ACCELERATORS FOR PHYSICS EXPERIMENTS: FROM
DIAGNOSTICS AND CONTROL TO DESIGN

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Abstract

This thesis develops techniques of control-methods, optimization, and diagnostics of accelerator equipment and the produced particle beams with emphasis on the Large Hadron Collider (LHC) project at CERN. From a solid knowledge of the characteristics of the manufactured accelerator equipment gained from in-depth measurements and analysis of measured data, a link to an enhanced equipment design can be made. These techniques will be demonstrated in applications related to the LHC magnet production and to the LHC upgrade studies.

The LHC is a 27 km long superconducting accelerator, which CERN, the European high-energy particle physics research organisation, is presently being commissioned in a tunnel 80 m underground in the Geneva region. This machine forms the last link in an interconnected chain of several particle accelerators at CERN. The overall system performance, i.e. the quality of particle beams being accelerated in this accelerator chain is directly related to the control of the quality of the superconducting magnets used in the last link, in the LHC. Different upgrade scenarios to reach the ultimate design luminosity and beyond that, implying major machine changes are presently being studied. These scenarios all pose very challenging design requirements for magnets situated in the beam collision regions where extremely radioactive environments have to be dealt with. The LHC is expected to produce very highly energetic and intense particle beams for a number of physics experiments during the next decades, making the subjects of the thesis both timely and important.

The work described has been performed at CERN, which has become the largest high-energy physics laboratory in the world. Here, a number of particle accelerators are connected in series to permit the acceleration of particles to unprecedented high energies to explore the nature of our universe. The accelerators at CERN are assembled of a large number of parts requiring a high level of technological know-how. Control systems and optimization procedures play a natural and necessary role to fulfil the requirements. Diagnostics and control system technology have been used to increase the efficiency of accelerator operation. An extensive analysis of the measured magnetic field have been used to optimize the delicate process of controlling the assembly of superconducting accelerator magnets for the LHC. This paper also describes the control procedures developed, to permit the adjustment of the geometric shape of the 15 m long dipole to optimize the field quality and beam aperture.

From a detailed statistical analysis of the collected geometry data from the 1232 LHC main dipole magnets unresolved issues concerning the measurements were explained and corrected, providing more accurate information for the alignment of the main dipoles and quadrupoles.

The LHC will start operation in 2008, after a most careful installation of all magnets and a huge volume of other equipment in the accelerator tunnel. In particular, the very specialized welding techniques and the brazing of tubes, bellows and conductors, have posed great challenges. Tenths of thousands of welds that have to withstand temperature changes of 300 K and operation with super-fluid helium at 1.9 K have been made. The magnet systems that create the conditions for particle collisions in the two main experiments, the insertion triplets, will have to be exchanged when upgrading the performance of the machine. The upgrade of the machine’s luminosity is expected after 4 years of LHC operation at nominal luminosity. Unless the new
magnets are very carefully designed and well shielded the particle debris from the increased collision rates will perturb their operation. Using a new superconductor technology, limiting the probability of magnet quenches, combined with a new layout of the insertion region can minimize the effect of the impinging debris. The necessary shielding layout to protect the magnet coils will be discussed.

The future of accelerators for particle physics is important: the development of accelerator technology to produce neutrino beams from beta decaying ions is one possibility for new physics. This subject will be treated from the aspect of energy deposition from decay products in superconducting magnet coils.
1. Introduction: CERN and the challenges ................................................................. 8
   1.1. The CERN laboratory .................................................................................. 9
   1.2. Background .............................................................................................. 10
   1.3. Physics motivation .................................................................................. 11
   1.4. Higher and higher energies ..................................................................... 13
   1.5. The CERN particle accelerators .............................................................. 15
2. Overview of presented papers and emphasis on particular contributions by the author ...... 18
   3.1. Experiments to test Beam Behaviour Under Extreme Space Charge Conditions .... 24
   3.2. Automated beam steering in the PS complex ........................................... 25
4. Superconducting magnets for LHC ..................................................................... 28
   4.1. Superconducting technology for hadron colliders ........................................ 28
   4.2. Building the LHC dipole ......................................................................... 31
   4.3. The magnetic field description of the dipole .............................................. 34
   4.4. What is the effect of the field errors in the LHC? ........................................ 41
   4.5. The measurements of the magnetic field in the LHC dipole ....................... 42
   4.6. The dipole magnetic field quality control and results for the quality of the assembly .... 43
   4.7. The software system for the quality control of the magnetic measurements ....... 43
   4.8. Requirements on the geometry of the dipoles for the LHC beam ................. 44
   4.9. The measurements of the geometry .......................................................... 48
   4.10. Adjustments of the geometry and final results ......................................... 49
5. Improving geometry measurements of the LHC magnets ...................................... 53
   5.1. The measurement errors .......................................................................... 54
   5.2. Observations ............................................................................................ 57
   5.3. The correction algorithm .......................................................................... 59
   6.1. The magnet evaluation board ..................................................................... 65
7. Design of large aperture superconducting dipoles for a beta beam decay ring .......... 66
   7.1. Neutrino production and neutrino physics ............................................... 66
   7.2. A beta beam facility at CERN .................................................................. 69
   7.3. The need for a 6T dipole ......................................................................... 71
   7.4. Dipole design .......................................................................................... 73
   7.5. Energy deposition in the dipole ............................................................... 75
   7.6. Energy deposition in the magnet coil ....................................................... 76
   7.7. More detailed simulations ...................................................................... 81
8. LHC upgrade projects .................................................................................... 84
   8.1. Energy deposition in the baseline LHC insertions ....................................... 84
   8.2. The LHC upgrade ..................................................................................... 89
9. Conclusion ...................................................................................................... 92
10. Acknowledgements ......................................................................................... 94
11. Appendix I ..................................................................................................... 95
12. Appendix II ..................................................................................................... 97
13. References ...................................................................................................... 99
1. INTRODUCTION: CERN AND THE CHALLENGES

The nature of our universe has always intrigued man. The exploration of what we are, why we are and where we are has been objects of large efforts since the beginning of our existence see Figure 1. Today, to construct and exploit the tools needed to continue this exploration require extensive collaboration efforts, in both economical and intellectual terms. The CERN laboratory is a fruit of a successful collaboration in Europe now housing a large number of different particle accelerators of varying sizes used to explore physics. Other non-European countries have joined CERN and its many physicists as partners to share this quest for new knowledge.

Particle accelerators can accelerate different kinds of particles such as electrons, positrons, protons, antiprotons and ions. The accelerated particles are formed into beams which can be guided using magnetic or electrical fields to strike and to interact with the target material or made to collide and interact with other accelerated particles. By studying the results of these interactions our knowledge about matter is successively improved. Increasing the energy of the accelerated particles provides us with a better tool to probe the structure of the particles making up matter and their interactions. An increase of the particle energy results in an increase of the power of resolution of our observation, which in turn brings us closer to the conditions that existed in our universe at its “birth”. This increase in particle energy has a price: either the magnets providing the guiding field are made stronger to contain the particles in the machine or the radius of the accelerator is enlarged.

The LHC machine, now being assembled at CERN [LHC11], actually uses both options. The magnetic field used in the main bending dipole magnet is an unprecedented 8.35 T and the circumference of the machine is a huge 27 km. The LHC machine is the last link in a chain of CERN accelerators that are required to permit the acceleration of protons from rest energy to 7 TeV, and important upgrades of all these machines have been made [Ben05] to enable the best possible performance. Many issues related to diagnostics are of vital importance for the technologically very challenging scientific instrument which is the LHC. Particle accelerators are equipped with extensive diagnostic tools and real-time controls. Automatic beam steering, beam tuning and detailed knowledge of the properties of the superconducting magnets, some of the subjects treated in this work, are major issues when trying to reach 7 TeV.
1.1. The CERN laboratory

CERN is located in the Geneva area, extending over both French and Swiss territory (Figure 2). It has 20 member states with 6,500 researchers of 85 nationalities using its facilities. Due to its success in particle physics research and the skills of its accelerator builders, the Organisation has been able to grow and presently CERN is the largest physics laboratory in the world dedicated to fundamental research only; all research results from CERN are freely available. The history of CERN is described for example in [Her87], [Her90] and [Her96]. Another overview with impressions from the real working environment at CERN is [Jac81].

Figure 2: Map of the region close to Geneva where the CERN site is located. The extent of the 27 km Large Hadron Collider is indicated.

The Organization’s budget today is of the order of 1 billion Swiss francs. Contributions are shared between the member states in proportion to their GNP: Germany, Italy, France and the United Kingdom are the main contributors. A number of major non-European nations participate in the LHC accelerator project having an observer status.

In the LHC experiments, ATLAS, CMS, ALICE and LHC-b (see Figure 3), universities and research institutes from all over the world collaborate and contribute to the common effort either with in-kind services and equipment or by sharing costs directly with funds.
Figure 3: Aerial view of the physics research facility CERN in Geneva (left). The Large Hadron Collider and the experiments Atlas, CMS, LHC-b are shown to the right.

ALICE, “A Large Ion Collider Experiment”, will observe proton and lead ion collisions in LHC. The experiment will study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected. ATLAS, “A Toroidal LHC Apparatus” and CMS, “The Compact Muon Solenoid”, look for the Higgs Boson, supersymmetry and aspects of heavy ion collisions. LHC-b, the LHC Beauty experiment, will make precision measurements of CP violation and rare decays.

1.2. Background

During the first half of the last century, European achievements and research dominated physics progress. After the Second World War, some of the leading physicists, Rabi, Amaldi, Auger and de Rougemont, realised, that only international co-operation could advance the science of physics and support the construction of new, powerful, expensive research facilities. The creation of a European high energy particle physics laboratory was recommended by a UNESCO meeting in Florence in 1950, and less than three years later a convention was signed by 12 countries creating the Conseil Européen pour la Recherche Nucléaire.

Many important ideas and innovations in the accelerator domain have originated at CERN and were developed at machines such as the Intersecting Storage Rings (ISR), the Super Proton Synchrotron (SPS) and the proton-antiproton collider, the $SppS$. The first $W$ and $Z$ particles were produced at $SppS$, confirming the unified theory of electromagnetic and weak forces. The Large Electron-Positron Collider (LEP) tested extensively, with measurements unsurpassed in quantity and quality, the “Standard Model” [Ait05]. LEP data are very accurate and have sensitivity to phenomena that occur at energies beyond those of the machine itself, permitting a speculative “preview” of exciting potential new discoveries.

The evidence from LEP data analysis indicates that new physics should be discovered at centre-of-mass energies for proton-proton collisions around 1 TeV. LHC has been designed for this search and it is now installed in the 27-kilometre tunnel. LHC will be injected with beams coming from CERN’s existing particle sources and accelerators. This reuse of existing
installations has been the hallmark of CERN since its beginning and is one of the major reasons for the laboratory’s success and longevity.

The LHC is a superconducting accelerator, by which is understood that the main bending and focussing magnet are built using superconducting technology. The main bending magnet has a field of 8.35 T at 7TeV proton energy. The LHC will be a versatile accelerator. It will accelerate proton beams to energies around 7 TeV collide them in beam crossing points, providing the experiments with high interaction rates. It will also be able to accelerate and bring into collision beams of heavy ions such as lead with a beam energy of 2.76 TeV/nucleon. Colliding lead ions will yield a total centre-of-mass energy of 2*208*2.76 TeV=1.15 PeV, about thirty times higher than the centre-of-mass energy available at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven Laboratory in the US. LHC has been designed for theoretically predicted phenomena; however the machine is also built to offer possibly new discoveries not predicted by current theory.

1.3. Physics motivation

Physics tries to give unified descriptions of the behaviour of matter and radiation. For a long time physicists considered matter to be constituted by fundamental particles and constructed an elaborate system of particle classification.

The present “Standard Model” of particle physics sorts the elementary particles into three families, see Table 1. There are two quarks (and their antiparticles) and two leptons in each family: the "up" and "down" quarks, the electron and the electron-neutrino are in the first; the "strange" and the "charm" quark, the muon and the muon neutrino in the second; the "top" and the "bottom" quark, the tau and the tau neutrino in the third.

The Standard Model contains both fermionic and bosonic fundamental particles. Fermions are particles which possess half-integer spin and obey the Pauli exclusion principle, which states that no fermions can share the same quantum state. Bosons possess integer spin and do not obey the Pauli exclusion principle. Informally speaking, fermions are particles of matter and bosons are particles that transmit forces.
### Generation 1 (ordinary matter)

<table>
<thead>
<tr>
<th>Fermion (Left -handed)</th>
<th>Symbol</th>
<th>Electric charge</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>e</td>
<td>-1</td>
<td>0.511 MeV</td>
</tr>
<tr>
<td>Electron neutrino</td>
<td>νₑ</td>
<td>0</td>
<td>&lt; 50 eV</td>
</tr>
<tr>
<td>Positron</td>
<td>e⁺</td>
<td>+1</td>
<td>0.511 MeV</td>
</tr>
<tr>
<td>Electron antineutrino</td>
<td>νₑ⁻</td>
<td>0</td>
<td>&lt; 50 eV</td>
</tr>
<tr>
<td>Up quark</td>
<td>u</td>
<td>+2/3</td>
<td>-5 MeV</td>
</tr>
<tr>
<td>Down quark</td>
<td>d</td>
<td>-1/3</td>
<td>-10 MeV</td>
</tr>
<tr>
<td>Anti-up antiquark</td>
<td>u⁺</td>
<td>-2/3</td>
<td>-5 MeV</td>
</tr>
<tr>
<td>Anti-down antiquark</td>
<td>d⁺</td>
<td>+1/3</td>
<td>-10 MeV</td>
</tr>
</tbody>
</table>

### Generation 2

<table>
<thead>
<tr>
<th>Fermion (Left -handed)</th>
<th>Symbol</th>
<th>Electric charge</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon</td>
<td>μ</td>
<td>±1</td>
<td>105.6 MeV</td>
</tr>
<tr>
<td>Muon neutrino</td>
<td>ν_μ</td>
<td>0</td>
<td>&lt; 0.5 MeV</td>
</tr>
<tr>
<td>Anti-Muon</td>
<td>μ⁻</td>
<td>+1</td>
<td>105.6 MeV</td>
</tr>
<tr>
<td>Muon antineutrino</td>
<td>ν_μ⁻</td>
<td>0</td>
<td>&lt; 0.5 MeV</td>
</tr>
<tr>
<td>Charm quark</td>
<td>c</td>
<td>+2/3</td>
<td>-1.5 GeV</td>
</tr>
<tr>
<td>Strange quark</td>
<td>s</td>
<td>-1/3</td>
<td>-100 MeV</td>
</tr>
<tr>
<td>Anti-charm antiquark</td>
<td>c⁺</td>
<td>-2/3</td>
<td>-1.5 GeV</td>
</tr>
<tr>
<td>Anti-strange antiquark</td>
<td>s⁺</td>
<td>+1/3</td>
<td>-100 MeV</td>
</tr>
</tbody>
</table>

### Generation 3

<table>
<thead>
<tr>
<th>Fermion (Left -handed)</th>
<th>Symbol</th>
<th>Electric charge</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tau lepton</td>
<td>τ</td>
<td>-1</td>
<td>1.784 GeV</td>
</tr>
<tr>
<td>Tau neutrino</td>
<td>ν_τ</td>
<td>0</td>
<td>&lt; 70 MeV</td>
</tr>
<tr>
<td>Anti-Tau</td>
<td>τ⁺</td>
<td>+1</td>
<td>1.784 GeV</td>
</tr>
<tr>
<td>Tau antineutrino</td>
<td>ν_τ⁻</td>
<td>0</td>
<td>&lt; 70 MeV</td>
</tr>
<tr>
<td>Top quark</td>
<td>t</td>
<td>+2/3</td>
<td>173 GeV</td>
</tr>
<tr>
<td>Bottom quark</td>
<td>b</td>
<td>-1/3</td>
<td>-4.7 GeV</td>
</tr>
<tr>
<td>Anti-top antiquark</td>
<td>t⁺</td>
<td>-2/3</td>
<td>173 GeV</td>
</tr>
<tr>
<td>Anti-bottom antiquark</td>
<td>b⁺</td>
<td>+1/3</td>
<td>-4.7 GeV</td>
</tr>
</tbody>
</table>

Table 1: Fermions: leptons and quarks
In the Standard Model, the theory of the electroweak interaction (which describes the weak and electromagnetic interactions) the forces between fermions are modeled by coupling them to bosons which mediate (or "carry") the forces. The bosons in the "Standard Model" are:

- Photons, which mediate the electromagnetic interaction.
- W and Z bosons, which mediate the weak electromagnetic force (discovered at CERN).
- Eight species of gluons, which mediate the strong nuclear force.
- The Higgs bosons, which are thought to be responsible for the existence of inertial mass.

The Higgs boson is a hypothetical massive scalar elementary particle predicted to exist in an attempt to make the Standard Model of particle physics coherent. The existence of the particle was first suggested in the 1960s by the British physicist Peter Higgs, and independently by others later. As of 2006, no experiment has directly detected the existence of the Higgs boson, but there have been some indirect observations that may be concluded in that direction.

The particle called Higgs boson is in fact the quantum number of one of the components of what is know as a Higgs field. In empty space, the Higgs field, which at all times permeates the universe, assumes a non-zero value. This expectation value of the Higgs field in vacuum is constant and has been calculated to be equal to 246 GeV. The existence of this non-zero Higgs field plays a fundamental role in the Standard Model: it gives mass to every elementary particle, including to the Higgs boson itself.

The Standard Model does not predict the value of the mass of the Higgs boson but it has been argued that the mass of the Higgs boson lies between about 130 and 190 GeV. Most theorists still expect that new physics beyond the Standard Model will emerge first at the TeV-scale.

A small number of events were recorded by the LEP experiment at CERN that could be interpreted as resulting from Higgs bosons, but the evidence is not conclusive. The physicists expect that the LHC with its nominal centre-of-mass collision energy of $7 + 7$ TeV will be able to confirm or disprove the existence of the Higgs boson.

1.4. Higher and higher energies

How was all this discovered? To be able to observe the constituents of matter, elementary particles can be used as a probe. In general, a structure can only be resolved by a probe, for example electromagnetic radiation, if the wavelength of the probe is small compared to the size of the structure being studied. To reach the dimensions required for elementary particle research wavelengths below \( \lambda < 10^{15} \) m are required since the proton size is approximately \( 10^{10} \) m and the substructure constituents’ size is about \( 10^{15} \) m. The de Broglie wavelength must be

$$\lambda_B = \frac{h}{p} = \frac{hc}{E}, \quad (1.1)$$
where $p$ and $E$ are the momentum and energy of the particle respectively, assuming $E/E_0 >> 1$, where $E_0$ is the rest energy. To be able to produce new particles we need the energy, according to the fundamental equation

$$E = mc^2.$$  \hspace{2cm} (1.2)

Most particles are only produced together with their antiparticles, for example electron and positron pairs are produced by letting high energy gamma-rays strike a target made of heavy nucleus matter. At the collision, the nucleus itself gains some energy (conservation of momentum) and this energy is lost for particle production. Thus the gamma-ray energy needed for particle production is therefore always higher than what is given in the relation (1.2) above and is:

$$E_\gamma > 2mc^2 = 1.022 \text{ MeV}$$ \hspace{2cm} (1.3)

The threshold energy required for the production of electron-positron pairs, where each particle has a mass $m_e = 9.109 \times 10^{-31} \text{ kg}$, corresponds to a rest mass of 511 keV.

This explains why the probe used needs higher and higher energies when the substructure of matter has to be explored in depth.

The first experiments in particle physics used particles from matter with natural radioactivity (alpha particles and electrons). But it was rapidly realised that higher energies than those provided by natural sources were needed to permit a deeper penetration into the atom’s nucleus. The first accelerating devices used electrostatic fields to increase the particle energy [Gra31] [Coc32]. Acceleration of protons was first made using linear accelerator technology at Berkeley [Alv46]. To further increase the available energy for acceleration, the machine builders moved to circular accelerator designs where the particles pass an electrostatic field at each revolution and gain energy as they circulate around the machine in the vacuum chamber. This design required the introduction of magnetic fields perpendicular to the trajectory corresponding to the change of momentum to keep the particles on their circular trajectories. The principle of “strong focusing” which is important to keep the expensive magnet aperture small was described first by [Chr50]. The principle of the alternating gradient synchrotron was published by Courant et al. [Cou59]. Strong focusing is based on a long-known result in classical optics: combined alternating focusing and defocusing lenses have a net focusing effect. A focusing quadrupole, in one plane, is defocusing in the other. In both planes we thus have a net focusing effect from a chain of alternating focusing and defocusing magnets (alternating-gradient focusing). All the circular accelerators at CERN are today synchrotrons, where both the revolution frequency and the fields vary with the energy of the accelerated particle.

