Main Results from Instabilities MDs and Simulation Studies

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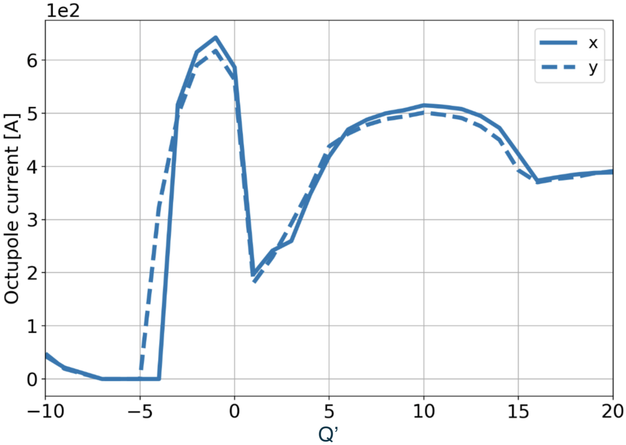
Many thanks to WP4, and WP5.

Outline

BTF for Chromaticity Measurement

The available chromaticity measurement method (the energy modulation) cannot be used with nominal beams at flat-top due to losses, while it would be important to control precisely Q' to stick to potential sweet spots.



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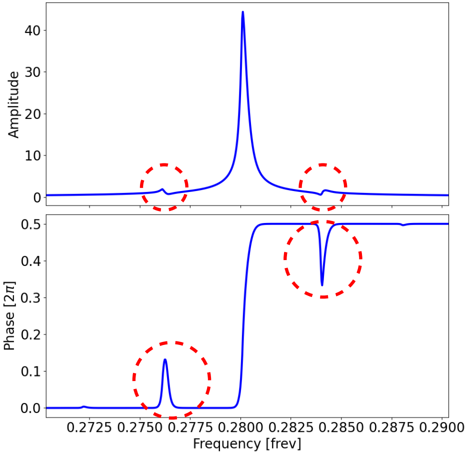

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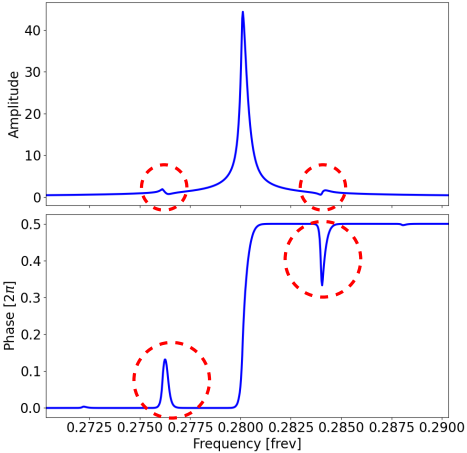

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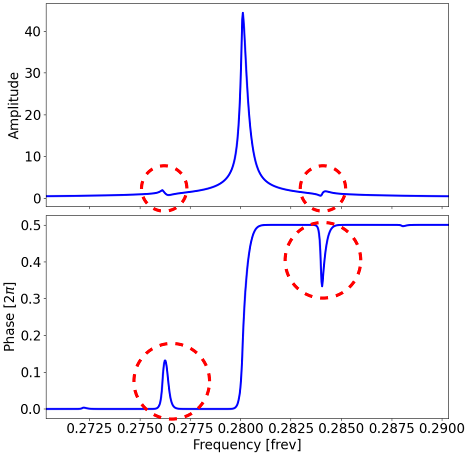
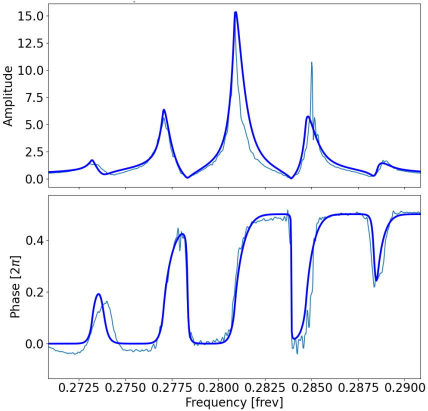
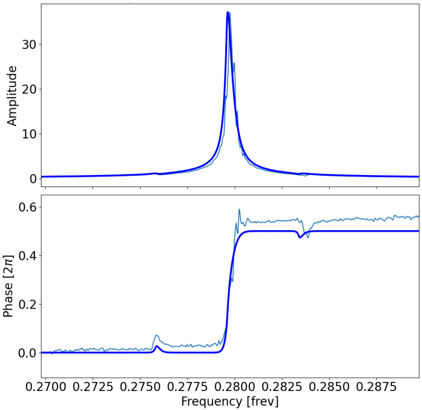
- IDEA: excite one bunch with noise and then reconstruct the BTF by measuring the beam response
- In postprocessing, we fit the theoretical BTF to the measured one and we obtain the measured Q’



