LHC Injection Beam Quality
During LHC Run I

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Abstract

The LHC at CERN was designed to accelerate proton beams from 450 GeV to 7 TeV and collide them in four large experiments. The 450 GeV beam is extracted from the last pre-accelerator, the SPS, and injected into the LHC via two 3 km long transfer lines, TI 2 and TI 8. The injection process is critical in terms of preservation of beam quality and machine protection. During LHC Run I (2009–2013) the LHC was filled with twelve high intensity injections per ring, in batches of up to 144 bunches of $1.7 \times 10^{11}$ protons per bunch. The stored beam energy of such a batch is already an order of magnitude above the damage level of accelerator equipment.

Strict quality and machine protection requirements at injection have a significant impact on operational efficiency. During the first years of LHC operation, the injection phase was identified as one of the limiting factors for fast LHC turnaround time.

The LHC Injection Quality Check (IQC) software framework was developed as a part of this thesis to monitor the beam quality and steer the injection process. Equipment in the SPS-to-LHC transfer lines and in the LHC injection regions, such as beam position monitors and beam loss monitors, are analysed in the IQC. The evolution of LHC injection quality over the years of LHC Run I has been studied and the results are discussed in this thesis.

Beam loss at injection caused by large SPS-to-LHC transfer line trajectory variations was a big concern during LHC Run I. The sources of slow trajectory drifts, shot-by-shot and bunch-by-bunch trajectory variations have been identified after an in-depth study. Several mitigations could be put in place to improve the trajectory stability. Measurements during a beam test confirm the reduction of the trajectory variations.

The other dominant source of beam losses at injection was large non-Gaussian tails in the transverse particle distribution. Systematic tail scraping in the SPS was found to be an efficient way to keep the losses under control. A study was carried out to determine the optimum scraping depth with respect to loss reduction and luminosity performance.

Many efficient mitigations have been put in place to improve injection quality and reduce the time spent at injection. A large number of these were identified from data collected and analysed in this thesis.
I would like to thank all my colleagues at CERN for the excellent collaboration. I am grateful to have been able to work with so many talented and driven people. The collaboration and discussion helped the work done for this thesis.

First of all I would like to thank my supervisor at CERN, Verena Kain. Her persistence and passion for her work helped inspire me and to build this thesis. She has been of great support on many levels.

I would also like to thank my supervisor at the University of Oslo, Professor Steinar Stapnes for his guidance with the PhD and help with all administrative matters.

I would like to thank everybody in the LHC and SPS operations team. There are too many to mention all, but I would like to particularly thank Jörg Wenninger and Karel Cornelis who are sources of great knowledge. I also appreciate the company of my many office mates throughout the years: Mario, Gabriel, Marek, Xavier, Nick, Dario, Michi and Maria.

The Injection Quality Check software framework and data collection relies on the contribution of many colleagues from BE/CO, BE/BI and BE/RF and especially the contribution from Roman Gorbonosov and Denis Khasbulatov who have been responsible for the IQC on the server side.

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I also would like to mention the excellent work done by Gilles Le Godec and his team on the power converters in the SPS.

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My thanks go to Genevieve Steele who kindly read through and commented on this thesis.

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Chapter 1  

Introduction

The Large Hadron Collider (LHC) at CERN is the highest energy particle accelerator ever built. It saw first beam in 2009 and has so far accelerated and collided proton beams at a centre-of-mass energy of up to 8 TeV. The LHC Run I (2009–2013) successfully resulted in the discovery of the long-sought-for Higgs Boson [1, 2]. In 2015, the LHC will re-start again after a two year long shutdown.

The injection energy of the LHC is 450 GeV. Two counter-rotating beams are prepared and pre-accelerated in a chain of accelerators of increasing size and energy. From the last pre-accelerator, the Super Proton Synchrotron (SPS), the beams are transferred via two 3 km long transfer lines and injected into the LHC. The beam quality and luminosity performance in the LHC depend on the performance of the pre-accelerators and on LHC injection quality. After a brief introduction to the LHC in Chapter 2, the LHC pre-accelerators and LHC injection process are described in Chapter 3.

Twelve high intensity injections per beam are needed to fill the machine. Automatic surveillance and analysis systems are in place to verify the beam quality before extraction from the SPS and at injection into the LHC. During LHC Run I several injection quality issues were present and the time required for LHC filling was significantly longer than what had been predicted. At the 2011 LHC Beam Operation Workshop [3], the injection phase was identified as one of the main limitations to the LHC availability for physics production necessitating the investigation of beam quality issues. This thesis is the result of more than three years of continuous monitoring and analysis of a large number of LHC injection parameters.

One of the automatic surveillance systems, the Injection Quality Check (IQC), was prepared as part of the work for this thesis. Not only did the IQC provide most of the data used in this thesis, but it also analysed each LHC injection in real time and decided on how to continue the injection process. Throughout LHC Run I, the IQC analysed more than 30,000 injections. The IQC software and analysis is presented in Chapter 4.
1. INTRODUCTION

Chapter 5, 6 and 7 are dedicated to some of the quality issues discovered such as beam losses in the injection region, transfer line trajectory variations and tails in the transverse beam distribution. The analysis revealed the main sources of trajectory variations allowing improved operational techniques to be proposed and hardware modifications to be implemented during technical stops. The evolution of transfer line stability and other issues are also presented.

In Chapter 8 the main results of this thesis are summarised. Most of the work in this thesis has been presented at conferences and internal meetings at CERN. First author papers presented at conferences and workshops can be found, as they were published, in Appendix A.
Chapter 2

The Large Hadron Collider at CERN

2.1 Particle Colliders

Understanding the constituents and dynamics of the universe is one of the main quests of physics today. The theory used to describe the interaction between and properties of visible matter is the Standard Model. Besides successfully explaining experimental results, predictions made by the standard model lead to the discoveries of new particles, such as for example the W Boson [4]. However, not all observed phenomena can be explained by it which indicates that the Standard Model is incomplete or part of a bigger picture. Particle physics experiments today aim to further test predictions of the Standard Model and search for evidence of physics beyond.

Most elementary particles are not stable and decay shortly after creation. These short lived particles can be re-created in high energy particle collisions, for example by cosmic rays colliding with the molecules in the earth’s atmosphere. Collisions of high energy particles allow for heavy particles to be created through the energy-mass equivalence, \( E = mc^2 \). Although early particle discoveries were made using the natural cosmic radiation, studying rare collision products in rare high energy cosmic ray collisions at non-predictable locations has its limitations for high precision measurements. Particle accelerators, on the other hand, have the advantage of producing a large number of collisions within a fixed energy range at the pre-defined location of a detector.

Since the 1930s particle accelerators have been used in research for nuclear and particle physics. In the first particle accelerators, the accelerated beam was extracted onto a fixed target. In a fixed target collision, the energy available for creation of particles, the centre-of-mass energy \( E_{CM} \), is proportional only to the square root of the beam energy, \( E_{CM} = \sqrt{2m_t c^2 E_b} \), where \( m_t \) is the mass of the target particle and \( E_b \) is the beam energy. This limitation can be overcome in a collider where the two beams collide head-on. The centre-of-mass energy is then the sum of the energy of the two beams. In case they have the same energy, the centre-of-mass energy is twice the beam energy, \( E_{CM} = 2 \times E_b \). The first particle colliders were built in the 1960s and could accelerate beams to a few 100 MeV. The most recent collider is the Large Hadron Collider (LHC) at CERN with a design centre-of-mass energy for protons of
$E_{CM} = 14$ TeV.

The collision energy is not the only important parameter. Often, the probability for a certain process to occur or a particle to be created in a collision is small. This probability, known as the production cross-section $\sigma$, is measured in units of barn ($10^{-24}$ cm$^2$). The study of processes with small cross-sections, requires a large number of collisions, hence the collision rate at a detector is a crucial factor in experiment design (for example the cross-section for an inelastic collision between two protons at 7 TeV is 60 mbarn [5]).

The rate of events $\frac{dR}{dt}$ produced in a collider is the product of the production cross-section $\sigma$ and the collider luminosity $\mathcal{L}$

$$\frac{dR}{dt} = \mathcal{L}\sigma. \quad (2.1)$$

Whereas the production cross-section is given by nature, the luminosity depends on the accelerator parameters. For a two beam circular collider, with bunched beams, the luminosity is proportional to

$$\mathcal{L} \propto f \frac{n_b N_1 N_2}{\sigma_x \sigma_y}, \quad (2.2)$$

where $N_1$ and $N_2$ are the number of particles per bunch in the two beams, $n_b$ is the number of colliding bunches, $f$ is the revolution frequency and $\sigma_{x,y}$ are the transverse beam sizes. Luminosity is measured in units of cm$^{-2}$s$^{-1}$.

The transverse beam size is defined as

$$\sigma_i = \sqrt{\frac{m_0 c}{p} \varepsilon_i \beta_i}, \quad (2.3)$$

where $\beta_{x,y}$ are the horizontal or vertical $\beta$-functions and $\varepsilon_{x,y}$ are the normalised energy-independent emittances. Often the horizontal and vertical emittance are the same for proton beams such as in the LHC. To maximise luminosity, the $\beta$-function is minimised at the interaction points where its minimum value is referred to as $\beta^*$. More about accelerator physics concepts such as $\beta$-function and emittance can be found in Appendix B.

The ratio $\frac{N}{\varepsilon}$ is called the brightness. As can be seen from Equation 2.2 and 2.3, for a given energy and $\beta^*$, the luminosity is proportional to the brightness. The emittance blow-up and particle losses have to be minimised through the chain of accelerators until the moment of collisions. The higher the brightness however, the more prone the beams are to beam instabilities, which lead to losses and emittance growth. Beam transfer between accelerators is a critical process for emittance conservation and beam losses. Beam quality issues related to beam transfer and injection will be treated in Chapter 3.

Whilst maximising the instantaneous luminosity is important, what ultimately counts for the experiments is the total number of collected events over a time $T$. This
is proportional to the integrated luminosity

\[ \int_0^T L \, dt. \quad (2.4) \]

The integrated luminosity is measured in units of inverse barn: \(10^{24}\text{cm}^{-2}\). The higher the instantaneous luminosity \(L\), the higher the integrated luminosity for a given time \(T\), likewise the longer the run time, the greater the integrated luminosity. Accelerators have scheduled maintenance periods and shutdowns, outside of which the time has to be used efficiently to produce as much integrated luminosity as possible. Downtime of equipment and beam availability in the accelerator chain play a key role in this as well as the accelerator turn-around time, the time from the end of collisions until the next period of collisions starts, which has to be kept short. For the LHC a significant fraction of this time is used for injection and filling of the accelerator rings. Efficient filling is fundamental for beam quality and minimising turn-around time. The issues for LHC injection efficiency and the solutions put in place are the main subject of this thesis.

### 2.2 The LHC at CERN

CERN, the European Organization for Nuclear Research, was founded as a European collaboration in 1954. The acronym is French and stands for "Conseil Européen pour la Recherche Nucléaire". The CERN site is located close to Geneva on the border between France and Switzerland. Today it is a collaboration between 21 member states \(^1\) and welcomes scientists of many more nationalities who participate via the CERN experiments.

The Large Hadron Collider (LHC) at CERN is the largest and most powerful accelerator in the world \([6]\). It is a 26.7 km long circular collider, designed to accelerate and collide proton beams at energies up to 7 TeV, giving a total centre-of-mass energy of 14 TeV. These collisions are recorded in four large experiments: ATLAS, ALICE, CMS and LHCb. To maximise the luminosity performance, the LHC is filled with a large number of bunches. For the nominal proton-proton scenario the number of bunches per beam is 2808 with \(1.15 \times 10^{11}\) protons per bunch and a normalised emittance of 3.75 \(\mu\text{m}\) resulting in a peak luminosity of \(1.0 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}\). The LHC nominal parameters for proton-proton operation are summarised in Table 2.1. Heavy ions can also be accelerated by the LHC. So far the LHC has accelerated and collided \(Pb^{+82}\) on \(Pb^{+82}\) and \(Pb^{+82}\) on protons \([7]\).

Keeping the 7 TeV proton beam on a circular orbit requires unprecedentedly high dipole fields. The strength of the bending magnets can be calculated via the well known relation

\[ \frac{P}{e} = B \rho. \quad (2.5) \]

\(^1\)At present, the CERN Member States are Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom.
2. THE LARGE HADRON COLLIDER AT CERN

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<th>Table 2.1: LHC design parameters [6]</th>
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<td>Collision energy [GeV]</td>
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<tr>
<td>Bunch intensity</td>
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<tr>
<td>Number of bunches per beam</td>
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<tr>
<td>Bunch spacing [ns]</td>
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<tr>
<td>Norm. emittance @ injection [µm rad]</td>
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<tr>
<td>Norm. emittance @ collision [µm rad]</td>
</tr>
<tr>
<td>Max. stored energy [MJ]</td>
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<tr>
<td>Peak luminosity IR1/IR5 [cm$^{-2}$s$^{-1}$]</td>
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To reach a momentum of $p = 7$ TeV/c with the LHC bending radius of $\rho = 2.8$ km, the magnetic fields of the bending magnets need to be $B = 8.3$ T. Magnetic fields above 2 T are achievable only with superconducting technology. The LHC main bending magnets use NbTi superconducting cables cooled to 1.9 K with super-fluid Helium. To be able to circulate two beams of same charge particles in opposite directions, the guiding fields for the two beams need to have opposite signs. Instead of using two magnets next to each other, the LHC main dipole magnets house both beam apertures in one magnet. The special coil geometry guarantees vertical dipole fields with different polarity in the two apertures. A cross-section of the twin-aperture LHC dipole magnet can be seen in Figure 2.1.

![Cross-section of an LHC dipole magnet](cern.ch)

The stored energy in the nominal 7 TeV proton beam of 2808 bunches is 360 MJ. However, the deposition of only a small amount (about 30 mJ/cm$^3$) of this total energy in the superconducting coils is sufficient to cause a quench, a state transition where the magnets lose their superconducting state and become normal conducting making beam operation impossible [6]. The 360 MJ stored energy in the LHC beam also exceeds the damage limit of equipment of about 170 kJ [8] by several orders of magnitude. The LHC must be protected against uncontrolled beam loss at all times, therefore a dedicated machine protection system is put in place. The machine protection system consists of
an ensemble of systems such as beam loss monitors, passive collimators and absorbers and many others. These monitoring and protection systems are connected to the beam abort system and trigger a beam abort in case of abnormal losses or deviation from the reference beam parameters.

2.2.1 The LHC Layout

![Schematic overview of the LHC](image.png)

Figure 2.2: Schematic overview of the LHC. The two beams circulate in opposite directions. Beam 1 (blue) is moving clockwise around the ring and beam 2 (red) moves counter-clockwise. The two beams can collide only in the regions containing the four experiments: ATLAS, ALICE, CMS and LHCb. *Image: cern.ch*

A schematic overview of the LHC layout is shown in Figure 2.2. The blue and red lines indicate the apertures of the two beams. Beam 1 (blue) circulates clockwise and beam 2 (red) circulates counter-clockwise. The accelerator is divided into 8 sectors. One sector extends from one straight section to the next containing one arc in between. The straight sections are named point 1 to point 8. The arc is filled with the dipole bending magnets in a regular FODO structure. The experimental regions with the detectors and other key equipment are placed in the straight sections.

In four straight sections, the two rings intersect and the beams share a common beam pipe for a short distance. These are the experimental insertions. Point 1 and point 5 house the general purpose high luminosity experiments, ATLAS and CMS.
ALICE is installed in point 2 to study ion collisions and LHCb is in point 8 to study mainly b-physics. The accelerating radio-frequency (RF) system is located in point 4 and consists of eight superconducting RF cavities per beam each delivering 3.5 MV at 400 MHz. In point 6, the beam can be extracted onto a dump block at the end of the operational cycle or in case the machine protection triggers an emergency beam abort. Two collimation insertions are installed in point 3 and point 7 for momentum cleaning and betatron cleaning respectively. The collimators are movable material blocks which are positioned close to the beam to absorb particles with large amplitude and momentum errors and protect the superconducting magnets against uncontrolled beam losses. The LHC injection areas are upstream of the experimental detectors in point 2 and point 8. More details about the insertions housing the injection equipment can be found in Chapter 3.

2.2.2 The LHC Operational Cycle

![Operational cycle](image)

Figure 2.3: The operational cycle: The black curve gives the beam energy corresponding to the main dipole current. In 2012 the collision energy was 4 TeV per beam. The blue and red line give the intensities of the two beams. In this example ring 1 is filled first and then ring 2. The plot is based on real data taken during LHC fill 3191 in 2012.

Figure 2.3 illustrates the LHC operational cycle. The evolution of the beam energy corresponding to the main dipole current and the beam intensity in the two beams is shown as a function of time. The operational phases known as beam modes are indicated by the labels. The LHC operational cycle or LHC fill starts after the beam abort of the previous fill. The corresponding beam mode is called beam dump. As part of the operational sequence to launch the ramp down of the magnets from collision to injection current, a new fill number is generated. Every LHC cycle can be uniquely identified by its fill number. The circuits are not just merely ramped down, but execute special pre-cycles or even de-gauss cycles to guarantee magnetic reproducibility. With the LHC Run I energy of 4 TeV the ramp-down/pre-cycle took 35 minutes.
This phase is followed by the *injection* phase. During Run I the injection phase was the least predictable phase in terms of duration due to the dependence on LHC injector chain availability and beam quality in the injectors. The minimum time to fill both rings was 30 minutes. When the machine is full, the energy *ramp* is launched. Here all magnet circuits, collimators and RF synchronously execute functions to go from their injection to flat-top energy settings. For the 4 TeV ramp the execution of the functions took around 15 minutes. Immediately afterwards the *squeeze* beam mode is launched. During the squeeze, the optics of the experimental mini-beta insertions is modified such to minimise $\beta^*$ at the interaction points. This process leads to very large $\beta$-functions and thus large beam sizes in the quadrupole magnets close-by. The squeeze is executed at top energy to profit from the natural emittance shrinkage with energy and therefore increased margin for large $\beta$-functions. The squeeze during Run I took 17 minutes.

The two beams are kept on separate non-colliding orbits for most of the cycle. After the squeeze, the beams are steered to collide head-on in the four interaction points. At this moment the operators declare the beam mode *stable beams* and the experiments start recording data. The machine will then keep running for many hours until the beams are dumped and the cycle starts once again.

The LHC is a slow machine in comparison to the LHC injectors which have cycles of several seconds. The LHC turn-around time, from beam dump to the next *stable beams*, is around $2\frac{1}{2}$ hours.

### 2.3 LHC Timeline

Construction of the LHC started in 2001, replacing the *Large Electron Positron collider* (LEP) which had been running since 1989. The first beams circulated in 2008, before an electrical fault occurred in a connection between two adjacent magnets. This resulted in a release of Helium under high pressure and damage to 69 superconducting magnets. Investigation afterwards showed that there were many connections around the LHC with non-conformities and it was therefore decided to start operating at a lower current in the dipole magnets resulting in 3.5 TeV per beam, half the nominal energy [9]. The LHC Run I started in November 2009 and lasted until February 2013, when the machine was stopped for the first long shutdown (LS1).

In 2009 and 2010 the machine was commissioned, carefully raising the energy up to 3.5 TeV and the number of bunches up to 368 per beam. This first part was dedicated primarily to test all the systems and only a small amount of integrated luminosity was collected. The 2011 run was dedicated to the intensity ramp up to 1380 bunches of 50 ns bunch spacing. To be able to use 50 ns bunch spacing, it was necessary to undergo a period of *scrubbing* at the beginning of the year to reduce the electron cloud instability [10]. Injection of beam with the nominal 25 ns bunch spacing was also attempted, but proved to be difficult due to the electron cloud effect. The 2012 run saw the increase of beam energy from 3.5 TeV to 4 TeV due to increased experience in operation and confidence in the simulations. The operation ended with a heavy ion
run in early 2013 before going into LS1 in preparation for the next run with the top energy increased to 6.5 TeV per beam. The achieved beam parameters in LHC Run I are summarised in Table 2.2.

Table 2.2: Achieved parameters in LHC Run I [11]

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<th>2010</th>
<th>2011</th>
<th>2012</th>
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<tbody>
<tr>
<td>Collision energy [GeV]</td>
<td>3500</td>
<td>3500</td>
<td>4000</td>
</tr>
<tr>
<td>Injected bunch intensity</td>
<td>$1.2 \times 10^{11}$</td>
<td>$1.5 \times 10^{11}$</td>
<td>$1.7 \times 10^{11}$</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>368</td>
<td>1380</td>
<td>1380</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>150</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Norm. emittance @ injection [µm rad]</td>
<td>$\approx 2.0$ [12]</td>
<td>$\approx 1.9$ [13]</td>
<td>$\approx 1.5$ [14]</td>
</tr>
<tr>
<td>Norm. emittance @ collision [µm rad]</td>
<td>$\approx 2.2$</td>
<td>$\approx 2.3$</td>
<td>$\approx 2.5$</td>
</tr>
<tr>
<td>Max. stored energy [MJ]</td>
<td>24</td>
<td>112</td>
<td>143</td>
</tr>
<tr>
<td>Peak luminosity IR1/IR5 [cm$^{-2}$s$^{-1}$]</td>
<td>$0.2 \times 10^{33}$</td>
<td>$3.5 \times 10^{33}$</td>
<td>$7.7 \times 10^{33}$</td>
</tr>
<tr>
<td>Integrated luminosity IR1/IR5 [fb$^{-1}$]</td>
<td>0.048</td>
<td>5.6</td>
<td>23.3</td>
</tr>
</tbody>
</table>

Despite the fact that the LHC was running at a lower energy and with fewer bunches, the peak luminosity was close to the design value due to the excellent performance of the injectors which provided bunch intensities and emittances beyond specifications. The integrated luminosity at the end of the run was nearly 30 fb$^{-1}$ in ATLAS and CMS. In Figure 2.4 the evolution of the integrated luminosity during LHC Run I is shown.

![Figure 2.4: The evolution of integrated luminosity in ATLAS/CMS per year of LHC operation. Image: courtesy of J. Wenninger [11].](image)

In 2012, after only a few years of operating the LHC, the ATLAS and CMS experiments announced the discovery of the Higgs boson confirming the success of the LHC project [1, 2]. The understanding of the properties of this new particle and the search for evidence of new physics will necessitate more data taking. With the LHC set to run for many years to come, including several shutdown periods and planned upgrades [15], it is hoped that there will be many more exciting discoveries to be made.
Chapter 3

The LHC Injection Process

The LHC beams are produced and pre-accelerated in a chain of accelerators. From the last pre-accelerator, the SPS, the 450 GeV beams are transferred and injected into the LHC via the two 3 km long transfer lines TI 2 and TI 8.

This chapter introduces the different machines in the LHC injector chain focusing on the systems used for transfer from the SPS to the LHC. The typical beam quality issues associated with beam transfer and injection will be discussed and the beam quality requirements for the SPS-to-LHC transfer will be summarised. The particularity of the SPS-to-LHC transfer with a transferred energy density of more than a factor 10 above the estimated equipment damage limit will also be introduced in detail. The implemented injection protection systems and concepts and their impact on operation will be detailed.

3.1 LHC Beam Production in the CERN Accelerator Chain and the LHC Filling Process

The LHC injection energy is 450 GeV. Beams are prepared and pre-accelerated in the CERN accelerator chain, often referred to as the LHC injectors, where the bunch spacing and beam brightness is defined. Performance in the injectors is therefore directly linked to the LHC luminosity performance.

As the main focus of this thesis is the LHC proton run, only the proton injector chain will be discussed in detail. After the CERN proton source, the $H^+$ ions are accelerated to 50 MeV by the linear accelerator LINAC 2. After the LINAC 2, the machines are all synchrotrons of increasing size. An overview of the CERN accelerator chain is given in Figure 3.1.

From the LINAC 2 the beams are injected into the PS Booster. The PS Booster consists of four storage rings. For LHC beams, each is filled with one bunch. The Booster then accelerates the proton bunches to 1.4 GeV which is the injection energy of the PS.

For the nominal LHC beam, a total of six bunches are injected from the Booster into the PS in two injections (four bunches in the first and two in the second injection). Whereas the maximum possible brightness is defined in the Booster, the bunch
3. THE LHC INJECTION PROCESS

Figure 3.1: The CERN accelerator complex. Before the beams are injected into the LHC they are pre-accelerated in a chain of accelerators of increasing size. The injection chain for protons is; LINAC 2, PS booster, PS and SPS. The heavy ion chain is; LINAC 3, LEIR, PS and SPS. The two SPS to LHC transfer lines TI 2 and TI 8 are also shown. Image: cern.ch
structure is produced in the PS. The PS has several RF systems running at different frequencies. By switching adiabatically between RF systems with higher and higher harmonics, the bunches from the Booster are split to finally end up with the LHC bunch spacing. During the first bunch splitting each Booster bunch is split into three by going from RF system with harmonic $h=7$ to RF system with $h=21$.

The next stage sees each bunch split into two at PS top energy (26 GeV) to end up with 36 bunches at 50 ns bunch spacing. For 25 ns bunch spacing another double splitting occurs shortly before extraction towards the last pre-accelerator, the SPS, to end up with 72 bunches in total. The bunch splitting is illustrated in Figure 3.2 [16].

![Figure 3.2](image)

Figure 3.2: In the PS the 6 bunches are split in two steps to obtain the desired bunch structure. First each bunch is split into three after injection. At flat top, the bunches are split again by four (25 ns bunch spacing) or by two (50 ns bunch spacing). Courtesy of H. Damerou.

The SPS takes up to four batches from the PS and accelerates them to the LHC injection energy, 450 GeV. Figure 3.3 shows the number of required magnetic cycles as well as the evolution of the beam intensity in the different machines. The beam production in the injectors takes around 25 seconds in total for each LHC injection.

![Figure 3.3](image)

Figure 3.3: The beam production in the injectors are shown. The SPS is filled by up to four injections from the PS. The PS takes two injections from the booster. Courtesy of V. Kain.

During the luminosity production phase of LHC Run I, the LHC was operating with
50 ns bunch spacing and 36 bunches per PS batch injected into the SPS. The bunch intensity was up to \(1.7 \times 10^{11}\) protons per bunch. The typical Run I filling pattern is illustrated in Figure 3.4. Twelve injections from the SPS were needed to fill each LHC ring. The LHC was filled with injections of either 72 or 144 bunches from the SPS. The gaps between the batches correspond to the LHC injection kicker rise time of 0.9\(\mu s\) and the large 3\(\mu s\) gap at the end has to be kept empty for the LHC beam dump kicker rise time. The plot also shows a small batch consisting of only 6 bunches at the beginning of the filling pattern. This is an intermediate intensity batch which always has to be injected before any full PS batches from the SPS can be transferred. The reason behind the intermediate intensity injections will be explained in section 3.4. To obtain 6 bunches in the injectors, only one bunch from the Booster is transferred to the PS.

