Feedback stabilisation of longitudinal quadrupole coupled-bunch oscillations in the CERN PS

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Low-Level RF Workshop 2022, Brugg-Windisch, Switzerland

Summary of PS Coupled-Bunch Feedback

Longitudinal instability

Mutipole mode m

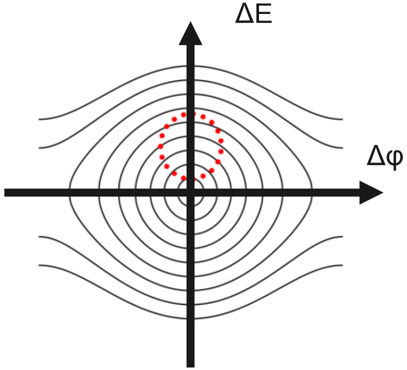
- determines shape in phase space

Coupled-bunch mode n

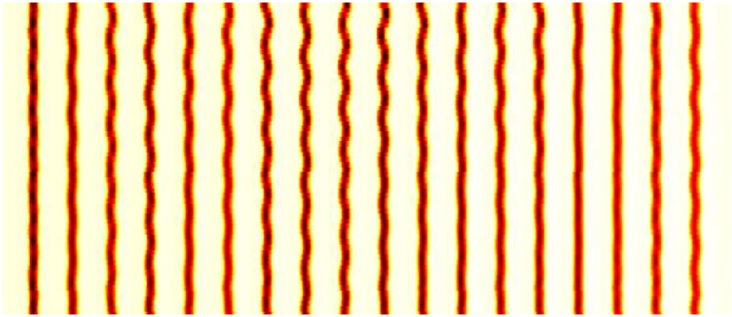
- determines phase shift between bunches
- N bunches = N possible modes

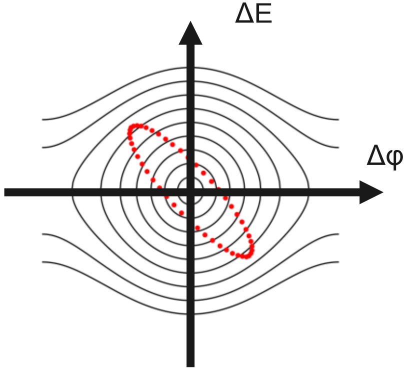
Produces sidebands in beam spectrum at $f = (n + kN)\, f_{rev} + m\, f_s$

Stabilised in the PS using a wideband Finemet kicker cavity

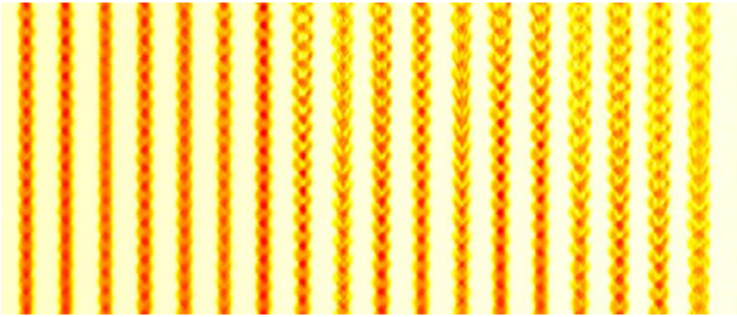


Example of dipole CB oscillations





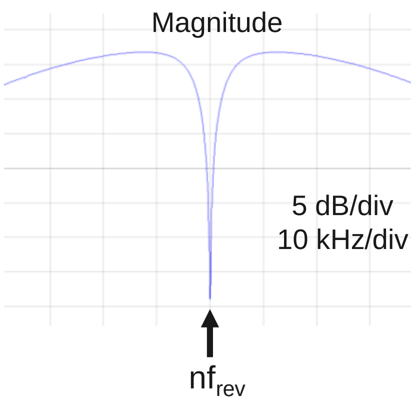
Example of quadrupole CB oscillations

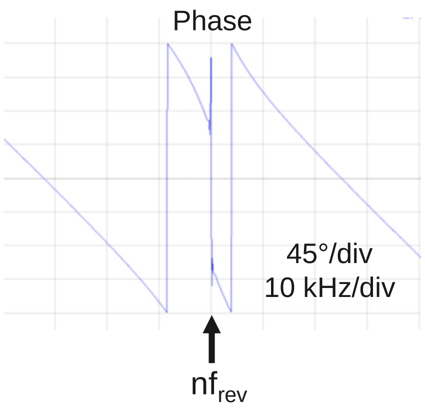


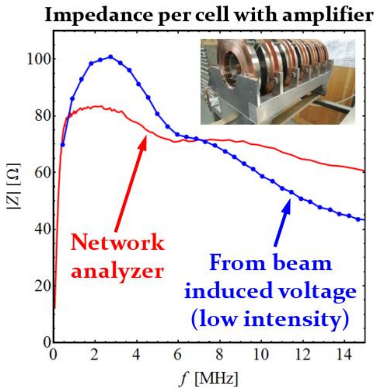
Dipole-Mode Feedback

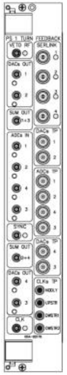
PS Dipole Coupled-Bunch Feedback

- **Frequency-domain approach**
  - Beam-synchronous h256 clock
  - Measure and feed back on n $f_{rev} \pm f_s$ sidebands
  - Central notch to remove f_{rev} harmonic
  - 10 signal processing channels spread over 3 PS One-Turn Feedback boards (Stratix-II FPGA, 16Mbit SRAM, 4 x 14-bit ADCs & DACs).
- **Higher cavity impedance at low frequencies, sidebands stronger at high frequencies**
  - Use symmetry of frequency spectrum: USB of h20 → LSB of h1, etc.
  - Each channel stabilises 2 modes: 180° phase jump
- **New features since LS2:**
  - Control of feedback gains and excitation parameters with programmable functions.
  - Acquisition of baseband signals at 10 kHz sample rate.