From the Data to the the BTF

To extract the chromaticity we have to fit a BTF to the data, which is not always straightforward:





- Chromaticity trim value: 16
- Chromaticity from BTF fit: 15:54

- Chromaticity trim value: 4
- Chromaticity from BTF fit: 1.69

Next steps

Data analysis: we need to improve our fitting algorithms to extract more robustly the theoretical BTF from the data. High dimensional multi-parametric fit → difficult task (neural networks might do the trick).

Repeat the experiment at flat top.

Slow vs fast octupole scans in nominal conditions

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Procedure:

- Fill 1:
  - Inject and ramp 3 nominal bunches per beam.
  - Every 15 minutes reduce the octupoles current by 20 A until an instability is observed on all bunches

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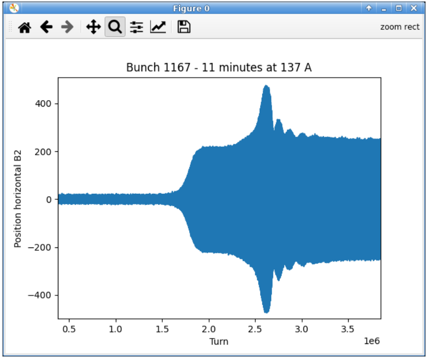
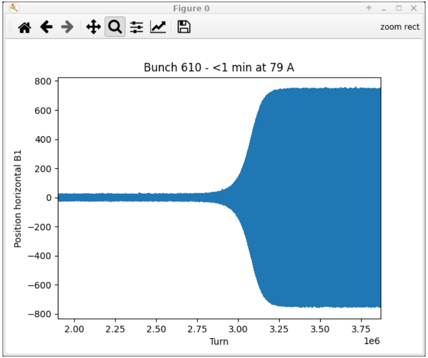
- Fill 2: Same as Fill 1 but reduce octupoles current every minute

Slow vs Fast Scan - Results

Slow scan threshold: 137-177A



Fast scan threshold: 79A



Slow vs Fast Octupole Scans MD

Strong effect of the latency on the instability thresholds, in agreement with the noise model (see paper by S. Furuseth and X. Buffat).

The instability thresholds we observed are significantly lower than expected from past measurement (see X. Buffat, et al, Transverse Instabilities, in Proceedings of Evian'19). Several factors could be decreasing the octupole thresholds, such as additional detuning coming from the optics, heavy transverse tails, impact of the longitudinal distribution... This should be investigated in order to gain better understanding of the thresholds.

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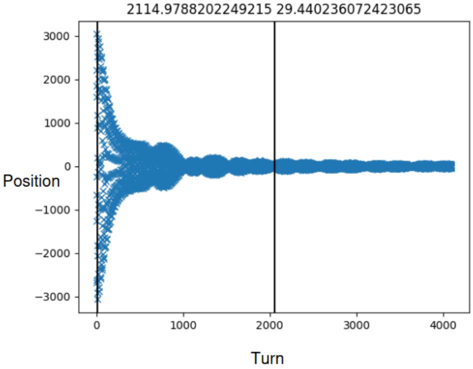
- We perform beam-based measurements of the newly installed TCSPMs and of some old collimators for reference
- To quantify the impedance of a collimator we measure the tune shift it induces on the beam (impedance and tune shift are proportional)

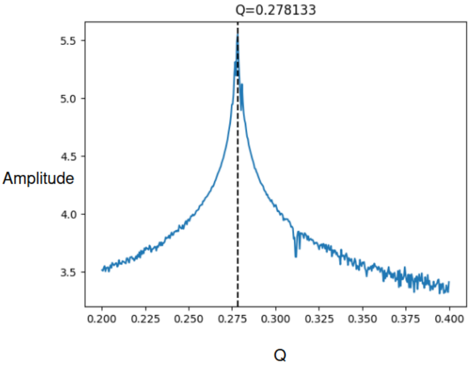
All the measurements have been performed in close collaboration with the collimation team and WP5.

