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

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

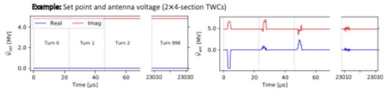
Abstract

To accurate 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

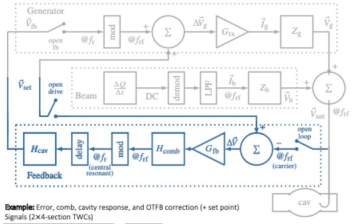
- Travelling wave cavities (**TWCs**) in the SPS [2–5]:
  - Until 2018: 2×4-section + 2×5-section LHC Runs 1 and 2
  - From 2021: 4×3-section + 2×4-section for HL-LHC beams
- To reduce the effective cavity impedance seen by the beam, a **cavity controller** with a **one-turn delay feedback** (**OTFB**) [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** $\Delta\phi_{bb}$ 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**.

Example: Set point and antenna voltage (2×4-section TWCs)

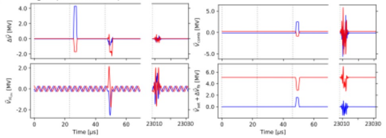


II. One-turn delay feedback

- 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.

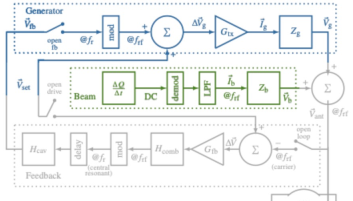


Example: Error, comb, cavity response, and OTFB correction (+ set point) Signals (2×4-section TWCs)

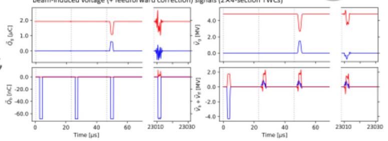


III. Generator-beam-cavity interactions

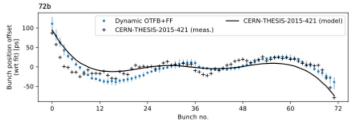
- The correction by the OTFB is used to **regulate** the generator drive.
  - **Generator current** given by the transmitter model.
- The **generator-induced voltage** is the convolution of the generator current and the impulse reponse from the cavity towards the generator.
- Likewise, the **beam-induced 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.

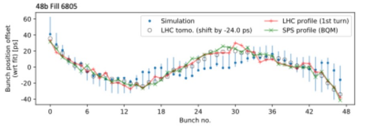


Example: Generator current, generator-induced voltage, rf beam current, and beam-induced voltage (+ feedforward correction) signals (2×4-section TWCs)



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.
- **Calibration** with measurements from **Run 2** to reproduce $\Delta\phi_{bb}$ patterns in 48b 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 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** $\Delta\phi_{bb}$ and **halo** dynamics can be achieved using the present cavity controller model.
  - These beam distributions are used is **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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Acknowledgments: H. Damerau, G. Hagmann, W. Höfle, T. Mastoridis, and E. Shaposhnikova (CERN).

References: [1] The High Luminosity LHC Project, https://hilumilhc.web.cern.ch, [2] G. Dôme, https://cds.cern.ch/record/319440, [3] T. Bohl *et al.*, https://cds.cern.ch/record/485855, [4] H. Damerau *et al.*, doi:10.5170/CERN-2014-006.127, [5] G. Hagmann *et al.*, doi:10.18429/JACoW-IPAC2019-THPRB082, [6] D. Boussard, doi:10.1109/TNS.1985.4333745, [7] P. Baudrenghien *et al.*, https://cds.cern.ch/record/485863, [8] H. Timko *et al.*, doi:10.18429/JACoW-HB2018- TUP1WA03, [9] L. Medina *et al.*, THPAB199, *this conference*, [10] L. Medina *et al.*, https://cds.cern.ch/record/2683350, [11] CERN BLonD Simulation Suite, http://blond.web.cern.ch, [12] CERN BLonD Simulation suite GitHub repository, https://github.com/blond-admin/BLonD, [13] H. Timko *et al.*, *to be submitted*, [14] D. Boussard, doi:10.5170/CERN-1995-006.415, [15] P. Baudrenghien *et al.*, CERN- ACC-NOTE-2020-0032, [16] T. Argyropoulos, https://cds.cern.ch/record/2285796, [17] I. Karpov *et al.*, https://indico.cern.ch/event/948799, [18] T. Mastoridi and P. Baudrenghien, private communication, [19] SciPy Reference Guide (scipy.signal.fftconvolve), https:// docs.scipy.org/

