SPS Crab Cavities instability MDs

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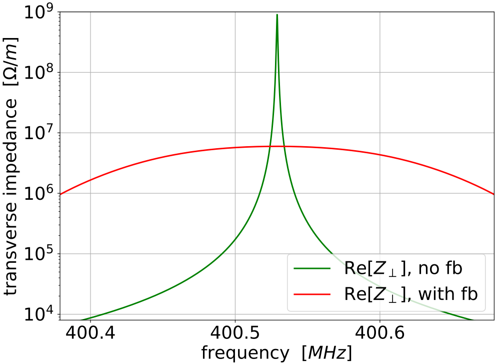
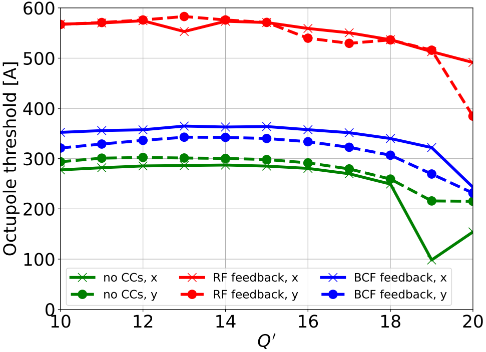
Many thanks to the SPS operators and coordinators and to the WP2 and WP4 teams.

Transverse impedance of the crab cavities



- $Z_{\perp}(\omega) = \frac{\omega_{RF}}{\omega} \frac{R_{\perp}}{1 - jQ(\frac{\omega_{RF}}{\omega} - \frac{\omega}{\omega_{RF}})}$
- $\omega_{RF} = 2\pi F_{RF}$
- In the HL-LHC: $F_{RF} = 400.789$ MHz
- In the SPS: $F_{RF} = 400.52895$ MHz
- $Q = 5 \cdot 10^5$
- $R_{\perp} = 9.03 \cdot 10^8 \frac{\Omega}{\mathrm{m}}$
- Very high, but narrow-band impedance
- Can be mitigated using an RF feedback system

Motivation



- HL-LHC octupole thresholds with Crab Cavities with RF feedback are too high
- Mitigations under study (e.g. betatron comb filter feedback, flat optics)

It is important to study this also with measurements!

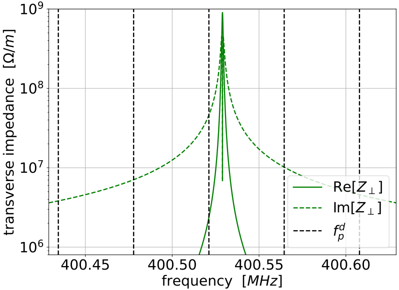
Betatron lines

According to Sacherer theory, for a completely filled machine the destabilizing effect of an impedance is computed by sampling the impedance at the discrete set of frequencies

$$f_p^d = (p + (1 - [Q_x]))f_{rev} \ \ p \in \mathbb{Z}^+,$$

where

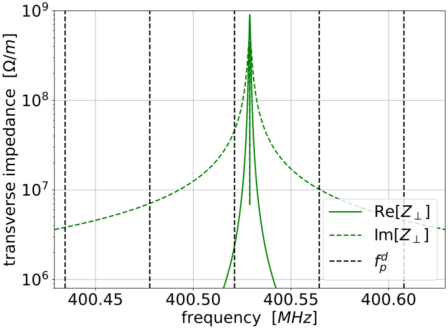
- $[Q_x]$ is the fractional part of the betatron tune (x or y)
- f_{rev} is the revolution frequency

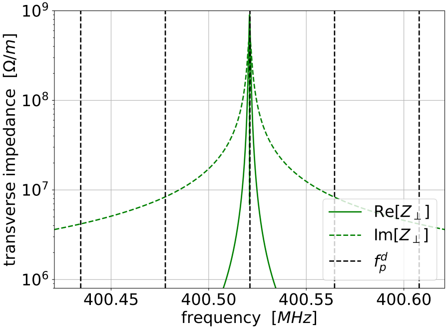


- In the SPS $f_{rev} \approx 43.450$ kHz
- The bandwidth of the cavities is very low compared to f_{rev}
- Hence, the contribution of the cavities is seen only on one betatron line

Detuning the cavities

If the fundamental frequency of the cavity is close to a betatron line, its impedance will have a more destabilizing effect.



