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LHC INJECTION LOSSES AND TRAJECTORIES DURING RUN 1 AND 2 AND OUTLOOK TO INJECTION OF HL-LHC BEAMS

W. Bartmann, C. Bracco, B. Goddard, F.M. Velotti, J. Wenninger, CERN, Geneva, Switzerland

Abstract

The LHC turn-around time is impacted by the control of injection losses and trajectories. While shot-to-shot trajectory variations dominated the injection efficiency during LHC Run 1, several improvements of hardware and operational settings allowed for a high rate of successful injections during Run 2. Injection losses and trajectories are analysed and presented for the high intensity proton runs, as well as for different beam types used from the injectors. Based on this analysis, an outlook is shown for the HL-LHC era, where double the bunch intensity will have to be injected.

EVOLUTION OF INJECTION LOSSES

The LHC injection quality monitoring includes several tens of loss monitors in the injection and primary collimator region to allow for an efficient analysis of each injection. The complete set of monitors is needed to detect issues which are specific to certain locations. When analysing the trend of injection losses over several years, many of these monitors give redundant information and can be reduced to the most representative ones distinguishing transverse and longitudinal losses. Transverse losses originate from transfer line collimators (TCDI) cutting the transverse beam tails and resulting in loss showers impacting beam loss monitors of the superconducting magnets in the ring from the outside. Longitudinal losses are caused by particles captured in buckets neighbouring the nominally filled buckets and transported until the injection in LHC. These satellite bunches are deflected by the rising and falling edges of the injection kicker and lost on the injection dump and primary collimators. For longitudinal losses the monitors on the injection dump TDI are most representative. Monitors on the matching quadrupoles Q8 for beam 1 (B1) and Q7 for B2 are the most sensitive to the transverse shower from the TCDIs. For B1 also the loss monitor on the dipole interconnect 7L2 (BOT) was included due to its particularly low dump thresholds and therefore relevance for injection efficiency.

In Fig. 1 the distribution of injection losses over dump threshold is shown for each production year of Run 1 (2011 and 2012) and Run 2 (2015-2018). Only injections with bunch trains of 12 bunches or more in periods of luminosity production with protons are taken into account. Periods of commissioning, machine development, special and ion runs are excluded from this analysis. The loss range is visualised for up to 120% of the dump threshold which cuts higher loss events. The ratios of loss events above 20% including the ones above 120% of the dump threshold are shown in Fig. 2.

In Fig. 1 it can be seen that injections in Run 1 were dominated by transverse losses which was the opposite in Run 2. Transverse losses dominate mostly in 2011, which

