

LHC INJECTION AND EXTRACTION LOSSES

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Abstract

Single pass losses at injection into LHC and extraction to the beam dump are distinguished regarding their origin. Potential mitigations as local shielding, injection gap cleaning or temporarily blinding the BLM system at injection are discussed. The limits for injecting higher intensities in 2011 due to losses above BLM thresholds together with the risk for quenching magnets are extrapolated from observed loss levels in 2010 operation.

OBSERVED LOSS LEVELS AT INJECTION

Injection is the main contributor in the turn-around time as shown in [1]. Beam loss levels close to the BLM dump thresholds can lead to significant delays in preparing the machine for stable beams. In Table 1 the main reasons for injection losses are listed. Collimators (TCDI) in the transfer lines TI 2 and TI 8 create particle showers which are detected by ring BLMs in the common parts of LHC and transfer line tunnels. These showers coming from the out-

Table 1: List of injection losses by cause and main elements affected.

Loss reason	Loss position
TCDI cutting transv. beam tails	Loss shower on cold elements: Q6, Q7, Q8, MSI
Uncaptured beam SPS	TDI upper jaw with shower on: TCTVB, MX, MBX, TCLI
Uncaptured beam LHC	TDI lower jaw, TCTVB, MQX, MBX, TCLI
Overinjection	TDI lower jaw, TCTVB, MQX, MBX,...
MKI failure	TDI upper jaw,...

side do not present any harm to LHC magnets since they are protected by the cryostats, however, a beam dump is triggered if the loss level exceeds the BLM thresholds. Monitors on the elements Q6, Q7, Q8 and the MSI are most affected. Another loss reason is uncaptured beam from both, the SPS and the LHC, which does not see the full MKI kick and therefore gets spread onto the upper (uncaptured beam SPS) or lower (uncaptured LHC beam) TDI jaws. Particle showers are created and detected mainly by the monitors of TCTVB, MQX, MBX, TCLI and the experiments ALICE and LHCb.

The lower TDI jaw is also used as a beam stopper when over-injecting a high-intensity bunch onto the low-intensity probe beam.

In case of a missing MKI kick the whole injected beam is dumped on the upper TDI jaw. Figures 1-4 show measured loss levels from bunch train injections with 8, 16, 24 and 48 bunches. In Fig. 1, a bad injection with 16 bunches (magenta curve) sticks out with 10% of the dump threshold at the MSIB and 6% at Q8 and Q5. The 24 bunch injection (yellow curve) gives 12% at the MBX and 3% at the MSIB. For B2, Fig. 2, losses from the TCDI shower

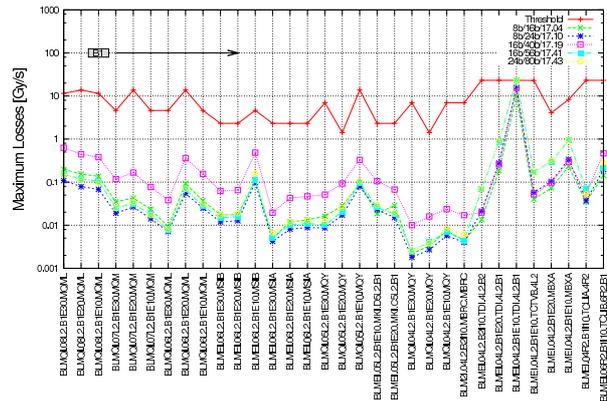


Figure 1: B1 injection losses with bunch train injections of 8, 16 and 24 bunches. 8b/16b/17.04 denotes 8 bunches injected at 17:04 with 16 bunches circulating. Data from 23rd, October 2010.

reach 5% of the dump threshold at Q7 and losses from the TDI shower 4% at MBX, otherwise the loss level is less than 1%. Figure 3 shows the loss level for the first 48

