# COMMISSIONING WITH BEAM OF THE LHC TRANSFER LINES AND INJECTION SYSTEMS

B. Goddard, CERN, Geneva, Switzerland

*Abstract*

Based on the TI 8 experience, the measures neeeded to reach the required state of readiness of TI 2 and TI 8 to deliver beam to the LHC during the commissioning phase are discussed. The main objectives for the performance of the transfer lines and injections at this stage of the LHC commissioning are outlined, and the impact of the lower demanded intensities in the initial phases on equipment and machine protection commissioning is addressed. Subsystem dependencies – radiation, instrumentation, controls – and the necessary pre-testing phases with beam are highlighted. The procedures for commissioning the first injection in the LHC are described.

## INTRODUCTION

Detailed descriptions of the transfer lines, Fig. 1, and injection systems, Fig. 2, can be found in the recent literature; in particular the layout and optics design of TI 2 and TI 8 [1], the trajectory correction scheme [2], the transfer line magnets [3], and tolerances on the beam parameters at injection into the LHC [4]. The LHC design report contains a full overview of the two systems [5, 6].

The transfer lines and injection systems must allow the beams to be injected onto the LHC orbit with high precision and reproducibility [7], while ensuring an adequate optical match and remaining sufficiently flexible to accommodate any future machine optics changes [8]. The machine protection elements in the lines should prevent the transfer of mis-steered high intensity beams into the LHC, either by interlocking or by passive protection devices [9].

This paper focuses on the commissioning of the transfer lines and injection systems with beam, during the early stages of the LHC beam commissioning.

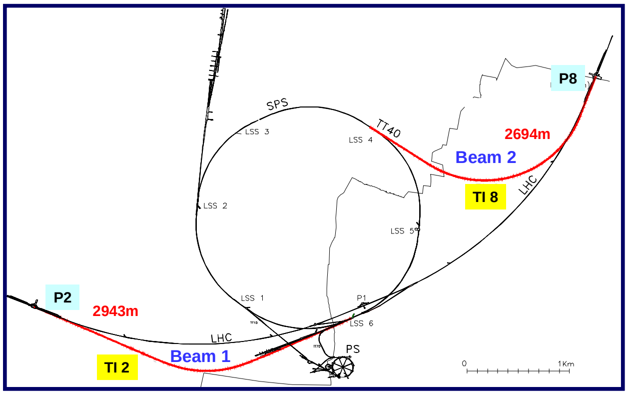


Figure 1. TI 2 and TI 8 transfer lines, linking the SPS and LHC machines.

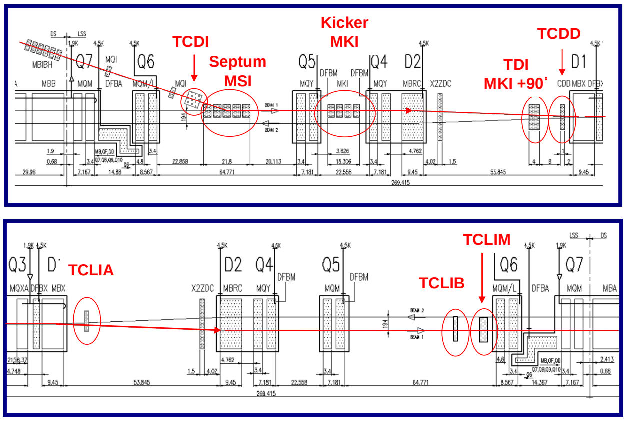


Figure 2. Plan view of main elements of injection system in IR2, left of the IP (top) and right of the IP (bottom).

## BEAM COMMISSIONING OBJECTIVES

### *Minimise commissioning time and impact*

Beam commissioning time must be minimised, as must the impact of this phase on the commissioning of the rest of the LHC. The requirements must be matched to the desired state of readiness of the LHC machine commissioning, with clear identification of the "exit status" which has to be attained at each phase. Only the essential tests and setting-up should be performed, with "MD like" activity postponed. Commissioning phases will have to be interleaved with machine operation, and a clear, detailed "roadmap" for the machine commissioning will be essential.

