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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).

Keywords: Accelerator modelling and simulations (multi-particle dynamics, single-particle dynamics); Beam dynamics; Coherent instabilities

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Contents

1 Introduction

The crab cavities are a fundamental component of the HL-LHC project, which allow colliding with a large crossing angle without a major loss of luminosity [1]. These special radio-frequency (RF) cavities act as transverse deflectors, therefore their fundamental mode has a strong transverse component. The main parameters of the fundamental mode are summarized in table 1 (the fundamental frequency is the instantaneous RF frequency). In the crabbing plane, the beam-coupling impedance of the fundamental mode of the crab cavities has a peaked dipolar component which is modelled through the formula

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

The resulting impedance curve is shown in figure 1, and the total transverse impedance model [2] including the crab cavities contribution, in figure 2. In the total impedance curves, the fundamental crabbing mode stands out due to its high shunt impedance. It is important to note that the fundamental frequency is at a $\sim$ 3 kHz offset with respect to the closest critical betatron side-band. In this paper, we study the machine configuration at 7 TeV energy before the beams are brought in collision (which is referred to as the flat-top stage) as it is the most critical phase for stability. We use the

Table 1. Crab cavities fundamental mode parameters.

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

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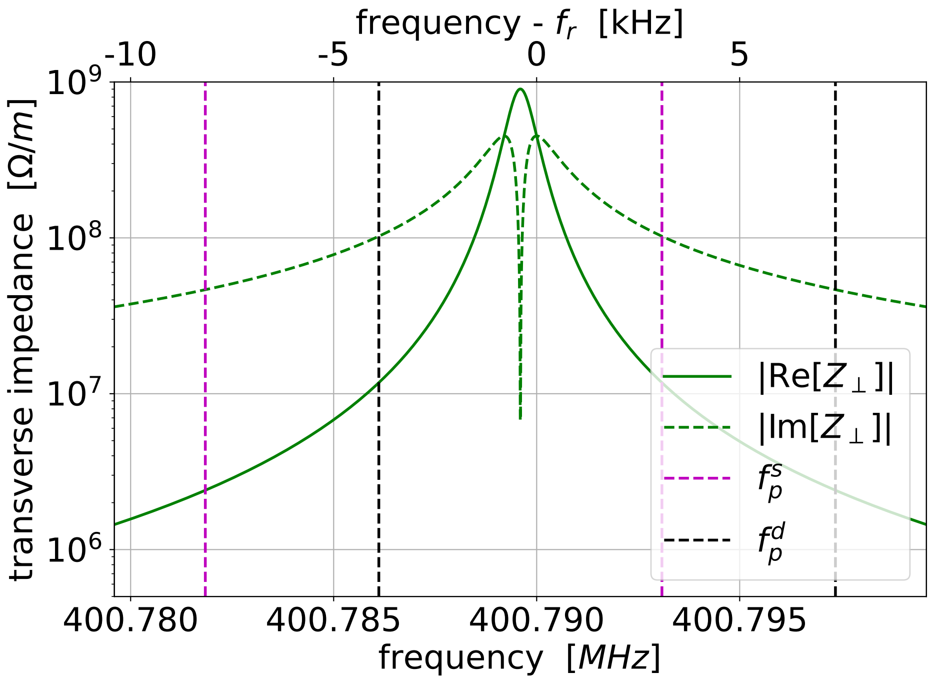

Figure 1. Beam-coupling impedance of the crab cavities fundamental mode. The dashed vertical lines represent the betatron frequencies.

