Machine Protection and Beam Quality during the LHC Injection Process

Mag. Verena Kain

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Univ.-Prof. Dr. Walter Kutschera
Institut für Kernphysik und Isotopenforschung
Universtität Wien

Dr. Rüdiger Schmidt
Europäisches Kernforschungszentrum
CERN/AB-CO, Genf

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Kurzfassung


Bevor die Protonen in den LHC injiziert werden, werden sie im SPS auf eine Energie von 450 GeV vorbeschleunigt und dann durch 3 km lange Transferlinien vom SPS zum LHC gelenkt. Die Strahlintensität bei Injektionsenergie ist bereits über eine Größenordnung über der Materialzerstörungsschwelle.

Diese Dissertation beschäftigt sich mit dem Maschinenschutzsystem für den Injektionsprozess des LHC. Der Schwerpunkt liegt auf einer detaillierten Spezifikation, Beschreibung und Performance-Validierung des Schutzsystems für den Transfer vom SPS und die Injektion in den LHC.

Die Konsequenzen von Strahlverlust in Material wurden numerisch berechnet, um den Schwellenwert für die Teilchenintensität zu definieren, die zu Schäden in typischen Materialien des Beschleunigers führt. Die Simulationsmethode wurde in einem speziellen Experiment, einem kontrollierten Materialbeschädigungstest, erfolgreich überprüft.


Die Resultate dieser Arbeit zeigen, dass der LHC mit dem vorgeschlagenen Schutzsystem ausreichend geschützt werden kann, und sie liefern detaillierte Spezifikationen für
Überwachungssysteme, Logik des Interlocksysteems und die Anforderungen für das passive Schutzsystem.
Abstract

The LHC proton beams with a momentum of 7 TeV/c per proton have an unprecedented energy of 360 MJ/beam, sufficient to heat and melt 500 kg of copper. Already at the injection energy of 450 GeV, accidental deflection of the beam into equipment would have a devastating effect. A particularly critical operation is the transfer of the beam from the SPS to the LHC, and the injection into the LHC ring, with the energy stored in the beam one order of magnitude above damage level.

This thesis is concerned with the machine protection system for the LHC injection process. It focuses on a detailed specification, description and performance validation of the protection systems for the transfer from the SPS and the injection into the LHC.

In order to provide the correct level of protection, the consequences of beam accidentally directed into equipment were studied. The limit for beam induced equipment damage at injection energy was derived numerically. The simulation methodology was successfully cross-checked in a dedicated experiment with beam, a controlled damage test.

Numerical simulations were used to design active (equipment monitoring to ensure correct settings) and passive (collimators and absorbers) protection systems, and to analyse their performance. The simulation methodology was based on two common computer codes: energy deposition simulations were done with FLUKA and particle tracking was done with the tracking module of MAD-X. A sophisticated simulation environment was set up to randomly sample the large parameter space needed to define the possible equipment states and to allow realistic failure simulations. Geometrical and optical mismatch, orbit tolerances, mechanical tolerances, power converter ripples, misalignment of elements and trajectory correction were all taken into account. The required protection settings, expected beam loss levels and achievable overall protection level for the injection process were evaluated with these simulation techniques. Beam quality aspects for the injected beam were also treated, quantifying the expected emittance degradation during the injection process. The results of the commissioning of one of the two transfer lines between the SPS and the LHC are summarised, including an experiment to align a collimator jaw with beam.

The results obtained demonstrate that the LHC can be fully protected with the proposed systems, and provide detailed specifications for the surveillance, interlocking and passive protection device performance requirements.
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Introduction

CERN’s Large Hadron Collider (LHC) will provide proton-proton collisions at a center-of-mass energy of 14 TeV and a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. It will be installed in the existing LEP tunnel and will reuse the existing CERN accelerators as injectors. In order to reach the required magnetic field strengths, superconducting magnets cooled with superfluid helium are used.

The energy stored in the beam of 360 MJ is a factor of 100 above that in other machines and the transverse energy density is a factor of 1000 higher. Accidental beam loss can lead to severe damage and long down-times. A sophisticated Machine Protection System is required to safely operate the LHC.

The intensity of the 450 GeV beam injected into the LHC, is already more than one order of magnitude above the equipment damage level. A protection system for the LHC injection is mandatory in view of the different possible failure scenarios associated with this ultra-rapid transfer and injection process and the very small aperture of the transfer lines and the LHC at injection energy.

This thesis focuses on a detailed specification, description and performance validation of the protection systems for the LHC injection process. Numerical simulations were used to design active and passive protection systems. The simulation methodology was based on two widely used computer codes: energy deposition simulations were done with FLUKA and particle tracking was done with the tracking module of MAD-X. A sophisticated environment was set up to randomly sample the large parameter space needed to define the possible equipment states and to allow realistic failure simulations. The achievable overall protection level for the injection process was evaluated with these simulation techniques. Beam quality aspects for the injected beam are also discussed and the results of the commissioning of one of the two transfer lines to the LHC are summarised.

The LHC accelerator and its main challenges are presented in Chapter 1. The main concepts and the functionality of the LHC Machine Protection System are introduced.

Chapter 2 summarises the main accelerator physics concepts used in this thesis and outlines the derivations of the most important formulae of transverse linear optics.

Chapter 3 describes the pre-injector chain of the LHC with the main focus on the last stage, where the beam is extracted from the SPS pre-injector, transferred through the LHC transfer lines and injected into the LHC. Performance requirements for all the stages are given.

The assumed equipment damage limit in terms of beam loss is derived in Chapter 4. The validity of this limit, which was obtained with static energy deposition calculations with FLUKA, was cross-checked in a controlled damage test with beam. The results of
the experiment and the comparison with simulations are presented.

Chapter 5 gives a detailed description of the machine protection strategy for the injection process, introducing the concepts of interlocking, active protection with monitoring systems and passive protection with absorbers and collimators. An accident during the high intensity commissioning of one of the SPS extractions is discussed. The concepts and proposed architecture of the important interlocking system for the transfer and injection process are explained.

In Chapter 7 emittance growth and attenuation of 450 GeV and 7 TeV proton beams in low-Z absorber elements are treated. The results are input for design studies of passive protection devices.

One of the passive protection systems involved in the injection process, the transfer line collimators, is described in Chapter 8. The results of the studies made to define the transfer line collimation scheme, the number of collimators, the basic collimator design and the required setting of the movable collimator jaws are presented.

In Chapter 9 the required setting of another passive protection system in the injection region to protect the LHC aperture is evaluated with particle tracking simulations.

The overall protection level which can be achieved with the systems proposed in the previous chapters is derived in Chapter 10. All error sources and setting-up tolerances for the passive protection systems were taken into account. Required reaction times of magnet power supply surveillance systems in case of powering failures are specified.

In Chapter 11 analytical calculations and the results of numerical simulations for expected beam emittance growth and beam tail repopulation from errors at LHC injection are presented and discussed.

Chapter 12 describes the outcome of measurements made for the commissioning of one of the LHC transfer lines with beam in autumn 2004. The simulation methodology used throughout the thesis was used for the preparation of the tests and analysis of the commissioning results. A beam-based method for transfer line collimator alignment was developed and tested during the commissioning.

In chapter 13 the main results of this thesis are summarised, together with the conclusions.
1

The LHC and its Protection System

1.1 The Large Hadron Collider at CERN

The Large Hadron Collider (LHC), which is being constructed at CERN, the European Organization for Nuclear Research near Geneva, Switzerland, will be the world’s most advanced high-energy physics tool, see Fig. 1.1. Consisting of two interleaved storage rings, each with a circumference of 26.7 km, it will provide proton-proton collisions at a centre-of-mass energy of 14 TeV and a luminosity (interaction rate per cross section) of $10^{34} \text{cm}^{-2}\text{s}^{-1}$ [1].

![Image of the LHC ring](image)

Figure 1.1: The LHC ring is situated in a tunnel crossing the French-Swiss border and lying largely beneath the plain between the West end of the lake of Geneva and the Jura mountains.

The motivation for building more and more energetic accelerators comes firstly from De Broglie’s relation $\lambda = h/p$, which relates the momentum of a particle to its quantum mechanical wavelength: in order to explore ever smaller structures, more and more energetic particles are needed. The exploration of finer and finer structures has lead to the
discovery of more massive short-lived particles. According to Einstein’s law $E = mc^2$, more massive particles need higher energies for their production.

One of the main goals of the LHC experiments in proton-proton-collisions is the discovery and study of the Higgs particle. The existence of this boson would be a strong indication of the Higgs field, which has been postulated to explain the mass differences between different particles. The stronger the interaction between a particle and the Higgs field, the heavier the particle.

This work will focus solely on the proton operation of the LHC. However, it is also planned to collide heavy nuclei (primarily Pb). The LHC will accelerate fully stripped ions and bring them into collision at an energy of about 1150 TeV (7 TeV per charge corresponding to 2.76 TeV/u) with a luminosity of more than $10^{27}$ cm$^{-2}$s$^{-1}$. It is expected that these ion collisions could cause phase transitions from nuclear matter into a quark-gluon plasma as might have existed $10^{-6}$ s after the Big Bang.

To analyse these proton-proton- (p-p) and ion-ion-collisions there will be 4 experiments. ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid) are particle detectors for proton-proton collisions, ALICE is a detector to study ion collisions and LHC-b will focus on the study of B physics.

The LHC will be installed in the already existing tunnel of the former Large Electron Positron collider (LEP) and will make use of the existing injector chain. Proton beams will be injected into the LHC at an energy of 450 GeV and accelerated to 7 TeV.

![Image of LHC layout](image_url)

Figure 1.2: Layout of the LHC.

The achievable LHC collision energy is limited by the technical feasibility of strong magnetic fields for the main dipole magnets. 1232 superconducting main dipole magnets with a nominal field of 8.3 T are required in the LHC to store two proton beams with an energy up to 7 TeV in the accelerator ring with the bending radius given by the
LEP tunnel. In total there will be about 8000 superconducting magnets which will be arranged in about 1700 electric powering circuits, and which will operate in superfluid helium (1.9 K). The anti-parallel guiding fields for the counter-rotating beams are provided by twin-aperture magnets. These magnets, necessitating only one cryostat, facilitate equipment installation in the limited space of the LEP tunnel at the expense of a technically challenging design. The nominal horizontal separation of the two beams is 194 mm.

The LHC consists of eight bending sections (arcs) separated by eight straight insertion regions (IRs). Fig. 1.2 shows a schematic layout of the LHC. Each arc is composed of 46 regular “half-cells” (see Fig. 1.3) with three 14.3 m-long dipoles and one 3.1 m-long quadrupole. The beams cross from one beam aperture to the other at the experiments’ locations in IR 1, 2, 5 and 8. In the remaining IRs there will be no beam crossings. IR 3 and 7 will be used for the collimation system. The other IRs will contain the beam dump system, RF and beam instrumentation.

![Figure 1.3: A half-cell in the arcs of LHC consisting of three main dipole magnets and one quadrupole magnet, together with various other elements.](image)

### 1.1.1 The LHC operational cycle

The LHC is a collider with a well-defined operational cycle. The nominal cycle with beam can be roughly divided into the phases filling, ramping, squeeze and physics store. The filling of both rings will take about 15 minutes; more details can be found in Chapter 3. The circulating beams are kept separated at this stage.

Ramping consists of acceleration of the beam from 450 GeV to 7 TeV, with a simultaneous ramping of the magnetic guide field according to the particle momentum change, and takes about 30 minutes.

Before the beams are brought into collision, the magnetic fields are changed in the experimental IRs to minimise the beam size at the collision point and to maximise the luminosity during the physics store. This “optics squeeze” takes between 5 to 10 minutes. With the beams colliding, the physics store can last between 5 to 15 hours under normal conditions and is terminated by extracting the beam in IR 6, where the beam is directed onto the beam dump.

Fig. 1.4 illustrates the magnet cycle associated with the different phases as time versus main bend current.
1.2 The Machine Protection System of the LHC

The LHC will enter a new regime in terms of beam energy and intensity. The proton momentum will be a factor of 7 above any existing accelerator, the energy stored in each beam a factor of 100 higher and the transverse energy density of the beam even a factor of 1000, see Fig. 1.5. The energy stored in one beam (about 360 MJ) is sufficient to melt 500 kg of Cu, initially at 1.9 K. Uncontrolled release of even a small fraction of the beam energy could obviously lead to severe equipment damage and long down-times. A machine protection system is therefore essential to safely operate the LHC.

Fig. 1.6 summarises the functionality of the LHC machine protection system consisting of active (interlocking of monitoring systems) and passive protection elements (collimators, absorbers) and the beam dump.

The purpose of the machine protection system is to protect the LHC against failures which could lead to accidental beam loss. The origin of failures is equipment in a wrong state - either due to wrong equipment settings (wrong voltage reference value in a power supply, vacuum valves closed instead of open, etc.) or a hardware problem causing e.g. an accidental switch-off of a device such as a magnet power supply. The state of the equipment has an effect on the beam; examples are distortion of the beam trajectory, beam particle scattering or creation of beam instabilities. In principle there are two ways to detect a failure and “actively” prevent damage - by monitoring directly the hardware, e.g. the magnet current, or by monitoring beam parameters, e.g. the beam position.
1.2. The Machine Protection System of the LHC

![Graph of energy stored versus beam momentum for different accelerators](image1)

*Figure 1.5: Energy stored in the beam versus beam momentum for different accelerators (courtesy R. Assmann).*

![Diagram of machine protection systems](image2)

*Figure 1.6: The functionality of the machine protection systems (courtesy B. Goddard).*
Failures

Each phase in the operational cycle of the LHC is associated with a set of possible failures.

Failures which can occur with circulating beam (after injection and before extraction) are classified according to the time which is needed to lead to beam loss [3, 4]. Normally this takes many turns, hence the naming “multi-turn failures”. With the 1700 electrical circuits, faults of magnets and/or the powering system are the most likely cause for multi-turn failures. The fastest mechanism among these is a power supply fault of the normal conducting separation/recombination-dipole (D1) in the experiment insertions IR 1 and IR 5. In this case the tails of a Gaussian particle distribution would touch the collimators in the cleaning insertions after about 10 turns ($\sim 890 \mu s$) [5, 6, 7, 8].

Also possible are much faster “single-turn failures”. An example would be a fast-pulsed magnet (kicker) erroneously deflecting the circulating beam in an unsynchronised way. Many potentially dangerous failures can arise during the LHC injection and the extraction (beam dumping) process. Undetected failures during these special transfer processes can lead to beam loss in less than one turn and beam-based surveillance systems like Beam Loss Monitors (BLMs) cannot be used. The classification for these failures is done according to the time constants for the change of critical parameters of equipment, like the current in a magnet power supply. The different possible extraction failures and the consequences for the LHC have been discussed in [9, 10, 11, 12]. The possible failures during the injection process are comprehensively treated in this thesis.

Monitoring

The effects on the hardware in case of failures can be detected by dedicated monitoring systems. These include software based settings monitoring for example for movable devices, the magnet Powering Interlock Controller (PIC), the quench protection system for superconducting magnets and magnet current monitoring. For the circulating beam, beam-based surveillance with BLMs, Beam Position Monitors (BPMs) or Beam Current Transformers (BCTs) detects deviations from the nominal values and produces an interlock. In case of the injected or extracted beam the beam monitoring signals cannot influence the transfer process, and can only be used to inhibit the next injection or extraction.

The Beam Interlock System

The different hardware and beam surveillance systems are connected to the Beam Interlock System (BIS) as inputs of beam interlock controllers (BICs). In the LHC ring, the BIS removes the “beam permit” in case one of these inputs transmits the signal FALSE, resulting in a beam dump request. The beam is then dumped within 270 $\mu s$. Sixteen BICs, 2 BICs per IR, are installed for the LHC beam interlock signals. These BICs are linked to each other with optical fibers, called “beam permit loops”. Two additional BICs, the injection BICs, are installed in the injection IRs 2 and 8. The extraction regions in the SPS and the transfer lines between the SPS and the LHC use BICs based on the LHC solution to actively protect the injection process. These BICs inhibit or permit the SPS extraction/LHC injection depending on the state of the user inputs. A
detailed description of the interlocking system for the LHC transfer and injection is given in Chapter 5.

**Beam-Cleaning Collimators**

Collimators are movable blocks of material designed to intercept the beam particles. There are two types of collimators; both play a role in protecting the LHC. The largest fraction of the LHC collimators were designed for the purpose of “beam cleaning”.

The LHC relies on superconducting magnets, where only a small fraction of the circulating beam lost (at 7 TeV: $10^{-8} - 10^{-7}$ [13]) could already produce a quench. Imperfections such as magnetic field errors, nuclear interactions at the interactions points or beam-gas scattering lead to the formation of a primary particle halo and thus to so-called continuous losses. Continuous losses normally do not lead to damage but possibly quench magnets; beam cleaning is therefore essential for efficient LHC operation. In insertion IR 7 cleaning will be performed to remove halo particles with large amplitudes, which could otherwise possibly be deposited in superconducting magnets. In insertion IR 3 particles with a large momentum offset are removed from the beam. Both cleaning systems are based on two-stage cleaning, using primary and secondary collimators. The secondary collimators are to capture the secondary halo generated in the primary collimators due to scattering [14, 15, 16]. The collimators will define the aperture of the accelerator throughout the entire cycle of the LHC for circulating beam, to restrict losses to the cleaning insertions.

**Passive Protection**

The other type of collimators are dedicated protection devices which cover the fastest and hence most dangerous failures.

The injection and extraction processes involve kicker magnets and potentially fast changing dipole magnets. Some failures of these elements cannot be covered by monitoring systems, as the required reaction time is too short to actively remove the beam (ultra-fast failures). Passive protection devices are required. For example, to protect the LHC aperture against failures of the LHC extraction kickers in IR 6, a 6 m long movable graphite absorber is installed in front of the superconducting quadrupole Q4. In addition, a fixed absorber is placed directly in front of the extraction septum MSD.

During the injection process, failures can lead to beam loss on the LHC aperture before reaching the beam cleaning insertions. Dedicated passive protection systems (movable collimators, absorbers or fixed masks) in the transfer lines and injection regions are used to capture the beam which could otherwise damage LHC machine elements. The passive protection systems required for the injection process are described in detail in Chapter 8 and 9.
2

Accelerator Physics Basics

In this chapter the basic concepts of accelerator physics for transverse beam dynamics are introduced. Important relations and formulae of the physics of high energy particle accelerators frequently used in this thesis are presented. Complementary information can be found in [17, 18, 19, 20, 21].

2.1 Introduction

Charged particles are accelerated by electromagnetic fields. The driving force is the Lorentz force:

\[ \vec{F} = e \cdot (\vec{E} + \vec{\nu} \times \vec{B}) \]  \hspace{1cm} (2.1)

Only electric fields lead to an increased energy with \( \mathcal{E} = \int \vec{F} \cdot d\vec{r} \) for a particle with charge \( e \).

The geometry of the accelerator determines the design orbit. To keep the particles around the design orbit, which is generally curved, bending and focusing is needed.

The particles in high energy accelerators have velocities \( |\vec{v}| \sim c \). In this case

\[ |\vec{E}| = c \cdot |\vec{B}| \]  \hspace{1cm} (2.2)

such that 1 Tesla corresponds to \( 3 \cdot 10^8 \) V/m. Macroscopic electric fields of this strength are technically not feasible. High energy accelerators therefore rely essentially only on magnetic fields for bending and focusing.

In the following the equation of motion for the transverse motion of a particle in an accelerator will be derived by expressing the magnetic field in the reference frame of the particle and will be solved for the linearised equation.

2.1.1 The magnetic field seen by the beam

The magnetic field is derived from the solution of the Maxwell equations (2.3) - (2.6), which will be solved in the reference frame of the beam and at the location of the beam for the ideal situation that the magnetic field is longitudinally homogeneous and perpendicular to the particle velocity. Fig. 2.1 shows the beam reference system, where the
s-axis is tangential to the particle trajectory.

$$\nabla \vec{E} = \frac{\rho}{\varepsilon_0}$$  \hspace{1cm} (2.3)

$$\nabla \vec{B} = 0$$  \hspace{1cm} (2.4)

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$  \hspace{1cm} (2.5)

$$\nabla \times \vec{B} = \mu_0 \vec{j} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$  \hspace{1cm} (2.6)

![Beam reference system](image)

Figure 2.1: Beam reference system. s is the longitudinal coordinate; x and y are the transverse coordinates.

The Maxwell equations in the magnet-current-free region in the beam pipe simplify to

$$\nabla \times \vec{B} = 0 \rightarrow \vec{B} = -\nabla \phi$$  \hspace{1cm} (2.7)

$$\nabla \vec{B} = 0 \rightarrow \nabla^2 \phi = 0$$  \hspace{1cm} (2.8)

with the magnetic scalar potential $\phi$ being the solution to the Laplace’s equation. The general solution for $\phi$ can be written as

$$\phi(x, y) = Re \sum_{m=0}^{\infty} iC_m (x + iy)^m$$  \hspace{1cm} (2.9)

where $C_m$ is a (complex) constant determined by the boundary conditions. The magnetic field is then

$$B_x = -\frac{\partial \phi}{\partial x} = -Re \sum_{m=1}^{\infty} mc_m (x + iy)^{m-1}$$  \hspace{1cm} (2.10)

$$B_y = -\frac{\partial \phi}{\partial y} = -Re \sum_{m=1}^{\infty} imC_m (x + iy)^{m-1}$$  \hspace{1cm} (2.11)

The general multipole expansion for a two-dimensional magnetic field in a current-free region is the combination of equations (2.10) and (2.11) [19]:

$$B_y + iB_x = -\sum_{m=1}^{\infty} imC_m (x + iy)^{m-1}$$  \hspace{1cm} (2.12)
Since
\[
-\imath mc^2 = \frac{1}{(m - 1)!} \left[ \frac{\partial^{m-1} B_y}{\partial x^{m-1}} \bigg|_{x \to -0} + \imath \frac{\partial^{m-1} B_x}{\partial x^{m-1}} \bigg|_{x \to -0} \right]
\]
equation (2.12) yields
\[
B_y + \imath B_x = \sum_{m=0}^{\infty} \frac{1}{m!} \left( B^{(m)} + \imath \tilde{B}^{(m)} \right)(x + \imath y)^m
\]
where
\[
B^{(m)} = \frac{\partial^m B_y}{\partial x^m} \bigg|_{x \to -0} ; \quad \tilde{B}^{(m)} = \frac{\partial^m B_x}{\partial x^m} \bigg|_{x \to -0}
\]
Writing out the first terms gives
\[
B_y = B_0 + B'x - \tilde{B}'y + \frac{B''}{2}(x^2 - y^2) - \tilde{B}''xy + \ldots
\]
\[
B_x = \tilde{B}_0 + \tilde{B}'x + B'y + \frac{\tilde{B}''}{2}(x^2 - y^2) + B''xy + \ldots
\]
The terms without wiggle are called “normal” terms, the others “skew” terms. The coefficients with subscript 0 are pure dipole terms, the ones linear in x or z are quadrupole terms, the quadratic terms are sextupole terms, etc.

<table>
<thead>
<tr>
<th>multipole</th>
<th>definition</th>
<th>effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>dipole</td>
<td>$\frac{1}{R} = \frac{z}{p} B_{y0}$</td>
<td>bending</td>
</tr>
<tr>
<td>quadrupole</td>
<td>$k = \frac{z}{p} B'$</td>
<td>focusing</td>
</tr>
<tr>
<td>sextupole</td>
<td>$m = \frac{z}{p} B''$</td>
<td>compensation of chromaticity*</td>
</tr>
</tbody>
</table>

Table 2.1: The most important multipole fields and their main effects on the beam. *Chromaticity refers to the dependence of the focusing function on momentum.

### 2.2 Linear Transverse Beam Dynamics

#### 2.2.1 Particle trajectory equations of motion in accelerators

We can express the particle trajectory $\vec{r}(t)$ in terms of a reference trajectory $\vec{r}_0(t)$ of a reference particle with momentum $\vec{p}_0$ that passes through the symmetry of all the idealised magnetic fields and constant energy (no acceleration, $\vec{E} = \vec{0}$). In this way equation the equation of motion
\[
\frac{d\vec{p}}{dt} = \frac{d}{dt} (m_0 \gamma \vec{v}) = \vec{F} = e(\vec{E} + \vec{v} \times \vec{B})
\]
leads to

\[ x'' = \frac{1}{\rho} \left( 1 + \frac{x}{\rho} \right) - \left( 1 + \frac{x}{\rho} \right) \frac{eB_y}{p} + y \frac{eB_z}{p} \left( 1 + \frac{x}{\rho} \right) \]  
(2.19)

\[ y'' = \left( 1 + \frac{x}{\rho} \right) \frac{eB_x}{p} - x' \frac{eB_z}{p} \left( 1 + \frac{x}{\rho} \right) \]  
(2.20)

\[ l' = \left( 1 + \frac{x}{\rho} \right) \]  
(2.21)

where \( \rho \) is the radius of the curvature, \( l \) is the path length on the real trajectory and \( x' = dx/ds \).