The maximum energy that a cyclic accelerator can give to a given particle is typically limited by the available strength of the magnetic bending field and the maximum radius the particle can have in the vacuum chamber. Higher particle energies need higher fields for a given machine radius and superconducting magnets, though complex and requiring elaborate infrastructures, are today used to obtain the required high magnetic fields.
In the CERN context the particles are extracted from the particle source, a device generating gas plasma. The particles are then extracted from the source and accelerated in a linear accelerator. The particles, now in the form of a bunched beam, are subsequently injected into a chain of synchrotron machines and accelerated up to the energy defined for any given physics experiments. The beams are made to collide, or alternatively, are extracted for fixed target physics. In the LHC case this staged acceleration means that a particle will have to pass through 5 different machines, each time increasing the energy of the particle as it passes through. In Section 1.5 an overview of the CERN accelerator complex is given.

1.5. The CERN particle accelerators

There is a variety of accelerator designs more or less suitable for given particles, energies, intensities, etc. However, to be able to substantially increase the kinetic energy of the particles accelerated, an interconnected chain of accelerators is necessary. Such a chain of machines permit an easier design and the optimization of the range of the different individual accelerator stages. Particles of different types can be accelerated in the machines depending on the experimental needs: electrons, positrons, protons, antiprotons and ions.

The particle sources, which provide the particles to be accelerated, can be of many types and at CERN there are proton, ion and electron sources. Particles can also be produced by collecting the debris created by primary beams hitting a target at high energy. In this case the particles created by the collisions are collected after the target station, refocused and accelerated or decelerated in down-stream machines. This is the classical method to create beams of anti-protons or positrons.

Protons are produced in a source, a duoplasmatron, see Figure 5, and injected into the Linac 2 which is a linear accelerator [Tur94]. In the Linac 2 the protons are bunched and accelerated to 50 MeV energy, split into 4 parts and injected into the next machine which has four vertically stacked circular vacuum chambers, the Booster rings (PSB), using a multi-turn injection technique, see Figure 5. In the PSB the four proton beams are simultaneously accelerated up to 1.4 GeV, extracted, recombined into a single beam and injected into the PS. The PS continues the acceleration of this single beam up to 28 GeV at which energy the beam is extracted and sent through a long beam line and injected into the SPS, see Figure 3. The SPS accelerates the beam up to a nominal energy of 450 GeV and it is either extracted for injection into LHC or into the North Zone for fixed target physics. The first extraction tests of a nominal LHC beam from the SPS into one of the LHC transfer lines, TI8, was successfully done in 2005.

The LHC will be able to accelerate both protons and lead ions. The Linac 3 in combination with the Low Energy Ion Ring (LEIR), see Figure 5, will create high density ion beams for LHC. LEIR will in this configuration act as an on-line accumulator of the beams coming from the Linac 3 machine. The accumulated beams in LEIR will be cooled by an electron cooler with quasi mono-energetic electrons to align the momentum vectors of the ions and minimize energy dispersion [Bud78]. When sufficiently many ions have been accumulated in LEIR they are extracted and transferred through the PS and the SPS machines to the LHC, where they will be accelerated and brought into collision for physics in the experiments.
The 1984 Nobel price in physics was attributed to Simon van der Meer and Carlo Rubbia for the discovery of the $Z^0$ and the W bosons, communicators of weak interaction [Rub94]. This discovery was made possible by colliding protons and antiprotons in the $SpP\bar{p}$ collider. Quantities of antiprotons usable for particle physics purpose were accumulated in a new machine, the Antiproton Accumulator. To be able to accumulate any appreciable amounts of antiprotons S. van der Meer applied his revolutionary technique, “stochastic beam cooling”, which permits precise control of the emittance of the stacked antiproton beam [Mer78]. An additional ring, the Antiproton Collector, (AC) was later built around the AA to increase the intensity of the antiproton source by one order of magnitude. In the early nineties, the AA was

Figure 4: A duoplasmatron to produce protons. Some of the reactions in the plasma of the hydrogen gas created by the magnetic field
dismantled and the AC was converted into the Antiproton Decelerator (AD) to serve as a source for antimatter experiments.

The versatility and flexibility of the PS complex is explained in [Sim96].

Figure 5: The PS (Proton Synchrotron) and the SPS (Super Proton Synchrotron) accelerator complex
2. OVERVIEW OF PRESENTED PAPERS AND EMPHASIS ON PARTICULAR CONTRIBUTIONS BY THE AUTHOR

The essential ideas of the work presented in this thesis are related to diagnostics methodologies and control of the behaviour of complex systems. The process that combines particle beams from several smaller machines connected in a sequence, steers the injection of the combined beam into yet another accelerator and then threads the resulting beam though another chain of accelerators while maintaining the beam properties, is one example of a controlled complex system. Another example of a complex system process is the control methodology applied to the distributed manufacturing process of 1232 high-performance superconducting magnets. This process with its advanced diagnostic tools was developed to maintain very tight manufacturing tolerances and to create a feedback mechanism to guide the assembly procedures in the assembly plants located in three different countries in Europe. To install, in an optimal way, the magnets around the LHC accelerator, many manufacturing aspects had to be taken into account. The magnet performance evaluation, done for each magnet, and used to select the appropriate magnet location, was the result of an intense teamwork in the Magnet Evaluation Board (MEB). A detailed analysis of the different measurements made showed itself to be very important for the correct understanding of industrial procedures and of the measurement processes. Analysis of large amounts of geometry measurements and the use of statistic methods provided insight into problems with the measurement systems. The analysis also gave a possibility to develop a posteriori remedy procedures with a better understanding of the characteristics of the measured equipment. This is an example of how diagnostics and remedial procedures can create a link to corrective actions and eventually be integrated in the design of new systems.

In this work, possible LHC insertion region upgrade scenarios are also discussed where criteria resulting from energy deposition calculations are included to guide the magnet designers. Monte Carlo codes, describing the physics processes of particle interaction with matter, have been used to calculate the effects of the impinging debris from proton-proton collisions on superconducting magnets. The additional load on the tightly dimensioned cryogenic system, caused by the higher luminosity upgrades, has also been evaluated.

The study presented in [Cap94] was an experiment to investigate proton beam behaviour under extreme space charge conditions. The experiment was done in the CERN PS accelerator complex. Since space charge issues rapidly becomes the limiting factors when trying to produce high intensity beams for physics makes it a subject of interest wherever such beams are needed. My particular contribution to this accelerator development experiment was to set up the injector machine, the CERN PS Booster, with the appropriate emittance parameters and to ensure a correct transfer of the beam into the Proton Synchrotron (PS). The Booster was set up for single bunch mode with harmonic number \( h = 1 \), which was not the standard setting up at that time. I wrote the application program for the 12\textsuperscript{th} harmonic compensation of the \( 2*Qy = 12 \) resonance and participated in the setting up of the conditions in the PS and did the emittance measurements. The experiment and its results are discussed in chapter 3.1.

[Aut96] describes the analysis, design and implementation of a set of tools to help accelerator operators produce a single well behaved proton beam by combining four proton beams using automated steering procedures in an interconnected chain of accelerators. The work
was presented at the European Conference on Particle Accelerators, EPAC [Aut96]. This work permitted me to write and test, together with B. Autin, basic optics software in Mathematica® which later became, with contributions from other co-authors, a complete symbolic optics program “Beam Optics” [Car98], now used for analytic design of accelerators. The operational version of the program was verified by me on the four-ring PS Booster machine to produce the theoretical transfer matrixes used for the beam steering. In the technical design report I specified the software for the automatic steering program for the four-beam recombination in the transfer line between the PS Booster and the PS. With my further improvements of the software it grew into generic system later used for other similar applications. When the automatic steering program for the beam recombination did not converge as expected at the first tests, my analysis led us to re-align the quadrupoles and pickups in the transfer lines. The subsequent tests were successful and gave the expected results. The application program defined the transfer matrixes for the four PS Booster beams to be recombined. The transfer of the booster beams to the PS machine is takes place partly in separate and partly in common beam lines. This represented a new concept of beam steering and was not implemented anywhere else before. The development was related to my responsibility as Engineer in Charge for the PS Booster operation; an increased efficiency of the setting up procedures, improving the quality of the beams and to minimize the time the operators needed for the setting up was of general interest. As the steering problem was common to other accelerators in the PS complex, by making the application generic it could also easily be re-utilized. This work is described in chapter 3.2.

Some more recent papers describe different aspects of the procedures (processes) that have been developed in the context: production steering for the manufacturing of the new superconducting LHC dipoles. The first, [Wil03], describes how to control the subcontracted assembly of superconducting magnets, using feedback from the analysis of the magnetic field components measured along the magnet axis. This paper [Wil03], presented orally at MT18 (Magnet Technology) in Japan, was published in IEEE Trans. on Superconductivity, Oct. 2003. In this procedure the magnet was put in a “hold” state if the field measured was not fully satisfactory. It was my responsibility to decide if the magnet had be opened and repaired, obviously a very costly procedure. By setting up and establishing a complete control process for the dipole cold masses, using the available statistical material for the control limits to be applied I could in a daily routine activity rapidly catch any magnets falling outside the specified tolerances. The process had to help us distinguish assembly errors from measurement errors and when required request re-measurements by the respective contractors. To speed up these holding point procedures, I automated the work by suggesting and specifying a web based software system which also ensured all contractual book-keeping issues. This typically includes the capture of measurement data, analysis procedures and their results and all electronic mail exchanges having contractual implications in the acceptation procedure. The system using modern J2EE JSP technology is connected to an ORACLE database. This development was an essential ingredient to enforce the quality tolerances of the magnet field analysis that was a part of the “Holding Point” procedures. The paper describing this is introduced in chapter 4.6.

In [Wil05] I develop the methodology used to tune the geometry of the LHC dipole magnets within a few tenths of mm precision. This work was presented at MT19 (Magnet Technology) in Genoa and published in IEEE Trans. on Superconductivity, 2005. As responsible for the dipole geometry I had to make sure that the geometry of the dipole as concerns its effects on the beam (such as available aperture and magnetic field feed down issues, see section 4.3)
was kept within the tolerances. To handle the entire monitoring process I set up a database system including the statistical evaluation and monitoring programs. The work described in the selected paper is related to the evaluation of the measurement procedures for fiducialization and installation of the dipole and quadrupole magnets. The particular problem, treated in the [Wil05], was the new requirement that one of two fiducialization measurements per dipole had to be dropped: only one measurement could be made since the production rate had to be increased. The consequence of this new requirement was a degradation of the achieved geometry quality: the first measurement was used to evaluate the corrections of the geometry to be applied to get the best possible geometry adjustment for a given magnet. A final measurement is always needed, as a final reference, to actually install the magnet. With the new requirement, only one measurement could be made and the magnet shape had to be accepted as it is without any shape corrections, this shape was baptized to “as is”. The idea I had to cope with this issue as well as possible was to evaluate statistically changes of the magnet shapes between measurements done at the assembly sites and those made at CERN. With this information it should be possible to make a correction that was the best possible with only one measurement executed at CERN. In addition I could show that the statistical behaviour of the magnets was different for the three assemblers. This permitted us to adjust statistically the magnets according to their assembly origin. Mean values of monitored parameters were perfectly adjusted by this procedure, even better than by individual adjustments. The spread over the total magnet population could be held within specified values by adjusting the geometry statistically by provenance and by carefully monitoring the achieved mean values at each assembly site. The paper describes my proposals. To ensure that the LHC accelerator physicist community would accept the concept, I had simulations done of the expected geometry shape changes of some hundred already measured magnets, as they would result from the proposed, also simulated, adjustment procedure. A mechanical model, combined with real measurements of the dipole shape was used for the simulations which were executed by a doctoral student and a fellow in a team under my supervision. The resulting geometrical shapes were fed through the standard acceptance calculation procedures used in the dipole database. All the important characteristics were calculated for the simulated set to see if the simulation of the proposed adjustment scheme gave acceptable results. As this was the case, my proposal was adopted. The final results of the adjustment procedure are fully consistent with my previsions. The new adjustment procedure increased the quality of the dipole geometry with respect to the result expected from adjustments “as is”. The scheme also allowed the preservation of the geometry within the specified limits. In this context it should be noted that the LHC dipole superconducting magnets are 15 m long, weighing almost 27 tons; their shape is however controlled to within a few tenths of a mm. The methodology to control the magnetic shape is treated in the paper introduced in Section 4.10.

For [Wil03] and [Wil05], in which various aspects of the superconducting magnets (magnetic field and geometrical shape issues) are discussed, a slightly more extensive background is given below.

To perform the required shape-adjustments of the magnets discussed in [Wil05], accurate geometry measurements were needed during all magnet production stages. All data was saved and secured in an ORACLE data base. Using the huge amount of geometry measurement data in a data-mining approach revealed new information about the measurement procedure and about the real geometry of the dipoles and quadrupoles. The standard processing of these measurements gave the impression that the magnet shapes and positions had changed in a way
that could not be explained by mechanical considerations only. Many theories about why the shapes changes were evoked among those concerned. Eventually, most of the strange effects could be explained by my proposed interpretation of the measurement data. This issue is discussed in [Wil071] presented at the Particle Accelerator Conference in Albuquerque, Mexico. As accelerator conference papers are limited to 3 pages, the paper only gives an overview of the work. An extensive and detailed report on the work is available in [Wil072], emphasizing the depth and requirement for new ideas to disentangle the measurement effect from other mechanical effects in the complex magnet assembly. Large measurement errors, compared to the tolerances of the measurement system, could be explained as being due to an unexpected refraction of the laser beam, used in the interferometric measurement of the excursion of the magnet cold bore tube centre. This explanation is based on an extensive statistics analysis of the measurement data and correct mechanical knowledge of the magnet’s structure. In addition I could propose a corrective algorithm for the measurements. Using a data base expert, I could rapidly collect and do the necessary analysis of the geometry measurement data. Although the phenomenology of the measurement problem had been observed years before, neither any conclusion of the effects on magnet geometry had been made or did any proposals for a corrective procedure exist. My contribution here was the analysis proposal, the conception and development of a remedy procedure while the data base programming and part of the statistical analysis were carried out by the co-author of the papers. The papers were written by me since the co-author left CERN early. The measurement analysis and correction of the magnet geometry is described in chapter 5.

The normal and superconducting magnets for the LHC have been carefully examined to ensure that each of the about 1900 dipole and quadrupole assemblies is suitable for accelerator operation. This work lasted four years. The problem to install each magnet in the most appropriate position in the machine lattice, taking into account all necessary criteria for maximum machine performance was a real challenge. It was met with an excellent team work where hardware experts and accelerator physicists offered their input to the magnet evaluation and acceptance process. We had to device complex magnet sorting procedures using geometry, field-quality and quench level performance as criteria. As the responsible for dipole and quadrupole geometry I participated in the Magnet Evaluation Board (MEB) which took the final magnet placement decision. The procedures and the results of the board’s work is described in [Bot07] where I contributed with my expertise of the geometry of the magnets, one of the most critical magnet characteristics for beam performance (mechanical aperture).

As MEB member and resident geometry expert I also created and made available to the board a number of tools for the evaluation and visualization of geometry performance of the magnets, including measurement error reduction. These results and the associated documentation were essential features to enable the evaluation and the sorting of the LHC magnets, to optimize the geometry and the LHC performance. More details about this specific part of my activities are available in the paper.

The work, presented at the Particle Accelerator Conference in Albuquerque, Mexico, 2007, is introduced in chapter 6.
**Neutrino beams** can be produced from beta decay of radioactive ions. EURISOL, the European Isotope Separation On-Line study, is a framework project to make a proposal for a European radioactive ion beam facility. Within this framework project, a working group is dedicated to the study of neutrino production using beta decaying ions. Such ions can be accelerated in a racetrack-type accelerator and the produced neutrinos can be targeted onto a detector to measure neutrino oscillations. A possible scenario for a beta beam facility at CERN has been proposed within the EURISOL framework. The radioactive ions are stored in the decay ring, where the useful neutrinos are produced in the straight sections of the ring and directed towards the experimental site that may be located many 100 kilometres away from the production site. In this project I was responsible for specifying the characteristics of the decay ring’s superconducting magnets so that they can operate in a highly radioactive environment; the detailed design work was executed by the co-author of [Wil07].

I made the first estimations of the deposition of energy from the impinging decaying daughter ion in the magnets, where I assumed an early break-up of the ions in matter (for simplicity I used protons in the simulations; the time available for this study was only a couple of weeks).

As the study was limited by the manpower available during this time period, a more elaborate study was made later during my 2 months visit to the TRIUMF Laboratory in Vancouver, Canada. At TRIUMF I collaborated with the person responsible for the accelerator beam tracking code used to simulate the production of the decayed particles and their properties. Here I first had to establish a representative model of the machine’s arc lattice. I had to interface the two simulation tools, the accelerator simulation code and the Monte Carlo particle tracking code. This linked simulation approach subsequently enabled us to simulate the impinging particles to where they stop and deposit energy in the material thus creating a more detailed picture of the energy deposition patterns.

This work implied also that new benchmarks for the beam code for this type of applications had to be established by us. Two papers, [Wil07] and [Jon07], describing the studies were presented at the Particle Accelerator Conference in Albuquerque, Mexico, 2007.

This work is described in more detail in a report for the FP6 European program for beta beams (EURISOL) was written [Wil073]. My work on the superconducting magnets in a highly irradiative environment was presented at NuFact 2006 (Neutrinos, Superbeams and Beta Beams), at the common EURISOL/EURONS town meting in Helsinki 2007 and at various Beta Beam meetings within the EURISOL project. The studies related to energy deposition in superconducting magnets in the beta beam decay ring, are described in chapter 7.

**The LHC upgrade projects** are targeting improvements of the machine luminosities with a factor of two compared to the present luminosity, i.e. \( \mathcal{L} = 2 \cdot 10^{34} \, \text{cm}^2 \cdot \text{s}^{-1} \). These ambitious projects have to take long lead-times of 5 to 15 years into account when developing the new technology required. Several phases of the upgrade projects have been identified of which the first, Phase I, is a consolidation of the inner triplets and it has no impact on the experimental infrastructure. The Phase I is expected to be terminated in 2012. The second phase, Phase II, planned to be completed 5 years later, may need entirely new magnet technology, not yet available for production, to reach the required fields having the appropriate margins for the collision debris energy deposition.
A novel method of protecting the magnets from the collision debris using thick liners inside the magnets enabled me to put forward a proposal using classical superconducting technology (cables using NbTi as superconductor). The proposed work includes extensive simulations using Monte Carlo type particle tracking code and a technical investigation on how the liners limit the energy deposition in the superconducting parts of the magnet system.

The paper [Wil08] deals with the upgrade Phase II, which goes beyond the nominal luminosity with an impressive factor of five, \( \mathcal{L} = 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \). In the study layouts “extrapolated” from Phase I were used, assumed to be the best guesses for the Phase II, to estimate the possible impact such high luminosities may have on the equipment. The ideas presented in this paper were found to be important also for the current Phase I studies. The detailed simulation work was done by a doctoral student and a fellow under my supervision. The results of the study were presented in October 2007 at the CARE\(^1\)-HHH\(^2\) workshop in Frascati, Italy, which was devoted to the LHC upgrade project.

The CARE program is now succeeded by the EUCARD program (European Coordinated Accelerator R&D). Simple scaling laws are difficult to apply to complex problems such as energy deposition in the presence of magnetic fields from the very large diversity of particles originating in the proton collisions. Some attempts have however been made and are reported in [Hoa073]. Under my supervision some comparisons with other Monte Carlo codes using different physics models were made with the actual LHC layout. [Hoa08, to be published].

