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STUDIES OF LONGITUDINAL BEAM LOSSES AT LHC INJECTION[*]

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Abstract

Due to higher beam intensities, the required rf power in the High-Luminosity LHC (HL-LHC) era is expected to be at the limit of the available rf power. To mitigate potential limitations of the rf system, the injection voltage can be reduced at the expense of beam losses. In this paper, the average and bunch-by-bunch losses are estimated from Run 2 beam intensity measurements in the SPS before extraction and in the LHC after injection. Macro-particle simulations are performed with CERN's Beam Longitudinal Dynamics code to reproduce the observed SPS-to-LHC capture and LHC flat-bottom losses. First estimates of injection losses for the HL-LHC at different injection voltages and injection energy errors are discussed.

INTRODUCTION

At the High-Luminosity LHC (HL-LHC) [1] nominal beam intensity of $2.3{\times}10^{11}$ protons per bunch (ppb), the 300 kW rf power presently installed in the LHC [2] is expected to be at the limit of the future power requirements [3, 4]. Operating with the half-detuning [5] beam-loading compensation scheme and given that the required generator power is dominated by beam-loading, power transients at injection determine whether the presently installed rf power will be sufficient.

Reducing the LHC injection rf voltage lowers the power demand (and improves beam stability due to better matching of the LHC bucket [6]). However, it makes the beam transfer from the SPS to the LHC more sensitive to injection errors and yields higher losses. To be able to operate the HL-LHC with the present rf system, the injection voltage has to be minimised within the acceptable beam losses limit. Injection losses are defined as the sum of capture and flat-bottom losses and can be seen at the start of ramp. In 2018, the reduction from 6 MV to 4 MV showed better beam stability, but with losses at the start of ramp getting close to the beam dump thresholds in some cases [7, 8]. Scaling the LHC 4 MV injection voltage yields 7–8 MV minimum for the HL-LHC, based on the expected relative momentum spread of the arriving bunches after the SPS voltage upgrade and for an average SPS bunch length between 1.50 ns and 1.65 ns (2018 LHC and HL-LHC nominal, respectively). At steady state, this voltage corresponds to the limit of the available rf power [9] with the $2.3{\times}10^{11}$ ppb HL-LHC nominal beam intensity.

Machine availability can also be affected by flat-bottom losses [8]. To reduce losses, an improved SPS-LHC energy matching is also under investigation [10]. The study of the injection dynamics is thus crucial to understand if the presently available rf power will limit the future machine performance. Particle tracking simulations with CERN's Beam Longitudinal Dynamics (BLonD) code [11, 12] were conducted to reproduce the injection losses observed in Run 2, as detailed in the following section. The generation of beam distributions at SPS extraction using typical bunch parameters based on the 2018 measurements is then described, and the corresponding loss estimations after injection into the present LHC are discussed. Finally, preliminary results for the HL-LHC as a function of injection voltage and injection energy errors are included.

2018 MEASUREMENTS

The average and bunch-by-bunch (BBB) SPS-to-LHC transfer losses are estimated from the ratio of the last intensity measurement along each batch in the SPS before extraction and the corresponding first measurement in the LHC after injection, from 2018 LHC fills with 4 MV and 6 MV. SPS and LHC bunch intensities are measured by the beam quality monitors (BQM) [13] and the fast beam current transformers (BCTF) [14], respectively, and are normalised to the total LHC dc BCT intensity per batch. Typically up to 20 injections are done per fill, each consisting of up to three batches of 48 bunches (48b) in the so-called BCMS scheme [15]. As a worst-case scenario, only batches from the eighth injection onwards are analysed where the action of the beam phase loop that corrects the average phase of all circulating bunches can be neglected. On average, injection losses of around 0.20 % are observed at 4 MV, decreasing by around half for 6 MV, see Fig. 1. Note that these *capture* losses are rough estimates due to the accuracy of the intensity measurements (they are not recorded at the exact moment of the SPS extraction nor of the LHC injection, and the monitors of each machine have different resolutions). The comparison of successive BCTF BBB intensities at flat-bottom with respect to the first measurement after injection shows an average flat-bottom loss rate of 0.05 % per minute.

