study revealed negligible losses from the primary particles, it can be assumed that these losses were from the absorption of secondary particles radiated from the intermediate and main dumps. Figure 5.8 confirms this, showing the forward photon flux leaking from the back of the intermediate dump, 73 m from the IP. The vertically asymmetric aperture profile is clearly visible in all three plots. As expected due to the deflection of the window-frame magnets, the main beam and cohplus beams produce photons in the lower region of the intermediate dump, whereas cohminus photons are produced mainly in the upper half. This is indicated by the location of the high density regions shown in red. It is the emerging flux from the intermediate dump that explains why photons are observed at the main dump despite the complete cohplus beam being incident on the absorber material of the intermediate dump.
Figure 5.9: Backscattered photon density from the intermediate dump entrance, 67 m from the IP. The top, left and right plots are the photons from the disrupted, cohplus and cohminus beam respectively. The asymmetric aperture of the intermediate dump is shown by the red region of high backscattered photon density.
Backscattered Photons from the Intermediate Dump Entrance

At Region B of Figure 5.1, 67 m from the IP, the backscattered photon density as depicted in Figure 5.9 is concentrated more on-axis than for the intermediate dump exit. This is because the showers at the exit will have developed through a greater depth of material. Clearly evident in these plots is that the entrance aperture of the intermediate dump is considerably larger than that of the exit due to the loss-optimised tapering profile of the aperture. The top-bottom asymmetry between the oppositely charged beams is evident in that the high density regions (shown in red) are at concentrated at \( y > 0 \) for the cohminus beam and \( y < 0 \) for the disrupted and cohplus beams. The greatest density of backscattered photons are observed within the vacuum pipe since the material of the absorber attenuates photons attempting to travel back towards the IP through its body.
Figure 5.10: Angular distribution of the backscattered photons relative to the beamstrahlung photon axis at the intermediate dump entrance, 67 m from the IP. The plot at the top is of the photons from the disrupted beam, to the left are those from the cohplus beam and to the right from the cohminus beam. The value of the horizontal axis is equivalent to the angle in radians for small values only. Photons with a value of $\sqrt{(p_x/p)^2 + (p_y/p)^2} > 0.0157$ radians are not incident on the IP.
The angular profile of the backscattered photons is shown in Figure 5.10. If the silicon vertex detectors and endcaps are assumed to be axially symmetric, it is more useful to consider the angle between the particle trajectory and the beamstrahlung photon axis than to consider the horizontal and vertical angles in isolation. Note that the interchangeability of \( \sqrt{\left(\frac{p_x}{p}\right)^2 + \left(\frac{p_y}{p}\right)^2} \) and angle in radians only applies for small angles. Using the arguments presented in Figure 5.5, the angle of IP incidence at Region B is 0.0157 radians, which is approximately 5 times larger than that for the main dump since the intermediate dump is closer to the IP. From the plots, it is difficult to estimate the number of photons incident on the silicon detectors at the IP. Instead, the calculated flux from simulation, assuming no magnets or masks between the intermediate dump and Region A, is presented in Table 5.1 from an extrapolation of the particle position and angle at Region B mapped onto Region A of Figure 5.1. These values will be compared to results where the magnets and masks are present later in the chapter to demonstrate the significant IP shielding effect the magnetic chicane provides.

Using the figures presented in this table, and assuming a Beamcal aperture radius of 20 mm [102], 6300 photons would be expected to enter the vertex detector per bunch crossing through the Beamcal aperture. The purpose of the aperture is to allow the collided beams to exit the IP, whilst monitoring the beamstrahlung photons for fast feedback of the luminosity.
Table 5.1: Table of estimated photon flux density within a 1 m radius of the beam-strahlung photon axis at Region A, assuming a direct line of sight (no magnets or masks between Region B and A).

<table>
<thead>
<tr>
<th></th>
<th>disrupted</th>
<th>cohplus</th>
<th>cohminus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons per Bunch Crossing per cm$^2$</td>
<td>106</td>
<td>39.6</td>
<td>356</td>
</tr>
<tr>
<td>Photons per Second ($\times 10^6$)</td>
<td>1.65</td>
<td>0.62</td>
<td>5.55</td>
</tr>
</tbody>
</table>
Figure 5.11: Energy distribution of the backscattered photons from the entrance to the intermediate dump, 67 m from the IP. The top, left and right plots are photons resulting from the disrupted, cohplus and cohminus beams respectively. In all three plots the 511 keV annihilation peak is clearly present due to the annihilation of positrons with atomic electrons in the materials under study. The energy spectrum for the disrupted and cohplus beams shows a distinct trough between 10 keV and 20 keV. This trough coincides with the region of high Compton scattering cross section in carbon [86], where photons of this energy are absorbed.
Figure 5.11 represents the backscattered photon energy distribution from the intermediate dump entrance. As is reasonable to expect, an annihilation peak exists at 511 keV. However, an extra feature is visible in all three beam species, but particularly prominent in the disrupted and cohplus beam data is the form of a dip between 10-100 keV. Since this trough coincides with a high Compton scattering cross-section for carbon in Figure 4.6, it is reasonable to assume that the energy spectrum is attenuated in this region due to photons being absorbed by the scattering process in the graphite absorbers. The energy profile is important since photons below approximately 200 keV cannot cause bulk damage (damage throughout the volume, not just the surface) in silicon detectors [101], yet this is the region most backscattered photons exist. From this, it can be concluded that the energy distribution is favourable for minimising detector damage due to photons from the post-collision line.

5.2.3 Photons Towards the IP

An important consideration when considering IP backgrounds is the timing at which the photons are received back at the IP. Assuming time of flight based on the speed of light, the information in Table 5.2 is calculated showing the expected time between a bunch passing through the IP and the backscattered photons it generates returning back to the IP.
Table 5.2: Background photon time of flight calculated from the round-trip distance and assuming particles moving at almost the speed of light.

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Distance from IP (m)</th>
<th>Time of Flight (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mask1a1b</td>
<td>29.0</td>
<td>193</td>
</tr>
<tr>
<td>Intermediate Dump</td>
<td>67</td>
<td>447</td>
</tr>
<tr>
<td>Main Dump</td>
<td>315.0</td>
<td>2101</td>
</tr>
</tbody>
</table>
CHAPTER 5. PHOTON BACKGROUND IN THE POST-COLLISION LINE

Figure 5.12: Time of flight profile for backscattered photons from the post-collision line. For all three beam types, the first photons to arrive back to the silicon vertex detector are no earlier than 200 ns after the first bunch of the train passes through the IP, which is also 34 ns after the last bunch of the train has passed. The last of the photons arrive back at the IP no later than 2200 ns after the passage of the first bunch through the IP, which is nearly 20 ms before the next bunch train passes through the detector.
The time of flight profile presented in Figure 5.12 show the time-of flight between the bunch crossing the IP and the backscattered photons arriving back at the IP. Since a bunch train contains 312 bunches spaced by 0.5 ns, all three sources of backscattered photons have a time-of-flight greater than the duration of a bunch-train crossing (156 ns). The next bunch train will not arrive until more than 19 ms after all the backscattered photons from the previous bunch train have passed through the IP. For this reason, it is possible to differentiate between genuine signal and backscattered photons from the post-collision line, as shown in Figure 5.13, which is a favourable characteristic in minimising the detection of false hits.

Combining the calculated time of flight in Table 5.2 and the results of the simulations in Figure 5.12, it is possible to use these to determine the source of the backscattered photons reaching the Beamcal. Despite absorbing approximately 10 MW of beam power, the main dump contributes very few backscattered photons to the IP, as indicated by the peak between 2100 ns and 2200 ns. This demonstrates the effectiveness of locating the dump further from the IP, and shielding the IP from it using the masks and intermediate dump. However, the intermediate dump itself is the largest contributor to IP photons, indicated by the peak between 400 ns and 500 ns. For the cohminus beam, this is particularly pronounced, which is to be expected since the loss locations of the cohminus beam have a direct line of sight to the IP.

The photon flux at the IP is calculated as a flux density through a 2 m x 2 m plane, 3.35 m from the IP since all silicon-based detectors are located within this cross-section. This was decided upon as an interface plane where the machine-detector inter-
face occurs, and was chosen since it is outside the Beamcal and Lumical [102] of the
detector. The total backscattered photon flux from disrupted, cohplus and cohminus
beams is calculated to be $10.7 \pm 1.1$ photons cm$^{-2}$ per bunch crossing, which equates
to $1.67 \pm 0.18 \times 10^5$ photons cm$^{-2}$s$^{-1}$. In Table 5.1, the expected flux, neglecting the
shielding effects was expected to be approximately 500 photons per cm$^2$ per bunch
crossing. The attenuation of the flux by a factor of 50 indicates the importance of
using a magnetic chicane to shield the IP from backscattered photons.

The flux presented in Table 5.3 is incident on the face of the Beamcal [102], which
will shield the silicon vertex detectors from the backscattered photon flux. The Beam-
cal has an aperture with a radius of 20mm to permit the incoming and outgoing beams
to pass through. The aperture has an area of $12.6$ cm$^2$, which will permit a total of 135
photons per bunch crossing to enter the vertex detector volume. Using the estimate
given for the ILC in [103], and the similarities between ILC and CLIC detector de-
signs, it is reasonable to expect only 3% of the photons incident to the detector volume to result in hits in the silicon, which is approximately 4 hits per bunch crossing of the 135 that entered the vertex detector volume. This is negligible compared to the 250 vertex detector hits per bunch crossing due to incoherent pairs expected at the ILC [104]. For this reason, and due to the ability to distinguish post-collision background events due to timing considerations, the CLIC post-collision line will have a negligible effect at the detector.

In summary for this section, it can be concluded that the effects of the post-collision line background on the detectors at the IP are minimal. The possibility for false hits being registered at the detector can be dismissed since it is excluded by timing arguments. Any post-collision line component that had been within 21.45 m of the IP would have a time of flight less than 156 ns, and so the backscattered photons from the first bunch of the bunch train would arrive at the IP before the last bunch of the train had passed. This would exclude the use of timing arguments to eliminate background signal generated from the post-collision line, but with the design presented in this thesis, the first component is at 27.5 m from the IP so associated backgrounds are distinguishable. In terms of potential damage to the detector, the post-collision line is expected to produce only four hits per bunch crossing, compared with 250 hits from incoherent events as calculated for the ILC. In a simple straight design with no magnetic chicane, approximately 200 hits per bunch crossing would be expected, which demonstrates the performance advantage of the post-collision line as it is presented here.
5.3 Power Losses in the Post-Collision Line

In chapter 3, the losses on the magnets were estimated using a hard-edged collimation model. That is to say, if a charged particle exceeded the aperture limitations of the element, its full energy was assumed to have been lost in that element. In reality, this is not true, with secondary particles being emitted, carrying away excess energy. This is confirmed by analysing the photons exiting the absorber material of the intermediate dump in Figure 5.8. By calculating the difference between the energy into and out of an element, a power loss figure may be calculated including electromagnetic interactions. The power loss is calculated using Equation 3.12 and presented in Figure 5.14 showing the main loss locations to be the main dump and intermediate dump. In the post-collision line, it is favourable to defer losses to as far from the IP as possible to minimise the impact of backscattered particles on the IP. With the intermediate dump at 67 m from the IP, and the main dump at 315 m from the IP, the losses are concentrated towards the end of the post-collision line. It is also apparent that magnets 2-7 have power losses exceeding a kilowatt, which for a 4 m magnet clearly exceeds the magnet power loss optimisation parameter in Chapter 3.

In the hard-edged collimation model of Section 3.5.2, losses in the magnets were optimised to be less than 100 W/m; a specification recommended after consultation with magnet engineers [63]. Due to photon flux leakage of the intermediate dump, magnets in its vicinity are subjected to higher energy losses within them than considering beam-loss only. In magnet 4, these losses are found to be 1199 W/m; more than an
Figure 5.14: Power losses along the post-collision line (total power loss per element). The two key loss locations are the main dump (maindmp, 315 m from the IP) and the intermediate dump (intdmp, 67 m from the IP).

order of magnitude above the recommended losses. However, the method used to generate this calculation calculates all energy losses between the entrance and exit faces of the magnet. This figure will include losses to the tunnel walls and to the entire magnet structure, not just the aperture.

In Table 5.4, the power losses obtained from both the DIMAD and GEANT4 calculations are compared. It is clear that the power deposited in the magnets is significantly higher when considering all the secondary particles that may be incident on the magnets. It is for this reason that the initial beam dynamics studies are complemented by a physics in matter simulation, particularly where beam loss is high. A key result that is essential to consider is the magnet lifetime under the action of electro-
CHAPTER 5. PHOTON BACKGROUND IN THE POST-COLLISION LINE

Table 5.4: Estimated Magnet Lifetime due to Losses in the Post-Collision Line using the technique described in Section 3.1.2, assuming the maximum dose of $10^7$ Gy.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Mass [kg]</th>
<th>Losses (DIMAD)[W]</th>
<th>Losses (GEANT4) [W]</th>
<th>Life [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>1505</td>
<td>2.2</td>
<td>42</td>
<td>113</td>
</tr>
<tr>
<td>1b</td>
<td>10534</td>
<td>314.7</td>
<td>381</td>
<td>88</td>
</tr>
<tr>
<td>2</td>
<td>23047</td>
<td>189.6</td>
<td>1128</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>40620</td>
<td>165.6</td>
<td>2590</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>67547</td>
<td>130.4</td>
<td>7958</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>74114</td>
<td>0.0</td>
<td>3559</td>
<td>66</td>
</tr>
<tr>
<td>6</td>
<td>74114</td>
<td>0.0</td>
<td>2215</td>
<td>106</td>
</tr>
<tr>
<td>7</td>
<td>74114</td>
<td>0.0</td>
<td>1527</td>
<td>154</td>
</tr>
<tr>
<td>8</td>
<td>74114</td>
<td>0.0</td>
<td>971</td>
<td>242</td>
</tr>
</tbody>
</table>

magnetic showers. The magnet lifetimes as a result of the GEANT4 simulations are estimated, assuming that the losses are absorbed by the whole body of the magnet, and presented in Table 5.4. The lifetime is calculated based on the procedure detailed in Section 3.1.2. Assuming that the magnets must have a lifespan exceeding 20 years based on the expected lifetime of high-energy colliders, this lifetime estimate indicates that the post-collision line presented in this thesis provides adequate protection for the magnets because of the magnet masks (for the window-frame magnets) and the influence of the intermediate dump (for the c-type magnets). In reality, the losses are not likely to be homogeneous throughout the magnet body, and due to the proximity of the coils to the beam, the insulation breakdown lifetime may be shorter than estimated in these simulations. For this reason, minimising the losses further would be desirable, using techniques suggested in the conclusion to this Chapter.
5.4 Conclusions

In this chapter, the four key points of interest in terms of secondary particles have been presented and analysed in detail. The photon flux at the IP has been found to be $10.7 \pm 1.1$ photons per cm$^2$ per bunch crossing. Due to photon timing considerations however, the backscattered photons arrive asynchronously to genuine signal, 44 ns after the last bunch of the train has passed through the IP and nearly 20 ms before the next bunch train, thus false-hits at the IP can be filtered using timing-based arguments, which are only possible if the post-collision line losses are more than 21.45 m from the IP. The number of vertex detector hits is found to be negligible at 4 hits per bunch crossing compared to direct incoherent pair hits at the ILC of 250 hits per bunch crossing. In this respect, any potentially damaging effect on the detector are negligible compared to those from other sources. The performance of the post-collision line with respect to minimising photon flux can be largely attributed to the shielding effect provided by the magnetic chicane, which serves to minimise the line of sight to backscattered photons. The number of vertex hits per bunch crossing is also minimised since the regions of high energy absorption, such as the intermediate dump and main dump are positioned far from the IP, reducing the solid angle of the IP seen by these sources.

The calculation for the power losses reveals that under the circumstances of secondary particles being emitted from the dumps and masks, the magnets are subject to losses in excess of 100 W/m, but that the magnet lifetimes due to aging effects appear to be acceptable at an estimated 45 years, where a typical high-energy collider
lifetime is expected to require only 20 years of operation. However, the magnet aging calculation does assume that the losses are absorbed by the whole magnet body. If the losses in the coils are found to be excessive, magnet losses can be reduced by changing the magnet mask material from carbon to iron since a higher-Z material has a shorter radiation length and will provide greater protection for the magnets [105]. Iron could be added to the end of the intermediate dump to minimise magnet losses in the c-type magnets, and to mask the main dump instrumentation from the photons escaping the intermediate dump.
Chapter 6

Neutron Background in the Post-Collision Line

In Chapter 5, hadronic processes were not included but in reality, the particles and photons produced from electromagnetic processes will, amongst other hadronic processes, interact with the nuclei of the atoms in material via photonuclear and electronuclear processes [82] [106]. From these processes, neutrons are liberated from the nuclei leading to a neutron background. Neutrons are of concern when considering IP backgrounds since they can cause degradation of the silicon vertex detectors by introducing defects due to displacement of the atoms in the lattice [107]. The neutron background within the post-collision line environment will lead to ageing effects [62] and implications with regards to radiation protection.

Since neutron production is dependent on the photons and electrons of the electromagnetic background, the predominant sources of neutron production are expected to
be the main and intermediate dumps. The main goals of this chapter are to present simulated neutron backgrounds originating from the CLIC post-collision line and discuss potential detrimental effects to silicon-based detectors at the IP, with an estimation for the charge collection efficiency degradation. The tools used in Chapter [82] will also be used in this simulation, but including the hadronic physics required for the simulation of the production of neutrons.

6.1 Neutron Backgrounds

In this section, the neutron backgrounds are presented at the same regions of interest as Chapter 5, with Region A at 3.35 m, Region B at 67.0 m and Region D at 315 m from the IP looking at backscattered neutrons at the Beamcal, intermediate dump and main dump respectively. Region C at 73 m and Region E at 325 m from the IP look at the forward neutrons from the intermediate and main dumps respectively. With hadronic processes included, the simulations presented in this chapter were found to be more computationally demanding by a factor of approximately 2.5 than those for the electromagnetic backgrounds due to the additional processes required to simulate hadronic physics. For this reason, less seed particles are included in these simulations which will lead to a poorer statistical error compared to the results presented for the photon background. The simulations presented here are the result of 24,400 disrupted, 24,525 cohplus and 22800 cohminus initial beam particles, with results normalised to the equivalent of one bunch crossing. The 'hadronic_standard' physics list is used,
which in addition to the purely electromagnetic processes includes the photon-nuclear, electron-nuclear and positron-nuclear processes, and the electro-nuclear and gamma-nuclear reactions, as is described in Section 4.4.2. The cuts for the photons and charged particles which generate the neutrons remains at 10 keV. BDSIM provides no option for defining an energy cut for neutrons, instead relying on a minimum step length to determine if a track is cut, which is set to 0.1 nm in these simulations [108].