### *Ensure machine protection*

In order to avoid the risk of damage to the machine during the commissioning, the relevant Machine Protection systems must be fully operational for each commissioning phase. Again, this implies that a detailed analysis of the commissioning phases be completed, with clear identification of the required machine protection functionality through the commissioning process.

### *Deliver required beam quality*

At the end of the commissioning the beam it must be possible to inject the beam with the necessary characteristics. These still need to be defined in detail, but will be relaxed during the early stages, compared to the design performance. Reproducibility initially will be more important than 100% availability, and the systems must be adequately understood. This includes the optics performance, beam instrumentation, equipment and application software.

## EQUIPMENT AND CONTROLS SYSTEMS TO COMMISSION

The equipment systems, Fig. 3, in the extraction, transfer lines and injections are numerous, with special magnet types in the beam transfer regions and many magnet families in the matching sections of the lines. Assuming that all services are available, and with the exception of the beam instrumentation and machine protection (treated separately) the main elements are:

- SPS extraction bumper magnets;
- SPS extraction kicker magnets;
- SPS extraction septum magnets;
- Transfer line matching quadrupoles;
- Transfer line main quadrupole families;
- Transfer line dipole families;
- Transfer line corrector magnets;
- Vacuum systems;
- Power convertors.

### *Beam instrumentation*

The beam instrumentation is a critical part of the equipment required for beam commissioning [10], since it will have to be operational before any detailed measurements or checks of other equipment performance can be carried out. An overview of the instrumentation available in the injection region is shown in Fig. 4. The systems involved in the extractions, transfer lines and injections are the classical instrumentation classes:

- Beam Position Monitors (BPMs), with both button and coupler types;
- Beam Screens (BTVs), of both luminescence and OTR types;
- Beam Current Transformers (BCTs);
- Beam Loss Monitors (BLMs).

### *Machine protection subsystems*

The systems dedicated to, or used for, machine protection, Fig. 5, must be commissioned without and with beam [9]. Formal testing and acceptance procedures for all critical interlock and machine protection systems should be specified. This will be included in the injection interlock specification being prepared. The machine protection subsystems include:

- Beam Interlock controllers and signal exchange;
- Beam current measurement system (SPS and LHC);
- LHC energy meter;
- LHC kickers (inhibit / injection permit);
- Movable protection devices (TED, TBSE, TCDI, TDI, TCDD, TCLI);
- Dedicated beam instrumentation (BLMs, BPMs, BTVs);
- Magnet current surveillance systems.

### *Software and controls*

The injection of beam into the LHC will require that a large subset of the controls system [11] and application software be fully functioning, and will also provide the ideal opportunity for deployment and testing of the remainder of the controls software. Requirements for the injection include:

- Controls infrastructure:
- Middleware, databases:
- Generic application software:
  - Equipment control, measurement, data visualisation, cycle visualisation, trim, trajectory / orbit control, logging, alarms,…;
- Dedicated injection application software:
  - Injection Steering;
  - Specific logging and post-mortem facilities;
  - Injection fixed displays;
  - Equipment expert applications;
  - Injection sequencer;
  - Injection machine protection status and control?
  - Online re-matching routines?

## KEY SYSTEM PREPARATIONS AND TESTS WITHOUT BEAM

A large number of tests can already be carried out without beam, in order to optimise the commissioning process and minimise the time required. For these tests, which will take place at the end of the hardware commissioning phase, detailed, comprehensive planning will be mandatory. The tests include:

### *Equipment*

- Magnet powering with machine cycle and functions;
- Injection kicker pulsing with machine cycle and timing;
- Beam instrumentation tests (calibration, acquisition, movements…).

### *Machine protection*

- Beam Interlock tests and formal acceptance (fault injection, data exchange, diagnostics);
- Software interlock system;
- Collimator jaw movement and motor tests;
- Power Convertor current monitoring and Fast Current Decay Monitoring.

