Measurements of the PSB LLRF multi-harmonic beam loading compensation system

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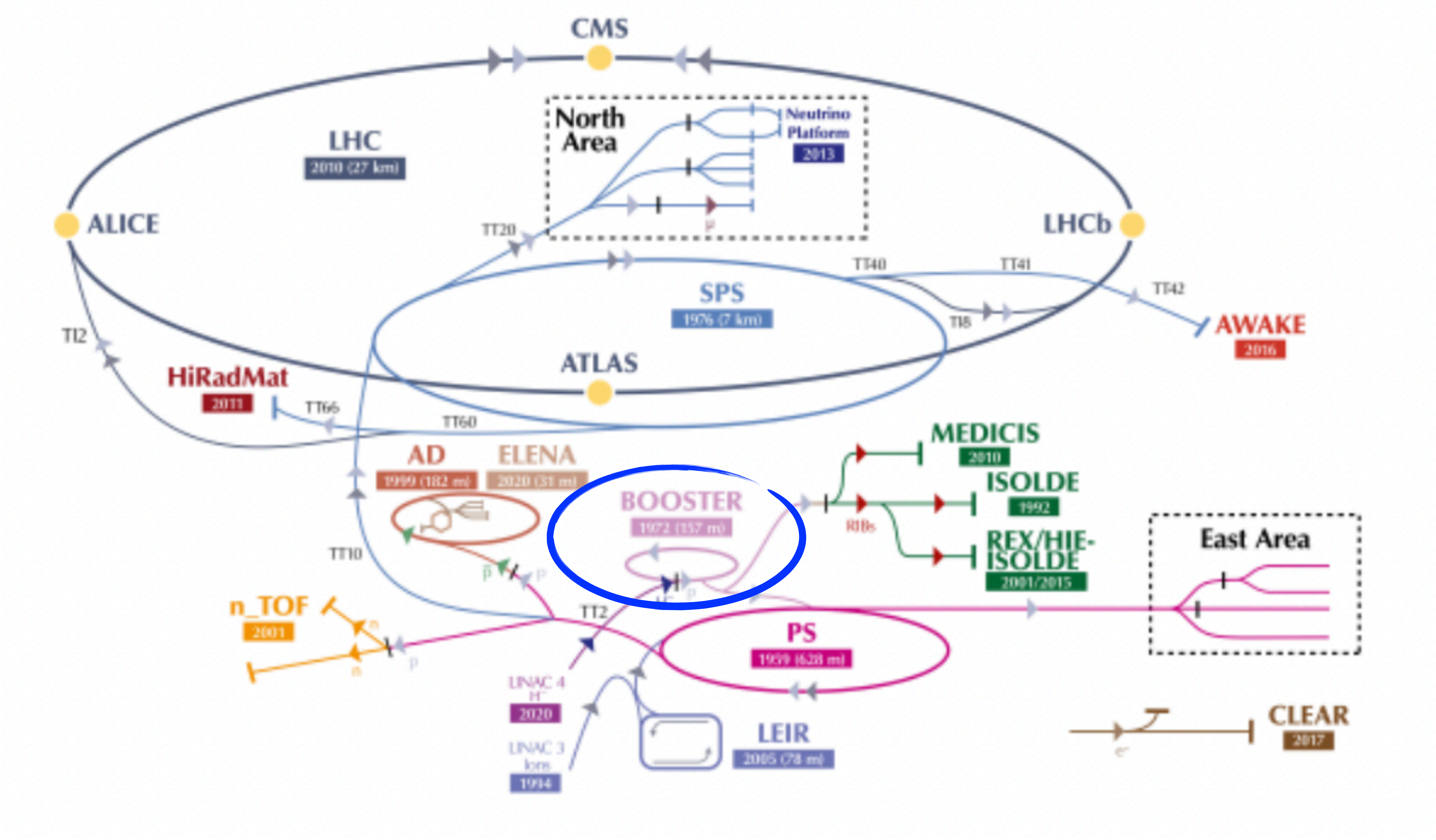
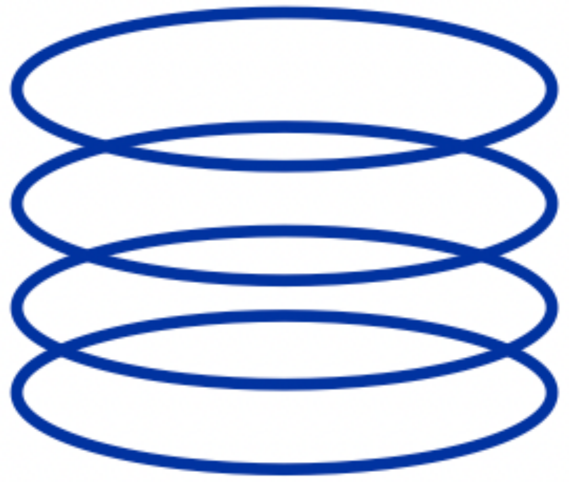
CONTEXT - CERN ACCELERATOR COMPLEX

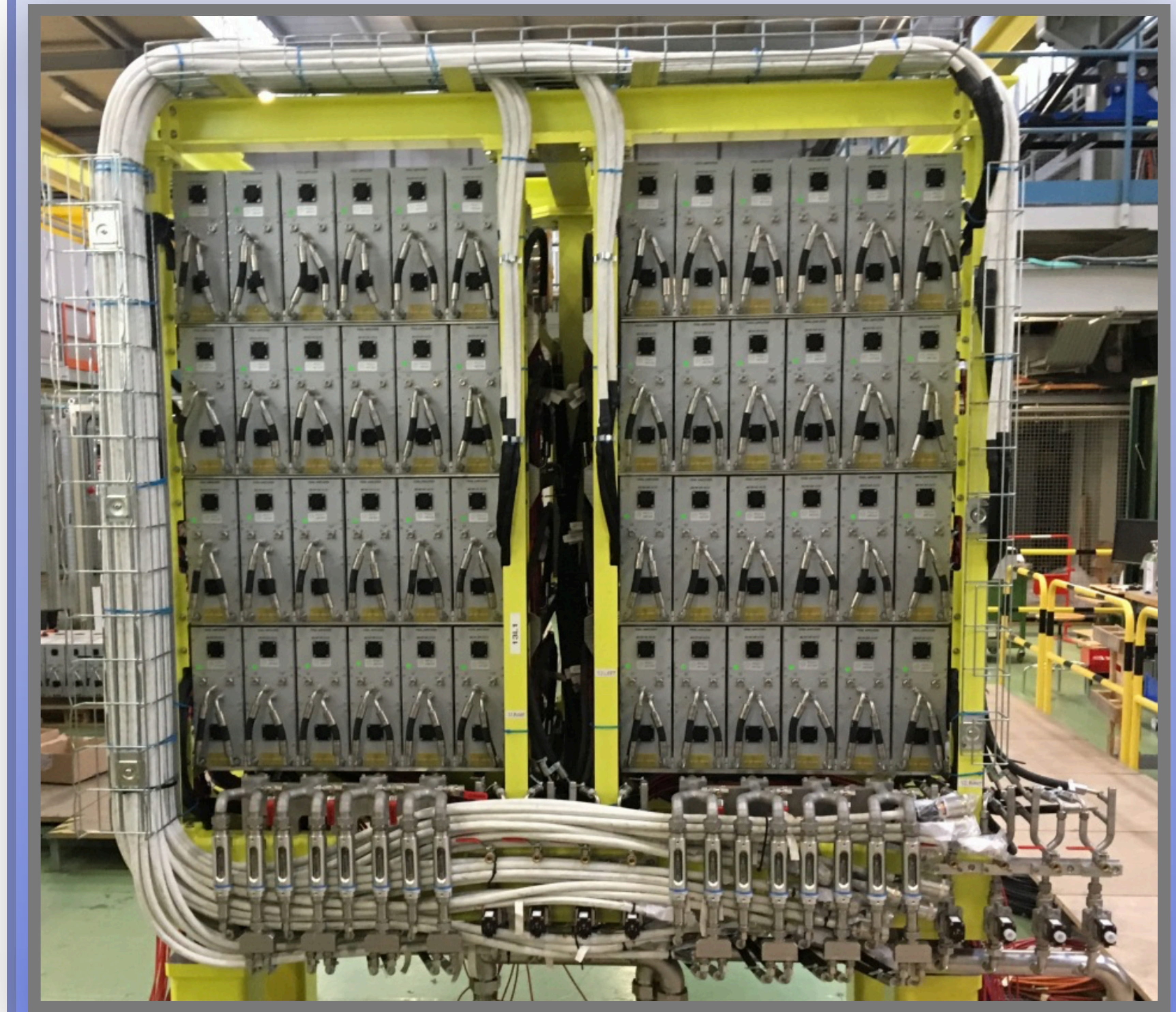


Proton Synchrotron Booster



- First synchrotron in LHC proton chain
- 4 super-posed rings
- Accelerating from 160 MeV to 1.4 - 2 GeV
- Large revolution frequency sweep: 0.994 kHz-1.81 MHz (factor of 2 increase)