![LHC beam 2 [1374 bunches]](image)

Figure 3.4: The filled RF buckets of beam 2 during fill 3192 are shown. Twelve high intensity injections (3\(\times\)72 + 8\(\times\)144 bunches + 6) are filled one after the other giving a total of 1374 bunches. At the end a 3.0\(\mu s\) abort gap is left empty to accommodate the rise time of the extraction kickers. The data is taken from the LHC beam quality monitor [17].

For a given filling pattern, the first bunch of each injection into the LHC has to end up in a well-defined, but different RF bucket. For this to be possible the SPS RF system is synchronised with and re-phased to the LHC RF system shortly before beam transfer via their common frequency \(f_c = \frac{f_{\text{LHC}}}{7} = \frac{f_{\text{SPS}}}{27} = 1.6\text{kHz}\). The \(f_c\)-pulse is generated by the LHC and sent to the SPS synchronization system. The delay of the \(f_c\)-pulse with respect to the LHC revolution frequency pulse corresponds to the requested bucket in the LHC [18].

### 3.2 The SPS-to-LHC Beam Transfer

#### 3.2.1 The SPS Extraction Systems

The LHC beams are extracted from the SPS by two fast extraction systems using kicker magnets. LHC Beam 1 is extracted from LSS 6 (Long Straight Section 6) to TT 60/TI 2 and LHC Beam 2 is extracted from LSS 4 to TT 40/TI 8. A closed orbit
bump is used to move the circulating beam close to the extraction channel to reduce the required strength of the extraction kicker magnets. The orbit bump is generated by four horizontal corrector magnets (extraction bumper magnets). To extract the beam, the fast kicker magnets are triggered and the beam is deflected into the extraction channel and into the field region of the extraction septum magnets, see Figure 3.5.

![Figure 3.5: The extraction in LSS 4 for LHC Beam 2 is shown. The black lines show the beam envelope of the circulating beam with the extraction bump. When the extraction kickers fire, the beam is deflected into the extraction channel (red beam envelope). The blue lines indicate the aperture in the SPS and the extraction channel. Courtesy of F. Velotti.](image)

During LHC Run I, the extraction system in LSS 4 was shared between LHC and CNGS beams [19]. This system consists of five fast pulsed kicker magnets (MKE.4 series) and six septum magnets (MSE.4 series) [20]. In LSS 6 the extraction system consists of three extraction kicker magnets (MKE.6 series) and two thin septum magnets (MST.6 series) followed by five MSE type magnets (MSE.6 series) [21]. The strengths of the extraction elements are given in Table 3.1 for LSS 4 and 3.2 for LSS 6 for the two LHC optics used in the SPS during LHC Run I, Q26 optics and Q20 optics.

<table>
<thead>
<tr>
<th></th>
<th>Q26 optics</th>
<th>Q20 optics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction kickers</td>
<td>MKE.4 (total)</td>
<td>0.52 mrad</td>
</tr>
<tr>
<td>MSH.41402</td>
<td>0.02 mrad</td>
<td>0.24 mrad</td>
</tr>
<tr>
<td>MPLH.41658</td>
<td>0.51 mrad</td>
<td>0.28 mrad</td>
</tr>
<tr>
<td>MPLH.41994</td>
<td>0.38 mrad</td>
<td>0.32 mrad</td>
</tr>
<tr>
<td>MSH.42198</td>
<td>0.15 mrad</td>
<td>0.12 mrad</td>
</tr>
<tr>
<td>Extraction septa</td>
<td>MSE.4 (total)</td>
<td>12.8 mrad</td>
</tr>
</tbody>
</table>

### 3.2.2 The SPS-to-LHC Transfer Lines

From the SPS to the LHC, the beams are transported via two ~ 3 km transfer lines, TT 60/TI 2 for LHC Beam 1 and TT 40/TI 8 for LHC Beam 2. The basic layout of
Table 3.2: SPS LSS6 extraction elements for two SPS optics, Q26 and Q20

<table>
<thead>
<tr>
<th>Extrac tion elements</th>
<th>Q26 optics (total)</th>
<th>Q20 optics (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction kickers</td>
<td>0.43 mrad</td>
<td>0.43 mrad</td>
</tr>
<tr>
<td>MKE.6</td>
<td>0.09 mrad</td>
<td>0.03 mrad</td>
</tr>
<tr>
<td>MPSH.61402</td>
<td>0.47 mrad</td>
<td>0.46 mrad</td>
</tr>
<tr>
<td>MPLH.61655</td>
<td>0.35 mrad</td>
<td>0.12 mrad</td>
</tr>
<tr>
<td>MPLH.61996</td>
<td>0.20 mrad</td>
<td>0.35 mrad</td>
</tr>
<tr>
<td>Extraction septa</td>
<td>1.06 mrad</td>
<td>1.06 mrad</td>
</tr>
<tr>
<td>MST.6 (total)</td>
<td>9.51 mrad</td>
<td>8.78 mrad</td>
</tr>
<tr>
<td>MSE.6 (total)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The SPS and the transfer lines including the injection points in the LHC are illustrated in Figure 3.6.

The transfer line optics is matched to the SPS and LHC optics at both ends. The matching is done by a series of individually powered quadrupole magnets at the beginning and the end of the transfer line. The rest of the lattice is a regular FODO lattice with quadrupole magnets powered in series. The $\beta$-function and dispersion for TI 2 are shown in Figure 3.7. The transfer lines also contain around 50 dipole trajectory corrector magnets which are used to match the trajectory to the LHC orbit and for minimising the trajectory excursions throughout the line for aperture reasons.
3.2 The SPS-to-LHC Beam Transfer

Figure 3.7: The $\beta$-function and dispersion for the TI 2 transfer line are shown. The transfer line optics is matched to the SPS and LHC at the beginning and the end of the line with individually powered quadrupole magnets. The central part of the transfer line optics consists of regular FODO cells.

3.2.3 The LHC Injection System

From TI 2 and TI 8 the beams are injected at the insertions of point 2 and point 8 respectively. These insertions are shared with the experiments ALICE in point 2 and LHCb in point 8. Beam 1 is injected clockwise, $\sim 150$ m left of IP 2. Beam 2 is injected counter-clockwise, $\sim 160$ m right of IP 8. Both beams follow the same injection scheme, see Figure 3.8 for a schematic drawing of the beam 2 injection. The beam is injected from the outside and from below the main ring. First five septum magnets (MSI) are used to deflect the beam horizontally by 12 mrad. Afterwards four fast pulsed kicker magnets (MKI) deflect the beam vertically by 0.85 mrad onto the LHC orbit. The MKI magnets have a flat-top length of about $8\mu$s which is required for a full SPS batch with 4 injections from the PS. Its rise time is less than $0.9\mu$s.

Figure 3.8: LHC beam 2 is injected at point 8 (IP 8) 160 m upstream of the experiment LHCb. The beam is deflected onto the circulating orbit by the injection septum (MSI) and injection kicker (MKI) magnets. Figure adapted from [6].
3.3 LHC Injection Quality Requirements

A trajectory offset at the injection point or optical mismatch due to optics errors at the extraction or injection point or in the transfer lines lead to emittance blow-up and possibly also to particle losses [22]. The total allowed budget for emittance blow-up through the LHC cycle at the design stage was 7%, where errors at injection should be below 5% [23]. According to the emittance measurements at injection during Run I, optics errors in beta function and dispersion are below 10%. The emittance blow-up is below the measurement resolution and was therefore of no concern [24].

Trajectory offsets at the injection point lead to injection oscillations all around the storage ring. Next to the concern for emittance blow-up, injection oscillations in the LHC have to be kept below about 1.5 mm to respect the limited aperture at injection energy. 1.5 mm correspond to roughly 1.5 $\sigma$ in the LHC arcs. If the injection oscillations are above the limit, the LHC filling process must stop for correction of the trajectory in the transfer line.

Uncorrected injection oscillations of 1.5 $\sigma$ lead to a significant emittance blow-up of more than 100% following [23]

$$\frac{\varepsilon}{\varepsilon_0} = 1 + \frac{1}{2} \Delta e^2,$$

(3.1)

where $\Delta e$ is the trajectory error measured in $\sigma$. In the LHC the transverse feedback system ADT, often referred to as transverse damper, ensures correction of the injection oscillations in the LHC before filamentation occurs [25]. Including damping, the emittance blow-up is reduced through

$$\frac{\varepsilon}{\varepsilon_0} = 1 + \frac{1}{2} \Delta e^2 \left( \frac{1}{1 + \tau_{DC}/\tau_d} \right),$$

(3.2)

where $\tau_{DC}$ is the filamentation time and $\tau_d$ is the damping time [23]. The damping time in the LHC at injection is in the order of 15 turns (1-2 ms), see Figure 3.9.

Even though the injection oscillations in the LHC were often close to 1.5 $\sigma$, emittance blow-up at injection was never of concern due to the excellent performance of the ADT. As mentioned earlier, no emittance blow-up from LHC injection was measured so far. However, for the ADT to work efficiently, the injection oscillations should not go beyond 2 mm amplitude.

Beam quality issues can also originate from injection errors in the longitudinal plane. If part of the beam is injected outside the LHC RF bucket due to small RF phase or energy errors, it will eventually be lost. This type of loss is called capture loss. The SPS has a 200 MHz RF system and hence larger RF buckets than the LHC with its 400 MHz RF system. The longitudinal emittance and bunch length of the SPS beam have to be small enough to fit into the smaller LHC buckets. An illustration of bucket-to-bucket transfer with an error from the SPS to LHC is shown in Figure 3.10.

The uncaptured beam then moves around the circumference outside the RF buckets and eventually populates the abort gap or ends up at the location where the next beam
3.3 LHC Injection Quality Requirements

Figure 3.9: After injection, the injection oscillations are damped by the ADT (transverse damper) to an acceptable level. The damping time is around 15 turns.

is to be injected. Particles in the location where beam is injected are kicked onto the aperture during injection. In case of abort gap population, these particles are lost on the LHC aperture in case the beam dump kickers are triggered. For both kicker systems, absorbers are placed downstream of the kickers which will be hit by these losses. The absorbers in the injection region will be described in the next section. Uncaptured beam is at the latest lost on the momentum collimators during the energy ramp as the particles’ momentum will not be synchronously increased with the machine’s. A way to maximise the RF acceptance in the LHC is to increase the RF voltage at injection.

Figure 3.10: Longitudinal injection errors leads to capture errors where part of the injected bunch ends up outside the LHC RF bucket. Courtesy of T. Mastoridis.
3. THE LHC INJECTION PROCESS

To improve capture losses in 2011, the capture voltage was increased from the initial 3.5 MV to 6 MV.

Satellite bunches coming from the injectors, small fractions of captured beam in buckets between the 50 ns (25 ns) spaced main bunches, can also create similar losses on the injection absorber as uncaptured beam if the first main bunch is close to the rising edge of the kicker waveform.

Equipment failures during the transfer process can lead to significant trajectory or optics errors and hence to losses that are not only a concern for beam quality, but can also damage equipment. This aspect is especially relevant for the high intensity SPS-to-LHC transfer.

3.4 The LHC Injection Protection System

The intensity of a full SPS nominal batch of 288 bunches with 25 ns spacing is more than an order of magnitude above the damage limit of accelerator components. The relevant beam parameters for LHC nominal and ultimate intensity are recalled in Table 3.3. A sophisticated machine protection system has therefore been put in place to protect the transfer lines and especially the LHC from damage in case of erroneous transfer [8].

<table>
<thead>
<tr>
<th>Intensity of injected batch</th>
<th>Norm. emittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>288 bunches of $1.15 \times 10^{11} p^+$</td>
</tr>
<tr>
<td>Ultimate</td>
<td>288 bunches of $1.7 \times 10^{11} p^+$</td>
</tr>
</tbody>
</table>

The currents of every circuit involved in the transfer, starting at the SPS extractions and including the LHC injection septa, are monitored by a dedicated SPS extraction Beam Interlock System (BIS). If the measured current of one of the circuits is outside a pre-programmed tolerance window a few ms before extraction, extraction will be prohibited by the interlock system. The LHC beam interlock system and an additional interlock loop monitoring equipment in the injection region are also connected to the extraction interlock to ensure that extraction is not allowed in case the LHC is not ready to receive beam.

Some of the circuits, such as the extraction septa in the SPS, have very small time constants in case of a power supply failure and the current can decay quickly. Even a few ms of decay after the last current monitoring check might be sufficient to result in a significant current error at the moment of extraction. For example the SPS extraction septa change the trajectory by approximately 40 $\sigma$ in 1 ms in case of a power converter failure. The aperture of the transfer line is about 10 $\sigma$. For these cases an additional monitoring system, the fast current change monitor, was implemented to react on current changes rather than absolute values. This system can inhibit extraction until a few tens of $\mu$s before it should occur [8].

However, in case of a failure of the extraction kicker or injection kicker system, no active monitoring system can cover all possible failures as some of the failures
develop on the \( \mu s \) scale. Therefore passive protection in the form of absorbers is located downstream of the kicker systems. The TDI injection beam stopper is installed 90° phase advance downstream of the LHC injection kickers to protect the LHC against any failures of the injection kickers. The transfer lines are equipped with a collimation system to take the beam in case of very fast failures and also as a redundant protection system in case of a failure of the active monitoring.

Beam Loss Monitors (BLMs) [26] with thresholds are installed in the SPS extraction regions, transfer lines, LHC injection regions and the rest of the LHC. The BLMs are ionization chambers fixed to magnets or vacuum chambers and measure deposited radiation in Gy. They are connected to the interlock systems. In the LHC and its injection regions, they request a beam dump and also inhibit SPS extraction in case the beam losses exceed pre-defined thresholds. The BLMs in the SPS extraction region and in the transfer lines are directly connected to the SPS extraction interlock system and will inhibit the next extraction if the beam loss during the previous one was too high.

The interlocks discussed so far are derived on a front-end system with output true or false transmitted to an interlock controller via cables or fibres. For more flexibility and surveillance of less critical systems also a software interlock system (SIS) exists.

The easily configurable SIS is written in JAVA and running on a JAVA server. The SIS can subscribe to any parameter published over the CERN Middle Ware (CMW), also those generated by other JAVA processes. The parameters are compared to thresholds or used in more complex checks. Several instances exist to have a dedicated system per accelerator. The summary output of the SIS is input to the hard-wired interlock system such that for instance an interlock in the injection SIS will inhibit SPS extraction.

### 3.4.1 The LHC Transfer Line Collimators (TCDIs)

The LHC transfer line collimation system is a generic passive protection system providing full phase coverage to protect against any failure from extraction or transfer upstream of the collimation system. The full phase space coverage is obtained via three collimators per plane each with two jaws, with \( 60 + n \times 180° \) phase advance between two neighbouring collimators. Each collimator is 1.2 m long and made of graphite with a density of 1.83 \( g/cm^3 \) to attenuate a full ultimate batch to a safe beam intensity [8, 27]. The transfer line collimators are set up once a year around the established reference trajectory with a setting of \( \pm 4.5 \) to \( \pm 5 \sigma_{\text{nom}} \). A collimator jaw position interlock ensures the correct setting for high intensity extractions. The collimator jaw position surveillance is connected to the SPS extraction interlock system. To cover the maximum number of possible failure cases the collimators are located as close as possible to the LHC at the end of the transfer lines, where the transfer lines are already in the LHC tunnel and close to superconducting magnets.
3.4.2 The LHC Injection Beam Stoppers (TDIs)

A schematic view of the LHC injection kicker system is given in Figure 3.11 [28]. The Pulse Forming Network (PFN) of the kicker is charged 2 ms before injection. The pulse into the magnet is triggered by closing the main switch. The dump switch is used to define the length of the pulse. Each magnet consists of 33 cells equipped with capacitors between a high voltage and a ground plate. The switches are gas tubes which may not fire or spontaneously self-fire giving an erratic pulse. In case one of the four kickers fires erratically, the others trigger immediately and the beam will be swept out over the whole deflected range.

![Figure 3.11: Schematic view of the MKI. The Pulse Forming Network (PFN) is charged by the Resonant Charging Power Supply (RCPS). To trigger the kicker, the main switch closes and the current is sent to the magnet. The dump switch is then used to control the length of the pulse. Courtesy of M. Barnes [28].](image)

Failures of the injection kickers are expected and therefore injection beam stoppers are installed 90° (70 m) downstream of the kicker magnets. The injection beam stoppers have two ∼4.2 m absorber jaws designed to take the full impact of the injected beam. The TDI jaws consist of a sandwich structure of different materials (2850 mm of hBn, 600 mm of Al and 700 mm of Cu). The TDI is complemented by the TCLIA and TCLIB collimators (at phase advances of $n \times 180 \pm 20°$) to protect in case the phase advance between the MKI and the TDI is not exactly 90° [8].

Another failure of the injection kickers is the flash-over which is a discharge between the capacitor plates during a pulse resulting in a kick between 0 and 200%. In this case the total deflection of the four kickers is between 75% and 125% of the nominal value which means the full incoming beam is kicked at the wrong angle.

The two jaws of the TDI protect against different types of failures, see Figure 3.12. In case of an erratic pulse, part of the circulating beam is potentially kicked onto the lower jaw of the TDI. The lower jaw also protects if circulating beam is kicked out during over-injection or in case there are satellites or uncaptured beam circulating when the kickers fire. If the kickers do not pulse when beam is extracted, the beam continues onto the upper jaw of the TDI. This can also occur if the kickers do not receive a trigger or if there is an interlock inhibiting injection. During LHC run I, multiple injection kicker failures occurred and in the worst cases several magnets quenched [29, 30, 31]
3.5 Operational Implications of High Intensity SPS-to-LHC Transfer

3.5.1 Impact on Injection Efficiency and Filling Pattern

Not all settings of equipment that is active on the beam are interlocked in the LHC. There is for example no verification for the current reference settings of all power supplies in the LHC. The SPS extraction interlock therefore allows high intensity extraction from the SPS only if there is beam already circulating in the LHC. Circulating beam in the LHC ensures integrity of the LHC settings. The extraction interlock system also takes care that only low intensity beam can be injected into an empty LHC. The allowed intensity of this probe beam is $5 \times 10^9$ protons, which is below the quench limit of the superconducting magnets. The LHC beam instrumentation system is able to measure this intensity. The detailed implementation of the interlocking logic involving the intensity measurements from beam current transformers in the SPS is described in [32].

Another restriction for first injections had to be added during LHC Run I. It was not part of the original design of the SPS extraction interlock concept. The first high intensity injection after the probe beam has to be intermediate intensity. The intermediate intensity during LHC Run I was 12, and later on 6, 50 ns spaced bunches. This intensity is still below the damage limit which was estimated to be about $2 \times 10^{12}$ protons [8]. One of the reasons for the intermediate intensity injection is more accurate reading of the Beam Position Monitors (BPMs) in the transfer lines and in the LHC with nominal bunches. The other reason is that high intensity beams (also including intermediate intensity) are produced on a different magnetic cycle in the SPS than the probe beam, possibly resulting in slightly different transferred trajectories. The magnet current settings are not necessarily the same for different cycles. Also the first verification shot after transfer line correction is only done with intermediate intensity.
3. THE LHC INJECTION PROCESS

The beams used for set-up and filling are summarised in Table 3.4.

Table 3.4: Beam parameters for beams commonly used during LHC Run I

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>Intensity of Injected Batch</th>
<th>Norm. Emittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC Run I Physics Beam</td>
<td>72–144 bunches of $1.7 \times 10^{11} p^+$</td>
<td>1.5–2.5$\mu$m</td>
</tr>
<tr>
<td>Probe Beam</td>
<td>1 bunch of $5 \times 10^9 p^+$</td>
<td>1$\mu$m</td>
</tr>
<tr>
<td>Intermediate Intensity Beam</td>
<td>6–12 bunches of $1.7 \times 10^{11} p^+$</td>
<td>1.5–2.5$\mu$m</td>
</tr>
</tbody>
</table>

These precautions obviously have an impact on the filling efficiency and filling pattern. If for any reason filling has to be re-started, the injectors have to switch back to probe beam production before continuing with high intensity. The probe bunch will not be part of the final filling pattern, it will be over-injected by requesting high intensity beam into the same RF bucket. The probe bunch will then be kicked onto the TDI injection stopper. The intermediate intensity bunches however cannot be over-injected due to beam loss limitations in the injection region. It has to be part of the final filling pattern.

If the transfer line trajectories degrade during filling and a trajectory correction is necessary, the next extraction after a correction has to be intermediate intensity to safely validate the new settings in the transfer line. This means deviating from the physics filling pattern and having to dump the beams before the filling for physics can be re-started.

3.5.2 Injection Losses

The thresholds of the beam loss monitors in the injection region are defined to protect the surrounding superconducting magnets from quenching in case particle loss occurs on the vacuum chamber and the showers propagate to the magnetic coils. As the transfer lines and hence transfer line collimators are so close to the LHC, showers generated by losses on the transfer line collimators will reach the BLMs on the superconducting LHC magnets. With BLMs directly hit by the secondary showers from the collimators, the BLM signal can be higher than the BLM thresholds even for small losses.

Because of the tight settings of the transfer line collimators combined with issues such as trajectory stability and transverse tail population, every injection, even with pilot intensity, is seen by the BLMs in the injection region. This type of beam loss was a concern during Run I and reduced the injection efficiency significantly. These problems will be treated further in Chapter 5, 6 and 7. A similar problem exists with showers from the injection absorbers hitting the BLMs around the downstream triplet magnets. Here the source of losses is mainly uncaptured beam.

3.6 Summary

The LHC beams are produced and pre-accelerated in the CERN accelerator chain before injection into the LHC. The beam production and the LHC injection process play
key roles for LHC beam quality and hence luminosity performance in the LHC. The transfer of the high intensity LHC beams require special considerations for machine protection. At every injection, the beam quality is carefully monitored by a dedicated software, the *Injection Quality Check* (IQC) which will be presented in the next chapter. Machine protection procedures and implementations as well as beam quality requirements have an impact on filling patterns and filling efficiency.
Chapter 4

Automatic LHC Injection Quality Monitoring

In Chapter 3 the LHC beam quality requirements and machine protection considerations were introduced. In this chapter the LHC Injection Quality Check (IQC) which analyses the quality of every LHC injection in real time will be described in detail.

4.1 Automatic Filling of the LHC

The production of the LHC beams was discussed in the previous chapter. For a typical LHC Run I filling pattern, 12 injections — 1 intermediate intensity and 11 high intensity injections — were required to fill the LHC. The physics filling pattern is pre-prepared to optimise the number of colliding bunches at the four LHC experiments according to their needs. The injections needed for the filling pattern is programmed in the form of a filling scheme in the LHC control system.

The Injection sequencer [33] requests the injections from the timing system according to the filling scheme. The two beams are filled separately and independently. The two filling processes are synchronised via the availability of the injector timing system CBCM (Central Beam and Cycle Management) for taking a new request [34]. Figure 4.1 shows a picture of the LHC injection sequencer graphical user interface (GUI).

During LHC filling, the LHC controls the production of the LHC beams in the injectors via the injection sequencer. The injectors run under LHC mastership for the LHC beam cycles. Each injection request contains information on whether the intensity is nominal or intermediate, how many batches from the PS should be injected into the LHC (1–4) and into which LHC RF bucket the first bunch of the next injection should be injected. With this information the injectors start producing the beam and the SPS RF system is synchronised to the LHC RF shortly before extraction to inject the beam into the correct bucket. To change between low intensity probe beam and high intensity beams, operator intervention is required. The magnetic cycle in the injectors has to be changed. If no request is made, no LHC beam is produced in the injectors.

Despite a successfully executed injection request, the beam might still not make
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4.1 Loading Different Filling Schemes

Several filling schemes can be found in the list on the left. The required injection requests for the two beams are listed in the Table Injection Ring 1 and Injection Ring 2. To be able to execute any injection requests, the injector timing system CBCM has to be set to LHC mastership. The state of the CBCM LHC mastership is indicated as well on the GUI. The GUI also shows the results of the LHC injection quality checks and reacts accordingly.

In case of equipment malfunctioning, beam instability or interlocks that prohibit extraction from the SPS, the injection sequencer must react and send the same injection request again instead of proceeding to the next injection. The injection sequencer also needs to cover the case where the beam was injected, but in the wrong RF bucket. This information is available only shortly after the injection. Every injection attempt must therefore be followed by a reasonably fast analysis to guide the filling process. This role is covered by the LHC Injection Quality Check software. After each notification by the LHC injection timing event, the injection quality check software analyses whether the beam was injected and injected at the correct location and whether the injected beam parameters were within acceptable limits. The result of the analysis is published and the injection sequencer subscribes to it for configuration of the next injection.

4.2 Results of Injection Quality Analysis

The main question to answer after each injection request is whether the beam was actually injected. If beam was injected, the injection sequencer will send the next injection request in the list of requests. If no beam was injected, the injection sequencer will repeat the same injection request which was just executed. In IQC terminology, the two associated IQC analysis results are called: SUCCESSFUL and REPEAT.
IQC results are also associated with a colour code. The colour of SUCCESSFUL was chosen to be green and REPEAT yellow. Every executed line in the injection sequencer carries the colour of the IQC result. This can be seen in the screenshot of the injection sequencer GUI in Figure 4.1.

To deal with all the different situations that can occur during the injection process and cover beam quality and data quality issues at the same time, the IQC has four additional outcomes: BAD, NO KICK, WARNING and UNKNOWN. In addition to the analysis result, the IQC also publishes an interlock parameter ($IqcPermitB1Par, IqcPermitB2Par = \text{true/false}$) which is picked up by the software interlock system and can inhibit further injections. While the IQC is analysing the LHC injection event, the interlock value is automatically set to false and then changes its value accordingly after the analysis is finished. In Table 4.1 and Figure 4.2 all IQC results, the resulting interlock state and the required reaction of the injection sequencer are summarised.

<table>
<thead>
<tr>
<th>IQC Result</th>
<th>Description</th>
<th>SIS interlock</th>
<th>Injection sequencer action</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUCCESSFUL</td>
<td>The beam was injected in the correct bucket and all quality checks are within limits.</td>
<td>true</td>
<td>Continue to next injection request.</td>
</tr>
<tr>
<td>BAD</td>
<td>The beam was injected, but at least one of the checks is outside limits.</td>
<td>false</td>
<td>Stop at next injection request.</td>
</tr>
<tr>
<td>REPEAT</td>
<td>No beam extracted.</td>
<td>true</td>
<td>Repeat same injection request.</td>
</tr>
<tr>
<td>NO KICK</td>
<td>The beam was extracted, but the injection kickers did not pulse and the beam went onto the TDI.</td>
<td>false</td>
<td>Stop at same injection request.</td>
</tr>
<tr>
<td>WARNING</td>
<td>The beam was injected and only beam losses were above thresholds.</td>
<td>true</td>
<td>Continue to next injection request.</td>
</tr>
<tr>
<td>UNKNOWN</td>
<td>The IQC could not determine whether the beam was injected or not. This occurs if the beam is dumped shortly after injection or if the data is missing or inconsistent.</td>
<td>false</td>
<td>Operator input is required to determine how to proceed.</td>
</tr>
</tbody>
</table>
Figure 4.2: There are six possible outcomes of the IQC analysis: SUCCESSFUL, WARNING, BAD, REPEAT, NO KICK or UNKNOWN. The results are given in the associated colour codes. The injection sequencer will proceed accordingly (white boxes). The SIS IqcPermitBxPar status goes to false if the result is BAD, NO KICK or UNKNOWN.