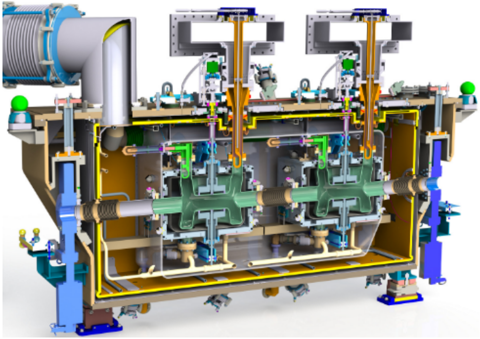


- $F_{RF} = 400.5289$ MHz
- The impedance is sampled below the maximum value

- $F_{RF} = 400.5289$ MHz -8 kHz
- The impedance is sampled at the maximum value

To measure the effect of the cavities, we should move their fundamental frequency close to a betatron line.

SPS MD set-up



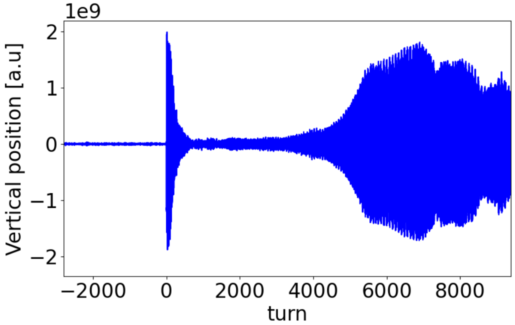
- 2 DQW cavities installed in the SPS
- They can be moved in and out of the beam line (normally they are out)
- A tuner allows to change the fundamental frequency of the cavities

MD on 28/09/2022: instability growth rate vs cavity frequency

Idea: measure the effect instability growth rate scanning the cavity frequency and **check if the growth rate is higher than when the fundamental frequency is closer to a betatron line.**

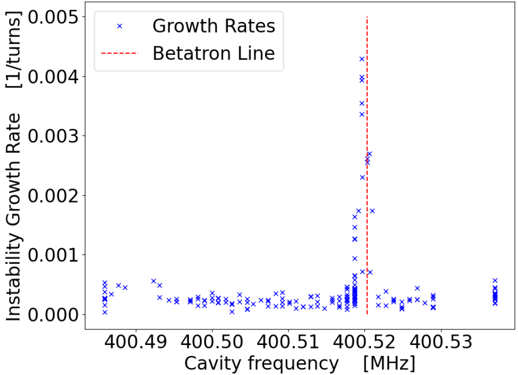
MD procedure:

- We use a long flat-bottom cycle with octupoles always off
- Inject a train of 72 bunches, remove transverse damper and then kick and record turn-by-turn data
- If an instability is observed, compute its growth rate
- Scan the cavity frequency, performing a few shots per frequency



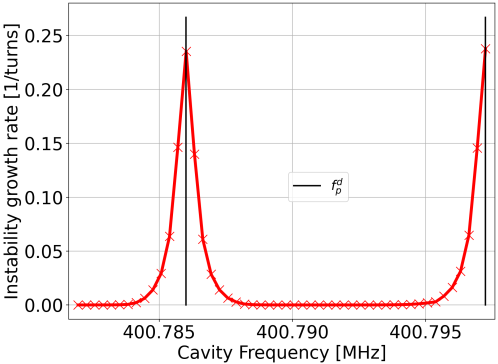
Instability growth rate vs cavity frequency

SPS (measurements):



The effect of the betatron line is clearly visible.

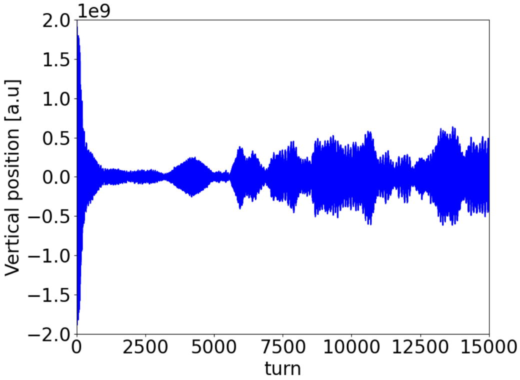
HL-LHC (simulations):