Modular RF System: Finemet Magnetic Alloy (MA) wide-band cavities



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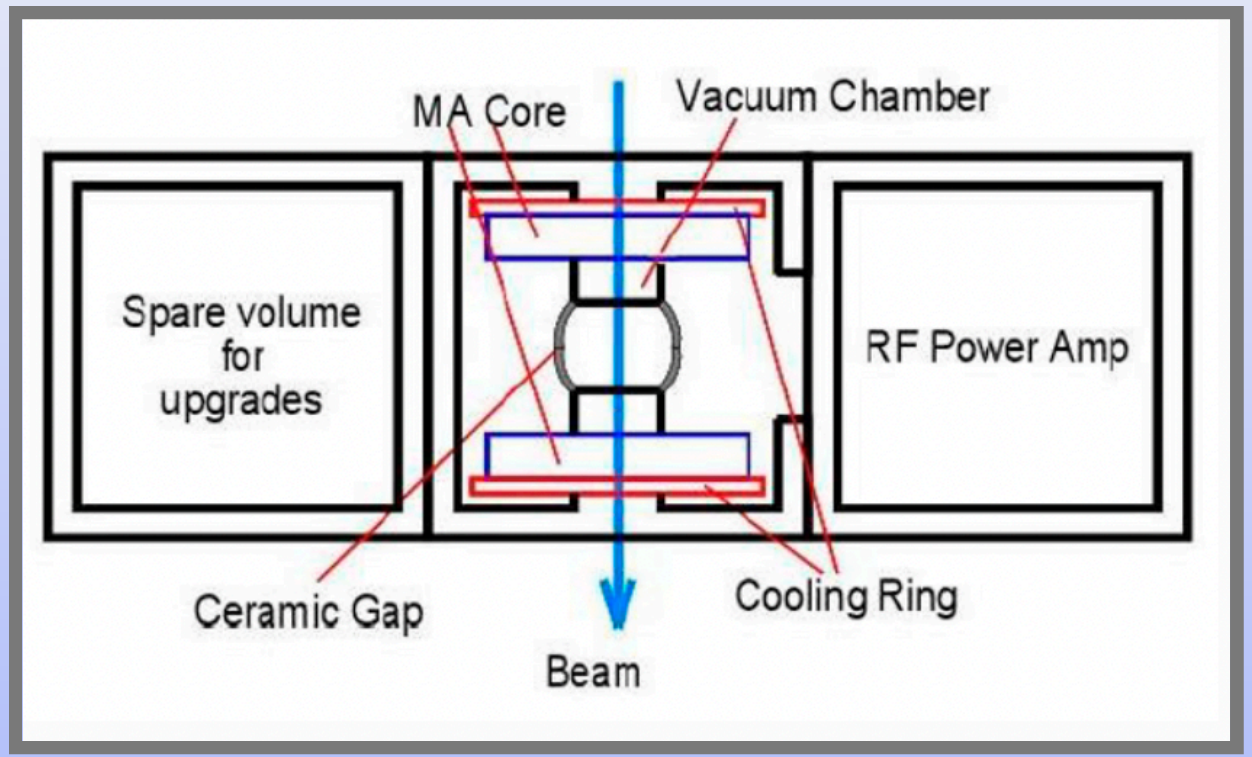
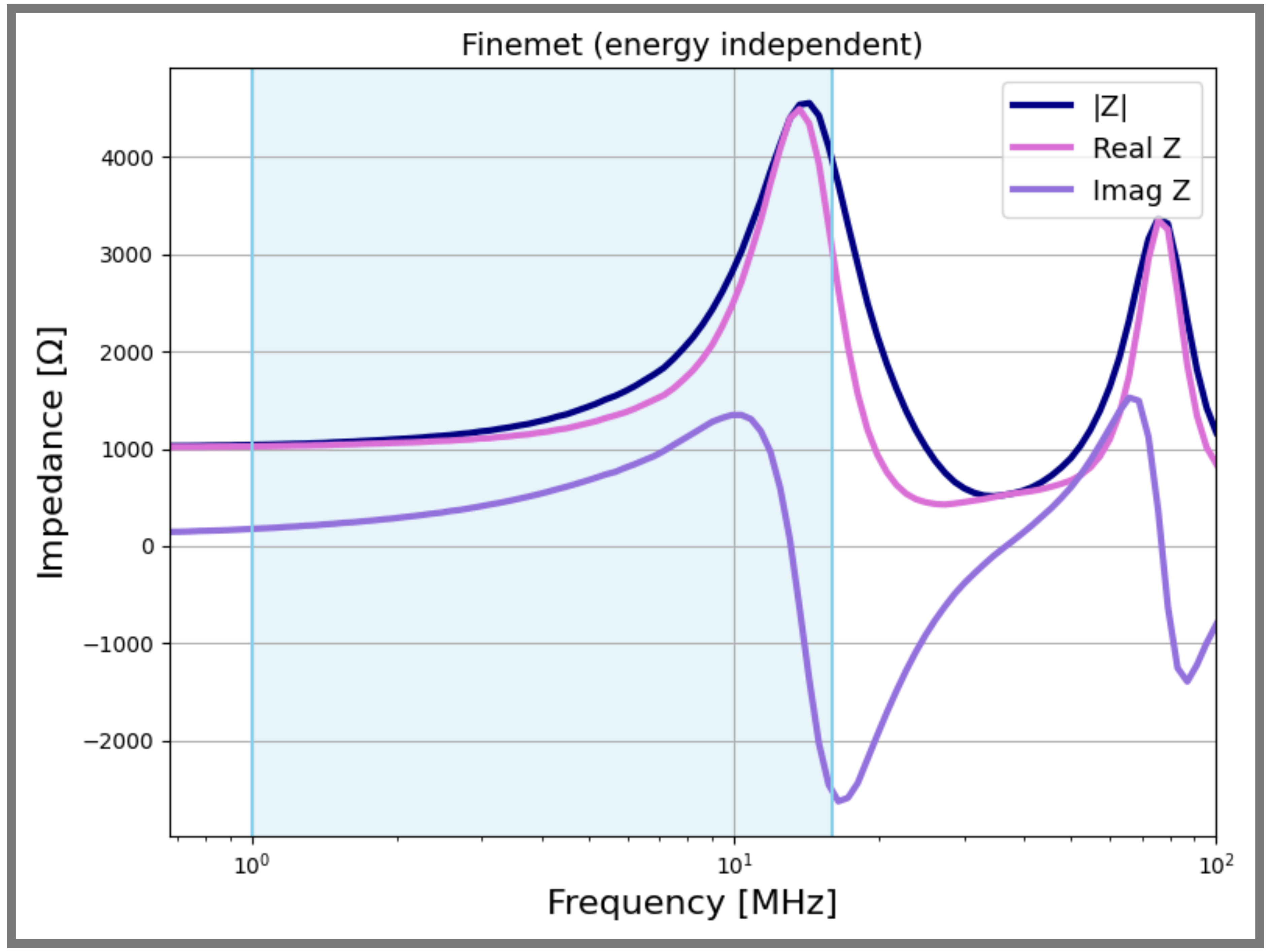


- 3 sectors per ring (S5, S7, S13)
- 12 cells per sector ⇒ 36 cells per ring
- Max V^{PK} = 8 kV per sector
- Multi-Harmonic operation ⇒ operational flexibility

CONTEXT - BEAM STABILITY

Wide-Band response of the Finemet loaded cells require actions on many harmonics



Longitudinal impedance:

- Mainly resistive in the operational range
- $f_{RF} = h \times f_{REV}$ ($h = 1,\dots,16$)
- Fast RF feedback applied

Further impedance reduction on the revolution frequency lines by **long delay feedback**

General: induced voltage by a beam undergoing longitudinal oscillations has power at the discrete frequencies:

$$f = f_{RF} \pm n f_{REV} \pm m f_S$$

At carrier frequency: Stationary beam loading

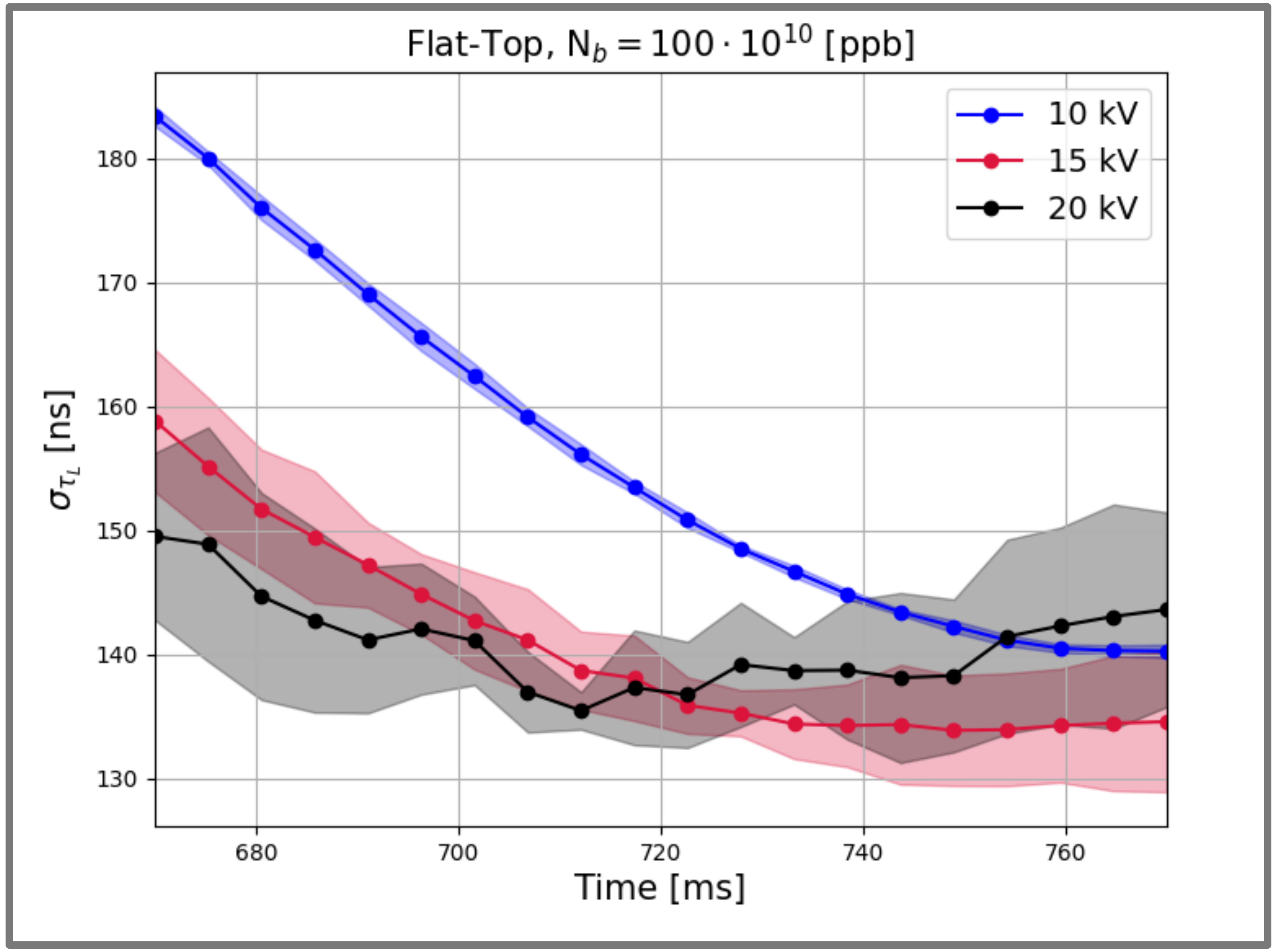
Side-Bands at f_{REV}: transient beam loading

Side-Bands at synchrotron frequency : f_{REV} with phase modulation at f_S

PSB: $f_{RF} = f_{REV}$ → Narrow-Band Multi-Harmonic feedback wit f_{REV} side-bands treated individually

CONTEXT - BEAM STABILITY

PSB 2 GeV cycle



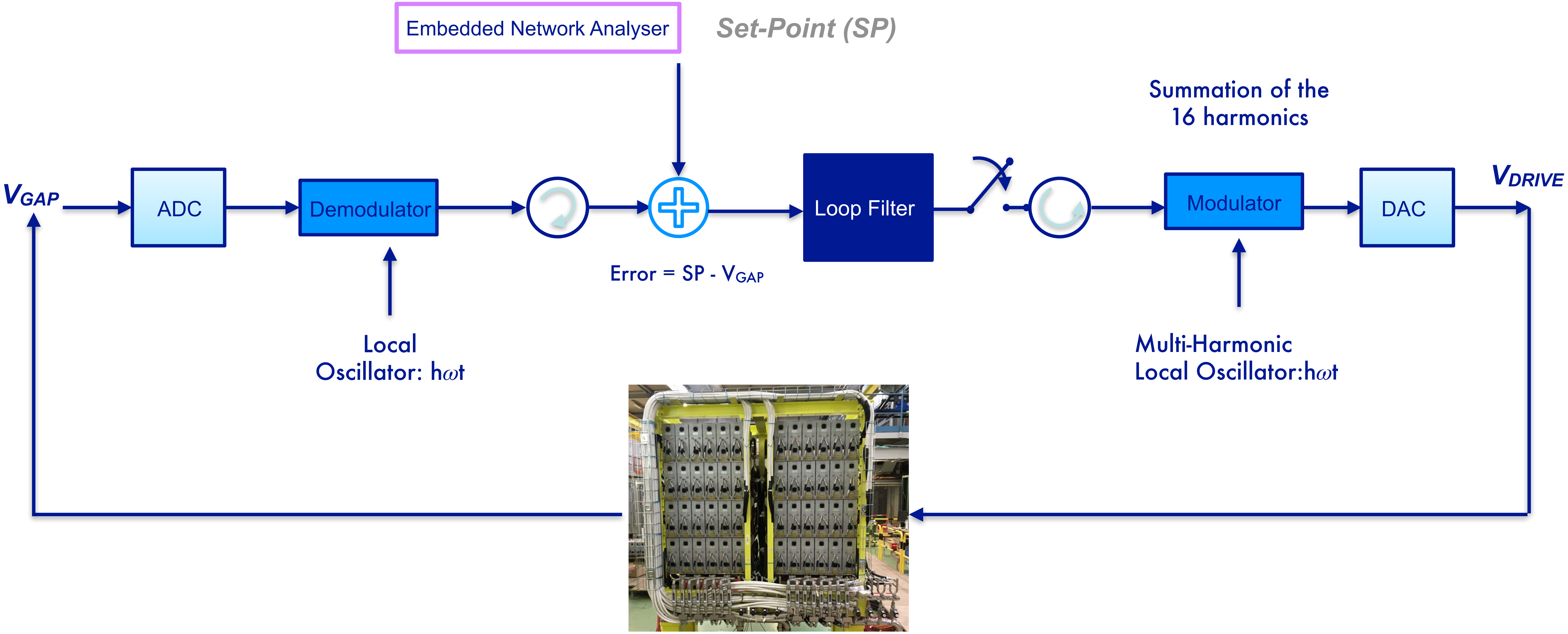
Longitudinal stability dependent on LLRF system configuration.

