Ph.D. in Accelerator Physics - Cycle XXXVIII

Longitudinal limitations for high-intensity beams in the upgraded CERN Proton Synchrotron Booster

Assessment Ph. D. Seminar

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Outline

1 **Motivation and research question**

PSB / RF / beam-dynamics context and push for high-intensity

2 **Tools and methods**

Beam-based measurements and techniques, numerical modelling

3 **Main findings**

Instability studies, reactive impedance, and high-intensity implications.

4 **Conclusions and perspectives**

Longitudinal limitations understanding and strategy for the future.

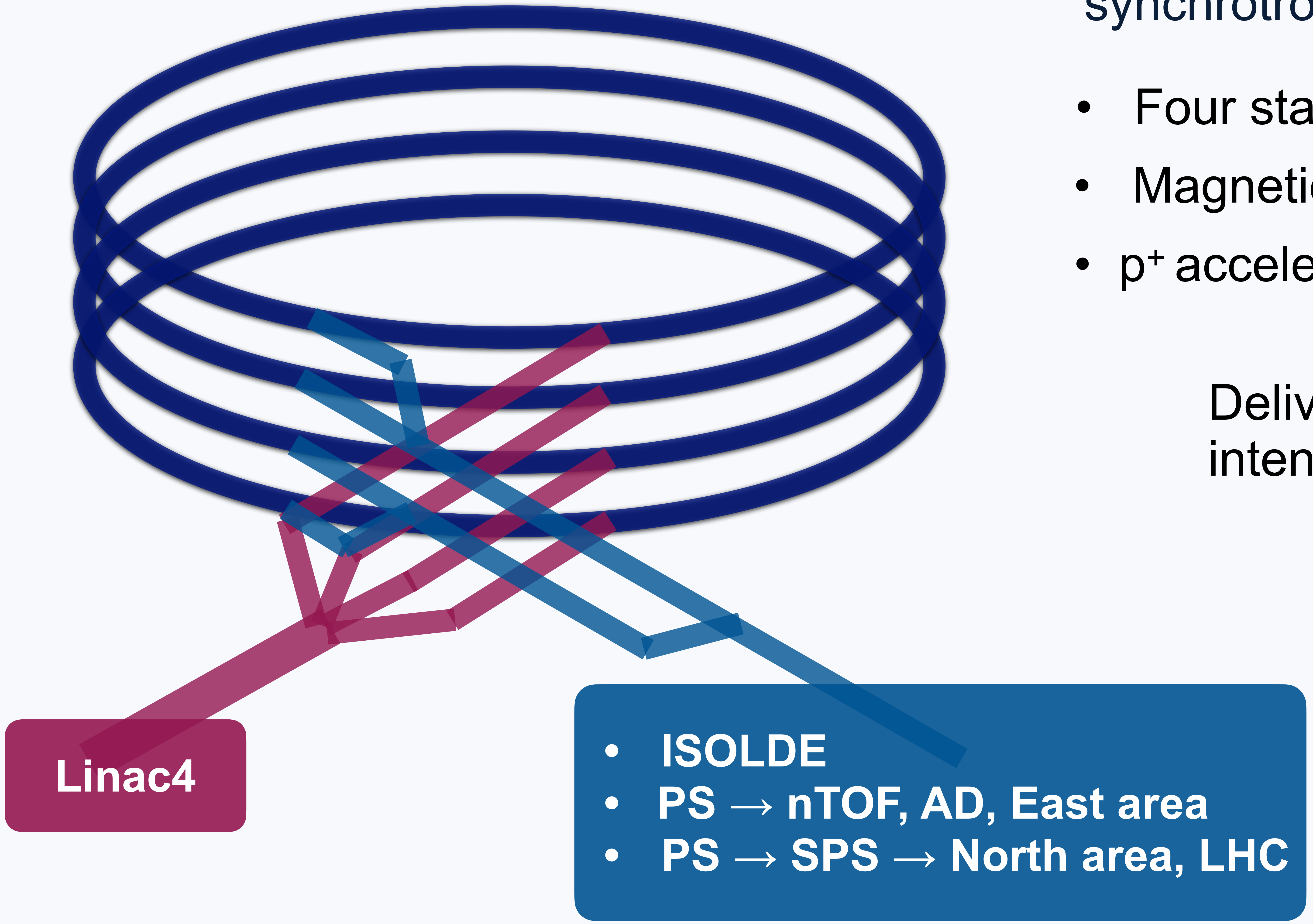
Outline

1 **Motivation and research question**

PSB / RF / beam-dynamics context and push for high-intensity

Motivation and research question

Machine context



- ISOLDE
- PS → nTOF, AD, East area
- PS → SPS → North area, LHC

The Proton Synchrotron Booster (PSB) is the first synchrotron in the CERN Proton accelerator chain.

- Four stacked rings with 157 m circumference.
- Magnetically coupled, but independent RF systems.
- p^+ accelerated every 1.2 s from 160 MeV to 1.4/2 GeV.

Delivers beams with a wide range of energies, intensities and emittances.

Flexibility and reliability are essential

Motivation and research question

LIU upgrade: new operating conditions

The PSB was extensively upgraded within the **LIU project**.

LIU objectives: higher brightness and intensity for the HL-LHC injector chain .

PSB LIU core changes
Linac4 injection at 160 MeV
Charge-exchange injection
New Finemet RF system
2 GeV extraction capability to the PS

PSB works below transition energy, space charge dominated.

LIU opened a new performance regime and raised new questions on longitudinal beam dynamics and RF limitations.

Motivation and research question

RF system

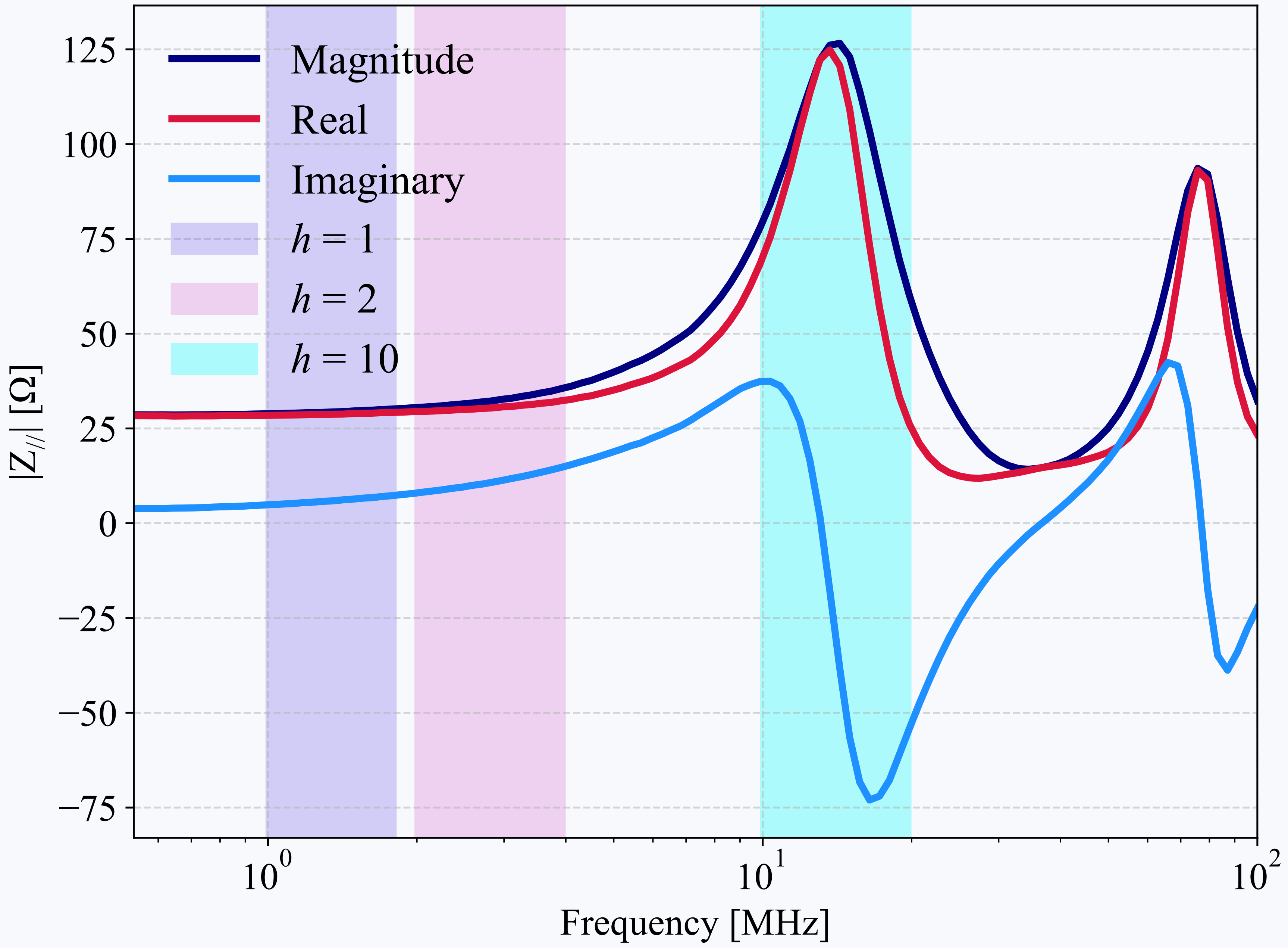
The upgraded RF system is both a performance enabler and a source of longitudinal limitations.

Enabler

- Broad frequency coverage (1 - 18 MHz).
- Multi-harmonic operation (16 harmonics of the revolution frequency).
- Bunch shaping and improved control of longitudinal distributions.

Limitation source

- Strong beam loading.
- Broadband longitudinal impedance.
- Feedback loops- induced perturbations.
- RF power and voltage constraints.



This work is centered around how the RF system shapes beam stability and intensity reach.

Outline

2 **Tools and methods**

Beam-based measurements and techniques, numerical modelling

Tools and methods

Beam-based studies and cavity control loops characterization

Impedance model validation and beam stability

Single-bunch longitudinal instabilities

- Dedicated measurements across cycle conditions and intensity range
- Different RF configurations and parameters
- Open and closed loop conditions

➡ Characterisation of instabilities

Quadrupole synchrotron frequency shifts

- Probe of the reactive longitudinal impedance
- Longitudinal space charge and imaginary Finemet impedance dominant sources
- Open and closed loop conditions

➡ Simulations versus measurements

Model useful as tool for future optimizations

Characterisation of transfer function of LLRF cavity loops

- Dedicated test-stand measured to get transfer function
- Measurements done on different loops to study trend and compare to design settings

Numerical modelling in frequency and time domain

- Accurate, dynamic Python model of the cavity loops
- Can be used alone or inside macro-particle tracking codes
- Possibility to study loops configurations

Outline

3

Main findings

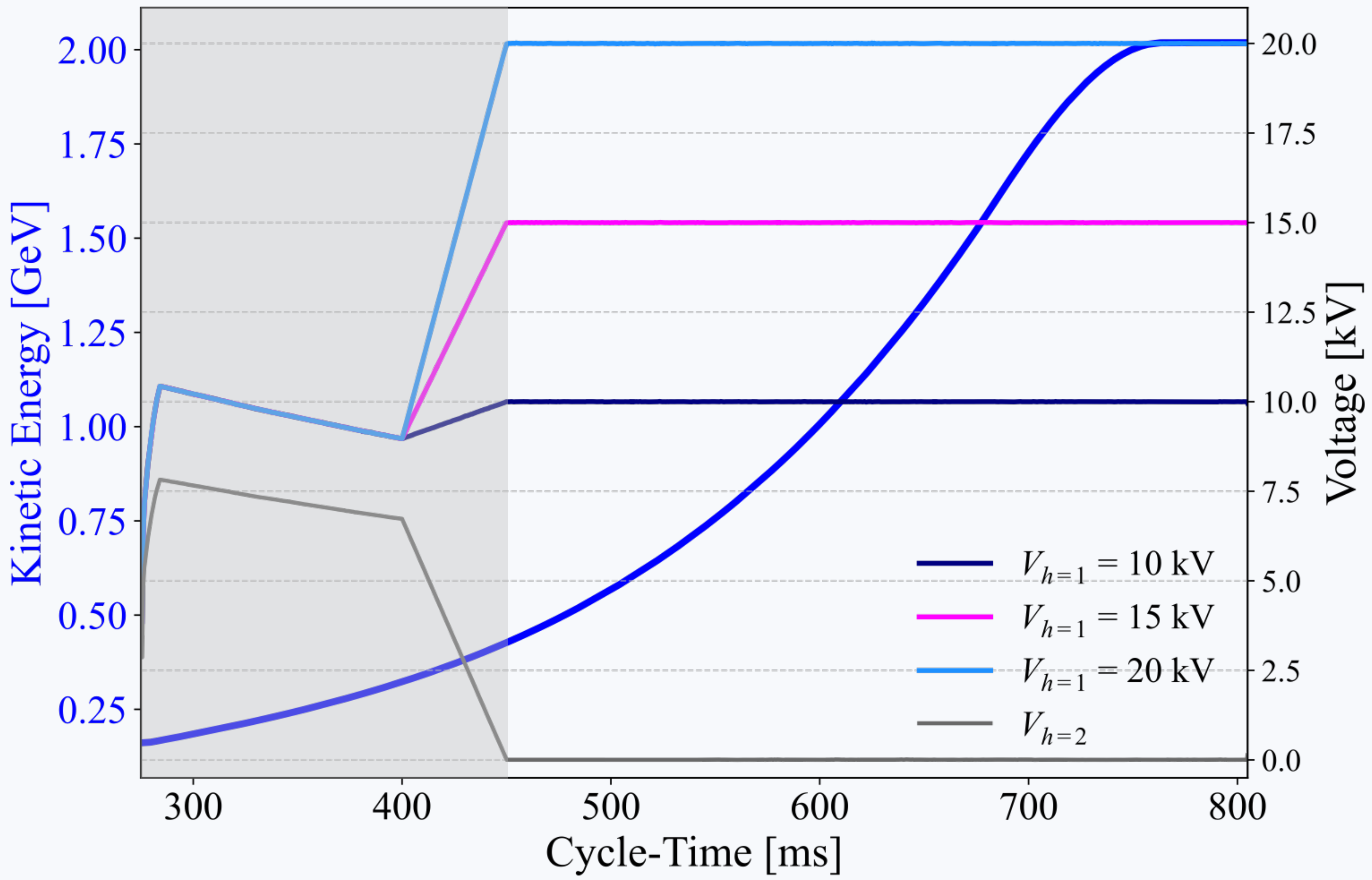
Instability studies, reactive impedance, and high-intensity implications.