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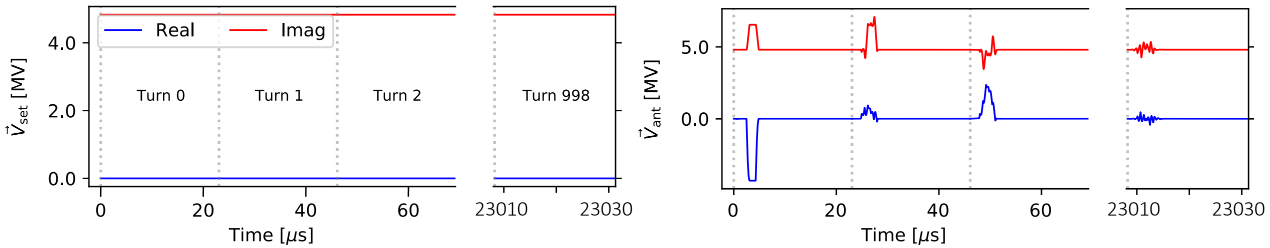

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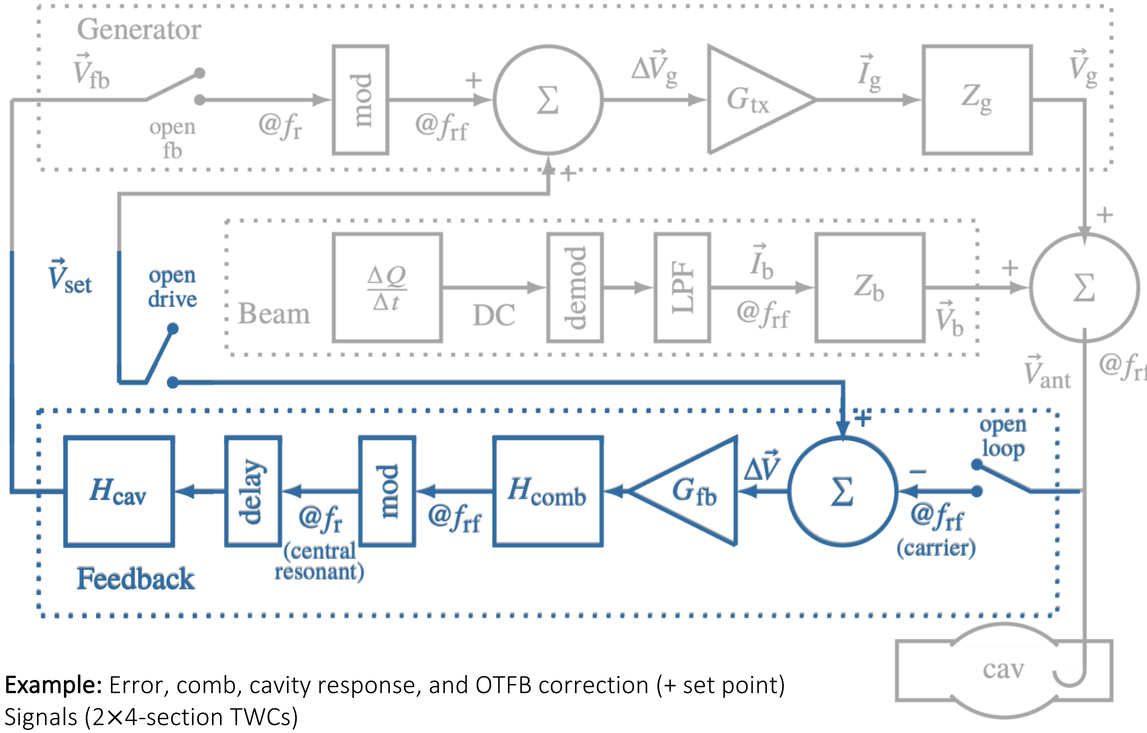