One example:
When servo-loops active observation of instabilities in Single RF operation starting at low intensities.

→ Characterization of the LLRF for model implementation in macro-particle simulator BLonD (Beam Longitudinal Dynamics) [2].

CONTEXT - FINEMET CAVITY SERVO-LOOPS

One servo-loop per each revolution harmonic:



Finemet cavity

CONTEXT - FINEMET CAVITY SERVO-LOOPS

One servo-loop per each revolution harmonic:

Finemet cavity

CONTEXT - FINEMET CAVITY SERVO-LOOPS

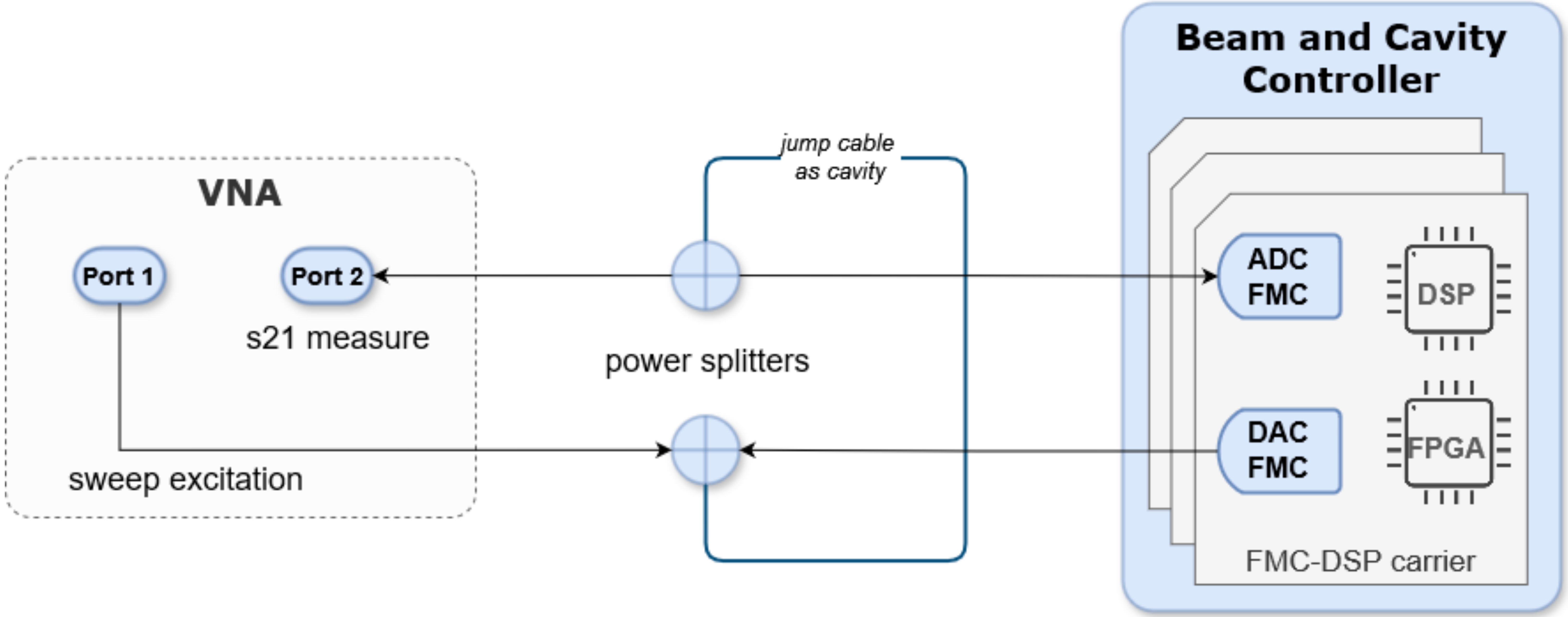
One servo-loop per each revolution harmonic:

Function Genarators

Finemet cavity

Measurements on a Test-Stand of the LLRF cavity control system isolated from the cavity.

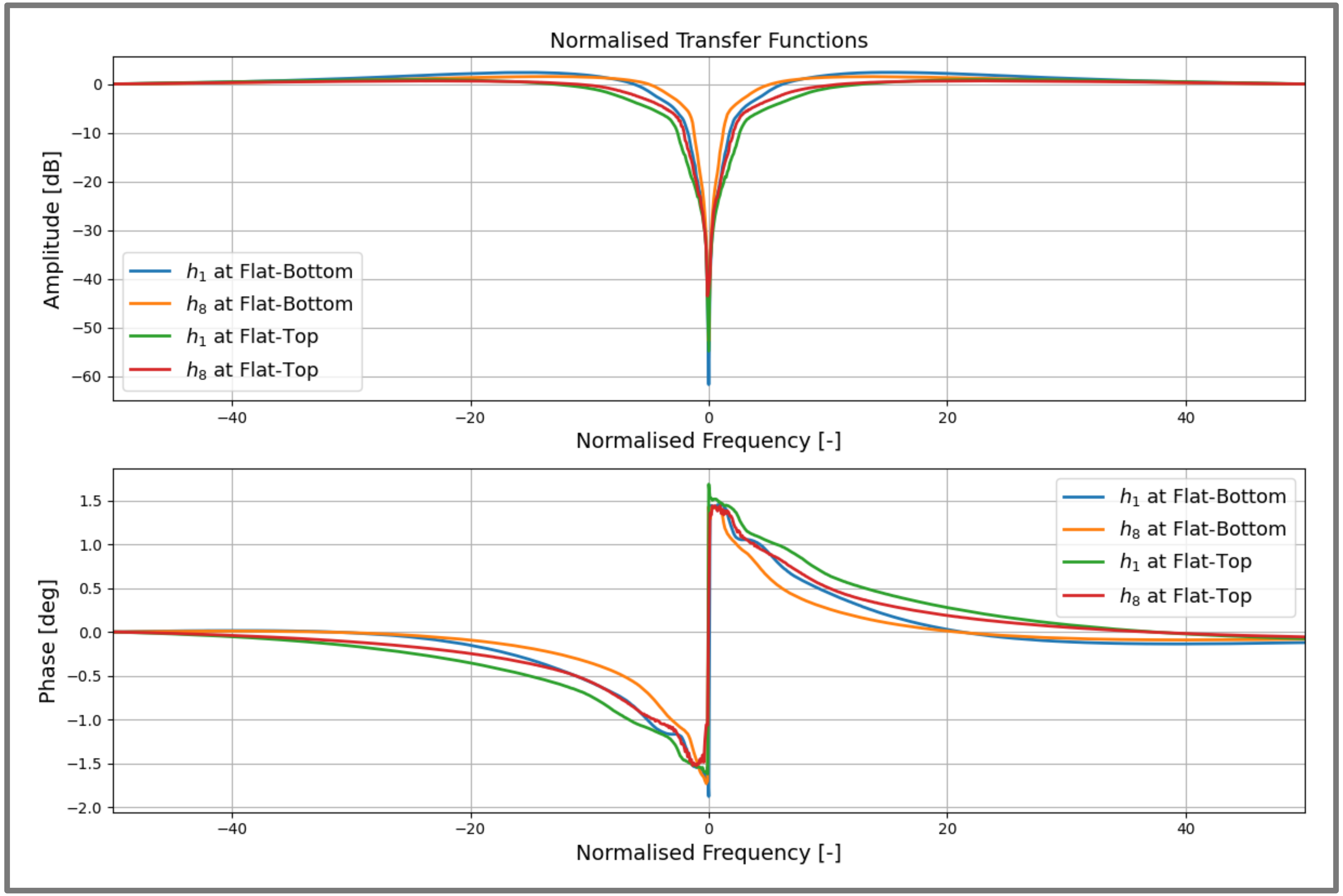
Measurement setup[3][4]



Configuration:

- Cavity emulated by cable
- Induced voltage to be compensated emulated by excitation given by the VNA
- VNA Port 1 gives the excitation
- VNA Port 2 detects the excitation
- Cavity loops suppress the excitation close to the revolution harmonic
- Set-Point to 0

HARDWARE CHARACTERIZATION - TEST-STAND MEASUREMENTS



Harmonic 1 at 1 MHz (Flat-Bottom):

- Attenuation: ~ - 60, -65 dB
- -3 dB Band-Width: 11.5 kHz

Harmonic 1 at 1.81 MHz (Flat-Top):

- Attenuation: ~ - 55, -60 dB
- -3 dB Band-Width: 16.4 kHz

Harmonic 8 at 1 MHz (Flat-Bottom):

