Update on SPS impedance reference measurements:

Head-tail mode zero growth rates and tune slopes vs chromaticity

IPP MD days 2025

Miguel Gonzalez, Elena de la Fuente, Ingrid Mases, Carlo Zannini

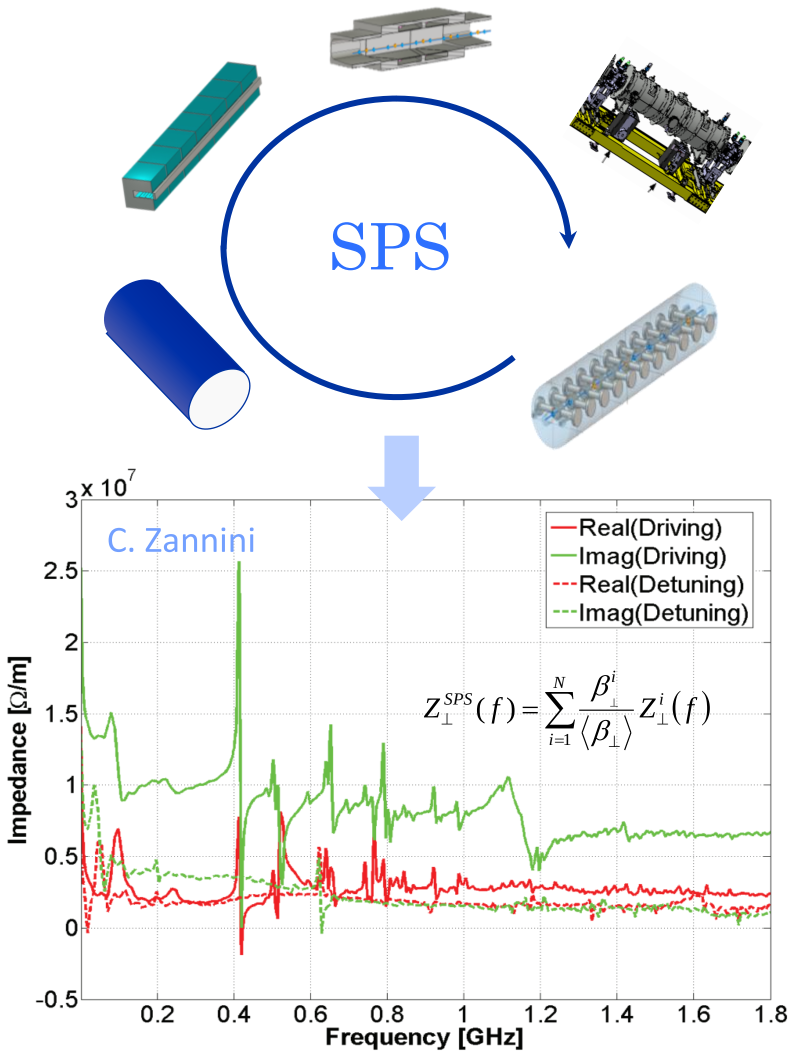
Special thanks to the SPS & PSB operators for all the help during the MDs, and to all the colleagues that contributed to the project

Impedance reference measurements

- The **SPS transverse impedance model** contains the major beam-coupling impedance sources in the accelerator.
  - Used as input for macroparticle tracking simulations (PyHeadtail, Xsuite) to predict beam behavior

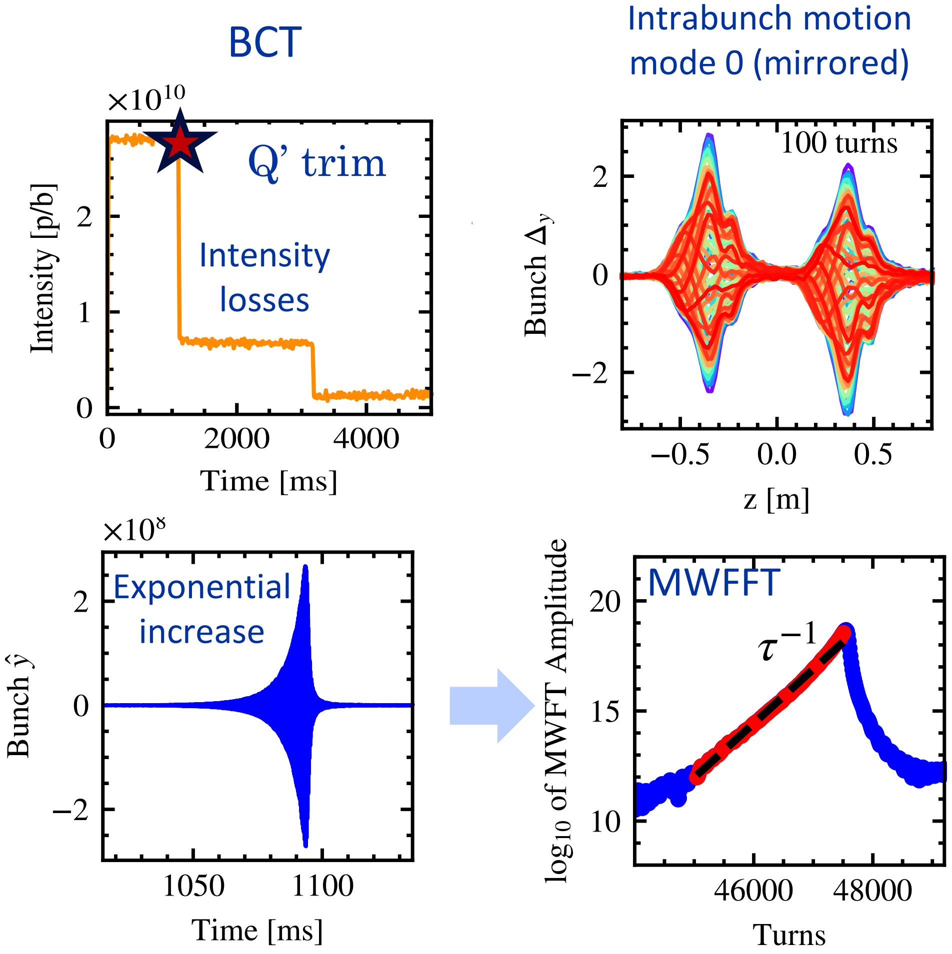
- We **benchmark this model** with beam-based measurements.
  - The Head-Tail mode zero growth rates τ^{-1} vs chromaticity ξ gives us information on the <u>**real part**</u> of the transverse effective impedance $Z_{\perp,dip}^{eff}$

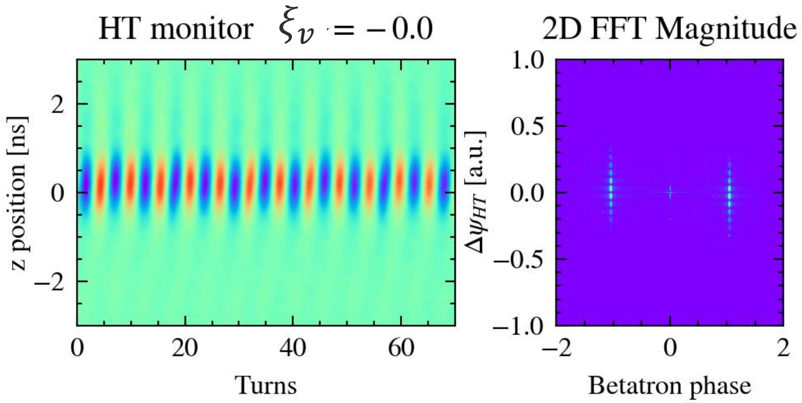
$$\tau^{-1}(\xi) = \Gamma\left(\frac{1}{2}\right)\frac{\mathrm{Re}\left[Z_{\perp,dip}^{eff}(\xi)\right] N r_0 c^2}{8\pi^2 \gamma Q_\perp \sigma_z}$$



Measurements methodology

- Measurements are performed with single bunch and low intensity ~ 3e10 p/b.
- The beam becomes unstable when the negative chromaticity trim (LSA QPH or QPV) is applied, triggering the Head-Tail mode zero observables.
- We perform a negative chromaticity scan in H or V plane, measuring the growth rates τ^{-1} for each LSA trim using the Moving Window FFT (MWFFT) technique.
- We crosscheck chromaticity value on-the-fly from HT monitor data*





Previous findings

*C. Zannini, MOPJE049, IPAC 15
**E. de la Fuente, WEPL155, IPAC 23

- During the **2022 campaign** we wanted to explore the high frequency region f_ξ> 1.5 GHz with **Q26 optics**.

