TRANSFER AND INJECTION

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Abstract

The transfer of high intensity, high energy protons and their injection into the LHC requires highest care. Dangers and potentially performance-affecting effects are reviewed, together with intended detection methods and counter-measures, pointing out likely implications for controls. Protection devices to be used for setting-up of injection and serving against possible kicker failures are presented.

1 INTRODUCTION

Two beam transfer lines with a combined length of 5.6 km and using over 700 room-temperature magnets, TI 2 and TI 8, are being built to transport 450 GeV/c protons from SPS to LHC.

An overview of these lines can be found in [1]; a summary has also been given in [2], together with a discussion of the beam requirements, a sketch of the possible commissioning phase and some of the resulting application software requirements.

Civil engineering for TI 2 and TI 8 is now well under-way. About one quarter of the new main dipoles and quadrupoles has been received. Refurbishment of the recuperated power supplies has started. The vacuum system has been fully specified and ordered from BINP, Novosibirsk, in the framework of the participation of the Russian Federation in the LHC project. Start of TI 8 commissioning is foreseen for fall 2003. TI 2 is planned to be commissioned in 2005.

2 BEAM PARAMETERS AND GOALS

The main beam parameters at injection are listed in table 1.

Table 1: Beam parameters at injection

Beam (proton) momentum	450 GeV/c
Nominal single bunch intensity	$1.1 \cdot 10^{11}$ p
Nom. batch intensity (3*81 bunches)	$2.67 \cdot 10^{13}$ p
Ultim. batch intensity (3*81 bunches)	$4.13 \cdot 10^{13}$ p
Bunch distance	25 ns
Nom. norm'd transverse emittance	3.5 μm rad

The destructive power of this beam – a nominal batch corresponds to 1.9 MJ – imposes high precision and very good protection during transfer and injection into the small aperture, superconducting LHC. The quench limit – through instantaneous energy deposition in a coil – is assumed to only 38 mJ/cm^3 [3], the damage limit to 87 J/cm^3 [4].

As repair is in general extremely costly and time-consuming damage to the LHC has to be avoided by all economically feasible means. Quenching should as well be restricted to rare accidental cases as it degrades magnet performance and will as well imply considerable recovery time [5].

The required delivery precision of the beam on the LHC closed orbit is ±1.5 σ, of which ±0.5 σ is accounted for SPS extraction kicker and LHC injection kicker ripple. The remainder must cover all other errors (SPS precision, transfer line power supplies, etc.). Respect of the emittance preservation requires a linear transfer line optics and good matching between the SPS and the LHC. In the absence of radiation damping the LHC damper becomes the key device to suppress – within given limits – the residual orbit oscillations of the injected beam.

In the following potentially safety- and performance-affecting effects will be reviewed, taking recent investigations into account, together with intended detection methods and possible counter-measures, pointing out likely implications for controls.

3 POTENTIALLY ADVERSE EFFECTS, THEIR DETECTION, AND COUNTER-MEASURES

3.1 SPS and Extraction

Possible errors concern the beam energy and trajectory at extraction. Whereas a wrong beam energy is only considered as resulting from an accidental situation (e.g. failure of the radial loop control), causing an immediate and massive effect during the usual injection setting-up (see below), a trajectory drift might result in a creeping performance degradation if undetected. Both types of effects could be detected through permanent surveillance of the trajectory in the transfer lines. The drift could then either be counter-acted by a correction of the SPS elements or a (preferentially automatic) re-steering of the transfer lines. Since the transfer lines contain no fast elements bunch-to-bunch-jitter and other statistical effects have to be dealt with by the LHC damper system.

To get a better feeling of the possible size of such effects an earlier proposal [2] to measure the stability and the reproducibility of an extracted LHC type beam is re-iterated, probably in parasitic mode and starting with intensities just sufficient to produce usable signals in the position monitors.