The magnetic field is now included as derived above. For simplicity only the idealised normal dipole and quadrupole fields are used in the expansion of the field about the reference orbit.

\[ B_y = B_0 + B_x + \Delta B_y(x, y, s) \]  
(2.22)

\[ B_x = B_0' + \Delta B_x(x, y, s) \]  
(2.23)

\[ B_z = \Delta B_1(x, y, s) \]  
(2.24)

This gives for (2.19), (2.20) and (2.21)

\[ x'' + x \left( k(1 - \delta) + \frac{1 - 2\delta}{\rho^2} \right) = \frac{\delta(1 - \delta)}{\rho} - \frac{\Delta B_y(x, y, s)}{B_0 \rho} \left( 1 - \delta + \frac{2x}{\rho} \right) \]

\[ + \quad y' \frac{\Delta B_x(x, y, s)}{B_0 \rho} \]

\[ - \quad x^2 \left( \frac{2k}{\rho} + \frac{1}{\rho^2} \right) + \frac{y'^2 k}{2\rho} \]  
(2.25)
\[ y'' - y k(1 - \delta) = \frac{\Delta B_s(x, y, s)}{B_0 \rho} \left( 1 - \delta + \frac{2x}{\rho} \right) \]
\[ - x' (1 - \delta) \frac{\Delta B_s(x, y, s)}{B_0 \rho} + xy \left( \frac{2k}{\rho} \right) \]  
(2.26)
\[ l' = \left( 1 + \frac{x}{\rho} \right) \]  
(2.27)

with the quadrupole strength \( k = eB^l/p_0 \) and the relative momentum deviation \( \delta = (p - p_0)/p_0 \). Only terms up to second order are kept in products of \( x, y, x', y' \) and \( \Delta \tilde{B} \). The linearised equations with \( \Delta \tilde{B} = 0 \) read
\[ x'' + x \left( k + \frac{1}{\rho^2} \right) = \frac{\delta}{\rho(s)} \]  
(2.28)
\[ y'' - y k = 0 \]  
(2.29)

### 2.2.2 Betatron oscillations

For \( \delta = 0 \) the differential equations (2.28) and (2.29) are of a Hill’s equation type; \( K(s) \) represents the \( s \)-dependent focusing properties of the accelerator.
\[ z''(s) - K(s) z(s) = 0 \]  
(2.30)

where \( K(s) = K(s + L) \) is periodic over the length \( L \) (\( z \) stands for \( x \) or \( y \)). The solution of equation (2.30) can be written as a linear combination of a cosine-like trajectory \( C(s) \), with \( C(s_0) = 1 \) and \( C'(s_0) = 0 \), and a sine-like one \( S(s) \), with \( S(s_0) = 0 \) and \( S'(s_0) = 1 \):
\[
\begin{pmatrix}
  z \\
  z'
\end{pmatrix}_s = 
\begin{pmatrix}
  C(s) & S(s) \\
  C'(s) & S'(s)
\end{pmatrix} \cdot 
\begin{pmatrix}
  z \\
  z'
\end{pmatrix}_\infty
\]  
(2.31)

The matrix in equation (2.31) is called \( M_{s_0 \rightarrow s} \), the transfer matrix from \( s \) to \( s_0 \), and has the same periodicity in its elements as \( K(s) \). One of its characteristics is \(| M | = 1 \). It can be written as
\[ M = I \cdot \cos \mu + \begin{pmatrix}
\alpha(s) & \beta(s) \\
-\gamma(s) & -\alpha(s)
\end{pmatrix} \cdot \sin \mu \]  
(2.32)

where \( I \) is the unitary matrix and \( \mu \) is the characteristic coefficient of the differential equation. This representation of \( M \) is known as Twiss representation. \( M \)’s characteristics allow to eliminate \( \gamma(s) \).
\[ \gamma(s) = \frac{1 + \alpha^2(s)}{\beta(s)} \]  
(2.33)

The periodicity of \( M \) in \( z_{s+L} = M \cdot z_s = e^{i\mu} z_s \) together with equation (2.32) leads to
\[ \frac{z'}{z} = \frac{\pm i - \alpha}{\beta} \]  
(2.34)
Differentiating equation (2.34) logarithmically, inserting the Hill’s equation (2.30) and using the fact that the elements of \( \mathbf{M}(s) \) are real, gives

\[
\alpha(s) = -\frac{1}{2} \beta'(s) \tag{2.35}
\]

and a nonlinear differential equation for \( \beta(s) \)

\[
\frac{1}{2} \beta \beta'' - \frac{1}{4} \beta'^2 + K \beta^2 = 1. \tag{2.36}
\]

All the elements of the transfer matrix \( \mathbf{M} \) are thus expressed in terms of a single function \( \beta(s) \), the well known beta function, and a phase parameter \( \mu \). The beta function has the unit [m].

The solution of the Hill’s equation can now easily be obtained by inserting equation (2.35) in equation (2.34) and integrating. The result is

\[
z_{1,2}(s) = a \sqrt{\beta(s)} e^{\pm i \psi(s)} \tag{2.37}
\]

with \( \psi'(s) = \frac{1}{\beta(s)} \) and \( a = \text{const.} \). The characteristic coefficient \( \mu \) of the differential equation is the phase advance per period \( L \).

\[
\mu = \int_s^{s+L} \frac{dt}{\beta(t)} \tag{2.38}
\]

A particle trajectory is described by the real part of equation (2.37).

\[
z(s) = a \sqrt{\beta(s)} \cdot \cos(\psi(s) - \phi) \tag{2.39}
\]

Equation (2.39) represents the so-called betatron oscillation around the reference orbit. The amplitude as well as the wavelength \( \lambda(s) = 2\pi \beta(s) \) of this oscillation depend on \( \beta(s) \), the beta function. The derivative of (2.39) is the angle of the trajectory

\[
z'(s) = -\frac{a}{\sqrt{\beta}} [\alpha(s) \cdot \cos(\psi(s) + \phi) + \sin(\psi(s) + \phi)] \tag{2.40}
\]

The tune \( Q \) of the accelerator is defined as the number of betatron oscillations per period \( L \), with \( L \) as the circumference of the accelerator.

\[
Q := \frac{1}{2\pi} \int_0^L \frac{ds}{\beta(s)} \tag{2.41}
\]

The functions \( \alpha, \beta \) and \( \psi \) are called the lattice or optics functions, and are only defined by the magnetic structure of the accelerator and not by the beam.

With \( z(0) = z_0 \), \( z'(0) = z'_0 \), \( \beta(0) = \beta_0 \), \( \alpha(0) = \alpha_0 \) and \( \psi(0) = 0 \) at \( s_0 \) one can easily find an expression for the integration constant \( \phi \) (or more accurately for \( \sin \phi \) and \( \cos \phi \)). Equations (2.39) and (2.40) can be written as:

\[
\begin{pmatrix}
  z(s) \\
  z'(s)
\end{pmatrix}
= A \cdot 
\begin{pmatrix}
  z_0 \\
  z'_0
\end{pmatrix} \tag{2.42}
\]
Comparing equation (2.42) with equation (2.31) indicates that the matrix \( A \) of equation (2.42) is the transfer matrix \( M \)

\[
M = A
\]  

(2.43)

and therefore

\[
M = \begin{pmatrix}
\sqrt{\frac{\beta}{\beta_0}} \cos \Delta \psi + \alpha_0 \sin \Delta \psi & \sqrt{\frac{\beta}{\beta_0}} \sin \Delta \psi \\
-\frac{[1+\alpha \alpha] \sin \Delta \psi + [\alpha-\alpha \alpha] \cos \Delta \psi}{\sqrt{\beta_0 \beta}} & \sqrt{\frac{\beta}{\beta_0}} \sin \Delta \psi - \alpha \sin \Delta \psi
\end{pmatrix}
\]  

(2.44)

2.2.3 The closed orbit

Particle trajectories in a circular accelerator are not necessarily closed. A trajectory that is not closed implies that the particle having coordinates \((x_0, y_0, s_0)\) at \( s_0 \) will have \((x, y, s)\) after one turn with \( x \neq x_0 \) and \( y \neq y_0 \). This is due to the fact that the tune \( Q \) of equation (2.41) must not be either integer or half-integer or any combination \( n/m \) with \( n \) and \( m \) small integers to avoid dangerous resonance conditions which could lead to unstable particle motion and possibly to beam loss.

The special trajectory with \( x = x_0 \) and \( y = y_0 \) is called the closed orbit. In general, particles’ trajectories are betatron oscillations around this closed orbit.

2.2.4 Emittance

The solution of the equation of motion given in equations (2.39) and (2.40) defines an invariant of motion. The trajectory of a particle in the e.g. horizontal phase-space of \((x, x')\) is an ellipse. Its equation is

\[
\gamma x^2 + 2\alpha_0 xx' + \beta x'^2 = a^2
\]

(2.45)

where \( \pi a^2 \) is the area of the ellipse. One defines the emittance \( \varepsilon_i \) of the particle trajectory with \( \sqrt{\varepsilon_i} = a \). This invariant, the so called Courant-Snyder Invariant, is a characteristic of a single particle motion. Fig. 2.3 shows the phase-ellipse in \( x \) and \( x' \).

The term emittance is also used for a beam characteristic in connection with the size of the beam (statistical emittance). The emittance of a beam is defined as

\[
\varepsilon_{\text{stat}} \equiv \varepsilon = \frac{\sigma^2}{\beta}
\]

(2.46)

where \( \sigma \) is the variance of the particles’ Gaussian distribution in \( x \) or \( y \). Due to Liouville’s theorem, which says that the phase-space volume is constant in time if the particles obey canonical equations of motion, the statistical emittance also remains constant.

The unit of the emittance used in this thesis is [\( \mu \text{m} \)]; note that other conventions frequently use [\( \mu \text{m mrad} \)] for the emittance according to Fig. 2.3. It is worthwhile mentioning that the beam size at a position \( s \) in the accelerator for a given emittance \( \varepsilon \) is obtained according to equation (2.46) with \( \beta(s) \) at this location

\[
\sigma = \sqrt{\varepsilon \beta(s)}
\]

(2.47)
The emittance varies with energy. The conserved quantity, the *normalised emittance*, is given by

\[ \varepsilon_n = \gamma \beta_{rel} \varepsilon \]  

(2.48)

with \( \gamma \) the Lorentz factor and \( \beta_{rel} \) the relativistic beta.

### 2.2.5 Normalised coordinates

The trajectory of a particle in phase-space \((z, z')\) is an ellipse. For some applications the concept of the phase-space is very useful. The following transformation transforms the elliptical trajectory into a circular one. The resulting transformed coordinates are called normalised coordinates.

\[
\begin{pmatrix}
\tilde{z}(s) \\
\tilde{z}'(s)
\end{pmatrix}
= \begin{pmatrix}
\frac{1}{\sqrt{\beta}} & 0 \\
0 & \sqrt{\beta}
\end{pmatrix}
\begin{pmatrix}
z(s) \\
z'(s)
\end{pmatrix}
= \begin{pmatrix}
A \cos(\psi(s) + \phi) \\
-A \sin(\psi(s) + \phi)
\end{pmatrix}
\]  

(2.49)

### 2.2.6 Dispersion function

Particles with momentum deviation \( \Delta p = p - p_0 \) travel on different orbits due to the momentum dependent bending in dipole magnets.

A homogeneous dipole field in the rectangle model over length \( s \) shall be considered for particles with a momentum deviation. In this case \( K(s) \) of equation (2.30) becomes \( 1/\rho^2 = const \), where \( \rho \) is the bending radius of the dipole magnet \( 1/\rho = B \cdot e/p \).

Considering a dipole magnet deflecting the beam in the horizontal plane, the relevant differential equation writes

\[ x'' + \frac{1}{\rho^2} x = \frac{1}{\rho} \delta \]  

(2.50)

where \( \delta = \Delta p/p_0 \). With \( \delta = 1 \) the solution of equation (2.50) is the dispersion function with the unit [m]. The solution of the homogeneous equation has already been derived.
for the quadrupoles where the constant $1/\rho^2$ was $k$. An ansatz for the inhomogeneous solution is the constant solution. Together with the initial conditions at $s = 0$ the solution for the dispersion trajectory writes

$$\begin{pmatrix} D(s) \\ D'(s) \\ 1 \end{pmatrix} = \begin{pmatrix} \cos \frac{s}{\rho} & \rho \sin \frac{s}{\rho} & \rho (1 - \cos \frac{s}{\rho}) \\ -\frac{1}{\rho} \sin \frac{s}{\rho} & \cos \frac{s}{\rho} & \sin \frac{s}{\rho} \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} D_0 \\ D'_0 \\ 1 \end{pmatrix}$$

(2.51)

The total displacement of a particle is the sum of the betatronic solution plus the dispersion trajectory times $\delta$

$$x(s) = x_\beta(s) + \delta \cdot D(s)$$

(2.52)

For a dipole magnet with bending radius $\rho$ the transfer matrix becomes

$$M_{\text{dipole}} = \begin{pmatrix} \cos \frac{s}{\rho} & \rho \sin \frac{s}{\rho} & 0 & 0 & \rho (1 - \cos \frac{s}{\rho}) \\ -(1/\rho) \sin \frac{s}{\rho} & \cos \frac{s}{\rho} & 0 & 0 & \sin \frac{s}{\rho} \\ 0 & 0 & 1 & s & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

(2.53)

In appendix A the most important accelerator and beam parameters of the LHC are summarised.
3

The LHC Injection Process – SPS Extraction, Transfer, LHC Injection

In this chapter the elements and performance requirements of the LHC injection process are described, including the chain of pre-injectors. The main focus will be on the process of transferring the beam from the SPS to the LHC – including extraction from the SPS, the beam transfer and finally the injection into the LHC.

3.1 The LHC Pre-Injectors and their Requirements

The LHC protons coming from the Linac 2 duoplasmatron source are pre-accelerated in the injector chain Linac 2 - Proton Synchrotron Booster (PSB) - Proton Synchrotron (PS) - Super Proton Synchrotron (SPS) [22]. The pre-accelerators have to meet the LHC requirements for the large number of high intensity bunches\(^1\) with a small transverse emittance. The emittance must be kept small throughout the whole injector chain to reach the design luminosity of the LHC. Fig. 3.1 shows a schematic view of the LHC pre-injector chain.

The Linac 2 accelerates the protons coming from the source to 50 MeV. In the PSB they reach 1.4 GeV. In the PS the beam is accelerated to 26 GeV and ejected towards the SPS, where it is brought up to the LHC injection energy of 450 GeV.

Emittance conservation and particle intensity requirements

The nominal bunch intensity of the LHC is \(1.15 \times 10^{11}\) and the normalised emittance 3.75 \(\mu\text{m}\). In order to reach this number of particles with the specified emittance the current from Linac 2 has to be 180 mA with a normalised emittance of 1 \(\mu\text{m}\). The required bunch intensity in the PSB is then \(1.38 \times 10^{12}\) protons with an emittance of 2.5 \(\mu\text{m}\). Six PSB bunches are injected into the PS to form one PS batch, with a required number of particles per batch of \(8.28 \times 10^{12}\) \(\text{p}^+\) and an emittance of 3 \(\mu\text{m}\). At maximum four PS batches are finally ejected towards the SPS to result in \(3.31 \times 10^{13}\) protons with an emittance of 3.5 \(\mu\text{m}\).

\(^1\)Beams in accelerators with RF acceleration are bunched.
LHC filling time

The overall length of the time from the beginning of the SPS filling until extraction towards LHC (the SPS supercycle) must be a multiple of the PS cycle length of currently 1.2 s. The time between two injections from the PS is 3.6 s. The SPS supercycle length is 21.6 s (= 18.1.2 s), in the case of four injections and ramping up from 26 GeV to 450 GeV and ramping down. 24 of such supercycles are needed to fill both LHC rings. At the end of the energy ramp the beam is either extracted in the SPS extraction region LSS6 into the transfer line TI 2 for LHC beam 1 or in the extraction region LSS4 into the transfer line TI 8 for beam 2. The nominal LHC filling time will therefore be about 10 minutes.

Different proton beams for the LHC

For first commissioning and setting-up of the SPS extraction, the transfer lines and the LHC, a “safe beam” with an intensity below the damage level is required. One option is to use the so-called “pilot” beam, which is a single bunch with an intensity of 5 × 10^9 protons.

However, for some measurements the resolution of the LHC instrumentation is not accurate enough with the pilot beam. A beam with intermediate intensity is therefore planned as well, consisting of 12 nominal bunches with a total intensity of 1.4 × 10^{12} protons. This is produced by using a single PSB bunch instead of the nominal six.

Initial LHC commissioning requires colliding beams with no crossing angle at the interaction points. This will be done with 43 bunches on 43 bunches. Only one PS bunch per batch is accelerated, and 2-4 batches are ejected towards the SPS. This beam is called “43 bunch” beam.
3.2 SPS Extraction

After scraping the beam tails in the SPS to 3.5 $\sigma$ [23], the beams will be fast extracted from the SPS. Only the extraction from LSS4 is described in detail. It is noteworthy that this extraction will also be used to transfer protons to a target for the Neutrinos to Gran Sasso (CNGS) facility [24].

The LSS4 fast extraction is based on a horizontal closed orbit bump generated by four orbit bumpers, 5 fast extraction kicker modules (MKE) and 6 DC electromagnetic septum (MSE) magnets [25]. The closed orbit bump is used to move the beam close to the septum magnets and to in this way reduce the strength needed of the fast kicker magnets. Three large aperture quadrupoles are installed in the extraction region to provide enough aperture for the bumped and the extracted beam. Their good field region extends to 90 mm instead of 70 mm (LSS4: QDA417 and QFA418). The also enlarged defocusing quadrupole QDA419 has an additional window in the coil through which the extracted beam passes. The stray field in this window is a quadrupole field but horizontally focusing with a gradient of -0.16 of the main gap field and the zero-axis displaced by 0.3009 m.

To extract the beam, the extraction kicker MKE field rises during a gap in the circulating beam and kicks the beam across the septum. There is only one extraction per SPS-cycle for the LHC beam and a flat top length for the kicker of 8 $\mu$s is required. (In the case of CNGS two extractions are needed which imposes short fall and rise times of 1.1 $\mu$s on the kicker. The flat top length for CNGS is about 10 $\mu$s.)

The MSE septa bend the beam by about 12 mrad out of the SPS vacuum chamber into the transfer line TT40, which is commonly used by the beam for LHC ring 2 and the CNGS beam. The MSE magnets are mounted on a girder and pre-aligned to follow the trajectory of the extracted beam to provide maximum aperture. The girder is motorised to allow retracting the septum and optimise the local aperture when setting up the SPS at injection.

The trajectory of the extracted beam was matched with MAD-X\(^2\), using as constraints that the orbit has to be flat outside the extraction region, the maximum extracted trajectory excursion should be about 85 mm in QFA418 and about 260 mm at the coil window of QDA419. The required element strengths for LSS4 and LHC beam 2 are summarised in Table 3.1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Strength [mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB1</td>
<td>-2.1e-03</td>
</tr>
<tr>
<td>HB2</td>
<td>0.565</td>
</tr>
<tr>
<td>HB3</td>
<td>0.383</td>
</tr>
<tr>
<td>HB4</td>
<td>0.162</td>
</tr>
<tr>
<td>MKE-S</td>
<td>0.100</td>
</tr>
<tr>
<td>MKE-L</td>
<td>0.105</td>
</tr>
<tr>
<td>MSE</td>
<td>2.074</td>
</tr>
</tbody>
</table>

Table 3.1: Nominal strengths of extraction elements in LSS4 for LHC beam.

\(^2\)For further information on MAD-X see Chapter 6.
Extraction protection

In front of the septa an absorber - the TPSG - is installed to protect the septa from kicker failures or mis-steered beam due to other reasons, see Fig. 3.2. This element provides dilution to a save level in case of beam loss to avoid damage of the MSE. The TPSG in LSS4 is a 2.9 m long sandwich diluter made of 2.1 m graphite (1.77 g/cm³) and 0.8 m aluminum alloy. The beam position at the extraction point, beam losses, bumper and septum currents, the kicker charging voltages and MSE girder position are all interlocked [26].

![Graph](image.png)

Figure 3.2: Trajectory (3σ envelope) for the bumped (black curve) and the extracted (red curve) beam in the extraction channel of LSS4. The aperture is given in blue.

### 3.3 Transfer between SPS and LHC

In the LHC Design Report [27] the LHC transfer lines T1 2 and T1 8, each about 2.8 km long, are described in detail. The main features of both lines are similar, but as the injection process was studied for LHC beam 2 in this thesis, the layout and optics design and required performance of T1 8 are presented.

Careful control of the trajectory and the preservation of the very small emittance during transfer and injection are of key importance, due to the limited mechanical aperture of the transfer line magnets, the high intensity and energy in the beam, the limited numbers of correctors and beam position monitors, and also the tight tolerances on the beam parameters at injection into the LHC [28].
3.3.1 Transfer line requirements

The transfer lines must allow the beams to be injected onto the LHC orbit with high precision and reproducibility [29], while ensuring an adequate optical match and remaining sufficiently flexible to accommodate any future machine optics changes. The machine protection elements in the lines should prevent the transfer of damaging beams into the LHC, either by interlocking or by the passive protection collimators TCĐI (Chapter 8). The main performance specifications for the lines are given in Table 3.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam emittance from SPS (1 σ normalised)</td>
<td>μm</td>
<td>3.5</td>
</tr>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>450</td>
</tr>
<tr>
<td>Maximum beam intensity</td>
<td>p⁺</td>
<td>4.9·10⁻¹⁵</td>
</tr>
<tr>
<td>Maximum beam energy spread (1 σ)</td>
<td>Δp/p*</td>
<td>0.0005</td>
</tr>
<tr>
<td>Energy acceptance</td>
<td>Δp/p*</td>
<td>±0.003</td>
</tr>
<tr>
<td>Injection precision in LHC</td>
<td>σ</td>
<td>±1.5</td>
</tr>
<tr>
<td>Tuning range for SPS optical parameters at extraction point (α, β)</td>
<td>%</td>
<td>±20</td>
</tr>
<tr>
<td>Tuning range for LHC optical parameters at injection point (α, β)</td>
<td>%</td>
<td>±20</td>
</tr>
<tr>
<td>Transverse amplitude transmitted into the LHC for failure</td>
<td>σ</td>
<td>±7.5</td>
</tr>
<tr>
<td>Aperture</td>
<td>σ</td>
<td>±6.0</td>
</tr>
</tbody>
</table>

Table 3.2: Main performance specification for the transfer lines (tolerance values). *In accelerators for ultra-relativistic particles the relative energy deviation is mostly sloppily designated as “Δp/p”, as the rest mass is small compared to the momentum contribution to the total energy.

3.3.2 Optics

Both lines use a FODO³ lattice with 90° phase advance per cell and a half cell length of 30.3 m with four dipoles per half cell similar to the SPS. Short straight sections with space for instrumentation and dipole corrector magnets follow each quadrupole. The main optical parameters and requirements for TI 8 are summarised in Table 3.3. The optics functions for TI 8 are shown in Fig. 3.3.

3.3.3 Optics design features and constraints

The arcs of the transfer lines are matched to the SPS and the LHC by means of dedicated quadrupole magnets on either end of the lines (the lattice functions at the extraction point and at the injection point must be the same between SPS and transfer line and transfer line and LHC). The SPS is matched to the six arc constraints in TI 8 with seven matching quadrupoles, four quadrupoles in TT40 and three in TI 8. On the LHC end, the line is equipped with 10 matching quadrupoles. With the present layout, the maximum gradient of 57 T/m for the matching quadrupoles in the line, the aperture constraint of ≥ 6σ in the arc and the aperture bottleneck towards the end of the lines, dispersion matching in

³FODO: most common magnetic structure of modern accelerators consisting of a focusing (F in FODO) and a defocusing (D in FODO) quadrupole, interspaced by bending magnets.
Table 3.3: Summary of main optics parameters for the transfer line TI 8.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_x \text{ max}$</td>
<td>m</td>
<td>240.8</td>
</tr>
<tr>
<td>$\beta_y \text{ max}$</td>
<td>m</td>
<td>274.6</td>
</tr>
<tr>
<td>$\beta_x \text{ max (arc section)}$</td>
<td>m</td>
<td>101.2</td>
</tr>
<tr>
<td>$\beta_y \text{ max (arc section)}$</td>
<td>m</td>
<td>101.1</td>
</tr>
<tr>
<td>$</td>
<td>D_x</td>
<td>\text{ max}$</td>
</tr>
<tr>
<td>$</td>
<td>D_y</td>
<td>\text{ max}$</td>
</tr>
<tr>
<td>$D_x \text{ R.M.S.}$</td>
<td>m</td>
<td>1.78</td>
</tr>
<tr>
<td>$D_y \text{ R.M.S.}$</td>
<td>m</td>
<td>0.20</td>
</tr>
<tr>
<td>$\mu_x \text{ total}$</td>
<td>$2\pi$</td>
<td>10.54</td>
</tr>
<tr>
<td>$\mu_y \text{ total}$</td>
<td>$2\pi$</td>
<td>10.32</td>
</tr>
<tr>
<td>Half-cell length</td>
<td>m</td>
<td>30.3</td>
</tr>
<tr>
<td>Number of half-cells</td>
<td></td>
<td>85</td>
</tr>
</tbody>
</table>

both planes on the LHC side is difficult and limits the tunability of the line [30]. The additional constraints imposed by the phase advance relations between the TCDI transfer line collimators limit the flexibility further.

Emittance conservation and tail repopulation

The total contribution of all possible mismatch effects from the SPS extraction to the LHC top energy must stay within the emittance growth budget of 7%, which presents quite a challenge. In Chapter 11 an estimate on the emittance growth for the injection process of beam 2 is given based on analytic calculations as well as simulations taking random and systematic effects into account. The repopulation of beam tails is also treated.

3.3.4 Aperture in the transfer lines

Magnets of the transfer line elements are equipped with very small vacuum chambers. The strongest aperture constraint comes from the main MBI dipoles, with their full gap height of only 25 mm. This aperture results in a maximum tolerable vertical trajectory excursion, near the defocusing quadrupoles, of $\pm 4.5$ mm. The aperture $N$ in number of sigma available to the beam is derived using [31]:

$$N = ([A - E_{\text{max}}(\beta/\beta_{\text{max}})^{1/2} - D \cdot \delta_p]k_{\beta})/\sigma$$  \hspace{1cm} (3.1)$$

where $A$ is the physical half-aperture remaining after mechanical and alignment tolerances and sagitta (total 1.5 mm) are taken into account. $k_{\beta} = 1.1$ is the factor to allocate imperfections to the beta function (beta beating factor), $\beta_{\text{max}}$ the maximum beta function in the regular arc, $E_{\text{max}} = 4.5$ mm the maximum allowed orbit excursion and $\delta_p = 0.0015$ the maximum momentum spread.

Fig. 3.4 illustrates the available aperture for the horizontal and vertical plane for the transfer line TI 8 using (3.1). This clearly shows the aperture bottlenecks at the end of
Figure 3.3: Beta functions ($\beta_x, \beta_y$) and dispersion ($D_x, D_y$) in TI 8.
the line, where $N$ from (3.1) decreases to about $4 \sigma$ at one of the MBI magnets and even to below $3 \sigma$ at the MSI injection septum. In the arc of the transfer line the aperture has its minimum at about $6 \sigma$ in the vertical plane and at $8 \sigma$ in the horizontal plane. Because of the apparent aperture limitation at the end of the line, the available aperture at the MSI was investigated more realistically based on a random sampling of different states of the line with trajectory correction for random power converter ripples and misalignment of vacuum chambers and quadrupoles\(^4\). The resulting average aperture at the MSI entrance amounted to about $7 \sigma$ in the vertical plane, see Fig. 3.5. In total 1000 different seeds have been analysed for these plots. Fig. 3.5 also shows the aperture at two other critical locations.

### 3.4 The LHC Injection System

The 450 GeV beams coming from the SPS are injected into the LHC in the combined experimental and injection insertions IR 2 and IR 8 [32, 33]. In both insertions the beams are injected from the outside of the accelerator ring and from below. Five Lambertson type septum magnets (MSI) deflect the beam in the horizontal plane by 12 mrad onto the horizontal orbit. The MSI is already part of the LHC equipment with apertures also for the two circulating beams, Fig. 3.6. It consists of two different types, MSLA and MSIB, which differ in the septum thickness (distance of the holes for the circulating beams from the pole) and the coil configuration and thus the field in the gap. The injected beam first

\(^4\)This sampling method is used throughout the thesis and will be described in detail in Chapter 6.
traverses three magnets of type MSIB, followed by two MSIA. Together with the gaps between the magnets, the septum stretches over 21.8 m.

After the MSI the beam continues off-center through the superconducting quadrupole Q5 and is kicked vertically by 0.85 mrad onto the orbit by the four kicker modules of the MKI, the injection kicker. The LHC will be filled with 12 SPS batches per ring of either 5.84 µs or 7.86 µs length. 11 of the gaps between the bunches will have a length of 0.94 µs corresponding to the injection kicker rise time. One gap is 3 µs long to allow for the rise time of the dump kicker and is called “abort gap”.

