Mitigation strategies for the instabilities induced by the fundamental mode of the HL-LHC Crab Cavities

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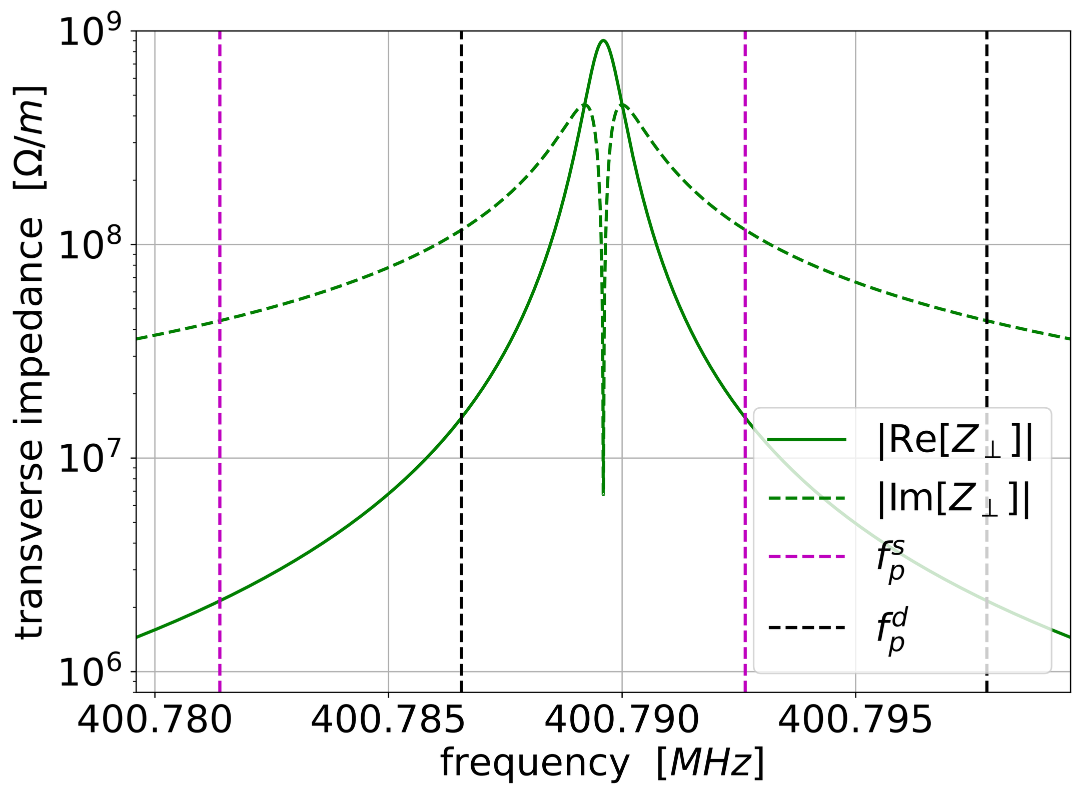
Abstract

The transverse impedance is one of the potentially limiting effects for the performance of the High-Luminosity Large Hadron Collider (HL-LHC). In the current LHC, the impedance is dominated by the resistive-wall contribution of the collimators at typical bunch-spectrum frequencies, and is of broad-band nature. Nevertheless, the fundamental mode of the crab cavities, that are a vital part of the HL-LHC baseline, adds a strong and narrow-band contribution. The resulting coupled-bunch instability, which contains a strong head-tail component, requires dedicated mitigation measures, since the efficiency of the transverse damper is limited against such instabilities, and Landau damping from octupoles would not be sufficient. The efficiency and implications of various mitigation strategies, based on RF feedbacks and optics changes, are discussed, along with first measurements using crab cavity prototypes at the Super Proton Synchrotron (SPS).

