EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS-2011-274

Controlling Beam Loss at Injection into the LHC

B. Goddard, F. Alessio, W. Bartmann, P. Baudrenghien, V. Boccone, C. Bracco, M. Brugger, K. Cornelis, B. Dehning, E. del Busto, A. Di Mauro, L. Drosdal, W. Höfle, E. B. Holzer, R. Jacobsson, V. Kain, M. Meddahi, V. Mertens, A. Nordt, J. Uythoven, D. Valuch, S. Weisz, CERN, Geneva, Switzerland
R.B. Appleby, University of Manchester and the Cockcroft Institute, UK

Abstract

Losses at injection into the superconducting LHC can adversely affect the machine performance in several important ways. The high injected beam intensity and energy mean that precautions must be taken against damage and quenches, including collimators placed close to the beam in the injection regions. Clean injection is essential, to avoid spurious signals on the sensitive beam loss monitoring system which will trigger beam dumps. In addition, the use of the two injection insertions to house downstream high energy physics experiments brings constraints on permitted beam loss levels. In this paper the sources of injection beam loss are discussed together with the contributing factors and various issues experienced in the first full year of LHC operation. Simulations are compared with measurement, and the implemented and planned mitigation measures and diagnostic improvements are described. An outlook for future LHC operation is given.

Presented at the 2nd International Particle Accelerator Conference (IPAC2011)
4-9 September 2011, San Sebastián, Spain

Geneva, Switzerland

November 2011

CONTROLLING BEAMLOSS AT INJECTION INTO THE LHC

B. Goddard, F. Alessio, W. Bartmann, P. Baudrenghien, V. Boccone, C. Bracco, M. Brugger, K. Cornelis, B. Dehning, E. del Busto, A. Di Mauro, L. Drosdal, W. Höfle, E. B. Holzer, R. Jacobsson, V. Kain, M. Meddahi, V. Mertens, A. Nordt, J. Uythoven, D. Valuch, S. Weisz, CERN, Geneva, Switzerland

R.B. Appleby, University of Manchester and the Cockcroft Institute, UK

Abstract

Losses at injection into the superconducting LHC can adversely affect the machine performance in several important ways. The high injected beam intensity and energy mean that precautions must be taken against damage and quenches, including collimators placed close to the beam in the injection regions. Clean injection is essential, to avoid spurious signals on the sensitive beam loss monitoring system which will trigger beam dumps. In addition, the use of the two injection insertions to house downstream high energy physics experiments brings constraints on permitted beam loss levels. In this paper the sources of injection beam loss are discussed together with the contributing factors and various issues experienced in the first full year of LHC operation. Simulations are compared with measurement, and the implemented and planned mitigation measures and diagnostic improvements are described. An outlook for future LHC operation is given.

INJECTION INTO LHC

After transfer through the ~3 km TI 2 and TI 8, injection into LHC takes place in the experimental straight sections IR2 and IR8, using Lambertson septa MSI and fast kicker magnets MKI. To protect against synchronisation or other kicker errors an absorber block TDI is 90 degrees in phase downstream of the MKI. There are also two auxiliary TCLI collimators. The injection is very close to the LHC experiments ALICE and LHCb, and cross-talk with some of the delicate experimental subsystems is a serious concern.

The LHC is filled by 10 injections per beam. The MKI kicker pulse length is 8 μs, with a rise time of 1 μs and a fall time of 2.5 μs. Filling each ring takes 8 minutes with the SPS supplying interleaved beams to other facilities.

The apertures in the injection region are very small, in particular at the MSI and the MKI. The physical radius of the protective mask immediately upstream of the MSI is 10 mm, from which orbit and alignment tolerances need to be subtracted. For the circulating beam the MSI provides 7.3 σ aperture in N1 notation [1]. The MKI has a ceramic chamber with 39 mm ID. The energy in each injected beam is about 2 MJ, which is about a factor 10 above that required to damage accelerator components in the event of direct impact. To protect the small apertures in the injection regions, and also to prevent injection into the LHC of beams with large oscillations, protection devices TCDI are set around the injected beam trajectory. There are three devices per plane, spaced at 60 degrees in betatron phases, with settings of ±4.5 σ [2]. The TCDIs are two-jawed movable devices, with 1.2 m of Carbon to intercept the beam.

The beam loss monitoring BLM system for the LHC ring is designed to protect the machine against quenches and damage from beam loss [3]. The location near the superconducting elements of some of the TCDI protection devices, together with the TDI and TCLIs, means that there is very strong cross-talk between injection losses and the beam loss signals. Although the loss limits are well below quench levels, the BLMs frequently trigger, reducing machine availability.

