LHC INJECTION

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Abstract

Losses at injection will be distinguished between the two main loss causes, transverse loss shower from the transfer line collimators and longitudinal loss shower due to satellites which are placed on the kicker field rise and thus improperly kicked into the machine. The dependence of this losses on the different beam types, TL stability and injector performance will be reviewed. A status and potential improvements of the injection quality diagnostics and new values for the SPS and LHC injection kicker rise times will be suggested.

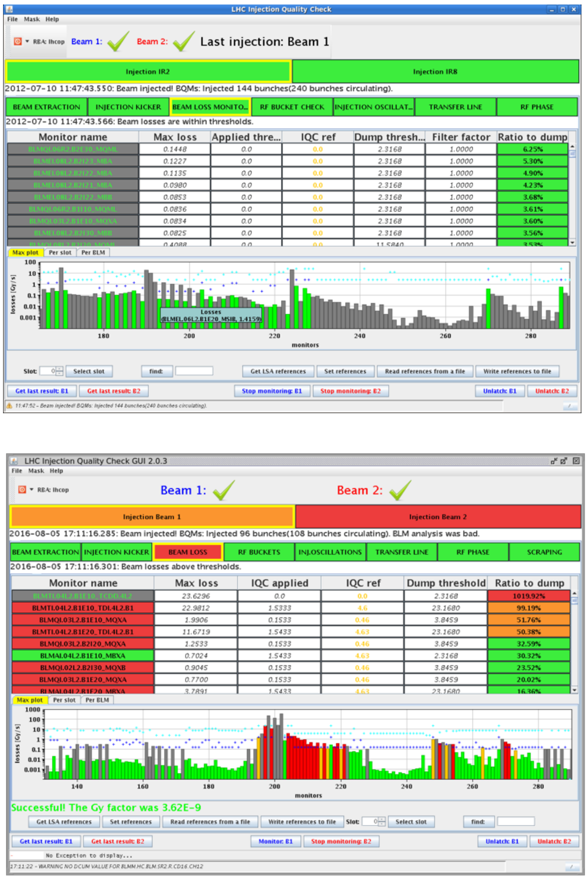
INJECTION LOSSES

Injection losses during run 1 were dominated by showers from the transfer lines TI 2 and TI 8 onto the ring beam loss monitors (BLM) of the matching regions in P2 and P8, Fig. 1. These showers were originating from the transfer line collimators (TCDI) and impacting the ionization chambers in the tunnel area common to ring and transfer lines from the outside, without attenuation from the cryostat. This loss scenario was mitigated by installation of additional shielding, opening the TCDIs from 4.5 to 5 σ and by stabilising the transfer line trajectory with filters on the SPS extraction septa power converters. In addition, a temporary inhibit of the interlock input from the BLM system was developed. This inhibit possibility is implemented but remains to be fully validated with trains of 288 bunches, which were never injected in run 2.

Since Long Shutdown 1 (LS1), the injection losses were dominated by particles which were outside the nominal filling pattern and therefore filling the gaps used for the SPS extraction and LHC injection kickers to rise and fall their magnetic fields. The particles in these gaps were sprayed on protection devices at SPS extraction (TPSG), in the transfer line (TCDI), onto the injection dump (TDI), and onto the collimators in P7. These losses can be well distinguished with the help of diamond detectors, Fig. 2.

Injection losses in 2016

The high intensity proton operation in 2016 can be separated in two periods. The first period until September is characterized by swapping between different beam types or machine configurations of which both have significant impact on injection loss levels. In the second period from September until the ion run a stable period of luminosity production with low injection loss levels was observed which allows to estimate loss levels for 2017. Transverse injection losses do not vary significantly during 2016 and the median loss level over the injection region is below 2% of the dump threshold. Also the maximum loss levels which are a factor 2-3 above the median provided a comfortable loss level to inject the beam. This was mainly due to the improved line stability and a trajectory reference which allowed for straightforward steering by the operators. The transverse



LHC Injection Quality Check

Last injection: Beam 1

2012-07-10 11:47:43.550: Beam injected! BQMs: Injected 144 bunches(240 bunches circulating).

2012-07-10 11:47:43.566: Beam losses are within thresholds.

