Modelling SPS and LHC Cavity Loops

for HL-LHC injection Studies

B. E. Karlsen-Bæck
Supervisors:

H. Timko, T. Argyropoulos
CERN, Geneva, Switzerland,

Introduction

HL-LHC injection studies - Want to see if the present LHC RF system will be able to capture an HL-LHC type beam without significant losses

- Expect RF power limitations at injection for the HiLumi intensity beam
- SPS cavity loop model to generate realistic beams at SPS flattop
- LHC cavity loop model to accurately model turn-by-turn and bunch-by-bunch power consumption and beam dynamics at injection

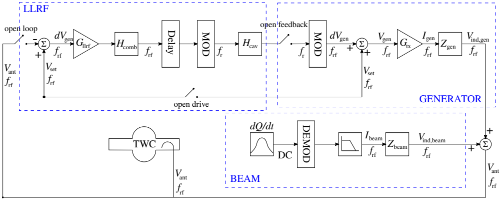
Cavity Loops

SPS Cavity Controller

Consisting of the One-Turn Delay Feedback (OTFB) and Feed-Forward (FF) systems

- Normal-conducting traveling wave cavities
- Coarse- and fine-grid resolution
- Time-domain filters
- Cavity impedance towards beam and generator
- Feed-forward (not plotted)

SPS One Turn Feedback

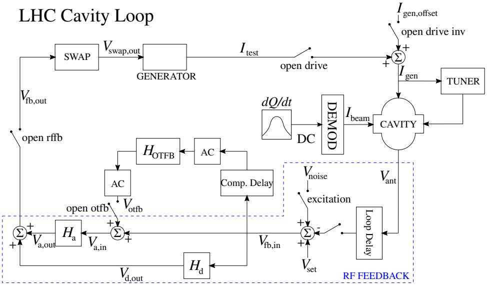


Block diagram of the SPS OTFB model

LHC Cavity Controller

Consisting of the Radio-Frequency Feedback (RFFB) and One-Turn Delay Feedback (OTFB) systems

- Superconducting standing wave cavities
- Coarse- and fine-grid
- Time-domain filters
- RF Feedback with digital (low-pass) and analog (high-pass) branches
- LHC one-turn delay feedback



Block diagram of the LHC cavity loop model

SPS Cavity Loop Benchmark

SPS Benchmark Strategy

- Unittests for each building block
- Testing and validation of Generator- and LLRF-part of model
- Full SPS OTFB model compared with theory for a full machine
- SPS OTFB model for standard 25 ns beam (4×72b) compared with measurements from Nov 2021
- Basic tests of the FF system

```python
def test_gen_response(self):
    # Tests generator response at resonant frequency.
    self.OTFB.I_GEN = np.zeros(2 * self.OTFB.n_coarse,
                               dtype=complex)
    self.OTFB.I_GEN[self.OTFB.n_coarse] = 1

    self.OTFB.TWC.impulse_response_gen(self.OTFB.TWC.omega_r,
                                       self.OTFB.rf_centers)
    self.OTFB.gen_response()

    sig = np.zeros(self.OTFB.n_coarse)
    sig[1:1 + self.OTFB.n_mov_av] = \
        4 * self.OTFB.TWC.R_gen / self.OTFB.TWC.tau
    sig[0] = \
        2 * self.OTFB.TWC.R_gen / self.OTFB.TWC.tau
    sig[self.OTFB.n_mov_av + 1] = \
        2 * self.OTFB.TWC.R_gen / self.OTFB.TWC.tau
    sig *= self.OTFB.T_s

    np.testing.assert_allclose(
        np.abs(self.OTFB.V_IND_COARSE_GEN[-self.OTFB.n_coarse:]),
        sig, atol=5e-5)
```

Example of a unittest

SPS OTFB Full Machine

- One bunch every fifth bucket, each with 2.3×10^{11} p/b and 1.2 ns bunch length
- Derive steady-state equations for generator current, assuming infinite gain
- Compare with simulation

$$V_{\mathrm{I,gen}} = 2\frac{R_{\mathrm{gen}}}{\tau\Delta\omega}\sin\left(\Delta\omega\frac{\tau}{2}\right) I_{\mathrm{I,gen}}$$

$$V_{\mathrm{Q,gen}} = 2\frac{R_{\mathrm{gen}}}{\tau\Delta\omega}\sin\left(\Delta\omega\frac{\tau}{2}\right) I_{\mathrm{Q,gen}}$$

$$V_{\mathrm{I,beam}} = -\frac{2R_{\mathrm{beam}}}{\tau^2\Delta\omega^2}\left(1-\cos\left(\Delta\omega\tau\right)\right) I_{\mathrm{I,beam}}$$

$$V_{\mathrm{Q,beam}} = -\frac{2R_{\mathrm{beam}}}{\tau\Delta\omega}\left(1-\frac{1}{\tau\Delta\omega}\sin\left(\Delta\omega\tau\right)\right) I_{\mathrm{I,beam}}$$

SPS OTFB Full Machine - IQ-vectors

- Without beam:

  theory → 439.8 kW (3-sec), 863.5 kW (4-sec)

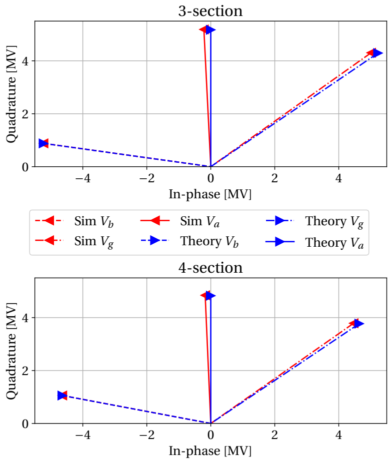
  sim → 430.1 kW (3-sec), 853.7 kW (4-sec)