6.1.1 Main Dump Neutrons

The electromagnetic background study indicated losses exceeding 10 MW in the main dump and so the majority of the neutron background will be generated within this region. Figure 6.1 shows the energy deposition profile of the disrupted and cohplus beams. The beam is offset from the axis by a vertical displacement of -120 mm, and due to dispersion effects is spread down from this position. The entrance to the main dump is 315 m from the IP, which according to the angular constraints of Figure 5.3 means that the solid angle of the IP seen by the dump is approximately $1.0 \times 10^{-5}$ sr. It is therefore important to analyse the angular distribution of the neutrons from the main dump towards the IP to estimate if these will be incident on the silicon vertex detector. It is also planned for the dump to be equipped with luminosity monitoring instrumentation, which should be designed to operate under the neutron background conditions generated by the dump.
CHAPTER 6. NEUTRON BACKGROUND IN THE POST-COLLISION LINE

Forward Neutrons from the Main Dump Exit

Since it is intended to place beamstrahlung detector apparatus downstream of the main dump, as detailed in Section 3.4.5, it is necessary to estimate the neutron fluxes these detectors will be exposed to. By counting the number of neutrons that pass through the sampler plane at the end of the main dump, and normalising to the equivalent of one bunch crossing, the GEANT4 simulations indicate that $1.4 \times 10^{11}$ neutrons are produced at the exit of the main dump per bunch crossing.

The kinetic energy of forward-travelling neutrons emerging from the main dump exit (325 m from the IP, Region E in Figure 5.1) is presented in Figures 6.2. For all three beam types, the distribution is approximately the same shape, with the peak neutron flux being between 0.0 and 3.0 MeV, and tailing off at higher energy. Since most
of the neutrons are above 3.0 MeV, these may be considered to be fast neutrons. Since the disrupted beam is the dominant source of neutrons, its neutron energy distribution is presented in Figure 6.3. Due to limited statistics, it is not possible to determine if the neutron energy extends down to thermal levels (less than 1 eV). At the exit to the main dump, it is intended to include Cerenkov muon detectors to monitor the collision quality, as described in Figure 3.15. Since the forward neutrons in this region will be incident on the photomultiplier tubes of the apparatus, they have the potential to damage the tubes or generate false signals, affecting the quality of the feedback. Figure 6.4 represents the neutron densities observed from simulation at the main dump exit, 325 m from the IP. These distributions are roughly isotropic, with the intensities of the coherent pair beams at least two orders of magnitude less than that for the main beam. Therefore, at the main dump exit, contributions from cohplus and cohminus beams are insignificant compared to the main beam. The disrupted beam neutron density at the top of Figure 6.4 has a slight central peak indicating that these neutrons were produced towards the end of the absorber, 325 m from the IP, and thus not experiencing sufficient length of absorber to scatter and distribute. The peak intensity is shown in red as approximately $10^6$ neutrons per cm$^2$ per bunch crossing, which would suggest it would be favourable to use an indirect detector scheme as given in Figure 3.15 to minimise damage to the photomultiplier tube. By locating the photomultiplier tubes more than 0.2 m offset from the beamstrahlung photon axis, the neutron flux is reduced by an order of magnitude. The beam dump thermometry equipment proposed in Section 3.4.5 also positions the laser and detecting equipment offset from the beam axes.
to minimise its exposure to neutron radiation.
Figure 6.2: Kinetic energy distribution of the neutrons from the exit of the main dump, 325 m from the IP. The top and left plots represent the neutrons resulting from the respective disrupted and cohplus beams being absorbed by the water of the dump. The plot on the right is due to the cohminus beam, of which the entire beam is lost on the absorbing material of the intermediate dump. The neutrons observed here are from the secondary particles that have emerged from the intermediate dump and travelled along the beam line tunnel to strike the main dump.
Figure 6.3: Kinetic energy distribution for lower energy neutrons generated by the disrupted beam between 0.0 MeV and 3.0 MeV.
Figure 6.4: Forward neutron density from the main dump showing the products of the disrupted beam (top), cohplus beam (left) and cohminus beam (right) at 325 m from the IP, centred on the beamstrahlung photon axis. For the cohminus and cohplus beams, the neutron density is sparse, and has a peak intensity of two orders of magnitude less than that for the disrupted beam. For the disrupted beam, a neutron density peak of approximately $10^6$ neutrons per cm$^2$, centred at y=-0.12 m.
Backscattered Neutrons from the Main Dump Entrance

The angular distribution plots at the main dump entrance in Figure 6.5 and Figure 6.6 confirm that the neutrons are radiated in all directions from the main dump due to the flat distribution in $\frac{p_x}{p}$ and $\frac{p_y}{p}$. The reason that the distributions tail off at $\pm 1.0$ is because these represent particles with a direction of motion perpendicular to the nominal beam direction, which will not pass through the sampler plane BDSIM uses to detect them. All components around the main dump, and the tunnel itself will be exposed to the neutron flux, leading to possible activation. Activation is an important consideration since it will determine the ease of which post-collision line components can be serviced or repaired. The number of neutrons backscattered from the disrupted beam is the dominant source, and since the angular distribution is flat in both planes, it is possible to estimate the neutrons within the solid angle of the IP as seen from the dump. From counting the number of neutrons observed at the sampler plane, the simulations reveal there are an estimated $1.23 \times 10^{11}$ backscattered neutrons per bunch crossing, which in free space, and assuming a flat angular distribution, would be evenly distributed over a hemispherical shell with a radius of 315 m. By taking the ratio of the cross-sectional area of the silicon vertex detector as seen from the dump (0.785 m$^2$) and that of the hemispherical shell ($6.23 \times 10^5$ m$^2$), the probability of any backscattered neutron being incident on the IP is $1.26 \times 10^{-6}$. This corresponds to $1.54 \times 10^4$ neutrons per bunch crossing incident on the IP if no upstream components existed to shield against it. Since the estimated neutron flux is inversely proportional to the distance from the
IP, positioning the dump further is considered desirable. The disadvantages of positioning the dump further away are the civil engineering costs of a longer tunnel, and the required increase in size of the dump entrance window.
Figure 6.5: Backscattered neutron horizontal angular distribution from entrance to the main dump showing the flux as a result of the disrupted, cohplus and cohminus beams shown top, left and right respectively. The results represent the neutrons travelling in the backward direction, towards the IP at 315 m from the IP.
Figure 6.6: Backscattered neutron vertical angular distribution from entrance to the main dump showing the flux as a result of the disrupted, cohplus and cohminus beams shown top, left and right respectively. The results represent the neutrons travelling in the backward direction, towards the IP at 315 m from the IP.
6.1.2 Neutrons from the Intermediate Dump

The intermediate dump differs considerably from the main dump in that it allows most of the beam to pass through. To accommodate the aperture, the intermediate dump uses water-cooled graphite absorbers rather than a water dump design proposed for the main dump (based on [73]). The intermediate dump is designed to absorb a few 100 kW rather than the approximately 10 MW of the main dump since it only has to absorb the cohminus beam and the low energy tail (less than 210 GeV) of the disrupted and cohplus beam. Neutron production in carbon will differ from that of water due to the differences in density and atomic mass numbers. Due to the intermediate dump being only 67 m from the IP, studying the neutron flux created by it is important when considering IP backgrounds.

Backscattered Neutrons from the Intermediate Dump

For the neutrons generated from the cohplus and cohminus beams, the angular distribution in Figures 6.7 and 6.8 are spread evenly across values of $p_x/p$ between -0.8 and 0.8 and $p_y/p$ between -0.8 and 0.8 for the intermediate dump entrance (67 m from the IP, Region B). Neutrons from the disrupted beam however exhibit a square peak in the distribution, approximately four times the intensity of the rest of the distribution. This peak represents neutrons originating from the main dump passing through the aperture of the intermediate dump. The minimum horizontal aperture of the intermediate dump is 450 mm, which would correspond to an opening angle of ± 1.86 mrad. Since these neutrons have traversed 242 m to reach the intermediate dump from the main
dump, what passes through the aperture is highly collimated in angle. These neutrons represent the greatest risk to the generation of IP backgrounds due to their angular trajectories being within that required to hit the silicon of the IP. Neutrons within 0.03 rad of the beam axis are likely to be incident on the IP based on angular constraints shown in Figure 5.5. As with the photons, the magnetic chicane of the post-collision line presents an obstacle to backscattered particles by reducing the line of sight. Neutrons must scatter from the materials of the magnets, masks and dumps to reach the IP, which heightens the chance of their energy being deposited within the material.
Figure 6.7: Horizontal angular distribution of the backscattered neutrons from the intermediate dump entrance, 67 m from the IP. The neutrons produced by the cohplus and cohminus beams are shown to the left and right respectively, and appear to evenly distributed in px/p for values between -0.8 and 0.8. For the neutrons from the disrupted beam (top), there is a pronounced peak in the distribution, which is attributed to the neutrons from the main dump passing through the aperture of the intermediate dump, with those neutrons outside the angular range of the peak being incident on the graphite aperture of the intermediate dump and thus attenuated.
Figure 6.8: Vertical angular distribution of the backscattered neutrons from the intermediate dump entrance, 67 m from the IP. The neutrons produced by the cohplus and cohminus beams are shown to the left and right respectively, and appear to evenly distributed in px/p for values between -0.8 and 0.8. For the neutrons from the disrupted beam (top), there is a pronounced peak in the distribution, which is explained in Figure 6.7.
6.2 Neutrons Towards the IP

The neutrons at the IP are defined as neutrons passing back through a $2 \times 2$ m plane, 3.35 m from the IP. In the simulations, the particles passing through the sampler plane located at Region A of Figure 5.1 are counted where their type is a neutron, their direction of travel is towards the IP and the neutron is within $\pm 1.0$ m of the beamstrahlung photon axis. The count is normalised to the equivalent flux per beam crossing and averaged over $4 \times 10^4$ cm$^2$ to give the flux per cm$^2$ per bunch crossing.

| Table 6.1: Summary of neutron backgrounds incident on the IP |
|-----------------|-----|-----|-----|
| Neutrons per Bunch Crossing | disrupted | cohplus | cohminus |
| Neutrons per Second ($\times 10^6$) | 26.6 | 3.80 | 8.63 |
| Neutrons per Second ($\times 10^6$) | 4.15 | 0.59 | 1.35 |

The disrupted beam is the major contributor to IP neutron background, as shown in Table 6.1 contributing over three times the neutrons of the cohminus beam. From the angular considerations at the intermediate dump, it may be assumed that many of these neutrons originated from the main dump, 315 m away, and have been deflected through the post-collision line either via a line of sight or indirectly by scattering from the beam line components. The total neutron flux is calculated as $39.0 \pm 4.9$ neutrons per bunch crossing per cm$^2$. Since neutrons travel at less than the speed of light, backscattered neutrons will not arrive back at the IP before the bunch train has passed. For the same reason as detailed for photons in Chapter 5, any background generated by neutrons
causing ionisation in silicon may be distinguished from genuine data by timing arguments. Therefore, the primary concern with background neutrons is the potential damage to the detectors. Due to the shielding effect of the Beamcal [102], and using the same analysis as in Section 5.2.3, an estimated $490 \pm 62$ neutrons are expected to pass through the aperture of the Beamcal to enter the silicon detector volume.

### 6.2.1 Silicon Detector Damage

![Neutron induced displacement damage in Silicon](image)

Figure 6.9: Neutron Induced Displacement Damage in Silicon (taken from [111]). The units of $D(E)$ are such that the damage of a 1.0 MeV neutron is $1.0 / 95$ MeV mb.

The data presented in Figure 6.9 shows the displacement damage in silicon as
a function of incident neutron energy. Using the 1 MeV neutron equivalent data from [109] and [110], the displacement damage of the backscattered neutrons at the IP can be estimated. For each neutron detected incident on the IP in the simulations, its energy is mapped to the closest value in the 1 MeV equivalent neutron data to give the 1 MeV equivalent neutron fluence for that particle. From this, the equivalent average fluence contribution per incident neutron can be calculated, and is found to be $1.1 \pm 0.41 /95\text{ MeV} \text{ mb}$, which has the equivalent damage of $1.1 \pm 0.41 \text{ 1.0 MeV} \text{ neutrons striking the detector.}$

![Schematic representation of a neutron incident on the silicon detectors at the IP. Diagram based on information given in [112].](image)

Figure 6.10: Schematic representation of a neutron incident on the silicon detectors at the IP. Diagram based on information given in [112].

From Figure 6.10, neutrons that are not prevented from entering the IP by the Beamcal may strike the silicon vertex detector and the silicon-based central tracking detectors. The 1 MeV equivalent neutron fluence is found by taking the product of the neutron flux and the average fluence contribution per neutron and multiplying this by the neutron flux. The results of this calculation are a 1 MeV equivalent neutron
fluence of \((6.69 \pm 0.84) \times 10^5\) cm\(^{-2}\) s\(^{-1}\). Assuming a required detector lifetime of five years per detector and since two detectors will be used in push-pull configuration [47], the neutron fluence integrated over 5 years is \((1.05 \pm 0.13) \times 10^{14}\) cm\(^{-2}\). From the data in [113] an estimate for the charge collection degradation may be made as being less than 15% over the detector lifetime. However, this is 50% more than is deemed acceptable in [113]. If this degradation in the charge collection efficiency is considered unacceptable, the solution would be to move the main dump further away from the IP, since this is the primary source of neutrons. The solid angle of the IP seen by the dump scales as the inverse of the distance squared as shown in Figure 5.3 and Equation 5.2. Therefore, to achieve a 33% reduction in the fluence observed at the IP, the distance between the dump and the IP would need to be increased by a factor of 1.22, placing it at 386 m from the IP. Increasing the distance between the IP and the dump is also beneficial for non-colliding beams since the additional beam growth will minimise the intensity on the dump entrance window.

6.3 Conclusions

It was the goal of this chapter to present a general introductory overview of the neutrons generated by the CLIC post-collision line, including the flux observed at the IP. This overview has been presented at the points of interest, and the IP flux calculated. Time-of-flight arguments exclude the potential for backscattered neutrons to generate false hits. The primary concern for backscattered neutrons from the post-collision line is
the potential for damage to the silicon detectors, which has been calculated in terms of the charge collection efficiency. The degradation in efficiency is expected to be approximately 15% over the detector lifetime in the parts of the silicon detectors that are exposed to the 1 MeV equivalent neutron fluence of \((6.69 \pm 0.84) \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}\). If the degradation of charge collection efficiency is considered unacceptable, a solution has been presented in the form of moving the dump a further 71 m from the design presented in Chapter 3 to reduce the fluence.
Chapter 7

Conclusion

7.1 Computational Beam Dynamics

In this chapter, the goals were to introduce the study of beam dynamics and its application in particle accelerator simulation such as the study presented in Chapter 3.

7.2 The CLIC Post-Collision Line

The purpose of this chapter was to present the CLIC post-collision line, and describe how it fulfils the requirements of transporting both the disrupted and nominal beams to the dumps, transporting with minimal losses yet having provision for post-collision monitoring. A design fulfilling the design criteria was presented, including a beam-loss optimisation scheme developed as part of this thesis. First of all, the design permits the transport of non-colliding beams, providing sufficient drift space to allow the
beams to expand. Secondly, the post-collision line transports the beam-beam products of collision whilst minimising losses in the magnets such that they are below 100 \( \text{Wm}^{-1} \), providing an estimated lifetime of 20 years which is the expected lifetime for a high-energy collider. Thirdly, the post-collision line separates the beams such that the beamstrahlung photons and charged particles can be identified and measured due to their transverse position. Finally, the post-collision line is shown to provide adequate space for the beam delivery system at a crossing angle of 20 mrad.

7.3 Physics in Matter

In this chapter, an overview of the relevant physics-in-matter processes were presented for the CLIC post-collision line. The tools used to simulate these processes computationally were introduced, and the model and method used to generate the background results of this thesis. A solution for the computing demands of this thesis was presented in the form of running BDSIM on the GRID.

7.4 Photon Backgrounds in the Post-Collision Line

7.4.1 Power Losses

A key criterion for the CLIC post collision line was to maintain losses within the magnets to below 100 W/m as advised by magnet engineers. In the hard-edged collimation model used in Chapter 3, the apertures of the magnet protection masks were refined
such that the 100 W/m criterion was met. In reality however, the masks are not perfect absorbers, and as such, energy leaks from them in the form of secondary particles. As such, the magnets are exposed to these fluxes, significantly increasing the energy deposited within their structure. The losses are found to be in excess of 100 W/m for magnets 2, 3, 4, 5, 6, 7, and 8, with the maximum loss attained in magnet 4 of 1199 W/m. These losses are the total loss within the slice occupied by the magnet, so will include losses to the tunnel walls. Further analysis revealed however that the expected magnet lifetime is satisfactory assuming losses are absorbed by the entire magnet body. Should additional protection of the magnets be required, iron could be used instead of carbon for the magnet protection masks since this is higher Z material. The proposal in [105] also includes a suggestion for an extra 2 m of iron shielding after the intermediate dump to protect the c-type magnets. Alternatively, the magnets will require radiation-hardening through new insulator materials, with extra cooling to account for the power losses [62].

7.4.2 Photon Backgrounds

The three key areas for consideration of the photon backgrounds are the IP, the intermediate dump and the exit of the main dump since all these regions will include detectors.
Photon Backgrounds at the Main Dump Exit

In this region it is expected to include photon detectors to monitor the beam collision quality for the provision of feedback to the beam delivery system. Of key importance here is the ability to distinguish beamstrahlung photons from photons generated by the energy deposition of the charged beam in the dump. Due to the offset of the charged beam relative to the uncharged beamstrahlung photons, the centres of the beamstrahlung and charged-beam photon cones are separated by 120 mm, which may be leveraged to identify beamstrahlung photons from those produced by the main beam on the dump.

Photon Backgrounds at the Intermediate Dump

Due to the losses of the disrupted and cohplus beams being mostly on the lower aperture of the intermediate dump, the separation between the same-charge and opposite-charge photon beams is approximately 250 mm.

Photon Backgrounds at the IP

The key calculation is to assess the effect of the post-collision line on the IP in terms of background performance. The post-collision line is a high-loss environment with many secondary particles potentially contributing to IP backgrounds. The photon flux of $10.7 \pm 1.1 \text{ photons cm}^{-2}$ per bunch crossing. However, due to time-of-flight considerations, the backscattered photons from the first bunch arrive at the IP 37 ns after the last bunch in the bunch train has passed the IP. Also, the photons from the last
bunch, and originating from the furthest point of the post-collision line will arrive over 19.9 ms before the first bunch of the next bunch train. For this reason, the photon background originating from the post-collision line is completely asynchronous to the bunch-train spacing, and thus easily distinguishable from genuine signal. The only factor for consideration is potential damage to the detectors. However, the post-collision line is expected to contribute less that 2% of the hit rate that the incoherent pairs will produce. Therefore, it may be concluded that the impact on detector damage due to photons from the post-collision line is negligible.