### *Software and controls*

- Application software deployment and full testing;
- Data acquisition, OASIS;
- Logging and post-mortem;
- Timing system;
- Injection sequencing;
- Inject and dump mode.

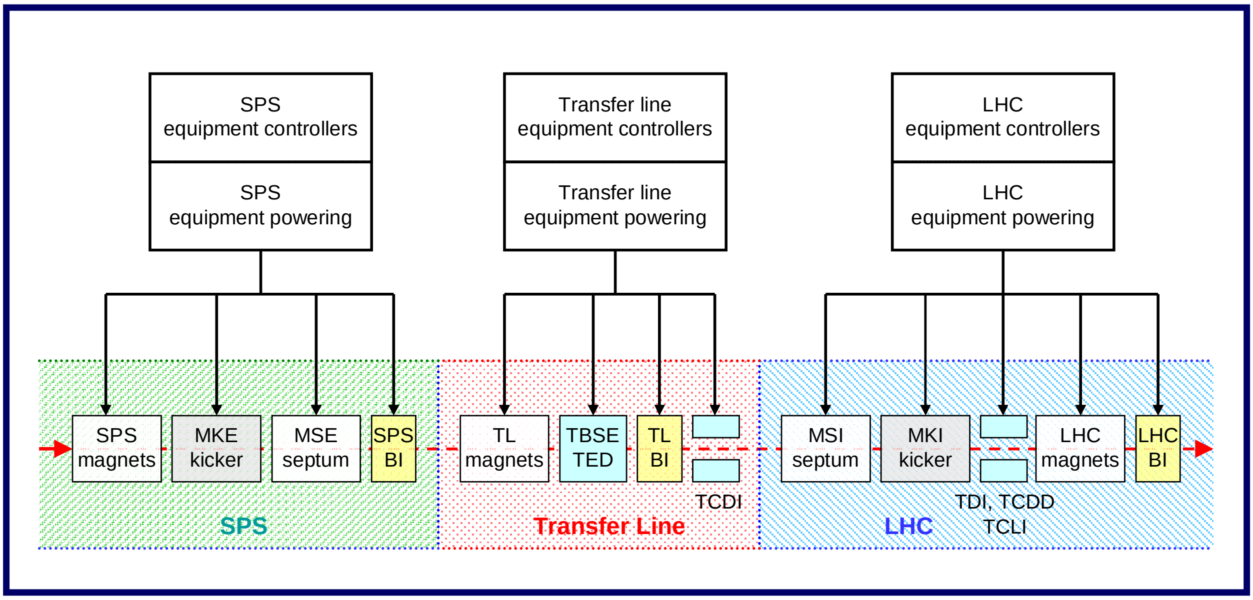


Fig. 3. Schematic of equipment systems associated with the injection process.

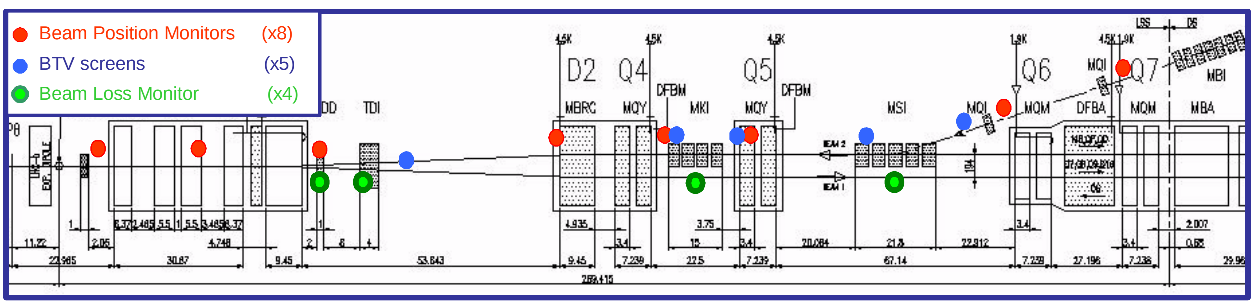


Fig. 4. Schematic of Beam Instrumentation in the Injection region in IR8.