Single-bunch longitudinal instabilities

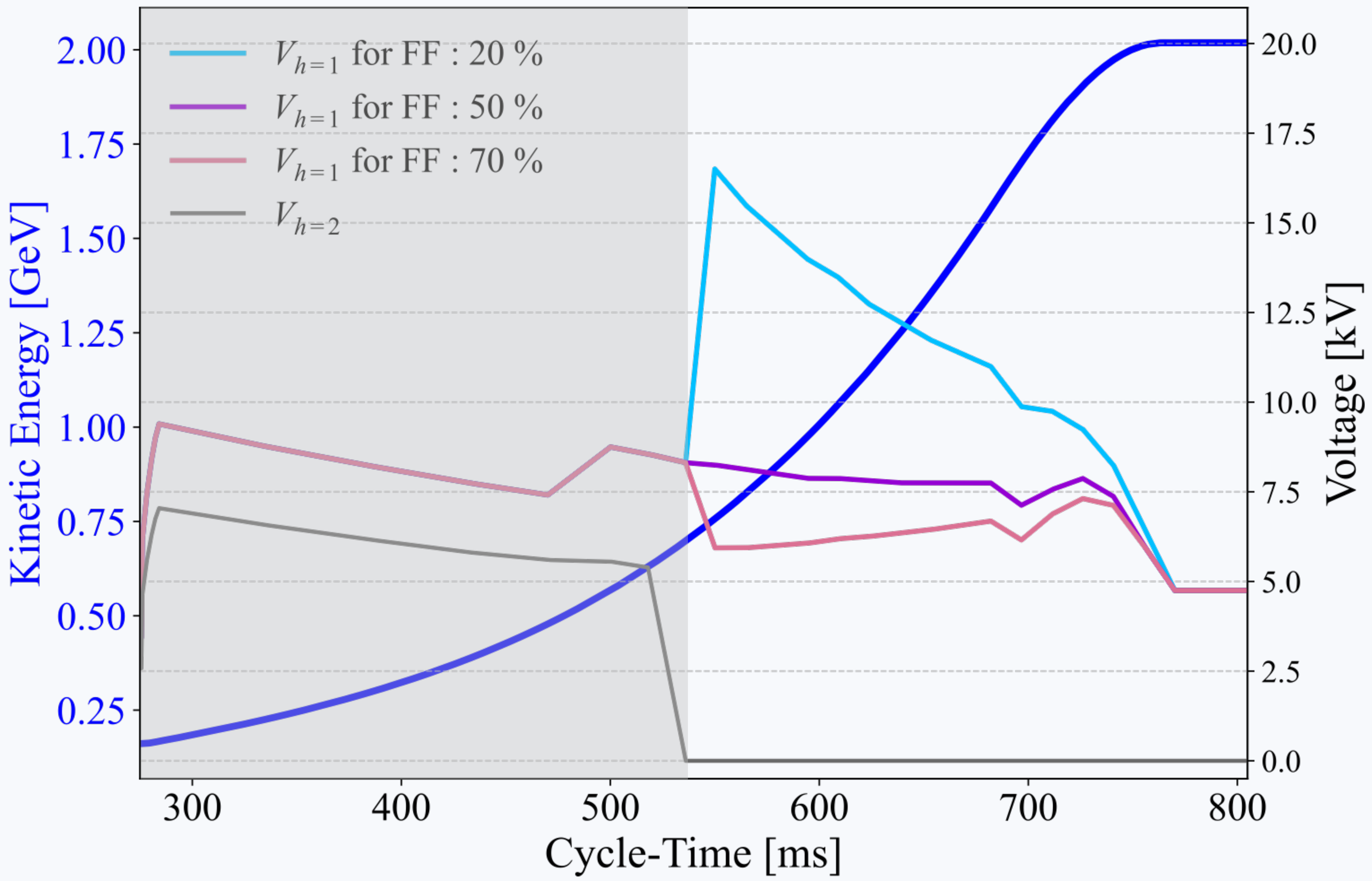
Single-Harmonic single-bunch stability study during acceleration

Double-Harmonic operation (BLM)

Constant Voltage



Constant Bucket Area



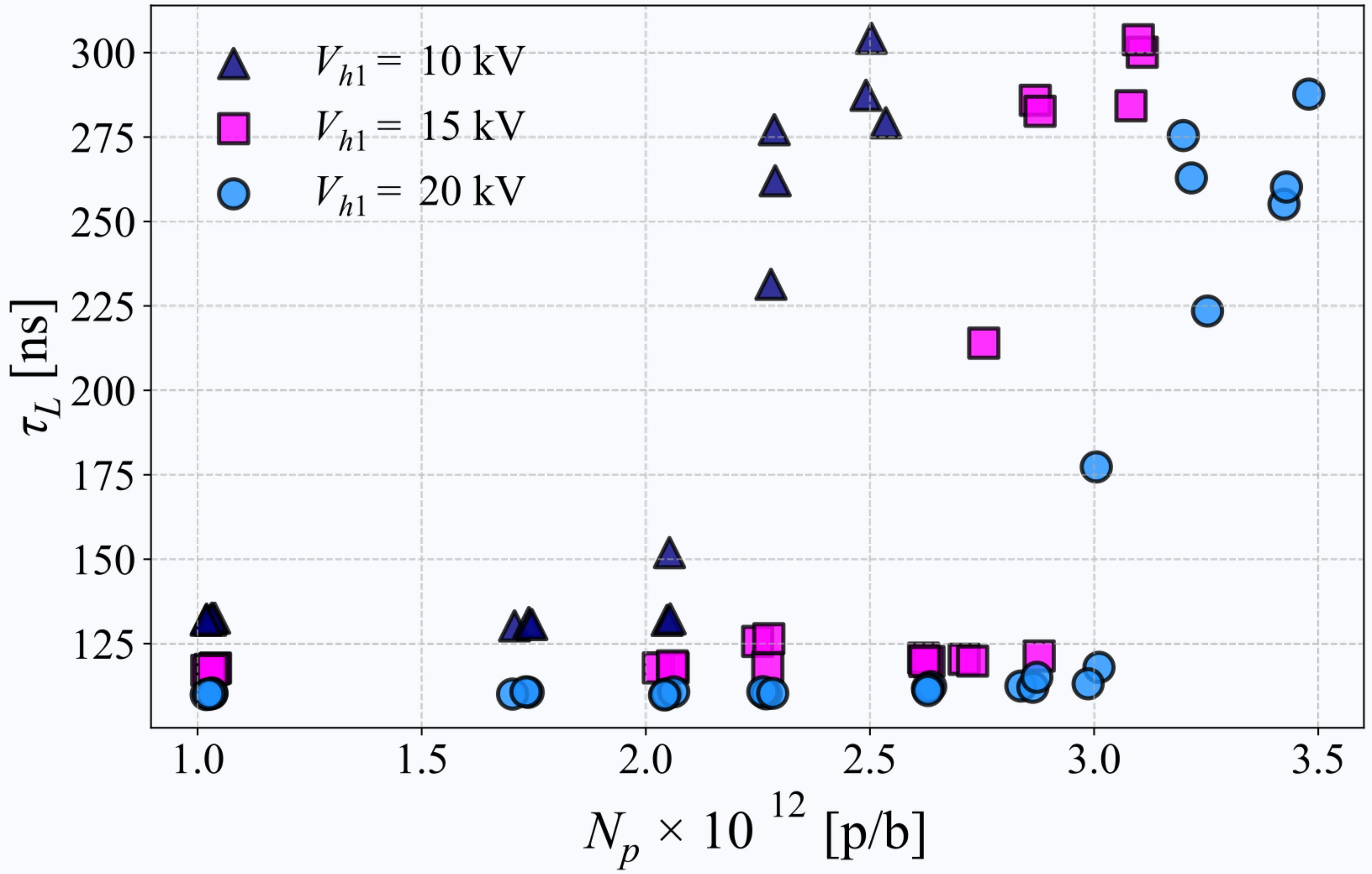
- 2 GeV cycle
- Intensity scan
- Open and closed loop conditions

Single-bunch longitudinal instabilities

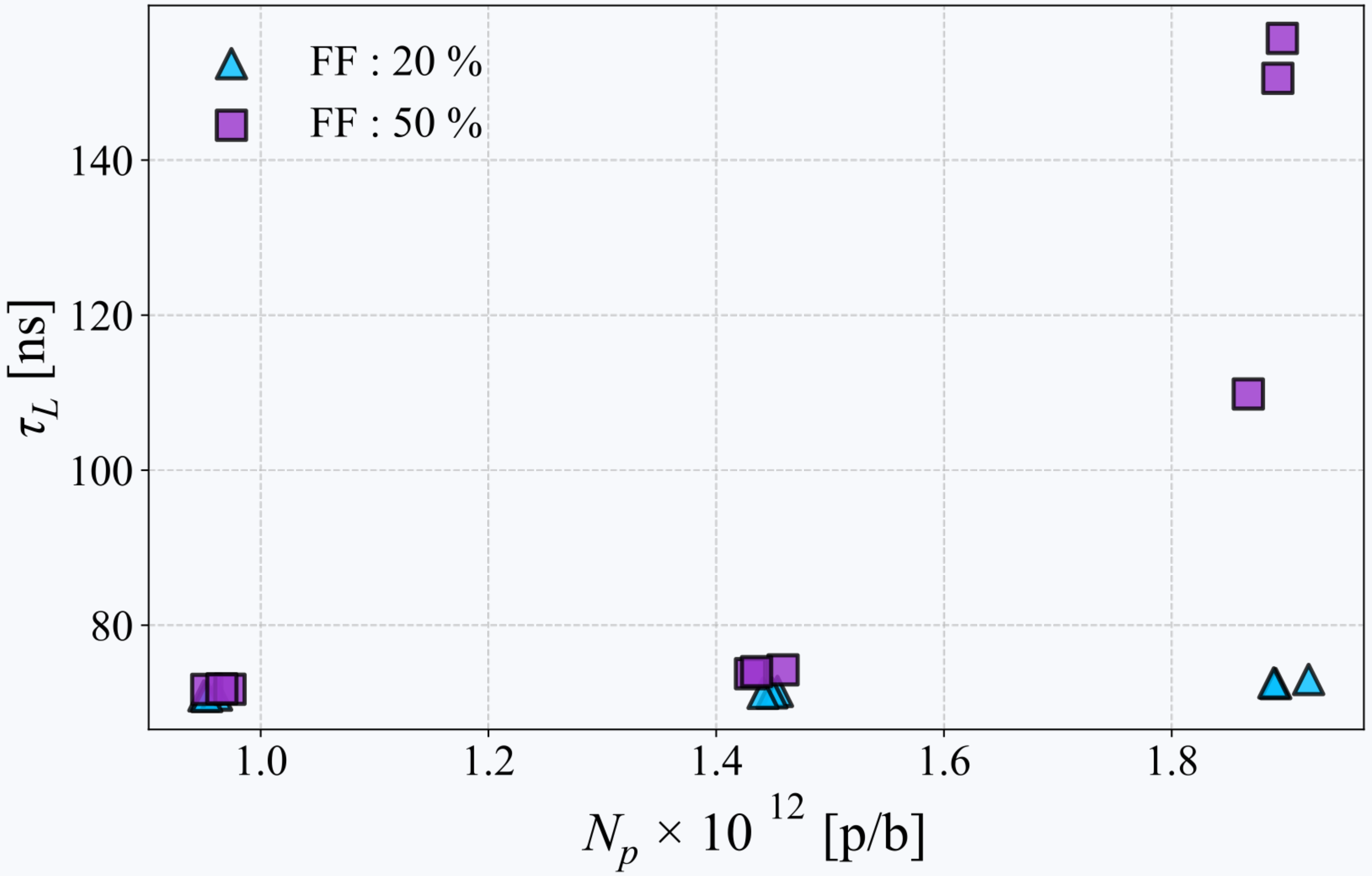
Instability thresholds: open-loop

At flat-top energy

Constant Voltage



Constant Bucket Area

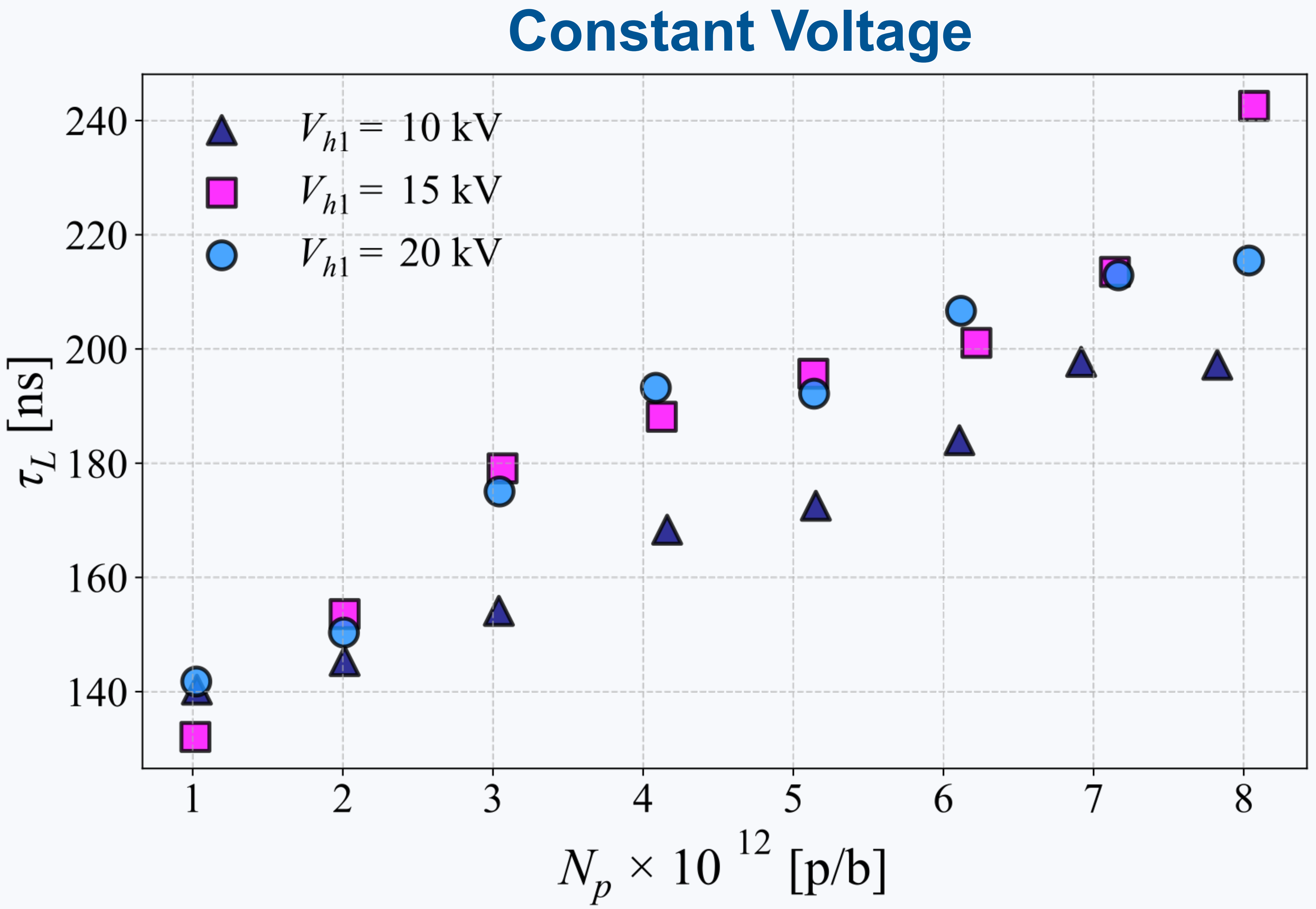


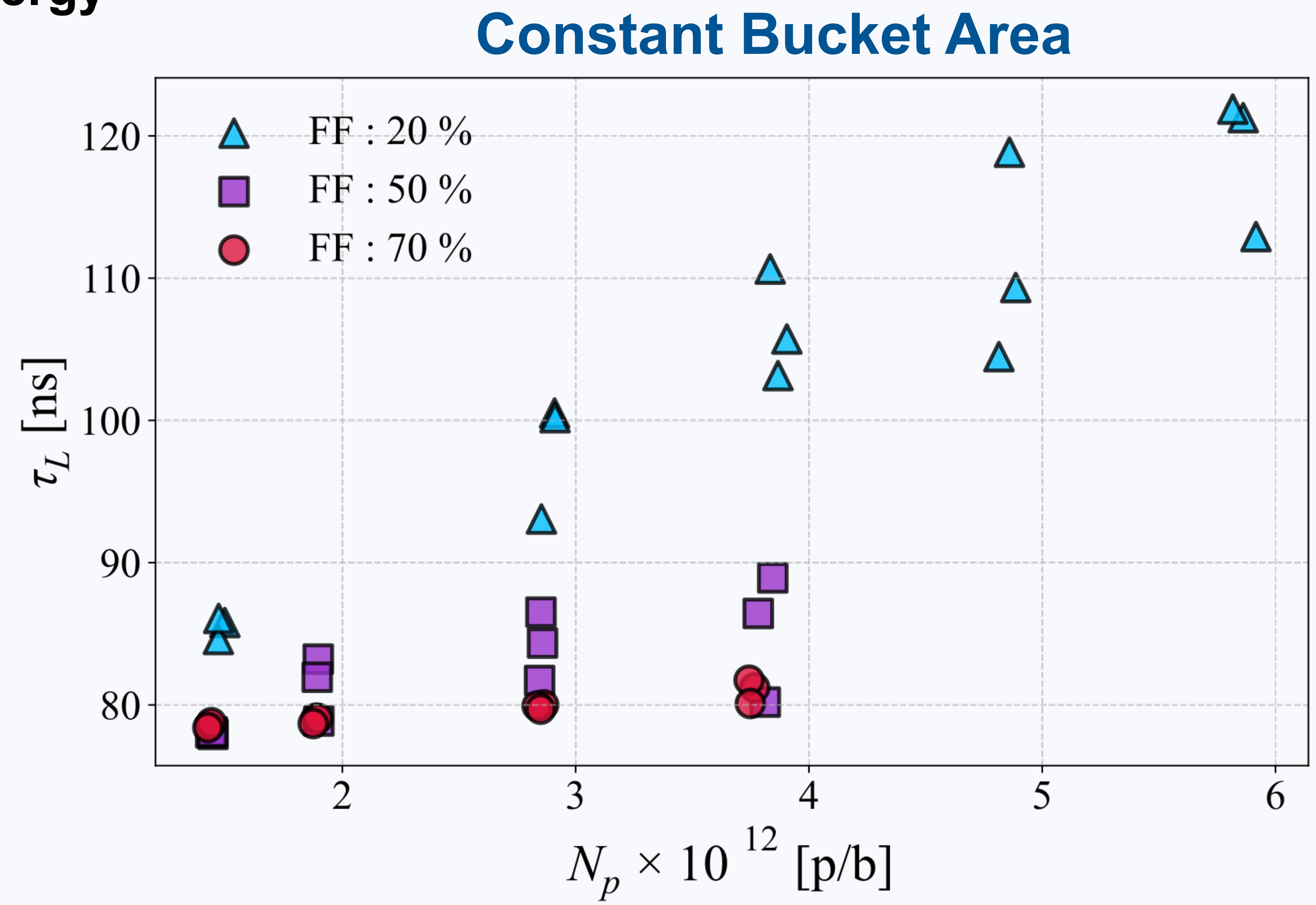
- Sharp instability thresholds observed
- Instability intensity scales as $\sqrt{V}$
- Fast beam blow-up and beam loss at defined intensities
- Dominated by beam-loading from cavity impedance