3.2 Transfer Lines

In order to finalize the power supply requirements the precision required to keep the emittance blowup small has recently been looked at. For all main dipoles and quadrupoles a basic precision of $\pm 10^{-4}$ is found sufficient. As expected the contribution from quadrupoles is negligible, as well as from correctors. Only for those groups of magnets which would otherwise deteriorate sensibly the beam quality a precision down to $\pm 2*10^{-5}$ has been specified. An economic solution to this requirement exists [6].

The beam parameters dictate that the bunches stay absolutely within the available aperture to avoid severe damage. On top of the maximally allowed corrected excursions of ±4.5 mm an error of 5 mm from a wrong power supply response can be tolerated in the transfer lines before an interlock has to be issued inhibiting the SPS extraction. For some of the power supplies this corresponds to an error of only 10^{-3}. Of course smaller deviations must already be signalled by a surveillance system to take preventive action.

A cost-effective scheme for trajectory correction has already been presented [7]. It exhibits some sensibility against missing monitors and rapidly degrading alignment. By further working on the correction algorithms it is hoped to improve its robustness and gain some redundancy without further hardware investment.

The effect on emittance from higher order field components of the new main dipoles and quadrupoles has also been investigated. If the received magnets continue to stay within the specification their influence on the emittance will be insignificant. A surveillance system has recently been elaborated [8] which cuts the circuit in case of coil temperatures above about 65° C (e.g. if the water flow is insufficient) and simultaneouly issues an interlock.

At first glance, there is a mismatch between the air cooling capacity and the heat load, in case of TI 8 of more than a factor 3. However, this is deemed to be no real reason of concern for routine operation since the injection period, during which the lines will only be powered, is supposed to be quite short. In addition, experience shows that the tunnel walls act as a considerable heat sink. Nevertheless, the mismatch could mean that one has from time to time to interrupt commissioning for a few hours to let the tunnel cool down. Too high temperatures might affect the electronics of the position monitors which is to be installed in the tunnels. Also $\int B\,dl$ of the magnets changes with temperature. Measurements are currently underway to find out the amount of this effect [9]. Tunnel and magnet temperature surveillance is foreseen and the application software must be prepared to deal with these kind of time-dependent effects, e.g. by applying correction factors to the power supply settings resp. by re-steering the lines automatically. In case more quantitative figures are desired it is suggested to carry out a thermal modeling of the transfer lines.

The need to preserve the transverse emittance requires good betatron and dispersion matching at both extremities of the lines. For this purpose, a number of independently powered quadrupoles at the beginning and the end of both lines is foreseen, providing also some flexibility to accommodate the evolution in the optics of both accelerators. Adequate beam instrumentation in the lines is required to measure the optical parameters with good precision and to adjust the matching if necessary. Feed-back from the several turns profile measurement of the LHC will also be an important input.

3.3 Injection

Special attention has to be given to the protection of the superconducting LHC machine against failures of the injection kickers. The present findings and recommendations of the LHC Injection Working Group have already been laid down [10]. Only a limited account will therefore be given here.

A schematic view of an injection region is given in figure 1. A mobile beam stopper (TDI) is placed downstream of the kicker (MKI) to reveice beam during setting-up before each injection and to protect machine elements in case of kicker failures. This stopper consists of two absorber blocks (one for the beam to be injected, the other for the circulating beam) positioned, during injection, a few mm above and below the nominal LHC orbit. Its main role is to protect the immediately following cold separation dipole D1.

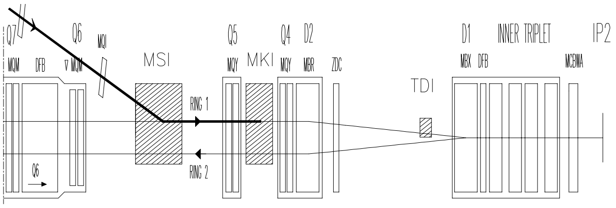

Figure 1: Schematic plan view of IP2 injection.