4.3 IQC Software Architecture

The IQC uses the Post Mortem (PM) data collection and analysis framework [35]. The PM framework was originally designed to collect and analyse relevant data following an LHC beam dump. It is however generic enough to be used for any transient data reading. Whenever triggered, client systems such as for example the BLM system push data directly to a post mortem server.

The PM event builder is triggered by a timing event and combines raw data files associated with this particular event, filtering the incoming data by type name and timestamp. The PM framework then relies on analysis modules which each analyses a selection of data. Analysis modules can also take other modules as input data. Each analysis module starts analysing once the input data is available, including the overall module which is launched once all module results are ready. The modular framework makes it easy to extend the analysis by simply adding new analysis modules.

The IQC data collection and analysis is triggered by the injection event. The difference to the analysis of a beam dump is that in case of missing data, the IQC has a time-out of 15 s before the analysis is launched regardless of missing data sets. The IQC analysis is written in JAVA and is running on a JAVA server for continuous monitoring of the injection quality.

The module results including the overall results are published through Java Messaging System (JMS) and are picked up by the injection sequencer, the SIS and the IQC GUI, see Figures 4.4-4.12. In addition, the IQC publishes four boolean parameters for the interlock system SIS: IqcPermitB1Par, IqcPermitB2Par, BpmInterlockB1Par and BpmInterlockB2Par. The interplay of the IQC with other systems is shown in Figure 4.3.
4.4 IQC Analysis

This section describes the data used in the IQC and how it is analysed in the different analysis modules. Table 4.2 and 4.3 summarise the devices and parameters acquired each injection for beam 1 and beam 2 respectively. In addition to these devices the IQC also picks up the machine configuration from the LHC control system. The LHC configuration data include: RF buckets in the requested filling pattern, beam number (1 or 2), particle type, fill number and other settings. The machine configuration is used by all the modules. The data is combined and analysed in eight analysis modules. The IQC analysis modules are: Beam Extraction, RF Bucket Check, Injection Kickers, Transfer Line, Beam Losses, Injection Oscillations, SPS Scraping and RF Phase Error. The results of these individual analyse modules are then combined in two result modules: IQC result and IQC fast result.

4.4.1 Module Beam Extraction

The data of two Beam Current Transformers (BCTs) per transfer line is used to evaluate whether the beam has beam extracted from the SPS. For reliability, both devices are included in the analysis, but only one is required to return a result. The result of this module is either SUCCESSFUL, if beam is extracted, or REPEAT, if it is not. In case the two devices give different values, the module returns WARNING.
### Table 4.2: Data from equipment used for IQC analysis of beam 1

<table>
<thead>
<tr>
<th>Devices</th>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transfer line BCTs</strong></td>
<td>TI2.BCTFI.29125 TI60.BCTF.610225</td>
<td>Expert Acquisition</td>
</tr>
<tr>
<td><strong>LHC BQM</strong></td>
<td>BQMLHC1</td>
<td>Combined IQC property (Acquisition-Results, GuruSettings, Attenuation)</td>
</tr>
<tr>
<td><strong>MKI IPOC waveform analysis</strong></td>
<td>MKI.UA23.IPOC.AB1 MKI.UA23.IPOC.BB1 MKI.UA23.IPOC.CB1 MKI.UA23.IPOC.DB1</td>
<td>FilteredWaveform, ResultI poc</td>
</tr>
<tr>
<td><strong>MKI Status</strong></td>
<td>MKI.UA23.GEN</td>
<td>Softstart Acquisition, Status</td>
</tr>
<tr>
<td><strong>MKI BETS</strong></td>
<td>MKI.UA23.MKCB.B1</td>
<td>Status</td>
</tr>
<tr>
<td><strong>MKI IPOC status</strong></td>
<td>MKI.UA23.IPOC.B1</td>
<td>GlobalStatus</td>
</tr>
<tr>
<td><strong>Transfer line BLMs</strong></td>
<td>BLMITI2UP BLMITI2DWN</td>
<td>Acquisition</td>
</tr>
<tr>
<td><strong>Transfer line BPMs</strong></td>
<td>BPMIT66 BPMITI2UP BPMITI2MID BPMITI2DWN</td>
<td>Acquisition</td>
</tr>
<tr>
<td><strong>LHC OFSU</strong></td>
<td>LHC.OFSU</td>
<td>Iqc Acquisition</td>
</tr>
<tr>
<td><strong>SPS BCTs</strong></td>
<td>SPS.BCTDC.31832 SPS.BCTDC.41435</td>
<td>Acquisition</td>
</tr>
<tr>
<td><strong>SPS Scrapers</strong></td>
<td>BSHV.11771 BSHV.11759 BSHV.51659</td>
<td>Combined IQC property (Acquisition, Setting, Status)</td>
</tr>
<tr>
<td><strong>RF Phase Error</strong></td>
<td>LHCALLLoopsDspB1</td>
<td>Obs Acquisition</td>
</tr>
</tbody>
</table>
### 4.4 IQC Analysis

<table>
<thead>
<tr>
<th>Devices</th>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer line BCTs</td>
<td>TI8.BCTFI.87750 TT40.BCTFI.400344</td>
<td>Expert Acquisition</td>
</tr>
<tr>
<td>LHC BQM</td>
<td>BQMLHC2</td>
<td>Combined IQC property (Acquisition-Results, GuruSettings, Attenuation)</td>
</tr>
<tr>
<td>MKI IPOC waveform analysis</td>
<td>MKI.UA87.IPOC.AB2 MKI.UA87.IPOC.BB2 MKI.UA87.IPOC.CB2 MKI.UA87.IPOC.DB2</td>
<td>FilteredWaveform, ResultIpoc</td>
</tr>
<tr>
<td>MKI Status</td>
<td>MKI.UA87.GEN</td>
<td>Softstart Acquisition, Status</td>
</tr>
<tr>
<td>MKI BETS</td>
<td>MKI.UA87.MKCB.B2</td>
<td>Status</td>
</tr>
<tr>
<td>MKI IPOC status</td>
<td>MKI.UA87.IPOC.B2</td>
<td>GlobalStatus</td>
</tr>
<tr>
<td>Transfer line BLMs</td>
<td>BLMITI8UP BLMITI8DNW</td>
<td>Acquisition</td>
</tr>
<tr>
<td>LHC OFSU</td>
<td>LHC.OFSU</td>
<td>IqcAcquisition</td>
</tr>
<tr>
<td>SPS BCTs</td>
<td>SPS.BCTDC.31832 SPS.BCTDC.41435</td>
<td>Acquisition</td>
</tr>
<tr>
<td>SPS Scrapers</td>
<td>BSHV.11771 BSHV.11759 BSHV.51659</td>
<td>Combined IQC property (Acquisition, Setting, Status)</td>
</tr>
<tr>
<td>RF Phase Error</td>
<td>LHCALLLoopsDspB2</td>
<td>ObsAcquisition</td>
</tr>
</tbody>
</table>
module is used as input to determine whether the beam was injected. The average intensity of both measurements is displayed in the IQC GUI, see Figure 4.4.

![Figure 4.4](image)

The extracted intensity was 338.841e+10 charges.

**4.4.2 Module RF Bucket Check**

It is essential that the injected bunches arrive in the correct RF buckets. The LHC longitudinal Beam Quality Monitor (BQM) uses the wall current monitors to provide the longitudinal positions of the injected bunches and report which RF buckets are filled [17]. In the RF bucket check module the IQC compares the information from the LHC BQM with the requested filling pattern in the machine configuration. In case of mismatch, the result of the module is BAD. If no new buckets are filled, the module reports REPEAT. If all requested buckets are filled correctly, the result is SUCCESSFUL. The corresponding analysis panel in the GUI is shown in Figure 4.5.

**4.4.3 Module Injection Kicker Checks**

The waveforms of the four injection kickers (MKIs) are analysed in the injection kicker analysis module. The IPOC (Internal Post Operational Check) provides the waveform characteristics in the data set ResultIpoc from the four injection kickers: the delay from the pre-pulse to the start of the waveform, the length of the flat-top, the rise and fall time of the waveform, the strength of the current and the maximum of the current [37]. The IQC has very tight tolerances for these parameters to notify immediately in case of deterioration. In addition the status of the kickers and related systems are checked. If the kickers do not pulse when beam is extracted, the result is NO KICK. If the kickers pulse, the result can be SUCCESSFUL or BAD depending on the quality checks. The values and thresholds are given and the waveforms are shown in the GUI,
Figure 4.5: The RF bucket check reports if the buckets are not correctly filled. Green = Correctly filled bucket, Blue = Expected bucket not filled, Red = Unexpected bucket filled.

see Figure 4.6. In Figure 4.7 the analysis of an MKI flash-over is shown. The flash-over occurred in MKLUA87.DB2 and resulted in a shortened waveform.

### 4.4.4 Module Beam Losses

Controlling and understanding injection losses was one of the main objectives when work started on injection quality. The Beam Losses module is still the most relevant to diagnose injection quality issues, as will be demonstrated in Chapter 5.

The IQC uses the special BLM study buffer with 40 $\mu$s integration time and a depth of 20 ms. Around 1000 monitors from four front-ends (BLM crates) in the injection region and downstream sectors are acquired. Whereas all data can be viewed, only a sub-selection of monitors at selected locations has defined IQC thresholds. The IQC BLM thresholds depend on the injected number of bunches $n_b$. For each BLM a threshold $RefIqc$ is defined, the applied threshold in the analysis is

$$RefIqc(n_b) = RefIqc(288) \times \frac{n_b}{288},$$

where $RefIqc(288)$ corresponds to 20 % of the interlock BLM threshold. The possible results of this module are SUCCESSFUL if all relevant BLM readings are within IQC thresholds or BAD if at least one monitor is outside IQC thresholds. The BLMs have interlocked thresholds and losses beyond these trigger a beam abort. Thus the LHC is protected against high losses by this mechanism. This is the reason why the IQC module result BAD for beam losses will only give WARNING as overall result and injection will not be stopped. In the IQC GUI the losses at the moment of injection at each monitor are shown as a bar graph, see Figure 4.8. The information of the interlock
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Figure 4.6: The waveforms of the injection kickers are checked against tight thresholds. In case of any deviation the result is BAD.

Figure 4.7: The shortened waveform of a flash-over of B2-MKI-D.
threshold for each monitor is also available, as well as the full 20 ms loss signal.

Figure 4.8: The beam losses module shows the maximum injection loss at each BLM in the injection region. Grey bars are monitors which are not actively checked, The other colours represent the beam loss with respect to the threshold: Green = Ok, Red = Above threshold, Orange = Above 50% of IQC threshold.

### 4.4.5 Module Injection Oscillations

The injection oscillations module uses the LHC OFSU and LHC BPM data sets. The LHC OFSU data provides the orbit at the different BPMs and the LHC BPM data the 50 turn bunch-by-bunch trajectory data triggered at the moment of injection. The injection oscillations are calculated by the module as the difference between the orbit and the first turn trajectory data. These are checked against thresholds in the IQC. During Run I, the amplitude threshold was 1.5 mm (except for beam 2 horizontal which was 1.75 mm). If more than 25% of the bunches are above the thresholds, the module returns BAD.

As large injection oscillations have an impact on the available aperture in the LHC and are therefore a machine protection concern, the IQC publishes an additional interlock parameter for the SIS (BpmInterlockB1Par, BpmInterlockB2Par = true/false). If the interlock is false, only intermediate intensity can be injected to correct the trajectory. The flag is automatically reset as soon as the injection oscillations are within limits again. In case 50% of the interlock level is reached, the module returns WARNING to pre-warn the operators that the interlock level might be reached soon.

### 4.4.6 Module Transfer Line Trajectories and Beam Losses

The transfer line module uses both the BLMs and BPMs in the transfer line. The data is analysed independently and combined for the module result. The beam loss monitors
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Figure 4.9: The injection oscillations module display the amplitude and RMS of the injection oscillations for each bunch. If more than 25% of the bunches are above thresholds the module returns BAD and the injection oscillations interlock in the SIS is triggered.

in the transfer line do not have IQC thresholds, but instead the module uses the actual thresholds of the monitors. If any of the monitors sees losses above these thresholds, the module result is BAD. From the beam position monitors this module receives bunch-by-bunch trajectories and also an average trajectory. Both the average trajectory and the maximum excursions at single monitors have defined IQC thresholds. The result is BAD if any value is above the limits. The module is only SUCCESSFUL if both the BLM and BPM checks are within limits. The transfer lines module can also detect if no beam was extracted from the BPM readings. In that case, the module returns REPEAT. In the IQC GUI, the beam losses and the average trajectory are shown, see Figure 4.10. Further information, such as bunch-by-bunch trajectories at each BPM, is also available.

4.4.7 Module SPS Beam Scraping

Beam scraping is important to avoid beam losses in the injection region and later in the LHC. The beam scraping module checks the scraping process in the SPS and reports the scraper settings and scraped intensity based on the beam intensity in the SPS. Currently there are no thresholds, the module reports BAD only if the scrapers are disabled, otherwise it returns SUCCESSFUL. In the GUI, the scraper settings and scraped amount is reported and the beam intensity through the SPS cycle is shown, see Figure 4.11.
Figure 4.10: In the transfer line module beam loss and trajectories are checked. The module returns BAD if either the beam losses or the trajectories are out of the defined limits.

Figure 4.11: The scraping module shows the intensity curve from the BCT through the SPS cycle and reports the scraped intensity. On the screen shot the module is masked for testing.
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4.4.8 Module RF Phase Error

The phase error of the injected beam with respect to the LHC RF phase is measured in RF front ends via the devices LHCALLLoopsDspB1 and LHCALLLoopsDspB2. In case the phase error is above $10^\circ$ the module result is BAD. The phase error GUI display is shown in Figure 4.12.

Figure 4.12: The RF phase error is displayed. The module is BAD if the threshold is exceeded. In this example the phase error is acceptably small.

4.5 IQC Fast Analysis and Overall Analysis

Finally the individual module results are combined in two result modules: a fast result based on a selection of data to report whether the beam was injected and a full result including all the quality checks. In Figure 4.13 the combination of the raw data in the analysis modules and the combination of the analysis modules into the result modules are visualised. The fast result is calculated based on the four modules: Beam extraction, Injection kickers, RF buckets and Transfer lines. This module can give only three outcomes: SUCCESSFUL, REPEAT or UNKNOWN. Based on the fast result, the injection sequencer can already prepare the next request (same or next injection request). Afterwards, the request can still be inhibited in case the overall result is BAD or NOKICK.

The fast result was introduced only towards the end of LHC Run I to increase operational efficiency. To profit from injection into the LHC every cycle in the SPS, the injection request must come a few seconds after the moment of extraction to be able to produce the beam in the injectors in time for the next cycle. The IQC analysis is fast, but the LHC BLMs and BPMs (including orbit data) regularly publish data only 13 s after injection. These data sets are very important to monitor the quality, but do not affect the decision on which injection request to send next. Taking into account only the modules, Beam extraction, Injection kickers, RF buckets and Transfer lines, the time needed for data acquisition and analysis is reduced to 2.5 s.
4.6 Summary

For each injection into the LHC the IQC collects and analyses data from key systems in the SPS, LHC and transfer lines to measure and control the injection quality by communicating with the software interlock system and the injection sequencer. The analysis is done in eight Post Mortem analysis modules which are combined in two result modules. The IQC data storage also provides means to do off-line analysis to monitor the quality over time and prepare appropriate action.

Figure 4.13: The IQC analyses data from devices in the LHC, SPS and transfer lines in eight analysis modules. Two result modules combine the result of the individual analysis modules.
Chapter 5

Injection Quality and Efficiency during LHC Physics Fills

In this chapter the operational efficiency during LHC Run I will be reviewed. The evolution of the Injection Quality Check (IQC) analysis results and beam losses in the injection region during 2011 and 2012 will also be presented.

5.1 Improved Injection Quality After 2010

Beam loss at injection was a major concern for LHC operation in 2010 leading to many beam dump triggers from the LHC Beam Loss Monitors (BLMs) in the injection regions and from the Beam Condition Monitors of the experiments ALICE and LHCb triggering on the showers from the TDI. The first mitigations were to increase the BLM thresholds and to install shielding between the transfer lines and LHC ring and also in the LHC downstream of the TDI [38].

Losses from uncaptured beam in the LHC were mitigated by improved RF capture in the LHC (larger capture voltage) and by the development of additional operational modes of the transverse damper in the form of an abort gap cleaner and an injection gap cleaner; the damper excitation is gated to clean away uncaptured beam in the abort gap to stop it from drifting around the ring and to remove uncaptured beam at the location of the next injected batch [39]. The combination of abort gap cleaning and injection gap cleaning was effective and reduced the losses on the TDI by about a factor 10, see Figure 5.1.

5.2 Beam Parameters in 2011 and 2012

Throughout the years 2011 and 2012 the LHC beam parameters were changing. The bunch intensity was increased from about $1.1 \times 10^{11}$ to $1.6 \times 10^{11}$ to push the performance of the LHC. The evolution of the bunch intensity is shown in Figure 5.2 for 2011 and in Figure 5.3 for 2012. The emittance, which has impact on injection losses with the tight transfer line collimator settings, also evolved, see Figure 5.4.
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Figure 5.1: Beam losses at the TDI for each injection in three LHC fills with the same conditions: With no cleaning the beam losses increase throughout the filling process because of uncaptured beam. With injection slot and abort gap cleaning the beam losses are reduced by nearly a factor 10. Courtesy of V. Kain.

Figure 5.2: Evolution of average bunch intensity in 2011: Towards the end of the 2011 proton run the average bunch intensity was pushed to $1.4 \times 10^{11}$ protons per bunch.

Figure 5.3: Evolution of average bunch intensity in 2012: The bunch intensity was pushed further towards $1.6 \times 10^{11}$ protons per bunch.
5.3 Evolution of Time at Injection During LHC Run I

Turnaround time and its impact on integrated luminosity was introduced in Chapter 2. At the end of each year during the LHC Run I, the turnaround time was carefully analysed and possible improvements to the LHC operational cycle proposed. The results were presented at the LHC Operation Workshops in Evian [43, 3, 44].

The evolution of the time spent in the different phases of the LHC operational cycle from 2010 to 2012 is summarised in Table 5.1. The average total turnaround time was greatly improved from 5h36 in 2010 to 2h16 in 2012 due to optimised sequencing and settings functions for the energy ramp, squeeze and collision, but also improvements for the LHC filling. Despite running for a longer time and with higher intensity beams, the number of beam dump triggers at injection decreased from 2011 to 2012, see Table 5.2.

The time spent at injection was the most critical and least predictable phase for turnaround time optimisation. However, not all of the time spent at injection is explained by issues from injection efficiency, quality and injectors. The time spent with probe beam in the machine was partly the time the injectors needed to finish prepar-
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Table 5.1: Time spent in each beam mode, given in seconds unless otherwise specified. Courtesy of M. Solfaroli, presented at the 2012 LHC Operation Workshop [44].

<table>
<thead>
<tr>
<th>Beam mode</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection probe beam</td>
<td>n.a. 180 min</td>
<td>n.a 87 min</td>
<td>n.a 52 min</td>
</tr>
<tr>
<td>Injection physics beam</td>
<td>n.a</td>
<td>n.a</td>
<td>n.a</td>
</tr>
<tr>
<td>Prepare ramp</td>
<td>n.a 504</td>
<td>n.a 270</td>
<td>n.a 259</td>
</tr>
<tr>
<td>Ramp</td>
<td>1400 1548</td>
<td>1020 1088</td>
<td>770 791</td>
</tr>
<tr>
<td>Flat-top</td>
<td>n.a 468</td>
<td>n.a 130</td>
<td>n.a 377</td>
</tr>
<tr>
<td>Squeeze</td>
<td>1041 2016</td>
<td>548 846</td>
<td>925 996</td>
</tr>
<tr>
<td>Adjust</td>
<td>108 792</td>
<td>60 654</td>
<td>220 513</td>
</tr>
<tr>
<td>Ramp-down</td>
<td>4000</td>
<td>2100</td>
<td>2100</td>
</tr>
<tr>
<td>Total excl. ramp-down</td>
<td>4h29</td>
<td>2h17</td>
<td>1h41</td>
</tr>
<tr>
<td>Total incl. ramp-down</td>
<td>5h36</td>
<td>2h52</td>
<td>2h16</td>
</tr>
</tbody>
</table>

Table 5.2: Protection beam dump and number of days operating for physics during LHC Run I

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam dumps @ injection</td>
<td>42</td>
<td>44</td>
<td>36</td>
</tr>
</tbody>
</table>

Injection remained the phase where most of the time was spent in the LHC operational cycle. Nevertheless, the average time spent in this phase was reduced from 180 min in 2010, to 87 min in 2011 and finally 52 min in 2012. This was achieved by improvements and novel ideas on many fronts throughout the years. Some of the improvements will be further discussed in the next two chapters. Table 5.3 summarises the different improvements.

One of the big remaining issues at LHC injection in addition to injection losses are the varying trajectories in the transfer lines. In addition to generating beam losses on the transfer line collimators, these instabilities lead to injection oscillations which could trigger the injection oscillation interlock via the IQC. The transfer line drifts therefore have to be corrected regularly and this has an impact on the injection efficiency.

If correction is necessary, in the order of 30 minutes to one hour is lost for LHC physics time. The correction frequency was about one correction campaign per week in the horizontal plane and one correction campaign per two weeks in the vertical plane in 2011. From 2011 to 2012 a small improvement could be achieved, see Figure 5.5. Several mitigations had been implemented: the transfer line collimators were opened from $\pm 4.5 \sigma_{\text{nom}}$ to allow for more margin, the ripple of the SPS MSE in LSS 6 was reduced and the extraction kicker delay for the MKE in LSS 4 was optimised. These mitigations will be further described in the next chapter.
5.3 Evolution of Time at Injection During LHC Run I

Table 5.3: Summary of improvements to injection efficiency in 2010-1012

<table>
<thead>
<tr>
<th>Effect on injection efficiency</th>
<th>Improvements done</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shorter injection probe beam time</td>
<td>Improved tune reconstruction, automated and continuous chromaticity measurement; Better FiDel corrections for b3 decay of main dipoles and b2 of main quadrupoles, better FiDel model for chromaticity taking fill length into account [45]; Faster preparation in the injectors due to fixed filling super cycles; Preparation of LHC beams in the SPS already during LHC ramp-down;</td>
</tr>
<tr>
<td>More efficient filling</td>
<td>Intermediate intensity and high intensity beam on the same super cycle; Interleaved filling from LHC injection sequencer; Implementation of IQC fast result;</td>
</tr>
<tr>
<td>Fewer interlocks</td>
<td>Injection gap and abort gap cleaning, larger capture RF voltage to reduce issue of capture losses; Increased BLM thresholds in the injection region; Shielding of LHC from transfer line collimator showers and TDI showers; Larger transfer line collimator gaps; Better transfer line stability due to improved stability of extraction septum power converters; Introduction of systematic beam scraping in the SPS; Continuously improving analysis of the SPS longitudinal beam quality monitor inhibiting extraction; More reliable transfer line trajectory correction with carefully chosen extraction kicker delay for MKE4;</td>
</tr>
</tbody>
</table>

![Figure 5.5: Transfer line correction frequency in 2011 and 2012 with Q26 optics (before the Q20 optics change): In 2012 the transfer line trajectories needed fewer corrections per week on average.](image-url)
However, during the period at the end of the year with Q20 optics in the SPS and the transfer lines, the correction frequency more than doubled, see Figure 5.6. In this period the injection losses for beam 1 were higher than previously as will be seen later in this chapter.

![Figure 5.6: Trajectory corrections after the Q20 optics change in the last technical stop: The frequency of transfer line corrections increased for both beams and planes.](image)

### 5.4 Evolution of IQC Analysis Results

Figure 5.7 and Figure 5.8 show the evolution of the weekly distribution of the IQC results SUCCESSFUL, BAD, WARNING, UNKNOWN, NOKICK and REPEAT in 2011 and 2012. Machine development periods are marked in blue and technical stops in green.

Despite of continuous improvements the fraction of results SUCCESSFUL went down from around 60 % to around 40 % end of 2011 and reached its lowest value at the beginning and end of 2012 with around 20 % only. At the same time the fraction of results BAD increased to around 15 % at the end of 2011 and more than 20 % at the end of 2012. The fraction of results WARNING anti-correlates with the result SUCCESSFUL. WARNING signifies that the beam losses at injection are above IQC limits. The maximum is reached end of October 2012 with a period of over 40 % of injections returning the result WARNING. This was the time when the optics change took place in the SPS and at the same time satellite bunches were requested.

The fraction of result REPEAT (beam not extracted from the SPS) stayed around 20 % throughout 2011 and 2012. Before extraction from the SPS, the beam is checked by the longitudinal Beam Quality Monitor (SPS BQM) and in case of poor quality or incorrect filling pattern, the beams are dumped. Other instabilities can also lead to beam dumps in the injectors. This means that roughly 5 additional injection requests are needed in a filling scheme with 12 injections per beam.

### 5.4.1 IQC Module Results

In Figure 5.9 the distribution of the module results giving the overall result BAD, WARNING, NO KICK or UNKNOWN are presented. These results indicate quality issues and except for the result WARNING will interrupt the injection process. Frequently several modules return BAD or WARNING at the same injection. For around
5.4 Evolution of IQC Analysis Results

Figure 5.7: The distribution of IQC results for most of the 2011 proton run. Machine development periods are marked in blue and technical stops in green.

Figure 5.8: The distribution of IQC results for most of the 2012 proton run are shown. Towards the end of the year, the number of BAD and WARNING results increased.
20% of all injections, the beam losses were above IQC thresholds (BLM = BAD), all other module results occur below 10% of the injections.

The fraction of the transfer line module (TL = BAD) and injection oscillations module (INJ.OSC. = BAD) increased between 2011 and 2012 despite the slight improvement of the MSE power converter for beam 1. SPS orbit drifts and fewer trajectory corrections are probably the cause of this.

In 4% of all injections, data quality problems caused the injection process to be interrupted (result UNKNOWN). The WARNING result of the extracted intensity module (BCT = WARNING) or UNKNOWN for injection oscillations (INJ.OSC. = UNKNOWN) indicate this type of issue. Either data was missing or inconsistent. More effort is needed to eliminate this avoidable problem.
5.5 Evolution of Beam Losses at Injection

The evolution of beam losses at the moment of injection at a selection of beam loss monitors in the injection regions has been analysed. For this purpose the monitors were divided into four groups according to the type of loss they are most susceptible to, see Table 5.4. The first group consists of monitors in the transfer lines around the transfer line collimators. The second group comprises the monitors on LHC magnets close to the transfer line collimators and downstream up to the TDI injection stopper. The two monitors on the TDI form group three and group four contains monitors downstream of the TDI, such as the monitors close to the TCLIA/B. Figure 5.10 shows a schematic drawing of the injection region indicating the different regions corresponding to the four groups.