Single-bunch longitudinal instabilities

Instability thresholds: closed-loop

At flat-top energy


Constant Voltage


Constant Bucket Area

- Suppresses fast beam-loading instability
- Enables higher intensity operation (up to ~8×10¹² p/b)
- Introduces gradual emittance growth, no clear thresholds
- Not uniform effect across RF parameters

Single-bunch longitudinal instabilities

Instability thresholds: closed-loop

Constant Bucket Area

- Severity of emittance growth depend on filling factor

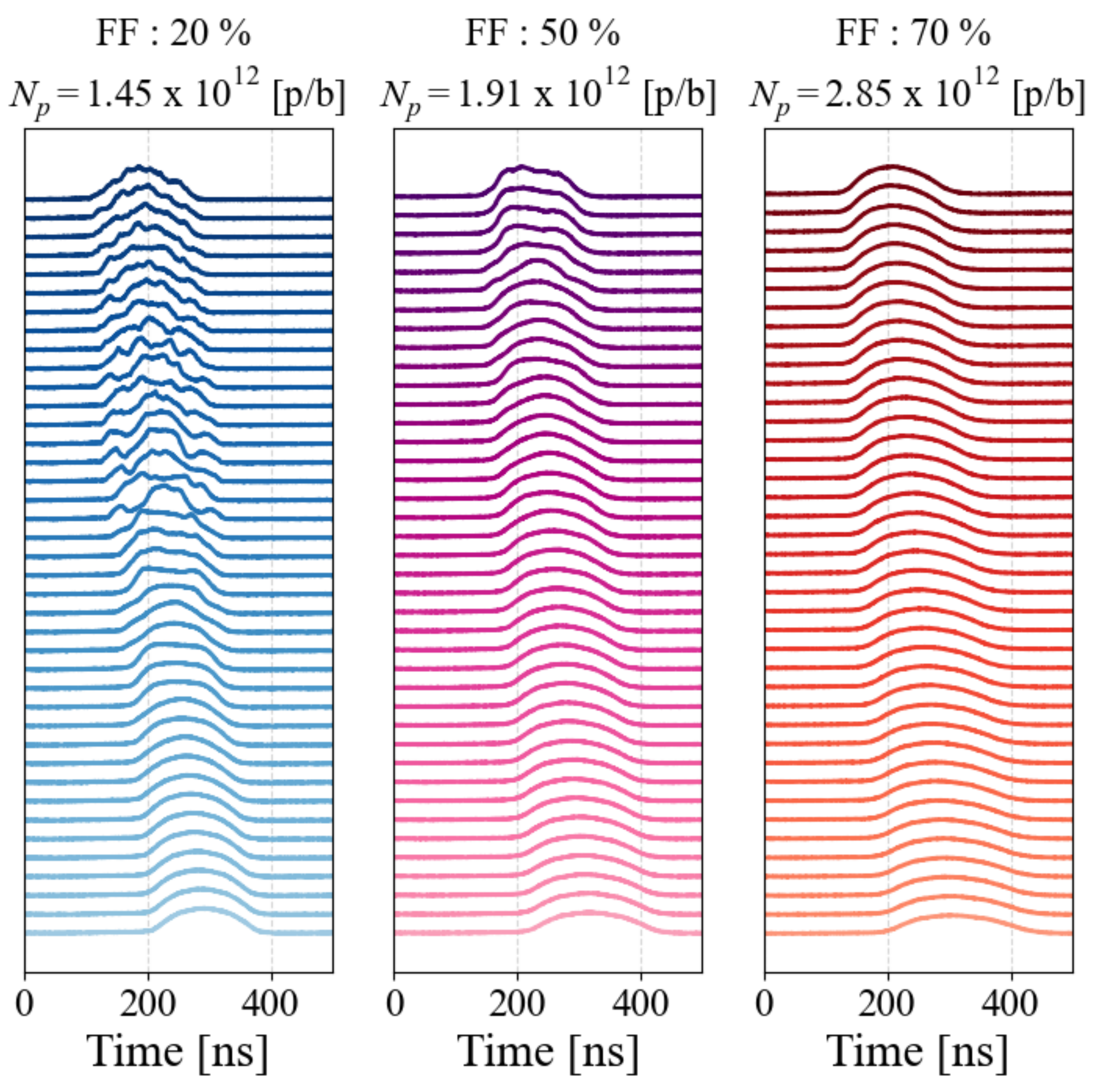
$$FF = \frac{\epsilon_l}{A_{bk}}$$

- Perturbations likely due to feedback loop dynamics (noise, bucket deformations)

- 20 % : most sensitive to perturbations
- 50 %, 70 % : delayed perturbations but beam is lost earlier

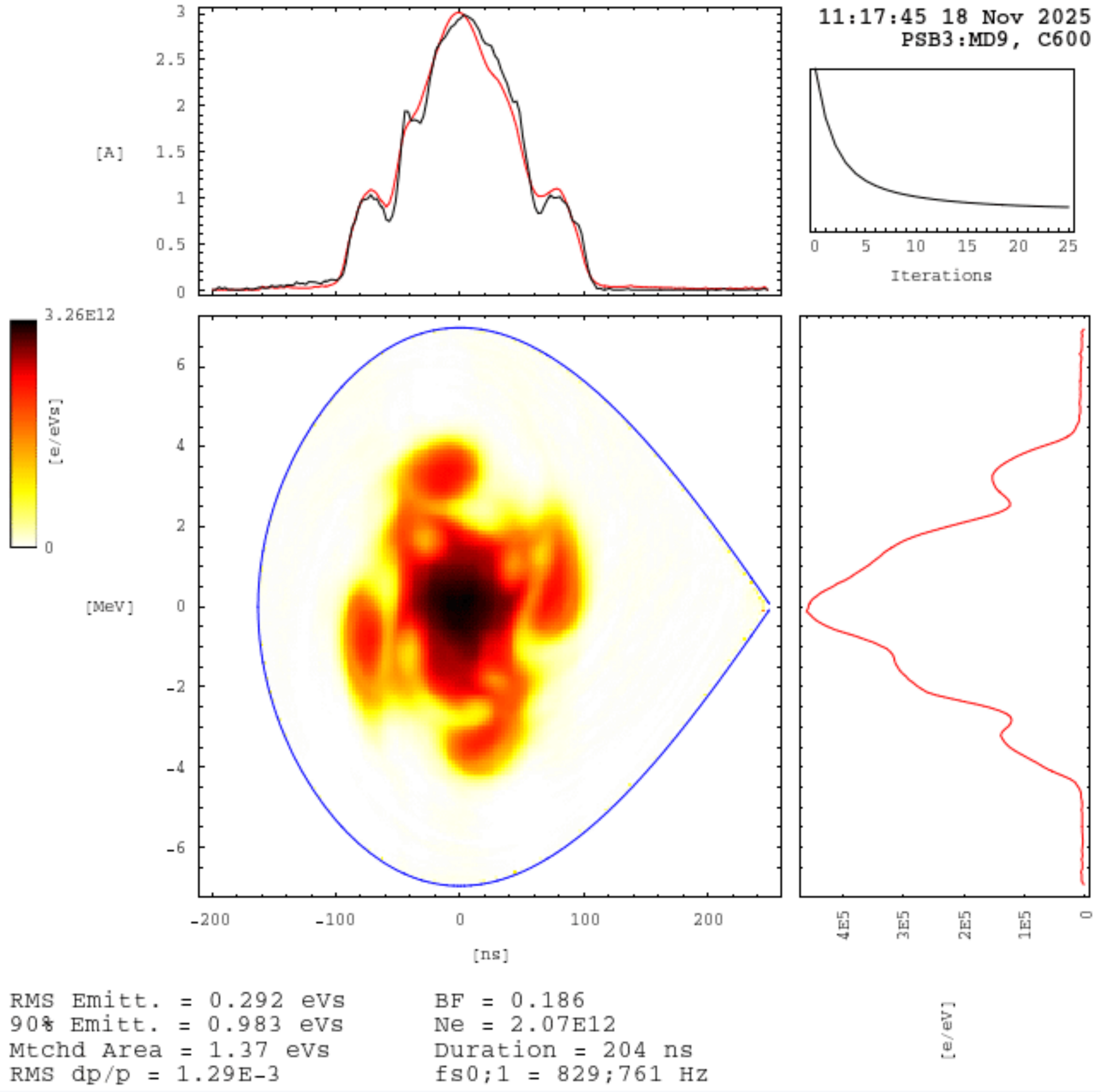
Interpretatio

- Low FF (larger bucket) :
  - higher f_s, narrow spread → less damping
  - Higher sensitivity to noise
- Higher FF (smaller bucket) :
  - lower f_s, broad spread → more damping
  - Lower acceptance



Single-bunch longitudinal instabilities

- On the basis of the 20% filling factor study-case, additional measurements taken
- Longitudinal bunch profiles acquired for different feedback loops configurations and intensities
- When all the loops are closed, octupolar oscillation appears
- But the azimuthal mode of excitation depends on which loops are disabled or not.



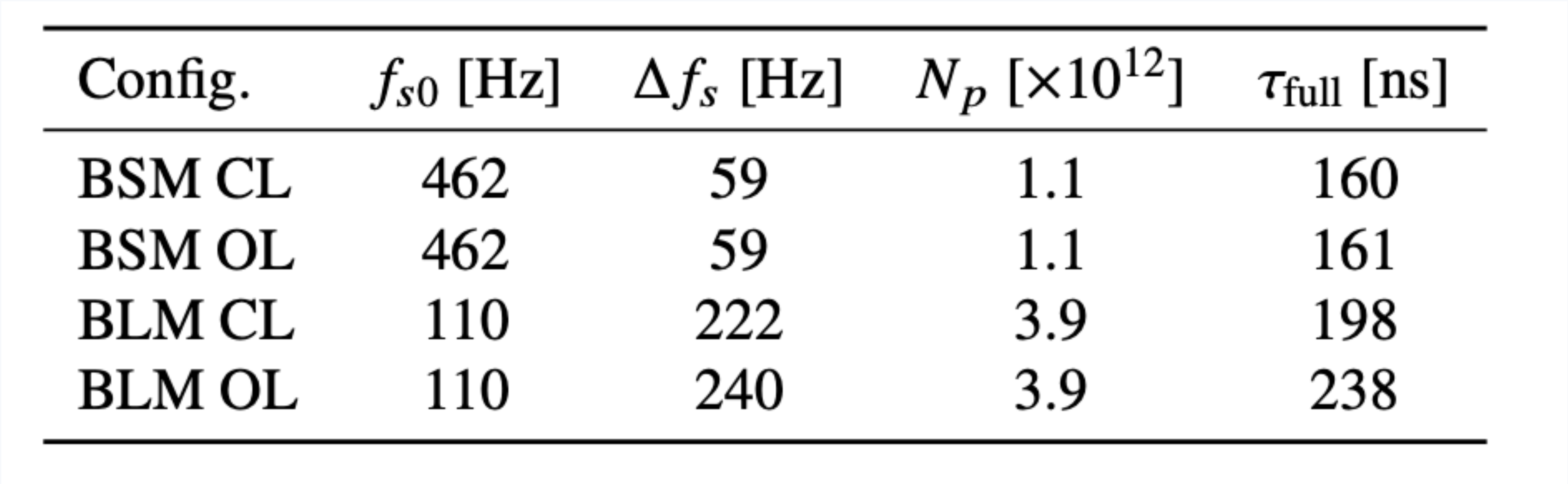
```
11:17:45 18 Nov 2025
PSB3:MD9, C600
```

```
RMS Emitt. = 0.292 eVs       BF = 0.186
90% Emitt. = 0.983 eVs       Ne = 2.07E12
Mtchd Area = 1.37 eVs        Duration = 204 ns
RMS dp/p = 1.29E-3           fs0;1 = 829;761 Hz
```

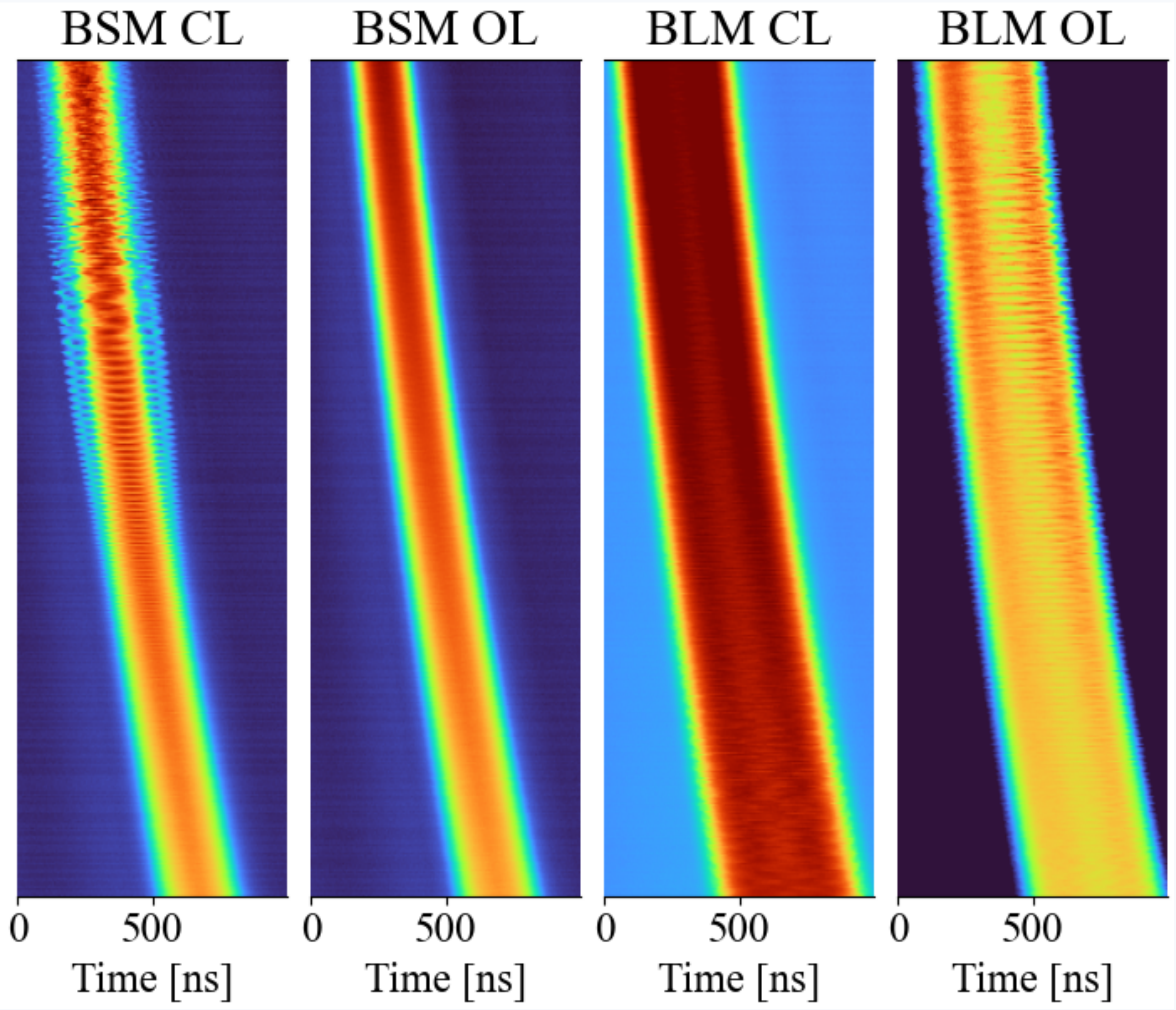
Single-bunch longitudinal instabilities

By operating the Double Harmonic operation, meaning applying voltage to the first and second harmonic the beam stability scenario changes.

