One-Turn Delay Feedback with a Fractional Delay Filter

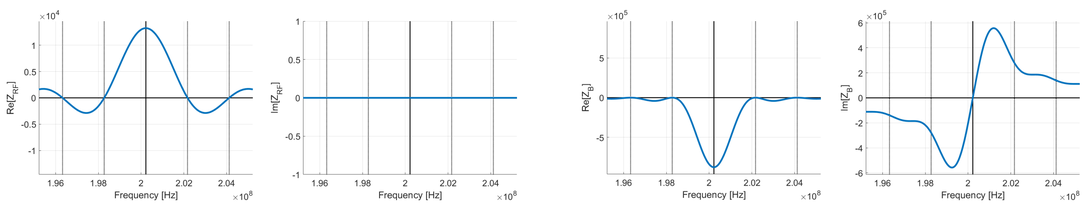
Lorenz Schmid, Philippe Baudrenghien, Gregoire Hagmann
CERN, Geneva, Switzerland

LLRF 2017
Barcelona

Overview Cavity Controller SPS TWC200

- The Super Proton Synchrotron (SPS) at CERN accelerates protons and ions, which require a large change in f_{rev} during acceleration. Acceleration performed by 200 MHz and 800 MHz travelling wave cavities.

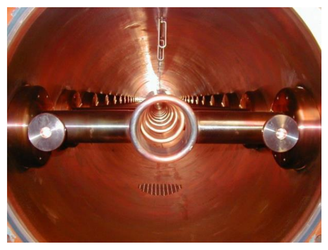
- Travelling Wave Cavities (TWC)
  - High bandwidth / low quality factor / low filling time (450 to 600 ns)
  - Different impedance seen by generator (RF) and beam (beam loading) [1] [2]:



Z_{RF} (4 section cavity) Z_{beam}

  - ➢ Z_{RF} crosses zero: Requires filter with phase inversion
  - ➢ $Z_{\mathrm{beam}} \neq 0$ when $Z_{\mathrm{RF}} = 0$: No compensation possible

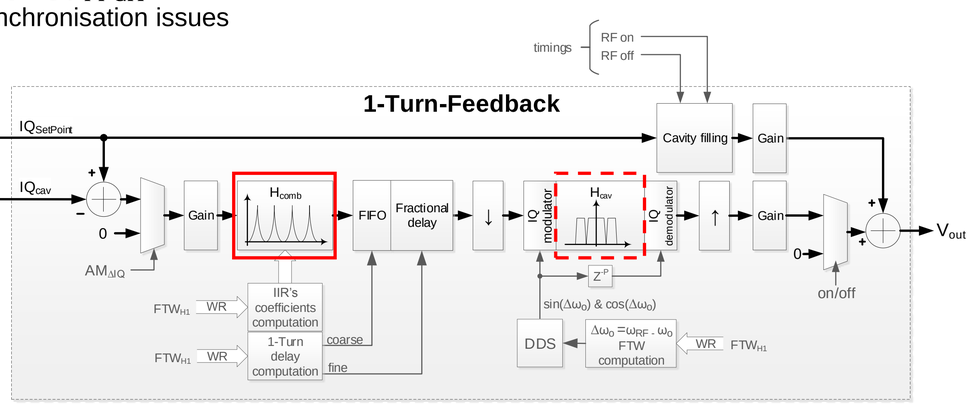
- LLRF feedback system compensates:
  - Cavity phase inversion: H_{cav} filter
  - Beam loading at harmonics of f_{rev}: H_{comb} filter compensated with delay of one turn (1-Turn-Feedback)



- Update of existing TWC 200MHz cavity controller for the High Luminosity LHC upgrade (until 2020) [3] to achieve higher gain and therefore, allow compensation for higher luminosity:

Current System
- Sampling frequency and FPGA clock are coupled to f_{rev}
- Allows **fixed filter settings** for H_{comb}
- As f_{rev} is increased during one cycle (particle acceleration) so is f_{FPGA}
- **Varying** f_{FPGA} risks to create synchronisation issues

New System
- Use fixed sampling frequency and FPGA clock, uncoupled to f_{rev}
- **Adapt filter settings continuously** to f_{rev}
- **Constant** f_{FPGA}, no synchroisation issues