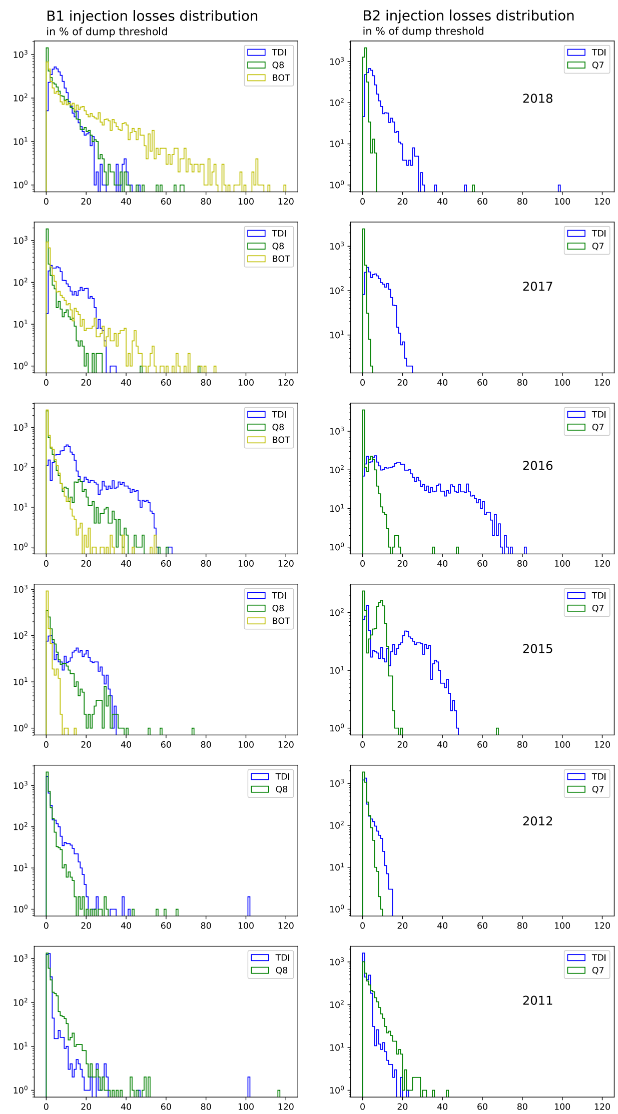

Figure 1: Distribution of injection losses for B1 (left column) and B2 (right column) from 2018 (top row) going backwards to Run 1. Transverse losses on Q8 and Q7 are shown in green, longitudinal losses on the TDI in blue.

was traced back to shot-to-shot variations of the injection line trajectory caused by power converter ripple of the SPS extraction septa [1]. This ripple was reduced by a factor 2 for the B1 extraction septum in the stop between 2011 and 2012 and improved in LS1 for the B2 extraction septum, which can be observed on the transverse losses of both lines.

From Run 1 to Run 2 transverse losses increase for B1, this is less pronounced for B2 which shows cleaner injections than B1 throughout both runs. The B1/B2 difference is most

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likely due to the different injection regions geometries and different sensitivity to showers from transfer line collimators.

Transverse losses scale almost linearly with the injected intensity, but there was little variation of the injected intensity from 2011 to 2018. The number of injected bunches stayed relatively constant at a maximum of 144 bunches per injection in production fills (maximum of 96 bunches per injection in 2016 due to the SPS beam dump limit) and the average bunch intensity stabilised along Run 2 at around $1.1 - 1.2 \cdot 10^{11}$ protons.

A bigger impact on losses than from the intensity is coming from different beam types. This can clearly be seen in the longitudinal losses on the TDI which strikingly increase between Run 1 and Run 2. The biggest change here was replacing the standard beam production in the PS by the BCMS scheme (batch compression and merging scheme) [2] which provides beams with significantly smaller emittances than the standard scheme. Due to its superior luminosity performance the BCMS beam was adopted for Run 2 operations. This beam scheme requires complicated RF gymnastics in the PS leading to increased particle population in empty buckets. These particles are mis-kicked by the LHC injection kicker rise or not kicked at all and lost on the TDI. Particles causing these losses are in the order of several 10^9, a loss level which is difficult to measure in the injector chain and while not being a machine protection concern in LHC at 450 GeV, it can reduce the machine availability during injection by triggering unnecessary beam dumps.

A widening to higher values of the longitudinal losses distribution can be seen between 2015 and 2016, more pronounced for B2 than B1. This is due to the different SPS extraction kicker configurations. The system for B2 was still configured for a fast-risetime double-extraction to CNGS and therefore a large part of the satellites was mis-kicked and lost already at SPS extraction. During the year end technical stop between 2015 and 2016 the B2 extraction kicker system was re-configured with magnets in series and terminated to ground, allowing to remove one magnet and thus reducing the machine impedance. This modification rendered a system with slower rise and fall times and a longer waveform, similar to the B1 system, which caused more of the satellites to be transferred to LHC injection and be lost on the TDI.

There were several mitigations to cure these satellite losses: reducing as much as possible the PS extraction kicker flattop, shortening the SPS flat-bottom length, cleaning the beam with the SPS tune kicker and improving the bunch rotation at PS extraction with the help of a second (spare) 40 MHz rf cavity [3]. The latter proved to have the biggest impact and explains - at least to a big extent - the reduction of longitudinal losses from 2017 onwards.