- When Double Harmonic system is played in Bunch Lengthening Mode, the loops-induced perturbations are mitigated.
- When Double Harmonic system is played in Bunch Shortening Mode, the loops-induced perturbations worsen.



Config.	f_{s0} [Hz]	Δf_s [Hz]	N_p [$\times 10^{12}$]	τ_{full} [ns]
BSM CL	462	59	1.1	160
BSM OL	462	59	1.1	161
BLM CL	110	222	3.9	198
BLM OL	110	240	3.9	238

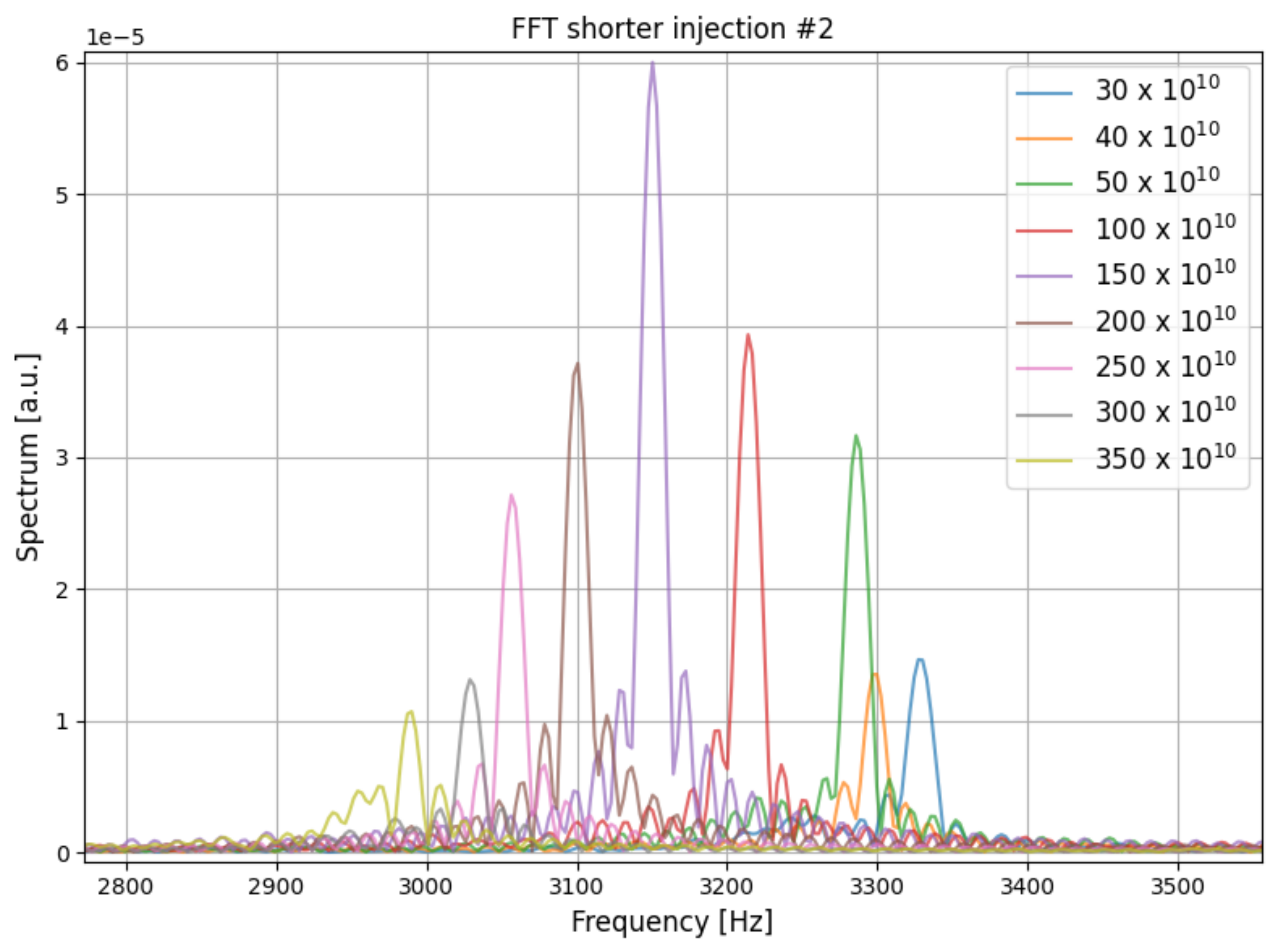


Quadrupole synchrotron frequency shifts

Quadrupole synchrotron frequency shifts provide a beam-based probe of the reactive longitudinal impedance. In the PSB, the dominant contributions are longitudinal space charge and the imaginary part of the Finemet RF impedance.

Method

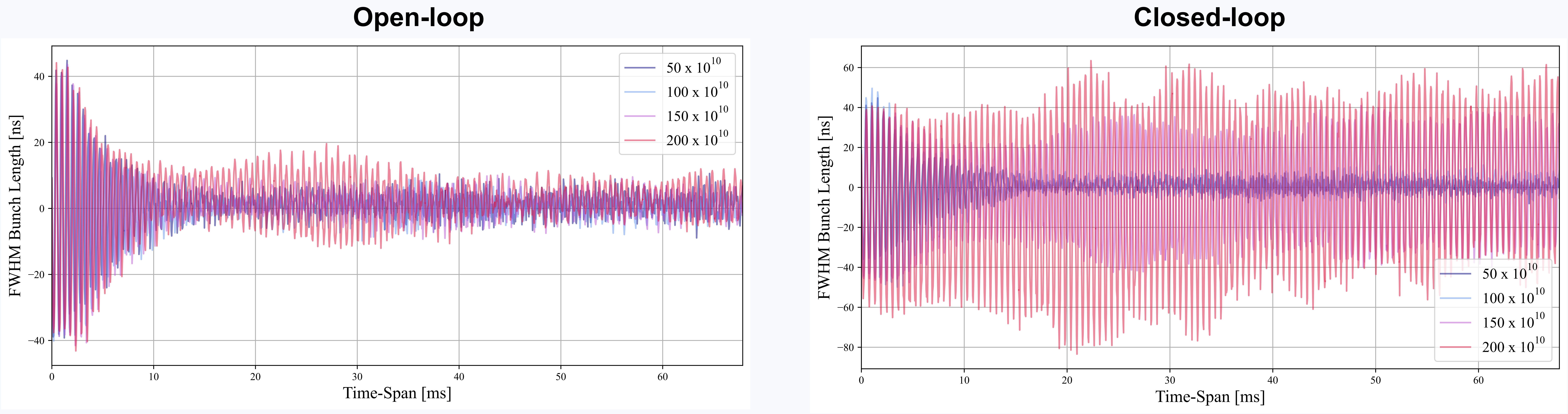
- Mismatch in the longitudinal phase space.
- Application of non-adiabatic kick to the voltage amplitude.
- Computation of bunch length oscillations.
- FFT to record shifts for each intensity.



Measurements carried-out in open and closed-loop condition. In closed-loop space charge compensation action reduced → bigger shift.

Quadrupole synchrotron frequency shifts

Impact of the LLRF cavity feedback loops on quadrupole synchrotron frequency shifts.

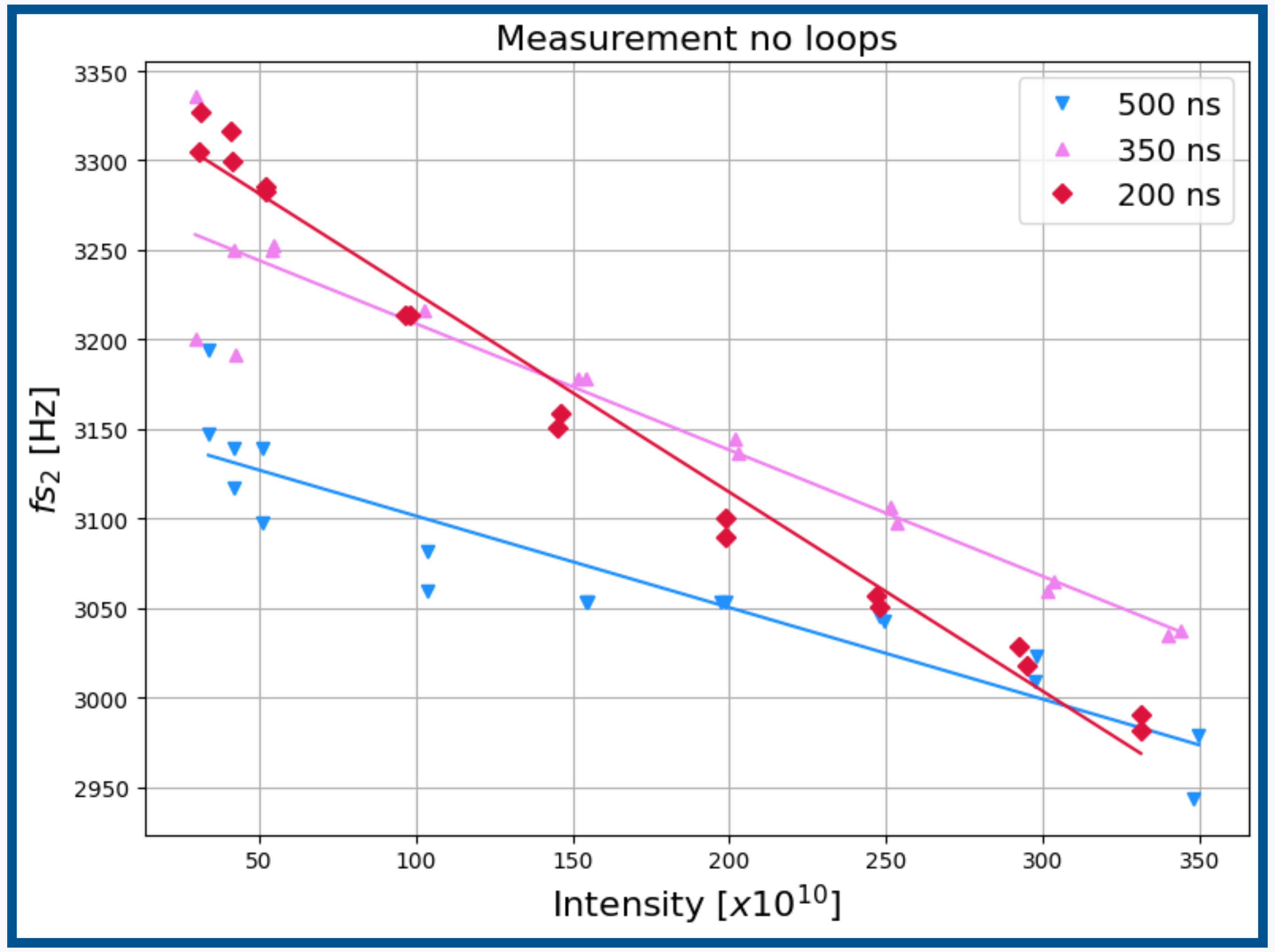


- **Finemet with LLRF loops inactive: fast damping of the oscillations due to large incoherent effect.**
- **Finemet with LLRF loops active: at higher intensity space charge effect visible (defocusing)**

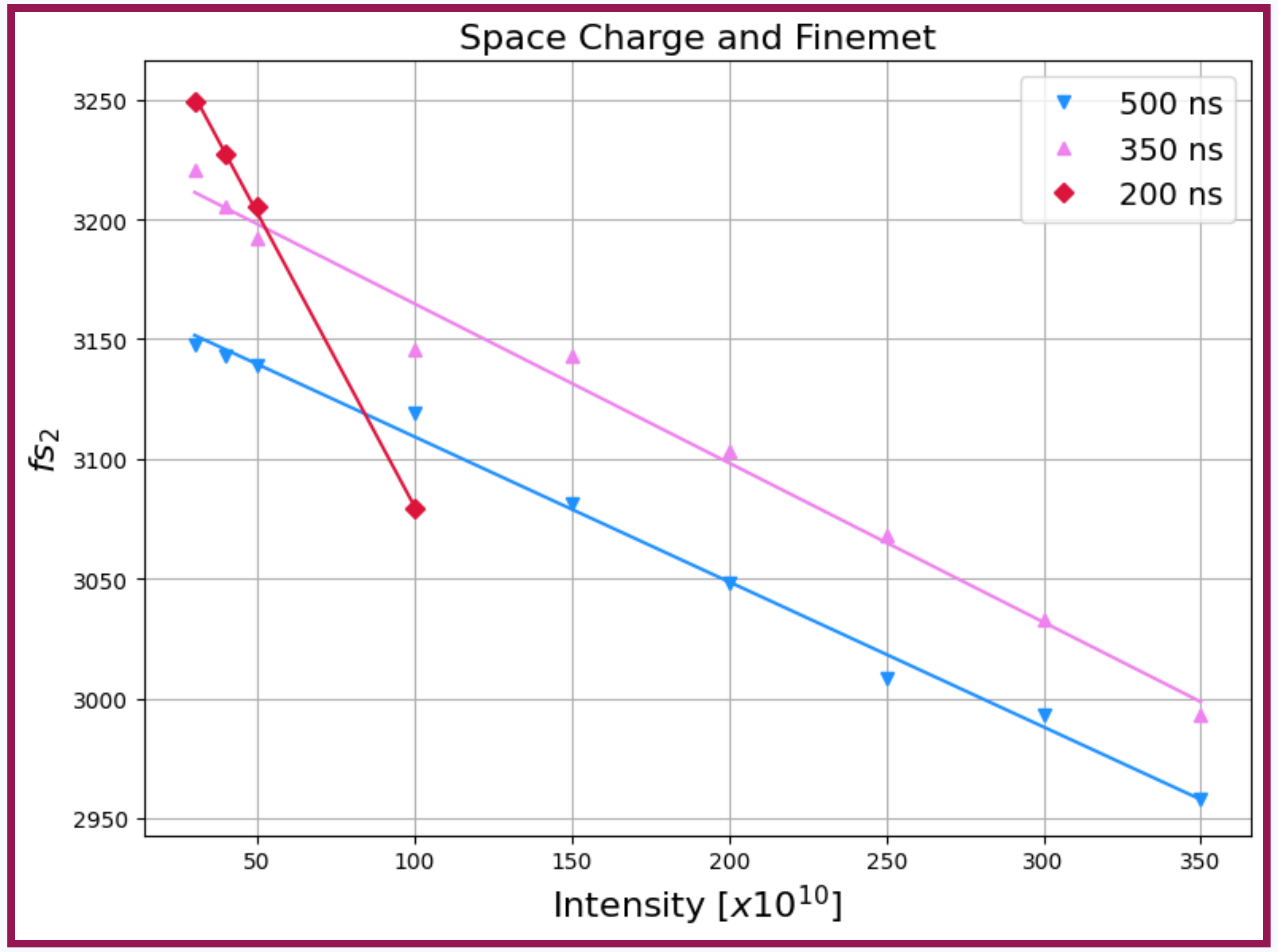
Quadrupole synchrotron frequency shifts

Open-loop measurements compared with BLonD simulation considering Finemet longitudinal impedance and longitudinal space charge as impedance sources.