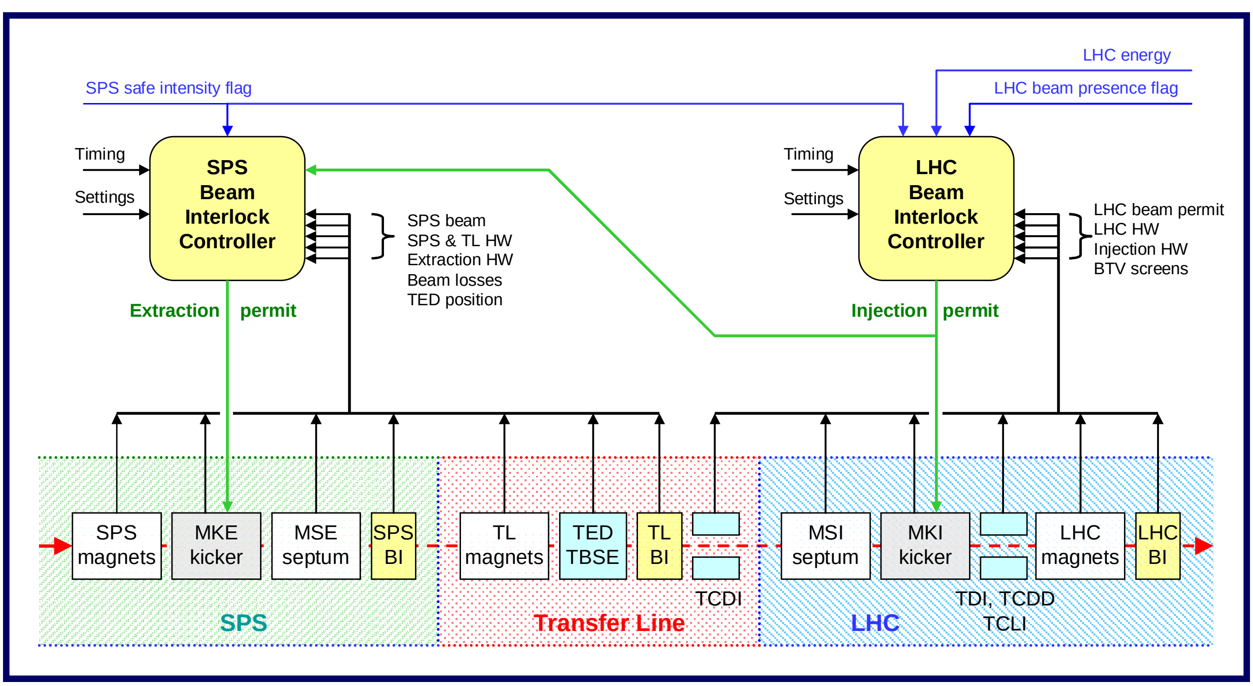


Fig. 5. Schematic of the systems associated with Machine Protection at injection.

## PRE-REQUISITES FOR BEAM COMMISSIONING

Before the beam commissioning can begin, a certain number of conditions must be met regarding the status of the equipment, controls and safety systems. The main pre-requisites are:

- Machine check-out completed:
  - Controls, software, equipment and services all tested and fully operational;
  - LHC 450 GeV settings and cycling deployed.
- SPS extractions and transfer lines operational:
  - Kickers, septa, magnets, powering, controls, interlocks, instrumentation, collimators.
- Specific injection elements operational:
  - Septa MSI (with associated power converter, controls, interlocks, current monitoring);
  - Kickers MKI (with controls, timing, pre-pulse, analogue acquisition);
  - Injection region beam instrumentation (with controls, timing, interlocks;)
  - TDI collimator (with controls, interlocks, radiation monitoring).
- A minimum set of LHC machine elements operational to take the beam to the TDI:
  - Q5, Q4, D2 right of IP8 (left of IP2);
  - Orbit correctors.
- Downstream LHC machine elements operational once the beam is through the TDI:
  - D1 and Inner Triplet left and right: cold and powered (inner triplet multi-pole compensation and spectrometer magnet + compensators off).