Measuring the Tune

Procedure to measure the tune:

- Inject and ramp a single nominal bunch
- Kick the bunch and measure turn-by-turn position
- Fourier-transform the position to obtain the tune



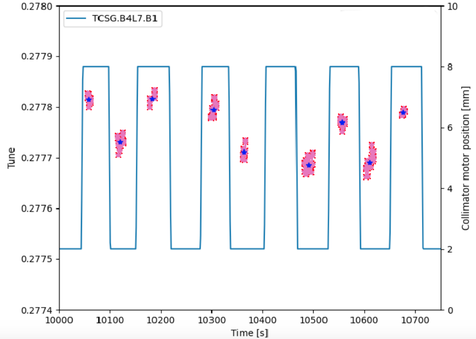


Tune Shift of a Single Collimator

How to measure the tune shift of a single collimator?

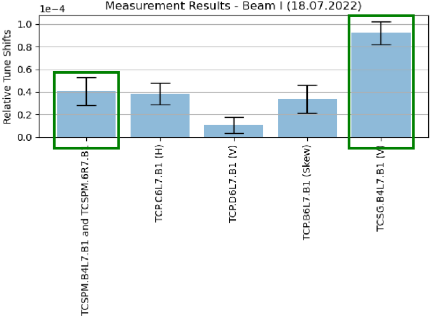
- Measure the tune with all the collimators in nominal postion
- Retract one collimator
- Measure the tune again
- Obtain the tune shift by subtraction

To obtain good statistical significance and to remove the slow tune jitter we repeat several times the procedure and each time we perform 10 tune measurements.

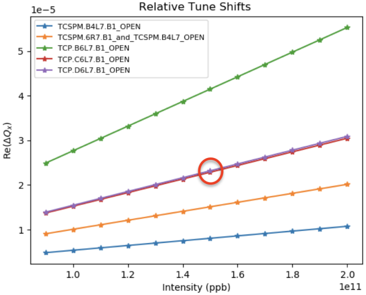


Measurements Results and Simulations (Beam 1)

Measurements:



Expected from Sacherer theory (only dipolar impedance)



- At first we did not manage to measure a tune shift from the TCSPMs at all
- We decided to measure the two TCSPMS together and to decrease their halfgaps to increase their effect
- We can conclude that the tune shift in nominal position is around 10^{-5}, which is within the measurement error bar
- The impedance of the TCSPMs is indeed very low
- All the simulations results are lower by a factor ~ 2 than measurements, at least partly due to the absence quadrupolar impedance in the simulations

Summary of MD Studies

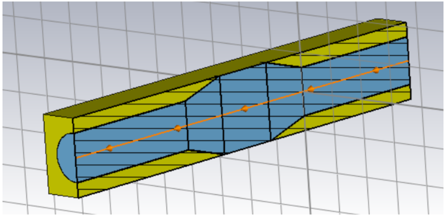
- A new method to measure the beam chromaticity was successfully tested
- The influence of noise on beam stability was observed
- The impedance of the new TCSPMs was confirmed to be much lower than that of the old TCSGs

Outline

- MD studies
  - MD 6803 BTF for Chromaticity Measurement
  - MD 6807 Slow vs fast octupole scans in nominal conditions
  - Collimators Impedance Beam Based Measurements
- Simulation Studies
  - New vacuum valves between TCLMB mask and Q4
  - Crab Cavities fundamental mode

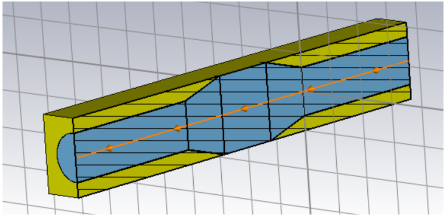
New vacuum valves between TCLMB mask and Q4

- Resonator-like structure



New vacuum valves between TCLMB mask and Q4

- Resonator-like structure
- Initially they were supposed to have 63mm diameter, but we were asked to evaluate the impact of increasing their diameter 100mm or 80mm