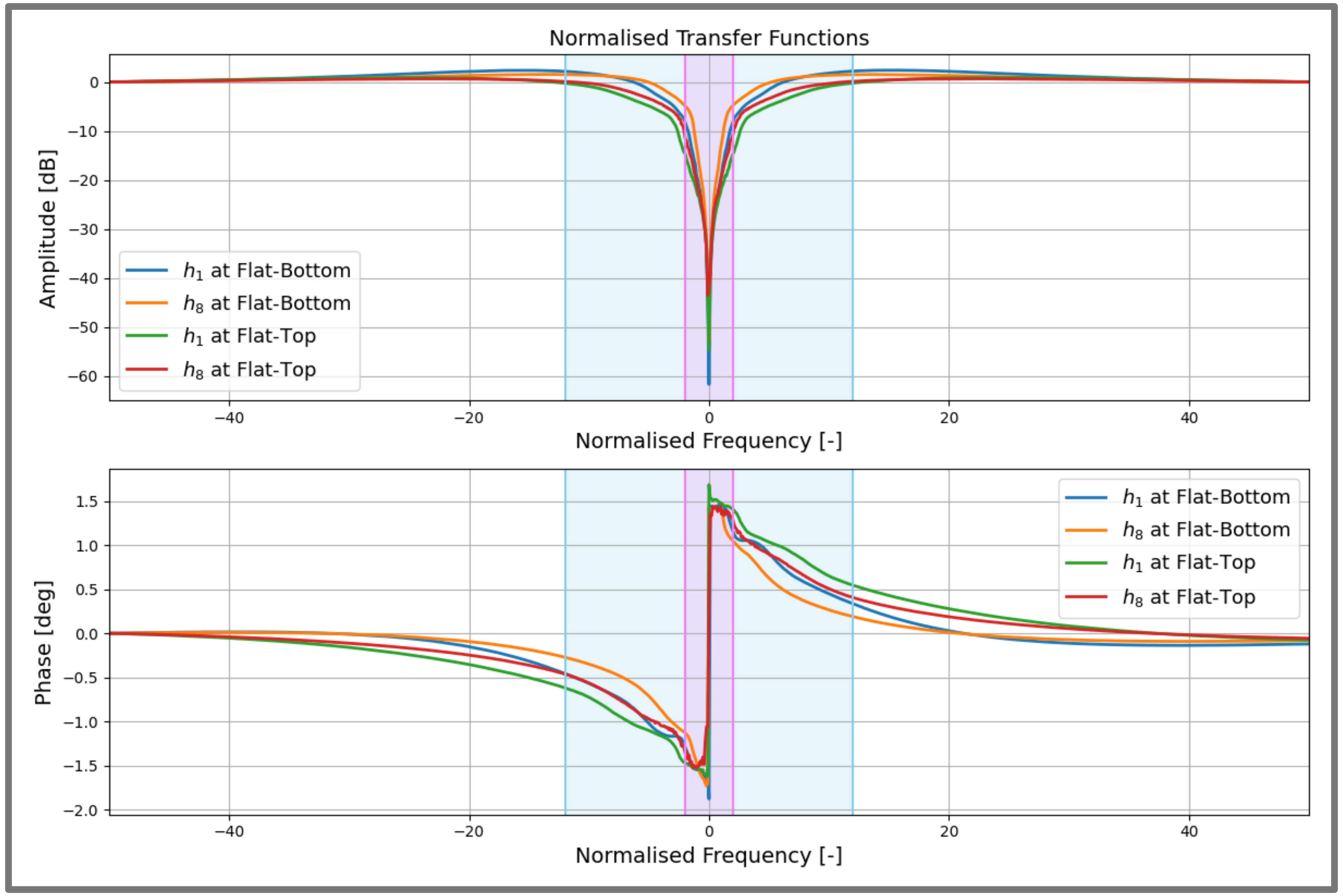
- Attenuation: ~ - 60, - 65 dB
- -3 dB Band-Width: 7.67 kHz

Harmonic 8 at 1.81 MHz (Flat-Top):

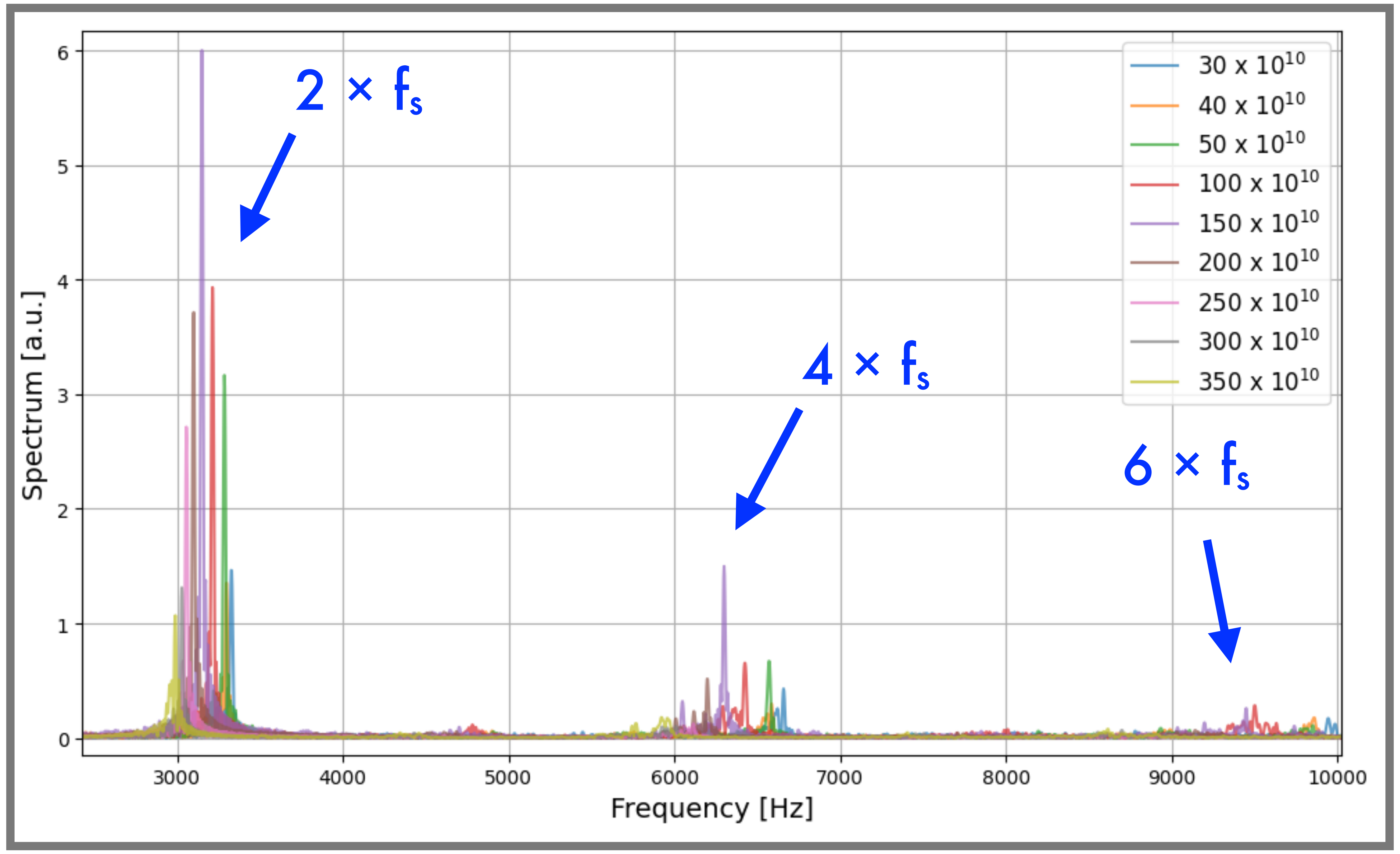
- Attenuation: ~ -60 dB
- -3 dB Band-Width: 12.2 kHz

HARDWARE CHARACTERIZATION - TEST-STAND MEASUREMENTS

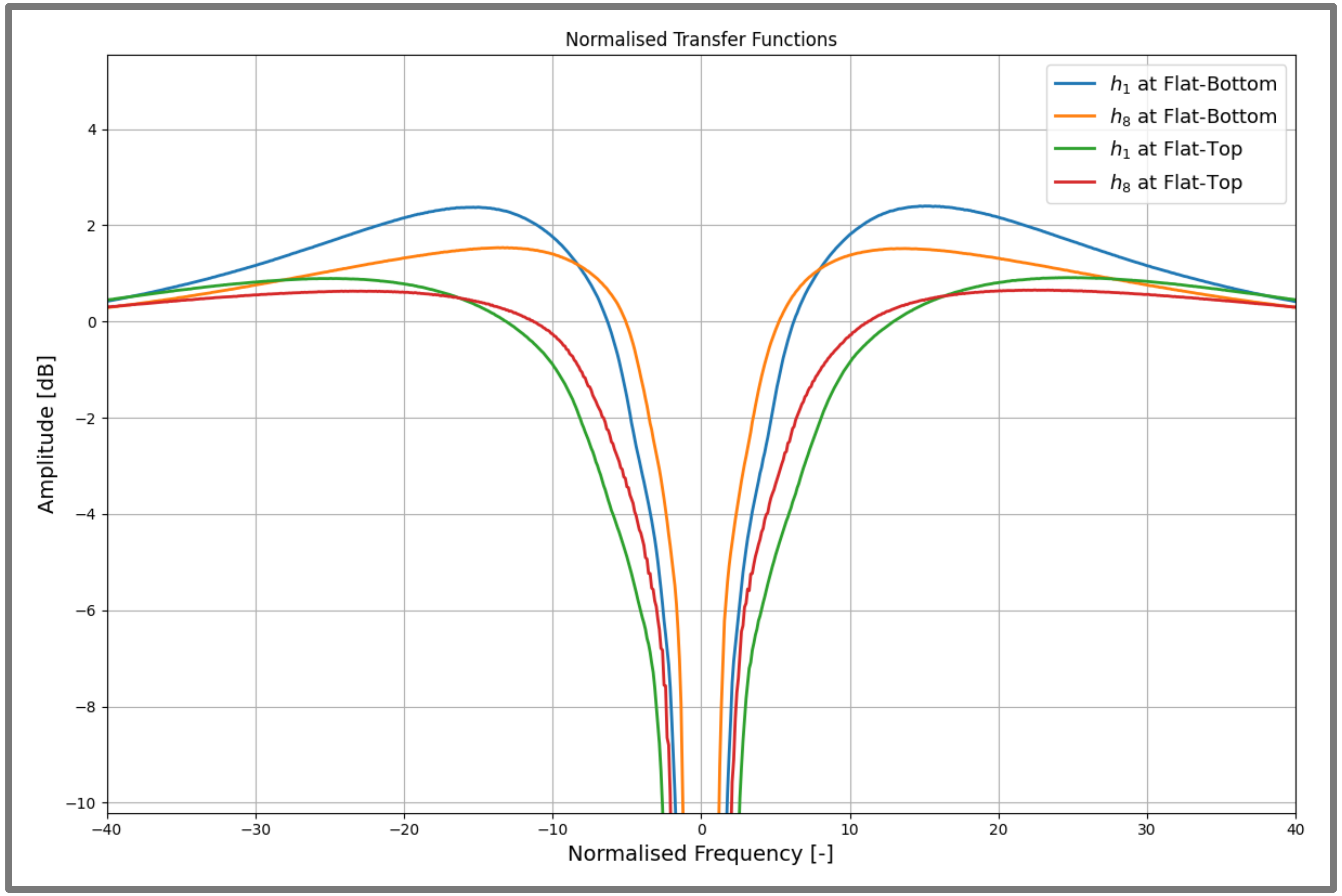
Evaluation of filter response in a frequency range around the resonant frequency spanning a f_S of 2 kHz (pink span) and 6 multiples of it (blue span).