A dedicated system of protection devices is foreseen against injection kicker failures, the system TDI-TCDD-TCLI. The system will be discussed in depth in Chapter 9.

3.5 Aperture available in the LHC at Injection Energy

In the following the available aperture of the LHC at injection energy is discussed. The tightest aperture locations for the circulating beam in the LHC at 450 GeV are not in the injection regions. Nevertheless, the fact that equipment elsewhere in the ring has a tighter aperture is relevant for injection as it determines the required injection delivery precision and the allowed tail repopulation such that damage/quenches after injection are avoided.

The available aperture in the LHC is defined by the mechanical size plus tolerances of the vacuum chambers and tolerances on the orbit and optics such as dispersion and beta
beating [34]. The definition of the available aperture uses normalised coordinates

\[
\begin{align*}
n_x &= \frac{x}{k_\beta \sigma_x} \\
n_y &= \frac{y}{k_\beta \sigma_y}
\end{align*}
\]

where \(k_\beta\) is the beta beating factor and \(\sigma_{x,y}\) are the nominal beam sizes. The aperture is calculated as the maximum transverse size of a beam in primary \(\sigma\) which can be inscribed in the vacuum chamber including the maximum displacement of the beam center due to machine imperfections and design offsets. The largest displacement is given by

\[
\Delta_{x,y}(s) = \text{CO}_{x,y}^{\text{peak}} + [\delta_{x,y}^{\text{mech}} + \delta_{x,y}^{\text{al}}(s)] + k_\beta \cdot D_{x,y}(s) \cdot \delta_p + [d_{x,y}^{\text{sep}}(s) + d_{y}^{\text{ini}}(s) + d_{x}^{\text{axis}}] \tag{3.2}
\]

\(\text{CO}_{x,y}^{\text{peak}}\) is the peak nominal closed orbit excursion and \(\delta_{\text{mech}}\) and \(\delta_{\text{al}}\) are the mechanical and alignment tolerances. The dispersion also contains a correction for parasitic coupling

\[
D_{x,y}(s) = D_{x,y}^{\text{linear}}(s) + k_D \cdot \sqrt{\frac{\beta_{x,y}(s)}{\beta_{QF,x}}} D_{QF}
\]

where \(k_D\) is the coupling coefficient, \(D_{QF}\) is the peak dispersion in focusing quadrupoles in the arc (about 2 m). In the formula for the maximum beam displacement the dispersion contribution is also corrected for beta-beating by the term \(k_\beta \cdot D_{x,y}(s) \cdot \delta_p\).

In the experimental insertions the beams share one beam pipe, as they have to collide at the interaction point. Orbit corrector magnets are used to steer the beams on slightly different trajectories and make them cross at the interaction point colliding at a small angle. This crossing angle prevents collisions other than at the interaction point. At injection where particles should not collide, the trajectories are separated also in the
other plane with separation bumps. This minimises the long-range beam-beam effect which causes global tune shift and tune spread.

The crossing angle, separation and vertical injection offset for the injected beam before the injection kicker MKI have to be taken into account in the formula for the maximum displacement. In the case of combination or separation magnets such as the D1 magnets, the magnetic axis does not necessarily coincide with the beam axis. All these contributions are considered in the term $d_{\text{axis}}$ of equation (3.2).

The nominal values for the coefficients at injection energy in equation (3.2) are given in Table 3.4.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak closed orbit excursion</td>
<td>$\text{COPeak}_{n,y}$</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>Beta beating</td>
<td>$k_{\beta}$</td>
<td>1.1</td>
</tr>
<tr>
<td>Momentum offset</td>
<td>$\delta_p$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Coupling coefficient</td>
<td>$k_D$</td>
<td>0.273</td>
</tr>
<tr>
<td>Peak dispersion in focusing quadrupoles</td>
<td>$D_{QF}$</td>
<td>$\sim 2$ m</td>
</tr>
<tr>
<td>Peak beta function in focusing quadrupoles</td>
<td>$\beta_{QF}$</td>
<td>$\sim 170$ m</td>
</tr>
</tbody>
</table>

Table 3.4: Parameters for calculation of available aperture.

The available aperture has been calculated for the LHC elements. The histogram in Fig. 3.7 shows the distribution at injection energy. The available aperture goes down to 7.5 $\sigma$. Particle amplitudes of larger than 7.5 $\sigma$ at injection hence have to be avoided at the 5% level for damage consideration and at the $10^{-4}$ level for quenches.

![Available aperture in the LHC at injection](image)

Figure 3.7: Available aperture in the LHC at injection (courtesy S. Redaelli).
4

Beam Induced Equipment Damage

The LHC performance depends on both beam quality and availability. Excellent beam quality is crucial to reach the specified performance of the LHC in terms of peak luminosity. With the intensity of the 450 GeV beam extracted from the SPS a new regime is entered, where system availability, correlated to integrated luminosity, becomes a major performance issue. Replacement of equipment in the case of beam induced damage is time consuming and costly. The aperture of the transfer lines and the LHC is small and the beam parameters must be well under control not to lose beam on the aperture. The damage limit for beam lost in equipment is more than one order of magnitude below the nominal injected intensity.

The assumptions on the limits for beam induced damage of equipment for LHC energies and intensities are based on energy deposition simulations, mostly by means of the particle transport Monte-Carlo program FLUKA (see below). The damage levels are derived from static energy deposition calculations; the bunch structure of the beam is generally not taken into account. In this chapter the damage limit at 450 GeV is estimated in the usual way and the results of an experiment, a controlled damage test, in TT40 are described which has been used to check the validity of this approach [35].

4.1 Equipment Damage Level

A hadron beam hitting material interacts with the target and generates a particle shower, depositing energy in the material, increasing the temperature and possibly leading to damage. The energy deposition reaches the maximum at a certain distance in the target; in solid copper this is at about 15 cm for a 450 GeV proton beam. The transverse extent of the shower also has a maximum at a certain depth in the material. Damage in the target is therefore a function of the longitudinal coordinate (parallel to the beam axis) as well as the transverse coordinates (perpendicular to the beam axis).

The equipment damage level at injection energy is derived from FLUKA energy deposition results in copper (the material copper was chosen because it is used in the LHC beam screen and the magnet coils). Fig. 4.1 shows the peak energy deposition in GeV/cm³ per proton as a function of the R.M.S. beam size for 7 TeV and 450 GeV. For a typical beam size of $\sigma = 1$ mm, a proton beam impacting on Cu results in a peak energy deposition of about $\Delta E = 10$ GeV/cm³/p⁺ in the material. The melting point of Cu is 1083 °C. A
estimate for the number $n_{\text{damage}}$ of particles needed to cause a temperature rise to reach the melting point (from room temperature) in case of a localised loss can be obtained with

$$n = \frac{\Delta T \cdot \rho \cdot C_p}{\Delta E} \quad (4.1)$$

where $\rho = 8.96$ g/cm$^3$ is the density of Cu and $C_p = 0.385$ J/(g·K) the heat capacity. Assuming that the material is damaged when the melting point is reached, the resulting number of particles leading to damage of Cu is

$$n_{\text{damage}} = 2.3 \times 10^{12} p^+ \quad (4.2)$$

For ultimate beam intensity a full injected batch contains $4.9 \times 10^{13}$ protons. Thus the damage limit in (4.1) corresponds to about 5 % of this intensity.

4.2 Material Damage Test in TT40

The target used in the beam test to compare FLUKA damage predictions with experimental results consisted of a series of tightly packed metal plates, see Fig. 4.2. This structure allows to understand the development of damage in the longitudinal direction. The plates were made of metals commonly used in the LHC such as copper and stainless steel (316L, INCONEL). In order to have a wide range of different melting points, zinc with its comparatively low melting point was also included. The dimensions of the plates were $6\, \text{cm} \times 6\, \text{cm} \times 2\, \text{mm}$. Placeholders of 0.5 mm thickness were installed between two plates to avoid plates sticking together in case of melting. In total the target consisted of 108 plates with an overall length of about 30 cm. Numbers were engraved on the plates to define the longitudinal position.
A special arrangement of the materials in the target was chosen. Packages of three plates with different materials, always in the same sequence, were assembled and installed one behind the other. Each package consisted of Zn, stainless steel and Cu, where Zn was always the first and Cu always the last plate (every third stainless steel plate was an INCONEL plate, in total 10 INCONEL plates were incorporated). In this way every material experienced every stage of the particle shower.

To limit irradiation of the environment, a double confinement was built around the target. The core with the plates was wrapped in a Ti-foil to protect the outer container from possible molten metal droplets. The air-tight outer container was made of Al and was equipped with a Ti entrance and exit window.

The target could be moved in and out of the beam and to different impact locations by a stepping motor. An Al₂O₃-screen, a beam observation device, installed on the outer confinement in front of the entrance window was used to steer the beam on the target. The target assembly was installed on a girder in air in front of the TED beam stopper in TT40 close to the extraction region LSS4 in the SPS. Fig. 4.3 shows the target with confinement, screen and motor mounted on the yellow girder in front of the TED.

Figure 4.2: Core of the target for the damage test in TT40.

Figure 4.3: The target installed in TT40 in front of the TED in air.
4.3 FLUKA Simulations for the Damage Test

FLUKA is a Monte-Carlo code able to simulate transport and interaction of electromagnetic and hadronic particles in any target material over a wide range of energies. The target is described in combinatorial geometry. It can simulate electromagnetic and muon interactions up to 100 TeV, neutron interaction and transport down to thermal energies, hadron-hadron and hadron-nucleus interactions up to 100 TeV and nucleus-nucleus interactions down to about 100 MeV/n [36].

Simulation scenarios

The geometry of the target was implemented in FLUKA including every relevant detail of the double confinement, see Fig. 4.4. The simulations were done for the nominal R.M.S. beam size at the location of the target in TT40: $\sigma_x = 1.1$ mm and $\sigma_y = 0.6$ mm.

![Target geometry implemented in FLUKA: (a) cut parallel to the beam axis (b) cut perpendicular to the beam axis.](image)

Figure 4.4: Target geometry implemented in FLUKA: (a) cut parallel to the beam axis (b) cut perpendicular to the beam axis.

For the experiment under consideration damage was defined as “visible” damage like melting, holes, etc. FLUKA simulations for energy deposition were used to define 4 different proton intensities at 450 GeV, A, B, C and D, which should cause melting on different ranges of the plates. Intensity A was chosen to be below the damage limit of all materials, intensity B should only cause melting of Zn plates, intensity C of Zn and Cu plates and intensity D should melt Zn, Cu and 316L. INCONEL should stay intact for all chosen intensities.

The highest intensity D was to be directed into the middle of the core of the target, next to it the second highest C and second lowest B (±1 cm from the middle, horizontally). The lowest intensity A was chosen to impact closest to the edge of the plates (-2 cm from the middle, horizontally). Only three different horizontal impact locations had to be simulated as the target is symmetric along the vertical axis (location B = C) and FLUKA calculates energy deposition per proton.

As FLUKA records the results as averaged energy deposition per volume bin, the obtained energy deposition depends on the user-defined volume bin-size. The rule of thumb is to
use half a beam sigma for the bin size in x and y to derive meaningful energy deposition values. The longitudinal bin-size was typically 0.5 mm in the simulation.

The energy deposition in the core was used to define the intensities A, B, C and D. Energy deposition was also recorded in parts of the confinement to check its integrity for the different beam intensities.

Simulation results

A given volume of material melts completely if the heat of fusion, the extra amount of energy to cause the phase transition between solid and liquid, is deposited at the melting temperature of the material. Table 4.3 summarises the physical properties of the materials used in the target.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [g/cm³]</th>
<th>Melting Point [°C]</th>
<th>Heat of Fusion [kJ/g]</th>
<th>Boiling Point [°C]</th>
<th>Heat of Vapouris. [kJ/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>7.14</td>
<td>419.58</td>
<td>0.112</td>
<td>907</td>
<td>1.763</td>
</tr>
<tr>
<td>316L</td>
<td>7.88</td>
<td>1398</td>
<td>0.267</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>INCONEL</td>
<td>8.19</td>
<td>1415</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cu</td>
<td>8.96</td>
<td>1083</td>
<td>0.205</td>
<td>2567</td>
<td>4.726</td>
</tr>
<tr>
<td>Al</td>
<td>2.702</td>
<td>660.37</td>
<td>0.4</td>
<td>2519</td>
<td>10.874</td>
</tr>
<tr>
<td>Ti</td>
<td>4.5</td>
<td>1668</td>
<td>0.323</td>
<td>3287</td>
<td>8.793</td>
</tr>
</tbody>
</table>

Table 4.1: Physical properties of the target materials.

The energy deposition per volume bin calculated by FLUKA is transformed into temperature via the heat capacity $C_p(T)$ with

$$\frac{dE}{dV} = \int_{T_0}^{T_0+\Delta T} C_p(T) \cdot dT$$  \hspace{1cm} (4.3)

As the heat capacity is a function of the temperature, equation (4.3) has to be solved numerically. In Fig. 4.5 the $C_p$ curves for all the materials used are given.

Fig. 4.6 shows the energy deposition per proton in the container wall parallel to the beam axis for the impact location on the plates closest to the wall. The maximum energy deposition reached in the Al container is 0.2 GeV/cm³/p⁺ for all four different impact locations. An intensity of $5.4 \times 10^{14}$ p⁺ would be needed to melt the container.

In Fig. 4.7 the energy deposition in GeV/cm³/p⁺ can be seen for a Cu plate at the energy deposition maximum and in a side-view of the plates around the maximum. The energy deposition between two plates, in the space filled with air and spaced by the Al-placeholders (the upper part of the plot), is shown in Fig. 4.8.

Fig. 4.9 gives the peak energy deposition along the series of plates. Every plate was divided into 4 longitudinal bins.

The four intensities A, B, C and D were defined according to the FLUKA results in Fig. 4.9, see Table 4.3. With these intensities the temperatures for the different materials and intensities can be calculated; an example for Cu is given in Fig. 4.10. The number of the first plate, where melting is expected, for the different materials and intensities can be derived in this way, see Table 4.4.
4.3. FLUKA Simulations for the Damage Test

Figure 4.5: Heat capacity for the materials used for the target. INCONEL [37]; Al, Zn, Cu, 316L [38].

Figure 4.6: Energy deposition in GeV/cm³/p⁺ in one of the two Al-container walls parallel to the beam axis for the impact location closest to the edge of the plates.

**Expected uncertainties of prediction**

The errors on the energy deposition values of the Monte-Carlo simulation statistics are between 5 to 9%. This imposes an uncertainty on the prediction accuracy for the plate number from where on melting should be observed. Table 4.5 gives for each predicted plate number the range around the predicted plate number corresponding to the errors of the energy deposition simulation.
4. Beam Induced Equipment Damage

4.4 Results of Experiment - Comparison with Simulation

Four separate shots were extracted from the SPS and directed on the target, in four different horizontal locations with the different intensities A, B, C and D in a dedicated test on November 8, 2004.

The first inspection of the target after the test and after having removed the confinement showed no damage in the entrance part and more and more damage towards the exit face, as expected. Visual inspection of the target plates was used to check whether there was any damage. No stress related damage had occurred, no cracks or twisting was noticed.

<table>
<thead>
<tr>
<th>Material</th>
<th>Max Value [GeV/cm³/p⁺]</th>
<th>Error [%]</th>
<th>Intensity for melting</th>
<th>vapourisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>6.62</td>
<td>8.5</td>
<td>1.88e+12</td>
<td>1.47e+13</td>
</tr>
<tr>
<td>316L</td>
<td>7.85</td>
<td>8.0</td>
<td>6.72e+12</td>
<td>5.04e+13</td>
</tr>
<tr>
<td>Inconel</td>
<td>7.22</td>
<td>8.6</td>
<td>8.0e+12</td>
<td>5.84e+13</td>
</tr>
<tr>
<td>Cu</td>
<td>8.9</td>
<td>7.3</td>
<td>3.92e+12</td>
<td>3.49e+13</td>
</tr>
</tbody>
</table>

Table 4.2: Summary of simulation results on the metal plates.
4.4. Results of Experiment - Comparison with Simulation

Figure 4.8: Energy deposition in GeV/cm³/p⁺ in air and Al (upper part of plot) between INCONEL and Cu plate 29.

<table>
<thead>
<tr>
<th>Intensity</th>
<th># bunches</th>
<th>#p⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 × 12</td>
<td>1.32 · 10¹²</td>
</tr>
<tr>
<td>B</td>
<td>2 × 12</td>
<td>2.64 · 10¹²</td>
</tr>
<tr>
<td>C</td>
<td>4 × 12</td>
<td>5.28 · 10¹²</td>
</tr>
<tr>
<td>D</td>
<td>6 × 12</td>
<td>7.92 · 10¹²</td>
</tr>
</tbody>
</table>

Table 4.3: The table summarises the chosen intensities for A, B, C and D.

Every plate was photographed for further analysis. The longitudinal development of damage in the target was compared with the simulation predictions. The results are summarised in Table 4.6.

Errors

The emittance during the test was about 15 % smaller than assumed for the simulations. A simple scaling law for the peak energy deposition in material can be derived from Fig. 4.1, where the peak energy deposition goes approximately with 1/σ. A systematic error on the beam emittance hence results from the relative error on the energy deposition
Figure 4.9: Peak energy deposition along the plates.

Figure 4.10: Temperature in the Cu plates for the different intensities.
Table 4.4: FLUKA results for the first plate number, where melting is expected, for intensities A, B, C and D.

<table>
<thead>
<tr>
<th>Intensity</th>
<th>protons $[10^{12}]$</th>
<th>melting starting in plate NR.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zn</td>
<td>Cu</td>
</tr>
<tr>
<td>A</td>
<td>1.3</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>2.6</td>
<td>16</td>
</tr>
<tr>
<td>C</td>
<td>5.3</td>
<td>9</td>
</tr>
<tr>
<td>D</td>
<td>7.9</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 4.5: Uncertainties on simulation predictions for the plate numbers, from where on melting should be observed, due to statistical errors.

$$
\Delta \left( \frac{\Delta E}{\Delta E_0} \right) = \Delta \sigma_0 / \sigma = \sigma_0 \sqrt{\frac{\epsilon - 3}{\beta}} \Delta \epsilon^2
$$

(4.4)

For the average beam size for the horizontal and vertical plane of 0.85 mm at the target location, the systematic error contribution from beam size errors gives about 6% on the peak energy deposition.

Other errors to influence the results come from the uncertainties on the intensity and the beta functions. The uncertainties on the intensity are in the order of 0.1% and were hence neglected. Beta function uncertainties are expected to be maximum 20%, normally anti-correlated in x and y. Errors on the beta functions of 20% result in a change of the peak particle intensity of 2% assuming anti-correlation in x and y and were hence not considered further. The thickness of some of the remaining unirradiated plates was checked after the test. The thickness can be up to 50 µm larger than specified.

Table 4.6: Simulation predictions and experimental results.
Assuming an error of 50 μm on every plate gives in total 5.4 mm more material traversed than assumed in the simulation. The accumulative effect of the thickness error is more important for the plates with higher plate number. In general compensation of errors of different sources is likely.

**Results for copper**

Fig. 4.11 and 4.12 show Cu plates after the irradiation; the yellow letters indicate the chosen intensity for the impact location.

Cu plate 12 is the first to show melting as predicted for nominal emittance and intensity D. Even when the smaller emittance is taken into account, plate 11 is not expected to melt. Hence the results agree well with the simulations.

For intensity C the prediction for Cu was plate 18 to be the first to melt. Including the effect of the emittance error, the required energy deposition of 6.95 GeV/cm³/p⁺ for the phase transition is already reached on plate 17. Plate 17 in fact shows melting for intensity C, see Fig. 4.12. This is also within the expected range due to statistical errors, see Table 4.6.

![Figure 4.11: Cu plates 11 and 12 after irradiation. Plate 11 only shows discolouration.](image1)

![Figure 4.12: Cu plates 16 and 17 after irradiation.](image2)
4.4. Results of Experiment - Comparison with Simulation

Results for zinc

Fig. 4.13 and Fig. 4.14 show the results for zinc plates 6, 7, 8 and 9. Plate 6 does not show any melting, as expected. Plate 7 melts as predicted for intensity D, the same is true for plate 8. On plate 9 melting is also observed for intensity C according to the prediction.

Fig. 4.15 shows the results for plates 13 and 14. Plate 14 melts for intensity B. According to the simulations it should have been plate 16 to be the first and plate 14 is also not in the expected range of the simulation’s statistical errors. However, including the effect of the smaller emittance the required energy deposition for intensity B of 4.74 GeV/cm²/p⁺ to reach the phase transition in zinc is just reached on plate 14.

![Figure 4.13: Zn plates 6 and 7 after irradiation.](image1.png)

![Figure 4.14: Zn plates 8 and 9 after irradiation.](image2.png)

Results for INCONEL & 316L

Both the INCONEL and 316L plates did not show any holes. Concerning INCONEL, this fits the prediction; INCONEL was expected not to be damaged by any intensity. 316L, however, should have melted for intensity D from plate number 23 onwards, which was not unambiguously visible. The most probable reason for the discrepancy comes
from the uncertainties on the heat of fusion and the heat capacity for this alloy. The heat capacity for example is only known to about 950° where the curve has a positive slope, such that the temperature rise due to energy deposition around the melting point of about 1400° might be overestimated. In addition a difficulty for the analysis after the test arose from the fact that the plates in front of the stainless steel plates were made of Zn. Splashes of Zn and also of Cu (via the holes in the Zn plates) ended up on the beam impact locations of the stainless steel plates and covered them partly, see Fig. 4.16. A future similar experiment could be equipped with carbon sheets between the plates to avoid this problem.

The transverse extent of the damaged area on the different plates was compared with the experimental result. The comparison was done for Zn, intensity C, and Cu, intensity D, see Fig. 4.17 and 4.18. According to the expectation, the radius of holes or molten area should correspond to the area where the melting point plus heat of fusion are exceeded in the simulation. The result however from the experiment shows that the measured radii are closer to the radii for the regions where only the melting point is reached. The smaller emittance during
Figure 4.17: Cu intensity D: Predicted radii for the area on the plates where the melting point (red) and for the area where the melting point plus heat of fusion (green) is exceeded; measured radii of damaged area (blue).

Figure 4.18: Zn intensity C: Predicted radii for the area on the plates where the melting point (green) and for the area where the melting point plus heat of fusion (red) is exceeded; measured radii of damaged area (blue).
the test does not explain this discrepancy. The simulation was re-run to check the change of the radii with the smaller emittance. The effect on the radii is negligible. A possible explanation is that the solid material at the melting point becomes soft enough to be moved outwards by the shock wave generated by the beam impact. This effect cannot be described with static energy deposition simulations only, other tools would have to be used [39, 40].

4.5 Conclusion

The results of the controlled damage test show reasonable agreement with the simulations. Zn- and Cu-plates are damaged at the predicted locations within the error bars. INCONEL did not show any holes according to the expectations. The transverse extent of the damaged area on the Zn- and Cu-plates could be predicted within about 30%. The results for 316L differ from the simulation predictions. This is most likely due to uncertainties on the input parameters such as the physical properties of the alloy, rather than errors in the energy deposition calculations with FLUKA. The outcome of the experiment confirms that beam induced damage limits for simple geometries can be adequately predicted with simulations. It is worth mentioning that no stress induced damage was observed when the energy deposition led to a temperature increase below the melting point. This experiment gives confidence that the 5% (2.3 × 10^{12} p^+) equipment damage level at 450 GeV is a reasonable assumption.
5

Machine Protection during the Injection Process

As already indicated in Chapter 1, machine protection during the injection process is important to maximise the LHC availability and hence the LHC performance. In this chapter the strategy for machine protection for the injection process is explained. The different active and passive protection systems are introduced and the important interlocking system is described in some detail.

5.1 Motivation

Wrong settings or powering failures of the magnetic elements can lead to beam loss during the injection process. As an example the MSE extraction septum has a very short time constant of only 23 ms for the current decay if the power converter is switched off. An accidental switch-off 1 ms before extraction can move the trajectory by 40 \( \sigma \) before the beam is extracted.

5.1.1 TT40 damage during 2004 high intensity SPS extraction

During the extraction of a high intensity beam from the SPS into TT40 on 25/10/04 an incident occurred in which the TT40 quadrupole magnet QTRF4002 was damaged [41]. The beam was a 450 GeV full nominal LHC injection batch of 3.3 \( \times \) \( 10^{13} \) \( \text{p}^+ \) in 288 bunches, which was needed for a robustness test of the prototype LHC collimator and for CNGS target rod tests. The beam was extracted from SPS LSS4 with the wrong trajectory due to a wrong MSE extraction septum current. A large vacuum leak was immediately apparent and coil insulation damage was found in later electrical tests of the magnet. The magnet had to be exchanged for a spare, which lead to a downtime of about 2 days including cool down due to the induced radiation.

Deficiencies in the extraction setting-up process, in the interlocking and in the operational procedures used for the high-intensity test were contributing factors.

The details of the incident could be reconstructed from the data recorded during the test and the damage to the vacuum chamber. Fig. 5.1 shows a beam screen shot of the BTVI4001 for the fatal extraction. The beam image is offset by about -10.8 mm with
respect to the previous correct extraction. The result of the analysis - the reconstituted trajectory of the wrongly extracted beam - is shown in Fig. 5.2. The reconstruction of the trajectory together with the recorded data allowed the temporal sequence of events to be determined:

- 13 ms before extraction, the MSE power supply tripped due to a signal picked up from the beam by the built-in the temperature gauges

- 7 ms before extraction, the current surveillance measured a -0.5 % error, but this was still in the tolerance window of ±0.1 % due to the averaging over the last 10 samples

- 3 ms before extraction, the current was recorded at about -2 %

- at extraction the current had decreased by 5.1 %

![Data for Cycle](image)

Figure 5.1: Beam screen monitor BTVI4001 capturing the fatal extraction (horizontal axis in m m). The beam is offset by -10.8 m m.

The beam impacted at about 35 m downstream of the exit of the septum MSE in the quadrupole QTRF4002. Fig. 5.3, 5.4 and 5.5 show the damaged beam pipe. Damage extended over more than 1 m. The damaging potential of only a tenth of the nominal LHC intensity at 450 GeV became obvious.

This incident triggered a series of precautions to be taken for future high intensity operation and demonstrated vividly that machine protection is a serious issue for LHC energies and intensities. High intensity commissioning must be carefully planned, preceded by formal acceptance tests of the involved machine protection equipment. Problems encountered with critical systems must be taken seriously and solved before commissioning can proceed. For high intensity commissioning, machine protection must take priority over efficiency.
5.1. Motivation

Figure 5.2: Reconstructed trajectory for the fatal extraction (±3.5 σ beam envelope). The physical apertures of the TT40 elements are shown. A 5.1 % too low deflection of the MSE septum was found. The red circle indicates the element where the beam impacted.