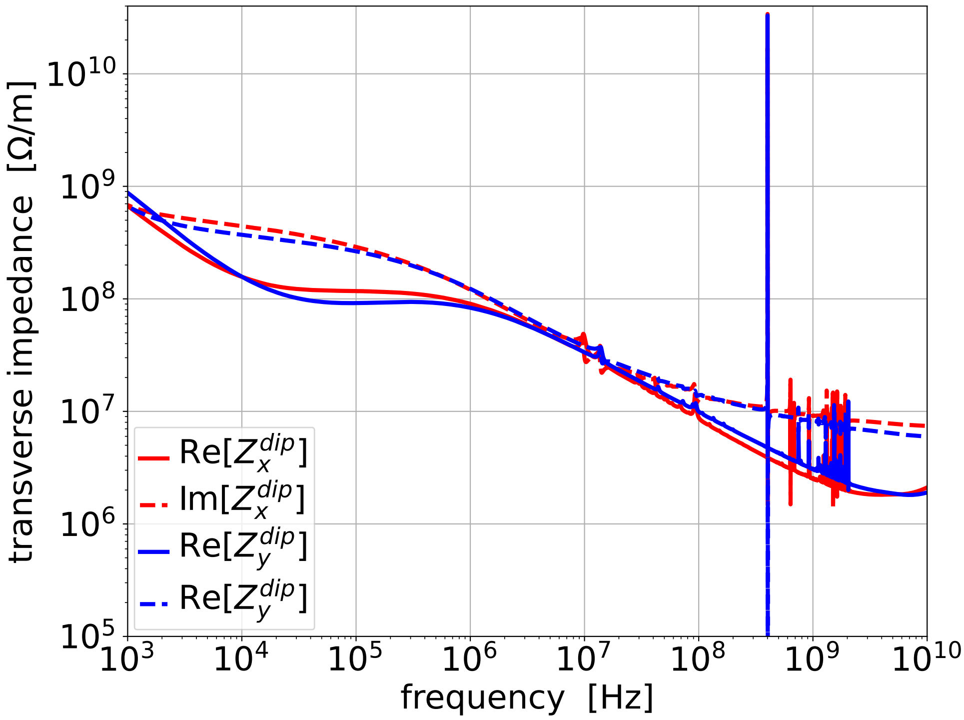

Figure 2. LHC dipolar impedances including the crab cavities fundamental mode, for round optics with $\beta_x^* = \beta_y^* = 1$ m.

$\beta_x^* = \beta_y^* = 1$ m round optics, which is the baseline configuration to be used at this point of the LHC cycle [3, 4]. After that, during the collision phase, the bunches colliding head-on in IP1 and IP5 experience a much stronger Landau damping, because of the beam-beam interactions, such that the impedance-induced instabilities are not harmful.

In section 2 we briefly introduce the concept of betatron frequencies and we show how it applies to the case of the crab cavities fundamental mode. In section 3 we present the results of instability growth rate measurements carried out in the SPS and use them to validate our model of the crab cavity fundamental mode impedance. In section 4 we use our model to provide estimates for the HL-LHC crab cavities, and in section 5 we discuss three potential mitigation strategies.

2 Fundamental mode and betatron frequencies

According to the theory based on the Vlasov equation [5], the calculation of the coherent complex tune shift induced by an impedance requires an evaluation only at a discrete set of frequencies, known as betatron frequencies:

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

where ν_* is the fractional part of the vertical or horizontal tunes, depending on the plane considered, and f_0 is the revolution frequency of the accelerator.

In principle the betatron frequencies should be detuned by the additional term $m f_s$, where m is the headtail mode number and $f_s = Q_s * f_0$ is the synchrotron frequency. The unstable mode number m is a priori unknown but is typically less than a few units (the instability growth rates are weaker with higher m), while the synchrotron tune is 0.01784 for the SPS and 0.002123 for the LHC. Hence, the term $m f_s$ is significantly less than the width of the fundamental mode (see figure 1), and we neglect it in the following.

The impedance at the f_p^d frequencies induce a destabilizing effect on the beam, while the f_p^s frequencies give a stabilizing effect. Therefore, if the frequency of a strong resonator, such as the crab cavities fundamental mode, is close to a destabilizing betatron frequency f_p^d, fast coherent instabilities are triggered. This is related to the fact that the real part of the resonator impedance features a peak at the resonant frequency, while its imaginary part crosses zero, which implies a strong effect on the instability growth rate and little to no impact on the tune shift. As we show in the next section, the effect of the destabilizing betatron lines can be observed in the Super Proton Synchrotron (SPS) where two prototypes of the crab cavities are installed.

3 Crab cavities and betatron frequencies

The crab cavities are not yet installed in the LHC, but two Double-Quarter Wave (DQW) crab cavity prototypes are already available in the SPS. Since these are the cavities used to deflect the beam vertically, in this section we only discuss coherent instabilities in the y-plane. The crab cavities are equipped with a tuning system which allows changing their frequency. Therefore, these devices offer a unique possibility to test the instability arising from the fundamental mode when it coincides with a betatron frequency. The SPS measurements are carried out without operating the crab cavities RF feedback so that the impedance of the fundamental mode can be modelled as a narrow-band resonator.

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As discussed in the following, this narrow-band impedance can excite a single betatron frequency, which is a study case that can be used to benchmark the theory and simulations. On the other hand, in HL-LHC the Crab-Cavities will always be operated with RF feedback, as we will see later on.

3.1 The SPS crab cavities

The full width at half maximum of the impedance of the fundamental mode of the crab cavities is $\frac{f_r}{2Q} \approx 900\,\mathrm{Hz}$, while the spacing between two consecutive destabilizing betatron frequencies is given by the SPS revolution frequency $f_0 \approx 43\,\mathrm{kHz}$. This means that the narrow band fundamental mode will excite a single betatron frequency when the resonating frequency of the cavities is tuned to be close to it. Conversely, when the cavity fundamental frequency is far from every betatron frequency, the effect from the fundamental mode impedance is not visible. During standard operation the cavities are tuned to operate synchronously with the beam, which means that the resonating frequency of the fundamental mode is set to be

$$f_r = f_{\mathrm{sync}}^{\mathrm{SPS}} = h^{\mathrm{SPS}} \cdot f_0,$$

where $h^{\mathrm{SPS}} = 9240$ is the SPS harmonic number. Assuming that the tune in the y-plane is $\nu_y = 0.18$ (as it is in the SPS during standard operations), one obtains that the distance between the fundamental frequency and the closest betatron line is

$$f_r - f_{h^{\mathrm{SPS}}}^{d} = \nu_y \cdot f_0 \approx 7802\,\mathrm{Hz},$$

which is almost 10 times larger than the full width half maximum of the cavities. For this reason, if the SPS crab cavities are well tuned with the synchronous frequency, their impedance at the destabilizing betatron lines is very low. On the other hand, if the cavities fundamental frequency is tuned close to a betatron frequency, then its impedance becomes visible. This concept is illustrated in figure 3.