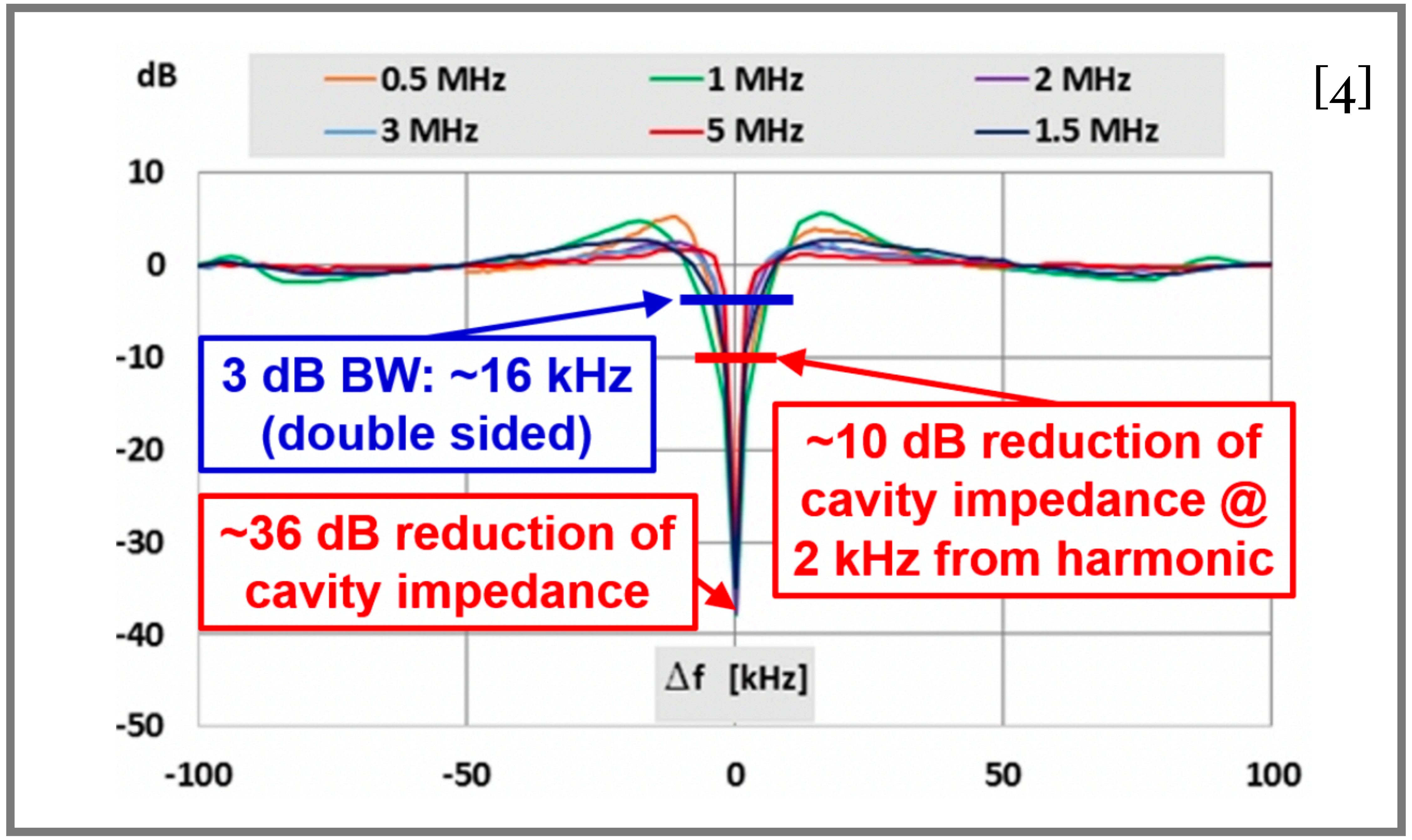
Measurement showing longitudinal oscillations at multiples of the synchrotron frequency



HARDWARE CHARACTERIZATION - COMPARISON

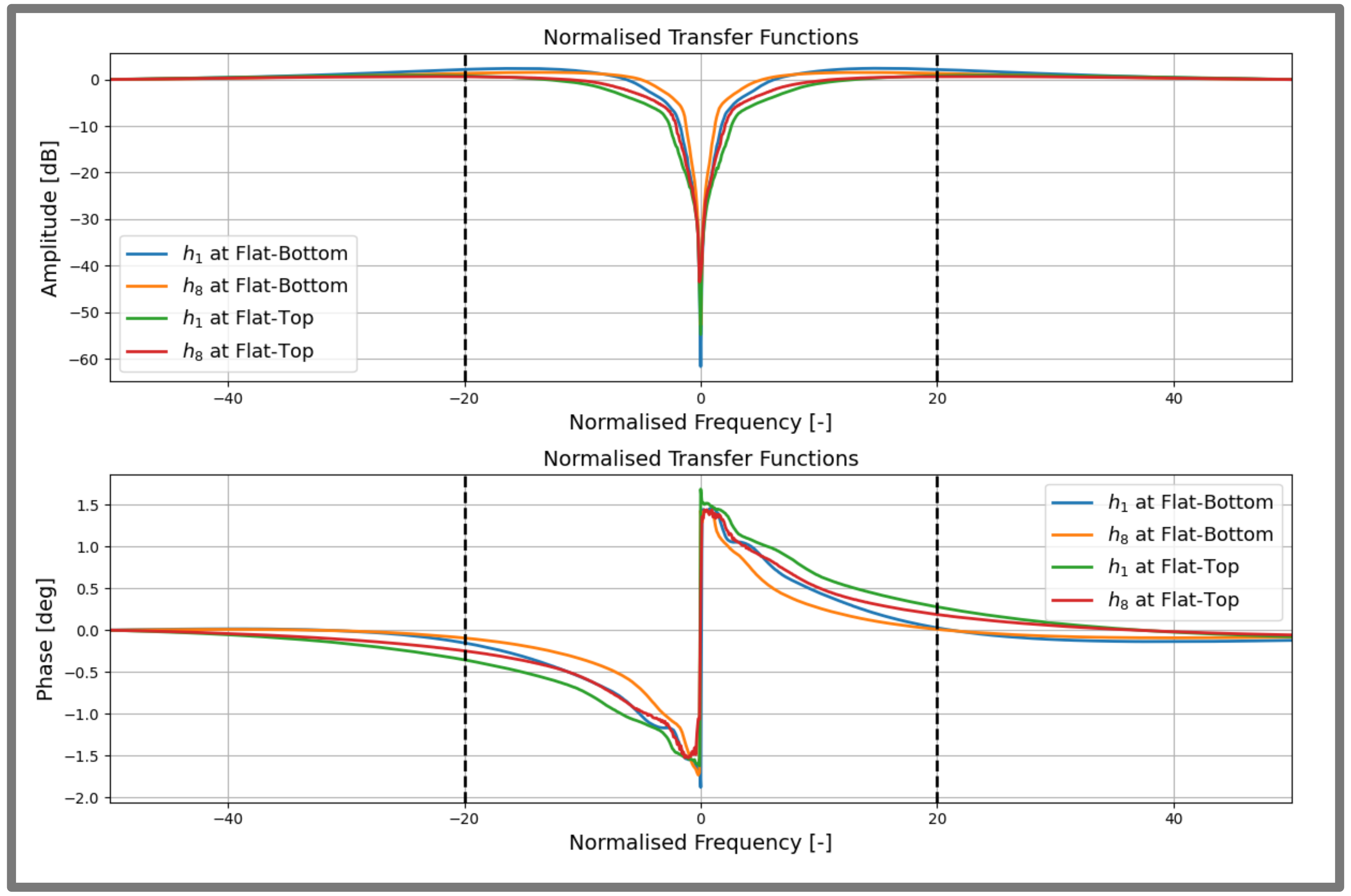


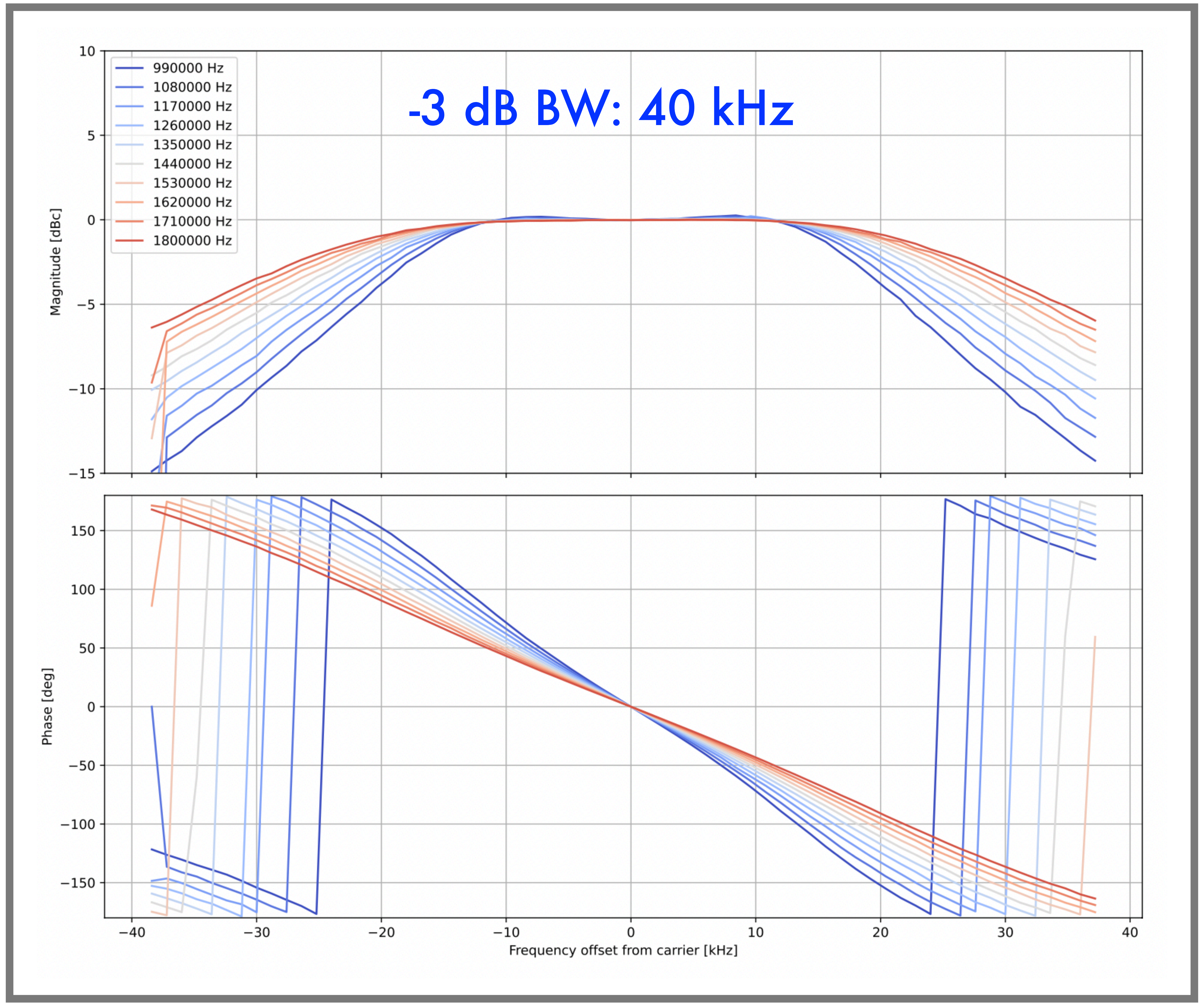
Same setup but LLRF connected to the cavity and Loop Filter implemented in DSP: large difference in gain, small in - 3dB BW



