# 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).

## 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 Fig. 1, and the total transverse impedance model [2] including the crab cavities contribution, in Fig. 2. In the total impedance curves, the fundamental crabbing mode stands out due to its high shunt impedance. Weighted by the beta function at the cavities, it is more than three orders of magnitude higher than the LHC impedance at the fundamental frequency $f_r$. It is important to notice that the fundamental frequency is at a $\sim$ 3 kHz offset with respect to the closest critical betatron side-band. In these proceedings, we study the flat-top machine configuration as it is the most critical phase for stability. We use the $\beta^*$ =1 m optics, which will be used before the beams are brought in collision. During the collision phase, the bunches colliding head-on in IP1 and IP5 experience such a strong Landau Damping because of the beam-beam interactions that the impedance-induced instabilities are not harmful.

Table 1: Crab Cavities Fundamental Mode Parameters

| Parameter | Value |
|---|---|
| Shunt impedance, $R_\perp$ | 0.9024 GΩ m$^{-1}$ |
| Loaded Quality factor, $Q_L$ | $5 \cdot 10^5$ |
| Fundamental frequency, $f_r$ | 400.789 MHz |

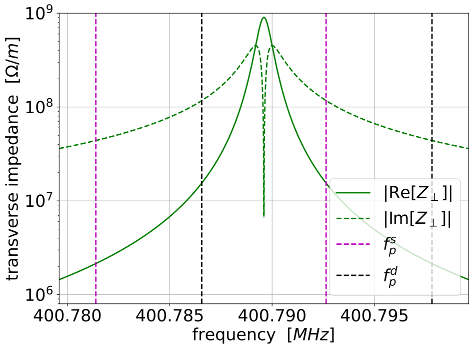

Figure 1: Beam-coupling impedance of the crab cavities fundamental mode. The dashed lines represent the betatron frequencies.

## FUNDAMENTAL MODE AND

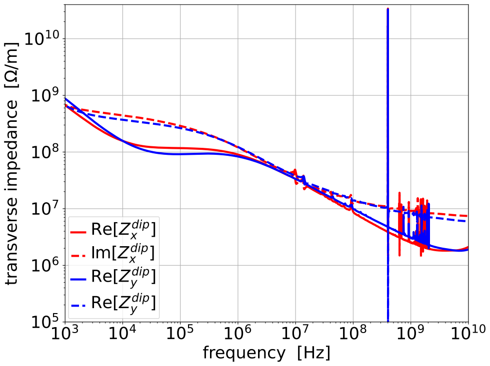

Figure 2: LHC dipolar impedances including the crab cavities fundamental mode.

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Table 2: Main DELPHI Simulation Parameters

| **Parameter** | **Value** |
|---|---|
| Energy, $E$ | 7 TeV |
| Bunch intensity, $N_b$ | $2.3 \cdot 10^{11}\ p$ |
| Bunch length, $\tau$ | 1 ns |
| Synchrotron tune, $Q_s$ | $\simeq 0.002$ |
| Fractional trans. tunes, $(\nu_x, \nu_y)$ | (0.31, 0.32) |
| Longitudinal distribution | Gaussian |
| Transverse damper gain, $d$ | 100 turns |

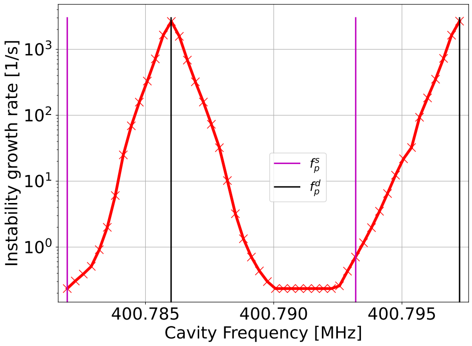

Figure 3: Simulated vertical instability growth rate vs crab cavity frequency in HL-LHC.

## BETATRON FREQUENCIES

According to the theory based on the Vlasov equation [3], the calculation of the coherent complex tune shift induced by an impedance requires evaluating it only at a discrete set of frequencies, known as betatron frequencies:

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

where $\nu_*$ is the fractional part of the vertical or horizontal tunes, depending on which plane is considered, and $f_0$ is the revolution frequency of the accelerator. 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 impedance peak, such as the crab cavities fundamental mode, is close to a destabilizing betatron frequency $f_p^d$, fast coherent instabilities are triggered. To illustrate this concept, we compute the multi-bunch instability growth rate induced by the HL-LHC impedance varying the frequency of the crab cavities. The instability growth rate is computed by means of DELPHI [4], a linearized Vlasov solver for beam dynamics. The main simulation parameters are reported in Table 2. The results of the resonant frequency scan, reported in Fig. 3, show clearly that, when the frequency of the crab cavities is close to a destabilizing frequency, the instability growth rate is more than 3 of orders of magnitude higher than in the other cases.

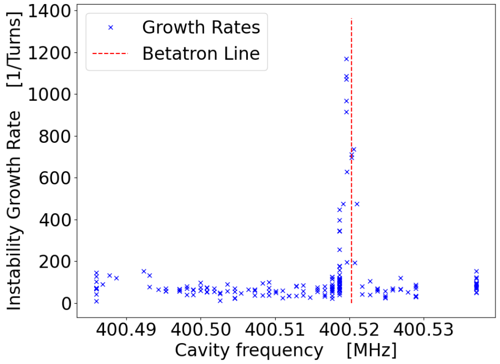

Figure 4: Measured vertical instability growth rate vs crab cavity frequency in the SPS.

