Update from the impedance and instabilities studies

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January 13, 2023

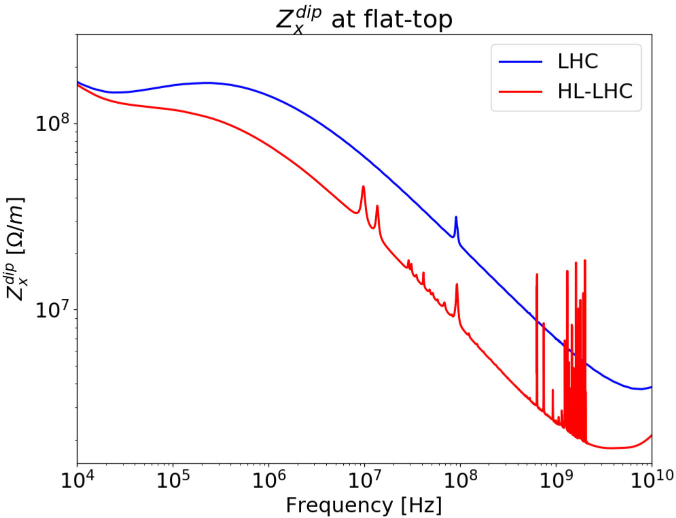
Outline

Updated HL-LHC Impedance Model

HL-LHC Octupole Thresholds

The Fundamental Mode of the Crab Cavities

Impedance Model - LHC vs HL-LHC (previous model – 2022)



Main differences:

- The impedance curve is generally lower thanks to the collimators upgrade
- There are many additional resonant modes (mainly coming from the Crab Cavities, the MKI and the detectors)
- Potentially dangerous for multi-bunch operations

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- Stainless Steel Warm Pipe
- New collimator materials
- Crab Cavities fundamental mode (work in progress)

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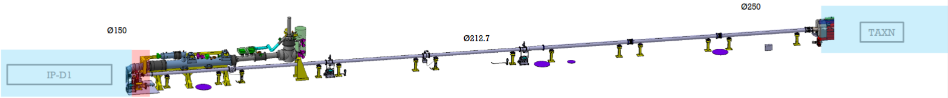
D1 – TAXN: VACUUM CHAMBERS

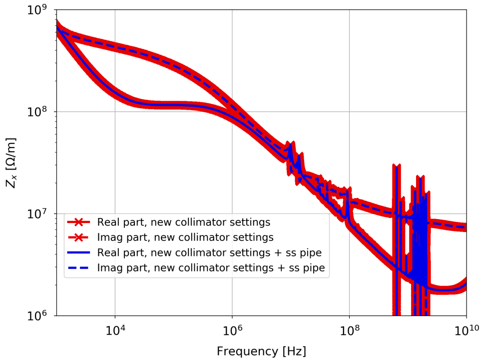


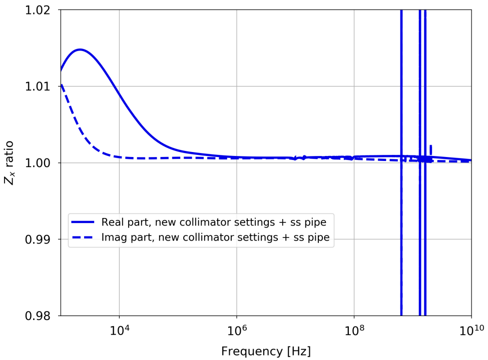
All vacuum chambers ID212.7 & 250 are in stainless steel
All vacuum chambers ID212.7 & 250 are **without** copper plating
All vacuum chambers ID212.7 & 250 are with NEG coating

All transition vacuum chambers:
- ID 250 -> 212.7: Copper plated (NO) + NEG coating
- ID 212.7 -> 150: Copper plated (NO) + NEG coating

From G. Bregliozzi et al, , 66th impedance meeting, 22/11/2022

Impedance Model with Stainless Steel Warm Pipe





The impedance increase is in the order of 0.1% in the freqencies of interest (GHz).

Modifications to the Model: Collimator Materials Update

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- **TCSPMs**: **Cu-coated graphite** option re-introduced (cost $\sim$ 8 times less than Mo-coated MoC),
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- The material's table LHC-TC-ER-0008 v.1 gathers studies' results coming from several years of extensive R&D.
- Following the materials assessment (mainly engineering, impedance, production time and cost considerations) the following jaw materials look appropriate:

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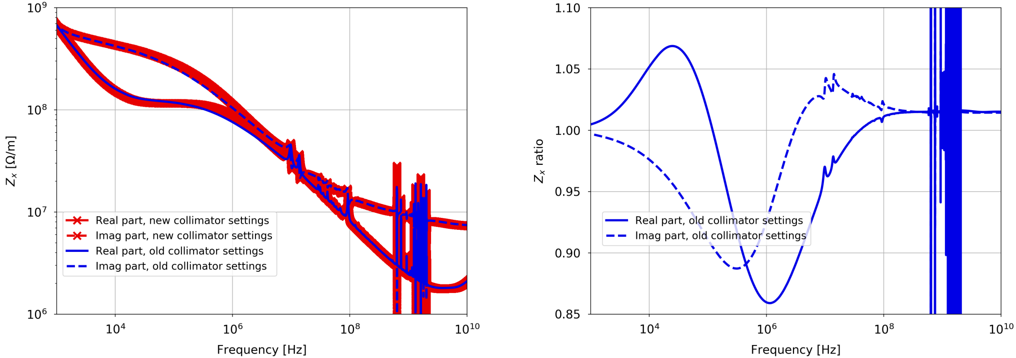
  ⇒ tests are planned to check if the graphite taper of the TCSPMs can be coated.

Impedance Model with Updated Collimator Materials



The new settings have a beneficial effect at low frequencies but a slightly detrimental one in the GHz range. We will have evaluate the effect of the new materials on the octupole thresholds (see next section).

Outline

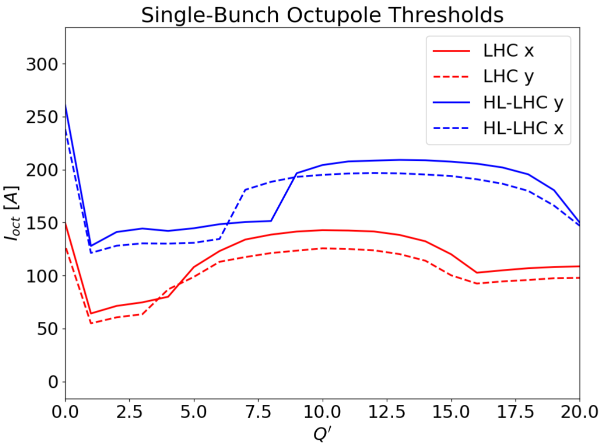
Beam and Machine Parameters

Throughout the rest of the presentation we will only consider the HL-LHC at flat-top (end of the ramp, $\beta^* = 100cm$) because this is the most critical situation. In collision the instabilities would be more critical, but the strong head-on tune spread provides enough Landau damping.

We consider a BCMS beam (which is the brigthest under consideration) with the following parameters:

Intensity [$1e11$p/bunch]	2.3e11
Energy [TeV]	7
Transverse Emittances x/y [μm]	2.3/2.1
Transverse distribution	Parabolic
Bunch length [ns]	1
Longitudinal Distribution	Gaussian
Damping time [turns]	100
RF voltage [mV]	16

Single-Bunch Thresholds LHC vs HL-LHC

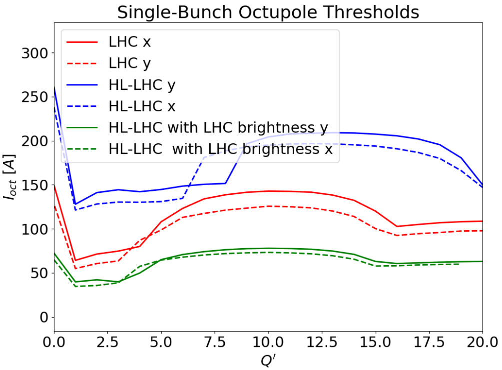


Even though the HL-LHC impedance is lower, the thresholds are higher due to:

- **Brighter beam**: higher intensity and smaller transverse emtittances (BCMS beam)
- We consider a **parabolic transverse distribution** (no tails)
- We assume a short bunch length (1 ns) as an equivalent of the **q-gaussian longitudinal profile** (to be studied)

The Role of Brightness on the HL-LHC Thresholds

It might seem that the efforts to reduce the impedance were not effective but the higher thresholds are a result of the higher brightness (and the assumptions on the distributions). To confirm this we can compare the LHC thresholds the HL-LHC thresholds computed on an LHC beam (case of the octupole threshold MD here).

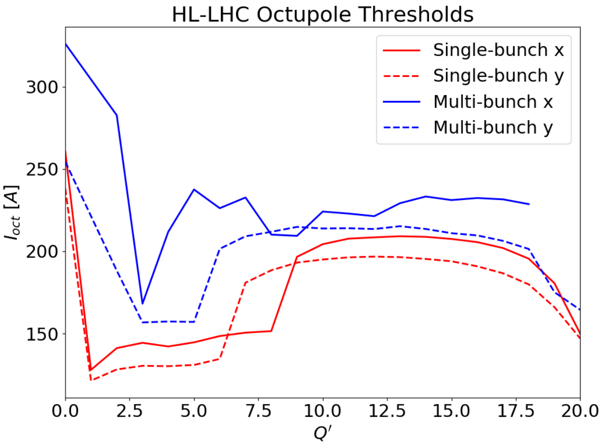


Main parameters:

	LHC	HL-LHC
Intensity [1e11p/bunch]	1.2e11	2.3e11
Emittance x/y [μm]	2.2/1.85	2.3/2.1
Transverse distribution	Gaussian	Parabolic
Bunch length [ns]	1.18	1

Single-Bunch vs Multi-Bunch Thresholds

In the HL-LHC impedance model we have several peaks given by resonating modes. These correspond to "long-lived" wakes which can excite coupled-bunch instability modes.