When equipment having a cylindrical geometry is placed closer to the interaction point in a proton collider, heat deposition issues become less critical [Hoa072], simply due to the intercepted solid angle and the distribution of the particle types and energies of the collision products [Hoa071]. Cylindrical forms are used for first calculations since they are ideal as simple models of superconducting magnets. There are advantages of locating the equipment close to the Interaction Point, e.g. better optics and increased aperture [Laf06] can be achieved. A special layout for the planned LHC upgrade, based on the ideas in [Laf06], was studied from the point of view heat deposition in the magnet coil [Wil074]. This work was initially intended to address also the problems with particle backscattering into the experimental detectors from accelerator equipment located inside the experimental area. However, only work related to the heat load calculations for the magnets were made since the backscattering phenomena was finally identified as being outside the study scope. Even simple estimates of particle fluxes from our models were considered as too approximate to have any real value for detector performance evaluation. The layout configuration I used is intended for Phase II of the LHC upgrade. I carried out the complete study and the deliverables were made available (the model and the results) to the experimental groups. The idea of having thick liners inside magnets to take up large heat loads in addition to the beam screen, used in the current upgrade studies, was an additional positive outcome from that work. An important conclusion from the study is that it is advantageous to distribute the heat load to a high temperature (15 K) system having a higher heat capacity.

The upgrade studies are described in chapter 8.

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\(^1\) CARE = Coordinated Accelerator R&D in Europe

\(^2\) HHH = for High energy, High intensity Hadron beams
3. DIAGNOSTICS AND OPTIMIZATION OF PROTON BEAMS

The two papers selected for discussion in this chapter deal with work on accelerator beams in the PS complex [Cap94] [Aut96].

3.1. Experiments to test Beam Behaviour Under Extreme Space Charge Conditions.

Research on new energy sources has today received renewed interest. Conditions for controlled fusion may be created by several heavy ion beams simultaneously striking a deuterium-tritium pellet [Rub91]. For such applications very dense beams of particles must be used. In the paper [Cap94] we describe some experiments that we carried out in the CERN PS accelerator with a proton beam of 1 GeV, the injection energy of the PS. Studies of space charge effects in the PS which had already been carried out for the LHC were the basis for the experimentation on beams for fusion studies. Proton beams for the LHC have to be very dense; in fact the density is at the limits of the present, injector complex performance described in [Ben05].

A particle in a beam experiences not only the field from the magnets and the accelerating structures in the accelerator but also the fields created by its neighbouring particles. The effect is large if many particles are close together and if the energy of the individual particles is low. All particles do not experience the same effects at the same instant, making it is a phenomena difficult to compensate for. Each particle gets a different contribution to its transverse oscillation, resulting in a change of the betatron tune $Q$, the number of transverse oscillations the particle makes per turn. The tune shift of a particle bunch is defined as the tune of the particle in the centre of the bunch with respect to the value of the tune at vanishing current. Phenomena influencing differently different particles are referred to as incoherent effects. See Ref. [Hof93].

The formulas for tune shifts that we used in the papers were elaborated in [Möh93].

Space charge effects limit the number of particles conventional accelerators can accelerate due to a “blow up” of the particle beam. A beam will “blow up” if the spread of the betatron frequencies of the particles become too large. A large spread increases the probabilities that some particles are trapped in resonant conditions and will amplify their oscillations rapidly until they are lost in the vacuum chamber wall. The frequency spread increases the area of the beam in the tune space $Q_h-Q_v$ (h and v stand for horizontal and vertical respectively). This area increase makes the transverse motion of a part of the beam sensitive to dangerous modes of excitation that increase the betatron amplitude as shown in the theory of non-linear oscillations.

In the experiment reported in [Cap94], the machine’s radiofrequency (RF) accelerating structures were used to compress the bunch in phase space in two different manners.

In the first test a 180 degree radiofrequency phase jump was used to put the bunch on the unstable phase where the bunch becomes deformed, it is stretched. When the stretching is finished, the bunch was brought back into the centre of the RF bucket and the now deliberately mismatched bunch starts to rotate. While rotating, during a short time interval the stretched bunch has a minimum duration, and can thus be considered to be maximally compressed. During this interval the space charge will be at its maximum and the transverse emittance of the bunch is measured before and after the bunch compression by a flying wire scan measurement.
A flying wire scan device drives rapidly a thin wire transversely through the circulating beam causing an emission of secondary electrons. These electrons are collected with standard techniques; by measuring the current induced by the wire’s passage through the beam, the beam’s transverse profile can be deduced. We compared the measured emittance after the compression to the initial emittance and we could get an indication of how the beam is affected by the strong space charge effects.

The second way to compress the bunch is done by quickly raising the RF voltage to force the bunch to start rotating. For this test, we set up the injector (the PS Booster) to deliver a beam of higher intensity than in the first case.

The conclusions drawn from this space-charge experiment was that although the two methods of bunch compression did not give a very good agreement, it seems possible to design compression rings having large tune shifts with a tolerable blow-up of the beam size.

### 3.2. Automated beam steering in the PS complex.

This section describes the work we made in the PS complex to improve the quality of the beams delivered to SPS and to physicists as well as diminishing the time taken to set up the various beams [Aut96].

Accelerator operators have access to individual equipment for setting up and controlling the beam, for example the setting of magnet currents via a power converter. Thousands of parameters have to be controlled and the acquired data analysed when actually operating a modern accelerator. Complex processes for optimizing beam trajectories, beam steering, needed time consuming efforts from experienced operators. The procedures were also fragile in the sense that they were often experimental, trying to compensate for many small drifts in the equipment that were not always fully understood.

To automate, by software, a beam steering procedure, the optics of the machines has to be fully understood. The alignment of quadrupoles and the diagnostic devices, the beam position pick-ups have to be well controlled and regularly monitored by the surveyors. A thorough cleaning up of these aspects was required before the automated procedures worked reliably. To become a robust daily tool for the operators, such tools must also fit into the standard control system environment and not become exceptions requiring special procedures, specific knowledge, time consuming debugging and setup time.

Due to field errors and misalignments of the steering magnets, the position of a beam is often offset from its ideal trajectory. The real beam trajectory has to be measured using beam position monitors to be able to correct any mismatch detected. At least four monitors per betatron (transverse oscillation) wave length are required, placed at approximately an equal phase distance, to be able to reconstruct the first harmonic of the beam oscillation. A compromise for the positioning of the monitors is often necessary since the betatron tune of the beam is different in the horizontal and vertical planes while a single position monitor usually is, for economical reasons, built to be able measure both planes. The monitors and the steering magnet coils are placed such that they have a betatron oscillation phase difference of, optimally, $\pi/2$. This comes from the fact that the response of a corrector magnet kick is largest at this value [Aut96].
Beam steering using an algorithmic approach is not new; see for example [Aut73]. The novelty in the concept we proposed was the creation of a generic model of beam steering that could be parameterised for all different kinds of beam steering in the different accelerators making up the PS complex. The implementation resulted in one module for the generation of the machine model and one generic linear solver module adaptable to the specific kind of steering to be solved (transfer lines, closed orbits or combinations thereof). With this concept we could also offer a robust, standardised, user interface to the generic solver for the operators in their daily work in the control room. A special beam optics program for lattice calculations [Car98] was written in Mathematica®, a symbolic manipulation language, and this program was also used for the creation of the steering matrices.

Three particle beam steering techniques will be briefly described below. The first method is the matrix inversion method, see Appendix 1 for the derivation. The basic idea is to specify a matrix describing the changes in position on the beam position monitors from changes in the corrector strengths.

The second method is called “the most effective correctors” method. An orbit shift is often caused by one particularly strong perturbation at a single point. The method is similar to the matrix inversion method, however only the smallest number of correctors satisfying the efficiency criterion is used to apply the correction. The efficiency criterion is taken to be some norm of the residual error of the orbit, see e.g. [Aut96]. To find the most efficient corrector, the available correctors are all tried out, and the most efficient corrector is retained. The method permits to avoid overcompensation by using too many correctors. This matrix does not necessarily have to be a square matrix, it is in general rectangular. The number of correctors to use may be chosen by specifying the value of the residual error.

The matrix inversion operation gives errors due to the finite resolution of monitors and to the finite corrector alignment. In such cases the “local orbit bumps” approach can be used. The corrector nearest to the beam position monitor is used to minimize the error on the monitor. Then the bump has to be closed to only have local effect. The displacement at the next monitor is minimized and so on. The method is limited by the fact that the bump generally extends over approximately a distance of $\pi$ in phase space, and the monitor separation is normally $\pi/2$ in phase space. The method leads to errors comparable to the matrix inversion method but the process is easier to control due to a small number of control devices for each step of the control procedure.

We used the “most efficient correctors” method to implement the steering in the PS complex [Aut96]. The interest to have comprehensive high level code that was easy to maintain for the implementation of the solver led to the choice of Mathematica®. The interface was written in the standard control system environment using C programming language. Basic settings of control system parameters like power converter current levels of one or several steering magnets had to be translated into quantities having a meaning for beam steering, such as a change in position for the passing beam, and checked carefully. Energy levels of the beam had to be checked and we had to perform a re-alignment of quadrupoles (a misaligned quadrupole acts as a dipole and steers the beam instead of focusing or defocusing it) and pickups.
The resulting application program system was applied to two cases: the correction and recombination of the four beam trajectories from the PS Booster ejection and to the correction of coherent oscillations at the injection to the PS. The resulting programs were very much appreciated by the operations team: the operators gained about 30 min each time the steering had to be adjusted (which happens several times a week) with a more accurate and reproducible result. The final errors in the injection channels before recombination in the Booster ejection line is now less than 2 mm which gives good injection conditions into the PS machine.
4. SUPERCONDUCTING MAGNETS FOR LHC

A brief background to superconducting magnet technology is given in this section to introduce the presented papers [Wil03], [Wil05] on issues for production control, assembly and geometry properties of the main dipoles of the LHC. The introduction to this work will be more detailed; the work is more recent and the geometry aspects of the dipole belong to my present main responsibilities.

4.1. Superconducting technology for hadron colliders

Many of the large hadron colliders, e.g. the LHC (see Figure 6) proposed or designed in the last two decades use superconducting magnets. The obvious reason is cost; the price per Tm of superconducting magnets is far lower than that of copper-conductor magnets. In addition the power consumption during the operation of the accelerator is also reduced [Rea77]. The wish to reach the highest possible energy in the available 27 km tunnel led the designers to push the different magnet technologies to their limits.

![Figure 6: The LHC and its experiments CMS, ATLAS, ALICE and LHC-b. A two-in-one magnet structure (see Figure 7) is used because it is well adapted to a proton-proton collider and reduces significantly both material costs and space occupancy in the available tunnel.](image1)

![Figure 7: The two-in-one structure allows a saving of about 40% of the Ampere-turns to get the same field B as in a magnet pair. The structure is adapted to proton-proton colliders where the same field in opposite direction is needed for the two counter-rotating beams.](image2)
Figure 8: Cross section of the LHC superconducting main dipole cold mass. The two beam tubes are surrounded by the coils carrying the current, around which the austenitic stainless steel laminated collars are mounted. Around the collars the iron yoke, needed as a magnetic flux return circuit and a force retaining component, is mounted. To retain the whole assembly a stainless steel cylinder is welded around the yoke structure. The inner diameter of the beam tubes is 56 mm at room temperature.

The high field magnet technology enables the machine to reach the high luminosity required with strongly focusing magnets in the experimental regions. As a side effect this also reduces the number of particles required and makes the beams less prone to collective instabilities. But the drawback is that the machine becomes extremely sensitive to beam losses and to synchrotron radiation.

The luminosity $\mathcal{L}$ is the principal parameter of interest to the physicists when a new collider is designed. The luminosity gives the number of physics events per second generated in the collisions, $N_{\text{event}}$, expressed as

$$N_{\text{event}} = \mathcal{L} \times \sigma_{\text{event}}$$

(4.1)

where $\sigma_{\text{event}}$ is the cross section of the process, a measure of the probability to observe particular events relative to crossing particle rates.

The cross sections of physics processes decrease like $\gamma^2$ where the relativistic $\gamma$ can be expressed as
\[
\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}, \quad (4.2)
\]

\(v\) being the particle speed and \(c\) the speed of light. Ideally the luminosity should thus scale with \(\gamma^2\). The luminosity depends both on the parameters of the machine and of the beam parameters; it can be expressed as (assuming Gaussian beam distribution for identical beams with similar cross sections):

\[
\mathcal{L} = \frac{N_b^2 n_b f_{\text{rev}} \gamma}{4 \pi \varepsilon_n \beta^* F}, \quad (4.3)
\]

where \(N_b\) is the number of particles per bunch, \(n_b\) the number of bunches per beam, \(f_{\text{rev}}\) the revolution frequency, \(\gamma\) the relativistic factor and \(\varepsilon_n\) the normalized transverse emittance. The parameter \(\beta^*\) is the value of the machine lattice optical beta function at the collision point.

The parameter \(F\) is a geometric scaling factor which depends on the beams’ crossing angle

\[
F = 1/\sqrt{1 + \left(\frac{\Theta z}{2 \sigma^*_z}\right)^2}, \quad (4.4)
\]

where \(\Theta z\) is the full crossing angle, \(\sigma_z\) is the standard deviation bunch length and \(\sigma^*_z\) is the transverse beam size at the interaction point. The machine lattice optical function describes the linear transverse motion of the particles in the accelerator.

The luminosity parameter also scales with the stored beam current. A classical machine needs a much larger circumference since it has a weaker magnetic field, to reach the same luminosity as a superconducting machine. It would have to store more particles to compensate for the lower revolution frequency, which imposes more constraints on injection and dumping systems.

The vacuum quality in a superconducting machine has a direct impact on machine performance. Residual gas molecules in the beam pipe affect the circulating proton beam. The vacuum of LHC is strongly influenced by desorption of molecules from the vacuum chamber by synchrotron radiation and by particles lost from the beam. To limit this effect, a dedicated extra screen, the beam screen, cooled to 1.9 K, is mounted inside the vacuum beam pipe, increasing the effective cryogenic vacuum pumping power.

In superconducting accelerators the beam losses must be kept as low as possible in the cold parts of the machine. Particles lost by the beam will deposit energy in any surrounding matter. A large beam loss may deposit sufficient energy to cause the cryogenic magnet system to quench. In a quench the magnet changes from a superconducting state to a resistive state since the cryogenic system is not able to extract the heat generated by the beam loss mechanism fast enough. To avoid magnet destruction, the stored energy in a quenching magnet must be rapidly
evacuated; this also forces any circulating beams to be dumped immediately by a sophisticated machine protection system in a controlled fashion.

Magnetic errors are much larger in superconducting magnets than in non-superconducting ones. The proton-antiproton ring, the Tevatron, at the Fermi National Laboratory in Batavia, Illinois, and the hadron-electron ring Hera at the DESY laboratory in Hamburg were among the first large scale projects to investigate the distortions of the magnetic field inherent in superconducting magnets.

The choice of the superconducting material used is of outmost importance for the performance of the magnets. To reach the ultimate field of 9 T the NbTi conductors selected for LHC need to be cooled to super-fluid helium temperatures of 1.9 K; at Hera, RHIC and for the Tevatron the magnetic fields were restricted to 5 T, 3.45 T and 4 T respectively. These lower fields require less challenging cryogenic system temperatures of only 4.2 K. The drawback of a working temperature of 1.9 K is a reduction of the heat capacity of the cables by almost one order of magnitude which increases the risk of quench behaviour.

4.2. Building the LHC dipole

The LHC dipole described in the LHC Design Report [LHC04] is a superconducting two-in-one magnet: the two LHC beams pass through the same magnet and parts of the structure are common for the two beam apertures (see Figure 8). The cold mass is 15 m long and is assembled in a cryostat where it is cooled to 1.9 K. Cryostating, which means to insert the dipole cold mass in its cryostat together with all the current leads and the service structure needed for the cool down and insulation, is done at CERN. A cryostated dipole can be seen in Figure 10 and a technical overview can be seen in Figure 11.

Figure 9: A photo of the collars and the coil (cut to show the structure of the coils and the common, for the two coils, collars around the coils) of the LHC main dipole.
A cross section of the dipole magnet (Figure 8) shows the coil blocks wound from a superconducting cable, 15.1 mm wide. The inter-beam distance is designed to be 194.00 mm when the LHC is cooled down; this corresponds to 194.52 mm at room temperature. The magnetic length is 14.3 m at cryogenic temperature. The geometry of the cross section of the magnet defines the magnetic field and a close monitoring of manufacturing tolerances is therefore required.

There were 3 cold mass assemblers, Noell in Germany, Alstom in France and Ansaldo in Italy, sharing the volume of production: 1232 dipole magnets in equal parts. The outsourcing of the manufacturing and assembly of the cold mass obviously required that a comprehensive set of quality assurance procedures were defined and that they were rigorously followed-up both by the Contractors and by the LHC project engineers. The LHC dipole and quadrupoles were designed at CERN following a long and extensive research and development program.
The reception and acceptance procedures of the magnets at CERN were important for payment and guarantee conditions. Decisions on responsibilities for repair; direct and indirect controls of the magnet performances and quality were made at the assembly sites and at CERN. Complete testing of the performance of the magnets was made at a large test stand at CERN, see Figure 12.

Tolerances of parts and correctness of the assembly were verified by measurements using tools and methods developed and provided by CERN. The magnetic field was measured at room temperature to check the geometric contribution of the components of the field. Dynamic contributions to the magnetic field at cryogenic temperature coming from decay of field components and hysteresis, for example, needed thorough measurements made at CERN. Material quality samples were controlled both by the suppliers and by CERN. Since some parameters can only be deduced indirectly, e.g. the field quality, a supplier cannot be held responsible for the field quality finally achieved. The supplier is however held responsible for procuring the appropriate materials, maintaining tolerances and following the detailed assembly procedures specified by CERN. To control the field quality statistically, any detected drifts of the magnetic field components were observed and fed back to the cold mass assemblers. Close observation of the magnetic fields in the produced dipoles enabled CERN to detect cold mass assembly problems, not only for the production in general but also for the individual magnets, by looking at the statistics of already produced magnets. If, by opening up the faulty magnet, it can be shown that the problem with the magnetic field is linked to problems in the assembly process, the cold mass assembler had to remedy the problem, without any extra costs to CERN. This is the reason why the procedure of being able to analyse the magnetic fields and feed back the anomalies to the assembling firm at early stages in production, before the reception and acceptance of the magnet at CERN, was set up.

Drifts detected in the field quality in a series of magnets, that should be identical, may indicate wear of tooling or a change in the assembly procedures. The magnetic field quality depends on the geometry of the transverse cross section. The total field felt by the particles also depends on the geometry of the windings in the coil ends. This contribution is relatively small
compared to the contribution from the whole magnet (less than 5%), but a control of it was included in the production steering procedures.

The geometry of the completed cold mass defines how well the cold bore tube, the vacuum tube in which the beam circulates, follows the desired trajectory. The trajectory of the tube centre in a produced magnet is the best fit of the measurement of the tube shape to the theoretical beam trajectory. Once the magnet is installed in the best possible way, excursions of the beam from the theoretical trajectory may cause beam losses into the magnet coils due to beam tube aperture restrictions. This in turn may induce magnet quenches. The position of the centre of the beam tube has a strict tolerance and magnets were rejected if this tolerance was exceeded. However, it should be noted that the tolerance required is really at the limit of what can be achieved in industry (around one mm over a 15 m long cold mass weighing 27 tons). By sorting the magnets and installing each of them in an appropriate position in the machine, we have been able to relax the tolerances somewhat for a limited number of magnets. Magnets with relaxed tolerances can be put in less critical positions in the LHC machine thus avoiding rejection or expensive rework on the magnet. Less critical dipole positions in the accelerator are those where the excursions of the particle trajectories are small. For example, magnets in the middle of the half cells of the lattice (the accelerator magnet structure) where the beam envelope is small are the least critical positions. A LHC lattice half cell consists of three dipoles and one quadrupole. The criteria and the sorting procedure are described in [Far04].

4.3. The magnetic field description of the dipole

The control procedure described in [Wil03] that we used to steer the magnet production is based on the measurements of field components in the cold bore aperture at ambient temperature. A magnetic field can be described by a series expansion where the coefficients for each term can be related to a specific effect on charged particles passing through the field.