**Magnet Aging Effects**

Under the influence of secondary particle production and resulting electromagnetic showering, the power losses in the magnets are found to exceed the estimated maximum of 100 Wm\(^{-1}\). Considering that each of the window frame magnets has a unique mass, the estimated lifetime was recalculated taking into account the mass of each magnet, and assuming a maximum dose of 10\(^7\) Gy. Under these conditions, and assuming uniform power absorption throughout the magnet body, the estimated lifetimes exceed the typical 20 year lifetime of a high-energy collider. For this reason, the magnets are expected to not require replacement for the lifetime of the collider, which is due the protection offered by the masks and the intermediate dump.
7.5 Neutron Backgrounds

Neutron backgrounds originating from the post-collision line may contribute to false hits in the detectors, but more crucially, have the potential to damage silicon-based detectors. In general-purpose detectors, the silicon vertex detectors are located at the deepest and most active part of the detector, making maintenance particularly difficult. For this reason, maximising the lifespan of the inner detectors is a practical requirement, and thus minimising the neutron background is favourable.

7.5.1 Neutron Backgrounds in the Post-Collision Line

The neutron background at the IP is calculated to be $39.0 \pm 4.9$ neutrons per bunch crossing per cm$^2$, which is approximately 4 times the flux observed for photons. The minimisation of the line-of-sight provides successful attenuation of photons, but is not effective against neutrons due to the nature in which they propagate. The neutrons propagate at approximately the speed of light, so the timing arguments of the photons apply to the neutron background, and thus the background generated from neutron ionisation is distinguishable from genuine signal. The primary concern is the damage to the detector, and electrical insulation used on the connectors between the detector components.

The degradation of the charge collection efficiency was estimated at 15% for the components of the silicon detectors that were exposed to the neutron flux through the Beamcal aperture. Should this degradation prove unacceptable, the main dump can be
positioned 71 m further from the IP to reduce the neutron flux density observed at the IP.

7.6 Final Conclusion

The primary objective of this thesis was to conceptually design a post-collision line suitable for transporting the beam-beam products of the CLIC collider. Through beam dynamics simulation, and modelling the production of secondary particles, the post-collision line provides various schemes of providing luminosity monitoring, whilst minimising its impact on the detectors and having an expected lifetime of 10-20 years. For these reasons, this post-collision line is now the accepted baseline design for the CLIC Conceptual Design Report [114].
Appendix A

GUINEA-PIG Input Parameters

GUINEA-PIG input parameters used to simulate the collision products at CLIC.

$ACCELERATOR:: CLIC$
{
  energy = 1500 ;
  particles = 0.37 ;
  beta_x = 8.0 ;
  beta_y = 0.1 ;
  sigma_z = 44 ;
  emitt_x = 0.660 ;
  emitt_y = 0.03 ;
  offset_x = 0 ;
  offset_y = 0 ;
}

$PARAMETERS:: LC-GENERAL$
{
  rndm_save=0;
  rndm_load=0;
  rndm_seed=1101;
  n_x=32 ;
  n_y=128 ;
}
n_z=24;
n_t=5;
cut_x=3.0*sigma_x.1;
cut_y=6.0*sigma_y.1;
cut_z=3.0*sigma_z.1;
n_m=372000;
force_symmetric=0;
integration_method=2;
electron_ratio=1.0;
ecm_min=400;
load_beam=0;
do_isr=0;
do_eloss=1;
do_espread=1;
store_beam=1;
do_photons=1;
store_photons=1;
do_pairs=1;
do_coherent=1;
do_compt=0;
do_hadrons=0;
do_jets=0;
do_lumi=0;
do_lumi_ee_2=0;
}
Appendix B

DIMAD Input File

Example DIMAD geometry file for main beam and cohplus particles.

! First chicane bend

LBVEXE1 := 4.0 ! length (m)
BBVEXE1 := 10.0 ! field (kG)
ABVEXE1 := BBVEXE1*Bscl * LBVEXE1/BRHO ! angle (rad)
GBVEXE1 := 0.209 ! full gap (m)

! BVEX1E : SBEN, L= LBVEXE1, ANGLE= ABVEXE1, E1= ABVEXE1/2, E2= ABVEXE1/2, &
! TILT, HGAP= GBVEXE1/2, FINT= 0.5, FINTX= 0.5

BVEX1EA : SBEN, L= LBVEXE1/8, ANGLE= ABVEXE1/8, TILT, E1=ABVEXE1/2,
&
E2=0.0, HGAP= GBVEXE1/2, FINT=0.5, FINTX=0.5
BVEX1EB : SBEN, L= LBVEXE1/8, ANGLE= ABVEXE1/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE1/2, FINT=0.5, FINTX=0.5
BVEX1EC : SBEN, L= LBVEXE1/8, ANGLE= ABVEXE1/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE1/2, FINT=0.5, FINTX=0.5
BVEX1ED : SBEN, L= LBVEXE1/8, ANGLE= ABVEXE1/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE1/2, FINT=0.5, FINTX=0.5
BVEX1EE : SBEN, L= LBVEXE1/8, ANGLE= ABVEXE1/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE1/2, FINT=0.5, FINTX=0.5
BVEX1EF : SBEN, L= LBVEXE1/8, ANGLE= ABVEXE1/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE1/2, FINT=0.5, FINTX=0.5
APPENDIX B. DIMAD INPUT FILE

BVEX1EG : SBEN, L= LBVEXE1/8, ANGLE= ABVEXE1/8, TILT, E1=0.0, & E2=0.0, HGAP= GBVEXE1/2, FINT=0.5, FINTX=0.5
BVEX1EH : SBEN, L= LBVEXE1/8, ANGLE= ABVEXE1/8, TILT, E1=0.0, & E2=ABVEXE1/2, HGAP= GBVEXE1/2, FINT=0.5, FINTX=0.5

! Second chicane bend

LBVEXE2 := 4.0 ! length (m)
BBVEXE2 := 10.0 ! field (kG)
ABVEXE2 := BBVEXE2*Bsc1 * LBVEXE2/BRHO ! angle (rad)
GBVEXE2 := 0.288 ! full gap (m)

! BVEX2E : SBEN, L= LBVEXE2, ANGLE= ABVEXE2, E1= ABVEXE2/2, E2= ABVEXE2/2, &
! TILT, HGAP= GBVEXE2/2, FINT= 0.5, FINTX= 0.5

BVEX2EA : SBEN, L= LBVEXE2/8, ANGLE= ABVEXE2/8, TILT, E1=ABVEXE2/2, & E2=0.0, HGAP= GBVEXE2/2, FINT=0.5, FINTX=0.5
BVEX2EB : SBEN, L= LBVEXE2/8, ANGLE= ABVEXE2/8, TILT, E1=0.0, & E2=0.0, HGAP= GBVEXE2/2, FINT=0.5, FINTX=0.5
BVEX2EC : SBEN, L= LBVEXE2/8, ANGLE= ABVEXE2/8, TILT, E1=0.0, & E2=0.0, HGAP= GBVEXE2/2, FINT=0.5, FINTX=0.5
BVEX2ED : SBEN, L= LBVEXE2/8, ANGLE= ABVEXE2/8, TILT, E1=0.0, & E2=0.0, HGAP= GBVEXE2/2, FINT=0.5, FINTX=0.5
BVEX2EE : SBEN, L= LBVEXE2/8, ANGLE= ABVEXE2/8, TILT, E1=0.0, & E2=0.0, HGAP= GBVEXE2/2, FINT=0.5, FINTX=0.5
BVEX2EF : SBEN, L= LBVEXE2/8, ANGLE= ABVEXE2/8, TILT, E1=0.0, & E2=0.0, HGAP= GBVEXE2/2, FINT=0.5, FINTX=0.5
BVEX2EG : SBEN, L= LBVEXE2/8, ANGLE= ABVEXE2/8, TILT, E1=0.0, & E2=0.0, HGAP= GBVEXE2/2, FINT=0.5, FINTX=0.5
BVEX2EH : SBEN, L= LBVEXE2/8, ANGLE= ABVEXE2/8, TILT, E1=0.0, & E2=ABVEXE2/2, HGAP= GBVEXE2/2, FINT=0.5, FINTX=0.5

! Third chicane bend

LBVEXE3 := 4.0 ! length (m)
BBVEXE3 := 10.0 ! field (kG)
ABVEXE3 := BBVEXE3*Bsc1 * LBVEXE3/BRHO ! angle (rad)
GBVEXE3 := 0.360 ! full gap (m)

! BVEX3E : SBEN, L= LBVEXE3, ANGLE= ABVEXE3, E1= ABVEXE3/2, E2= ABVEXE3/2, &
APPENDIX B. DIMAD INPUT FILE

! TILT, HGAP= GBVEXE3/2, FINT= 0.5, FINTX= 0.5

BVEX3EA : SBEN, L= LBVEXE3/8, ANGLE= ABVEXE3/8, TILT, E1=ABVEXE3/2, &
E2=0.0, HGAP= GBVEXE3/2, FINT=0.5, FINTX=0.5
BVEX3EB : SBEN, L= LBVEXE3/8, ANGLE= ABVEXE3/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE3/2, FINT=0.5, FINTX=0.5
BVEX3EC : SBEN, L= LBVEXE3/8, ANGLE= ABVEXE3/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE3/2, FINT=0.5, FINTX=0.5
BVEX3ED : SBEN, L= LBVEXE3/8, ANGLE= ABVEXE3/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE3/2, FINT=0.5, FINTX=0.5
BVEX3EE : SBEN, L= LBVEXE3/8, ANGLE= ABVEXE3/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE3/2, FINT=0.5, FINTX=0.5
BVEX3EF : SBEN, L= LBVEXE3/8, ANGLE= ABVEXE3/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE3/2, FINT=0.5, FINTX=0.5
BVEX3EG : SBEN, L= LBVEXE3/8, ANGLE= ABVEXE3/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE3/2, FINT=0.5, FINTX=0.5
BVEX3EH : SBEN, L= LBVEXE3/8, ANGLE= ABVEXE3/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE3/2, FINT=0.5, FINTX=0.5

! Fourth chicane bend

LBVEX4 := 4.0 ! length (m)
BBVEX4 := 10.0 ! field (kG)
ABVEX4 := BBVEX4*Bsc1 * LBVEXE4/BRHO ! angle (rad)
GBVEX4 := 0.430 ! full gap (m)

! BVEX4E : SBEN, L= LBVEXE4, ANGLE= ABVEXE4, E1= ABVEXE4/2, E2= ABVEXE4/2, &
! TILT, HGAP= GBVEXE4/2, FINT= 0.5, FINTX= 0.5

BVEX4EA : SBEN, L= LBVEXE4/8, ANGLE= ABVEXE4/8, TILT, E1=ABVEXE4/2, &
E2=0.0, HGAP= GBVEXE4/2, FINT=0.5, FINTX=0.5
BVEX4EB : SBEN, L= LBVEXE4/8, ANGLE= ABVEXE4/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE4/2, FINT=0.5, FINTX=0.5
BVEX4EC : SBEN, L= LBVEXE4/8, ANGLE= ABVEXE4/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE4/2, FINT=0.5, FINTX=0.5
BVEX4ED : SBEN, L= LBVEXE4/8, ANGLE= ABVEXE4/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE4/2, FINT=0.5, FINTX=0.5
BVEX4EE : SBEN, L= LBVEXE4/8, ANGLE= ABVEXE4/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE4/2, FINT=0.5, FINTX=0.5
BVEX4EF : SBEN, L= LBVEXE4/8, ANGLE= ABVEXE4/8, TILT, E1=0.0, &
APPENDIX B. DIMAD INPUT FILE

E2=0.0, HGAP= GBVEXE4/2, FINT=0.5, FINTX=0.5
BVEX4EG : SBEN, L= LBVEXE4/8, ANGLE= ABVEXE4/8, TILT, E1=0.0, &
E2=0.0, HGAP= GBVEXE4/2, FINT=0.5, FINTX=0.5
BVEX4EH : SBEN, L= LBVEXE4/8, ANGLE= ABVEXE4/8, TILT, E1=0.0, &
E2=ABVEXE4/2, HGAP= GBVEXE4/2, FINT=0.5, FINTX=0.5

! First chicane back-bend

LBVEXE5 := 4.0 ! length (m)
BBVEXE5 := -9.73 ! field (kG)
ABVEXE5 := BBVEXE5*Bscl * LBVEXE5/BRHO ! angle (rad)
GBVEXE5 := 0.450 ! full gap (m)

BVEX5E : SBEN, L= LBVEXE5, ANGLE= ABVEXE5, E1= ABVEXE5/2, E2= ABVEXE5/2, &
TILT, HGAP= GBVEXE5/2, FINT= 0.5, FINTX= 0.5

! Second chicane back-bend

LBVEXE6 := 4.0 ! length (m)
BBVEXE6 := -9.73 ! field (kG)
ABVEXE6 := BBVEXE6*Bscl * LBVEXE6/BRHO ! angle (rad)
GBVEXE6 := 0.450 ! full gap (m)

BVEX6E : SBEN, L= LBVEXE6, ANGLE= ABVEXE6, E1= ABVEXE6/2, E2= ABVEXE6/2, &
TILT, HGAP= GBVEXE6/2, FINT= 0.5, FINTX= 0.5

! Third chicane back-bend

LBVEXE7 := 4.0 ! length (m)
BBVEXE7 := -9.73 ! field (kG)
ABVEXE7 := BBVEXE7*Bscl * LBVEXE7/BRHO ! angle (rad)
GBVEXE7 := 0.450 ! full gap (m)

BVEX7E : SBEN, L= LBVEXE7, ANGLE= ABVEXE7, E1= ABVEXE7/2, E2= ABVEXE7/2, &
TILT, HGAP= GBVEXE7/2, FINT= 0.5, FINTX= 0.5

! Fourth chicane back-bend

LBVEXE8 := 4.0 ! length (m)
BBVEXE8 := -9.73 ! field (kG)
APPENDIX B. DIMAD INPUT FILE

ABVEXE8 := BBVEXE8*Bscl * LBVEXE8/BRHO ! angle (rad)
GBVEXE8 := 0.450 ! full gap (m)

BVEX8E : SBEN, L= LBVEXE8, ANGLE= ABVEXE8, E1= ABVEXE8/2, E2= ABVEXE8/2, &
TILT, HGAP= GBVEXE8/2, FINT= 0.5, FINTX= 0.5

! Collimators to check beam loss in chicane bends

! XDEXB1E := 0.15
XDEXB1E := 0.195
! XDEXB2E := 0.20
XDEXB2E := 0.264
! XDEXB3E := 0.25
XDEXB3E := 0.331
! XDEXB4E := 0.35
XDEXB4E := 0.397

! YDEXB1E := 0.250
YDEXB1E := 0.282
! YDEXB2E := 0.600
YDEXB2E := 0.632
! YDEXB3E := 0.950
YDEXB3E := 0.982
! YDEXB4E := 1.300
YDEXB4E := 1.332

XDEXB5E := 0.400
XDEXB6E := 0.400
! XDEXB6E := 0.54768
XDEXB7E := 0.400
! XDEXB7E := 0.55428
XDEXB8E := 0.400
! XDEXB8E := 0.56

YDEXB5E := 1.200
YDEXB6E := 1.200
! YDEXB6E := 1.64304
YDEXB7E := 1.200
! YDEXB7E := 1.66284
YDEXB8E := 1.200
! YDEXB8E := 1.68
APPENDIX B. DIMAD INPUT FILE

! CBVEX1E : RCOLL, L=1e-10, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2
CBVEX1A : RCOLL, L=1e-10, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2
CBVEX1B : RCOLL, L=1e-10, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2
CBVEX1C : RCOLL, L=1e-10, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2
CBVEX1D : RCOLL, L=1e-10, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2
CBVEX1E : RCOLL, L=1e-10, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2
CBVEX1F : RCOLL, L=1e-10, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2
CBVEX1G : RCOLL, L=1e-10, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2
CBVEX1H : RCOLL, L=1e-10, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2

! CBVEX2E : RCOLL, L=1e-10, XSIZE= XDEXB2E/2, YSIZE= YDEXB2E/2
CBVEX2A : RCOLL, L=1e-10, XSIZE= XDEXB2E/2, YSIZE= YDEXB2E/2
CBVEX2B : RCOLL, L=1e-10, XSIZE= XDEXB2E/2, YSIZE= YDEXB2E/2
CBVEX2C : RCOLL, L=1e-10, XSIZE= XDEXB2E/2, YSIZE= YDEXB2E/2
CBVEX2D : RCOLL, L=1e-10, XSIZE= XDEXB2E/2, YSIZE= YDEXB2E/2
CBVEX2E : RCOLL, L=1e-10, XSIZE= XDEXB2E/2, YSIZE= YDEXB2E/2
CBVEX2F : RCOLL, L=1e-10, XSIZE= XDEXB2E/2, YSIZE= YDEXB2E/2
CBVEX2G : RCOLL, L=1e-10, XSIZE= XDEXB2E/2, YSIZE= YDEXB2E/2
CBVEX2H : RCOLL, L=1e-10, XSIZE= XDEXB2E/2, YSIZE= YDEXB2E/2

! CBVEX3E : RCOLL, L=1e-10, XSIZE= XDEXB3E/2, YSIZE= YDEXB3E/2
CBVEX3A : RCOLL, L=1e-10, XSIZE= XDEXB3E/2, YSIZE= YDEXB3E/2
CBVEX3B : RCOLL, L=1e-10, XSIZE= XDEXB3E/2, YSIZE= YDEXB3E/2
CBVEX3C : RCOLL, L=1e-10, XSIZE= XDEXB3E/2, YSIZE= YDEXB3E/2
CBVEX3D : RCOLL, L=1e-10, XSIZE= XDEXB3E/2, YSIZE= YDEXB3E/2
CBVEX3E : RCOLL, L=1e-10, XSIZE= XDEXB3E/2, YSIZE= YDEXB3E/2
CBVEX3F : RCOLL, L=1e-10, XSIZE= XDEXB3E/2, YSIZE= YDEXB3E/2
CBVEX3G : RCOLL, L=1e-10, XSIZE= XDEXB3E/2, YSIZE= YDEXB3E/2
CBVEX3H : RCOLL, L=1e-10, XSIZE= XDEXB3E/2, YSIZE= YDEXB3E/2

! CBVEX4E : RCOLL, L=1e-10, XSIZE= XDEXB4E/2, YSIZE= YDEXB4E/2
CBVEX4A : RCOLL, L=1e-10, XSIZE= XDEXB4E/2, YSIZE= YDEXB4E/2
CBVEX4B : RCOLL, L=1e-10, XSIZE= XDEXB4E/2, YSIZE= YDEXB4E/2
CBVEX4C : RCOLL, L=1e-10, XSIZE= XDEXB4E/2, YSIZE= YDEXB4E/2
CBVEX4D : RCOLL, L=1e-10, XSIZE= XDEXB4E/2, YSIZE= YDEXB4E/2
CBVEX4E : RCOLL, L=1e-10, XSIZE= XDEXB4E/2, YSIZE= YDEXB4E/2
CBVEX4F : RCOLL, L=1e-10, XSIZE= XDEXB4E/2, YSIZE= YDEXB4E/2
CBVEX4G : RCOLL, L=1e-10, XSIZE= XDEXB4E/2, YSIZE= YDEXB4E/2
CBVEX4H : RCOLL, L=1e-10, XSIZE= XDEXB4E/2, YSIZE= YDEXB4E/2

CBVEX5E : RCOLL, L=1e-10, XSIZE= XDEXB5E/2, YSIZE= YDEXB5E/2
CBVEX6E : RCOLL, L=1e-10, XSIZE= XDEXB6E/2, YSIZE= YDEXB6E/2
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CBVEX7E : RCOLL, L=1e-10, XSIZE= XDEXB7E/2, YSIZE= YDEXB7E/2
CBVEX8E : RCOLL, L=1e-10, XSIZE= XDEXB8E/2, YSIZE= YDEXB8E/2

! Drifts can be converted to collimators for tracking with beam loss.