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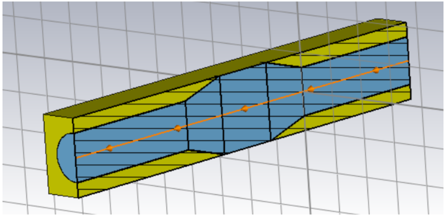

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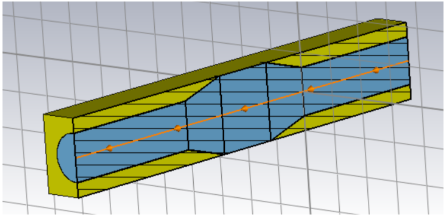

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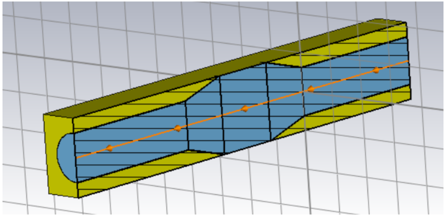

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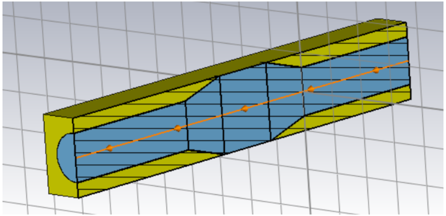

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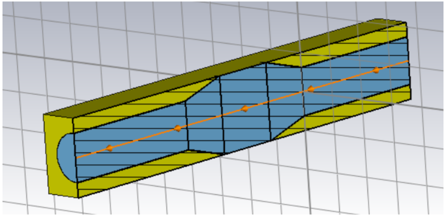

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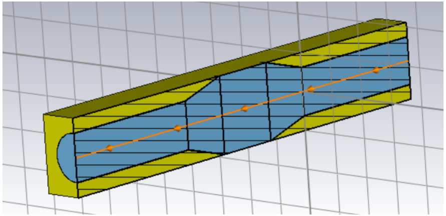
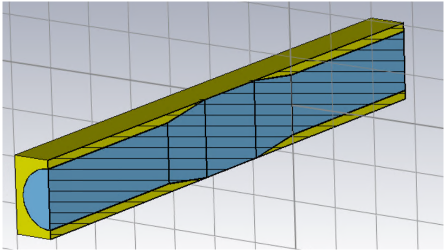
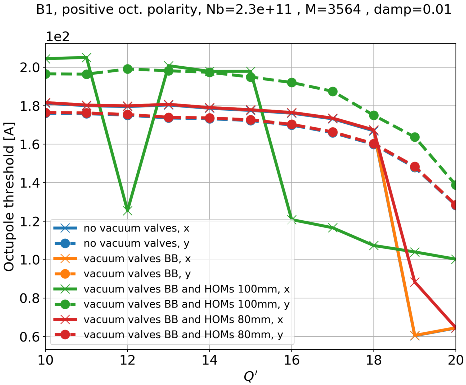
- The broad-band component is the same for the two designs, while the HOMs are very different





Effect on beam stability



- Very low impact of the broad-band impedance and of the 80mm design HOMs
- 20A added octupoles current for the HOMs of the 100mm design (rather high)
- Therefore we recommended the 80mm design

The Crab Cavities Impedance

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- The parameters of the cavities (shunt impedance, Q-factor) have been updated since then
- Some studies were performed on simplified models (see talk by P. Baudrenghien at WP2 meeting on 21/03/2014)
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Recent estimates for the EIC Crab Cavities by Michael Blaskiewicz (talk at WP2 meeting on 09/08/2022) showed that the impedance of the fundamental mode can drive strong instabilities.

