Studies of Longitudinal Beam Losses at LHC Injection*

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

Abstract

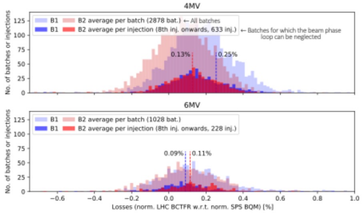
While reducing the injection voltage mitigates possible rf power limitations in the HL-LHC era, it also yields larger losses. Estimation of average and bunch-by-bunch injection losses from LHC Run 2 is presented. Macroparticles simulations with CERN's BLonD tracking code were conducted to reproduce the 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 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 → **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

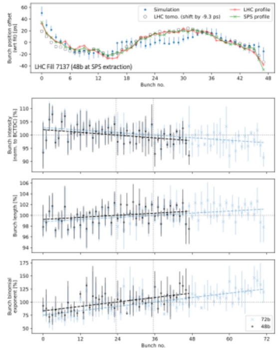
- **SPS-to-LHC** transfer **losses**: **ratio** of the bunch-by-bunch (BBB) intensity measurements in the **SPS** before **extraction** and **LHC** after **injection** from **2018** LHC fills with **4 MV** and **6 MV**.
  - 48-bunch BCMS batches [13] for which the phase loop can be neglected are analysed (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 succesive 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 ~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 simulations**: Step 1 Generate **realistic beam** in **SPS**; Step 2 **Inject** into the **LHC** for **loss** estimates
- **Bunch parameters** (intensity N_b, bunch length τ, binomial exponent μ) 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.



IV. Beam Injection into the LHC

- 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 (τ = 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].

V. 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.
  - 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].

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References: [1] O. S. Brüning *et al.*, doi:10.5170/CERN-2004-003-V-1, [2] The High Luminosity LHC Project, https://hilumilhc.web.cern.ch, [3] H. Timko *et al.*, CERN-ACC-NOTE-2019-0005, [4] L. Medina *et al.*, https://cds.cern.ch/record/2683350, [5] D. Boussard, doi:10.1109/PAC.1991.164995, [6] H. Timko *et al.*, doi:10.18429/JACoW-HB2018- TUP1WA03, [7] H. Timko *et al.*, http://cds.cern.ch/record/2750299, [8] L. Medina *et al.*, *to be submitted*, [9] H. Timko, https://indico.cern.ch/event/806637, [10] T. Argyropoulos *et al.*, https://indico.cern.ch/event/977192, [11] CERN BLonD Simulation Suite, http://blond.web.cern.ch, [12] H. Timko *et al.*, *to be submitted*, [13] H. Damerau *et al.*, https://accelconf.web.cern.ch/IPAC2013/papers/wepea044.pdf, [14] G. Papotti, https://accelconf.web.cern.ch/e08/papers/thpc144.pdf, [15] D. Belohrad *et al.*, https://epaper.kek.jp/d09/papers/mopd43.pdf, [16] G. Dôme, https://cds.cern.ch/record/319440, [17] D. Boussard *et al.*, doi:10.1109/TNS.1985.4333745, [18] P. Baudrenghien *et al.*, https://cds.cern.ch/record/485863, [19] L. Medina *et al.*, THPAB200, this conference, [20] I. Karpov *et al.*, doi:10.1103/PhysRevAccelBeams.24.011002, [21] N. Mounet *et al.*, https://indico.cern.ch/event/915032, [22] I. Karpov *et al.*, doi:: 10.23732/CYRCP- 2020-009.312

