Cavity Control Modelling for SPS-to-LHC Beam Transfer Studies*

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Abstract

To accurately simulate injection losses in the LHC and HL-LHC [1], a realistic beam distribution model at SPS extraction is needed. To achieve this, the beam-loading compensation by the SPS cavity controller must be included. Its implementation, which includes models of the feedback, feedforward, and generator-beam-cavity interaction, in CERN’s BLonD particle tracking code is described. Benchmarking with beam measurements is included.

I. Introduction

• Travelling wave cavities (TWCs) in the SPS [2–5]: Until 2018: 2X4-section; 2X5-section LHC Runs 1 and 2: From 2021: 4X5-section for HL-LHC beams
• To reduce the effective cavity impedance seen by the beam, a cavity controller with a one-turn delay feedback (OTFB) [6,7] is used in the machine for each cavity.
• Cavity control modelling is necessary to generate realistic beams at SPS extraction. In particular, the bunch-by-bunch phase offsets $\delta_{\phi,n}$ with the rf buckets and beam halo.
• Beams are used in HL-LHC injection simulations where a reduced injection voltage is studied as means to mitigate possible power limitations of the present rf system (8–10).
• As in operation, the design (set point) voltage is partitioned between the two groups of TWCs. For simplicity, a single cavity controller is assigned per partition in BLonD [11–13].
• The total rf voltage is the sum of the cavity (antenna) voltage regulated by each controller.

II. One-turn delay feedback

• Turn-by-turn, each OTFB calculates the correction needed to recover the partition's design voltage.
• First, the difference between the antenna and the set point voltage is computed.
• Signals sampled at the rf (carrier) frequency.
• This error signal is processed by a comb filter, effectively removing beam-loading [14].
• The TWCs' filling time is taken into account in the one turn (exact) loop delay.
• The signal is then modulated to the TWCs central frequency.
• The cavity response is modelled as a moving average at 40 MS/s.

III. Generator-beam-cavity interactions

• The correction by the OTFB is used to regulate the generator drive.
• The generator induced voltage is the convolution of the generator current and the impedance response from the cavity towards the generator.
• Likewise, the beam induced voltage is the result of convolving the beam impulse response with the rf component (at the carrier frequency) of the beam current.
• The feedback, implemented as a FIR filter, improves the feedback correction [15].
• The continuity of all signals must be ensured.

IV. Benchmark and Calibration

• Benchmark with measured $\delta_{\phi,n}$ of a 72-bunch batch in a previous analysis [16] with a static impedance-reduction model.
• Better agreement with measurements: added advantage of more realistic halo dynamics.
• Calibration with measurements from Run 2 to reproduce $\delta_{\phi,n}$ patterns in 488 batches from 2018 fills (e.g. Fill 6805). More details in L. Medina et al., paper THPAB199, this conference.
• For realistic HL-LHC beams, SPS power limitations must be considered [17,18]. Power clamping implemented in the model; benchmarking is ongoing.
• Calculation of matrix convolutions [19] is computationally heavy, mainly due to the duration of the signals involved. Further performance optimisation is to be explored.

V. Conclusions

• Mirroring the system in the real machine, the implementation of the SPS cavity controller and its different filters has been done in CERN’s BLonD particle tracking code.
• In simulation, beam generation at SPS flat-top with realistic bunch phase offsets $\delta_{\phi,n}$ and halo dynamics can be achieved using the present cavity controller model.
• These beam distributions are used in studies of HL-LHC injection losses.
• As the bucket-by-bucket correction to the rf voltage is calculated on a turn-by-turn basis, special care was taken to ensure that the different current and voltage signals in the one-turn delay feedback, generator, and beam models are continuous, and computationally accurate.
• Work on coupling the cavity feedback with global feedback systems (such as the SPS beam phase loop) is ongoing.


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  From 2021: 4×3-section + 2×4-section for HL-LHC beams

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- Cavity control modelling is necessary to generate realistic beams at SPS extraction.
  
  - In particular, the bunch-by-bunch phase offsets $\Delta \phi_{\text{bb}}$ w.r.t. the rf buckets and beam halo.

- Beams are used in (HL-)LHC injection simulations where a reduced injection voltage is studied as means to mitigate possible power limitations of the present rf system [8—10].

- As in operation, the design (set point) voltage is partitioned between the two groups of TWCs. For simplicity, a single cavity controller is assigned per partition in BLonD [11—13].

  - The total rf voltage is the sum of the cavity (antenna) voltage regulated by each controller.
  
  - Each antenna voltage is the sum of the generator- and beam-induced voltages.
II. One-turn delay feedback

- Turn-by-turn, each OTFB calculates the correction needed to recover the partition’s design voltage.

- First, the **difference** between the antenna and the **set point** voltage is computed.
  - Signals sampled at the rf (carrier) frequency.

- This error signal is **processed** by a **comb filter**, effectively removing beam-loading [14].

- The TWCs’ filling time is taken into account in the one turn (exact) loop delay.

- The signal is then **modulated** to the TWCs central frequency.

- The **cavity response** is modelled as a moving average at 40 MS/s.
The correction by the OTFB is used to **regulate** the generator drive.

- **Generator current** given by the transmitter model.

The **generator-induced voltage** is the convolution of the generator current and the impulse reponse from the cavity towards the generator.

Likewise, the **beam-induced voltage** is the result of convolving the beam impulse response with the **rf component** (at the carrier frequency) of the **beam current**.

The **feedforward**, implemented as a FIR filter, improves the feedback correction [15].

The continuity of all signals must be ensured.
IV. Benchmark and Calibration

- **Benchmark** with measured $\Delta \phi_{bb}$ of a 72-bunch batch in a previous analysis [16] with a static impedance-reduction model.
  - Better agreement with measurements; added advantage of more realistic halo dynamics.

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- Calculation of matrix convolutions [19] is computationally heavy, mainly due to the duration of the signals involved. Further performance optimisation to be explored.
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