3.2 Measurements in the SPS

The two prototype crab cavities installed in the SPS were used to demonstrate the betatron frequency concept with measurements. In a machine development session, one of the two cavities was kept on tune with the synchronous frequency $f_{\mathrm{sync}}^{\mathrm{SPS}}$, while the frequency of the other cavity was scanned crossing the first destabilising betatron line $f_{h^{\mathrm{SPS}}}^{d}$. The instability growth rate was repeatedly measured at each step in frequency by performing the following procedure:

1. A train of 72 bunches is injected while the transverse, bunch-by-bunch damper is active.

2. The damper is turned off and a vertical dipolar kick is applied to all the bunches of the beam (with the system which is normally used to measure the tune) in order to trigger an instability. The kick is uniform on all bunches.

3. The turn-by-turn average beam position is recorded using the beam position monitors of the BBQ system [6].

4. The beam is dumped after about 20 seconds.

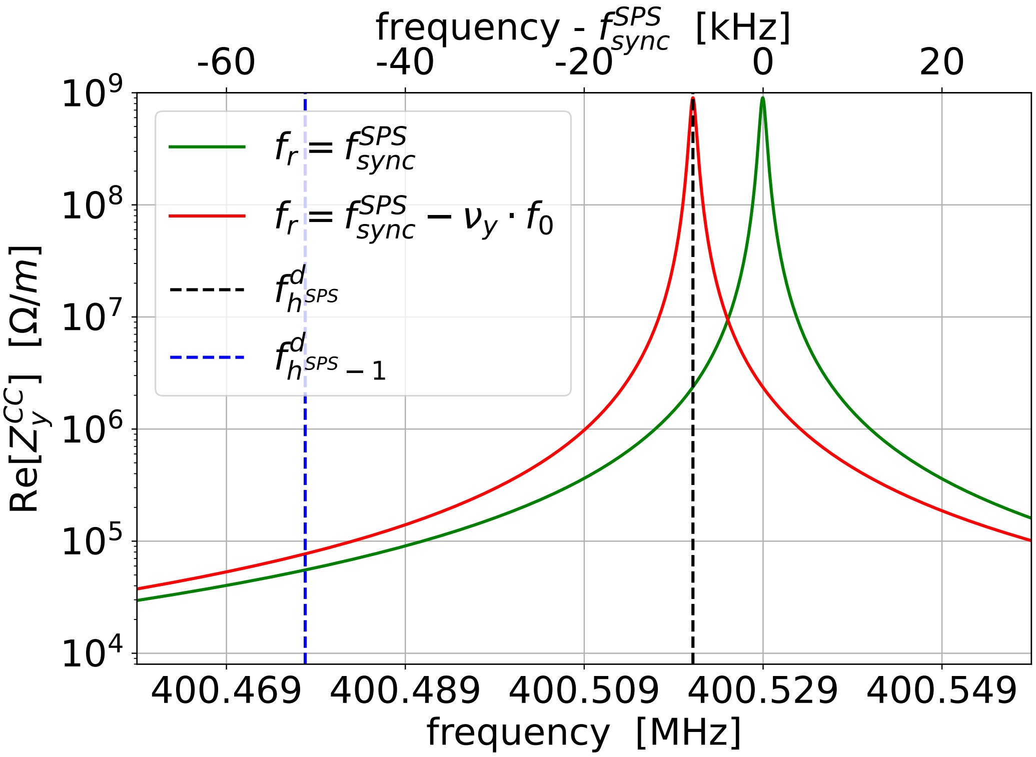

Figure 3. Impedance of an SPS DQW crab cavity, on tune with the SPS synchronous frequency $f_{\mathrm{sync}}^{\mathrm{SPS}}$ (green), or detuned by $\nu_y \cdot f_0$ (red). The black and blue vertical dashed lines show the two closest betatron frequencies to the resonant frequency of the cavities.

Table 2. Main parameters of the SPS measurements.