- With beam:

  theory → 752.3 kW (3-sec), 1324.7 kW (4-sec)

  sim → 718.2 kW (3-sec), 1282.2 kW (4-sec)

- Uncompensated negative real part of the antenna voltage → error in power

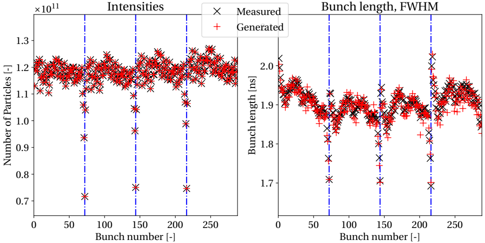


SPS OTFB with standard 25 ns beam

Measurement Conditions

Table: Notice the uncertainty in gain

Parameter	200 MHz	800 MHz
V	6.7 MV	1.27 MV
h	4620	18480
ϕ_s	0	π
α_{comb}	31/32	-
G_{LLRF}	16-20	-
E_s	440 GeV	-



Generated and measured bunch intensities and bunch lengths for standard 25 ns beam (4×72b)

SPS OTFB with standard 25 ns beam

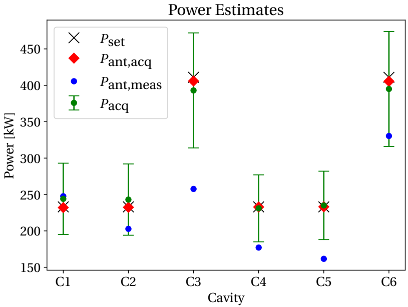
Uncertainties in Measurements

- Power measurement error from transmission line ± 20 %
- Flat-bottom measurements indicate -11 % error in antenna voltage
- TWC resonant frequency measurements:

  designed $\rightarrow$ 200.222 MHz,

  2018 $\rightarrow$ 200.1 MHz,

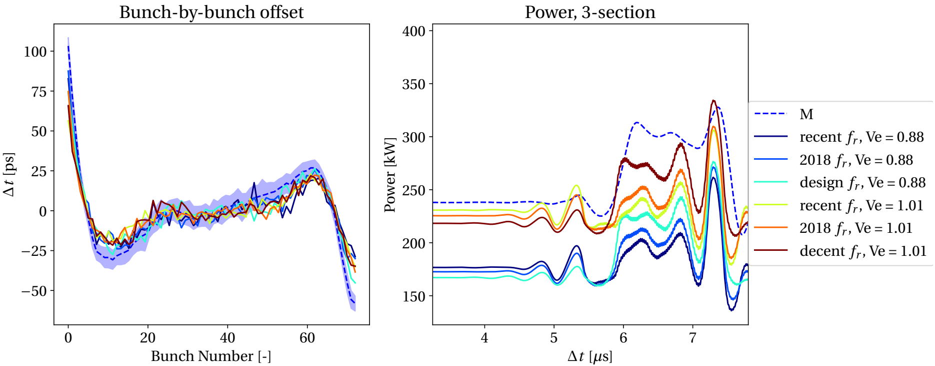
  recent $\rightarrow$ 199.995 MHz (4-sec) and 200.038 MHz (3-sec)



Different estimates of the power in no-beam segment

SPS OTFB with standard 25 ns beam

Recreation in simulations



Simulations with best-case and worst-case antenna voltages

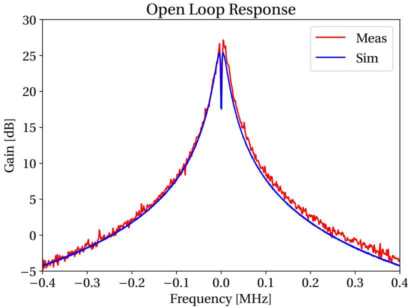
LHC Cavity Loop Benchmark

LHC Benchmark Strategy

- Comparing open loop and closed loop responses of the RFFB with measurement (without beam)
- Forseen for the future:
  - Benchmarking the OTFB closed-loop response
  - Benchmarking with beam against measurements

LHC Open Loop Transfer Function

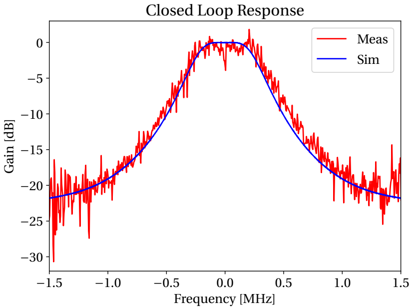
- The open loop response is dominated by the cavity response
- This measurement is used to calibrate the Q_L (17082 in figure)
- Good agreement between simulation and measurement



Measurement of cavity 1B1 and simulated model

LHC Closed Loop Transfer Function

- Closed loop response is used to adjust the gain and the phase of the RFFB to have a flat response at $\pm$ 300 kHz band
- Comparison with well adjusted RFFB
- Some discrepancy on the width, but the gain, phase and overall behavior are well described



Measurement of cavity 1B1 and simulated model

Outlook

- Waiting to acquire data for SPS FF implementation and simulate the SPS FF with beam
- Final refinement of the LHC OTFB (FIR filters) and benchmark with beam measurements
- Coupling the BLonD cavity- and beam-control loops
- After all this, we are ready to perform injection simulations with the implemented models

Conclusion

- The SPS OTFB is now extensively benchmarked and shows good agreement with measurement and theory
- The SPS FF implementation agrees with design, a benchmark with beam is yet to be performed
- The LHC RFFB shows good agreement in open- and closed loop transfer function measurements
- LHC OTFB refinement is ongoing

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