SPS Impedance benchmarks

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Acknowledgments: Kostas, David, Lorenzo, Tirsi

12/09/2024

Overview

- **Introduction to the project**
- **Methodology**
- **The dark impedance**
- **Simulation work**
- **Tune shift benchmarks**
- **Conclusions and future work**

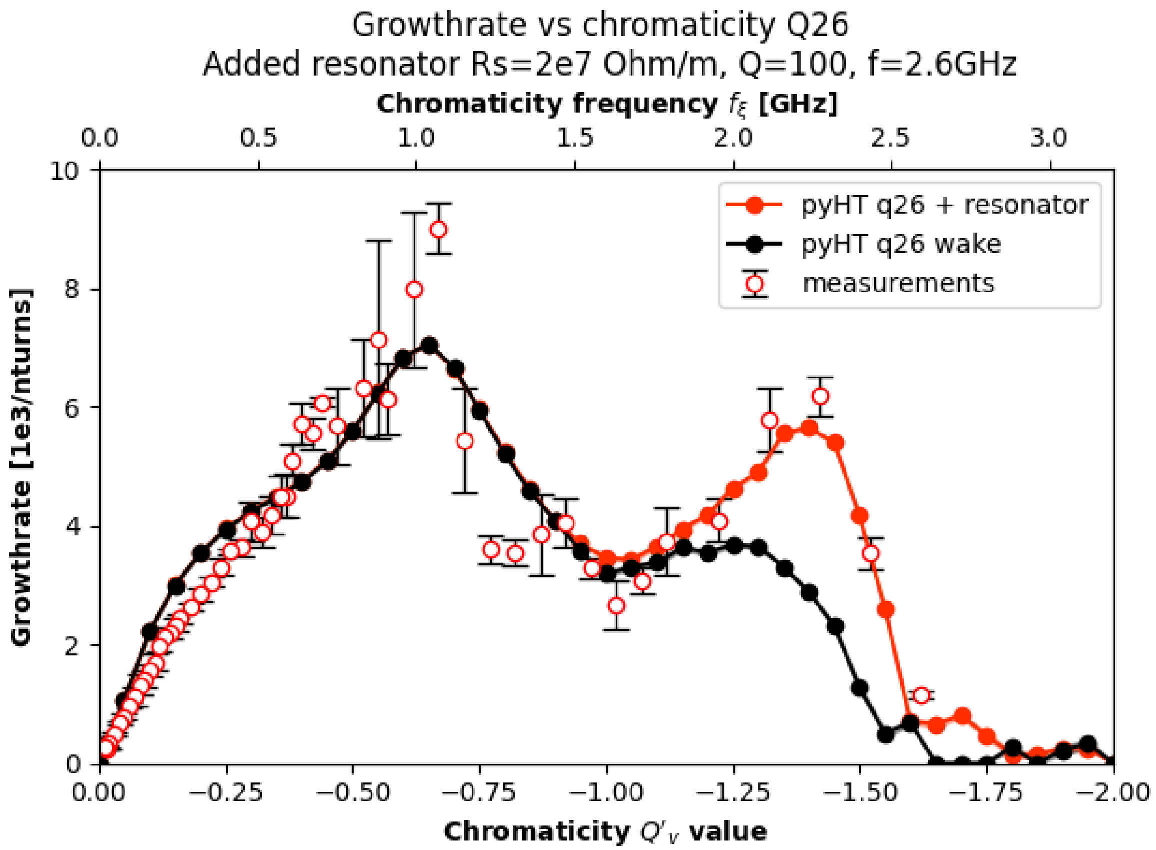
Introduction to the project

Motivation

- The benchmarking of the SPS impedance model is a project carried out since the year 2000 after each LS. During the 2022/23 measurements a second peak was discovered at higher frequencies.

Goals

- The goal is to test the “dark” impedance in the SPS, to see if we can still measure it at different tunes and energies.
- Carry out tune shift benchmarks to see if this missing impedance also extends to the imaginary part.



2023 growth rate measurements vs chromaticity
“The dark impedance”

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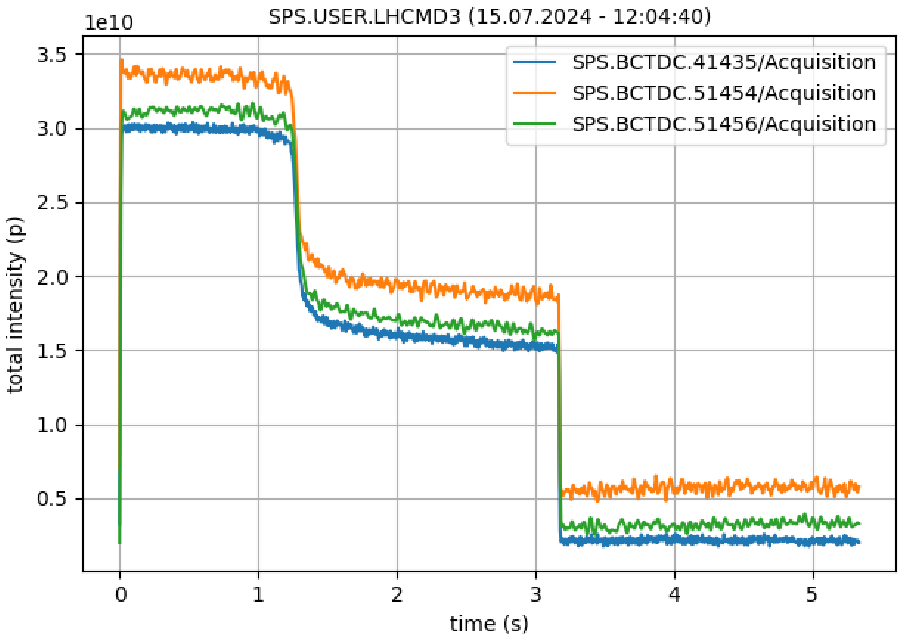
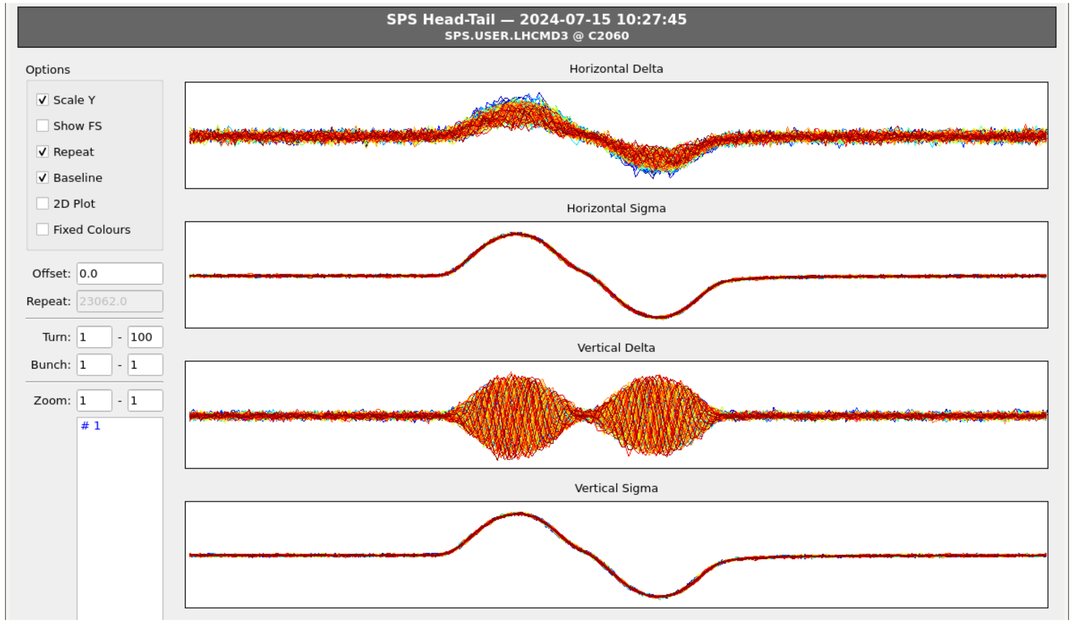
Methodology

We take the following steps:

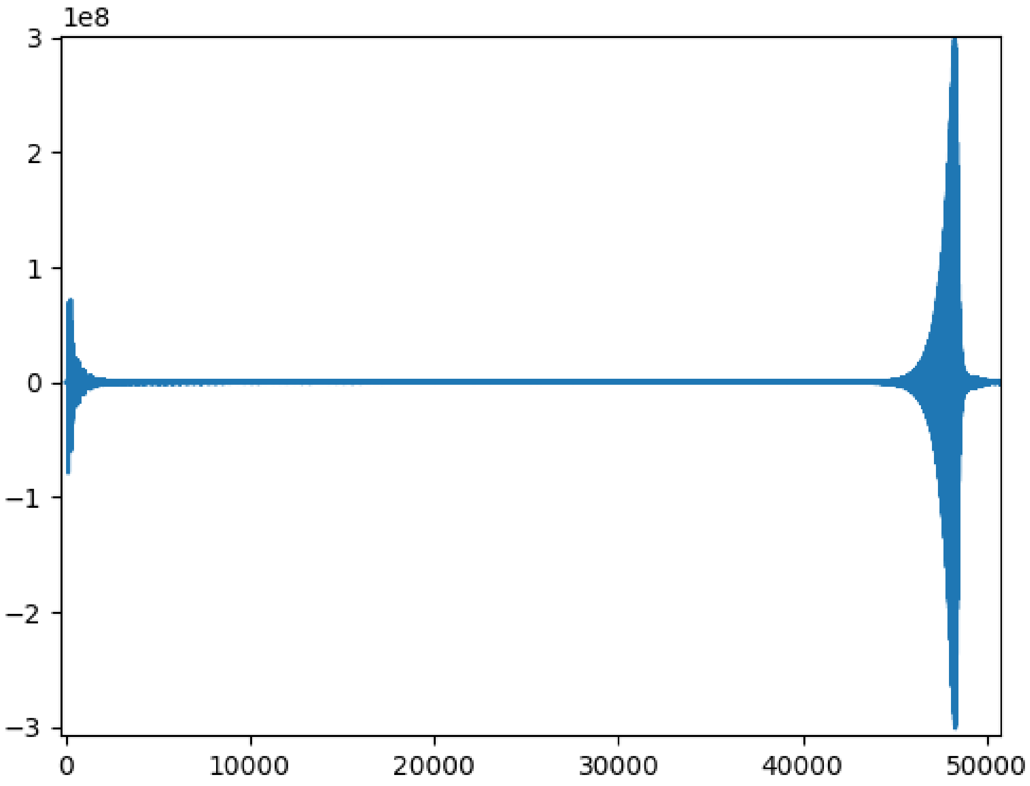
- Data acquisition during SPS MDs.
- Processing data using the mean bunch position.
- Simulation of the chromaticity scan using PyHT and the impedance model.
- Our observables are the growth rate of the mean vertical position's exponential growth; the sudden dropoff in intensity and the intra-bunch headtail motion.

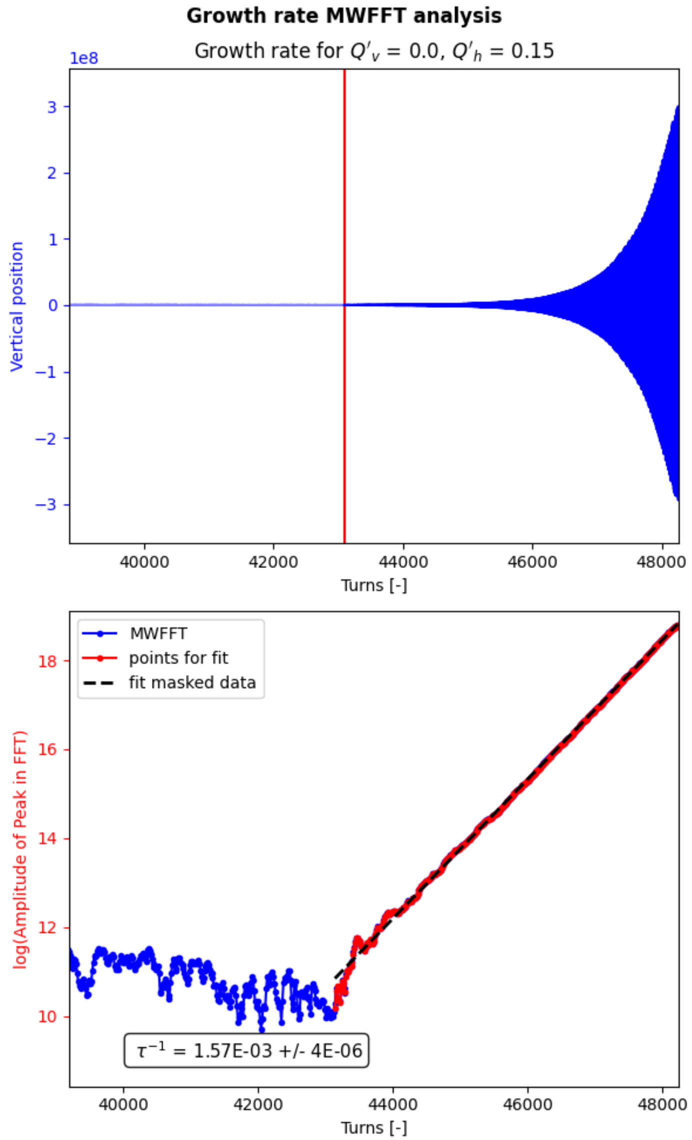




Typical signal processing

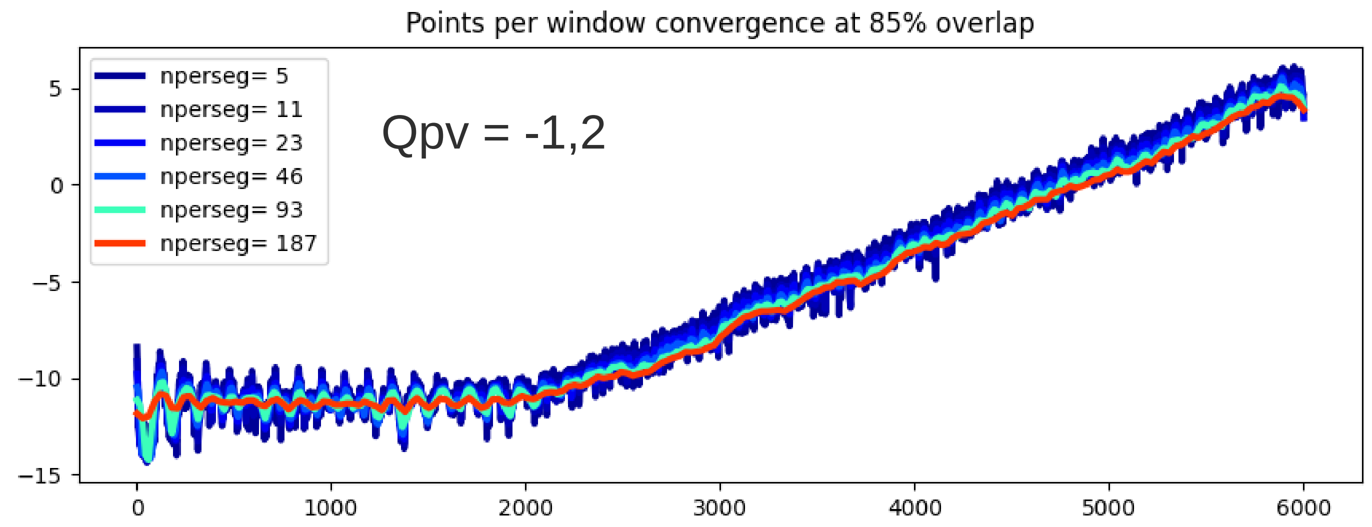
Average bunch position during cycle

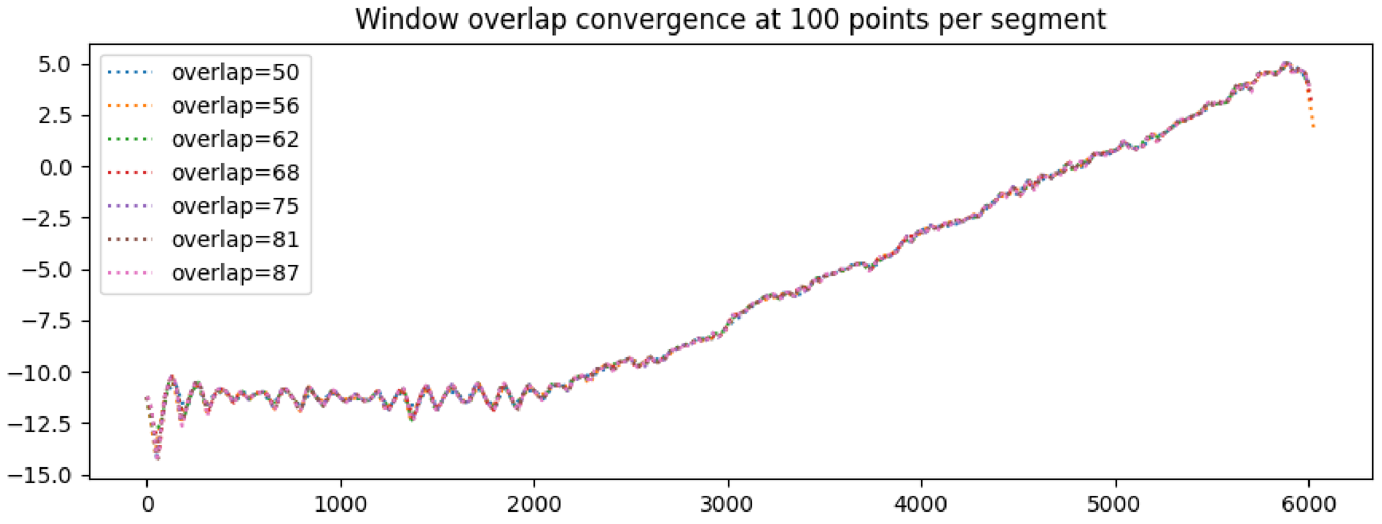




Moving Window FFT parameters

- Two main parameters: Number of points per window and window overlap.
- Results converge at 100 points per window aprox.
- Overlap doesn't matter if we keep it above 50%