Energy	$E = 26\,\mathrm{GeV}$
Machine circumference	$C = 6911.5662\,\mathrm{m}$
Bunch intensity	$N_b = 1.2 \cdot 10^{11}\ p^+/\mathrm{bunch}$
Bunch length	$\tau = 2.9\,\mathrm{ns}$
Transverse tunes	$\nu_x = 20.13, \quad \nu_y = 20.18$
Chromaticity	$Q' = 2.4$

Whenever an instability is observed, its growth rate is extracted by fitting an exponential curve to the amplitude of the beam average position. The most relevant beam parameters are given in table 2. As shown in figure 4, a peak in the measured instability growth rate is observed when the cavity frequency is close to the betatron frequency. Far from the betatron frequency a large relative variance in the measured data is observed, due to the fact that the machine is almost stable with the chosen parameters and the measured instability growth rates are very noisy. On the other hand, when the cavity frequency is close to the betatron frequency, the growth rate is at least one order of magnitude higher. The tracking code PyHEADTAIL [7, 8] was used to simulate the same experiment. The simulated growth rates close to the betatron line, shown in figure 4, are in very good agreement with the measurement results.

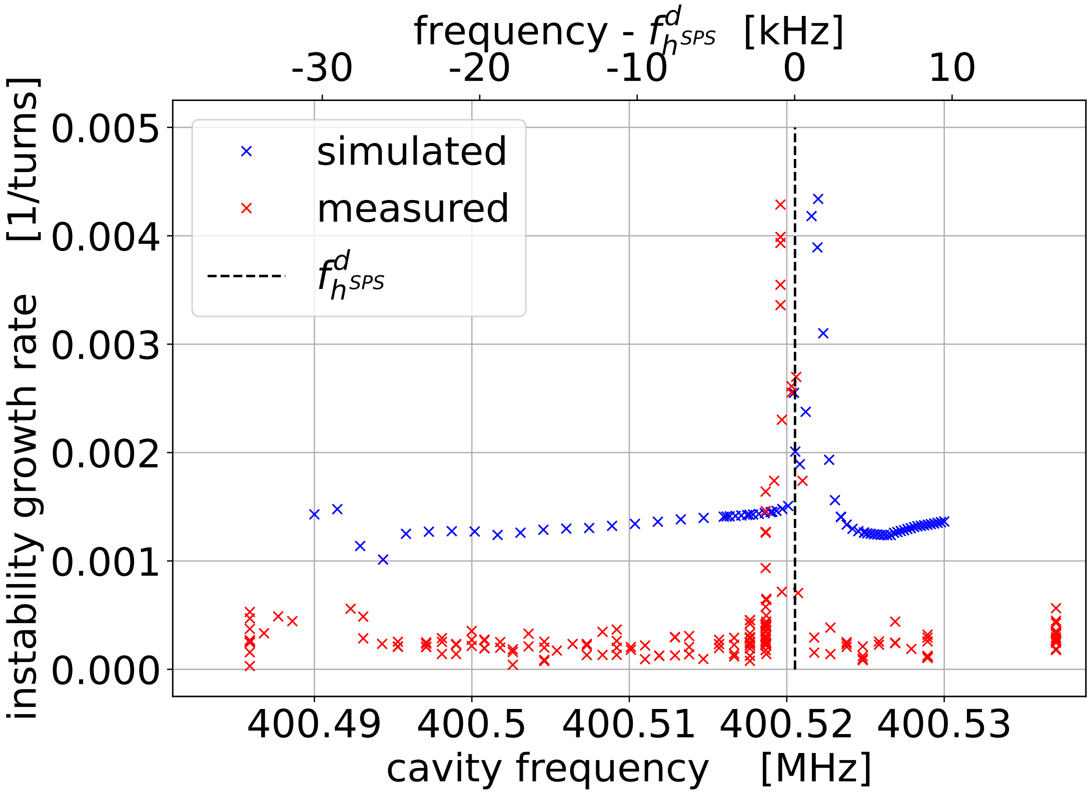

Figure 4. Vertical instability growth rate vs. crab cavity frequency, as measured in the SPS and as simulated with PyHEADTAIL.

4 The RF feedback

In the previous section we validated quantitatively our modelling of the crab cavities impedance and the induced instabilities in the SPS. We therefore can apply the same models to give estimates for the HL-LHC crab cavities. In order to compensate for the beam loading and to control the cavity frequency, the HL-LHC crab cavities are equipped with an RF feedback system [9]. With this feedback the effective impedance peak of the crab cavities becomes lower and wider, and can be modelled through the formula

$$Z_{\perp}^{FB}(f) = \frac{Z_{\perp}(f)}{1 + Ge^{-i\tau\omega^*} Z_{\parallel}(f)},$$

where

$$\omega^* = \omega - \omega_r \operatorname{sgn}(\omega),$$
$$Z_{\parallel}(f) = \frac{1}{1 - iQ_L\left(\frac{f_r}{f} - \frac{f}{f_r}\right)},$$

with $\omega = 2\pi f$ and $\omega_r = 2\pi f_r$. The feedback gain G and loop delay τ are related to the electronic implementation of the system — in our case we have $G = 150$ and $\tau = 1200\ ns$. The impedance of the