! Drift from IP to the first magnet (30 m)

LDEX0E := 20.0
XDEX0E := XDEXB1E
YDEX0E := YDEXB1E

LDX0STR := 7.5
DX0STR : RCOLL, L=LDX0STR, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E00 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E01 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E02 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E03 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E04 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E05 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E06 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E07 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E08 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2

! Return of Coll0 to protect Magnet1 from cohminus

! XCOLL0 := 0.12
! YCOLL0 := 0.22
! COLL0 : ECOLL, L=LDEX0E/40, XSIZE= XCOLL0/2, YSIZE= YCOLL0/2

DX0E09a : RCOLL, L=LDEX0E/20, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
DX0E09b : RCOLL, L=LDEX0E/20, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2
! DX0E09 : RCOLL, L=LDEX0E/10, XSIZE= XDEX0E/2, YSIZE= YDEX0E/2

! Drift between magnets 1a and 1b (split magnet1 - 2.5m)

LDXSSTR1 := 1.0
DXSSTR1 : RCOLL, L=LDXSSTR1, XSIZE= XDEXB1E/2, YSIZE= YDEXB1E/2

LDXSSTR2 := 0.25
XDXSSTR2 := 0.195
YDXSSTR2 := 0.130
DXSSTR2 : ECOLL, L=LDXSSTR2, XSIZE= XDXSSTR2/2, YSIZE= YDXSSTR2/2

LDXSSTR3 := 0.25
APPENDIX B. DIMAD INPUT FILE

XDXSSTR3 := 0.195
YDXSSTR3 := 0.130
DXSSTR3 : ECOLL, L=LDXSSTR3, XSIZE=XDXSSTR3/2, YSIZE=YDXSSTR3/2

LDXSSTR4 := 1.0
DXSSTR4 : RCOLL, L=LDXSSTR4, XSIZE=XDEXB1E/2, YSIZE=YDEXB1E/2

! Drift between magnets 1 and 2 (4.0 m)

LDX1STRA := 1.25
XDX1STRA := XDEXB1E+1.25*(XDEXB2E-XDEXB1E)/4.0
YDX1STRA := YDEXB1E+1.25*(YDEXB2E-YDEXB1E)/4.0
DX1STRA : RCOLL, L=LDX1STRA, XSIZE=LDX1STRA/2, YSIZE=YDX1STRA/2

LDX1E1 := 0.300
XDX1E1 := XDEXB1E+1.55*(XDEXB2E-XDEXB1E)/4.0
YDX1E1 := YDEXB1E+1.55*(YDEXB2E-YDEXB1E)/4.0
DX1E01 : RCOLL, L=LDX1E1, XSIZE=XDX1E1/2, YSIZE=YDX1E1/2

LDX1E2 := 0.300
XDX1E2 := XDEXB1E+1.85*(XDEXB2E-XDEXB1E)/4.0
! YDX1E2 := YDEXB1E+2*(YDEXB2E-YDEXB1E)/5
! DX1E02 : RCOLL, L=LDX1E2, XSIZE=XDX1E2/2, YSIZE=YDX1E2/2
YDX1E2 := 0.184
! YDX1E2 := 0.21364
DX1E02 : ECOLL, L=LDX1E2, XSIZE=XDX1E2/2, YSIZE=YDX1E2/2

LDX1E3 := 0.300
XDX1E3 := XDEXB1E+2.15*(XDEXB2E-XDEXB1E)/4.0
! YDX1E3 := YDEXB1E+3*(YDEXB2E-YDEXB1E)/5
! DX1E03 : RCOLL, L=LDX1E3, XSIZE=XDX1E3/2, YSIZE=YDX1E3/2
YDX1E3 := 0.184
! YDX1E3 := 0.21364
DX1E03 : ECOLL, L=LDX1E3, XSIZE=XDX1E3/2, YSIZE=YDX1E3/2

LDX1E4 := 0.300
XDX1E4 := XDEXB1E+2.45*(XDEXB2E-XDEXB1E)/4.0
! YDX1E4 := YDEXB1E+4*(YDEXB2E-YDEXB1E)/5
! DX1E04 : RCOLL, L=LDX1E4, XSIZE=XDX1E4/2, YSIZE=YDX1E4/2
YDX1E4 := 0.184
! YDX1E4 := 0.21364
DX1E04 : ECOLL, L=LDX1E4, XSIZE=XDX1E4/2, YSIZE=YDX1E4/2
APPENDIX B. DIMAD INPUT FILE

LDX1E5 := 0.300
XDX1E5 := XDEXB1E+2.75*(XDEXB2E-XDEXB1E)/4.0
YDX1E5 := YDEXB1E+2.75*(YDEXB2E-YDEXB1E)/4.0
DX1E05 : RCOLL, L=LDX1E5, XSIZE=DX1E5/2, YSIZE=YDX1E5/2

LDX1STRB := 1.25
XDX1STRB := XDEXB1E+4.0*(XDEXB2E-XDEXB1E)/4.0
YDX1STRB := YDEXB1E+4.0*(YDEXB2E-YDEXB1E)/4.0
DX1STRB : RCOLL, L=LDX1STRB, XSIZE=DX1STRB/2, YSIZE=YDX1STRB/2

! Drift between magnets 2 and 3 (4.0 m)

LDX2STRA := 1.25
XDX2STRA := XDEXB2E+1.25*(XDEXB3E-XDEXB2E)/4.0
YDX2STRA := YDEXB2E+1.25*(YDEXB3E-YDEXB2E)/4.0
DX2STRA : RCOLL, L=LDX2STRA, XSIZE=DX2STRA/2, YSIZE=YDX2STRA/2

LDX2E1 := 0.300
XDX2E1 := XDEXB2E+1.55*(XDEXB3E-XDEXB2E)/4.0
YDX2E1 := YDEXB2E+1.55*(YDEXB3E-YDEXB2E)/4.0
DX2E01 : RCOLL, L=LDX2E1, XSIZE=DX2E1/2, YSIZE=YDX2E1/2

LDX2E2 := 0.300
XDX2E2 := XDEXB2E+1.85*(XDEXB3E-XDEXB2E)/4.0
! YDX2E2 := YDEXB2E+2*(YDEXB3E-YDEXB2E)/5
! DX2E02 : RCOLL, L=LDX2E2, XSIZE=DX2E2/2, YSIZE=YDX2E2/2
YDX2E2 := 0.476
! YDX2E2 := 0.55488
DX2E02 : ECOLL, L=LDX2E2, XSIZE=DX2E2/2, YSIZE=YDX2E2/2

LDX2E3 := 0.300
XDX2E3 := XDEXB2E+2.15*(XDEXB3E-XDEXB2E)/4.0
! YDX2E3 := YDEXB2E+3*(YDEXB3E-YDEXB2E)/5
! DX2E03 : RCOLL, L=LDX2E3, XSIZE=DX2E3/2, YSIZE=YDX2E3/2
YDX2E3 := 0.476
! YDX2E3 := 0.55488
DX2E03 : ECOLL, L=LDX2E3, XSIZE=DX2E3/2, YSIZE=YDX2E3/2

LDX2E4 := 0.300
XDX2E4 := XDEXB2E+2.45*(XDEXB3E-XDEXB2E)/4.0
! YDX2E4 := YDEXB2E+4*(YDEXB3E-YDEXB2E)/5
! DX2E04 : RCOLL, L=LDX2E4, XSIZE=DX2E4/2, YSIZE=YDX2E4/2
YDX2E4 := 0.476
! YDX2E4 := 0.55488
DX2E04 : ECOLL, L=LDX2E4, XSIZE=DX2E04/2, YSIZE=YDX2E4/2

LDX2E5 := 0.300
XDX2E5 := XDEXB2E+2.75*(XDEXB3E-XDEXB2E)/4.0
YDX2E5 := YDEXB2E+2.75*(YDEXB3E-YDEXB2E)/4.0
DX2E05 : RCOLL, L=LDX2E5, XSIZE=DX2E05/2, YSIZE=YDX2E5/2

LDX2STRB := 1.25
XDX2STRB := XDEXB2E+4.0*(XDEXB3E-XDEXB2E)/4.0
YDX2STRB := YDEXB2E+4.0*(YDEXB3E-YDEXB2E)/4.0
DX2STRB : RCOLL, L=LDX1STRB, XSIZE=DX1STRB/2, YSIZE=YDX2STRB/2

! Drift between magnets 3 and 4 (4.0 m)

LDX3STRA := 1.25
XDX3STRA := XDEXB3E+1.25*(XDEXB4E-XDEXB3E)/4.0
YDX3STRA := YDEXB3E+1.25*(YDEXB4E-YDEXB3E)/4.0
DX3STRA : RCOLL, L=LDX3STRA, XSIZE=DX3STRA/2, YSIZE=YDX3STRA/2

LDX3E1 := 0.300
XDX3E1 := XDEXB3E+1.55*(XDEXB4E-XDEXB3E)/4.0
YDX3E1 := YDEXB3E+1.55*(YDEXB4E-YDEXB3E)/4.0
DX3E01 : RCOLL, L=LDX3E1, XSIZE=DX3E1/2, YSIZE=YDX3E1/2

LDX3E2 := 0.300
XDX3E2 := XDEXB3E+1.85*(XDEXB4E-XDEXB3E)/4.0
! YDX3E2 := YDEXB3E+2*(YDEXB4E-YDEXB3E)/5
! DX3E02 : RCOLL, L=LDX3E2, XSIZE=DX3E2/2, YSIZE=YDX3E2/2
YDX3E2 := 0.809
! YDX3E2 := 0.94216
DX3E02 : ECOLL, L=LDX3E2, XSIZE=DX3E2/2, YSIZE=YDX3E2/2

LDX3E3 := 0.300
XDX3E3 := XDEXB3E+2.15*(XDEXB4E-XDEXB3E)/4.0
! YDX3E3 := YDEXB3E+3*(YDEXB4E-YDEXB3E)/5
! DX3E03 : RCOLL, L=LDX3E3, XSIZE=DX3E3/2, YSIZE=YDX3E3/2
YDX3E3 := 0.809
! YDX3E3 := 0.94216
DX3E03 : ECOLL, L=LDX3E3, XSIZE=DX3E3/2, YSIZE=YDX3E3/2

LDX3E4 := 0.300
XDX3E4 := XDEXB3E+2.45*(XDEXB4E-XDEXB3E)/4.0
APPENDIX B. DIMAD INPUT FILE

! YDX3E4 := YDEXB3E+4*(YDEXB4E-YDEXB3E)/5
! DX3E04 : RCOLL, L=LDX3E4, XSIZE=DX3E4/2, YSIZE=YDX3E4/2
YDX3E4 := 0.809
! YDX3E4 := 0.94216
DX3E04 : ECOLL, L=LDX3E4, XSIZE=DX3E4/2, YSIZE=YDX3E4/2

LDX3E5 := 0.300
XDX3E5 := XDEXB3E+2.75*(XDEXB4E-XDEXB3E)/4.0
YDX3E5 := YDEXB3E+2.75*(YDEXB4E-YDEXB3E)/4.0
DX3E05 : RCOLL, L=LDX3E5, XSIZE=DX3E5/2, YSIZE=YDX3E5/2

LDX3STRB := 1.25
XDX3STRB := XDEXB3E+4.0*(XDEXB4E-XDEXB3E)/4.0
YDX3STRB := YDEXB3E+4.0*(YDEXB4E-YDEXB3E)/4.0
DX3STRB : RCOLL, L=LDX3STRB, XSIZE=DX3STRB/2, YSIZE=YDX3STRB/2

! Drift between magnet 4 and separation (9.0 m)

XDEXB45 := 0.400
YDEXB45 := 2.500
CBVEX45 : RCOLL, L=1e-10, XSIZE= XDEXB45/2, YSIZE= YDEXB45/2

LDX4E1 := 1.0
XDX4E1 := XDEXB4E+1*(XDEXB45-XDEXB4E)/9.0
YDX4E1 := YDEXB4E+1*(YDEXB45-YDEXB4E)/9.0
DX4E01 : RCOLL, L=LDX4E1, XSIZE=DX4E1/2, YSIZE=YDX4E1/2

LDX4E2 := 1.0
XDX4E2 := XDEXB4E+2*(XDEXB45-XDEXB4E)/9.0
YDX4E2 := YDEXB4E+2*(YDEXB45-YDEXB4E)/9.0
DX4E02 : RCOLL, L=LDX4E2, XSIZE=DX4E2/2, YSIZE=YDX4E2/2

LDX4E3 := 1.0
XDX4E3 := XDEXB4E+3*(XDEXB45-XDEXB4E)/9.0
YDX4E3 := YDEXB4E+3*(YDEXB45-YDEXB4E)/9.0
DX4E03 : RCOLL, L=LDX4E3, XSIZE=DX4E3/2, YSIZE=YDX4E3/2

LDX4E4 := 1.0
XDX4E4 := XDEXB4E+4*(XDEXB45-XDEXB4E)/9.0
YDX4E4 := YDEXB4E+4*(YDEXB45-YDEXB4E)/9.0
DX4E04 : RCOLL, L=LDX4E4, XSIZE=DX4E4/2, YSIZE=YDX4E4/2

LDX4E5 := 1.0
APPENDIX B. DIMAD INPUT FILE

XDX4E5 := XDEXB4E+5*(XDEXB45-XDEXB4E)/9.0
YDX4E5 := YDEXB4E+5*(YDEXB45-YDEXB4E)/9.0
DX4E05 : RCOLL, L=LDX4E5, XSIZE=XDX4E5/2, YSIZE=YDX4E5/2

LDX4E6 := 1.0
XDX4E6 := XDEXB4E+6*(XDEXB45-XDEXB4E)/9.0
YDX4E6 := YDEXB4E+6*(YDEXB45-YDEXB4E)/9.0
DX4E06 : RCOLL, L=LDX4E6, XSIZE=XDX4E6/2, YSIZE=YDX4E6/2

LDX4E7 := 1.0
XDX4E7 := XDEXB4E+7*(XDEXB45-XDEXB4E)/9.0
YDX4E7 := YDEXB4E+7*(YDEXB45-YDEXB4E)/9.0
DX4E07 : RCOLL, L=LDX4E7, XSIZE=XDX4E7/2, YSIZE=YDX4E7/2

LDX4E8 := 1.0
XDX4E8 := XDEXB4E+8*(XDEXB45-XDEXB4E)/9.0
YDX4E8 := YDEXB4E+8*(YDEXB45-YDEXB4E)/9.0
DX4E08 : RCOLL, L=LDX4E8, XSIZE=XDX4E8/2, YSIZE=YDX4E8/2

LDX4E9 := 0.5
XDX4E9 := XDEXB4E+8.5*(XDEXB45-XDEXB4E)/9.0
YDX4E9 := YDEXB4E+8.5*(YDEXB45-YDEXB4E)/9.0
DX4E09 : RCOLL, L=LDX4E9, XSIZE=XDX4E9/2, YSIZE=YDX4E9/2

LDX4STR := 0.5
XDX4STR := XDEXB4E+9.0*(XDEXB45-XDEXB4E)/9.0
YDX4STR := YDEXB4E+9.0*(YDEXB45-YDEXB4E)/9.0
DX4STR : RCOLL, L=LDX4STR, XSIZE=XDX4STR/2, YSIZE=YDX4STR/2

XPHSEP := 0.400
YPHSEP := 2.380
COLLSEP : RCOLL, L=1e-10, XSIZE= XPHSEP/2, YSIZE= YPHSEP/2

XPHDP1 := 0.240
! YPHDP1 := 0.800
YPHDP1 := 0.70625

! Drift through and after dump 1 (10 m)

LDP1E0 := 0.25
XDP1E0 := XPHSEP
YDP1E0 := YPHSEP
DP1E00 : RCOLL, L=LDP1E0, XSIZE=XDP1E0/2, YSIZE=YDP1E0/2
APPENDIX B. DIMAD INPUT FILE

LDP1E1 := 0.25
XDP1E1 := XPHSEP
YDP1E1 := YPHSEP
DP1E01 : RCOLL, L=LDP1E1, XSIZE=XDP1E1/2, YSIZE=YDP1E1/2

LDP1E2 := 0.25
XDP1E2 := XPHSEP
YDP1E2 := YPHSEP
DP1E02 : RCOLL, L=LDP1E2, XSIZE=XDP1E2/2, YSIZE=YDP1E2/2

LDP1E3 := 0.25
XDP1E3 := XPHSEP
YDP1E3 := YPHSEP
DP1E03 : RCOLL, L=LDP1E3, XSIZE=XDP1E3/2, YSIZE=YDP1E3/2

LDP1E4a := 0.5
XDP1E4a := XPHSEP+1*(XPHDP1-XPHSEP)/4
YDP1E4a := YPHSEP+1*(XPHDP1-XPHSEP)/4
DP1E04a : RCOLL, L=LDP1E4a, XSIZE=XDP1E4a/2, YSIZE=YDP1E4a/2

LDP1E4b := 0.5
XDP1E4b := XPHSEP+2*(XPHDP1-XPHSEP)/4
YDP1E4b := YPHSEP+2*(XPHDP1-XPHSEP)/4
DP1E04b : RCOLL, L=LDP1E4b, XSIZE=XDP1E4b/2, YSIZE=YDP1E4b/2

LDP1E4c := 0.5
XDP1E4c := XPHSEP+3*(XPHDP1-XPHSEP)/4
YDP1E4c := YPHSEP+3*(XPHDP1-XPHSEP)/4
DP1E04c : RCOLL, L=LDP1E4c, XSIZE=XDP1E4c/2, YSIZE=YDP1E4c/2

LDP1E4d := 0.5
XDP1E4d := XPHSEP+4*(XPHDP1-XPHSEP)/4
YDP1E4d := YPHSEP+4*(XPHDP1-XPHSEP)/4
DP1E04d : RCOLL, L=LDP1E4d, XSIZE=XDP1E4d/2, YSIZE=YDP1E4d/2

LDP1E5 := 2.0
XDP1E5 := XPHDP1
YDP1E5 := YPHDP1
DP1E05 : RCOLL, L=LDP1E5, XSIZE=XDP1E5/2, YSIZE=YDP1E5/2

LDP1E6 := 0.5
XDP1E6 := XPHDP1+0.5*(XDEXB5E-XPHDP1)/5.0
APPENDIX B. DIMAD INPUT FILE

YDP1E6 := YPHDP1 + 0.5*(YDEXB5E - YPHDP1)/5.0
DP1E06 : RCOLL, L=LDP1E6, XSIZE=XDP1E6/2, YSIZE=YDP1E6/2

LDP1E7 := 0.5
XDP1E7 := XPHDP1 + 1.0*(XDEXB5E - XPHDP1)/5.0
YDP1E7 := YPHDP1 + 1.0*(YDEXB5E - YPHDP1)/5.0
DP1E07 : RCOLL, L=LDP1E7, XSIZE=XDP1E7/2, YSIZE=YDP1E7/2