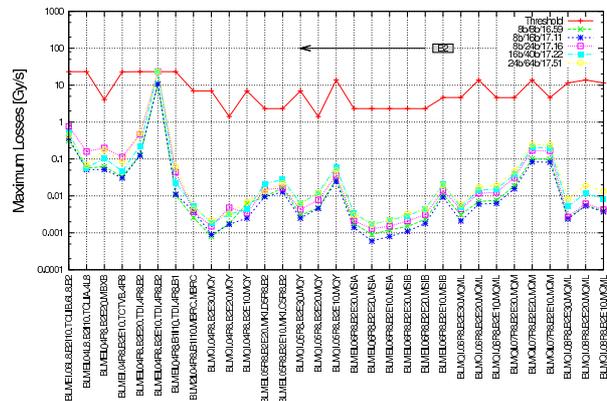


Figure 2: B2 injection losses with bunch train injections of 8, 16 and 24 bunches. Data from 23rd, October 2010.

bunch train injection. The loss peaks reach 23% at MSIB, 20% at MBX and 15% at Q8. These values have to be taken with caution though, since there was not much time spent in optimising beams or injection. For B2, Fig. 4, the loss level amounts to 24% at Q7, 8% at TCLIB and 5% at the MKI. Figure 5 shows the Post Mortem analysis of an

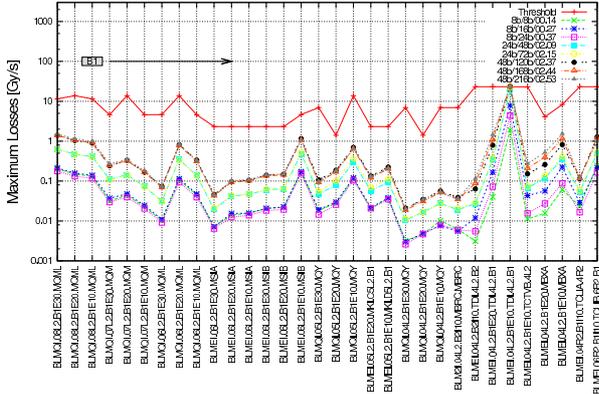


Figure 3: B1 injection losses with bunch train injections of 8, 24 and 48 bunches. There was not much time spent in optimising the injection. Data from 18th, November 2010

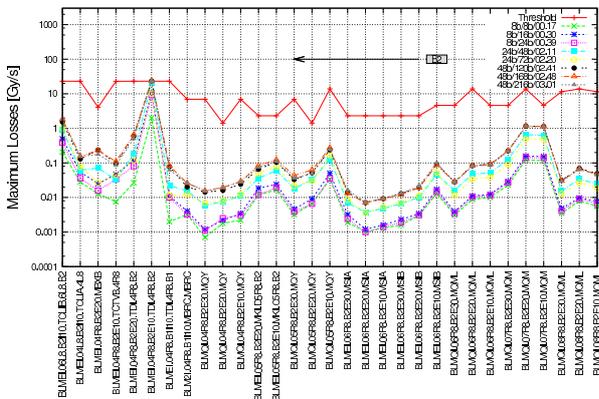


Figure 4: B2 injection losses with bunch train injections of 8, 24 and 48 bunches. There was not much time spent in optimising the injection. Data from 18th, November 2010

attempt to inject 32 bunches into the abort gap. The abort gap keeper prevented the MKI from firing and thus, the train of 32 bunches was directly dumped on the upper TDI jaw in P2 which is designed to withstand a full SPS batch of 288 bunches with nominal intensity. ALICE is prepared for the full batch impacting the TDI and could confirm their simulations with losses from TDI grazing tests.

EXPECTATIONS ON LOSS EVOLUTION

As injected beam intensity progression for 2011 are assumed 96 or 108 bunches for operation, possibly 144 bunches with 50 ns spacing for injection tests and maybe 25 ns bunch spacing injections for electron cloud studies. Another ingredient in the loss evolution is the intensity de-



Figure 5: Post mortem analysis of dumping 32 bunches on the upper TDI jaw in P2.

pendency of the uncaptured beam in the LHC. The present threshold of triggering the dump by BLMs has been measured on 30th, September 2010 and was found to be $1 \cdot 10^{10}$ protons per injection which corresponds to $3.3 \cdot 10^6$ protons per m [2]. The limit was originally assumed to be $2.6 \cdot 10^8$, thus the situation is expected to be worse by a factor 100 for the nominal bunch scheme.

