SPS-CC instability studies & RF feedback gain along HL cycle

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Outline

DQW studies in 2022 - 2023

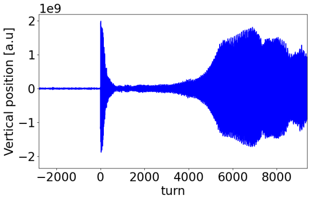
Proposal for an MD in 2025

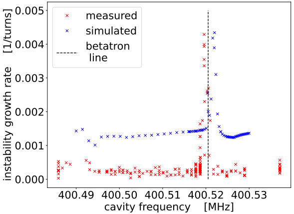
RF feedback gain along the HL cycle

DQW studies in 2022 - 2023

Measurements were carried out on the DQW prototypes and several interesting lessons were learned.

- Merit: that the Crab Cavities induce fast instabilities when they are tuned closed to a betatron frequency
- The model predicts well the existence and the position of the destabilizing betatron line
- If it were possible, it would be great to repeat this experiment with the RFD
- It would also be interesting to refine the scan close to the betatron line to observe potential effects of the betatron satellites

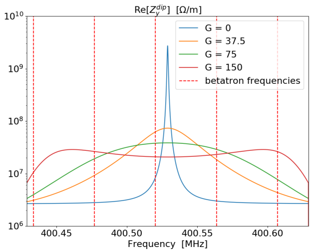


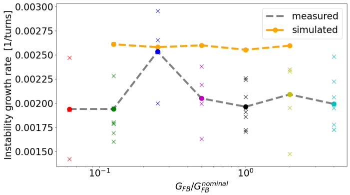


DQW studies in 2022 - 2023

Instability growth rate vs. crab cavity standard RF feedback gain

- We measured the instability growth rate while scanning the RF feedback gain (standard feedback)
- It was an attempt to show the effectiveness of the standard feedback
- No clear dependence on the feedback gain (in the range explored) as expected from simulations
- We know that in the SPS the standard RF feedback is more effective than in the HL-LHC
- If possible we would like to do a similar MD in 2025 with the RFDs having the cavities tuned at the destabilizing betatron frequency





We would like to continue this measurement campaign on the RFDs in 2025.

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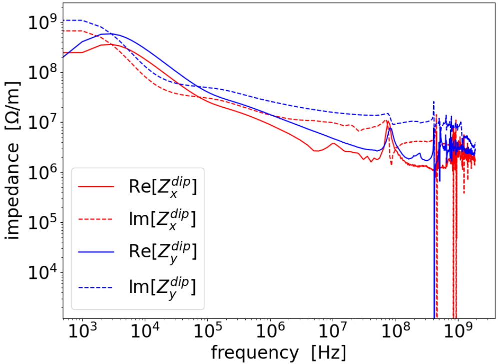
RFD measurements

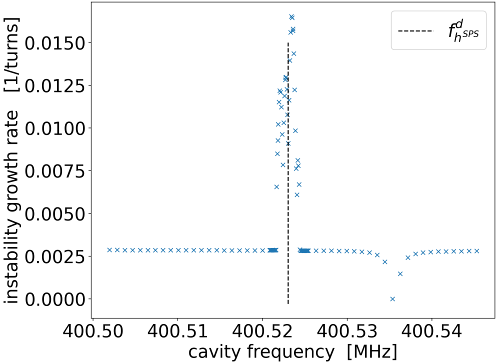
Measuring the RFD in 2025 will be very interesting but there is the additional difficulty that the horizontal beta function at the location of the cavities is lower than the vertical one ($\beta_x^{CC} =\sim 40m$, $\beta_y^{CC} =\sim 80m$). This could mean that the weighted impedance of the cavities is lower than the SPS impedance.

On the other hand, this is partially compensated by the fact that the horizontal SPS impedance is lower than the vertical one.