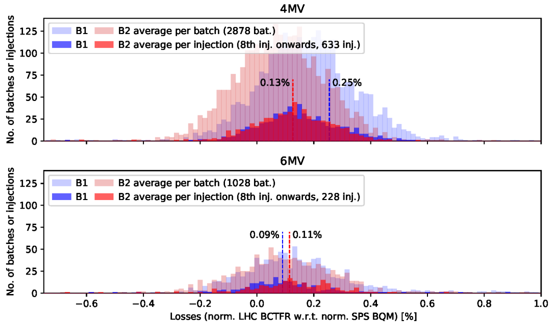

Figure 1: LHC beam 1 (blue) and beam 2 (red) average beam losses per batch and injection for 2018 fills with injection voltages of 4 MV (top) and 6 MV (bottom). The vertical lines indicate the means of each distribution.

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This figure doubles for bunches at the head and tail of each batch as a result of the bunch-by-bunch phase shift due to beam-loading compensation in the SPS [16].

BEAM GENERATION IN SPS AT EXTRACTION

Beam losses originate mainly from the beam halo, especially from the first and last bunches of the injected batch due to their larger phase offset with respect to their bucket centre. Injection with large relative energy and/or phase errors leads to larger losses. Thus, to accurately simulate LHC injection losses via BLonD tracking studies, realistic beams must be first generated in the SPS in simulations.

Beam generation in the SPS is typically done with 1×10^6 macroparticles per bunch, with the bunch intensity (N_b) and bunch length (τ) taken directly from measurements. While accurate modelling of the halo population is imperative, it is very challenging in practice, as it cannot be measured in the machine. For this, each processed bunch profile is fit to a binomial distribution $\lambda(t) = \lambda_0[1-(2t/\tau)^2]^{\mu+1/2}$; the resulting binomial exponent (μ) describes well the bunch core, and the bunch tails are assumed as an approximation and are subject to further scans.

The BBB phase (or position) offsets $\Delta\phi_\mathrm{bb}$ within their respective rf bucket along a batch are regulated by the SPS low-level rf (LLRF) system for beam-loading compensation [17–19]. Therefore, realistic distributions can only be generated with an accurate simulation of the feedback and feedforward loops in it. As in the real machine, the one-turn delay feedback (OTFB) of the LLRF implemented in BLonD [16] performs a bucket-by-bucket regulation of the rf voltage in amplitude and phase and allows the study of generator power transients. A first benchmark was done against a previous analysis of 2015 data using a static model for beam-loading compensation [20]. The dynamic OTFB also has the benefit of realistically enhancing the beam halo as bunches are tracked for several synchrotron periods at flat-top. Intensity effects with the latest SPS longitudinal impedance model [21] are taken into account.

Further benchmark and calibration of the OTFB model are conducted against measurements of several fills from the 2018 voltage reduction campaign (48b BCMS). In general, good agreement is observed between the simulated beams and their corresponding measurements, in particular, in terms of $\Delta\phi_\mathrm{bb}$. Figure 2 shows the BBB phase offsets obtained for the first batch of the penultimate B2 injection of Fill 7137 and their comparison with the offsets computed directly from the SPS and LHC (first turn) profile measurements (offsets from the reconstructed distribution via tomography in the LHC after injection are also included) [16]. Fine-tuning of the feedback and feedforward loops in the OTFB is expected to improve these results, especially at the batch head.

To improve the generation of realistic beams, the typical BBB variations of bunch parameters (N_b, τ, μ) in the present LHC are analysed. Figure 3 shows their BBB average over several fills normalised to their respective batch average. Extrapolating these *average-beam* models to 72-bunch batches (keeping the linear trend of each parameter and preserving the behaviour at the batches' head and tail), allows to easily derive distributions for each parameter with realistic BBB variations for the HL-LHC nominal scheme. These distributions are necessary for injection losses studies with standard beams for the LHC future operation; in this case, the SPS OTFB model is re-calibrated accordingly.