The shower from TCDIs is assumed to increase linearly with the intensity increase per injection. In Table 2 the loss levels shown in Figures 1-4 are summarised in percent of the BLM dump threshold. The values shown in *italic* are expectations for future loss levels. The losses for 48 bunch injections do not follow the trend which is due to not optimising these injections. How do these injection losses limit

Table 2: Measured losses in % of dump threshold for B1/B2 up to 48 bunches per train, expected loss levels for 96 and 144 bunches are shown in *italic*.

Loss type	8b	16b	24b	48b	96b	144b
TCDI shower	1/2	3/5	4/6	23/24	< 50?	< 75?
Uncapt. beam	4/2	12/3	12/5	20/8	< 40?	< 60?

the performance reach? MKI failure and overinjection need interlocking and a good procedure. Transverse losses coming from the TCDIs and detected by LHC BLMs will increase by roughly a factor 2 and should therefore not limit 2011 operation. The factor 6 intensity increase - when going to the nominal scheme - needs loss reduction. The situation is more severe for the uncaptured beam in the LHC. Already for 2011 operation injection cleaning is probably needed. The factor 100 loss increase for the full nominal injection scheme will demand several mitigation techniques which are presented in the following section.

MITIGATION TECHNIQUES

Following mitigation techniques are considered to overcome transverse losses from the TCDI collimators:

- Local shielding between TCDIs and LHC
- Beam scraping in the SPS
- Opening TCDIs (discussed in detail in [3])
- BLM sunglasses (temporal inhibit of BLM channels)

Losses due to uncaptured beam shall be counteracted by:

- Local shielding downstream of TDI
- Minimisation of capture losses
- Injection and abort gap cleaning
- Carefully monitoring beam quality in injectors (transverse beam size and shape, bunch length, satellites)
- BLM sunglasses

Local shielding of TCDI collimators

Three problematic TCDIs have been spotted, in TI 2 the vertical collimator TCDIV.29234 and the horizontal one TCDIH.29205 and in TI 8 the horizontal collimator TCDIH.87904. Figure 6 shows the shielding concept for TI2 based on results from FLUKA simulations and Fig. 7 shows the shielding blocks installed at the technical stop in the end of 2010.

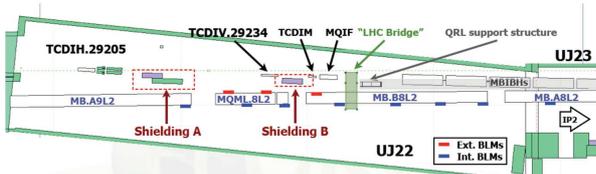


Figure 6: Shielding concept for TI 2 based on FLUKA simulations.



Figure 7: Shielding blocks installed in UJ22. On the right the incoming TI 2 line, upstream view.

Figure 8 illustrates the spatial constraints for shielding installations. From simulations the loss reduction by shielding is expected to be a factor 8 at TCDIV.29234, a factor 5 at TCDIH.29205 and a factor 4 at TCDIH.87904.



Figure 8: Limited space for shielding at TCDIH.87904.

Beam scraping in the SPS

Figures 9 and 10 show measurements of the transverse beam distribution in the transfer lines with blue lines indicating the collimator jaw position. The measurement with-

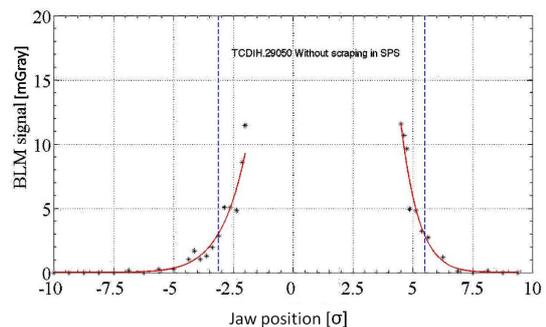


Figure 9: Transverse beam tails at TCDIH.29050 without scraping in the SPS, the blue lines indicate the position of the collimator jaws.