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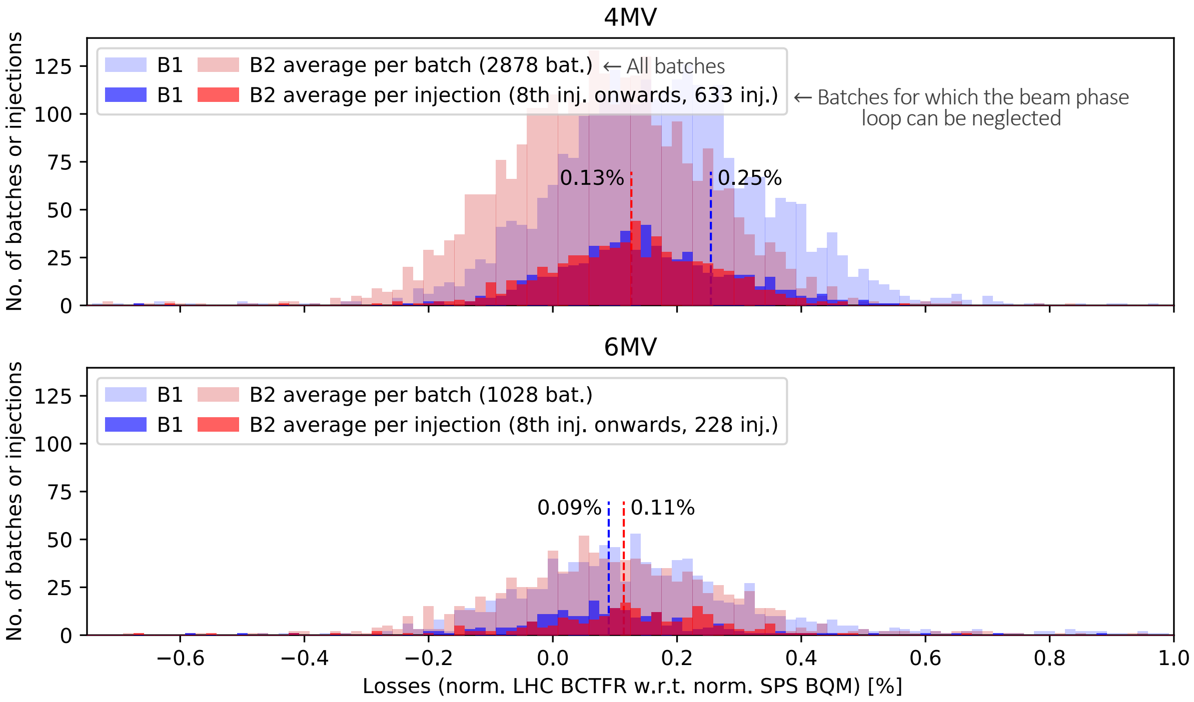

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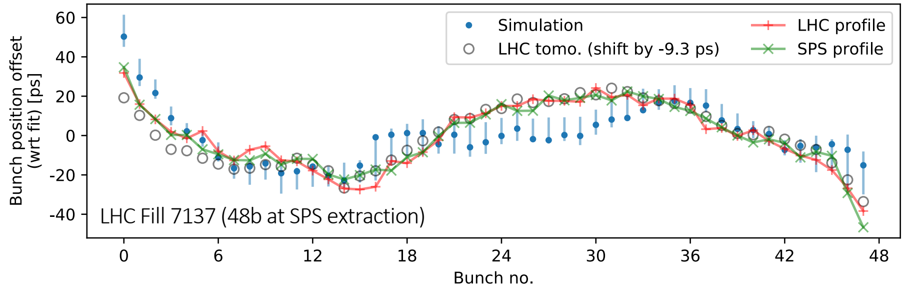