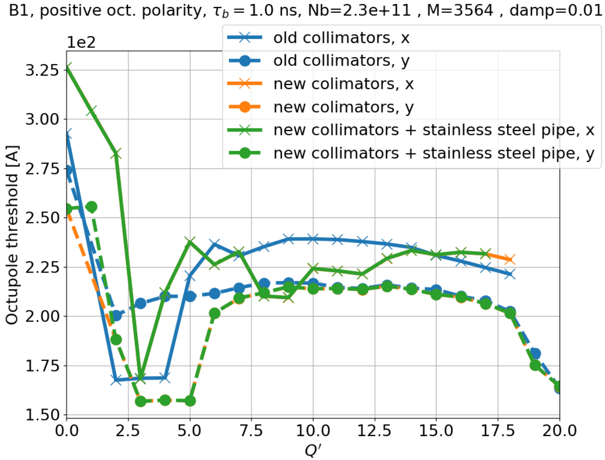


For $Q' = 15$ the threshold is ~ 25 A higher.

For HL-LHC we always need to compute multi-bunch thresholds.

Updated HL-LHC Multi-Bunch Thresholds

We compare the octupole thresholds with the new additions to the model.



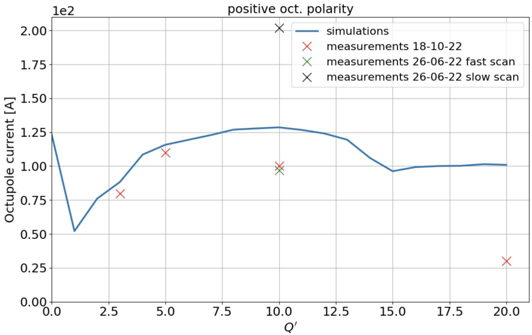
The new collimator settings give an improvement around $Q' = 10$ region, while the stainless steel warm pipe doesn't give a significant contribution.

Latency Effects

In the past the octupole thresholds predicted for the LHC have been found to be lower than the ones measured in the machine. Does latency play a role?

To quantify the effect of latency on octupole scans we performed an MD in which we carried out two types of scan:

- Fast: unaffected by latency
- Slow: affected by latency



Result: if we want to take into account these effects we need to multiply the measurements of fast scans by 2.

For HL, the octupole threshold at $Q' = 15$ taking into account only impedance and latency is then $225A \cdot 2 = 450A$ (for a BCMS beam, without the crab cavities fundamental mode – see next section).

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Crab Cavities Fundamental Mode Impedance

The fundamental mode of an RF cavity contributes to the impedance of the device like every other resonant mode but:

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- $Z_{\perp}(\omega) = \frac{\omega_{RF}}{\omega} \frac{R_{\perp}}{1 - jQ(\frac{\omega_{RF}}{\omega} - \frac{\omega}{\omega_{RF}})}$

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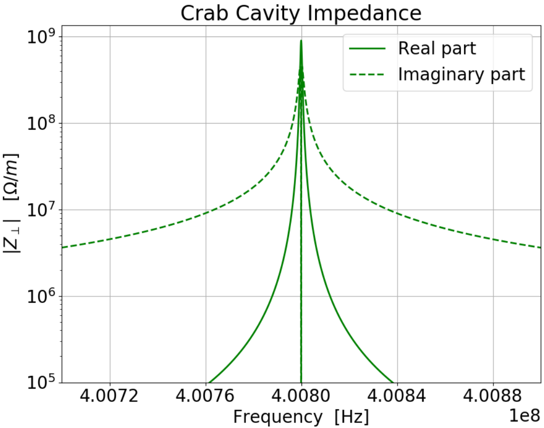
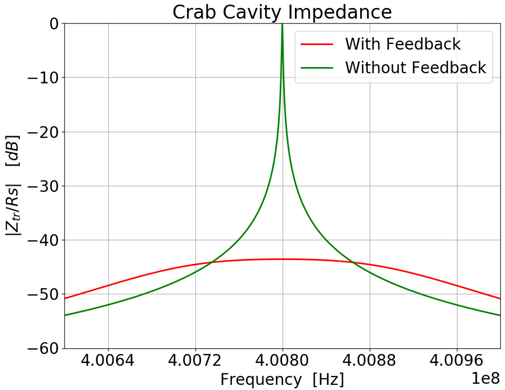
- $Q = 5 \cdot 10^5$
- $R_{\perp} = 9.03 \cdot 10^8 \frac{\Omega}{m}$
- Very high, but narrow-band impedance



Using the RF Feedback to Mitigate the Crab Cavity Impedance

The RF feedback system can act on the fundamental mode of the cavity, so it can be used to reduce the impedance peak.