Another contribution to increasing longitudinal loss levels between Run 1 and 2 was the shortening of the injection kicker waveform length and the reduction of the inter-batch spacing in the filling scheme. A longer kicker waveform allows to inject the highest intensity satellites which are located in buckets neighbouring the train cleanly into the machine. Apart from avoiding to stress the hardware, a

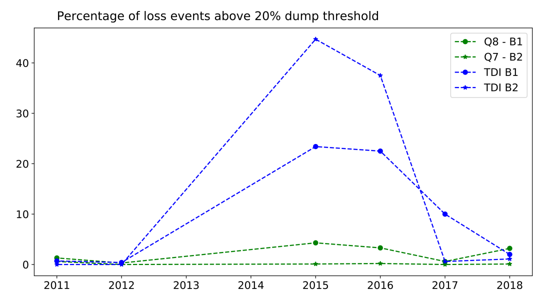

Figure 2: Percentage of injections with losses above 20% of the dump threshold, longitudinal losses in blue, transverse losses in green.

waveform reduced to the injected train length allowed also injecting more bunches in the machine. The reduced batch spacings required placing the first bunch as close as possible to the rising edge of the kicker which also caused more satellites being lost in Run 2 compared to Run 1.

EVOLUTION OF INJECTION TRAJECTORIES

Careful control of injection trajectories and oscillations into the ring is important for a safe beam transfer and minimum possible emittance growth due to filamentation. Typical injection oscillations of around 0.5 mm peak-to-peak are well below the specification of the transverse damper system and can be efficiently damped without any measurable effect on the transverse emittance. Several active and passive systems limit the impact of large amplitude oscillations into the ring aperture. Thus, reducing machine activation and optimising the machine availability is the main reason to steer the beams with as little as possible losses into the ring. The aperture bottlenecks to steer the beam are three transfer line collimators per plane limiting the beam transversely to 5 σ of nominal beam size from the reference trajectory. The reference trajectory is set up in the beginning of a year after the ring orbits of SPS and LHC have been defined. The TCDIs

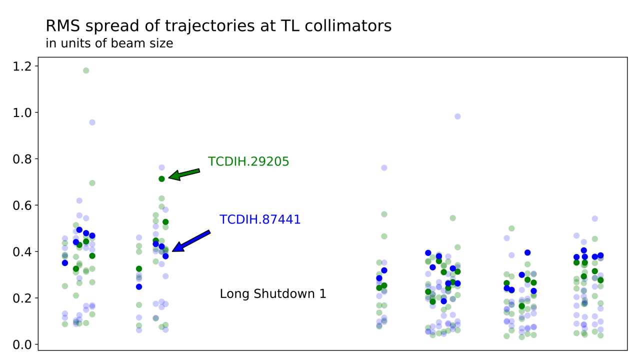

Figure 3: Spread (rms) of trajectories at TI 2 collimators (green) and TI 8 collimators (blue) in units of beam size at the respective collimator. The two critical collimators causing most of the shower on the ring loss monitors are shown in solid colours.

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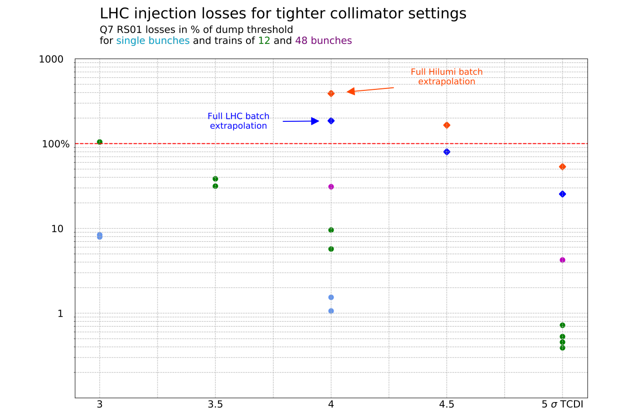

Figure 4: LHC B2 transverse injection losses on Q7 for different collimator settings and beam types.

are aligned with respect to this reference and - under normal conditions - not changed until the end of the run. Changes in the SPS orbit, power converter ripple of extraction devices, and energy drifts of the beam lead to deviations from the reference trajectory and consequently to increased losses at the collimators. In Fig. 3 the rms spread of the beam position at the TCDIs is shown in units of the beam size at the respective location. Each circle refers to a period of physics production without interruption by technical stops, development periods or special runs. The beam position spread at the collimators TCDIH.29205 and TCDIH.87441 is most relevant due to the distinct correlation of losses on these collimators with losses on the matching quadrupoles Q8 and Q7, as shown in [4]. Figure 4 helps to get an understanding of loss levels