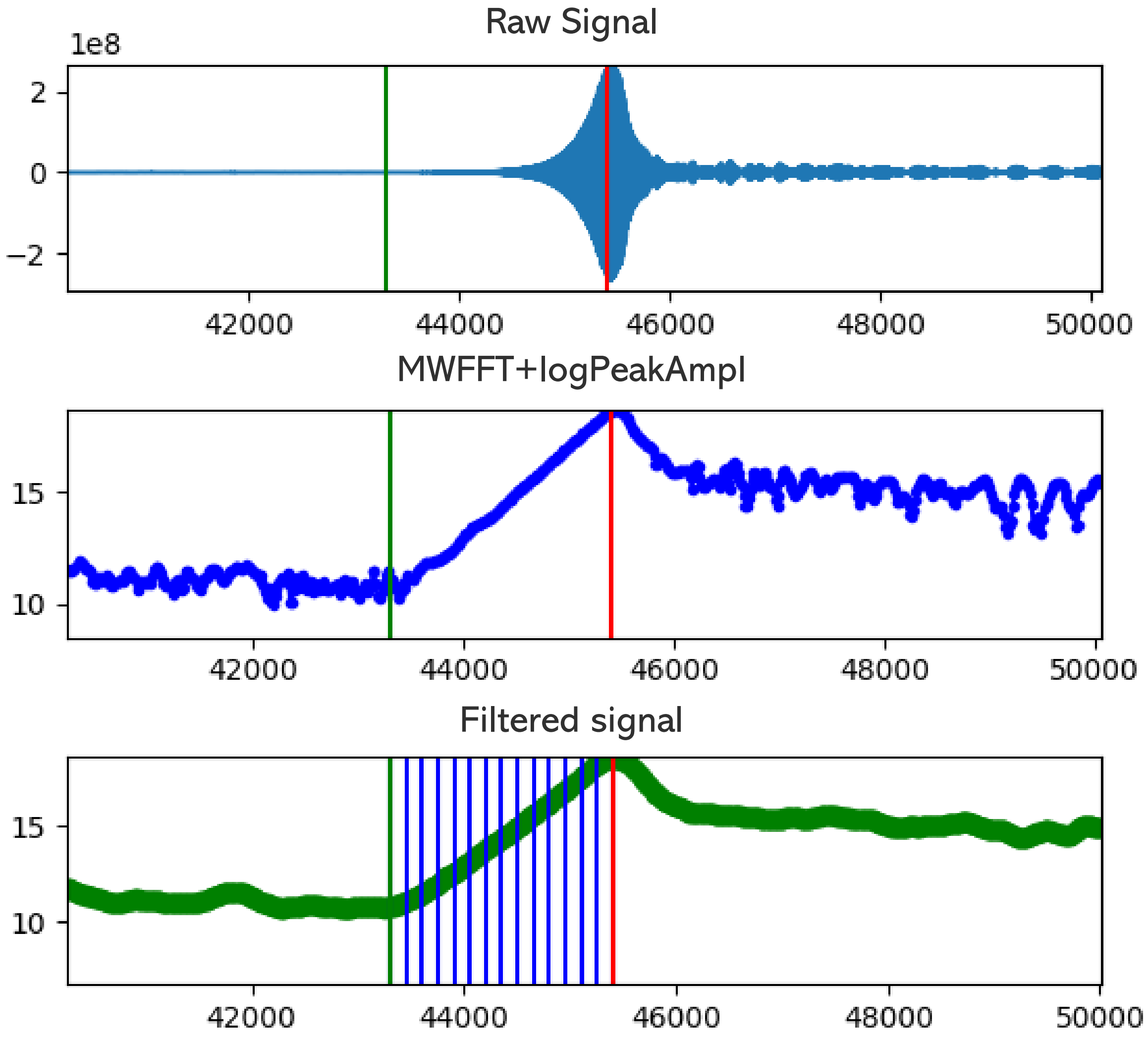




Automatic growth start detection

Some improvements in the processing:

- I developed a simple tool to automatically determine the start of the instability, which used to be a manual task.
- Consist of filtering the MWFFT signal, then starting from the top steeping backwards taking windows of the signal.
- By taking the slope of those segments we can figure out when does the growth start.



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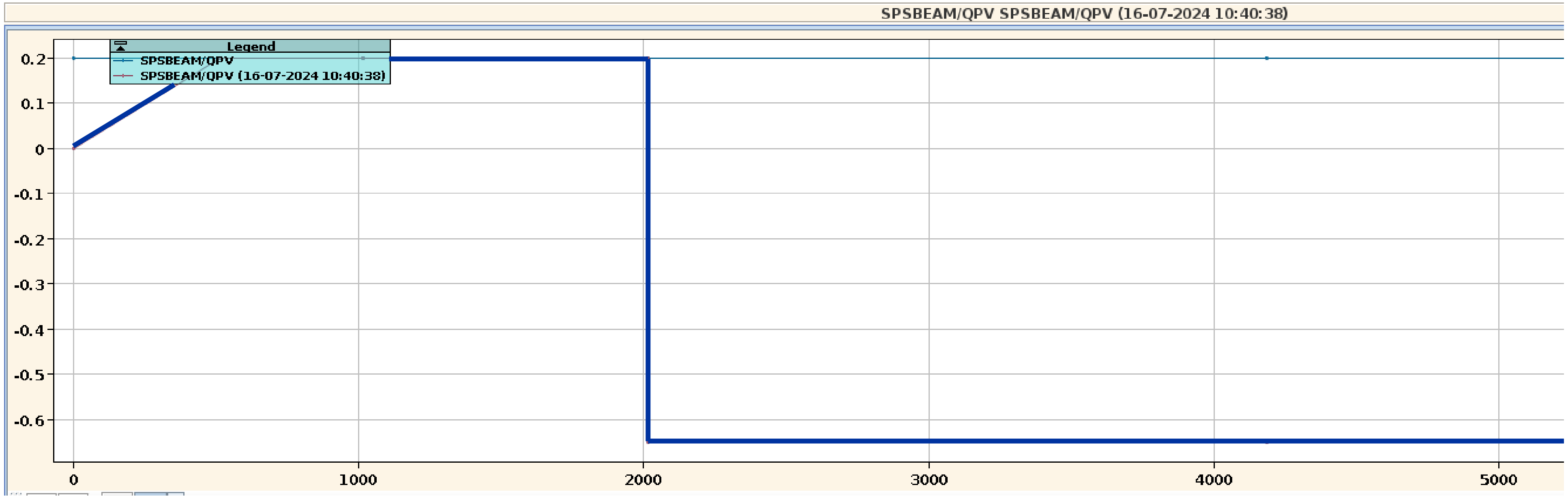
The dark impedance

First steps:

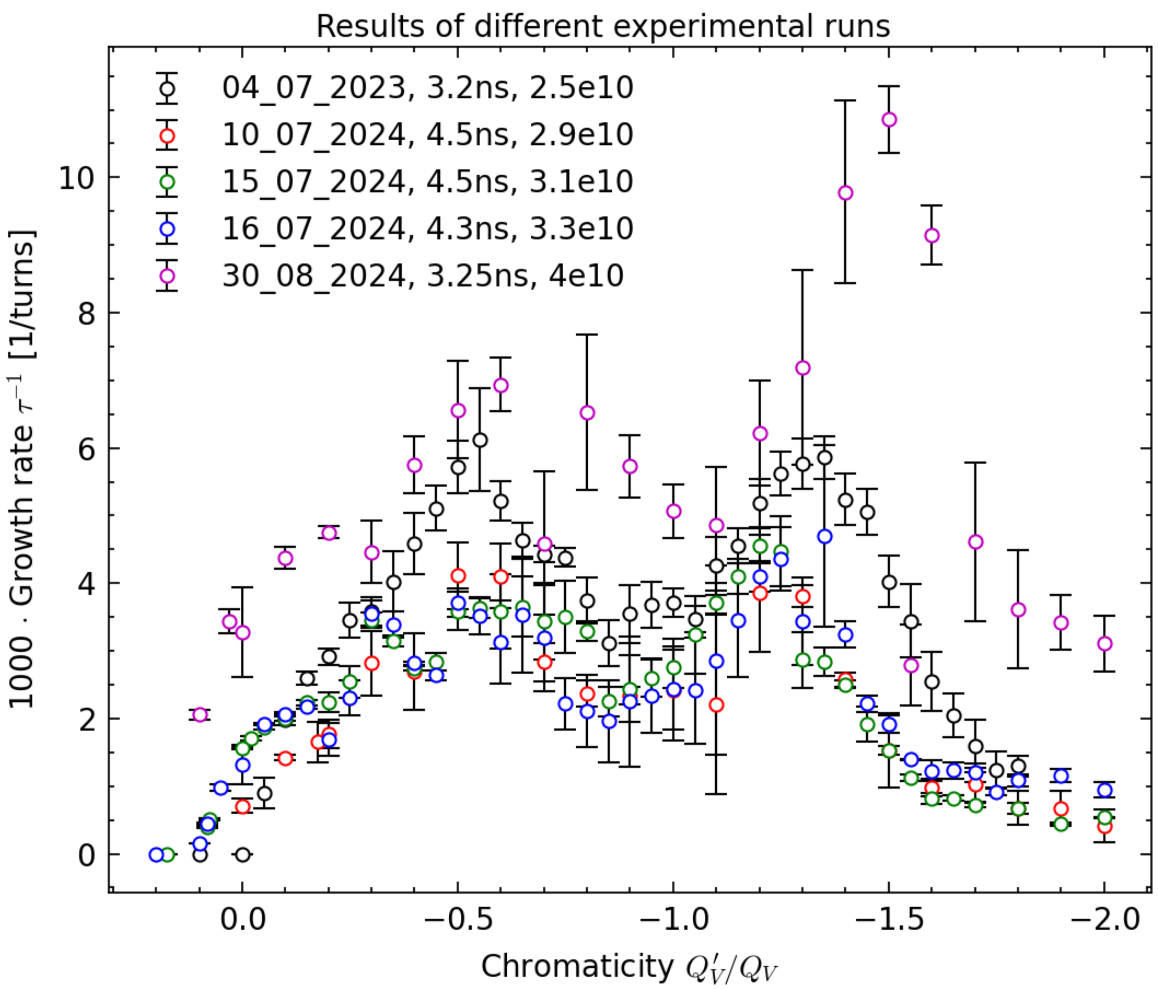
- The Growth rate of the head-tail made zero instability at negative chromaticities is related to the real part of the impedance.
- Thanks to applying the trim with a delay we can measure up to qpv=2 (3,2 GHz) and even further.

$$\tau^{-1}(\xi) = \Gamma\left(\frac{1}{2}\right)\frac{\mathrm{Re}\left[Z_{\perp,dip}^{eff}(\xi)\right]Nr_0c^2}{8\pi^2\gamma Q_\perp\sigma_z}$$



Growth rate Benchmarking

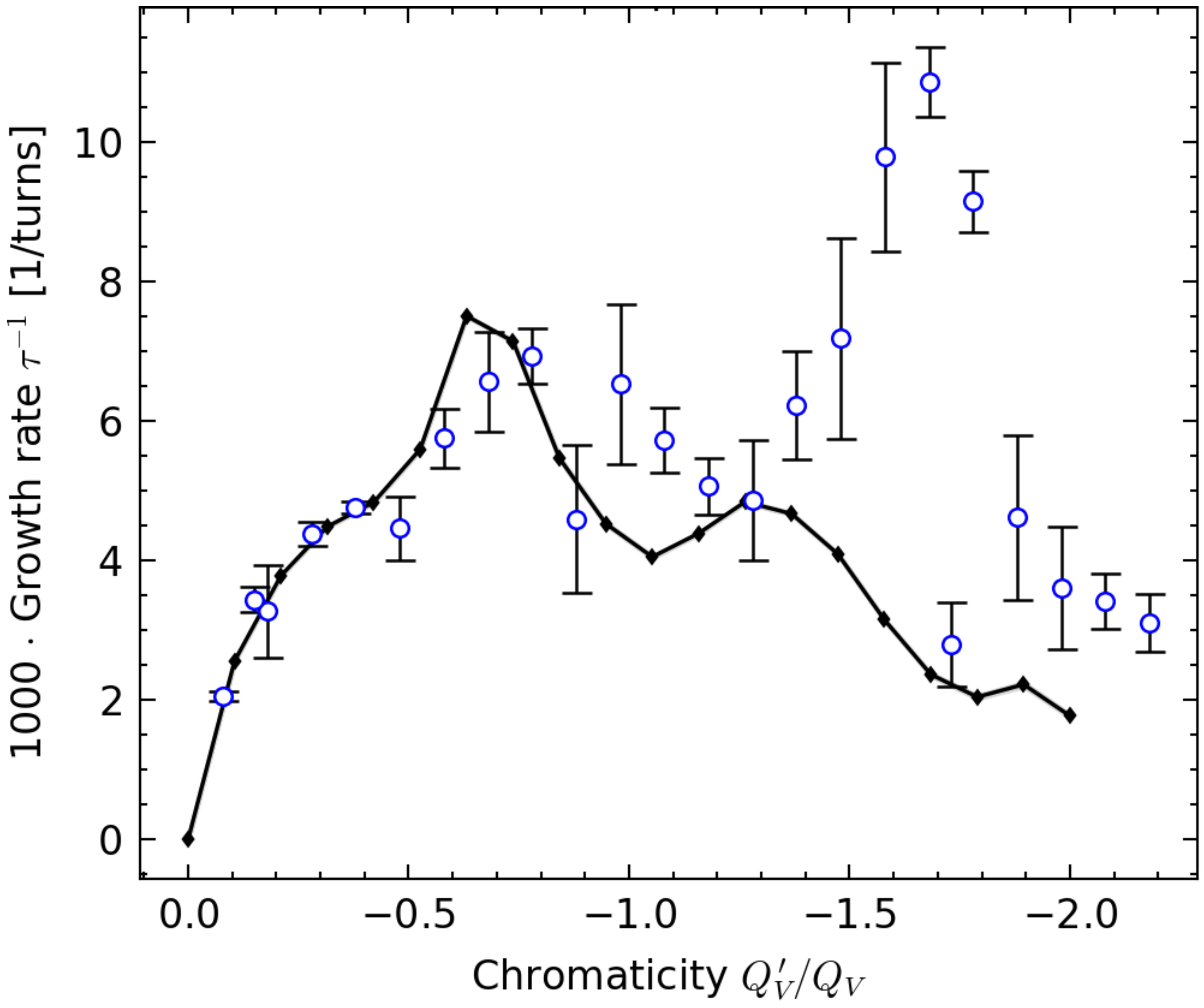
- Repeat of last year's measurements
- Differences caused by intensity, bunch length and user.
- Consistent second peak
- Logbooks: 04_07_2023, 10_07_2024, 15_07_2024, 16_07_2024, 30_08_2024



Growth rate Benchmarking

We have a disagreement with the model!