For each injection in a physics fill, the integrated beam losses per group are calculated. These values are then averaged over the fill and plotted in Figure 5.11 for 2011 and Figure 5.12 for 2012. The data is plotted by date and special periods are marked: machine development (MD) periods in blue and technical stops (TS) in green. Only 144 bunch injections were taken into account. Machine development periods were excluded from the analysis.

Table 5.4: Groups of BLMs for analysis

<table>
<thead>
<tr>
<th>Monitors</th>
<th>$N_{B1}$</th>
<th>$N_{B2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer line BLMs</td>
<td>22</td>
<td>23</td>
</tr>
<tr>
<td>Showers from transfer line collimators, up to injection beam stopper (TDI)</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>LHC BLMs at TDI</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>LHC BLMs downstream of the TDI</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 5.10: Groups of beam loss monitors in beam 1 injection region: The first group (blue) of beam loss monitors are in the transfer line. The second group (green) are beam loss monitors in the LHC up to the TDI. Two monitors located at the TDI compose the third group (red). The last group (purple) consists of monitors downstream of the TDI, including the BLMs at the TCLIA and TCLIB.

5.5.1 Discussion of Beam Loss Evolution

The losses seen by the monitors downstream on the transfer line collimators (group 2) are clearly correlated with the losses seen by the transfer line BLMs (group 1), see the upper two plots of Figure 5.11 and Figure 5.12. These losses mainly come from
Figure 5.11: The integrated beam losses over sets of beam loss monitors in different regions, averaged over each fill in 2011. The loss spike at the end of July in the third plot comes from an erratic of the MKI in point 2.
Figure 5.12: The integrated beam losses over BLMs in different regions as given in Table 5.4, averaged over each fill in 2012.
tails in the transverse particle distribution, trajectory offsets at the collimators and shot-by-shot trajectory changes.

In 2011, the loss minimum on the transfer line collimators (TCDIs) is reached end of July, beginning of August. At this time 5 to 10 % of beam was scraped off by the SPS scrapers (normally 3 % of the beam is removed by scraping). The intensity evolution through an LHC cycle in the SPS with normal and hard scraping is shown in Figure 5.13.

![Figure 5.13: Beam intensity though an LHC cycle in the SPS with (a) normal scraping (∼ 3 %) and (b) hard scraping (∼ 15 %). The scraping is done at the end of the cycle.](image)

The dashed vertical line (26th of September 2011) in the plots indicates the time when the transfer line collimators settings were increased from ± 4.5 \( \sigma_{\text{nom}} \) to ± 5 \( \sigma_{\text{nom}} \). As a consequence the beam losses were reduced especially for beam 1. The setting of the transfer line collimators remained at ± 5 \( \sigma_{\text{nom}} \) for most of 2012.

Losses on the TDI (group 3) seem to have a different origin and do not follow the loss evolution of the transverse losses on the TCDIs as can been seen in Figure 5.11. These losses are mainly capture losses. The losses downstream of the TDI (group 4) close to the TCLIA and TCLIB follow the losses on the TDI.

On the 29th of July 2011 an erratic on the injection kickers in point 2 (beam 1 injection) occurred [46]. This resulted in beam losses a factor 50 above normal on the TDI (plot 3 in Figure 5.11).

At the beginning of August 2011, the intensity was gently pushed above \( 1.2 \times 10^{11} \) and this led to an increase of the loss on the TDI by a factor 2. The further increase of the bunch intensity after the technical stop caused another factor 2 increase of the TDI loss levels.

During 2012 the transverse losses on the transfer line collimators were mostly lower than those in 2011, see upper two plots in Figure 5.12. Especially for beam 2 the losses had improved. Also for the 25 ns period at the end of the run (pink area) no significant increase of the losses occurred. However, for the period with Q20 optics in the SPS and transfer lines (purple area), the losses increased for beam 1 compared to the period before. This was due to the fact that the collimator gaps had not been adapted to the
5.6 Summary

The injection efficiency and Injection Quality Check results throughout LHC Run I have been reviewed. After many improvements the average time at injection was improved from 180 min in 2010 to 52 min in 2012. Despite the fact that the bunch intensity was increased from $1.2 \times 10^{11}$ to $1.6 \times 10^{11}$ protons per bunch throughout the years, the beam quality and injection losses could be reduced or stayed around the same levels due to many mitigations. In the next two chapters, some of the injection quality issues in LHC Run I will be analysed in detail.

<table>
<thead>
<tr>
<th>TI 2</th>
<th>Half gap[$\sigma_{\text{nom}}$]</th>
<th>TI 8</th>
<th>Half gap[$\sigma_{\text{nom}}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCDIH.29050</td>
<td>4.9</td>
<td>TCDIH.87441</td>
<td>5.1</td>
</tr>
<tr>
<td>TCDIH.29205</td>
<td>4.6</td>
<td>TCDIH.87904</td>
<td>5.8</td>
</tr>
<tr>
<td>TCDIH.29465</td>
<td>5.0</td>
<td>TCDIH.88121</td>
<td>5.0</td>
</tr>
<tr>
<td>TCDIV.29012</td>
<td>6.3</td>
<td>TCDIV.87645</td>
<td>4.7</td>
</tr>
<tr>
<td>TCDIV.29234</td>
<td>4.7</td>
<td>TCDIV.87804</td>
<td>5.4</td>
</tr>
<tr>
<td>TCDIV.29509</td>
<td>5.0</td>
<td>TCDIV.88123</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Chapter 6

Trajectory Stability of SPS-to-LHC Transfer Lines

During LHC Run I it was discovered that the trajectories in the SPS to LHC transfer lines, TI 2 and TI 8, are unstable. To limit injection oscillations and beam losses at injection, the transfer line trajectories are corrected regularly. As introduced in Chapter 5 the trajectories were corrected more than once per week in 2011 for both transfer lines. Frequent correction campaigns and beam dumps buy into the availability for LHC physics.

Correcting the transfer lines was non-trivial due to several complications; The trajectory corrections need to simultaneously optimise injection oscillations in the LHC and trajectory excursions at the transfer line collimators at the end of the transfer lines. In addition shot-by-shot trajectory variations and bunch-by-bunch trajectory variations reduce the margins for acceptable trajectory drifts. In this chapter the observations and origins of trajectory instabilities will be discussed.

6.1 Observations During LHC Proton Physics Run in 2011

Throughout the 2011 proton run, the trajectory stability in the transfer lines was monitored for every LHC fill. At each beam position monitor in the transfer line, the maximum position change within the fill was calculated. Because the variations are larger for some monitors due to the varying $\beta$-function, the analysis has been done in values of nominal beam size $\sigma_{\text{nom}} = \sqrt{\frac{\text{mac}}{p} \varepsilon_{\text{nom}} \beta}$, with the nominal energy-independent emittance of $\varepsilon = 3.5 \mu$m. 1 $\sigma_{\text{nom}}$ corresponds to 0.9 mm where $\beta = 100$ m. In Figure 6.1 and Figure 6.2 the results are shown for TI 2 and TI 8 respectively.

The stability studies revealed large trajectory variations in the horizontal plane for both transfer lines. In 2011, the trajectory in the horizontal plane changed by up to 1.1 $\sigma_{\text{nom}}$ in TI 2 and 1.0 $\sigma_{\text{nom}}$ in TI 8. In the vertical plane, the variations are smaller, up to 0.4 $\sigma_{\text{nom}}$ in TI 2 and 0.2 $\sigma_{\text{nom}}$ in TI 8. These large shot-by-shot variations reduce the static injection oscillations margins in the horizontal plane and therefore increase the frequency of corrections for trajectory drifts.
Figure 6.1: For each LHC fill the maximum trajectory variations over all 144 bunch injections have been calculated. In the horizontal plane the trajectory variations per fill are on average $0.6 \sigma_{\text{nom}}$, but could be as large as $1.1 \sigma_{\text{nom}}$. In the vertical plane the trajectories are much more stable with variations below $0.2 \sigma_{\text{nom}}$ on average.
6.1 Observations During LHC Proton Physics Run in 2011

Figure 6.2: The analysis of the TI 8 transfer line stability per fill reveal trajectory variations in the horizontal plane of up to 1.0 $\sigma_{\text{nom}}$ (0.6 $\sigma_{\text{nom}}$ on average). In the vertical plane the trajectories are much more stable with variations below 0.1 $\sigma_{\text{nom}}$ on average.
6.2 Analysis of Beam Position Monitor Data

In a transfer line, the trajectory change from a dipole error affects only the elements downstream of the error source. The resulting position measured at a beam position monitor with phase advance $\mu_i$, from a dipole error $\theta_j$, located at a phase advance of $\mu_j$ is given by

$$x_i = \begin{cases} \theta_j \sqrt{\beta_j} \sqrt{\beta_i} \sin(\mu_i - \mu_j) & \mu_i > \mu_j \\ 0 & \mu_i \leq \mu_j, \end{cases}$$ (6.1)

where $\beta_i$ and $\beta_j$ are the $\beta$-functions at the monitor and the dipole respectively. In Figure 6.3 the resulting trajectory from a simulated dipole error is shown. The result is an oscillation down the line. In the same way an oscillation in the transfer line can be corrected by a corrector magnet by superposing its effect on the existing oscillation.

![Figure 6.3: A dipole error in a transfer line affects only the downstream elements. The resulting trajectory is a betatron oscillation.](image)

The measured trajectory in the transfer line is a combination of many dipole error sources and applied corrections. Static errors are not a concern, what matters for injection efficiency are trajectory changes. To understand the origin of trajectory variations, a large number of trajectories are analysed. The trajectories are analysed with respect to a reference trajectory. For this analysis the average trajectory in the data set was used as reference.

By separating the trajectory variations into spatial and temporal patterns, the sources of the variations can be identified. Model Independent Analysis (MIA) provides the algorithm for this technique [47].

6.2.1 Model Independent Analysis (MIA)

For a set of $P$ pulses (or in our case injections), with $M$ beam position monitors, a matrix $B(P, M)$ is constructed, where row $p$ gives the measured pulse $\vec{b}_p = (b^1_p, b^2_p, ..., b^M_p)$, and column $m$ gives the measurements at monitor $m$. 
6.2 Analysis of Beam Position Monitor Data

In MIA the trajectory variations for a shot \( p \), originating from a number of independent sources, are expressed by the sum

\[
\hat{\vec{b}}_p = \frac{\vec{b}_p - \langle \vec{b} \rangle}{\sqrt{P}} = \sum_s q_s f_s + \hat{n}_p, \tag{6.2}
\]

where \( f_s \) are spatial vectors corresponding to a given source, \( q_s \) are the temporal variations for shot \( p \) and \( \hat{n}_p = \frac{n_p}{\sqrt{P}} \) is a noise term. For all pulses this can be written in matrix form as

\[
\hat{B} = QF^T + \hat{N}. \tag{6.3}
\]

The sources causing trajectory variations in space and time are in general unknown. To help identify the corresponding vectors a Singular Value Decomposition (SVD) of the matrix \( \hat{B} \) is used

\[
\hat{B} = U \Lambda V^T. \tag{6.4}
\]

The result of the SVD is a set of eigenmodes with eigenvalues \( \lambda_i \), organised by increasing value along the diagonal of \( \Lambda \). The two orthonormal matrices, \( U \) and \( V^T \) contain the temporal and spatial eigenvectors respectively.

The normalised eigenvalues \( \hat{\lambda}_i = \frac{\lambda_i}{\sqrt{M}} \) represent the average RMS strength of the variation originating from a given source. In most cases there are only a few significant eigenmodes corresponding to sources affecting the beam motion. The actual sources are linear combinations of these modes. Most eigenvalues are small and correspond to noise. The noise on the data can be suppressed by setting the smaller eigenvalues to zero.

6.2.2 Application of MIA on Example Data

The method and its limitations are best understood by some examples. In the following, MIA is applied to test cases where several single sources are simulated in MAD-X [48]. The simulations were done with T12 optics using dipole errors as sources. For simplicity the same model (optics and corrector positions) was used in both planes. The resulting trajectories are analysed by MIA.

In the first simulation a single error source was simulated in each plane. In the vertical plane, measurement errors of \( \sigma_{RMS} = 50 \mu m \) for the beam position monitors were assumed. In the horizontal plane the simulated trajectories did not include measurement errors. The resulting difference trajectories are shown in Figure 6.4. The corresponding eigenvalues found by the MIA analysis are given in Figure 6.5.

In both planes, only one significant eigenvalue is found. Without any other sources or measurement errors, this eigenvalue corresponds to the RMS of the difference trajectories as can be seen from the simulation in the horizontal plane. The remaining eigenvalues in the vertical plane correspond to monitor noise. The squared sum of all the eigenvalues equal the squared RMS of the difference trajectories: \( \sum_i \lambda_i^2 = \sum_p \sum_m (b_{mp})^2 / MP \).

The spatial modes corresponding to the significant eigenvalues can be used to ex-
Figure 6.4: The difference trajectories from the simulation with one dipole error per plane are shown. For both planes a single source was simulated. In addition, the monitors were given measurement errors in the vertical plane.

Figure 6.5: The eigenvalues from simulations of one error source yield single significant eigenvalues. In the horizontal plane, all other eigenvalues are zero. In the vertical plane, the remaining eigenvalues correspond to noise and are not significant.
amine the sources of variation. In Figure 6.6, the first spatial mode in the vertical plane is shown. It corresponds to a betatron oscillation starting around the twelfth monitor as can be seen by the lower plot.

![TI2-TEST MIA modes](image)

Figure 6.6: The spatial mode corresponding to the significant eigenvalue can be used to identify the source. **Upper plot:** The first spacial mode scaled by the eigenvalue. **Lower plot:** The spatial mode has been divided by the beta function at each monitor and fitted by a sine function. It matches a betatron oscillation.

A second test case was prepared with multiple error sources, two in the horizontal plane and three in the vertical plane. Measurement errors were included in both planes. The resulting data was analysed using MIA and the resulting eigenvalues are shown in Figure 6.7. In this case there are two significant eigenmodes in both planes and MIA can no longer be used to distinguish the sources. In summary, if MIA detects two strong eigenmodes there are two or more sources.

![TI2-TEST MIA Eigenvalues](image)

Figure 6.7: In the simulations of multiple sources, two significant eigenvalues are found even if there are more than two sources present.
6.3 LHC Transfer Line Shot-by-Shot Trajectory Variations

The transfer line trajectories are saved for all LHC injections. Nevertheless, there are only 12 injections per fill. Dedicated stability studies are therefore needed to get enough statistics within a short time period to study fast shot-by-shot trajectory variations.

6.3.1 2011 Stability Studies

**TI 2 dedicated study: June 2011**

![TI2 Difference data [June 2011]]

Figure 6.8: The trajectories variations in TI 2 for 84 shots over 1h18min taken in June 2011 are shown. In the horizontal plane the trajectory varies by up to 0.79 mm.

The first dedicated study of the transfer line trajectory stability was done in June 2011 for TI 2. For a short period of time the beam was extracted repeatedly onto the beam stopper (TED) at the end of the transfer line and not injected into the LHC. In 1h18min, 84 shots were recorded. To track changes only, the average trajectory over all the shots was used as a reference and subtracted from the data. The set of difference trajectories with respect to the average is shown in Figure 6.8. In the horizontal plane there are differences of more than 0.7 mm at certain BPMs. In the vertical plane the variations are below 0.3 mm. MIA was used to analyse this data. The resulting eigenvalues are shown in Figure 6.9. A few eigenvalues are pronounced, but the only significant eigenmode is the 86 µm mode in the horizontal plane.

The corresponding spatial eigenvector is shown in Figure 6.10. The lower plot shows that it fits with a betatron oscillation starting at the beginning of the transfer line. This mode accounts for most of the variations and if removed, the variations in the horizontal plane would be around the same as in the vertical plane.

To identify the source of this oscillation, the spatial mode has been compared to simulated error sources. Because the oscillation starts at the beginning of the line, extraction elements in the SPS (septa, bumper magnets, kickers) are checked as well.
Figure 6.9: The normalised eigenvalues of the MIA analysis are shown. There is one eigenvalue which stands out: 86 µm in the horizontal plane. In addition there are a few smaller eigenvalues which are just above the noise floor.

Figure 6.10: The spatial mode corresponding to the largest eigenvalue is shown on the top plot. The eigenvector is scaled by the normalised eigenvalue. On the bottom plot the \( \beta \)-functions has been taken into account. The result fits a sine function and hence a betatron oscillation.
6. TRAJECTORY STABILITY OF SPS-TO-LHC TRANSFER LINES

as some elements in TT 60, the first part of the transfer line. The best match is an oscillation originating from an error in the extraction septa, MSE.6, see Figure 6.11. The thin extraction septa, MST.6 could also be a candidate.

Figure 6.11: The main mode found in the analysis matches a simulated trajectory with a dipole error at the SPS extraction septa, MSE.6 or MST.6.

Figure 6.12: The trajectories variations in TI 8 for 117 shots over 1h36min taken in November 2011 are shown. The variations in the horizontal plane are up to 0.78 mm.

The trajectory stability in TI 8 was measured in November 2011. The difference data from 117 shots over 1h36min is shown in Figure 6.12. Also for TI 8 there are large trajectory variations in the horizontal plane of more than 0.7 mm. This is also reflected in the eigenvalues of the MIA analysis which are shown in Figure 6.13. The largest eigenvalue in the horizontal plane is 108\(\mu\)m. However, the second one is also
fairly large, 57\(\mu m\). In the vertical plane there are no significant eigenvalues consistent with the small trajectory variations.

![TI8 MIA Eigenvalues](image)

Figure 6.13: For TI 8 there are two significant eigenvalues in the horizontal plane at 108\(\mu m\) and 57\(\mu m\).

The spatial eigenvectors of the two significant modes are shown in Figure 6.14. Both modes are betatron oscillations starting at the beginning of the transfer line. Thus also here SPS extraction elements are suspected. By simulating field errors on the extraction elements in MAD-X the spatial pattern from each source could be compared to the spatial eigenmodes. For the first mode, errors in the extraction septa MSE.4 or one of the extraction bumpers MPSH.41402, could be a match, see Figure 6.15. For the second mode, an error on the extraction kickers, MKE.4, or another bumper, MPLH.41658 could fit, see Figure 6.16. As was discussed earlier, with two strong eigenvalues, two or more error sources could be responsible for the trajectory variations.

![TI8 MIA modes](image)

Figure 6.14: The spatial eigenvectors corresponding to the two main modes are shown. Both modes are betatron oscillation starting at the beginning of the transfer line.
Figure 6.15: The spatial pattern of the main mode for TI8 could be a match to either the extraction septa (MSE.4) or one of the extraction bumpers.

Figure 6.16: For the second smaller mode, the spatial pattern could match the extraction kickers (MKE.4) or one of the extraction bumpers.
6.3 LHC Transfer Line Shot-by-Shot Trajectory Variations

6.3.2 Investigations of SPS Extraction Elements

At each SPS extraction, the currents of the septa and other extraction elements are logged. The logged currents were analysed over a period of \(~\)2 weeks in June. The currents are presented in Table 6.1. The logged currents of the MSE.6 are plotted in Figure 6.17. The plot shows a large spread already at short time scales with a significant variation from shot to shot.

Table 6.1: Strength, average logged current and relative standard deviation of the logged current of SPS extraction elements [June 2011]

<table>
<thead>
<tr>
<th>Element</th>
<th>Strength</th>
<th>Avg. current</th>
<th>Rel.StD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSE.6</td>
<td>9.51 mrad</td>
<td>20.3 kA</td>
<td>0.200 \times 10^{-3}</td>
</tr>
<tr>
<td>MST.6</td>
<td>1.06 mrad</td>
<td>5.67 kA</td>
<td>0.273 \times 10^{-3}</td>
</tr>
<tr>
<td>MSE.4</td>
<td>12.8 mrad</td>
<td>22.6 kA</td>
<td>0.194 \times 10^{-3}</td>
</tr>
<tr>
<td>MPSH.41402</td>
<td>-15.1 \mu rad</td>
<td>18.7 A</td>
<td>1.157 \times 10^{-3}</td>
</tr>
<tr>
<td>MPLH.41658</td>
<td>515 \mu rad</td>
<td>169 A</td>
<td>0.132 \times 10^{-3}</td>
</tr>
<tr>
<td>MKE.4</td>
<td>522 \mu rad</td>
<td>51.3 kA</td>
<td>0.270 \times 10^{-3}</td>
</tr>
</tbody>
</table>

Figure 6.17: The logged currents of the MSE.6 septa in June 2011 are shown. Each dot represents one measurement and the dark areas represent areas with a high density of measurements. The relative standard deviation of the current variations is 0.200 \times 10^{-3}. Also the average current changes over a few days.

The relative standard deviations of the current variations were then used as input for MAD-X simulations of field errors on these elements. From 150 seeds, the resulting transfer line trajectory variations were calculated. The resulting excursions at one of the monitors with large amplitudes, BPMI.25004 in TI 2, is shown in Figure 6.18. The effect of the observed current variations at the MSE.6 are large enough to fit the observed trajectory variations. A difference of only 20 A (\(~\)0.1 %) on this strong element gives a kick of around 10 \mu rad which correspond to \pm 0.5 mm at this monitor.
For the MST.6 the resulting trajectory variations are not large enough. It can therefore be excluded as a candidate.

For TI 8, the trajectory excursions at BPMI.85204 are shown in Figure 6.19. Also here the effect of the current variations of the MSE.4 are large enough to explain the observed trajectory variations. The effect of current variations at other extraction elements is not significant. For both transfer lines the extraction septa seem to be the main source of shot-by-shot trajectory variations. A second, weaker mode is present for TI 8, but the source remains unknown.

Figure 6.18: The observed current variations of MSE.6 and MST.6 were used to simulate field errors. The resulting excursions at BPMI.25004 [S=2.3 km] are shown.

Figure 6.19: The effect of current variations at extraction elements in LSS 6 have been calculated at BPMI.85204 [S=2.3 km].

After the MSE.6 had been identified as the source of shot-by-shot trajectory variations in TT 2, the stability of the power converters was investigated. Towards the end of the 2011 proton run, the current output filter was modified in the power converter.
As a result of the work done by the power converter team, the peak-to-peak ripple could be improved by a factor 2, from 18 A to 9 A peak-to-peak [49]. The stability of the MSE.4 (TI 8) could not be improved due to lack of time.

The MSE.6 improvement was confirmed by analysing the maximum trajectory variations per fill at the start of the 2012 run. As before, the maximum position change in the transfer line was calculated in values of $\sigma_{\text{nom}}$. For TI 2 the trajectory variations had been reduced on average from 0.6 to 0.4 $\sigma_{\text{nom}}$ in the horizontal plane, see Figure 6.20. This is supported by the logged currents of the MSE.6, where the relative error was reduced from $0.200 \times 10^{-3}$ to $0.110 \times 10^{-3}$. The stability analysis of TI 8 is shown in Figure 6.21. The dedicated stability studies were repeated for both transfer lines.

![Stability TI2 Horizontal [Spring 2012]](image)

![Stability TI2 Vertical [Spring 2012]](image)

Figure 6.20: The shot-by-shot stability per fill was calculated by finding the monitor with the maximum position change in $\sigma_{\text{nom}}$ for each LHC fill. After the intervention on the MSE at the end of 2011, the trajectory variations in the horizontal plane were reduced from 0.6 to 0.4 $\sigma_{\text{nom}}$.

### 6.3.3 2012 Stability Studies

**TI 2 dedicated study: April 2012**

When the stability study for TI 2 was repeated in April 2012, 148 shots were taken in 1h38min. The data and resulting eigenvalues are shown in Figure 6.22 and 6.23. There are still significant variations in the horizontal plane, but the main mode had been reduced in RMS strength from 86 to 54$\mu$m. Errors on the MSE.6 still match as the main source, see Figure 6.24.
Figure 6.21: The stability per fill for TI 8 for the first part of the 2012 run is shown.

Figure 6.22: The difference trajectories from the average trajectory for the stability study of TI 2 in April 2012 are shown.
6.3 LHC Transfer Line Shot-by-Shot Trajectory Variations

**Figure 6.23**: The eigenvalue spectrum shows that the main source in the horizontal plane has been reduced from 86 to 54µm.

**Figure 6.24**: The MSE.6 is still the main source of trajectory variations in TI 2 in April 2012. The variations in the horizontal plane have been reduced since 2011.
TI 8 dedicated study: April 2012

Figure 6.25: The TI 8 trajectory variations are shown. The variations in the horizontal plane are still significant, but are reduced with respect to the previous year.

Although no changes were done on the MSE.4, the TI 8 stability study was also repeated in April 2012. Over a period of 1h28min, 224 shots were recorded for analysis. The data is shown in Figure 6.25. The variations are smaller than in 2011 and the MIA analysis shows that the number of sources had been reduced to 1, see Figure 6.26. This source matches errors on the MSE.4 as found in the previous study.

Figure 6.26: The eigenvalue spectrum has only one large mode at 73µm in the horizontal plane.

6.3.4 2014 Stability Studies

Work continued to also improve the stability of the MSE.4 power converter over the shutdown in 2013 and 2014 (LS1). In November 2014, towards the end of the shutdown
6.3 LHC Transfer Line Shot-by-Shot Trajectory Variations

TI8 source matching to 1 modes

Figure 6.27: In April 2012, the only significant mode matches the variations of a field error on the extraction septa, MSE.4.

period, a first test with beam in the transfer lines was carried out. During this test the transfer line stability was measured in a dedicated test extracting beam continuously down the transfer lines on the TED beam stopper.

TI8 dedicated study: November 2014

Figure 6.28: The data taken for the stability study during the transfer line test in November 2014 is shown.

The measured trajectories in TI8 (with respect to the average in the set) are shown in Figure 6.28. This data was analysed with MIA and the result was one significant source in the horizontal plane, see Figure 6.29. This source matches the SPS extraction septa, MSE.4, but the strength has been reduced by almost a factor two with respect to the previous stability study, which is a significant improvement.
Figure 6.29: The eigenvalue spectrum for TI 8 gives only one significant source. This source still matches the MSE.4, but the strength has now been reduced by almost a factor 2.

**TI 2 dedicated study: November 2014**

Figure 6.30: The data taken for the stability check during the transfer line test in November 2014 is shown.

The difference trajectories measured in the TI 2 stability study are given in Figure 6.30. The stability of the MSE.6 had already been improved by a factor 2 before the previous stability test and only a small further improvement could be seen in the eigenvalues, see Figure 6.31. The main source is still the MSE.6.
6.4 Long Term Trajectory Drifts and SPS Orbit Stability

On time scales of around 1 week, the transfer line trajectories drift so much that the trajectories must be corrected to maintain small injection oscillations and beam losses at injection. In the following, the slow transfer line trajectory variations are analysed.