Fundamental Mode Impedance

The fundamental mode of an RF cavity contributes to the impedance of the device like every other resonant mode but:

- Usually has a very high shunt impedance and Q-factor (dangerous especially for multi-bunch operations)
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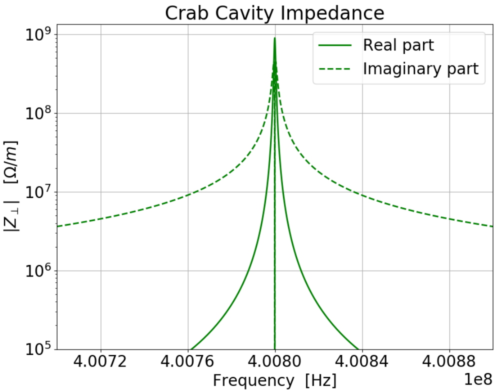
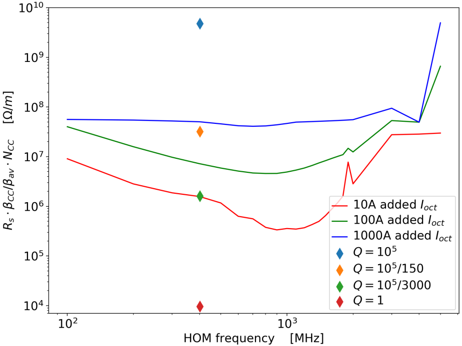
- $Z_\perp(\omega) = \frac{\omega_{RF}}{\omega} \frac{R_\perp}{1 - jQ(\frac{\omega_{RF}}{\omega} - \frac{\omega}{\omega_{RF}})}$
- $\omega_{RF} = 2\pi F_{RF}$, $F_{RF} = 400.8 MHz$
- Q $= 5 \cdot 10^5$ (loaded Q)
- $R_\perp = 9.03 \cdot 10^8 \frac{\Omega}{m}$
- Very high, but narrow-band impedance



Fundamental Mode Impedance - Reducing the Shunt Impedance $R_\perp$

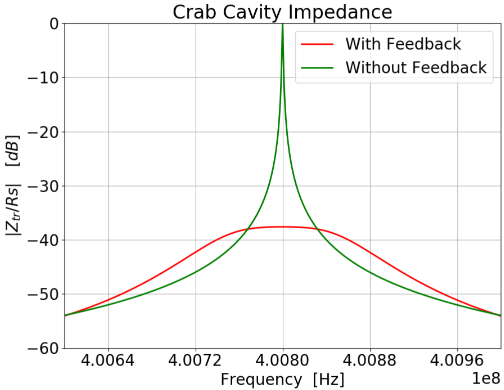
By how much do we need to damp the Q of the fundamental mode to ensure beam stability?



It is clear that if the fundamental mode is not damped enough it will produce in stability issues.

Using the RF Feedback to Mitigate the Crab Cavity Impedance

The RF feedback system can act on the fundamental mode of the cavity, so it can be used to reduce the impedance peak.

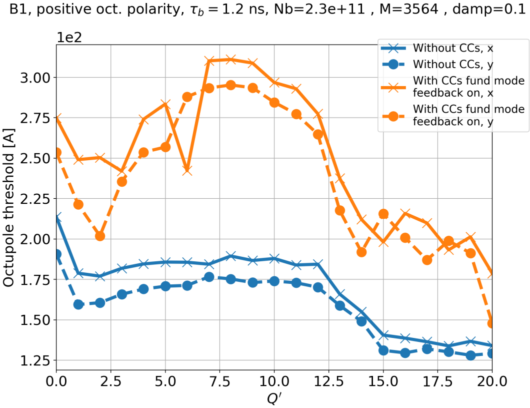


Closed Loop cavity impedance

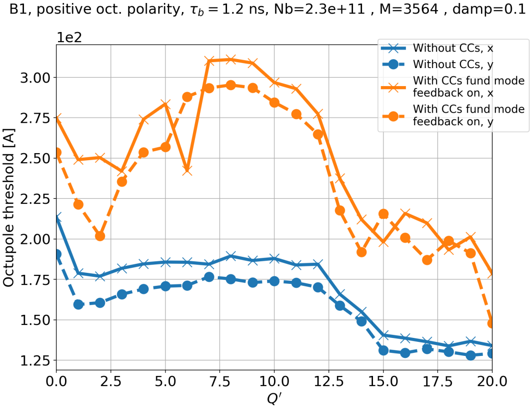
- $Z_{\perp}^{CL}(\omega) = \dfrac{Z_{\perp}(\omega)}{1 + Ge^{-j\tau(\omega-\omega_{RF})}Z_{\parallel}(\omega)}$
- $Z_{\parallel}(\omega) = \dfrac{1}{1 - jQ(\frac{\omega_{RF}}{\omega} - \frac{\omega}{\omega_{RF}})}$
- $G = 150$
- $\tau = 1175ns$

Thanks P. Baudrenghien!