LDP1E8 := 0.5
XDP1E8 := XPHDP1 + 1.5*(XDEXB5E - XPHDP1)/5.0
YDP1E8 := YPHDP1 + 1.5*(YDEXB5E - YPHDP1)/5.0
DP1E08 : RCOLL, L=LDP1E8, XSIZE=XDP1E8/2, YSIZE=YDP1E8/2

LDP1E9 := 0.5
XDP1E9 := XPHDP1 + 2.0*(XDEXB5E - XPHDP1)/5.0
YDP1E9 := YPHDP1 + 2.0*(YDEXB5E - YPHDP1)/5.0
DP1E09 : RCOLL, L=LDP1E9, XSIZE=XDP1E9/2, YSIZE=YDP1E9/2

LDP1STR := 3.0
XDP1STR := XPHDP1 + 5.0*(XDEXB5E - XPHDP1)/5.0
YDP1STR := YPHDP1 + 5.0*(YDEXB5E - YPHDP1)/5.0
DP1STR : RCOLL, L=LDP1STR, XSIZE=XDP1STR/2, YSIZE=YDP1STR/2

! Drift between magnets 5 and 6 (4.0 m)

XDX5E0 := XDEXB5E
YDX5E0 := YDEXB5E

LDX5STRA := 1.5
DX5STRA : RCOLL, L=LDX5STRA, XSIZE=XDX5E0/2, YSIZE=YDX5E0/2

LDX5E0 := 1.0
DX5E00 : RCOLL, L=LDX5E0, XSIZE=XDX5E0/2, YSIZE=YDX5E0/2

LDX5STRB := 1.5
DX5STRB : RCOLL, L=LDX5STRB, XSIZE=XDX5E0/2, YSIZE=YDX5E0/2

! Drift between magnets 6 and 7 (4.0 m)

XDX6E0 := XDEXB6E
YDX6E0 := YDEXB6E

LDX6STRA := 1.5
APPENDIX B. DIMAD INPUT FILE

DX6STRA : RCOLL, L=LDX6STRA, XSIZE=XDX6E0/2, YSIZE=YDX6E0/2

LDX6E0 := 1.0
DX6E00 : RCOLL, L=LDX6E0, XSIZE=XDX6E0/2, YSIZE=YDX6E0/2

LDX6STRB := 1.5
DX6STRB : RCOLL, L=LDX6STRB, XSIZE=XDX6E0/2, YSIZE=YDX6E0/2

! Drift between magnets 7 and 8 (4.0 m)

XDX7E0 := XDEXB7E
YDX7E0 := YDEXB7E

LDX7STRA := 1.5
DX7STRA : RCOLL, L=LDX7STRA, XSIZE=XDX7E0/2, YSIZE=YDX7E0/2

LDX7E0 := 1.0
DX7E00 : RCOLL, L=LDX7E0, XSIZE=XDX7E0/2, YSIZE=YDX7E0/2

LDX7STRB := 1.5
DX7STRB : RCOLL, L=LDX7STRB, XSIZE=XDX7E0/2, YSIZE=YDX7E0/2

! Drift after magnet 8 (4.0 m)

XDX8E0 := XDEXB8E
YDX8E0 := YDEXB8E

LDX8STRA := 1.5
DX8STRA : RCOLL, L=LDX8STRA, XSIZE=XDX8E0/2, YSIZE=YDX8E0/2

LDX8E0 := 1.0
DX8E00 : RCOLL, L=LDX8E0, XSIZE=XDX8E0/2, YSIZE=YDX8E0/2

LDX8STRB := 1.5
DX8STRB : RCOLL, L=LDX8STRB, XSIZE=XDX8E0/2, YSIZE=YDX8E0/2

XDUMPM := 0.4000
YDUMPM := 10.000

! Drift to the dump (116.0 m)

LDX000 := 4.0
XDX000 := 0.40
APPENDIX B. DIMAD INPUT FILE

YDX000 := YDUMPM
DMP000 : ECOLL, L=LDX000, XSIZE=XDX000/2, YSIZE=YDX000/2

LDX00A := 2.0
XDX00A := 0.20
YDX00A := YDUMPM
DMP00A : ECOLL, L=LDX00A, XSIZE=XDX00A/2, YSIZE=YDX00A/2

LDX00B := 68.0
XDX00B := 0.40
YDX00B := YDUMPM
DMP00B : ECOLL, L=LDX00B, XSIZE=XDX00B/2, YSIZE=YDX00B/2

LDX00C := 132.0
XDX00C := 0.40
YDX00C := YDUMPM
DMP00C : ECOLL, L=LDX00C, XSIZE=XDX00C/2, YSIZE=YDX00C/2

! Markers
MIP : MARKER ! at IP
MEX1 : MARKER ! exit of first magnet
MEX2 : MARKER ! exit of second magnet
MEX3 : MARKER ! exit of third magnet
MEX4 : MARKER ! exit of fourth magnet

! Beam lines
PART1: LINE=( MIP, DX0STR, DX0E00, DX0E01, DX0E02, DX0E03, &
DX0E04, DX0E05, DX0E06, DX0E07, DX0E08, &
DX0E09a, DX0E09b, BVEX1EA, CBVEX1A, DXSSTR1, &
DXSSTR2, DXSSTR3, DXSSTR4, BVEX1EB, &
CBVEX1B, BVEX1EC, CBVEX1C, BVEX1ED, CBVEX1D, &
BVEX1EE, CBVEX1E, BVEX1EF, CBVEX1F, BVEX1EG, &
CBVEX1G, BVEX1EH, CBVEX1H, MEX1 )
PART2: LINE=( DX1STRA, DX1E01, DX1E02, DX1E03, DX1E04, DX1E05, &
DX1STRB, BVEX2EA, CBVEX2A, BVEX2EB, CBVEX2B, &
BVEX2EC, CBVEX2C, BVEX2ED, CBVEX2D, BVEX2EE, &
CBVEX2E, BVEX2EF, CBVEX2F, BVEX2EG, CBVEX2G, &
BVEX2EH, CBVEX2H, MEX2 )
PART3: LINE=( DX2STRA, DX2E01, DX2E02, DX2E03, DX2E04, DX2E05, &
DX2STRB, BVEX3EA, CBVEX3A, BVEX3EB, CBVEX3B, &
BVEX3EC, CBVEX3C, BVEX3ED, CBVEX3D, BVEX3EE, &
APPENDIX B. DIMAD INPUT FILE

CBVEX3E, BVEX3EF, CBVEX3F, BVEX3EG, CBVEX3G, & BVEX3EH, CBVEX3H, MEX3 )
PART4: LINE=( DX3STRA, DX3E01, DX3E02, DX3E03, DX3E04, DX3E05, & DX3STRB, BVEX4EA, CBVEX4A, BVEX4EB, CBVEX4B, & BVEX4EC, CBVEX4C, BVEX4ED, CBVEX4D, BVEX4EE, & CBVEX4E, BVEX4EF, CBVEX4F, BVEX4EG, CBVEX4G, & BVEX4EH, CBVEX4H, MEX4 )
PART5: LINE=( DX4E01, DX4E02, DX4E03, DX4E04, DX4E05, & DX4E06, DX4E07, DX4E08, DX4E09, DX4STR, CBVEX45, & COLLSEP, & DP1E00, DP1E01, DP1E02, DP1E03, & DP1E04a, DP1E04b, DP1E04c, DP1E04d, & DP1E05, DP1E06, DP1E07, DP1E08, DP1E09, DP1STR )
PART6: LINE=( BVEX5E, CBVEX5E, DX5STRA, DX5E00, DX5STRB, & BVEX6E, CBVEX6E, DX6STRA, DX6E00, DX6STRB, & BVEX7E, CBVEX7E, DX7STRA, DX7E00, DX7STRB, & BVEX8E, CBVEX8E, DX8STRA, DX8E00, DX8STRB )
PART7: LINE=( DMP000, DMP00A, DMP00B, DMP00C)

! Full beamline

EXLINE: LINE=(PART1, PART2, PART3, PART4, PART5, PART6, PART7)

!=================================================================
Example DIMAD run file for cohplus particles.

\[
\text{BRHO} := 1500/0.0299792458 \\
\text{Bscl} := 0.8 \\
\]

\[
\text{!CALL, FILENAME} = "exline-20mrad-clic2008-plus-stretched.geom" \\
\text{!CALL, FILENAME} = "exline-20mrad-clic2008-plus-stretched-dac.geom" \\
\text{CALL, FILENAME} = "exline-20mrad-2010-plus-315m.geom" \\
\text{USE, EXLINE} \\
\]

\[
\text{DIMAT} \\
\text{CHROMATIC PRECISION OPTION ARMED} \\
1, \\
\text{CONSTANT EXPULSION FACTOR REDEFINITION} \\
9 1000.0, \\
\]

\[
\text{MISALIGNMENT DATA FOR VERTICAL OFFSET} \\
\text{BVEX1EA} 0.0 0.0 0 1.99862E-05 0.0 0.0 0 2, \\
\text{CBVEX1A} 0.0 0.0 1.99862E-05 1.99862E-05 0.0 0.0 0 2, \\
\text{DXSSTR1} 0.0 0.0 1.99862E-05 0.00179875 0.0 0.0 0 2, \\
\text{DXSSTR2} 0.0 0.0 0.00179875 0.00219848 0.0 0.0 0 2, \\
\text{DXSSTR3} 0.0 0.0 0.00219848 0.0025982 0.0 0.0 0 2, \\
\text{DXSSTR4} 0.0 0.0 0.0025982 0.00419709 0.0 0.0 0 2, \\
\text{BVEX1EB} 0.0 0.0 0.00419709 0.00479668 0.0 0.0 0 2, \\
\text{CBVEX1B} 0.0 0.0 0.00479668 0.00479668 0.0 0.0 0 2, \\
\text{BVEX1EC} 0.0 0.0 0.00479668 0.00579599 0.0 0.0 0 2, \\
\text{CBVEX1C} 0.0 0.0 0.00579599 0.00579599 0.0 0.0 0 2, \\
\text{BVEX1ED} 0.0 0.0 0.00579599 0.00719502 0.0 0.0 0 2, \\
\text{CBVEX1D} 0.0 0.0 0.00719502 0.00719502 0.0 0.0 0 2, \\
\text{BVEX1EE} 0.0 0.0 0.00719502 0.00899377 0.0 0.0 0 2, \\
\text{CBVEX1E} 0.0 0.0 0.00899377 0.00899377 0.0 0.0 0 2, \\
\text{BVEX1EF} 0.0 0.0 0.00899377 0.01119225 0.0 0.0 0 2, \\
\text{CBVEX1F} 0.0 0.0 0.01119225 0.01119225 0.0 0.0 0 2, \\
\text{BVEX1EG} 0.0 0.0 0.01119225 0.01379045 0.0 0.0 0 2, \\
\text{CBVEX1G} 0.0 0.0 0.01379045 0.01379045 0.0 0.0 0 2, \\
\text{BVEX1EH} 0.0 0.0 0.01379045 0.01678838 0.0 0.0 0 2, \\
\text{CBVEX1H} 0.0 0.0 0.01678838 0.01678838 0.0 0.0 0 2, \\
\text{DX1STRA} 0.0 0.0 0.01678838 0.02478284 0.0 0.0 0 2, \\
\text{DX1E01} 0.0 0.0 0.02478284 0.02670151 0.0 0.0 0 2, \\
\text{DX1E02} 0.0 0.0 0.02670151 0.02862019 0.0 0.0 0 2, \\
\]
APPENDIX B. DIMAD INPUT FILE

DX1E03 0.0 0.0 0.002862019 0.003053886 0.0 0.0 0 2,
DX1E04 0.0 0.0 0.003053886 0.003245753 0.0 0.0 0 2,
DX1E05 0.0 0.0 0.003245753 0.00343762 0.0 0.0 0 2,
DX1STRB 0.0 0.0 0.00343762 0.004237067 0.0 0.0 0 2,
BVEX2EA 0.0 0.0 0.004237067 0.004576832 0.0 0.0 0 2,
CBVEX2A 0.0 0.0 0.004576832 0.004576832 0.0 0.0 0 2,
BVEX2EB 0.0 0.0 0.004576832 0.004956569 0.0 0.0 0 2,
CBVEX2B 0.0 0.0 0.004956569 0.004956569 0.0 0.0 0 2,
BVEX2EC 0.0 0.0 0.004956569 0.005376278 0.0 0.0 0 2,
CBVEX2C 0.0 0.0 0.005376278 0.005376278 0.0 0.0 0 2,
BVEX2ED 0.0 0.0 0.005376278 0.00583596 0.0 0.0 0 2,
CBVEX2D 0.0 0.0 0.00583596 0.00583596 0.0 0.0 0 2,
BVEX2EE 0.0 0.0 0.00583596 0.006335614 0.0 0.0 0 2,
CBVEX2E 0.0 0.0 0.006335614 0.006335614 0.0 0.0 0 2,
BVEX2EF 0.0 0.0 0.006335614 0.00687524 0.0 0.0 0 2,
CBVEX2F 0.0 0.0 0.00687524 0.00687524 0.0 0.0 0 2,
BVEX2EG 0.0 0.0 0.00687524 0.007454839 0.0 0.0 0 2,
CBVEX2G 0.0 0.0 0.007454839 0.007454839 0.0 0.0 0 2,
BVEX2EH 0.0 0.0 0.007454839 0.00807441 0.0 0.0 0 2,
CBVEX2H 0.0 0.0 0.00807441 0.00807441 0.0 0.0 0 2,
DX2STRA 0.0 0.0 0.00807441 0.009673303 0.0 0.0 0 2,
DX2E01 0.0 0.0 0.009673303 0.010057038 0.0 0.0 0 2,
DX2E02 0.0 0.0 0.010057038 0.010440772 0.0 0.0 0 2,
DX2E03 0.0 0.0 0.010440772 0.010824506 0.0 0.0 0 2,
DX2E04 0.0 0.0 0.010824506 0.011208241 0.0 0.0 0 2,
DX2E05 0.0 0.0 0.011208241 0.011591975 0.0 0.0 0 2,
DX2STRB 0.0 0.0 0.011591975 0.013190868 0.0 0.0 0 2,
BVEX3EA 0.0 0.0 0.013190868 0.013850412 0.0 0.0 0 2,
CBVEX3A 0.0 0.0 0.013850412 0.013850412 0.0 0.0 0 2,
BVEX3EB 0.0 0.0 0.013850412 0.014549927 0.0 0.0 0 2,
CBVEX3B 0.0 0.0 0.014549927 0.014549927 0.0 0.0 0 2,
BVEX3EC 0.0 0.0 0.014549927 0.015289415 0.0 0.0 0 2,
CBVEX3C 0.0 0.0 0.015289415 0.015289415 0.0 0.0 0 2,
BVEX3ED 0.0 0.0 0.015289415 0.016068876 0.0 0.0 0 2,
CBVEX3D 0.0 0.0 0.016068876 0.016068876 0.0 0.0 0 2,
BVEX3EE 0.0 0.0 0.016068876 0.01688308 0.0 0.0 0 2,
CBVEX3E 0.0 0.0 0.01688308 0.01688308 0.0 0.0 0 2,
BVEX3EF 0.0 0.0 0.01688308 0.017747714 0.0 0.0 0 2,
CBVEX3F 0.0 0.0 0.017747714 0.017747714 0.0 0.0 0 2,
BVEX3EG 0.0 0.0 0.017747714 0.018647091 0.0 0.0 0 2,
CBVEX3G 0.0 0.0 0.018647091 0.018647091 0.0 0.0 0 2,
BVEX3EH 0.0 0.0 0.018647091 0.019586441 0.0 0.0 0 2,
CBVEX3H 0.0 0.0 0.019586441 0.019586441 0.0 0.0 0 2,
APPENDIX B. DIMAD INPUT FILE

DX3STRA 0.0 0.0 0.019586441 0.02198478 0.0 0.0 0 2,
DX3E01 0.0 0.0 0.02198478 0.022560382 0.0 0.0 0 2,
DX3E02 0.0 0.0 0.022560382 0.023135983 0.0 0.0 0 2,
DX3E03 0.0 0.0 0.023135983 0.023711585 0.0 0.0 0 2,
DX3E04 0.0 0.0 0.023711585 0.024287186 0.0 0.0 0 2,
DX3E05 0.0 0.0 0.024287186 0.024862788 0.0 0.0 0 2,
DX3STRB 0.0 0.0 0.024862788 0.027261128 0.0 0.0 0 2,
BVEX4EA 0.0 0.0 0.027261128 0.02824045 0.0 0.0 0 2,
CBVEX4A 0.0 0.0 0.02824045 0.02824045 0.0 0.0 0 2,
BVEX4EB 0.0 0.0 0.02824045 0.029259744 0.0 0.0 0 2,
CBVEX4B 0.0 0.0 0.029259744 0.029259744 0.0 0.0 0 2,
BVEX4EC 0.0 0.0 0.029259744 0.030319011 0.0 0.0 0 2,
CBVEX4C 0.0 0.0 0.030319011 0.030319011 0.0 0.0 0 2,
BVEX4ED 0.0 0.0 0.030319011 0.03141825 0.0 0.0 0 2,
CBVEX4D 0.0 0.0 0.03141825 0.03141825 0.0 0.0 0 2,
BVEX4EE 0.0 0.0 0.03141825 0.032557461 0.0 0.0 0 2,
CBVEX4E 0.0 0.0 0.032557461 0.032557461 0.0 0.0 0 2,
BVEX4EF 0.0 0.0 0.032557461 0.033736645 0.0 0.0 0 2,
CBVEX4F 0.0 0.0 0.033736645 0.033736645 0.0 0.0 0 2,
BVEX4EG 0.0 0.0 0.033736645 0.034955801 0.0 0.0 0 2,
CBVEX4G 0.0 0.0 0.034955801 0.034955801 0.0 0.0 0 2,
BVEX4EH 0.0 0.0 0.034955801 0.036214929 0.0 0.0 0 2,
CBVEX4H 0.0 0.0 0.036214929 0.036214929 0.0 0.0 0 2,
DX4E01 0.0 0.0 0.036214929 0.038773158 0.0 0.0 0 2,
DX4E02 0.0 0.0 0.038773158 0.041331387 0.0 0.0 0 2,
DX4E03 0.0 0.0 0.041331387 0.043889616 0.0 0.0 0 2,
DX4E04 0.0 0.0 0.043889616 0.046447845 0.0 0.0 0 2,
DX4E05 0.0 0.0 0.046447845 0.049006074 0.0 0.0 0 2,
DX4E06 0.0 0.0 0.049006074 0.051564303 0.0 0.0 0 2,
DX4E07 0.0 0.0 0.051564303 0.054122532 0.0 0.0 0 2,
DX4E08 0.0 0.0 0.054122532 0.056680761 0.0 0.0 0 2,
DX4E09 0.0 0.0 0.056680761 0.057959875 0.0 0.0 0 2,
DX4STR 0.0 0.0 0.057959875 0.05923899 0.0 0.0 0 2,
CBVEX45 0.0 0.0 0.05923899 0.05923899 0.0 0.0 0 2,
99,