6.4.1 Trajectory Drifts

The trajectory data recorded every physics fill was used to study long term drifts. No dedicated study was necessary. The effect of applied trajectory corrections are calculated and subtracted to observe the natural variations over time. Only 144 bunch injections (average trajectory over all the bunches) were studied. As before, the average trajectory in the data set is used as a reference.

The data from around one month at the end of 2012 is presented in Figure 6.32 and 6.33 for TI 2 and TI 8 respectively. In the horizontal plane the trajectories vary by more than 2.5 mm at certain locations for both transfer lines. On this time scale, there are also significant trajectory variations in the vertical plane. The trajectory variations in the vertical plane are below 1.5 mm.

This data was analysed with MIA and the resulting eigenvalues are shown in Figure 6.34 for TI 2 and in Figure 6.36 for TI 8. There are now several significant eigenvalues in both planes with the horizontal plane still dominating. The spatial eigenmodes corresponding to the two largest eigenvalues for each line are shown in Figure 6.35 and 6.37. All of these modes are betatron oscillations starting at the beginning of the transfer lines. In addition to the extraction elements, drifts of the SPS orbit at the location of extraction could be a source of slow trajectory variations.
Figure 6.32: TI 2 trajectory variations over a period of one month in 2012 are shown. In the horizontal plane there are variations of up to 2.6 mm.

Figure 6.33: The trajectory variation in TI 8 over one month in 2012 are shown. The maximum trajectory variations in the horizontal plane are 3.3 mm.
6.4 Long Term Trajectory Drifts and SPS Orbit Stability

**Figure 6.34**: The eigenvalue spectrum for trajectory drifts in TI 2 is shown. There are now several significant modes in the horizontal plane and also the variations in the vertical plane have become significant.

**Figure 6.35**: The two spatial eigenmodes for trajectory variations in TI 2 over a period of one month are betatron oscillations starting at the beginning of the transfer line.
Figure 6.36: For TI 8 there are also several significant eigenvalues when studying trajectory drifts over a period of one month.

Figure 6.37: For TI 8 the main spatial eigenmodes for the slow drifts are betatron oscillations starting at the beginning of the transfer line.
6.4 Long Term Trajectory Drifts and SPS Orbit Stability

6.4.2 Investigations of SPS Orbit Drifts

SPS orbit data was systematically saved for analysis towards the end of the 2012 proton run. The orbit data was taken at 450 GeV, 300 ms before extraction. As mentioned in Chapter 3, in the extraction region a horizontal orbit bump of more than 35 mm is applied to move the circulating beam as close as possible to the extraction septum and reduce the required strength of the extraction kicker.

Large aperture BPMs are used in the extraction region, for example BPCE.61805 for extraction from LSS 6 to TI 2 and BPCE.41801 for extraction from LSS 4 to TI 8. The data of these BPMs have large errors due to the large aperture and cannot be used directly to accurately measure the beam position at the extraction point. A fit based on many BPMs was therefore used to obtain a better estimate. Each orbit is fitted using the function

\[ X(s) = \left[ A \times \sin(\mu(s)) + B \times \cos(\mu(s)) \right] \times \sqrt{\beta(s)} + \frac{dp}{p} \times D(s), \]  

(6.5)

which represents a betatron oscillation plus a dispersion orbit due to momentum offset \( dp/p \). The fit parameters \( A \), \( B \) and \( dp/p \) are calculated by a least square fit routine in python. The fitted difference orbits at these two monitors with respect to a reference orbit within the analysis period (marked by a grey line) are shown in Figure 6.38. In the horizontal plane the orbit is drifting by up to 1.4 mm at BPCE.61805 and 1.8 mm at BPCE.41801. In the vertical plane the orbit changes by less than 0.5 mm at both monitors.

6.4.3 Effect of SPS Orbit on Trajectory Variations

The next step was to study the effect from the variations of the SPS orbit on the transfer line trajectories. This is calculated by taking the fitted orbit variations (position and angle) at the start of the extraction septa and simulating the resulting trajectories in MAD-X. Then the effect is subtracted from the corresponding measured trajectory.

This new set of trajectory data is analysed in the MIA framework. The difference data and corresponding eigenvalues for TI 2 are shown in Figure 6.39 and 6.40. The RMS of the data has now been reduced from 318 to 158\( \mu \)m in the horizontal plane and 126 to 102\( \mu \)m in the vertical plane, showing that SPS orbit variations is a significant source of trajectory variations. After the SPS orbit effect has been removed, some of the remaining variations can be explained by the shot-by-shot variations of the MSE.6. Other weaker sources are also present.

Also for TI 8, the SPS orbit can explain a large part of the variations. When the effect of the SPS orbit is subtracted, the RMS trajectory variations in TI 8 are reduced from 348 to 198\( \mu \)m in the horizontal plane and 138 to 106\( \mu \)m in the vertical plane, see Figure 6.41. The corresponding eigenvalue spectrum is shown in Figure 6.42. There are still several small eigenvalues remaining. The spatial eigenvector of the largest mode matches the extraction septa (MSE.4), see Figure 6.43.
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Figure 6.38: The orbit variations calculated at BPCE.61805 (TI 2) and BPCE.41801 (TI 8) show a significant orbit drift in the horizontal plane with respect to the reference orbit (grey line).

Figure 6.39: When the SPS orbit effects has been removed, the remaining trajectory variations are reduced from maximum 2.6 to 1.5 mm in the horizontal plane and from 1.1 to 0.9 mm in the vertical plane.
6.4 Long Term Trajectory Drifts and SPS Orbit Stability

Figure 6.40: The eigenvalue spectrum for TI 2 still show several sources after the effect of the SPS orbit is removed, but they are significantly reduced.

Figure 6.41: When removing the effect of the SPS orbit, the TI 8 trajectory variations are reduced from 3.3 to 2.3 mm in the horizontal plane and from 1.4 to 1.1 mm in the vertical plane.
Figure 6.42: Excluding the SPS orbit, there is one significant mode in the horizontal plane left and several smaller ones in both planes.

Figure 6.43: The main mode of variations in TI 8 excluding the SPS orbit matches to the extraction septa, MSE.4.
6.4.4 Origins of SPS Orbit Drifts

When the MIA analysis is applied to the orbit data, two large eigenvalues are found, see Figure 6.44. The two modes are both betatron oscillations and are of similar size. When there are two strong modes, two or more sources might be present. The analysis period has been divided into two periods. From Figure 6.38 two natural choices appear: 13/10–24/10 and 29/10–4/11. For both periods there are significant variations in the horizontal plane, but in the eigenvalue spectra the number of significant modes is reduced to one per period, see Figure 6.45.

![SPS ORBIT MIA Eigenvalues](image)

Figure 6.44: Two strong eigenmodes are found from the MIA analysis, indicating that there are multiple sources.

As there are many more elements in the SPS, the MICADO [50] correction algorithm was used to find the best correction element matching the variations. The effect of the most promising correction elements was compared to the eigenmodes found with MIA.

For the first period, the elements that are most frequently selected by MICADO are the MDHB.61804 (orbit corrector) and the septum MST.617 in LSS6, see Figure 6.46. These two elements have a difference in phase advance of only $2^\circ$. The MSE.618 is only $4^\circ$ upstream of the MDHB. The MSE.418 in LSS4 also shows up frequently, however only for small orbit differences. The same elements all match the MIA eigenmodes, see Figure 6.47.

Different correction elements are proposed for the second period. From the MICADO algorithm, the best element was found to be the dipole MBA.606, see Figure 6.48. For the MIA eigenmode the best match is the extraction bumper MPSH.62199, followed by MBA.606 and MPLH.61655 (extraction bumper magnet). The MSE.418 also fits reasonably well. All these elements cover the same phases. Sources with the same phase advance $+N \times 180^\circ$ cannot be distinguished in MIA.

Elements in LSS6 are most frequently proposed as correctors by MICADO for both periods. For the extraction bumpers the logged currents were therefore checked for drifts, but the variations were found to be too small to cause the observed orbit variations. The MDHA.61804 is not used at top energy and was therefore excluded.
Figure 6.45: When two shorter analysis periods are used one strong eigenmode appears for each period.

Figure 6.46: For the first period (13/10–24/10) the MST.617 and MDHB.61804 show up most frequently as correction elements for the observed orbit variations.
Figure 6.47: The best matches for error sources in the period 13/10–24/10 are shown.

As the extraction septa have already been identified as sources of short term trajectory variations in the transfer lines, their effect on the orbit was further investigated. Normally the circulating beam is shielded from the field of the septa. However stray fields exist. Lab measurements show that the strengths of the stray fields depend on the distance from the septum, but should otherwise be static [51]. The small current change of the septa do not significantly change the stray fields. The only change could come from an already existing orbit drift.

Because of the extraction bump, the distance to the septa varies strongly over the length of the septum magnet, see Figure 6.50. Therefore a model of the bump and septum was made to estimate the enhancement of orbit changes due to stray fields. The outcome of the study is however that the stray fields of the MSE and MST in LSS6 are too weak. Even in the presence of a 1 mm orbit change at the septa, the
6. TRAJECTORY STABILITY OF SPS-TO-LHC TRANSFER LINES

29/10-4/11 source matching to 1 modes

![Graph showing source matching to 1 modes](image)

Figure 6.49: The best matches for error sources in the period 29/10–4/11 are shown.

An additional excursion from the stray field change is only about 14 and 7 μm at the extraction points for the MSE and MST respectively, which is too small to explain the drifts assuming the measured stray fields.

![Extraction bump and septa](image)

Figure 6.50: Extraction bump and septa for LSS6 extraction of LHC beam 1: The distance of the bump to the MST varies between 18 and 22 mm and 23 to 63 mm to the MSE.

Recently, a new hypothesis on the origin of the SPS orbit drifts has been put forward. As shown earlier, the error sources seem to be located in the extraction regions of LSS 6 and LSS 4. However, the extraction elements themselves most likely do not create varying dipole fields. If however the main quadrupole fields of the quadrupole magnets located within the large extraction bumps change, the orbit will change. A study showed that a horizontal tune change of $\Delta \mu_x = 0.02$ changes the position at the extraction point in LSS 4 by more than 0.5 mm, see Figure 6.51. The tune in the SPS at the extraction flattop was not controlled better than $\Delta \mu_x = \pm 0.01$. Unfortunately the main quadrupole currents were not logged during LHC Run I. More measurements
and simulations will be done in 2015.

Figure 6.51: Simulations of small tune changes in the SPS show that the effect of small tune changes is clearly visible on the SPS orbit, particularly in SPS LSS 4 (LHC Beam 2 extraction). Simulated with 2014/2012 operational optics. Courtesy of F. Velotti.

As the sources of orbit drifts may not be possible to mitigate easily, an orbit correction strategy was developed [52]. Using the extraction bumper magnets, the orbit at the extraction points could be corrected back to a reference. This would save time for the LHC as corrections can be done without injecting beam into the LHC, for example while the LHC is preparing for the next fill. Orbit correction for SPS orbit drifts will be tested in 2015.

6.5 Bunch-by-Bunch Trajectory Variations

For operation with 144 bunch injections in 2011, the IQC analysis revealed large bunch-by-bunch variations in the injection oscillation amplitudes for beam 2 in the horizontal plane, as shown in Figure 6.52.

A trajectory correction must be followed by an intermediate intensity injection (up to 12 bunches) for validation. However, in this case the average trajectory for 12
bunches is not the same as the average trajectory for 144 bunches due to bunch-by-bunch differences. Bunch-by-bunch trajectory variations could originate from a non-flat kicker waveform. Because the variations were seen only in the horizontal plane and only for beam 2, the SPS extraction kicker, MKE.4 was suspected.

![Graph of B1 Injection oscillations](image1)

**Figure 6.52:** Injection oscillation amplitudes recorded by the IQC for two consecutive injections (beam 1 on top and beam 2 bottom). The bunch-by-bunch injection oscillations amplitude for beam 2 vary by about 1 mm in the horizontal plane.

6.5.1 MKE Waveform Measurements

In October 2011, the waveform of the MKE.4 was scanned with beam. A single bunch was extracted and the horizontal position was measured on a optical transition radiation screen in the transfer line downstream of the kicker while varying the delay of the kick with respect to the extracted beam.
Figure 6.53: The MKE.4 waveform scan shows a large ripple of the extraction kicker waveform. The 144 bunch batch (red) sees an average difference of 2.8 µrad in the kick. There is also a difference of 4.7 µrad between the average kick seen by the 144 bunch and the 12 bunch batch (orange).

Figure 6.54: By changing the delay of the kicker timing with respect to the extracted beam from 54.0 µs to 53.2 µs the effect of the ripple could be reduced. The average difference over 144 bunches is now 2.5 µrad and the difference between 12 (green) and 144 bunches (blue) is reduced from 4.7 µrad to 0.6 µrad.
The result of the scan is presented in Figure 6.53. The location of the extracted batch on the waveform is shown in red (144 bunches) and orange (12 bunches) on top of the scanned waveform (black). Within the range of the 144 bunch batch there is a difference of 2.8µrad on average in the received kick. The scan also shows why the intermediate (12 bunches) batch had different injection oscillations and also a different trajectory in TI 8; there is difference of 4.7µrad between the waveform seen by a 144 bunch batch and a 12 bunch batch (intermediate intensity).

During the short winter shutdown (2011–2012) there was not enough time to improve the flatness of the kicker waveform. As a first mitigation, it was therefore decided to shift the delay of the kick with respect to the beam to avoid the worst part at the beginning of the waveform. An improvement could be made by changing the kicker delay by 0.8µs from 54.0µs to 53.2µs, see Figure 6.54. The difference in the kick for the 144 bunch batch is reduced to 2.5µrad. The most important change however, is that the difference in the average kick between the 144 and 12 bunch batch is reduced from 4.7µrad to 0.6µrad. This means that transfer line corrections calculated for intermediate intensity are also valid for high intensity injections.

During the LHC long shutdown (LS1) in 2013 and 2014, the Pulse Forming Networks (PFN) of the MKE.4 were adjusted to flatten the waveform. During the transfer line test of TI 2 and TI 8 at the end of 2014, the waveform was re-measured and the resulting scan is given in Figure 6.55. The flatness of the MKE.4 waveform for an optimised delay with respect to the extracted beam of 48.1µs is improved from 2.5µrad on average to 1.7µrad.

![MKE.4 Waveform Scan [2014]](image)

Figure 6.55: The MKE.4 waveform (black) was re-measured during the transfer line test in November 2014. The optimum kick delay was calculated and the resulting location of the 144 bunch batch (blue) and 12 bunch batch (violet) are shown.

The waveform of the MKE.6 was also measured for completeness even though no changes were expected, see Figure 6.56.
6.6 Summary

The trajectory stability of the SPS to LHC transfer lines has been studied in detail. In addition to slow trajectory drifts, there are shot-by-shot and bunch-by-bunch trajectory variations coming from different sources. These effects reduce the margins available for trajectory drifts. Frequent corrections of the transfer line trajectories are needed to limit injection oscillations and beam losses. The horizontal plane is most affected.

Large shot-by-shot trajectory variations are seen in the horizontal plane for both transfer lines. The sources of these variations have been identified to be current variations at the SPS extraction septa, MSE.6 (TI 2 extraction) and MSE.4 (TI 8 extraction). Much work has been put into improving the stability. For both septa the stability could be improved by a factor two by the end of Long Shutdown 1 (LS1). The origin of slow trajectory drifts is mainly SPS orbit changes. The most probable source causing these orbit changes is tune changes in the order of $10^{-2}$ units. More tests will be needed after the LHC start-up to confirm this hypothesis and propose a solution.

For beam 2 there are also bunch-by-bunch trajectory variations in the horizontal plane. These variations are caused by a ripple on the waveform of the MKE.4 extraction kickers. During LS1, the flatness of the waveform was improved. The waveform was re-measured and was indeed found to be flatter, but bunch-by-bunch differences will still be present. The optimum kick delays have been calculated to minimise the effect bunch-by-bunch differences in 2015.

As a result of these studies and the improvements done, the LHC transfer lines will be significantly more stable for LHC Run II than during LHC Run I.

Figure 6.56: The waveform of the MKE.6 was measured in November 2014. Within the measurement errors, this waveform is flat. The optimised setting of the delay of the kick with respect to the beam was calculated to be 38.5\(\mu\)s and the resulting location of the beam on the waveform is shown in blue (144 bunches) and violet (12 bunches).
Chapter 7

SPS Transverse Beam Scraping for LHC Beams

The transverse profile of the LHC beams in the injectors have large non-Gaussian tails. Optical mismatch at SPS injection due to the a change in the trajectory of the extracted beam from the PS was one of many sources that was identified and cured [53]. The generation of tails in the SPS however has not been eliminated. The beam was close to the stability limit in the SPS [54]. With the tight transfer line collimators and large shot-by-shot trajectory changes, large tail population lead to intolerable losses at injection into the LHC. With systematic scraping in the transverse plane before extraction from the SPS, the losses could be kept under control. The scraping process will be reviewed in this chapter. The relationship between scraping and losses at injection as well as the beam profile after scraping will be described.

7.1 Beam Losses at Transfer Line Collimators and Transverse Tails

Large beam losses at the transfer line collimators was a concern already in 2010. By repeatedly extracting the beam from the SPS and scanning the transverse position of the TCDIH.29050 collimator in TI 2, the transverse particle distribution was measured. The beam loss monitor signal at the close by transfer line BLMs was recorded and is plotted in Figure 7.1. The dashed vertical lines on the plot indicate the nominal collimator jaw positions. The scan revealed large transverse tails which extend beyond the collimator jaws.

The same scan was repeated with beam scraping in the SPS. The result of the scan is given in Figure 7.2. The particle distribution fills almost the entire gap, but no particles touch the collimator jaw. Since the 2011 start-up, SPS transverse beam scraping is systematically used for LHC beam production.
Figure 7.1: A transfer line collimator scan done in 2010 revealed large transverse tails of the beam distribution. The tails extend into the collimator jaws. The nominal jaw positions are indicated by the dashed lines. The transverse tails are lost on the collimators each injection into the LHC. The scan has been fitted with $\frac{1}{2}(1-erf\left(\frac{x-x_0}{\sigma\sqrt{2}}\right))$. 
*Courtesy of C. Bracco.*

Figure 7.2: After scraping in the SPS, the collimator scan was repeated. The particle distribution fit between the collimator jaws without significant beam losses during LHC injections. *Courtesy of C. Bracco.*
7.1 Beam Losses at Transfer Line Collimators and Transverse Tails

7.1.1 Beam scraping in the SPS

Three scraper systems are installed in the SPS, each consisting of a vertical and horizontal single-sided scraper jaw: BSHV.11771 and BSHV.11759 in LSS1 and BSHV.51659 in LSS5. Throughout LHC Run 1 only BSHV.11771 was used, the others were kept as spares. Each of the jaws is $10 \times 12 \times 70$ mm and made of graphite. Figure 7.3 shows a picture of a SPS scraper system. The horizontal and vertical scrapers are moved independently to an adjustable distance from the beam centre. A slow movement (4.5 cm/s) in the scraping plane moves the scraper to the required position. This movement is followed by a faster movement (8 cm/s) in the plane perpendicular to the scraping plane to ensure scraping of the full extent of the transverse profile.

![Figure 7.3: Picture of one of the scrapers in the SPS.](image)

The particles are removed over many turns. The resulting particle distribution in phase-space is a truncated two-dimensional Gaussian. For an ideal scraping process no particle amplitudes in phase-space exist beyond the scraping distance from the beam centre after scraping. This is illustrated in Figure 7.4, where ideal scraping at $2.5 \sigma$ from the beam centre is simulated.

In the SPS the LHC beams are scraped at the end of the energy ramp, at an energy of about 406 GeV. Figure 7.5 shows an SPS super cycle configuration with three different magnetic cycles (white traces) in the super cycle. The first two are two types of fixed target beam cycles and the last cycle is an LHC beam cycle. The yellow traces show the evolution of the intensity through the cycle. The scraping on the LHC cycle is indicated by the dip in intensity shortly before the end of the acceleration.

7.1.2 Beam Profile Measurements by Scraper Scans in the SPS

The transverse beam profile can be measured by scanning the beam with the scraper and recording the beam intensity at each step. For beams with a Gaussian distribution,
Figure 7.4: Left: The distribution in phase space assuming a Gaussian profile. Right: By making a cut over many turns (exaggerated at 2.5 σ for visibility), the particles in the tails of the Gaussian distribution are removed.

Figure 7.5: A SPS super cycle is displayed. The traces of the magnetic cycles (corresponding to beam energy) are shown in white. The last one is the LHC cycle. The yellow traces give the intensity of the beam. Four injections of 36 bunches are required for a full LHC batch in the SPS. The LHC beams are scraped towards the end of the ramp (at ~ 406 GeV) before extraction at 450 GeV.
the remaining intensity after scraping at a position \( x \) is given by

\[
I(x) = I_0 \times e^{-\frac{(x-x_0)^2}{2\sigma^2}},
\]

(7.1)

where \( I_0 \) is the initial intensity, \( \sigma \) is the beam size and \( x_0 \) is the beam centre \([55]\). Using equation 7.1 to fit intensity versus scraper position, the beam size and beam position at the scraper can be estimated. An example of such a measurement is given in Figure 7.6. Only one measurement point can be taken per SPS cycle, as the scraper system can only move once per cycle. Thus the full scan is obtained over many cycles. The measurement errors therefore always include the typical cycle by cycle intensity variations.

An example of a scraper scan is given in Figure 7.6. Equation 7.1 assumes a Gaussian profile, this fit is given as a red line in the plot. However, as non-Gaussian tails exist, the intensity evolution is better approximated with a double-Gaussian function

\[
I(x) = I_1 \times e^{-\frac{(x-x_0)^2}{2\sigma_1^2}} + I_2 \times e^{-\frac{(x-x_0)^2}{2\sigma_2^2}}, \quad I_1 + I_2 = I_0.
\]

(7.2)

The result of the double-Gaussian fit is shown as green line in Figure 7.6. The result of several scraper scans are given in this chapter. To be able to compare different scraper measurements, the parameters are given in units of the nominal beam size \( \sigma_{\text{nom}} = \sqrt{\frac{\mu c}{\sigma_0 \varepsilon_{\text{nom}} \beta}}, \) assuming a nominal emittance of \( \varepsilon = 3.5 \mu m \). At the location of the scraper and beam energy at the time of scraping this corresponds to \( \sigma_{\text{nom}} = 0.7 \text{ mm} \) in both planes.

### 7.1.3 Beam Scraping and LHC Injection Losses

To assess the effectiveness of scraping on injection losses, the injection losses at the transfer line collimators measured at LHC BLMs in the injection region were recorded as a function of the scraping depth during a machine development study in 2012. The scans were done only in the horizontal plane, with the vertical scraper at a fixed position scraping around 3% of the beam in the vertical plane. Before starting the measurements in the LHC, a beam scan was done in the SPS to determine the profile and intensity in the tails, see Figure 7.6. Large transverse tails were present.

During the study, the beam was injected into the LHC while varying the scraper depth. The emittance in the SPS and beam losses at injection into the LHC were measured for each scraper setting. The measurements were carried out with an intermediate intensity beam of 6 bunches. The losses at the BLMs were scaled to 144 bunches and compared to the BLM interlock thresholds. The transfer line collimators were at \( \pm 5 \sigma_{\text{nom}} \).

Figure 7.7 shows the results for the TI 2/LHC beam 1 collimators and Figure 7.8 for the TI 8/LHC beam 2 collimators. As soon as the the scraping depth is more than 2 \( \sigma_{\text{nom}} \) from the beam centre, the emittance of the beam is reduced and core particles are scraped. Scraping at 3 \( \sigma_{\text{nom}} \) from the beam centre however does not have an impact on emittance, but reduces the losses at the collimators to an acceptable level, see Figure 7.7.
7. SPS TRANSVERSE BEAM SCRAPING FOR LHC BEAMS

Figure 7.6: A beam profile scan was carried out in the SPS using a beam of 6 nominal bunches for injection loss measurements. The double Gaussian fit indicates that there are large tails. The calculated fit parameters are \( \sigma_1 = 0.520 \pm 0.039 \), \( \sigma_2 = 1.201 \pm 0.066 \), \( I_2/I_0 = 0.413 \pm 0.050 \). 1-Gauss stand for the single Gaussian fit and 2-Gauss for the double Gaussian fit.

Figure 7.7: Beam losses for varying scraper depths are shown for beam 1. All beam loss monitors in the IQC before the TDI have been included. The losses are scaled to 144 bunches and plotted with respect to the LHC dump thresholds. If the beam is not scraped the losses are close to dump thresholds. Scraping reduces the losses to an acceptable level already at \( 3 \sigma_{\text{nom}} \) while the emittance is not reduced until around \( 2 \sigma_{\text{nom}} \).
Figure 7.8: Beam losses at injection for beam 2 for all IQC beam loss monitors up to the TDL. The loss reduction is not as clear as for beam 1, but is still significant. At a depth of 3 \( \sigma_{\text{nom}} \), only BLMQI.07R8.B2E10_MQM has losses above 5\% of the dump threshold.

for beam 1. Without any scraping in the horizontal plane, the losses are close to the BLM interlock thresholds. For this particular beam 2 scan, the results are less clear, see Figure 7.8. The transfer line trajectory was possibly not perfectly corrected in the collimator region. For Gaussian beams scraping at 3 \( \sigma \) reduces luminosity by around 1\% following [56].

### 7.1.4 Evolution of the Operational Scraper Settings

Several scraper beam profile measurements were carried during 2012. The measured beam positions and operational scraper settings are plotted in Figure 7.9. The typical scraping depth was around 2 mm which is close to 3 \( \sigma_{\text{nom}} \).

During the period where the SPS orbit data was systematically saved at SPS extraction flattop (October–November 2012), the beam position was reconstructed at the scraper location, see Figure 7.10 and 7.11. The operational scraper settings follow the changes in beam position in the horizontal plane. In the vertical plane the scraper settings were evolving despite a fairly stable beam position. The small fluctuations of the total scraped intensity could be explained by this.

### 7.2 Tail Population at the LHC Injection Plateau after SPS Scraping

A machine development study was dedicated to investigate whether the tails would be re-populated on the LHC injection plateau once they had been removed in the SPS. Because of a problem with the vertical scraper, the studies were carried out only in the horizontal plane, but a similar result is expected in the vertical plane. The test
Figure 7.9: Several scraper scans were done in 2012. The measured beam position and the operational scraper settings at the time of the scans are shown. The settings follow the changes in beam position. The distance between the lines indicates the scraping depth which was about 2 mm.

Figure 7.10: The logged scraper position in the horizontal plane together with the fitted beam position and the scraped intensity. The scraper position was adjusted regularly to follow the changes in beam position.
7.2 Tail Population at the LHC Injection Plateau after SPS Scraping

Figure 7.11: The scraper position in the vertical plane, fitted beam position and scraped intensity for around one month are shown. The scraper is adjusted despite the fact that the beam position was fairly stable.

consisted of first scanning the beam profile in the SPS with the horizontal scraper and scanning it again after injection using the primary ring collimators operated as scrapers [37]. The horizontal collimators TCP.C6L7.B1 and TCP.C6R7.B2 were used for this study. Only low intensity beam could be used to be able to scrape the beam in the LHC. Thus the beam consisted of 3 bunches only.