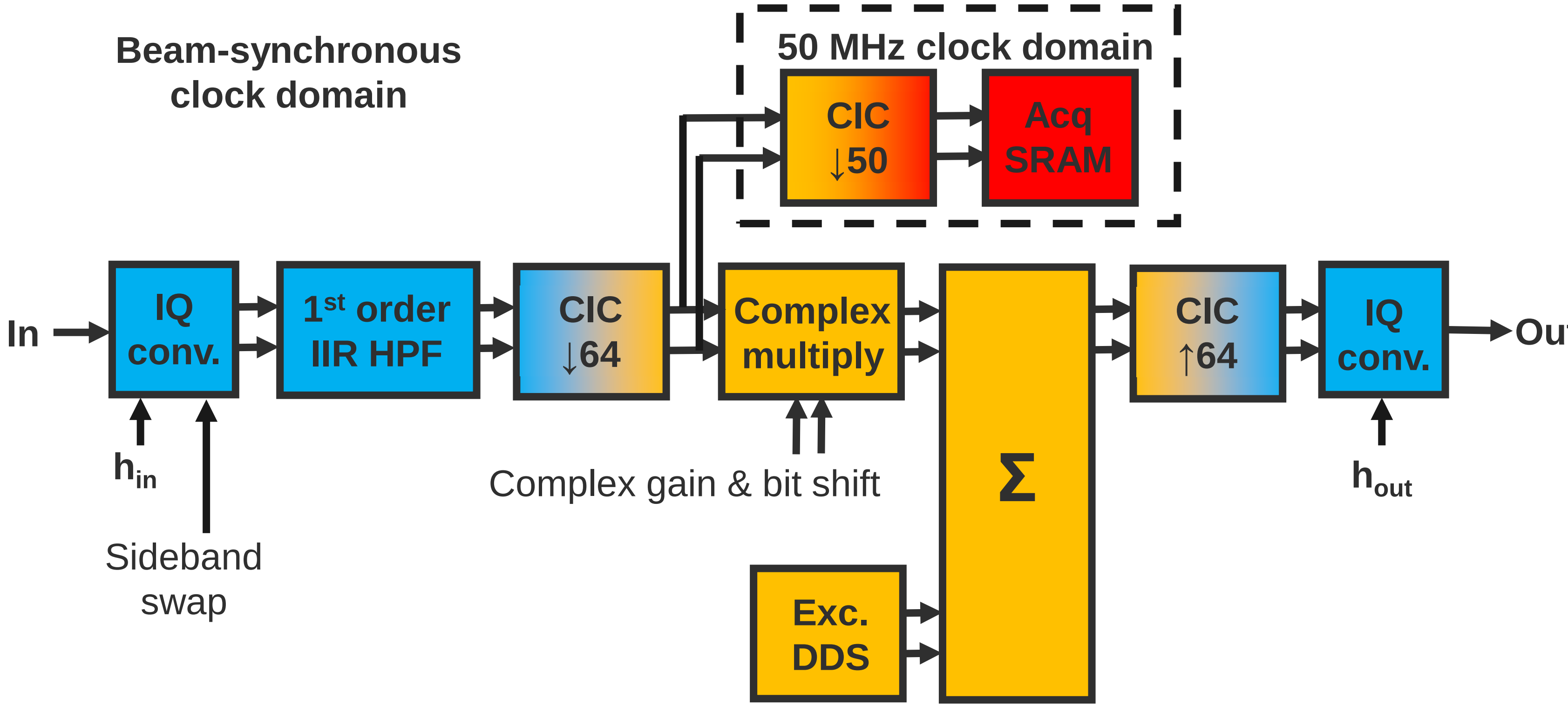








DSP Channel Simplified Block Diagram

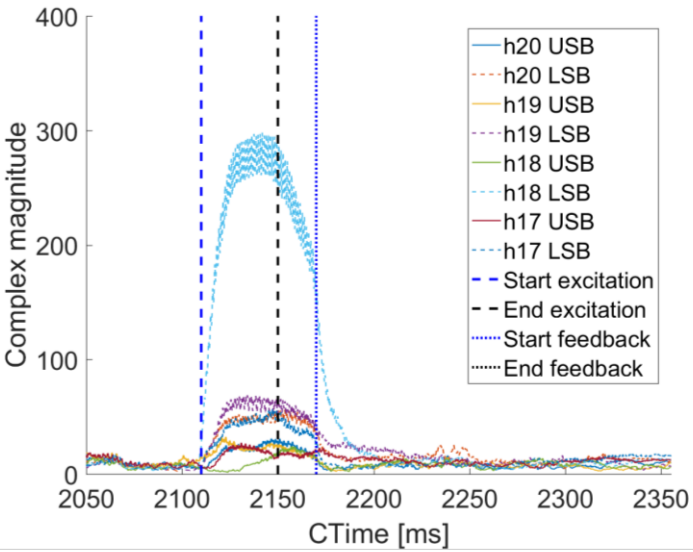


sample rates: 30 MHz 468 kHz 10 kHz

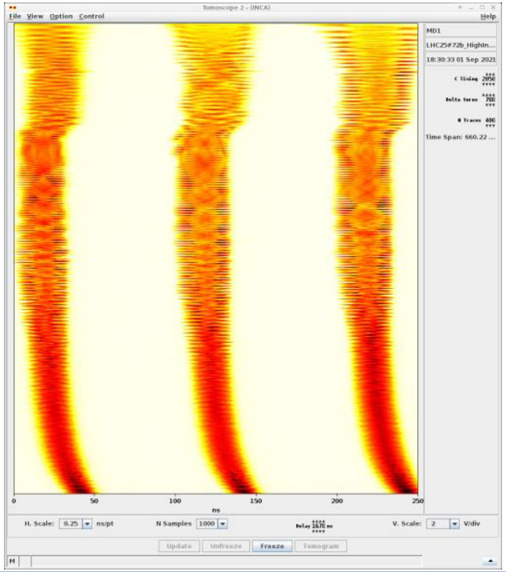
Use in Operations

- **Internal acquisition provides a useful diagnostic of coupled-bunch modes**
- **Essential for LHC-type beams at LIU intensity, even with h84 Landau cavity**
- **Residual quadrupolar oscillations**

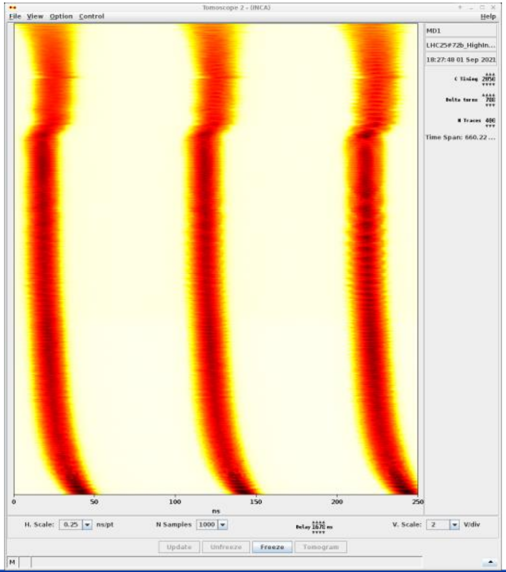
Mode amplitudes after excitation test:



Without feedback:



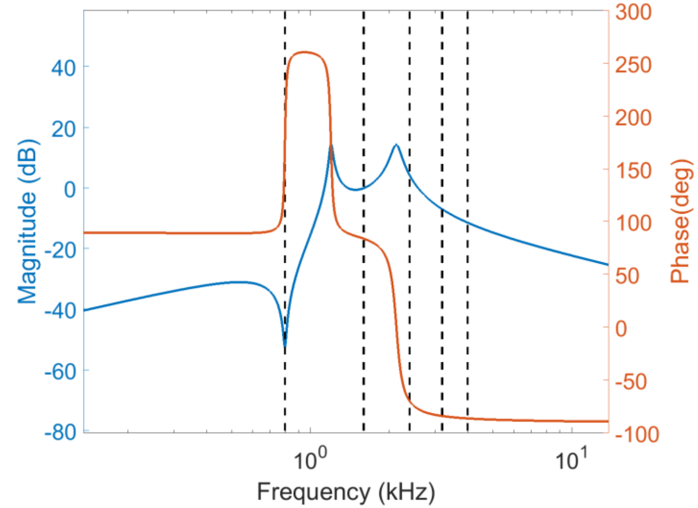
With feedback:

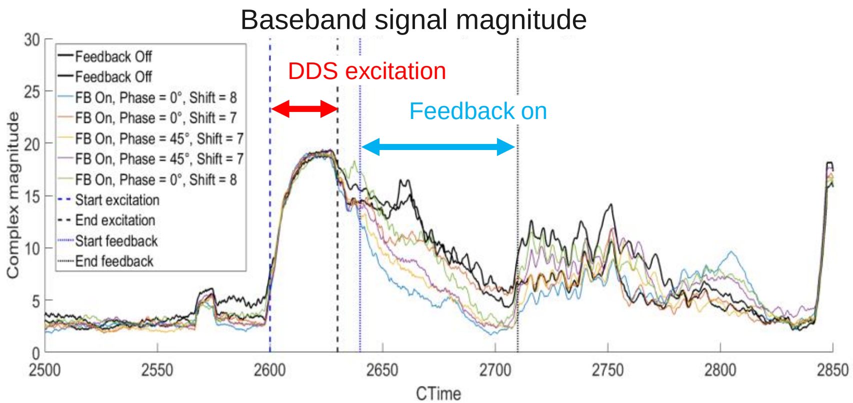


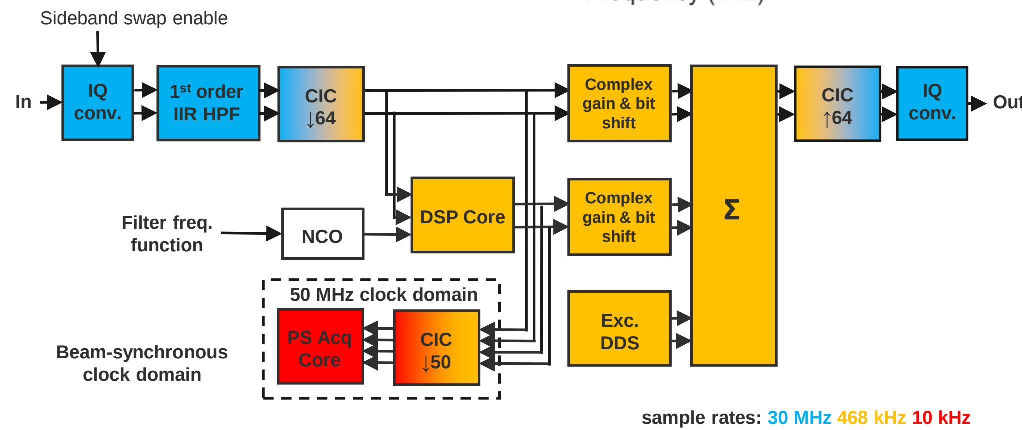
Quadrupole-Mode Feedback

First Attempt : Narrowband Filters

- **New feedback channel for quadrupole modes only**
- **Attenuate dipole (±1*f_s) sidebands with IIR filters**
  - Filter needs to track synchrotron frequency during ramping: IIR filter sample rate controlled by programmed function.
- **Rejection of dipole oscillations worked well**
- **Poor damping, difficult to tune**

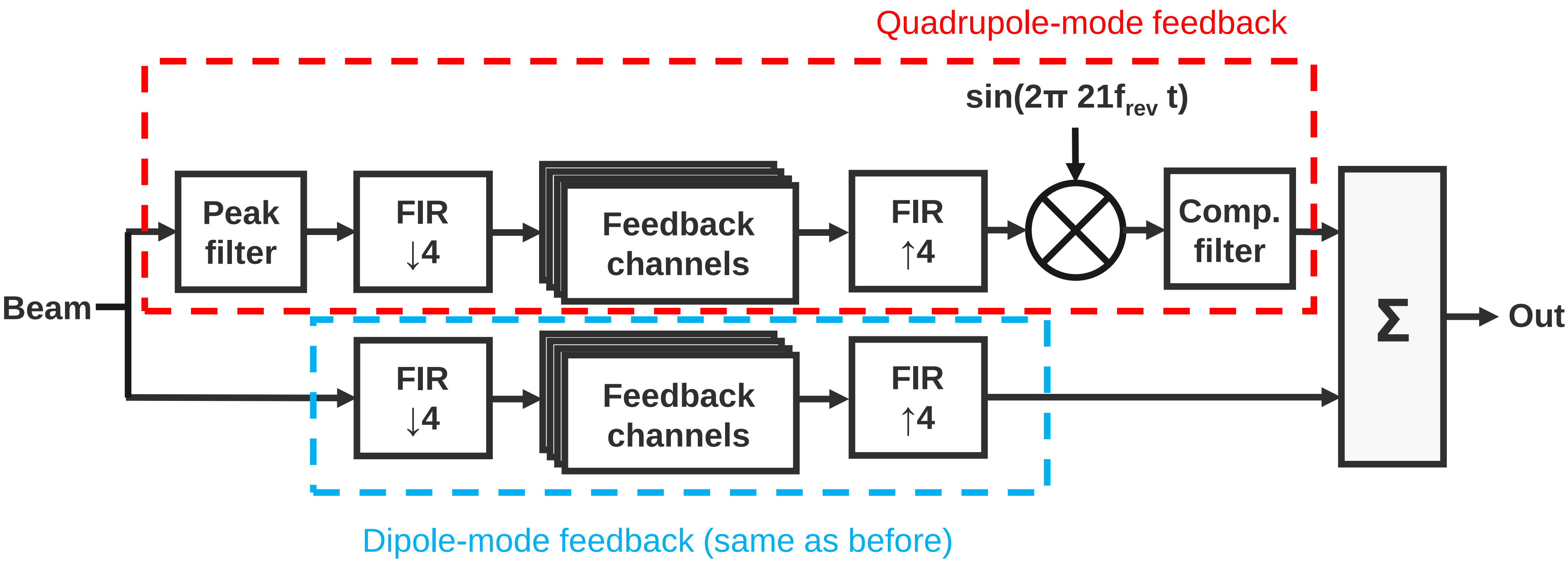






Second Attempt

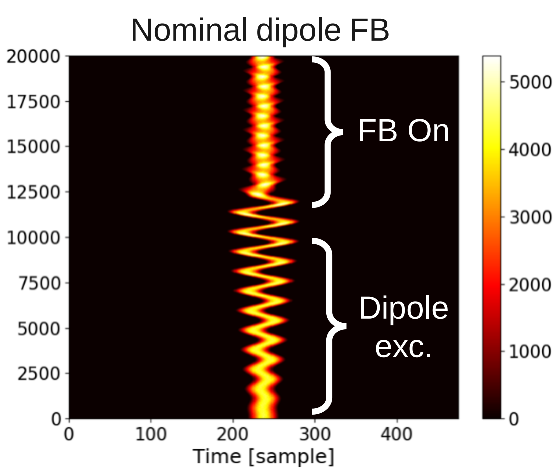
- **Transient response of narrow filters caused issues**
- **Try to decouple quadrupole and dipole signals in a broadband manner**