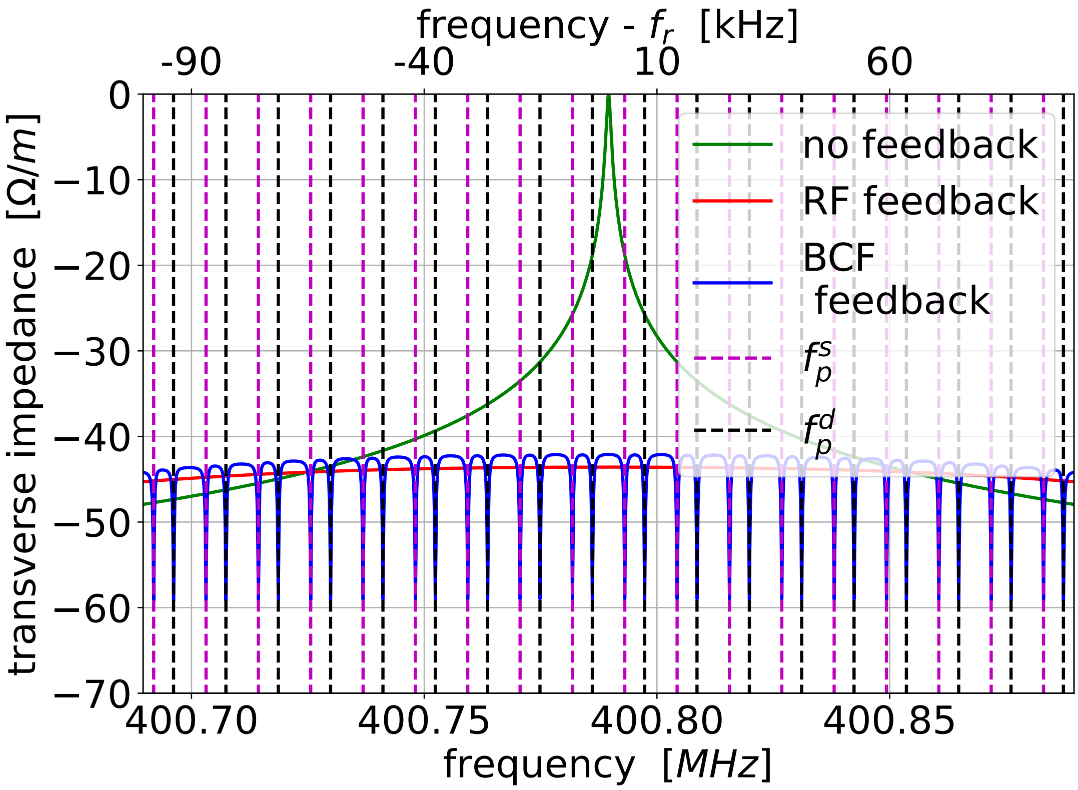

Figure 5. Complex modulus of the HL-LHC crab cavities fundamental mode impedance without feedback (green), with RF feedback (red) and with betatron comb filter (BCF) feedback (blue)—see section 5.2.

HL-LHC cavities with the RF feedback is shown in figure 5. With the RF feedback, the contribution of the fundamental mode impedance at each betatron frequency is lower, but more betatron frequencies have to be taken into account, in particular in the HL-LHC case as the betatron frequencies are much closer to each other than in the SPS case ($f_0 \approx 11.2\,\text{kHz}$).

In the most likely operational scenario of the crab cavities, the RF feedback will be already in action at top energy right before the beams are brought into collision, which is the most critical phase in terms of beam stability. During this phase we rely on two complementary means to stabilize the beam: the transverse damper (ADT) and the octupole magnets (which are used as a source of Landau damping). The best performance of the damper is achieved when its gain is set to 100 turns, while the strength of the Landau octupoles can be increased up to the limits imposed by the machine dynamic aperture (DA), which with the current optics should be above 400 A [3]. In order to find the minimal octupole current needed to stabilize the beam (known as the octupole threshold), we compute the complex tune shift induced by the machine impedance with DELPHI [10] (using the parameters in table 3) and then calculate the octupole threshold using the stability diagram theory, assuming positive octupole polarity. In figure 6 we plot the octupole thresholds obtained for a range of chromaticities with and without crab cavities. With the RF feedback switched on, we obtain thresholds in the range 500 A to 600 A, when including the effect of noise (which is obtained, in good approximation, by multiplying the thresholds by a factor of two [11, 12]). The octupole thresholds

