Probing Transverse Impedances in the High Frequency Range at the CERN-SPS

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Overview

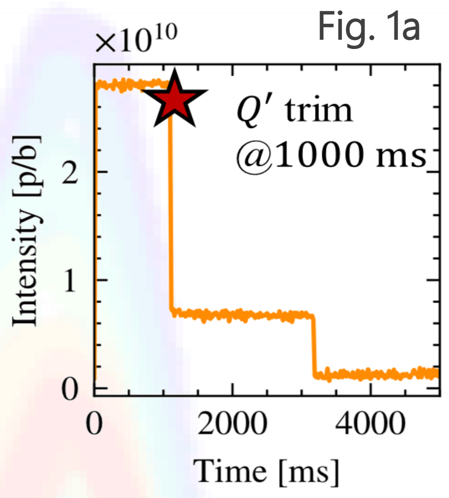
The SPS transverse impedance model, which includes the major impedance contributions in the machine, can be benchmarked through measurements of the Head-Tail mode zero instability. Since the SPS works above transition energy, the head-tail mode zero is unstable for negative values of chromaticity. The measured instability growth rate is proportional to the real part of the transverse impedance. Studies performed after the LHC Injectors Upgrade (LIU) showed a relevant impedance contribution around 2 GHz with high-gamma transition optics (Q26).

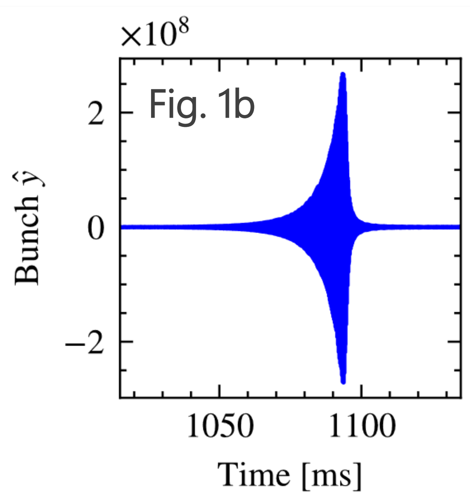
This paper presents a follow-up to probe the behavior of this beam coupling impedance contribution. Our studies include measurements of instability growth rates in both vertical and horizontal planes, spanning a broad spectrum of negative chromaticity values. To address the uncertainties in the high chromatic frequency range, the SPS Head-Tail monitor data is used to calculate the intrabunch chromatic content through a bi-dimensional frequency domain analysis.

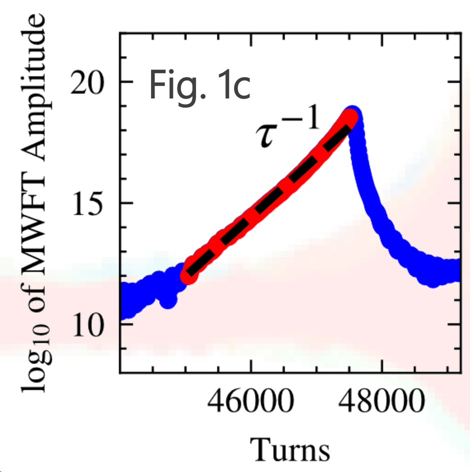
GROWTH RATE MEASUREMENTS

Studying the instability growth rate for a wide range of negative chromaticities $\xi = Q'/Q < 0$ provides information on the frequency dependence of the SPS transverse impedance $Z^{eff}_{\perp,dip}$. The smaller slip factor η of the high-gamma transition Q26 optics [1] together with the delayed trim strategy presented in [2] allows to explore the high frequency regime $f_\xi = \xi Q f_{\mathrm{rev}}/\eta > 1.2$ GHz.

Fig. 1a







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

SEQUENCE

I. When a negative chromaticity trim is applied, the beam becomes unstable, showing sharp intensity losses (Fig. 1a)

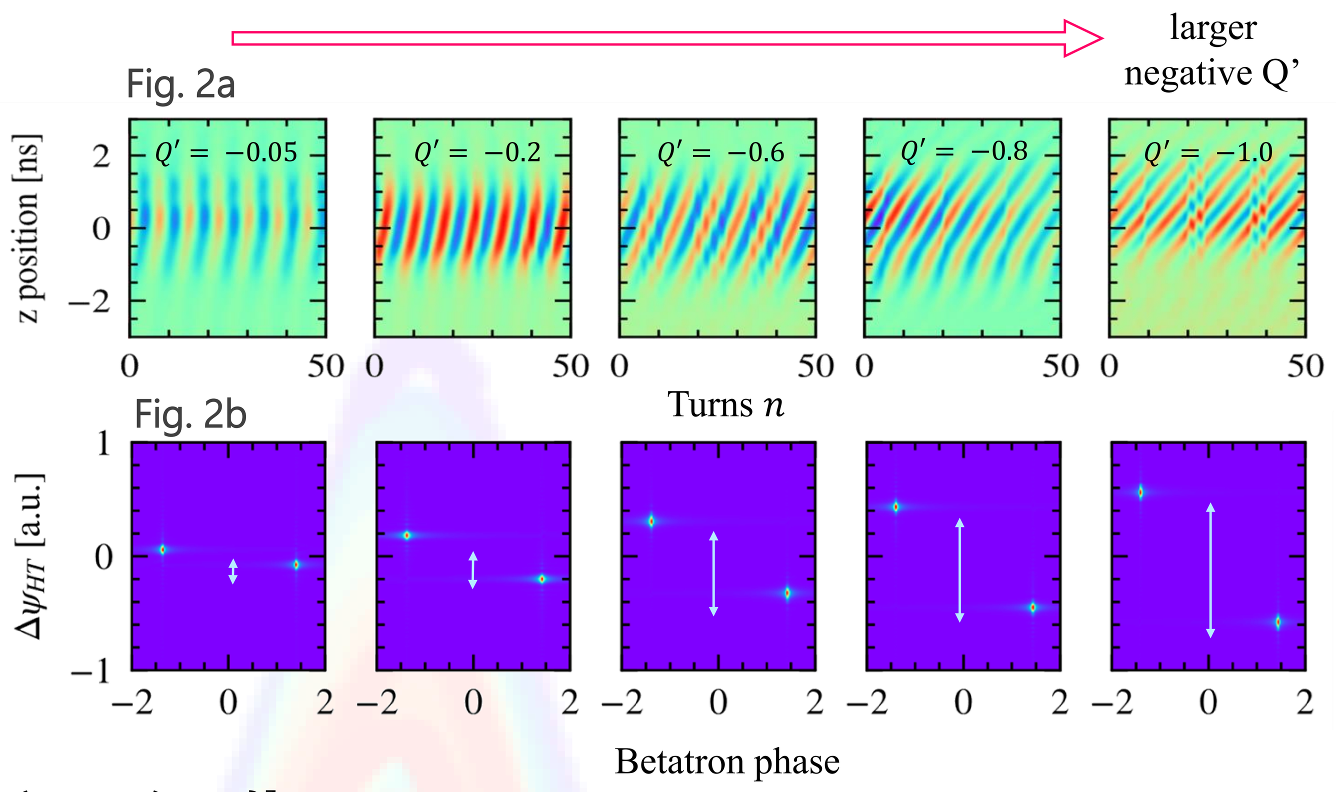
II. If the scan of negative chromaticity is performed in the vertical plane, the bunch vertical centroid position $\hat{y}$ exhibits an exponential growth (Fig. 1b)

III. The growth rate τ^{-1} of the turn-by-turn $\hat{y}$ data is obtained using the Moving Window Fourier Transform (Fig. 1c)

CHROMATICITY FROM HEAD-TAIL MONITOR

During the 2022 studies [2], the RF modulation method (MultiQ) to measure chromaticity provided unreproducible values for $\xi < -0.6$, adding an uncertainty to the growth rate data in the high frequency regime.

As an alternative, chromaticity can be deduced from the instability's intrabunch motion using the Head-Tail phase shift technique: [3]

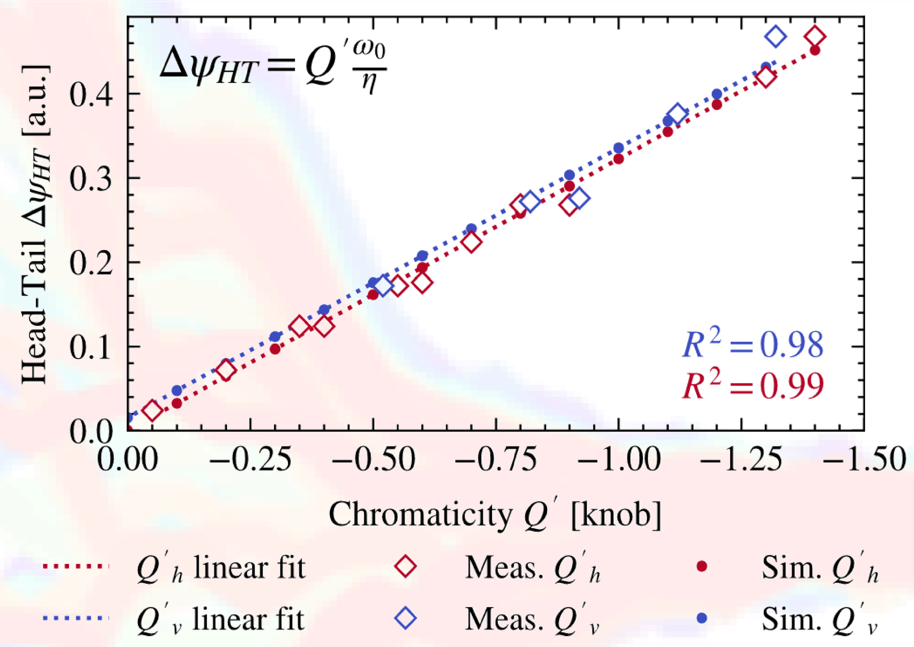


$$y(n) = A\cos[2\pi nQ + \Delta\psi_{HT}\{\cos(2\pi Q_s n) - 1\}]$$

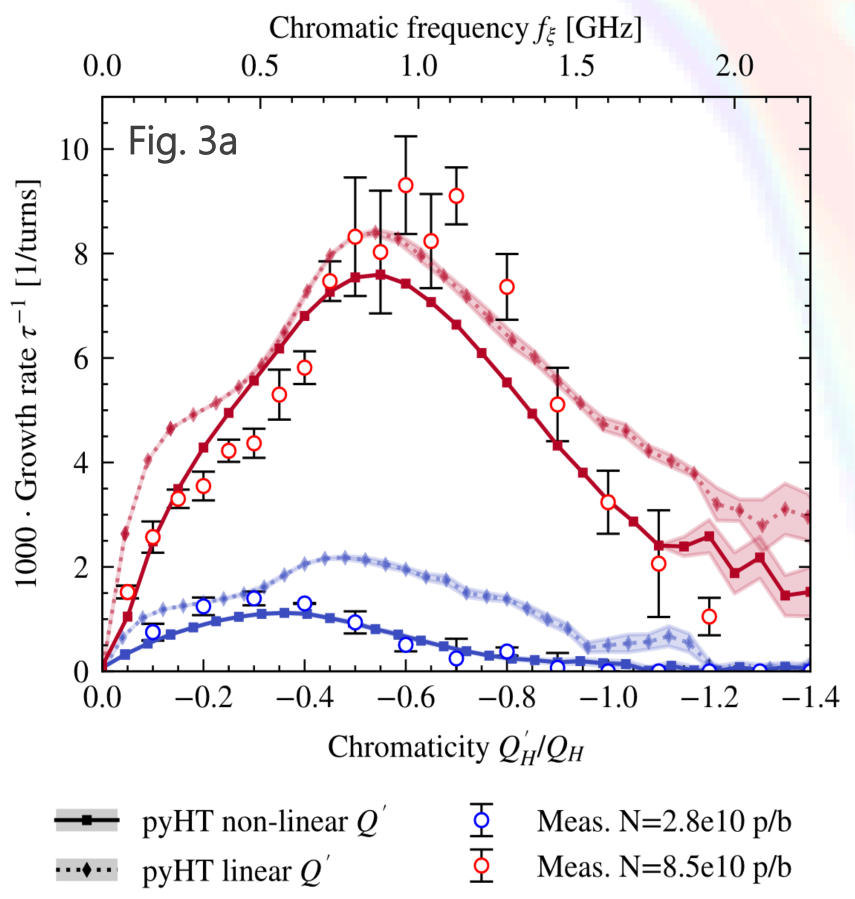
Each bunch slice $y(n)$ suffers a betatron phase modulation that translates into a longitudinal crabbing of the bunch:

- The crabbing angle depends on the chromaticity value $\Delta\psi_{HT} = Q'\omega_0/\eta$, clearly observed in SPS Head-Tail monitor measurements (Fig. 2a).
- Applying a 2D FFT, one can deduce $\Delta\psi_{HT}$ by measuring the offset between the two local maximums (Fig. 2b).
- (Fig. 2c) probes the linearity of the $\Delta\psi_{HT}$ offset when varying the chromaticity value, for both measurements and PyHEADTAIL simulations, resolving the uncertainty of ξ in the high frequency regime.

Fig. 2c



COMPARISON WITH SIMULATIONS



Simulations of the instability growth rates using the latest Q26 SPS transverse impedance model's wake [4] have been matched to beam observations using the PyHEADTAIL macroparticle tracking code [5], including an updated non-linear chromaticity model with coefficients Q'', Q''' measured anew in 2023.