In a current free region of space the field fulfills the following simplified Maxwell equations:

\[ \nabla \cdot B = 0 \text{ and } \nabla \times B = 0. \]  

(4.5)

If a two dimensional field is present, with only two non-zero Cartesian components \( B_x \) and \( B_y \), the following equations can be derived from equation 4.5:

\[ \frac{\partial B_x}{\partial x} = -\frac{\partial B_y}{\partial y} \quad \text{and} \quad \frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x}. \]  

(4.6)

In a reference system, where the unit vectors of the x and y components are orthogonal, and where \( z = x + iy, x = \text{Re}(z) \) and \( y = \text{Im}(z) \), the total magnetic field \( B \) is defined in complex notation as:
\[
\ddot{B}(x, y) \equiv B_z(x, y) + iB_y(x, y)
\] (4.7)

This expression corresponds to the Cauchy-Riemann conditions, which provide a necessary and sufficient condition for the complex function \( B(x, y) \) to be analytic in \( z \). We can thus expand the field as a Taylor series in the following way

\[
\ddot{B}(x, y) \equiv \sum_{n=1}^{\infty} C_n (x + iy)^n = \sum_{n=1}^{\infty} C_n z^{n-1},
\] (4.8)

where the complex coefficients of the series can be written as

\[
C_n \equiv B_n + iA_n.
\] (4.9)

\( A_n \) and \( B_n \) are the field harmonics, the multipoles. We normalize the field expansion with respect to a reference field \( B_{\text{ref}} \) at a reference radius \( R_{\text{ref}} \). This gives the following equation

\[
\ddot{B}(x, y) \equiv B_{\text{ref}} \sum_{n=1}^{\infty} (b_n + ia_n) \frac{z^{n-1}}{R_{\text{ref}}^{n-1}},
\] (4.10)

where \( b_n \) and \( a_n \) are referred to as the normalized normal and skew multipoles respectively. For LHC they are given in units of \( 10^{-4} \) relative field error at a radius of 17 mm [Wol96] [LHC06].

How to create a suitable field from current distributions? As a demonstration the field expansion from a current line parallel to the magnet axis, the \( z \)-direction, will be given, see Figure 13.

![Figure 13: Field from an infinitely long, thin current filament located in the origin. Current is flowing perpendicular to the x/y plane](image)

By applying Ampere’s law we can find the field expansion. Ampere’s law in vacuum gives
\[ \tilde{B} = \mu_0 \tilde{H} = \frac{\mu_0 I}{2\pi r} \Theta, \]  

where \( \mu_0 = 4\pi \times 10^{-7} \) Henry/m is the permeability of free space, \( I \) is the current carried by the filament at the origin, \( \Theta \) and \( r \) are the coordinates of the point for which we want to get the field expansion. Using equation 4.7 we can write

\[ \tilde{B}(x, y) \equiv (B_y + iB_x) \exp(-i\Theta) = \frac{\mu_0 I}{2\pi r} \exp(i\Theta) = \frac{\mu_0 I}{2\pi \zeta}, \]  

where \( \zeta = \exp(i\Theta) \). This expression can be generalized to give the field expansion from a current filament at an arbitrary location, see Figure 14.

![Figure 14: Illustration for the derivation of the field harmonics from a line conductor positioned at (xc,yc), carrying the current I at an arbitrary location (x,y).](image)

We have

\[ \tilde{B}(x, y) = \frac{\mu_0 I}{2\pi |r|} \left( \frac{\tilde{I}}{||\tilde{I}||} \times \frac{\hat{r}}{||\hat{r}||} \right). \]  

This can be written in the reference system of Figure 14.

\[ \tilde{B}(x, y) = \frac{\mu_0 I}{2\pi |\tilde{r} - \tilde{r}_c|} \left( \frac{\tilde{I}}{||\tilde{I}||} \times \frac{\tilde{r} - \tilde{r}_c}{||\tilde{r} - \tilde{r}_c||} \right). \]
With complex notation, the position vectors (see Figure 14) can be defined as

$$\zeta_c = x_c + iy_c$$  \hspace{1cm} (4.15)

and using

$$\zeta = x + iy$$  \hspace{1cm} (4.16)

the field can be written as

$$\vec{B}(x, y) = |B| e^{-i\alpha} = B_y + iB_x = \frac{\mu_0 I}{2\pi |\zeta - \zeta_c|}$$.  \hspace{1cm} (4.17)

We can expand this in the following way.

$$\frac{1}{\zeta - \zeta_c} = -\frac{1}{\zeta_c} \sum_{n=1}^{g} \left( \frac{\zeta}{\zeta_c} \right)^{n-1} = \sum_{n=1}^{g} \frac{\zeta^{n-1}}{\zeta_c^n}$$,  \hspace{1cm} (4.18)

which converges for

$$\frac{\zeta}{\zeta_c} < 1$$.  \hspace{1cm} (4.19)

We now have for the line conductor

$$\vec{B} = B_y + iB_x = \frac{\mu_0 I}{2\pi} \sum_{n=1}^{g} \frac{\zeta^{n-1}}{\zeta_c^n} = \sum_{n=1}^{g} C_n \zeta^{n-1}$$.  \hspace{1cm} (4.20)

From 4.20 we see that we have multipoles of arbitrary order. In an accelerator, magnets of specific pure orders, dipoles, quadrupoles, sextupoles, octupoles etc. are needed. Using derivations of the field from current densities of arbitrary cross sections it can be shown that some specific theoretical current distributions give exact solutions to the most important simple field shapes. By superposing conductors with elliptical cross sections, see Figure 15, one can obtain pure fields. The resulting expression of the current in this configuration is [Mes96] [Jai98]

$$I(\Theta) = I_0 \cos(m\Theta)$$,  \hspace{1cm} (4.21)

where the current I varies with the cosine of the angle \(\Theta\). For \(m = 1\) we have a dipole, \(m = 2\) gives a quadrupole etc. [Jai98].
Figure 15: A pure dipole field can be obtained from superposing elliptical conductors with constant current density.

The LHC dipole design has such a “cosine-theta” configuration. It is not possible, with physical cables of constant cross sections, to design magnets which create exactly the current distribution needed. There are harmonics resulting from the positioning of the 6 coil blocks (see Figure 16). If these harmonics become large, the magnet has to be equipped with small corrector magnets. In the LHC magnets there are correctors for the normal harmonic components $b_3$, $b_4$ and $b_5$. These correctors are mounted inside the cold mass of the dipole. Their position with respect to the theoretical beam trajectory is obviously of importance for the performance of the machine. A displaced or misaligned corrector’s magnet field will create undesired harmonics of lower order influencing the stability of the accelerated beam. The effect is known as a field harmonic “feed down” and is due to the fact that the series expansion of a field in different reference systems, gives different values of the coefficients (resulting of course in different field harmonics in a real magnet).

Figure 16: The calculated flux plot of the main LHC dipole shown for a quarter of an aperture: the field is close to a pure dipole field in the aperture. The scale indicates the field in Tesla in the coils. The six coil blocks used in the LHC dipole design are shown.
There are also multipoles generated by defects in the magnet assembly. Such harmonics are not compensated for and have to be carefully monitored and avoided. When harmonic coefficients begin to deviate from design values this may give a hint of problems with the assembly. In the LHC project this is one of the indicators used to control the quality of the dipole magnets.

The total magnetic field is defined by the field generated by the coils as discussed above but we also have to take into consideration collar magnetisation and the deformations of the coil coming from the pre-stress imposed on the magnet. These effects are evaluated using Boundary Element Methods or Finite Element Methods. The total field harmonics can be expressed as

\[
b^\text{cc}_n \equiv b^\text{coil}_n + b^\text{ccdef}_n + b^\text{collars}_n,
\]

where \(b^\text{coil}_n\), \(b^\text{ccdef}_n\) and \(b^\text{collars}_n\) are the components coming from the coil, the collared coil deformations and from the collar magnetization respectively.

When the yoke is added the main dipole field is increased. Since all multipoles are expressed relative to the main dipole field, the collared coil contribution is rescaled by the main dipole field increase. This factor, \(k \approx 118\), due to the enhancement of the main field from the iron yoke, gives:

\[
b^\text{cm}_n \equiv \frac{b^\text{cc}_n}{k} + b^\text{cmdef}_n + b^\text{iron}_n.
\]

The field in the dipole also varies along the magnet axis. The particles in the beam experience the integral of the different field harmonics along their trajectory in the magnet.

The geometrical contribution to the harmonics is related to changes of the geometry of the coil and the effects of the materials around it when the magnet is cooled down to 1.9 K. In a first approximation this contribution can be modelled as a sum due to the cold mass change and an offset \(b^\text{cool}_n\). These calculations have been carried out using a mechanical FEM model [Bon96].

At low fields, the multipoles will also be affected by the contribution of persistent currents \(b^\text{pers}_n\) in the coils. This term can be evaluated with a model that takes into account the measured magnetization and the coil geometry [Wol00]. At high magnet field (i.e. at the collision energy for LHC) the effect of iron saturation \(b^\text{satur}_n\) and of deformations \(b^\text{emdef}_n\) induced by electromagnetic forces are also present:

\[
b^\text{geo}_n \equiv b^\text{cm}_n + b^\text{cool}_n, \quad b^\text{geo}_n \equiv b^\text{geo}_n + b^\text{pers}_n, \quad b^\text{coll}_n \equiv b^\text{geo}_n + b^\text{satur}_n + b^\text{emdef}_n.
\]
To reach the nominal magnetic field, very close control of the tolerances maintained by the suppliers and the magnet assemblers have to be kept. The magnetic field in an assembled dipole is measured at CERN at cryogenic temperature where all effects discussed above are present. With these tests it has been confirmed that the expressions defined here can be used to deduce the magnetic field at cryogenic conditions from a magnetic field measured at room temperature. The fields of all magnets are measured at room temperature at the assembly sites (the collared coil assembly and the cold mass assembly). This permits an early detection of assembly defects that may not only affect the magnetic field but also could jeopardize the correct functioning of the magnet (short circuits, quenches and other).

The sum of the tolerated field errors for the machine in the design stage can be distributed over the different types of magnets; the main dipoles occupy 2/3 of the circumference of the LHC. They are mainly located in the arc (see Figure 17) regions. When injection optics is used, at 450 GeV, the dipole field quality plays a very important role for the behaviour of the machine, since the beam is large and the effect of the multipoles depends on the distance of the particle from the theoretical trajectory.

For physics, the optics in the interaction regions is changed, to make the beam more dense in the collision region. Then the beams are steered by special dipole magnets to bring the beams together for collisions in the 4 interaction regions at 7 TeV + 7 TeV. This squeezing of the optical β functions in the collision points makes the beams very large, locally, inside the insertion magnets. This requires good field quality of the so called insertion quadrupoles. The squeeze is done by changing the current in a few quadrupoles outside the insertion region, in the matching section. The current in the insertion region magnets is not changing during the squeeze.

Figure 17: LHC experiments CMS, ATLAS, ALICE and LHCb are located in the insertion region around the interaction points, where the regular optics in the arcs is changed to a special optics to make it possible for the beams to cross. When collision conditions are reached the beams are steered to collide.
4.4. What is the effect of the field errors in the LHC?

There are a number of beam parameters of the LHC that have to be controlled and kept within limits. Some of them are related to the magnetic field. Specific performance criteria are set on parameters like the coupling of transverse oscillations, the closed beam orbits, \( \beta \)-beating, chromaticity and field corrector powering. These parameters are influenced by the magnetic field’s total quality, i.e. both controllable and non-controllable multipoles (imperfections in the manufacturing). The arc dipole (the main magnet) field is a major contributor to the total effect caused by multipoles simply because there are so many of them.

As an example, the closed beam orbit in each ring is limited by the small aperture of the vacuum tube in the magnets and the effects of non-linear field imperfections. In particular the collimation and beam dump areas (points 3, 6, 7) are parts of the machine that have very tight orbit requirements. The orbit may also be affected by feed down effects of quadrupolar \((b_2, a_2)\) field errors. Coupling between the two beam planes comes from skew components of the field; such field components transfer particle energy between the horizontal and the vertical planes. This may cause resonance effects and eventually impose limits on beam stability. The \( \beta \)-beating effect, the total relative difference between the nominal optical \( \beta \) function and the real \( \beta \) function, may change if quadrupole field errors \((b_2, a_2)\) or, by feed down, sextupole \((b_3, a_3)\) errors, are present, see also Table 2. The existence of these field imperfections may change the machine tune, the number of oscillations the particle makes around the machine, and limits stability again. The specification of the limits of the field errors for the LHC magnets is based on experience from operation of existing hadron storage rings [Pro95].

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Injection optics (450\text{ GeV})</th>
<th>Injection optics (7\text{ TeV})</th>
<th>Collimation optics (end of ramp)</th>
<th>Systematic uncertainty (max. value)</th>
<th>Random uncertainty (max. value)</th>
<th>Criteria used</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_0) (including MB roll angle)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>None</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>(b_2)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>1.4</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>(a_2)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>0.9</td>
<td>2.3</td>
<td>1.6</td>
</tr>
<tr>
<td>(b_3)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>1.0</td>
<td>1.4</td>
<td>1.8</td>
</tr>
<tr>
<td>(a_4)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>1.5</td>
<td>(\beta)-beating and (Q^2) and MQS strength at 7 TeV</td>
<td></td>
</tr>
<tr>
<td>(b_4)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>0.2 (from Table 9903)</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>(a_6)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>0.13 (from Table 9903)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>(b_6)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>1.1 (including the bias due to uncertainty)</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>(a_8)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>0.4 (from Table 9903)</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>(b_8)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(-0.3 &lt; (b_7) &lt; 0.1)</td>
<td>0.2 (from Table 9903)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 2: Specifications of the dipole magnetic field multipoles: surrounded in fat are the criteria on the LHC that may be influenced by the unwanted multipoles. Source: LHC Design Report [LHC04].
Since field errors cannot be completely excluded, they have however to be kept as small as possible. They can be corrected by special correction magnets. The correctors, in turn, have to be well aligned to the theoretical beam axis in order not to induce yet other field error components due to displacement of the “centre” of the magnetic field in the corrector.

4.5. The measurements of the magnetic field in the LHC dipole

The measurement of the magnet field and the verification of the assembly procedures are parts of the LHC magnet quality control program. Knowledge of the measurement systems’ performance and the prescribed measurement procedures are important to be able to distinguish measurement problems from problems with the assembled magnets.

The fields [Bil02] in the magnet apertures are measured with rotating coils, where a loop of wire brought to rotation in the magnetic field. The coils used for measuring the field are tangential coils, see Figure 18 and measure the radial component $B_r$ of the magnetic field at a defined radius, the reference radius, $r_c$. During the measurement procedure, the rotating coils have to be kept properly aligned parallel to the magnetic axis to avoid the introduction of additional errors.

![Figure 18: The principle of a rotating coil for magnetic field measurement in magnet apertures](image)
The coil rotates at a constant angular speed $\omega$ inside the magnet aperture. Fourier analysis of the acquired signal of the flux in the coil permits extraction of the magnetic field harmonics. The opening angle $\Delta$ of the coil should be large enough to give a good signal and small enough to be able to detect the field harmonics with the required precision. The radius $r_c$ has to be maximized to get a good signal strength for higher harmonics. The reference radius for the measurements for LHC has been defined to be 17 mm and the length of the rotating coil is 0.75 m. The field and the field harmonics are measured at twenty different positions along the length of the magnet (~ 14 m of the magnetic field extension, the cold mass is 15 m long).

4.6. The dipole magnetic field quality control and results for the quality of the assembly

Many measurements and tests are made on the magnets at the assembly sites and at CERN: electrical tests, dimension tests, examination of weld joints and leak tests. The magnetic fields of all dipoles are measured at room temperature, once after the stage of collaring and again after cold mass assembly. After these measurements are performed, the data are sent to CERN for analysis and control. These specific stages in the assembly procedure are designated as “holding points”; the assembly process cannot progress further if any of these measurements has any anomaly in the quality of the measurement, in the main field or for any of the multipole values. The control procedure used for the assembly quality checks is described in [Wil03]. We have been able to distinguish that around 3% of the measurements (2003) were not correct, which indicate that the measurement system was reliable and suited for a high production rate environment. Since the production was immediately stopped if the magnet did not pass a holding point, a very careful follow up of the measurement system performance was required.

4.7. The software system for the quality control of the magnetic measurements

For the holding point at the magnetic measurements, a web based control system was implemented using J2EE JSP technology. The documentation of this project is not yet publicly available\(^3\). The system can be accessed at [http://at-mas-pda-root.web.cern.ch/at-mas-pda-root/](http://at-mas-pda-root.web.cern.ch/at-mas-pda-root/) (limited access). The interface to the system can be seen in Figure 19. The software permits uploading of data at the assembly sites in a strictly controlled manner, download and analysis at CERN, automatic registration in data bases of all acquired data and the action finally taken by the analysts. Communication of results and comments were managed via automatically created electronic mail messages. It could be noted that this project was also used as a successful test bench for the public deployment of J2EE to a wider CERN audience.

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\(^3\) LHC Project Note by E.Wildner, project leader, G. Bevillard and N.Emelianenko, to be published.
4.8. Requirements on the geometry of the dipoles for the LHC beam

The geometry of the 15 m long dipole cold mass structure has to be maintained to within a tolerance of a few tenths of a mm. The cold mass weighs 27 tons and is supported in 3 points below the magnet. Three important aspects of the magnet geometry relevant to beam physics issues will be discussed, viz.

1. the cold bore vacuum tube excursions along the magnet with respect to the magnet axis,

2. the positioning of the various magnet field corrector magnets,

3. the tunnel installation adjustments of the magnets using information fed back from the geometry measurement.

Points 1 and 3 are related to the aperture as they are seen by the circulating beams. As mentioned earlier, too many high energy particles lost in a superconducting dipole magnet could quench it and subsequently stop the LHC. Point 2 is relevant for the handling of magnet field errors: the corrector has to correct the field error for which it is designed. If it is not placed correctly on the
beam orbit the corrector field will instead have a different effect on the beam than what is expected, due to the feed down effects.

Contributions to the aperture specification of the dipole come from the beam requirements and from realistically achievable mechanical tolerances as described in [LHC04]. The aperture, expressed in beam size units σ (one standard deviation of the distribution), is about 10 σ. Beam-cleaning, which removes particles drifting out from the beam core, is always active and the primary beam aperture is delimited by the movable gap of the primary collimators. The secondary beam aperture is defined as the edge of the secondary halo; the efficiency of the complete collimation system is designed to make the tertiary particle flux harmless to the magnets. However, now a tertiary collimation system is also considered.

The beam size, after collimation by the primary collimators that present an octagonal mask to the beam halo, is:

$$X^2 + Y^2 = n_1^2,$$

where $n_1$ is the primary aperture and X and Y are normalized coordinates:

$$X = \frac{x}{(1 + k_\beta)\sigma_x}, \quad Y = \frac{y}{(1 + k_\beta)\sigma_y}.$$

$k_\beta$ is the β-beat factor and the indexes x and y correspond to the two transverse directions, x and y. This factor indicates the change of beam envelope, σ, due to the modification in focusing from errors in the focussing strength along the machine. The secondary halo is contained in a circle of radius $n_r$ and cut in the horizontal and vertical directions at $n_a$ (see Figure 20), with

$$n_r = 1.4n_1, \quad n_a = 1.2n_1.$$

![Figure 20: The geometry of the primary beam and the secondary halo in normalized coordinates.](image-url)
These values have been chosen to have the secondary collimation aperture at

\[ n_z = \frac{7}{6} n_t . \]  

(4.29)

This value comes from the Monte Carlo simulation of particle trajectories in the machine, a certain fraction of which impinges on the collimators.

To protect the superconducting dipole magnet from the synchrotron radiation, which will heat it up, a beam screen is inserted in the cold bore tube. The cold bore tube inner diameter is 50 mm. The height of the beam screen, \( v_{bs} \), is 35.4 mm and its horizontal diameter, \( d_{bs} \), is 45.2 mm, see Figure 21 below.

![Figure 21: beam screen in the cold core tube, one quadrant.](image)

The information presented above now permits us to express the requirements for the dipole aperture. The real closed orbit (CO), which is the beam trajectory around which all particle trajectories oscillate, may be displaced with respect to the ideal closed orbit. To this closed orbit we have to add the growth of the beam size due to the dispersion of the optics in the magnet. These two contributions are shown as \( (\Delta x, \Delta y) \) in Figure 22. The mechanical tolerance of the beam screen in the cold bore tube is \( r_t \). The normalised beam size after collimation is \( n_t \).