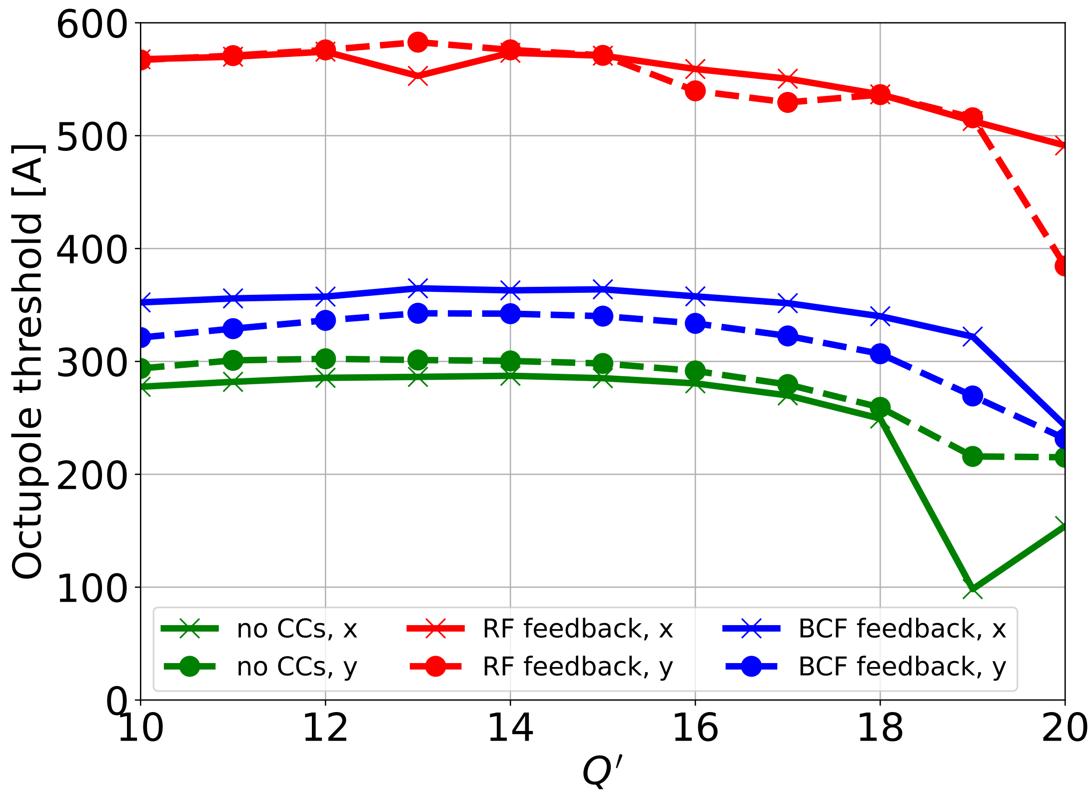

Figure 6. Octupole thresholds in HL-LHC without crab cavities (green), with RF feedback (red) and with BCF feedback (blue) — see section 5.2.

are higher than 500 A, hence potentially too high to ensure a good DA. In the next section we will discuss three strategies to reduce the thresholds.

5 Mitigation strategies

In this section we report three strategies that could be put in place to reduce the effect of the impedance of the crab cavities fundamental mode. We discuss the potential benefits of each strategy as well as their limitations.

5.1 Cavity detuning

The HL-LHC revolution frequency is approximately 11 kHz, which is one order of magnitude higher than the full width at half maximum of the crab cavity impedance. Therefore, we can imagine that, similarly to the SPS case, for the HL-LHC it would also be possible to detune the cavities to make their impedance contribution at the betatron lines negligible. In figure 7 we report the results of a simulation study carried out with DELPHI, where we compute the HL-LHC instability growth rate scanning the crab cavity frequency, similarly to the experiments carried out in the previous section for the SPS. Due to the lower revolution frequency of the HL-LHC, the range of frequencies where the growth rate stays constant at the value obtained without crab cavities, is narrower than in the SPS, but it is still clearly visible. Therefore, in principle a good strategy to reduce the octupole thresholds at flat-top could be to keep the cavities detuned without operating the RF feedback until the start of the collision phase, and then shift the cavities frequency to the synchronous one and turn on the RF feedback. Ideally this recipe would ensure a lower octupole threshold and hence a good DA during the period between the end of the ramp and the beginning of the collision phase, which, as already discussed, is the most critical part of the HL-LHC cycle for the impedance-induced instabilities. At the time being, this mitigation strategy does not seem feasible in practice because it requires controlling precisely the resonating frequency of the cavities while they are not operated, hence with the RF feedback off, which does not seem possible. On the other hand, if a strategy to turn on the RF feedback just during the collision phase will be devised, then detuning the cavities would be an effective mitigation.