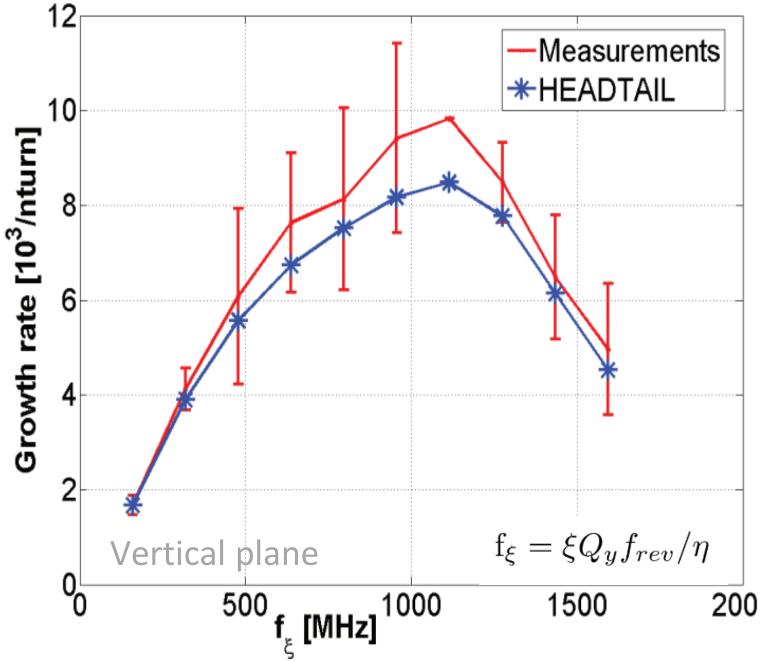
✓ We could reproduce the lower frequency region (<1.5GHz) as in Pre-LS2

X The newly explored high frequency region showed an unexpected discrepancy with the model, hinting at a missing impedance

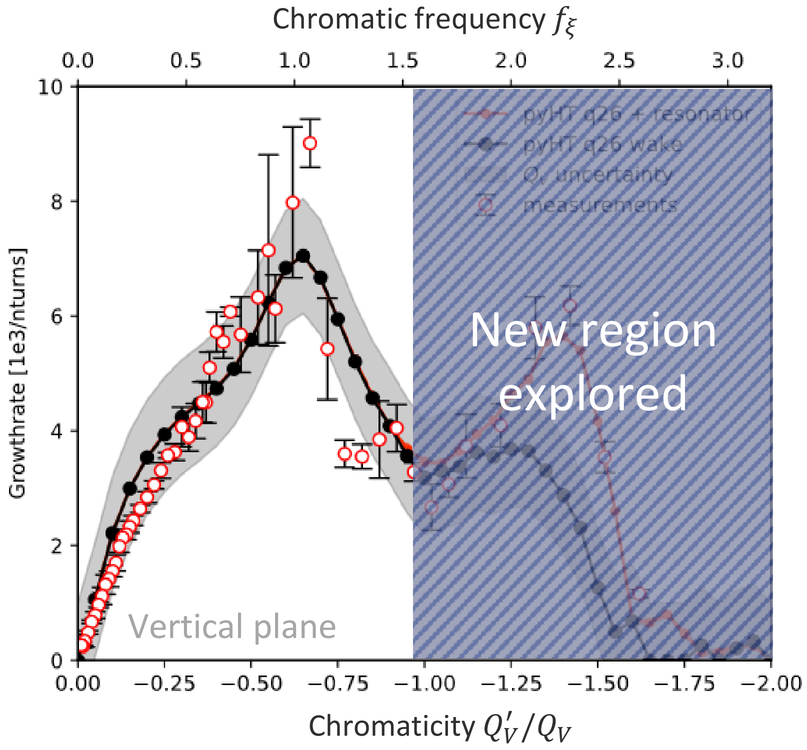
In **2024, new measurements** to certify the existence of such impedance:

- Different working point / vertical tune
- Different energy
- Tune shift slope vs chromaticity

2013 measurements*
Pre-LS2



2022-23 measurements**



Added resonator parameters:

Rs=2e7Ω/m, Q=100, f=2.5 GHz

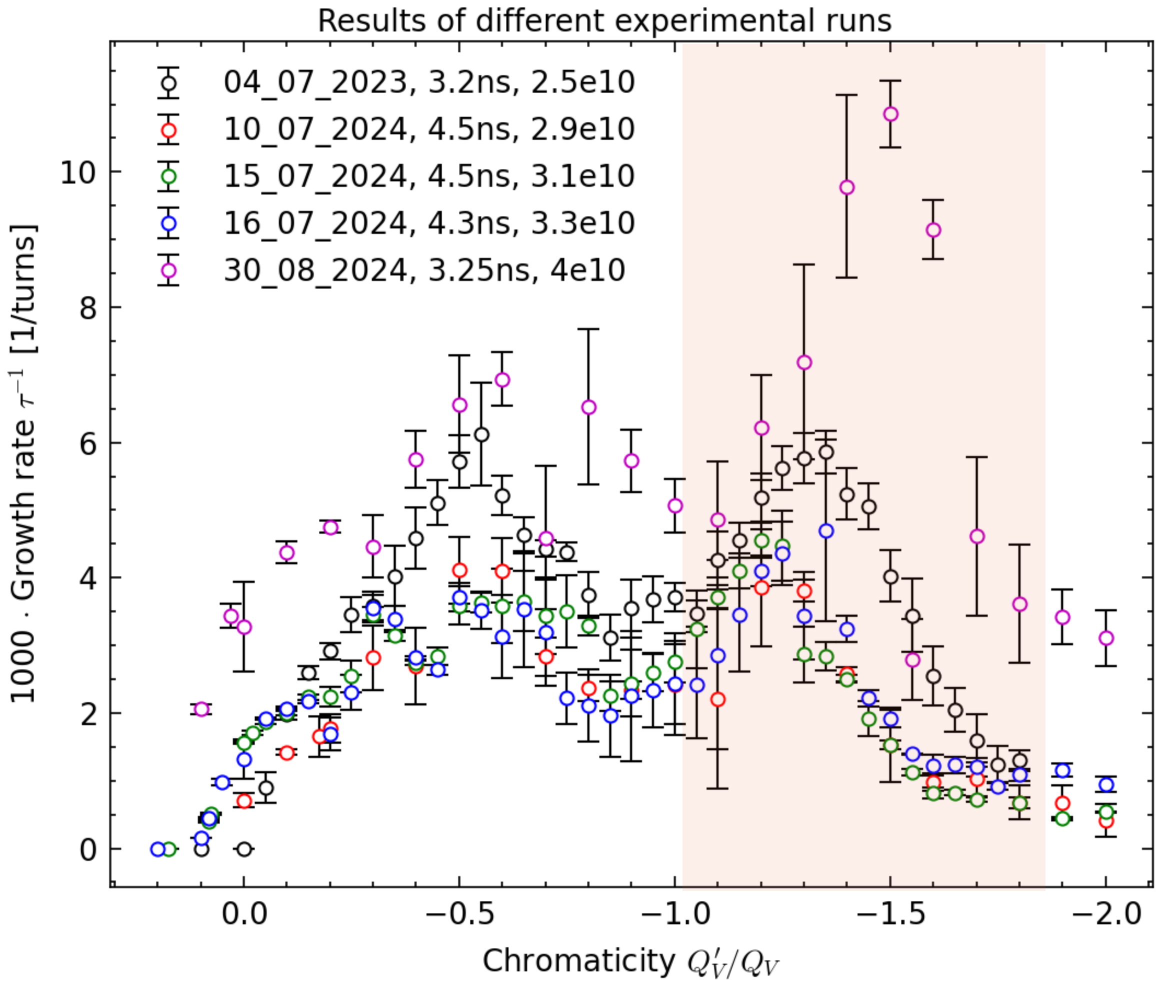
2024 Growth rate measurements*

*Miguel Gonzalez Torre, CEI meeting 12th Sept 2024

- Growth rate MDs: 04_07_2023, 10_07_2024, 15_07_2024, 16_07_2024, 30_08_2024 (logbook links)

- Measurements taken at different intensities (2 - 4e10 p/b), bunch lengths (3 - 4.5 ns) and emittances (1.6 – 2.5 μm)

- Second peak at $\xi_V = -1.5$ ($f_\xi = 2.4$ GHz for Q26 optics) always observed

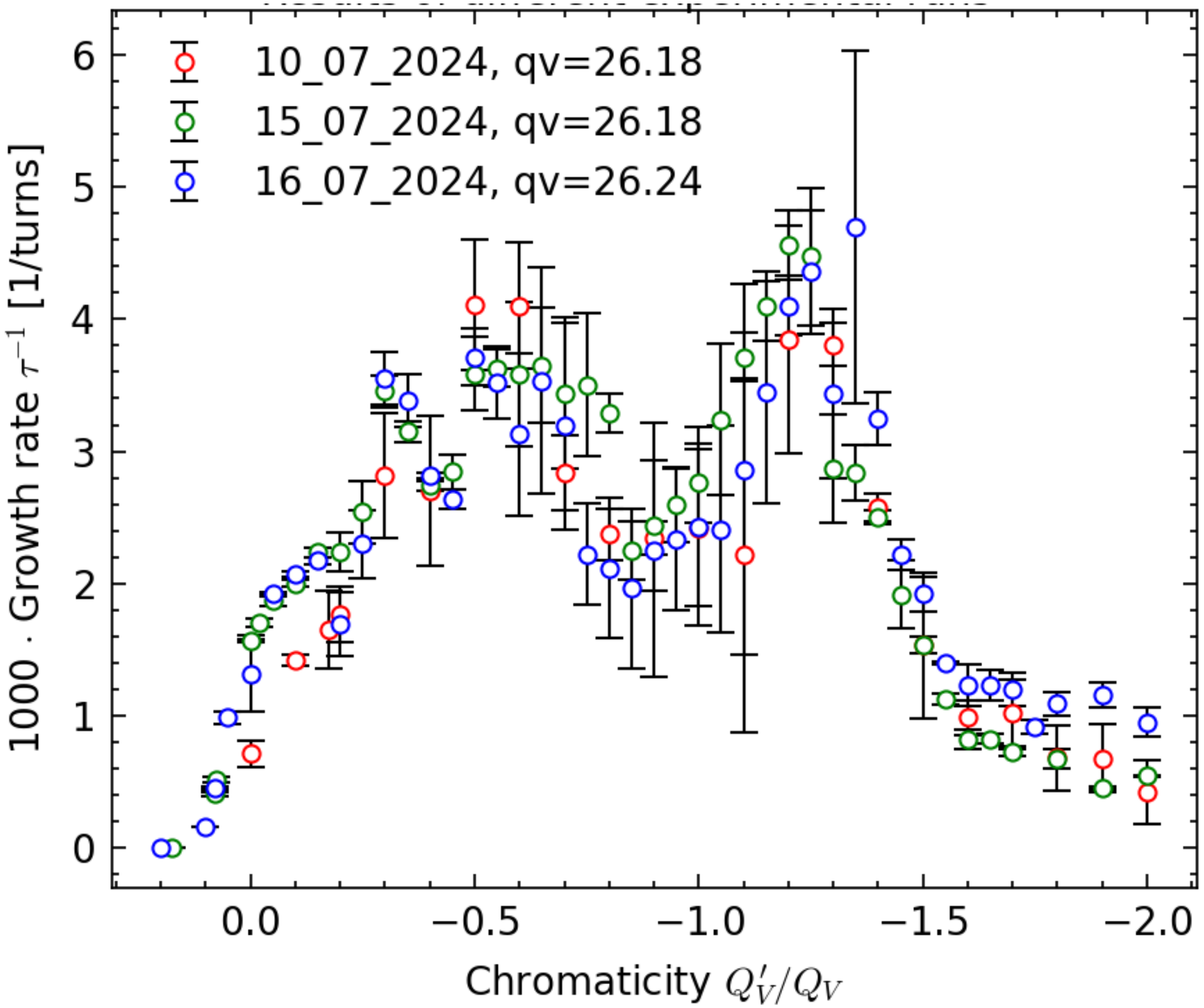


Changing working point (I)