For the geometry of the dipole cold mass the excursion of the cold bore tube measured along the magnet has to be smaller than the tolerance \( t_r \), since \( t_r \) also takes into account the tolerance of the beam screen inserted in the cold bore tube. Magnets not fulfilling the 1.3 mm horizontal tolerance may be accepted and put in the less critical positions in the lattice only if they are not exceeding a certain number defined by the lattice structure and sorting criteria at the magnet allocation procedure.
Figure 22: Aperture in the dipole: The contribution from the beam comes from the displacement of the closed orbit and the contribution from the dispersion ($\Delta x, \Delta y$), the mechanical tolerance of the beam screen and the cold bore tube with respect to the theoretical position, $t_r$, and the contribution from the beam, $n_1$, and from the geometry of the secondary halo.

The theoretical shape of the dipole is shown in Figure 23.

Figure 23: The theoretical geometry of the dipole in the horizontal plane. The figure is not to scale for obvious reasons. The dipole is around 16.5 m long, ancillaries included. The magnetic length is 14.3 m. The magnet is bent with a sagitta of 9.11 mm. The distance between the cold bore tubes, $h$, is 194 mm, all at cryogenic conditions, at a temperature of 1.9 K. The connection side is where the magnet is electrically connected. The bending radius, $\rho_c$, where the subscript c stands for cold, is 2803.98 m. Shown in the figure are also the corrector magnets, the sextupolar, MCS, and the octupolar/decapolar, MCDO.
Many geometrical parameters of the dipole are measured. For the beam physics requirements we only check a limited number of criteria. Most of the parameters have strict tolerances that the contractors have to respect; the magnet is not accepted for shipping if the measured parameters do not comply with the requirements. However, when the magnet comes to CERN, the shape may have changed due to the transport. There are some contingencies for such changes in the tolerance specification of the magnet after the cryostating and cold test phases. We have introduced a system where all measurements are collected in an ORACLE database and implemented statistical control programs to monitor the geometry evolution as the magnets move between the assembly sites and CERN. The results of this statistical process control are described in [Wil04] together with the specification for the magnet shape in all production stages.

The original dipole magnet design support system had only two positions horizontally, but the change of the shape during the transport to CERN, from the different assembly sites, was too important and an additional support had to be added. The decision to increase the magnets' mechanical support in the horizontal direction by blocking the middle support post was taken after analysis in an internal working group; the summary is described in [Jea03]. The middle support post can also be used to fine tune the final overall geometrical shape. Local deformations can however not be compensated for.

The final shape of the dipole as it is installed in the LHC tunnel has a crucial impact on the beam behaviour. The position of the corrector magnets, installed inside the dipole, is also very important due to the accumulation of erroneous magnetic fields seen by the beam if they are not correctly aligned with the theoretical trajectory. The positions of the correctors have manufacturing and assembly tolerances. But the real criteria are statistical: the effect of a possible corrector misalignment is integrated over the whole LHC. The criteria for the corrector alignments are: the mean misalignment has to be within 0.3 mm with a standard deviation of less than 0.4 mm at the last complete measurement of the magnet before it is installed in the tunnel.

4.9. The measurements of the geometry

The measurements are carried out by measuring the position of a reflector mounted on a cylindrical measurement mole centred transversely with a mechanical system, in the cold bore tube. This mole is displaced along the magnet axis and a sophisticated optical system, using a dedicated acquisition computer, reads all data points [Baj02]. The corrector magnets are placed on their nominal positions, and measured. After closing of the cold mass, the corrector magnets are not accessible and their position at later measurement stages has to be deduced from the movement of visible, well defined points on the outside of the cold mass.

The magnet geometry is completely measured at the contractors’ sites before shipping. It is also re-measured at CERN after the cold testing. At the assembly sites the reference system of the measurement of the cold bore tube excursion is defined by making a best fit of the measurement point to the theoretical trajectories. At CERN the same calculation of the reference system is made using the measured points. The magnet now is cryostated, so this reference system can also be related to alignment targets located on the outside of the cryostat. The reference system calculated in this way will be the final installation reference. Using this approach, if the sagitta of the magnet changes, the position of the correctors will also move,
since the reference system will not be the same. This is one of the main issues for the adjustment of the magnet shape.

All measurements are collected in a database. Two typical measurements at different stages can be seen in Figure 24, displayed in the coordinate system relative to the best fit of the measurement to the theoretical beam trajectories. The viewer [Bev05] is accessible via the web using the same address as for the magnetic measurement analysis system, already mentioned. We can see the shape of the magnet in the horizontal plane as it was registered at the assembly site and at CERN, after an adjustment of the geometry.

![Figure 24: Example of geometry of the magnet as extracted from the measurement database via the web: cold bore tube excursion with respect to the theoretical bent cold bore tube shape. Horizontal plane, the x-axis points to the centre of the LHC.](image)

4.10. Adjustments of the geometry and final results

The fact that the magnet design permitted a geometry change when the support moved during transport forced a blocking of the central support post. The support post is initially blocked in the cryostating phase in whatever position it has when it arrives at CERN. It is then used to adjust the shape of the magnet when the magnet is measured after the cold test. The industry measured shape corresponds to an initial target shape and the corrector magnets are
positioned using the reference system calculated from this measurement. After the decision to block the central support [Jea04], the geometry is adjusted to be as close as possible to the cold mass geometry at the assembly sites. This kind of adjustment needs 2 measurements, one to measure the shape to be able to calculate the needed adjustment value and a second to verify the result. The resulting geometry has been analysed, and for all three assembly sites the geometry achieved for all magnets are within the requirements after the cold tests at CERN [Wil04].

The increasing production rate in industry and the ramping up of the installation rate of the dipoles in the LHC tunnel did not permit taking the necessary time to measure the magnet twice after cold test. A new way of adjusting the dipole geometry had to be implemented and a statistical method was proposed [Wil05], which permits good control of the geometry with only one measurement. The paper discusses why adjusting the magnets using a statistical estimate of the shape change after transport to CERN is sufficient. The magnets from the three assembly sites all have different average shape changes, making a statistically adjusted geometry feasible. As the mean value of the shape change is very stable, in the order of the accuracy of the shape adjustments, only very small corrections of the statistical adjustment values have been necessary. This feedback mechanism permits the mean value of the corrector magnet positions to be adjusted to be very close to zero. The spread of the shape change cannot be controlled in any other way except by a mixing-in of a population of magnets with more accurate shape adjustments (adjustment to the shape achieved at the assembly sites). However this has not been necessary; the measurements show that the position of correctors and connection flanges at the opposite ends of the magnets are within tolerances, with only the statistical adjustment procedure.

The advantage of adjusting the magnet shape back to the shape the magnet had at the assembly sites, before their transport to CERN, is that the final magnet shape can confidently be predicted. Such individual prediction is of course not possible when a statistical adjustment is used. The prediction is however important for the installation procedure: some critical positions in the accelerator need particularly good geometry. From the moment that some time contingency was available for measuring twice the magnets, this extra time was used to adjust magnets to the shape they had after assembly.

The total result of geometry shape adjustments, statistical and individual, gave a very good result and we could guarantee the specification values despite of the constraints imposed by the affordable number of measurements (production speed constraints). The web based applications that we implemented can be used to see the final results graphically and in table form, see Figures 24, 25 and 26. In Figure 25, we see the evolution of the mean value and the spread of the corrector positions month by month for all produced magnets. Figure 26 gives an example of the evolution of the shape criteria, the different aperture classes, also every month. Figure 27 gives the positions of the correctors with respect to the theoretical beam trajectory.
Figure 25: Example of the results of the adjustment procedure follow-up: field corrector magnet positions.

Figure 26: Example of the adjustment procedure follow-up: results for the aperture classes used for the sorting of magnets. Enough “golden” magnets with perfect geometry also for the most optically sensitive positions are required. Not too many of the magnets that may be put in less sensitive mid cell positions can be accepted.
Figure 27: Example of the adjustment procedure follow-up: results for the sextupolar field correctors. We can see the good overall results for the mean value of the positions and the spread.

The sextupole and the octupole/decapole corrector position mean values are close to zero for both planes. The spread is also within the magnet’s specification of 0.4 mm rms. The magnets are put into goodness classes according to criteria based on the LHC lattice aperture requirements. We have also managed to get the required number of magnets for each requirement class, in order to satisfy the aperture needs of the machine. The results also gave contingency for some sorting, where also other criteria than geometry had to be considered for the allocation of magnet tunnel positions. This process is described in [Wil05].
5. IMPROVING GEOMETRY MEASUREMENTS OF THE LHC MAGNETS

The LHC magnet axes are optically measured from the opposing ends of the magnet. These two redundant measurements are combined to get a reliable measurement result and to compensate for calibration errors. When the two measurements were combined, a “saw tooth” effect was observed due to the fact that the two measurements are, in general, not identical. The study was motivated by noting that the effect is larger than should be expected from the accuracy of the measurements. The influence of temperature gradients on measurements in the cold bore tube of the magnet during measurements has been observed [Ain99]. We show in the study, that this effect is the most probable explanation for the observations of the geometry measurements in the vertical plane. What we want to measure is the geometrical shape deformations of the magnets. The aim is first to disentangle the measurement inaccuracies from the real magnet shape deformations, and second, to develop an algorithm to filter the effect out and improve the measurement results. The evidence of a measurement system problem and not of a problem of real shape change could be demonstrated by a statistical approach and by making comparisons of the magnet’s corrected shape to the shape achieved in the magnet assembly where the measurement problem was observed to a lesser extent. The issue could be solved once a statistically significant set of magnets, where we could exclude the influence of other factors affecting the magnet shape, could be identified.

The origin of the problem is difficult to eliminate since the environment at the magnet assembly sites and at CERN have temperature variations and air flows that may influence the measurements despite shielding efforts at the measurement stations. The effect is relatively small but for some magnets the displacement is up to -0.3 mm compared to the magnet positioning accuracy which is 0.1 mm. Our analysis shows that by applying the correction we can ensure the best positioning of the magnets (including the spool pieces) in the tunnel in the vertical plane. The positions of the corrector magnets follow the movements of the two ends of the magnets, where they are mounted, and also have to be closely monitored.

The work on the quality of the measurements to be able to diagnose apparent changes in the magnet’s local shapes, which are not consistent with the mechanical predictions, will now be introduced. The quality analysis initially made shows that the origin of the problem had been mentioned in work done some years ago. The new progress in the analysis has been achieved by linking the measurement quality issues to the magnet shape characteristics. The important result is that we can now explain not only the shape changes but also that a correction procedure could be set up. The effect on the measurement results could not be cured during the measurements due to the very high production rate: one cause is e.g. non uniform magnet temperature when measuring.

As mentioned in chapter 4 the measurements are carried out by interferometric measurement with a reflector mounted on a cylindrical measurement mole, centred mechanically, transversely, in the cold bore tube. The mole is displaced along the cold bore tube axis and a sophisticated optical system, with the automatic assistance from a computerized control system, registers all data points [Baj02].
5.1. The measurement errors

As explained in 4, the shape-measurements are represented in a coordinate system defined by the 3-dimensional ideal beam trajectories in the magnet. This is done using a best fit of the measurement points (from the two opposite ends and both apertures) on the ideal beam trajectories [Mis02],[Mis04]. The xy-plane in this coordinate system is the magnet mean-plane and the magnet will be installed in the tunnel such that this plane is aligned with the machine’s horizontal plane. The z-coordinate is taken to be positive opposite to the direction of the gravitational force. When the two measurements are put together in the same reference system, we observe a “saw tooth” behaviour of the results, see Figure 28. When the measurements from the two opposite sides were displayed separately, a suspicion arose that a phenomenon deviating the measurement laser beam rather than a limited repeatability of the measurement caused the saw tooth effect.

We define the “saw tooth” height as the difference between the two measurements at the same longitudinal position of the magnet. The saw tooth height may be larger at one end of the magnet. The difference between the measurements has been fit to a 1st order polynomial. The coefficients of the 1st and 0th degree terms represent, respectively, the slope and shift of the saw tooth. The characterization of the saw tooth, necessary for the systematic statistical analysis, is discussed in detail in [Wil072].

![Figure 28](image.png)

Figure 28: The left plot shows the vertical measurement of the main dipole number 2248 in industry (dark) and at CERN (light). In the plot to the right the measurements from the two sides of the measurement at CERN have been plotted separately. The crosses represent the position of the spool pieces. The lowest points, starting close to the spool pieces are measured close to the laser tracker.

To be able to continue the work according to this assumption, we had to look at the known error contributions documented by the measurement device manufacturer and by the measuring system setup. The mole used for supporting the reflector also gives some contribution from the limitations of the centring of the device. The specifications, from [Mis04], are listed below:
1) Linkage of the laser tracker positions characterized by the bundle adjustment \((ba)\) limited to 0.08 mm at one standard deviation.

2) Measurement error \((me)\) of a point by the laser tracker as given by the manufacturer to 5 ppm at one standard deviation.

3) Centring error \((ce)\) of the measurement device (the mole) inside the cold bore tube is measured as 0.07 mm at one standard deviation.

Therefore the 3 standard deviation difference between the two measurements from the opposite ends of the magnet is given by:

\[
dev = 3 \cdot \sqrt{ba^2 + (d1 \cdot me)^2 + (d2 \cdot me)^2 + 2 \cdot ce^2} \tag{5.1}
\]

where \(d1\) is the distance from a point to the laser tracker in position 1, measuring from one end, and \(d2\) is the distance of the same point to the laser tracker in position 2, measuring from the opposite magnet end.

This gives a limit of 0.47 mm, at 3 standard deviations. In [Mis02] it is stated that if the difference between two consecutive measurement points exceeds this value it has to be redone.

From observing the measurements, we see that this limit is not respected, see for example the measurement in Figure 28, because even if the measurement was repeated the same errors were present. It is also shown in [Wil072] that the saw tooth effect is more often present during the winter period and also less pronounced as the magnets have been warmed up from a cryogenic state (several measurements after cryogenic cold tests are available for some magnets). Despite a careful control of linkage error and calibration errors, the difference of the measurements from the two sides is larger than 0.47 mm probably due to additional effects of different origins that are not mentioned above and which we will discuss further.

The misplacement of the mole, due to limited calibration accuracy of the mole centring, is not observed in the vertical plane, because the error is the same for the measurements from the opposite sides of the magnet. However, as a consequence, the magnet position in the machine will induce the same error contribution to the integrated magnetic field as the mole positioning error. The reason is that the magnet is aligned vertically using the mean value of the vertical measurement, i.e. the mean centre of the cold bore tube. If the mole is not positioned correctly in the centre of the cold bore tube, the magnet will be installed and aligned displaced from the real centre.

In the horizontal plane the mole centring error will be automatically compensated since the error from the misplacement of the mole is the same in the measurement from either side but with different signs (the measurement mole is turned to be entered from the other side of the cold bore tube), see Figure 29. However, the measurements will still show a saw tooth effect due to the centring error, i.e. they will have a contribution to the saw tooth from the centring errors. In the vertical plane the saw tooth effect will not appear. This means that for the statistical analysis,
where we compare the horizontal and the vertical planes to distinguish if a specific effect in the vertical plane exists, we have a conservative situation. If we see a larger saw tooth contribution in the vertical plane, we know that the mole centring error is not the reason.

We have made an analysis of the measurement uncertainty for a single measurement, from one side of the magnet only, in the annex 1 of [Wil072]. This analysis confirms that the specifications of the measurement device are maintained.

![Diagram](Image)

**Figure 29: Illustration of the contribution of a calibration error to the difference in CBT centre position values, measured from opposite ends of the magnet.**

The two measurements, from opposite magnet ends, require moving the laser tracker and hence to measure several times the reference network to establish a reference frame. These movements are the origin of the bundle error. The resulting uncertainties in the reference frame were studied in [Gub042] where the reference network measurement errors were simulated by adding Monte Carlo-generated errors. The tolerances and error estimations were extracted from the system specifications of the Leica laser device which was used for the measurements. Ground movements and instabilities simulated included e.g. a lowering of the Leica into the ground. Data from this analysis has been compared to the measurements made and the result is shown in Table 3. The notation Firm a and Firm b refers to the data acquired from two different measurements of the same dipole magnet. These two measurements of the magnet shape are made respectively immediately after the welding of the steel shells surrounding the magnet with its laminations and just before the mounting of the cold mass end covers. Measurement errors are located, as expected, between the errors generated by a simulation of steady state and a simulation taking into account floor movements. The differences in the slopes and the shifts are very small compared to the variations. For the horizontal plane we have small mole errors and bundle errors which correspond to the simulations.
In the horizontal plane the measurements are within the specification tolerances.

5.2. Observations

We use the height and the slope as statistical criteria to qualify the geometrical shape, see Figure 30. The identifier ITP15 corresponds to the manufacturing step where measurements are made immediately after the welding of the cold mass and the identifier ITP20 refers to the manufacturing step where measurements are made just before the shipping of the dipole from the assembler site. We observe a significant change in the data for the measurements done at CERN (identifier WP08-FID) in the vertical plane only: an increase in the saw tooth height and slope and a significant decrease in the shape shift are visible. In the horizontal plane the measurements at the different manufacturing steps (ITP15, ITP20 and WP08) do not show any significant differences whether done at the assembly sites or at CERN after the cold tests.

Indeed, the number of magnets exceeding the recommended maximum saw tooth height of 0.47 mm and thus causing re-measurements, is 12% for the CERN made measurements and 2% for the measurements made at the assembly sites [Wil072].

<table>
<thead>
<tr>
<th></th>
<th>Height avg [mm]</th>
<th>Height std [mm]</th>
<th>Slope avg [rad]</th>
<th>Slope std [rad]</th>
<th>Shift avg [mm]</th>
<th>Shift std [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim. (steady)</td>
<td>0.065</td>
<td>0.010</td>
<td>-3.0E-07</td>
<td>4.6E-06</td>
<td>0.040</td>
<td>0.040</td>
</tr>
<tr>
<td>Sim. (+floor)</td>
<td>0.125</td>
<td>0.095</td>
<td>-2.4E-07</td>
<td>4.0E-06</td>
<td>-0.015</td>
<td>0.160</td>
</tr>
<tr>
<td>Firm a</td>
<td>0.083</td>
<td>0.050</td>
<td>-9.5E-08</td>
<td>7.0E-06</td>
<td>0.016</td>
<td>0.110</td>
</tr>
<tr>
<td>Firm b</td>
<td>0.085</td>
<td>0.048</td>
<td>9.3E-07</td>
<td>8.4E-06</td>
<td>0.011</td>
<td>0.112</td>
</tr>
<tr>
<td>CERN</td>
<td>0.091</td>
<td>0.053</td>
<td>3.2E-06</td>
<td>6.9E-06</td>
<td>-0.016</td>
<td>0.112</td>
</tr>
</tbody>
</table>

Table 3: Simulations and measurements, horizontal plane
Figure 30: Some saw tooth criteria applied to measurements at the assembly sites (ITP15, ITP20) and at CERN (WP08). We see a significant change in the data for the CERN measurements (WP08-FID), made after cold test, in the vertical plane only.

[Ain99], [Sch04] and [Smi99] describe the evidence that a deflection of the measurement laser beam at the entrance of the cold bore tube may be due to temperature gradients creating a convection cell. The effect of a convection cell on a light beam is illustrated in Figure 31.

The hypothesis is that the measurement points are linearly deflected towards higher z-values when the mole with the reflector enters the cold bore tube and moves away from the laser device.
5.3. The correction algorithm

To demonstrate that the beam deflection really was the cause of the apparent magnet deformation, a correction algorithm based on this assumption was developed. Then, after correction using this procedure for the suspected measurements, the different magnet shapes measured after the assembly and the shapes measured after cold test at CERN had to be compared. Our conviction was that the shapes would be only deformed globally [Lac06] and would show very little local deformation. We could show that the magnet shapes indeed were very similar (within 0.1 mm) from the assembly stage until after the cold test stage, by applying the algorithm. The algorithm also permitted to estimate the shape in the vertical plane more accurately.

In Figure 32 we show a dipole measurement where we have separated the two measurements that constitute a complete cold bore tube excursion measurement. We have also indicated the points that are close to and far from the Leica laser tracker system. In the figure the position of the corrector magnets, which at the assembly sites were mounted at the zero nominal position with an accuracy of 0.1 mm rms is flagged.