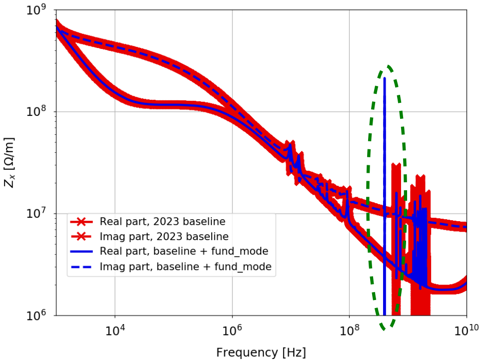


Closed Loop cavity impedance

- $Z_{\perp}^{CL}(\omega) = \dfrac{Z_{\perp}(\omega)}{1 + Ge^{-j\tau(\omega-\omega_{RF})}Z_{\parallel}(\omega)}$
- $Z_{\parallel}(\omega) = \dfrac{1}{1 - jQ(\frac{\omega_{RF}}{\omega} - \frac{\omega}{\omega_{RF}})}$
- feedback gain $G = 150$
- loop delay $\tau = 1200ns$

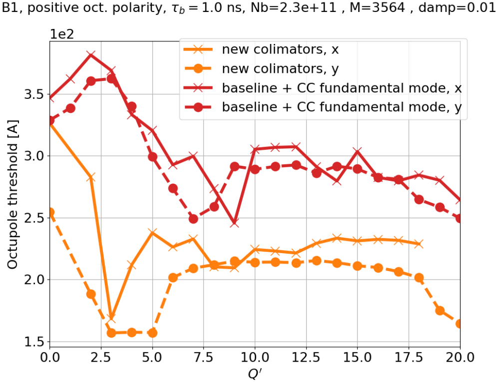
Thanks P. Baudrenghien!

HL-LHC Impedance Model with CCs Fundamental Mode



Even with the RF feedback the fundamental mode is one order of magnitude higher than the HOMs.

Octupole Thresholds with the CCs Fundamental Mode

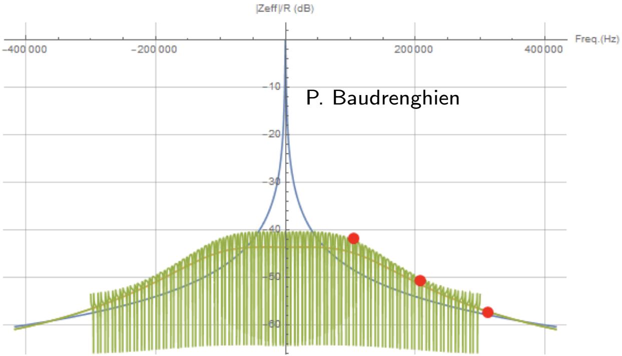


For $Q' = 15$ the octupole threshold is increased by $75A$. Including the latency factor the total threshold becomes **600** A. This increase would reduce significantly the DA and the new threshold is higher to the hardware limit (590 A).

Mitigation Strategies for the CCs Fundamental Mode

Three mitigation strategies under evaluation:

- **Flat optics**: it would reduce the beta functions at the cavities, reducing the effect of their impedance. It can yield a factor 2 reduction, which could be combined with higher octupoles (if ok for DA). Studies ongoing.
- **The betatron comb filter**: it is a more advanced RF feedback which selectively reduces the impedance of the cavities on the betatron lines. It works best if the tune is known with high accuracy. Otherwise we need a more advanced design with wider notches. Presentation by P. Baudrenghien. Studies ongoing (and MD foreseen).
- **Amplitude feedback**: the cavities can be used as an amplitude feedback in order to damp the head-tail oscillation mode. Studies ongoing.



Conclusion

- The HL-LHC impedance has been effectively reduced with respect to the LHC, but several high order modes have been added to the model.
- The single-bunch instability thresholds are anyways higher than the LHC ones due to the high brightness of the beams and other assumptions on the beam distributions.
- The added stainless steel sections of the warm pipe play a negligible role.
- The thresholds obtained from the simulations need to be multiplied by a factor ~ 2 to reproduce the effect of latency.
- The updated collimator materials slightly improve the situation but the resistivity of the tapers is still not taken into account.
- The fundamental mode of the Crab Cavities gives an unacceptable impedance increase but mitigation strategies are under study.