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Overview of (HL-)LHC injection losses studies

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82nd BLM Thresholds WG Meeting

09 April 2021

Acknowledgements to P. Baudrenghien, H. Damerau, W. Hofle, I. Karpov, N. Mounet, M. Palm, B. Salvachua, E. Shaposhnikova, K. Turaj, and J. Wenninger

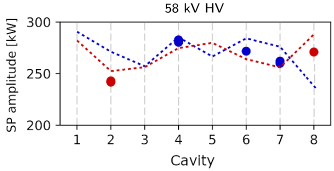
Outline

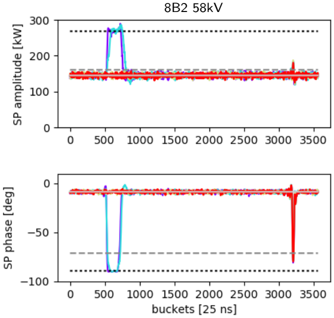
Introduction

- The problem: potential **RF power limitations** (300 kW max. presently installed) at **(HL-)LHC injection** due to **higher beam intensity** and beam loading.
  - Further constraints due to power transients.
- A **reduced RF injection voltage lowers power** demand (and increases beam stability thanks to better SPS-to-LHC bunch-to-bucket matching), but is more sensitive to **injection errors** and yields **higher losses** → **optimum injection voltage**?
  - Better energy matching (factor of ~ 2) under investigation.
  - 6 MV → 4 MV tested during 2018 MDs and operation.
  - Start-of-ramp losses close to dump thresholds. → Limited by BLM thresholds?
- Studying present injection losses is crucial to understand if present **RF power available** is limiting future machine **performance**.
  - Flat-bottom losses appear at start of ramp and can affect machine **availability**.
- **BLonD simulations** to reproduce average and bunch-by-bunch LHC capture and flat-bottom **losses** observed in **Run 2**.
  - Predictions for **HL-LHC** intensities and different **injection voltage** or **energy errors**.

Present and expected RF power

- In the half-detuning scheme (required for injection), cavity phase and amplitude are kept constant.
- **Power** saturation observed at **250–280 kW** max. (58 kV HV).
  - Discrepancy w.r.t. theoretical 300 kW being investigated.
- With 2.30×10^{11} ppb and 1.20 ns bunches ($I_{b,rf,pk} = 2.2$ A), 7.8 MV at the limit of operation ($\sim$270 kW steady state): feasible for baseline, but no margins left.
- Large **power transients** (largest power demand) at injection can be the main limiting factor:
  - Realistic model of the LHC RF cavity controller developed for BLonD to study them.
- **Is the present RF power enough?** It depends on how much the **injection voltage** can be **reduced** and how much **losses** can be tolerated.



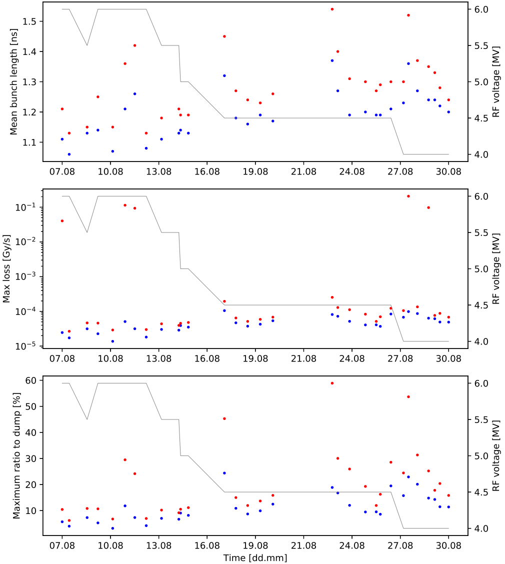


Reduction of RF injection voltage: 2018 measurements (I)

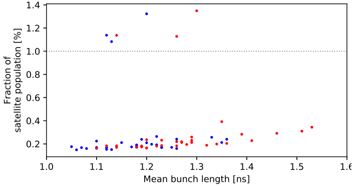
- **Lower voltage** good for **RF power consumption** and **beam stability** vs. **higher voltage** preferable to **reduce capture losses.**
- The matched LHC voltage w.r.t. momentum spread ($\Delta p/p$) of a typical 2018 SPS bunch is about 2–3 MV and cannot be used operationally due too high injection losses.
  $\rightarrow$ **4 MV minimum**.
- Simple scaling from 4 MV based on the arriving bunches' $\Delta p/p$ after the SPS voltage upgrade to 10 MV (Q20) for an average bunch length of 1.50–1.65 ns at SPS extraction:
  - 6–7 MV for Run 3.
  - 7–8 MV for HL-LHC $\rightarrow$ At the limit of installed RF power.