Figure 5.3: Damage observed on the outside of the vacuum chamber. A cut approximately 25 cm long was clearly visible, at about 70 cm from the start of the chamber.

Figure 5.4: Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was visible, starting at about 30 cm from the entrance.
5.2 Failure Classification for the Injection Process

The MSE extraction septum is not the only dipole family that can lead to damaging amplitudes in a very short time. The failure classification is made according to the time before extraction at which the equipment needs to have a fault such that at extraction the trajectory would be unsafe (the shorter this time the more dangerous the failure case, since there is less time to detect the failure and react).

The different types of failures are divided into three classes, depending on the time required to change the trajectory by about $10 \sigma$ (amplitude that can lead to damage):

- **slow**: $> \sim 10$ ms;
- **fast**: $\sim 0.1$ to $\sim 10$ ms;
- **ultra-fast**: $< \sim 0.1$ ms;

Examples for ultra-fast failures are failures of the extraction or injection kickers; failures of the extraction septum MSE belong to the fast failures. Other examples can be found in Table 5.1.

<table>
<thead>
<tr>
<th>Family</th>
<th>$\tau$ [ms]</th>
<th>$10 \sigma$ reached [ms]</th>
<th>class</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSE</td>
<td>23</td>
<td>0.25</td>
<td>fast</td>
</tr>
<tr>
<td>MSI</td>
<td>1010</td>
<td>7</td>
<td>fast</td>
</tr>
<tr>
<td>MBI</td>
<td>894</td>
<td>3</td>
<td>fast</td>
</tr>
<tr>
<td>MBIBV</td>
<td>1296</td>
<td>8</td>
<td>fast</td>
</tr>
<tr>
<td>MBHC</td>
<td>1010</td>
<td>9.1</td>
<td>fast</td>
</tr>
<tr>
<td>MPLHC</td>
<td>100</td>
<td>12.8</td>
<td>slow</td>
</tr>
<tr>
<td>MCIBH</td>
<td>391</td>
<td>14.3</td>
<td>slow</td>
</tr>
<tr>
<td>MBIAH</td>
<td>2631</td>
<td>15</td>
<td>slow</td>
</tr>
<tr>
<td>MBIAV</td>
<td>2453</td>
<td>58.4</td>
<td>slow</td>
</tr>
<tr>
<td>3 x MCIAV</td>
<td>487</td>
<td>185</td>
<td>slow</td>
</tr>
</tbody>
</table>

Table 5.1: Classification of some dipole families involved in the injection process of beam 2.
5.3 Machine Protection Strategy

The main objective of the injection protection system is to protect LHC equipment. In order to always make sure that only well controlled beam is injected into the LHC, injection protection must start at the SPS extraction. All three stages of the injection process must be covered: SPS extraction, transfer and LHC injection. Furthermore, the extraction regions and the transfer lines themselves need to be protected against damage. In the following the principles of an adequate machine protection system for the injection process are discussed.

5.3.1 Avoidance

The most efficient and hence most important protection strategy is avoidance: concepts and operational procedures to avoid any kind of dangerous situations. Two crucial concepts are described, the safe beam flag and the beam presence flag [42].

Safe beam flag

The nominal intensities for the from the SPS extracted and into the LHC injected beam are above the equipment damage limit. Commissioning of parts of the machine, e.g. first SPS extraction or first injection into the LHC, has to be done with a “safe” intensity, which does not cause damage in case the beam is lost. This is also required for setting up equipment such as collimators. In Chapter 3 the so-called pilot beam (5 × 10⁹ protons) has been introduced. The pilot intensity is orders of magnitude below the damage limit, however, the resolution of beam instrumentation with this very low intensity beam is not accurate enough for verifying all beam parameters. The safe beam intensity is presently defined as \( \sim 10 \) nominal bunches (\( \equiv 10^{12} \) protons), which gives sufficient beam instrumentation resolution. Clearly, a prerequisite for this concept is a reliable beam intensity information, as the safe beam will allow to get the LHC or the transfer lines into a state which could cause severe damage with high intensity beam, e.g. testing equipment or setting up protection devices.

Beam presence flag

The beam presence flag is a safety concept for the LHC ring.

Before injecting beam into the LHC, every relevant system of the LHC must be in the correct state and ready for injection. This is checked via software. However, this check is not considered to be failsafe. A probing of the LHC with low intensity beam before injecting high intensity was recommended. In [42] the following general rule was proposed:

1. If there is no beam circulating in the LHC, only safe beam is allowed to be injected.

2. To inject high intensity beam, beam must already be circulating in the LHC (any intensity).
With this concept severely wrong settings leading to immediate beam loss after injection can be avoided. Again, this flag highly depends on a reliable intensity measurement in the LHC ring (of the possibly circulating beam) and a reliable intensity measurement of the SPS beam before extraction (injection of safe or non-safe beam). The beam presence condition must be guaranteed to within 1 ms before injection. The system 'LHC safe parameters' deals with the distribution of the 'safe beam flag' and the 'beam presence flag' [43]. If beam is circulating, a high intensity beam can be injected. It is over-injected on the low intensity beam, which is dumped on the lower jaw of the injection stopper TDI (for TDI see below).

5.3.2 Protection

Avoidance strategies like the "beam presence" concept cannot protect against spurious failures with short time constants like kicker failures or an accidental switch-off of the power converter of a magnet family. A protection system is required consisting of active and passive elements to complete the machine protection system.

Active protection

Active protection comprises a variety of surveillance systems. Hardware and beam parameters are monitored. Examples are the surveillance of the bumped beam position in the extraction region of the SPS, and power converter surveillance (PCS) for all magnet families involved in the injection process. If the surveyed parameters deviate from their reference values, extraction or injection is inhibited. Slow failures can be fully covered with active protection. The core of the active injection protection system is a beam interlocking system.

The extraction region and the transfer line magnets are pulsed. The magnet currents have their nominal values (flat top) for a certain time around extraction and transfer. E.g. the extraction septum MSE has a flat top of about 500 ms where extraction takes place. The comparison of the measured values with reference values within the surveillance systems is only valid shortly before extraction.

The complication from machines with different modes (LHC: injection, ramping, collision, etc.; SPS extraction: CNGS beam, LHC beam, etc.) becomes obvious. The reference values might be mode dependent and the different surveillance systems must hence be "mode aware". Problems like how to make sure that every monitoring system is using the right table of reference values during a particular mode have to be solved. Central surveillance of the local surveillance via software is planned.

Passive protection

In the case of a fast failure close to extraction there might not be enough time to detect the failure and react in time before the beam passage. Additional passive protection against mis-steered beam is foreseen with collimators and absorbers. Collimation systems can be divided into generic and dedicated collimation systems. Generic systems protect tight aperture against any failure upstream; dedicated collima-
tion systems are designed to locally intercept mis-steered beam arising from one particular failure.

**TCDI transfer line collimation:** The transfer line collimators (TCDI) are a generic protection system against any failure upstream of the collimation section. Their objective is to protect the LHC aperture. They have been located at the end of the transfer line to also provide local protection of the tight injection septum aperture. The TCDI system is explained in detail in Chapter 8.

**Dedicated collimators against kicker failures:** Both the extraction kicker and the injection kicker are followed by dedicated protection against kicker failures 90° betatron phase advance downstream. In the case of the extraction kicker MKE, the diluter TPSG is in place to protect the coils of the extraction septum against MKE failures. The vertical injection stopper TDI and the auxiliary collimators TCLI protect the LHC aperture against failures of the injection kicker MKI. More information on the TDI and TCLIs can be found in Chapter 9.

No dedicated collimators are foreseen against septum failures. Specifically, there is no passive protection in the horizontal plane in the injection region mainly due to space constraints. The protection for septum failures relies solely on hardware surveillance.

Fig. 5.6 summarises the principle of the protection system for the injection process.

![Diagram](image)

**Figure 5.6:** Summary of the strategy of machine protection for the injection process comprising active and passive protection systems.
5.3.3 Interlocking

A hardwired, very reliable and very fast beam interlocking system collects all the information of all the monitoring systems and inhibits or permits injection/extraction depending on the state of the inputs. Input signals come from many sources including the power converter surveillance, the kickers, the settings surveillance of the passive protection devices (jaw position) and the position of the beam stoppers in the transfer lines (TEDs).

As mentioned, injection protection starts at the SPS extraction and cannot be disentangled from the main LHC ring protection. Adequate injection protection implies signal exchange between the LHC beam interlocking system and the SPS beam interlocking system.

The LHC Beam Interlock System [44], as already briefly described in Chapter 1, is based on Beam Interlock Controllers (BICs) distributed around the machine and linked by optical fibers to gather user permits (UPs) from different monitoring systems. Based on the status of the surveyed systems, the interlock system gives the “beam permit”. Without the beam permit from the LHC ring, injection is inhibited and the beam dump is triggered to remove any circulating beam in a safe way. In the injection regions IR 2 and IR 8, injection BICs will be installed which are not part of the LHC ring interlocking loop.

The interlocking system developed for extraction and transfer [45] uses the same distributed technical solutions as in the LHC. It must be such that no stage of nominal beam extraction depends on an operator decision. Settings of critical elements are monitored and can only be changed securely. At the same time the interlocking system has to be flexible enough to allow for commissioning the machines; many of the settings reference values have to be defined with beam (e.g. collimator setting). Additional functionality is also required to cover the timing aspects inherent to the cycling SPS (beam to LHC, beam to CNGS, etc.). A schematic view of the transfer line TI 8 also showing the beam line to the CNGS target, TT41, is given in Fig. 5.7.

Figure 5.7: Schematic view of the transfer line TI 8 and beam line TT41 with extraction in SPS/LSS4 and injection of beam 2 in IR 8.
To cope with these additional requirements for the injection process two interlocking concepts were applied: “masking” of interlocking signals with safe beam and segmented interlocking architecture (plus OR logic) with a “master” beam interlock controller. Most of the following will be described on the example of the interlocking for LSS4, TI 8 and IR 8. The interlocking set-up for the injection process of beam 1 is the same without the additional complication of a second beam line like TT41 for TI 8.

**Masking:** Interlock signals are divided into two groups, maskable signals (user inputs) and non-maskable user inputs. Maskable signals are ignored in the BIC in the case of safe beam intensity. An example for maskable signals are the transfer line collimator positions. The collimators need to be set up with beam. During this period the jaw positions must be variable without inhibiting extraction. With safe beam these protection devices are not required and the jaw position interlocking signal can be ignored in the BIC. An example for a non-maskable user input is the bumped beam position in the extraction region, which is a prerequisite for being able to extract.

**Segmented Interlocking:** There are two beam stoppers (TED) in each transfer line. One is installed in TT40 (TT60 respectively) and the other one is at the end of the line, some hundred meters from the LHC injection point. The TEDs are 4.3 m long with a weight of 21.6 t consisting of a 80 mm diameter graphite core, fitted in an Al tube (diameter 80/160 mm) and then in a Cu tube (160/310 mm) with iron shielding. They have been designed to be able to absorb a full injected batch each SPS cycle [46]. With the TT40-TED in the line, no beam can pass into TI 8; with the TI 8-TED in the line no beam can pass into the LHC. Operational flexibility is enhanced if the extraction can be studied and adjusted with the TT40-TED in the line and without requiring the permit of the LHC or the TI 8 permit. The same is true for studying the line TI 8, where the LHC beam permit should not be required.

A segmented interlocking system will hence be implemented. The segmentation follows the functional layout of the transfer lines according to the blocks divided by the TED beam stoppers in Fig. 5.7:

- **LSS4/TT40:** SPS LSS4 extraction and TT40 transfer line, to the TT40 TED beam dump;
- **TT41:** the CNGS beam line TT41, to the CNGS neutrino target;
- **TI 8:** TI 8 transfer line, to the TI 8 TED beam dump at the end of TI 8;
- **IR 8 injection:** last part of TI 8 and the IR 8 injection region to the TDI injection stopper.

Every segment will have at least one BIC collecting the local user permits. The logic implemented in the BICs must allow for the following operating modes, pre-defined by the segmentation:

1. **Beam to TT40 TED** (setting up of the SPS extraction);
2. **Beam onto downstream TI 8 TED** (setting up of transfer line);
3. **Low intensity beam into the LHC** (setting up of the LHC injections, etc.),

4. **High intensity beam into the LHC** (filling the LHC);

5. **Beam to CNGS.**

![Diagram](image)

Figure 5.8: Proposed interlocking architecture for LSS4, TT40, CNGS, TI 8 and IR 8.

**Master BIC:** The design of the BIC is based on failsafe hardware, easy testing procedures and maintenance [47]. The logic the standard LHC and transfer line BIC uses to generate the beam permit is solely based on AND relations. All user inputs must be .TRUE. for beam permit except maskable inputs with safe beam. However, such a BIC cannot fulfill the special requirements needed to cope with the different modes of extraction. A “hierarchy of BICs” has therefore been proposed [45]. A special extraction BIC will be installed, the extraction “master” BIC. It will use OR besides AND relations between user inputs. Table 5.2 lists the “truth-table” which has to be implemented in the logic of the “master” BIC to provide for different operating modes in a safe way.  

All the local BICs for the extraction equipment, TT40, the transfer line and LHC injection have so-to-say a single line in their truth-tables and their architecture entirely follows the LHC BIC architecture with AND relations only and with the possibility of masking inputs in the case of safe intensity from the SPS. Hence the SPS safe intensity flag is
<table>
<thead>
<tr>
<th>Mode</th>
<th>Inputs</th>
<th>User inputs</th>
<th>Dumps</th>
<th>SPS/LHC</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LSS4 extraction/TT40 user permits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TT41/CNGS user permits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TI 8 upstream and downstream user permits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Beam to</td>
<td>LSS4/TT40 TED</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>TI 8 TED</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>LHC beam protection flag</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LHC safe beam flag</td>
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<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LHC beam type (magnet signal)</td>
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<td>0</td>
<td>1</td>
<td>0</td>
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<tr>
<td></td>
<td>CNGS beam type (magnet signal)</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>SP S LSS4 extraction permit</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LHC IR 8 injection permit</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.2: LSS4/TT40/TT41/TI 8/IR 8 machine mode interlocking. For each of the 5 defined machine modes, the output permits are set to the indicated values only if the input conditions designated by “1” in the corresponding row are .TRUE., and conditions designated by “0” are .FALSE. Inputs designated by “x” are not taken into account. The software channels are not shown.

distributed to all BICs involved in the injection process. Fig. 5.8 finally presents the proposed interlocking architecture for extraction, transfer and injection of beam 2.
6

Simulation Methodology

The performance of the proposed protection system for the injection process was evaluated with numerical simulations. Beam quality, aperture and energy acceptance were also investigated. The simulations were mainly based on two commonly used simulation codes. Energy deposition simulations were done with FLUKA and particle tracking was done with the tracking module of MAD-X. FLUKA was used in the standard way, special pre- or post-processing routines will be described when needed. For MAD-X tracking, a sophisticated environment was set up to randomly sample the large parameter space required to define the possible equipment states and to allow realistic failure simulations. Some features for the tracking of failures with MAD-X are summarised in this chapter.

6.1 Tracking with MAD-X

MAD-X is an accelerator design tool for charged particle optics in alternating-gradient accelerators and beam lines. Its uses include linear lattice parameter calculation, linear lattice matching, transfer matrix matching, survey calculations, error definitions, closed orbit correction, particle tracking, chromatic effects and resonances [48].

For all studies the elements of the accelerator or beam line of interest must be read into MAD-X via a sequence file. The sequence defines the name of the accelerator, its length and contains every active element. Elements like beam pipes not acting on the beam are normally not included. Every element is defined with its name, length, longitudinal position in the accelerator and the attributes characterising its effect on the beam, like dipole field strength and direction in the case of a dipole magnet.

For tracking studies of failure scenarios, the accelerator model must be complemented by an aperture model. In MAD-X this done by allocating aperture information to every element in the sequence in the form of an “rectellipse” array: apertype = rectellipse, aperture = \{a, b, r_a, r_b\}, where a and b are the horizontal and vertical half-axis of a rectangle and r_a and r_b the half-axis of an ellipse. This was initially designed to describe the LHC beam screen shape inscribed in the cold bore of superconducting magnets, but most of the other mechanical apertures in the LHC and transfer lines can also be defined in this way. The aperture of vacuum elements which are not part of the sequence can be introduced via additional “markers” (at least one marker at the beginning and at the
end of a beam pipe. Markers are elements in MAD-X with zero length and no effect on the beam, but can have aperture. The command “seqedit” of MAD-X is used to add new elements to a sequence.

With the option of inserting an arbitrary number of markers in a sequence, an aperture model to any accuracy can be built (typical resolution ~ 1 m). For the MAD-X tracking module the sequence has to be transformed into a “thin lens” version, where all elements have zero length. The MAD-X command “makethin” is used for this purpose. To preserve the tune and aperture model resolution the several m long “thick” elements are “sliced” into many (~ 10) slices with the same command.

With the tracking module particle coordinates are tracked from element to element. The module uses the magnetic information to calculate the trajectory and the aperture information to check at every element whether the particle coordinates are within the given aperture. If the coordinates exceed the aperture, the particle is considered to be lost and is not tracked any further. The output of the tracking module tells for every particle where it has been lost; if it survives, it gives the final particle coordinates. Post-processing routines independent of MAD-X can transform this data into loss maps as number of lost particles versus longitudinal coordinate.

### 6.1.1 Extraction - transfer - injection sequences

Tracking studies for injection have to cover the whole transfer process, starting at the first horizontal extraction bumper in the SPS and ending after the last injection protection device, the TCLIB on the other side of the injection insertion in the LHC. A sequence file was required, starting in the SPS and ending in the LHC. Separate sequence files for the whole LHC itself, the whole SPS and the transfer lines (to some extent) existed.

The injection process studies were made for beam 2. A sequence only covering the extraction region LSS4 in the SPS and another one only covering the injection region IR 8 in the LHC, starting after the last element of the transfer line sequence, had to be prepared together with strength files for the the injection region and the extraction region with the bumpers, kickers and septum at extraction settings.

Special precautions had to be taken concerning the sign of the magnetic fields for the injection region sequence. The beam in the SPS always behaves like a “beam 1”-type beam (rotating clockwise, positive horizontal axis on the left), even if ring 2 in the LHC is to be filled. The magnetic fields for the transfer line TI 8 have also been set up for a “beam 1”-type beam. The fields of the magnets in ring 2 of the LHC, however, have been defined for beam 2, which rotates anti-clockwise with the positive horizontal axis on the right. Expressing the lattice functions of a “beam 1”-type beam line for a “beam 2”-type beam results in a change of the sign of all the derivatives of the lattice functions (like \( \alpha(s) \)) as seen for a particle going through the line in inverted direction.

The input for the sequence which was built for IR 8 was derived from the official LHC sequence V6.5. The order of the elements of the new sequence is in the direction of beam 2 (the order in the official version is in the direction of beam 1). The signs for quadrupole and dipoles strengths had to be adjusted such that transfer line and injection region sequence fit together. In general, sequences linking two machines (like the SPS and the LHC) where there may be different reference systems, require particular attention to ensure that all sign conventions are correct.
<table>
<thead>
<tr>
<th>Error</th>
<th>Distribution</th>
<th>Unit</th>
<th>Width</th>
<th>Truncation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main quadrupole lateral alignment</td>
<td>Gaussian</td>
<td>mm</td>
<td>0.2 (1 $\sigma$)</td>
<td>$\pm 3 \sigma$</td>
</tr>
<tr>
<td>Main quadrupole tilt</td>
<td>Gaussian</td>
<td>mrad</td>
<td>0.2 (1 $\sigma$)</td>
<td>$\pm 4 \sigma$</td>
</tr>
<tr>
<td>Main dipole (MBI) field</td>
<td>Gaussian</td>
<td>$\Delta B/B_{\text{nom}}$</td>
<td>2.5 $\cdot 10^{-4}$ (1 $\sigma$)</td>
<td>$\pm 2 \sigma$</td>
</tr>
<tr>
<td>Main dipole tilt</td>
<td>Gaussian</td>
<td>mrad</td>
<td>0.2 (1 $\sigma$)</td>
<td>$\pm 4 \sigma$</td>
</tr>
<tr>
<td>Extraction position</td>
<td>Gaussian</td>
<td>mm</td>
<td>0.1 (1 $\sigma$)</td>
<td>$\pm 3 \sigma$</td>
</tr>
<tr>
<td>Extraction angle</td>
<td>Gaussian</td>
<td>mrad</td>
<td>0.001 (1 $\sigma$)</td>
<td>$\pm 3 \sigma$</td>
</tr>
<tr>
<td>Power supply ripple (MBI)</td>
<td>Gaussian</td>
<td>$\Delta I/I_{\text{nom}}$</td>
<td>2.5 $\cdot 10^{-6}$</td>
<td>$\pm 2 \sigma$</td>
</tr>
<tr>
<td>Power supply ripple (other families)</td>
<td>Gaussian</td>
<td>$\Delta I/I_{\text{nom}}$</td>
<td>5.0 $\cdot 10^{-5}$</td>
<td>$\pm 2 \sigma$</td>
</tr>
<tr>
<td>Mis-match from the SPS</td>
<td>Flat</td>
<td>%</td>
<td></td>
<td>$\pm 20$</td>
</tr>
<tr>
<td>BPM position / electrical</td>
<td>Flat</td>
<td>mm</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1: Tolerances assumed for the tracking studies.

### 6.1.2 Random errors

A realistic model of the accelerator has to include field errors as well as alignment errors. Field errors are mainly due to power converter ripple with typical values of some $10^{-4}$ of the nominal field. Alignment errors of quadrupole magnets lead to a dipole field proportional to the misalignment for particles on the nominal trajectory at the quadrupole location. The alignment precision is in the order of some tenths of a mm. Tilt errors of quadrupole magnets in the transverse plane cause coupling between the x and the y plane. The jitter on the extracted beam position and angle lead to oscillations around the nominal trajectory and betatron mis-match from the SPS to beta beating.

Table 6.1 summarises the tolerances for field errors and mis-alignments used in the simulations in the following chapters.

In summary the different random error sources cause a distortion both of the trajectory (deviation from the geometrical zero) and of the optics. In MAD-X the random errors are allocated to the elements with the MAD-X error routines for field errors, misalignments and tilts. Fig. 6.1 shows an example of an uncorrected vertical trajectory in T1 8 for one seed with all the random errors included.

### 6.1.3 Trajectory correction in transfer lines

At some locations the trajectory in Fig. 6.1 exceeds 1 cm, which is not acceptable for the required operational flexibility in the line with the limited aperture. The trajectory thus must be corrected in reality as well as in the simulation. Corrector magnets and beam position monitors are used for this purpose.

A correction scheme is used in T1 8 in which two out of every four adjacent cells of the transfer lines in each plane are equipped with correctors and beam position monitors (BPMs) with more correctors and BPMs at the beginning and end of the line. T1 8 uses 43 correctors together with 46 BPMs to keep the maximum trajectory excursion amplitude to below 4.5 mm. One method to correct a trajectory on the basis of the measured beam position is SVD (Singular Value Decomposition).
SVD algorithm

This algorithm [49] uses the following correlation: a certain corrector setting $c$ (for $n$ correctors in the line) results in a certain BPM reading $b$ (for $m$ BPMs in the line). Corrector setting and BPM reading are correlated via the response matrix $A$.

$$
\begin{pmatrix}
  b_1 \\
  b_2 \\
  \vdots \\
  b_m
\end{pmatrix} =
\begin{pmatrix}
  a_{11} & a_{12} & \cdots & a_{1n} \\
  a_{21} & a_{22} & \cdots & a_{2n} \\
  \vdots \\
  a_{m1} & a_{m2} & \cdots & a_{mn}
\end{pmatrix}
\begin{pmatrix}
  c_1 \\
  c_2 \\
  \vdots \\
  c_n
\end{pmatrix}
$$

(6.1)

To correct a trajectory, a corrector setting must be found to give zero trajectory excursions at the BPM locations:

$$
b - A \cdot c = 0
$$

(6.2)

The problem is then solved with

$$
c = A^{-1} \cdot b
$$

(6.3)

However, in general $n \neq m$ and $A$ is not invertible. Instead of inverting $A$, the norm

$$
|b - A \cdot c|
$$

is minimised, where $|x| = (\sum_{i=1}^{m} |x_i|^2)^{1/2}$. To solve the problem the ansatz for the response matrix is $A = U W V^T$, where $U$ and $V$ are orthogonal matrices with $V^{-1} = V^T$. $W$ is a
pseudo diagonal matrix

\[ W = \begin{pmatrix}
\sigma_{11} & \cdots & 0 \\
\sigma_{22} & \ddots & \cdots \\
\vdots & \ddots & \ddots \\
0 & \cdots & \sigma_{kk}
\end{pmatrix} \]  \hspace{1cm} (6.5)

and \( k=\min(n,m) \). \( c \) in (6.4) is unknown. The ansatz for \( c \) according to (6.3) is with a pseudo-inverse matrix of \( A \): \( c = VW^{-1}U^T \cdot b \)

\[ W^{-1} = \begin{pmatrix}
1/\sigma_{11} & 0 & \cdots \\
0 & 1/\sigma_{22} & \cdots \\
\vdots & \vdots & \ddots \\
0 & \cdots & 1/\sigma_{kk}
\end{pmatrix} \]  \hspace{1cm} (6.6)

Fig. 6.2 shows the result of the application of MAD-X’s correction module with the SVD algorithm on the trajectory of Fig. 6.1. The maximum trajectory excursions are now well below 4.5 mm. The tolerances on the BPM misalignment used for the correction can be found in Table 6.1.

![Figure 6.2: Vertical trajectory after correction.](image)

The expected correction performance of the transfer lines was checked for TI 8 with 1000 seeds. Fig. 6.3 shows the distribution of expected maximum trajectory excursions after correction in the horizontal and vertical plane with the BPM tolerances of Table 6.1.
The correction system satisfies the requirements on the maximum trajectory excursions. Fig. 6.4 gives the distribution of maximum corrector strength for all the correctors in TI 8 for the horizontal and vertical plane for the same 1000 seeds. The strengths stay below the maximum allowable strength of 70 \( \mu \text{rad} \), showing that the line can be corrected with the available BPMs and correctors.

![Distribution of maximum x-trajectory excursions after correction](image1)

![Distribution of maximum y-trajectory excursions after correction](image2)

Figure 6.3: Distribution of maximum amplitudes for TI 8, based on 1000 trajectory corrections simulated with all errors.

### 6.1.4 Aperture model

**LHC – IR 8**

For most of the elements in the LHC sequence the aperture had been defined in 2004. The model is almost complete. The aperture model in the IR 8 injection region is based on the official LHC model as far as active elements are concerned. Missing gaps were filled by hand by installing additional markers. In Fig. 6.5 the aperture model used in the simulations in this thesis is illustrated.

