Abstract

While reducing the injection voltage mitigates possible rf power limitations in the HL-LHC era, it also yields larger losses. Estimation of average and bunch-by-bunch injection losses from LHC Run 2 is presented. Macroparticles simulations with CERN’s BLonD tracking code were conducted to reproduce the SPS-to-LHC capture and LHC flat-bottom losses. First estimates for HL-LHC losses as function of injection voltage and energy errors are also included.

I. Introduction

• The presently-installed rf power [1] is at the limit of the requirements for HL-LHC [2–4].
  • Power transients at injection, the main limiting factor (half detuning beam-loading compensation scheme [5]).
• Reducing the LHC injection voltage: ✓ lowers demand power ✓ improves beam stability ✓ beam transfer more sensitive to injection errors and yields higher losses
• Injection losses are the sum of capture and flat-bottom losses and are seen at start of ramp.
• Reduction 6 → 4 MV in 2018 [7,8] ✓ better stability ✓ Start of ramp losses close to dump thresholds
• 7 – 8 MV minimum needed for HL-LHC based on scaling [9] from 4 MV based on:
  • Expected momentum spread of arriving bunches from SPS after extraction voltage upgrade to 10 MV:
    • For an average bunch length of 1.50 ns (2018:1.65 ns; HL-LHC nominal).
• Improved SPS-LHC energy matching under investigation [10] to further reduce losses.
• Particle tracking simulations with CERN’s Beam Longitudinal Dynamics (BLonD) [11,12] to reproduce Run 2 typical beams at SPS extraction and observed LHC injection losses.
• Preliminary HL-LHC loss estimates vs. injection voltage and injection energy errors.

III. Beam generation in SPS at extraction

• Losses originate mainly from bunches at the head and tail of a bunch, and from the beam halo.
  • BLonD simulations: throw 1 Inject into the LHC for low losses
  • Bunch parameters (intensity Nb, bunch length r, bipolaron axial error) extracted from measurements.
  • Analysis of average SPS beam parameters variations from 48b and extrapolation to 72b for Run 3 and HL-LHC beams.
  • Realistic modulation of bunch phase offsets Δφb for beam loading compensation [16–18] using the purpose-built (BLonD) implementation of the SPS one-turn delay feedback (OTDF) model [19]. More details in L. Medina et al., paper TUP2020/091, this conference.
  • Δφb of selected 2018 bunches well reproduced.
  • Added benefit of realistic dynamics of halo-particles.

II. 2018 Measurements

• SPS-to-LHC transfer losses: ratio of the bunch-by-bunch (BBB) intensity measurements in the SPS before extraction and LHC after injection from 2018 LHC fills with 4 MV and 6 MV.
  • 48-bunch BLonD batches [18] for which the phase loss can be neglected are analysed (as worst case).
  • Rough estimates: the last SPS BQM [14] and first LHC BCT [15] intensity measurements are not recorded exactly at extraction and injection energy, and monitors have different resolutions.
  • Both measurements are normalised to the LHC bunch intensity (BCTD).
• Average injection losses of 0.20% for 4 MV (beam 1 slightly larger) decreasing by half for 6 MV (similar for both beams).
• Average flat-bottom loss rate of 0.055%min⁻¹ from the comparison of successive BCTF BBB intensities w.r.t. the first measurement after injection.
  • Up to double this rate for bunches at the head and tail of each bunch.

IV. Conclusions

• Driven by possible rf power limitations in the HL-LHC, studies of the minimum LHC injection voltage with operationally acceptable injection losses are ongoing.
• Challenging, as capture losses cannot be measured directly.
• Generation of realistic beams at SPS extraction in simulation (bunch-by-bunch phase offsets, halo) is crucial.
• Using the simulated 2018 measurements reproduced using BLonD’s OTDF model and bunch parameters from the analysis of SPS and LHC bunch profile measurements.
• Analysing the typical SPS beams of variable bunch parameters in Run 2 and extrapolating from 48b to 72b allowed to generate realistic beams for study of the injection.
• Available in operation from Run 3, systematic bunch topography will provide more accurate and frequent bunch measurements.
• Injection losses from simulated beam distributions based on 2018 fills are in line with the average LHC capture and flat-bottom losses estimated from BBB intensity measurements.
• Preliminary HL-LHC loss estimates to be re-evaluated with improved longitudinal impedance model, currently in development.
• As the largest rf power consumption is at the injection transients, simulations with a realistic LHC cavity controller model are also ongoing [12].

Acknowledgments: H. Karpov, T. Argyropoulos, M. Palm, B. Salvachúa, D. Shaposhnikova, E. Tong, and L. Werninger (CERN). References:

12th International Particle Accelerator Conference (IPAC’21)
Campinas, SP, Brazil, May 24—28th, 2021

Studies of Longitudinal Beam Losses at LHC Injection

L. Medina, † T. Argyropoulos, R. Calaga, H. Timko, CERN, CH-1211 Geneva, Switzerland

* Research supported by the HL-LHC project.
† lmedinam@cern.ch
The presently-installed rf power [1] is at the limit of the requirements for HL-LHC [2–4].