Figure 32: The two measurements, from the opposite ends of a dipole, separated. Points close to the laser tracker device and far from the laser tracker device are indicated.
The basic assumptions for the correction algorithm are the following:

- Points close to the laser tracker are measured with more accuracy than points further away from the tracker.

- We assume that the deflection of the measurement beam is located at one single point at the entrance of the cold bore tube [6].

- The laser beam deflections at the two opposing ends of the magnet are not related.

- No change in the reference system is made at the correction, which means that all parameters used by the surveyors to align the magnet are unchanged after the correction.

- We assume that the points close to the tracker are the most accurate measurement points. These points are taken as “good” points and are not changed by the correction procedure. Thus, at the opposite magnet ends there is at least this one “correct” measurement point, which will serve as reference.

- It may happen that there is a convection cell at only one end of the magnet.

There are points measured outside the cold bore tube of the magnet which are not affected by the convection cell in the cold bore tube (end cover positions). These external points can be used as checkpoints.

If after measurements made at CERN, we can recover the shape of the magnets had when they left the assembly sites and reconstitute the respective end cover positions the algorithmic approach is successful. Obviously we have to adjust for the inevitable measurement errors. The magnet’s vertical shape may indeed be changed by errors in the adjustment of the central support [Wil05] and has to be taken into account when comparing magnet shapes. Measurements of magnets with correctly adjusted shapes and measured at CERN after cold tests, have to be selected from the measurement data base to avoid introducing additional errors originating from the adjustment procedure.

The proposed correction scheme is based on the assumption that the Leica laser beam gets a significant deflection only at one point situated at a short distance from the cold bore tube opening [6]. Using this assumption we can propose that the measurements should overlap (within some norm) and that the “good” points are the points located closer to the Leica tracker system: those points can be kept without correction. The points assumed to be disturbed by the convection lens effect are interpolated linearly (similar to mean plane calculation). This interpolation line of measurement points should overlap with the interpolated points at the cold bore tube ends. Linear interpolation is similar to the method used by the magnet geometry measurement team to calculate the magnet’s mean plane.

In Figure 33 we see two measurements made at the two opposite magnet ends, two convections cells are assumed to be located at 0.2 m from the cold bore tube openings (sometimes
there is only one convection cell) and the linear interpolations of the two measurements. We see also the “reference line” which is a linear interpolation of the points not affected by the deviation of the beam). We propose that the interpolated lines of the two measurements should coincide with the reference line. A good accuracy of the measurements of these points is important for the mean plane estimation and is achievable if care is exercised during the measurement process. The points we take into account to establish the reference line also include the flange centre position which is measured with a more accurate device, outside the cold bore tube.

![Diagram](image)

**Figure 33: Illustration of the correction method, see text.**

Equation (2) below describes how the points are superposed for the measurement from the connection side:

\[
z_{\text{corr},i} = z_i - (z_{\text{connectionfit}}(y_i) - z_{\text{ref}}(y_i))
\]

(2)

where the variables are described in Figure 34. The measured point \(z_i\) should be corrected by the difference between the two interpolated curves at the corresponding cold bore axis coordinate.
After correction of the acquired data from each cold bore tube measurement we can calculate a new mean plane (3 dimensions, both cold bore tubes) to evaluate the “misplacement” of the magnet shapes due to the saw tooth effect. The measurement points best fitted to the theoretical beam line are used to define the best position of the magnet in the machine lattice. This calculation can therefore be used to evaluate the best correction shifts for the magnets at their installation. We have to prove, however, that the new mean plane calculated is closer to the real mean plane than the mean plane calculated from the uncorrected measurements.

After the correction has been applied, tests can be made to check the approach’s success by comparing how the shapes have evolved throughout the production process, remembering that the local mechanical stability of the magnets should be guaranteed by the rigidity of the structure. Several detailed examples of individual magnets are discussed in [Wil072], where their shape changes are less than 0.1mm after the correction has been applied. It is however important to verify if, statistically, from a set of magnets with large saw tooth characteristics, we can recover measurements made independently. It should thus be possible to control the correction applied by using measurements from another device which does not suffer from the convection cell distortion.

For 33 dipole magnets measured which have large saw teeth, > 0.47 mm, we have a shift in the position of -0.17 mm at the non-connection side and -0.10 mm at the connection side (average values). For both sides the difference after correction is close to zero (0).

<table>
<thead>
<tr>
<th>Difference CERN industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orig connection</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Average [mm]</td>
</tr>
<tr>
<td>Stdev [mm]</td>
</tr>
</tbody>
</table>

Table 4: Result of the correction procedure applied to a set of magnets: the position of the end cover at CERN is very close to the position in industry after measurement data correction.
A supplementary verification can be made by recovering the geometry classes of the magnets. The classification of the magnets is made according to specific shape criteria defined mathematically [Far04]. For the same set of magnets we could see that even this criterion could be satisfied after the corrections have been applied.

The measurement errors have resulted in that the magnets have been installed with an unwanted shift in the vertical plane. The effect is however relatively small.

The total statistics gathered (up to February 2007) for the positions of the magnets where the measurement values have been corrected can be seen in Figure 35. The mean of the magnet mean plane is -0.06 mm (the magnet mean plane is by using a best fit of the measurements close to zero) and the standard deviation is 0.06 mm. We have 179 dipole magnets with position errors between 0.1 and 0.2 mm (the final magnet positioning in the tunnel is controlled to within 0.1 mm by the Magnet Evaluation Board). According to this statistical evaluation there are around 40 magnets having a real mean plane more than 0.2 mm below the measured (Leica system) mean plane. The positive tail in the statistics gives us an indication of the contribution from the bundle adjustment. The contribution from the bundle adjustment should be centred about zero mm with a standard deviation of between 0.04 mm and 0.16 mm according to simulations made (see e.g. [Lac06]). The effect on the machine’s aperture of the mean plane position has to be evaluated case by case according to the measured magnet shape. Some outlying measurement points come from other effects than those caused by the convection cells deflecting the Leica beam.

The magnetic field angle is affected by the measurement errors since the two cold bore tubes seldom suffer from identical measurement problems. This results in a roll around the axis of the magnet as the tilted mid plane is calculated with erroneous measurement data. The magnet will be installed aligned with this mid plane and consequently installed with a roll that modifies the magnetic field vector. The mean value of the roll effect is 0.0 mrad with a standard deviation of 0.21 mrad, see Figure 36. For comparison we note that the roll error at the assembly sites is estimated to be 0.3 mrad. This value corresponds to the standard deviation of the difference between the mean plane measured with a jig and the magnetic field direction measured by a magnetic field measurement mole [Vol06].

The data base, set up for the geometry data, contained useful information from recorded measurement data. Data mining identifies trends within data that go beyond simple analysis. The data was used to extract important features of the geometry, in particular the shape of the magnet. We had to convert the information to knowledge. A shape is not a single valued information, and we had to define a number of characteristic criteria from the shape information, like the sagitta. We also had to use the fact that the two measurements made from each end of the magnet gave us important information like how well the two measurement could be fit together: if the difference was linear, quadratic etc. This gave us information about the reason for the measurement problems; a linear difference indicated that we had to do with a single convection cell deviating the laser beam. These criteria were derived and stored in the database. Statistical evaluations and trend analysis, using the derived characteristics, gave us important information on the measurements and on the real shape of the magnets. In data mining, metadata, or data about a given data set, is important. We needed to include information about how the measurements were made, mole calibration, temperature conditions during measurements (the time between measurements and the cold tests). The term data mining is often used to apply to the two separate
processes of knowledge discovery and prediction. Knowledge discovery provides explicit information. Forecasting, or predictive modeling provides predictions of future events. We could, by our analysis, get knowledge about the system, in fact both the magnets and the measurement system. Data mining may also give the possibility of prediction. In our case we can only imagine, that by knowing more about the convection cell (the temperature is the most likely parameter for the formation of these cells) we could also predict the outcome of a measurement (no accurate temperature measurement were made in the magnet cold bore tubes).

Figure 35: Total result (1200 measurements at CERN) of magnet positioning after correction of measurement data (saw tooth). MEB corrections of the aperture shift are included. The mean value is also shown.

Figure 36: Total result (1200 measurements at CERN) of magnet roll after correction of measurement data (saw tooth).

Some errors causing a saw tooth effect cannot be corrected by the algorithm; they have a different origin than the assumed convection cell. If a magnet has large saw tooth error in both planes one can assume that the magnet has been moved between the two measurements. The saw tooth study is based on the assumption that errors having other origins are smaller than the errors we observe for a majority of the magnets and that we can retrieve the position of specific points measured by other methods than those made with the reflection mole.
THE MAGNET EVALUATION PROCESS

6.1. The magnet evaluation board

The Magnet Evaluation Board, the MEB, comprised accelerator physicists, the engineers in charge of the magnet assembly and installation, experts in various magnet specialities such as electrical performance, magnet protection, field quality, magnet geometry and alignment. In practice, the mission of the MEB was to find suitable lattice locations for the magnets as they became available while preserving and possibly optimizing the accelerator’s performance. The manufactured magnets’ parameters were all within the specified tolerances, but to optimize the machine performance, all parameters of the magnets had to be taken into account and the lattice position assignment done accordingly. The MEB had to follow the installation schedule, and included provisions to face day-to-day events, e.g. non-conformities or faults discovered during the preparation of the magnets for installation had to be handled immediately. The appropriate management methods and associated tools had to be developed at the same time.

If the finished magnet installation is compared to an installation using a random magnet position allocation, the MEB supervised sorting has improved the installed machine characteristics significantly. The mechanical aperture gain is estimated to be 1.5 mm, the diminished loss of dynamic aperture is estimated at 1 standard deviation, and the diminished increase of beta-beating by 5 to 10 % fully justifying the efforts expended.
7. DESIGN OF LARGE APERTURE SUPERCONDUCTING DIPOLES FOR A BETA BEAM DECAY RING

7.1. Neutrino production and neutrino physics

The evolution of neutrino physics demands new schemes to produce intense, collimated and pure neutrino beams.

The lightest known elementary particle of matter is the neutrino. The neutrino is so light that until the 1990s physicists thought they were mass-less. Neutrinos interact only weakly with normal matter. They easily pass through matter and are hardly affected. The evidence for their mass came from the observation of 'mixing' between the three different types of neutrinos, indicating that some were overtaking others since they do not all travel at exactly the speed of light but some were slightly slower due to a finite mass.

One of the fundamental questions in physics is why there is more matter than anti-matter in the Universe. This asymmetry could be explained by a difference between neutrinos and their anti-matter partners, both of which are members of the lepton family of particles. If neutrinos have mass, which the standard model of particle physics do not predict, they could oscillate between three different flavours - electron, muon and tau - as they propagate through space. These oscillations could produce CP-violation effects, which will generate an asymmetry between matter and anti-matter.

CP is the product of two symmetries: C for charge conjugation, which transforms a particle into its antiparticle, and P for parity, which creates the mirror image of a physical system. The strong interaction and electromagnetic interaction seem to be invariant under the combined CP transformation operation, but this symmetry is slightly violated during certain types of weak decay. Historically, CP-symmetry was proposed to restore order in the physics model after the discovery of parity violation in the 1950s.

Super-Kamiokande is a 50,000 ton water Cherenkov detector, which started observation in 1996 after 5 year of construction. The detector is operated by a collaboration with about 120 researchers from 32 collaboration institutes in Japan, United States, Korea, China and Poland. Recent measurements of atmospheric and solar neutrino oscillations by Super-Kamiokande and other experiments imply that neutrinos have mass, and further measurements are required to fully explore the physical properties of the neutrino. A Neutrino Factory could produce an intense beam of neutrinos which will be used to make precise measurements of the parameters describing neutrino oscillations and CP-violation for leptons. Such measurements, together with results from other experiments such as BaBar, T2K and Cobra would eventually give a more complete picture of CP-violation and why it generates the observed matter - anti-matter asymmetry in the Universe. The BaBar experiment at SLAC (Stanford Linear Accelerator Center) was built to study CP-violation in the decaying B-mesons which are produced by the PEP-II e+e- collider. The experiment searches for differences in the decays of B mesons compared to their antimatter partner, the B-bar mesons, in the hope of understanding better the prevailing matter-antimatter asymmetry in the universe. The T2K project, due to begin in 2009, has the primary goal of measuring, for the first time, the mixing angle $\theta_{13}$ by observing the appearance of electron-type neutrinos from an initial beam of muon-type neutrinos that have traversed 295km of subterranean
Japan. Along with the proposed Nova experiment, T2K is the first of the “next generation” of oscillation experiment designed to use high intensity neutrino beams. The beams are accelerated to energies that will maximise the probability of oscillations to occur and utilizes “near” detectors. These are situated close to the neutrino source, and are able to measure the flux/content of the beam thus drastically reducing any systematic effects. The T2K far detector is the tried and tested Super-Kamiokande 50kt water Cherenkov detector. Although it has not yet been observed, there is also interest in a process in which no neutrinos are released - neutrinoless double beta decay:

\[(A, Z) \rightarrow (A, Z + 2) + 2\alpha\]  \hspace{1cm} (7.1)

The lepton number violating process of neutrino-less Double-Beta Decay, is forbidden in the Standard Model and therefore, if it could be observed, would imply new physics. Among a considerable list of important physics topics accessible with this process two are of interest here. First, it is considered to be the unique channel to probe the fundamental character of neutrinos, i.e. whether they are Majorana (neutrino is its own antiparticle) or Dirac particles. Second, the process provides access to the absolute mass scale of neutrinos, i.e. the half-life of this process is directly related to the effective neutrino mass. This is what is studied at Cobra (Cadmium-Telluride O-neutrino double-Beta Research Apparatus).

Returning to the Neutrino Factory, a possible layout of this facility is the one shown in Figure 37 where the intense neutrino beam would be produced from the decay of muons in the last element of the accelerator complex.

Figure 37: A possible layout of a neutrino factory (from http://hepunx.rl.ac.uk/uknf/wp1/uknfnote_28.doc).
Even at this early stage of research and conceptual design of neutrino factories using the muon decay, a new neutrino factory concept is proposed that could possibly produce beams of high intensity, known energy spectrum and with a single neutrino flavour (electron–antineutrino or electron–neutrino). The scheme has the advantage to use existing accelerator and detector technology. The demand for better neutrino beams is correlated to the considerable improvement in neutrino detector technology, and to the recent exciting claims of evidence for neutrino oscillations made by various experiments. In particular, solar, atmospheric and accelerator neutrinos appear today to oscillate (and therefore should have nonzero masses) in a way that it is hard to accommodate in a unique picture, given the current theoretical understanding. Speculation and ad-hoc theories abound in the absence of experiments for involving neutrinos. Obviously, a high intensity neutrino source of a single flavour, with an improved background and known energy spectrum and intensity could be decisive both for oscillation searches and precision measurements of the lepton mixing parameters.

It is proposed, see [Zuc02], to produce a collimated $\nu_e$ beam by accelerating, to high energy, radioactive ions that will decay through a beta process, following the reactions

$$ ^6\text{He}^{2+} \rightarrow ^6\text{Li}^{3+} + e^- + \bar{\nu} $$  \hspace{1cm} (7.2)

for Helium and

$$ ^{18}\text{Ne}^{10+} \rightarrow ^{18}\text{F}^{9+} + e^+ + \nu $$  \hspace{1cm} (7.3)

for Neon, see Feynman diagram in. Figure 38.

![Feynman diagram of the beta process.](image)

Radioactive ion production and acceleration to low energy (several MeV) have already been made for nuclear studies, and various techniques have been developed, e.g. the CERN ISOLDE facility. Acceleration of the positively charged atoms to about 150 GeV/nucleon is standard practice in the CERN PS/SPS accelerators for the heavy-ion programme. Storage of the radioactive ion bunches in a storage ring could be very similar in principle, to what is being studied for the muon-based neutrino factory schemes.
The resulting neutrino beam would have three distinctive and novel features:

- A single neutrino flavour, essentially background free;
- Well-known energy spectrum and intensity;
- Low energy combined with strong collimation resulting from the low neutrino energy in the centre-of-mass system and the large Lorentz boost of the parent ions.

The energy of the neutrinos is boosted in the forward direction as:

$$E_\nu \leq 2\gamma Q$$

(7.4)

and the angle as:

$$\Theta = 2\gamma Q$$

(7.5)

where Q is the difference between the mass of a decaying particle and the sum of masses of daughter particles; $\gamma$ is the usual relativistic factor.

### 7.2. A beta beam facility at CERN

A Beta Beam facility starts with a proton driver, followed by an ISOL target to produce the radioactive species of interest. The ISOL technique uses isotope production at rest in thick targets via fragmentation or fission of a target nucleus. The isotope creation phase is followed by extraction, ionization, separation and acceleration of the desired isotopes to modest energies. In lieu of the beam conditioning section of the Neutrino Factory, the Beta Beam facility requires an ECR source to ionize and bunch the selected species into a beam. Thereafter, the beam is accelerated, first in a linac and then in a series of synchrotrons, to reach its final energy and stored in a decay ring with suitably oriented long straight sections. In the CERN-based scenario illustrated in Figure 39, the decay ring has a circumference of 6900 m and a straight section length of about 2500 m. Because of the limitations of the existing SPS ring, the new proposed decay ring could store a $^6\text{He}^{2+}$ beam with a maximum $\gamma=150$ or a $^{18}\text{Ne}^{10+}$ beam with a maximum $\gamma=250$. Both species have been chosen to have $\gamma=100$. 
To produce the required $^{18}$Ne beam intensity is a major technical challenge. The presently estimated possible $^{18}$Ne intensity is roughly a factor of 20 below the desired production rate. This issue is under active study. An entirely new approach to producing the required unstable ion beams has recently been suggested by Rubbia et al. [Rub06]. Here it is proposed to use a small ionization cooling ring (see Figure 40) to produce light unstable particle species, such as $^8$Li and $^8$B, via reverse kinematics. The nuclear reactions considered are $^8$H($^6$Li, $^8$Li)$^9$H and $^3$He($^6$Li, $^8$B)n, respectively. The beam cooling process is similar to that used in the ionization cooling channel for the muon beam of a Neutrino Factory. Although the ion beams are more sensitive to losses from nuclear scattering, the estimates are that the beam will continue to circulate, and maintain its equilibrium emittance, for many thousands of turns. The radioactive ions are collected off-axis in a catcher: an ion-source system that is heated to permit the radioactive species to rapidly diffuse out of the catcher foils as neutral atoms. Although there remain many details to work out, this novel approach offers the possibility of increasing the production rate of selected species by several orders of magnitude.
Figure 40: Schematic of ionization cooling ring for producing beta unstable ions such as $^8$Li or $^8$B.

7.3. The need for a 6T dipole

The scenario, which has been used for the investigation of the impact of the decaying ions on superconducting magnets [Wil06], is the production of highly energetic pure electron neutrino and anti-neutrino beams coming from $\beta$-decay of $^{18}$Ne$^{10+}$ and $^6$He$^{2+}$ ion beams in a beta beam decay ring. The decay products, since they have different magnetic rigidities than the ion beam, are deviated inside the dipole. The aperture and the length of the magnet have to be optimized to avoid that the decay products hit the superconducting coil. The decay products are intercepted by absorber blocks inside the beam pipe between the dipoles to protect the following dipole. To optimize the ratio between the straight sections and the arcs of the decay ring, proposed for the EURISOL (http://www.ganil.fr/eurisol/EURISOLproject.html) beta beam project for neutrino production (http://www.eurisol.org/site01/tasks_details.php), a superconducting 6T dipole has been designed. Several options exist, however this preliminary study only deals with a “cosine theta” approach. The aperture of the dipole has to be large to house the decaying ion beam and the decay products simultaneously. This dipole is protected by energy absorbers installed inside the beam-pipe. Using an initial preliminary dipole design, a study of the heat deposition in the coil from different absorber materials was made to see if, at all, the concept was feasible.

The result is that the proposed 6T arc dipole with a cosine theta layout of the coil having an aperture of 80 mm fulfils the optics requirements.