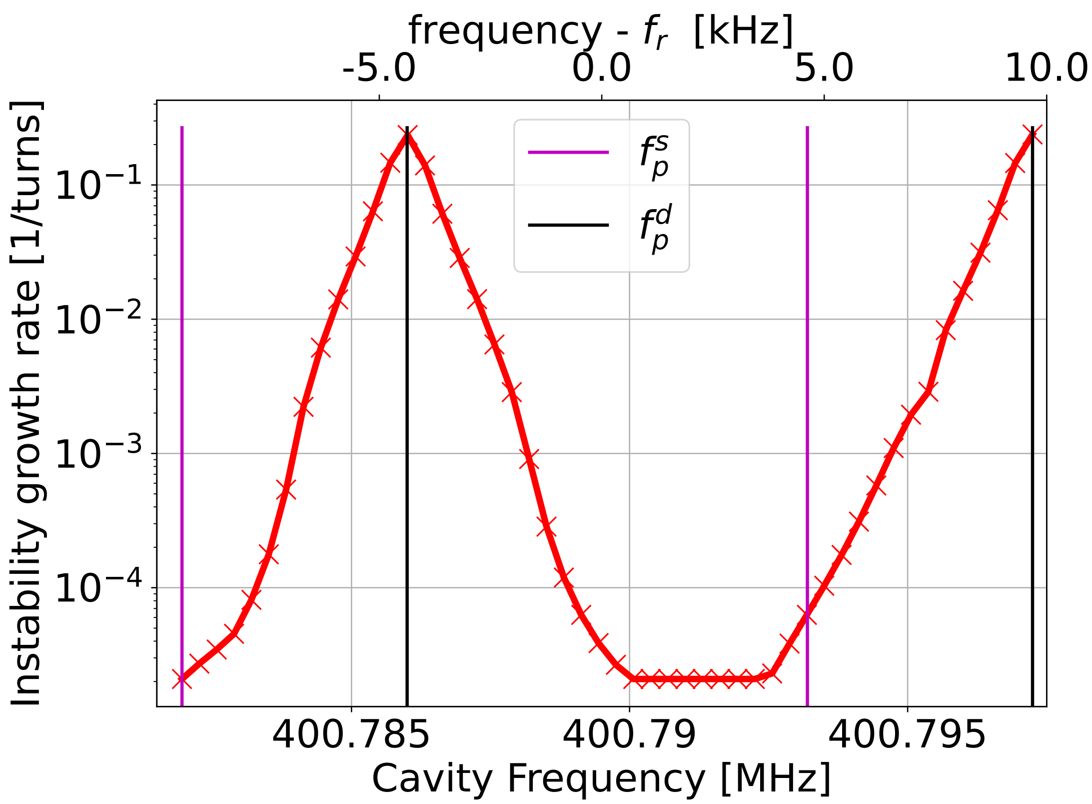

Figure 7. Simulated vertical instability growth rate vs. crab cavity frequency in HL-LHC (without RF feedback).

5.2 The Betatron Comb Filter feedback

It is possible to construct a more advanced feedback system which reduces the impedance specifically at the betatron frequencies, called the Betatron Comb Filter (BCF) [9]. Feedback systems based on comb filters were implemented to reduce the longitudinal impedance of the accelerating cavities in several machines, such as PEPII [13], the SPS [14], and the LHC [15]. These comb filter implementations need to be modified when working in the transverse plane since the betatron tune must be taken into account to locate correctly the betatron frequencies. The transverse impedance

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with this feedback system is the following:

$$Z_{\perp}^{BCF}(f) = \frac{Z_{\perp}(f)}{1 + G\,[1 + 2H(\omega)e^{i\tau'\omega^*}]\,e^{-i\tau\omega^*}Z_{\parallel}(f)},$$

where

$$H(\omega) = \begin{cases} \frac{H_{BB}(\omega-\omega_r)+H_{BB}(\omega+\omega_r)}{2}, & \text{if } |\omega| < \frac{3\cdot 10^5}{2\pi}, \\ 0 & \text{otherwise,} \end{cases}$$

$$H_{BB}(\omega) = K(1-a)\left[\frac{e^{i(2\pi\nu_* - \frac{\omega}{f_0})}}{1 - ae^{i(2\pi\nu_* - \frac{\omega}{f_0})}} + \frac{e^{i(-2\pi\nu_* - \frac{\omega}{f_0})}}{1 - ae^{i(-2\pi\nu_* - \frac{\omega}{f_0})}}\right],$$

and $K = 10$, $a = 31/32$, $\tau' = 2800\,\mathrm{ns}$. The resulting impedance is given by the blue curve in figure 5. As shown in figure 6 the BCF would strongly mitigate the instabilities induced by the crab cavities fundamental mode. On the other hand, this feedback system works well if the betatron tunes are known with sufficient precision, otherwise the notches of the filter are located at the wrong frequencies. Simple estimates show that the BCF will work well if the tune uncertainty is lower than $5 \cdot 10^{-3}$, which is achievable according to the HL-LHC specifications [3]. Studies are ongoing to check the feasibility, given the various sources of tune uncertainties from e.g. e-cloud, jitter, and wake fields.

5.3 Flat optics

Another option to reduce the effect of the crab cavities impedance is to reduce the β functions in the crabbing plane at the location of the cavities. This can be achieved using special optics, known as flat optics [16]. In particular we consider the flat optics configuration in which $\beta^* = 2.8\,\mathrm{m}$ in the crossing plane and 0.7 m in the separation plane. In the original round optics, at the crab cavities we have on average $\beta_{\perp} \approx 641\,\mathrm{m}$ in the crossing plane, while with the considered flat optics $\beta_{\perp} \approx 209\,\mathrm{m}$. The octupole thresholds obtained with such flat optics, shown in figure 8, are therefore significantly lower. In the case of flat optics the thresholds have been re-scaled to a telescopic index of 1 (see ref. [17] for a definition), for comparison purposes — they would have been lower if they had been computed with the correct index for these optics.[1]

Note that thanks to recent improvements in the IR7 and IR3 optics [18], the impedance of the LHC collimators could be reduced by a significant amount (in the order of 20%) and hence some margin with respect to the DA limit could be gained.