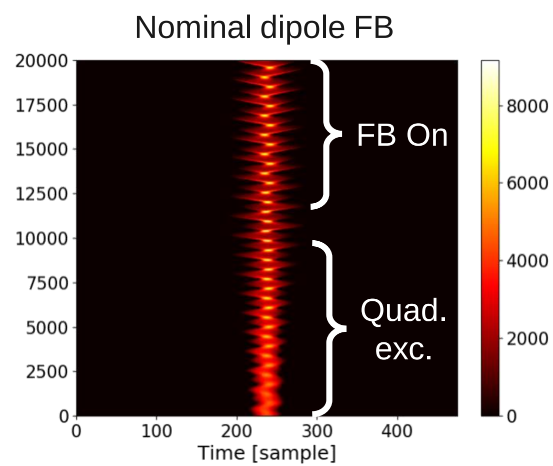


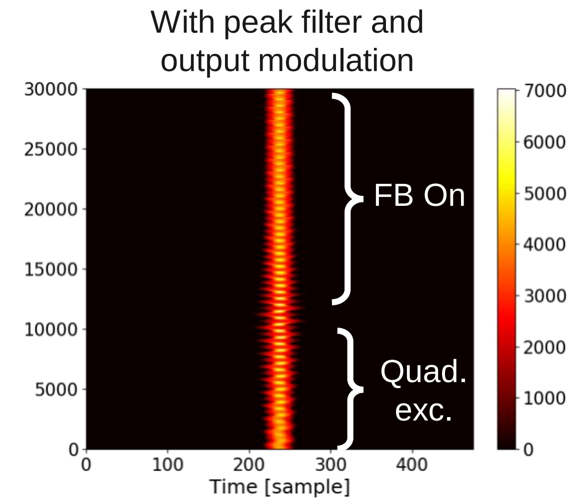
BLonD : Comparison of Feedback Designs

- **Performed a series of longitudinal beam dynamics simulations using BLonD to evaluate alternative schemes.**
  - Minimal model of PS : 15 GeV, 21 bunches of 4*2.6e11 p^+ each, V_{RF} = 168 kV, no impedances
  - Implement model of existing dipole feedback as a test
  - Excite coupled-bunch mode for 10000 turns, then turn feedback on 2000 turns later.

- **Nominal dipole feedback tends to excite dipole oscillations instead of damping quadrupole oscillations**
  - Modifications work well to decouple quadrupole and dipole feedbacks