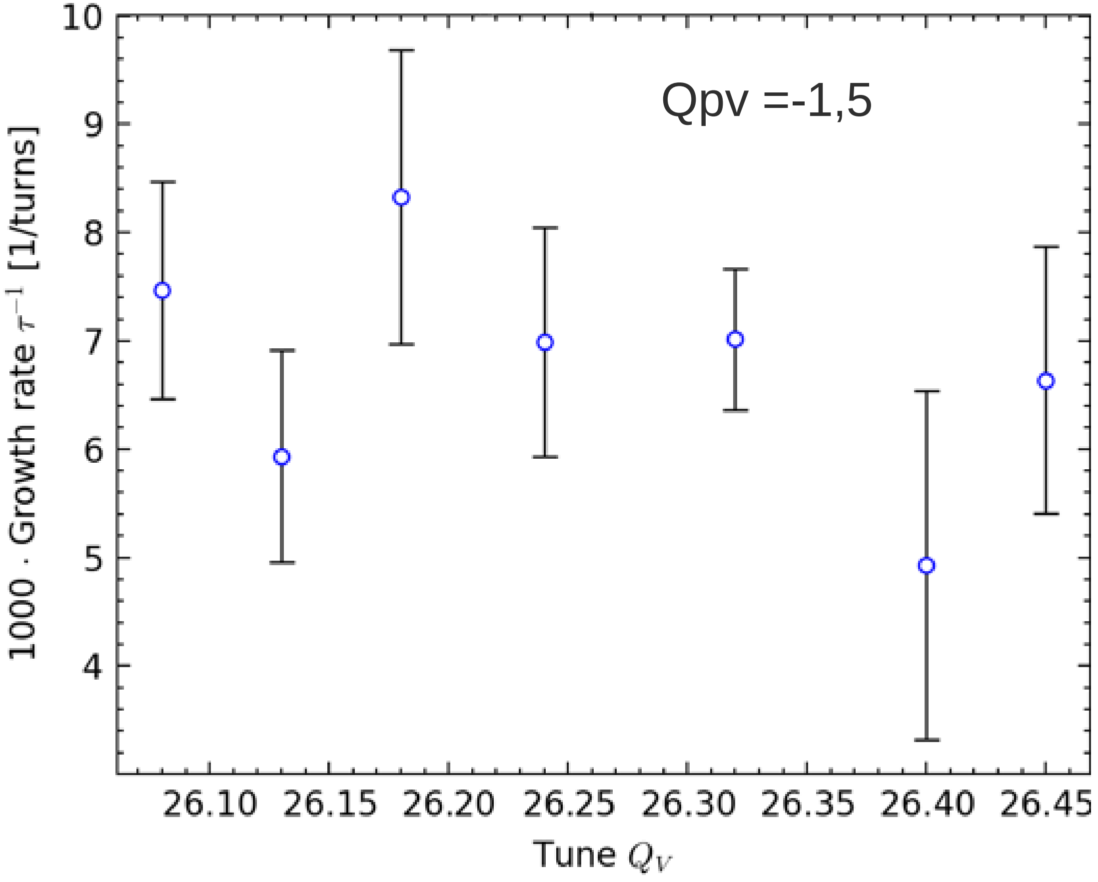
Logbook



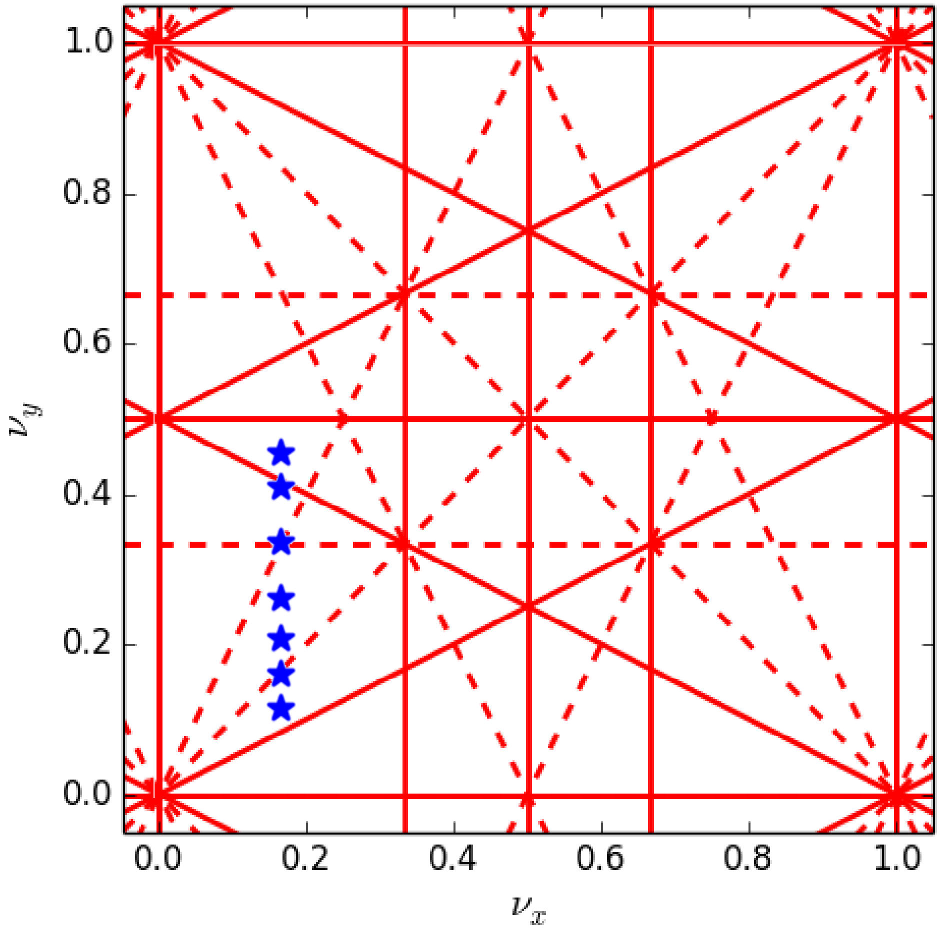
Analysis at same qpv different tunes

We cannot explain the second peak through tune alone

Growth Rate at different tunes

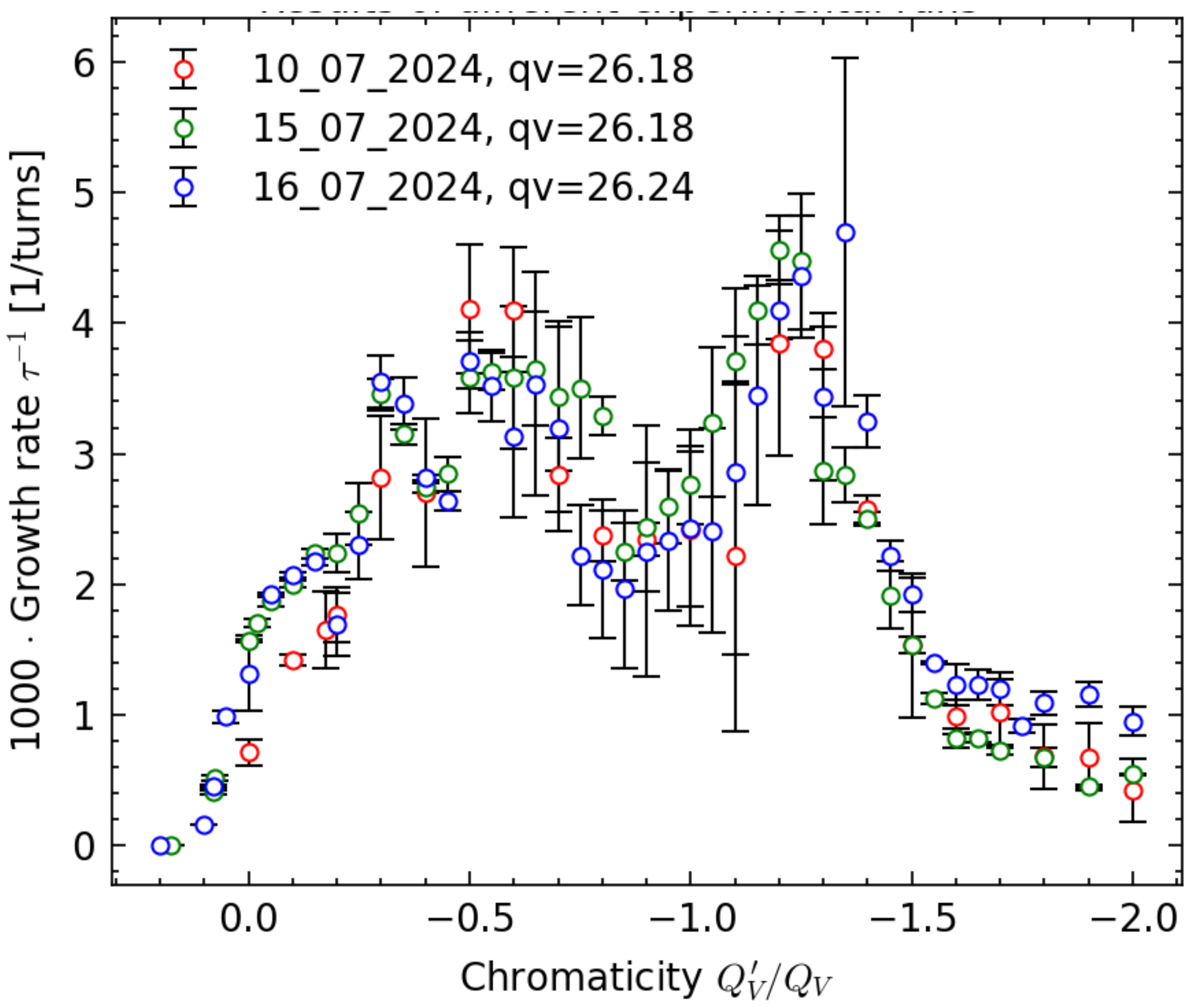


Points measured on resonance map



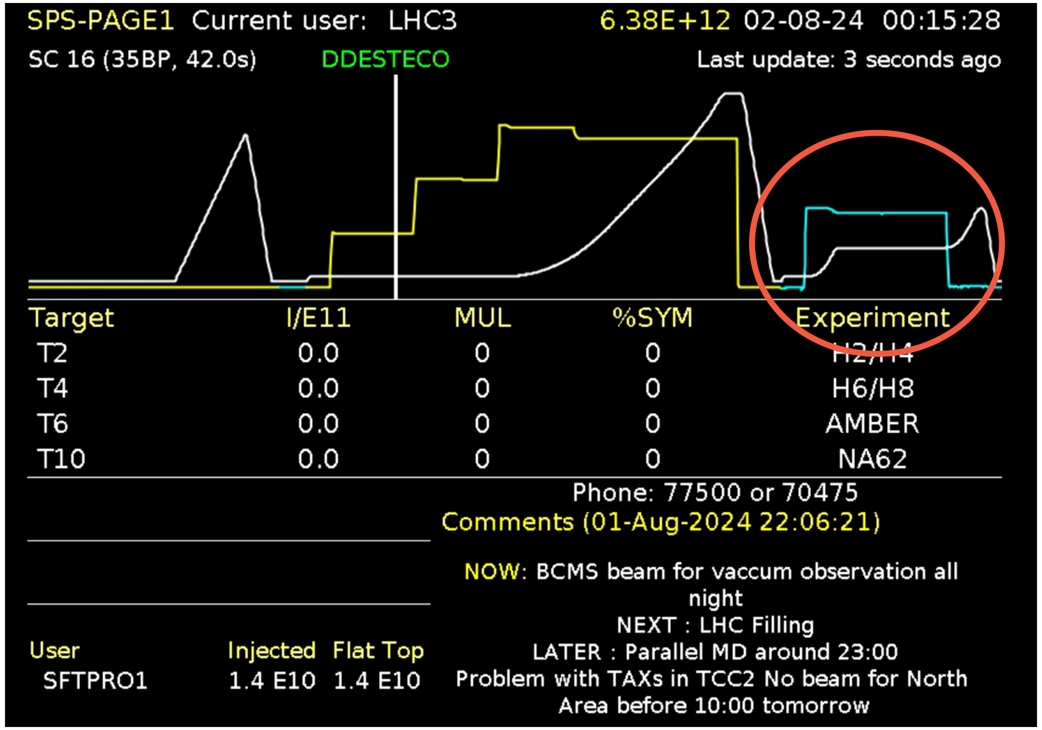
Analysis at same qpv different tunes

Complete scans at different tunes show no shifting of the second peak.