### *SPS Measurements*

The two prototype crab cavities installed in the Super Proton Synchrotron (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, while the frequency of the other cavity was scanned crossing the first destabilising betatron line. As shown in Fig. 4, a peak in the measured instability grow rate is observed when the cavity frequency is close to the betatron frequency, similarly to what is predicted for HL-LHC. Note still that the instability growth rate in the SPS is very different from that in HL-LHC, due to the very different machine parameters.

## THE RF FEEDBACK

In order to compensate for the beam loading, the crab cavities are equipped with an RF feedback system [5]. 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

$$\omega^* = \omega - \omega_r sgn(\omega),$$

$$Z_\parallel(f) = \frac{1}{1 - iQ_L\left(\frac{f_r}{f} - \frac{f}{f_r}\right)},$$

$\omega = 2\pi f$ and $\omega_r = 2\pi f_r$. The feedback gain $G$ and loop delay $\tau$ are related to the electronic implementation of the system and in our case we have $G = 150$ and $\tau = 1200$ ns. The impedance of the cavities with the RF feedback is shown in Fig. 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 the most likely operational scenario of the crab cavities, the RF feedback will be already in action at top energy 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 tools to stabilize the beam: the transverse damper (ADT) and the octupole magnets (which

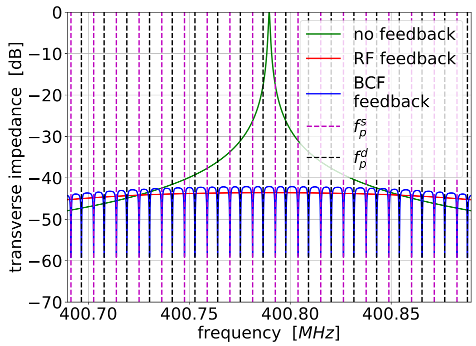

Figure 5: Modulus of the crab cavities fundamental mode impedance without feedback (in green), with RF feedback (in red) and with BCF feedback (in blue).

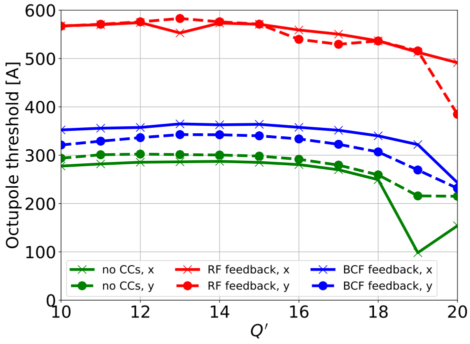

Figure 6: Octupole thresholds without crab cavities (in green), with RF feedback (in red) and with BCF feedback (in blue).

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 [6]. 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 (using the parameters in Table 2) and then calculate the octupole threshold using the stability diagram theory, assuming positive octupole polarity. In Fig. 6 we plot the octupole thresholds obtained for a range of chromaticities with and without crab cavities. With the RF feedback we obtain thresholds in the range 500 A to 600 A, when including the effect of noise [7]. The octupole thresholds are higher than 500 A, hence potentially too high to ensure a good DA. In the next section we will discuss two strategies to reduce the thresholds.

## MITIGATION STRATEGIES

### *The Betatron Comb Filter Feedback*

It is possible to construct a more advanced feedback system which reduces the impedance at the betatron frequencies, called the Betatron Comb Filter (BCF) [5], similar to the one planned for the accelerating cavities[8]. The transverse impedance with this a feedback system is the following:

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

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 Fig. 5. As shown in Fig. 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 wrong frequencies. Simple estimates show that the BCF will work well if the tune uncertainty is lower than $5 \cdot 10^{-3}$. Studies are ongoing to check the feasibility, given the various sources of tune uncertainties from e.g. e-cloud, jitter, and wake fields.

### *Flat Optics*

Another option to reduce the effect of the crab cavities impedance is to reduce the $\beta$ functions in the crabbing plane at the location of the cavities. This can be achieved using special optics, known as flat optics [9]. 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 $\beta_{\perp} \approx 641\,\mathrm{m}$, while with the considered flat optics $\beta_{\perp} \approx 209\,\mathrm{m}$. The octupole thresholds obtained with such flat optics, shown in Fig. 7, are therefore significantly lower. In the case of flat optics the thresholds have been rescaled to a telescopic index of 1 [10] for comparison purposes, and they would be lower if they were computed with the correct index for these optics.

## CONCLUSION

The crab cavities fundamental mode is a potential source of performance limitation for HL-LHC as it would increase strongly the octupole threshold at flat top, right before beams are put in collisions, even with an RF feedback. Two efficient mitigations are found: a betatron comb filter, or the use of flat optics, both on top of the RF feedback. Nevertheless, question marks remain, in particular on the compatibility of the tune variation with the former.

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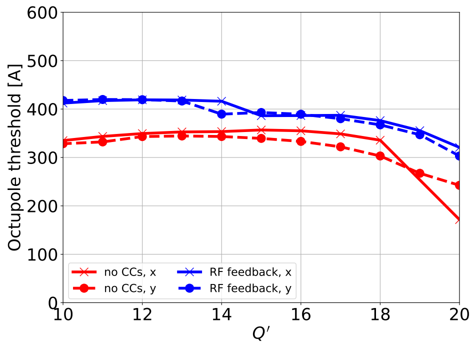

Figure 7: Octupole thresholds without crab cavities (in red) and with RF feedback and flat optics (in blue).

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