BEAM STEERING IN THE LHC ERA

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Abstract

The LHC demands high intensity proton beams with small transverse emittance from its injectors. The implications of these demands for beam steering and matching of the transfer from the PS to the SPS and the transfer from the SPS to the LHC are explored. Injection into the LHC, orbit acquisition and the orbit correction requirements of the LHC itself are briefly addressed.

1. Introduction

High intensity 26 GeV/c protons will be sent via existing lines from the PS to the SPS from where, after acceleration to 450 GeV/c, transfer will take place down new lines to the LHC. The beam has to fit into the tiny LHC dynamic aperture at injection while providing enough intensity to ensure high luminosity. The essential challenges of the injector chain, of concern here, are to maintain a small transverse emittance and to steer carefully the beam to avoid material damage in the lines and quenches or worse in the LHC itself.

In the following the requirements of the LHC are briefly outlined, the on-going work on the transfer to the SPS described and a brief overview of the the new transfer line provided. Finally a cursory look at LHC orbit acquisition and correction requirements is afforded.

2. Beam Requirements of the LHC

The requirements of the LHC of its injectors are well established [1]. The LHC is designed to deliver high luminosity in the beam-beam regime and nominally requires 2835 bunches of 1.1x10^{11} protons, with an ultimate figure of 1.66x10^{11} protons per bunch. During commissioning the bunch intensity will be considerably smaller with ideally the nominal transverse beam density.

To avoid excessive beam-beam effects the transverse emittance should have a nominal value of ϵ_n = 3.75x10^{-6} m. Herein lies one of the major challenges for the injector chain and beam steering: maintaining the small transverse emittance of the high intensity proton beam.

3. Transfer to SPS

The TT2-TT10 transfer lines which bring 26 GeV/c protons from the PS to the SPS have already received some concerted attention in attempts to minimize the blow-up at injection into the SPS caused by mismatch between the lines and the ring [3, 4]. The LHC beam has a large momentum spread meaning that good dispersion matching is particularly important.

A consistent model of the complete TT2-TI10 line, for input into MAD, has been established together with precise knowledge of the initial conditions at the start of the line. The has enabled accurate matching of the betatron and dispersion functions, with the measurements performed on a LHC like beam. The geometry of the lines has been cross-checked with the survey data, and the magnetic behaviour of the elements confirmed.

For betatron matching, twiss parameters have been measured and tracked back to the PS extraction point. The input parameters thus obtained reduced considerable the mismatch factor.

For dispersion the momentum of the PS was varied (typically 5 values) and, using the SPS as a continuation of the lines, a long range fit has been performed. These measurements have allowed the dispersion amplitude to be brought down to near its design va lue.

Tuning knobs have also been developed to attack the residual mismatch. SVD techniques have been used to generate the requisite matrices and these knobs were tested using OTR screens which provide turn-by-turn beam size measurements [4].

4. Transfer to LHC

Two new lines, TI2 and TI8, are being constructed to transfer the 450 GeV/c proton beam from the SPS to the LHC [5]. These lines are long and use warm magnets with relatively tight aperture. Fast extraction takes place into the lines from the SPS. Both lines have a FODO structure with 30.3 m half-cell length with 4 dipoles per half cell.

With regard to beam in the lines, of primary importance is the stability of the extracted beams, precise control of the beam over the full length of the line and the safety and precision of the injection into the LHC. The high intensity beam must stay within the available aperture to avoid damage: to enable this and minimise the required number of correctors a 2-in-4 correction scheme has been proposed in which 2 out of 4 cells are fully equipped with BPMs and correctors [6]. Simulations have shown the scheme to be effective for trajectory control.

Again the need to preserve the transverse emittance requires very good betatron and dispersion matching, and there are independently powered quadrupoles in matching sections at the start and end of the lines. Adequate beam instrumentation is, of course, required.

The LHC has a small available aperture, both dynamic and physical, and the risks of quenches because of beam loss are high. This puts stringent requirements on the quality of injection into the LHC.

Given these needs the following requirements of a beam steering system may be identified:

- Threading of low intensity bunches to establish a trajectory. Measurement, display and correction of trajectories.
- Measurement and display of optical parameters, emittances and profiles. Matching of betatron and dispersion functions.
- The trajectory in the line must be stable and if necessary a feedback system should deal with temperature and/or power supply drifts.
- Injection optimization requires orthogonal steering.
- Threading will also be required in the LHC to establish circulating beam.
- The orbit in the injection regions must be very stable. The dumps and collimators will need to be adjusted to the closed orbit.
- Surveillance, interlocks and post-mortem analysis will be critical.

The need for trajectory, injection and orbit stability from pulse to pulse implies the need for automation with feedback systems in place to effect the necessary adjustments.

5. Orbit correction in the LHC

The orbit and trajectory system of the LHC will consist of some 500 BPMs per ring with a 40 MHz acquisition system that will acquire and digitise consecutive turns of all 2835 bunches [7]. 250 local systems (4 BPMs per station) will return the closed orbit or turn-by-turn information. The closed orbit will be available, if required, at something like 20 Hz.

Closed orbit feedback will be required at something like 1 to 10 Hz and will be particularly important during the so-called "snapback" at the start of the ramp. Higher frequency local orbit feedback might be necessary in the cleaning sections. The usual set of applications will, of course, be required including a threader, tools for 1000 turn analysis, fitting. interpolation etc. Of particular importance will be the ability to perform post-mortem analysis.

6. Conclusion

One of the main requirements that LHC has of the injected beams is a small transverse emittance. This implies a very tight emittance budget and means that dispersion and betatron matching between the line and rings must be nigh on perfect. Happily the techniques and instrumentation required for this are being actively developed already and have seen considerable success in optimizing the transfer between PS and SPS. The importance of an accurate optics model is clear, as is the need for a diligent and disciplined approach to the problem.

The transfer to the LHC from the SPS will be via new transfer lines (TI2 and TI8), these lines are long and have a small aperture. The dangers of beam loss are high with the consequence that beam steering will have to be fast and very reliable. Surveillance and interlocks will be crucial. In addition the injection into the LHC must be very well controlled to reduce beam loss to an absolute minimum. Good matching will again be important. Remote control of steering in the lines and of injection optimisation is likely to be necessary.

Orbit acquisition in the LHC will be via approximately 500 beam position monitors per ring, and the system will acquire and digitise consecutive turns of all 2835 bunches per beam. Both global (1 to 10 Hz) and, perhaps even faster, local feedback is envisaged. Again reliability will be crucial, the risks to the machine of inadvertent beam loss are serious in the extreme.

In conclusion, the two main requirements: respecting a tight emittance budget and the control of the explosive power of the LHC beams demand reliable facilities for threading, steering and matching. Matching will be very important if beam sizes are to be controlled properly. The small aperture involved demand fast and rigorous control of trajectories, injection and orbit. The room for error is minimal and reliable automated feedback facilities will be required. Effective monitoring feeding a robust interlock system will also be required. The demands of the LHC pose a tough set of challenges for beam steering and associated applications.

Acknowledgements

This is very much a review article and draws heavily on the work of others. In particular: Gianluigi Arduini and Klaus Hanke and their work matching TT2-TI10; the new lines to the LHC are very much the responsibly of Alain Hilaire, Volker Mertens and Eberhard Weisse. I am also indebted to Alan Burns for his input on the LHC orbit system.

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