SET MISALIGNMENT FOR VERTICAL OFFSET
0 100
BVEX1EA 0,
CBVEX1A 0,
DXSSTR1 0,
DXSSTR2 0,
DXSSTR3 0,
APPENDIX B. DIMAD INPUT FILE

DXSSTR4 0,
BVEX1EB 0,
CBVEX1B 0,
BVEX1EC 0,
CBVEX1C 0,
BVEX1ED 0,
CBVEX1D 0,
BVEX1EE 0,
CBVEX1E 0,
BVEX1EF 0,
CBVEX1F 0,
BVEX1EG 0,
CBVEX1G 0,
BVEX1EH 0,
CBVEX1H 0,
DX1STRA 0,
DX1E01 0,
DX1E02 0,
DX1E03 0,
DX1E04 0,
DX1E05 0,
DX1STRB 0,
BVEX2EA 0,
CBVEX2A 0,
BVEX2EB 0,
CBVEX2B 0,
BVEX2EC 0,
CBVEX2C 0,
BVEX2ED 0,
CBVEX2D 0,
BVEX2EE 0,
CBVEX2E 0,
BVEX2EF 0,
CBVEX2F 0,
BVEX2EG 0,
CBVEX2G 0,
BVEX2EH 0,
CBVEX2H 0,
DX2STRA 0,
DX2E01 0,
DX2E02 0,
DX2E03 0,
DX2E04 0,
APPENDIX B. DIMAD INPUT FILE

DX2E05 0,
DX2STRB 0,
BVEX3EA 0,
CBVEX3A 0,
BVEX3EB 0,
CBVEX3B 0,
BVEX3EC 0,
CBVEX3C 0,
BVEX3ED 0,
CBVEX3D 0,
BVEX3EE 0,
CBVEX3E 0,
BVEX3EF 0,
CBVEX3F 0,
BVEX3EG 0,
CBVEX3G 0,
BVEX3EH 0,
CBVEX3H 0,
DX3STRA 0,
DX3E01 0,
DX3E02 0,
DX3E03 0,
DX3E04 0,
DX3E05 0,
DX3STRB 0,
BVEX4EA 0,
CBVEX4A 0,
BVEX4EB 0,
CBVEX4B 0,
BVEX4EC 0,
CBVEX4C 0,
BVEX4ED 0,
CBVEX4D 0,
BVEX4EE 0,
CBVEX4E 0,
BVEX4EF 0,
CBVEX4F 0,
BVEX4EG 0,
CBVEX4G 0,
BVEX4EH 0,
CBVEX4H 0,
DX4E01 0,
DX4E02 0,
APPENDIX B. DIMAD INPUT FILE

DX4E03 0,
DX4E04 0,
DX4E05 0,
DX4E06 0,
DX4E07 0,
DX4E08 0,
DX4E09 0,
DX4STR 0,
CBVEX45 0,

TRACKING OF COHPLUS.DAT
-1 -1 5 1
-0.258377E-07 0.107806E-03 -0.916134E-09 -0.132253E-05 0.00000 -0.714644
-0.505226E-07 0.110736E-03 0.537564E-09 0.499280E-04 0.00000 -0.544847
0.186615E-07 -0.508108E-03 -0.503511E-09 -0.348044E-04 0.00000 -0.916344
0.279323E-07 -0.353679E-03 -0.144212E-09 0.123732E-04 0.00000 -0.910367
0.315107E-07 -0.243234E-03 -0.220635E-08 -0.350094E-04 0.00000 -0.782496
;
STOP
Appendix C

GRID Submission Scripts

Files used for submitting BDSIM jobs to the GRID.

C.1 standalonebdsim.sh

tar -zxvf sabdsim.tar.gz
mv *.dat standalonebdsim/disrupted.dat
cd standalonebdsim/
export ROOTSYS=root
export LD_LIBRARY_PATH=$ROOTSYS:/lib:.$LD_LIBRARY_PATH
chmod a+x bdsim
/bdsim –batch –output=root –file=completelattice_disrupted.gmad

C.2 autowms.conf

VirtualOrganisation = "vo.northgrid.ac.uk";
WMProxyEndPoints =
"https://legwms01.gridpp.rl.ac.uk:7443/glite_wms_wmproxy_server",
"https://legwms02.gridpp.rl.ac.uk:7443/glite_wms_wmproxy_server",
"https://wms01.grid.hep.ph.ic.ac.uk:7443/glite_wms_wmproxy_server",
"https://wms02.grid.hep.ph.ic.ac.uk:7443/glite_wms_wmproxy_server",
"https://svr023.gla.scotgrid.ac.uk:7443/glite_wms_wmproxy_server", 234
"https://svr022.gla.scotgrid.ac.uk:7443/glite_wms_wmproxy_server";
]

C.3 bdsim-run.jdl

Type = "Job";
JobType = "Normal";
Executable = "standalonebdsim.sh";
InputSandbox =
"standalonebdsim.sh",
"sabdsim.tar.gz",
../../d/accelerators-clic/mick_backup/bdsim_091010/disrupted_00500.dat"
StdOutput = "standalonebdsim.out"
StdError = "standalonebdsim.err"
OutputSandbox =
"standalonebdsim.out","standalonebdsim.err","standalonebdsim/output_0.root"
VirtualOrganisation = "vo.northgrid.ac.uk"
Rank = - other.GlueCEStateEstimatedResponseTime;
Appendix D

BDSIM and Mokka Post-Collision Line Model

D.1 main.gmad

option, beampipeRadius = 10*cm, !option not actually used in simulation
boxsize = 10.0*m, !maximum component size
tunnelRadius = 10.0*m,
beampipeThickness = 0.1*cm, !option not actually used in simulation
deltaIntersection = 0.00000001*m, !boundary intersection precision
deltaChord = 0.001*m, !chord finder precision
chordStepMinimum = 0.0000000001*m, !minimum step length
lengthSafety = 0.00001*m, !element overlap safety
thresholdCutCharged = 10*KeV,
thresholdCutPhotons = 10*KeV;

IPTOM1Aa:drift, l=3.35*m, material=“Vacuum”;
IPTOM1Ab:drift, l=24.15*m, material=“Vacuum”;

MAG1A:element,geometry=“mokka:mag1a_geomlist.sql”,l=0.5*m;
M1ATOCOLL1A1B:drift, l=1.0*m, material=“Vacuum”;
COLL1A1B:element,geometry=“mokka:coll1a1b_geomlist.sql”,l=0.5*m;
COLL1A1BTOM1B:drift, l=1.0*m, material=“Vacuum”;

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APPENDIX D. BDSIM AND MOKKA POST-COLLISION LINE MODEL

MAG1B:end,geometry="mokka:mag1bGeomlist.sql", l=3.5*m;
M1BTOM11a:drift, l=1.25*m, material="Vacuum";
M1BTOM11b:drift, l=0.30*m, material="Vacuum";
COLL11:element,geometry="mokka:coll11Geomlist.sql", l=0.9*m;
COLL11TOM2a:drift, l=0.30*m, material="Vacuum";
COLL11TOM2b:drift, l=1.25*m, material="Vacuum";

MAG2:end,geometry="mokka:mag2Geomlist.sql", l=4.0*m;
M2TOM33a:drift, l=1.25*m, material="Vacuum";
M2TOM33b:drift, l=0.30*m, material="Vacuum";
COLL33:element,geometry="mokka:coll33Geomlist.sql", l=0.9*m;
COLL33TOM4a:drift, l=0.30*m, material="Vacuum";
COLL33TOM4b:drift, l=1.25*m, material="Vacuum";

MAG3:end,geometry="mokka:mag3Geomlist.sql", l=4.0*m;
M3TOM44a:drift, l=1.25*m, material="Vacuum";
M3TOM44b:drift, l=0.30*m, material="Vacuum";
COLL44:element,geometry="mokka:coll44Geomlist.sql", l=0.9*m;
COLL44TOM5a:drift, l=0.30*m, material="Vacuum";
COLL44TOM5b:drift, l=1.25*m, material="Vacuum";

MAG4:end,geometry="mokka:mag4Geomlist.sql", l=4.0*m;
M4TOMINTDMP:drift, l=9.0*m, material="Vacuum";

INTDMP1:end,geometry="mokka:intdumpGeomlist1.sql", l=0.5*m;
INTDMP2:end,geometry="mokka:intdumpGeomlist2.sql", l=0.5*m;
INTDMP3:end,geometry="mokka:intdumpGeomlist3.sql", l=0.5*m;
INTDMP4:end,geometry="mokka:intdumpGeomlist4.sql", l=0.5*m;
INTDMP5:end,geometry="mokka:intdumpGeomlist5.sql", l=2.0*m;
INTDMP6:end,geometry="mokka:intdumpGeomlist6.sql", l=0.8*m;
INTDMP7:end,geometry="mokka:intdumpGeomlist7.sql", l=1.2*m;

INTDMP7:drift, l=4.0*m, material = "Vacuum";
MAG5:end,geometry="mokka:mag5Geomlist.sql", l=4.0*m;

M5TOM6:drift, l=4.0*m, material = "Vacuum";
MAG6:end,geometry="mokka:mag6Geomlist.sql", l=4.0*m;

M6TOM7:drift, l=4.0*m, material = "Vacuum";
MAG7:end,geometry="mokka:mag7Geomlist.sql", l=4.0*m;

M7TOM8:drift, l=4.0*m, material = "Vacuum";
APPENDIX D. BDSIM AND MOKKA POST-COLLISION LINE MODEL

MAG8:element, geometry="mokka:mag8_geomlist.sql", l=4.0*m;

M8TOMAINDUMP:drift, l=210.0*m, material="Vacuum";
MAINDUMP:element, geometry="mokka:maindump_geomlist.sql", l=10.04*m;

mip:marker;
m01p:marker;
m02p:marker;
m03p:marker;
m04p:marker;
m05p:marker;
m06p:marker;
m07p:marker;
m08p:marker;
m09p:marker;
m10p:marker;
m11p:marker;
m12p:marker;
m13p:marker;
m14p:marker;
m15p:marker;
m16p:marker;
m17p:marker;
m18p:marker;
m19p:marker;
m20p:marker;
m21p:marker;
m22p:marker;
m0p:marker;

postcollision:line=(mip, IPTOM1Aa, m01p, IPTOM1Ab, m02p, MAG1A, m03p, M1ATOCOLL1A1B, COLL1A1B, COLL1A1BTOM1B, m04p, MAG1B, m05p, M1BTOCOLL12a, M1BTOCOLL12b, COLL12, COLL12TOM2a, COLL12TOM2b, m06p, MAG2, m07p, M2TOCOLL23a, M2TOCOLL23b, COLL23, COLL23TOM3a, COLL23TOM3b, m08p, MAG3, m09p, M3TOCOLL34a, M3TOCOLL34b, COLL34, COLL34TOM4a, COLL34TOM4b, m10p, MAG4, m11p, M4TOINTDMPa, m12p, INTDMP1, INTDMP2, INTDMP3, INTDMP4, INTDMP5, INTDMP6, INTDMP7, m13p, INTDMP5TOM5, m14p, MAG5, m15p, M5TOM6, m16p, MAG6, m17p, M6TOM7, m18p,
MAG7, m19p, M7TOM8, m20p, MAG8, m21p, M8TOMAINDUMP, m22p, MAINDUMP, mop);

use, period=postcollision;

option, ngenerate=25, physicsList="em_standard",
useEMHadronic=0, randomSeed=-1;

sample, range=mip;
sample, range=m01p;
sample, range=m02p;
sample, range=m03p;
sample, range=m04p;
sample, range=m05p;
sample, range=m06p;
sample, range=m07p;
sample, range=m08p;
sample, range=m09p;
sample, range=m10p;
sample, range=m11p;
sample, range=m12p;
sample, range=m13p;
sample, range=m14p;
sample, range=m15p;
sample, range=m16p;
sample, range=m17p;
sample, range=m18p;
sample, range=m19p;
sample, range=m20p;
sample, range=m21p;
sample, range=m22p;
sample, range=mop;

beam, particle="e-", energy=1500*GeV,
distrType="E[GeV]:x[mum]:y[mum]:z[m]:xp[rad]:yp[rad]",
distrFile="disrupted.dat";
D.2 Mokka Geometry Definition

D.2.1 Mokka SQL Table Definition

In each of the .SQL geometry files, the same two table definitions are used to generate the geometries. These tables represent a G4Box and G4EllipticalTube:

```sql
CREATE DATABASE MOKKAELEMENT;
USE MOKKAELEMENT;

CREATE TABLE MOKKAELEMENTB_BOX (PARENTNAME VARCHAR(32), #
INHERITSTYLE VARCHAR(32), #
RED DOUBLE(10,3), #
GREEN DOUBLE(10,3), #
BLUE DOUBLE(10,3), #
VISATT VARCHAR(32), # I = INVISIBLE, S = SOLID, W = WIREFRAME
POSX DOUBLE(10,3), #
POSY DOUBLE(10,3), #
POSZ DOUBLE(10,3), #
LENGTHX DOUBLE(10,3), #
LENGTHY DOUBLE(10,3), #
LENGTHZ DOUBLE(10,3), #
FIELDX DOUBLE(10,3), #
MATERIAL VARCHAR(32), # MATERIAL, CGALITERAL NAME
NAME VARCHAR(32) # NAME);

CREATE TABLE MOKKAELEMENTE_ELLIPTICALTUBE (PARENTNAME VARCHAR(32), #
INHERITSTYLE VARCHAR(32), #
RED DOUBLE(10,3), #
GREEN DOUBLE(10,3), #
BLUE DOUBLE(10,3), #
VISATT VARCHAR(32), # I = INVISIBLE, S = SOLID, W = WIREFRAME
POSX DOUBLE(10,3), #
POSY DOUBLE(10,3), #
APPENDIX D. BDSIM AND MOKKA POST-COLLISION LINE MODEL

POSZ DOUBLE(10,3), #
LENGTHX DOUBLE(10,3), #
LENGTHY DOUBLE(10,3), #
LENGTHZ DOUBLE(10,3), #
FIELDX DOUBLE(10,3), #
MATERIAL VARCHAR(32), # MATERIAL, CEA LITERAL NAME
NAME VARCHAR(32) # NAME
);

D.2.2 mag1a.sql

INSERT INTO MOKKAELEMENTB
BOX VALUES
("","",&lt;S"",0.0,0.0,0.250,0.494,0.976,0.500,0.00,0.0,
"Iron","IRON_BOX");
INSERT INTO MOKKAELEMENTB
BOX VALUES
("","",&lt;S"",0.0,0.1,0.0,0.0,0.0,288.5,250.0,222.0,127.0,500.0,0.0,
"Copper","COIL_BOX");
INSERT INTO MOKKAELEMENTB
BOX VALUES
("","",&lt;S"",0.0,0.1,0.0,0.0,-288.5,250.0,222.0,127.0,500.0,0.0,
"Copper","COIL_BOX");
INSERT INTO MOKKAELEMENTB
BOX VALUES
("IRON_BOX","SUBTRACT",0.0,0.0,0.0,0.0,222.0,450.0,505.0,0.8,
"Air","AIR_BOX");
INSERT INTO MOKKAELEMENTE
ETUBE VALUES
("","",&lt;S"",0.0,0.1,0.0,0.0,0.0,200.0,132.0,501.0,0.0,
"Vacuum","VACUUM_ETUBE");

D.2.3 coll1a1b.sql

INSERT INTO MOKKAELEMENTB
BOX VALUES
("",1.0,1.0,0.0,"S",0.0,0.0,250.0,500.0,1000.0,500.00,0.0,
"Graphite","CARBON_BOX");
INSERT INTO MOKKAELEMENTE
ETUBE VALUES
("CARBON_BOX","SUBTRACT",0.0,0.1,0.1,0.1,0.0,200.0,
440.0,505.0,0.8,"Vacuum","VACUUM_ETUBE");
D.2.4  **mag1b.sql**

```
INSERT INTO MOKKAELEMENTB_BOX VALUES (""",1.0,0.0,0.0,"S",0.0,0.0,1750.0,494.0,976.0,3500.0,0.0,0.0,"Iron","IRON BOX");
INSERT INTO MOKKAELEMENTB_BOX VALUES (""",0.0,1.0,0.0,"S",0.0,288.5,1750.0,222.0,127.0,3500.0,0.0,0.0,"Copper","COIL_BOX");
INSERT INTO MOKKAELEMENTB_BOX VALUES (""",0.0,0.0,0.0,"S",0.0,-288.5,1750.0,222.0,127.0,3500.0,0.0,0.0,"Copper","COIL_BOX");
INSERT INTO MOKKAELEMENTB_BOX VALUES (""",0.0,0.0,0.0,"S",0.0,0.0,1750.0,222.0,450.0,3500.0,0.0,0.8,"Air","AIR BOX");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES (""",0.0,1.0,1.0,"S",0.0,0.0,1750.0,222.0,450.0,3500.0,0.0,0.8,"StainlessSteel","BEAMPIPE_ETUBE");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES (""",0.0,0.0,0.0,"S",0.0,0.0,1750.0,200.0,440.0,3500.0,0.0,0.8,"Vacuum","VACUUM_ETUBE");
```

D.2.5  **coll12.sql**

```
INSERT INTO MOKKAELEMENTB_BOX VALUES (""",1.0,0.0,2.0,"S",0.0,-385.625,450.0,771.25,771.25,900.0,0.0,0.0,"Graphite","CARBON BOX LOWER");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("CARBON BOX LOWER","SUBTRACT",0.0,1.0,1.0,"S",0.0,385.625,0.0,308.5,256.0,901.0,0.0,"Vacuum","VACUUM_TUBE_LOWER");
INSERT INTO MOKKAELEMENTB_BOX VALUES (""",1.0,0.0,2.0,"S",0.0,385.625,450.0,771.25,771.25,900.0,0.0,0.0,"Graphite","CARBON BOX_UPPER");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("CARBON BOX_UPPER","SUBTRACT",0.0,1.0,1.0,"S",0.0,-385.625,0.0,308.5,174.0,901.0,0.0,"Vacuum","VACUUM_TUBE_UPPER");
```
D.2.6 mag2.sql