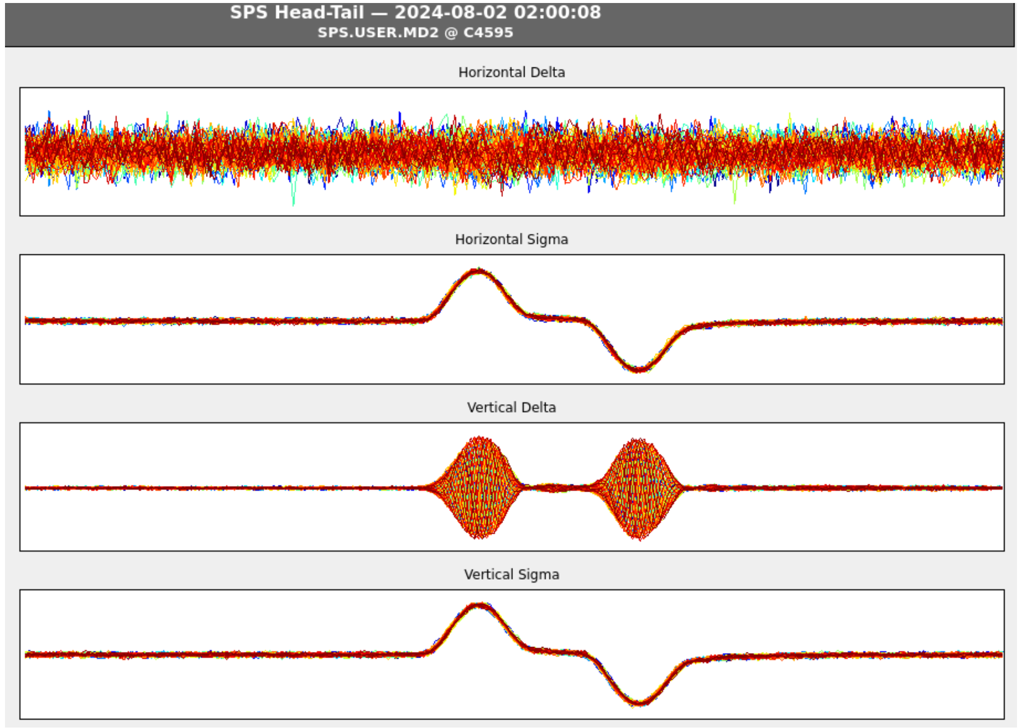


100 GeV measurements

Cycle for 100GeV measurements

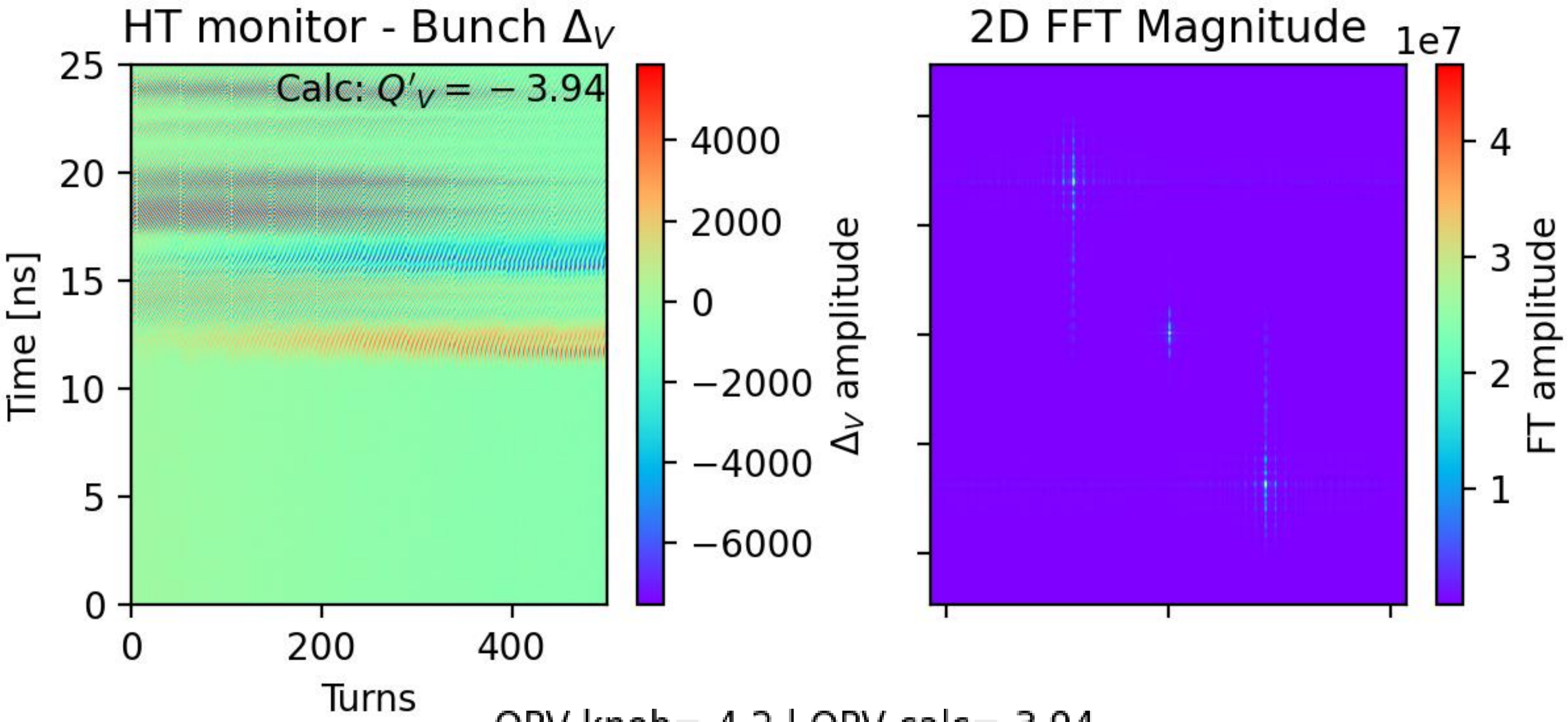


Head-Tail motion at very high chromaticities (up to $\mathrm{QPV}_{knob} = -4$)



Measuring qpv through particle motion

- We stayed in head-tail mode 0 motion and extracted the chromaticity online cycle-by-cycle

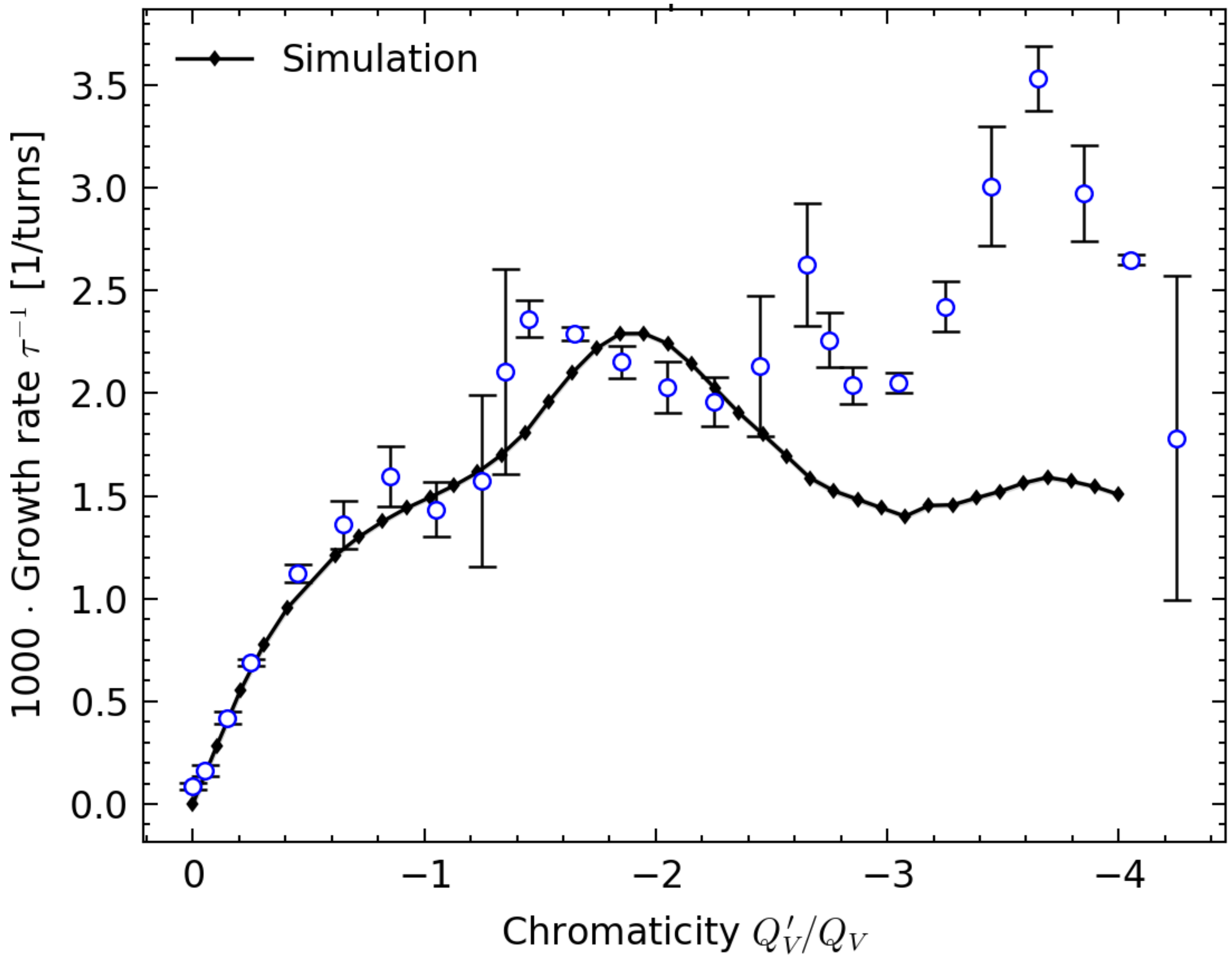


QPV knob=-4.2 | QPV calc=-3.94

100 GeV measurements

- We keep the second peak!
- Took gamma, slip factor and bunch length from LSA to simulate.
- Simulation time had to be increased as high chromas delay the instability.

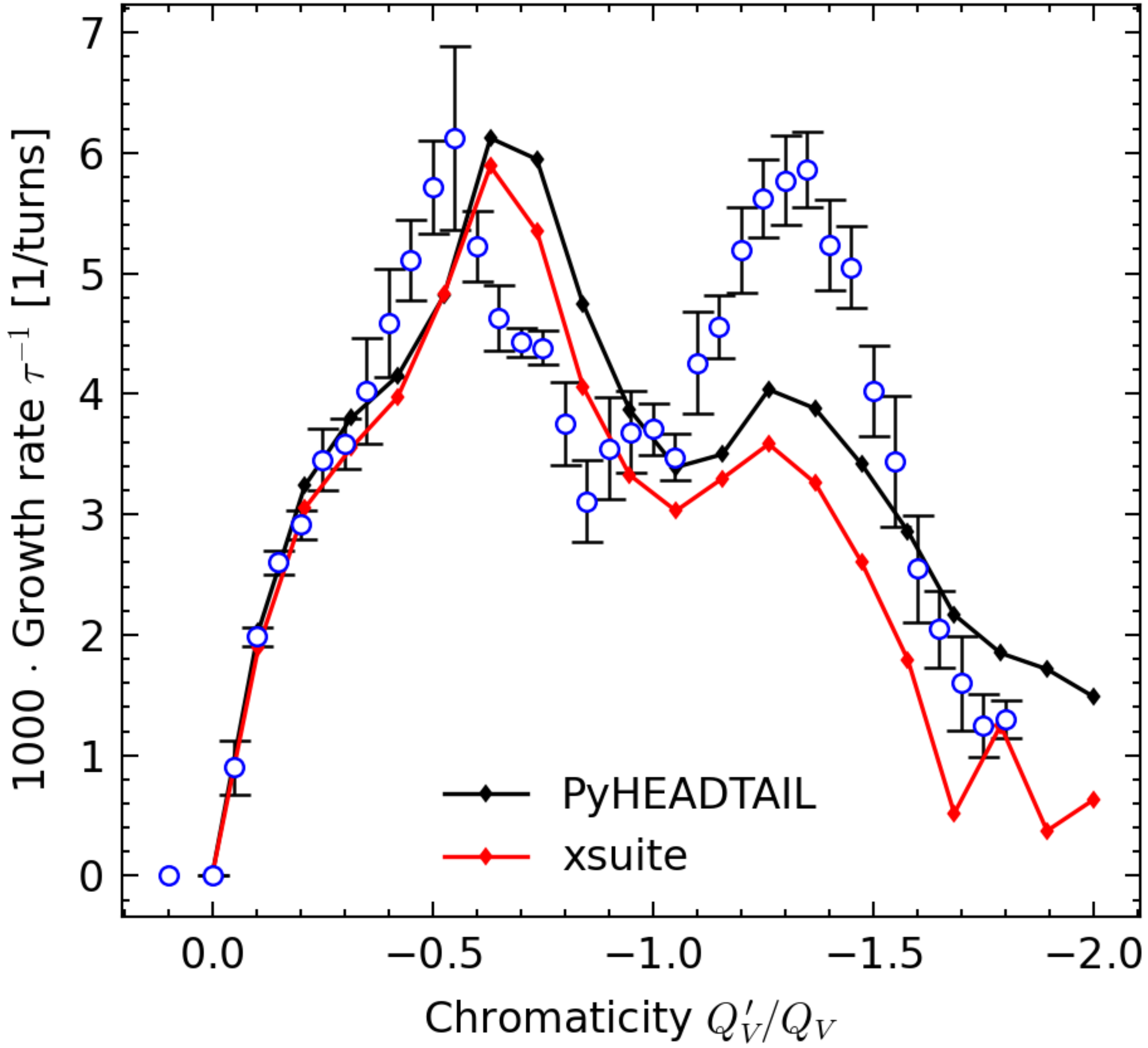
Measurement results



Is the dark impedance real?

- We reproduced the missing impedance with new measurements
- Carried out a scan on the tune to evaluate the influence of the integer resonance.
- Measurements at different energy with shrinked RF bucket, bunch length, slip factor…

We have always observed a missing impedance in the model



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Simulations

- Most of the simulation work done with PyHEADTAIL
- It is a macro-particle code for simulating beam dynamics in particle accelerators with collective effects. (link)
- We use a one-turn map.

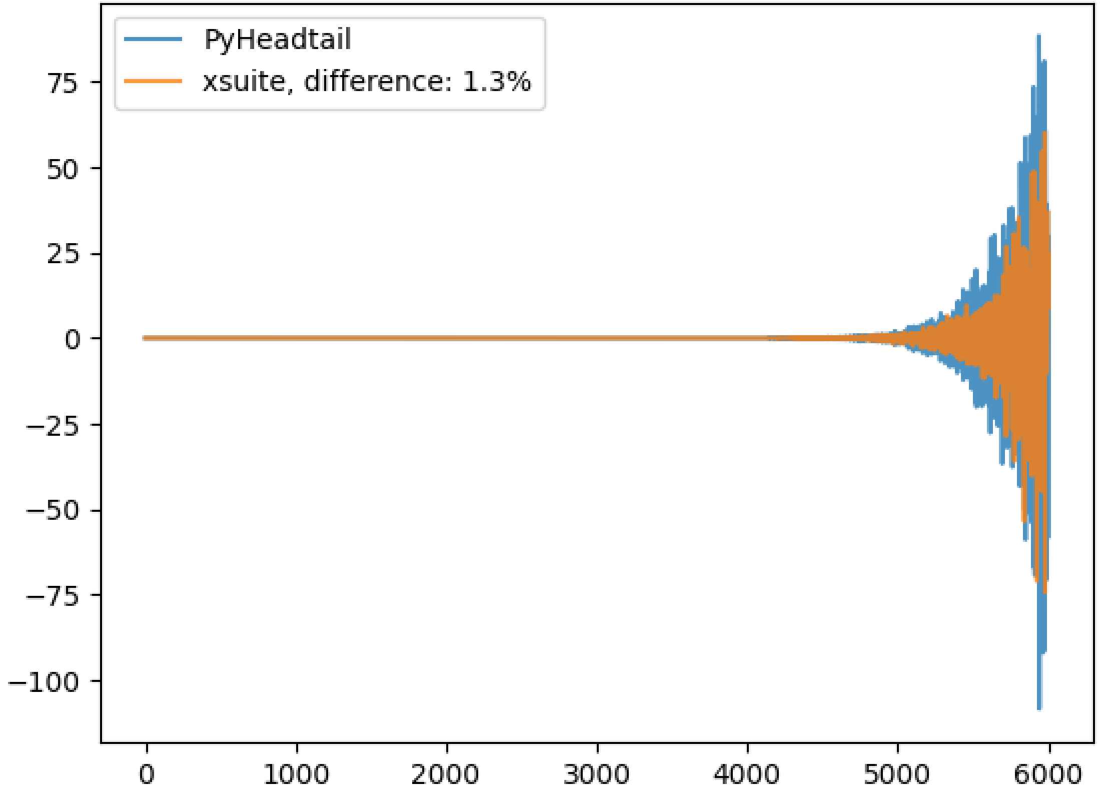
```
machine = Synchrotron(
        optics_mode=optics_mode, circumference=circumference,
        n_segments=n_segments, s=s, name=name,
        alpha_x=alpha_x, beta_x=beta_x, D_x=D_x,
        alpha_y=alpha_y, beta_y=beta_y, D_y=D_y,
        accQ_x=accQ_x, accQ_y=accQ_y, Qp_x=Qp_x, Qp_y=Qp_y,
        app_x=app_x, app_y=app_y, app_xy=app_xy,
        alpha_mom_compaction=alpha, longitudinal_mode=longitudinal_mode,
        h_RF=np.atleast_1d(h_RF), V_RF=V_RF, dphi_RF=dphi_RF, p0=p0, p_increment=0.,
        charge=charge, mass=mass, wrap_z=wrap_z)
```

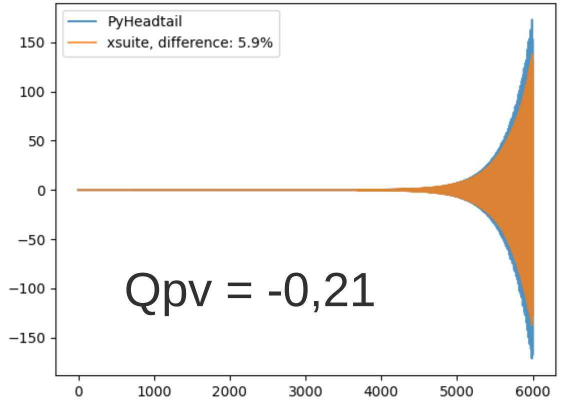
```
n_turns_wake = 5  #number of turns the wakefield is alive
wakefile1 = ('new_model_corr.wake')            # complete impedance model 2024

ww1 = WakeTable(wakefile1, ['time', 'dipole_x', 'dipole_y', 'quadrupole_x', 'quadrupole_y'], n_turns_wake=n_turns_wake)
wake_field = WakeField(slicer_for_wakefields, ww1)
                        #mpi='linear_mpi_full_ring_fft', Q_x=accQ_x, Q_y=accQ_y, beta_x=beta_x, beta_y=beta_y)
```

Xsuite

- Xsuite is a more complete software that allows us so do multiparticle simulations of particle accelerators. (link)
- I developed a one-turn map using this program. (Thanks to Kostas, Lorenzo, David, Tirsi)
- An XSUITE model using the full sequence has also been developed but requires further testing.
- Github for SPS_xsuite models.