TRANSVERSE LOSSES ON TRANSFER LINE COLLIMATORS

The nominal emittance for the LHC beam transfer and injection is 3.5 μm. The emittances injected into the LHC in the years 2010 and 2011 have slowly been reduced from about 3.0 μm to below 2.0 μm, the latter made possible by the change to double-batch injection with the 50 ns beam. The larger emittances required transverse blowup in the SPS, which resulted in non-Gaussian tails visible as losses on the TCDIs in the transfer lines [4]. With the reduction in emittance, the specific losses per proton injected have decreased, despite the increase in injected intensity, Fig. 1.

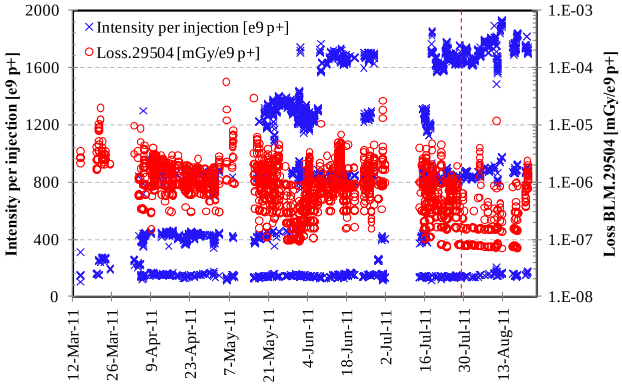

Figure 1: Normalised beamloss at TI 2 TCDI.29504 collimator in 2011. The trend is downward: the step in July coincides with stopping transverse blowup in SPS.

After increasing the thresholds of the LHC BLMs, the next mitigation was to add local shielding between the critical TCDIs and the LHC elements. This shielding was optimised after a series of FLUKA simulations [5]. The reduction factor in beam loss per proton at the affected BLMs was expected to be a factor 3, and was measured in MD [6] to be slightly less, at around a factor 2-2.5, Fig. 2.

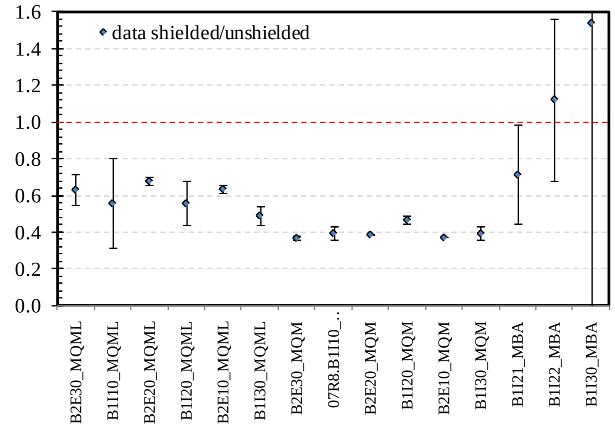

Figure 2: Measured reduction in beam loss signal with shielding at TCDIs in the injection region P8, for Beam 2.

The key factors for losses on TCDIs are transverse blowup and scraping of tails in the SPS – the effect of switching off this blowup on 24th July is clearly visible as a downward step in losses per p+ in Fig. 1. The effect of the SPS scraping was investigated during dedicated MD [7], where scraping was found to be essential, even for 2.0 µm beams, to reduce the losses on TCDIs. Scraping provides a factor of about 10 improvement, Figure 3. In addition, the MD showed that injection of 3.5 µm emittance beams is possible with similar loss levels to 2 µm, an important result for future LHC operation.

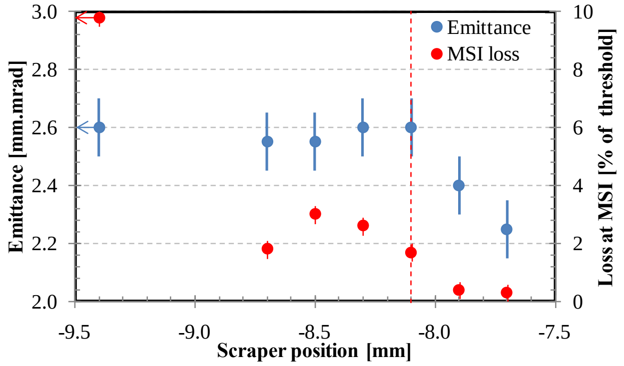

Figure 3. Beam loss on MSI and emittance as a function of horizontal SPS scraper setting. The operational setting reduces injection losses by about a factor 10.