## EARLY BEAM INTENSITIES

The initial commissioning objective of the LHC is currently to obtain high energy collisions with 43 x 43 bunches of about 3 $10^{10}$ p+ each [12]. This means a maximum injected intensity of about 1.2 $10^{11}$. The main intensity steps for this early beam commissioning are:

- Pilot single bunch (~$5\times10^9$);
- Intermediate single bunch (~$3 \times 10^{10}$);
- 4 x 1 bunch, for 43 x 43 (4 x ~$3\times10^{10}$).

## COMMISSIONING PHASES OF THE LINES AND INJECTIONS

The commissioning with beam of the transfer lines and injection systems comprises three distinct phases, Fig. 6, the SPS extraction systems and first hundred metres of transfer lines up to the first movable beam dump TED, the main 2.5 km part of the transfer line up to the second TED, and the last hundred metres of line and the LHC injection systems. Each of these can be further broken down into separate parts. For all three phases, the commissioning without beam looks similar:

**Commissioning without beam:**

1. Closing of access zones and safety tests;
2. Pre-testing of equipment systems;
3. Pre-testing of application software and controls;
4. Pre-testing of interlock systems;
5. Setup of cycle and timing.

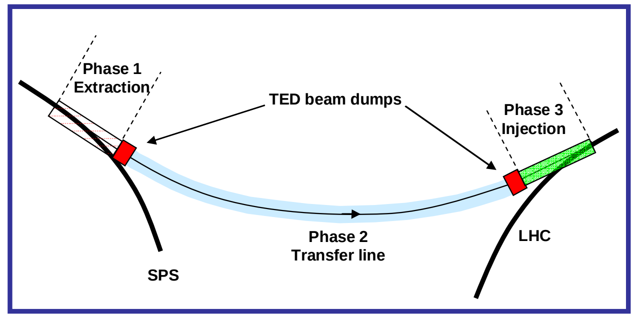


Fig. 6. The three separate commissioning zones of the transfer lines and injection systems.

### *Zone 1: SPS extraction systems and start of the transfer line*

In this phase the SPS fast extraction systems [13, 14] in LSS4 and LSS6 are commissioned with beam, and the first part of the transfer lines TT40 and TT60 up to the first mobile TED. The main commissioning steps for this phase are:

**I. Low intensity single-bunch (LHC pilot):**

1. Setup beam in SPS (orbit in extraction region);
2. Setup of extraction bump;
3. Commissioning of extraction (kickers + septa);
4. Testing of beam-dependent interlocks;
5. Optimisation of kicker timing;
6. Commissioning of Beam Instrumentation;
7. Steering along the line onto the TED;
8. Optics checks and measurements;
9. Optimisation of trajectory (losses, aperture);
10. Corrector / BPM polarity checks;
11. Instrumentation performance measurements;
12. Stability measurements.

**II. Moderate intensity (~$10^{12}$ p+) in few bunches:**

1. Tests of intensity-dependent instrumentation;
2. Tests of beam-dependent interlocks;
3. Optimisation of trajectory (losses, aperture);
4. Radiation measurements.

The LSS4 extraction and TT40 are already operational [15]; for LSS6 and TT60 the commissioning will take place in 2006, decoupled from the beam commissioning of TI 2.

The time required for this phase is around 2 days per line. For LSS4/TT40 commissioning in 2003, the split into 2 periods separated by a few weeks was very useful to enable data to be analysed and faults corrected.