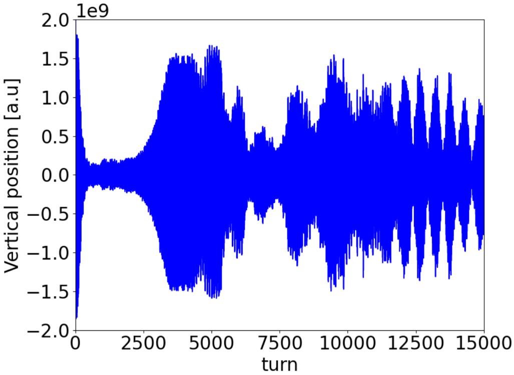
The growth rate enhancement at the peak, is in qualitative agreement with the predictions (performed around 400.8 MHz).

Slow vs fast instability

Away from the peak:



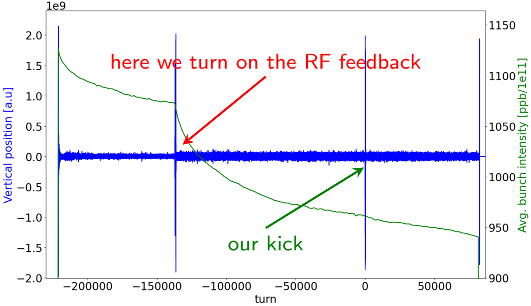
On the peak:



Issues with the RF feedback

We tried to test the effectiveness of the RF feedback to mitigate the instabilities.

Interestingly, switching on the RF feedback seemed to damp every instability, even those that would be observed without cavities.



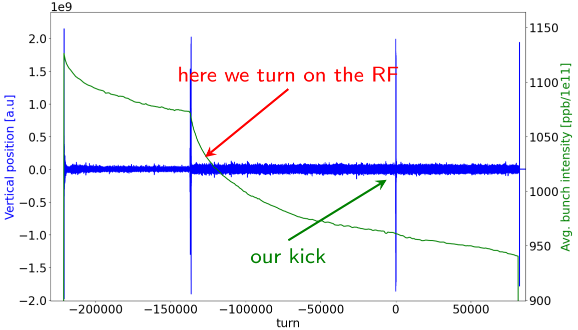
Something was kicking the beam, which could be enough to explain why no instability would appear. Therefore, we could not draw any conclusion on the effectiveness of the RF feedback.

Summary of 2022 MDs

- In the SPS the Crab Cavities the impedance is only effective on one betatron line.
- This was confirmed measuring the instability growth rate for different cavity frequencies.
- Unexpected losses were observed with RF feedback on, therefore we could not study instability mitigations.
- We asked new MD time to fix the RF feedback issue and repeat the experiment scanning the RF feedback gain.

MD on 31/05/2023: solving the issues with the RF feedback

In 2022 RF was turned on after injecting. When using trains of bunches, the beam would receive a spurious kick when the RF was turned on. This was only observed with trains.

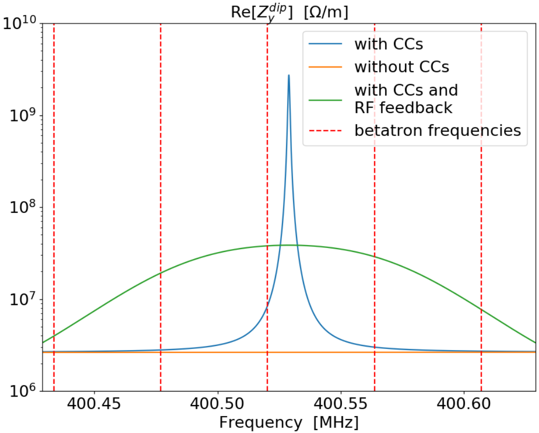


Thanks P. Baudrenghien, R. Calaga and team!

This issue was solved by turning on the RF before injecting the beam and re-phasing after injection (see R. Calaga's talk).