out scraping in the SPS, Fig. 9, results in a beam interception of up to 2% of the total intensity. The number of

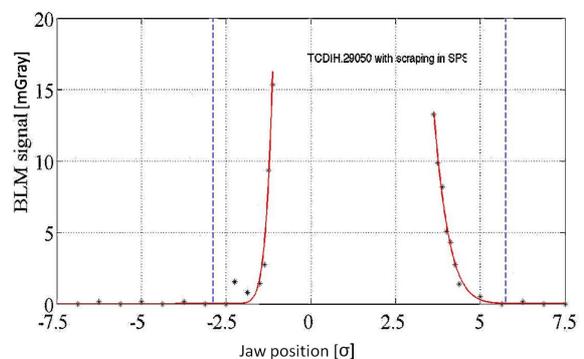


Figure 10: Transverse beam tails at TCDIH.29050 with scraping in the SPS, the blue lines indicate the position of the collimator jaws.

particles lost on the TCDIs can be reduced using scraping

in the SPS by a factor ~ 1000 , Fig. 10.

BLM sunglasses

Since the major part of the BLM loss levels described above are caused by particle showers from outside the cryostat, and thus not harmful to LHC magnets, it is considered to investigate possible changes of the BLM system itself. Adding complexity to the BLM system or its input to the interlock system has to be carefully evaluated regarding consequences to machine protection. The term "sunglasses" might allude to a signal attenuation but should be rather understood as a temporal inhibit of BLM channels. Following options are considered:

1. Update of all LHC BLMs with new functionality, but only BLMs in injection regions to receive triggers \rightarrow **impact on all LHC BLMs**
2. Add/separate new BLM system with new functionality, keep all old monitors for acquisition (increase/disable thresholds at 450 GeV) \rightarrow **additional new BLM system**
3. Rearrange/add new BLM system to enter a new BIC with masking capability, with masking of interlock signal triggered by pre-pulse \rightarrow **additional new BIC system**
4. Reroute affected BLMs to BIC channel, and introduce a timing system triggered blank of the signal for these channels only \rightarrow **best compromise, no changes to BLM or BIC systems (at FPGA levels)**

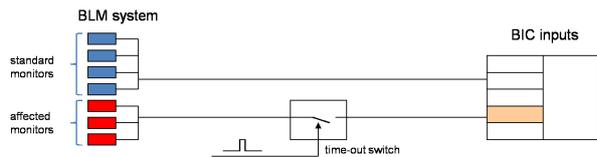


Figure 11: Sketch of option 4 for the BLM sunglasses with a time-out switch.

Local shielding downstream of TDI

Simulation show that a 2 m concrete block downstream of the TDI gives a loss reduction by a factor 3 for the triplet monitors while only a 30% reduction is reached for the TCTVB collimator. Here, either more sophisticated shielding or increasing the BLM threshold is required.

Minimisation of capture losses

It is not expected to improve the capture losses in the injectors. An RF voltage reduction as used for ions was found to create significant satellite population and it is not planned to be used for protons.

Injection gap cleaning

In analogon to abort gap cleaning it is foreseen to resonantly excite and thereby remove the unbunched particles in the injection kicker gap [4]. One method uses an excitation pulse after the last injected bunch train. This pulse together with the pulse from the abort gap cleaning confines the debunching particles and is therefore called *barrier method*. Here, the cleaning should be kept as long as possible while the injection part length is not important. Figure 12 shows results from measurements with abort and injection gap cleaning. For later injections the losses mea-