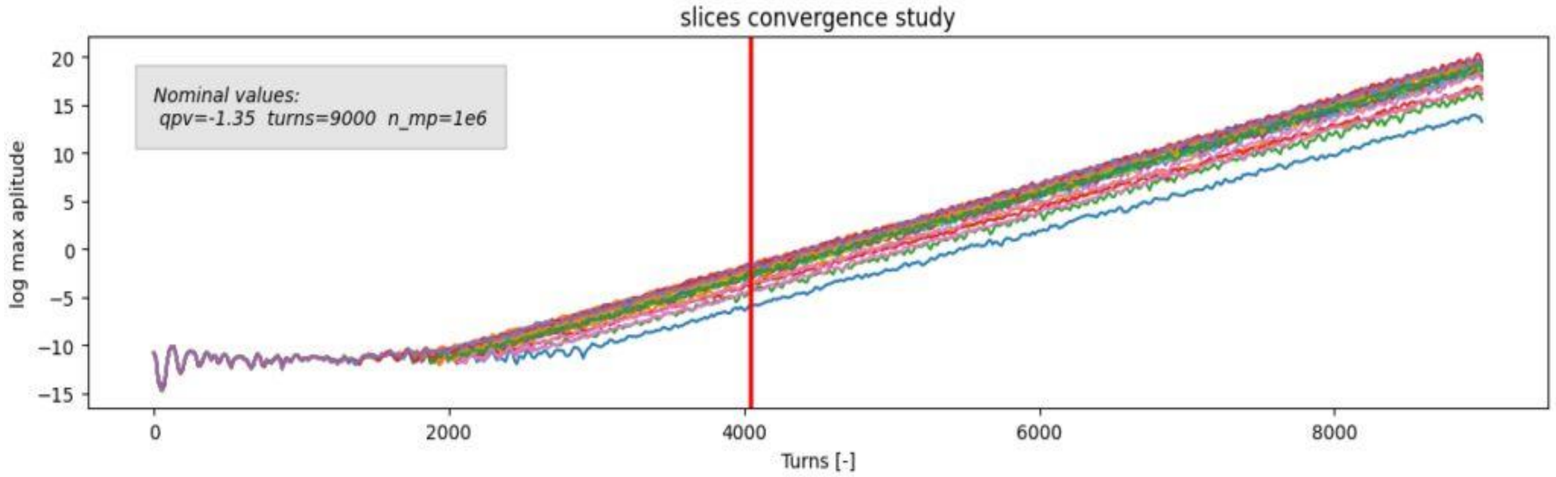
Benchmark of xsuite simulation Qpv =-1,35

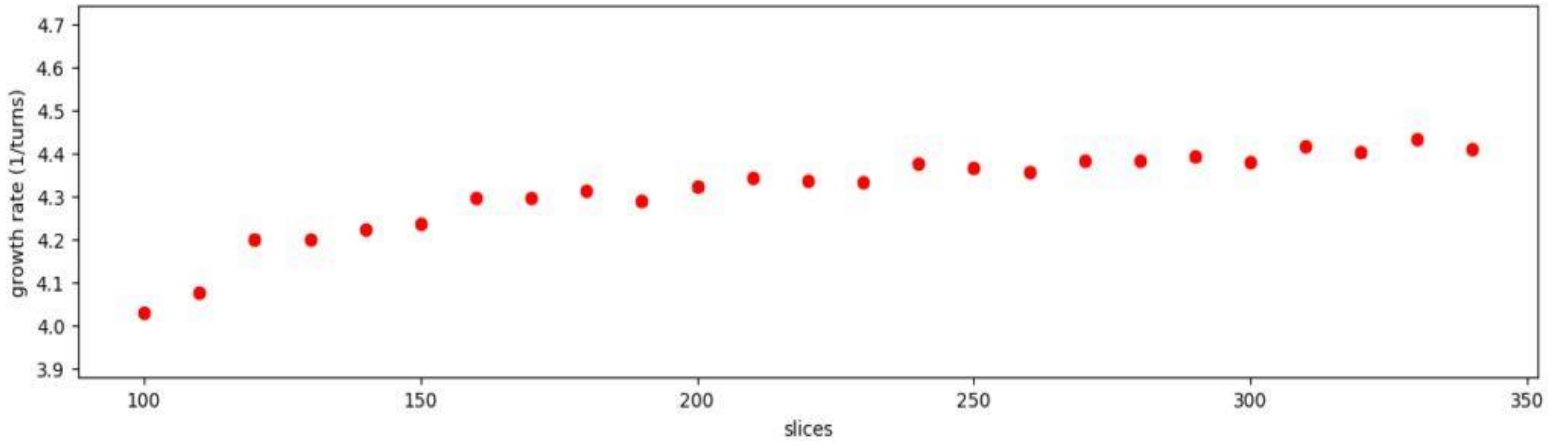




PyHeadtail Convergence studies

- Convergence analysis of three parameters: simulation time, macroparticle number and bunch slices.
- Carried out at low and high chromaticities (-0,2 and -1,35)



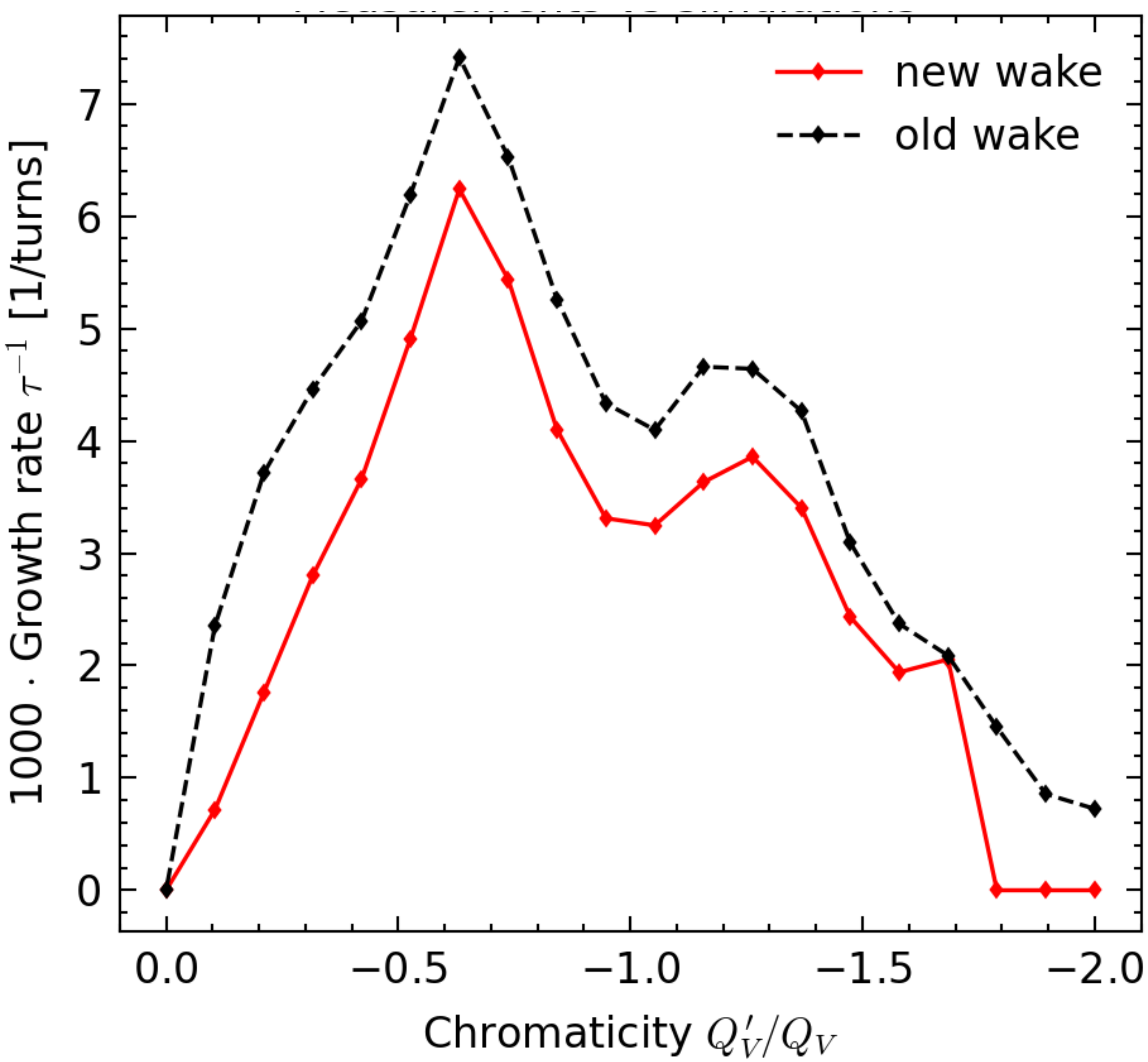


Main takeaways:

- The Growth Rate observable converges at roughly 300 slices.
- One must keep the ratio macroparticles/slices above 3000 (1e6 mp).

Wake file analysis

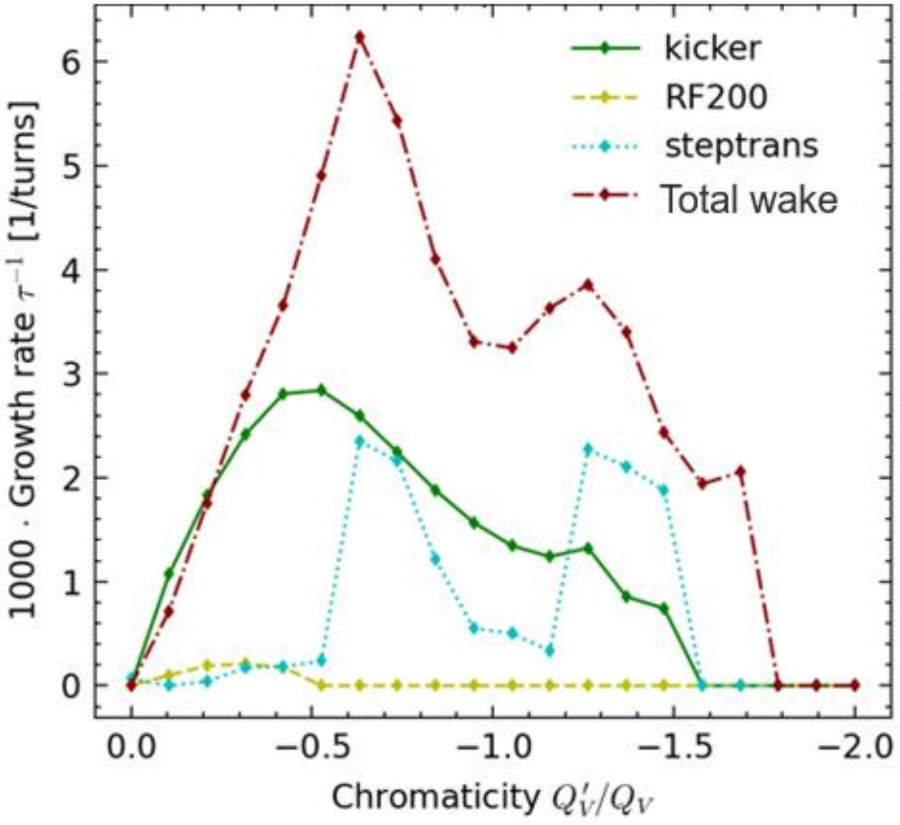
- In this kind of simulations, we import a wake table containing the SPS impedance model.
- We observed a significant difference between the old wake model and newly computed one (SPS_IW_merged_SingleMulti_bunch_model)
- Gitlab to generate wakes

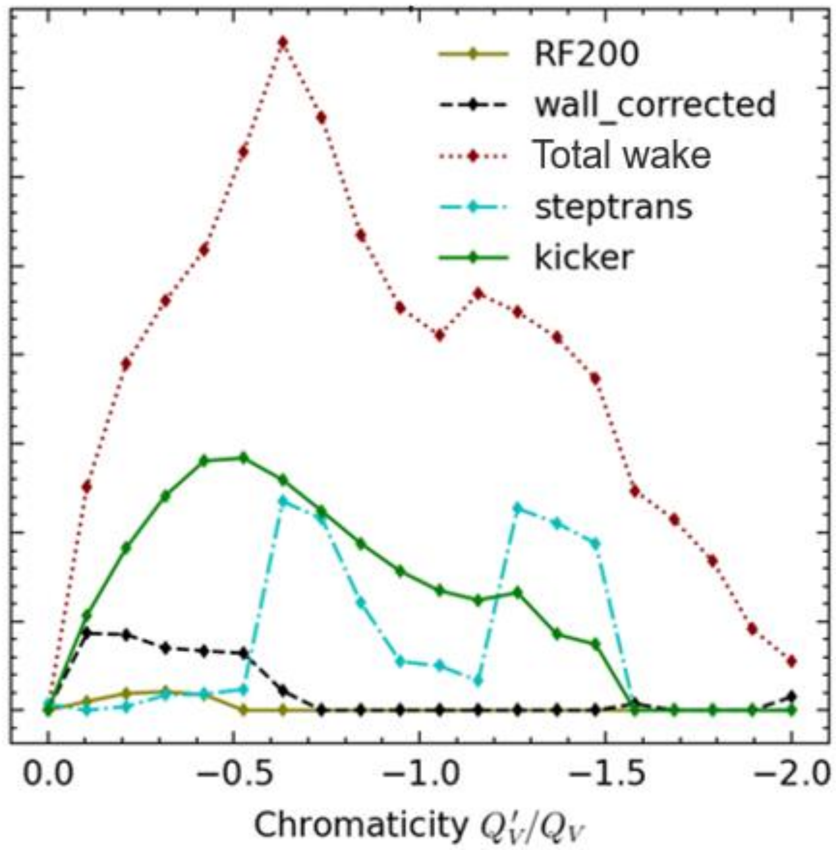


Decomposition of each contribution

Differences in new wake:

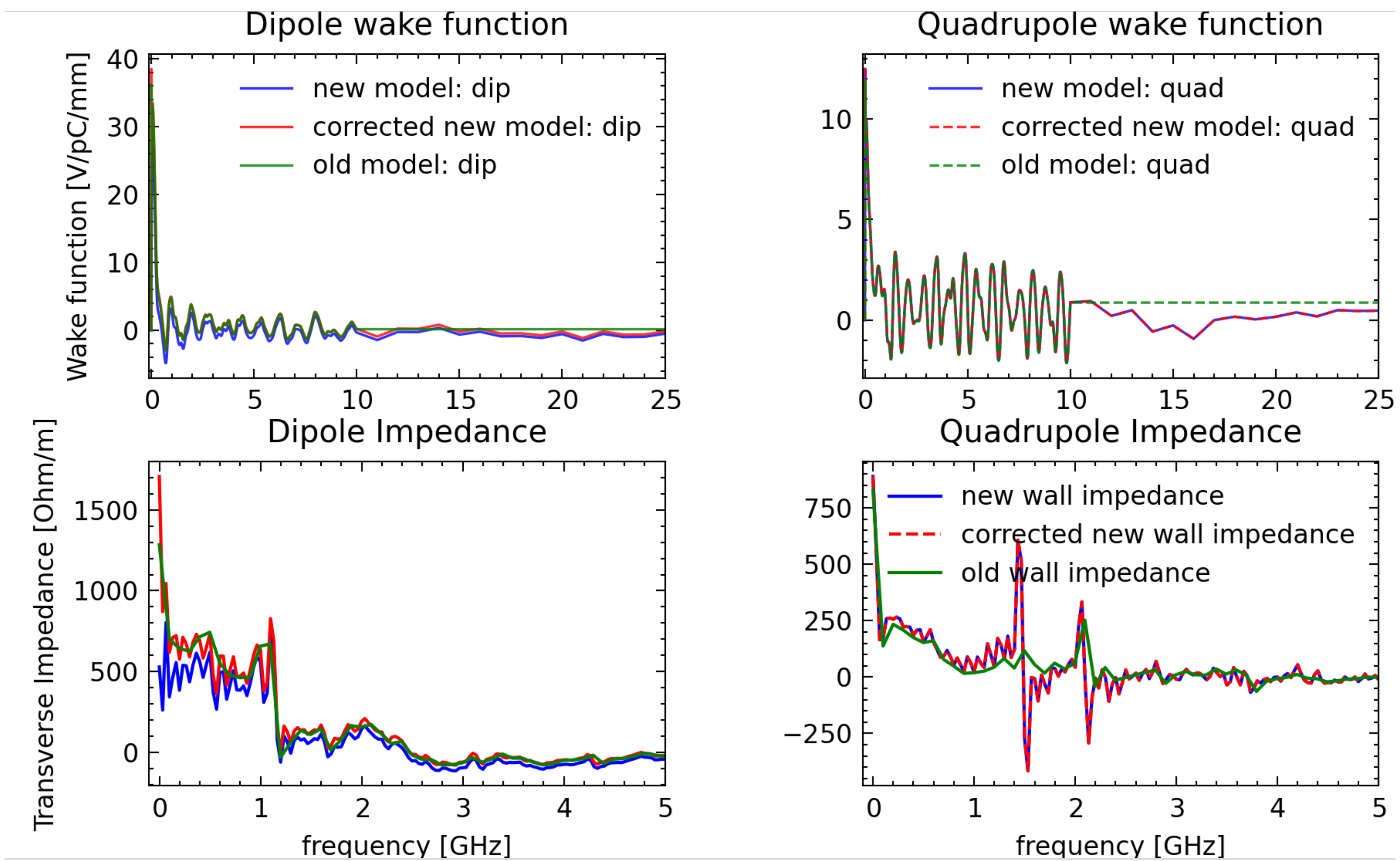
- We noticed a significant difference in the simulated growth rate values of the two model versions
- After simulating every element of the wake separately, we found the resistive wall did not to contribute to the model.



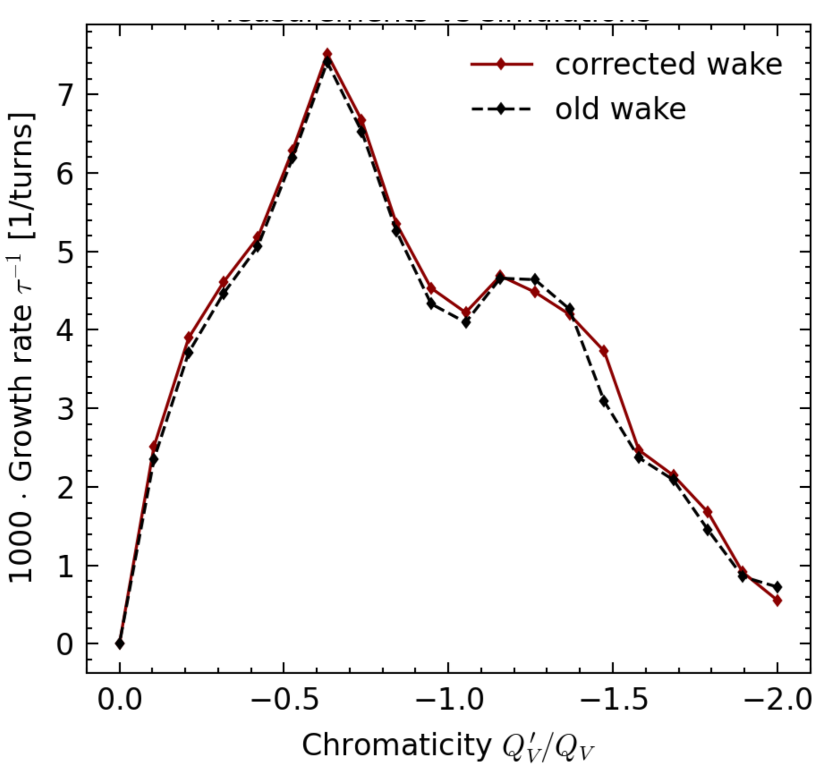


Validation of wake file

Vertical Wake Plots



Comparison of resulting growth rates



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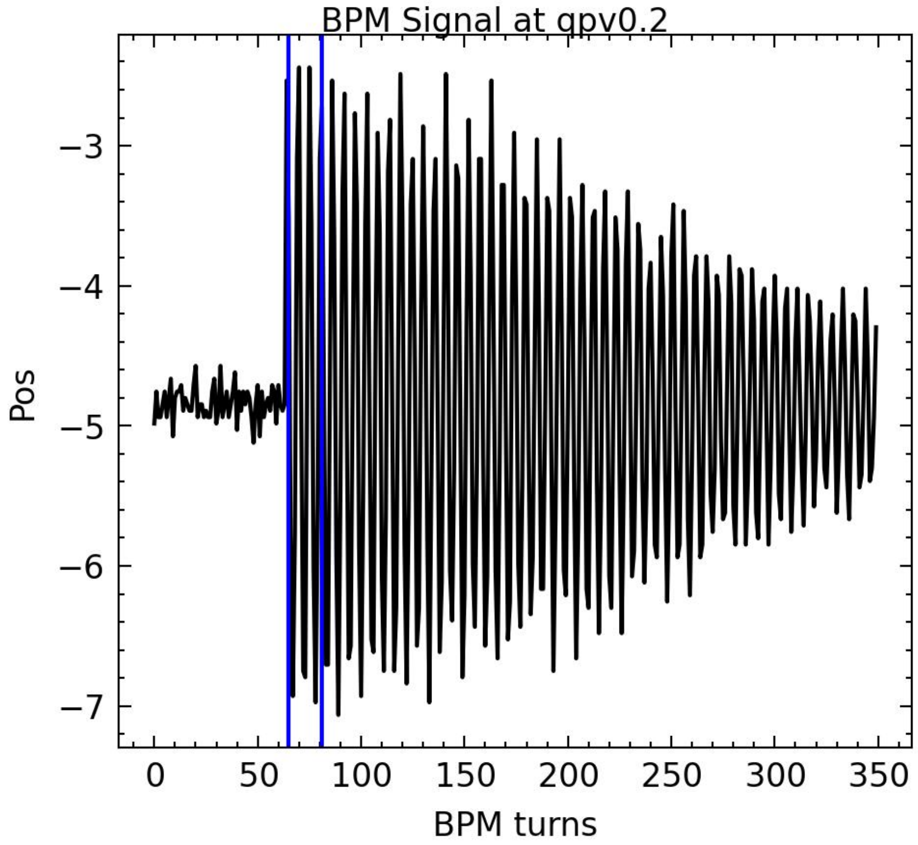
Tune shift benchmarking

- Measuring Tune shift allows us to benchmark the imaginary part of the impedance.
- One must measure the tune at different intensities, the resulting slope is the tune shift.
- Tune is measured though the frequency content of the vertical position oscillations after the kick.

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



Tune shift benchmarking

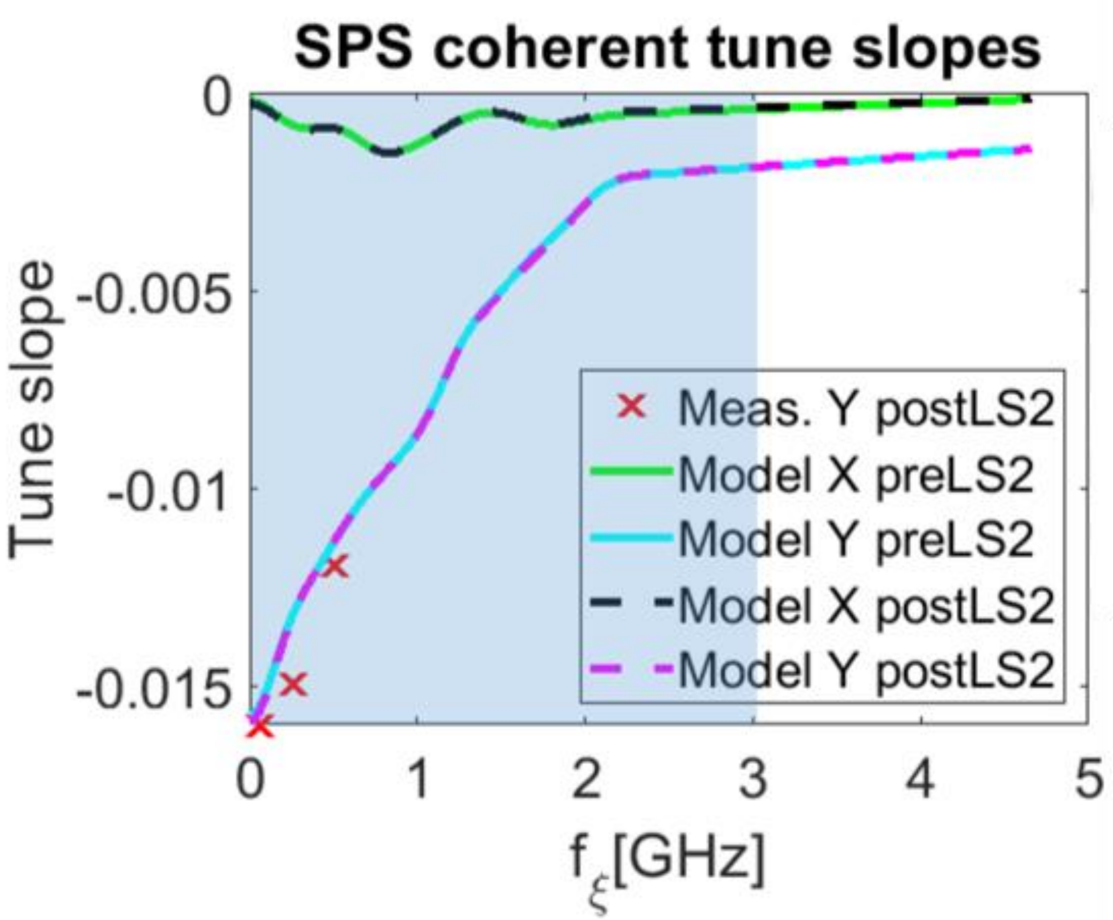
Work done on previous years

- Measurements done at low chromaticity
- Q20 optics
- Up to 0,5 GHz aprox

New measurements

- Q26 optics
- More points
- Use of LHCBPM
- Up to 1,6 GHz

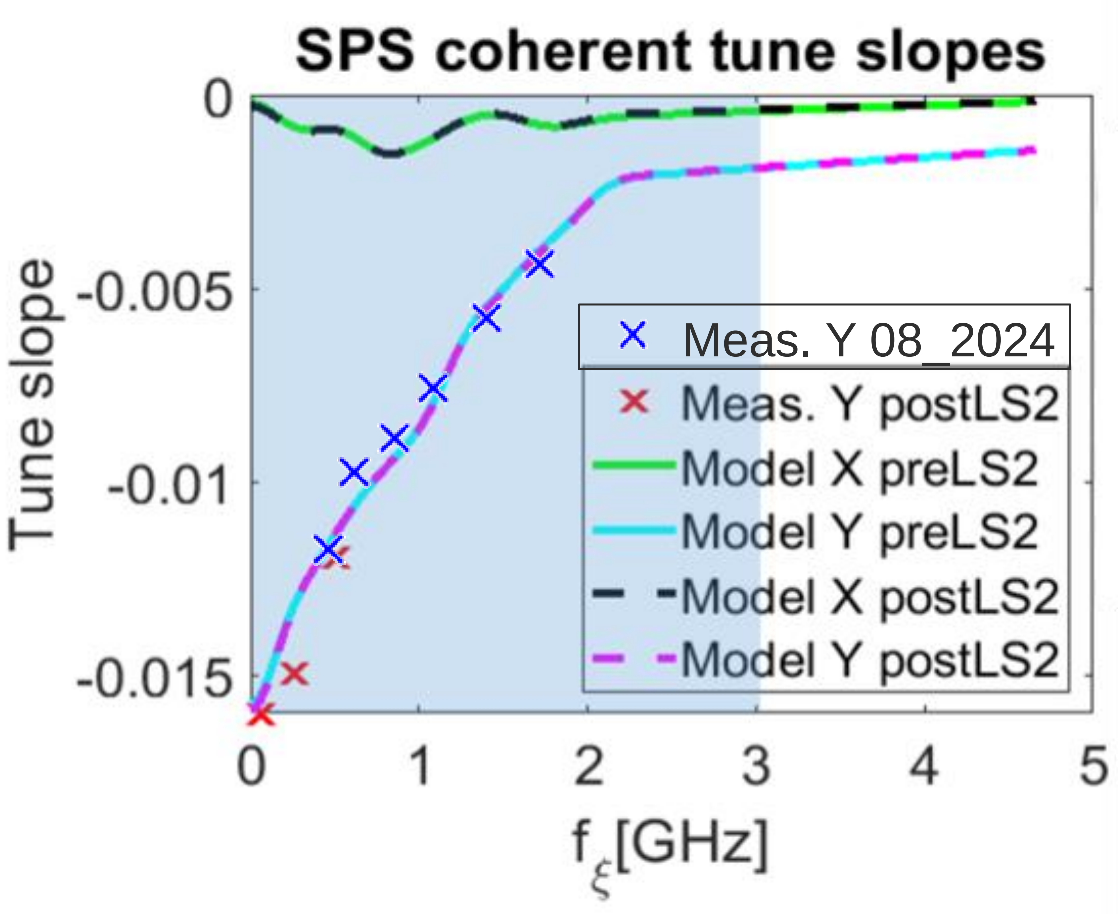
2022 measurements (link)



Measurement results

Results of the tune shift measurements

- Hard measurements, took two days
- Points taken chromaticity-wise (possible variations in the Supercycle)
- It is important to make the kick after the injection oscillations are already over. These measurement were made with a delay of 1500ms and a kick of 2,5kV
- Special thanks to Ingrid for her help
- Logbook links: first day, second day