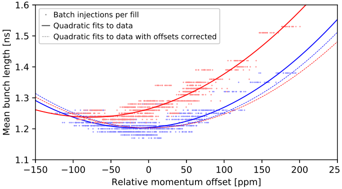
Reduction of RF injection voltage: 2018 measurements (II)

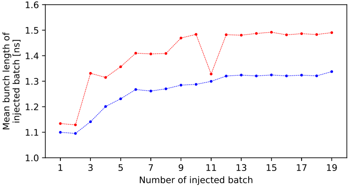
- Observations when lowering 6 MV to **4 MV**:
  - **Reduced power consumption** from 100 kW to 70 kW.
  - Reduced beam oscillation amplitude and **increased beam stability**.
  - Observed **bunch lengths scale** with voltage **as expected** but large fill-to-fill spread.
  - **Increased start-of-ramp losses**, specially at P3: lifetime drops to $\sim$ 1h in the beginning of ramp.



Reduction of RF injection voltage







- Relative **satellite population** (BSRL) at arrival to flat-top **not degraded** with lower injection voltage: remains low (0.2–0.3%) for well-adjusted PS bunch rotation.
- **Energy errors at injection:** Energy matching between SPS and LHC varies over time. In some fills, large blow-up due to filamentation is observed: phase loop only damps the injection error of the first batches. Better matching expected for Run 3.

- For HL-LHC, we can **expect larger emittances** arriving from SPS (higher extraction voltage, larger $\Delta p/p$, and longer bunch length, all for stability), which calls for larger injection voltage.

(HL-)LHC injection losses studies: Introduction

What? To estimate the **minimum acceptable injection voltage** based on injection **losses**, as a means to mitigate power limitations in the LHC future operation.

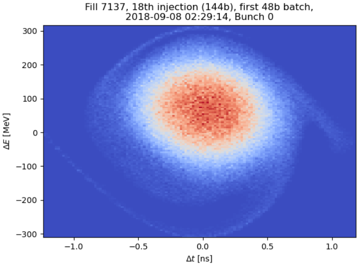
- To provide additional **guidelines** for **changes** to **BLM thresholds**.

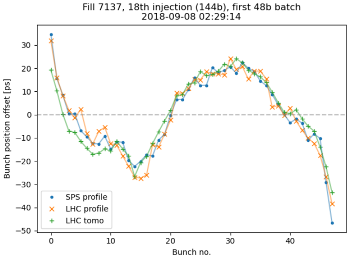
How? Estimation of losses via **BLonD tracking simulations**: **realistic beams** are generated in the **SPS** at flat-top and **injected** into the **LHC**.

- Benchmark with present LHC Run 2 measurements.
- Predictions for HL-LHC: scans on **bunch parameters**, **injection voltage**, and **injection energy errors**.

(HL-)LHC injection losses studies: Challenges

- **Losses** originate mainly from **beam halo**, specially from **first/last** bunches of the batch and for **large injection errors**. → **Realistic SPS beam distributions** are imperative. But:
  - Accurate modelling of **beam halo** is challenging as it **cannot be measured** in the machine.
  - **Bunch positions** within the RF bucket along the batch are regulated (for **beam loading** compensation) by the **SPS low-level RF** (LLRF). Realistic distributions can only be generated with an accurate **implementation** of the feedback/feedforward loops in **simulations**. Specially important for HL-LHC.
- For simulations at flat-bottom, need of a more **accurate longitudinal impedance model** of **present LHC**, **Run 3**, and **HL-LHC** (originally a by-product of transverse studies). → Work in progress.



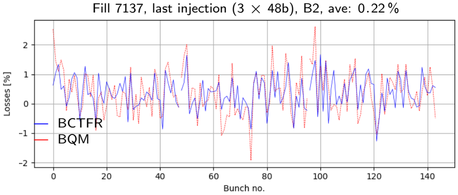


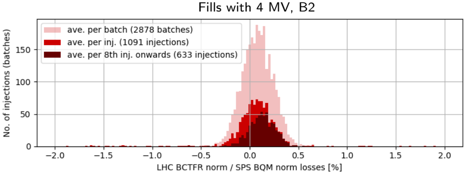
Injection losses from Run 2 measurements

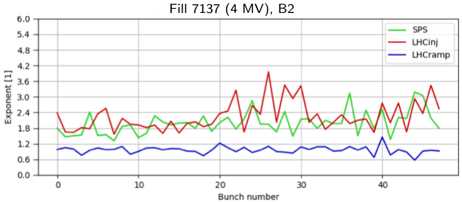
- Analysis of **SPS-LHC transfer losses** from the **ratio** of **bunch-by-bunch** (BBB) **intensities**:*

$$\left(1 - \frac{\text{First LHC BCTF or BQM meas. (norm.)}}{\text{Last SPS BQM meas. (norm.)}}\right) \cdot 100\,\%$$

  - Ave. losses of **0.20%** for **4 MV** for B1 (slightly higher for B2).
  - Ave. loss rate of **0.05%/min** ($\times 2$ in head/tail) with expected pattern from SPS.
- Correlation with energy errors not possible due to large noise levels.
- Typical bunch parameters from analysis of **bunch profiles**: SPS before extraction and dedicated measurements LHC 1st turn:
  - **Bunch length** (τ) and **bunch shape** (exponent μ in binomial approximation) for simulations.