*Miguel Gonzalez Torre, CEI meeting 12th Sept 2024

Logbook 16/07/24

- Previous measurements were performed at Q26 nominal tune: (26.13, 26.18)
- Suspicion that the **second peak** could be caused by interaction with ½ integer resonance due to high chroma*
- **Plot showing:** Results from the full scan performed at nominal vs working point (26.13, 26.24) with no substantial change of 2nd peak amplitude/frequency



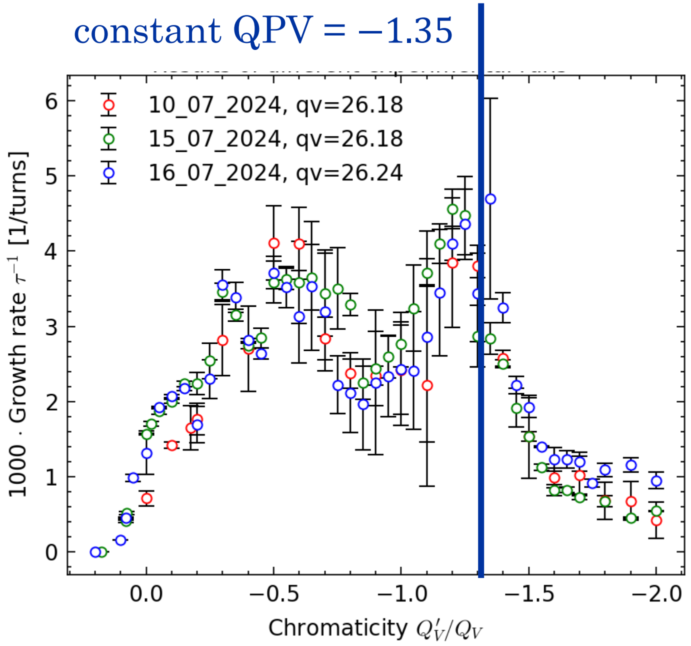
*Many thanks to K. Paraschou

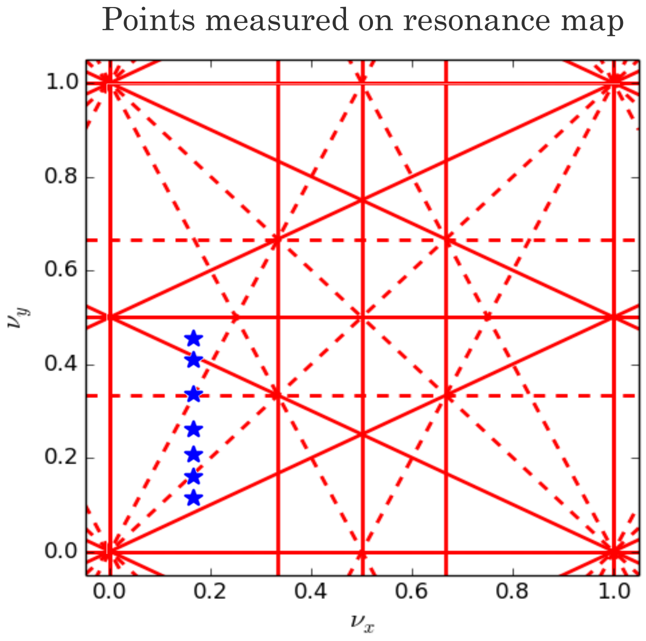
Changing working point (II)

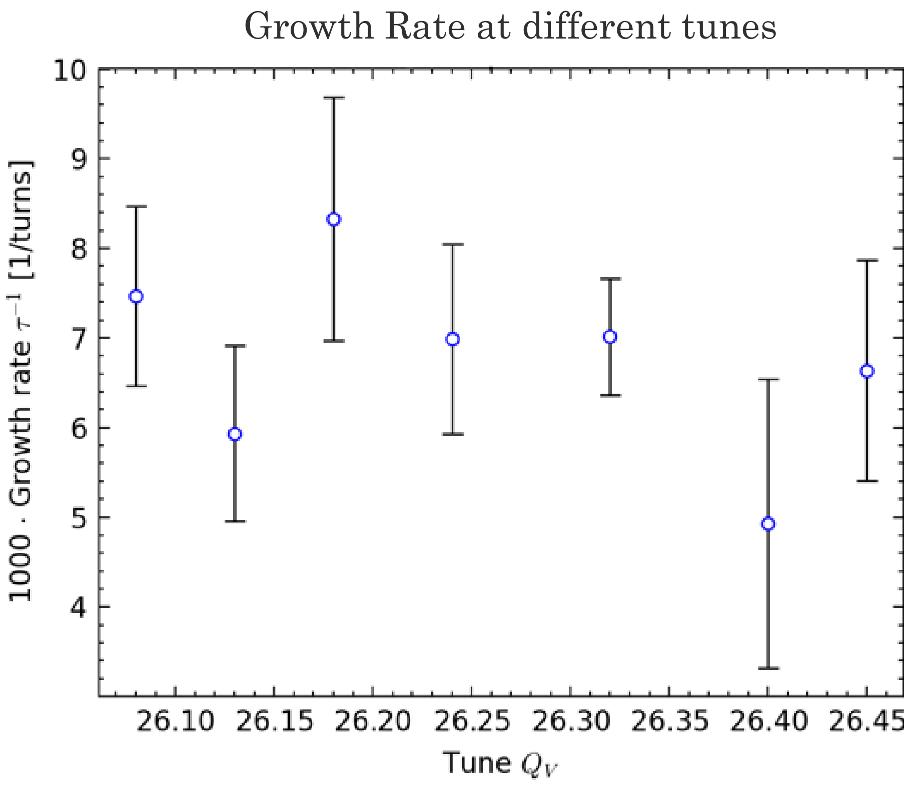
*Miguel Gonzalez Torre,
CEI meeting 12th Sept 2024

Logbook 26/07/24

- Performed a scan of vertical tune Q_V at the second peak chromaticity to exclude resonance effects and tune dependency