```sql
INSERT INTO MOKKAELEMENTB_BOX VALUES ('",1.0,0.0,0.0,"S",0.0,0.0,2000.0,692.0,1362.0,4000.0,0.0,"Iron","IRON_BOX");
INSERT INTO MOKKAELEMENTB_BOX VALUES ('",0.0,1.0,0.0,"S",0.0,419.5,2000.0,296.0,127.0,4000.0,0.0,"Copper","COIL_BOX");
INSERT INTO MOKKAELEMENTB_BOX VALUES ('",0.0,1.0,0.0,"S",0.0,-419.5,2000.0,296.0,127.0,4000.0,0.0,"Copper","COIL_BOX");
INSERT INTO MOKKAELEMENTB_BOX VALUES ('",0.0,0.0,0.0,"S",0.0,0.0,2000.0,296.0,712.0,4000.0,0.8,"Air","AIR_BOX");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ('",0.0,1.0,1.0,"S",0.0,0.0,2000.0,296.0,712.0,4000.0,0.8,"StainlessSteel","BEAMPIPE_ETUBE");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ('",0.0,0.0,0.0,"S",0.0,0.0,2000.0,270.0,702.0,4000.0,0.8,"Vacuum","VACUUM_ETUBE");
```

D.2.7 coll23.sql

```sql
INSERT INTO MOKKAELEMENTB_BOX VALUES ('",1.0,0.2,0.0,"S",0.0,-473.125,450.0,946.25,946.25,900.00,0.0,"Graphite","CARBON_BOX_LOWER");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("CARBON_BOX_LOWER","SUBTRACT",0.0,1.0,1.0,"S",0.0,473.125,0.0,378.5,570.0,901.0,0.0,"Vacuum","VACUUM_TUBE_LOWER");
INSERT INTO MOKKAELEMENTB_BOX VALUES ('",1.0,0.2,0.0,"S",0.0,473.125,450.0,946.25,946.25,900.00,0.0,"Graphite","CARBON_BOX_UPPER");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("CARBON_BOX_UPPER","SUBTRACT",0.0,1.0,1.0,"S",0.0,-473.125,0.0,378.5,504.0,901.0,0.0,"Vacuum","VACUUM_TUBE_UPPER");
```
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**D.2.8 mag3.sql**

```
INSERT INTO MOKKAELEMENTB BOX VALUES
("",1.0,0.0,0.0,"S",0.0,0.0,0.2000.0,914.0,1828.0,4000.00,0.0,
"Iron","IRON BOX");
INSERT INTO MOKKAELEMENTB BOX VALUES
("",0.0,1.0,0.0,"S",0.0,578.5,2000.0,370.0,127.0,4000.0,0.0,
"Copper","COIL BOX");
INSERT INTO MOKKAELEMENTB BOX VALUES
("",0.0,0.0,0.0,"S",0.0,0.0,2000.0,370.0,1030.0,4000.0,0.8,
"Air","AIR BOX");
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("",0.0,1.0,1.0,"S",0.0,0.0,2000.0,370.0,1030.0,4000.0,0.8,
"StainlessSteel","BEAMPIPE ETUBE");
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("",0.0,0.0,0.0,"S",0.0,0.0,2000.0,340.0,1020.0,4000.0,0.8,
"Vacuum","VACUUM ETUBE");
```

**D.2.9 coll34.sql**

```
INSERT INTO MOKKAELEMENTB BOX VALUES
("",1.0,0.0,0.0,"S",0.0,-560.625,450.0,1121.25,1121.25,900.00,0.0,
"Graphite","CARBON BOX LOWER");
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("CARBON BOX LOWER","SUBTRACT",0.0,1.0,1.0,"S",0.0,-560.625,0.0,
448.5,926.0,901.0,0.0,"Vacuum","VACUUM TUBE LOWER");
INSERT INTO MOKKAELEMENTB BOX VALUES
("",1.0,0.0,2.0,"S",0.0,560.625,450.0,1121.25,1121.25,900.00,0.0,
"Graphite","CARBON BOX UPPER");
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("CARBON BOX UPPER","SUBTRACT",0.0,1.0,1.0,"S",0.0,-560.625,0.0,
448.5,870.0,901.0,0.0,"Vacuum","VACUUM TUBE UPPER");
```
D.2.10  mag4.sql

INSERT INTO MOKKAELEMENTB_BOX VALUES
("",1.0,0.0,0.0,"S",0.0,0.0,2000.0,1164.0,2378.0,4000.0,0.0,0.0,"Iron","IRON_BOX");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("",0.0,1.0,0.0,"S",0.0,765.5,2000.0,444.0,127.0,4000.0,0.0,0.0,"Copper","COIL_BOX");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("",0.0,1.0,0.0,"S",0.0,-765.5,2000.0,444.0,127.0,4000.0,0.0,0.0,"Copper","COIL_BOX");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("",0.0,0.0,0.0,"S",0.0,0.0,2000.0,444.0,1404.0,4000.0,0.8,0.0,"Air","AIR_BOX");

INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("",0.0,1.0,1.0,"S",0.0,0.0,2000.0,444.0,1404.0,4000.0,0.8,0.0,"StainlessSteel","BEAMPIPE_ETUBE");

INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("",0.0,0.0,0.0,"S",0.0,0.0,2000.0,410.0,1394.0,4000.0,0.8,0.0,"Vacuum","VACUUM_ETUBE");

D.2.11  intdump1.sql

INSERT INTO MOKKAELEMENTB_BOX VALUES
("","",1.0,0.2,0.0,"S",0.0,-787.5,250.0,1700.0,1575.0,500.0,0.0,"Iron","IRON_BOX_LOWER");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX_LOWER","SUBTRACT",0.0,0.0,1.0,"S",0.0,187.5,0.0,450.0,1200.0,500.0,0.0,"Vacuum","CUTOUT_BOX_LOWER");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("","",0.0,0.0,1.0,"S",0.0,-600.0,250.0,450.0,1200.0,500.0,0.0,0.0,"Graphite","ABSORBER_BOX_LOWER");

INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("ABSORBER_BOX_LOWER","SUBTRACT",0.0,0.0,0.0,"T",0.0,412.26,0.0,450.0,2000.0,501.0,0.0,"Vacuum","VAC_TUBE_LOWER_1");

INSERT INTO MOKKAELEMENTE_BOX VALUES
("ABSORBER_BOX_LOWER","SUBTRACT",0.0,0.0,0.0,"T",0.0,442.5,0.0,450.0,60.48,501.0,0.0,"Vacuum","VAC_BOX_LOWER_1");

INSERT INTO MOKKAELEMENTE_BOX VALUES
("","",1.0,0.2,0.0,"S",0.0,787.5,250.0,1700.0,1575.0,500.0,0.0,"Iron","IRON_BOX_UPPER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX_UPPER", "SUBTRACT", 0.0, 0.0, 1.0, "S", 0.0, 0.0, 0.0, 450.0, 1575.0, 500.0, 0.0, "Vacuum", "CUTOUT_BOX_UPPER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("", "", 0.0, 0.0, 1.0, "S", 0.0, 787.5, 250.0, 450.0, 1575.0, 500.0, 0.0, "Graphite", "ABSORBER_BOX_UPPER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("ABSORBER_BOX_UPPER", "SUBTRACT", 0.0, 0.0, 0.0, "I", 0.0, -756.76, 0.0, 450.0, 115.501, 0.0, "Vacuum", "VAC_TUBE_UPPER_1");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("ABSORBER_BOX_UPPER", "SUBTRACT", 0.0, 0.0, 0.0, "I", 0.0, -787.5, 0.0, 450.0, 60.48, 501, 0.0, "Vacuum", "VAC_BOX_UPPER_1");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("", "", 1.0, 0.0, 0.0, "S", -325.0, 345.0, 250.0, 200.0, 2460.0, 500.0, 0.0, "Aluminium", "COOLING_BOX_LEFT");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("", "", 1.0, 0.0, 1.0, "S", 325.0, 345.0, 250.0, 200.0, 2460.0, 500.0, 0.0, "Aluminium", "COOLING_BOX_RIGHT");

D.2.12 intdump2.sql

INSERT INTO MOKKAELEMENTB_BOX VALUES
("", "", 1.0, 0.2, 0.0, "S", 0.0, -787.5, 250.0, 1700.0, 1575.0, 500.0, 0.0, "Iron", "IRON_BOX_LOWER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX_LOWER", "SUBTRACT", 0.0, 0.0, 1.0, "S", 0.0, 345.0, 0.0, 450.0, 885.0, 500.0, 0.0, "Vacuum", "CUTOUT_BOX_LOWER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("", "", 0.0, 0.0, 1.0, "S", 0.0, -442.5, 250.0, 450.0, 885.0, 500.0, 0.0, "Graphite", "ABSORBER_BOX_LOWER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("ABSORBER_BOX_LOWER", "SUBTRACT", 0.0, 0.0, 0.0, "I", 0.0, 0.411.62, 0.0, 360.0, 1620.501, 0.0, "Vacuum", "VAC_TUBE_LOWER_2");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("ABSORBER_BOX_LOWER", "SUBTRACT", 0.0, 0.0, 0.0, "I", 0.0, 0.442.5, 0.0, 360.0, 61.76, 501, 0.0, "Vacuum", "VAC_BOX_LOWER_2");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("", "", 1.0, 0.0, 2.0, "S", 0.0, 787.5, 250.0, 1700.0, 1575.0, 500.0, 0.0, "Iron", "IRON_BOX_UPPER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX_UPPER", "SUBTRACT", 0.0, 0.0, 1.0, "S", 0.0, 0.0, 0.0,
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450.0,1575.0,500.0,0.0,0.0,"Graphite","CUTOUT_BOX_UPPER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("","","0.0,0.0,1.0","S",0.0,787.5,250.0,450.0,1575.0,500.0,0.0,0.0,"Graphite","ABSORBER_BOX_UPPER");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("ABSORBER_BOX_UPPER","SUBTRACT",0.0,0.0,0.0,0.0,0.0,0.0,-756.12,0,
360,130,501.0,0,"Vacuum","VAC_TUBE_UPPER_2");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("ABSORBER_BOX_UPPER","SUBTRACT",0.0,0.0,0.0,0.0,0.0,0.0,-787.5,0,
360,61.76,501.0,0,"Vacuum","VAC_BOX_UPPER_2");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("","","1.0,0.0,1.0","S",-325.0,345.0,250.0,200.0,2460.0,500.0,0.0,0.0,"Aluminium","COOLING_BOX_LEFT");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("","","1.0,0.0,1.0","S",325.0,345.0,250.0,200.0,2460.0,500.0,0.0,0.0,"Aluminium","COOLING_BOX_RIGHT");

D.2.13 intdump3.sql

INSERT INTO MOKKAELEMENTB_BOX VALUES
("","","1.0,0.2,0.0","S",-787.5,250.0,1700.0,1575.0,500.0,0.0,0.0,"Iron","IRON_BOX_LOWER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX_LOWER","SUBTRACT",0.0,0.0,1.0,0.0,0.0,0.0,345.0,0.0,0.0,450.0,885.0,500.0,0.0,0.0,"Vacuum","CUTOUT_BOX_LOWER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("","","0.0,0.0,1.0","S",-442.5,250.0,450.0,885.0,500.0,0.0,0.0,0.0,"Graphite","ABSORBER_BOX_LOWER");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("ABSORBER_BOX_LOWER","SUBTRACT",0.0,0.0,0.0,0.0,0.0,0.0,410.98,0,
270,1240,501.0,0,"Vacuum","VAC_TUBE_LOWER_3");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("ABSORBER_BOX_LOWER","SUBTRACT",0.0,0.0,0.0,0.0,0.0,0.0,63.04,0.0,0.0,270,63.04,501.0,0,"Vacuum","VAC_BOX_LOWER_3");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("","","1.0,0.2,0.0","S",0.0,787.5,250.0,1700.0,1575.0,500.0,0.0,0.0,"Iron","IRON_BOX_UPPER");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX_UPPER","SUBTRACT",0.0,0.0,1.0,0.0,0.0,0.0,442.5,0.0,0.0,270,63.04,501.0,0,"Vacuum","CUTOUT_BOX_UPPER");
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D.2.14 intdump4.sql

```
INSERT INTO MOKKAELEMENTB_BOX VALUES ("",",",1.0,0.2,0.0,"S",0.0,-787.5,250.0,1700.0,1575.0,500.0,0.0,
"Iron","IRON_BOX_LOWER");
INSERT INTO MOKKAELEMENTB_BOX VALUES ("IRON_BOX_LOWER","SUBTRACT",0.0,0.0,1.0,"S",0.0,342.5,250.0,450.0,885.0,500.0,0.0,
"Graphite","ABSORBER_BOX_LOWER");
```