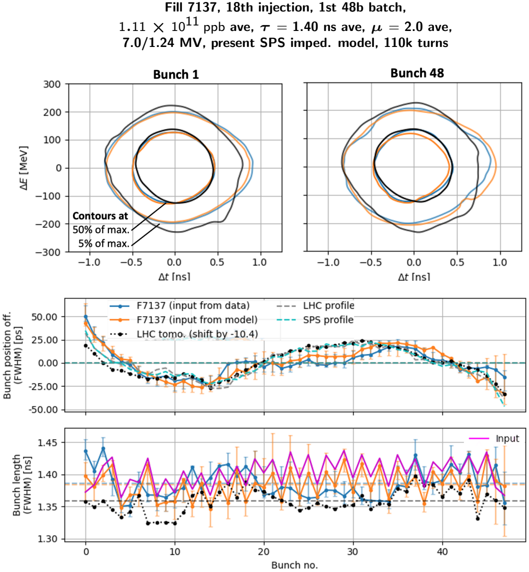




* Last injections of each fill of the voltage reduction campaign as worst-case (phase loop not effective).

Beam generation at SPS extraction

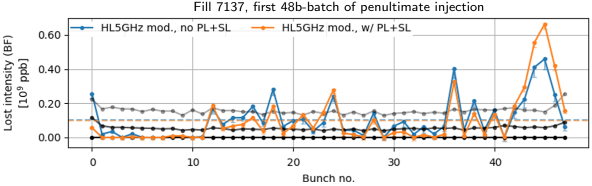
- **Implementation** of SPS LLRF (**feedback/ feedforward loops**) as in real machine: **benchmark** (e.g. with [1]) and **calibration** of model's parameters to reproduce 2018 data (48b BCMS).
- Good agreement between the simulation results and measurements (selected fills):
  - **Bunch distributions**: **similar cores**, larger **discrepancy in tails** (but tomography not reliable below ∼5 %).
  - **Bunch position offset**: **similar** to measurements, further **LLRF** adjustments **needed**.
- Beam generation with **typical BBB** variations (**intensity**, τ, μ) based on analysis of typical fills: extrapolation to **72b** for HL-LHC studies.



[1] CERN-THESIS-2015-421.

Injection into (HL-)LHC

- **Ave. capture losses** and loss ratio from simulation **consistent** in **magnitude** and BBB distribution with losses from **SPS BQM** and **LHC BCTF**:
  - E.g. 0.20 % + 0.10 %/min for Fill 7137 (4 MV, 60 MeV inj. error).
- HL-LHC losses close to ∼2 % threshold for low injection voltage and large injection energy errors.
  - Estimates for both present **LHC** (further benchmark) and **HL-LHC to be updated** after latest improvements to the BLonD SPS LLRF model.



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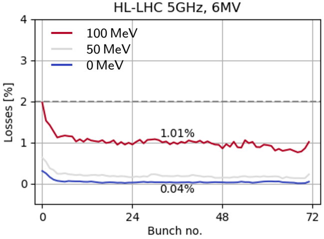

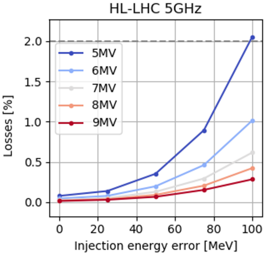

- Simulations of the beam evolution in LHC after injection highlight the importance of having an **improved longitudinal impedance model** (realistic $f_{\text{cutoff}} \sim 5$ GHz).
  → Ongoing work.

Summary

- Studies to estimate the **optimum injection voltage** based on injection **losses**, as a means to mitigate possible power limitations in the LHC future operation.
- Corresponding estimates of LHC capture losses similar to direct beam **measurements** in **LHC Run 2**.
- Implementation of **improved SPS LLRF model** for beam loading compensation (benchmark and calibration ongoing). $\rightarrow$ Very important for realistic **bunch position offsets** and **beam halo** modelling, specially for HL-LHC.
- **Average losses reproduced** for **present LHC** and **preliminary HL-LHC** simulations showing losses close to threshold for large injection errors and reduced injection voltage.

Outlook

- Estimates of of **injection losses** for present LHC (further benchmark), Run 3, and **HL-LHC to be re-evaluated** with improved SPS LLRF model and more accurate longitudinal impedance model.
- Systematic bunch **tomography** planned in operation for **Run 3**.
- Frequent **SPS-LHC energy matching** planned.

Discussion

BLM thresholds should be reviewed during Run 3 and tested in MDs:

- Assessment of LHC injection losses in simulation has been a challenging and slow process, with **both accurate bunch parameters** (for simulation input) and the corresponding **injection losses** (for their benchmark) being **difficult** to **measure experimentally**.
- Run 3 MDs crucial to improve simulation model.
- Gaining operational **margins** for further **reduction** of the **injection voltage** in case is necessary to limit **RF power** consumption even after improved energy matching (to be seen during Run 3).
- If 7–8 MV are required for HL-LHC, may need to install **2 extra cavities** per beam but development and installation would take many years.
- If **BLM thresholds** can be **increased** then **voltage** can be **lowered**, and the **present RF** might be **sufficient**.

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