In addition to the beam size and tails, trajectory instability in the transfer lines can increase losses on TCDIs. The stability of the lines has been analysed in detail, reported in [8]; the main conclusion is that the main source of errors are shot-to-shot variations in the horizontal plane, likely due to extraction septa in the SPS. The lines need correcting about once per week, which gives enough operational margin for injection beamlosses. Importantly, this is sufficient to run without repeated setup of the TCDI collimators, despite their close settings of ±4.5 σ – up to September 2011 the lines have operated with the same TCDI settings for the full year. This is crucial for operation since setting up (and validation) of the TCDI positions takes at least 8 hours per transfer line.

The devices in the horizontal plane with large normalised dispersion D/√β experience largest losses, complicated by downstream jaws intercepting secondary showers and scattered primaries. One or two horizontal TCDIs per line are most critical in terms of alignment. In MD, increasing the bunch length at SPS extraction from 1.5 to 2.2 ns doubled the losses on these collimators [7].

LONGITUDINAL LOSSES ON TRANSFER LINE AND LHC COLLIMATORS

For the injected beam, the momentum spread and presence of satellites or uncaptured beam increases the losses at the TCDIs, and the latter two effects also cause beam loss at the TDIs, as beam is swept across the jaws.

For the LHC, uncaptured circulating beam leads to beam loss on the TDI when the injection kicker pulses; this was a major problem in 2010 operation [9], leading to many beam dumps from the LHC BLMs and from the Beam Condition Monitors in ALICE and LHCb.

The first mitigation was to increase BLM thresholds to avoid dumping, especially on TCTVB collimators. FLUKA simulations were performed to understand energy deposition and to optimise shielding design. The results agree with the measured beam loss between the TDI and the inner triplet, Fig. 4, and a 1 m shield will reduce the signal in triplet BLMs by about 40%, Fig. 5.

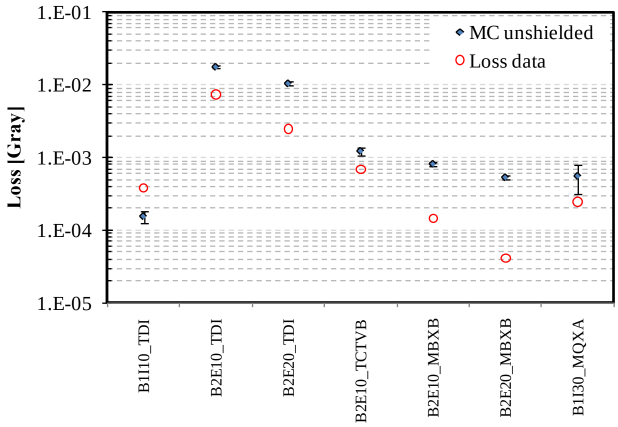

Figure 4. Comparison of FLUKA simulation and measured BLM response for beam loss on the TDI in P8.

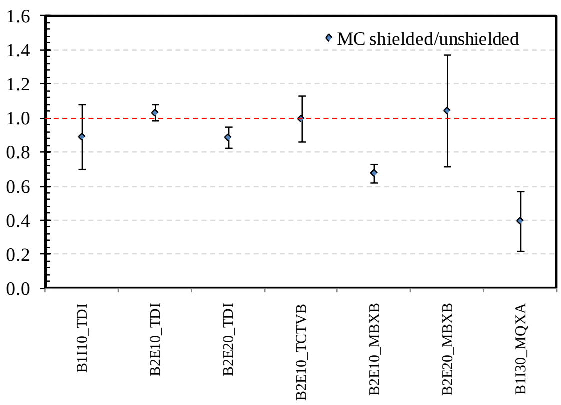

Figure 5. Expected reduction in BLM signal for shielding downstream of the TDI in P8.

The mitigations against losses from uncaptured beam in the LHC are the increased RF capture voltage [10], and the deployment at injection in regular operation of the transverse damper for both abort gap cleaning AGC and a new mode of "injection gap cleaning" IGC [11]. The damper excitation is gated such as to clean away uncaptured beam which would otherwise drift around the ring and be swept onto the TDI by the MKI pulse. The combination of AGC and IGC is effective, and reduces the beam loss on the TDI by a factor of about 10, Fig. 6.

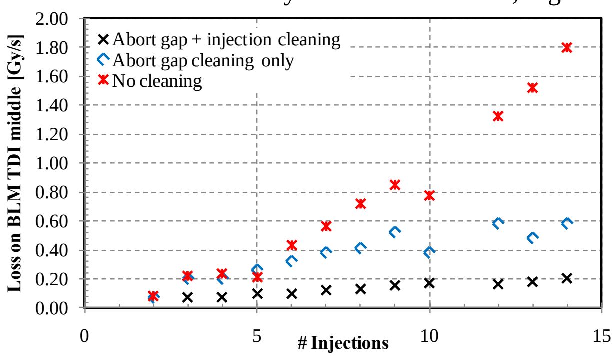

Figure 6. Injection losses at TDI with AGC and IGC.