RFD frequency vs instability growth rate study

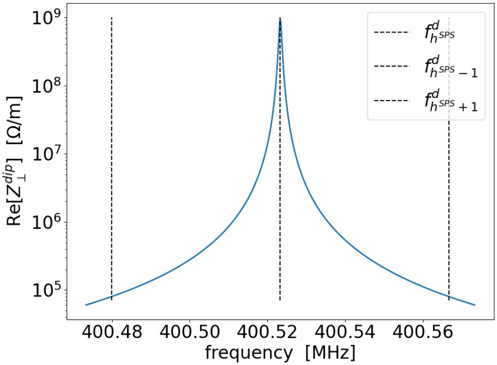
In order to check that the instabilities induced by the RFD impedance could be measured in the SPS, we simulated with PyHEADTAIL the instability growth rate, varying the RFD frequency.



The instabilities which happen when the RFD is tuned close to the betatron line, are faster than those of the bare machine, therefore the effect of the RFD is clearly visible.

Single-notch filter feedback

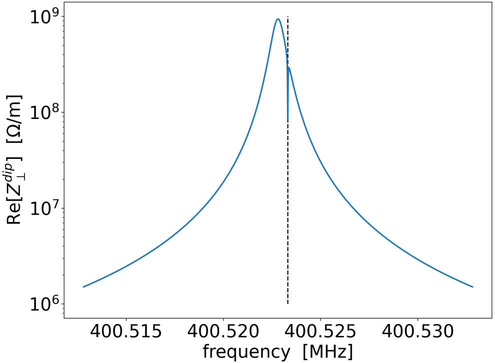
In the SPS the revolution frequency is 4 times larger than in the LHC (43 kHz vs 11 kHz) therefore it is enough to reduce the impedance at one betatron frequency to reduce the instability growth rate.



According to the RF colleagues, it could be doable to build a feedback system providing impedance reduction at a single line. Measuring this impedance reduction would be a first step towards the validation of the strategy to use a betatron comb filter to mitigate the fundamental mode instability.

Single-notch filter feedback

For the purpose of studying the effect of adding the notch we can produce the impedance with the notch by subtracting a narrower resonator from the crab cavity fundamental mode impedance.

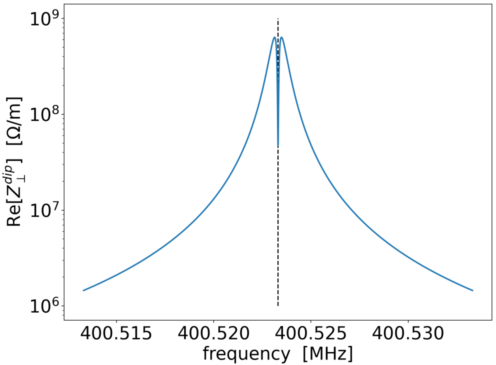


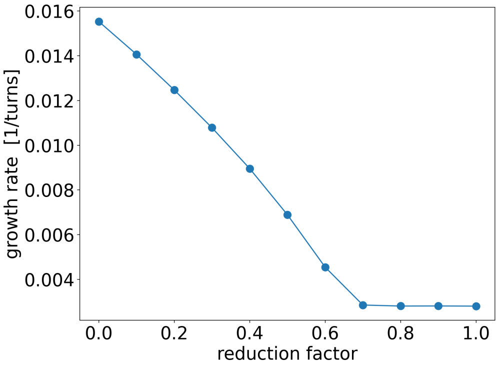
We can then play around with shunt impedance, quality factor and frequency of this resonator to study the effect and properties of the notch.

Clearly this is not a perfectly realistic description of the impedance with single-notch filter feedback, but it is a good starting point for our simulations.

Scan in reduction with RFD tuned on the betatron line

The easiest experiment to test the reduction given by the single-notch filter is to tune the RFD on the betatron line and perform instability growth rate simulations with PyHEADTAIL, scanning the depth of the notch.





The growth rate is significantly reduced, and this could be measured in an MD. Then we would have a first demonstration of the effectiveness of the betatron comb filter.