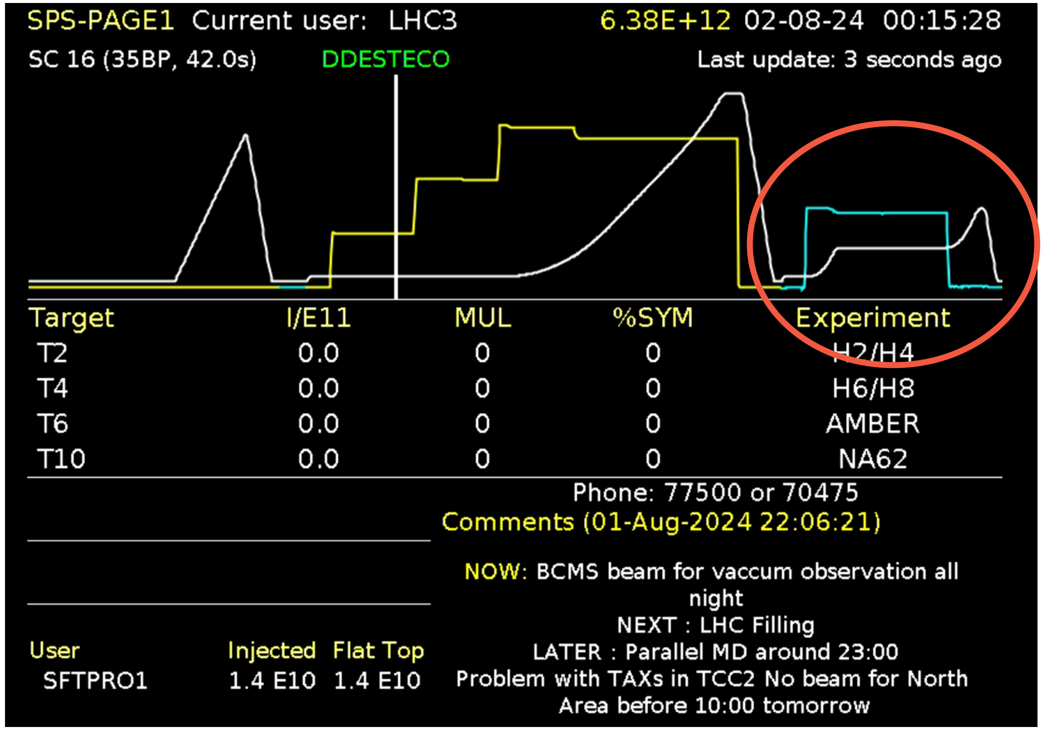


- No clear correlation observed

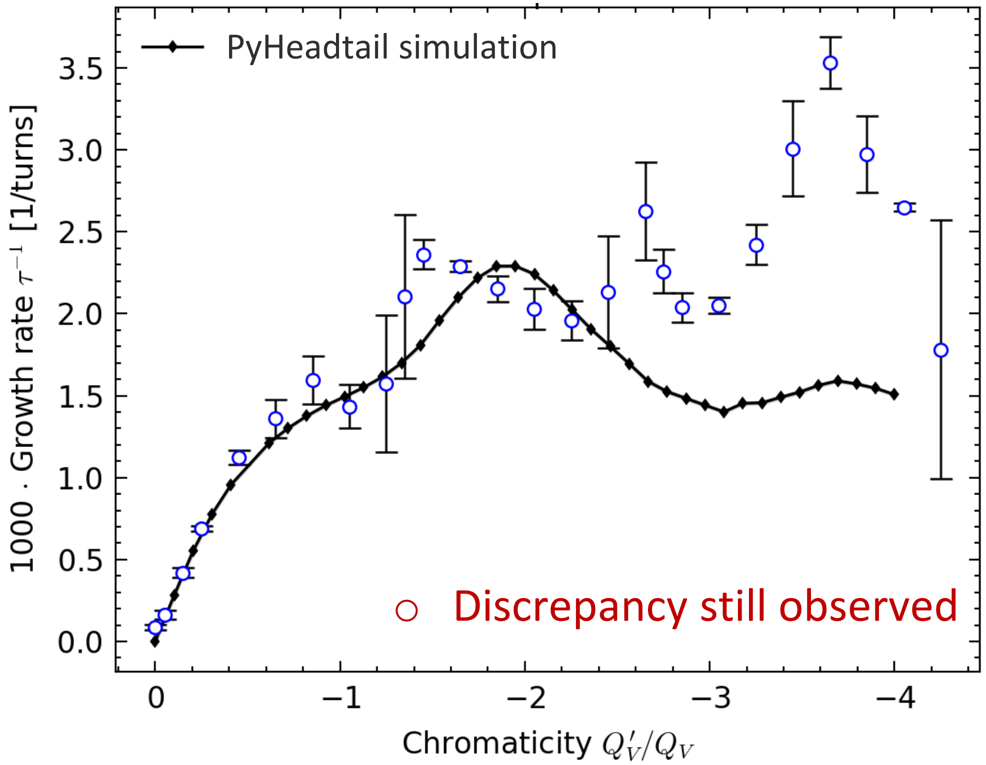
Measurements at 100 GeV

Logbook 02/08/24

- To exclude space charge effects, the cycle with a plateau at 100 GeV was used*
  - Measurements were performed well in the plateau, with bunch length ~2.5 ns
  - Change in γ, slip factor η -> needed to reach higher chromaticity values up to $\xi_V = -4.2$ knob



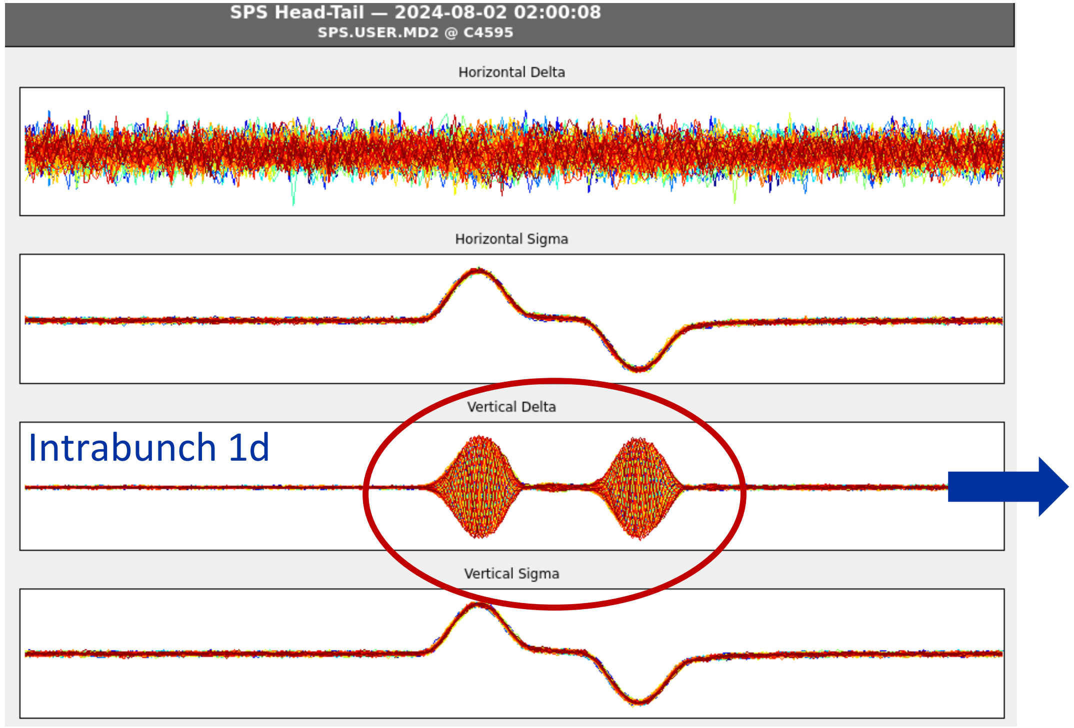
Courtesy of Miguel Gonzalez Torre



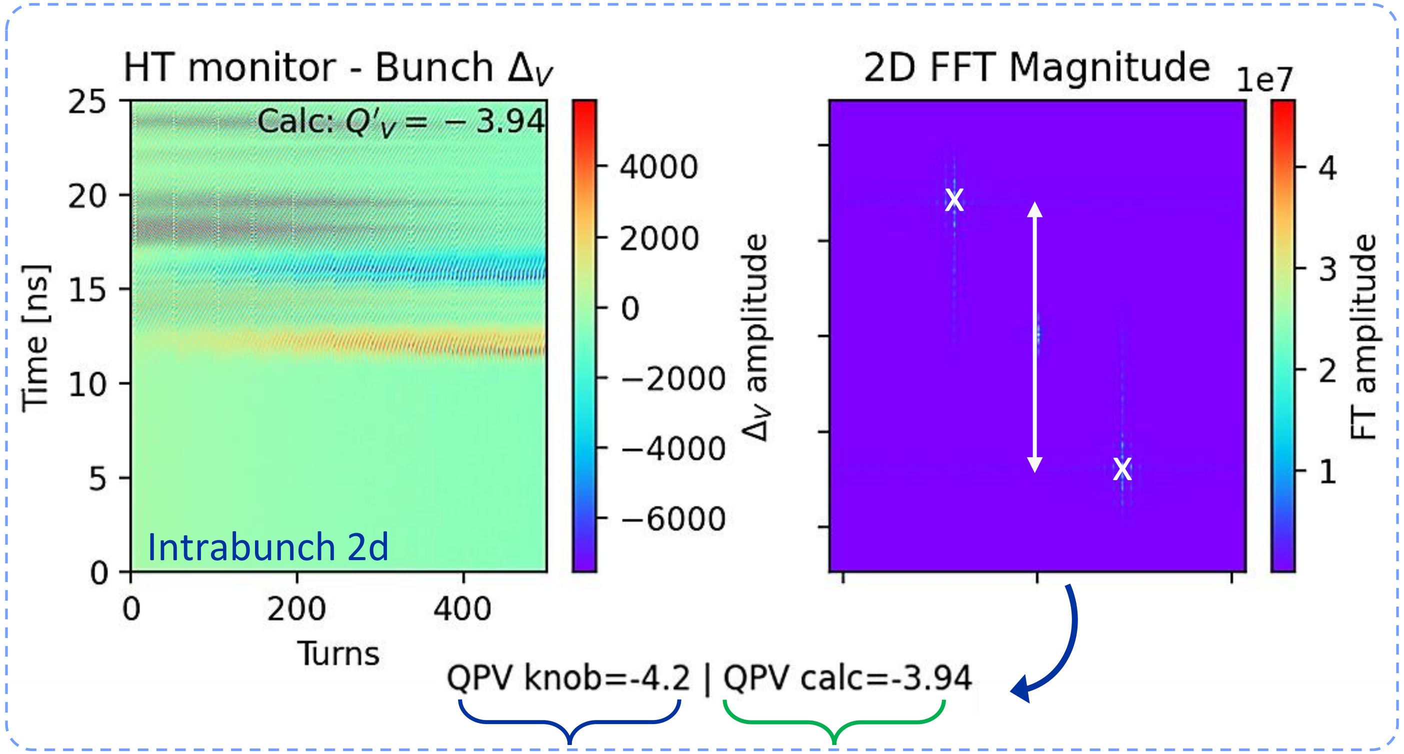
*Many thanks to D. Veres

Measurements at 100 GeV (II)

- The instability intrabunch motion captured with the **HT monitor** allows for a shot-by-shot chromaticity measurement* using a 2D-FTT analysis to verify we are measuring at the right chroma