Improvements in the online data analysis and diagnostics have been made. A comprehensive online post-mortem and surveillance system of injection quality checks IQC [12] surveys beam losses in the LHC and transfer lines, injection oscillations, kicker parameters, filling pattern and injected intensity. The IQC blocks injection when parameters are out of tolerance, and provides a full playback of all injection events. The diagnostic hardware has been improved with the addition of very fast BLMs at the TDIs in the LHC and the extraction elements in the SPS, with ns time resolution. The time resolution of these monitors will help distinguish between uncaptured beam from the SPS, satellites, and uncaptured beam in LHC.

INJECTION KICKER FAILURES

During 2011 several failures have occurred on the MKI, leading to beam impacting the TDI. In two cases the beam has grazed the TDI surface, which is the worst case in terms of energy transmitted into the LHC. In the first case, 36 nominal intensity bunches grazed the TDI in P8, which led to about 10 magnets quenching and losses through the arc 78, Fig. 7.

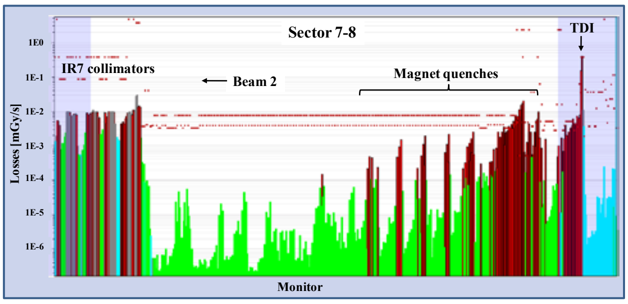

Figure 7. Losses in P8 and sector 78 after MKI flashover. 11 LHC magnets quenched with 36 bunches grazing TDI.

In the second case, 144 bunches grazed the TDI in P2, but only three magnets quenched. Between these events the TDI jaws were realigned with a better technique [6], and the auxiliary TCLI collimators were retracted by two sigmas, because of concerns about the effects on the downstream Q6 magnets of showers from primary beam impact on these collimators. During this second event the ALICE detector was badly affected with the loss of some calibration channels – studies are ongoing to reduce the detector sensitivity to these losses.

An accurate setup of the TDI jaws is extremely important for machine protection, in the light of the occurrence of several injection kicker failures per year with high injected intensity – the fact that no machine damage occurred with a worst-case failure and half-nominal injected intensity is encouraging.

SUMMARY AND CONCLUSION

The high sensitivity of the LHC BLMs, coupled with the presence in the injection regions of protection devices with jaws very close to the beam, mean that controlling injection losses is important for LHC operation. The machine availability has been improved in 2011 by a series of mitigation measures, including SPS scraping, smaller emittance, better trajectory control, better diagnostics, better RF capture and regular line steering. The utility of the injection protection systems has been demonstrated several times with beam impact on the TDI, which has led to magnet quenches but no LHC damage.

The intensity injected into the LHC will increase in the coming years by at least a factor two, and very probably more with the upgrade of the injectors. Continued effort on injection loss mitigation is required – in addition to the methods described above, other possibilities being actively explored are the relocation of the most critical TCDI collimators to locations where there is less cross-talk, and the addition of a mechanism for the BLMs to temporarily ignore the high losses for a short (ms) time after injection. Injection will remain a critical area for LHC, in terms of availability and machine protection.

REFERENCES

[1] J.B.Jeanneret, R.Ostojic, CERN-LHC-Note-111.
[2] V.Kain, CERN-THESIS-2005-047.
[3] E.B.Holzer et al., CERN-AB-2006-009.
[4] B.Goddard et al., CERN-ATS-Note-2010-034.
[5] V.Boccone, private communication.
[6] C.Bracco et al., CERN-ATS-Note-2011-040.
[7] V.Kain et al., CERN-ATS-Note-2011-063.
[8] V.Kain et al., 2nd International Particle Accel. Conf. IPAC, San Sebastian, Spain 2011.
[9] V.Kain et al., Proc. Chamonix 2011, Workshop on LHC Performance, pp.51-55, 2011.
[10] P.Baudrenghien, 2nd Int. Particle Accel. Conf. IPAC, San Sebastian, Spain 2011.
[11] E.Gianfelice et al., CERN-ATS-Note-2010-050.
[12] V.Kain et al., Proc. 1st International Particle Accel. Conf. IPAC, Kyoto, Japan, pp. 1672-1674, 2010.