**Transfer line**

A maintainable, configurable model of the physical aperture of the two lines was produced with the C program “BAD” [50], containing around 1000 elements for each line, including bending, focusing and correction magnets, as well as instrumentation, collimators and safety devices, together with the real vacuum pipes, flanges and bellows. The model allows interpolation at arbitrary intervals, and is fully interfaced to MAD-X, taking as
Figure 6.4: Distribution of maximum corrector strengths for TI 8, based on 1000 trajectory corrections simulated with all errors.

Figure 6.5: The aperture model for IR 8 used in the simulations (the plot shows the half-aperture). The aperture of the protection devices TDI, TCLIA and TCLIB is not included. (IP 8: interaction point of the LHC-b experiment in IR 8.)
input the sequence files for the lines, together with the specific configuration files for the apertures. It produces a sequence-edit file containing all aperture information and markers.

Fig. 6.6 and 6.7 show the aperture model of TI 8 in the horizontal and vertical plane obtained with BAD and used in the simulations.

![Diagram](image_url)

Figure 6.6: Theoretical mechanical aperture in TI 8, horizontal plane.

### 6.1.5 Settings of protection devices

Collimators and other movable absorbers do not have a fixed aperture. Their setting is given in a number of beam sigma according to the protection requirements. In the simulations the setting also has to include tolerances like uncertainties on the beam size measurement, tolerances on the collinearity between the collimator jaws and the beam axis, mechanical tolerances and uncertainties on the beam axis measurement (see Table 6.2 and 6.3 for the TCDI transfer line collimators and the injection stopper TDI and its auxiliary collimators TCL1).

Two different ways for positioning the collimator jaws in the simulations were applied. Either the jaws were set to the nominal setting plus the maximum tolerance or the jaw setting was redefined every run to a random setting around the nominal jaw position. The aperture of collimators was defined with markers in the simulation input. At least 3 markers were used per collimator. In this way the longitudinal extent of the collimator jaws as well as the angular misalignment between jaw and beam could be treated correctly, see Fig. 6.8.

The arithmetic sum of the tolerances for the transfer line collimators TCDI in Table 6.3 corresponds to 1.2 $\sigma$. For most of the design studies a sum of tolerances of 1.4 $\sigma$ was
Figure 6.7: Theoretical mechanical aperture in TI 8, vertical plane.

<table>
<thead>
<tr>
<th>Device</th>
<th>Mechanical [mm]</th>
<th>Orbit [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDI</td>
<td>±0.2</td>
<td>±0.05</td>
</tr>
<tr>
<td>TCLI</td>
<td>±0.075</td>
<td>±0.05</td>
</tr>
</tbody>
</table>

Table 6.2: Tolerances for the setting of TDI-TCLI.

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-jaw parallelism (half-gap)</td>
<td>μm</td>
<td>50</td>
</tr>
<tr>
<td>Jaw axis wrt tank (half-gap)</td>
<td>μm</td>
<td>100</td>
</tr>
<tr>
<td>Tank axis wrt beam axis (half-gap)</td>
<td>μm</td>
<td>180</td>
</tr>
<tr>
<td>Surface flatness</td>
<td>μm</td>
<td>50</td>
</tr>
<tr>
<td>Knowledge of beam position</td>
<td>μm</td>
<td>44*</td>
</tr>
<tr>
<td>Knowledge of beam size + beating</td>
<td>σ</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 6.3: Tolerances for the setting of the transfer line collimators. For a typical beam size of 0.5 mm, the arithmetic sum of the tolerances corresponds to about 1.2 σ. *Value for 95% confidence limit: single shot tolerance = 100 μm, assumed number of shots = 25.
Figure 6.8: Three markers are used to define the aperture of a collimator.

assumed. Initially the contribution of the uncertainty on the beam position knowledge was overestimated with a shot-to-shot\(^1\) variation of 150 µm. During the commissioning of the transfer line TI 8, however, it turned out that the beam jitter is well below 100 µm, see Chapter 12. This gives an additional safety margin on all simulation results involving TCDI collimators.

\(^1\)Shot-to-shot: from SPS extraction to SPS extraction.
7

Attenuation and Emittance Growth of 450 GeV and 7 TeV Proton Beams in Low-Z Absorber Elements

All LHC passive protection devices protecting against failures during beam transfer, injection and dumping must withstand the impact of LHC beams. Hence all are made of low-Z materials such as carbon to be robust enough. The damaging potential of the beam depends on the number of particles and transverse beam size, hence on the transverse energy density. In these "diluters", the reduction of the beam energy density is determined both by the attenuation due to inelastic nuclear collisions and by the emittance growth of the surviving protons due to elastic scattering processes. The physics principles leading to attenuation and emittance growth for a hadron beam traversing matter are summarised. The predicted attenuation and emittance growth is compared with FLUKA simulations for carbon diluter elements, at proton energies between 450 GeV and 7 TeV, diluter lengths between 20 and 700 cm, and carbon densities between 1.77 and 3.00 g/cm³. The overall dilution efficiency is derived using a simulation of the peak energy deposition variation with beam emittance [51]. The results determined the design criteria for the transfer line collimators.

7.1 Scattering Processes

For an increase in the angular spread of the beam by $\Delta \theta$ the emittance growth is given by $(\epsilon_{\text{new}}/\epsilon_0 - 1)/\beta = \Delta \theta^2 / \epsilon_0$ where $\beta$ is the conventional $\beta$-function and $\epsilon_0$ the initial emittance.

Inelastic nuclear scattering

Inelastic scattering is characterised for our purposes by an interaction length $\lambda_I$, with the primary protons removed from the beam by the interaction. For the energies under consideration, $\lambda_I$ is typically 45 cm in carbon. After traversing a length $L$ of the diluter, the attenuation $N_0/N(L)$ of the primary proton beam is $\exp(L/\lambda_I)$. 
Elastic nuclear scattering

For elastic scattering the interaction length is typically 100 cm in carbon. The proton survives and is scattered with a relatively large angle. The process can be described by an optical diffraction model, with an R.M.S. scattering angle $\theta_e$ in each of the two transverse planes given by [52]:

$$1 / \theta_e^2 = 1/3 \ A^{2/3} \ (p / 0.135)^2 \ [\text{rad}] \quad (7.1)$$

where $A$ is the mass number of the target and $p$ the proton momentum in GeV/c. The probability $P$ of observing $n$ interactions in a length $L$ with interaction length $\lambda_e$ is given by:

$$P(L/\lambda_e, n) = e^{-L/\lambda_e} \ (L/\lambda_e)^n / n! \quad (7.2)$$

After $n$ scattering events each of angle $\theta_e$, the total angle is $\sqrt{n} \ \theta_e$.

Multiple Coulomb scattering

The multiple Coulomb (Rutherford) diffusion process is treated statistically, and after traversing a length $L$ of the diluter, an approximately Gaussian angular distribution is obtained with the R.M.S. proton scattering angle $\theta_{mc} \ [\text{rad}]$ in each of the two transverse planes given by [52]:

$$\theta_{mc} = 0.0136 / p \sqrt{L/X_0} \ [\text{rad}] \quad (7.3)$$

where $p$ is the proton momentum in GeV and $X_0$ the radiation length, typically 20 cm for carbon.

7.2 FLUKA Simulation

The primary beam attenuation and emittance increase, as a function of carbon density, diluter length, beam energy and the geometry, were calculated with FLUKA. A pencil beam with zero initial divergence was incident perpendicular to the front face of a carbon jaw. The number and exit angles of the surviving primary protons were recorded. The main systematic error contributions are associated with the uncertainties on the reaction cross sections. From comparison with experimental data for graphite, this error is well below 10% for the energy range considered. Statistical errors are of the order of 1% for most of the simulations, except for long diluter lengths, where the error reaches 15% for 500 cm length.

7.3 Results

Two of the most important parameters are the elastic and inelastic nuclear interaction lengths. The values in carbon obtained from FLUKA are shown in Table 11.1 and 7.2, as a function of beam energy and material density, assuming that the attenuation depends on the length as described above.
Table 7.1: Inelastic ($\lambda_I$) and elastic ($\lambda_E$) interaction length vs. beam energy for protons impacting a carbon diluter of $\rho = 1.77 \text{ g/cm}^3$.

<table>
<thead>
<tr>
<th>Energy (TeV)</th>
<th>0.45</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_I$ (cm)</td>
<td>46.1</td>
<td>44.9</td>
<td>44.4</td>
<td>43.9</td>
<td>43.0</td>
<td>42.1</td>
</tr>
<tr>
<td>$\lambda_E$ (cm)</td>
<td>118</td>
<td>113</td>
<td>109</td>
<td>107</td>
<td>102</td>
<td>99.0</td>
</tr>
</tbody>
</table>

Table 7.2: Inelastic ($\lambda_I$) and elastic ($\lambda_E$) interaction length vs. carbon density $\rho$ for protons impacting a carbon diluter at 450 GeV.

<table>
<thead>
<tr>
<th>$E = 0.45 \text{ TeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
</tr>
<tr>
<td>$\lambda_I$ (cm)</td>
</tr>
<tr>
<td>$\lambda_E$ (cm)</td>
</tr>
</tbody>
</table>

Figure 7.1: Angular distribution of 450 GeV protons traversing a 1.2 m long, 1.77 g/cm$^3$ carbon diluter. In blue the analytical functions for elastic and multiple Coulomb scattering are given. The black curve is the FLUKA result. The red curve is the superposition of elastic scattering and multiple Coulomb scattering with the analytical formulae. The green curve is an equivalent Gaussian giving the same proton density at the center of the distribution as the FLUKA results.
7.4 Emittance Growth by Scattering

The angular distribution from FLUKA of the surviving protons for the impact of 450 GeV protons on a 1.2 m 1.77 g/cm³ carbon jaw is shown in Fig. 7.1. The two distinct scattering processes produce two superposing angular distributions. The expected curves from the formulae quoted above are also shown, with the superposition shown in red of the expected angular distributions considered for n = 1, 2 ... multiple elastic scattering events per proton - for 0 elastic scattering events the angular distribution is given by the multiple Coulomb scattering alone. To extract a quantitative figure for the peak proton density, an equivalent Gaussian giving the same proton density at the center of the distribution was computed (dashed line) - this has an R.M.S. of 152 µrad. For a typical beta function of 50 m and the nominal emittance of 3.75 µrad, this corresponds to a beam emittance increase of a factor of about 150.

![Formulae FLUKA](image)

Figure 7.2: Effective emittance growth / β for 450 GeV and 7 TeV protons after traversing a 1.77 g/cm³ carbon diluter, as a function of length.

In Figs. 7.2 to 7.4 the emittance growth ((ε_{new}/ε_0 - 1)/β for protons impacting on a carbon diluter are shown as a function of the diluter length, beam energy and diluter density, respectively. It should be noted here that the values shown need to be multiplied by the β value at the diluter location to calculate the actual emittance increase.

7.5 Overall Dilution Efficiency

The overall dilution efficiency is determined by both the attenuation in the diluter and the divergence of the surviving proton beam since the divergence will affect the beam size and hence the energy deposition in material. To evaluate this efficiency, the energy deposition as a function of the transverse beam size for energies of 450 GeV and 7 TeV, for a proton beam impacting a copper target, was simulated with FLUKA for a range...
Figure 7.3: Effective emittance growth / $\beta$ after traversing a 1.2 m long 1.77 g/cm$^3$ carbon diluter as a function of proton energy.

Figure 7.4: Effective emittance growth of 450 GeV protons traversing a 1.2 m carbon diluter, as a function of density.

of beam emittances, with typical transverse $\beta$ values of 50 m (corresponding to nominal beam sizes of 0.6 mm for 450 GeV and 0.2 mm for 7 TeV). The results are shown in Fig. 7.5.

The dilution efficiency is defined as the ratio of the energy deposition for an undiluted beam with nominal normalised LHC emittance of 3.75 $\mu$m, to the actual energy deposition for a beam having traversed the diluter. This was calculated for various diluter configurations using Fig. 7.5. The results are shown in Figs. 7.6 to 7.8 as a function of
7.5. Overall Dilution Efficiency

Figure 7.5: Peak energy deposition $E$ in GeV/p+;/cm$^3$ in a copper target vs. beam size $\sigma$ for 0.45 and 7 TeV. In both cases, $E \propto 1/\sigma$.

Figure 7.6: Dilution efficiency vs. diluter length for 450 GeV protons traversing 1.77 g/cm$^3$ carbon.

the diluter length for 450 GeV and 7 TeV, and also as a function of the carbon density for 450 GeV.
7.6 Discussion

The beam intensity required to damage the accelerator components varies with beam size and energy. When this is taken into account an overall dilution effectiveness can be derived. At injection energy, the emittance growth contributes significantly to the overall dilution efficiency for particles having traversed diluter elements, see Fig. 7.2. The results show that short (~ 1 m) diluters can be effective for beams injected into the LHC, since here the energy and intensity are low enough to allow sufficient energy density attenuation. At higher beam energies, in the LHC ring proper, the required diluter length...
quickly becomes very long. In some particular applications where there is no alternative, low-Z (carbon) diluters of \( \sim 6 \) \( \text{m} \) length will be used, like the TCDQ element, which protects against an unsynchronised beam dump [53].
8

The TCDI Transfer Line Collimation System

The active protection system to protect the LHC during the injection process is complemented by the passive protection with transfer line collimators. The studies made to define the transfer line collimation scheme, the number of collimators, the basic collimator design and the required setting of the movable collimator jaws are discussed in this chapter, together with the performance of the final system chosen.

8.1 Transfer Line Collimation Schemes

The necessity of transfer line collimators, TCDI, was emphasized in [54] in 2002 in view of the different possible failure scenarios in the pulsed transfer lines, the very small aperture of the injection septum MSI and the fact that there is no passive horizontal protection in the LHC injection region. At this stage a “two-phase” collimation system in both planes with two jaws per collimator was proposed. Two-phase collimation in each plane means that two collimators per plane are used separated by $90^\circ$ betatron phase advance. In 2003 further work [55] defined a setting of the collimator jaws of $5\,\sigma$ from the beam axis. The objective was to protect locally the MSI aperture and globally the LHC aperture. Additional collimators in high dispersion regions were also foreseen to capture off-momentum particles.

The available aperture in the LHC at 450 GeV is $7.5\,\sigma$, see Chapter 3. Fig. 8.1 illustrates the maximum phase-space coverage obtainable with a two-phase collimation system. According to the formula

$$n_{\text{max}} = \frac{n_{\text{setting}}}{\cos(90^\circ/2)}$$

(8.1)

the maximum particle amplitudes in $\sigma$ which can pass through the collimation section into the LHC in failure cases are $7.07\,\sigma$ for a collimator setting of $n_{\text{setting}} = 5\,\sigma$. No tolerances or machine imperfections are included in this number. Taking imperfections into account the maximum amplitudes escaping the system can be more than $0.5\,\sigma$ larger than $n_{\text{max}}$ and hence protection of the LHC aperture cannot be guaranteed with a two-phase system. A “three-phase” collimation system consists of three collimators per plane with $n \times 180 + 60^\circ$ between two adjacent collimators. The achievable phase-space coverage is illustrated.
A “four-phase” collimation scheme with four collimators in each plane with \( n \times 180 + 45^\circ \) between two collimators gives even better phase-space coverage, see Fig. 8.3, with maximum amplitudes of only \( 5.4 \sigma \) escaping the system. Both the three-phase and four-phase system provide sufficient phase coverage with a setting of \( 5 \sigma \). T18 was the first LHC transfer line where it was tried to fit a collimation scheme into the existing lattice. A four-phase scheme was proposed.
8.2 TCDI Design Studies

The TCDI collimators are required to intercept mis-steered beam before it is lost on LHC equipment. These collimators hence have to be robust enough themselves to survive the beam impact. Lower Z values for the jaw material have the advantage that less energy is deposited; however, low-Z jaws attenuate the beam energy less. FLUKA simulations were used to specify the design of the TCDI collimators [56].

8.2.1 Initial energy deposition studies

The temperature in the yoke material (Fe) of magnets or the material of the coils (Cu) should not exceed 100°C to avoid deterioration of the magnetic properties. FLUKA simulations were performed to check local energy deposition from shower and scatter products from TCDI jaws. The results were obtained for the layout of the four-phase system only.

A typical collimator location (TCDIH090) was chosen and the geometry of the equipment downstream, consisting of flanges, vacuum pipes, bellows and a quadrupole magnet, together with the collimator jaws was implemented in FLUKA in a simplified version. At this stage of the project the collimator length was still a variable; Fig. 8.4 illustrates the simple model used in the FLUKA simulations with graphite jaws of 2 m length. There are about 5.5 m between the exit face of the collimator and the quadrupole.

Different impact parameters\(^1\) of a full injected batch on the TCDIH090 were studied. FLUKA results for a 1 σ (≈ 0.55 mm) impact on a 2 m long graphite jaw (density \(\rho = 2 \text{ g/cm}^3\)) are shown in Fig. 8.5. The jaws were set to 5 σ. The left plot shows the temperature rise in the copper part in a cross-section of the quadrupole at the energy deposition maximum. A Cartesian binning of the geometry was used for this calculation.

---

\(^1\)Impact parameter: distance from the edge of the collimator jaw in the material.
The distribution of the temperature rise in the different bins in this cross-section (transverse bin size: half a beam sigma in both planes) is shown in the histogram on the right side of Fig. 8.5. A temperature rise of more than 200° C is reached in the magnet.

8.2.2 Simulations with secondary masks

The reason for the relatively large temperature rise in the magnet downstream of the collimator is out-scattering from the edge of the jaw for small impact parameters, as illustrated in Fig. 8.6. This effect could not be significantly ameliorated with longer jaws. A cure, however, was found with a “secondary mask” made of stainless steel (iron in the simulation), 50 cm long, to shadow the coils of the quadrupole. The mask had to have the same aperture as the vacuum chamber in the magnet. Fig. 8.7 shows the modified layout with the mask in front of the quadrupole.

As can be seen in Fig. 8.8, the mask causes a reduction of the peak temperature rise from about 150 - 200° C to about 50° C, for 3 m as well as 2 m long jaws. Even in the case of 1 m long jaws, the energy deposition for the impact of a full nominal injected batch leads to a maximum temperature rise of only about 60° C. In Fig. 8.9 the temperature rise in a cross-section of the quadrupole at the energy deposition maximum for a 1.2 m long graphite jaw with a 1 σ impact is illustrated.
8. The TCDI Transfer Line Collimation System

Figure 8.6: Small impact parameters in the order of 1 beam sigma lead to high probability of out-scattering of particles from the edge of the jaw. These particles do not traverse the whole length of the jaw. For this part of the beam the collimator is not very effective.

Figure 8.7: Shielding in the form of an iron mask in front of the quadrupole is proposed to capture the out-scattered beam, before it impacts on the quadrupole.

8.2.3 Collimator design choice

One of the design criteria for the TCDI jaw material and length was to attenuate an impacting full batch to a safe level for the LHC, which means by a factor of 20 (5 % equipment damage limit). A preferable solution for the TCDI collimator design was to adopt as much as possible the existing design of the LHC secondary collimator TCS [57]. The TCS design has two jaws per collimator made of C-C (Carbon-Carbon composite). The movable jaws of an assembled horizontal TCS collimator can be seen in Fig. 8.10. Using the TCS design, the maximum possible jaw length is 1.2 m.

In Chapter 7 it was demonstrated that at injection energy relatively short low-Z protection devices can sufficiently dilute the beam due to the effect of emittance growth for the beam traversing a jaw. These results justified to use a simplified TCS design with 1.2 m long graphite jaws for the transfer line collimators. The graphite density was chosen to be 1.83 g/cm³. This leads to a maximum obtainable attenuation of the beam to 7 % instead of the initially specified 5 %. With the effect, however, of the emittance growth (factor 150 for 50 m β) the overall dilution factor in terms of energy deposition is 163, which is largely sufficient.

8.2.4 Energy deposition simulations for the entire transfer line collimation section

The results from above indicate, that significant energy deposition in equipment caused by the partly transparent 1.2 m TCS-type jaws can be avoided with the additional shielding of secondary iron masks.

However, the magnetic field of the quadrupole was not taken into account in these initial energy deposition simulations, and also the distance between the collimator exit face and the entrance face of the downstream equipment varies for different TCDI locations and could change the conclusions significantly. It was thus decided to check the validity of the
results by implementing the entire collimation section of the transfer line TI 8 (~300 m) in FLUKA with magnetic fields and simulating worst case impact scenarios with various impact parameters on the different TCDIs using the TCS design (graphite, 1.2 m long, 1.83 g/cm³ density) and masks.

The line itself is vertically and horizontally tilted, defined by the dipole bending angles, which significantly complicates the implementation of the geometry in FLUKA. A preprocessing program was therefore developed in the programming language C to transform a MAD-X Twiss output together with a vacuum sequence (listing bellows, vacuum valves, beam instrumentation, magnet pipes etc. in the right order) into a geometry file which is then transformed into FLUKA format with ALIFE, an editor and parser for FLUKA geometries [58]. The C program consists of modules for the different magnets, vacuum equipment, collimators and pipes containing geometry and material description derived from equipment drawings. The MAD-X files are used to define the orientation of the equipment according to the dipole bending angles and for the magnetic field description in FLUKA.

These FLUKA simulations were only done for the four-phase collimation scheme. The temperature rise in all the simulations was calculated for ultimate beam intensity. The

Figure 8.8: Illustration of the distribution of number of bins in the cross-section with the energy deposition maximum in the quadrupole versus temperature rise. The mask lowers the temperature rise in the case of 3 m, 2 m and 1 m long significantly from above 150 - 200° C without mask to finally 50 - 60° C with mask.
Figure 8.9: Temperature rise in [K] in the cross-section of the quadrupole at the energy deposition maximum for a 1.2 m long 2 g/cm³ graphite jaw with a 50 cm iron mask in front of the magnet.

results of this study can be found in appendix B.

With the outcome of the simulations, a rule of thumb could be established to avoid unacceptable energy deposition in the magnets from collimator showers and out-scattered primaries. A distance of at least 5 m between collimator jaw and downstream magnets is required and the beta function at the collimator location should be larger than 15 m. This study demonstrated that with the final TCDI layout and secondary masks, the temperatures in all transfer line elements during accidental beam loss on the collimators remains below 100° C. For all TCDI locations, except those close to the MSI, this mask will be made of ferrite stainless steel with a length of 50 cm. An outer diameter of 100 - 150 mm is sufficient, the inner diameter and shape has to be the one of the vacuum chamber of the element to be protected [59].

Figure 8.10: Picture of the two movable jaws of an assembled horizontal TCS collimator (courtesy O. Aberle).
A special mask is required for the vertical and horizontal collimator at the MSI. Due to their objective of serving as a local protection of the MSI, these collimators have to be located very close to the septum, contrary to the rule of the thumb explained above. The temperature rise in the MSI from the secondary shower was thus a serious concern. Fig. 8.11 shows where the energy deposition maximum occurs in the MSI for a beam impact on the vertical MSI collimator. A longer mask made of a different material had to be proposed to keep the temperature below 100° C in the magnets and not to destroy the mask itself during impact on TCDIVMSI.

![Energy in MSIB-C6R8 in (GeV/cm^3/μ)](image)

Figure 8.11: Cross-section of the first MSIB (seen from the SPS) at the longitudinal energy deposition maximum. The transverse energy deposition maximum occurs close to the beam pipe.

Fig. 8.12 shows the FLUKA results as temperature in the transfer line section downstream of the MSI collimators after a 10 σ impact on TCDIVMSI for different mask configurations (different materials and lengths). The final choice was an 80 cm INCONEL mask. For this mask the maximum temperature in the MSI is 52° C. The mask reaches about 930° C. INCONEL is a high temperature stainless steel and is supposed to survive a thermal shock of more than 900° C without mechanical deformation. Spare masks for the MSI will nevertheless have to be foreseen in view of possible damage.

### 8.3 Final Choice of Collimation Scheme

The optimum phase-space coverage can only be achieved if the collimators are within a few degrees of their nominal phase locations.
Figure 8.12: Longitudinal temperature profile in the section downstream of TCDIV-MSI for different mask materials. The pure Fe mask is 50 cm long. In all other cases the masks are 80 cm long. Al2O3 with its low Z value would survive the thermal shock, but would not protect the MSI adequately. The final solution was found with the material INCONEL, which brings down the temperature in the MSI to 52°C and can itself withstand the temperature rise from the energy deposition of the showers from the TCDIV-MSI.

### 8.3.1 Robustness of phase-space coverage towards machine imperfections

The phase-space coverage of the different possible schemes, two-phase, three-phase and four-phase, was simulated with machine imperfections (ripple on the quadrupole power converters, mismatch from the SPS and to the LHC, etc.) [60]. 100 seeds for different machine states of T1 8 were investigated with a uniform particle distribution filling initially the 10 σ phase-space vertically and horizontally. Particles were tracked through the transfer line and TCDI collimation section with MAD-X. In view of the large maximum tolerance on the effective jaw position of 1.4 σ (see Chapter 6) the nominal setting of the collimators was chosen to be 4.5 σ for the studies and they were set to 4.5 σ plus the maximum tolerance of 1.4 σ (corresponding to one motor per jaw) in the simulations. Equipping the collimator jaws with two motors (one motor at each jaw end) to adjust the collinearity between beam axis and collimator jaw could reduce the maximum tolerances by 0.3 σ. Additional runs were hence made where the collimator jaws were assumed to be equipped with two motors per jaw with a maximum tolerance of 1.1 σ on the setting. The histograms for the maximum amplitudes of the surviving particles for the different schemes with one or two motors per jaw are shown in Fig. 8.13.

From Fig. 8.13 it can be seen that both the four-phase (maximum amplitudes: 6.4 σ) and the three-phase scheme (maximum amplitudes: 6.8 σ) provide adequate phase-space coverage even in the presence of machine imperfections.
8.3. Final Choice of Collimation Scheme

8.3.2 Layout integration and optics considerations

The zero degree collimators (TCDIHMSI and TCDIVMSI) have to be close to the injection septum MSI. Also the protection of the LHC is more effective (as more possible upstream failures are covered) the closer the collimators are to the end of the line. Thus the collimation section is located in the last 300 m of the transfer line, which however coincides with the matching section of the line with the LHC. Any optics changes at the LHC injection point require an adjustment of the transfer line optics and hence have an influence on the phase advance in the matching section. In practice this perturbs strongly the phase advance between the TCDIs and ergo degrades the phase-space coverage.

During the last big optics change from LHC optics version V6.4 to V6.5 [30] the optics changed at the injection points, requiring re-matching of the line. The original solution for a four-phase collimation scheme in TI 8 did not fit any more and no appropriate space for the four-phase collimators could be found with the new line optics. As an example, the horizontal 90°-collimator ended up at 83.9° and the 225°-collimator was at 238.8° after the change.