The TDI/D1 ensemble has been simulated using FLUKA [11] for different TDI constructs. For the present “reference TDI”, consisting of two blocks with 8*8 cm profile and a material sequence of 2.5 m graphite, 1 m aluminium, 0.5 m copper and 0.3 m tungsten, the obtained energy deposition in the D1 coil is given in table 2. Case 1 refers to a full impact (kicker off), as e.g. used intentionally during setting-up. Case 2 represents the “beam sweep”, which might occur occasionally, e.g. as result of a wrong kicker timing or an accidental prefiring. In this case close to 100 bunches could be deposited onto various locations of the TDI, and close to 20 bunches (worst case) could escape through the remaining gap. Case 3 designates the case where one of the four kicker modules fails completely (deemed rare). Case 4, finally, gives the results for the worst case where, through an internal kicker flashover, the full batch would just be deposited at the TDI edge (supposed to be extremely rare).

Table 2: Energy deposition in D1 coil for the "reference TDI" (preliminary)

Case	Error	Energy deposition in D1 coil [J/cm^3]		
	[%]	$1.1*10^{11}$ p	$2.67*10^{13}$ p	$4.13*10^{13}$ p
1	50	$1.8*10^{-5}$	$4.3*10^{-3}$	$6.7*10^{-3}$
2	50		6.8	10.5
3	50	$2.3*10^{-2}$	5.6	8.7
4	25	0.25	60.3	93.3

Comparing to the limits given in paragraph 2, case 1 would not lead to a quench, even at highest intensity. Full batches in case 2 and 3 would, without additional measures, quench D1. Case 4 approaches the assumed damage limit for a nominal batch and surpasses it slightly for an ultimate intensity batch. Since extending the TDI does not help, the effect from additional shielding was tested by introducing a copper cylinder ($25 \leq r \leq 140$ mm, 1m long) in the simulation, at 3 m in front of D1. This reduced the energy deposition by about a factor 120, thus excluding damage to D1 under all circumstances. Whereas such a shield would only be mandatory for case 4 with highest intensity, it is of course also beneficial in the other cases. The figure for the sweep case at nominal batch intensity is then close to the quench level. Some further shield optimisation will allow to fall short of the quench level for this case.

A preliminary design of the TDI exists. Each absorber block (weight about 200 kg) will have two servo motors allowing a vertical adjustment with a precision of about 0.1 mm, corresponding to about 0.2 σ.

The effect of injected bunches missing the TDI on other parts of the LHC than D1 has also been looked at. Two worst cases are considered: firstly, the case 2 where close to 20 bunches could be swept between the orbit and the TDI edge, starting to oscillate around the orbit. The mean particle density is about $2*10^{10}$ p / 0.1 σ. The damage level is estimated to be 10^{12} p lost per m, the quench level 10^{9} p lost per m. Damage seems therefore excluded, but to avoid a quench the TDI must be set such that it covers entirely the downstream machine aperture of 8.5 σ. Secondly, the case 4 with a full batch just missing the TDI edge. Here the worst case particle density is about $1.6*10^{12}$ p / 0.1 σ (peak). Excluding machine damage with certainty would again require a sufficient closure of the TDI.

Two additional collimators, positioned at a phase advance $\Delta\mu \approx \pm 20°$ from the TDI (at around Q6/Q7 on the other side of the injection insertions), with the same aperture setting, would provide the same protection as the TDI in the presence of phase errors.

4 PRESENT VIEW OF THE ROUTINE INJECTION PROCEDURE

To get accustomed to the probable steps involved and to illustrate likely implications of controls the present view of the routine injection procedure is given below, as far as injection related equipment is involved.

Once the decision to fill, resp. re-fill, has been taken, the following procedure is presently thought to take place: firstly it has to be checked that the beam stopper at the end of each transfer line (TED, not to be confounded with the TDI) is in its "IN" position. This allows to test the full injector chain (PS, SPS, transfer lines), without interfering with a still circulating beam in the LHC.