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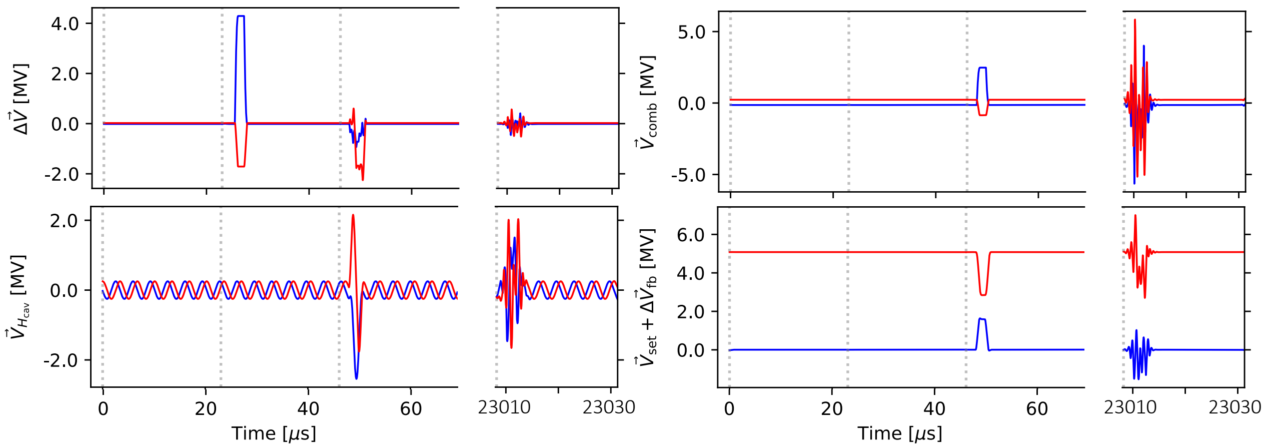

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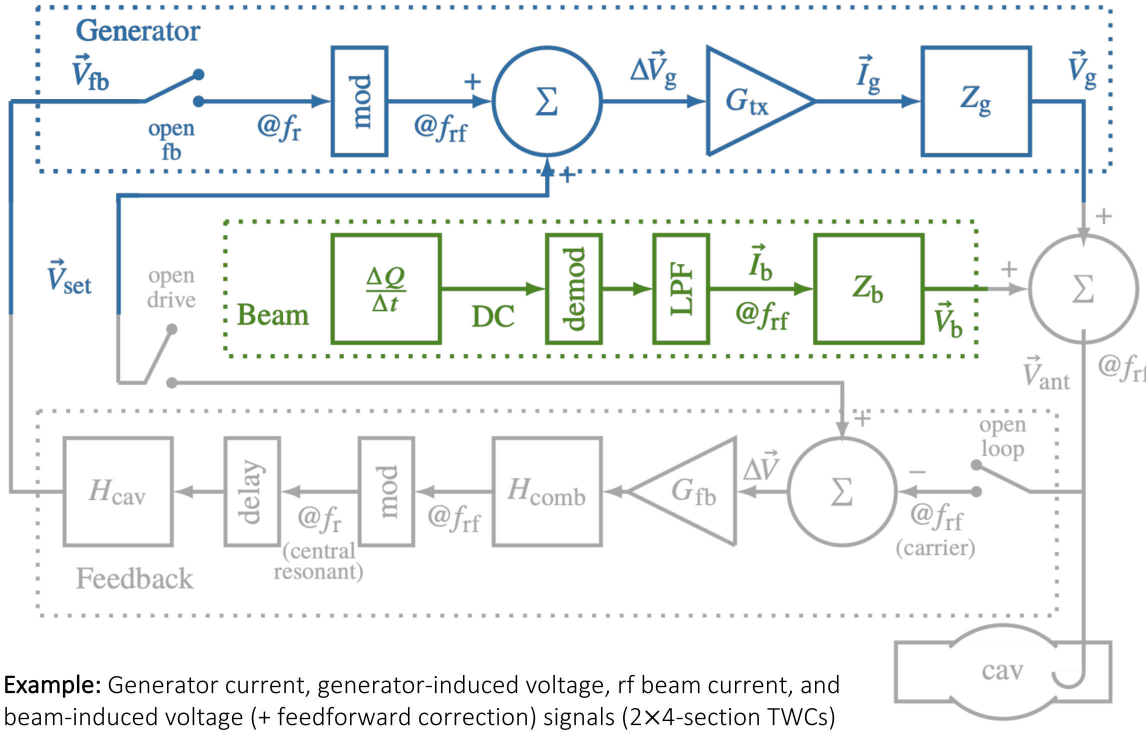