However, with fewer phase relations to simultaneously satisfy, the TI 8 optics could be easily adapted for a three-phase collimation scheme. The final three-phase scheme in TI 8 has horizontal collimators at 60° and 300° from TCDIHMSI and vertical ones at 60° and 120° from TCDIVMSI. The optics for the final TCDI locations can be found.
<table>
<thead>
<tr>
<th>Name</th>
<th>$\beta$ [m]</th>
<th>dispersion [m]</th>
<th>$\Delta \mu$ to TCDIMSI [$^\circ$]</th>
<th>distance to next magnet [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCDIHM31</td>
<td>68.9</td>
<td>0.3</td>
<td>0</td>
<td>5.8</td>
</tr>
<tr>
<td>TCDIVMS1</td>
<td>209.1</td>
<td>0.06</td>
<td>0</td>
<td>4.3</td>
</tr>
<tr>
<td>TCDIHO60</td>
<td>21.9</td>
<td>0.5</td>
<td>61.5</td>
<td>30.3</td>
</tr>
<tr>
<td>TCDIVO60</td>
<td>31.9</td>
<td>-0.05</td>
<td>58.9</td>
<td>13.1</td>
</tr>
<tr>
<td>TCDIV120</td>
<td>64.1</td>
<td>-0.5</td>
<td>121.4</td>
<td>6.3</td>
</tr>
<tr>
<td>TCDI300</td>
<td>13.5</td>
<td>-1.4</td>
<td>299.4</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Table 8.1: Optics parameters for the TCDI locations for the final three-phase scheme. The distance to the downstream element is the distance between exit face of the collimator and entrance face of the magnet.

in Table 8.1. The three-phase locations ended up close to the four-phase ones, thus the energy deposition simulations did not have to be repeated. The rule of thumb with at least 5 m between collimators and magnets and $\beta$-function larger than 15 m could be satisfied for all locations, except TCDIHM300 where $\beta_x = 13.5$ m. The distance, however, to the downstream magnet is almost 10 m.

As can be seen in the table, the TCDI collimation system is not a pure betatron collimation system. The dispersion at the collimator locations is not zero. In some cases the figure of merit $D/\sqrt{\beta}$ is not favorable (TCDIHM300). The consequences for the phase-space coverage in connection with energy errors are discussed below. Because of the combined momentum betatron collimation system at the end of the line, the momentum collimator at the beginning of TI 8 can in theory be suppressed. (For T12 $D/\sqrt{\beta}$ is still larger at the momentum collimator.)

### 8.3.3 One or two motors per jaw

Fig. 8.13 also shows that similar results in terms of maximum amplitudes escaping the system can be expected for a four-phase system with one motor per jaw and a three-phase system with two motors per jaw. It was hence decided to equip the jaws of the TCDI three-phase system with two motors (maximum amplitudes: 6.5 $\sigma$) and in this way restore the protection level of a four-phase system. In the case that the jaw alignment procedures with two motors fail, the achievable protection level would still be sufficient (maximum amplitudes escaping: 6.8 $\sigma$).

### 8.4 Performance Studies: Protection Level versus Beam Loss and Energy Error

The TCDI collimators are protection devices. Under normal conditions, no beam should impact on the jaws to avoid the generation of secondary beam halo and minimise the activation of the collimators. The TCDI collimators are, however, positioned very close to the beam to provide the required protection level. In addition the collimator locations are not dispersion free.
The loss level on the collimators under normal operation and the deterioration of the protection level in combination with energy errors from the SPS was evaluated for the final three-phase system with a particle tracking for 1000 seeds for transfer line states including mismatch and machine imperfections as discussed in Chapter 6. The protection level was derived from a tracking with uniform particle distributions initially 10 $\sigma$ in horizontal and vertical phase-space. For the simulations of the nominal losses a realistic particle distribution was assumed: scraped Gaussian distribution. The kicker waveforms during the time of beam passage for the MKE extraction kicker and MKI injection kicker were taken into account, Fig. 8.14. These waveforms lead to different kick strengths for different bunches in the same bunch train. Angular misalignment, uncertainty of beam size measurement at the collimator location and uncertainty of beam axis knowledge were randomly allocated to the different TCDI collimators to set the jaws around the nominal 4.5 $\sigma$.

Fig. 8.15 summarises the results. A run (out of 1000 runs) was regarded as safe, if the maximum amplitudes escaping the system were below 7.5 $\sigma$. For the evaluation of the nominal losses at the collimators, the runs were divided into ones with total losses at the collimators below 0.1 $\%$ and runs with total losses at the collimators below 1 $\%$.

The red curve in Fig. 8.15 gives the fraction of safe runs as a function of the nominal collimator setting for zero energy error from the SPS. The blue curve shows the same results as the red curve but with an energy error of $\pm 0.1 \%$. The green curve gives the fraction of runs as function of the collimator setting for the total losses on the TCDIs below 0.1 $\%$ under normal conditions, the pink curve for total losses below 1 $\%$.

![Figure 8.14: The waveform for the injection kickers MKI and extraction kickers MKE.](image)

These simulations showed that with a nominal transverse setting of 4.5 $\sigma$ for the TCDI collimators and zero energy error from the SPS, a sufficient phase-space coverage can be guaranteed. The total losses on the collimators under normal conditions are always below 1 $\%$ of the injected beam intensity, in 70 $\%$ of the runs the losses are below 0.1 $\%$. The collimators are equipped with beam loss monitors. In case the beam loss monitor reading exceeds a limit to be defined, the collimator setting or the trajectory will have to be re-adjusted.

---

2The beams are scraped to 3.5 $\sigma$ in X, Y and XY in the SPS.
8.4.1 Consequences of beam energy error and non-zero dispersion at the TCDI locations

The blue curve in Fig. 8.15 illustrates that for an energy error of $\pm 0.1\%$ the required protection level is only reached in 20\% of the possible states of the transfer line for a nominal setting of $4.5\sigma$. This is due to the large dispersion at some of the transfer line collimators (e.g. TCDIH300: $D_x = 1.4\text{ m}$). Combined failures, where a magnet in the line trips with at the same time an energy error from the SPS might not be sufficiently covered.

Fig. 8.16 shows the fraction of safe runs as function of the nominal setting as well as energy error from the SPS. In order to guarantee an adequate protection level of the transfer line collimators with a setting of $4.5\sigma$, the SPS energy must be interlocked at an energy deviation of $\delta = \pm 5 \times 10^{-4}$.

8.5 Summary

Simulations with FLUKA and MAD-X were extensively used to define the transfer line collimation scheme and the collimator design and to check the achievable protection level for the LHC and also the local protection level not to exceed temperature limits on adjacent equipment. The transfer line collimators will be a three-phase collimation system with three TCDIs per plane and $n \times 180+60^\circ$ phase advance between two adjacent collimators. The collimator design is based on the LHC secondary collimator design with two motors per 1.2 m long graphite jaw. Secondary masks must be installed in front
of the next magnet downstream of a TCDI to shield its coils against collimator shower and scatter products. With the specified nominal setting of 4.5 $\sigma$ and an interlock on the SPS energy at an energy deviation of $\delta = \pm 5 \times 10^{-4}$, the LHC and MSI aperture are sufficiently protected. The total beam loss on the TCDI collimators under normal conditions is below 1 % of the total injected batch and with a probability of 0.3 above 0.1 %.
9

The Injection Protection System
TDI-TCDD-TCLI

Injection kicker (MKI) failures belong to the group of ultra-fast failures, for which passive protection absorber elements consisting of the TDI, TCDD and TCLIs are foreseen to prevent damage to the LHC [61]. A detailed particle tracking, taking realistic mechanical, positioning, injection, closed orbit and local optical errors into account, has been used to determine the required settings of the absorber elements to guarantee protection against different MKI failure modes. The expected protection level of the combination of TDI with TCLI, with a new TCLI layout for one of the TCLI locations, is presented. Conclusions are drawn concerning the expected damage risk level.

9.1 MKI Injection Kicker

The injection kicker system consists of four traveling-wave kicker magnets with a total vertical deflection angle of 0.85 mrad and an integrated dipole field of 1.2 Tm.

![Diagram](image)

Figure 9.1: Schematic of the circuit for one MKI module.

Fig. 9.1 shows the circuit diagram for a single MKI magnet. A PFN (pulse-forming network) powers the magnet. The PFN is charged by the Resonant Charging Power Supply (RCPS). Each RCPS charges two PFNs. Two switches on each side of the PFN are needed to vary the pulse duration, the dump switch and the main switch. The design voltage of the PFN is 60 kV (the voltage on the kickers is half the PFN voltage), the design voltage of the magnet is 35 kV [62]. The operating voltage of the PFNs is 54 kV. Each magnet consists of 33 cells equipped with matching capacitors between a high voltage and a ground plate. Between the plates there are ceramic-metal insulators.
9.1.1 Possible MKI faults

The switches mentioned above are gas tubes (thyratrons). These can spontaneously self-fire, which results in “erratic” pulses or not fire which then gives “missing” pulses. Another reason for the kicker system not firing is the missing of the prepulses from the RF system. Erratics are expected to happen a few times a year. In this case the other kickers are immediately triggered afterwards and the beam will be swept over the whole deflection range. The probability of erratics can be reduced by charging the PFNs only 2 ms before injection (after injection the kicker is switched off). Another reason for a sweep is wrong kicker timing.

One of the most dangerous failures is a “flash-over”, where a discharge occurs between one of the high voltage plates and ground in one of the 33 magnet cells. Depending on in which cell the flash-over happens, the resulting kick of this module is between 0 and 200 %. Thus in total the kick from the MKI system during a flash-over can be any value between 75 % and 125 % of the nominal total kick. The whole injected beam would be kicked with the wrong angle [33].

9.2 Injection Protection against MKI Failures

![Image of injection region in IR 2 (distance MSI-TCLIB: ~ 420 m).](image)

9.2.1 The TDI absorber

For injection tests with pilot bunches and to protect the LHC aperture in case of malfunctioning of the vertical injection kickers, a movable two-sided 4.25 m long vertical injection beam stopper, the TDI, is placed $\mu_k = 90^\circ$ ($\sim$ 70 m downstream of the kicker) from the MKI. The TDI is 15 m upstream of the superconducting recombination-separation dipole D1. The upper jaw is needed in the case the injected beam is not sufficiently kicked by the MKI. In the case of over-injection or an erratic which deflects the circulating beam, the beam would end up on the lower jaw.

The TDI jaws consist of a sandwich of different absorbing materials held together by an Al frame. The robust low-Z material hBN is followed after 2850 mm by 600 mm Al and then by 700 mm Cu. The TDI is not actively cooled. In order to keep the impedance low for the circulating beams, the hBN is coated with 3 $\mu$m of Ti and the Al block and
the Al frame with 10 $\mu$m of Cu. A beam screen of stainless steel 316LN, Cu coated, is installed on each side of the jaw [63].

A 1 m long mask made of Cu, the TCDD, is in the layout to protect the superconducting coils of the D1 from the showers generated in the TDI in case of impact, see Fig. 9.2.

### 9.2.2 The TCLI collimators

In case the phase advance between the MKI and the TDI is not exactly $90^\circ$ the protection against kicker failures is complemented by two double-jaw vertical auxiliary collimators, TCLIA and TCLIB [61]. To accommodate a $\pm 20^\circ$ phase difference, TCLI locations were assigned at $n \times 180^\circ \pm 20^\circ$ from the TDI. TCLIB is close to the insertion quadrupole Q6 at $\mu_y = 360 - 20^\circ$ from the TDI, TCLIA is at the downstream end of the cold separation dipole D1 on the other side of the insertion at $\mu_y = 180 + 20^\circ$.

### 9.3 Simulations

The importance of the TDI is demonstrated in Fig. 9.4, which shows a loss map along the injection insertion region for MKI failures resulting in different kicks when the TDI is not correctly positioned (combined failure). The loss maps illustrate that MKI failures with the TDI accidentally retracted can result in severe damage of the D1 or the inner quadrupole triplet.

In the following, the simulations used to define the setting for the combined system TDI and TCLI are described. The simulations were performed for the most dangerous case only, a flash-over of the MKI [64]. The input parameters and assumptions are given, and protection levels for a given minimum cold-bore aperture and damage risk are derived. A proposal for a TCLI layout and preliminary collimator design requirements are presented.
Figure 9.4: MKI failure with no TDI. Different possible kick strengths are shown with the corresponding beam loss maps along the injection insertion region. The red line gives the relative number of particles lost of the injected batch. On top of the plots the extent of relevant LHC equipment in the injection insertions is illustrated. The damage limit is 0.05 on the vertical scale. (Horizontal axis: distance from centre of MKI [m].)
9.3.1 Simulation methodology

The protection level during an MKI flash-over is defined by the number of particles escaping the TDI-TCLI protection system having an amplitude greater than the cold-bore aperture, as a function of the nominal setting of the system. This number is obtained with MAD-X, with particle tracking through the transfer line and the injection region in the LHC. The simulations were done for the latest LHC optics version V6.5.

A “typical” state of the transfer line was defined with a Monte-Carlo for the random errors of power converter ripples, line drifts and SPS extraction error. These values were scaled to give a 95 % confidence level for the injection error at the injection point in the LHC.

In the simulation a kick range from -0.15 to 0.15 mrad was scanned, with the maximum kick strengths of the range reaching about $10\sigma_y$ ($\sigma_y$: vertical R.M.S. beam size) at the TDI. At the same time a scan of the settings of the TDI and TCLI from 6 $\sigma_y$ to 10 $\sigma_y$ was done. The number of particles above the cold-bore aperture defines the required setting of the protection devices. Fig. 9.5 shows the results for such a scan with an effective cold-bore aperture of 7.5 $\sigma$.

The load on the protection devices was also derived. Simulations were done for all protection devices having the same setting, as well as for the TDI retracted by 1 $\sigma_y$ or 2 $\sigma_y$ compared to the TCLI.

![Figure 9.5: Number of particles getting into the LHC with amplitudes greater than 7.5 $\sigma_y$ as a function of the setting of TDI and TCLI and of the MKI kick.](image-url)
9.3.2 Parameters and assumptions

The initial parameters for the simulation are summarised in Table 9.1. Only the injection region of IR 8 was studied. For IR 2 no major differences are expected, due to the similar layout and optics.

The injection error was taken as twice the R.M.S.-value of the expected vertical delivery offset [29]. The value of the orbit precision corresponds to the value achievable at the location of the protection devices. The damage limit corresponds to 5 % of an ultimate batch. The phase difference was obtained by changing the strength of Q4, the only quadrupole between MKI and TDI, by ±20 %.

<table>
<thead>
<tr>
<th>Injection error (y)</th>
<th>±0.45 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDI mechanical</td>
<td>±0.2 mm</td>
</tr>
<tr>
<td>TCLI mechanical</td>
<td>±0.075 mm</td>
</tr>
<tr>
<td>Orbit precision</td>
<td>±0.05 mm</td>
</tr>
<tr>
<td>Cold-bore aperture</td>
<td>7.5 σy</td>
</tr>
<tr>
<td>Damage limit</td>
<td>2.3 · 10^{12} p⁺</td>
</tr>
<tr>
<td>MKI-TDI phase error</td>
<td>±20°</td>
</tr>
</tbody>
</table>

Table 9.1: Input parameters.

9.3.3 Issues not included in the simulation

The simulations were done without any aperture model in the transfer line nor in the injection region of the LHC, apart from the protection devices themselves (a rough investigation showed that the aperture of elements other than the protection devices around IP 8 is larger than 9 σ).

The sweep effect of the MKI waveform was not taken into account. This effect will distribute the bunches within one batch around a certain amplitude; the assumptions are slightly conservative in this respect. Additional failures like power converter faults in the transfer line were neglected.

9.4 Results

Fig. 9.6 shows the maximum number of particles for the simulated kick range and for a certain protection setting getting into the LHC with amplitudes larger than 7.5 σ. The horizontal line in the plot indicates the damage level in the LHC (5 % of an ultimate batch). The simulations were done for 0° and ±20° MKI-TDI phase change as well as for positive and negative sign of the injection error. Table 9.2 summarises the required settings for different cold-bore apertures, to stay below the 5 % damage level for any MKI flash-over.

In Fig. 9.7 to 9.9 the relative load on the different devices is given as a function of setting and kick of the MKI for 0°, +20° and -20° phase advance shift between TDI and MKI. For the case of a phase advance shift of +20°, the load on TCLIB (at 340° from the
Figure 9.6: Maximum number of particles getting into the LHC with amplitudes greater than 7.5 $\sigma$ as a function of the setting.

<table>
<thead>
<tr>
<th>LHC cold-bore $\sigma$</th>
<th>phase shift</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>8.2</td>
<td>7.8</td>
</tr>
<tr>
<td>7.8</td>
<td>7.4</td>
</tr>
<tr>
<td>7.5</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Table 9.2: Required settings of injection protection system.

TDI) increases from about 15% to 50%, whereas the load on TCLIA (at 200° from the TDI) decreases to below 5%. For a phase advance shift of -20°, the load on TCLIA rises significantly as for TCLIB before, and the one for TCLIB decreases.

### 9.4.1 Risk quantification for a damaging MKI kick

Under the assumption that the results obtained for IR 8 also hold for IR 2, and only considering flash-overs, the risk for a damaging MKI kick was quantified. Fig. 9.10 shows the results for a flash-over probability of 1 MKI flash-over per 8 magnets per year. Results for cold-bore apertures 7.5 $\sigma$ and 8.2 $\sigma$ are plotted for 0° and ±20° phase change between MKI and TDI. For a cold-bore aperture of 7.5 $\sigma$ and risk level of one damaging kick in 20 years, a setting of ≤ 7 $\sigma$ is required.
9.4. Results

Figure 9.7: Beam load versus MKI kick (y-axis) and setting in beam sigma (x-axis): Relative load on first metre of TDI, TCLIA and TCLIB as function of setting and kick from MKI. Phase advance between TDI and MKI is $\mu_y=90^\circ$.

Figure 9.8: Beam load versus MKI kick (y-axis) and setting in beam sigma (x-axis): Relative load on first metre of TDI, TCLIA and TCLIB as function of setting and kick from MKI. Phase advance between TDI and MKI is $\mu_y=110^\circ$.

Figure 9.9: Beam load versus MKI kick (y-axis) and setting in beam sigma (x-axis): Relative load on first metre of TDI, TCLIA and TCLIB as function of setting and kick from MKI. Phase advance between TDI and MKI is $\mu_y=70^\circ$. 
9.4.2 TDI further retracted

The results indicate that the TDI/TCLI jaws have to be moved very close to the beam (< 7σ) to guarantee sufficient protection. This may result in an unacceptable load from the secondary halo, either for the uncooled TDI or the downstream D1 (out-scattering from the TDI) and hence require the retraction of the TDI compared to the TCLIs. The consequences for the load on the TCLIs were investigated. In Fig. 9.11 the load on one of the TCLIs is plotted. Without any MKI-TDI phase error and with the same setting for TDI and TCLI more than 10 % of the total batch can end up on the TCLI. With a phase advance of 90 ± 20° between MKI and TDI the load reaches more than 40 %. If the TDI is retracted by 1 σ the load goes up to 70 %, for 2 σ retraction to more than 80 %.

9.5 TCLI Layout

The simulations showed that a large fraction of the injected batch can end up on the TCLIs in case of failures. The jaws must therefore be robust and will be made of low-Z material such as graphite. Studies for beam impact on low-Z material have shown that due to attenuation combined with emittance blow-up, 1 m long low-Z jaws dilute a 450 GeV proton beam sufficiently well, see Chapter 7. Additional shielding outside the vacuum chamber is foreseen downstream of TCLIB to protect the superconducting quadrupole Q6 from scattering products, as needed for the transfer line collimators [59]. The TCLIs will have 1 m long jaws, fully movable, water cooled and with tapering. For TCLIB, the LHC secondary collimator (TCS) design can be used. The TCLI A close to D1 will need a dedicated design, as at this location both beams share a common beam
9.5. TCLI Layout

Figure 9.11: Load on TCLI at Q6 for same setting of TCLI and TDI as well as TDI retracted by 1 σ or 2 σ.

pipe with an inter-beam separation of about 20 mm. A special “half-jaw” design will be applied, making sure that only one beam, namely beam 1 in IR 2 or beam 2 in IR 8, is collimated without disturbing the other beam, see Fig. 9.12. The final design will need to take account of impedance issues, RF heating, and the requirement of a relative large aperture for the ZDC detector in IR 2.

Figure 9.12: TCLI-cross-section at the D1 location for IR 2. Both beams share one beam pipe, and are drawn with a 8.4 σ ellipse at the maximum possible excursion, corresponding to the maximum secondary halo extent. Protection does not interfere with the other beam.
9.6 Summary

The simulations showed that the TDI-TCLI system can give sufficient injection protection for the LHC. With the TDI and two additional TCLIs and a setting of 6.8 $\sigma$, a risk probability of one damaging MKI flash-over in 20 years for any phase error between MKI and TDI and an effective LHC cold-bore aperture of 7.5 $\sigma$ was derived. Robust TCLI collimators are required to cope with the beam load which can be more than 40 % for identical TDI and TCLI settings, and even more if the TDI needs to be retracted by 1 or 2 $\sigma$. A preliminary design for TCLIA close to D1 has been worked out satisfying both protection efficiency and local constraints. For TCLIB close to Q6, the LHC secondary collimator design will be used.
10

The Overall Performance of the Injection Protection System

The different passive injection protection systems have now been introduced and their locations and settings defined. The interlocking system takes care that these devices have their nominal settings during the injection process.

This chapter deals with the achievable protection level of the proposed system [65, 66]. The whole injection process starting at the SPS extraction and ending in the LHC downstream of the injection insertion was simulated for different fault conditions. The entire passive protection system was included in the simulations. The outcome served as a means to evaluate the overall protection level. The results also demonstrated where the active protection system needed upgrading while defining requirements for detection levels and reaction times of magnet current monitoring systems.

10.1 Simulations of the Overall Protection Level

The overall protection level for the present layout of the protection systems was evaluated in a Monte-Carlo simulation combined with a particle tracking. The whole injection process was simulated - connecting the SPS extraction region, the transfer line and the injection region in the LHC. The Monte-Carlo was used to sample different possible random states of the extraction, the line and injection region. The tracking was done with the MAD-X tracking module for LHC beam 2: the particles were extracted from the SPS in LSS4, transferred through the transfer line TI 8 and injected into the LHC in IR 8. The last element included in the tracking was the LHC quadrupole Q6 downstream of the second TCLI on the other side of the insertion. The criterion for safe injection was that particle losses on the aperture had to be below the 5 % damage limit during the whole process.

Mismatch between SPS and transfer line and transfer line and LHC was randomly chosen between ±20 %, anti-correlating vertical and horizontal plane. Random effects for power converter ripples, misalignments and tilts of accelerator equipment, beam jitter, etc. were included. For every seed the transfer line was corrected to give a realistic trajectory. All passive protection elements were taken into account and set to the required protection setting plus maximum tolerance. A full aperture model for the transfer line and the
injection region was used [50].

Single failures and grouped failures were studied. Power converter faults lead to a switch-off of the magnet family which is supplied by this power converter. These failures are referred to as single failures; only one magnet family is affected. Single failures were investigated for all dipole families playing a role in the injection process.

Different power converters can be connected to the same transformer. A fault at the level of the transformer can lead to a trip of all families connected to the transformer. These failures are called grouped failures. Fig. 10.1 shows the powering scheme of the magnet families for the injection process via T1 8. The grouped failures studied are marked with the letters A, B, C, D and E. For example, case B corresponds to a failure scenario where all magnet families connected to transformers in the building BA4 are accidentally switched off.

Each case, single or grouped failure, was studied with 1000 different seeds and 1000 particles per run (since only %-level statistics are required to check for damage). For each run, loss patterns along the line and injection region were calculated and after the last element of the tracking the number of particles outside the LHC aperture of 7.5 σ in phase-space was evaluated. Fig. 10.2 illustrates the results for the fastest magnet circuits found with the simulations: the MSE extraction septum; the MBHC, a dipole family at the beginning of the line; the MBI main dipoles in T1 8; the MBIAH, a dipole family towards the end of the line.

Post-processing routines finally determined for each magnet family the maximum tolerable error in bending angle. From this the required reaction time was derived for interlocking the power converter in the case of single failures, see Table 10.1, or the maximum allowable time after the switch-off in the case of grouped failures, see Table 10.2. The last two columns of Table 10.1 and 10.2 show whether the transfer line or the LHC
are protected and by which protection system (see section 10.2). The calculation of the required reaction times for single and grouped failures is based on the conservative assumption of an exponential decay of the current after the switch-off with the time constant $\tau = L/R$, where $L$ is the inductance and $R$ the resistance of the circuit (not applicable for kickers). The additional output filtering at the power converter, which can slow down the decay of the current, is not taken into account. The obtained numbers thus contain an additional safety margin for many of the failures.

### 10.2 Surveillance Systems

#### 10.2.1 Existing power converter surveillance

The conventional power converter surveillance (PCS) is based on magnet current surveillance via the so-called ROCS software in the local equipment front-ends [67]. Time windows between measurement points plus actual reaction time after detection amount to $> 3$ ms. The PCS is obviously not adequate to cover failures of e.g. the MSE ($40 \sigma$ trajectory change in 1 ms).

#### 10.2.2 Requirement of additional magnet current monitoring

An additional monitor, a so-called Fast Magnet Current Change Monitor (FMCM), is required to detect sub-ms current changes as the required reaction time for several families in Table 10.1 is either below the reaction time of the PCS or at the limit. This is especially true for the case of the extraction septum MSE with its required reaction time of only 100 $\mu$s. The main bending magnets of the transfer lines, the MBI, and dipole families at the beginning of the line, the MBHC, and at the end of the line, the MBIAH, also need to be equipped with such a device.

<table>
<thead>
<tr>
<th>Family</th>
<th>Tolerable error $[\Delta k/k_0]$</th>
<th>Required reaction time [ms]</th>
<th>LHC</th>
<th>TL covered by</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPLH</td>
<td>0.185</td>
<td>201.0</td>
<td>TCDI</td>
<td>PCS</td>
</tr>
<tr>
<td>MKE</td>
<td>0.125</td>
<td>-</td>
<td>TCDI</td>
<td>-</td>
</tr>
<tr>
<td>MSE</td>
<td>0.005</td>
<td>0.1</td>
<td>TCDI</td>
<td>FMCM</td>
</tr>
<tr>
<td>MBHC</td>
<td>0.005</td>
<td>5.1</td>
<td>TCDI</td>
<td>FMCM</td>
</tr>
<tr>
<td>MBHA</td>
<td>0.012</td>
<td>31.5</td>
<td>TCDI</td>
<td>PCS</td>
</tr>
<tr>
<td>MBI</td>
<td>0.004</td>
<td>3.6</td>
<td>TCDI</td>
<td>FMCM</td>
</tr>
<tr>
<td>MCIBH</td>
<td>0.630</td>
<td>389.0</td>
<td>TCDI</td>
<td>PCS</td>
</tr>
<tr>
<td>MBIAH</td>
<td>0.003-0.012, 0.027</td>
<td>7.9</td>
<td>PCS</td>
<td>FMCM</td>
</tr>
<tr>
<td>MBIBV</td>
<td>0.003</td>
<td>43.4</td>
<td>PCS</td>
<td>PCS</td>
</tr>
<tr>
<td>3MCIAV</td>
<td>0.183</td>
<td>98.43</td>
<td>PCS</td>
<td>TCDI</td>
</tr>
<tr>
<td>MSI</td>
<td>0.0035</td>
<td>3.5</td>
<td>FMCM</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 10.1: Results of numerical simulations for single failure tracking. PCS: conventional power converter surveillance with ROCS software. FMCM: Fast Magnet Current Change Monitor.
10.3 Discussion of Results

The MBIAH family is located within the collimation section and the remaining TCDI still downstream of the MBIAH do not cover the whole phase-space. Amplitudes above 7.5 $\sigma$...
can reach the LHC if the relative error on the dipole field is larger than 0.003 and smaller than 0.012. If the error is between 1.2 % and 2.7 %, the resulting particle amplitudes are large enough to end up on the collimators even though the phase advance is not optimal. For errors of the field larger than these values the beam is lost in the transfer line even before reaching the collimators.