Monitor name	Max loss	Applied thre...	IQC ref	Dump thresh...	Filter factor	Ratio to dump
BLMQI.06R2.B2E30_MQML	0.1448	0.0	0.0	2.3168	1.0000	6.25%
BLMEI.08L2.B2I23_MBA	0.1227	0.0	0.0	2.3168	1.0000	5.30%
BLMEI.08L2.B2I22_MBA	0.1135	0.0	0.0	2.3168	1.0000	4.90%
BLMEI.08L2.B2I21_MBA	0.0980	0.0	0.0	2.3168	1.0000	4.23%
BLMEI.08L2.B2I22_MBB	0.0853	0.0	0.0	2.3168	1.0000	3.68%
BLMQI.06R2.B1I10_MQML	0.0836	0.0	0.0	2.3168	1.0000	3.61%
BLMQI.03L2.B1E10_MQXA	0.0834	0.0	0.0	2.3168	1.0000	3.60%
BLMEI.08L2.B2I30_MBB	0.0825	0.0	0.0	2.3168	1.0000	3.56%
BLMQI.08L2.B2I20_MQML	0.4088	0.0	0.0	11.5840	1.0000	3.53%

11:47:52 - Beam injected! BQMs: Injected 144 bunches(240 bunches circulating).

LHC Injection Quality Check GUI 2.0.3

2016-08-05 17:11:16.285: Beam injected! BQMs: Injected 96 bunches(108 bunches circulating). BLM analysis was bad.

2016-08-05 17:11:16.301: Beam losses above thresholds.

Monitor name	Max loss	IQC applied	IQC ref	Dump threshold	Ratio to dump
BLMTI.04L2.B1E10_TCDD.4L2	23.6296	0.0	0.0	2.3168	1019.92%
BLMTI.04L2.B1E10_TDI.4L2.B1	22.9812	1.5333	4.6	23.1680	99.19%
BLMQI.03L2.B1E10_MQXA	1.9906	0.1533	0.46	3.8459	51.76%
BLMTI.04L2.B1E20_TDI.4L2.B1	11.6719	1.5433	4.63	23.1680	50.38%
BLMQI.03L2.B2I20_MQXA	1.2533	0.1533	0.46	3.8459	32.59%
BLMAI.04L2.B1E10_MBXA	0.7024	1.5433	4.63	2.3168	30.32%
BLMQI.02L2.B2I30_MQXB	0.9045	0.1533	0.46	3.8459	23.52%
BLMQI.03L2.B1E20_MQXA	0.7700	0.1533	0.46	3.8459	20.02%
BLMAI.04L2.B1E20_MBXA	3.7891	1.5433	4.63	23.1680	16.36%

Successful! The Gy factor was 3.62E-9

No Exception to display...

17:11:22 - WARNING NO DCUM VALUE FOR BLMM.HC.BLM.SR2.R.CD16.CH12

Figure 1: Injection losses in 2012 (top) were dominated by transverse showers, the losses in 2016 (bottom) by longitudinal losses on the TDI.

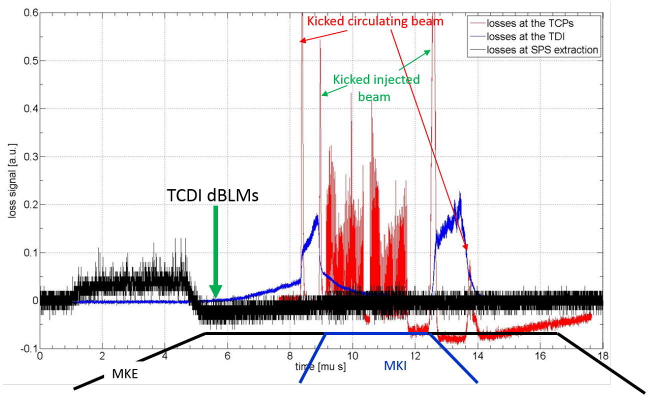


Figure 2: Injection losses as measured by the diamond detectors and kicker waveforms schematically.