HORIZONTAL PLANE

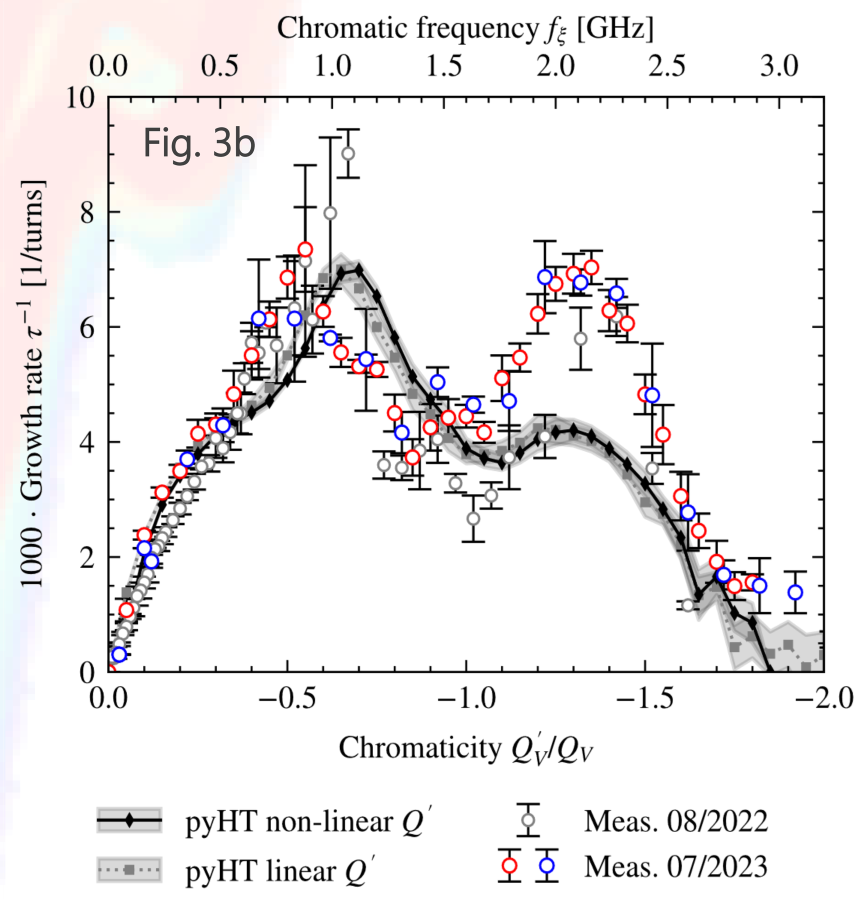
Two sets of Q'_H scans with different intensities are compared to simulations (Fig. 3a).

- For the set at lower intensity the exponential growth rate was not visible, yielding $\tau^{-1}\sim 0$ for $Q'_H < -0.6$.
- Thus, a set of measurements was conducted at higher intensity to enhance the instability growth rate τ^{-1} at higher f_ξ.

VERTICAL PLANE

The new set of Q'_V scans, together with 2022 data, are compared with simulations (Fig. 3b).

- The discrepancy around 2.0 GHz is found once more, and hints to a possible impedance contribution that is not present in the current impedance model.
- This missing impedance could be modelled by a broad-band resonator with $R_s/Q = 2\cdot 10^5\ \Omega$ at $f_R = 2.3$ GHz.



Conclusions

As part of the LHC-LIU initiative, a further benchmarking of the current transverse SPS impedance model was conducted through reference impedance measurements of the mode-zero Head-Tail instability in both transverse planes, extending to high chromatic frequencies with the Q26 optics.

- To address the uncertainty of negative chromaticity values, we employed a 2D Fourier analysis to measure the head-tail phase shift, proportional to the machine's chromaticity.
- Comparing our measurements with PyHEADTAIL simulations, incorporating the latest Q26 transverse wake and non-linear chromaticity model, we found good agreement in the horizontal plane. However, in the vertical plane, measurements confirmed a discrepancy around 2.0 GHz, consistent with previous findings.

Future work will involve dedicated studies aimed at refining the existing impedance model in the high-frequency regime.

References

[1] C. Zannini, et al., "Benchmarking the CERN-SPS Transverse Impedance Model with Measured Headtail Growth Rates," in 6th IPAC, MOPJE049. [2] E. de la Fuente, et al., "Head-tail mode zero instability growth rate studies in the CERNSPS." IPAC'23, Venice, Italy, WEPL155. [3] R. Jones and H. Schmickler, "The Measurement of Q' and Q" in the CERN-SPS by Head-Tail Phase Shift Analysis," in Proc. PAC'01. [3] http://impedance.web.cern.ch [4] https://github.com/PyCOMPLETE/PyHEADTAIL

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