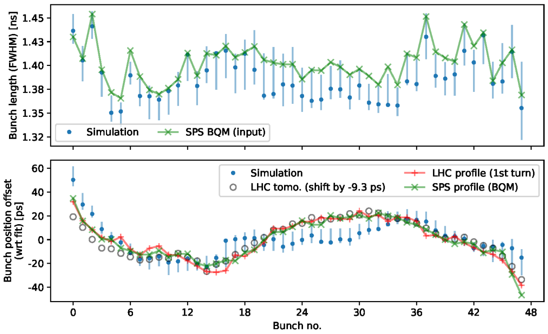

Figure 2: Bunch phase (position) offsets $\Delta\phi_\mathrm{bb}$ of the simulated (blue) beam reproducing a 48-bunch batch ($N_b = 1.1\times10^{11}$ ppb ave., $\tau = 1.36$ ns ave.) in Fill 7137 generated in SPS at flat-top w.r.t. measurements (red, green, circles).

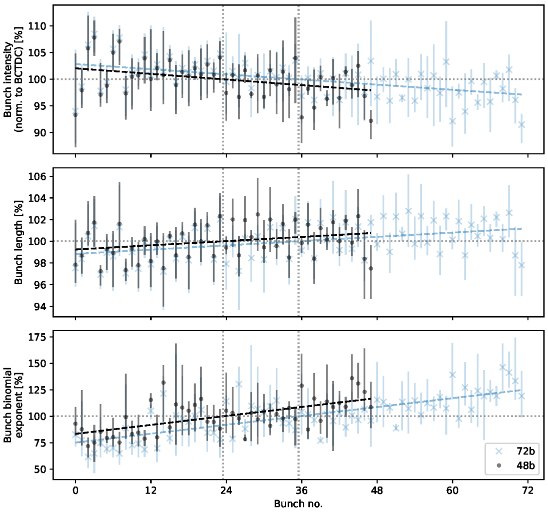

Figure 3: Average bunch-by-bunch intensity, bunch length, and binomial exponent relative to their batch-average for 48b batches from several 2018 fills, and model extrapolation to 72b batches.

BEAM INJECTION INTO THE LHC

Beam losses are estimated based on the integrated bunch profiles. Most of the injection losses come from the SPS-to-LHC bunch-to-bucket capture; afterwards, rf noise and intra-beam scattering (not modelled in simulation) will drive losses at a smaller rate. In simulation, capture losses are computed after several synchrotron periods to allow uncaptured particles to drift away from the main bunches. Formally, losses can also be calculated based on the bucket separatrix. Both estimates are close, with the latter being usually slightly higher and faster to reach the linear region, but its accuracy depends on the consideration of intensity effects.

In simulations, using the modelled beam distributions based on 2018 fills, injection losses are first benchmarked against their corresponding estimates from the SPS BQM and LHC BCTF data. While a precise comparison is challenging due to the large noise in the measurements, the average and BBB capture losses are found to be consistent in magnitude with them. For example, the extracted SPS batch reproduced in Fig. 2 shows average capture losses of 0.20 % after being transferred into the LHC with the operational injection voltage of 4 MV and measured energy error of 60 MeV (one of the largest energy deviations measured), as observed in Fig. 4. After 60 s (the BCTF acquisition rate), the loss ratio at flat-bottom is found to be around 0.02 %/min. The addition of rf noise (with a power spectral density of 1×10^{-8}–1×10^{-7} rad^2/Hz [22]) and an improved OTFB calibration (for a better phase offset regulation at the batch head) brings the simulation loss rate closer to the measurements. No additional injection phase errors are considered in simulation.