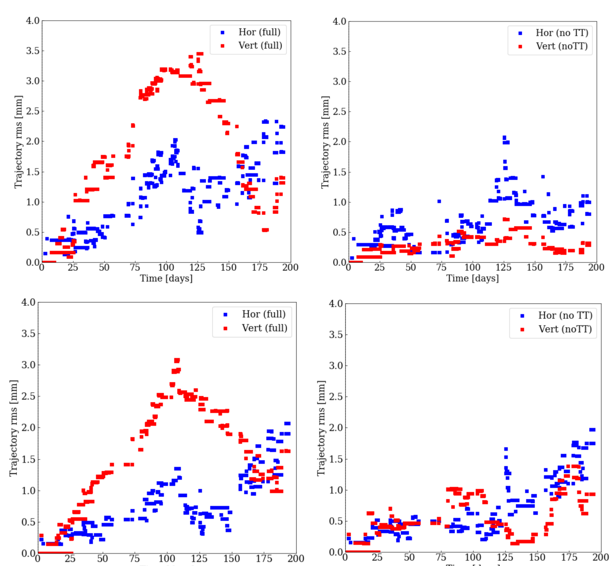

Figure 5: RMS trajectory evolution in 2018, after unfolding correction kicks. The two top plots show unfolding the corrections all over the TI 2 line (left) or only the downstream part which means leaving TT60 corrections in (right). The two bottom plots show the TI 8 trajectories, all unfolded (left) and only downstream part unfolded (right).

with respect to number of beam sigma trajectory deviation. Here different beam types (single bunches, 12 bunches and 48 bunches) were injected for various settings of the transfer line collimators. Assuming that moving the beam or the collimator jaw is almost equal (closing both jaws might lead to a marginally higher loss level) shows that 0.5 σ of trajectory deviation leads to a loss increase of a factor 5 on the ring monitors. What can also be observed in Fig. 3 is a general reduction of the trajectory jitter from Run 1 to Run 2 and, as also seen in the loss evolution, 2017 being the year with the best performance. These trajectories are a combination of all kind of variations, shot-to-shot as well as long term trends over several months.

In Fig. 5 the trajectories of TI 2 and TI 8 are shown unfolded from the correction kicks throughout the year. This shows that the lines have a long term trend to deviate from the trajectory. In the right side plots only the correction of the downstream parts of the lines were unfolded, which shows that the SPS orbit is the biggest contributor to the long term trajectory drift.

OUTLOOK TO RUN 3 AND FORESEEN IMPROVEMENTS

The worst case HL-LHC beam for injection losses will be the standard beam with 288 bunches with the bunch intensity of $2.3 \cdot 10^{11}$ in 2.1 µm emittance. This gives about a factor 4 intensity increase and a different tail cut-off at the collimators. Using 2017 and 2018 as basis for extrapolation, the ratio of transverse losses above 20% of dump threshold on Q8 for B1 (most critical case) might be in the range of 8-32%, 2-10% above half of the threshold and around 1% of the B1 injections triggering dumps. As mitigation it is foreseen to better control the long term trajectory drifts via regular single value decomposition corrections, e.g. after technical stops. This should allow to reset the accumulation of corrections over several weeks and ease steering in daily operation. Steering checks at each fill are encouraged and facilitated by potentially dynamic filling schemes depending on the need of steering. With these measures, the trajectory performance of 2017 which represents the lower end of the above mentioned loss ranges should be reached which is acceptable for operation. In case early Run 3 experience shows higher loss levels than expected which are well understood, a temporary inhibit of the beam loss monitor interlock signal at injection can be deployed. The same fall-back solution applies for unexpected longitudinal losses, which are not expected to significantly deteriorate for HL-LHC beams compared to Run 2.

CONCLUSIONS

In this paper the long term trends for injection losses and trajectories are correlated to hardware and beam type changes during LHC Run 1 and Run 2. The available loss data was extrapolated to HL-LHC beam parameters which shows that an improved control of injection trajectories should render a high availability injection operation in Run 3.

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