Measurement



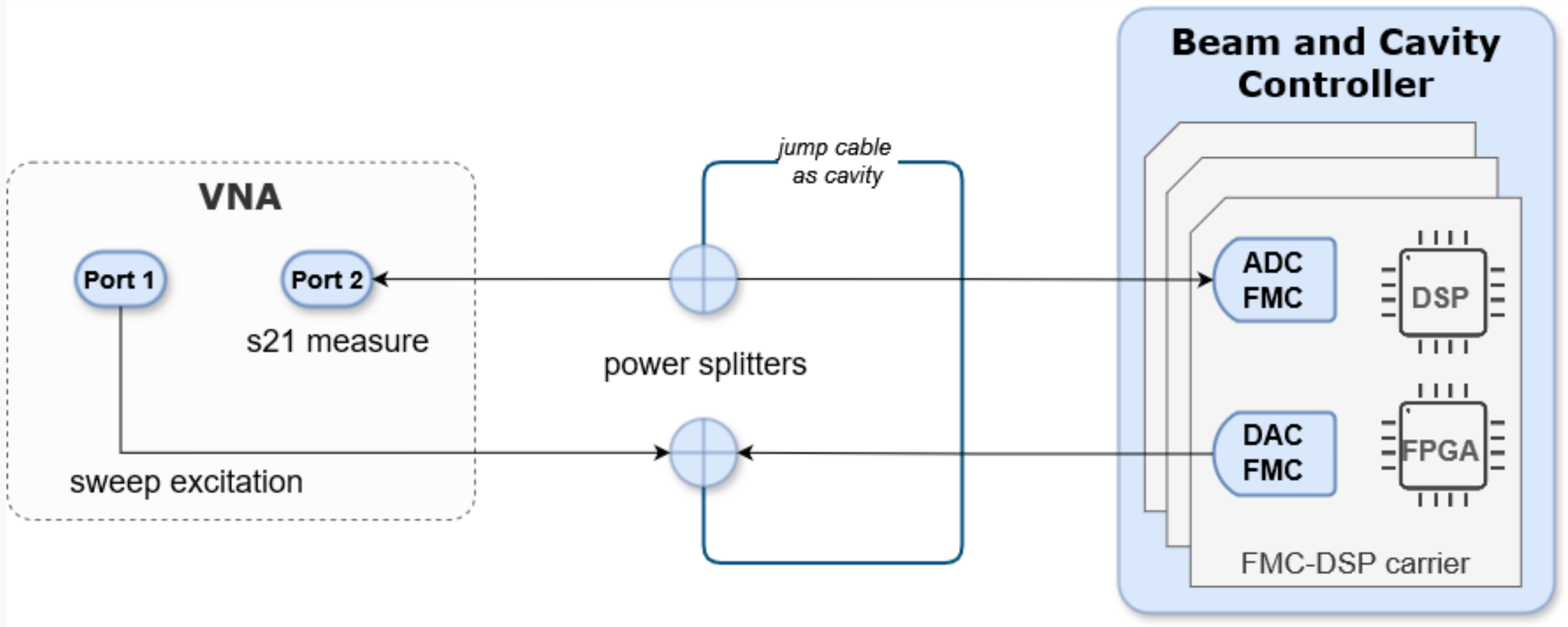
Simulation



- **Quadrupole synchrotron frequency shifts in agreement between measurement and simulations for intermediate bunch lengths.**
- **For very short bunch length the simulated slope is steeper, possible high-frequency components not included in the model.**

Characterisation of the LLRF cavity loops

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



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

Characterisation of the LLRF cavity loops

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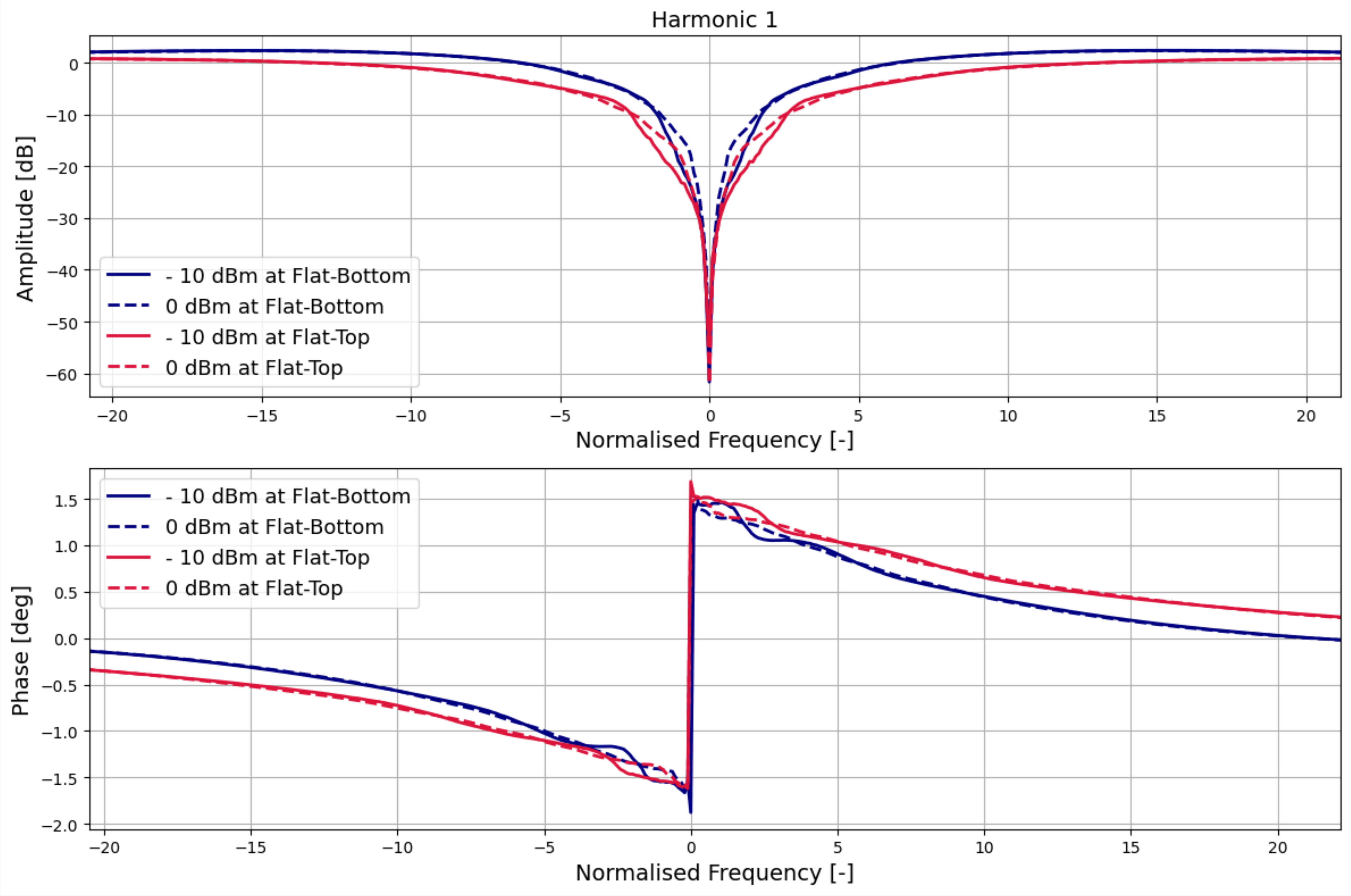

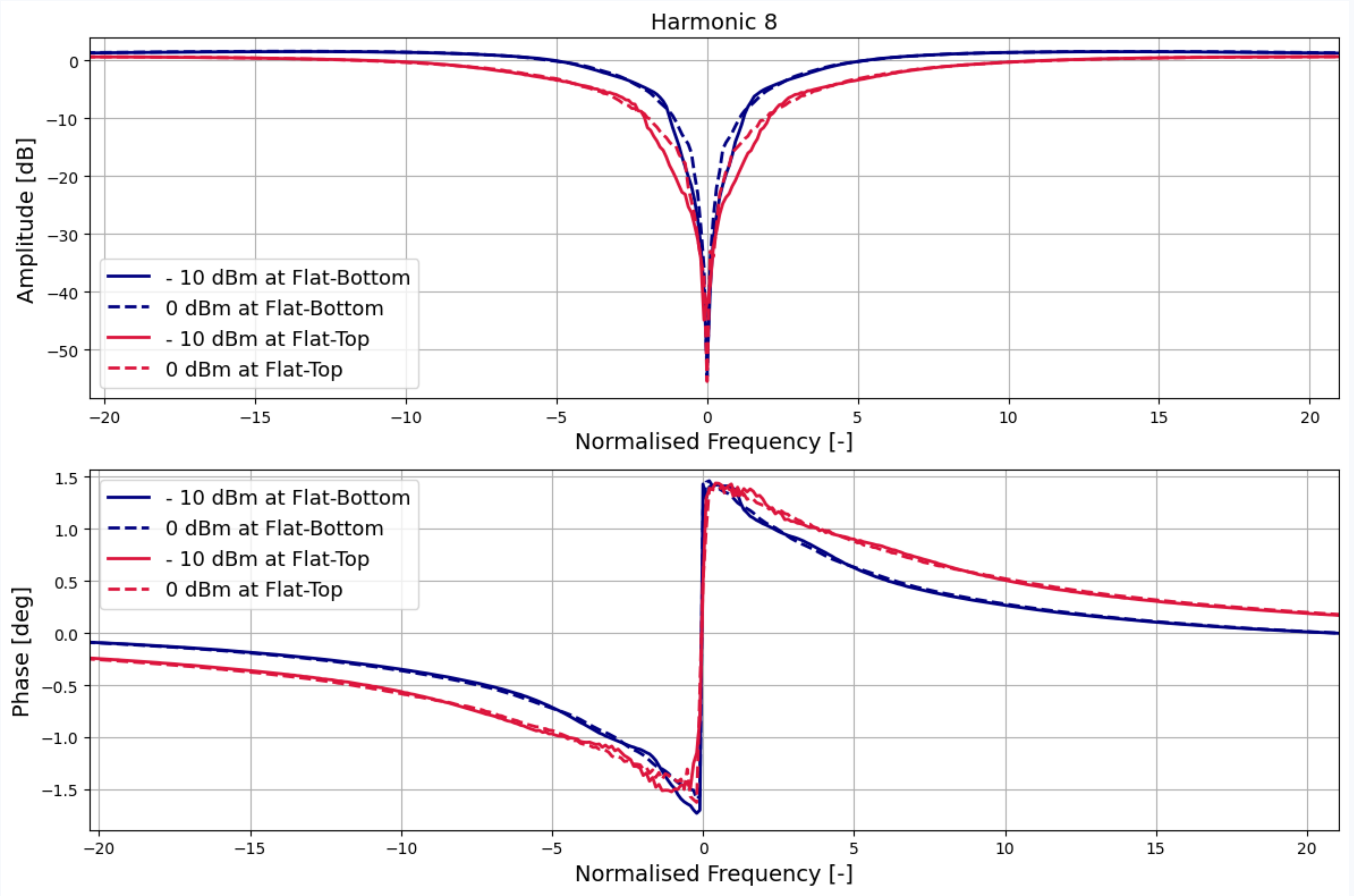

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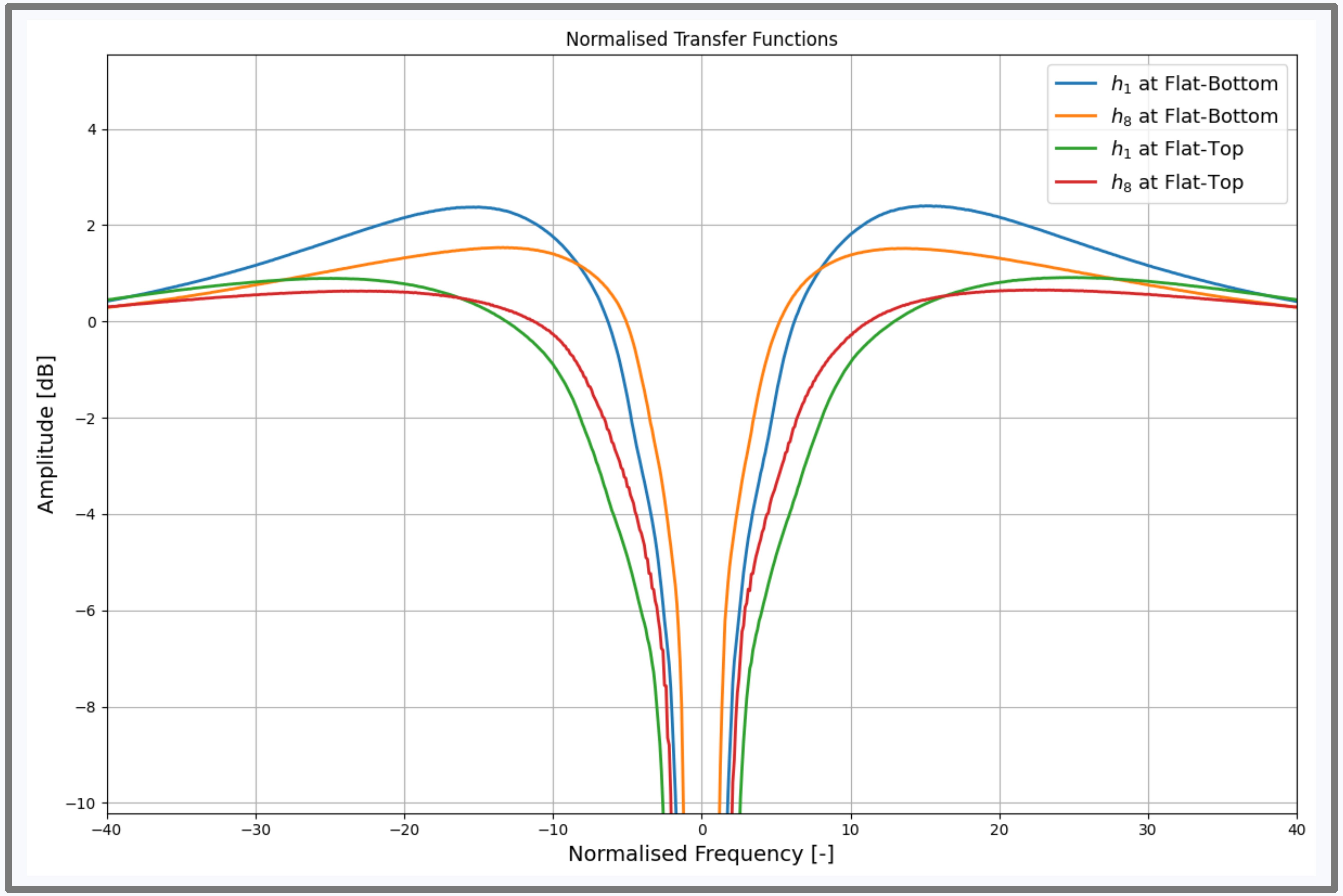
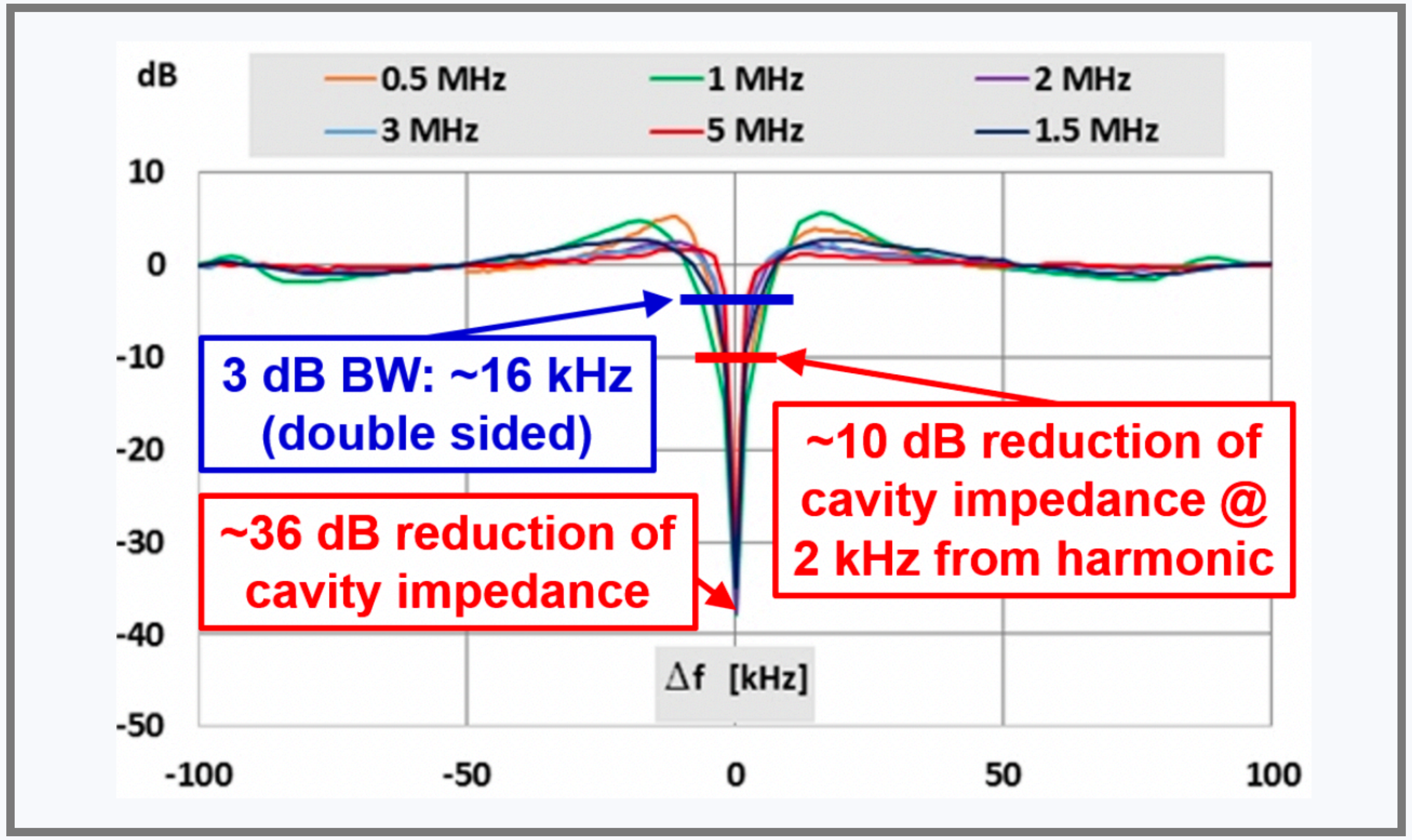