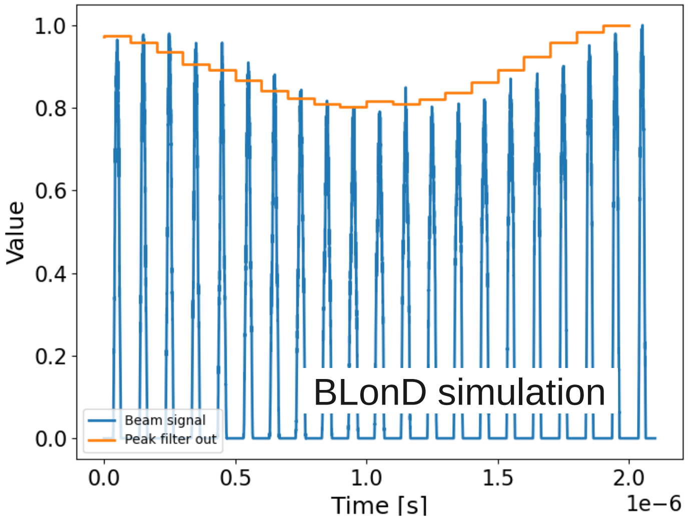


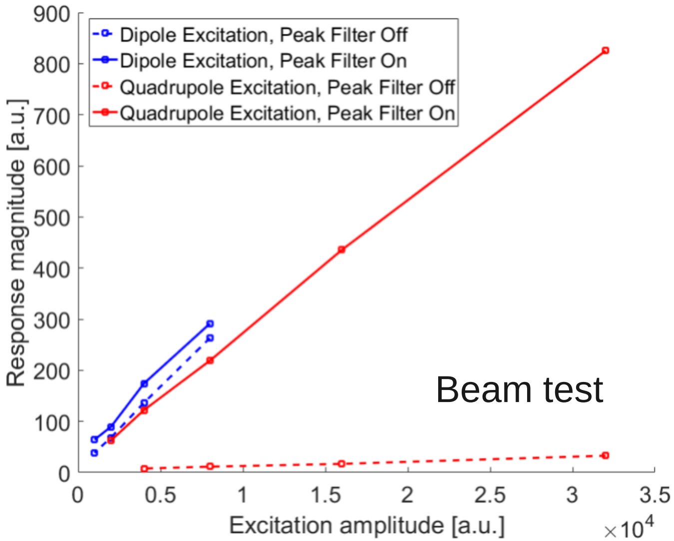




Peak Detection Filter

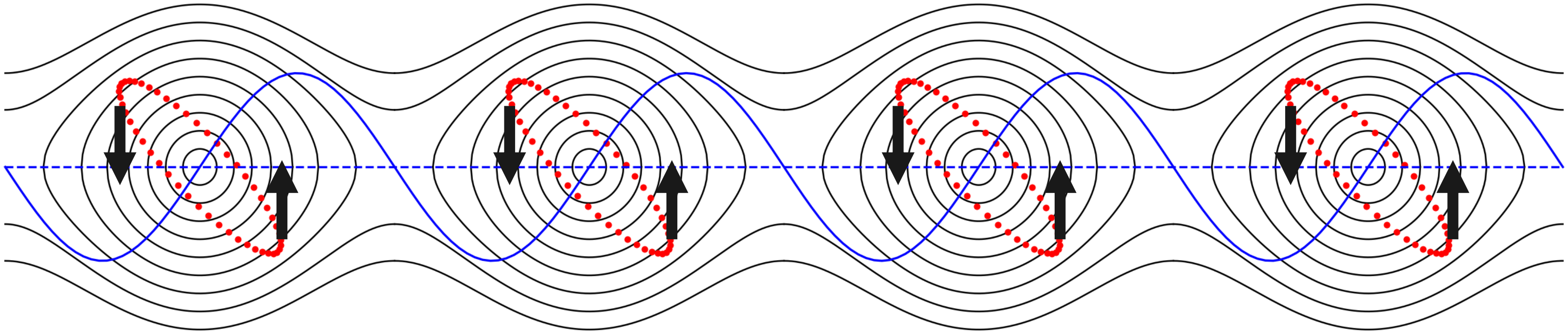
- **'Peak detection filter' applied to input signal before downmixers**
  - Find the peak value in each bucket, then populate all the samples corresponding to that bucket with the peak value.
  - Small dipole oscillations do not change peak bunch current: rejected by peak filter.
  - No sideband swapping since Nyquist limit is h10.5
- **Relative dipole mode rejection of factor 30**



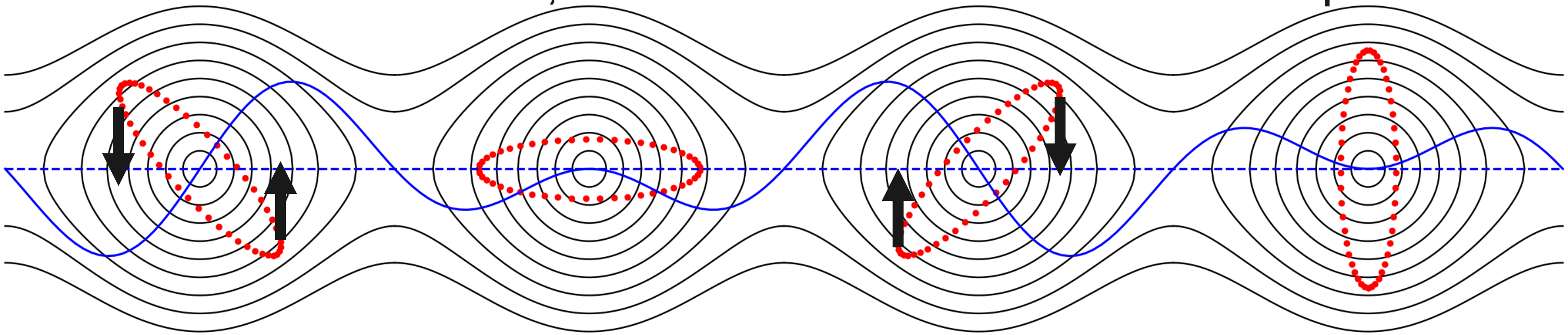


Quadrupole Correction: Modulation Example

Mode 0 oscillation with 4 bunches, correction voltage is h4 sinusoid:



Mode 1 oscillation with 4 bunches, correction is h4 sinusoid modulated with h1 amplitude modulation:

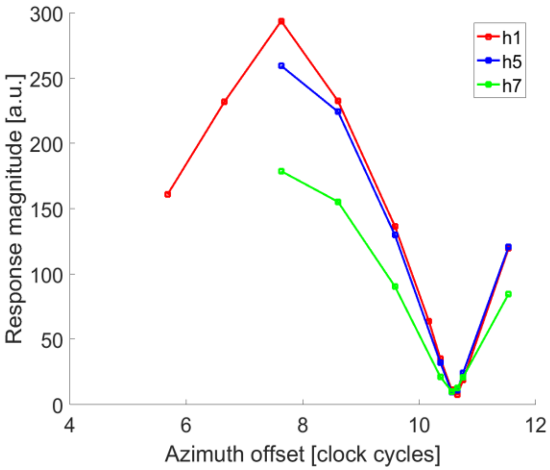


Blue line: correction voltage vs. phase

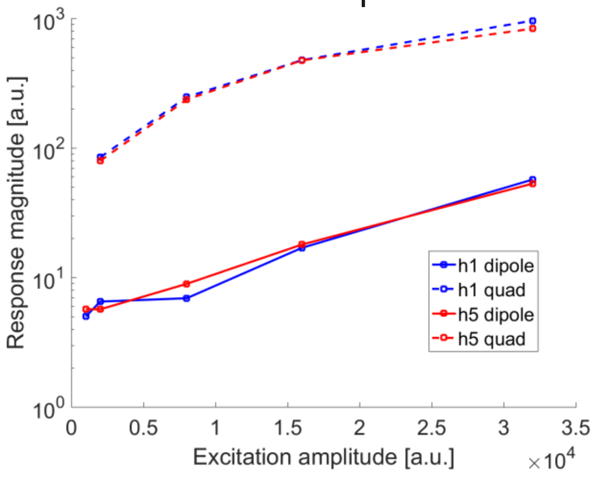
Output Modulation Test

- **Tuning of azimuth offset: zero-crossings of carrier signal should align with bunch centres**
  - Order of magnitude dipole-mode excitation reduction
- **High-pass FIR filter to compensate for Finemet system roll-off**

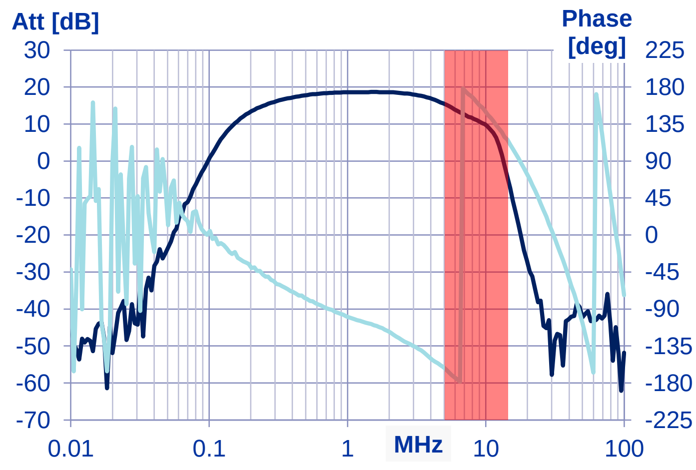
Dipole oscillation amplitude vs carrier phase offset



Oscillation amplitude vs excitation amplitude



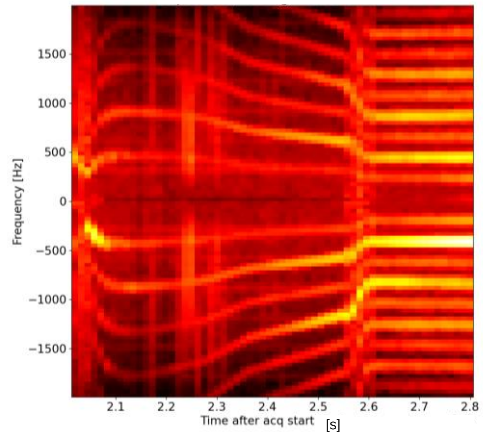
Finemet kicker S_{21} (Matthias Haase)