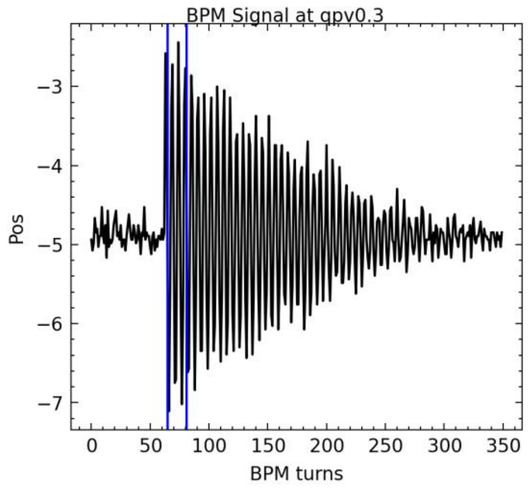
Issues with simulation

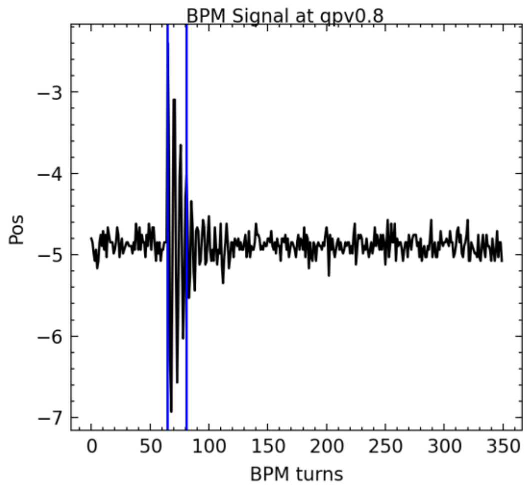
- The attempt to simulate the tune shift with PyHT was unsuccessful.
- The kicks get damped a lot earlier, meaning we are not able to extract the tune for higher chromas

qpv = 0,3

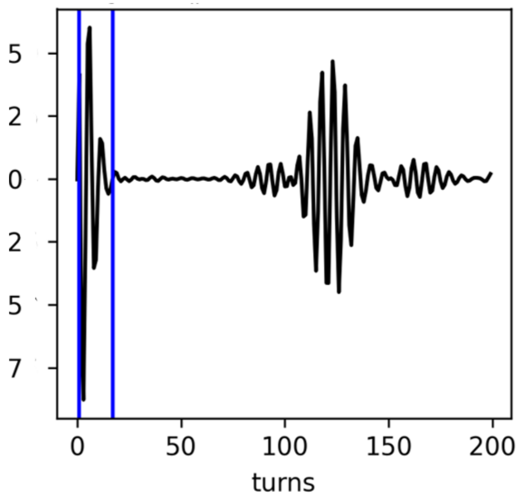
qpv = 0,8

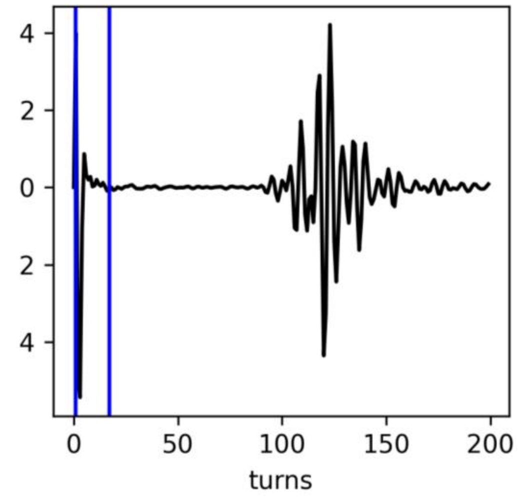
Measurement





Simulation

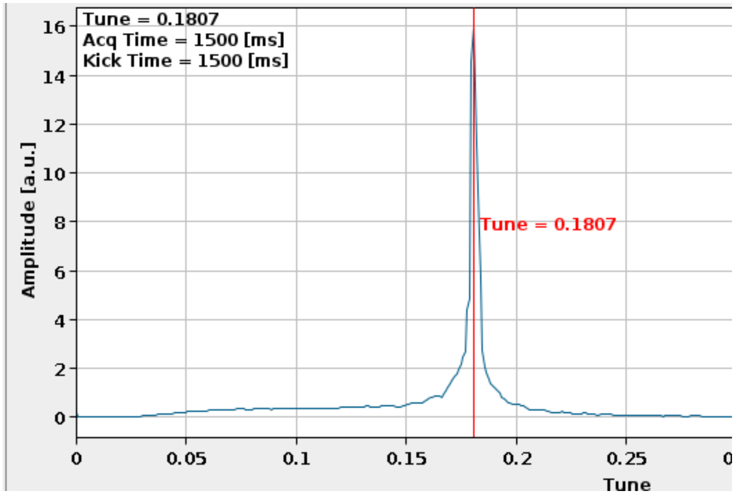




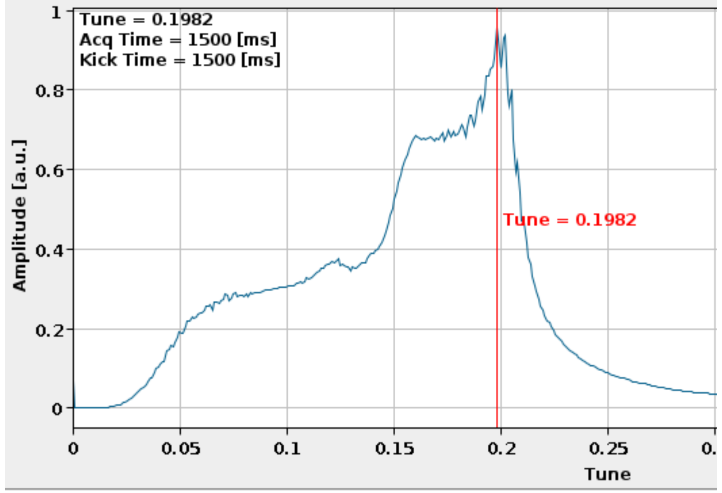
Lessons learned

- The tune becomes very hard to measure at higher chromaticities
- Higher intensities allow us to dampen these effects, but issues appear beyond the 8e10 ppb mark; bunch length blowup, TMCI, etc…
- We were able to measure until qpv = 1,0 (1,6 GHz) , and from 3e10 to 8e10 ppb

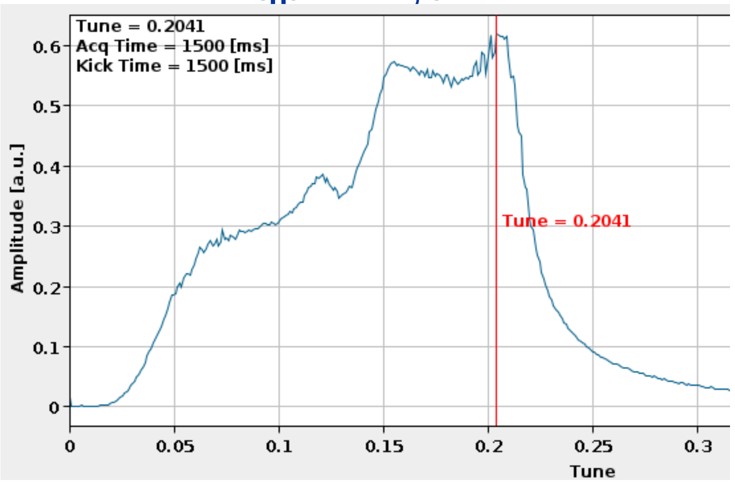
qpv = 0,45



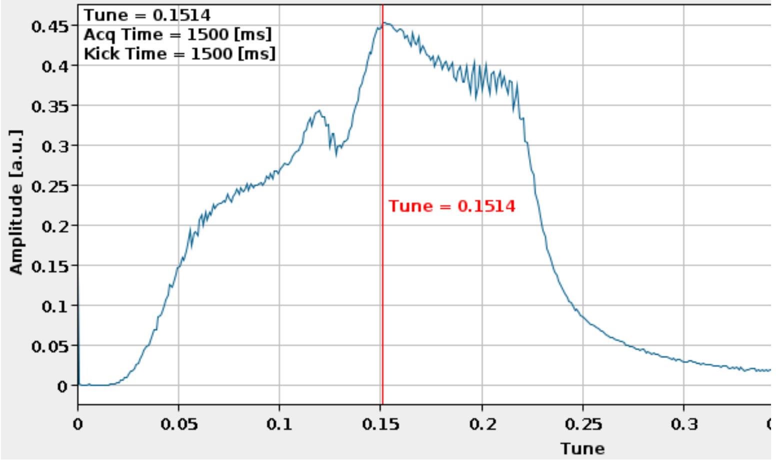
qpv = 0,8



qpv = 1,0



qpv = 1,15



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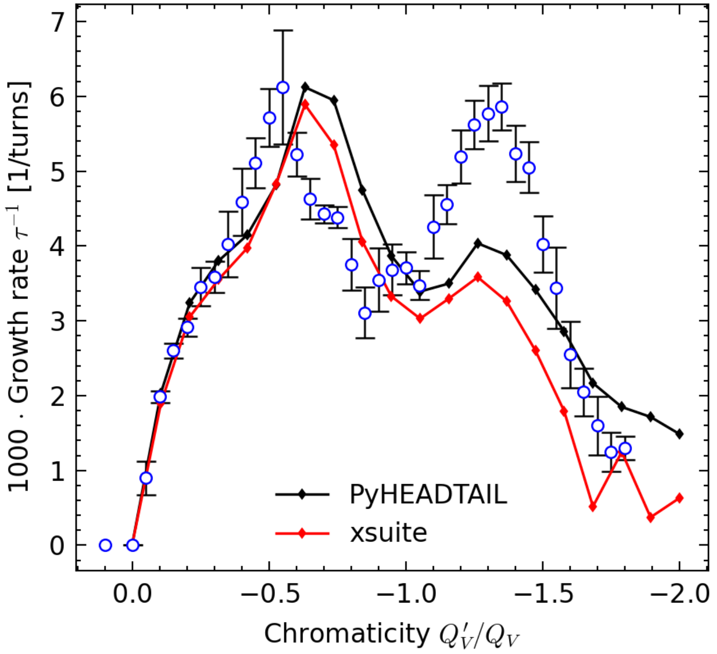
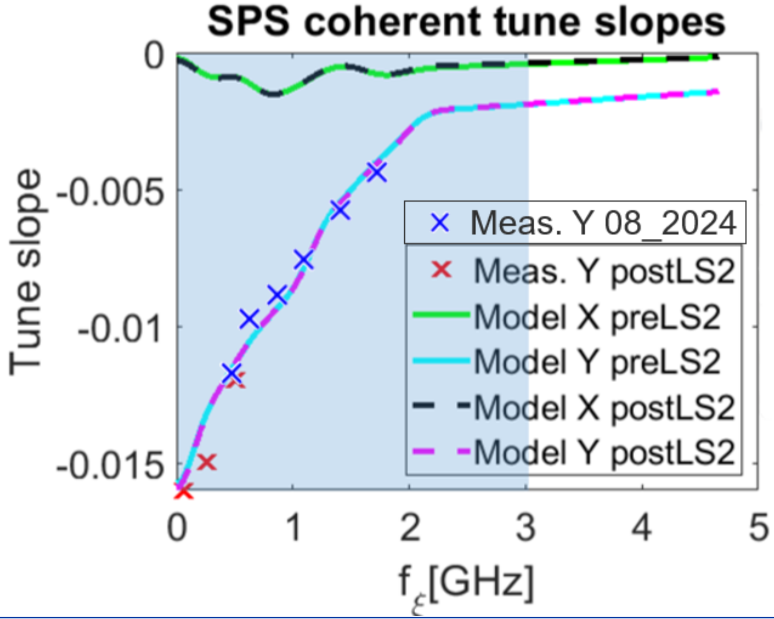
Conclusions

- Carried out a careful analysis of the methodology
- Benchmark of the real part of the impedance shows a missing impedance in the model consistent with a resonator cavity.
- Simulation work to compare against the measurements. Done at different energies, tunes and with different programs.
- Tune shift benchmark did not show difference with the model. Explored the limits of the current measurement method.





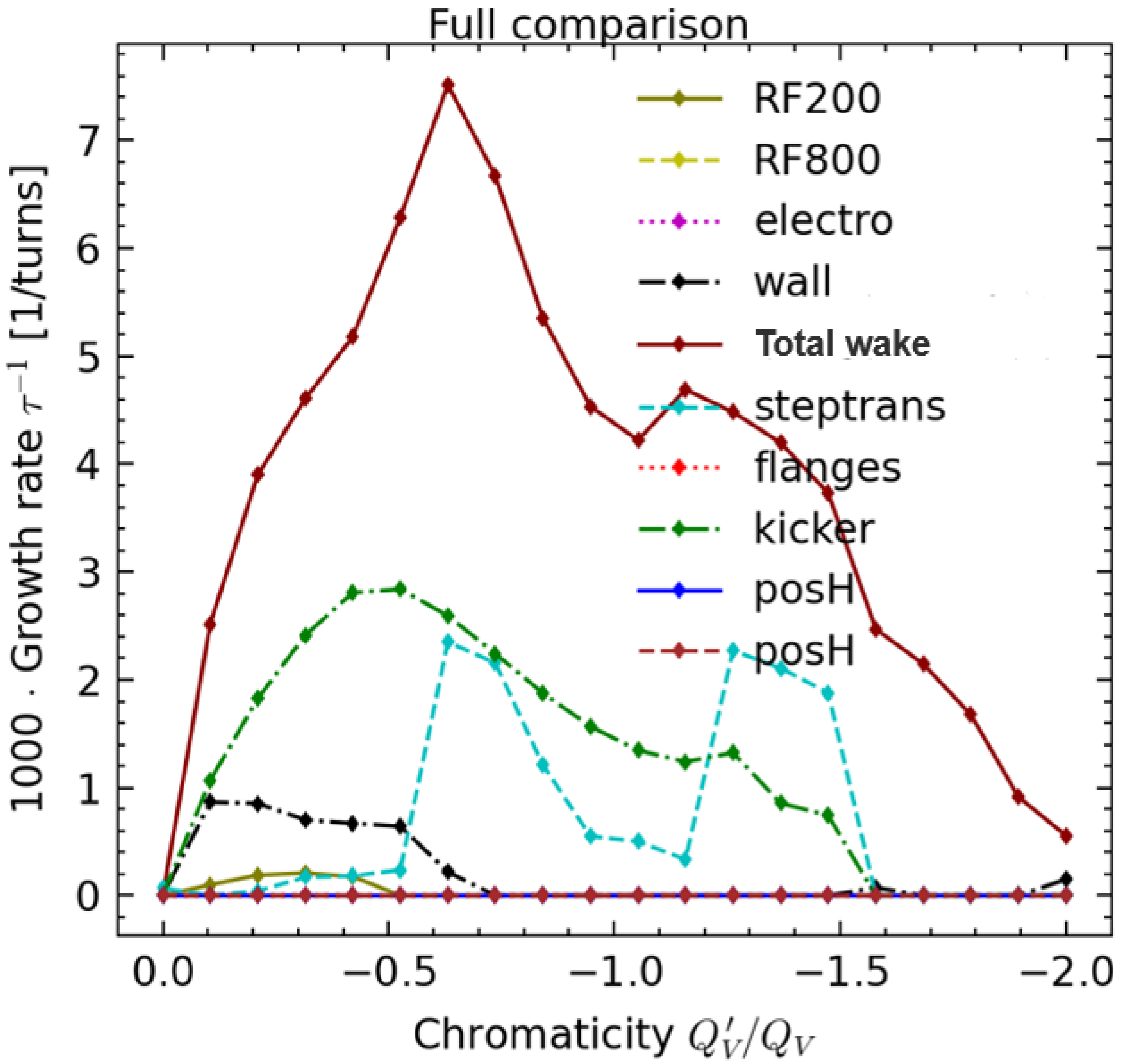
Future work

Growth rate:

- Explore the possibility that the “dark” impedance is caused by a missing element in the model.
- Hints: missing impedance resonator near SPS pipe cutoff frequency, asymmetric in V/H

Tune Shift:

- Use of other tune measuring techniques to benchmark the imaginary impedance at higher frequencies.
- Develop working simulation for tune shift