Octupole Thresholds at Flat-Top

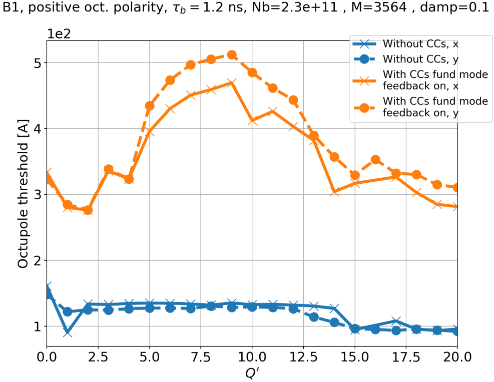


Octupole Thresholds at Flat-Top



Require added octupole current of 100A, our usual recommendation for HOMs is that the added current must be less than 10A.

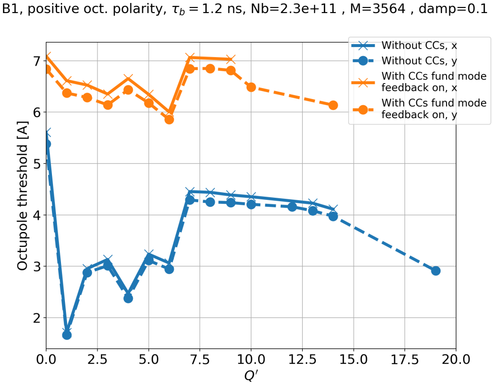
Octupole Thresholds During Collisions - End of Levelling $\beta^* = 20cm$



Intensity is 2.3e11 because we are not considering burn-off, which is a conservative assumption.

Because of the higher β's at the cavities the thresholds are even higher, but during collisions strong head-on tune spread is enough to stabilize the beams (confirmed with stability diagrams, see talk at the 162nd TCC meeting).

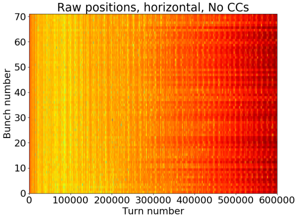
Octupole Thresholds at Injection

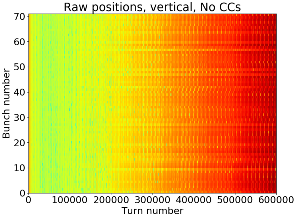


In absolute numbers the situation looks less critical at injection.

Macroparticles Tracking Simulations

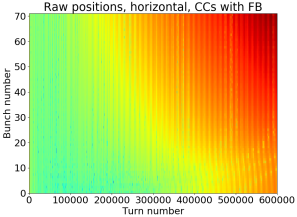
To confirm the results obtained with the Vlasov solver DELPHI, we computed the wakes corresponding to the impedance of the HL-LHC at flattop and we used it to track a train of 72 bunches using PyHEADTAIL.

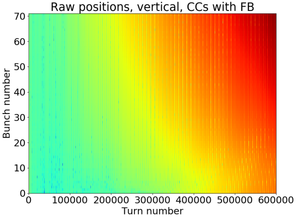

Raw positions, horizontal, No CCs


Raw positions, vertical, No CCs

$$\sigma_x = 0.17\ 1/s$$

$$\sigma_y = 0.24\ 1/s$$


Raw positions, horizontal, CCs with FB


Raw positions, vertical, CCs with FB

$$\sigma_x = 0.27\ 1/s$$

$$\sigma_y = 0.35\ 1/s$$

- Simple extraction of the rise time: exponential fit to the average turn-by-turn position
- Clear impact of the cavities on growth rates and on coupled bunch motion

Summary and Ongoing Work on the Crab Cavities

Summary:

- The impedance of the fundamental mode of the Crab Cavity increases the octupoles stability threshold by a large amount.
- This is confirmed by simulations with both the Valsov solver DELPHI and the macroparticle code PyHEADTAIL.
- This is a critical issue.

Ongoing and future work:

- Studying the cavity already installed in the SPS both with simulations and MDs.
- Studying improvements to the RF feedback using a betatron comb filter as proposed by P. Baudrenghien.
- Checking the benefits of flat optics, which can help to reduce the beta functions at the cavities location, and hence their impedance.