Online script



LSA

Calculated

**Based on the work by R. Jones and T. Levens, ROAB006, PAC'01

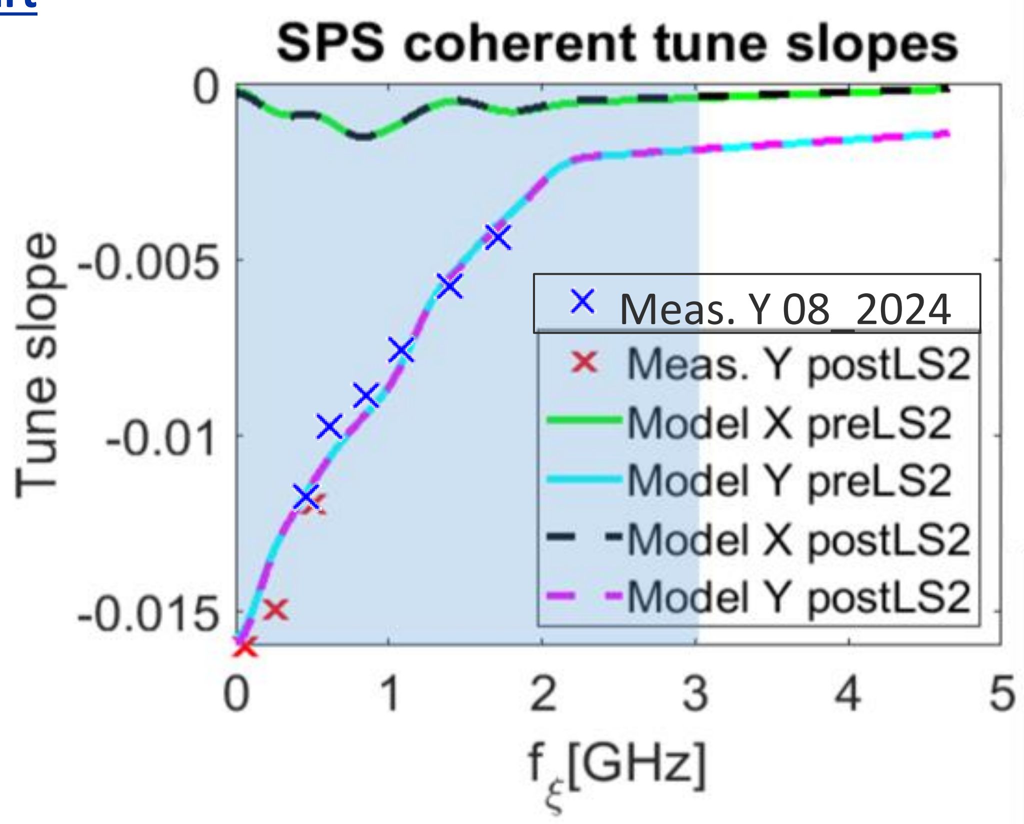
Tune slopes vs chromaticity measurements

Logbook links: first MD, second MD

- Tune shift intensity slopes $\frac{\Delta Q_\perp}{N}$ allow to **benchmark the imaginary part** of the SPS transverse impedance model $\mathrm{Im}[Z_\perp^{eff}(\xi)]$

$$\frac{\Delta Q_\perp}{N}(\xi) = -\Gamma\left(\frac{1}{2}\right)\frac{\mathrm{Im}[Z_\perp^{eff}(\xi)]\, r_0 c^2}{8\pi^2\gamma\omega_\beta\sigma_z}$$

- Challenging measurements, thanks to I. Mases and the SPS and PSB operators for the help
  - Each f_ξ point requires tune measurements over 10 intensity points {1e10 – 3e11} depending on TMCI
- Explored further in chromatic frequency f_ξ** using Q26 optics and LHCBPM data
  - Very good agreement with Sacherer theory's predicted coherent tune slopes



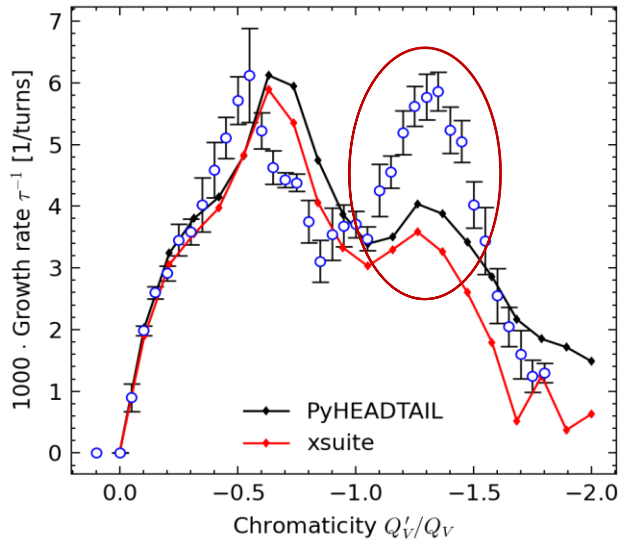
* Original plot C. Zannini, CEI meeting 21 Oct. 2021

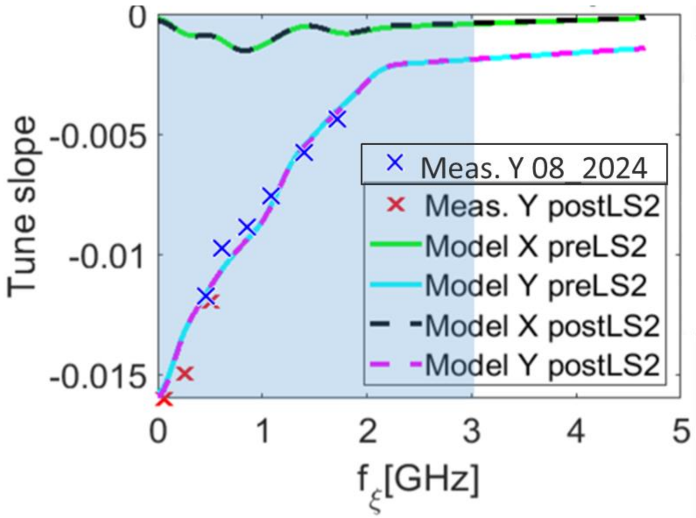
** New points courtesy of Miguel Gonzalez Torre

Conclusions

- Studied Head-Tail mode zero growth rate measurements to benchmark the **real part of the SPS transverse impedance model** and study the discrepancy in the high frequency regime
  - Changing working point: No dependency with vertical tune was observed
  - Measurements at higher energy: Discrepancy still observed in measurements at 100 GeV
  - PyHeadtail/Xsuite simulations: Latest impedance model in simulations cannot reproduce the measurements for $f_\xi > 1.5$ GHz

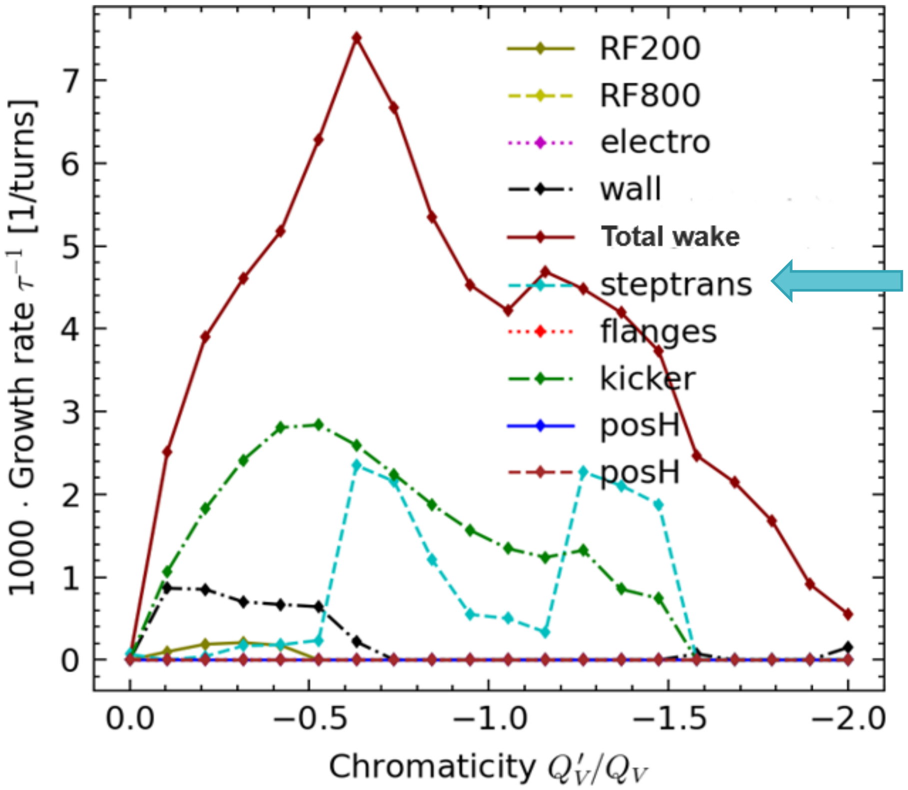
- Studied Tune slopes vs chromaticity to benchmark the **imaginary part of the model**
  - Found very good agreement with analytical predictions
  - Xsuite/PyHT simulations proven challenging & not available





Conclusions & future work

Courtesy of Miguel Gonzalez Torre



- Simulations of separated impedance contributions of the SPS model hint at the step transitions
  - Real-valued impedance contribution at the right frequency
  - Model developed focusing on the imaginary part to match the tune shifts

Future work:

- Transitions model will be revised and refined (ongoing)
- PyHeadtail/Xsuite simulations will be done with the refined impedance model
- No more MDs needed this year ☺

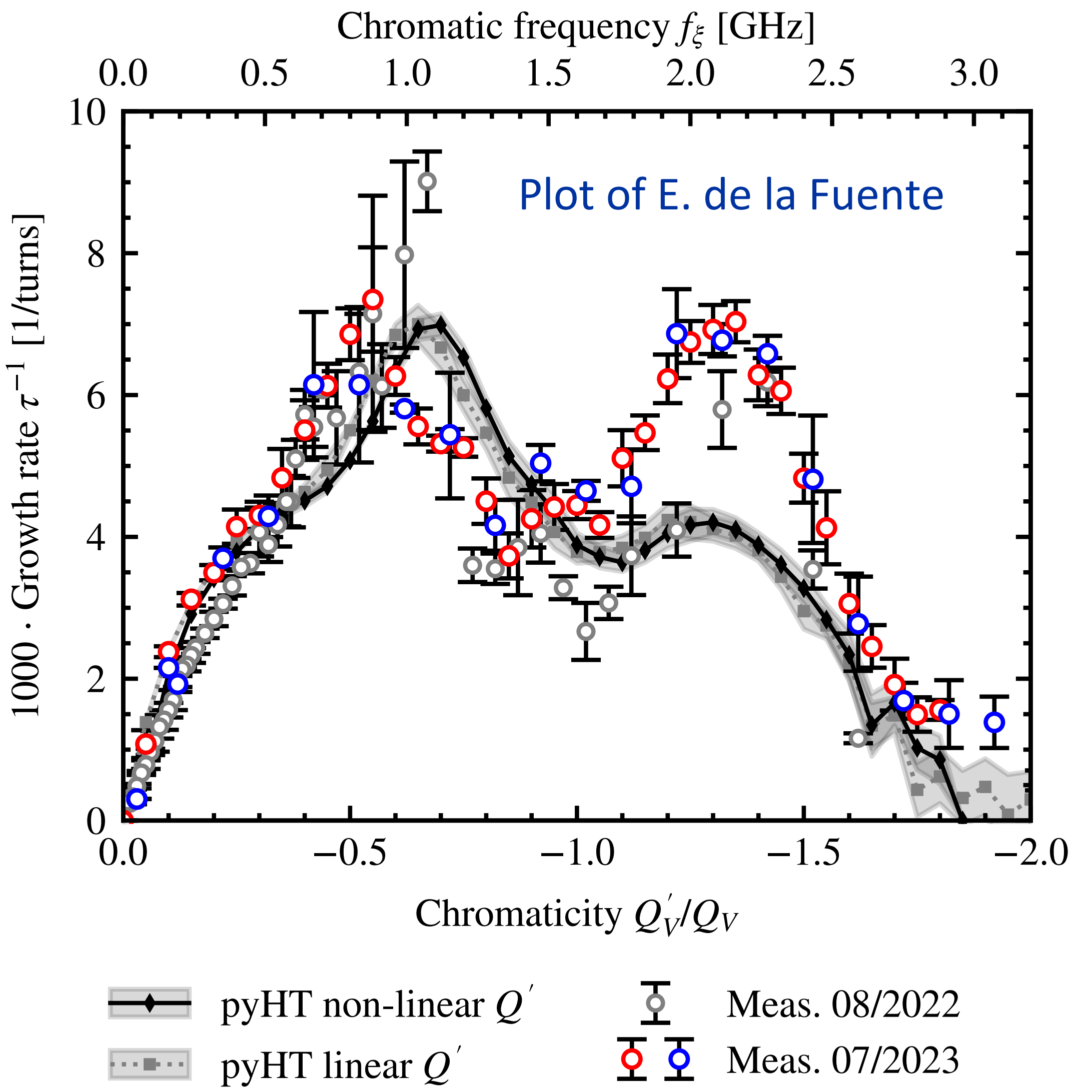
Thank you ☺

Update on SPS reference impedance measurements

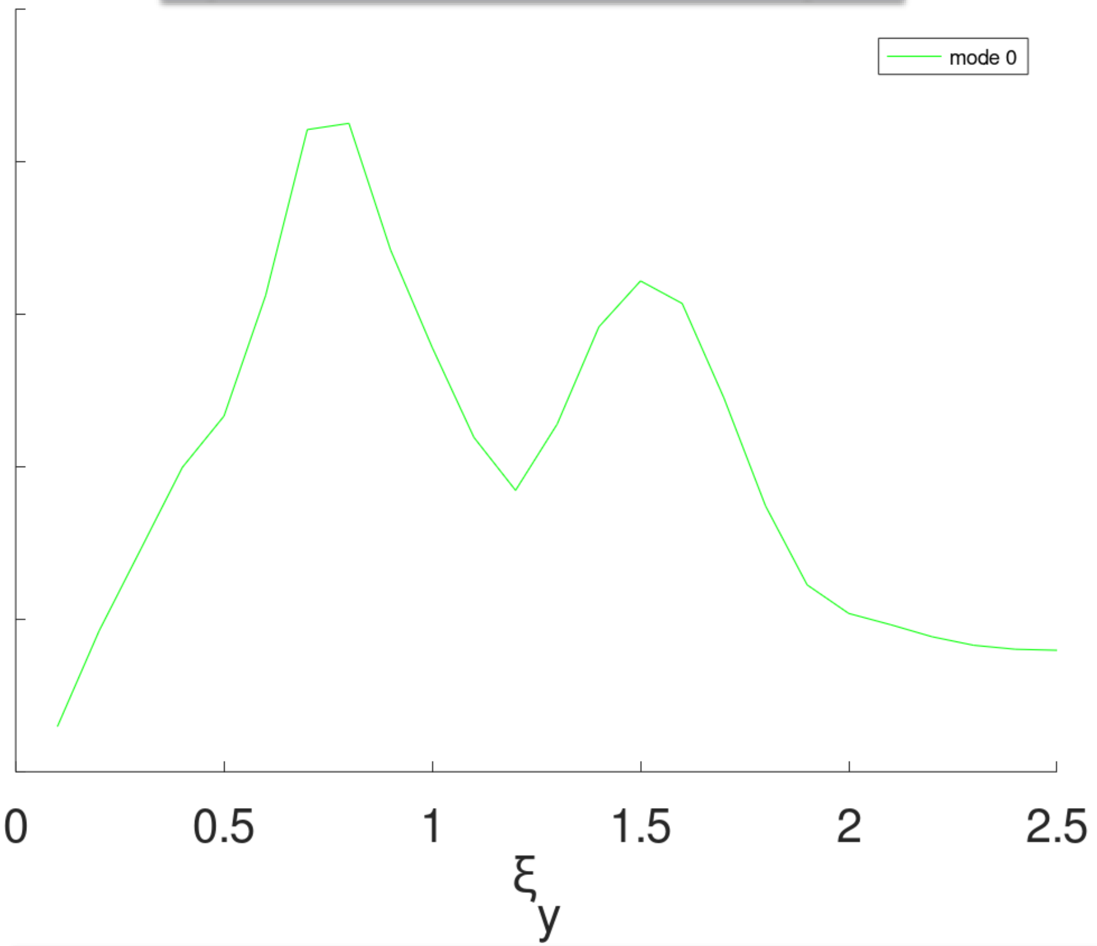
Elena de la Fuente García (BE–ABP–CEI)

SPS dark impedance

C. Zannini ABP-CEI-meeting: https://indico.cern.ch/event/1457364/



Expectation from Sacherer theory



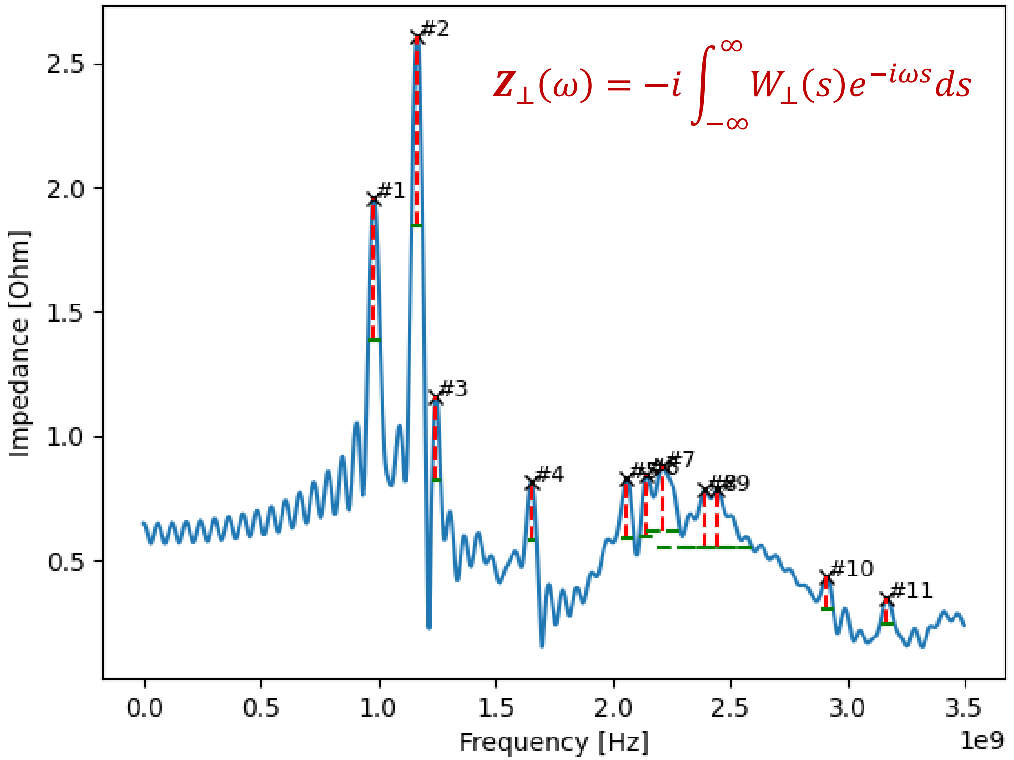
To be understood why is not observed in PyHEADTAIL simulations (wake potential approximation?)