Two cases were studied, no beam scraping and hard beam scraping (scraping around 15 % of the beam intensity). The beam was first scanned in the SPS, see Figure 7.12. For both cases — beam with and without SPS scraping — both LHC rings were investigated. Beam 1 was scanned first in the LHC and beam 2 about 30 min after injection. The exact conditions and times are summarised in Table 7.1.

Table 7.1: Parameters for LHC beam scans

<table>
<thead>
<tr>
<th></th>
<th>Time after injection</th>
<th>Scan duration</th>
<th>SPS scraped intensity</th>
<th>Emittance $\epsilon_H \ [\mu m]$</th>
<th>$\epsilon_V \ [\mu m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>13 min</td>
<td>13 min</td>
<td>17.8 %</td>
<td>1.25</td>
<td>1.06</td>
</tr>
<tr>
<td>B2</td>
<td>32 min</td>
<td>18 min</td>
<td>16.6 %</td>
<td>1.52</td>
<td>1.31</td>
</tr>
<tr>
<td>B1</td>
<td>8 min</td>
<td>17 min</td>
<td>0 %</td>
<td>1.39</td>
<td>1.21</td>
</tr>
<tr>
<td>B2</td>
<td>27 min</td>
<td>16 min</td>
<td>0 %</td>
<td>1.55</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Figure 7.13 and 7.14 summarise the results of the LHC scans at 450 GeV. They confirm the large transverse tails in case beams are not scraped before injection. In Table 7.2 the fit results for the double Gaussian (Equation, 7.2) are given in units of nominal beam size $\sigma_{nom}$. For the beam which is not scraped the fitted parameters are
Figure 7.12: The beam profile scan done in the SPS before the collimator scans in the LHC. The double Gaussian fit shows that there are significant tails present. The depth of the scraping for the LHC test is given by the dashed line.

very close to those of the SPS scan. The emittances calculated from the single Gaussian fit of the scraped beams correspond to 1.6µm for beam 1 and 2.0µm for beam 2. The encouraging result is that in case the beams are scraped in the SPS, the tails do not re-populate in the LHC even after significant waiting time at 450 GeV.

Table 7.2: Comparison of fit results

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_1[\sigma_{nom}]$</th>
<th>$\sigma_2[\sigma_{nom}]$</th>
<th>$I_1/I_0$</th>
<th>$I_2/I_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS</td>
<td>0.60±0.26</td>
<td>1.27±0.31</td>
<td>0.54±0.29</td>
<td>0.46±0.29</td>
</tr>
<tr>
<td>LHC B1 - scraping off</td>
<td>0.59±0.05</td>
<td>1.33±0.05</td>
<td>0.53±0.04</td>
<td>0.47±0.04</td>
</tr>
<tr>
<td>LHC B1 - scraping on</td>
<td>0.67±0.04</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LHC B2 - scraping off</td>
<td>0.65±0.04</td>
<td>1.36±0.05</td>
<td>0.58±0.05</td>
<td>0.42±0.05</td>
</tr>
<tr>
<td>LHC B2 - scraping on</td>
<td>0.76±0.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

7.3 Summary

The LHC beams in the injectors have significant transverse tails. Beam scraping in the SPS is vital to control beam losses at injection into the LHC. The effect of beam scraping on beam losses at injection and beam profiles after scraping was investigated in LHC machine development studies. A scraper setting of 3 $\sigma_{nom}$ from the beam centre was found to be optimum to reduce injection losses to an acceptable level. With transfer line collimators at 5 $\sigma_{nom}$, this leaves a 2 $\sigma_{nom}$ margin for trajectory variations. Transverse profile scans in the LHC demonstrated in addition that once the tails are removed in the SPS, they are not re-populated during LHC injection or on the injection plateau.
Figure 7.13: Collimator scans in the LHC after injection of beam with and without tail scraping in the SPS are shown. Both a double and a single Gaussian function have been fitted to the data. For the scraped beam the tails are much smaller and the profile is very close to a Gaussian.

Figure 7.14: Collimator scans for beam 2 with and without scraping are shown. Both a single Gaussian and a double Gaussian have been plotted. For the beam which has been scraped the two lines are identical.
Chapter 8

Summary

The Large Hadron Collider (LHC) at CERN is designed to accelerate and collide two counter-rotating protons beams at an energy of 7 TeV with an unprecedented luminosity of $1.0 \times 10^{34}$ cm$^{-2}$s$^{-1}$. During LHC Run I (2009-2013) the LHC was operating with energies up to 4 TeV per beam and beam intensities up to $1380 \times 1.7 \times 10^{11}$ protons.

Excellent beam quality and high operational efficiency are essential to maximise the integrated luminosity. During LHC Run I, the injection process was one of the most critical periods in the LHC operational cycle concerning these aspects. In this period the LHC was operating with injected batches of up to 144 bunches of $1.7 \times 10^{11}$ protons per bunch. Already at injection energy (450 GeV) the stored beam energy was a factor 10 above the damage limit of accelerator equipment. The LHC is protected against failures at injection by the LHC machine protection system. Transfer line collimators with tight settings of $\pm 4.5$ to $\pm 5 \sigma_{nom}$ are installed in the transfer lines close to the LHC. In the LHC injection regions sensitive Beam Loss Monitors protect the LHC superconducting magnets against uncontrolled beam losses. Constraints on beam quality and machine protection impact on the operational efficiency.

The LHC Injection Quality Check (IQC) software framework was developed to monitor the quality of every injection into the LHC. The twelve injections needed to fill each LHC ring are programmed in a filling scheme. After each injection, the IQC automatically collects and analyses data from monitoring systems in the LHC, SPS and transfer lines and reports to the Injection sequencer which controls the automatic filling process. In case the quality checks are not within limits, the IQC issues an interlock and prevents further injections. The data collected by the IQC is saved and has been analysed in further detail in this thesis.

Beam loss at injection was already a concern in 2010 and several mitigations were put in place before the 2011 run to improve the situation. One of the remaining issues was the stability of the LHC-to-SPS transfer line trajectories. The trajectories in the transfer lines are drifting over time and as a consequence regular trajectory corrections are needed to minimise injection oscillations and beam losses at injection. This is further complicated by shot-by-shot and bunch-by-bunch trajectory variations which
8. SUMMARY

reduce the available error margins. Frequent corrections and beam dumps due to beam losses decrease the operational efficiency. Analysis methods were developed using the algorithm Model Independent Analysis (MIA) together with MAD-X simulations to investigate the origins of trajectory variations.

The shot-by-shot trajectory changes in the horizontal plane in both transfer lines, TI 2 and TI 8, were successfully identified to originate from a current ripple of the power converters of the SPS extraction septa, MSE.6 in TI 2 and MSE.4 in TI 8. A current ripple of 0.2 % resulting in trajectory variations in both transfer lines of up to 1 \( \sigma_{\text{nom}} \). The current ripple was reduced by 50 % in the period 2011–2014. This improvement was demonstrated in a dedicated study at the end of 2014 in preparation for the LHC start-up in 2015.

The LHC beam 2 injection also suffers from bunch-by-bunch trajectory variations in the horizontal plane. Insufficient flatness of the extraction kicker waveform of the extraction kicker in SPS LSS 4, MKE.4 was identified to be the source. During the shutdown in 2013–2014 (LS1) the flatness of the kicker waveform could be improved by about 30 %. In addition, the optimum delay with respect to the extracted beam has been calculated to minimise the effect of remaining waveform ripple.

Over a period of one month, the trajectories drifted by more than 2 \( \sigma_{\text{nom}} \) during LHC Run I. The slow drifts in the transfer lines were tracked back to changes of the SPS orbit. Investigations of SPS orbit variations have only just started. The orbit changes may be caused by small tune changes in the SPS. Further studies are needed after the start-up to confirm this hypothesis.

Another important ingredient to limit beam losses at injection is transverse beam scraping in the SPS. If the tails of the transverse beam distribution are not removed, they impact on the transfer line collimators and result in large beam losses at injection into the LHC. With scraping, the losses can be reduced to an acceptable level without sacrificing luminosity performance. It was found that a scraper setting at 3 \( \sigma_{\text{nom}} \) from the beam centre gives optimum performance. With the transfer line collimators at 5 \( \sigma_{\text{nom}} \), this leaves 2 \( \sigma_{\text{nom}} \) for trajectory errors.

The combination of correct scraping in the SPS and better stability of the SPS-to-LHC transfer line trajectories increases the operational margins at injection and eases operation of the LHC. The first mitigations helped reduce the mean filling time of the LHC from 57 min in 2011 to 46 min in 2012. During the shutdown further improvements have been put in place and the stability should be even better for LHC Run II. However, injection will remain a critical area for the LHC in terms of availability and machine protection.
Appendix A

Conference Papers

A.1 Automatic Injection Quality Checks for the LHC

Poster presentation at the International Conference on Accelerator \\& Large Experimental Physics Control Systems (ICALEPCS), October 2011 in Grenoble, France [58].
AUTOMATIC INJECTION QUALITY CHECKS FOR THE LHC


Abstract

Twelve injections per beam are required to fill the LHC with the nominal filling scheme. The injected beam needs to fulfill a number of requirements to provide useful physics for the experiments when they take data at collisions later on in the LHC cycle. These requirements are checked by a dedicated software system, called the LHC injection quality check. At each injection, this system receives data about beam characteristics from key equipment in the LHC and analyzes it online to determine the quality of the injected beam after each injection. If the quality is insufficient, the automatic injection process is stopped, and the operator has to take corrective measures. This paper will describe the software architecture of the LHC injection quality check and the interplay with other systems. Results obtained during the LHC run 2011 will finally be presented.

INTRODUCTION

The LHC is filled through two transfer lines (TI2 and TI8) from the last pre-injector, the SPS. Currently the LHC runs with 1380 bunches per beam, which require 12 injections (plus one low intensity bunch) per ring. The maximum number of bunches per injection is 144 corresponding to 1 MJ stored energy.

Injection is a complicated process. The correct number of PS batches has to be injected in the correct RF bucket in the LHC. The injector timing system [1] and the LHC RF system ensure LHC dynamic injection requests and synchronisation. The extraction event from the SPS is forwarded to the LHC timing system as LHC injection event to trigger beam instrumentation.

The series of required injections is pre-programmed as an injection sequence driven by the injection sequencer. According to the filling scheme requests are sent to the injector timing system. At each injection the injection quality check (IQC) analyses data from key equipment in the LHC and the transfer lines and provides a result instructing the injection sequencer how to proceed: continue, stop or repeat the same request.

The IQC also provides software interlocks which are picked up by the software interlock system (SIS) and inhibit injections. A GUI for visual display of the detailed result is provided for monitoring and operator interaction, see Fig 1. The interplay of the IQC with other systems is shown in Fig. 2. There is also a playback tool for reviewing events. This paper presents the IQC architecture and results from the LHC run 2011.

LHC INJECTION QUALITY CHECKS

The injection quality check analysis is triggered automatically at each LHC injection event. Only data which has a time stamp within a certain time window around the injection time stamp are accepted. This window is set individually for each system and ranges from 1 s before the injection to 6 s after. The analysis is composed of separate analysis modules which are launched as soon as the required data is ready. The different modules are combined to an overall result at the final stage.

Data collection takes on average 4.5 s and analysis about 0.5 s. In case of missing data the analysis automatically times out after 10 s. The injection sequencer and IQC analysis are independent for beam 1 and beam 2. In this way the next injection can already be requested while the analysis on the other beam is still ongoing.

IQC Architecture

The IQC uses the LHC post mortem framework for data storage and analysis [2]. Data collection as well as analysis are written in JAVA and are running on JAVA servers. The results are published through Java Messaging System (JMS) and are picked up by the by the injection sequencer, the SIS and the IQC GUI.

For threshold management the IQC analysis uses the LSA Management of critical settings [3]. The thresholds can be modified by experts in the IQC GUI.

Event data stored on the post mortem server can be replayed offline on a separate, but identical application. This feature can be used for diagnostics of previous events, for testing and to make statistics.
ANALYSIS MODULES

Correctly Filled Bunch Pattern

Not every injection request is successful. Due to bad beam quality beam might not even be extracted from the SPS. To determine whether the beam was injected into the LHC, the results of the upstream and downstream BCTs in the transfer lines are combined with the BQM result. Three devices are used for the analysis due to reliability issues of the BCTs in the transfer lines. If the devices disagree the overall outcome of the IQC is UNKNOWN.

The LHC BQM uses the wall current monitors to find the longitudinal positions of the injected bunches [4]. In the module RF bucket check, the IQC compares this information with the requested filling pattern. In case of inconsistency the IQC stops the injection sequencer.

Injection Kicker Checks

The LHC injection kicker system (MKI), consisting of four vertical kicker magnets per beam, needs to have a short kicker rise time of less than 1 µs, little ripple on about 8 µs long flattop and fall times not longer than 3 µs, [5]. The characteristics of the injection kicker waveforms generated by oscilloscopes in the tunnel are analysed by the IQC after each injection. With the tight IQC thresholds deterioration of the kicker characteristics are noticed immediately.

Beam Losses

The module which is used mostly and provides very useful information for injection tuning is the beam loss module. At each injection the beam loss monitor crates of interest are triggered to produce a special buffer for the IQC, consisting of 512 beam loss samples per monitor around the injection event with 40 µs integration times.

The transfer line collimators (TCDIs) are at the end of the lines and losses on these are seen on the BLMs of the LHC superconducting magnets. The BLMs have low dump thresholds and small losses on the transfer line collimators can already lead to a beam dump while filling the LHC. The loss profile from the transfer line collimators is a valuable diagnostic for beam quality problems in the transverse plane.

Also the losses around the protection devices (TDI, TCLLa, TCLLb) protecting against injection kicker failures are shown. Losses from uncaptured circulating beam, satellites or uncaptured beam from the injectors as well as nominal beam in case of kicker problems ends up on these. The loss signature for the different cases is typical and is used for problem identification. Fig. 3 shows the loss distribution plot from the IQC BLM panel.

In addition to the LHC ring data the beam loss monitors in the transfer lines are also recorded.

Injection Oscillations and Transfer Line Trajectory

The setting of all the protection devices in the LHC is valid for a given aperture in the machine. The settings have to include tolerances for orbit distortions, energy errors, beta beat and injection oscillations. If the injection oscillations are larger than the tolerance, protection against beam impacting the aperture during e.g. injection kicker errors cannot be guaranteed.

Orbit information as well as turn-by-turn data from BPMs triggered at injection is acquired by the IQC in the LHC injection regions. The injection oscillation amplitudes have to be below the IQC limit of 1.5 mm (1.75 mm for T1 2 H).

If the limit is exceeded, the SIS inhibits injection of high intensity for that particular beam. A special flag is provided by the IQC for the SIS for that purpose. Low intensity (about 10^{12} protons) can be injected to correct. The flag is automatically reset as soon as the injection oscillations are within limit again.

The reading of the BPMs in the transfer lines are also recorded in the IQC. The trajectory offsets in the transfer line collimators have to be minimised to reduce losses.

2011 EXPERIENCE

Since the first running period in 2010 the IQC analysis has become an integral tool of understanding injection problems and optimising injection efficiency. The beam loss monitor results are used routinely.

Statistics From Mid July to Mid August 2011

60 LHC fills from mid July to mid August 2011 were analysed. Within this period 1483 IQC analyses were triggered. The IQC latched 7.9% of the time indicating quality issues. For 11.7% of the events the expert warning result was given due to beam losses. The full distribution...
of results is given in Fig. 4. For a detailed distribution of failures see Fig. 5.

During the period of these 60 fills the injections were very clean. The beam scraping in the SPS was used at maximum to cut beam tails. No other injection issues occurred. The less than 1% of IQC result “UNKNOWN”, associated with missing data, indicate the good performance of the overall system.

![Distribution of IQC results over a period of 60 fills.](source.png)

Figure 4: Distribution of IQC results over a period of 60 fills. In total there were 1483 injection events, where 7.9% latched.

### IQC Module failures

<table>
<thead>
<tr>
<th>Module</th>
<th>Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLM</td>
<td>204</td>
</tr>
<tr>
<td>TRANSFER LINE</td>
<td>68</td>
</tr>
<tr>
<td>OSCILLATIONS</td>
<td>18</td>
</tr>
<tr>
<td>RF BUCKET</td>
<td>9</td>
</tr>
<tr>
<td>MKI LIMITS</td>
<td>1</td>
</tr>
<tr>
<td>DATA QUALITY</td>
<td>0.7%</td>
</tr>
<tr>
<td>Unknown</td>
<td>0.7%</td>
</tr>
<tr>
<td>Repeat</td>
<td>14.3%</td>
</tr>
<tr>
<td>Warning</td>
<td>11.7%</td>
</tr>
<tr>
<td>No kick</td>
<td>0.1%</td>
</tr>
<tr>
<td>Successful</td>
<td>66.1%</td>
</tr>
</tbody>
</table>

![IQC Module failures](source.png)

At the beginning of injecting full SPS batches into the LHC, consisting of 144 bunches, spaced by 50 ns, the IQC indicated large injection oscillations in the vertical plane for beam 1, see Fig. 6. It turned out that the injection kick length had not been long enough and some of the beam was kicked on the falling edge of the waveform. It was subsequently prolonged.

![Injection oscillations in vertical plane for 144 bunches](source.png)

Figure 6: Injection oscillations in the vertical plane for 144 bunches. The last bunches had larger oscillation amplitudes due to too short kicker waveform. [23:21:38 20/6-2011]

The transfer lines suffer from trajectory stability problems in the horizontal plane [6]. Slow drifts, shot-by-shot and also large bunch-by-bunch variations have been recorded. The IQC injection oscillation analysis was very useful to detect the large bunch-by-bunch differences for beam 2 H, see Fig. 7. The source for these is probably the horizontal extraction kicker in the SPS. The issue is still under investigation.

![Injection oscillations in horizontal plane for 144 bunches](source.png)

Figure 7: Injection oscillations amplitudes in the horizontal plane for 144 bunches for beam 2. A bunch-by-bunch variation of more than 1 mm was discovered. [01:28:57 25/9-2011]

On 18th of April 2011, 11 magnets were quenched during a high intensity injection attempt when an injection kicker flashover of one of the four beam 2 magnets occurred. The problem could be diagnosed immediately with the IQC MKI analysis indicating the shortened waveform for one of the four kicker magnets, see Fig. 8.

The IQC BLM buffer is now also used for studying very fast beam loss phenomena occurring shortly after injection, called UFOs [7].

### Data Collection Issues

The IQC is depending on a large number of data sets from many sources. In case of missing data the IQC automatically stops injection. During the commissioning run of 2010 events with missing data were frequent. All data collection problems could be solved during the winter shutdown and the beginning of the LHC run in 2011. The remaining issue is the data quality from the transfer line BCTs we still frequently have issues with the data quality. During the analysed period of above for 47.9% only one of the BCTs produces data or the two BCTs give inconsistent data. For the total of 60 fills analysed for only 18 events (1.2%) a data set was missing and caused an injection interlock.

### Beam Quality Issues Discovered

In this section examples are presented where beam quality issues could be discovered due to the IQC results.
The IQC analysis is used offline and online on a routine basis to tune and improve injection. It has played a major role to achieve routine LHC filling with 1 MJ beams.

REFERENCES

A.2 Transfer Lines - Stability and Optimization

Oral presentation at the LHC Beam Operation Workshop, December 2011 in Evian, France [59].
Abstract

During the LHC proton run 2011 large drifts, shot-by-shot and even bunch-by-bunch trajectory variations were observed with the consequence of high losses at injection and frequent lengthy trajectory correction campaigns. The different effects will be quantified and an estimate for downtime caused by them in 2011 will be given. The sources of the instabilities, solutions for 2012 and achievable improvements will be discussed. Possible future upgrades will also be mentioned.

INTRODUCTION

Beam is injected from the SPS into the LHC from two transfer lines: TI 2 for beam 1 and TI 8 for beam 2. The trajectory in the transfer line must be well controlled in order to limit losses at the transfer line collimators and to minimize injection oscillations for the available aperture in the LHC [1].

Many mitigation measures had been put in place between 2010 and 2011. The strategy for setting up the TCDIs and establishing reference trajectories had also been greatly improved. Nevertheless transfer lines were still a concern. As it turned out throughout the course of the year the main problem is trajectory variations. Several partly independent issues have been identified: trajectory drifts, shot-by-shot variations of the trajectory and even bunch-by-bunch variations. In this paper studies to identify sources of variations in the transfer line trajectories will be presented. Impact on operations and mitigations will also be discussed.

DRIFTS

The transfer lines are drifting and need to be steered regularly. Frequently the same correctors are proposed. For TI 2 it is mainly RCIBH.20804 which is in phase with the MST and MSE (SPS extraction septa). The kick strength seems to be drifting back and forth, see Fig. 1. The cause of the drifts is still unclear and not further treated in this paper.

SHOT-BY-SHOT VARIATIONS

Large shot-by-shot variations have been observed in the horizontal plane for both transfer lines [2]. The transfer line stability (maximum variations at BPMs) was investigated using IQC (Injection quality check [3]) data from 144 bunch injections during the summer 2011. The variations were around 0.6 mm in the horizontal plane for TI 2 and about 0.4 mm for TI 8. In the vertical plane they were about 0.1 mm for both lines.

To investigate the sources of the variations dedicated stability studies were performed. For sufficient statistics repeated extractions on to the downstream TED were recorded for a period of 1.5 hours.

Form this data the difference trajectories from the average were calculated. The data was then analysed using model independent analysis (MIA) to find the eigenmodes of oscillation [4]. [5]. MIA uses singular value decomposition to separate the spatial and temporal eigenvectors of a series of trajectories. From the result the trajectories corresponding to the strongest sources of oscillation can be obtained.

TII 2

For TI 2 a dedicated stability study was done in June 2011. 82 shots were recorded and analysed using MIA. For the horizontal plane the variations from the average trajectory was up to 760 μm, see Fig. 2. In the vertical plane the variations are smaller, up to 260 μm.

From this data set the MIA analysis gives one strong eigenmode of oscillation in the horizontal plane, see Fig. 3. All other eigenvalues are at an acceptable level and are not considered further.

The corresponding spatial eigenvector is a betatron os-
cillation beginning at the start of the line meaning that the source is a single kick before the start of the transfer line, see Fig. 4. To investigate possible sources MAD-X simulations of various errors were used. For the MSE the simulation matches the result of the MIA analysis. See Fig. 5 for a comparison of the trajectories.

For the same period logged power converter currents of possible sources were investigated. The current variations were used as field errors in a simulation. The resulting excursions at a relevant BPM is given in Fig. 6. The MSE ripple correlates best with this BPM and its ripple is large enough to produce the variations observed. For the MST and other magnets investigated the observed current variations are not large enough.

**TI 8**

In November the same study was done for TI 8, giving 117 shots used in MIA. The maximum variations from average in the set were 770 μm in the horizontal plane and 260 μm in the vertical plane. See Fig. 7 for the full set of trajectories with respect to the average for the horizontal plane.

Using this data set in MIA, two strong eigenvalues were found in the horizontal plane, see Fig. 8. The corresponding eigenvectors are also betatron oscillations starting at the beginning of the line pointing to errors from the SPS extraction system or upstream of the line.

Possible sources are found simulating field errors by MAD-X. For the two largest spatial eigenvectors a good match is found with the MSE and the MKE (SPS extraction kicker), see Fig. 9.

For the MSE this is confirmed by the logged current variations. The simulation shows that the observed cur-
Evolution of stability

The power converter team was informed about the MSE6 (TI 2) current variations and work was started to improve the stability. As a result the peak-to-peak ripple could be improved by a factor 2 by the end of the run. Variations measured using IQC data also seem to show a reduction, see Fig. 11. More statistics are necessary to confirm this. No further improvements have been done for TI 8.

MKE waveform scans

For beam 2, two separate scans were performed extracting pilot beams on the upstream TED varying the kick delay. For the waveform scan a strong ripple up to 4% on the waveform was observed, see Fig. 13. From specifications this should be no larger than 1%. Reviewing a previous measurement, the ripple was already present in 2009. For 2012 the delay will be adjusted to avoid the worst part of the waveform ripple.
Figure 11: Stability of TI 2 for the 2011 proton run. Work was done to improve the MSE power convertors in two interventions marked by yellow lines. By the end of the run the stability seemed to have improved.

Figure 10: Simulations of logged current variations of the MSE gives high excursions at BPMI.80704.

Figure 12: IQC plot showing large variations for the bunch-by-bunch injection oscillations amplitudes of the injected batch in the horizontal plane for beam 2.

For beam 1 this issue does not exist. A waveform scan (albeit fewer points) confirms this.

**IMPACT ON OPERATIONS**

Due to drifts of the transfer lines frequent correction has been necessary. For the 2011 proton run steering was required several times a week (by the end of the run every second day). Because of shot-by-shot instabilities and bunch-by-bunch variations steering was complicated and time-consuming. Also the transfer line trajectory and LHC orbit eventually had drifted apart making it difficult to optimize for both LHC injection oscillations and losses due to the trajectory at the transfer line collimators. The typical time spent for steering of the transfer lines was 0.5-2 hours. Roughly approximating the expected time spent on steering in 2012: 1h x 0.5/days x 120 days = 60h.

**SUMMARY**

The main issues were tracked down to trajectory instabilities, especially in the horizontal plane. Much time was spent on steering the transfer lines in 2011. Steering was complicated due to trajectory drifts, shot-by-shot variations and bunch-by-bunch variations. Studies have been done to investigate the sources of trajectory variations.

Shot-by-shot instabilities in the horizontal plane for TI 2 seem to be caused by variations in the current of the MSE6. Work has started to improve the stability of the power convertor.

For TI 8 both shot-by-shot instabilities and bunch-by-
bunch variations were observed in the horizontal plane. Two sources of shot-by-shot variations were found: MSE4 and possibly the MKE4. Variations of the MKE4 still need to be investigated. The bunch-by-bunch variations are caused by a large ripple of the MKE4 waveform.

REFERENCES

A.3 SPS Transverse Beam Scraping and LHC Injection Losses

*Poster presentation* at the *International Particle Accelerator Conference (IPAC)*, May 2012 in New Orleans, USA [60].
SPS TRANSVERSE BEAM SCRAPING
AND LHC INJECTION LOSSES

L. Drosdal, V. Kain, W. Bartmann, C. Bracco, K. Cornelis, B. Goddard, M. Meddahi, E. Veyrunes, CERN, Geneva, Switzerland

Abstract

Machine protection sets strict requirements for the quality of the injected beam, in particular in the transverse plane. Losses at aperture restrictions and protection elements have to be kept at a minimum. Particles in the beam tails are lost at the tight transfer line collimators and can trigger the LHC beam abort system. These particles have to be removed by scrapers in the vertical and horizontal plane in the SPS. Scraping has become vital for high intensity LHC operation. This paper shows the dependence of injection quality on the SPS scraping and discusses an improved scraper setting up strategy for better reproducibility with the current scraper system.