6 Conclusion

The impedance of the fundamental mode of the crab cavities is a potential source of performance limitation for the HL-LHC as it would increase strongly the octupole threshold at flat top, right before beams are put in collisions. The instabilities induced by the fundamental mode of the DQW cavities (which act in the vertical plane) have been observed and measured in the SPS, and we showed that they can be mitigated by operating the cavities with a frequency far from a betatron frequency. However, in the current HL-LHC operational scenario, the RF feedback will have to be activated at all times. With RF feedback the fundamental mode impedance becomes broader and detuning the cavities is

[1]On the other hand, also the DA limit would be reduced — more studies are actually needed in the case of flat optics.

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Table 3. Main DELPHI simulation parameters.

Energy	$E = 7\,\mathrm{TeV}$
Machine circumference	$C = 26658.8832\,\mathrm{m}$
Bunch intensity	$N_b = 2.3 \cdot 10^{11}\ p$
Bunch length	$\tau = 1\,\mathrm{ns}$
Synchrotron tune	$Q_s \simeq 0.002$
Fractional transverse tunes	$\nu_x = 0.31, \quad \nu_y = 0.32$
Longitudinal distribution	Gaussian
Transverse damper gain	$d = 100$ turns

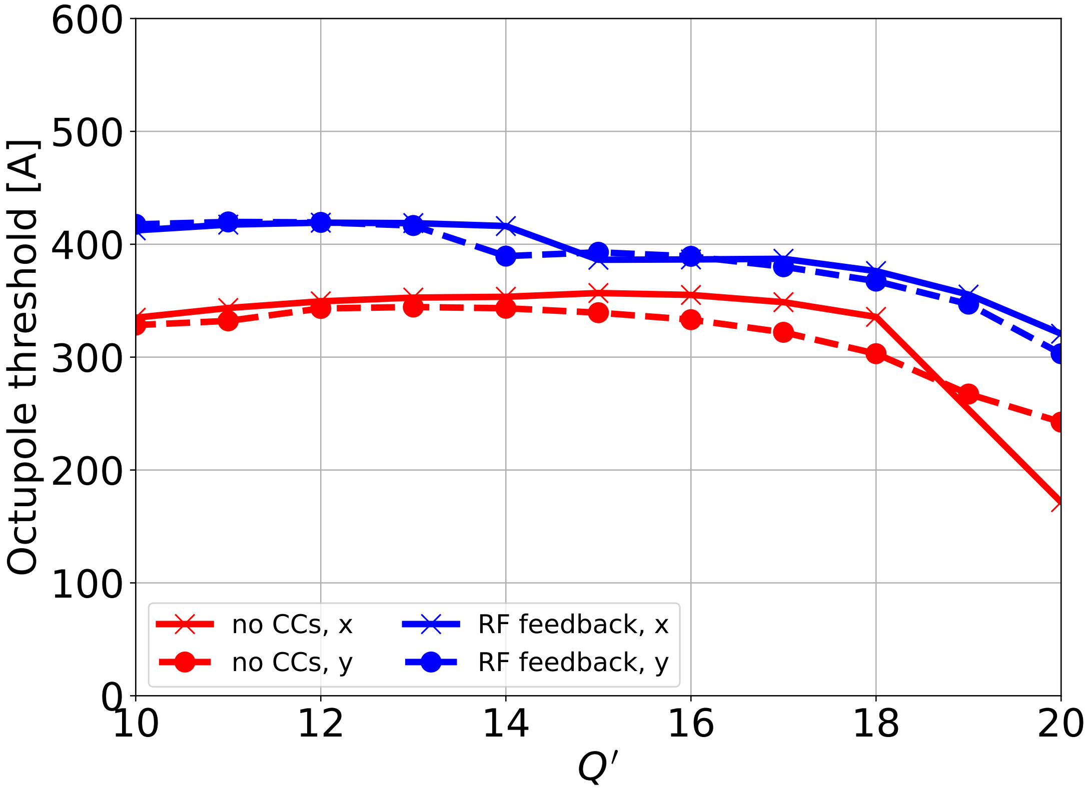

Figure 8. Octupole thresholds without crab cavities (in red) and with RF feedback and flat optics (in blue).

ineffective. Therefore, two other efficient mitigations are found: a betatron comb filter, or the use of flat optics, both on top of the RF feedback. Nevertheless, open points remain, in particular on the compatibility of the tune variation with the betatron comb filter. Ultimately, the safest scenario would be to operate with the betatron comb filter and flat-optics together. Future work will aim at testing the effect of the RF feedback in the SPS. In addition, the new installed horizontal RF dipole cavities will be tested as well. Moreover, the use of negative octupole polarity is being investigated as an alternative option to relax the DA constraint.

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