```sql
INSERT INTO MOKKAELEMENTB_BOX VALUES ("IRON_BOX_LOWER","SUBTRACT",0.0,0.0,1.0,"S",0.0,450.0,500.0,0.0,
"Vacuum","CUTOUT_BOX_LOWER");
```
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("ABSORBER_BOX_UPPER","SUBTRACT",0.0,0.0,0.0,0.0,0.0,-754.84,0,
180,160,501.0,0.0,"Vacuum","VAC_TUBE_UPPER_4");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("ABSORBER_BOX_UPPER","SUBTRACT",0.0,0.0,0.0,0.0,0.0,-787.5,0,
180,64.32,501.0,0.0,"Vacuum","VAC_BOX_UPPER_4");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("",",",1.0,0.0,1.0,0.0,0.0,-325.0,345.0,250.0,200.0,2460.0,0.0,
"Aluminium","COOLING_BOX_LEFT");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("",",",1.0,0.0,1.0,0.0,325.0,345.0,250.0,200.0,2460.0,0.0,
"Aluminium","COOLING_BOX_RIGHT");

D.2.15 intdump5.sql

INSERT INTO MOKKAELEMENTB_BOX VALUES
("",",",1.0,0.2,0.0,0.0,-787.5,1000.0,1700.0,1575.0,2000.0,0.0,
"Iron","IRON_BOX_LOWER");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX_LOWER","SUBTRACT",0.0,0.0,1.0,0.0,0.0,345.0,0.0,0.0,
450.0,885.0,2000.0,0.0,"Vacuum","CUTOUT_BOX_LOWER");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("",",",0.0,0.0,1.0,0.0,-442.5,1000.0,450.0,885.0,2000.0,0.0,
"Graphite","ABSORBER_BOX_LOWER");

INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("ABSORBER_BOX_LOWER","SUBTRACT",0.0,0.0,0.0,0.0,0.0,-407.78,0,
180,860,2001.0,0.0,"Vacuum","VAC_TUBE_LOWER_5");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("ABSORBER_BOX_LOWER","SUBTRACT",0.0,0.0,0.0,0.0,0.0,442.5,0.0,450.0,1575.0,2000.0,0.0,0.0,
"Iron","IRON_BOX_UPPER");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX_UPPER","SUBTRACT",0.0,0.0,1.0,0.0,0.0,345.0,0.0,0.0,
450.0,1575.0,2000.0,0.0,"Vacuum","CUTOUT_BOX_UPPER");

INSERT INTO MOKKAELEMENTB_BOX VALUES
("",",",0.0,0.0,1.0,0.0,0.0,0.0,345.0,0.0,1575.0,0.0,0.0,0.0,
"Graphite","ABSORBER_BOX_UPPER");

INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("ABSORBER_BOX_UPPER","SUBTRACT",0.0,0.0,0.0,0.0,0.0,-752.28,0,
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180,160,2001,0.0,"Vacuum","VAC_TUBE_UPPER.5");
INSERT INTO MOKKAELEMENTBBOXVALUES
("ABSORBER_BOX_UPPER","SUBTRACT",0.0,0.0,0.0,"T",0.0,-787.5,0,
180,69.44,2001,0.0,"Vacuum","VAC_BOX_UPPER.5");
INSERT INTO MOKKAELEMENTBBOXVALUES
("",","1.0,0.0,1.0,"S",325.0,345.0,1000.0,200.0,2460.0,2000.0,0.0,
"Aluminium","COOLING_BOX_LEFT");
INSERT INTO MOKKAELEMENTBBOXVALUES
("",","1.0,0.0,1.0,"S",325.0,345.0,1000.0,200.0,2460.0,2000.0,0.0,
"Aluminium","COOLING_BOX_RIGHT");

D.2.16 intdump6.sql

INSERT INTO MOKKAELEMENTBBOXVALUES
("",","1.0,0.0,2.0,0.0,"S",0.0,-787.5,400.0,1700.0,1575.0,800.0,0.0,
"Iron","IRON_BOX_LOWER");
INSERT INTO MOKKAELEMENTBBOXVALUES
("IRON_BOX_LOWER","SUBTRACT",0.0,0.0,1.0,"S",0.0,345.0,0.0,
450.0,885.0,800.0,0.0,"Vacuum","CUTOUT_BOX_LOWER");
INSERT INTO MOKKAELEMENTBBOXVALUES
("",","1.0,0.0,1.0,"S",0.0,-442.5,400.0,450.0,885.0,800.0,0.0,
"Graphite","ABSORBER_BOXLOWER");
INSERT INTO MOKKAELEMENTE cheatingTUBEVALUES
("ABSORBER_BOX_LOWER","SUBTRACT",0.0,0.0,0.0,"T",0.0,405.22,0,
180,860,801.0,0,"Vacuum","VAC_TUBE_LOWER.6");
INSERT INTO MOKKAELEMENTBBOXVALUES
("ABSORBER_BOXLOWER","SUBTRACT",0.0,0.0,0.0,"T",0.0,442.5,0,
180,74.56,801.0,0,"Vacuum","VAC_BOXLOWER.6");
INSERT INTO MOKKAELEMENTBBOXVALUES
("",","1.0,0.0,2.0,0.0,"S",0.0,787.5,400.0,1700.0,1575.0,800.0,0.0,
"Iron","IRON_BOX_UPPER");
INSERT INTO MOKKAELEMENTBBOXVALUES
("IRON_BOX_UPPER","SUBTRACT",0.0,0.0,1.0,"S",0.0,0.0,0.0,
450.0,1575.0,800.0,0.0,"Vacuum","CUTOUT_BOX_UPPER");
INSERT INTO MOKKAELEMENTBBOXVALUES
("",","1.0,0.0,1.0,"S",0.0,787.5,400.0,450.0,1575.0,800.0,0.0,
"Graphite","ABSORBER_BOX_UPPER");
INSERT INTO MOKKAELEMENTE ellipticalTUBEVALUES
("ABSORBER_BOX_UPPER","SUBTRACT",0.0,0.0,0.0,"T",0.0,-749.72,0,
180,160,801.0,0,"Vacuum","VAC_TUBE_UPPER.6");
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D.2.17 intdump7.sql

INSERT INTO MOKKAELEMENTBOX VALUES
("ABSORBER_BOX_UPPER","SUBTRACT",0.0,0.0,0.0,0.0,-787.5,0,
180,74,56,801,0.0,"Vacuum","VAC_BOX_UPPER.6");

INSERT INTO MOKKAELEMENTBOX VALUES
("","",1.0,0.0,1.0,"S",-325.0,345.0,400.0,200.0,2460.0,800.0,0.0,
"Aluminium","COOLING_BOX_LEFT");

INSERT INTO MOKKAELEMENTBOX VALUES
("","",1.0,0.0,1.0,"S",325.0,345.0,400.0,200.0,2460.0,800.0,0.0,
"Aluminium","COOLING_BOX_RIGHT");

D.2.18 mag5.sql

# FLUX RETURN

INSERT INTO MOKKAELEMENTBOX VALUES
("","",1.0,0.2,0.0,"S",0.0,-787.5,2000.0,0.0,1770.0,1498.0,4000.0,0.0,
"Iron","IRON_BOX");
450.0,1326.0,4001.0,0.0,0.0,"Vacuum","VACUUM_BOX");

# COILS
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","SUBTRACT",1.0,0.5,0.0,"S",-325.0,-145.0,0.0,0.0,
200.0,288.0,4001.0,0.0,"Vacuum","COIL_GAP_3");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","SUBTRACT",1.0,0.5,0.0,"S",325.0,-145.0,0.0,0.0,
200.0,288.0,4001.0,0.0,"Copper","COIL_GAP_4");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","SUBTRACT",1.0,0.5,0.0,"S",325.0,-145.0,0.0,0.0,
200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_1");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","SUBTRACT",1.0,0.5,0.0,"S",325.0,893.0,0.0,0.0,
200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_2");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","SUBTRACT",1.0,0.5,0.0,"S",-325.0,-145.0,0.0,0.0,
200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_3");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","SUBTRACT",1.0,0.5,0.0,"S",-325.0,893.0,0.0,0.0,
200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_4");

# BEAM PIPE
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("","",0.0,0.0,1.0,"S",0.0,-45.318,2000.0,0.0,
410.0,210.0,4000.0,-0.784,"StainlessSteel","STEEL_UPPER");
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("STEEL_UPPER","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0,
400.0,200.0,4001.0,-0.784,"Vacuum","STEEL_UPPER_CAVITY");
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("STEEL_UPPER","SUBTRACT",0.0,0.0,0.0,"S",0.0,-100.0,0.0,0.0,
1000000.0,200.0,4002.0,0.0,"Vacuum","STEEL_UPPER_HALVED");
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("","",0.0,0.0,1.0,"S",0.0,-134.02,2000.0,0.0,
410.0,1350.0,4000.0,-0.784,"StainlessSteel","STEEL_LOWER");
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("STEEL_LOWER","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0,
400.0,1340.0,4001.0,-0.784,"Vacuum","STEEL_LOWER_CAVITY");
INSERT INTO MOKKAELEMENTE ELLIPTICALTUBE VALUES
("STEEL_LOWER","SUBTRACT",0.0,0.0,0.0,"S",0.0,670.0,0.0,0.0,
1000000.0,1340.0,4002.0,0.0,"Vacuum","STEEL_LOWER_HALVED");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("","",0.0,0.0,1.0,"S",0.0,-89.7,2000.0,0.0,410.0,88.84,4000.0,-0.784,
"StainlessSteel","STEEL_BOX");
INSERT INTO MOKKAELEMENTB_BOX VALUES
D. 2.19 mag6.sql

# FLUX RETURN
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","SUBTRACT",1.0,0.5,0.0,"S",325.0,-145.0,0.0,0.0,0.0,1498.0,0.0,200.0,288.0,4000.0,0.0,"Copper","COIL_Box_1");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","SUBTRACT",1.0,0.5,0.0,"S",325.0,-145.0,0.0,0.0,0.0,1498.0,0.0,200.0,288.0,4000.0,0.0,"Copper","COIL_Box_2");
APPENDIX D. BDSIM AND MOKKA POST-COLLISION LINE MODEL

INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","",1.0,0.5,0.0,"S",-325.0,-145.0,0.0,0.0,
200.0,288.0,4000.0,0.0,0.0,"Copper","COIL_BOX_3");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("IRON_BOX","",1.0,0.5,0.0,"S",-325.0,893.0,0.0,0.0,
200.0,288.0,4000.0,0.0,0.0,"Copper","COIL_BOX_4");

# BEAM PIPE
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("","",0.0,0.0,1.0,"S",0.0,-54.687,2000.0,0.0,
410.0,250.0,4000.0,0.0,0.0,"StainlessSteel","STEEL_UPPER");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("STEEL_UPPER","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0,
400.0,240.0,4001.0,0.0,0.0,"Vacuum","STEEL_UPPER_CAVITY");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("STEEL_UPPER","SUBTRACT",0.0,0.0,0.0,"S",0.0,-120.0,0.0,0.0,
10000000.0,240.0,4002.0,0.0,"Vacuum","STEEL_UPPER_HALVED");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("","",0.0,0.0,1.0,"S",0.0,-155.487,2000.0,0.0,
410.0,1350.0,4000.0,0.0,0.0,"StainlessSteel","STEEL_LOWER");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("STEEL_LOWER","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0,
400.0,1340.0,4001.0,0.0,0.0,"Vacuum","STEEL_LOWER_CAVITY");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("STEEL_LOWER","SUBTRACT",0.0,0.0,0.0,"S",0.0,670.0,0.0,0.0,
10000000.0,1340.0,4002.0,0.0,"Vacuum","STEEL_LOWER_HALVED");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("","",0.0,0.0,1.0,"S",0.0,-105.0,872000.0,0.0,410.0,100.8,4000.0,0.0,0.0,
"StainlessSteel","STEEL_BOX");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("STEEL_BOX","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0,
400.0,101.8,4000.0,0.0,0.0,"Vacuum","STEEL_BOX_CAVITY");

# VACUUM CHAMBER
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("","",0.0,0.0,0.0,0.0,0.0,-54.687,2000.0,0.0,
400.0,240.0,4000.0,0.0,0.0,"Vacuum","VAC_UPPER_CAVITY");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("VAC_UPPER_CAVITY","SUBTRACT",0.0,0.0,0.0,0.0,0.0,0.0,-120.0,0.0,0.0,
10000000.0,240.0,4003.0,0.0,0.0,"Vacuum","VAC_UPPER_HALVED");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("","",0.0,0.0,0.0,0.0,0.0,-155.487,2000.0,0.0,
400.0,1340.0,4000.0,0.0,0.0,"Vacuum","VAC_LOWER_CAVITY");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("VAC_LOWER_CAVITY","SUBTRACT",0.0,0.0,0.0,0.0,0.0,0.0,670.0,0.0,0.0,
APPENDIX D. BDSIM AND MOKKA POST-COLLISION LINE MODEL

10000001.0,1340.0,4003.0,0.0,"Vacuum","VAC_LOWER_HALVED");
INSERT INTO MOKKAELEMENTBOX VALUES
("","","","","","Vacuum","VAC_LOWER_HALVED");

D.2.20 mag7.sql

# FLUX RETURN
INSERT INTO MOKKAELEMENTBOX VALUES
("","","1.0,0,0,0,0."S",0.0,-774.582,2000.0,0.0,1770.0,1498.0,1498.0,0.0,
"Iron","IRON_BOX");
INSERT INTO MOKKAELEMENTBOX VALUES
("IRON_BOX","SUBTRACT",0.0,0,0,0,0."S",0.0,374.0,0.0,0,0.0,
450.0,1326.0,4001.0,0.0,"Vacuum","VACUUM_BOX");
# COILS
INSERT INTO MOKKAELEMENTBOX VALUES
("IRON_BOX","SUBTRACT",1.0,0,5,0,0,"S",-325.0,-145.0,0,0,0,
200.0,288.0,4001.0,0.0,"Copper","COIL_GAP_3");
INSERT INTO MOKKAELEMENTBOX VALUES
("IRON_BOX","SUBTRACT",1.0,0,5,0,0,"S",325.0,-145.0,0,0,0,
200.0,288.0,4000.0,0.0,"Copper","COIL_GAP_4");
INSERT INTO MOKKAELEMENTBOX VALUES
("IRON_BOX","SUBTRACT",1.0,0,5,0,0,"S",325.0,893.0,0,0,0,
200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_1");
INSERT INTO MOKKAELEMENTBOX VALUES
("IRON_BOX","SUBTRACT",1.0,0,5,0,0,"S",-325.0,-145.0,0,0,0,
200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_2");
INSERT INTO MOKKAELEMENTBOX VALUES
("IRON_BOX","SUBTRACT",1.0,0,5,0,0,"S",-325.0,-145.0,0,0,0,
200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_3");
INSERT INTO MOKKAELEMENTBOX VALUES
("IRON_BOX","SUBTRACT",1.0,0,5,0,0,"S",-325.0,893.0,0,0,0,
200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_4");
# BEAM PIPE
INSERT INTO MOKKAELEMENTEIRTUALTUBE VALUES
("","","0.0,0,0,0,1.0."S",0.0,-61.08,2000.0,0.0,
410.0,290.0,4000.0,-0.784,"StainlessSteel","STEEL_UPPER");
INSERT INTO MOKKAELEMENTEIRTUALTUBE VALUES
("STEEL_UPPER","SUBTRACT",0.0,0,0,0,0,"S",0.0,0,0,0,0,0,
400.0,280.0,4001.0,-0.784,"Vacuum","STEEL_UPPER_CAVITY");
INSERT INTO MOKKAELEMENTEIRTUALTUBE VALUES
APPENDIX D. BDSIM AND MOKKA POST-COLLISION LINE MODEL

("STEEL_UPPER","SUBTRACT",0.0,0.0,0.0,"S",0.0,-140.0,0.0,0.0, 10000000.0,4002.0,0.0,"Vacuum","STEEL_UPPER_HALVED");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("","","","","S",0.0,-169.56,2000.0,0.0, 410.0,1350.0,4000.0,-0.784,"StainlessSteel","STEEL_UPPER_HALVED");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("STEEL_UPPER","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0, 400.0,1340.0,4001.0,-0.784,"Vacuum","STEEL_UPPER_CAVITY");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("STEEL_LOWER","SUBTRACT",0.0,0.0,0.0,"S",0.0,670.0,0.0,0.0, 10000000.0,1340.0,4002.0,0.0,"Vacuum","STEEL_LOWER_HALVED");
INSERT INTO MOKKAELEMENTE_BOX VALUES ("","","","","S",0.0,-115.32,2000.0,0.0, 410.0,108.48,4000.0,-0.784,"StainlessSteel","STEEL_BOX");
INSERT INTO MOKKAELEMENTE_BOX VALUES ("STEEL_BOX","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0, 400.0,109.48,4001.0,-0.784,"Vacuum","STEEL_BOX_CAVITY");
# VACUUM CHAMBER
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("","","","","I",0.0,-61.08,2000.0,0.0, 400.0,280.0,4000.0,-0.784,"Vacuum","VAC_UPPER_CAVITY");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("VAC_UPPER_CAVITY","SUBTRACT",0.0,0.0,0.0,"S",0.0,-140.0,0.0,0.0, 10000001.0,280.0,4003.0,0.0,"Vacuum","VAC_UPPER_HALVED");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES ("VAC_UPPER_CAVITY","SUBTRACT",0.0,0.0,0.0,"S",0.0,670.0,0.0,0.0, 10000001.0,1340.0,4003.0,0.0,"Vacuum","VAC_LOWER_HALVED");
INSERT INTO MOKKAELEMENTE_BOX VALUES ("","","","","I",0.0,-115.32,2000.0,0.0, 410.0,108.48,4000.0,-0.784,"Vacuum","VAC_BOX_CAVITY");

D.2.21  mag8.sql

# FLUX RETURN
INSERT INTO MOKKAELEMENTE_BOX VALUES ("","","","","S",0.0,-779.699,2000.0,0.0,1770.0,1498.0,4000.0,0.0, 0.0,0.0,0.0,0.0,"Iron","IRON_BOX");
INSERT INTO MOKKAELEMENTE_BOX VALUES ("","","","","S",0.0,-115.32,2000.0,0.0,400.0,108.48,4000.0,-0.784, 0.0,0.0,0.0,0.0,"Iron","IRON_BOX");
APPENDIX D. BDSIM AND MOKKA POST-COLLISION LINE MODEL

("IRON_BOX"","SUBTRACT",0.0,0.0,0.0,"S",0.0,374.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0, "Vacuum","VACUUM_BOX");

# COILS

INSERT INTO MOKKAELEMENT_BOX VALUES
("IRON_BOX"","SUBTRACT",1.0,0.5,0.0,"S",-325.0,-145.0,0.0,0.0,200.0,288.0,4001.0,0.0,"Copper","COIL_GAP_3");

INSERT INTO MOKKAELEMENT_BOX VALUES
("IRON_BOX"","SUBTRACT",1.0,0.5,0.0,"S",325.0,-145.0,0.0,0.0,200.0,288.0,4001.0,0.0,"Copper","COIL_GAP_4");

INSERT INTO MOKKAELEMENT_BOX VALUES
("IRON_BOX"","SUBTRACT",1.0,0.5,0.0,"S",325.0,893.0,0.0,0.0,200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_1");

INSERT INTO MOKKAELEMENT_BOX VALUES
("IRON_BOX"","SUBTRACT",1.0,0.5,0.0,"S",-325.0,893.0,0.0,0.0,200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_2");

INSERT INTO MOKKAELEMENT_BOX VALUES
("IRON_BOX"","SUBTRACT",1.0,0.5,0.0,"S",-325.0,-145.0,0.0,0.0,200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_3");

INSERT INTO MOKKAELEMENT_BOX VALUES
("IRON_BOX"","SUBTRACT",1.0,0.5,0.0,"S",-325.0,893.0,0.0,0.0,200.0,288.0,4000.0,0.0,"Copper","COIL_BOX_4");

# BEAM PIPE

INSERT INTO MOKKAELEMENT_ELLIPTICALTUBE VALUES
("","",0.0,0.0,1.0,"S",0.0,-64.597,2000.0,0.0,410.0,330.0,4000.0,-0.784,"Vacuum","STEEL_UPPER");

INSERT INTO MOKKAELEMENT_ELLIPTICALTUBE VALUES
("STEEL_UPPER","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0,400.0,320.0,4001.0,-0.784,"Vacuum","STEEL_UPPER_CA VITY");

INSERT INTO MOKKAELEMENT_ELLIPTICALTUBE VALUES
("STEEL_UPPER","SUBTRACT",0.0,0.0,0.0,"S",0.0,-160.0,0.0,0.0,10000000.0,320.0,4002.0,0.0,"Vacuum","STEEL_UPPER_HALVED");

INSERT INTO MOKKAELEMENT_ELLIPTICALTUBE VALUES
("","",0.0,0.0,1.0,"S",0.0,-176.277,2000.0,0.0,410.0,1350.0,4000.0,-0.784,"Vacuum","STEEL_LOWER");

INSERT INTO MOKKAELEMENT_ELLIPTICALTUBE VALUES
("STEEL_LOWER","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0,400.0,1340.0,4001.0,-0.784,"Vacuum","STEEL_LOWER_CA VITY");

INSERT INTO MOKKAELEMENT_ELLIPTICALTUBE VALUES
("STEEL_LOWER","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0,400.0,1340.0,4002.0,0.0,"Vacuum","STEEL_LOWER_HALVED");

INSERT INTO MOKKAELEMENT_BOX VALUES
("","",0.0,0.0,1.0,"S",0.0,-120.47,2000.0,0.0,410.0,111.68,4000.0,-0.784,"StainlessSteel","STEEL_BOX");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("STEEL_BOX","SUBTRACT",0.0,0.0,0.0,"S",0.0,0.0,0.0,0.0,
400.0,112.68,4001.0,-0.784,"Vacuum","STEEL_BOX_CAVITY");

#VACUUM CHAMBER
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("","","0.0,0.0,0.0,"I",0.0,-64.597,2000.0,0.0,
400.0,320.0,4000.0,-0.784,"Vacuum","VAC_UPPER_CAVITY");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("VAC_UPPER_CAVITY","SUBTRACT",0.0,0.0,1.0,"S",0.0,-160.0,0.0,0.0,
10000001.0,320.0,4003.0,0.0,"Vacuum","VAC_UPPER_HALVED");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("","","0.0,0.0,0.0,"I",0.0,-176.277,2000.0,0.0,
400.0,1340.0,4000.0,-0.784,"Vacuum","VAC_LOWER_CAVITY");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("VAC_LOWER_CAVITY","SUBTRACT",0.0,0.0,1.0,"S",0.0,670.0,0.0,0.0,
10000001.0,1340.0,4003.0,0.0,"Vacuum","VAC_LOWER_HALVED");
INSERT INTO MOKKAELEMENTB_BOX VALUES
("","","0.0,0.0,0.0,"I",0.0,-120.437,2000.0,0.0,400.0,111.68,4000.0,-0.784,
"Vacuum","VAC_BOX_CAVITY");

D.2.22 maindump.sql

INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("","","1.0,0.0,0.0,"S",0.0,0.0,5020.0,1840.0,1840.0,10000.0,0.0,
"StainlessSteel","JACKET");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("JACKET","",0.0,0.0,0.0,"S",0.0,0.0,0.0,1800.0,1800.0,10020.0,0.0,
"Vacuum","JACKET_HOLE");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("JACKET","",0.0,1.0,1.0,"S",0.0,0.0,0.0,1800.0,1800.0,10000.0,0.0,
"Water","WATER_TUBE");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("","","1.0,0.0,0.0,"S",0.0,0.0,10030.0,1840.0,1840.0,20.0,0.0,
"StainlessSteel","ENDCAP");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("","","1.0,0.0,0.0,"S",0.0,0.0,10.0,1840.0,1840.0,20.0,0.0,
"StainlessSteel","STARTCAP");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("STARTCAP","",1.0,0.0,0.0,"S",0.0,0.0,300.0,300.0,300.0,40.0,0.0,
"Vacuum","STARTCAP_HOLE");
INSERT INTO MOKKAELEMENTE_ELLIPTICALTUBE VALUES
("STARTCAP","",0.0,1.0,0.0,"S",0.0,0.0,0.0,0.300,0.300,0.20,0.0,0.0,
"TitaniumAlloy","STARTCAP_HOLE");
Bibliography


[33] G. Moortgat-Pick et. al. The Importance of Positron Polarization and the Detrimental Effects of the Beam/Bremmstrahlung on the Measurement of Supersymmetric Particle Masses and other Parameters, presented at the Linear Collider Workshop 2005, Colorado University, Boulder, USA.


[59] H. Braun et. al. CLIC 2008 Parameters: Drive Beam Generation and Decelera-

[60] A. Ferrari, V. Ziemann, R.B. Appleby, M.D. Salt, Conceptual design of a beam line for post-collision extraction and diagnostics at the multi-TeV Compact Linear Collider Physical Review Special Topics - Accelerators and Beams, 12, 021001 (2009).


[74] K. Witterung, The PIN-diode Beam Loss Monitor System at HERA, DESY-HERA-00-03, Deutsches Elektronen Synchrotron, DESY, Hamburg, Germany.


[80] Appleby, Keller, Markiewicz, Seryi, Walz, Sugahara, The International Linear Collider Beam Dumps 2005 ALCPG & ILC Workshops - Snowmass, U.S.A.


[83] P. Chomaz, Collective Excitations in Nuclei, Ecole Joliot Curie (1997), GANIL P 98 01, PB 5027, 14076 CAEN Cedex 5, FRANCE.


[101] Professor Stephen Watts, University of Manchester, Manchester, United Kingdom, Personal Communication.


[103] O. Dadoun, P. Bambade, *Backscattering of Secondary Particles into the ILC Detectors from Beam Losses along the Extraction Line*, Proceeding of PAC07, Albuquerque, New Mexico, USA.