INTRODUCTION

Injection efficiency into the LHC depends on the quality of the beam delivered from the injectors. At injection the LHC is protected by collimators in the transfer line and the injection regions. Showers from high beam losses at these collimators are picked up by the LHC beam loss monitor (BLM) system due to proximity and can trigger a protection beam dump [1].

The LHC beams produced in the injectors have a larger tail population than truly Gaussian beams. These large amplitude tail particles do not contribute significantly to the luminosity [2], but impact on the transfer line collimators, see Fig. 2. Due to the tails, beam loss of ~ 25 % of the dump threshold is reached already for a 12 bunch injection. A full injected LHC batch in 2011 consisted of 144 bunches. The run conditions towards the end of the LHC proton run are summarized in Table 1. The LHC beams need scraping in the last pre-injector, the SPS, before extraction towards the LHC.

The beam distribution tails of all LHC beams (except the very low intensity pilot beams, bunch intensity of $5 \cdot 10^9$) are removed by means of scrapers in the horizontal and vertical plane. An example of a scraper is shown in Fig. 1. Scraping takes place towards the end of the SPS ramp. The effect of scraping on the losses at the transfer line collimators is illustrated in Fig. 3. For 50 ns LHC physics beams about 3 % of the total produced beam intensity are scraped off in the SPS.

Figure 1: Picture of a copper scraper installed in the SPS. Courtesy of H. Burkhardt.

Figure 2: Tail scan at horizontal transfer line collimator (TCDIH.29050): The nominal collimator position is marked with blue lines. Without scraping the tails of the beam distribution impact the collimators.

Figure 3: Tail scan at horizontal transfer line collimator (TCDIH.29050) after scraping: Scraping removes the particles in the tails. The number of particles impacting the collimator is much reduced. (Nominal collimator position in blue).

The transverse emittances with the 50 ns beams, see Table 1, are smaller than the 3.5 $\mu$m emittance of the nominal bunch spacing of 25 ns. We will show in this paper that even for nominal emittances injection losses are no issue as long as the scraping is well set up.

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INJECTION QUALITY STUDIES

The dependency of injection losses on longitudinal and transverse beam quality was studied during a dedicated machine test [3]. The effects of several longitudinal parameters were investigated: satellite population, bunch length, radial steering in the SPS, momentum spread at SPS extraction and wrong settings in the SPS 800 MHz RF system. The effect on injection losses was small and the studies showed that the SPS Beam Quality Monitor (BQM) prevents extraction in case of degradation for most of the parameters.

Injection losses depend however heavily on any degradation in the transverse plane: transfer line trajectory changes [5] and scraping depth in the SPS. The dependence of injection quality on SPS scraper settings was studied in detail. The studies were performed with the 50 ns intermediate injection quality on SPS scraper settings was studied in detail. The beam sigma and beam center with respect to the core. The optimum scraper setting just removes the particle distribution tails. For small and larger emittances the scraper offset can be obtained through Eq. 1, [4].

\[ I(x) = I_0 e^{-\frac{(x-x_0)^2}{2\sigma_x^2}} \]  

Figure 4: Measured emittance in the horizontal plane and losses at the MSI versus horizontal scraper position for initially nominal emittance beam (3.5 μm). The horizontal scraper was kept constant at -8.1 mm. Losses are reduced from 25.8% (no scraping) to 1.3% of dump thresholds with the scrapers at nominal setting. Moving the scraper further into the beam does not significantly reduce the losses further.

The results for the 3.5 μm beams for the vertical and horizontal plane are shown in Fig. 4 and 5. In both planes scraping reduced the losses from 25% to less than 1.5% of dump threshold at the MSI beam loss monitor. 1.5% is more than acceptable for 12 bunches and gives sufficient margin for the full injected batch of 144 bunches. To optimize LHC luminosity performance, the beam population in the beam core must not be reduced by scraping. At one point scraping deeper does not further reduce the losses at MSI, but reduces the emittance and thus starts cutting into the core. The optimum scraper setting just removes the particle distribution tails. For small and larger emittances the same scraper settings were valid during the test (indicated as dashed lines in Figs. 4 and 5).

The positive outcome of this study is that nominal 3.5 μm emittance beams can be injected into the LHC at a similar loss level as the low emittance 50 ns beams as long as the scraper settings are correct.

SCRAPER SCANS - REPRODUCIBILITY

Correct scraper settings can be found via scans as illustrated in Fig. 4. The LHC transfer lines have to be well corrected during this exercise. The distance of the scraper from the beam center can be found by scanning the scraper position and recording scraped intensity versus scraper setting. The beam sigma and beam center with respect to scraper offset can be obtained through Eq. 1, [4].

\[ f(x) = I_0 e^{-\frac{(x-x_0)^2}{2\sigma_x^2}} \]  

In case the SPS orbit is reproducible, the scrapers settings should not have to be changed during the LHC run. The reproducibility of the beam position at the scraper over a short period was checked during another test. The scans

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**Table 1: 2011 LHC run conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bunches - nominal injection</td>
<td>144</td>
</tr>
<tr>
<td>Number of bunches - intermediate injection</td>
<td>12</td>
</tr>
<tr>
<td>Maximum bunches circulating</td>
<td>1380</td>
</tr>
<tr>
<td>Injected emittance</td>
<td>~ 2 μm</td>
</tr>
<tr>
<td>Intensity per bunch (protons)</td>
<td>1.5 x 10^11</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>50 ns</td>
</tr>
</tbody>
</table>

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**Figure 5:** Measured emittance in the vertical plane and losses at the MSI versus vertical scraper position for initially nominal emittance beam (3.5 μm). The vertical scraper was kept constant at -8.1 mm. Losses are reduced from 25.8% (no scraping) to 1.3% of dump thresholds with the scrapers at nominal setting. Moving the scraper further into the beam does not significantly reduce the losses further.

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were performed keeping one scraper constant while moving the other stepwise into the beam. For each plane a scan of 5 points and another one of 3 measurement points were carried out with a time of \(\sim 1.5\) h in between. Five measurements were taken per point for statistics. Fitting the obtained curves using Eq. 4 gives beam position and beam size, see Fig. 6, 7, 8 and 9. Three scan points are enough to fit the beam parameters, provided a good fraction of the beam is scraped off (\(\sim 25\%\)). The scans show that the beam position at the scraper is sufficiently stable and loss variations at the transfer line collimators are more likely to come from shot-by-shot variations of the trajectories [5]. The reproducibility of the SPS orbit will have to be further investigated in 2012. Scans will have to be repeated several times through the LHC run and the evolution of the scraper settings through the year will be investigated.

**SUMMARY**

Transverse beam scraping in the SPS is vital to keep losses at injection into the LHC under control. No scraping of full SPS batches of 144 bunches for 50 ns or 288 bunches for 25 ns will lead to beam abort at the moment of injection due to losses from large tails on the transfer line collimators. Methods have been established to optimize the scraper settings. Correctly set up scrapers reduce the losses sufficiently at injection without cutting into the core of the beam distribution. Provided that the scrapers are at the correct positions, injection of nominal emittances of 3.5 \(\mu\)m beam leads to the same low loss levels as the 50 ns low emittance beams.

**REFERENCES**

A.4 Sources and Solutions for LHC Transfer Line Stability Issues

Poster presentation at the International Particle Accelerator Conference (IPAC), May 2012 in New Orleans, USA [61]
Abstract

The LHC is filled through two 3 km long transfer lines from the last pre-injector, the SPS. During the LHC proton run 2011 large drifts, shot-by-shot and even bunch-by-bunch trajectory variations were observed with the consequence of high losses at injection and frequent lengthy trajectory correction campaigns. The causes of these instabilities have been studied and will be presented in this paper. Based on the studies solutions have been proposed. The effect of the solutions will be shown and the remaining issues will be summarized.

INTRODUCTION

Beam is injected from the SPS into the LHC through two transfer lines: TI 2 for beam 1 and TI 8 for beam 2. The trajectory in the transfer line must be well controlled in order to limit losses at the transfer line collimators and to minimize injection oscillations for the available aperture in the LHC (<1.5 mm) [1]. The main source of losses are trajectory variations; during the 2011 run shot-by-shot variations, bunch-by-bunch variations and long time drifts were observed [2].

Frequent trajectory correction (steering) of the transfer lines was necessary in 2011 impacting LHC efficiency. Steering the lines was complicated due to the large shot-by-shot and bunch-by-bunch variations and had to be repeated several times per week taking 0.5 - 2 h per correction campaign [3]. The typical correction strength is about 10 μrad.

BUNCH-BY-BUNCH-VARIATIONS

The bunch-by-bunch analysis of the automatic LHC Injection Quality Check (IQC [4]) indicated large bunch-by-bunch differences of the injection oscillation amplitudes in the horizontal plane for beam 2 (TI 8) see Fig. 1. An insufficient flatness of the waveform of the SPS extraction kicker, MKE4 was suspected. A waveform scan indeed revealed a large ripple of 3.8% (specification: 1%), see Fig. 2.

Due to machine protection reasons trajectory correction is done with 12 bunches only. In 2011 the part of the waveform which was sampled with the first 12 bunches was unfortunately not representative for the full batch (144 bunches) as indicated also in Fig. 2. The first 12 bunches were following a very different trajectory from the rest of the bunches due to the large ripple at the beginning of the waveform. For the 2012 run the MKE delay was changed from 54 μs to 53.2 μs to only sample the region after the second overshoot. This should make steering with 12 bunches more straight forward. The waveform could however not be flattened in the short shutdown between the 2011 and 2012 run.

SHOT-BY-SHOT VARIATIONS

Large trajectory variations were observed from one shot to the next. The analysis of the 2011 proton data recorded by the IQC show that the shot-by-shot variations are particularly large in the horizontal plane, around 0.6 mm for TI 2 and 0.4 mm for TI 8. The variations are around 0.1 mm in the vertical plane for both lines [3].

To understand the phenomenon dedicated stability studies were carried out extracting beam onto the beam stoppers.
(TEDs) at the line ends and recording about 90 trajectories. The difference trajectories were analysed using Model Independent Analysis (MIA [5]) to find the eigenvalues and eigenvectors of the trajectories over time. The spatial eigenvectors corresponding to the strongest eigenvalues are then compared with trajectories from error sources.

The stability test of TI 2 was carried out in June 2011. MIA indicates one strong eigenvalue in the horizontal plane for the recorded data, see Fig. 3. The corresponding trajectory matches an error on the SPS extraction septum MSE, see Fig. 4. The MSE is a single loop, low inductance magnet with a big deflection of $\sim 12$ mrad.

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Most of the issues with injection losses were observed in TI 2 (also due to the topology of the transfer line collimators). After the first analysis results from IQC data on transfer line stability, efforts were made to improve the stability of the MSE power converter. The flat-top ripple was improved from 18 A to 9 A peak-to-peak. During the 2012 start-up a stability test in TI 2 was repeated showing indeed and improvement of the MSE eigenvalue in MIA by a factor 2, see Fig. 5. Investigations are still ongoing to even further improve the stability of the power converter. Another factor 2 would be desirable.

The stability test for TI 8 was done only in October 2011. Two strong eigenvalues show up in the horizontal plane when analysing with MIA, see Fig. 6. The eigenvalues correspond to errors from the MSE and MKE in the SPS extraction region LSS4, see Fig. 7.

In March 2012 the TI 8 stability check was repeated. The MSE is still a strong source, but the strength has been reduced by a factor 2.

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MKE eigenvalue was suppressed, the MSE one stayed at a similar level as in 2011, see Fig. 8. The MKE result is still not understood. Later on in the 2012 run, the MKE instability seemed to become stronger again. Further investigations are still ongoing. Another stability test is scheduled after the start-up period.

Figure 8: At the beginning of 2012 the stability study for TI 8 was repeated. An MKE error source was not present.

**DRIFTS**

In addition to the shot-by-shot changes the 3 km long transfer line trajectories are also drifting. After a period of 2 to 5 days a correction with 1 or 2 correctors of less than 10 μrad is needed to stay close to the reference trajectory. Drifts are stronger in the horizontal plane than in the vertical plane. The trajectories of all physics injections from 3rd to 21st of April were used for MIA analysis. The effect of the applied corrections in the period of reference had been removed from the trajectory data. The MIA results are shown in Fig. 9 and Fig. 10. The transfer line drifts seem to have many origins as shown by the several strong eigenvalues found for both beams. Also, the vertical eigenvalues are large. The extraction septa are among the sources for both lines. The other sources still have to be determined.

Figure 9: Eigenvalues found by MIA analysis of TI 2 over a period of 3 weeks in the beginning of 2012. Several sources are found in both planes.

Figure 10: Eigenvalues found by MIA analysis of TI 8 using data taken over 3 weeks in the beginning of 2012. The result show several sources in both planes.

**SUMMARY**

The LHC transfer lines suffer from large shot-by-shot trajectory variations in the horizontal plane (~ 500 μm). In addition there are bunch-by-bunch variations of up to 1 mm in the horizontal plane for beam 2 due to a large ripple on the SPS extraction kicker waveform.

Sources of trajectory variations in the transfer line have been analyzed using Model Independent Analysis (MIA). For TI 2 the source of shot-by-shot variations was identified as the SPS extraction septum. Due to improvements on the MSE power converter the trajectory variations could be reduced by a factor 2 by the end of 2011. Studies are ongoing to improve the stability even further. For TI 8, two sources of trajectory variations have been identified: the extraction septum MSE and the extraction kicker MKE. In the vertical plane the shot-by-shot stability is acceptable.

Long term drifts are due to several independent sources and will therefore be more difficult to get under control. Even though the drifts are stronger in the horizontal plane, the vertical plane also shows large variations with time for both beams. The investigations concerning long term drifts have only started.

**REFERENCES**

A.5 Beam Stability and Tail Population at SPS Scrapers

*Poster presentation at the ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB), September 2012 in Beijing, China [62]. Presented by M. Meddahi.*
BEAM STABILITY AND TAIL POPULATION AT SPS SCRAPERS

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Abstract

Before injection into the LHC the beams are scraped in the SPS to remove the tails of the transverse particle distributions. Without scraping the tail population is large enough to create losses above the beam abort thresholds of the LHC beam loss monitor system when injecting. The scrapers are only effective if correctly set up. This paper shows the results of periodical scraper scans. The beam position and beam size at the scraper is changing with time. The scraper settings hence need to follow accordingly. The scans also give insight into the transverse tail population and could therefore provide useful beam quality diagnostics. The impact on new scraper designs and setting up strategy are discussed.

INTRODUCTION

The beams produced by the injectors for the LHC can have a large non-Gaussian tail population. These tails must be removed before injection to avoid high losses on the injection elements and later in the LHC cycle on the ring collimators. If these particles are not removed the losses can be high enough to trigger a beam abort in the LHC [1]. The tails are removed in the last LHC pre-injector, the SPS, by means of a horizontal and vertical scraper. Graphite plates are moved close to the beam towards the end of the SPS ramp and scatter the large amplitude particles. The particles are lost in the SPS during the remainder of the ramp.

The 2012 LHC 50 ns full SPS batch consists of 144 bunches with bunch intensities of typically $1.6 \times 10^{11}$ protons. 3 - 5 % of the intensity is scraped off before each LHC injection. The intensity reduction is clearly visible towards the end of the SPS, see Fig. 1. Tests have shown that correct positioning of the scrapers with respect to the beam is essential to control injection losses. Correct positioning implies removing the tails without touching the core of the beam and hence conserving the emittance [2].

During the run of 2012 it was noticed that the scraped intensity can change significantly. This could be due to changes of the beam position at the scraper location, the emittance or the tail population. The strategy of the SPS operations crew was to change the scraper setting to keep the scraped intensity constant. Scraper scans were carried out over the summer 2012 to investigate the sources of the continuous change of scraping conditions. The results are summarized in this paper.

Figure 1: The SPS super cycle configuration during LHC filling. The traces of different magnetic cycles are shown in white. The last one is the LHC cycle. The yellow traces show the intensity of the beam. 4 injections of 36 bunches are required for a full SPS batch of LHC 50 ns beam. The LHC beams are scraped towards the end of the ramp (scraping at 409 GeV) before extraction to the LHC (extraction at 450 GeV).

SCRAPER SCANS

Because the scraper scans give a detailed description of the beam distribution they can be used as a tool to measure the tail distribution. The beam is scanned by moving the scraper step-wise closer to the beam core and recording the intensity removed by the scrapers. The beam size, $\sigma$, and beam position, $x_0$, with respect to the scrapers can be calculated by Eq. (1) [3].

$$I_1(x) = I_0 e^{-\frac{(x-x_0)^2}{2\sigma^2}}$$  

Eq. (1) assumes Gaussian beams, but the scans done reveal that the beams can have large non-Gaussian tails. A double Gaussian function as in Eq. (2) fits the resulting distribution better. The corresponding fit parameters are beam position $x_0$, two beam sizes $\sigma_1$ and $\sigma_2$ for the different Gaussians and the fraction of the amplitudes in each distribution, denoted by $c$.

$$I_2(x) = I_0(1-c) e^{-\frac{(x-x_0)^2}{2\sigma_1^2}} + I_0ce^{-\frac{(x-x_0)^2}{2\sigma_2^2}}$$  

(2)

Tails can only be studied if the whole beam is scraped. Each plane has to be scanned separately. To minimize the losses only 36 bunches are used instead of a whole 144 bunch batch. Nevertheless, part of the beam loss monitor system close to the scrapers has to be temporarily masked not to trigger beam aborts in the SPS during the scans.
An example of a scraper scan result is shown in Fig. 2. The Gaussian fit was done using only points where more than 50% of the intensity was scraped. The Gaussian as well as a double Gaussian fit are shown in the plot. The difference of the integral of the two fit functions gives an estimate for the tail population.

With the current system, the scraper can assume only one scraping position per cycle. With about 15 steps per scan and 3 measurements per step a full scan takes about 30 minutes per plane and is therefore not done routinely.

Figure 2: Scan of the beam in the horizontal plane at the end of the ramp (operational scraper setting) done 9. July 2012. The scan shows that the beam has a large tail population.

### STABILITY OF BEAM PARAMETERS AT SCRAPERS

During the summer months of 2012 several scraper scans as described in the previous section were performed. All scans were done at the moment in the cycle where scraping occurs for LHC physics beams (409 GeV, cycle time = 17.35 s).

#### Beam Position Change at Scrapers

Figure 3 shows the results for the beam positions at the scrapers in the horizontal and vertical plane obtained from the fits of the scan profiles. The plots also show the setting of the operational scraper settings used during that period. The change of applied setting tracks the change of beam position well and indicates correct setting up of the scraping. Large changes to the beam position can occur. The reason for the SPS orbit changes has to be investigated further. The evolution of the scraper settings from beginning of July 2012 to beginning September 2012 is depicted in Fig. 4. The plot indicates that despite the fact that orbit jumps can occur, the beam position at the scraper remains the same within ±1 mm. Some of the outliers are also due to periods with increased scraping (6 - 10 % instead of 3 %).

Figure 3: The beam position at the vertical scraper changed by up to ~ 4 mm during the measurements and in the horizontal plane by up to ~ 1 mm. The operational scraper settings follow the beam position changes well.

Figure 4: Logged scraper settings versus LHC fill number for the period of beginning of July to beginning of September: at a few occasions the applied scraper settings changed significantly. The overall stability is however within ±1 mm, which is reasonable.

#### Beam Size and Tails

Figure 5 shows the horizontal emittances calculated from the beam sizes obtained by the scraper scans and compares them to the wire scan emittances. $\sigma_1$ of a double Gaussian seems to underestimate the beam size whereas $\sigma$ of Gaussian core fit overestimates the beam size. The emittances did not change significantly over the period of interest as indicated by the wire scanners. The variation for the beam size from the double Gaussian fit is larger. Except for one measurement with a large error, the emittances from the Gaussian core fit follow the wire scanner results.

Also for the vertical plane the emittances based on the Gaussian core fits follow the emittance trends measured by the wire scanner. There is a discrepancy between the emittances from Gaussian or double Gaussian with the emittances from the wire scanner. Possible uncertainties from the position calibration of the scrapers and other sources still have to be investigated.

The evolution of the tail population for the different scans is shown in Fig. 7. Here the scraped intensity at 3 $\sigma$
Figure 5: Normalized emittance calculated from $\sigma_1$ of double Gaussian fits and $\sigma$ of the Gaussian core fit compared to the measurements from the wire scanners in the horizontal plane. The Gaussian core fit emittances follow the wire scan emittances reasonably well.

Figure 6: Normalized emittance calculated from $\sigma_1$ of double Gaussian fits and $\sigma$ of the Gaussian core fit compared to the measurements from the wire scanners in the vertical plane. In the vertical plane the wire scan measurements are larger than both curves, but follow the single Gaussian fit closest.

Figure 7: Difference between the scraped intensity at 3 $\sigma$ and the one expected from a purely Gaussian particle distribution is between 4 % and 12 % for all the scraper scans.

Figure 8: Three series of scans were done to monitor the evolution of tails through the SPS cycle. Tails are generated or increased through the LHC cycle. The origin is still unclear.

For the horizontal plane only one series of measurements could be done. The results are similar, see Fig. 10.

**EVOLUTION OF TAILS THROUGH SPS CYCLE**

The LHC beams always have non-Gaussian tails at the SPS flat top. To investigate the origin of the tails, scans were done at various points through the SPS cycle: flat bottom (26 GeV, at 2.0 s and 9.0 s in the SPS cycle), during the ramp (at 13.0 s, 17.3 s and 17.35 s in the cycle) and at the flat top (450 GeV, at 18.2 s in the cycle).

In the vertical plane 3 series of scans were done. The results are shown in Fig. 8. This investigation revealed that even if tail free beams are injected into the SPS, tails are generated in the course of the SPS cycle, see Fig. 9 for the beam profiles at injection and during the ramp on 6. August 2012. In case the beams are already injected with tails, the tails are further enhanced. The growth occurs already during the injection plateau and continues in the ramp. The mechanism is not clear. Further studies are planned to investigate this phenomenon.

**LHC INJECTOR UPGRADE: NEW SCRAPER DESIGN**

The current scraper system has limitations. As already mentioned above only one scraper setting per cycle can be chosen. Thus a scraper scan has to be done over many cycles. This takes a long time and introduces additional errors due to shot-by-shot variations of beam parameters.

For the LHC Injector Upgrade (LIU) a new scraper design has been proposed. The new design is based on local
Figure 9: Two beams scans from 6. August 2012, show the appearance of tails later in the cycle. The first scan show the beam 2.0 s after injection without tails. 9(a). Later in the cycle tails are present 9(b).

Figure 10: One series of scraper scans through the SPS cycle was done in the horizontal plane. The plot shows the tail population at 3σ. The tail population is growing through the SPS cycle.

ORBIT BUMPS IN BOTH PLANES WHICH MOVE THE BEAM TOWARDS A FIXED MASK RATHER THAN MOVING SCRAPPERS TOWARDS THE BEAM. POWER CONVERTERS CAN BE PROGRAMMED IN A MORE FLEXIBLE WAY THROUGH THE SPS CYCLE THAN THE CURRENT SCRAPER SYSTEM. SCANS DURING THE INJECTION PLATEAU AND THE FLAT TOP WILL BE ABLE TO BE CARRIED OUT WITHIN ONE CYCLE. SCRAPER SCANS CAN BECOME ROUTINE OPERATIONAL MEASUREMENTS WITH THE NEW SCRAPER DESIGN.

The specifications foresee possible beam position changes of 9 mm in the horizontal plane and 7 mm in the vertical plane, which is largely sufficient for what has been observed so far.

CONCLUSION

The correct setting of the transverse scrapers in the SPS is essential for injection quality and transmission through the LHC cycle. The 50 ns LHC beams have significant non-Gaussian tails. The scrapers reduce these to acceptable values.

During the summer months of 2012 several scraper scans were carried out to track the change of beam parameters like the beam position at the scrapers and tail population. The beam position at the scraper can change by several mm for certain periods, but is otherwise constant within ±1 mm. The scraper settings are tracking the beam position changes well. Currently the scraper settings are chosen such to give constant amount of scraped intensity at flat top. Full beam scans are necessary to fit the measurement results due to the significant tails. The scraper scans proved to be a useful technique to measure the tail population of the LHC beam in the SPS.

With the planned upgrade of the SPS scraper based system on a magnetic bump and fixed bump, scraper scans will become routine operation. This will guarantee correct scraping under all conditions and could provide a very sensitive diagnostics tool to measure tail population.

REFERENCES

A.6 SPS Scraping and LHC Transverse Tails

Poster presentation at the International Particle Accelerator Conference (IPAC), May 2013 in Shanghai, China [63].
SPS SCRAPING AND LHC TRANSVERSE TAILS

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Abstract

All high-intensity LHC beams have to be scraped before extraction from the SPS to remove the non-Gaussian transverse tails of the particle distributions. The tail particles would otherwise cause unacceptably high losses during injection or other phases of the LHC cycle. Studies have been carried out to quantify the scraping using injection losses and emittance measurements from wire scanners as diagnostics. Beams scraped in the SPS were scraped again in the LHC with collimators to investigate possible tail repopulation. The results of these studies will be presented in this paper.

INTRODUCTION

Before injection into the LHC the high intensity beams are scraped to remove transverse tails. The scraping is done in the last injector, the SPS, at the end of the ramp. Around 3% of the intensity is removed for normal operations. These particles are high amplitude particles that do not contribute significantly to the luminosity, but if they are not removed they cause beam loss at the collimators in the injection region or later in the LHC cycle [1].

During a machine development study in October 2012 the effect of scraping in the SPS on the injected beam was investigated. The beams were first scanned at the scraper in the SPS to know the beam profile and then injected into the LHC. Only data at the SPS scraper in the horizontal plane could be obtained. Scans in the vertical plane were erroneous due to controls problems. The measured beam profiles were fitted by a double Gaussian function, see Eq. 1, which describes the LHC particle distributions with their non-Gaussian tails well. A single Gaussian fit of the beam core is included in the analysis for comparison. To be able to compare different scans the measurements are given in units of nominal beam size assuming a normalized emittance of $\varepsilon^* = 3.5 \mu m$.

$$I(x) = I_1 \cdot e^{-\frac{(x-x_0)^2}{2\sigma_1^2}} + I_2 \cdot e^{-\frac{(x-x_0)^2}{2\sigma_2^2}} \quad (1)$$

LHC SCRAPED BEAM PROFILES

The evolution of the transverse profiles in the LHC, after they had been scraped in the SPS, was studied by scanning the tails again in the LHC using a similar technique as in the SPS. The LHC primary collimators were operated as scrapers for this study [2]. For comparison, beam without scraping in the SPS as well as beam with scraping was scanned. Only low intensity beam consisting of three bunches could be used for these studies. The beam was first scanned in the SPS as a reference, see Fig. 1.