Impedance of the SPS crab cavities with RF feedback

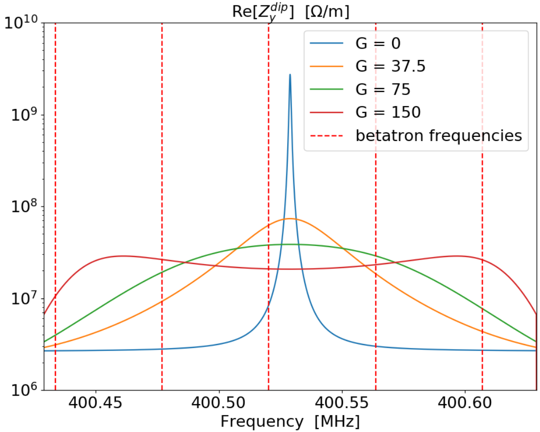
SPS impedance model with two DQW CCs:



- The impedance at the betatron lines is actually higher than without feedback
- This is an effect of the high revolution frequency and it is not true in the HL-LHC case

RF feedback gain scan

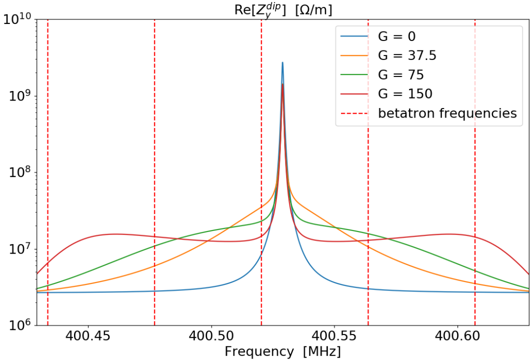
We check how the impedance changes increasing or reducing the RF feedback gain:



Understanding the effect of the RF feedback is not trivial, therefore it can be interesting to measure the instability growth rates scanning the RF feedback gain.

MD on 07/06/2023: RF feedback gain scan

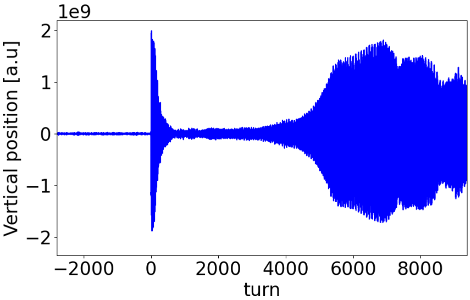
- Vertical chromaticity was set to $\xi = 0.33$, at which value we could see reproducible instabilities without dumping on losses.
- The two cavities were counter-phased (i.e. no overall crabbing)
- Cavity 1 tripped several times with RF feedback on and beam, so the RF feedback was finally kept off
- The gain of the RF feedback G_{FB} of cavity 2 was scanned



Feedback gain scan MD procedure

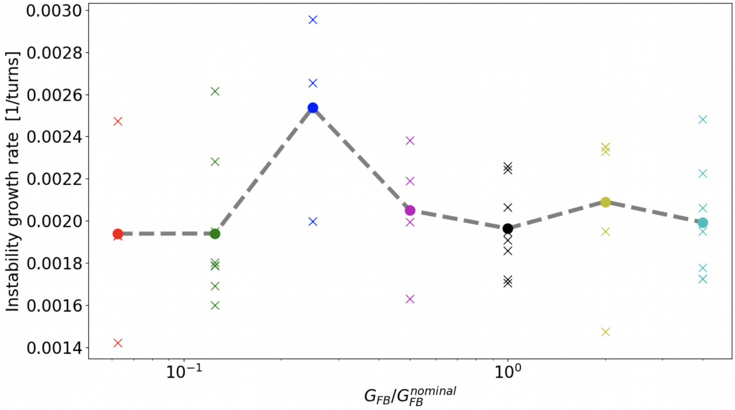
Procedure: for each step in G_{FB} repeat a few times the following steps:

- Turn on transverse damper at injection
- Inject a train of 72 bunches ($1.3 \cdot 10^{11}$ p/b)
- After 5 seconds turn off the damper and kick the beam shortly after
- Record the turn-by-turn vertical position and in post-processing extract the growth rate.



Measurement results

Measured growth rates for different RF feedback gains:



No clear effect of the RF feedback observed. We could try to repeat this experiment tuning the cavities close to a betatron line.

Conclusion

- The effect of the fundamental mode impedance of the Crab Cavities without and with RF feedback was studied with MDs in the SPS
- Three MDs were carried out:
  - Groth rate vs cavity frequency
  - RF feedback studies
  - Growth rate vs RF feedback gain
- The measured growth rates do not exhibit a clear dependence G_{FB}
- Simulation studies are ongoing.

We strongly support requesting more MD time next year. For example to repeat the growth rate vs feedback gain measurement with the cavities tuned on a betatron line

Will it be possible to test the betatron comb filter in the SPS?