Normalised Transfer Functions

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



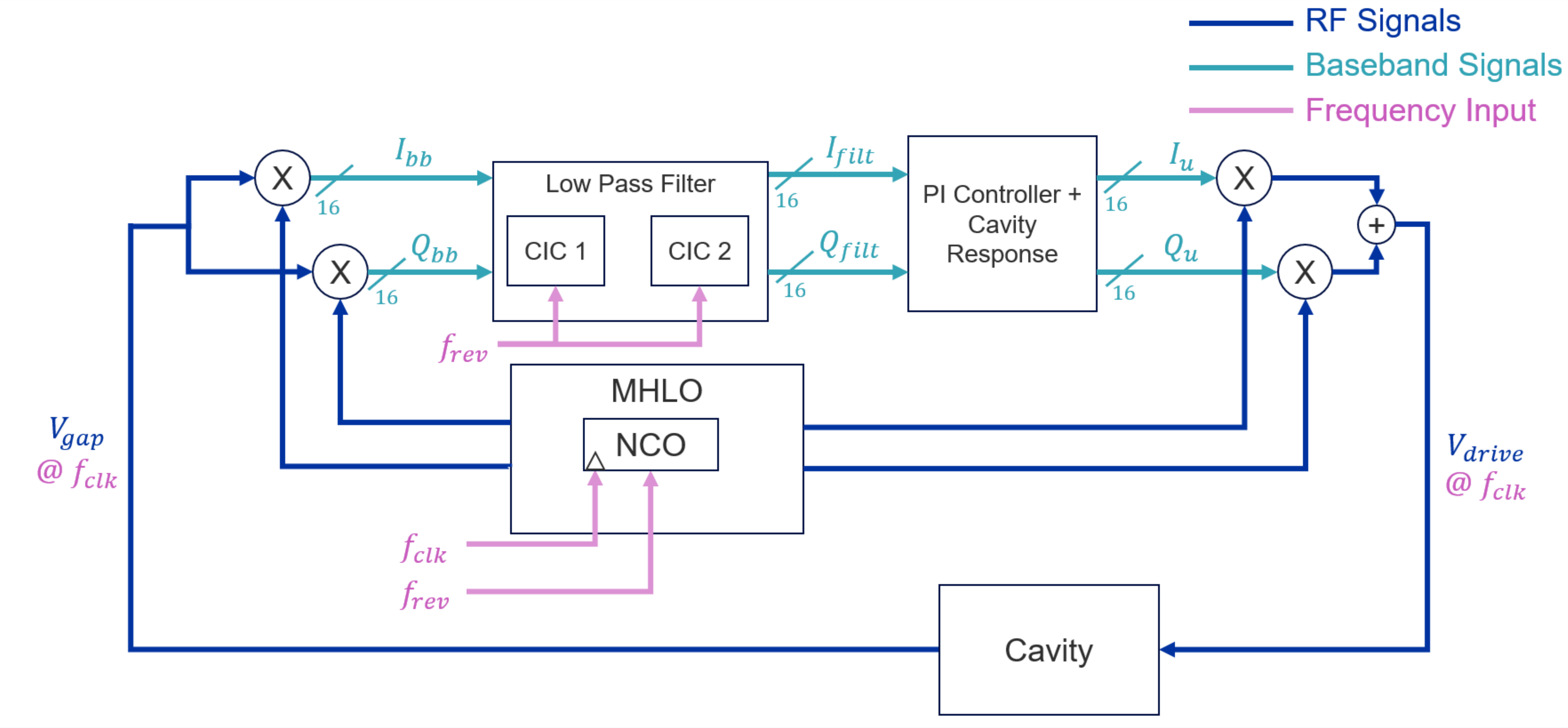
3 dB BW: ~16 kHz (double sided)

~10 dB reduction of cavity impedance @ 2 kHz from harmonic

~36 dB reduction of cavity impedance

Characterisation of the LLRF cavity loops

Detailed, dynamic model of the LLRF cavity feedback loops.
Fixed frequency clock architecture and revolution frequency tracking.



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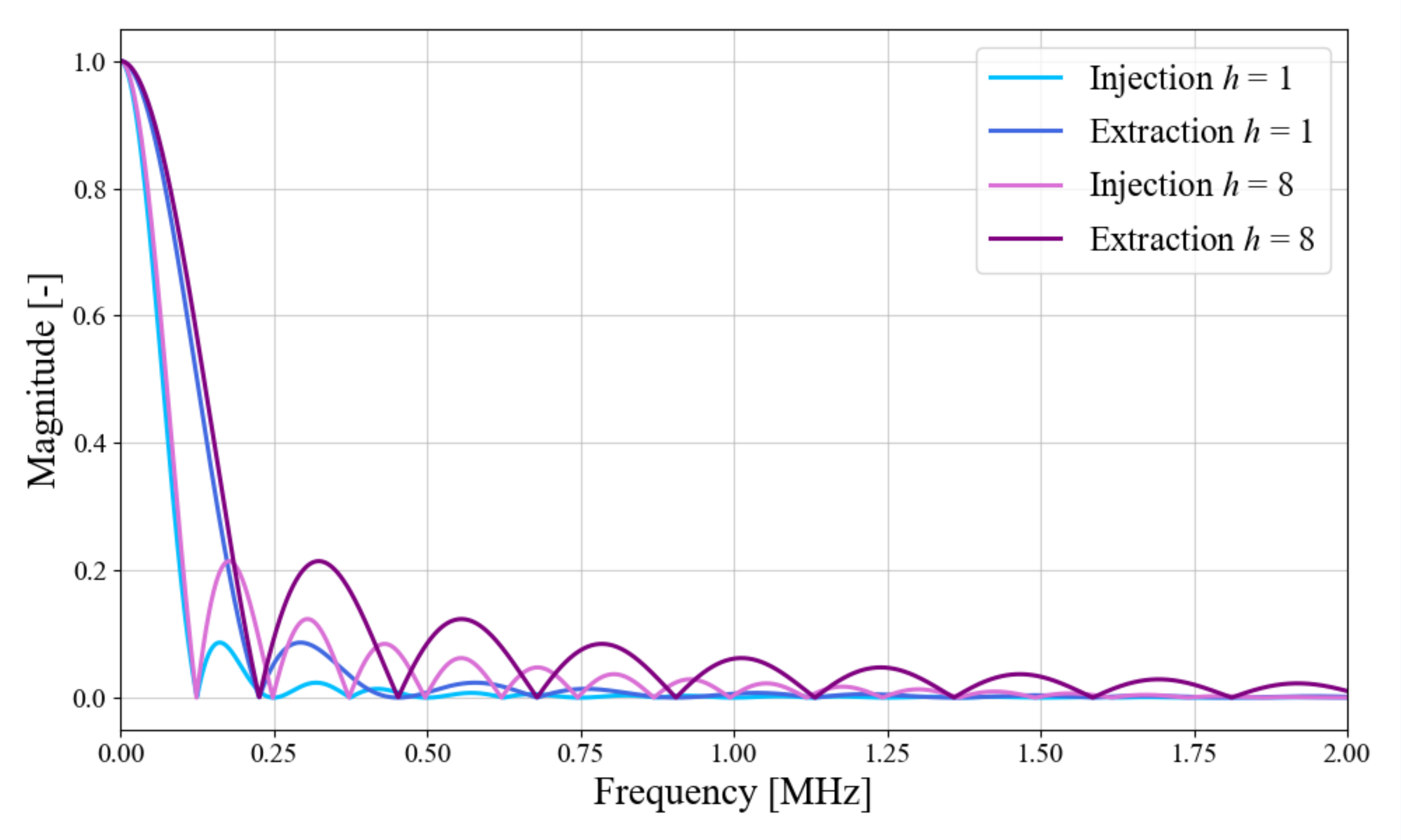
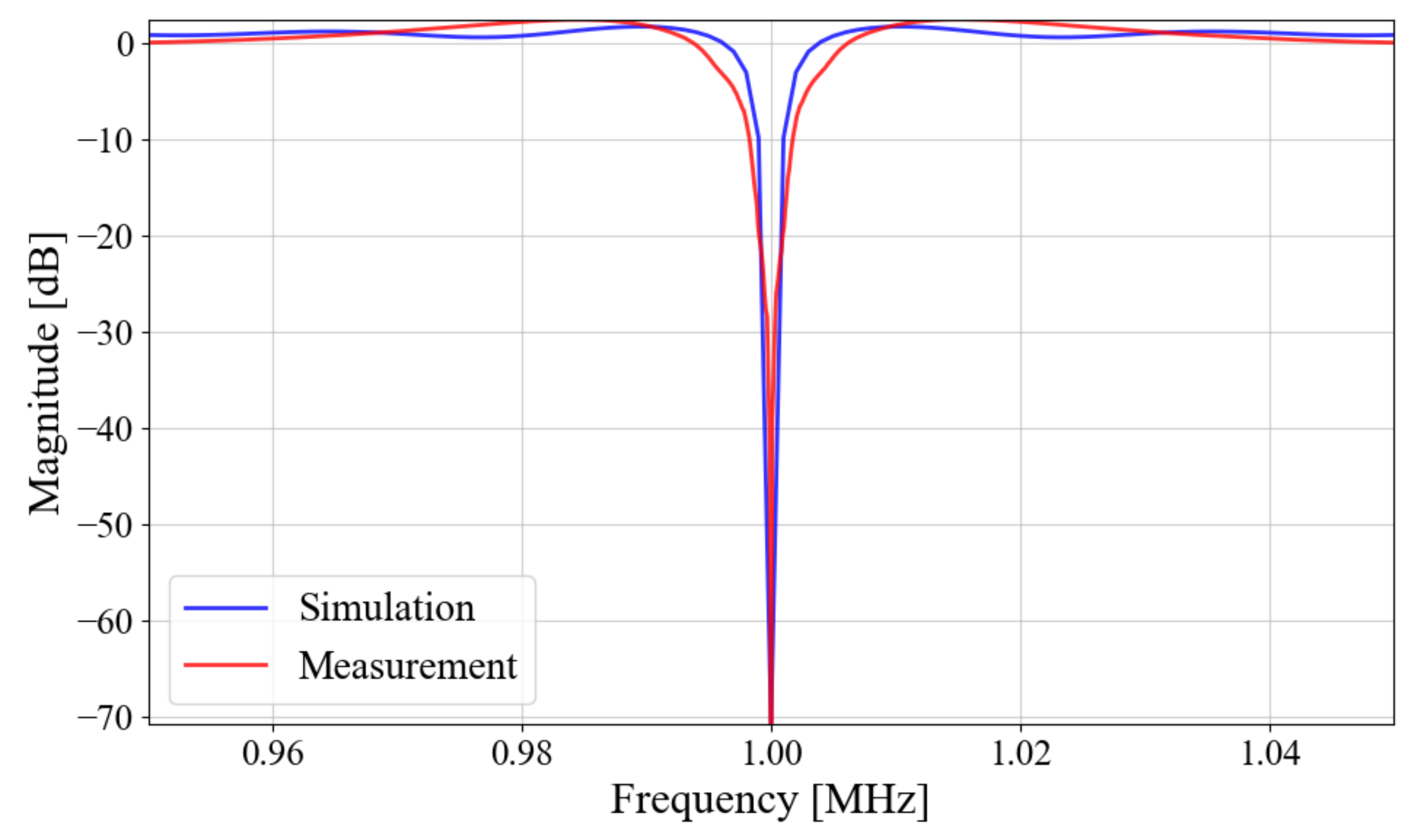
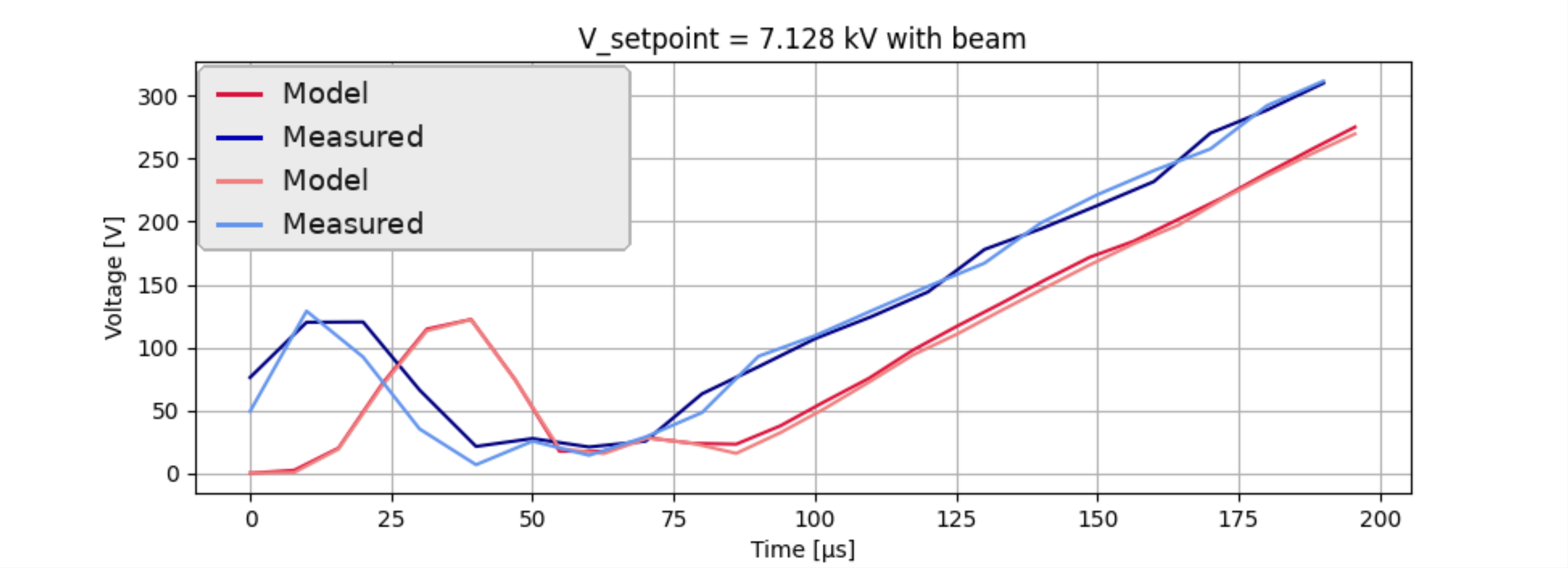