Fundamental mode impedance

Resonator impedance:

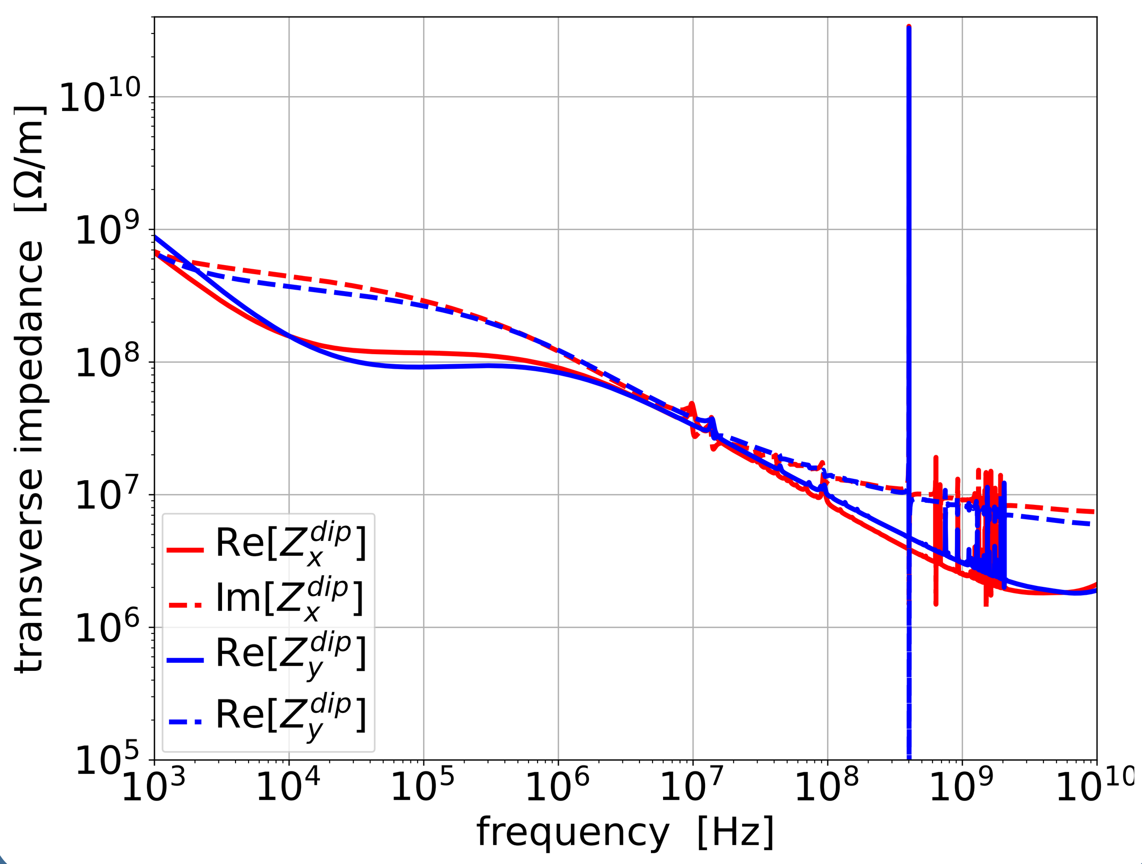


$$Z_\perp(f) = \frac{f_r}{f}\frac{R_\perp}{1 - iQ_L\left(\frac{f_r}{f} - \frac{f}{f_r}\right)}.$$

Shunt impedance	$R_\perp = 0.9024\,\mathrm{G\Omega\,m^{-1}}$
Loaded Quality factor	$Q_L = 5 \cdot 10^5$
Fundamental frequency	$f_r = 400.789\,\mathrm{MHz}$

HL-LHC flat-top impedance

With $\beta^* = 1\,\mathrm{m}$, at $7\,\mathrm{TeV}$ energy before collapse:



Acknowledgments

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The betatron frequencies

The impedance is only sampled at the frequencies

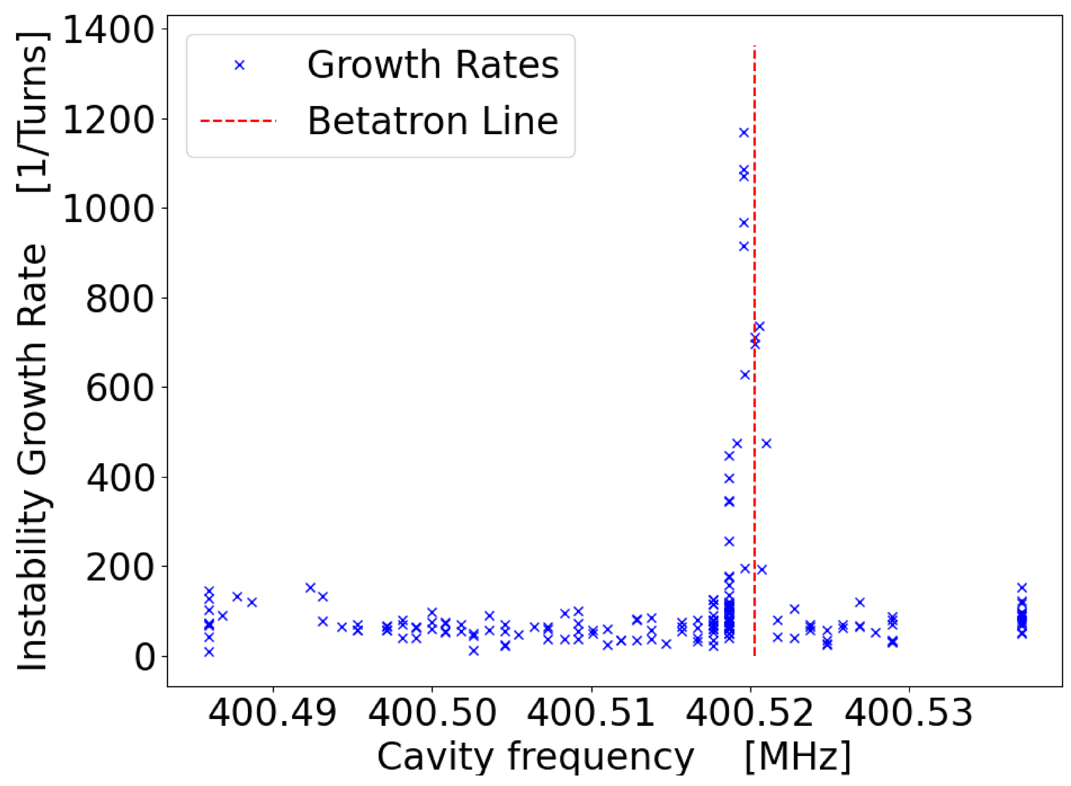
$$f_p^s = (p + \nu_*) f_0 \quad \forall p \in \mathbb{N}$$
$$f_p^d = (p + (1 - \nu_*)) f_0$$

where

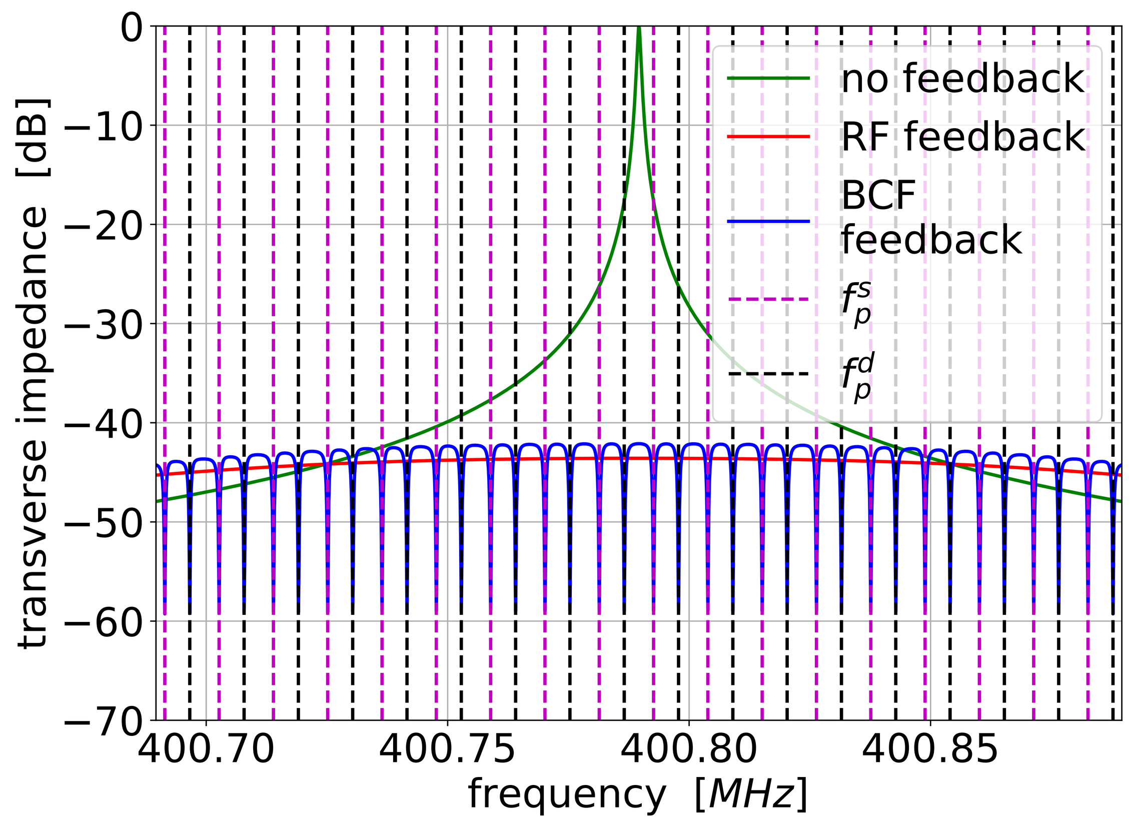
- ν_* is the fractional part of the tune
- f_0 is the revolution frequency