If the injector chain is available, any remaining LHC beam is dumped and the machine prepared for injection. During this the TED can be retracted. Once the machine is empty the TDI and shield can be set to a position around the most probably new LHC orbit, and pilot pulses can be sent up to the TDI, with the kickers still off.

Before really injecting beam onto the LHC orbit, checklists have to be worked through to make sure that the LHC is ready to receive beam (e.g. "beam dump ok ?"). Afterwards, pilot pulses can again be injected and circulated to re-establish the orbit. If the orbit differs from the previous one the TDI and the potential further injection collimators need to be re-adjusted for optimum protection.

Full injection might now take place. On-line tracking is supposed to be necessary to follow the orbit development during the injection procedure. If there are any drifts in the transfer lines during this period also these elements need to be re-adjusted in real time. Once the injection is finished the TDI, the shield and the injection collimators have to be retracted. For safety reasons the TED should be moved in again already now.

During this whole period all relevant parameters should be kept for off-line studies, like optimization and understanding of failures. To be most useful their re-play should be coherent (unambiguous time-stamping) and user-friendly.

It should be noted that a lot will only be learned during commissioning and the first years of operation. The exact sequence of events during injection will depend on how the LHC really behaves. As a result some of the above steps might be skipped once sufficient experience has been gained.

5 FURTHER WORK AND THINKING

5.1 Injection Scenarios

With routine injection still quite some years ahead going into details in this subject may seem premature. However, as the moment approaches when the foundation stones of the LHC control system will be laid and the re-engineering project of the SPS software [12] is in full swing, touching (again) upon a few issues might be in order, since they may have an impact on the controls requirements.

One of the open points concerns the filling scheme, i.e. what is the likely sequence to inject the batches (first all batches of one ring then all of the other, or one batch of one ring followed by one batch of the other, or schemes between both) ? What is the impact of possible interleaved CNGS cycles ? Should pilot pulses better be kicked out onto the TDI when injecting real batches, or separately, using the beam dump ? Should one re-inject any batch immediately if its intensity is unsatisfactory ? Or rather dump the full beam and re-inject from the beginning ? Or even re-cycle the whole machine first ?

In the light of these open questions it is obvious that a future control system must be very flexible to be rapidly adaptable to evolving needs. The real-time aspect is also particularly important.

5.2 Hardware

The performance specification and the exact placement of the beam instrumentation in TI 2 and TI 8 – other than the position monitors – must now be worked out, i.e. for all profile, intensity and loss monitors.

The design of the TDI and the D1 shielding needs to be optimized, including the layout of the vacuum chambers.

A decision on the additional injection collimators in the Q6/Q7 region needs to be taken before the cryostat design in the region is finalized.

Likewise, the usefulness of potential collimators in the transfer lines should be studied, supposed to procure additional protection (e.g. to the LHC in the horizontal plane) in case of yet unforeseen failures.

5.3 Software

In view of the fact that the start of the TI 8 commissioning is only a little over 3 years away it seems now appropriate to start working on the specifications of the application software. The need to arrive at an integrated solution between SPS, the transfer lines and the first turns of the LHC is emphasized, in order to facilitate commissioning.

4 CONCLUSIONS

The destructive beam power and the LHC characteristics as superconducting and small-aperture machine imply highest care during transfer and injection. All failures which can be anticipated should be anticipated and appropriate counter-measures be taken. For the transfer lines and the injection equipment up to the TDI and D1 shield every effort is made to ensure a safe transfer and injection reaching the main goals, within the given financial constraints.

Above that the demands on controls and operation will be high. A comprehensive and user-friendly software suite is needed which integrates the whole transfer and injection process, most likely involving a high degree of automation (cycle changes, sequencing, steering). It should be able to deal with potential time-dependent effects (transfer line drifts, LHC orbit). Good surveillance and post-mortem information are more important than ever. Well-thought and well-maintained interlocks are primordial. Last, but not least, operational procedures must be rigorously applied.

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