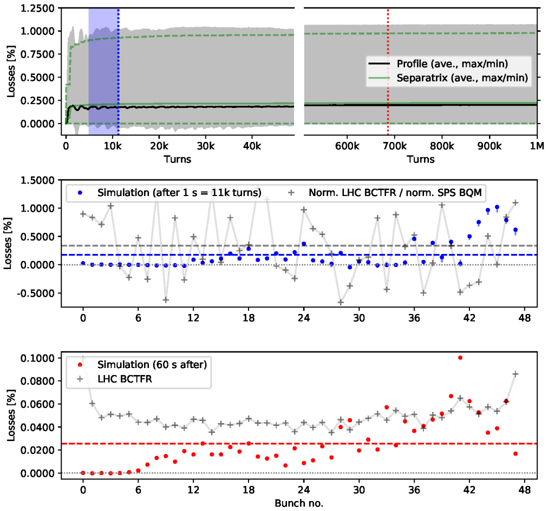

Figure 4: Injection losses from the SPS beam in Fig. 2 into the LHC.

The injection of beams generated in the SPS, with given average bunch parameters, into the HL-LHC allows predicting the expected losses as a function of the injection voltage and energy errors for a wide range of scenarios. Assuming an average bunch length of 1.65 ns for a 72b batch with the nominal HL-LHC intensity, for example, total losses get close to around 2 % for low injection voltage and large energy errors after 1×10^5 turns at flat-bottom, with most of them being capture losses. In simulation, intensity effects, instabilities due to energy mismatch, and the effect of the LHC beam phase loop drive losses at flat-bottom. It must be noted that the loss behaviour in Fig. 5, should be taken qualitatively as the beam evolution and losses showed a strong dependence in simulations on the cut-off frequency assumed in the longitudinal impedance model [23] (for Fig. 4, a 5 GHz cut-off frequency is assumed). This has triggered an effort to improve the model [24, 25] for the present and future machine configurations, originally a by-product of transverse impedance modelling.

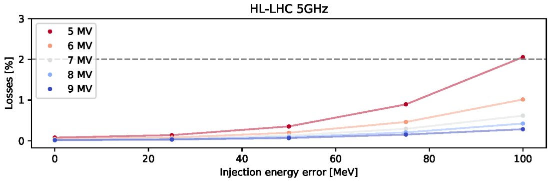

Figure 5: Preliminary HL-LHC injection losses for a 72b batch ($N_b = 2.3 \times 10^{11}$ ppb ave., $\tau = 1.65$ ns ave.) as a function of the injection energy error for different injection voltages.

CONCLUSION

Studies of the minimum capture voltage with operationally acceptable beam injection losses are ongoing and driven by possible rf power limitations for HL-LHC beam currents. Generating realistic beam distributions at SPS extraction with an accurate model of the beam halo and bunch phase offsets is crucial as the halo is the main source of beam losses at capture and during flat-bottom. Using the dynamic SPS OTFB model in BLonD and bunch-by-bunch parameters obtained from the analysis of measured beam profiles in the SPS and LHC, beam distributions similar to 2018 measurements can be reproduced. While in 2018 many measurements were performed on demand, systematic bunch tomography in operation will be available during Run 3, providing more accurate and frequent measurements for improved beam generation. Analysing the typical bunch-by-bunch variations of beam parameters in Run 2 and extrapolation from 48b to 72b allowed to generate realistic beams for the HL-LHC era.

The simulations reproduce well the average losses for several 2018 LHC fills, with their corresponding estimates of capture losses and loss rate at flat-bottom being similar to their computed counterparts from measurements. The estimation of LHC capture and flat-bottom losses is a challenging task since the capture losses, in particular, are difficult to measure experimentally. Finally, the benchmarks with the 2018 LHC measurements, as well as the studies for Run 3 and HL-LHC are planned to be re-evaluated following the latest improvements to BLonD's SPS OTFB model and the LHC longitudinal impedance model. As the largest rf power consumption is expected during the injection transients, simulations with a realistic LHC cavity controller model are also ongoing [9, 26].

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