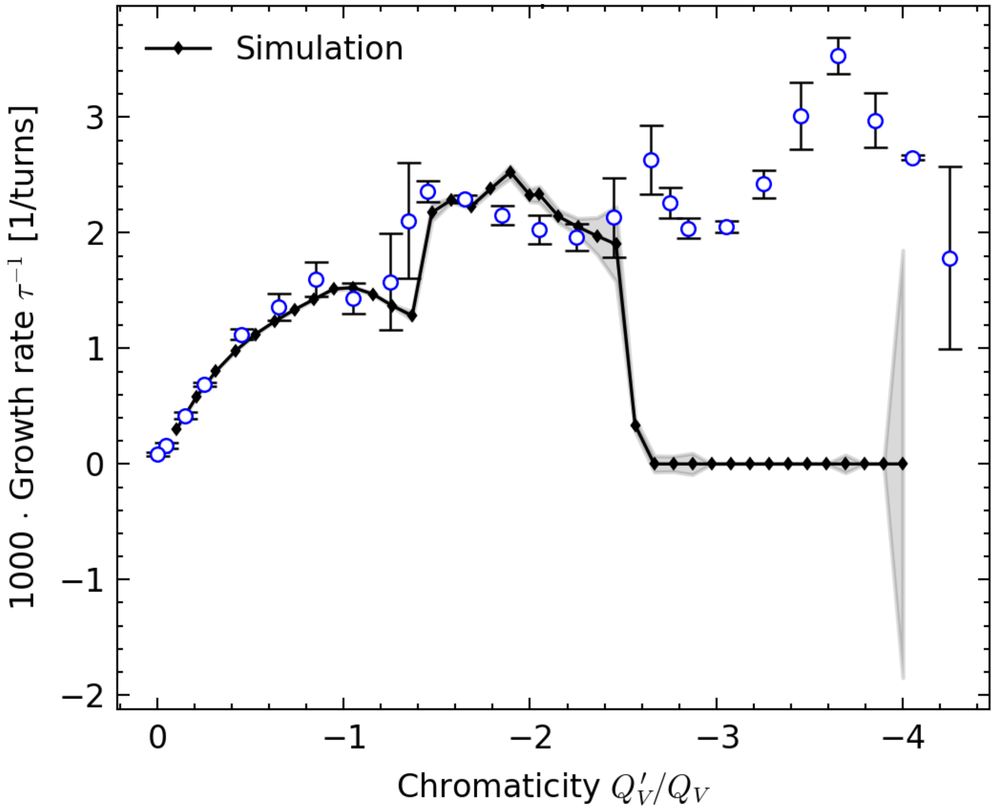


Thank you

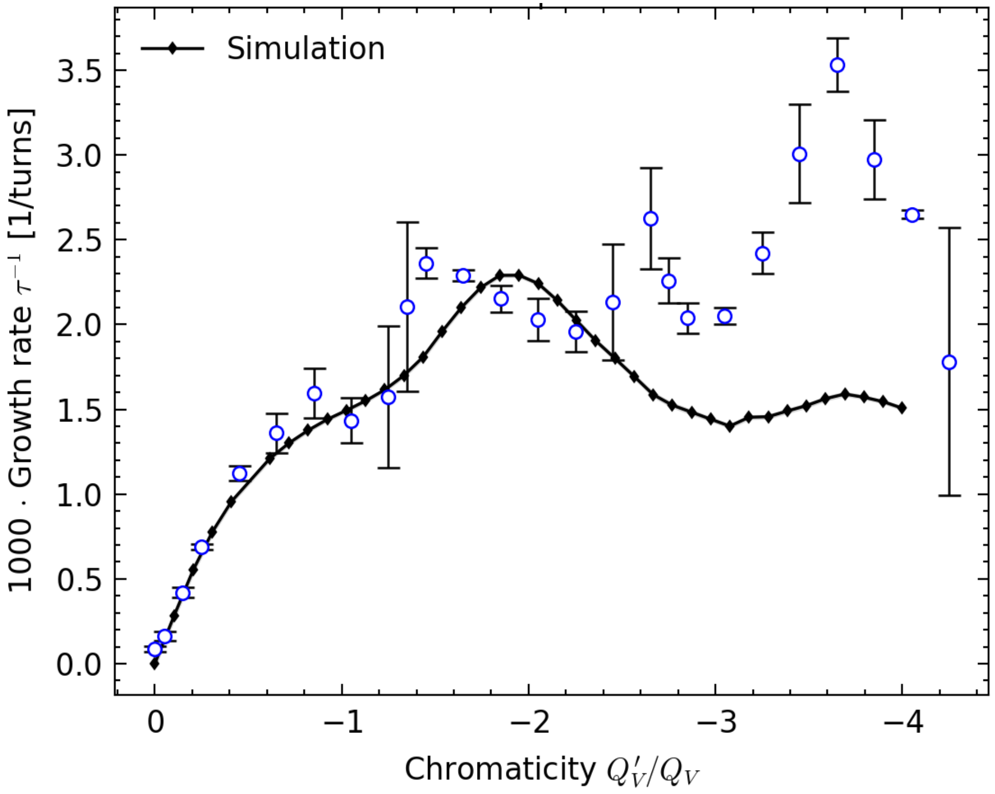
Backup Slides

Quirks of high energy simulations

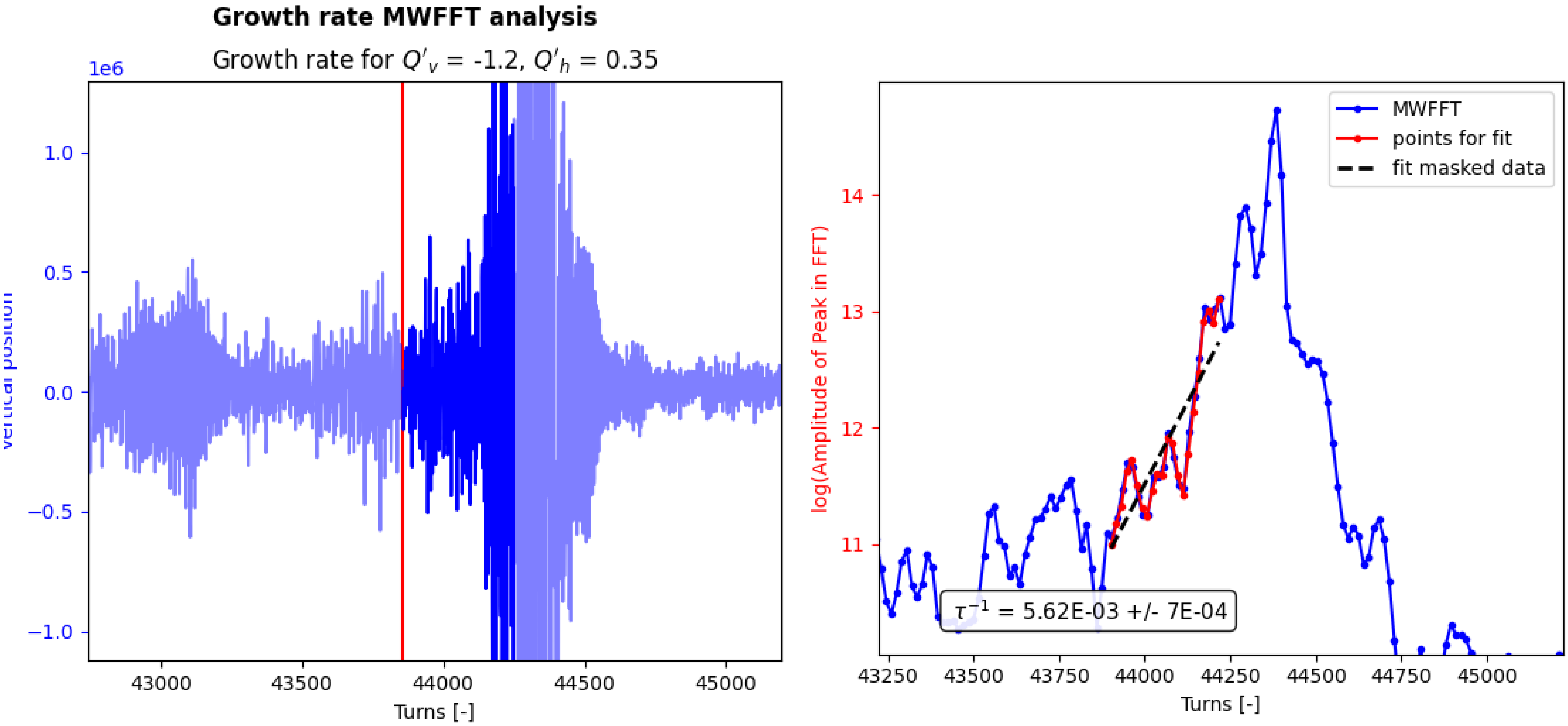
6000 turns simulations



20.000 turns simulations

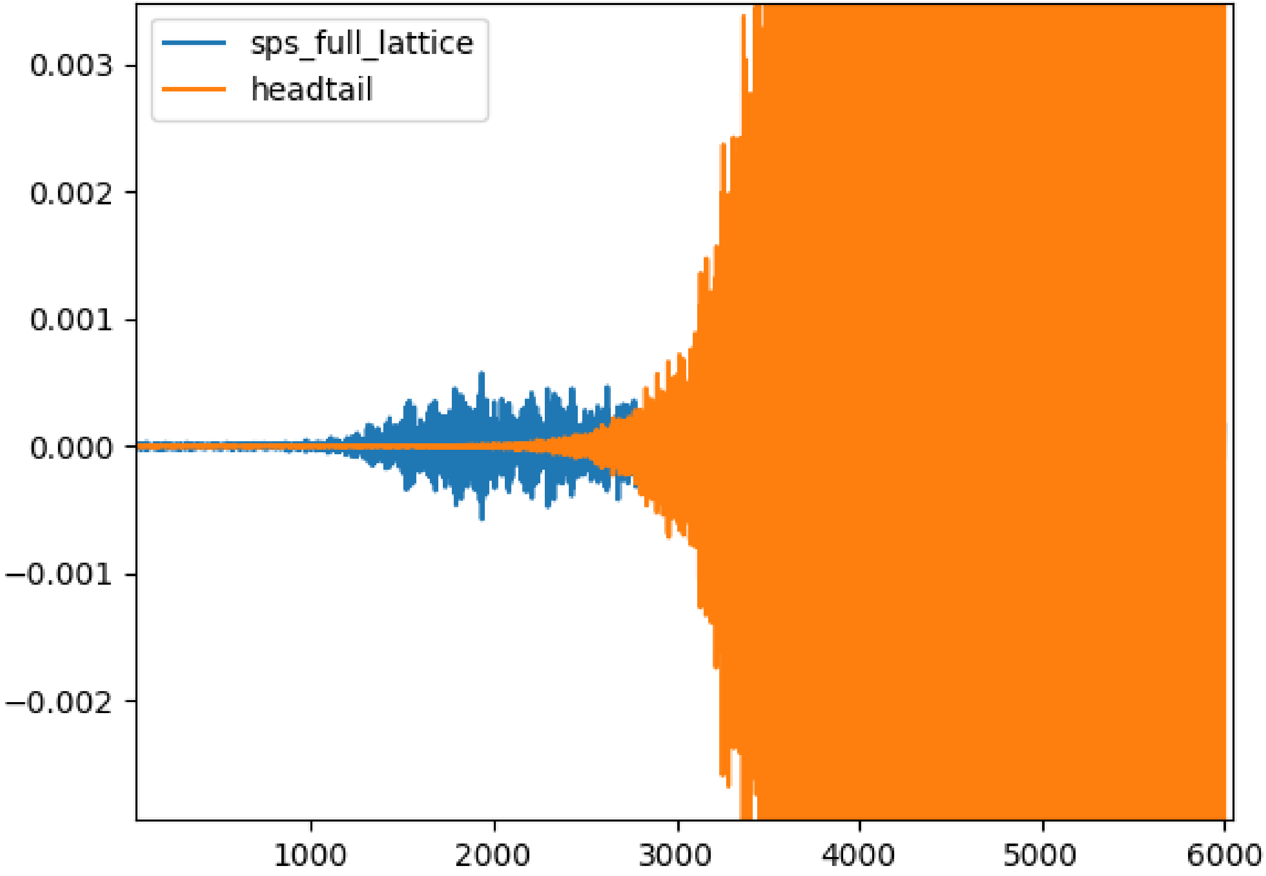


Difficulties in processing signals at high qpv



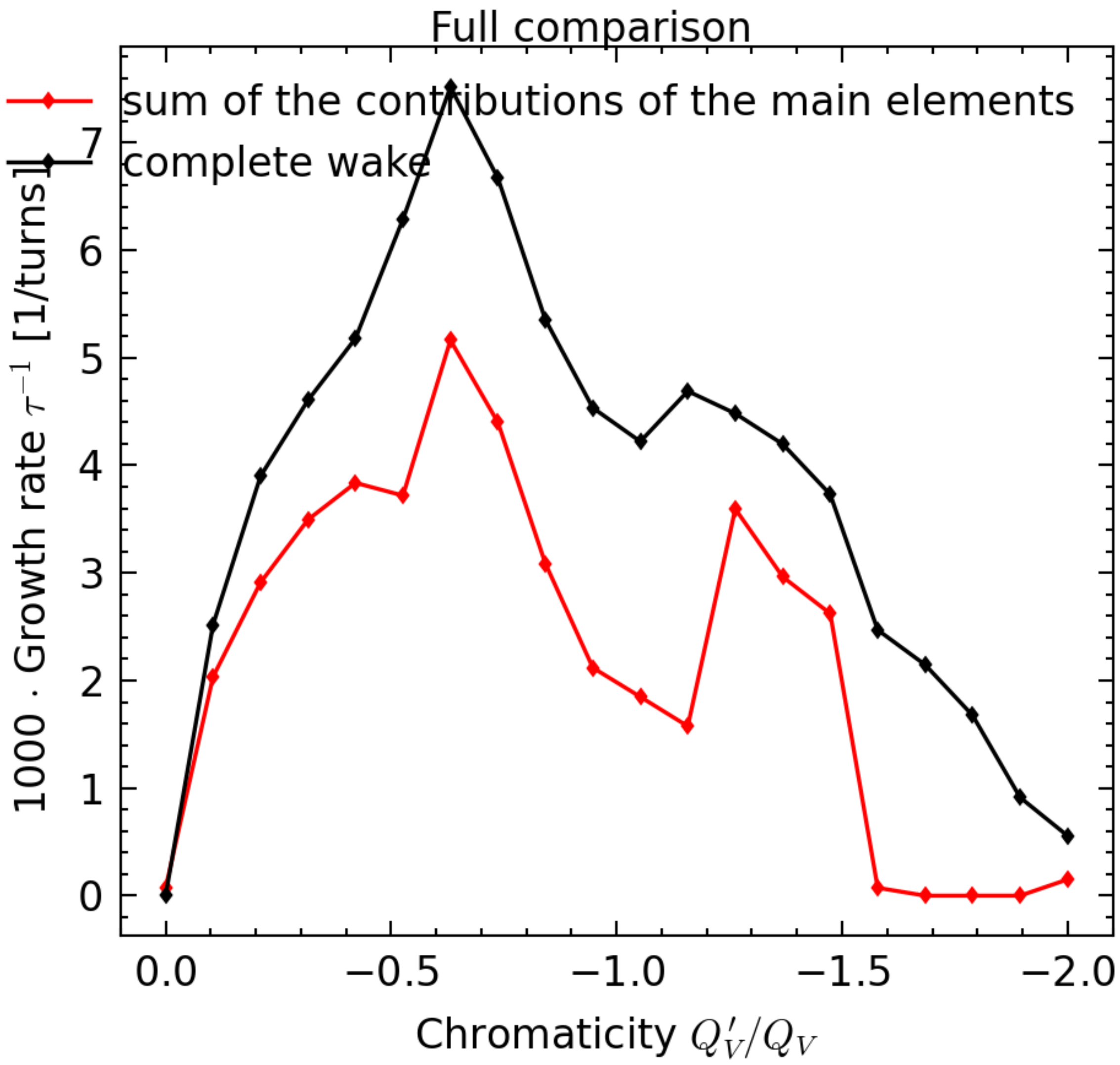
Improvements to be had in xsuite

The sequence includes aperture, and thus makes comparison difficult



Importance of elements in wake

The sum of individual contributions to the wake is les than their combined effect



Numerical variancè

If we do not respect the recommended mp/slice ratio we observe very high variance for the same simulation for high chromaticities.