Step transitions revised [PRELIMINARY]

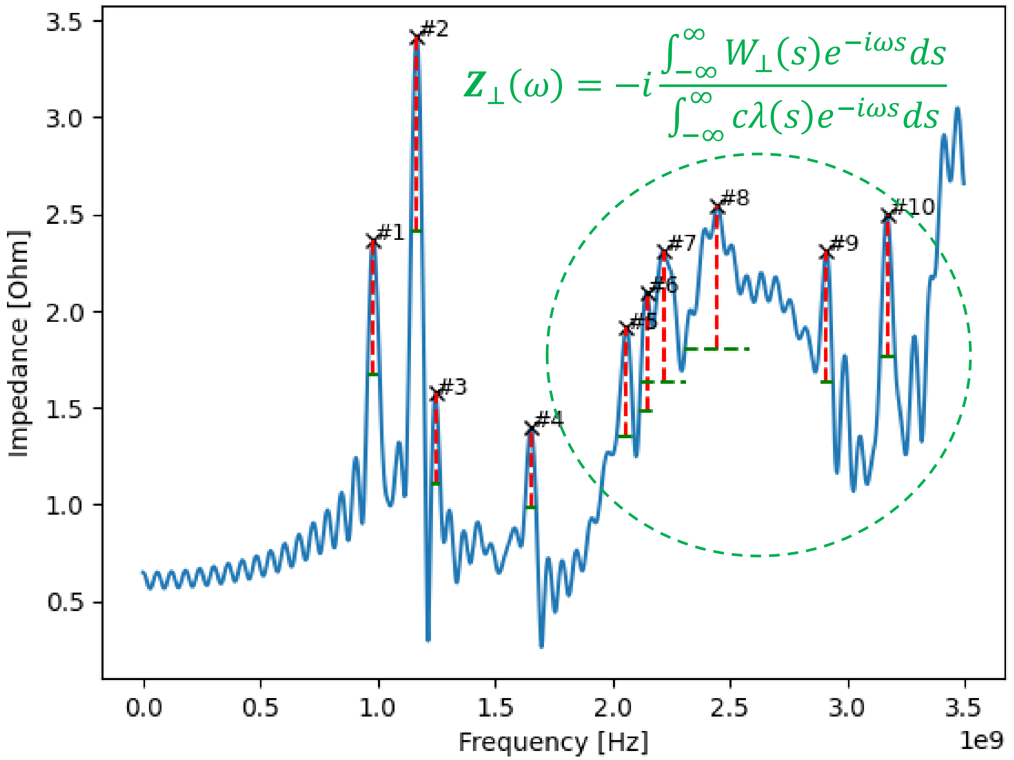
*Improving impedance model using IDDEFIX

- **Step transitions** were simulated with CST Studio® wakefield solver with very short bunch $\sigma_z \sim 10^{-11}$ ns to consider the wake a wake function instead of a wake potential

Impedance from the wake model using FFT only



Impedance from the wake model using deconvolution

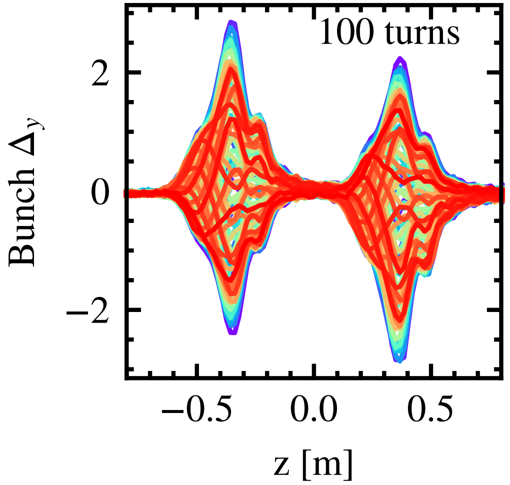


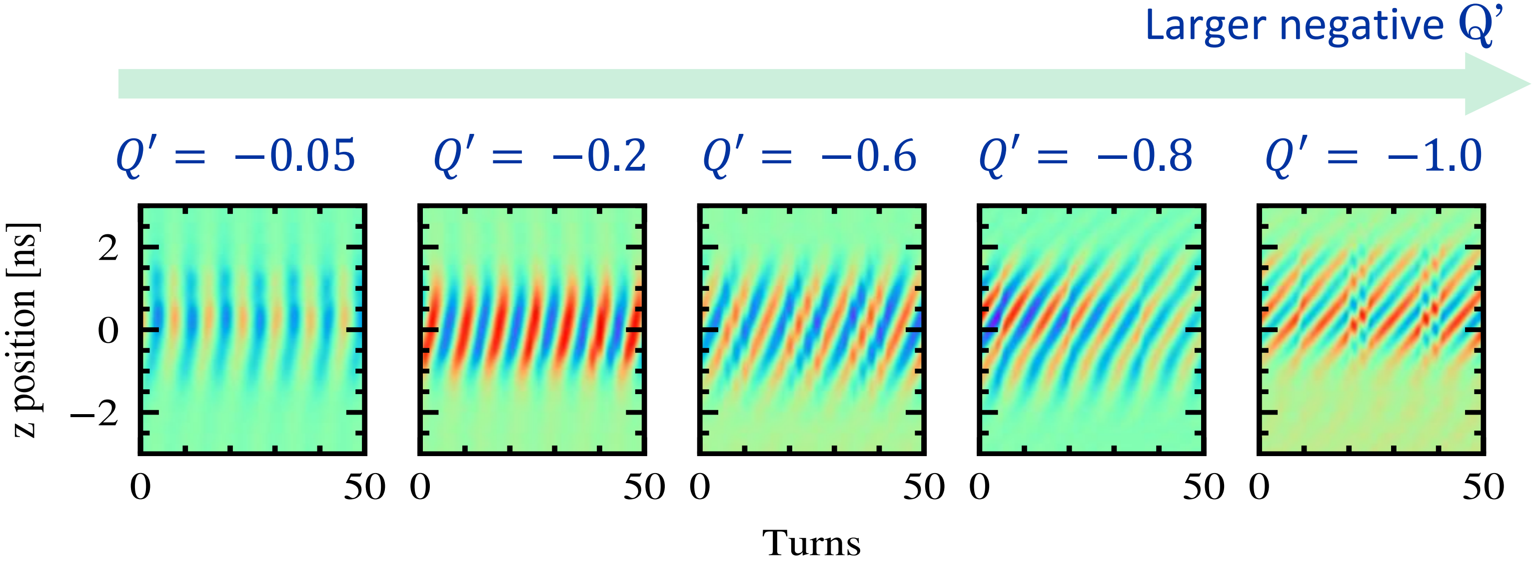
*R. Jones, ROAB006, PAC01

Chromaticity from intrabunch motion

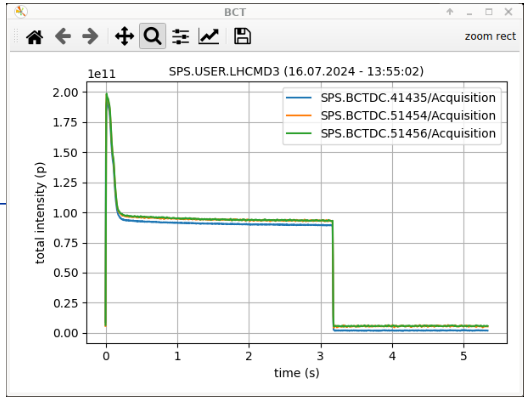
- When plotting the SPS Head-Tail Monitor measurements over the longitudinal position z and number of turns, we could observe a distinctive pattern when going to more negative values.
- The information of chromaticity Q' is encoded in the observed head-tail phase modulation*