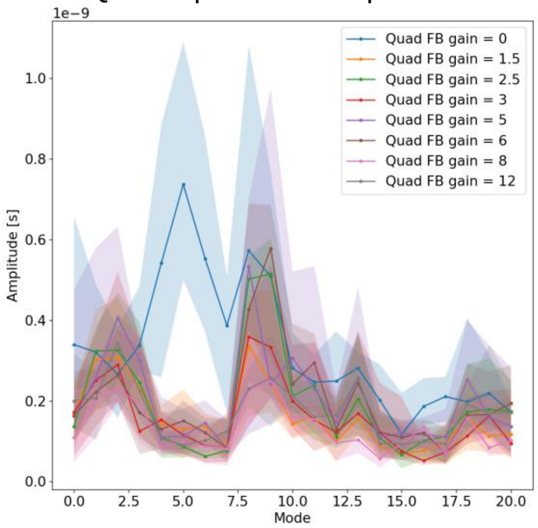
Feedback Tests

- **Series of measurements with LHC-type cycle (intensity = 2.2e11 p/b)**
  - 40 MHz cavity, normally used for Landau damping and double splittings, turned off
  - Quadrupole instabilities developed naturally at flat-top
- **Turn on prototype quadrupole feedback acting on harmonics 4, 5, 6 & 7**
  - Phase previously tuned with same method as dipole feedback
  - Feedback on between C2550 ms and C2710 ms (end of acceleration and flat-top)

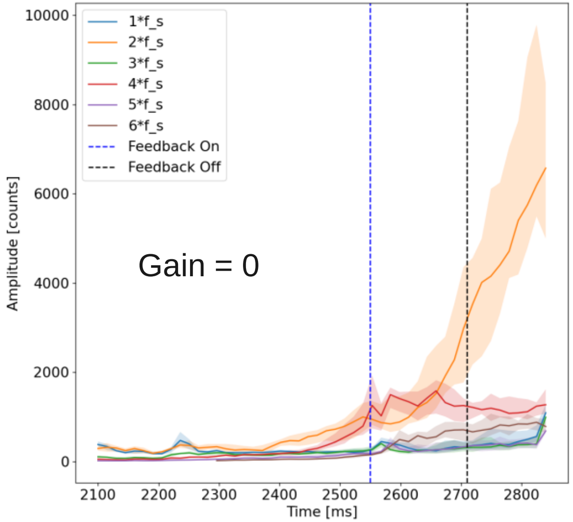
h5 internal acquisition



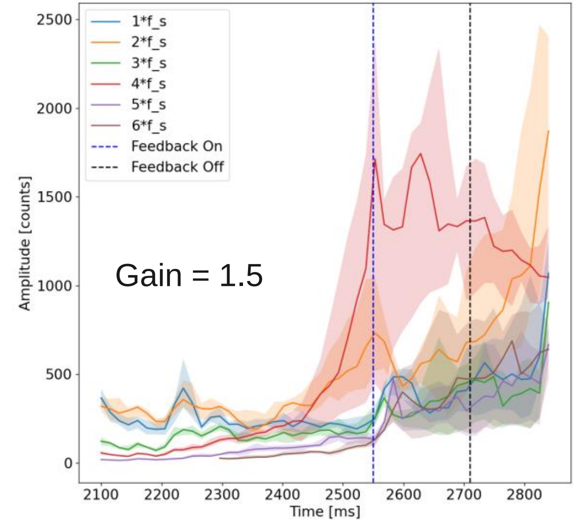
Quadrupole mode spectrum



Multipole modes vs time at h5



Multipole modes vs time at h5



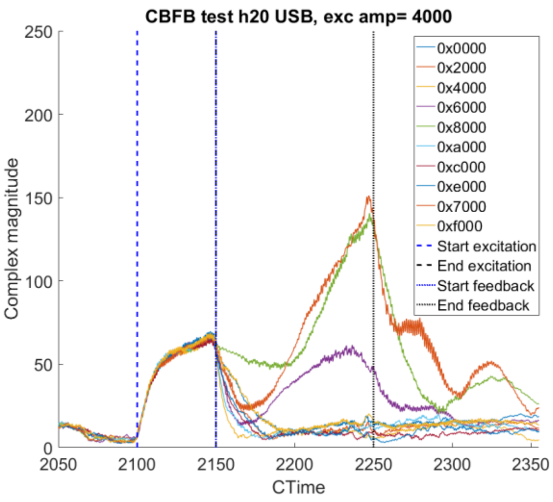
Summary

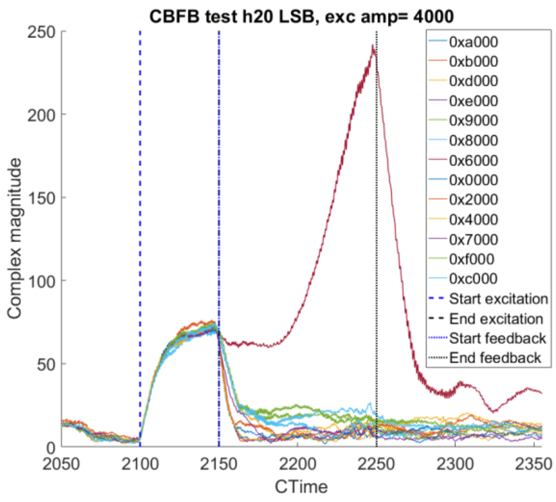
- **Dipole-mode feedback working reliably**
- **Quadrupole-mode feedback:**
  - Problems with filter method
  - Better results with separating kick and detection of dipole and quadrupole modes
  - Good results with beam tests with 4 feedback channels
- **Tests with more than 4 channels to be done soon**

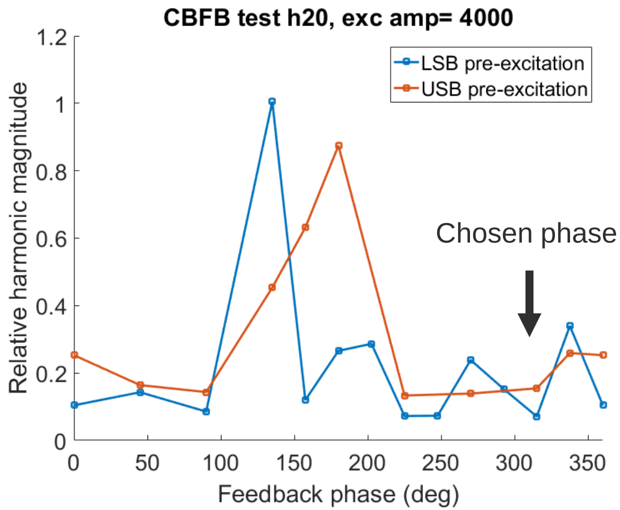
home.cern

Tuning

- **Use the DDS to excite coupled-bunch oscillations (both sidebands separately)**
  - Ensures consistent level of oscillations between shots
- **Turn excitation off, then turn feedback on with different phase values**
- **Measure mean oscillation amplitude using internal acquisition**
- **Pick the phase value in the centre of the stable range.**