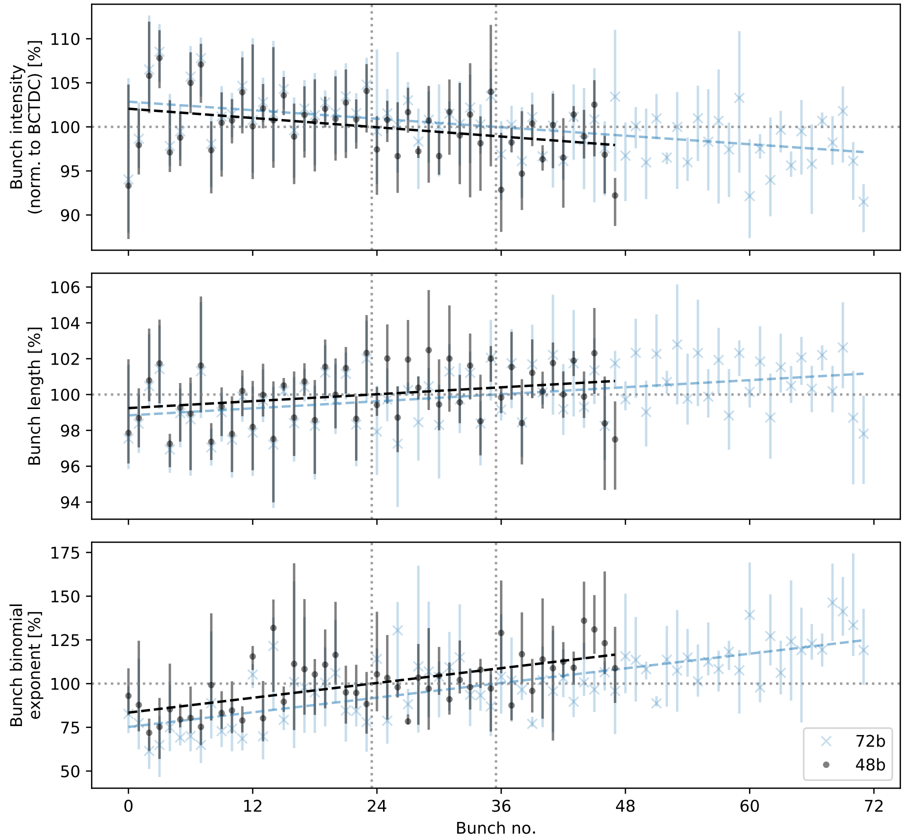

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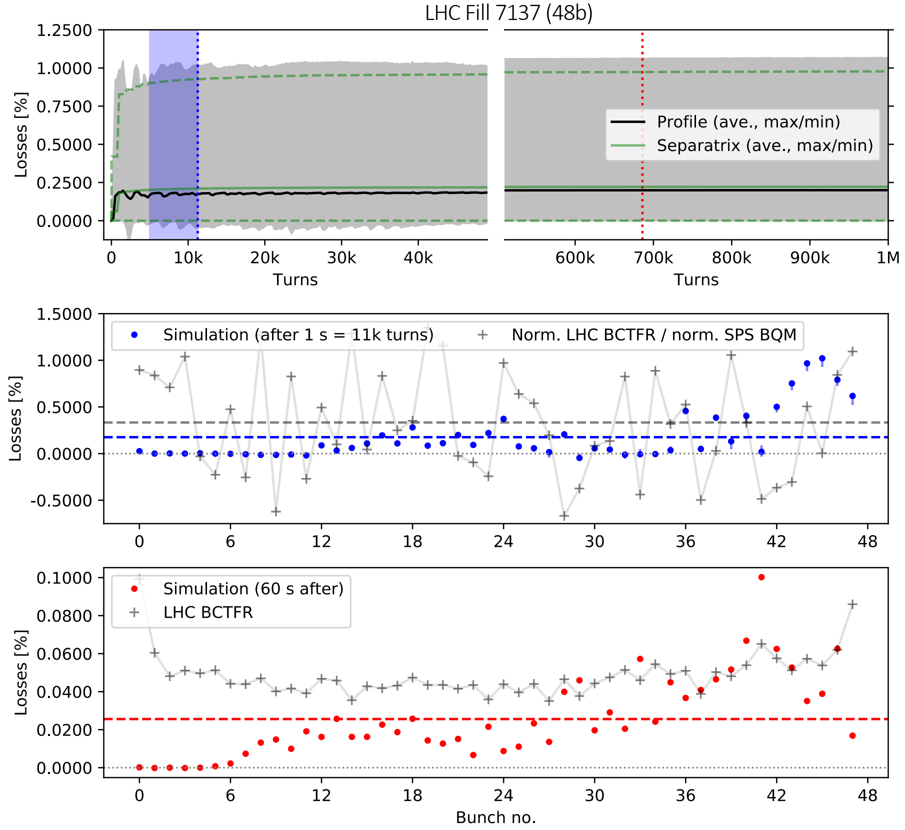

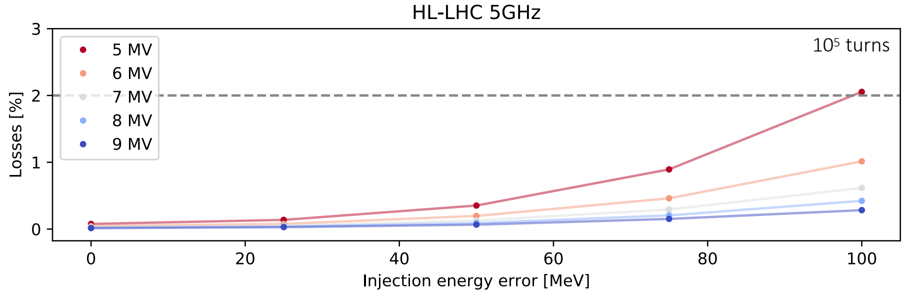

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