The regular FODO lattice in the two arcs of the proposed decay ring is designed to limit the aperture needed for the dipoles; the optical function $B_\phi$ and the dispersion have to be small. There are ten 38.7 m long periods in each arc. At the position where the decay products would hit the
lattice dipole in the arc, it is split into two independent dipoles and an absorber is inserted to intercept the decayed particles. The half-cell is thus composed of two dipoles and two quadrupoles with a total arc length of 994 m. See [Cha06].

Splitting the arc dipole to handle the particle interception is possible since the ion beams and their decay products have different magnetic rigidity. The ion decay products will follow different trajectories compared with the parent beam and the position where they hit the vacuum chamber can be determined. In Figure 41 we show the trajectories of two species as they start decaying at the entrance of a dipole. Here we see how the dipole length and aperture have been chosen [Cha06] to avoid that the beams impinge on the material inside the dipole. For $^{6}\text{He}^{2+}$ the choice is a dipole length of 5.7 m for a field of 6 T. The main ion beam needs a half-aperture of 40 mm; however the dipole aperture has to be large enough to let also the decaying ions in the child beams pass. These decaying ions can be intercepted after exiting the dipoles by an absorber. The decay products of $^{18}\text{Ne}^{10+}$ have to be intercepted after exiting the second dipole in the half-cell.

![Figure 41: Decay products (child beams) and the ion beam follow different trajectories due to different magnetic rigidity. The length and the aperture of the magnet are optimized to avoid that the particles stray outside the aperture inside the dipole.](image)

The resulting dipole parameters are shown in Table 5.

<table>
<thead>
<tr>
<th>Arc Dipole</th>
<th>Bp (Tm)</th>
<th>Radius (m)</th>
<th>Angle (rad)</th>
<th>Length (m)</th>
<th>Arc β [h],[v] (m)</th>
<th>Arc D [h],[v] (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>156</td>
<td>$\pi/86$</td>
<td>5.7</td>
<td>$[201.2/2.6],[290.8/3.8]$</td>
<td>10.98/-0.24</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Dipole and optics parameters for the beta beam decay ring arc.
7.4. Dipole design

The main bending dipole magnet is a classical cos-θ design (see Chapter 4, this work) with 5 coil blocks in two layers and a circular aperture of 80 mm radius. The Nb-Ti cable which is used for the LHC main dipole inner layer has been chosen as a starting point since its characteristics are well known. The layout of the magnet cross-section with the dipole field distribution is shown in Figure 42. A simple circular iron yoke with an inner radius of 132 mm is surrounding the coil (not shown). The keystoning of the cable, however, is not sufficient for a circular alignment around the mandrel for this magnet, which means that extra wedges are needed in the cross-section to achieve the required field quality.

![Figure 42: Cross-section of the main bending dipole with an 80-mm aperture with main field lines and peak field distribution in the coil.](image)

A rather large space has been left separating the two blocks of the outer layer which allows the insertion of a cooling pipe close to the inner layer, if needed. The required cooling should, if this magnet design is retained (other possibilities will be investigated) be studied further.

From the simulation it is concluded that a main field of 6.1 T is achievable with field errors at a reference radius of 53 mm (i.e. 2/3 of the aperture radius) given in Table 6. Due to the symmetry in the coil design, the skew multipoles vanish.

<table>
<thead>
<tr>
<th>b_3</th>
<th>1.31</th>
<th>b_7</th>
<th>23.81</th>
</tr>
</thead>
<tbody>
<tr>
<td>b_5</td>
<td>-20.10</td>
<td>b_9</td>
<td>-10.97</td>
</tr>
</tbody>
</table>

Table 6: Calculated multipole errors relative to the main field, in units 10^-4, at a reference radius of 53 mm.
We must have a sufficiently large margin to the load-line allowing even a small quantity of heat load to be taken by the coil without causing a quench, if needed. For block 3 (block with highest peak field of 7.1 T in the cross-section), we are at 73.2% of the margin on the load line. The goal, however, is to intercept all particles by the absorbers after each dipole and to avoid that they impinge on the coil.

The coil end has been designed in dimensions as compact as possible in order to leave enough space for the absorbers, resulting in a maximum peak field in the coil end of 6.3 T.
The force distribution in the cross-section of the arc dipole is important since it permits us to determine the stress on the coil midplane by calculating the azimuthal force in each conductor. Figure 45 shows the resulting force vector on each block. It can be seen from the plot that the forces concentrate on three blocks and that the inner layer is pressing against the outer in the high field regions whereas in the outer layer only an azimuthal force occurs. The stress on the midplane, which gives shearing forces between the windings, adds up to 15.7 MPa and 11.3 MPa in the inner and outer layer, respectively. These numbers correspond to 1.04 MN/m in the inner layer and 0.7 MN/m and are within the accepted values for this cable (for comparison, in the LHC this cable is subjected to a horizontal force component at nominal field of 1.8 MN/m [LHC04]).

Figure 45: Force distribution in the coil cross-section. Arrows show the resulting force in for each block.

7.5. Energy deposition in the dipole

For this dipole, which is designed to fulfil the optics requirements for the decay ring, we also made a preliminary estimation of the energy deposition. For the stored beams in the decay ring, the estimated power lost into the magnets is around 10 W/m. Absorbers have been inserted, after each dipole, to intercept the losses where it is best. In Figure 46 we see the projection on a plane perpendicular to the ion beam direction. The decay products for the two ion species are absorbed but the aperture is large enough for the circulating ion beam.
Figure 46: Transverse projection of the beams, the absorber and the aperture for the ion beam.

In Figure 47 we see the dipoles, the two decayed beams and the absorbers, projected on the horizontal plane.

Figure 47: Projection on the horizontal plane of the arc lattice half cell: the circular ring shaped absorbers have been inserted between the dipoles to intercept the decay products $^6\text{Li}^{3+}$ and $^{18}\text{F}^{9+}$.

7.6. Energy deposition in the magnet coil

The defined dipole heat deposition model only takes into account the absorbers inside the stainless steel beam pipe. Absorber material should be non-magnetic, iron and lead should be avoided. The optics has been designed such that the major part of the decay products from the
beam impinges on the absorbers. In the straight sections, the decay products are not bent by the dipole field and they follow the ion beam. When entering the dipole, all decayed ions accumulated in the straight sections form a concentrated beam. This beam will be absorbed by the absorbers. It can be seen from Figure 47 that, in the second half of the second dipole, some of the continuous loss in the first dipole will not be absorbed. The absorbers between the magnets absorb the peaks of the decay products and the resulting heat deposition in the coils has been estimated to see if the absorber is efficient and well designed. The peak losses (see Figure 48) have been simulated by including in the model all particles, decaying in the straight section up to the following dipole \(1.4 \times 10^9\) particles/s). Care has been taken to verify that, for this simple model, heat from the simulated beam is not deposited in the second half of the dipole (we would like to avoid accumulated loss from the simulated beam and from the continuously decaying beam in the dipoles).

![Figure 48: The peak energy deposition is designed to happen between the dipoles. Some of the particles decay in the dipole and impinge on the walls in the second half of the next magnet (around 1 W/m). s is the longitudinal coordinate of the machine.](image)

The particles used for the simulation are assumed to form a pencil beam of \(^{6}\text{Li}^{3+}\) with the same momentum, 94 GeV/nucleon, as the ion beam. The modelling was made using protons and not the ions with the arbitrary assumption that the ions break up when traversing the material. More detailed studies (see later) included simulation using ions. The beam is bent in the dipole and impinges on the absorber in the beam pipe. The model is shown in Figure 49. Further refined studies have to take into account all possible decayed particle trajectories along the machine by detailed tracking. In the heat deposition model the coils are simply modelled as hollow cylinders inside the yoke, also a cylinder. The beam-pipe and the insulation between the pipe and the coil are implemented in the model. The absorbers are placed inside the vacuum chamber to avoid backscattering into the vacuum chamber from particles impinging at small angles onto the vacuum pipe.
Figure 49: Model for heat deposition calculation in the large aperture dipole coil.

We used the FLUKA [Fas05] code for the calculations. The geometry was generated using Simplegeo [The06] and the resulting model can be seen in Figure 50.

Figure 50: The geometry modelled in Simplegeo, to the left the complete model and to the right we have taken out the first dipole to show the absorber in the beam pipe.

We have verified the heat deposition model using carbon, stainless steel and tungsten as absorber material and also verified the case without absorber insertions. Heat deposition has only
been scored in the dipole coil, in cells with sizes corresponding to the transverse dimension of each cable (15 mm radial and 1.5 mm azimuthal width) and with a length of 20 mm. A recent update of the value [The07] of the scoring volume could be to use the length of the twist pitch of the magnet to calculate the volume. This length is for the LHC cable around 10 cm. The values that were used are however conservative since the integration volume that was used is smaller and this can only increase the peak values. The energy deposited in this scoring volume corresponds to local heat deposition in steady state beam operation. The results are shown in Table 7, where the values in the cell with the highest heat deposition in the magnet coil are shown. The distance from the dipole entrance and the angular position of the maximum is also shown. Statistical variations in the calculations are estimated to less that 0.5 mW and for stainless steel and tungsten the values found were below 0.5 mW.

<table>
<thead>
<tr>
<th>Absorber Material/Quantity</th>
<th>Max Heat (mW/cm³)</th>
<th>Distance from dipole entrance (cm)</th>
<th>Azimuthal angle for max (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>&gt;30</td>
<td>~200</td>
<td>~0</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.4</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>&lt;0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tungsten</td>
<td>&lt;0.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 7: Maximum deposited heat in the coil for different absorber materials.

The distribution of the deposited energy for a carbon absorber can be seen in Figure 51. In the figure we show the heat deposition around the magnet at the distance from the entry where we find the highest heat deposition. For comparison, for the LHC magnet the energy deposition quench threshold in the coil is 4.3 mW/cm³ including necessary margins. The maximum lies in the mid plane according to the simulations.

Interesting is also to see where the energy is deposited along the magnet. To be conservative, the energy from the pencil beam of accumulated particles should be deposited essentially in the first half of the magnet. In the second half we have the additional energy deposition from the particles decaying inside the dipole. For this first, simplified estimation we want to make sure that the essential part of the deposited energy falls in the first half dipole, see Figure 51. In the figure the vertical line in the middle of the dipoles corresponds to the middle of the dipole and is shown to make sure that the deposit heat spot is in the first half so that we do not accumulate heat deposition from the continuously decaying beams in the dipoles.
Figure 51: The heat deposition from the modelled beam falls essentially in the first half of the dipole which is important to make sure we have limited overlap with the decayed beam created inside the dipole. The scale is the same for all cases but has no meaning for absolute values.

The influence of possible absorbers in the beam pipe on beam stability has to be evaluated by impedance studies. A first estimation [Jen06] shows that the structure having absorbers inside the beam-pipe would create too large impedances. However, a “beam screen” covering a large enough area, leaving an opening for the decaying beams, could be enough to keep the impedances within required limits, see Figure 52.

Figure 52: To reduce impedances a liner can be installed above and below the beam inside the absorbers. A cooling pipe in the “beam screen” to cool the absorbers can be envisaged.
7.7. More detailed simulations.

Starting from the work described in the previous paragraphs, where the energy deposition in the superconducting 6T magnet were well below critical limits, a more detailed energy deposition investigation on one decay ring cell using this dipole and a design of an existing superconducting quadrupole (the now dismantled Intersecting Storage Rings) was launched.

For the arcs in the beta beam decay ring we assume that the situation is in a steady state, this is typical after a topping-up of the machine. This state would also represent a worst case for the number of decaying particles and consequently for the power deposition and the risk of a quench. The used beam simulation code takes into account all absorbers in the ring; the absorbers are modelled as blocking irises for the particles. Under this assumption the arc-cell is representative of the whole arc. See Figure 53. The details of the simulation conditions for the two ion species can be found in [Wil073].

![Figure 53: Arc cell in the model: the half cell is composed of (from the starting point) one quadrupole, and two dipoles. At the end of the cell a quadrupole of the next arc is added to check the similarity to the first one.](image)

Particles entering into the cell model and particles decaying in the cell were simulated with the beam code ACCIM [Jon97]. Particle positions and their momenta were expressed in the coordinates of the beam code: s (along the longitudinal theoretical trajectory), x and y (the transverse coordinates). A module was written (presently in Mathematica™) to convert the machine coordinates into Cartesian coordinates. This needed a description of the machine layout and a survey option, developed for the purpose, giving the machine coordinates for the particles in an external fixed coordinate system. This did not exist and was developed in the new module. We also had to calculate the direction cosines of the momenta in the FLUKA system. The FLUKA
A model was described in a classical way in Cartesian coordinates, to have a first simple model of the system. However, to be able to score easily the heat deposition in the cable, a scoring in cylindrical coordinates was necessary. This can be done by using a special mode of modelling in FLUKA and using the so called “Lattice” option. The results for Helium ions were analysed qualitatively using the classical Cartesian model and used to estimate the total energy deposition in the magnets. The loss patterns corresponded well to simple particle tagging methods and the total heat dispatched in the arc was below the required limits, see Figure 54 and [Wil073]. Qualitatively this pattern is compatible with the loss patterns given in Figure 48.

Figure 54: Energy deposition in the magnets in the arc cell (\( ^6\text{Li}^{3+} \)), the units are [cm] and [mW/cm\(^3\)] for the deposited heat.

However the deposited energy is located on a small region in the magnet mid plane. This means that the locally deposited power is high and we exceed the allowed values to avoid magnet quench (4.3 mW/cm\(^3\) for NbTi cables). However this value is reached in the area where the absorber is not protecting, see Figure 56. The values indicate that by introducing a beam pipe and a beam-screen (see discussions in the upgrade of LHC below) we can protect the magnet. However to avoid the absorbers and heavy material inside the magnet, new ideas like an open midplane, costheta cross-section, dipole magnet will be explored. This will be the next step, for the beta beam decay ring main magnet design. The energy deposition in the quadrupoles is below the recommended values.
Figure 55: Transverse projection of the energy deposited in the magnet cable. The units in the plot are [cm] and [mW/cm³] for the deposited heat.

Figure 56: The peak energy deposition in each longitudinal bin along the superconducting cable on the four dipoles in the lattice cell. Recommended quench value is 4.3 mW/cm³.
8. **LHC UPGRADE PROJECTS**

The present focus of the LHC project is obviously related to the baseline LHC design and the commissioning of the infrastructure, the hardware and finally the machine with beams. However, to be timely, the upgrade phases of LHC have to be studied already at this stage to offer a reasonable lead-time for the development of new magnets and new magnet technologies. A period of 5 to 15 years may be needed depending on the technology chosen and of available resources.

LHC results will however guide the choices, both for the performance improvements and the physics expected. Upgrade studies will have to identify the necessary hardware and the necessary R&D programs to make sure that manufacturing and assembly in industry, at CERN and at collaborating laboratories can be delivered timely for the next phase of the LHC.

CERN has partners for the upgrade program committing resources for the development of the next generation magnets using Nb$_3$Sn superconductors and for the optics of the insertion regions. The US-LARP (U.S. LHC Accelerator Research Program) is one of the partners. CARE–HHH has been assigned three work-packages, Advancements in Accelerator Magnet Technologies, Novel Methods for Accelerator Beam Instrumentation and Accelerator Physics and synchrotron Design. The NED project (New European Dipole) is also involved in the upgrade project: NED is a networking activity launched in 2004 to promote the development of high-performance Nb$_3$Sn conductors in collaboration with European industry. NED aims at a non-copper critical current density of 1500 A mm$^{-2}$ at 4.2 K and 15 T. The project will also assess the suitability of Nb$_3$Sn technology for the next generation of accelerator magnets with an aperture of 88 mm and a conductor peak field of ~15 T. NED is a part of the Coordinated Accelerator Research in Europe (CARE) project, which involves eight collaborating institutes, and is partly funded by the European Union. These programs will later be succeeded by general programs in the FP7 (Framework Programme 7) and the already existing FP 7 project EUCARD (European Coordination for Accelerator Research and Development).

8.1. **Energy deposition in the baseline LHC insertions**

The work presented here as part of the thesis is a study of energy deposition resulting from collision debris products. This debris is generated when the proton beams are brought to collision in the machine’s insertion regions and the study is related to the energy deposited specifically in the magnet coils. An important parameter is the total heat load the superconducting magnet is subjected to; all heat has to be transported away by the liquid helium at cryogenic temperatures. The baseline insertion layout was modelled in the Monte-Carlo code MARS, see [Mok04] and [Mok07], in 2004. The same work was implemented using FLUKA for comparison reasons; see [Fas03] and [Fas05]. The work on the baseline (nominal) LHC work serves as a reference for the upgrade work.

The insertion layout for IR1 (ATLAS) is shown in Figure 57 and the FLUKA model in Figure 58 includes for the moment only the inner triplet, i.e. starting from the magnet closest to the IP (collision point) to the Q3 magnet. A triplet is a special magnet configuration which focuses
the incoming proton beam strongly to the collision point. The beam-pipe, the beam-screen, the
absorbers and the corrector magnets have been included in the model.

Figure 57: Insertion region 1 (ATLAS). The triplet consists of the Q1-Q3 magnets and close to the interaction
region we have an absorber to protect the front face of the first triplet magnet. The D1 is a separator magnet
for the two counter-rotating beams, the optics matching is done by Q4 to Q6. The TAN absorbs mostly
neutral particles. The heat deposition model we have implemented so far is the triplet and the front face
absorber. The first absorber, the TAS, is positioned around 19 m from the interaction point and the first
quadrupole at 23 m.

Figure 58: Insertion region 1 modelled in FLUKA.

The comparison of the results from the two simulation codes was within 20%, which is less
than 30% stated for the physics models compared to benchmarking for FLUKA models
(http://www.fluka.org/references/talks/amt/img0.html). A specific study with a reduced model was
also done to compare the MARS and FLUKA [Hoa081] model results. The energy deposited in
the different regions of a “toy model” made of one insertion quadrupole and an absorber including
a beam pipe is shown in ..Except for the yoke and for the beam pipe, made of iron and stainless
steel respectively, similarity is within some 5 %. For the regions with iron or stainless steel, the differences are up to 20%. The reason for this difference is still under investigation. The cross sections for iron can in FLUKA be chosen according to purity (“self-shielding”) and temperature. Experimental data exists for 87K and for room temperature conditions. We have arbitrarily chosen room temperature values and natural iron for our FLUKA model.

All heat loads generated have to be absorbed by the cryogenic system for the superconducting magnets. For the TAS, the absorber of the secondary particles impinging on the front face of the first quadrupole magnet, see Figure 57, a dedicated cooling system is installed. The design must obviously ensure that the energy deposited can be absorbed by the available resources. LHC has two cryogenic helium loops in the inner triplet area, one 1.9 K loop and one 4.5 K loop. The power extracted by the 1.9 K loop is just sufficient for the heat load expected in the inner triplet for a luminosity of $\mathcal{L} = 2.0 \times 10^{34}$ (slightly less than the luminosity for upgrade phase I - $\mathcal{L} = 2.3 \times 10^{34}$). It is here assumed that the power generated by the debris coming from the interaction point and by the primary beam itself (synchrotron radiation, electron cloud) is dissipated into the 1.9 K loop. If the same power would extracted at 4.5 K instead (e.g. by using a thicker beam-screen) some margin would be gained. New ideas concerning future development of beam screens or absorbers are being discussed in the different upgrade scenarios. The concept of an energy absorber inserted between the beam screen and the cold bore tube is one interesting solution to study further. In Table 8 the total heat loads on the different magnet regions is displayed.

| Total heat loads in the insertion region elements (W) for upgrade luminosity $L=10^4 L_0$ |
|---------------------------------|-------------|-------------|-------------|--------|
| FLUKA +/-% | MARS +/-% | Ratio FLUKA/MARS |
| TAS 1853.7 0.5 | 1827.3 0.1 | 1.01 |
| Beam pipe 89.1 1.0 | 97.9 0.4 | 0.91 |
| Q1 cable 158.0 0.6 | 159.1 0.2 | 0.99 |
| yoke 96.3 0.9 | 78.5 0.4 | 1.23 |
| aluminium layer 2.3 0.6 | 2.4 0.5 | 0.98 |
| mylar insulation 19.5 0.8 | 20.4 0.3 | 0.96 |
| stainless steel vessel 16.8 0.8 | 17.3 0.3 | 0.97 |

Table 8: Heat loads in “toy model” for comparison between the two codes FLUKA and MARS.