<table>
<thead>
<tr>
<th>Group</th>
<th>Tolerable time after switch-off [ms]</th>
<th>LHC covered by</th>
<th>TL covered by</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.3</td>
<td>TCDI</td>
<td>FMCM on MBHC</td>
</tr>
<tr>
<td>B</td>
<td>0.1</td>
<td>TCDI</td>
<td>FMCM on MSE</td>
</tr>
<tr>
<td>C</td>
<td>15.8</td>
<td>TCDI</td>
<td>PCS</td>
</tr>
<tr>
<td>D</td>
<td>3.5-6.4, &gt; 20</td>
<td>FMCM on MSI</td>
<td>TCDI/PCS</td>
</tr>
<tr>
<td>E</td>
<td>4.2-11.8, &gt; 20</td>
<td>FMCM on MBIAH, MSI</td>
<td>FMCM on MBIAH</td>
</tr>
</tbody>
</table>


Provided that the MSI will be equipped with an FMCM, the protection of the LHC from injection failures can be guaranteed. The transfer line collimators give full protection from any upstream failures.

However, transfer line damage cannot be fully excluded. A failure of the extraction kicker MKE could lead to damaging amplitudes in the transfer line. A potential solution could be to adopt the aperture defined by the extraction protection device TPSG, 90° downstream of the MKE, in front of the MSE. Consequences of single quadrupole failures have been studied analytically in [29] and are less severe.

The grouped failure cases containing the extraction septum MSE are dominated by the effect of the septum with its very short time constant of only 23 ms (case B in Table 10.2). Other grouped failures, such as group D and E consisting of families at the end of the line - either in the collimation section or even after such as the MSI, show the effect of the TCDI leading to time windows which could cause damage, whereas after this time the collimators intercept the mis-steered beam before it impacts downstream, similar to a single failure of the MBIAH, see Fig. 10.4.

Table 10.2 shows that the protection system required to protect against single failures also protects against grouped failures. No additional FMCMs are required. However, grouped failures can be 5 times faster than single failures (compare group A in Table 10.2 and MBHC in Table 10.1). Hence covering grouped failures needs an improved performance of the protection system.
10.4 Fast Magnet Current Change Monitor

The specification for an FMCM resulting from the study is to detect a current change of $\Delta I/I = 0.1\%$ with a reaction time of 50 $\mu$s. Recent tests of a system developed at DESY have been carried out at CERN for the normal conducting D1 in the LHC and the extraction septum MSE in the SPS and have shown the feasibility of these requirements [68].

10.4.1 Principle of the FMCM

The FMCM measures the voltage of a critical magnet or powering system and performs a real time calculation of the current by means of a low pass filter. This simulated signal then passes a high pass filter to amplify fast current changes, which might stem from a powering failure. A comparator checks whether the changes are inside a tolerance window. If the comparison indicates a fast current change, an output switch is opened. The output switch can be directly connected to the beam interlock controller requesting extraction or injection inhibit in the case of extraction, transfer or injection equipment. The device is shown in Fig. 10.5.

![Image](image_url)
10.4.2 Outcome of the FMCM test on the MSE test bench

The specifications for the FMCM for the injection process are basically defined by the requirements of the MSE as it has the smallest time constant of all concerned circuits. Fig. 10.6 shows the response of the FMCM developed at DESY during the nominal ramp cycle of the pulsed MSE. The FMCM triggers on current changes, and hence does not give the user permit during the ramp (the blue curve is the measured voltage, the green curve is the change of the simulated current and the pink curve is the status of the output to the BIC). At flat top the device needs a certain time to settle down until it gives the user permit.

Fig. 10.7 illustrates the response of the MSE for an immediate switch-off, resembling a powering failure with a time constant of 23 ms. The achievable detection level was about 0.3 % due to the large ripple on the MSE test-bench power converter of 0.17 % instead of the nominal 0.04 %. (For the test on the test-bench of the LHC magnet D1 a detection level of well below the required $3.5 \times 10^{-4}$ could be reached with the same device.) Assuming the nominal ripple, the specification of $\Delta I/I = 0.1 \%$ can be met. The electronic delay from measuring the voltage until detecting and producing an inhibit adds up to about 25 $\mu$s. The overall reaction time, including the signal transmission to the BIC, is expected to be below 50 $\mu$s.

It should be noted that the FMCM does not compare absolute current values with reference values, it only detects current changes. This means that wrong settings of the magnet voltage would not be detected by an FMCM, but by the conventional power converter surveillance PCS. The FMCM is hence a complementary system to the PCS for critical magnet families.

![Figure 10.6: FMCM response during nominal ramp: the MSE input voltage in blue, the change of the simulated current in green and the signal created to the BIC (either 1 or 0) in pink.](image)

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17:17:15
Figure 10.7: FMCM response during fast switch-off: the MSE input voltage in blue, the change of the simulated current in green and the signal created to the BIC (either 1 or 0) in pink.

10.5 Summary

Results of comprehensive tracking simulations showed that the transfer lines and the LHC were not fully protected against transfer line failures even in the presence of the transfer line collimators. However, provided a Fast Magnet Current Change Monitor is implemented for several magnet families, protection against almost all single and grouped failures can be guaranteed with the foreseen combination of active and passive protection systems. The only exception are failures of the extraction kicker MKE, which can still cause transfer line damage. Possible solutions will be investigated.
11

Expected Emittance Growth and Beam Tail Repopulation from Errors at Injection into the LHC

As mentioned, the preservation of the transverse emittance of the LHC proton beam is crucial for luminosity performance. The population of the beam tails is also important for beam losses and collimation. The transfer and injection process is particularly critical in this respect, and several effects can contribute to emittance increase and tail repopulation, like optical and geometrical mismatch, injection offsets and coupling, etc. In this chapter the various effects are described, together with the tolerance limits on the parameters, and the expected contributions evaluated analytically where possible. The emittance growth and tail distributions are also simulated numerically using realistic errors [69]. The implications for the tolerances on the matching of the transfer lines are discussed.

11.1 Requirements

The total emittance increase budget between the SPS extraction and the LHC at collision energy is only $\Delta \epsilon/\epsilon_0 \leq 1.07$ [22]. This places stringent requirements on the various mismatch factors for transfer and injection. For the effects identified below, each contribution should be below a few %, and the total below 5 %.

The details of the particle distributions are also important, since large tail populations can cause transient losses at injection which risk quenching superconducting magnets. The beams will be scraped to about 3.5 $\sigma$ in the SPS, but some mismatch effects (for example the geometrical tilt) can lead to significant tail repopulation at large amplitudes, although the effect on the emittance may remain small.

11.2 Analytical Estimates of Emittance Growth

Steering error

The beam stability at the injection point has direct consequences on the emittance growth. An injection angle or position error leads to an emittance increase [70] of:
\[
\frac{\epsilon}{\epsilon_0} = 1 + \frac{1}{2} \frac{\Delta x^2 + (\beta \Delta x' + \alpha \Delta x)^2}{\beta \epsilon_0} = 1 + \frac{1}{2} \Delta \epsilon^2
\]  
(11.1)

In the LHC the steering errors are normally dealt with by the damper system, and the emittance blow-up will be a function of the injection errors, the damper strength and the filamentation time. The emittance increase after damping is given by:

\[
\frac{\epsilon}{\epsilon_0} = 1 + \frac{1}{2} \Delta \epsilon^2 \left( \frac{1}{1 + \tau_{DC}/\tau_d} \right)^2
\]  
(11.2)

where \( \tau_{DC} \) and \( \tau_d \) are the 68 ms filamentation time and the 5 ms damping time, respectively [71]. The 1.5 \( \sigma \) [29] maximum injection error gives an emittance increase of 0.5 %.

**Betatron mismatch**

The \( \alpha \) and \( \beta \) of the injected beam may not match those of the LHC at the injection point, due to errors in the SPS, the transfer line or the LHC. For a mismatch factor \( \lambda \) the emittance increase [18] is:

\[
\frac{\epsilon}{\epsilon_0} = \frac{1}{2} (\lambda^2 + \lambda^{-2}) = \frac{1}{2} (\beta_1 \gamma_2 + \beta_2 \gamma_1 - 2 \alpha_1 \alpha_2)
\]  
(11.3)

where subscripts 1 and 2 refer to the matched (lattice) and mismatched (beam) ellipses, respectively. The TI 8 tests in 2004 [74] showed that \( \lambda \) could be expected to be corrected to about 1.10. The total mismatch is estimated at 1.15, which includes a 5 % margin for drifts of the LHC optics during the injection process. The expected emittance increase from this source is then 3.9 %.

**Dispersion mismatch**

The dispersion may be mismatched at the injection point. For dispersion mismatch factors \( \delta D, \delta D' \), a relative momentum spread \( \delta p/p \) gives an emittance increase [70] of:

\[
\frac{\epsilon}{\epsilon_0} = 1 + \frac{1}{2} \frac{\Delta D^2 + (\beta \Delta D' + \alpha \Delta D)^2}{\beta \epsilon_0} \left( \frac{\delta p}{p} \right)^2
\]  
(11.4)

The expected dispersion mismatch is of the order of 0.2 m and 0.002 rad, for \( \Delta D \) and \( \Delta D' \) respectively, which include contributions of the order of 0.05 m from imperfect matching to the separation and crossing bumps at the injection points, together with about 0.15 m of spurious dispersion in the LHC ring. With the nominal energy spread of \( 5 \times 10^{-4} \), the emittance increase is 2.4 %.

**Energy error**

With dispersion \( D \) at the injection point and an energy error of \( \Delta p/p \), the emittance increase is:

\[
\frac{\epsilon}{\epsilon_0} = 1 + \frac{1}{2} \frac{D^2}{\beta \epsilon_0} \left( \frac{\Delta p}{p} \right)^2
\]  
(11.5)
For the nominal dispersion of about 0.1 m, an energy error of $5 \times 10^{-4}$ gives an emittance increase of 0.2 %.

**Geometrical (tilt) mismatch**

A horizontal bending dipole aligned with an inclination (slope) angle phi ($\phi$) with respect to the reference coordinate system introduces a small tilt (roll) angle psi ($\psi$) into the beam, which for small angles is proportional to the product of the magnet bending angle $\alpha$ and the slope $\phi$. Normally for transfer lines this effect can be neglected, but for long lines with many horizontal bending magnets on relatively steep vertical slopes relative to the reference frame, a non-negligible tilt angle $\psi$ can accumulate between the local beam plane and the reference alignment system. This can result in mismatch at injection with subsequent emittance blow-up, and other undesirable effects, such as non-orthogonal trajectory measurement and correction.

There is a geometrical mismatch between the LHC transfer lines due to the uncorrected rotation between the beam XZ (parallel to the beam axis) plane and that of the LHC [72]. If $\theta$ is the angle between these planes, the emittance increase in the horizontal plane for $\epsilon_{0x} = \epsilon_{0y}$ is:

$$\frac{\epsilon_x}{\epsilon_{0x}} = 1 + \frac{1}{2}(\beta_x \gamma_y + \beta_y \gamma_x - 2\alpha_x \alpha_y - 2) \sin^2 \theta$$  \hspace{1cm} (11.6)

with an equivalent expression for the vertical plane.

For the TI 8 injection point the tilt mismatch is about 52 mrad. Correction could only be accomplished by rotating the plane of the beam with a system of skew quadrupoles at the end of each line. However, for the 52 mrad angle between TI 8 and the LHC, the emittance increase is 1.3 %. (For TI 2, with a 20 mrad angle, this effect contributes only 0.3 %.) A potentially more important effect is the repopulation of the transverse tails of the beam, which are removed by the scrapers in the SPS. The coupling between the planes induced by the tilt can populate the beam tail significantly, with amplitude growths of around 20% [73]. An effective remedy is to remove particles in the tails which have simultaneous large horizontal and vertical amplitudes by means of a tilted XY scrapers in the SPS (beam scraping in the SPS, see below).

**Coupling**

For a coupling factor $\kappa = \gamma / \bar{x}$ (the amplitude of an oscillation launched in the x plane coupled into the y plane), the emittance increase is given simply by:

$$\frac{\epsilon_x}{\epsilon_{0x}} = 1 + \frac{1}{2}\kappa^2$$  \hspace{1cm} (11.7)

For the LHC transfer lines $\kappa$ should be zero, and was measured in 2004 in TI 8 at $\sim 3$ % [74]. The resulting emittance increase is 0.05 %.

**Scattering from beam instrumentation screens**

The R.M.S. Multiple Coulomb scattering angle $\theta_s$ for 450 GeV protons is given by the screen thickness $L$ and material radiation length $L_{rad} (\gg L)$:
\[ \theta_s \approx 3.13 \times 10^{-5} \sqrt{L/L_{rad}} \]  

(11.8)

At a screen location with beta function \( \beta \), the emittance increase \([18]\) is given by:

\[ \frac{\epsilon}{\epsilon_0} = 1 + \frac{1}{2} \frac{\beta}{\epsilon_0} \theta_s^2 \]  

(11.9)

The LHC transfer line screens are made of 12 \( \mu m \) thick titanium, with \( L_{rad} = 0.036 \) m. The \( \beta \) functions at the screens are in the range 60 – 220 m. The emittance increase from one screen, if in the beam, is 0.1 – 0.55 % per plane.

### 11.2.1 Summary of expected contributions

The various contributions are given in Table 11.1. Assuming that these add quadratically, the expected emittance increase is 4.8 %, compared to the 7 % budget. It is assumed that no screens are left in the line during LHC filling; however, their individual contributions are small, of the order of 0.5 %, and so the presence of several screens would be acceptable (10 such screens left in the line would increase the emittance by about 1.5 %).

<table>
<thead>
<tr>
<th>Error</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>( \Delta \epsilon/\epsilon_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steering</td>
<td>( \Delta \epsilon )</td>
<td>( \tau_{DC}/\tau_d )</td>
<td>( \sigma )</td>
<td>1.5</td>
</tr>
<tr>
<td>(damped)</td>
<td>( \lambda )</td>
<td></td>
<td></td>
<td>11.15</td>
</tr>
<tr>
<td>Betatron</td>
<td>( \Delta D )</td>
<td></td>
<td>m</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>( \Delta D' )</td>
<td></td>
<td>rad</td>
<td>0.002</td>
</tr>
<tr>
<td>Dispersion</td>
<td>( \Delta p/p )</td>
<td></td>
<td></td>
<td>( 5 \times 10^{-4} )</td>
</tr>
<tr>
<td>Energy</td>
<td>( \theta )</td>
<td></td>
<td>rad</td>
<td>0.052</td>
</tr>
<tr>
<td>Tilt</td>
<td>( \kappa )</td>
<td></td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Coupling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 11.3 Numerical Simulations

To obtain a more realistic picture of how the expected effects combine and to check for any overlooked effects, the emittance increase and tail repopulation were estimated by numerical simulation. All contributing effects were incorporated with systematic and random components, including trajectory correction, power supply ripples, extraction and injection kicker waveforms, energy error and spread, optical (betatron and dispersion) mismatch, tilt mismatch and magnet and BPM misalignments. The study was made for TI 8. Scrapped beam distributions were assumed for the studies.
11.3.1 Beam scraping in the SPS

A small fraction of the nominal injected beam intensity (about 0.01%) is sufficient to quench a superconducting magnet in the LHC. The quench limit for an instantaneous loss at injection is $5 \times 10^9$ particles. In addition, the beams are largest at injection energy and the aperture tightest. For a Gaussian injected beam, the number of particles above 3 $\sigma$ would still be above the quench limit by 2 orders of magnitude. Large amplitude particles are hence scraped off in the SPS. The scraping depth was decided to be at 3.5 $\sigma$, in both planes and coupled at 45° in XY at a location with $\beta_x=\beta_y$. The impact on the luminosity reach in this way is negligible [23].

With three scrapers, the cut of amplitudes above 3.5 $\sigma$ is not perfect (a perfect cut would result in a round distribution in XY, normalised). The resulting distribution in XY, normalised, is an octagon, see Fig. 11.1.

![Figure 11.1: Particle XY distribution after scraping](image)

Emittance increase

For 1020 seeds, 10,000 particles were generated with a realistic scraped Gaussian initial distribution. The optics perturbations were calculated for the transfer line with all errors. The transformed particle distributions were produced at the injection point, and the new phase-space amplitude distributions and emittance increases calculated. The initial and final XY distribution for particles in the horizontal plane for one seed can be seen in Fig. 11.2 (here using a uniform initial particle distribution for illustration). The tilt mismatch effect is just discernible.

The results for the relative emittance increases with scraped Gaussian beams are shown in Fig. 11.3. The maximum values observed are 7-10 %, larger than the corresponding analytical estimate of 4.8 % above. The average (mean) increase is 2.8 % for the H plane and 2.7 % for V; the 95 % confidence limits are at 5.9 % and 4.4 % for H/V, respectively.
Figure 11.2: Initial (blue) and transformed (red) particle XY distribution (1 seed).

Figure 11.3: Distribution of expected emittance increases for transfer into LHC ring 2, via TI 8 (1020 seeds).
Particle distributions and tail repopulation

To estimate the tail repopulation with all mismatch effects, transformed distributions of 500,000 particles were compared with the initial distributions. A typical result is shown in Fig. 11.4, where it can be seen that the tails of the distribution (initially scraped to 3.5 σ) are repopulated to beyond 4 σ.

160 seeds were considered. The edge of the final distribution was estimated by measuring the particle amplitude at the 10⁻⁵ level. The distribution of the resulting tail repopulation for the 160 seeds is shown in Fig. 11.5. The average (mean) repopulation is to 3.86 σ in H and 3.98 σ in V, with 95% confidence limits at 4.03 σ and 4.13 σ for H/V, respectively. The repopulated distribution appears Gaussian to within about 0.2 σ of these values.

![Diagram](image)

Figure 11.4: Initial (red) and repopulated (blue) tails, which stay Gaussian up to about 3.8 – 4 σ (1 seed).

### 11.4 Discussion

The maximum emittance increases observed from the full numerical simulations confirm the analytical estimates. The results indicate an average emittance increase of about 3 %. The results are encouraging and show that the transfer and injection process do not violate the LHC design specification of 7 % emittance growth - however, the effects can be relatively large, with the 95 % confidence limit at 5.9 % and 4.4 % in the horizontal and vertical planes, respectively. The most critical effects have been identified: optical mismatch (both betatron and dispersion) and tilt mismatch. The latter is a design
feature, with no correction currently planned. The betatron mismatch $\lambda$ must be kept to $\leq 1.15$, including static and dynamic effects on the injection plateau. The dispersion mismatch must be kept to $\sim 0.2$ m, including changes of bump polarity and spurious dispersion in the LHC. The presence of a few screens will not increase the emittance significantly.

The repopulation of the tails was also quantified with simulations showing an average repopulation to 3.9 $\sigma$, which comes mainly from the tilt mismatch. This may be an issue for clean injection in IR 8; if it proves problematic the scraping depth in the SPS could be made deeper, or in the long term, a correction studied for the tilt mismatch.
12

Results of TI 8 Commissioning with Beam

The first of the two LHC transfer lines, TI 8, was commissioned in the autumn of 2004 with beam [75]. Beam reached the second beam stopper TED, located 2.5 km downstream of the SPS extraction point, at the first extraction from the SPS, without the need of any threading\footnote{Threading: correcting a distorted trajectory due to misalignments and other machine imperfections until beam passes.}. Fig. 12.1 shows the image of the first beam on an Optical Transition Radiation (OTR) screen in front of the second TED.

![Image of the first beam on an OTR screen](image)

**Figure 12.1:** Screen image of the first beam which traveled down TI 8, taken on October 23, 2004.

Two 48 hour periods were allocated for beam tests, separated by two weeks. In order to minimise induced radiation for the work ongoing after the test in the LHC tunnel right downstream of the second TED, the intensities had to be limited to pilot intensity for most purposes. To improve the resolution of beam instrumentation some single shots were done with 3-4×10\(^{10}\) protons.

An in-depth understanding of the characteristics of the LHC transfer lines is crucial to meet the tight injection tolerances into the LHC. A large number of optics measurements was carried out [74]. The dispersion was measured in both test periods. The measurement during the first period showed that two quadrupoles were set to wrong values by about 20\%. This was corrected for the second test, which resulted in a good agreement between model and measurement.
The emittance and local Twiss parameters were measured via the 11 OTRs in the line. The entrance Twiss functions were traced back in this way as well. A maximum mismatch between SPS and TI 8 of in the order 10 to 20% was measured agreeing with assumptions used in simulations. The coupling between the horizontal and vertical plane stemming from quadrupole misalignment was found to be smaller than 3%.

A method for setting up the transfer line collimators was also tested and will be described in detail below, along with the beam stability measurement of TI 8, the verification of the aperture of the line and the energy acceptance.

12.1 Beam based Alignment of the LHC Transfer Line Collimators

The required setting of the 1.2 m long graphite TCDI collimator jaws is 4.5 $\sigma$ from the beam axis, and accurate setting is crucial to cope with the small tolerances at injection. Adjusting the collinearity of a collimator jaw with the beam could contribute greatly to the achievable alignment accuracy, as the mechanical angular misalignment can amount to 350 $\mu$m, with typical beam sizes of 500 $\mu$m. Each collimator jaw is hence equipped with two motors. The alignment of the TCDI will be fairly time consuming, and will only be done occasionally e.g. after shut-down periods.

A beam-based alignment method to improve the collinearity between the beam and the jaw for pulsed beam lines such as the LHC transfer lines has been developed. The results of simulations and a proof-of-principle test of the method during the beam commissioning of the transfer line TI 8 in 2004 are presented [76].

12.1.1 Transmission measurement for collimator jaw alignment

The proposed alignment procedure is based on a transmission measurement; instead of local beam loss monitors (BLMs) as commonly used for collimator setting-up methods, the signals of beam current transformers (BCTs) and BLMs far downstream are used. A prerequisite for the procedure is an accurate knowledge of the beam trajectory at the collimator location, which is normally obtained via interpolation between measurements of two nearby beam position monitors.

Each jaw is aligned individually. The edge of the jaw is closed to the assumed beam axis, where ideally it samples half of the beam intensity. BCTs up- and downstream are used to measure the beam transmission. One complication is that the short low-Z jaw material (1.2 m graphite jaw) is not a perfect absorber: it acts partly as diluter, such that for ideal alignment the expected beam transmission is slightly greater than 50%. The method relies on the fact that any angular misalignment results in a reduced transmission with respect to the maximum achievable value.

The two ends of the jaw can be moved individually, since each jaw is equipped with two stepping motors. The collinear alignment is optimised by varying the angle while keeping the average position the same, using both motors, and hence producing a scan of transmission versus difference between the steps of motor 1 and motor 2, Fig. 12.2.
12.1. Beam based Alignment of the LHC Transfer Line Collimators

![Diagram of beam alignment](image)

Figure 12.2: An illustration of the alignment scan. Both jaw ends are moved by the same amount of steps in opposite directions.

This will produce a maximum in the transmission curve when the jaw is collinear with the beam.

### 12.1.2 Simulated measurement

The proposed method was tested in a simulation including realistic parameters and tolerances (for tolerances see Chapter 6). The beam impacting the collimator is attenuated depending on the length of traversed matter. The attenuation is calculated according to \( \exp(-l/L) \), where \( l \) is the traversed length and \( L \) the interaction length of the material (for the TCDI graphite jaws \( L \sim 45 \) cm).

Particles which traverse the collimator jaw (or parts of the jaw) will have an increased divergence from scattering processes, resulting in larger Courant-Snyder invariants. The effect of multiple Coulomb scattering [51] is included by convoluting the particle distributions with the probability densities for the different scattering processes. It is assumed that only particles with a normalized Courant-Snyder invariant smaller than a certain cut-off parameter (assumed to be 8 \( \sigma \)) survive; the rest are lost on the aperture.

The simulation result in Fig. 12.3 shows the outcome of a transmission scan for an initially perfectly aligned jaw, with \( a \) and \( b \) as shown in Fig. 12.2. From this curve it appears that an alignment accuracy |\( a-b \)| of better than 100 \( \mu \)m should be possible with such a scan.

### 12.1.3 Test of the method during TI 8 beam commissioning

The proposed method was tested during the TI 8 commissioning. The goal of this first test of the alignment procedure was a qualitative check of the method.

An LHC horizontal secondary collimator (TCS) installed in TT40 for a robustness test of its jaw material with LHC beam extracted from the SPS was used with low intensity beam \( (3 \times 10^{10} \) protons) for the alignment test.
Figure 12.3: Simulated result of alignment scan. The maximum of the curve corresponds to the maximum achievable collinearity between beam and jaw.

The beam position at the collimator location was \(-1.8 \text{ mm} \pm 0.27 \text{ mm}\), obtained with the interpolation between two BPMs in TT40 for 100 shots.

Fig. 12.4 shows the transmission versus time as ratio between the intensities at the BCT at the end of the line and the BCT in the SPS. The parts of the graph in red mark the areas where one collimator jaw was moved in.

During period 2 the jaw was moved to the interpolated beam position with the assumed motor calibration and kept at the same position for 30 minutes. (The data from this period was used to define the beam stability at the collimator location [77].) From the transmission (only \(\sim 30\%\) rather than \(\sim 50\%\)) it is clear that either the alignment of the jaw or the calibration of the motor steps was not perfect.

During period 3 the same jaw was moved back to the interpolated beam position. Since the transmission was still only about 30\%, the jaw was retracted by 0.5 nominal \(\sigma\) (1 real \(\sigma\) with the small emittance beam used for the test), corresponding to measurement point b1. This position change, of 300 \(\mu\text{m}\), is clearly visible in the transmission, Fig. 12.4. This clear effect on the transmitted intensity indicates that it should be possible to align the jaws to better than 150 \(\mu\text{m}\) with this method.

For measurement points b2 and b3, a single jaw end was moved further into the beam by 2 \(\sigma\) (corresponding to 1 nominal \(\sigma\)), while the other jaw end stayed at the setting of b1. The effect on the transmission was even more obvious.

Each measurement point was obtained with about 20 shots (about 6 minutes per measurement point). A full scan with about 10 measurement points per jaw would take two hours per collimator.