HARDWARE CHARACTERIZATION - COMPARISON

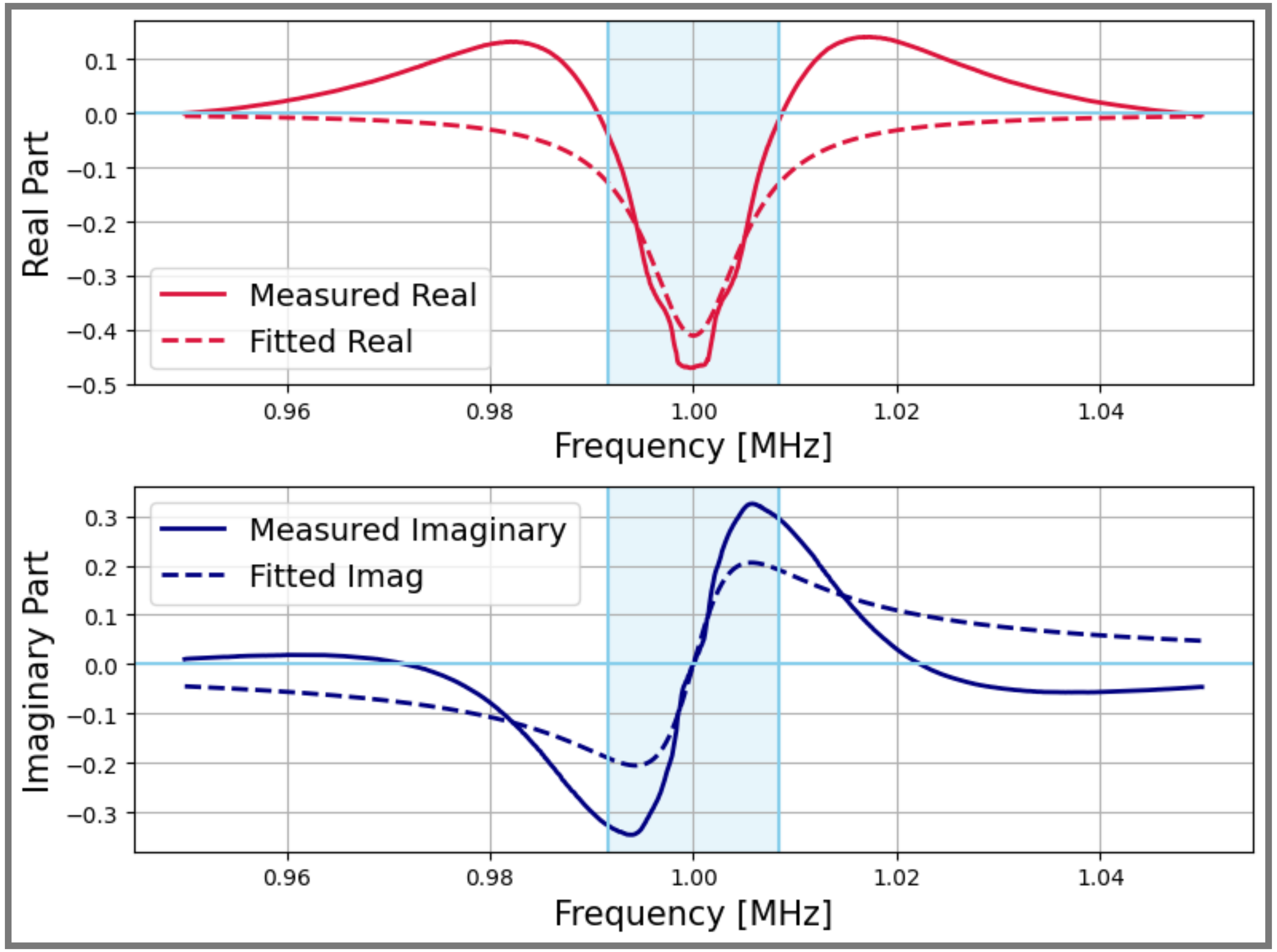
Total Transfer Function with external VNA and closed loop response measured with the Embedded VNA.[5]





The embedded Network Analyser sweeps the the RF Drive signal itself. ➔Action of the loop chain on the signal without the compensation
⇒ Pass-band response

HARDWARE CHARACTERIZATION - MODELING



For simulation purposes: need a model reliably describing the filter action to be used to benchmark measurements and validate impedance model.

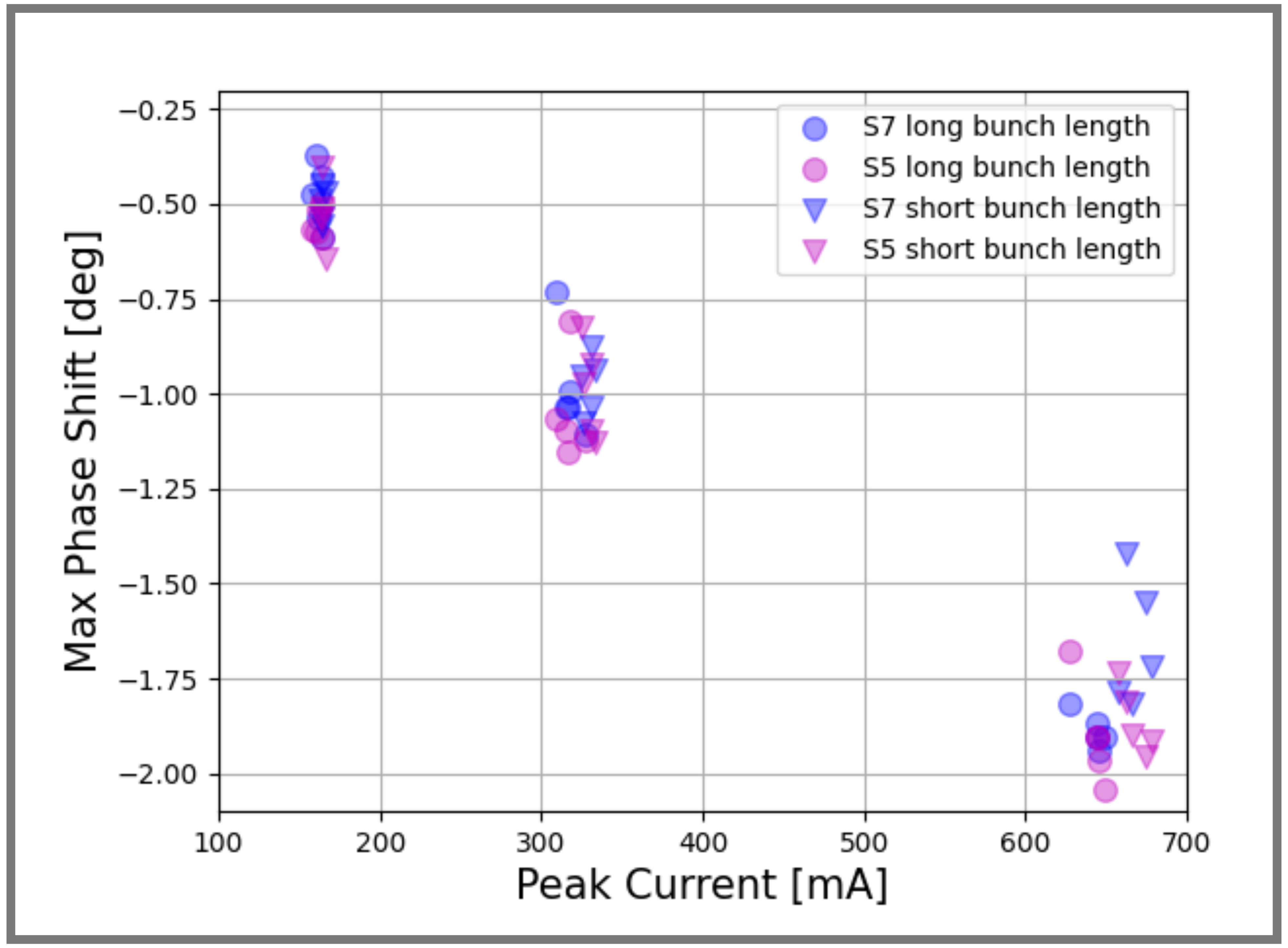
→Fit with **Resonator** model based on test-stand measurements:
Not accurate enough to describe the filter steady-state transfer function.

Working on a better fit and beam-based measurements to gain information about transient beam loading behaviour.

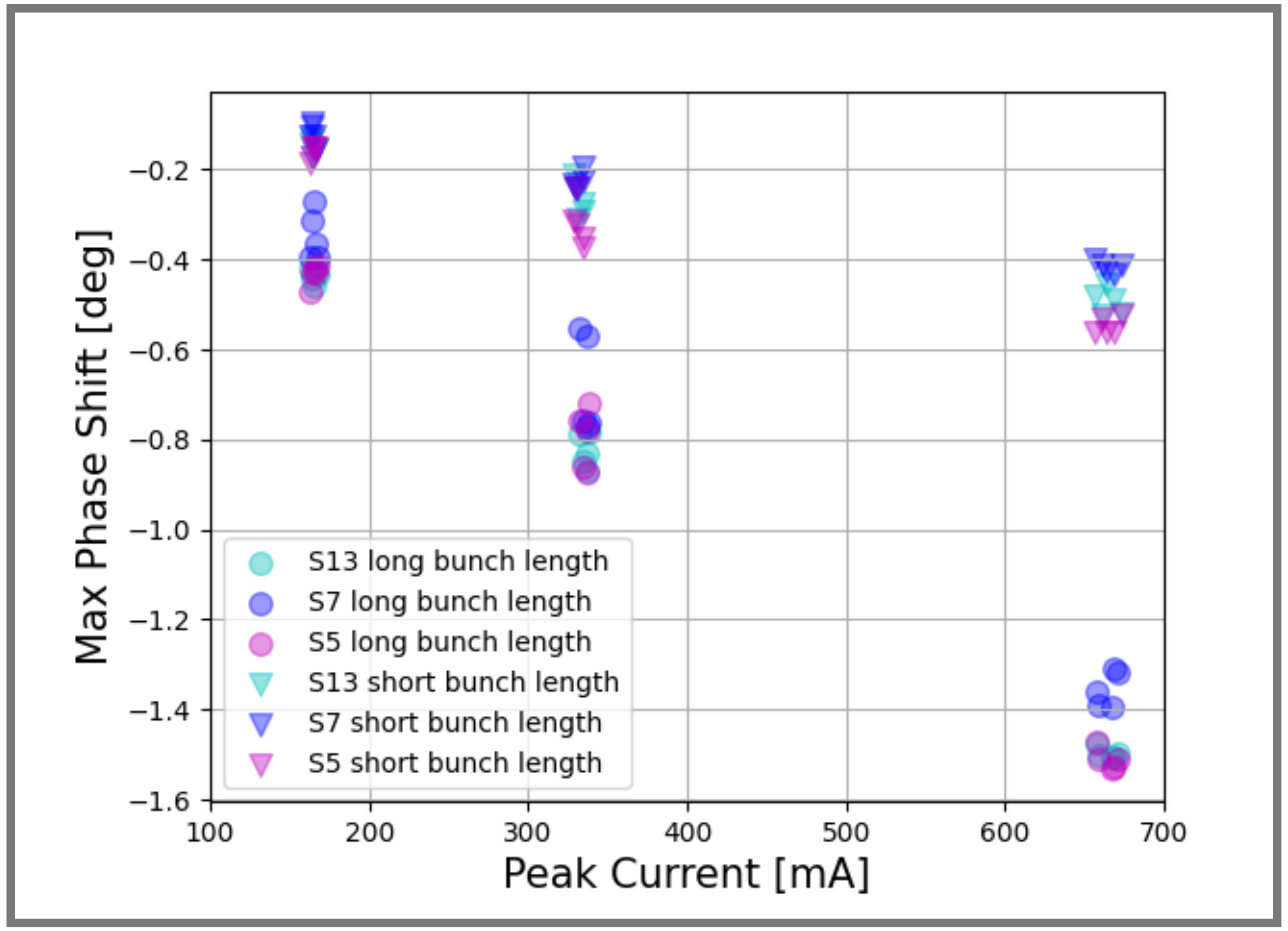
Measurements in Single RF at injection (160 MeV): transient state. Scans in intensity to evaluate beam loading through the demodulated I and Q components.