$$y(n) = A\cos[2\pi nQ + \Delta\psi_{HT}\{\cos(2\pi Q_s n) - 1\}]$$

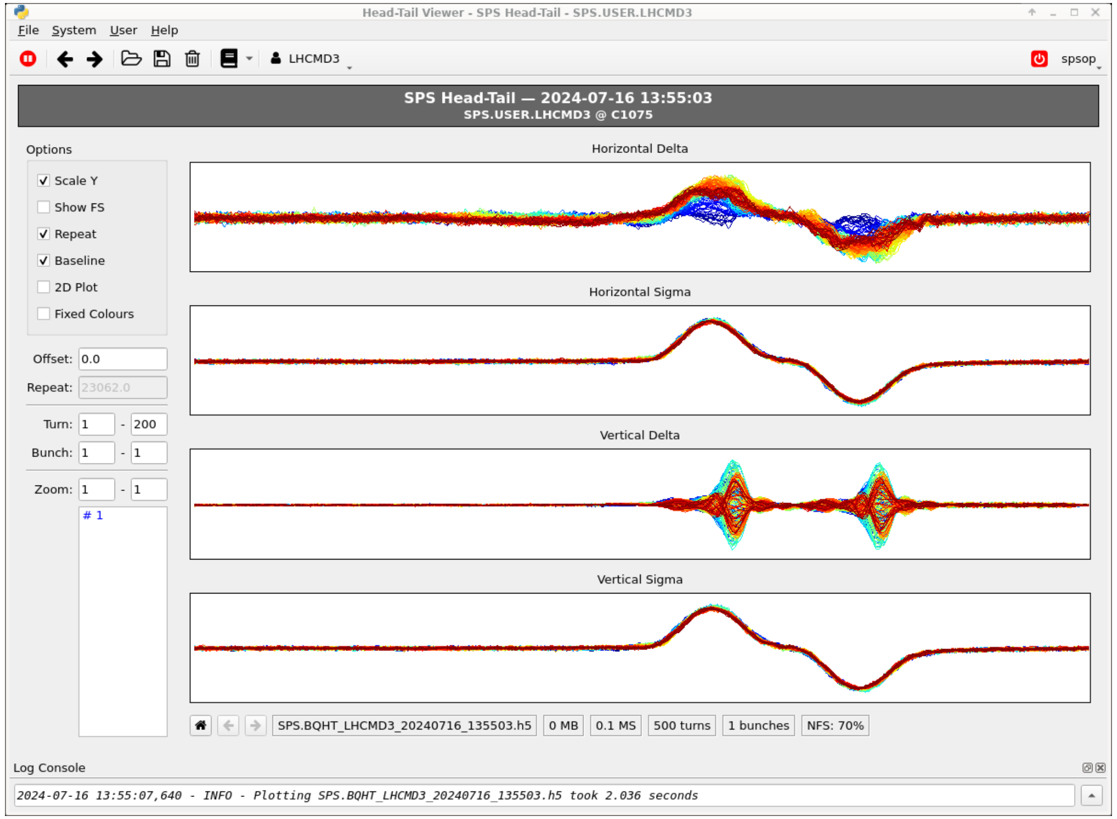


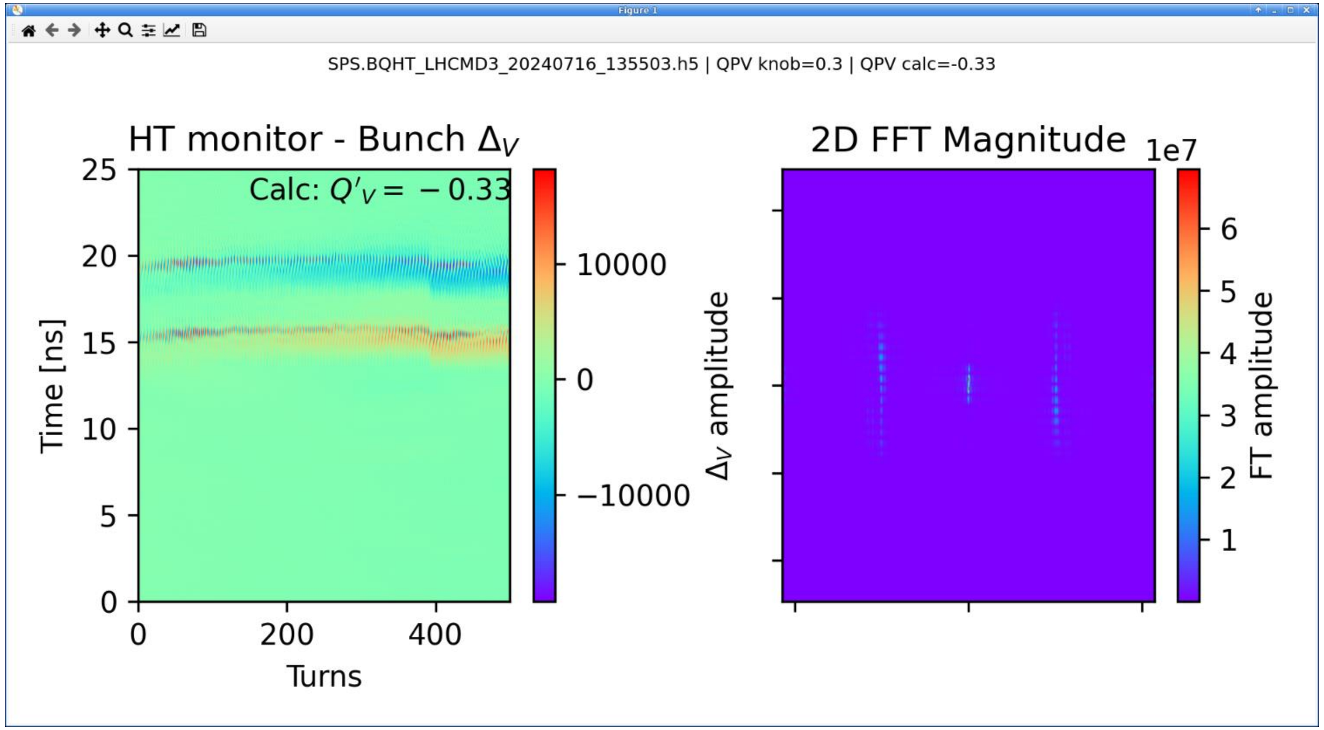


Positive chromaticity measurements TMCI



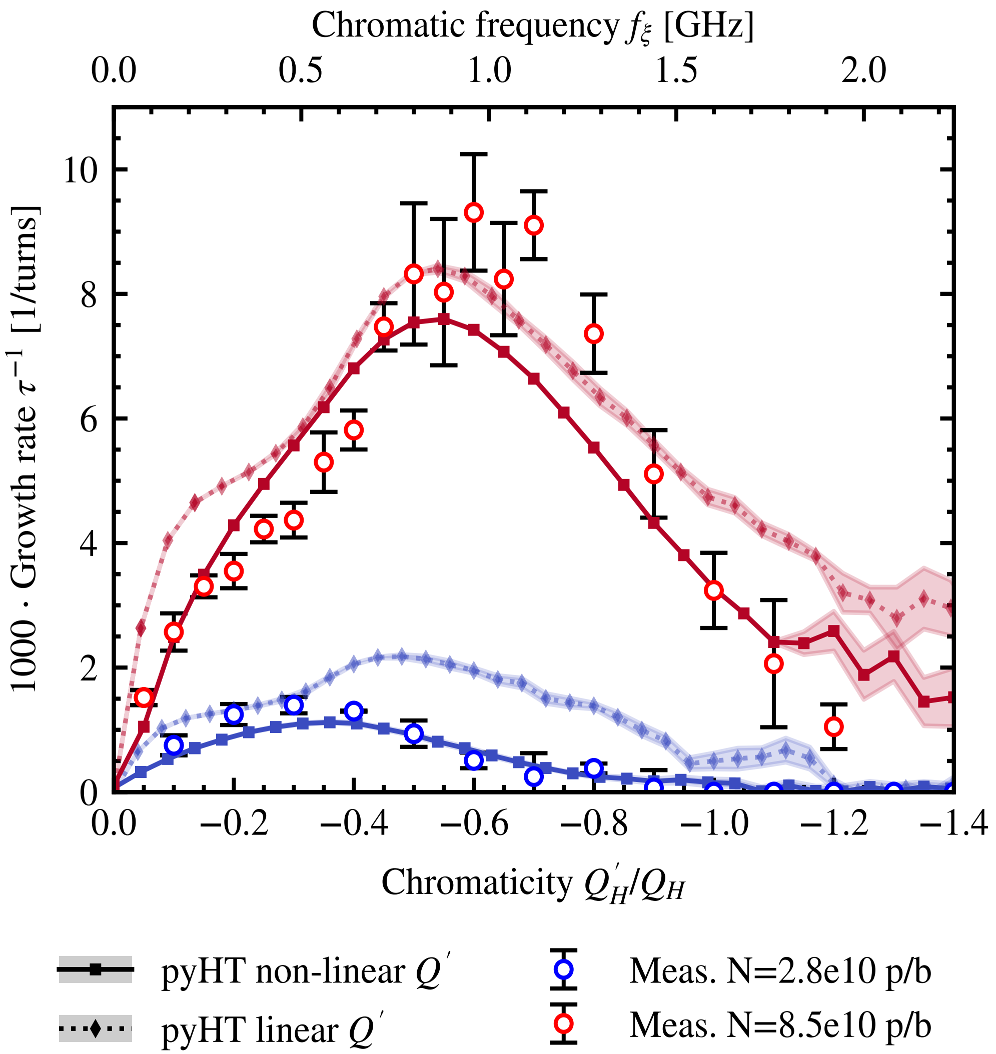
We tried to measure positive chromaticity by going above the TMCI threshold (2e11 for Q26) with our single bunch, and we successfully retrieved the intrabunch chromaticity





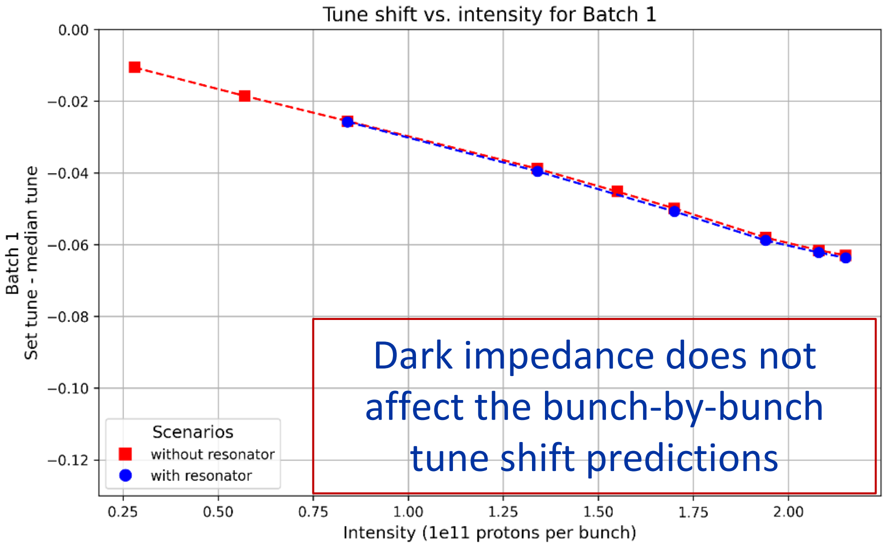
What about the Horizontal plane?

*E. de la Fuente, THAFP01, HB'23



*Courtesy of Ingrid Mases

Bunch-by-bunch tune shifts w/ dark impedance



Dark impedance does not affect the bunch-by-bunch tune shift predictions