$f_r \approx f_p^d \implies$ strong destabilizing effect

We demonstrated this concept in the SPS measuring the instability growth rate scanning the crab cavity frequency.

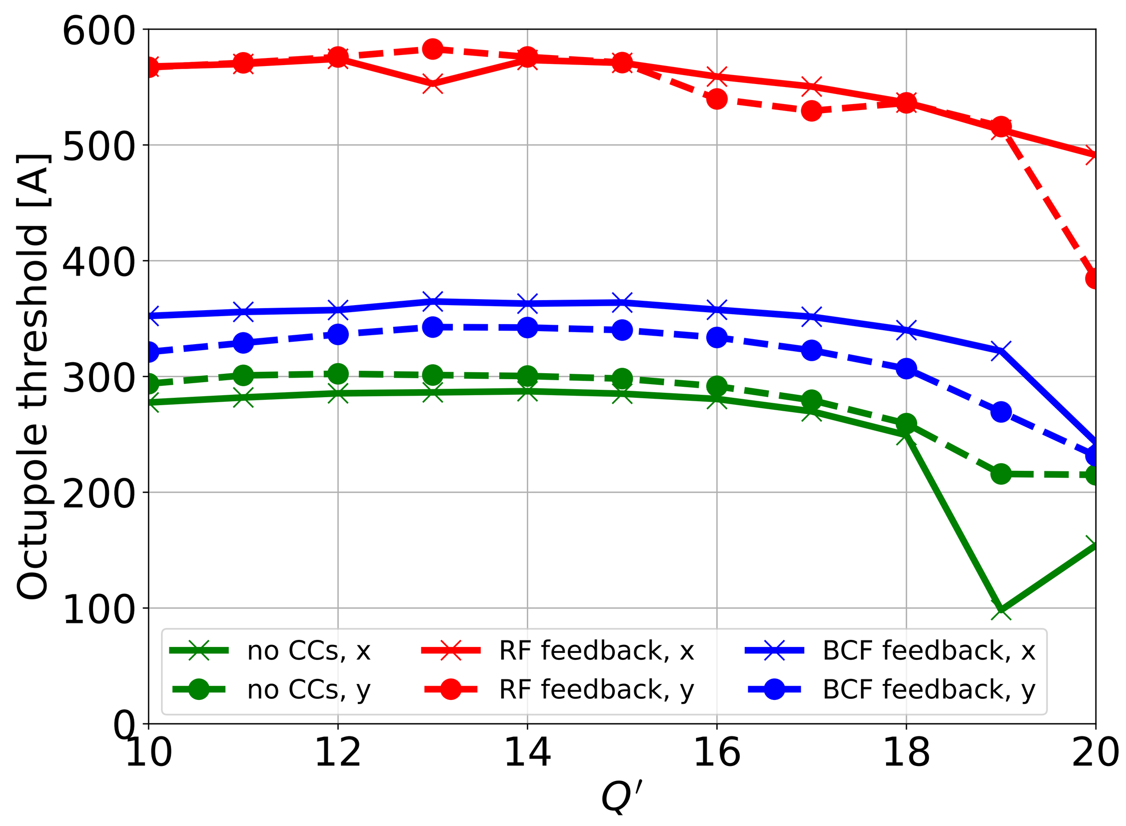


RF feedback



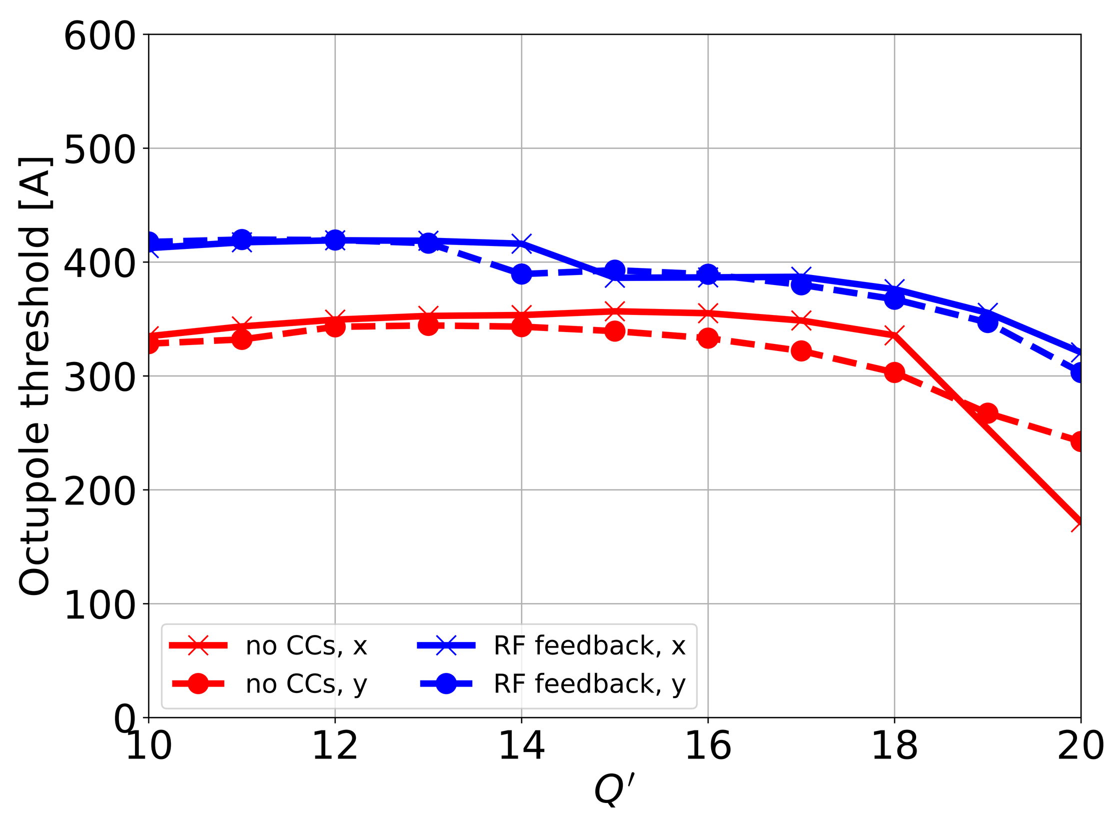
- The RF feedback is used to compensate the beam loading in the cavities
- With the RF feedback the impedance peak is lower but wider
- The octupole stability thresholds are too high to ensure good dynamic aperture

- A betatron comb filter can be used to reduce the impedance at the betatron frequencies
- The octupole stability thresholds are reduced to acceptable levels
- In the past, it has been only used for the longitudinal impedance
- The tune must be known with $5 \cdot 10^{-3}$ accuracy



Flat-optics

- Flat-optics: special optics in which $\beta_x^* \neq \beta_y^*$
- With the considered optics the β in the crabbing plane at the location of the cavities is reduced by a factor 3
- The effect of the cavities impedance scales linearly with the β in the crabbing plane
- The octupole thresholds are reduced but they remain high
- It could be attractive if combined with other impedance reduction strategies (e.g. IR7 optimized optics)



Conclusion

The impedance of the crab cavities fundamental mode with RF feedback must be mitigated:

- Flat-optics partly mitigate the issue, but the octupole threshold increase is still significant
- An RF feedback based on a betatron comb filter can fix the issue, but its implementation is not trivial