Time needed at injection to compensate beam loading is inversely proportional to the -3 dB BW.

Single RF



Double RF



CONCLUSIONS

- PSB Finemet RF System introduces large broad-band longitudinal impedance
- Fast and slow RF feedback action required to reduce beam loading effects
- Unstable behaviour at low intensity happening in Closed-Loop and Single RF operation
- LLRF modular cavity control system acting on multiples of the revolution frequency
- TEST-STAND MEASUREMENTS
  - Small effects of harmonics and frequencies on Transfer Function (TF) parameters
  - Consequential change in the TF at higher multiples of f_S
- INJECTION TRANSIENT MEASUREMENTS
  - No effect from bunch length at $h = 1$
  - Effect from peak current and bunch length at $h = 2$
- MODELING
  - Previous model does not accurately reproduce the steady-state behaviour
  - Transient behaviour to be included

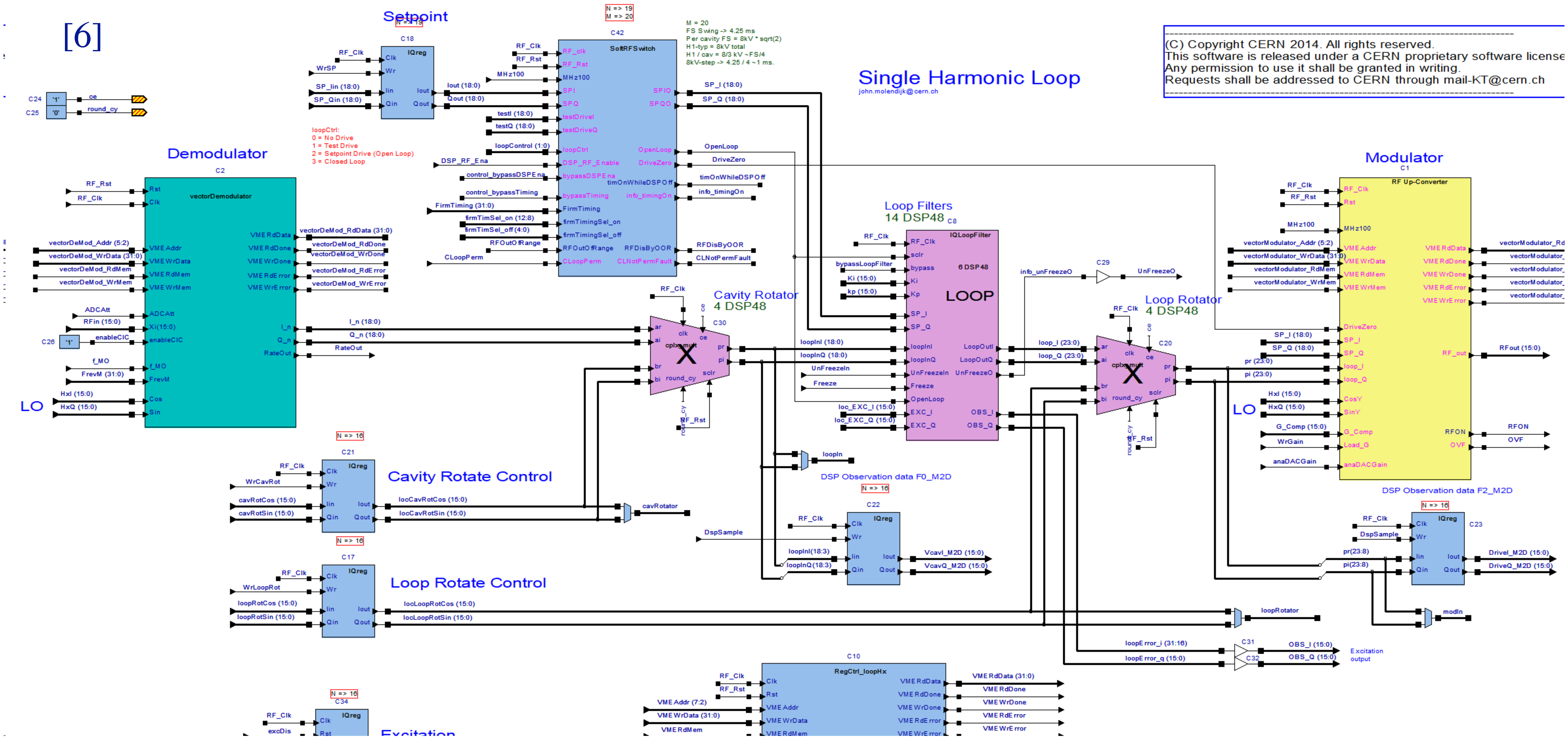
References

- [1] Courtesy of Mauro Paoluzzi, CERN
- [2] H. Timko et al., Phys. Rev. Accel. Beams, vol. 26, 2023.
- [3] Courtesy of Marco Niccolini, CERN
- [4] M.E. Angoletta *et al.*, "Control and Operation of a Wideband RF System in CERN's PS Booster", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, paper THPAB141, pp. 4050-4053, ISBN: 978-3-95450-182-3.
- [5] D. Barrientos, S. C. P. Albright, M. E. Angoletta, A. Findlay, M. Jaussi, and J. C. Molendijk, "A New Beam Loading Compensation and Blowup Control System Using Multi-Harmonic Digital Feedback Loops in the CERN Proton Synchrotron Booster", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 907-910.
- [6] Courtesy of Diego Barrientos, CERN
- [7] Courtesy of John C. Molendijk, CERN

Back-Up Slides

CONTEXT - FINEMET CAVITY SERVO-LOOPS

[6]