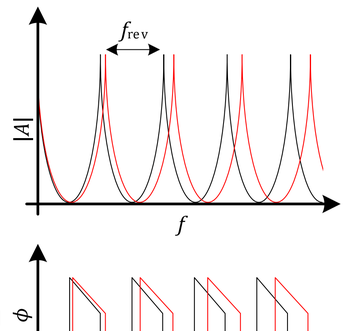


Biquad Filter with Fractional Delay Filter

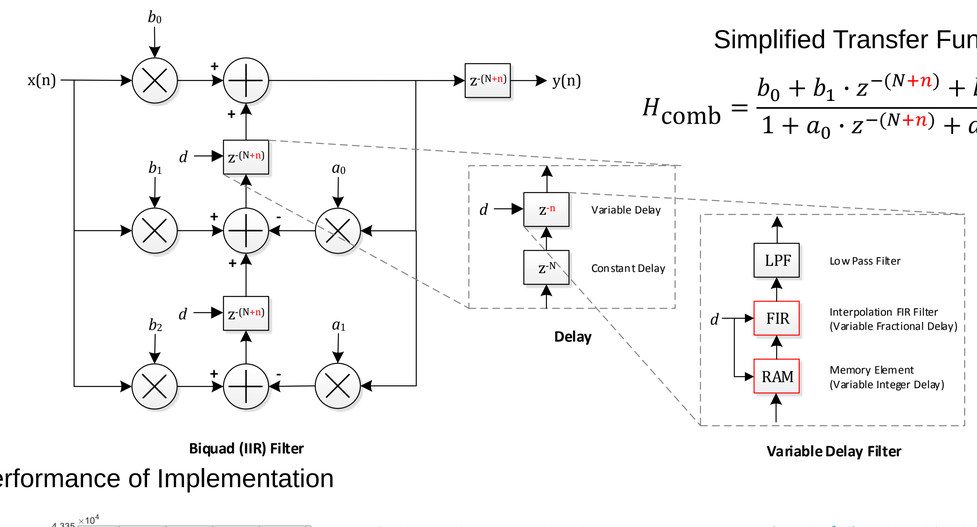
- Beam loading is compensated with a **Biquad (IIR) filter**, H_{comb}
  - Homothetic repetition of peaks at $k \cdot f_{\mathrm{rev}}$ in spectrum
  - f_{rev} is proportional to f_{RF}, thus varies during acceleration

- Properties
  - Exact peak-to-peak distance of f_{rev} (around 43.3 kHz)
  - Low $\partial f_{\mathrm{rev}}/\partial t$ change rate of maximal 492 Hz/s
  - High gain of 32 dB
  - Sampling frequency of 62.5 MHz
  - Bandwidth of ± 3 MHz around cavity center frequency, f_{cav} (200.222 MHz)
  - Extremely narrow resonance bandwidth of 100 Hz (single sided)
  - Data path resolution of 24 bit signed

Filter Response



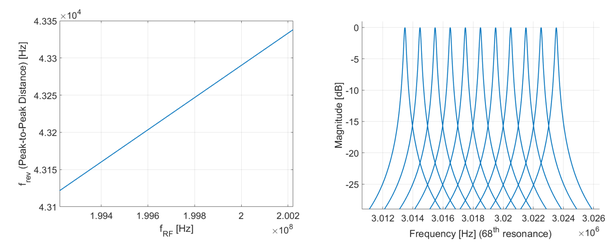
- Peak-to-peak distance given by **internal delay** in Biquad filter
  - Variable delay filter adapts internal delay to varying f_{rev} during operation
  - **Variable integer delay**:
    - ➢ Memory Element with variable integer delay via addressing
  - **Variable fractional delay**:
    - ➢ Fractional Delay Filter (FDF) based on a 4th order Lagrange polynomial interpolation
    - ➢ Low Pass Filter to avoid instabilities in closed loop feedback



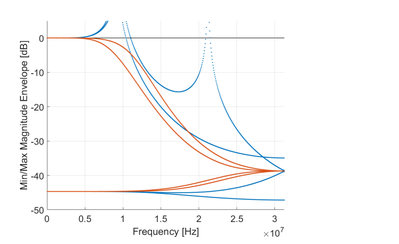
Simplified Transfer Function

$$H_{\mathrm{comb}} = \frac{b_0 + b_1 \cdot z^{-(N+n)} + b_2 \cdot z^{-2(N+n)}}{1 + a_0 \cdot z^{-(N+n)} + a_1 \cdot z^{-2(N+n)}}$$

Performance of Implementation



Linearity: $f_{\mathrm{RF}} = 199.222 \rightarrow 200.222$ MHz

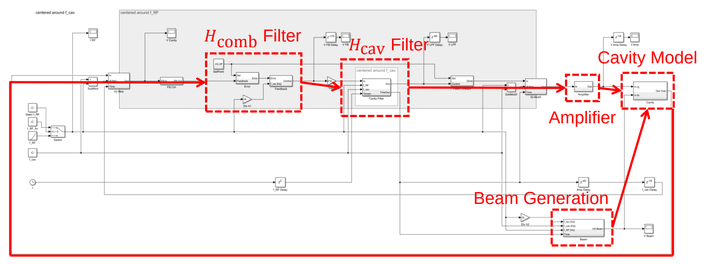


Bandwidth & Stability (with/without LPF)