**Beam loss monitors for transmission measurement**

Fig. 12.5 shows the intensity signal at the BCT at the end of the line and also a loss signal for a BLM 700 m downstream from the collimator location during period 2. The two signals show an anti-correlation and either signal could serve as basis for the alignment. The collinear motor setting would correspond to the minimum of the curve BLM signal versus difference between steps of motor 1 and motor 2. The BLM signal seems less noisy.
than the BCT signal, which would clearly be an advantage, and BLMs far downstream of the collimator jaw could give complimentary information in the case of alignment with low resolution BCTs.

## 12.2 Beam Stability of the LHC Beam Transfer Line TI 8

Since the beam position monitor signal fluctuations were dominated by noise with the low intensity beam used during the TI 8 commissioning, the beam stability could not be obtained from a simple comparison of consecutive trajectories. Instead model independent analysis (MIA) techniques as well as scraping on collimators were used to estimate the intrinsic stability of the transfer line. The analysis methods and the resulting stability estimates are presented.

### 12.2.1 Trajectory measurements

During the TI8 tests a 6 hour period was devoted to the measurement of the transfer line stability. To minimise the amount of beam sent to the second TED, beam was only sent down the line for about 15 minutes every hour, resulting in a total of 145 acquired trajectories. The single shot resolution of the BPMs for the pilot beam intensity of $5 \times 10^9$ protons is 200 $\mu$m. A simple visual inspection of the trajectory differences between the start and the end of this period reveals no significant signal, implying that over such a period the line drift is below the BPM resolution of 200 $\mu$m. A more in depth analysis of the trajectory sample collected during this measurement period was performed using the MIA approach [78, 79]. The idea behind this technique is to analyse large data samples to unveil correlations between measurements, for example trajectory jitter on the basis of SVD. More details can be found in [77].
A very good agreement was obtained assuming that the unique source for the beam position variation is the SPS extraction septum (MSE) at the start of the line. With MIA analysis it is possible to obtain the associated R.M.S. variation of the trajectory (beam jitter) and the corresponding ripple of the MSE power converter. The R.M.S. kick is 1.4 μrad and the R.M.S. ripple $1.2 \times 10^{-4}$. The oscillation amplitude or beam jitter (at $\beta = 100$ m) associated to the R.M.S. kick is $100 \mu$m which corresponds to $\sigma_{beam}/8$. All other possible contributions are consistent with random noise.

The effect of the temperature of the cooling water and of the magnet coils on the trajectory was investigated by switching off the transfer line power converters for a period of 2 hours and by measuring the trajectory difference before switching off and just after switching back on. The trajectory difference is consistent with a momentum change of $10^{-4}$ in the line.

### 12.2.2 Beam stability measurement with collimator scraping

The proposed alignment method with beam for transfer line collimators is very sensitive to shot-to-shot beam jitter. The results of the test therefore also served as beam jitter measurement at the collimator location.

The measurement had to be calibrated with three different BCTs. The collimator was installed in TT40 close to the first beam stopper in the line; two BCTs, one in TT40 and one at the end of TI 8 before the second beam stopper, were used. The intensity measurement of these BCTs was normalised with the intensity measurement of the BCT in the SPS before extraction.

#### Calibration of measurement

The BCT measurement errors were defined during the time period marked with number 1 in Fig. 12.4. Both collimator jaws were out of the beam and beam jitter did not influence
the intensity measurement.
With the assumption that both BCTs in the transfer line have the same accuracy and that apart from calibration errors the ratio of the intensities $I_{T18}/I_{TT40}$ should be 1, the relative error of the BCT measurement at the end of TI 8 could be estimated to 5%. For the same period, number 1 in Fig. 12.4, the measurement error of the SPS BCT was defined, where again the average of all measurements should be 1 for $I_{T18}/I_{SPS}$ using a scaling factor for the right calibration. With the relative TI 8 BCT error from above, the relative error on the SPS BCT measurement is 0.5%, in agreement with the expected resolution of $10^8$ charges.

Scraping and beam stability
For period 2 in Fig. 12.4, where one of the jaws was closed and left at the same position for about half an hour, the variation of the intensity at the BCT at the end of the line depends on the variation of the intensity in the SPS and the variation of the beam position at the collimator jaw.
The average transmission during this time was $I_{T18}/I_{SPS} = 0.305$. At this reduced intensity the BCT resolution determined above decreases to 8%. This value is obtained by comparison with measurements performed for intensities of $5 \times 10^9$ protons. The resulting intrinsic measurement error on $I_{T18}/I_{SPS}$ due to instrument resolution is therefore 0.024. The measured error on $I_{T18}/I_{SPS}$ is 0.034, with a contribution from the beam jitter of $\sigma_{\text{jitter}} = \sqrt{0.034^2 - 0.024^2} = 0.024$.
The collimator was a horizontal collimator at a location with a horizontal beam size of $\sigma_{\text{beam}} = 0.3 \text{ mm} (\beta_x \approx 50 \text{ m}, \epsilon = 1.8 \cdot 10^{-3} \text{ m})$. The average beam axis was hence 0.153 mm inside the collimator jaw (a Gaussian particle distribution was assumed). The R.M.S. error on the transmission measurement generated by the beam jitter translates into a beam stability at this location of

$$\sigma_{\text{RMS}} = 0.02 \text{ mm} \quad (12.1)$$

which corresponds to about 0.07 $\sigma_{\text{beam}}$. The result obtained with the limited data sample gives confidence that the R.M.S. beam stability is well below 100 $\mu$m at this location. The stability obtained from the transmission analysis is clearly consistent with the stability estimated from the MIA analysis.

12.3 Aperture Studies of the SPS to the LHC Transfer Lines
As described in Chapter 6, an aperture model for the lines has been developed in MAD-X format, with a full description of all installed vacuum elements and the possibility to interpolate at any length interval. This model has been used with tolerances and errors to simulate the expected line aperture available for the beam. The results from aperture measurements made during the TI 8 beam commissioning in 2004 are presented and compared to the expectations [50].
12.3.1 Aperture measurements

The aperture measurements were made by exciting betatron oscillations with different dipole groups to maximise phase coverage. To minimise the amount of beam lost and hence induced activity, the measurements were all performed with single bunches of \( 5 \times 10^6 \) protons. The measured normalised emittances were \( 0.46 \mu m \) (H) and \( 0.26 \mu m \) (V). The successful transmission of the beam was monitored using the BCT at the end of the line, on the BPMs along the line and also on the BLMs. The aperture was probed by varying the strength of the dipoles, in steps of 1 nominal beam \( \sigma \), until the transmission measured by the BCTs dropped below 1 or a significant BLM signal was recorded. The envelope of the aperture was then derived by estimating the position of the real edge of the beam (assumed to be at \( 3 \sigma \)), calculated with the measured emittances. The resulting envelopes were superposed to show the available aperture, and compared with the expected aperture in \( \sigma \) calculated with the expression for \( N \) from Chapter 3:

\[
N = ([A - E_{max}(\beta/\beta_{max})^{1/2} - D \Delta p/p]/k_\beta)/\sigma
\]

First test with perturbed optics

In the first series of measurements, an undetected 20 \% calibration error in the reference values for two matching quadrupoles at the start of the line meant that the optics was strongly perturbed. The aperture scans were (unwittingly) made using this perturbed optics (the error was discovered after the test, and the optics used in the calculation adjusted accordingly). For this test, the maximum horizontal beta values in the arc sections were of the order of 500 m, rather than the nominal 100 m. The aperture of the line was significantly reduced as a result; however, the test measurements still showed a good agreement with the expected aperture as calculated with the perturbed optics, Figs. 12.6 and 12.7.

Second test with nominal optics

The second series of measurements used the nominal optics, with 100 m maximum beta in both planes in the arcs. The aperture was only measured in the horizontal plane, due to time restrictions. Again, a good agreement with the expected aperture was obtained, Fig. 12.8. The measured aperture is 8.2 \( \sigma \), larger than the specified value, which indicates that the actual line alignment and/or trajectory correction are somewhat better than assumed.

12.3.2 Energy acceptance measurements

The energy acceptance of the line is a function of the aperture, the optics and the corrected trajectory. For TI 8 the acceptance was checked by simulating the transmission of a beam as a function of the energy offset, using the full aperture model and the various mechanical errors, machine imperfections and mismatch, for 1000 corrected trajectories. The simulated distribution of transmissions is shown in Fig. 12.9. Defining the acceptance
Figure 12.6: Expected and measured horizontal aperture in TI 8, for the perturbed beam optics. The measured aperture is about 3.8 nominal σ.

Figure 12.7: Expected and measured vertical aperture in TI 8, for the perturbed beam optics. The measured edge of the beam envelope (red) is compared to the calculated aperture (black). The measured aperture is about 5.1 nominal σ.

as the 90 % transmission limit, the simulation predicts an energy acceptance for TI 8 of around ± 0.003.

The energy acceptance was measured with beam during the TI 8 commissioning tests, by
Figure 12.8: Expected and measured horizontal aperture in T1 8, for the nominal beam optics. The measured aperture is about 8.2 nominal $\sigma$.

varying the RF frequency in the SPS which changes the beam energy and measuring the transmission through T1 8 of a pilot bunch as a function of energy offset. The results are also shown in Fig. 12.9, where a good agreement with the simulation is evident. It is also possible from this measurement to see that the central energy appears to be mismatched by about 0.0005.

12.4 Summary

A method for aligning collimator jaws in pulsed beam lines such as the SPS to LHC transfer lines has been presented. The measurement of the transmitted intensity rather than local beam loss serves as alignment criterion. The method has been simulated numerically, where an alignment precision of about 100 $\mu$m was obtained. The method has also been tested experimentally, where the first tests with beam during the T1 8 commissioning showed a clearly visible change of the transmitted intensity for a 300 $\mu$m change of the angular misalignment with a low intensity beam. The beam tests demonstrated that alignment below 150 $\mu$m (corresponding to angle of 150 $\mu$rad for a TCS jaw) accuracy can be reached with this technique. It was also demonstrated that signals of beam loss monitors far downstream from the collimator location can be used as complimentary feedback during the alignment procedure.

The T1 8 transfer line was found to be very stable, with practically no visible drifts over a period of 48 hours. Two measurement methods have been presented. The dominant source for trajectory instability was found from MIA analysis to be consistent with a ripple of the SPS extraction septum of a few parts in ten thousand. The stability measurement with a collimator gave a beam jitter of well below 100 $\mu$m at the collimator location, consistent with the trajectory analysis. Both methods consistently indicate that the
R.M.S. beam jitter is of the order of $\sigma_{beam}/10$.
The aperture of the SPS to LHC transfer lines has been modeled using MAD-X, and compared to measurements made during the TI 8 commissioning tests. First results show that the line aperture is in good agreement with the simulations, with a slightly larger aperture than expected in the horizontal plane for the nominal optics, indicating a better alignment and/or trajectory correction than assumed. The energy acceptance of the line was measured at $\pm 0.003$, as specified and in good agreement with simulations.

### 12.5 Overall Outcome

A milestone towards the LHC was achieved with the TI 8 beam commissioning. One major contribution to the success of the TI 8 tests stems from the overall good functioning of the beam instrumentation, the control system and the part of the machine protection system which was already installed.
The TI 8 transfer line is now qualified ready for the planned sector test end of 2006, where the arc between insertion IR 8 and IR 7 of the LHC with a temporary beam dump in IR 7 will be tested with beam for the first time. Before the sector test TI 8 will be re-commissioned to test the last 100 m of the transfer line downstream of the second TED with beam, to gather deeper understanding of the transfer line’s beam dynamics and also to commission the line with high intensity beam.
13

Conclusion

Injection into the LHC requires beam extraction from the SPS, transfer through the LHC transfer lines TI 2 and TI 8 and finally injection into the LHC in IR 2 and IR 8. The nominal intensities extracted from the SPS are over an order of magnitude above the damage limit. Beam loss will cause severe damage to the SPS, the transfer lines or the LHC. A machine protection system consisting of active (monitoring plus interlocking) and passive (collimators and absorbers) protection for the LHC injection process is hence mandatory.

The injection process for LHC beam 2 in proton mode was studied in depth. Beam 2 is extracted from the SPS in LSS4, transferred via the transfer line TI 8 and injected into the LHC in IR 8. Simulations were used to define the equipment damage limit at injection energy in terms of allowed beam loss, to specify the requirements for the active and passive protection systems for the injection process, to check the performance of the proposed protection system and to evaluate the performance of transfer and injection in terms of beam quality. The simulation techniques were cross-checked in real tests with beam. The overall agreement between simulations and experiments was good and confirms the choice of methods, models and tools.

The equipment damage limit at injection energy derived with FLUKA using static energy deposition calculations was found to be 5 % of an ultimate injected batch ($4.9 \times 10^{13}$ protons). The validity of this approach was successfully cross-checked in a controlled material damage test with beam, where LHC-type beam was extracted from the SPS and directed onto a specially designed target. The results of the experiment showed reasonable agreement with the FLUKA predictions and gave confidence that beam induced damage limits for simple geometries can be adequately predicted in simulations, and that the 5 % assumed generic damage limit is reasonable.

FLUKA and MAD-X simulations were used to a great extent for the design studies of the passive protection collimators TCDI in the transfer lines. It was shown that the chosen collimation scheme and collimator design fulfill the objective of fully protecting the LHC and injection septum aperture from any upstream failures. Full phase space coverage can be guaranteed, which was checked with simulations including machine and collimator setting-up imperfections. The collimator jaw length and material was determined such that the beam is diluted to a safe level. It was demonstrated that close-by equipment has to be protected from collimator shower and scatter products with secondary iron masks. The required setting of the injection stopper TDI in the LHC injection region and its
auxiliary collimators TCLI was defined for the most dangerous MKI injection kicker failure, a flash-over, based on a Monte-Carlo sampling of transfer line states and resulting injection errors. A preliminary layout and design specification for the TCLI collimators were prepared.

An adequate interlocking system for extraction, transfer and injection was designed to accomplish safely operational flexibility and different machine modes with high intensity beam. Key aspects are the “beam permit” from the LHC to inject, “beam presence” to inject high intensity beam, segmentation of the interlocking system according to function and the “safe beam” concept for setting-up and machine development.

The overall performance of the protection system for the injection process was evaluated with a Monte-Carlo simulation combined with a particle tracking. The simulation included all passive protection devices mentioned above and machine imperfections starting in the extraction region of the SPS, transferring the particles through the transfer line and injecting the simulated beam in the LHC injection region. The studies identified the requirement of Fast Magnet Current Change Monitors for the extraction region, the transfer lines and also the LHC injection region (for the injection septum), to detect fast magnet powering failures. It was demonstrated that the LHC is fully protected against any injection failures provided these Fast Magnet Current Change Monitors are implemented. Also the transfer lines and extraction regions are well protected with the only remaining danger being failures of the SPS extraction kicker.

Beam quality issues were treated as well. In order to reach the design luminosity of the LHC the beam emittance must be kept small. The expected emittance growth and beam tail repopulation from errors at injection into the LHC were evaluated with numerical simulations. The most critical effects were identified and limits specified. The average emittance increase was found to be about 3 % in both planes below the LHC design specification of 7 % emittance growth. The results showed that beam tails, originally scraped to 3.5 $\sigma$ in the SPS, are repopulated to 3.9 $\sigma$. The reason for repopulation is mainly geometrical tilt mismatch.

The simulation techniques thus developed were also applied in the commissioning of the transfer line TI 8 with beam in autumn 2004. The energy acceptance and aperture of the line were simulated and checked with beam. Simulation assumptions, such as 20 % optical mismatch or coupling of a few %, were verified. An alignment method for the transfer line collimators with beam was developed and tested. The beam tests showed good agreement with the simulation results.

The simulation methodologies developed for the various analyses described in this thesis proved to be well suited for understanding and optimising the performance of the accelerator systems concerned. The techniques were successfully used for the validation of the LHC injection process taking into account sources of error and all imperfections, and will be applied for future machine protection studies for circulating beam in the LHC ring.
Appendix A

Nominal LHC parameters in p-p-collision mode

The specified machine and nominal beam parameters for the LHC are summarised in Table A.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (collision)</td>
<td>$\mathcal{E}$</td>
<td>[TeV]</td>
<td>7.0</td>
</tr>
<tr>
<td>Dipole field</td>
<td>$B$</td>
<td>[T]</td>
<td>8.3</td>
</tr>
<tr>
<td>Energy (injection)</td>
<td>$\mathcal{E}_i$</td>
<td>[GeV]</td>
<td>450</td>
</tr>
<tr>
<td>Circulating current/beam</td>
<td>$I_{\text{beam}}$</td>
<td>[A]</td>
<td>0.53</td>
</tr>
<tr>
<td>Normalised transverse emittance</td>
<td>$\varepsilon_n$</td>
<td>[µm]</td>
<td>3.75</td>
</tr>
<tr>
<td>$\beta$-value in the arcs</td>
<td>$\beta$</td>
<td>[m]</td>
<td>~100</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>$k_b$</td>
<td></td>
<td>2808</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$n_b$</td>
<td></td>
<td>$1.15 \times 10^{11}$</td>
</tr>
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At collision energy:

<table>
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<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
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</thead>
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<tr>
<td>$\beta$-value at IP</td>
<td>$\beta^*$</td>
<td>[m]</td>
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</tr>
<tr>
<td>R.M.S. beam radius at IP</td>
<td>$\sigma^*$</td>
<td>[µm]</td>
<td>16</td>
</tr>
<tr>
<td>R.M.S. divergence at IP</td>
<td>$\sigma'^*$</td>
<td>[µrad]</td>
<td>32</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>$\Phi$</td>
<td>[µrad]</td>
<td>285</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L$</td>
<td>[cm$^{-2}$s$^{-1}$]</td>
<td>$10^{34}$</td>
</tr>
<tr>
<td>Stored energy per beam</td>
<td></td>
<td>[MJ]</td>
<td>360</td>
</tr>
</tbody>
</table>

Table A.1: LHC parameters.

The LHC nominal luminosity (interaction rate per cross section), given in Table A.1, is indirectly proportional to the beta function at the interaction point, which is called $\beta^*$. It is proportional to the number of particles per bunch squared and number of bunches. With the large beam current in the LHC and the small nominal $\beta^*$, a high luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ is achieved by colliding the two counter-rotating beams. The luminosity is given by

$$ L = \frac{N^2 k_b f \gamma}{4 \pi \varepsilon_n \beta^*} F $$

(A.1)

where $N$ is the number of protons per bunch, $k_b$ the number of bunches, $f$ the revolution
frequency, $\gamma$ the relativistic factor, $\varepsilon_n$ the normalised emittance and $F$ the reduction factor caused by the crossing angle ($\sim 0.9$ for LHC).
Appendix B

Results of Energy Deposition Simulations for the TCDI Collimation System

Detailed energy deposition simulations were carried out for every four-phase collimator location to investigate the level of local protection. In Table B.1 the optics parameters of the four-phase locations are summarised.

<table>
<thead>
<tr>
<th>Name</th>
<th>s  [m]</th>
<th>( \beta_x ) [m]</th>
<th>Dx  [m]</th>
<th>( \sigma_{xd} ) [mm]</th>
<th>( \beta_y ) [m]</th>
<th>Dy  [m]</th>
<th>( \sigma_{yd} ) [mm]</th>
</tr>
</thead>
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<td>TCDIMOM</td>
<td>670.67</td>
<td>91.73</td>
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Table B.1: The optics parameters of the obsolete four-phase collimation scheme. This input was used for the FLUKA simulation to specify local secondary masks.

The temperature rise in all the simulations was calculated for ultimate beam intensity. Graphite jaws of a length of 1.2 m (based on the TCS-design) with a density of 1.83 g/cm³ were used.

TCDIV135

Fig. B.1 shows a side-view of the FLUKA geometry for the elements downstream of TCDIV135. This consists of simple vacuum chambers with bellows and flanges, followed by MQID877 with its corrector magnet MCIAV and a chain of vertical dipole magnets,
the MBIBVs. The orientation of the beam pipe follows the direction defined by the bending angle of the MBIBVs.

Figure B.1: Side-view of the geometry in the part of transfer line T18 downstream of TCDIV135 including the quadrupole MQID877, the mask in front of it and the chain of vertical dipoles, the MBIBVs.

The geometry of Fig. B.1 was used in a FLUKA simulation with an impact parameter of 1 \( \sigma \) on TCDIV135 for a 450 GeV proton beam. This results in an energy deposition in GeV/cm\(^{3}\)/p\(^{+}\) as shown in Fig. B.2. The energy deposition in the mask, which is at Z-location \( \sim 2200 \) cm in Fig. B.2 is shown in Fig. B.3. The summary for the different simulations (with and without mask, 1 \( \sigma \) and 10 \( \sigma \) impact parameter) is given in Fig. B.4. The resulting temperature along the elements downstream of TCDIV135 is shown. The mask in this case reduces the maximum temperature in the quadrupole MQID877 from 50\(^\circ\) C to 30\(^\circ\) C for a 1 \( \sigma \) impact. Any impact on this collimator is safe for the downstream equipment due to the large (> 20 m) longitudinal distance between collimator and first element downstream.

**TCDIH315**

Fig. B.5 shows the energy deposition in the quadrupole, corrector and chain of MBI dipole magnets after a 20 \( \sigma \) impact on the TCDIH315. Fig. B.6 gives the temperature along the downstream section for this collimator. The temperatures in the downstream elements stay below the limit. Between TCDIH315 and the first magnetic element there is another horizontal collimator, TCDIH225, which due to the small horizontal beta function at this location, see Table B.1, is very close to the beam and takes part of the shower stemming from the impact on TCDIH315.
Figure B.2: Energy deposition caused in the transfer line section downstream of TCDIV135 for a $1 \sigma$ impact on this collimator. The magnetic fields of all magnets are taken into account.

Figure B.3: Energy deposition in the mask of MQID877 for a $1 \sigma$ impact on TCDIV135. Most of the energy deposition occurs close to beam aperture in the mask.
Figure B.4: Longitudinal temperature profile in the section of T18 downstream of TCDIV135 for different impact parameters on this collimator with and without mask.

Figure B.5: Energy deposition in the section downstream of TCDIH315 (top-view) for 20 $\sigma$ beam impact. The elements depicted are TCDIH225, next to the mask protecting MQID875, and a chain of MBI magnets.
Figure B.6: Longitudinal temperature profile in the section downstream of TCDIH315 for different impact parameters. Part of the shower escaping TCDIH315 impacts on TCDIH225.

The location of TCDIH225 had two disadvantages: a very small horizontal beta function of only about 7 m and a distance between exit face of the collimator and entrance face of the quadrupole of only 74 cm. Impact on this collimator would lead to a temperature of 170° C in the downstream MBI magnets, 70° C above the allowed limit, see Fig. B.7. As a consequence a rule of thumb for the choice of locations for the final three-phase collimation system was established. At least a distance of 5 m between collimator jaw and downstream magnets is required and the beta function at the collimator location should be larger than 15 m.

**TCDIH090 and TCDIV045**

The results of the energy deposition simulations for TCDIH090 and TCDIV045 are summarised in Fig. B.9 and B.10. In both cases the downstream equipment is protected. For an impact on TCDIV045 the mask reduces the temperature at the beginning of the MBIAH dipoles from about 110° C to about 70° C.

**TCDIHMSI and TCDIVMSI**

The results for the locations of TCDIHMSI and TCDIVMSI are presented in Chapter 8.

**Compatibility of four-phase system results with the final three-phase system**

The final three-phase collimator locations ended up close to the studied four-phase positions. The energy deposition results are hence still valid. The four-phase collimators
Figure B.7: Longitudinal temperature profile in the section downstream of TCDIH225 for different impact parameters on TCDIH225. At the beginning of the MBIs a temperature above the 100° limit is reached.

Figure B.8: Longitudinal temperature profile in the section downstream of TCDIH315 for different impact parameters on this collimator. TCDIH225 has been removed.
Figure B.9: Longitudinal temperature profile in the section downstream of TCDIHO90 for different impact parameters on this collimator with and without mask.

Figure B.10: Longitudinal temperature profile in the section downstream of TCDIV045 for different impact parameters on this collimator with and without mask.
with their three-phase equivalents:

- \( \text{TCDIH090} \rightarrow \text{TCDIH060} \)
- \( \text{TCDIH315} \rightarrow \text{TCDIH300} \)
- \( \text{TCDIV045} \rightarrow \text{TCDIV060} \)
- \( \text{TCDIV135} \rightarrow \text{TCDIV120} \)

The study has demonstrated that for all the final TCDI locations with masks, impact on a collimator jaw is safe for the downstream equipment.
Appendix C

Glossary

BAD…Computer code to generate transfer line aperture model in MAD-X format
BCT…Beam Current Transformer
BIC…Beam Interlock Controller
BIS…Beam Interlock System
BLM…Beam Loss Monitor
BPM…Beam Position Monitor
CNGS…CERN Neutrinos to Gran Sasso project
D1…Separation/recombination dipole in the LHC
FLUKA…Monte-Carlo computer code for particle transport in matter
FMCM…Fast Magnet current Change Monitor
hBN…Hexagonal boron nitride
IP*…Interaction (collision) point in the LHC
IR*…Insertion region in the LHC
LEP…Large Electron Positron collider
LHC…Large Hadron Collider
LSS4 and LSS6…Long Straight Sections in the SPS; extraction regions
MAD-X…Accelerator designer computer code
MB*…Bending magnet

MBI…Main bending magnets in the transfer lines

MIA…Model Independent Analysis

MQ*…Quadrupole magnet

MSD…Extraction septum in the LHC

MSE…Extraction septum in the SPS

MSI…Injection septum in the LHC

OTR…Optical Transition Radiation screen

PCS…Power Converter Surveillance

PFN…Pulse-forming network to power kicker magnets

RF…Radio frequency

SPS…Super Proton Synchrotron

TCDD…Target Collimator Dump Dipole; mask to protect the coils of the superconducting D1 dipole

TCDI…Target Collimator Dump Injection; transfer line collimators

TCDIHM5I…Horizontal transfer line collimator upstream of the MSI

TCDIVMSI…Vertical transfer line collimator upstream of the MSI

TCDQ…Target Collimator Dump Quadrupole; 6 m long graphite absorber in IR 6 to protect the LHC aperture, especially the quadrupole Q4, against dumper kicker failures

TCLI…Target Collimator Long Injection; auxiliary collimators in the injection region to complete the protection against injection kicker failures

TCS…Target Collimator Secondary; LHC secondary collimator

TDI…Target Dump Injection; injection stopper in the LHC injection regions to protect the LHC aperture against injection kicker failures
**TED**... Target External Dump; beam stopper in the transfer line

**TI**... Transfer lines between the SPS and the LHC

**TPSG**... Target Protection Septum Graphite; absorber to protect the aperture of the extraction septum in the SPS

**TT40**... Beam line between the SPS and TI 8 or TT41

**TT41**... Beam line to the CNGS target

**UP**... User Permit for BIC

**ZDC**... Zero Degree Calorimeter; physics detector in IR 2 to measure spectator protons from IP 2
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