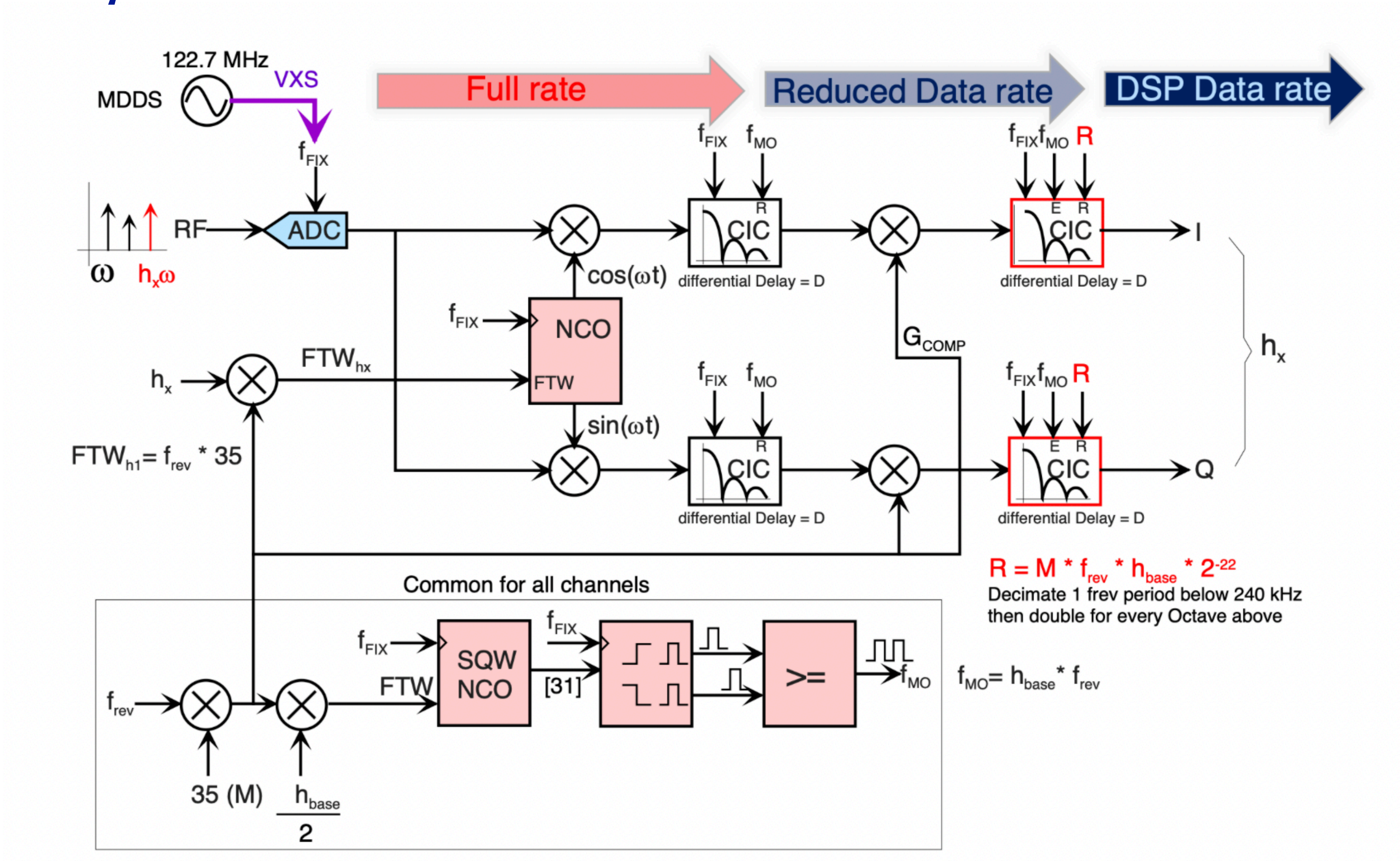


CONTEXT - FINEMET CAVITY SERVO-LOOPS

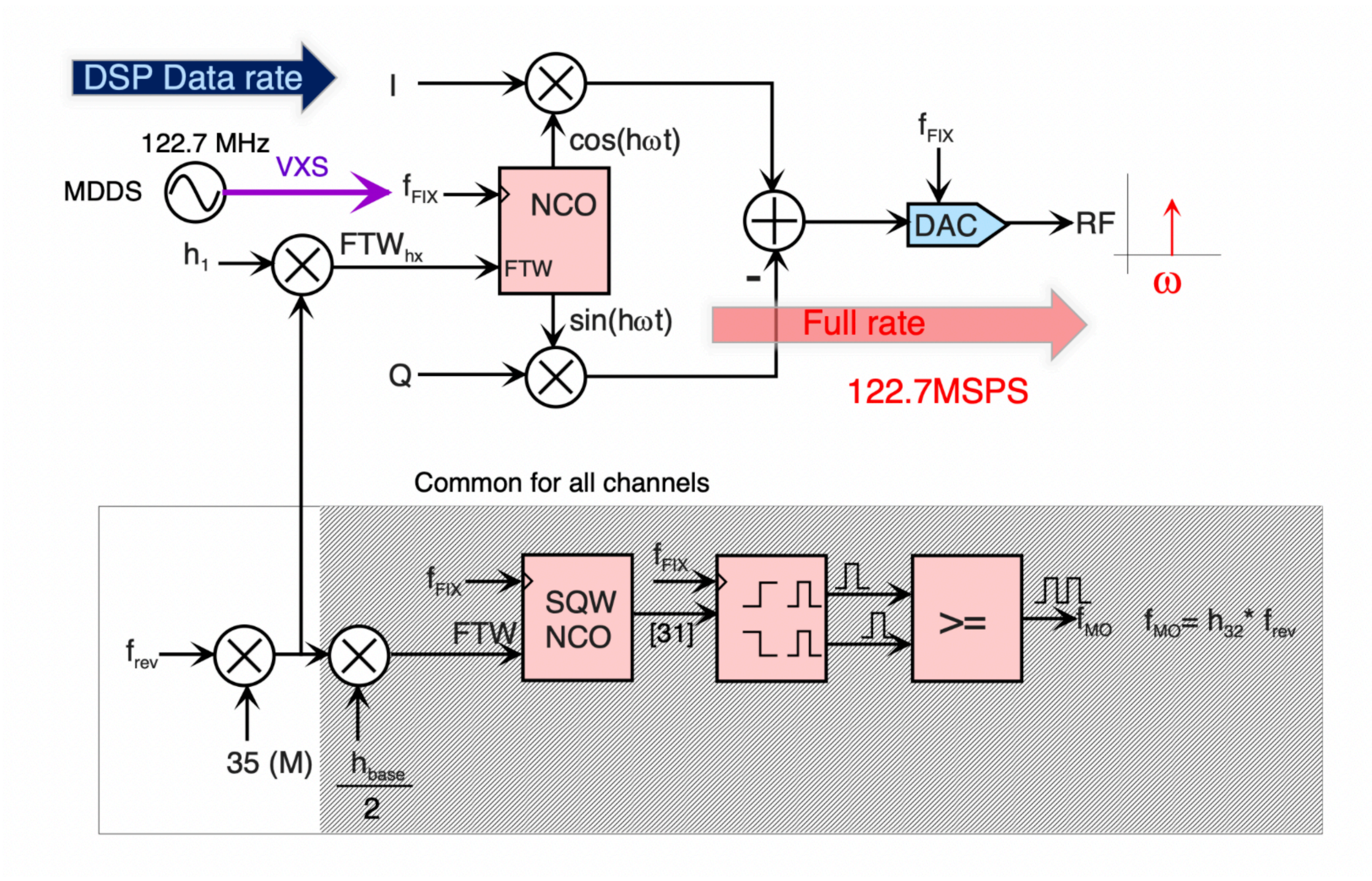
Electrical delay : < 1 us between LLRF and Finemet
Field regulation using DSP with T = 10 us
Fixed frequency Clock with f_{fix} = 122.7 MHz

[7]

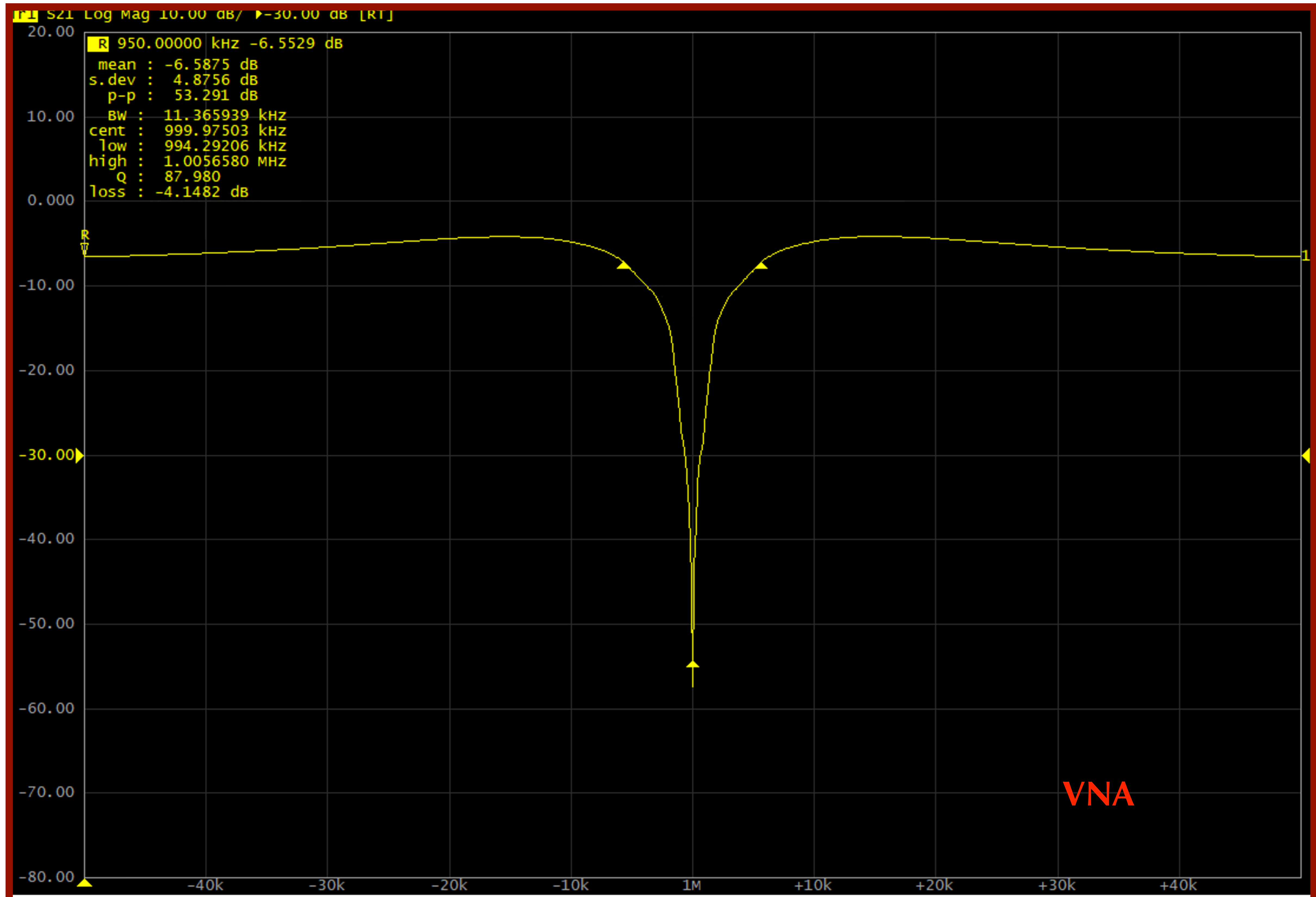
Receiver:



Modulator:

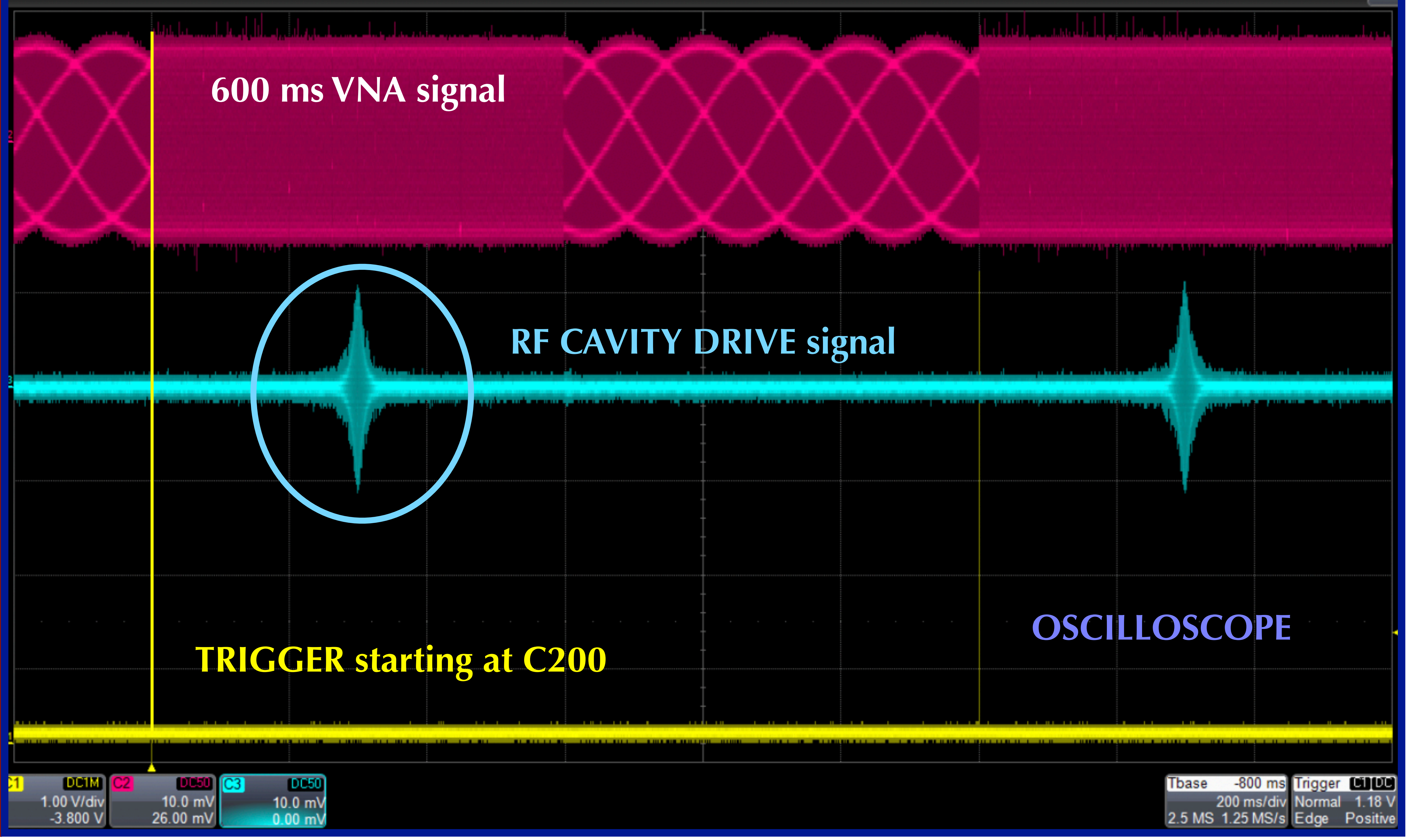


HARDWARE CHARACTERIZATION - TEST-STAND MEASUREMENTS



- Optimised span around each revolution harmonic:
  - ➔ Resolution Band-Width = 104 Hz
- Excitation signal sweep time : 600 ms
- Notch filter like frequency response

When the VNA sweep passes by the set revolution frequency the servoloop response is maximal and the RF drive output increases to compensate the emulated beam loading.



HARDWARE CHARACTERIZATION - BEAM - BASED MEASUREMENTS

Measurements in Double RF at Flat-Top (1.4 GeV cycle): sector with accelerating RF off and servo-loops not active. Static induced voltage.