Crab cavity HOM impedance requirements and transverse damper upgrade

N. Biancacci,
K. Li, E. Métal and B. Salvant

HiLumi WP2 Task Leader meeting
02-10-2015

Acknowledgements: R. Calaga, R. De Maria
Outline

1. Introduction
   - Update of HOM list

2. HOM & octupole thresholds
   - Growth rate
   - Octupole threshold
   - Single bunch octupole thresholds
   - Coupled bunch octupole thresholds

3. Crab Cavities statistical simulations
   - Coupled bunch studies
   - Single bunch studies
   - Gain increase

4. Conclusions and next steps
The crab cavities impedance model has been recently updated to last HOM tables:

- **DQW update**: EDMS - 1518298, 03-07-2015, (*HOM impedance reference model*)

What changed?

- No change for the DQW that still presents the high HOM ≈1.75 GHz with $R_s \approx 362 \, M\Omega/m$.
- Last update from RCalaga (30-09-2015) → this HOM has been reduced to $R_s \approx 0.8 \, M\Omega/m$. This is being checked with BNL to assess if other HOMs are affected.
- The RFD HOMs stay below few $M\Omega/m$. 
We systematically study the effect of an HOM added to the HL-LHC baseline:

- $R_s \in (100 \, k\Omega/m, ..., 100 \, G\Omega/m)$
- $f_{res} \in (100 \, MHz, ..., 2 \, GHz)$
- $Q = 1000$ fixed in order to be overlapping with single and coupled bunch spectral lines.

**Scenario:** Single bunch, 50 turns damper, $Q' = 5$, $N_b = 2.2 \cdot 10^{11}$ ppb, $\sigma_z = 8.1$ cm.

**HL-LHC impedance baseline:** Low impedance collimators (MoC$+5\mu m$ Mo on IP7).

**HL-LHC optics:** $\beta^* = 15 cm$, V1.1.
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![Graph](image)

\( \rightarrow \) From \( R_s \approx 1 \, G\Omega/m \) we exceed the baseline impedance model.
Projecting over a single frequency we can define the threshold looking at the Growthrate vs $R_s$:

→ From $R_s \approx 1 \, \text{G\Omega/m}$ we exceed the baseline impedance model.
We now investigate what is the octupole current needed to stabilize each HOM at a given frequency, assuming:

- $\varepsilon_n = 2.5 \, \mu m$,
- Gaussian distribution,
- Positive octupole sign (similar for negative sign).

$\rightarrow$ For each frequency we can now determine what $R_s$ will provoke an arbitrarily chosen increase of stabilizing octupole current w.r.t. baseline.

$\rightarrow$ In this way we can draw an octupole threshold curve in function of the HOM frequency.
Single Bunch (SB) stability limits considering an increase of 10, 50 and 100 A w.r.t. the HL-LHC baseline normalized to $Q$ and weighting the HOMs by $\beta_{crab}/\beta_{av} \approx 50$ for 1 cavity.

**Reminder:** baseline octupole threshold @ $Q'$=5 is 30 A for negative octupole sign, 70 A for positive sign.

This plot can be used in a design stage tuning each of the modes below the thresholds.

→ Both DQW and RFD are well below the octupole threshold for an increase of 10 A.
→ N.B.: Each HOM point is a worst case (i.e. if the SB line falls on it). For very narrow modes, a statistical analysis completes the picture (see next slides).
→ N.B.: No interplay from the modes is assumed.
With a similar approach we derive the Coupled Bunch (CB) stability limits considering an increase of 10, 100 and 1000 A w.r.t. the HL-LHC baseline.

**Reminder:** baseline octupole threshold @ $Q' = 5$ is 30 A for negative octupole sign, 70 A for positive sign as in SB.

→ The DQW presents the mode at 1.75 GHz who leads to more than 1000 A increase of octupole current if a CB spectral line falls on it.

→ Less critical is the DQW 920 MHz mode (+100 A).

→ The RFD is below within the 10A threshold.
We performed a set of 100 simulations of possible crab cavities HOM configurations on top of the baseline HL-LHC impedance model accounting for:

- 16 crab cavities in total (baseline now to 8: to be updated).
- Variable frequency spread of $\pm 3\, MHz$ between each cavity in each simulation.

For the RFD design, considering the octupole current required for each simulation and deriving the probability density function, we get:

$\rightarrow$ For positive octupole sign, the threshold is increased from $\approx 70\, A$ to $\approx 150\, A$.
$\rightarrow$ For negative octupole sign, the threshold is increased from $\approx 30\, A$ to $\approx 70\, A$. 