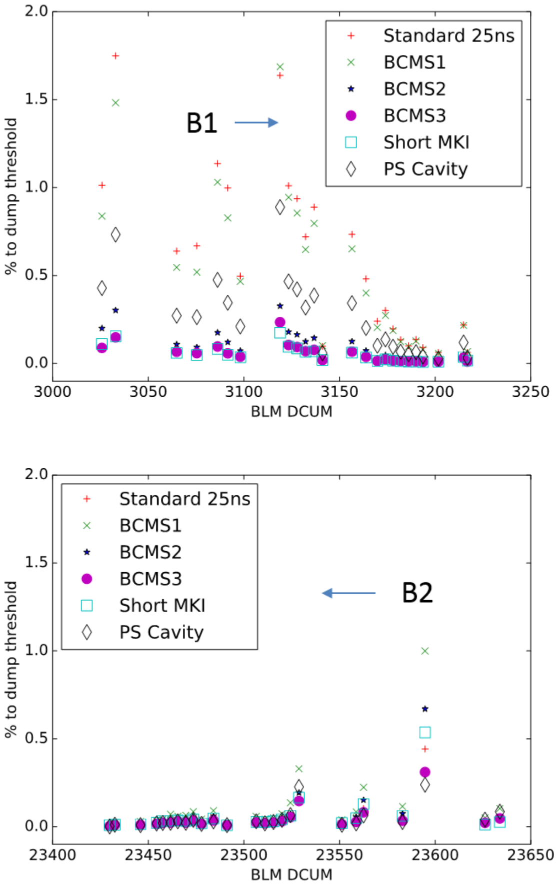


Figure 3: Median of transverse losses from TCDI shower onto the matching region of the ring for B1 (top) and B2 (bottom) for the period from September until the end of the run.

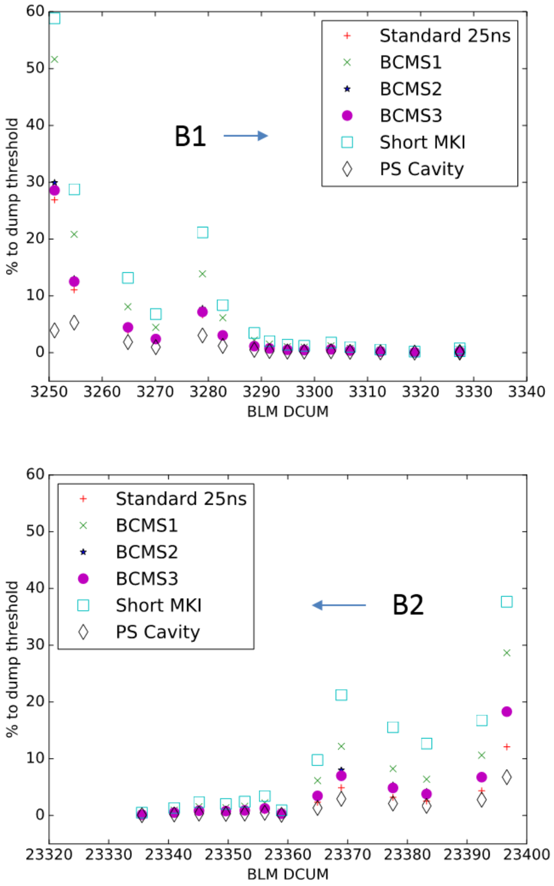


Figure 4: Median of longitudinal losses for B1 (top) and B2 (bottom) for the period until September. A significant loss reduction between the different running scenarios of up to a factor 10 can be seen. Courtesy C. Xu.

losses scale linearly with the total injected beam intensity, thus there are no issues expected with injection of 288 bunch trains from the SPS.

The longitudinal losses were much more sensitive to changes in beam types or machine configuration. Figure 4 shows the high loss level of up to 50-60% of dump threshold for the median for the period when changing from standard to BCMS beam and again after reducing the MKI flattop length. Such a high median level resulted in several beam dumps at injection when the beam quality was only slightly deteriorating. In order to maintain a high availability at injection, the loss levels should be below 20% of the dump threshold. A significant improvement of these loss levels was reached by improving the transfer from the PS to the SPS where a bunch rotation at PS extraction is required to reduce the bunch length from about 11 ns to 4 ns to fit into the 200 MHz rf structure of the SPS. Deployment of a second 40 MHz cavity during the bunch rotation improved the PS to SPS transfer such that losses at LHC injection were reduced by a factor 10.

The second period of the year from September until the end of the run showed a remarkable stability at low loss levels during injection, see Fig. 5. Only the ion run has strikingly high losses given the low intensity during the transfer of 28 bunches. The ion run setup suffered from several machine problems and therefore setup time was reduced which explains the poor injection performance compared to the high intensity proton run. While the absolute loss levels during the ion run were acceptable with median loss levels below 5%, the spread in loss levels between good and bad injections was much higher than for the late proton run. While the maximum losses for protons were a factor 2-3 above the median, the ion losses even caused several dumps at injection. Both, the proton and ion run show that it requires a phase of several fills until beam parameters at LHC injection are tuned and stable.