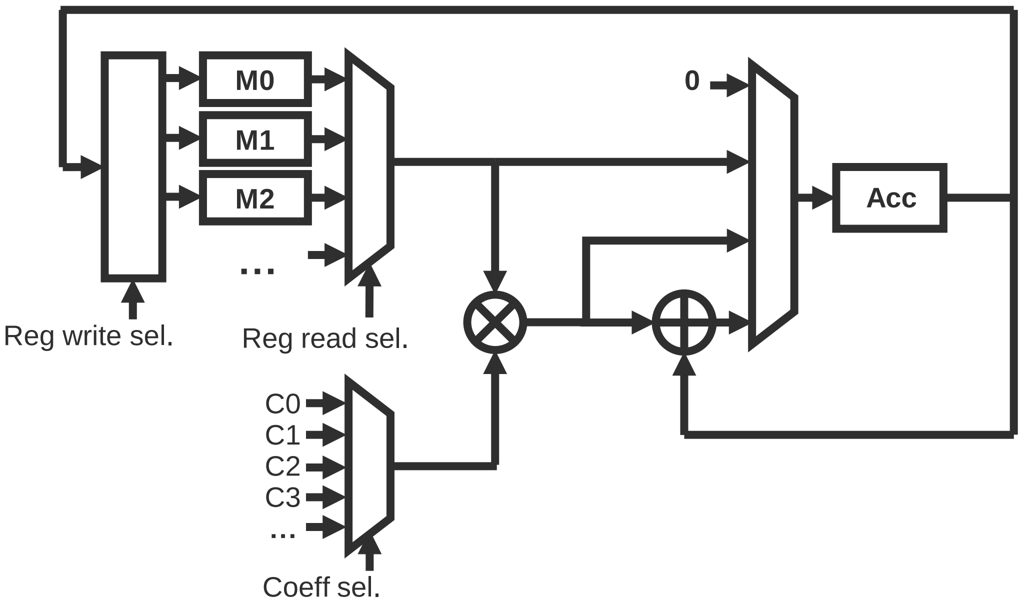






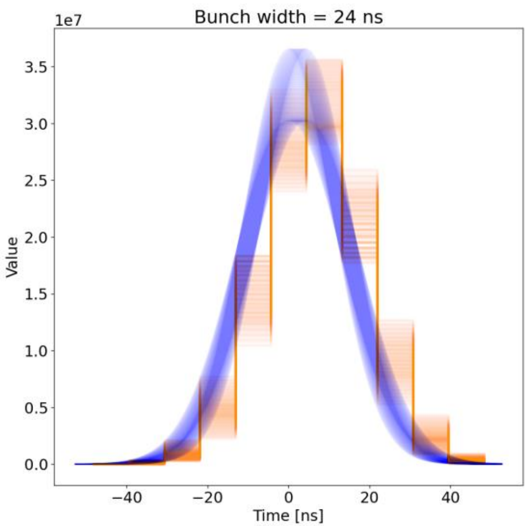
DSP Core

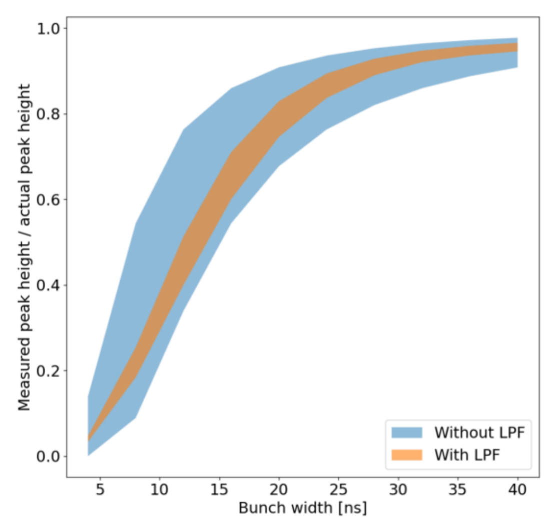
- **Simple DSP core for quadrupole mode filtering.**
- **36x36 bit multiply-accumulate unit**
- **Fixed program length: 128 instructions**
  - Runs once every start strobe.
- **Coefficients and program:**
  - Hard-coded defaults, or read from mem-map
- **No pipelining**
  - Simplifies both programming and firmware
  - High latency: runs at half RF clock

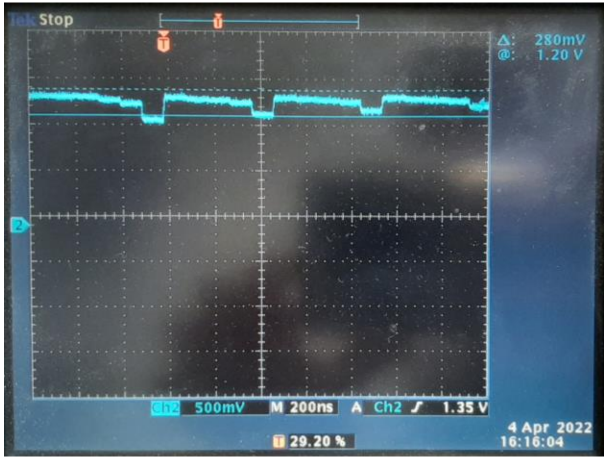


Peak Detection Filter Lab Test

- Measure sensitivity to pulse offset with respect to sample clock pulse widths
  - Measured negligible sensitivity variation for pulse widths ≥ 19 ns.
  - 20% variation measured with 14 ns pulses (22% variation in simple simulation)
- Typical ADC sample period : 8.2 ns; typical bunch length : 24 ns







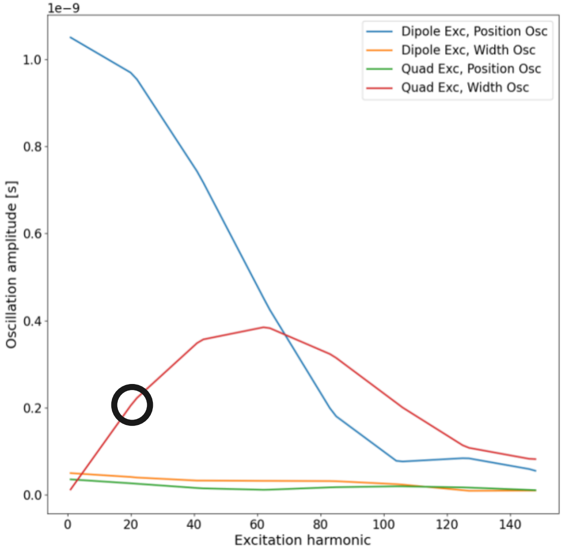
BLonD : Excitation Harmonic Studies

Test the modulation scheme in BLonD by applying a fixed excitation voltage at different harmonic numbers ($f = n f_{rev} + f_s \; \forall \; n \in \{1, 20, 22, 41, 43, \ldots\}$) and measuring the resulting oscillation amplitude.