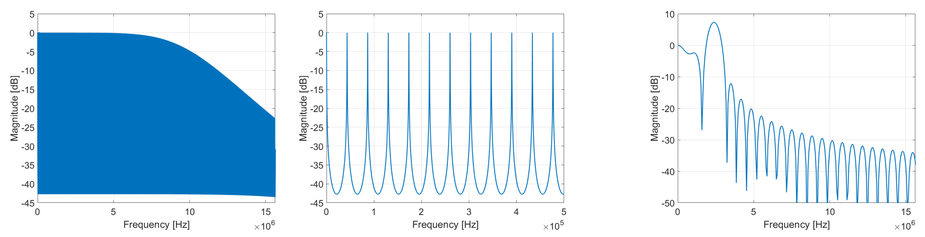
Cavity Loop Simulation

- Complete low level RF simulation:
  - Cavity Controller
  - Cavity model (T. Mastoridis and J. Galindo)
  - Beam disturbance
  - Correct 1-Turn Delay
  - Up-/Down modulation around baseband

- Implemented in MATLAB Simulink / System Generator
  - Models based on S-functions
  - HW implementation for Xilinx Series 7
- Allows verifying cavity controller during f_{rev} variations

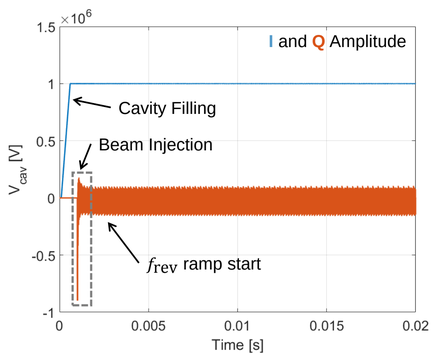


Filter Frequency Response

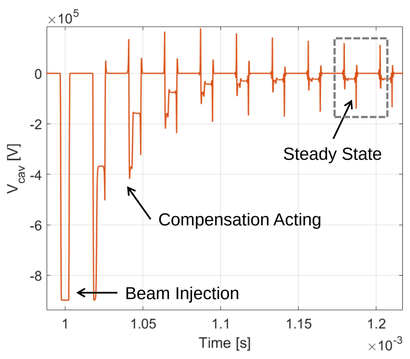


H_{comb} H_{cav}

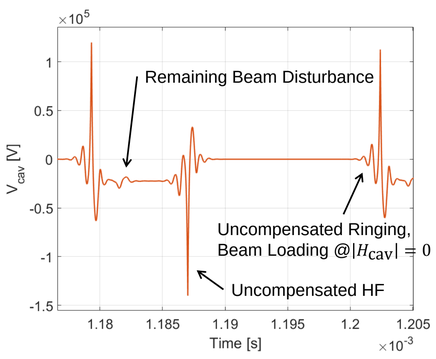
Beam Loading Compensation Simulation



f_{rev} ramp of 49.2 kHz/s ($\times 100$)

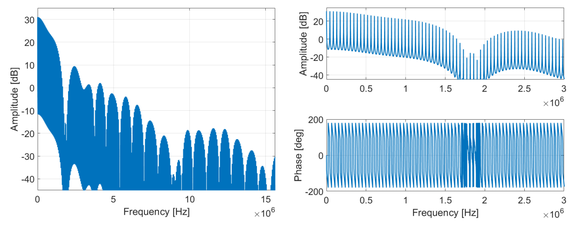


All beam disturbance on Q channel ($f_{\mathrm{RF}} = f_{\mathrm{cav}}$ @ $t_{\mathrm{sim}} = 0$)

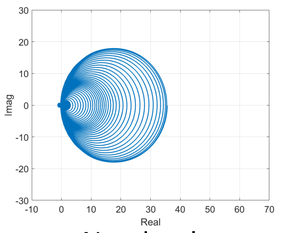


Compensation Gain of 32 dB

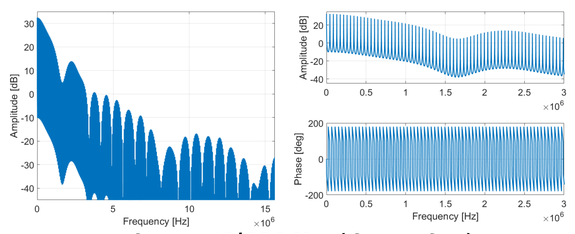
Simulation Frequency Response (Open Loop)



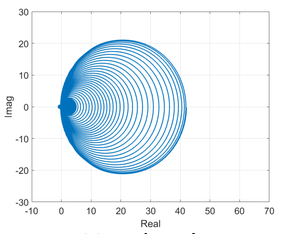
$f_{\mathrm{rev}} = 43'230$ Hz



Nyquist plot



$f_{\mathrm{rev}} = 43'338$ Hz ($f_{\mathrm{RF}} = f_{\mathrm{cav}}$)



Nyquist plot

POSTER P-77

lorenz.schmid@cern.ch

REFERENCES

[1] G. Dome, *The SPS Acceleration System*, Proc. 1976 Proton Linac Conf. Chalk River, Canada, 138-147 (1976)
[2] P. Baudrenghien, G. Lambert, *Reducing the Impedance of the Travelling Wave Cavities Feed-Forward and One Turn Delay Feedback*, Proc. of the Workshop on LEP-SPS Performance Chamonix, France, 94-101 (2000)
[3] G. Hagmann & al., *SPS LLRF Upgrade project*, LLRF Workshop 2017, Barcelona, Spain, Poster P-92