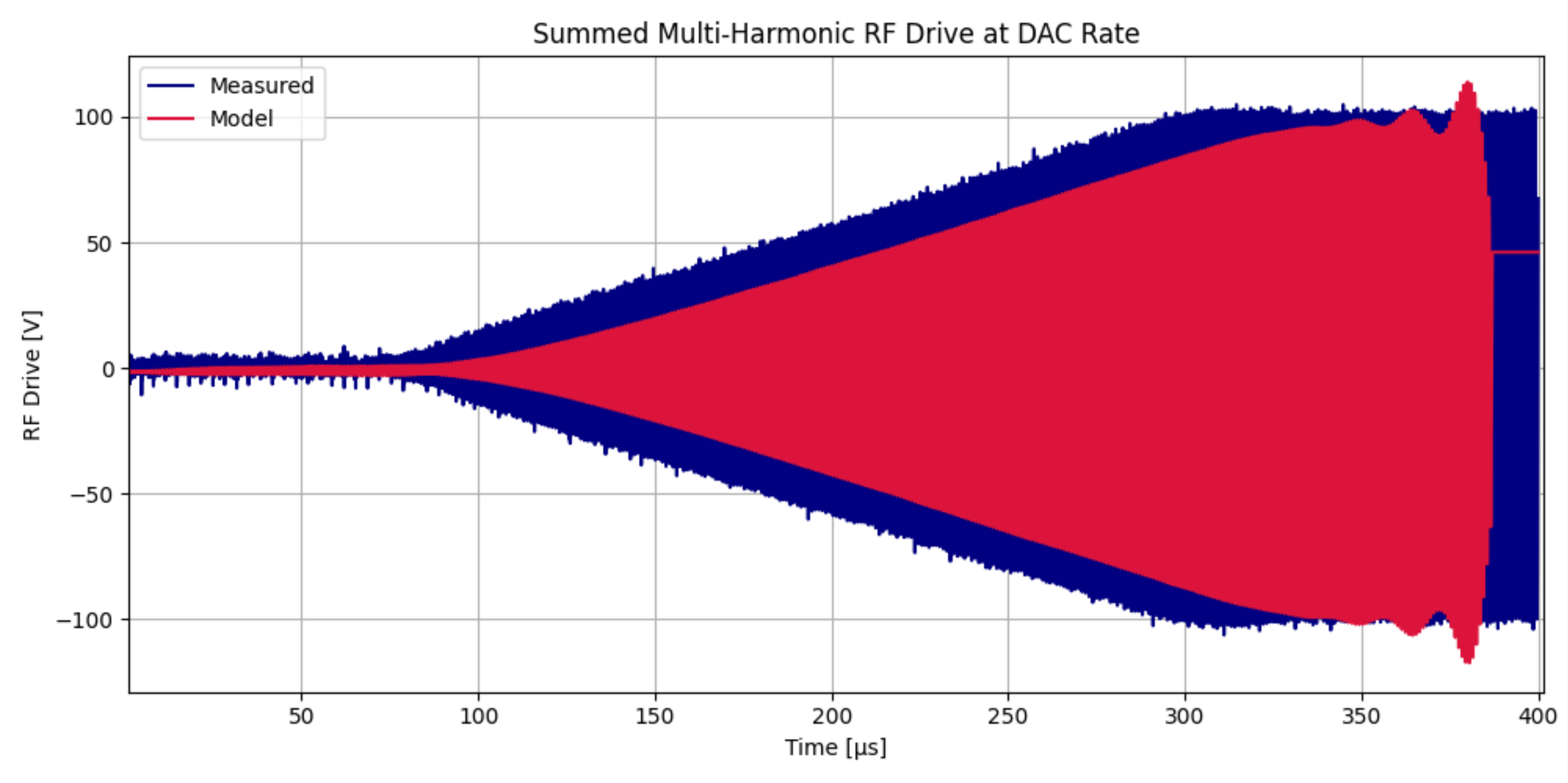


Signal processing of the model in frequency domain. It reproduces closely the measured transfer function.

Characterisation of the LLRF cavity loops

Dedicated digital signal processing measurements performed to benchmark the model in time domain.



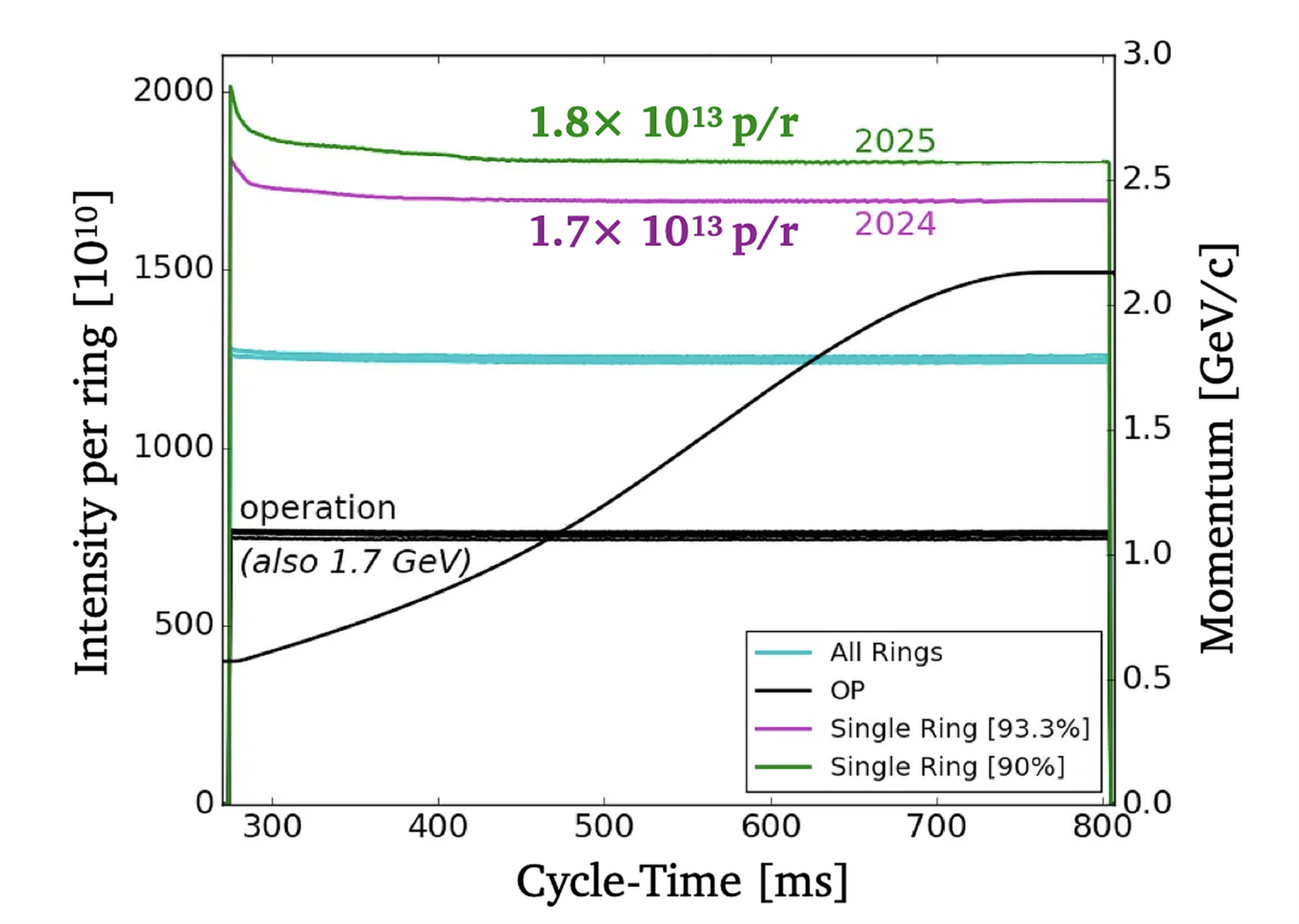


Signal processing of the model in time domain reproduced. The model can be used to optimize the loops configurations and impact on beam.

High-intensity tests in the PSB

- **Run 3**:
  - LIU upgrades + optimizations → high transmission and operational reliability.
  - Studies to probe PSB headroom beyond routine operation.
- **User-driven motivation**: meet current and future users requests → prepare for higher-intensity / higher-energy needs (IP-FiT, ISOLDE 2 GeV feasibility).
- **Scope of the tests**: step-wise intensity scans (1.4 GeV and 2 GeV) while monitoring transmission, losses and **RF limits.**
- **Goal**: identify main bottlenecks and quantify performance gain achievable via operational optimization (injection, line density, cycle shaping) versus hardware constraints (**RF interlocks**).
- Long-term studies are needed to ensure high intensities are compatible with routine operation, specifically for equipment availability and lifetime.

PSB intensity map



High-intensity tests in the PSB

RF power stage DC current

- The DC current drawn by the Finemet power supply I_{DC} can be a limiting factor for high-intensity operation, especially at 2 GeV.
- The interlock threshold is set for operational needs; temporarily raised only for MD to quantify intensity reach.

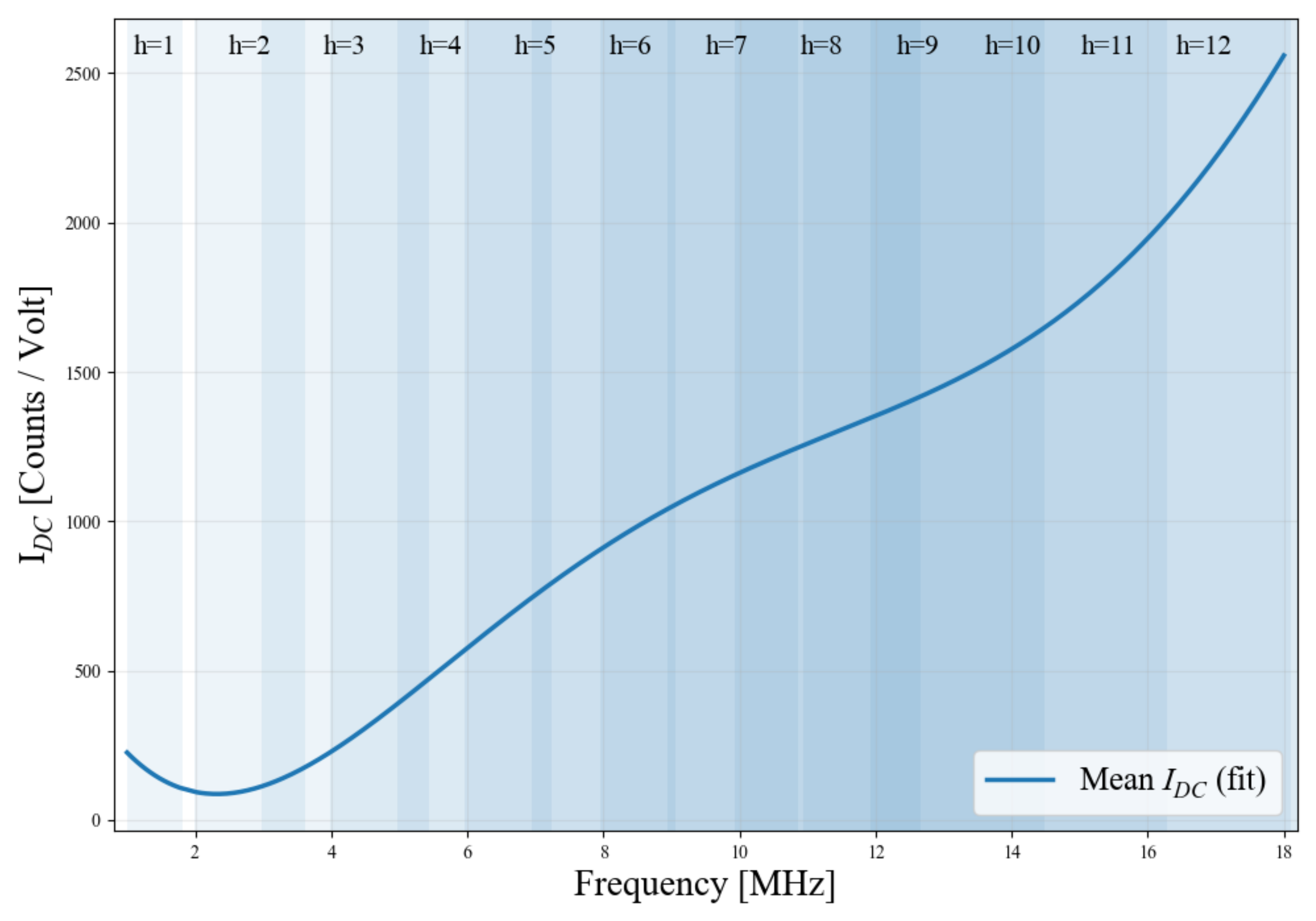
Observable: why I_{DC}?