Figure 1: A beam scan done by the scraper in the SPS as a reference for scans in the LHC after injection. The measurements are fitted by a single and a double Gaussian. Because of the large tails the double Gaussian function gives the best approximation.

In the LHC the horizontal collimators TCP.C6L7.B1 and TCP.C6R7.B2 were used. For the two cases, profile scan with and without scraping in the SPS, both beams were injected into the LHC at the same time. Beam 1 was scanned first and beam 2 about 30 min after injection. This allowed to also to conclude on the possible re-generation of the tails on the injection plateau. See Table 1 for a list of parameters for the four scans done. The emittances were measured after injection by the LHC wire scanners.

Table 1: Parameters for LHC Beam Scans

<table>
<thead>
<tr>
<th>Time after injection</th>
<th>Scan duration</th>
<th>SPS scraped intensity</th>
<th>Emittance $\varepsilon_H [\mu m]$</th>
<th>Emittance $\varepsilon_V [\mu m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>13 min</td>
<td>13 min</td>
<td>17.8 %</td>
<td>1.25</td>
</tr>
<tr>
<td>B2</td>
<td>32 min</td>
<td>18 min</td>
<td>16.6 %</td>
<td>1.52</td>
</tr>
<tr>
<td>B1</td>
<td>8 min</td>
<td>17 min</td>
<td>0 %</td>
<td>1.39</td>
</tr>
<tr>
<td>B2</td>
<td>27 min</td>
<td>16 min</td>
<td>0 %</td>
<td>1.55</td>
</tr>
</tbody>
</table>

The beam scans done in the LHC are shown in Fig. 2 for beam 1 and in Fig. 3 for beam 2. The LHC scans confirm the large transverse tails in case the beams are not scraped before injection. When the beams are scraped this measurements show that scraping in the SPS successfully removes the tails and that the tails are not repopulated through the injection process or any other mechanism during the injection plateau. The 30 minutes waiting time before the beam 2 scan could be started corresponds roughly to the time the LHC filling takes.

In Table 2 the fit results for the double Gaussian (Eq. 1) are given as a reference for the three cases.

Table 2-Gauss

<table>
<thead>
<tr>
<th>Time after injection</th>
<th>Scan duration</th>
<th>SPS scraped intensity</th>
<th>Emittance $\varepsilon_H [\mu m]$</th>
<th>Emittance $\varepsilon_V [\mu m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
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<td>17.8 %</td>
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</tr>
<tr>
<td>B1</td>
<td>8 min</td>
<td>17 min</td>
<td>0 %</td>
<td>1.39</td>
</tr>
<tr>
<td>B2</td>
<td>27 min</td>
<td>16 min</td>
<td>0 %</td>
<td>1.55</td>
</tr>
</tbody>
</table>
SPS SCRAPING AND LHC INJECTION LOSSES

The last part of the machine development study was dedicated to investigate scraping depth versus losses on the collimators in the transfer lines between the SPS and the LHC. The transfer line collimators are located close to the LHC injection point and the losses on the collimators are picked up by the LHC beam loss monitoring system [3].

The setting of the transfer line collimators was $5\sigma$. Before starting the measurements in the LHC another beam scan was done in the SPS to determine the profile and intensity in the tails, see Fig. 4. Large transverse tails were apparent. An intermediate intensity beam of 6 bunches was used for this study. The test then consisted of recording the losses in the injection region and emittance in the SPS as a function of the scraper settings.

Without scraping the losses scaled to a 144 bunch injection reach 50\% of dump threshold for beam 1 and 30\% for beam 2. Injection with tighter collimator settings (e.g. 4.5 $\sigma$ as in the beginning of the LHC run 1) or of a full 25 ns batch of 288 bunches would trigger a beam dump without scraping in the SPS.

As can be seen from Fig. 5 and 6 low enough losses are reached with a scraper setting of about 3 $\sigma$ from the beam center, where $\sigma$ is calculated assuming nominal emittance. At this level the emittance of the beam is not affected, only tails are scraped. This corresponds to scraping around 2-3\% of the beam intensity, as can be seen from Fig. 4. This is similar to the operational values used during LHC fills, see Fig. 7. For beam 2 one of the BLMs still show some losses as this point, to be investigated further together with losses coming from trajectory offsets. At this scraping level a 2 $\sigma$ margin is left for offsets in the transfer line trajectories. For the original 4.5 $\sigma$ setting of the LHC transfer line collimators scraping of about 5\% of the intensity would have been required for similar loss levels.

Table 2: Comparison of fit results, and the LHC with (*) and without scraping in the SPS.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_1[\sigma]$</th>
<th>$\sigma_2[\sigma]$</th>
<th>$I_1$</th>
<th>$I_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS</td>
<td>0.60±0.26</td>
<td>1.27±0.31</td>
<td>0.54±0.29</td>
<td>0.46±0.29</td>
</tr>
<tr>
<td>LHC B1*</td>
<td>0.44±0.07</td>
<td>0.78±0.05</td>
<td>0.29±0.08</td>
<td>0.71±0.08</td>
</tr>
<tr>
<td>LHC B1</td>
<td>0.59±0.05</td>
<td>1.33±0.05</td>
<td>0.53±0.04</td>
<td>0.47±0.04</td>
</tr>
<tr>
<td>LHC B2*</td>
<td>0.77±0.03</td>
<td>8.27±106</td>
<td>1.00±0.02</td>
<td>0.00±0.02</td>
</tr>
<tr>
<td>LHC B2</td>
<td>0.65±0.04</td>
<td>1.36±0.05</td>
<td>0.58±0.05</td>
<td>0.42±0.05</td>
</tr>
</tbody>
</table>
Figure 7: The amount scraped for LHC fills is given in black. Normally 2-4 % of the beam is scraped to remove tails. The beam losses are given for a number of BLMs in the injection region.

Figure 5: Beam losses at injection for varying scraper depths are shown for beam 1. The losses are scaled to 144 bunches and taken with respect to the LHC dump thresholds. If the beam is not scraped the losses are above 50 % of dump thresholds. Scraping reduce the losses to an acceptable level already at 3 \( \sigma \) while the emittance is not reduced until around 2 \( \sigma \).

**SUMMARY**

The effect of transverse tail scraping in the SPS on injection losses and tail population in the LHC has been studied. The tests were done using a low intensity beam of 3-6 bunches. At the end of the LHC injector chain the transverse distribution of the beams has substantial non-Gaussian tails. To achieve acceptable losses at injection into the LHC around 3 % of the intensity need to be scraped in the SPS. This corresponds to a scraper setting at around 3 nominal \( \sigma \) from the beam center.

By scraping the whole beam and recording at the same the scraped intensity as function of scraper position one can reconstruct the original transverse profile. This technique was used in the SPS with the scrapers and also in the LHC.

**REFERENCES**

A.7 Analysis of LHC Transfer Line Trajectory Drifts

Poster presentation at the International Particle Accelerator Conference (IPAC), May 2013 in Shanghai, China [64].
ANALYSIS OF LHC TRANSFER LINE TRAJECTORY DRIFTS

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Abstract

The LHC is filled from the SPS via two 3 km long transfer lines: TI2 for beam 1 and TI8 for beam 2. In the first years of LHC operation large trajectory variations were discovered. The sources of bunch-by-bunch and shot-by-shot trajectory variations had been identified and improved by the 2012 LHC run. The origins of the longer term drifts were however still unclear and significant time was spent correcting the trajectories. In the last part of the 2012 run the optics in the SPS was changed to lower transition energy. Trajectory stability and correction frequency will be compared between before and after the optics change in the SPS. The sources of the variations have now been identified and will be discussed in this paper. Remedies for operation after the long shutdown will be proposed.

INTRODUCTION

After the first two years of LHC operation the machine had proven to be working remarkably well, but there were still issues to be addressed. One of the concerns was the long turnaround time, especially influenced by the time spent at injection [1]. The time spent at injection was higher partly due to unstable trajectories in the SPS-to-LHC transfer lines, TI 2 and TI 8, which required correction to avoid high beam loss at injection [2].

By the start of 2012 sources of bunch-by-bunch trajectory variations and short term trajectory variations had been identified and mitigated. The main source of trajectory variations was found to be the SPS extraction septa (MSE). After efforts of the power converter team the MSE current ripple could be reduced and the trajectory variations went down by a factor 2 [3].

TRAJECTORY CORRECTIONS

During the 2012 run the LHC was operating with 50 ns bunch spacing. The filling scheme consisted of a low intensity pilot bunch injection and an intermediate injection of 6 bunches, then 11 high intensity injections (72 or 144 bunches). For safe operation, transfer line corrections need to be followed by test injections of lower intensity (6 or 12 bunches) and time is lost as the beam must be dumped to refill with the correct filling pattern afterwards. On average a steering campaign requires 30 minutes.

For most of the 2012 run transfer line corrections were required 1-2 times per week to keep injection oscillations and injection losses within predefined limits. Towards the end of the run, after LHC Technical Stop 3 (17-21 September 2012), the frequency increased to once a day, see Fig. 1. During this technical stop the optics in the SPS had been changed to the lower transition energy optics Q20 [4]. It was suspected that there was a relation to the increased correction frequency.

ANALYSIS OF TRAJECTORY DRIFTS

To investigate trajectory variations in the transfer line a large number of trajectories were analysed. In order to find the true variations, the effect of corrections was calculated and subtracted from the measured trajectories. From these trajectories the difference trajectories with respect to the average of the set were calculated and analysed. The eigenmodes of these difference trajectories were obtained by Model Independent Analysis (MIA) [5]. Through singular value decomposition, MIA finds the eigenmodes corresponding to independent sources of oscillation and gives the spatial and temporal eigenvectors.

Two periods were used to examine if there was degradation due to the change in SPS optics: July-September with Q26 optics and October-November with the new Q20 optics after the technical stop.

TI 2 Results

![TI2 Eigenmodes](image)

Figure 2: The observed variations for a period before the last technical stop is shown in grey. The variations are around 3 mm peak-to-peak in the horizontal plane. The MIA eigenmodes are given in the plot scaled by their eigenvalues. Only the two largest ones give a significant contribution indicating that there are two sources of variation. In the vertical plane the variations are small.

In Fig. 2 and 3 the difference trajectories in the two periods are shown. For both periods there are large variations in the horizontal plane. In the vertical plane the variations are
Figure 1: Frequency of transfer line corrections are shown for a period in summer with normal optics and for a period after the SPS optics change during the technical stop (shown in grey). The correction frequency dramatically increased from 1-2 times per week to almost daily in the second period.

Figure 3: The plot shows trajectory variations after the SPS optics change. The variations have approximately the same size as before, but the pattern is different.

TI 8 Results

For TI 8 the calculated variations are shown in Fig. 4 and 5. Also for TI 8 the variations are stronger in the horizontal plane. After the optics change the variations are similar, also here the pattern is slightly different. Nevertheless for both cases there are two strong eigenmodes indicating the same two sources.

Sources

The sources of variation can be found as linear combinations of the significant eigenmodes. The eigenmodes were matched to simulations of possible sources, see Fig. 6 for TI 2. The data used are from the second period. As expected the MSE is still a source. Other elements were also investigated, but are not strong enough to cause the variations observed in the transfer lines. The orbits in the SPS were monitored over a period of a few weeks and the resulting variations at the extraction point calculated. The orbit variations match the second source of trajectory variations in the transfer lines.

Even larger SPS orbit changes than seen during regular
INJECTION LOSSES

Trajectory corrections are often initiated by beam losses in the injection region or at the primary collimators, which are above the reference thresholds. Increased losses after the technical stop are seen at the BLMs at the TDI (injection protection element) and the TCP (downstream LHC collimators). Losses at the transfer line collimators (observed at MSI BLMs) did not increase, see Fig. 7. This signature indicates that the losses come from the longitudinal rather than the transverse plane. In this case transfer line corrections do not reduce the losses. The losses could possibly come from an increased satellite population (low intensity bunches between the nominal 50 ns spaced nominal bunches), but need to be investigated further. The losses at the TCP are very high and often above 50 % of the dump thresholds which could explain why the operators felt compelled to correct the transfer lines. The diagnostics will be improved to better guide the operators on when to steer the transfer lines.

REFERENCES

A.8 Investigations of SPS Orbit Drifts

*Poster presentation* at the *International Particle Accelerator Conference (IPAC)*, June 2014 in Dresden, Germany [65]. Presented by C. Bracco.
INVESTIGATIONS OF SPS ORBIT DRIFTS
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E. Gianfelice-Wendt, Fermilab∗, Batavia

Abstract
The LHC is filled from the last pre-injector, the Super Proton Synchrotron (SPS), via two 3 km long transfer lines, TI 2 and TI 8. Over the LHC injection processes, a drift of the beam trajectories has been observed in TI 2 and TI 8, requiring regular correction of the trajectories, in order to ensure clean injection into the LHC. Investigations of the trajectory variations in the transfer lines showed that the main source of short term trajectory drifts are current variations of the SPS extraction septa (MSE). The stability of the power converters has been improved, but the variations are still present and further improvements are being investigated. The stability over a longer period of time cannot be explained by this source alone. The analysis of trajectory variations shows that there are also slow variations in the SPS closed orbit at extraction. A set of SPS orbit measurements has been saved and analysed. These observations will be used together with simulations and observed field errors to locate the second source of variations.

INTRODUCTION
The trajectories in the SPS to LHC transfer lines are drifting and must be corrected frequently. Each correction campaign costs significant time and buys into the availability for LHC physics. The variations are seen mainly in the horizontal plane. An analysis of the origin of the trajectory variations revealed several sources. The ripple of the 20 kA power supply of the SPS extraction septum (MSE.6 for TI 2 and MSE.4 for TI 8) is one of the main sources for both transfer lines. After the improvement of the ripple between the LHC runs 2011/2012, the shot-by-shot stability was greatly improved, but trajectory drifts prevail. In addition to the MSE, the variation of the SPS orbit is suspected to be a large source [1, 2]. Towards the end of LHC run 1, SPS orbit data during LHC physics beam cycles was collected and analysed to localise the source of the orbit drifts.

OBSERVATIONS OF SPS ORBIT DRIFTS
SPS orbit data was only stored towards the end of LHC run I and therefore limited data is available for analysis. To isolate effects on the circulating orbit from extraction, the orbit data was saved at the flat-top (T=18500 ms), 300 ms before extraction. By taking the difference orbit from a reference, the changes are tracked. The orbits were filtered to take into account only data where the beam was successfully extracted and injected in the LHC.

In the extraction region, a horizontal orbit bump of more than 35 mm is applied to move the circulating beam as close as possible to the extraction septum and reduce the required strength of the extraction kicker. The data of the larger aperture Beam Position Monitors (BPMs) in the extraction region have large errors and cannot be used directly to define the beam position and angle at the extraction point. A fit based on many BPMs was used to obtain a better estimate. Each orbit is fitted using the function
\[ X(s) = [A \times \sin(\mu(s)) + B \times \cos(\mu(s))] \times \sqrt{\beta(s)} + \frac{dp}{p} \times D(s) \]
which represents a betatron oscillation plus a dispersion orbit due to momentum offset, dp/p. The fit parameters A, B and dp/p are calculated by a least square fit routine in python.

From the fitted parameters the orbit excursions at two BPMs in the extraction region are calculated. Fig. 1 shows the orbit drifts at BPCE.61805 and BPCE.41801 for extraction from SPS LSS6 to TI 2 and SPS LSS4 to TI 8 respectively. In the horizontal plane the orbit is drifting by 1.4 mm at BPCE.61805 and 1.8 mm at BPCE.41801. In the vertical plane the orbit is stable.

Figure 1: The orbit variation calculated at BPCE.61805 (TI 2) and BPCE.41801 (TI 8) shows a significant drift in the horizontal plane with respect to the reference orbit (grey line).
MATCHING SPS ORBIT DRIFTS TO TRANSFER LINE TRAJECTORY DRIFTS

For the transfer line trajectory drifts previous analysis showed that there are many sources without any clear candidates [2]. Using the fitted SPS orbit data now available, the effect of orbit drifts in the transfer lines were calculated in MAD-X and subtracted from the corresponding measured trajectories. Only the betatron motion was included. For TI 2 the total RMS was reduced from 318 to 158 μm in the horizontal plane and from 126 to 102 μm in the vertical plane. For TI 8 the reduction was 348 to 198 μm in the horizontal plane and from 138 to 106 μm in the vertical plane. The jitter of the extraction septa (MSE6 for TI 2 and MSE4 for TI 8) explain part of the remaining variations. The remainder is a mix of several smaller sources in both planes.

SPS SOURCE INVESTIGATIONS

To investigate the sources of orbit drifts, the orbits have been analysed by Model Independent Analysis (MIA) [3]. Through singular value decomposition MIA separates the temporal and spatial eigenmodes of the orbit data. The spatial eigenmodes with significant eigenvalues can be used to identify the sources of variation. In this case there are two large eigenvalues in the horizontal plane, see Fig. 2. In the vertical plane the eigenvalues are small and will not be considered further.

Figure 2: Two strong eigenmodes are found from the MIA analysis, indicating that there are multiple sources.

When there are two strong modes, the actual sources may be a mix of those modes. Therefore the analysis period has been divided into two periods. From Fig. 1 two natural choices appear: 13/10-24/10 and 29/10-4/11. For both periods there are significant variations. There is only one significant eigenmode for each period, see Fig. 3.

Because the SPS has many elements, there could in principle be many sources that match with the same phase advance. To identify the location of the sources, MICADO was used to find the best single corrector among all elements in the machine for all orbits within a given period. Afterwards, a selection of elements, including all extraction elements was compared to the MIA eigenmodes.

For the first period the best correctors were found to be: MDHB.61804 (orbit corrector) and the MST.617 (thin septum) in LSS6, see Fig. 4. These two elements have a difference in phase advance of 2°. The MSE.618 is only 4° upstream of the MDHB. The MSE.418 in LSS4 also shows up frequently, however only for small orbit differences. The same elements all match the MIA analysis, see Fig. 5.

For the first period the MST.617 and MDHB.61804 show up as the main correctors.

The above found sources do not fit for the second period. From the MICADO algorithm, the best corrector was found to be the dipole MBA.606, see Fig. 6. For the MIA eigenmode the best match is the extraction bumper MPSH.62199 followed by MBA.606 and MPLH.61655 (extraction bumper.
Figure 5: Best matches for the 359 µm spatial mode in the period 13/10-24/10.

The MSE.418 also fits reasonably well. Sources with the same phase advance $+N \times 180^\circ$ cannot be distinguished and therefore several candidates match as a source. Elements in LSS6 are most frequently proposed as correctors by MICADO for both periods.

Figure 6: The best corrector for this period is the dipole MBA.606, followed by QD.133 and MBB.606.

Figure 7: The best matches for the period 29/10 - 4/11. For the extraction bumpers the logged currents were checked for drifts, but the variations were found to be too small to cause the observed orbit variations. The MBHA.61804 current is not logged, but this orbit corrector should not be active at flat-top. For the MSE and the MST, the circulating beam only sees the stray fields. Lab measurements show that the strength of the stray fields depend on the distance from the septum [4]. Because of the extraction bump the distance to the septa varies strongly over the length of the septum magnet, see Fig. 8. Therefore a model of the bump and septum was made to estimate the effect of the stray field due to a 1 mm change of the orbit. The outcome of the study is however that the stray field of the MSE and MST in LSS6 give additional orbit deviations of only 14 and 7 µm peak-to-peak respectively, which is too small to explain the drifts.

Figure 8: Extraction bump and septa for LSS6 extraction of LHC beam 1. The distance of the bump to the MST varies between 18 and 22 mm and 23 to 63 mm to the MSE.

SUMMARY

SPS orbit data collected over one month have been analysed to find the sources of orbit drifts and consequently transfer line trajectory drifts. Combining the data with transfer line trajectory data showed that the SPS orbit drift is the main contribution to drifts in the transfer lines.

Analysis of orbit data over a month shows that there are two large sources. Several candidates where checked and have the correct phase advance, however no element has been identified with large enough errors to cause the observed variations. In parallel an orbit correction strategy has been investigated [5].

REFERENCES

Appendix B

Basic Concepts of Accelerator Physics

There are many books and lectures on the topic of accelerator physics. In this appendix only a small selection will be covered, mainly focusing on the transverse beam dynamics. For a thorough introduction see for example Particle accelerator physics by H. Wiedemann [66] or Accelerators for pedestrians by S. Baird [67].

Coordinate System

To describe the particle motion on a ring it is useful to transform the coordinates into a system that follows the accelerator circumference: \((s, x, y)\), where \(s\) gives the position on the circumference and \(x\) and \(y\) are transverse coordinates with respect to \(s\) in the horizontal and vertical plane, see Figure B.1.

![Coordinate System](image)

Figure B.1: A rotating coordinate system \((s, x, y)\) which follows the longitudinal motion along the accelerator is used to describe the particle motion. *Figure from [67].*

Magnetic fields

The force on a charged particle in electric and magnetic fields is given by the Lorentz force

\[
\vec{F} = q \left( \vec{E} + \vec{v} \times \vec{B} \right).
\]  

(B.1)

In particle accelerators both components are used. Electric fields are used to give energy to the particles and magnetic fields are used to guide the particles on the desired trajectory.
B. BASIC CONCEPTS OF ACCELERATOR PHYSICS

Dipole fields

The basic magnetic structure in an accelerator is composed of dipole and quadrupole magnets. To contain the particles on a circular orbit, dipole fields are used. The required strength of the dipole field can be calculated by

\[ \frac{mv^2}{\rho} + e(\vec{v} \times \vec{B}) = 0, \]  

(B.2)

where \( \rho \) is the bending radius. Assuming that the magnetic field is perpendicular to the particle motion we have

\[ |\vec{B}| = \frac{p}{\rho e}. \]  

(B.3)

Quadrupole fields

The second important component is the quadrupole field. Quadrupole fields have a linear dependency on the particle distance from the central axis

\[ B_x \propto y, B_y \propto x. \]  

(B.4)

Quadrupole magnets are focusing in one plane and defocusing in the other.

The FODO cell

A series of dipole and quadrupole magnets are organised in a FODO lattice. One FODO cell contains one focusing quadrupole (QF) and one defocusing quadrupole (QD) with a number of dipole magnets in between, see Figure B.2. The FODO cell is the most common lattice use in accelerators and long transfer lines and gives a net focusing effect.

![FODO cell diagram](image)

Figure B.2: A FODO cell consisting of a focusing and a defocusing quadrupole with drift space or dipole magnets in between. *Figure from [67]*.
Equations of Motion

The particles oscillate around the central orbit experiencing the focusing and defocusing force of the quadruple magnets, see Figure B.3. These oscillations are called betatron oscillations. The particle motion in each plane can be described by Hill’s equation

\[
\frac{d^2x}{ds^2} + K(s)x = 0, \tag{B.5}
\]

where \( K \) is the restorative force created by the quadrupole magnets. The solution to Hill’s equation is

\[
x(s) = \sqrt{\varepsilon \beta(s)} \cos(\mu(s) + \mu_0) \tag{B.6}
\]

and

\[
x'(s) = -\sqrt{\frac{\varepsilon}{\beta(s)}} \left( \alpha(s) \cos \left[ \mu(s) + \mu_0 \right] + \sin \left[ \mu(s) + \mu_0 \right] \right), \tag{B.7}
\]

where \( \alpha(s) = -\frac{\beta(s)'}{2} \). \( \beta(s) \) is the \( \beta \)-function and \( \mu(s) \) is the phase advance. The parameters \( \varepsilon \) and \( \mu_0 \) are constants which depend on the initial conditions. The \( \beta \)-function depends on the focusing properties of the lattice. In Figure B.3 the \( \beta \)-function in a FODO lattice is illustrated. The focusing effect and thus the \( \beta \)-function is maximum in the focusing quadrupole magnets. The phase advance \( \mu(s) \), also depend on the focusing properties of the lattice

\[
\frac{d\mu(s)}{ds} = \frac{1}{\beta(s)}. \tag{B.8}
\]

The tune \( Q = \frac{\Delta\phi(s)}{2\pi} \), is the phase advance over one turn.

Emittance

The constant \( \varepsilon \) is the beam emittance and relates to the beam size \( \sigma \), by

\[
\sigma = \sqrt{\varepsilon \beta}. \tag{B.9}
\]

The beam size here refers to the RMS of the particle distribution in the beam. The emittance shrinks with energy during acceleration and a normalised energy independent emittance is defined as

\[
\varepsilon^* = \frac{p}{m_0c} \varepsilon. \tag{B.10}
\]

The normalised energy independent emittance can be used as a measure of the beam quality under acceleration. In this thesis emittance normally refers to the normalised energy independent emittance. The emittance is a constant of motion in an accelerator or storage ring, however as seen in Chapter 3 there are processes which lead to emittance growth.

The beam size and thus emittance is important for the collider luminosity

\[
\mathcal{L} \propto f \frac{n_b N_1 N_2}{\sigma_x \sigma_y}. \tag{B.11}
\]
B. BASIC CONCEPTS OF ACCELERATOR PHYSICS

Figure B.3: The resulting $\beta$-function in the horizontal and vertical plane of a FODO cell is shown. A focusing quadrupole field in the horizontal plane is defocusing in the vertical plane. The $\beta$-function is a result of the focusing and defocusing fields. At the focusing quadrupoles the $\beta$-function is maximum. In the defocusing quadrupoles on the other hand, the $\beta$-function is minimum. Below each plot the phase space at the quadrupole magnets are shown. 

*Figure from [67]*.
Here $N_1$ and $N_2$ are the number of particles per bunch in the two beams, $n_b$ the number of colliding bunches and $f$ the revolution frequency.

**Dispersion and Chromaticity**

For particles with a different momentum $\frac{dp}{p}$, the movement through the dipole and quadrupole fields will be different. This gives a contribution to the transverse motion

$$\Delta x(s) = D(s) \frac{dp}{p}, \tag{B.12}$$

where $D(s)$ is the dispersion function. The dispersion can be suppressed in some regions like the interaction points by inserting a dispersion suppressor cell. Another effect of momentum spread is tune spread, $\frac{dQ}{Q} = \xi \frac{dp}{p}$, where $\xi$ is called the chromaticity.

**Transport Matrix**

The equations of motion can be described by a transfer matrix. By setting $\mu_0 = 0$ at $s = 0$ we have the matrix

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \frac{\sqrt{\beta}}{\sqrt{\beta_0}} (\cos \mu + \alpha_0 \sin \mu) & \frac{\sqrt{\beta_0} \sqrt{\beta} \sin \mu} \\ (\alpha_0 - \alpha) \frac{\cos \mu - (1 + \alpha \alpha_0) \sin \mu} {\sqrt{\beta} \sqrt{\beta_0}} & \frac{\sqrt{\beta_0}}{\sqrt{\beta}} (\cos \mu - \alpha \sin \mu) \end{pmatrix} \times \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}. \tag{B.13}$$

From this matrix we can calculate the particle trajectory $x, x'$ from $\beta, \alpha$ and $\mu$. These parameters are called the twiss parameters. Normally the twiss parameters and resulting particle trajectories are calculated using an optics code called MAD-X [48].
References


REFERENCES


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