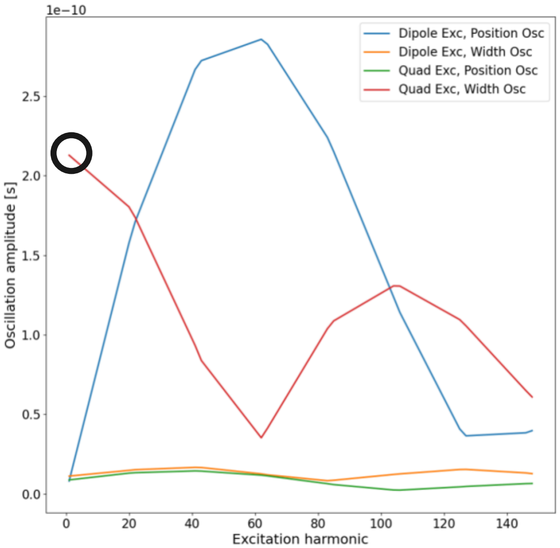
h21 carrier modulated with h1 envelope showed very low excitation of dipole mode.

- Oscillation amplitude similar to single-harmonic excitation at h20 and h22.

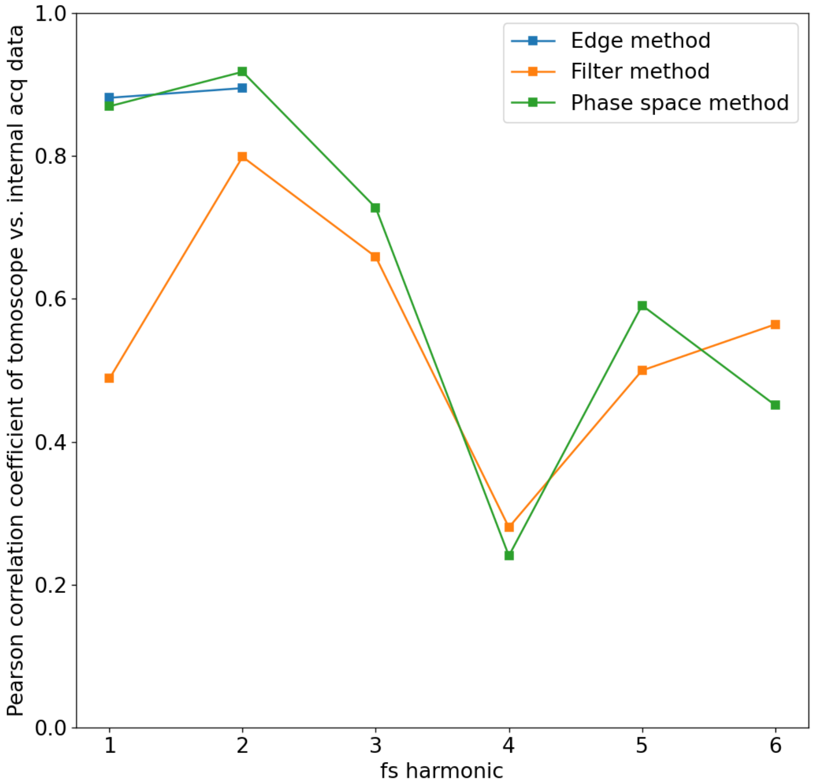
Excitation at single harmonic:



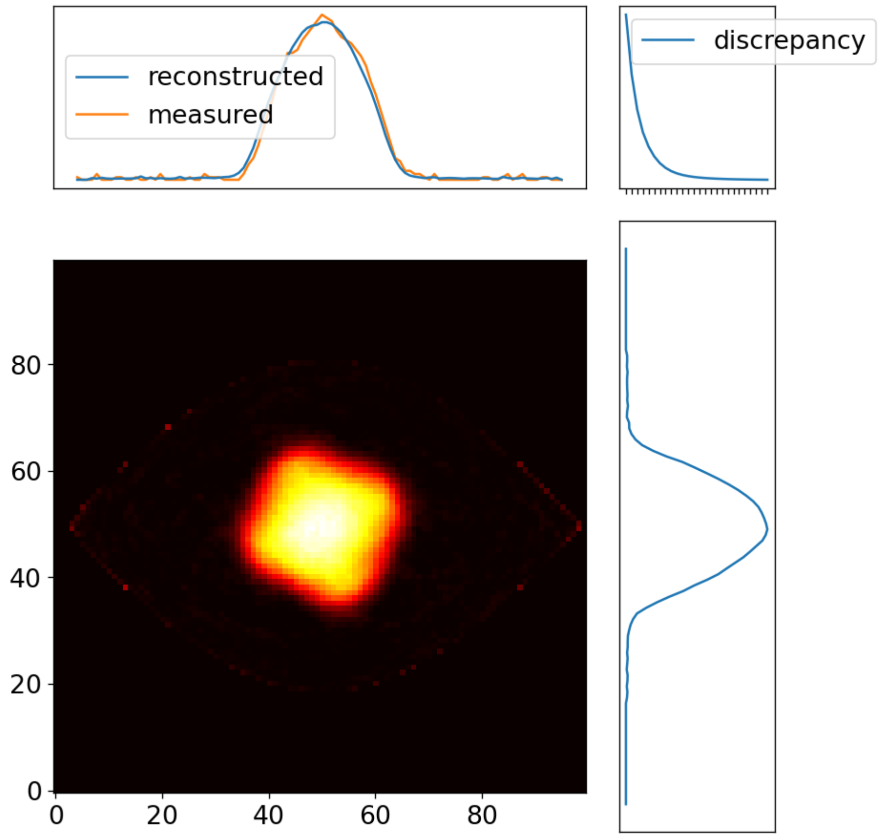
Excitation with h21 carrier:



Comparison of Different Tomoscope Data Analysis Methods



Octupole Modes



Tests at Higher Intensities

- **Tests at higher intensities (3.0e11 and 3.3e11 p/b)**
  - 40 MHz cavity on for Landau damping turns on at C2550 ms
  - All modes seem to be damped even with feedback on 4 channels only.