RFD update Qp5 d0p02 plane x M2748 gaussian eps2.5um Nb2.2e11 $\sigma_z=0.081m$
The **DQW design** is compared with the 1.75 GHz mode . . .

![DQW design comparison](image)

. . . and without it:

![DQW without 1.75 GHz](image)

1) The 1.75 GHz would provoke machine dumps the 60% of the time ($I > I_{\text{max}} = 550$ A).

2) Removing it, the driving mode is expected to be the 920 MHz (threshold moved to $\approx 150$ A for negative octupole sign, and $\approx 320$ for positive sign.

3) Allowing for a smaller $R_s$ for the 1.75 GHz mode (R. Calaga update), would place it in the shadow of the 920 MHz mode: the situation would not deviate much from the case 2).
Single bunch results for **DQW design**:

![DQW update](image)

→ In both cases the increase in octupole current is negligible (< 10A).

Single bunch results for **RFD design**:

![RFD update](image)
For the negative sign of the octupole we require:

1. A current of 70 A for the RFD design.
2. A current of 150 A for the DQW design (without 1.75 GHz mode).

Can we reduce the CB octupole threshold required by increasing the damper gain?
For the negative sign of the octupole we require:

1. A current of 70 A for the RFD design.
2. A current of 150 A for the DQW design (without 1.75 GHz mode).

→ For the baseline HL-LHC model, there is no reduction when adding damper gain over different $Q'$.  
→ Statistical simulations with Crab cavities on top of the HL-LHC are still on-going...
Conclusions I

- We developed a method to assess *a priori* the compatibility of an HOM with the octupole current budget of the HL-LHC at $\beta^* = 15 \text{ cm}$, both for single bunch (SB) and coupled bunch (CB) cases.
  
  $\rightarrow$ An HOM with $\beta_{\text{crab}}/\beta_{\text{av}} \cdot R_s/Q \simeq 1 \text{ M}\Omega/m$ (or equivalently $R_s/Q \simeq 20 \text{ k}\Omega/m$) requires $\approx 10 \text{ A}$ to be stabilized in SB regime.
  
  $\rightarrow$ An HOM with $\beta_{\text{crab}}/\beta_{\text{av}} \cdot R_s \simeq 10 \text{ M}\Omega/m$ (or equivalently $R_s/Q \simeq 200 \text{ k}\Omega/m$) requires $\approx 10 \text{ A}$ to be stabilized in CB regime.

- The RFD and DQW design have been found to be compatible with respect to single bunch stability threshold:
  
  $\rightarrow$ Both RFD and DQW design require an increase of the octupole current needed $\approx 10\text{A}$.

- The DQW design, as it is now, is not compatible with current the HL-LHC CB stability limits:
  
  $\rightarrow$ The 1.75 GHz mode provokes exceeding of the maximum octuple current 60% of the cases simulated.

- If the 1.75 GHz mode of the DQW is reduced to the level of $0.8 \text{ M}\Omega/m$ (as it should now be...) it would require, together with the other HOMs:
  
  $\rightarrow$ $\approx 150 \text{ A}$ for negative octupole sign (HL-LHC baseline respectively at 30 A).
  
  $\rightarrow$ $\approx 320 \text{ A}$ for positive octupole sign (HL-LHC baseline respectively at 70 A).
Conclusions II

- The RFD design is compatible with current the HL-LHC stability limits for CB:
  - For positive octupole sign, the threshold is increased from \( \approx 70 \, \text{A} \) to \( \approx 150 \, \text{A} \).
  - For negative octupole sign, the threshold is increased from \( \approx 30 \, \text{A} \) to \( \approx 70 \, \text{A} \).

- Increasing the damper gain from 50 to 20 turns is not reducing the baseline octupole current needed for the HL-LHC.
  - For \( Q' = 5 \) the baseline threshold is increased of a factor \( \approx 2 \).
  - For \( Q' = 10 \) the baseline threshold is almost unchanged (50 A).
  - Statistical simulation on baseline + Crab cavities on going...

- If we collide at \( \beta^* = 70 \) we can gain a factor \( \approx 5 \) and lower accordingly the octupole current thresholds.
Next steps and open questions

- Simulations for the present crab cavity scenario (8 crabs instead of the 16 simulated here), and mixed RFD-DQW scenario.

- How do we include in this frame the recent measurements on the LHC showing a factor 5 increase in octupole current?

- …
Thank you for your attention!
LHC single and coupled bunch octupole thresholds.