The overall result from the modelling in FLUKA of the nominal LHC configuration (with a peak energy distribution) can be seen in Figure 59. The figure shows the estimated maximum value of the deposited energy in a 10 cm longitudinal slice of the magnet coil cable which is located immediately outside the beam tube. The 10 cm value is chosen as a bin size compatible with thermal equilibrium. The resulting values are below the recommended limits (4.3 mW/cm$^3$). We see that there is a difference between the two insertions which essentially comes from the beam crossing angles that are different for IR1 (ATLAS) and IR5 (CMS). The influence of the magnetic field of the magnets and the crossing angles on the deposited heat has been elaborated in [Hoa082]. This study is the base for our future proposals for protections, positioning and apertures of magnets in the insertion regions.
Figure 59: FLUKA, longitudinal distribution of peak power density in the first cable (3.5<R<4.6 cm) in Q1 and Q3, (3.5<R<5 cm) in Q2a and Q2b, where R is the Radial coordinate. From [Hoa082]

The TAS absorbs the debris from the two colliding proton beams and protects the front face of the first magnet. At around 20 cm from the front face of the magnet the energy deposition however increases rapidly - the effect of the TAS is negligible. Conclusion: the TAS has limited protective action on the superconducting magnet at a distance 20 cm from the magnet’s front face.

Notwithstanding the above conclusion, if the magnetic field is switched off, we can observe how the TAS “shadows” the first part of the inner triplet: the effect of the TAS shadow now extends up to the Q2b magnet, see Figure 60. In Figure 61 we see a simple geometric sketch exemplifying the shadowing effect of the TAS. The TAS opening is smaller that the triplet aperture and depends on the value of the lattice beta function in the TAS; the TAS opening must let the beams through with the required margins. These margins include e.g. the separation distance of the two beams and the unavoidable mechanical tolerances. The two arrows in the figure represent the largest angle (with respect to the beam axis) particles that can pass the absorber and we see that the first part of the triplet is protected. This shadowing effect can be used also by putting a thick liner, more than 1 cm thick, in the first quadrupole to protect the second one.
Accelerators for physics experiments: from diagnostics and control to design

Figure 60: Energy deposition in the four triplet insertion magnets: When the magnetic field is switched off the shadowing effect of the TAS can be observed for the first two magnets.

With magnetic fields present the situation becomes different, due to the spectrometric effect of the magnets. The peaks in the power deposition in the first parts of the magnets are due to the gap between the magnets, where particles do not get absorbed by the magnet. This observation led to proposals to extend the cold absorbers in the magnet apertures over the space between the magnets for the LHC upgrades when luminosities and deposit energies increase. These observations and many others discussed in [Hoa082] have been useful for the shielding design considerations in the upgrade scenarios.

Figure 61: Illustration of the shadowing effect of the front face absorber for a neutral particle.
The experimental vacuum chamber in the layout is very carefully dimensioned to be transparent to the collision debris. If this would not be the case, the experiments would be disturbed by irrelevant events. The experimental vacuum chamber gives one of the most critical contributions to particle backscattering to the experiments [Hut07]. The experimental beam-pipe may also induce energy deposition in the triplet [Bro08]. The above considerations induced us to exclude the experimental vacuum chambers for our upgrade studies, where we do not have the detailed layout configuration available.

In addition to the magnetic fields other parameters relevant for the energy deposition studies are the lengths and apertures of the magnets. The many differently charged particles comprising the debris products (see Appendix II), having different energies, react on the field, the magnet apertures and magnet lengths in a way that is not intuitive. Specific studies on the different particle families and energy ranges are planned, with the aim to better understand the patterns to create the best design possible for the upgrade shielding layouts.

8.2. The LHC upgrade

The LHC upgrade project is for the time being divided in three phases. The first one deals with the inner triplet consolidation (i.e. a replacement of these magnets is planned) for a \( \mathcal{L} = 2.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \). To reach this, originally nominal, luminosity will be difficult due to the increase in beam-beam crossing angle, the introduction of beam screens and the increase of the impedance since the collimator jaws have to be moved closer to the beam core. The beam screen is required not only for synchrotron radiation protection but also to serve as a cold pumping surface for the vacuum system.

In addition this upgrade phase should avoid any interference with the experimental detectors. The implementation is expected to be fast which implies the use of standard technologies like NbTi superconductors, avoiding R&D issues for magnet performance and long lead times. No new beam dynamics will be implemented, again with the objective to insure a rapid machine performance increase. The luminosity increase needs lattice optics changes, a smaller beam size at the collision point and a larger beam-beam crossing angle. The introduced modifications and their effects on equipment have to be investigated, in particular has energy deposition issues to be studied in detail. The progress in the energy deposition studies will be described below. Higher luminosities will increase the risk for instabilities due to the closeness of the beam to the halo collimators and have to be compensated. By only replacing the magnets in the area close to the collision points disturbances of the beam conditions in the rest of the ring will be minimized.

The phase I upgrade requirements would be satisfied if the NbTi magnet apertures are increased and several different proposals already exist. In [Kou07] the apertures are increased from 70 mm to 130 mm and a symmetric optics solution is demonstrated where the \( \beta^* \) is 0.25 m; the baseline \( \beta^* \) is 0.5 m. Using same magnet cross section for all inner triplet magnets as this solution proposes would be a clear advantage for the magnet manufacturing phase and for the magnet costs. Other proposals are described in [Bru07]. With large aperture solutions we could reach the ultimate LHC luminosity with a safety margin of 50% while removing the need for the
halo collimators to be installed close to the beam. In this hardware upgrade proposal the spare LHC dipole cable could be used. The phase I upgrade target year is 2012. Intense work on energy deposition in the insertion regions for this upgrade phase is presently ongoing.

Next upgrade phase, which aims at luminosities up to $10 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$, would probably again need a change of the inner triplet magnets. To use the already installed magnet components would be impossible due to the very high activation and consequently very high handling costs. The magnets will be safely stored and new ones will be installed in the tunnel.

The upgrade phase II has to include some creative ideas [Zim07]. The luminosity depends, see formula (8.1), on the form factor ($F$) which contains the crossing angle ($\theta$), the variation of the optical function $\beta$ along the bunch, the longitudinal beam size ($\sigma_\parallel$), the number of bunches and the transverse beam size ($-\epsilon^\parallel \beta^*$). The dependence of $\beta^*$ and $\sigma_\parallel$ is denoted by $H$; this is known as the hourglass effect due to the hourglass shaped beta function around the collision point. $F$ decreases with decreasing $\beta^*$ and increases with $k_b$, $N_b$ and $\sigma$. $H$ is in the range $\{0.9, 1\}$ for practical $\beta^*$. $k_b \times N_b^2$ is related to the stored beam current.

$$L \cdot F(\theta, [\beta^*, k_b, N_b], \sigma_\parallel, \beta^*, \epsilon_N) \cdot H \left( \frac{\beta^*}{\sigma_\parallel} \right) \frac{k_b \times N_b^2}{\epsilon_N \beta^*}$$  \hspace{1cm} (8.1)

There are two directions [Zim07] presently explored to increase the luminosity: either to decrease the optical beta function at the collision points or to increase the beam current. Many challenges have to be faced for both directions. Proposals have been put forward also to install optics elements deep inside the experiment to relax the conditions around the crossing. As concerns our issues, the energy deposition in the triplet elements, the increased current does not imply any new equipment deep inside the experimental regions. The backscattering scales linearly with the luminosity and introducing new equipment close to detectors would increase the background even more. A new triplet to reach a $\beta^* 0.25 \text{m}$ has to be installed in order to accommodate the new larger beam and absorbers inside the magnets have to be installed. One may profit from the ongoing research on new superconductors, since Nb$_3$Sn has a higher critical current than the presently used NbTi it has consequently a higher quench limit for the allowed deposited heat (around 3 times).

Very small $\beta$-values in the collision point combined with large crossing angles to avoid that the large bunches interact after crossing are needed to increase the luminosity at constant current. However the bunches become large in this case due to the rapidly varying $\beta$-function around the collision point.

Not having a precise idea about the scheme for phase II, we simply used 3 upgrade scenarios for Phase I described in [Kou07] and [Bru07] and assumed a particle flux corresponding to a luminosity of $10 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$. We chose one case where the magnet cross sections and fields were the same and where the magnet lengths are symmetric around the midpoint of the triplet (the “symmetric” case). Long triplets with very large apertures were also chosen to have a completely different configuration. In this way we would see the gross behaviour of the energy deposition with triplet length, magnet fields and apertures. The study we performed in [Wil08] had to answer the challenging question if NiTi technology is compatible with such high luminosities. The
question could be answered by a preliminary yes, by inserting sufficiently thick liners of good shielding material e.g. tungsten or, if the apertures are large enough use stainless steel, depending on the available beam clearance. Magnet apertures are limited by the magnet field: the larger the aperture for the same field the higher is the maximum field in the magnet and consequently the risk of quench due to energy deposition is higher. So this has to be evaluated in detail.

Developing these ideas could be a fallback solution if the Nb$_3$Sn magnets do not reach the necessary performance. Some perturbation studies were included in [Wil08], for example the influence of crossing angles and of the TAS efficiency. We could also see that the energy deposition pattern for the 3 cases were not considerably different.

The layout described in [Laf06] also needed some first estimation for heat deposition dealing also with the problem of backscattering into the detector region, due to the closeness to the IP of the magnets. To cope with the energy deposition, the idea of thick liners gave a first indication that this is way to be explored. A new magnet design was included in the upgrade proposal and this magnet was used for the calculations. The backscattering was after the study started considered to be the entire responsibility of the experimental groups: they include our models in their complete background calculations for the detectors.

Future studies will deal with radiation hardness of magnet components like the insulation made by different materials and the possible alteration of the cable with time. Alignment of the magnets may also be a possible source of energy deposition peaks, since the debris particles do not have the same properties at different solid angles. And the optimization of the liners, their position thickness and the material will continue in collaboration with the teams developing the beam screens and the cooling systems.
9. CONCLUSION

The papers presented in this work deal with different aspects of control and diagnostics in the particle accelerator domain. Feedback from diagnostics, remedies and wishes for improvement are carried over to the design of new magnets in conjunction with new ideas. The experience with deep knowledge of complex systems also contributes to fast prototyping of new projects. The work reported in the recent papers deals essentially with new challenging projects related to both the LHC and to future other accelerator projects and has benefited from our extensive experience. Control and diagnostics procedures for accelerator beams, with the emphasis on generic methods to insure maintenance and re-use of code and methods for generation of new similar applications have been developed for the Proton Synchrotron Complex. The implementation of the automated procedures required hardware adjustments such as re-alignment of correctors and monitors. The result of the development was a clear gain in the adjustment time for the operations team and the results were also more accurate.

The testing and installation of the superconducting magnets for the new Large Hadron Collider was a really challenging project. The automated statistical production follow-up of the magnetic field quality was used to pin-point problems in the assembly procedures. All magnets which had to be opened, due to identified magnetic field deviations, were found by applying the established fault detection based on statistics and showed assembly defects that could be remedied. The idea of statistical geometry adjustment of the dipoles, to save half of the planned measurements, and which was necessary to speed up the delivery of magnets to the tunnel, gave very good results for the corrector magnet positions and for the general shape adjustment needed to guarantee the aperture requirements for the beam.

Strange behaviour in the change of the shapes of the dipole magnets, where non-physical movements of the magnet ends were concluded, could be understood by associating experimental results made several years before and applying them to the measurements. Not only the measurement results could be understood, but a corrective algorithm could be established to find a more correct positioning of the dipole magnets in the LHC tunnel. We also concluded that the observed shape changes and bad positioning of the magnet ends were due to measurement artefacts.

Future physics may go in the direction of exploring neutrino oscillations to shed light on for example the CP-violation phenomena. One way of producing neutrinos is the beta decay process. This is exploited in the ideas of beta beams, where beta emitting ions are accelerated to high relativistic energies, permitting neutrinos to be emitted in a small forward cone. The ions decay in a straight section in a race track accelerator ring, which is aligned to a detector placed at a tuned distance, many hundreds of kilometres away, for observation of the transformed neutrinos. The child products from the ion decay are impinging the accelerator walls and have to be collimated, absorbed and dumped to minimize activation and quench risk in superconducting magnets. The absorption system for the decay products in the arcs was designed and the energy deposition in the superconductors was evaluated and found within limits that can be technically handled.

To equip the inner triplet with NbTi magnets in the LHC experimental areas, ATLAS and CMS, with thick liners to absorb the energy at the temperature of 15 K instead of 1.9 K could be
a fallback solution when developing magnets using new emerging magnet technology (Nb$_3$Sn). This new technology would permit higher temperature on the super-conducting cables before reaching the quench limits. Such new-technology magnets would be a possible implementation for the phase two upgrade. However, long lead-times for R&D and construction may imply the use of well known NbTi-technology. By introducing thick absorbing liners inside the magnets, I show that not only the deposited heat in the cables can be handled, but in addition we would save load on the low temperature system (1.9 K) and move it to 15 K to gain refrigeration capacity. If needed, this would even open a possibility to use well known “classical” NbTi technology
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11. APPENDIX 1

The matrix inversion method is described in [Wil00]. In this method all “effective” steering coils out of the $n$ available are used. At the various monitors, the beam positions

$$\vec{u} = (u_1, u_2, \ldots, u_m)$$

are measured. The steering coil at position $i$ of strength $\kappa_i$ creates a beam displacement of $a_{ij}(k_i)$ at the $j^{th}$ monitor. This displacement with respect to a reference orbit has to be minimized. The relation between the monitors and the corrector coils is described by the following equation

$$\vec{u} - \overline{A} \kappa = \vec{r},$$

where the vector $\vec{\kappa}$ contains the corrector values and $\overline{A}$ is a matrix describing the response of the beam to a set of correcting fields. $\vec{r}$ is the residual error that should be minimized by the algorithm.

$$r_i(\kappa_i) = \sum_{j=1}^{m} (u_j - x_{ij}(\kappa_i))^2 = \sum_{j=1}^{m} (u_j - \kappa_i a_{ij})^2,$$  

where

$$a_{ij}(\kappa_i) = \kappa_i a_{ij}.$$  

If we extend this to all steering-coils we can write

$$r(\kappa_1, \kappa_2, \ldots, \kappa_n) = \sum_{j=1}^{m} \left( u_i - \sum_{i=1}^{n} \kappa_i a_{ij} \right)^2.$$  

We now have to find a set of corrector strengths that minimise a given error function. A necessary, and in this case also sufficient condition for this to be true is that all partial derivatives

$$\frac{\partial}{\partial x_p} r(x_1, x_2, \ldots, x_n) = 0,$$  

with $p = 1, 2, \ldots, n$  

should vanish. This condition leads to

$$\frac{\partial r}{\partial \kappa_p} = -2 \sum_{j=1}^{m} \left( u_j - \sum_{i=1}^{n} \kappa_i a_{ij} \right) a_{pj} = 0$$  

and hence
\[
\sum_{j=1}^{m} \left( u_j a_{pj} - \sum_{i=1}^{n} \kappa_i a_{pi} a_{pj} \right) = 0 . \tag{11.8}
\]

Reorganizing gives

\[
\sum_{j=1}^{m} u_j a_{pj} = \sum_{i=1}^{n} \left( \sum_{j=1}^{m} a_{pj} a_{ij} \right) \kappa_i . \tag{11.9}
\]

and we can set

\[
U_p = \sum_{j=1}^{m} u_j a_{pj} \tag{11.10}
\]

and

\[
H_{pi} = \sum_{j=1}^{m} a_{pj} a_{ij} . \tag{11.11}
\]

Now we have

\[
U_p = \sum_{i=1}^{n} A_{pi} \kappa_i \tag{11.12}
\]

and this gives

\[
\bar{U} = \bar{A} \bar{\kappa} \tag{11.13}
\]

so now this can be written in matrix form

\[
\bar{\kappa} = \bar{A}^{-1} \bar{U} . \tag{11.14}
\]

This last expression finally gives us the strength of the correctors that should be applied.
12. APPENDIX II

In particle colliders and high intensity machines the particles may impact the magnets and if these magnets are superconducting the effects may be quenching of the magnet with a machine stop as a consequence. The halo of the beam may have to be collimated and secondary particles may impact the surroundings, the collisions result in a large number of different particles that have to be absorbed by special design of the insertion regions. In some applications, like beta beams, the decayed beam has to be absorbed. We also have to deal with mishaps from failures deteriorating the beam.

Of interest here, related to work for the LHC upgrade, is the proton-proton collisions at 14 TeV center of mass energy. The collisions can be simulated by event generators like the Monte Carlo event generator DPMJET, to study particle production in high-energy nuclear collisions. Lead ions are also accelerated in the LHC and lead ions collisions have to be studied also (future work).

In [Hoa071] the outcome of a simulation with DPMJET is discussed (for DPMJET see http://sroesler.web.cern.ch/sroesler/dpmjet3.html). In Figure 62 the most predominant particles created in this reaction are displayed. The multiplicity is on average 120 particles per collision. The contribution to the deposited energy depends on the distance to the collision point and at what solid angle the articles are absorbed.

Figure 62: Some of the predominant particles created in proton-proton collisions (simulations by DPMJET).

The Stability of the particles is shown in Figure 63. We see that the $\pi^0$ is decaying to photons before entering the insertion zone.
Accelerators for physics experiments: from diagnostics and control to design

<table>
<thead>
<tr>
<th>Secondary particles</th>
<th>$\tau$ Mean life time</th>
<th>Decay products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>Stable $&gt;10^{10}$ years</td>
<td>-</td>
</tr>
<tr>
<td>Electrons and positrons</td>
<td>Stable</td>
<td>-</td>
</tr>
<tr>
<td>Photons</td>
<td>Stable</td>
<td>-</td>
</tr>
<tr>
<td>Neutrons</td>
<td>Unstable 885.7 s</td>
<td>$n \rightarrow p + e^- + \bar{\nu}_e$</td>
</tr>
</tbody>
</table>
| Pions + Pions -     | $2.6\times10^{-8}$ s | $\pi^+ \rightarrow \mu^+ + \nu_\mu, \pi^- \rightarrow \mu^- + \bar{\nu}_\mu(99.9877\%)$
|                     |                     | $\pi^+ \rightarrow e^+ + \nu_e, \pi^- \rightarrow e^- + \bar{\nu}_e(0.0123\%)$ |
| Pionzeroes          | $0.84\times10^{-18}$ s | $\pi^0 \rightarrow 2\gamma(98.799\%)$
|                     |                     | $\pi^0 \rightarrow \gamma + e^+ + e^-(1.198\%)$ |

Figure 63: Stability of the predominant particles created from 14 TeV proton proton collisions.

The energy range of the secondary particles spans mainly from 1 GeV to 1000 GeV. The contribution from the different types of particles can be seen in Figure 64.

![Secondary particles from p-p collisions](image)

Figure 64: Contribution to the total energy from the different collision products (proton-proton collisions).

Particles are grouped, for interaction with matter, according to if they are charged (electrons, protons, nuclei, charged pions for example), photons, hadrons or neutral particles. Charged particles may be subject to multiple scattering, ionization energy loss or Bremsstrahlung and are interacting mainly with the atomic electrons. Photons also interact mainly with electrons. Neutrons interact with the nucleus. Showers of these different classes of particles stop in different ways in matter, electromagnetic showers decay exponentially and hadron showers have a more distinct stopping. All these phenomena are described in school books. A nice, very short, overview can be found at the web address [http://www.whfreeman.com/modphysics/PDF/12-2c.pdf](http://www.whfreeman.com/modphysics/PDF/12-2c.pdf).
13. REFERENCES


[Cou59] E. Courant, H Snyder, Annalen der Physik 3, 1, 1959


[Ver00] A. Verdier, “Geometry of the muon storage ring”, Neutrino factory note 13, 2000, url: citeseer.ist.psu.edu/verdier00geometry.html

[Vol06] C. Vollinger, Study presented in “Main Ring Committee” meeting at CERN.


[Wil06] Betabeam note


[Wil074] E. Wildner, Heat deposition and backscattering for one of the configurations of the IR for LHC upgrade, AT-MCS Internal Note, 2007-02

[Wil08] E. Wildner, C. Hoa, E. Laface, G. Sterbini, “Are large aperture NiTi magnets compatible with $1 \times 10^{-3}$ ??” CERN-Yellow Report, to be published