- Power transients at injection, the main limiting factor (half-detuning beam-loading compensation scheme [5]).

**Reducing the LHC injection voltage:**

- Lowers power demand
- Improves beam stability [6]
- Beam transfer more sensitive to injection errors and yields higher losses

Injection losses are the sum of capture and flat-bottom losses and are seen at start of ramp.

Reduction $6 \rightarrow 4$ MV in 2018 [7,8]:

- Better stability
- Start-of-ramp losses close to dump thresholds

7—8 MV minimum needed for HL-LHC based on scaling [9] from 4 MV based on:

- Expected momentum spread of arriving bunches from SPS after extraction voltage upgrade to 10 MV.
- For an average bunch length of 1.50 ns (2018 LHC)—1.65 ns (HL-LHC nominal).

**Improved SPS-LHC energy matching** under investigation [10] to further reduce losses.

Particle tracking simulations with CERN’s Beam Longitudinal Dynamics (BLonD) [11,12] to reproduce Run 2 typical beams at SPS extraction and observed LHC injection losses.

- Preliminary HL-LHC loss estimates vs. injection voltage and injection energy errors.
II. 2018 Measurements

- **SPS-to-LHC transfer losses**: ratio of the bunch-by-bunch (BBB) intensity measurements in the SPS before *extraction* and LHC after *injection* from 2018 LHC fills with 4 MV and 6 MV.
  
  - 48-bunch BCMS batches [13] for which the phase loop can be neglected are analysed (as worst-case).
  - Rough estimates: the last SPS BQM [14] and first LHC BCTF [15] intensity measurements are not recorded *exactly* at extraction and injection, respectively, and monitors have different resolutions.
  - Both measurements are normalised to the LHC batch intensity (BCTDC).

- **Average injection losses** of 0.20% for 4 MV (beam 1 slightly larger) decreasing by half for 6 MV (similar for both beams).

- **Average flat-bottom loss rate** of 0.05%/min* from the comparison of successesive BCTF BBB intensities w.r.t. the first measurement after injection.
  
  - Up to double this rate for bunches at the head and tail of each batch.

* The BCTF acquisition rate is \(\sim 1\) min.
III. Beam generation in SPS at extraction

- Losses originate mainly from bunches at the head and tail of a batch, and from the beam halo.
- BLonD: Step 1 Generate realistic beam in SPS simulations; Step 2 Inject into the LHC for loss estimates
- Bunch parameters (intensity $N_b$, bunch length $\tau$, binomial exponent $\mu$) from measurements.
- Analysis of average BBB parameters variations from 48b and extrapolation to 72b for Run 3 and HL-LHC beams.
- Realistic modulation of bunch phase offsets $\Delta \phi_{bb}$ for beam-loading compensation [16–18] using the purpose-built BLonD implementation of the SPS one-turn delay feedback (OTFB) model [19]. More details in L. Medina et al., paper THPAB200, this conference.
  - $\Delta \phi_{bb}$ of selected 2018 batches is well reproduced.
  - Added benefit of realistic dynamics of halo particles.
In simulation, losses are estimated based on the integrated bunch profiles after a several synchrotron periods.

Using the modelled beams based on 2018 fills, the average loss estimates correspond to those from the SPS BQM and LHC BCTF data.

- For example, 0.2% + 0.02%/min for Fill 7137 (4 MV, 60 MeV injection error, one of the largest measured).

Preliminary HL-LHC loss estimates:

- Using beams generated in SPS with given ave. bunch parameters.
- Done as a function of injection voltage and energy errors.
- Total losses close to 2% for low injection voltage and large energy errors ($\tau = 1.65$ ns ave.). To be re-evaluated as it was found...

... a strong dependence of beam evolution with the longitudinal impedance model [20]; triggered effort to improve it [21].
Driven by possible rf power limitations in the HL-LHC, studies of the minimum LHC injection voltage with operationally acceptable injection losses are ongoing.

- Challenging, as capture losses cannot be measured directly.

Generation of realistic beams at SPS extraction in simulation (bunch-by-bunch phase offsets, halo) is crucial.

- Beam distributions similar to 2018 measurements reproduced using BLonD’s SPS OTFB model and bunch parameters from the analysis of SPS and LHC bunch profile measurements.
- Analysing the typical BBB variations of beam parameters in Run 2 and extrapolating from 48b to 72b allowed to generate realistic beams for HL-LHC studies.

Available in operation from Run 3, systematic bunch tomography will provide more accurate and frequent bunch measurements.

Injection losses from simulated beam distributions based on 2018 fills are in line with the average LHC capture and flat-bottom losses estimated from BBB intensity measurements.

- Preliminary HL-LHC loss estimates to be re-evaluated with an improved longitudinal impedance model, currently in development.

As the largest rf power consumption is at the injection transients, simulations with a realistic LHC cavity controller model are also ongoing [22].