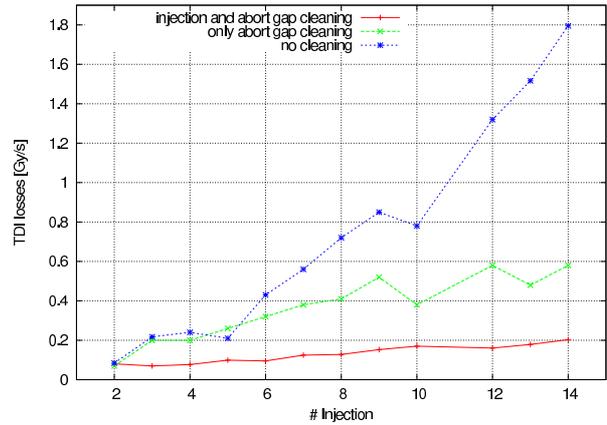


Figure 12: Reduction of losses at the TDI for a series of injections without cleaning (blue), with only abort gap cleaning (green) and with abort and injection gap cleaning (red).

sured on the TDI can be reduced by a factor 3 with abort gap cleaning only and a factor 9 with both cleaning pulses. Another method, called injection gap cleaning, uses a pulse located at the position of the next injected bunch train. For operational reasons this method will be used for commissioning in 2011.

Monitoring beam quality of injectors

In order to more sensitively detect satellites coming from the SPS, the according BQM thresholds have been tightened from 20% to 3-4% where 100% are given by the bunch with the highest wall current monitor signal. The diagnostics of the 800 MHz RF system in the SPS and the 80 MHz system in the PS is being improved [5]. Diagnostics is also installed to monitor the SPS scraping. At SPS extraction and LHC injection it is foreseen to install fast BLMs to distinguish between uncaptured beam coming from the SPS or LHC.

EXTRACTION LOSSES

The most critical situation extractionwise are asynchronous dumps with the risk to quench Q4 and Q5 in P6. Debunched beam dumps at 450 GeV show low losses with a factor 3 above the dump threshold for Q4. These were carefully tested with different bump heights and frequency offsets. Figure 13 shows the loss pattern in P6 for a dump

after 90 s debunching time with collisions in P1 and P5 at 3.5 TeV. The beam was intentionally steered away from the TCDQ to simulate the worst case scenario orbitwise. The losses on Q4 and Q5 are a factor 180 and 30, respectively, above the BLM dump threshold. These losses are mainly showers from TCDQ which does not allow to draw conclusions on the quench limit. The BLM thresholds are set to 1/3 of the assumed quench limit. From simulations a loss level of 50 % of the dump threshold is expected on Q4 and Q5. Figure 14 shows a similar loss pattern for a debunched



Figure 13: Post mortem analysis of debunched beam dump with collision settings.

dump (90 s) with end of ramp settings, energy 3.5 TeV, crossing angle of $170 \mu\text{rad}$, β^* of 11.0/10.0 m (P1/P5). The losses are a factor 230 and 40 above the dump threshold for Q4 and Q5, also losses on the dump septum MSD. The leakage to the TCT in P5 for all dumps is $\sim 1 \cdot 10^{-3}$.



Figure 14: Post mortem analysis of debunched beam dump with end of ramp settings.

INJECTION COMMISSIONING

The following time line is assumed to commission the injection systems in 2011:

- Injection set-up

– 2 shifts

- First injection protection set-up with validation

– 1 shift for TCDI set-up

– 0.5 shifts for TDI/TCLI set-up

– 1 shift for TCDI validation checks

– 0.5 shifts for MKI failure validation checks

- Protection Maintenance

– 1 shift every 2-4 weeks for TL steering or TCDI re-centering after trajectory change or increased TL loss levels

- Injection cleaning to be operational

– 2-3 shifts

- Analysis of regular operational data

CONCLUSION

The foreseen increase of a factor 2 in number of bunches per injection for 2011 operation looks feasible regarding injection losses. Injection tests with higher intensities (144 bunches per injection) might need mitigation of TL shower and capture losses. Extraction losses are dominated by the shower from TCDQ and thus do not allow to draw conclusions on the quench limit. Loss mitigation at injection is necessary to go beyond the operational intensity scope. Techniques already deployed are scraping in the SPS and partially shielding in TI 2. There is heavier shielding installed in TI 2 which has not seen beam yet and further shielding planned for TI 8 and the TDIs in P2 and P8. There is more diagnostics being added in the injectors to monitor the beam quality. Injection gap cleaning needs to be commissioned to be operational in 2011 and BLM sunglasses are in the design phase.

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