Injection quality check

The injection quality check tool IQC has become an orphan in the control room and was rarely used by the operators. Most likely this is caused by two problems. First, the tool is not maintained since LS1 and therefore adapting of internal

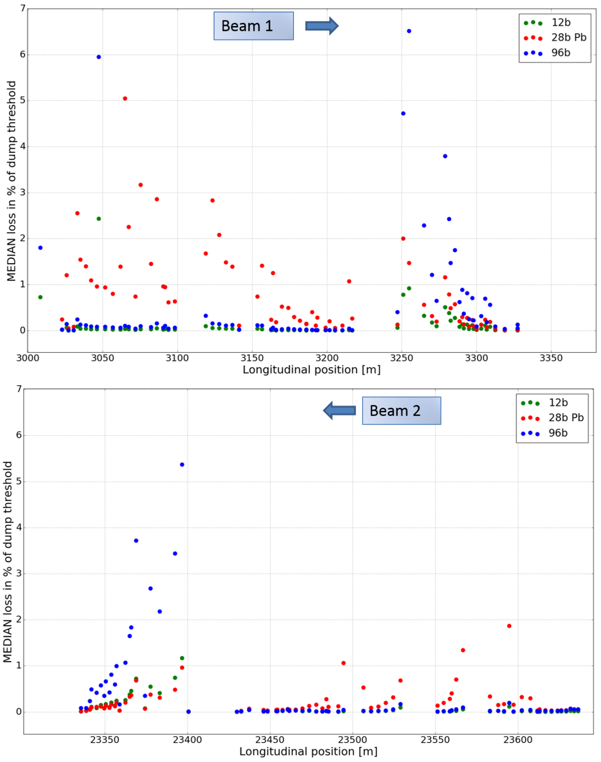


Figure 5: Injection losses for B1 (top) and B2 (bottom) for the period from September until the end of the run.

thresholds to beam types did not happen. This caused the monitoring tool to be on red alert for too many cases and it got ignored. The second problem is that that too much information is displayed.

As improvement it was suggested to simplify the internal thresholds and raise the level for red alert to become meaningful again. Transverse loss scaling can remain as it is, longitudinal thresholds should be adapted at the TDI to show green for losses less than 30% of dump threshold, orange between 30% and 50%, and red above 50%. If the loss level is above 50%, operation should be focussed to solve the cause of this loss level. The triplet magnets in the shower of the TDI should have colour limits of 10% between green and orange, and 25% between orange and red. Also, an overall reduction of the displayed information is suggested. These improvements are pending implementation by the operations group.

The above mentioned diamond loss monitors showed to be very useful in detecting where losses are caused, Fig. 2. During the development phase of these devices, their maintenance became very diverse over different groups. At this stage their functionality is mature enough to be added into online monitoring tools as already done in the SPS. It is suggested to also add a diamond tab in the IQC.

INJECTION PROCESS

Time spent at injection energy of LHC is a significant contributor to the turn-around-time. Stability of the injectors is not the cause because the orbit position at SPS extraction is very stable over several hours, Fig. 6. So in order to minimize the waiting time for beam while LHC is ready, it is suggested to automatize the preparation of the LHC in the injectors as soon as LHC starts its ramp down. In the injectors there could be an automatic fall-back to a prepared supercycle for LHC filling. A disadvantage is that several supercycle templates have to be maintained in parallel. The automatization should have almost no impact on non-LHC physics program compared to a dedicated LHC filling cycle. There is most likely some impact on MD programs in the injectors in case LHC is not ready for injection as expected. Daily tuning of the LHC beams is very valuable and lead to impressive beam quality at SPS extraction. This daily tuning is supported by a continuous improvement of beam quality monitoring in the injectors which should help for automatizing the LHC beam preparation process.

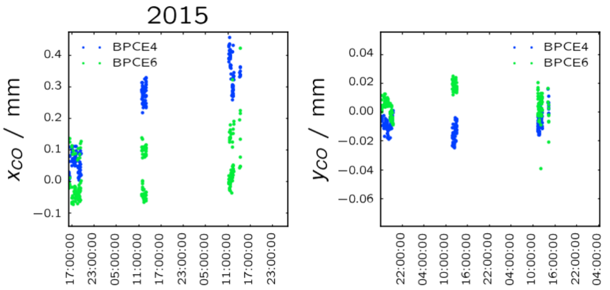


Figure 6: Closed orbit stability at SPS flattop in 2015.