### *Zone 2: Main part of the transfer lines*

For this phase the main parts of the transfer lines TI 2 and TI 8 are commissioned with beam, up to the second mobile TED some 100 m from the injection point into the LHC. The main commissioning steps for this phase are:

**I. Low intensity single-bunch (LHC pilot):**

1. Removal of first TED;
2. Commissioning of Beam Instrumentation;
3. Steering along the line onto second TED;
4. Optics checks and measurements;
5. Corrector / BPM polarity checks;
6. Optimisation of trajectory (losses, aperture);
7. Testing of beam-dependent interlocks;
8. BDI performance measurements;
9. Stability and temperature measurements.

**II. Moderate intensity (~$10^{12}$ p+) in few bunches:**

1. Tests of intensity-dependent instrumentation;
2. Tests of beam-dependent interlocks;
3. Optimisation of trajectory (losses, aperture);
4. Radiation measurements.

This commissioning should be decoupled as far as possible from LHC machine commissioning. The downstream TI 2 installation, hardware commissioning, machine checkout and beam commissioning all take place after the LHC magnet installation finishes, which places this activity on the critical path, especially since injected beam 1 will be required in the LHC at essentially the same day as beam 2. Possible solutions will need to be explored, for example beam commissioning of TI 2 in parallel with Ring 2 beam commissioning or with LHC hardware commissioning. For TI 8, this part is essentially already operational following commissioning in 2004 [16], and should clearly be kept that way in 2006, with further tests and MD to be scheduled. The issue of interleaved running with CNGS could then be addressed and solved at this time.

The time required for this phase is around 4 days per line. Again, for TI 8 commissioning in 2004, splitting the time into 2 distinct periods was a big advantage.

### *Phase 3: End of the transfer lines and LHC injection systems*

For this phase the final ~100 m of the transfer lines TI 2 and TI 8 are commissioned with beam, and the LHC injection systems are also commissioned, up to the injection collimator TDI, which also serves as a dump for injection setting up with pilot beams

**I. Low intensity single-bunch (LHC pilot):**

1. Injection kickers off. TDI in dump position;
2. TDI setup as injection dump (movement, instruments, interlocks);
3. Removal of second TED;
4. Commissioning of BDI;
5. Threading beam to TDI (last 130 m of line; LHC MSI; Q5, Q4, D2);
6. Optics checks and measurements;
7. Optimisation of trajectory (losses, aperture);
8. Testing of beam-dependent interlocks;
9. Switch on MKI with TDI still in dump position;
10. Optimisation of MKI (timing, strength);
11. BDI performance measurements;
12. Machine protection tests (MKI, TDI position);
13. Rough TCDI alignment;
14. Move TDI to "injection collimation" position;
15. Steering beam through the TDI;
16. Injection trajectory adjustment
17. Rough TDI alignment as collimator;
18. Rough TCLI alignment;
19. Injection optimisation, start of "first turn".

**III. Moderate intensity (~$10^{12}$ p+) in few bunches:**

1. Tests of intensity-dependent instrumentation;
2. Tests of beam-dependent interlocks;
3. Optimisation of trajectory (losses, aperture);
4. Radiation measurements.

This commissioning phase can only take place with part of the LHC installed and operational. The end of TI 8 and the IR8 injection can hopefully be commissioned prior to a sector test at the end of 2006, and should be operational well before LHC beam commissioning. The requirement for both beams at day 1 of the LHC beam commissioning means that special attention will be needed to ensure the rapid commissioning of the final part of TI 2 and the IR2 injection. It is estimated that each injection system can be commissioned with beam in about 1 day.

## MAIN AREAS OF CONCERN AND OUTSTANDING ISSUES

There are several areas of concern which remain to be addressed in the near future. The main ones are:

- The clear roadmap for the beam commissioning of the LHC, including transfer lines, injectors and LHC machine phases;
- Scheduling TI 2 and IR2 hardware commissioning, machine check-out, beam commissioning, in order to avoid a crash programme at the same time as LHC beam commissioning;
- The planning and preparation for the sector test in 2006, which involves keeping TI 8 operational and improving performance;
- The specification and design of the dedicated application software;
- The full specification of the injection interlocking and formal acceptance tests;
- The definition and implementation of the 'Inject & dump' mode.