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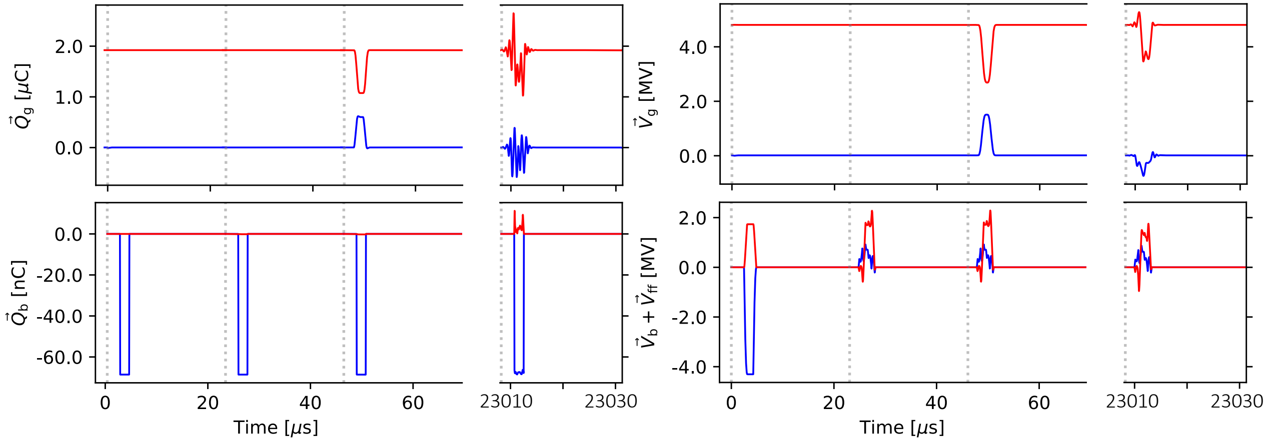

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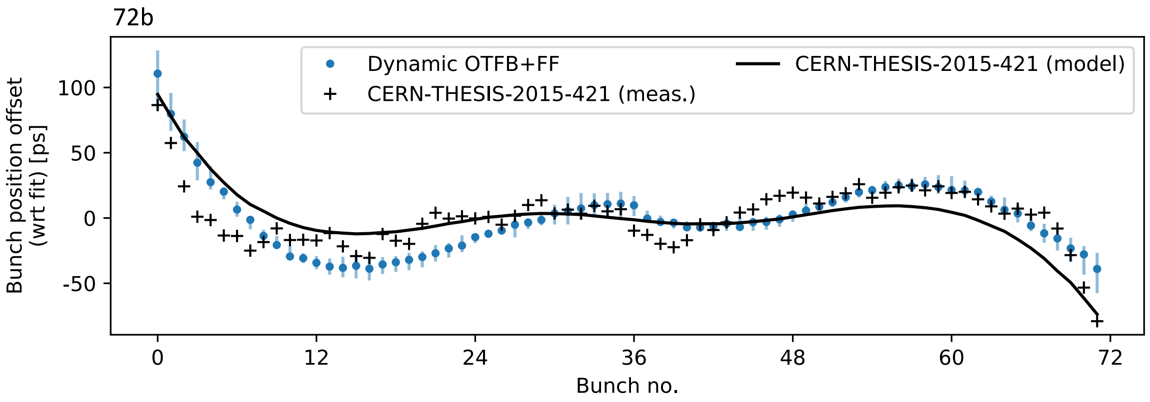

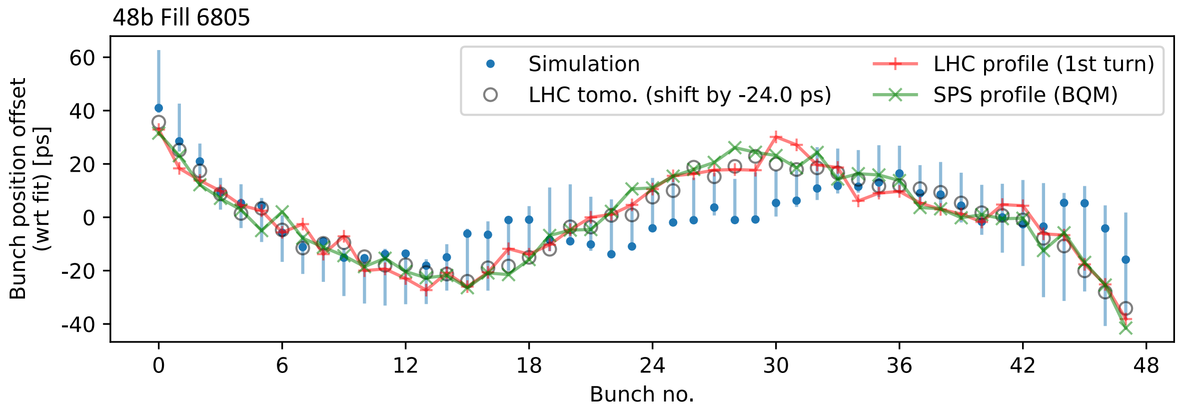

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