SPS AND LHC BATCH SPACINGS

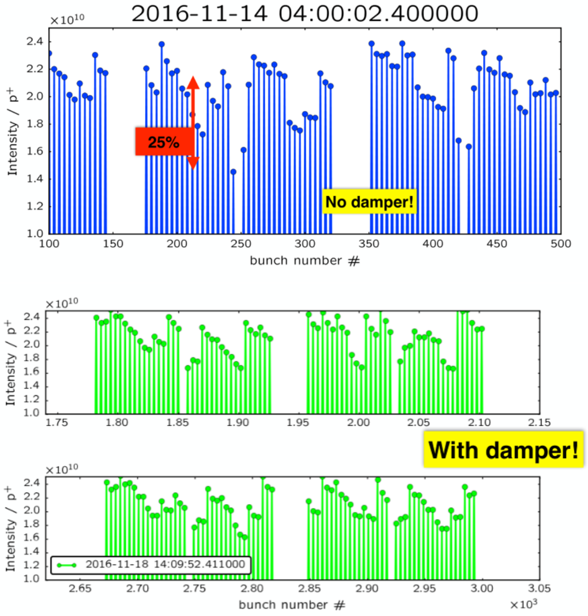


Figure 7: Intensity along the batch for 200 ns batch spacing without damper (top) and with damper (bottom).

The batch spacings for the SPS and LHC injection kickers have both been reduced for the ion run after performance measurements. The SPS batch spacing was first increased from the nominal 225 ns to 250 ns after load balancing between the different units of the injection kicker hardware which lead to a possible increase of the rise time. Tuning the timing of each unit allowed finally to reduce the batch spacing to 200 ns with an acceptable effect on the beam quality.

In Figure 7 the intensity loss of the first and last bunch of a batch is shown. Without damper this lead to an intensity loss of 25% while this effect is barely visible with the transverse damper working. The drawback of a 200 ns batch spacing is the higher sensitivity to synchronisation drifts of the injection kicker switches. This might require regular tuning in the SPS, which is however transparent to LHC beam time. The minimum required batch spacing in the LHC was measured with low intensity bunches and bunch trains, observing injection oscillations and emittance growth.

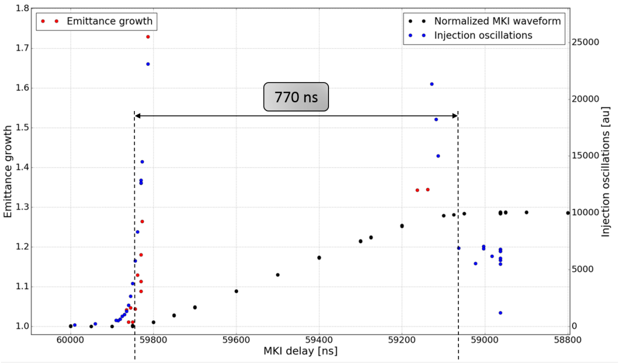


Figure 8: Emittance growth and injection oscillations as a function of the batch spacing at LHC injection.

By reducing the batch spacing from the nominal 900 ns to 800 ns increased injection oscillations for the last and first bunches of a train can be measured, Fig. 8. The growth of the emittance of these bunches is however well within the variation along a batch.

CONCLUSIONS

During run 2 injection losses were dominated by satellites being kicked onto the injection dump. These loss levels were reduced by a factor 10 by improving the PS to SPS transfer. After this improvement, the proton operation showed a very good loss performance at injection. There are no issues expected with injection of 288 bunches. Ion run losses were high compared to the proton run given the low intensities injected. This is mostly due to the limited time spent during setup.

The injection quality check identified the various loss scenarios but requires updates on its thresholds to be less sensitive and also to reduce its visual over-stimulation.

Diamond loss detectors are ready to migrate from being only available for experts to be included in the injection quality check application.

In order to reduce the idle time at injection it is suggested to fully automatize the LHC beam preparation in the injectors.

Batch spacings of 200ns for the SPS and 800 ns for the LHC injection kickers have been fully validated and should be deployed in 2017.