## CONCLUSIONS

The commissioning of the LHC transfer lines and injectors has already started, with TI 8 being operational in 2004. The 2003 and 2004 experience has shown that detailed, comprehensive preparation is essential for all commissioning phases, in order to be able to maximise the amount of work done during beam time, and to prepare as far as possible without beam by identifying and taking advantage of opportunities for parallelism. This will be especially true for TI 2 where the schedule will be very compressed. Much of the equipment and software commissioning can and must take place without beam. The machine must be ready for beam in every sense, with equipment functioning correctly, the real machine cycle deployed and tested, all application software working etc. To this end, the use of scheduled 'Dry Run' periods will be very important, where operational phases (i.e. the injection sequence from the SPS to fill both LHC rings) are fully tested without beam.

Clearly, for the commissioning of the injections, a sector test end 2006 would be a big advantage. This would be invaluable for TI 8 and IR8 injection commissioning, and would continue the hitherto successful stepwise approach (2003 TT40, 2004 TI 8, …) which has been shown to be excellent for developing experience, for solving problems in a structured and piecewise way, and also for providing challenging and measurable project milestones.

Concerning machine protection, the awareness of the issues involved must have highest priority. The commissioning with low intensity relaxes but does not remove machine protection constraints, and safety must come before beam quality. The formal definition of acceptance tests without and with beam, and for each intensity step in the commissioning process, is essential. The commissioning process must not progress until these requirements have been proved to have been met at each stage.

## REFERENCES


[1] A. Hilaire, V.Mertens, E.Weisse, "Beam Transfer to and Injection into LHC", EPAC'98, Stockholm, June 1998, and CERN/LHC Project Report 208.

[2] V.Mertens, Y.C.Chao, "Analysis and Optimisation of Orbit Correction Configurations Using Generalised Response Matrices and its Application to the LHC Injection Transfer Lines TI 2 and TI 8", CERN-SL-2001-053-BT, 2001.

[3] A. Hilaire, V.Mertens, E.Weisse, The Magnet System of the LHC Injection Transfer Lines TI 2 and TI 8, LHC-Project-Note-128, CERN, 1998.

[4] O. Brüning, J. B. Jeanneret, "Optics Constraints Imposed by the Injection in IP2 and IP8", CERN/LHC Project Note 141 (1998).

[5] O. Brüning et al., "LHC Design Report Volume I - the LHC Main Ring" CERN-2004-003, 2004.

[6] O. Brüning et al., "LHC Design Report Volume III – the LHC Injector Chain" CERN-2004-003, 2004.

[7] B.Goddard, "Expected Delivery Precision of the Injected LHC Beam", CERN/LHC Project note 337, 2004.

[8] H.Burkhardt, "Overview of the LHC and Transfer Line Optics Configurations and Tolerances", Second LHC Project Workshop, Chamonix XIV, 2005.

[9] V.Kain, "Safe Injection Into the LHC", Second LHC Project Workshop, Chamonix XIV, 2005.

[10] H.Schmickler, "Beam Instrumentation", Second LHC Project Workshop, Chamonix XIV, 2005.

[11] R.Schmidt, "Controls", Second LHC Project Workshop, Chamonix XIV, 2005.

[12] M.Lamont, "Overall Beam Commissioning Strategy", Second LHC Project Workshop, Chamonix XIV, 2005.

[13] B.Goddard et al., "The new SPS extraction channel for LHC and CNGS", Proc. EPAC '00 7th European Particle Accelerator Conference pp. 2240, 2000.

[14] B.Balhan et al., "The design of the new SPS LSS6 Fast Extraction Channel for the LHC", EPAC '04; 9th European Particle Accelerator Conference 2004.

[15] B.Goddard et al., "Beam Commissioning of the SPS LSS4 Extraction and TT40 Transfer Line", EPAC '04; 9th European Particle Accelerator Conference 2004.

[16] J.Uythoven, "Experience with TI 8 and TT40 Tests", Second LHC Project Workshop, Chamonix XIV, 2005.