I_{DC}: summed DC-bus current of the output stage, proportional to the instantaneous electrical power draw.

$$P_{DC} = V_{DC} I_{DC} \qquad P_{RF} \approx \eta P_{DC}$$

$$\longrightarrow \qquad I_{DC} \approx \frac{P_{RF}}{\eta V_{DC}}$$

$$P_{\mathrm{RF}} \approx \underbrace{V_1 I_{b,1} \cos\phi_s}_{P_{\mathrm{beam}}\ (beam\ \ loading)} + \underbrace{\sum_h \frac{V_h^2}{2\,R_{\mathrm{sh}}(f_h)}}_{P_{\mathrm{cav}}\ (freq.\text{-}dep.)} + \underbrace{P_{\mathrm{ctrl}}}_{transients\ /\ control}$$

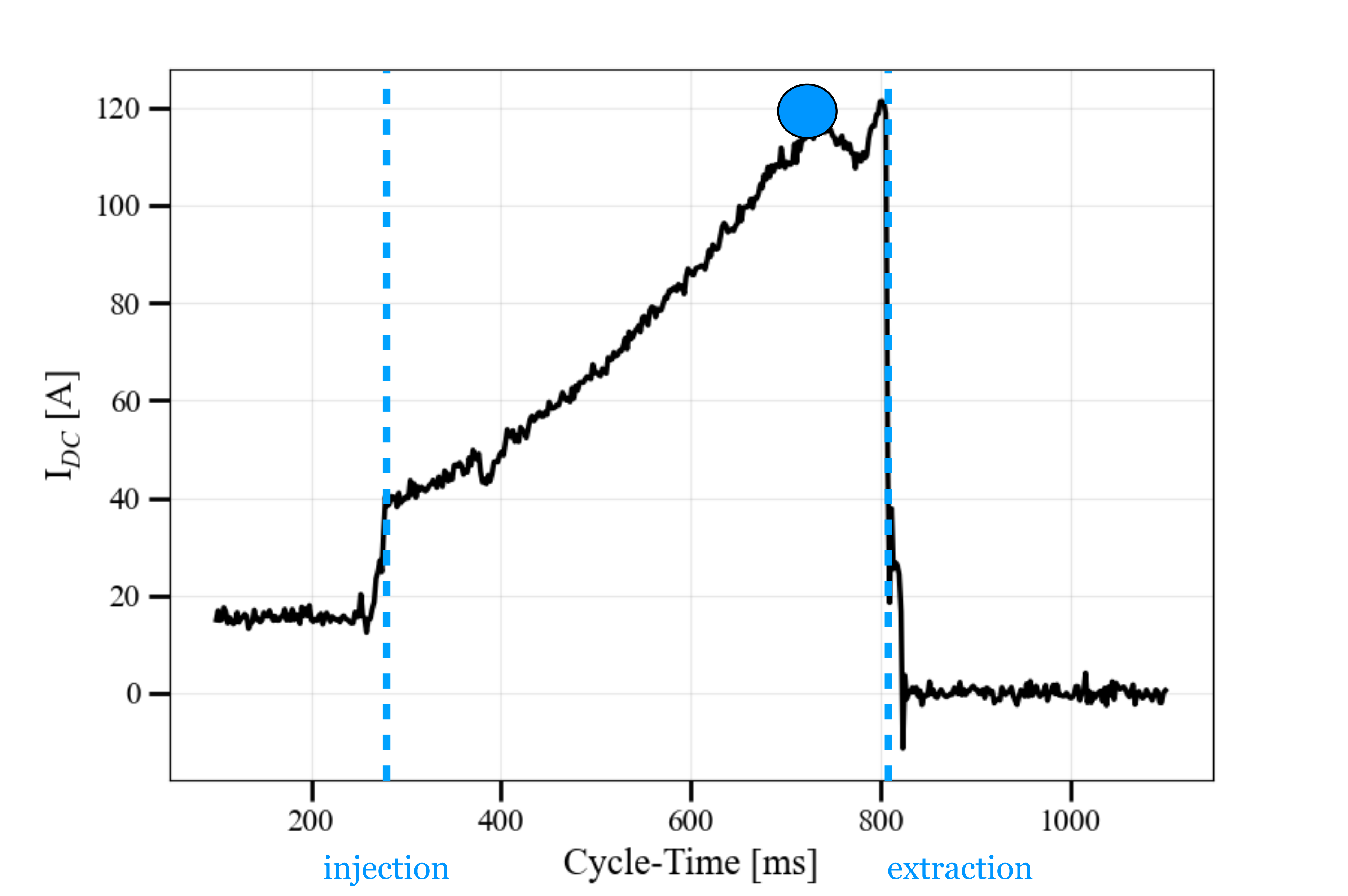


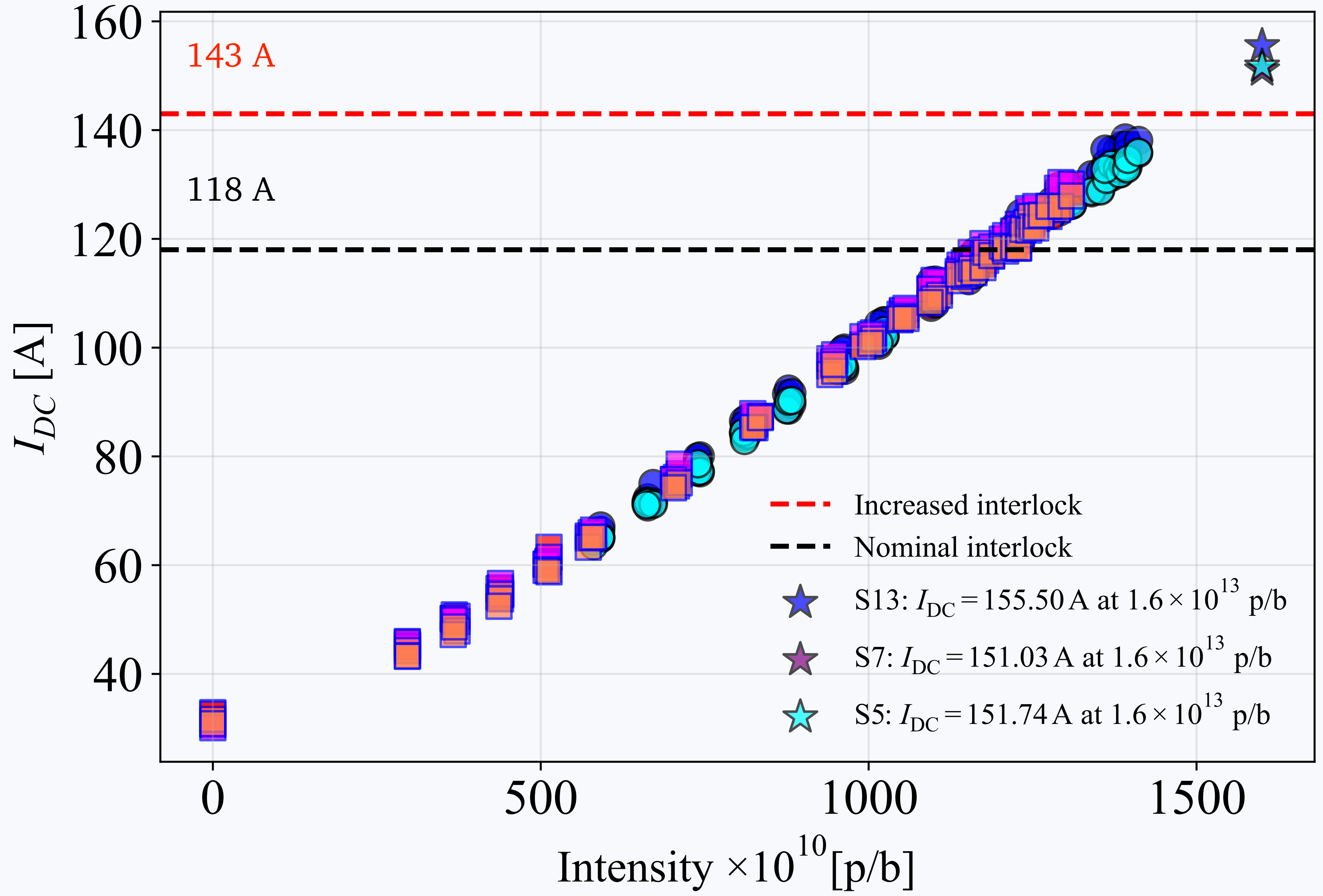
High-intensity tests in the PSB

I_{DC} vs intensity: peak acceleration demand

- Increase intensity (N_p) step-wise; record I_{DC} in one cell at a fixed time in the cycle.
- $P_{RF} = f(dB/dT, I_b) \rightarrow$ **I_{DC}** determined by acceleration rate and beam loading.

$$\max(\dot{B}) \;\rightarrow\; \max\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right) \;\rightarrow\; \max\left(P_{\mathrm{beam}}\right) \;\rightarrow\; \max\left(I_{\mathrm{DC}}\right)$$





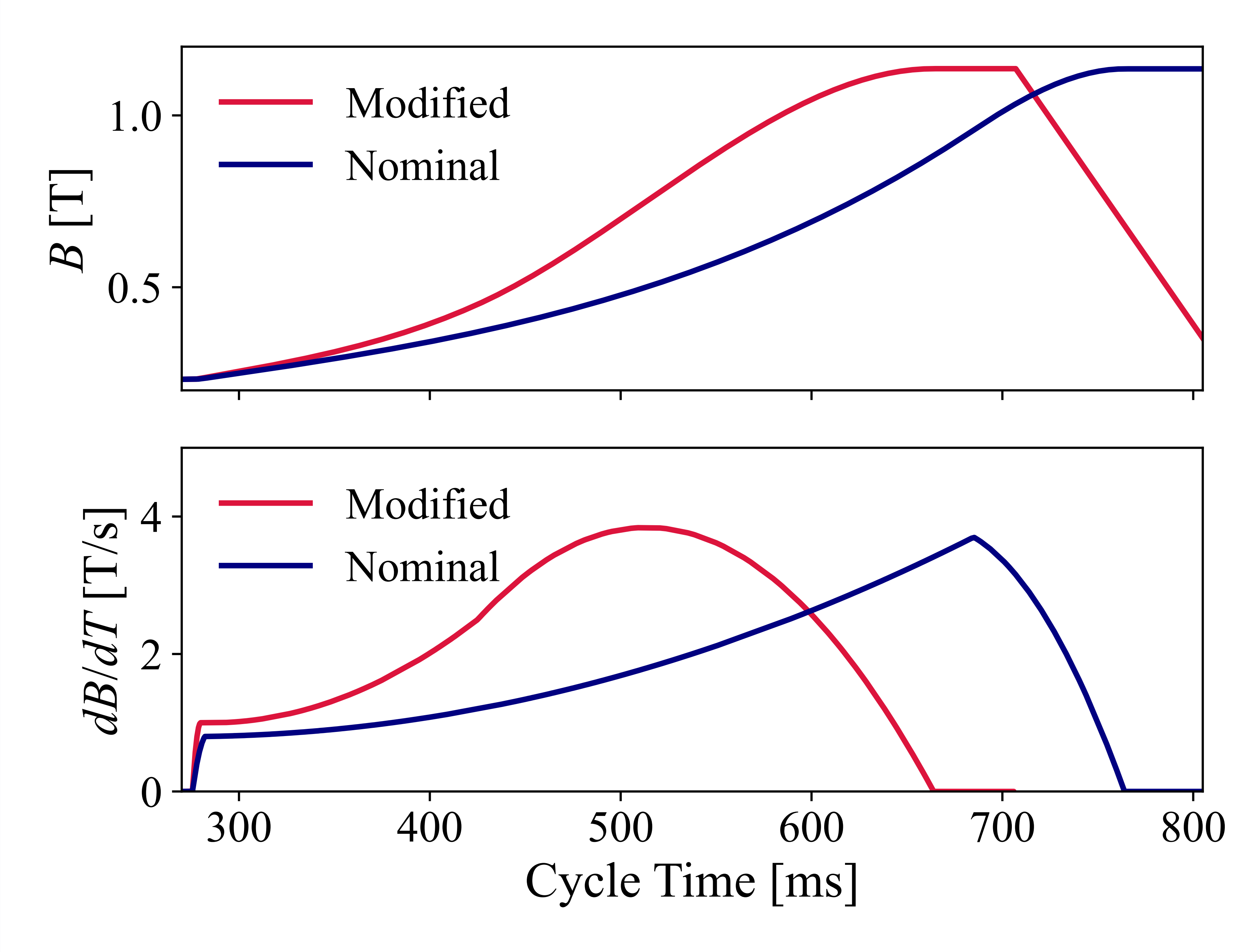
- Nominal interlock (118 A): $N_p \sim 1.1 \times 10^{13}$ p/b
- Increased interlock (143 A): $N_p \sim 1.4 \times 10^{13}$ p/b

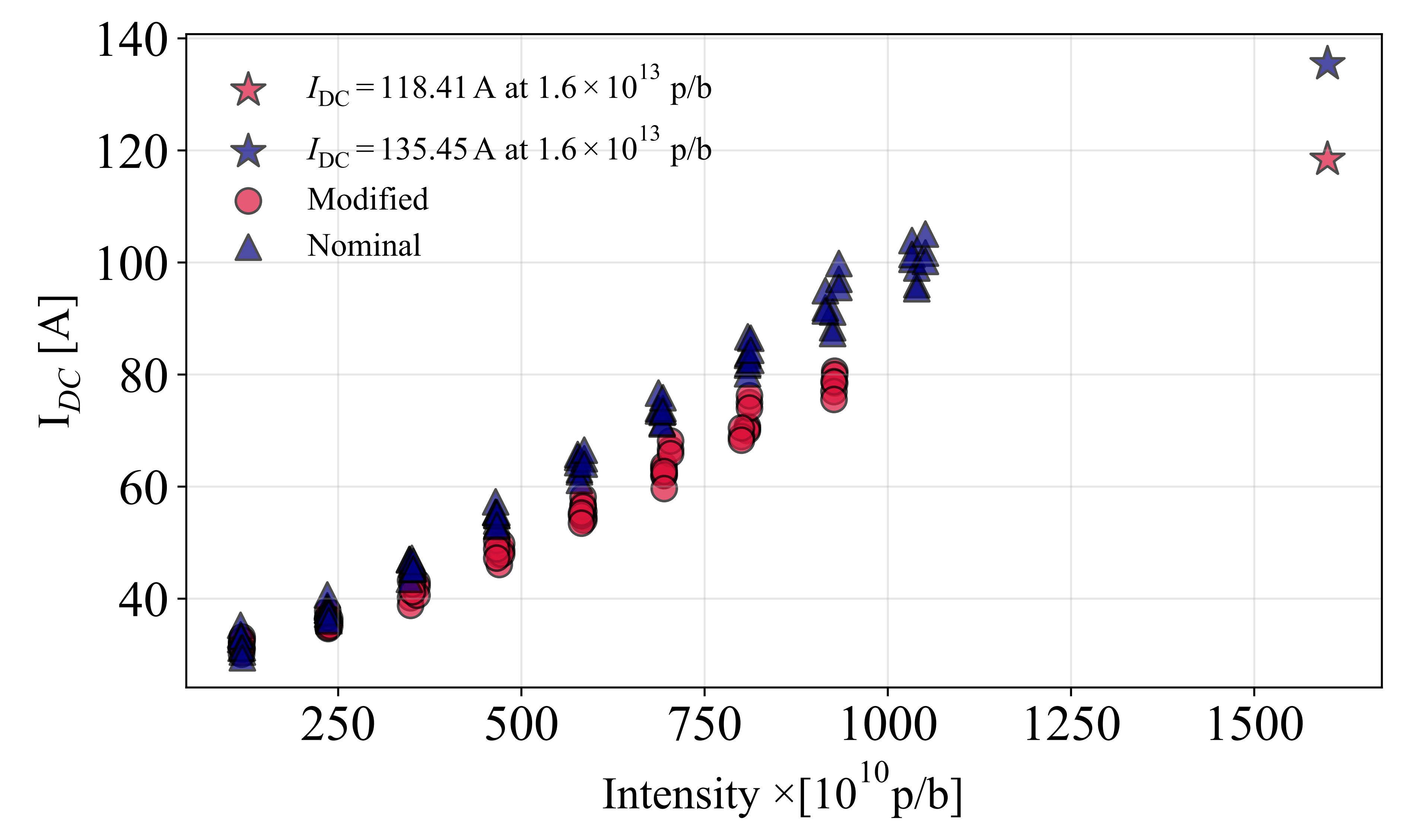
Need either more RF power headroom or lower peak power demand (e.g. cycle / bunch shaping)

High-intensity tests in the PSB

Cycle shaping: different benefits at low and high-energy

- Magnetic cycle fixes the required acceleration rate: $p \propto B\rho$.
- Peak $\dot{B}$ sets dE/dt → peak P_{RF} → peak I_{DC}.
- Idea: shape $\dot{B}$ to ramp faster at low energy (reduce space charge exposure) and ramp slower at high energy (lower I_{DC}).





- For high intensities, modified cycle reduces I_{DC}.
- RF voltage program influences the I_{DC} request: the operational 2 GeV TOF cycle is less demanding than the MD cycle previously used, which was designed to push the intensity reach.
- Further headroom possible through longitudinal bunch shaping.

Outline

4 **Conclusions and perspectives**

Longitudinal limitations understanding and strategy for the future.

Conclusions

- Upgraded PSB characterized in terms of longitudinal beam dynamics and hardware in the last few years
- Current and future requests shaping the needs in high-intensity operation
- Beam-based techniques carried-out to probe longitudinal impedance model and longitudinal stability
- LLRF cavity loops mitigate beam loading but add perturbations, which degrade beam quality
- Double Harmonic operation used in Bunch Lengthening Mode keeps longitudinal stability at high-intensity
- Numerical, dynamic model of the cavity loops developed, to be used in the future fir further optimizations
- Intensity push and hardware bottleneck identification and characterization performed in 2024 / 2025
- Engineering-physics dependencies and possible mitigation strategies evaluated
- In preparation for future requests, an extended high-intensity run is planned in 2026