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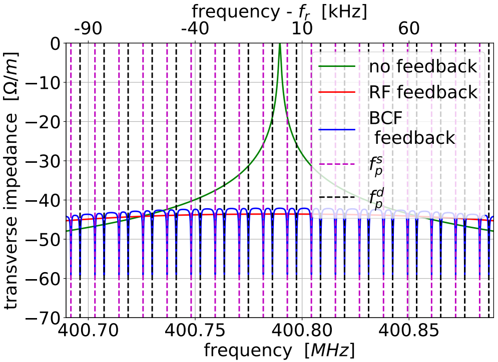
RF feedbacks

Two levels of feedback:

- Standard: reduction of the shunt impedance of the fundamental mode (but broadening of the peak).
- Betatron comb filter: wide-band reduction of the impedance at the betatron lines.



Standard:

- gain: G^{STD}=150
- delay: τ^{STD} = 1200 ns

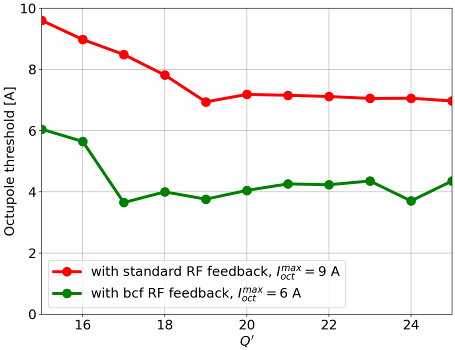
Betatron comb filter:

- gain: G^{BCF}=10
- delay: τ^{BCF} = 2800 ns
- notch width: a^{BCF} = 0.96875
- comb bandwidth: ^{bcf} = 600 kHz

Injection ($\beta^* = 6$ m)

At injection energy the required octupole current ($\sim$ 40 A) is dominated by the e-cloud instabilities, while the threshold for impedance would be smaller than 5 A.

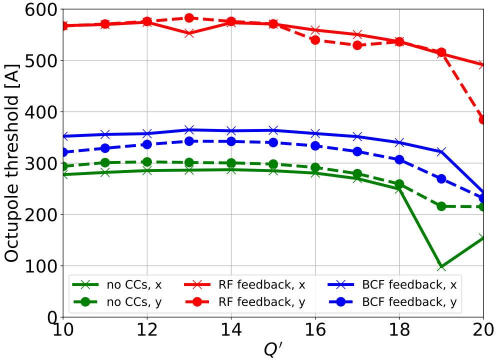
On the other hand, the injection situation must be monitored carefully because the octupole current should remain small for lifetime considerations.



Even with the standard feedback the thresholds remain relatively small.

End of ramp - Start of collapse ($\beta^* = 1$ m)

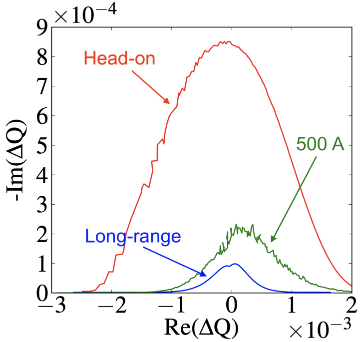
This is the most dangerous part of the cycle for impedance instabilities.



At this stage of the cycle we need the betatron comb filter with the nominal specs and full efficiency.

Colliding beams ($\beta^* = 1$ m $\rightarrow \beta^* = 20 - 15$ cm)

When the beams are colliding, the head-on beam-beam effect induces a strong Landau damping, which stabilizes the beams.



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Stability Diagram: an oscillation mode is stable if the associated tune-shift falls below the SD boundary

Scaling: head-on gives ~10 times more Landau damping than with 500 A of octupole current.

Thanks to this effect the beams will be stable also with the standard RF feedback.

Conclusions

- In 2022 and 2023 we could perform measurements on the SPS DQW cavity where the fundamental mode instability was clearly observed when its frequency is close to a betatron line
- More measurements could be performed in 2024 to test the mitigation of the instabilities induced by the crab cavities fundamental mode using a betatron comb filter
- For the moment we propose three MDs:
  - Instability growth rate vs crab cavities frequency
  - Standard RF feedback gain scan with the cavities tuned at a destabilizing betatron frequency
  - Tune the cavity on the closest betatron frequency, apply single-notch filter and measure the reduction in growth rate scanning the depth of the notch.
- RF feedback during the cycle: