# Numerical Evaluation of the Tuning, Pressure Sensitivity and Lorentz Force Detuning of RF Superconducting Crab Cavities

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**INTRODUCTION**: Crab cavities are key components of the HL-LHC update. They provide a deflecting kick to the particle bunch that maximizes the beam overlap and therefore the number of collisions. Two concepts have been developed: the Double Quarter Wave (DQW) and the RF Dipole (RFD).

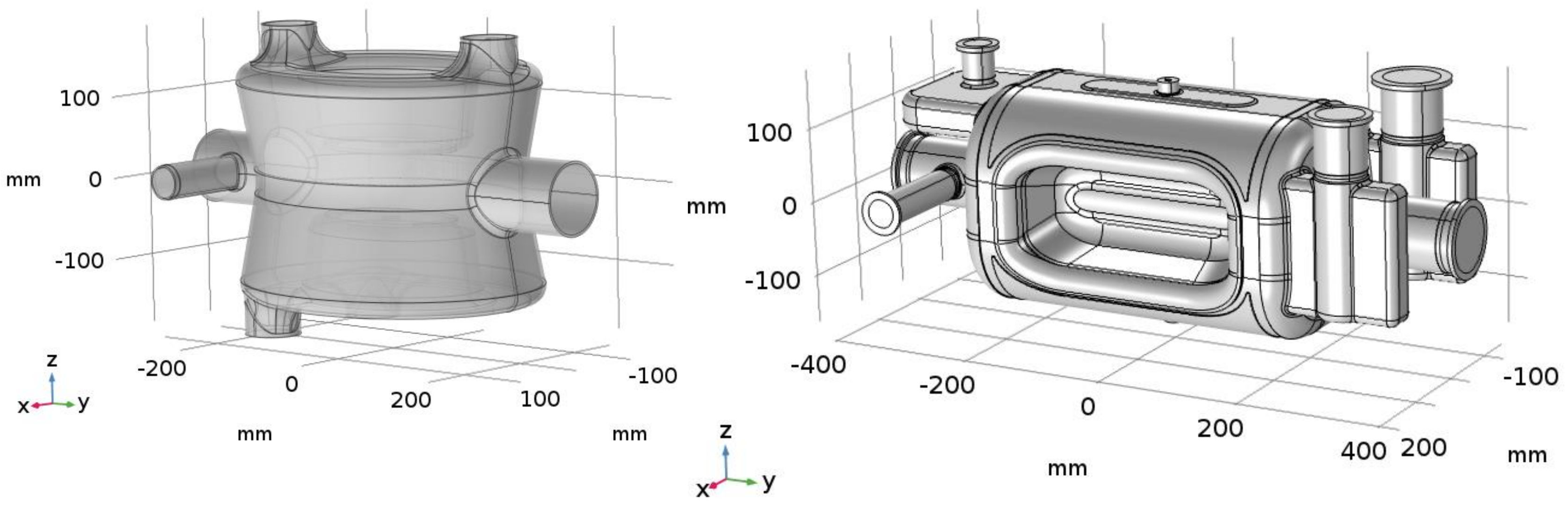

**Figure 1**. DQW and RFD cavities numerical models

**THEORY**:

- *Tunability* – Ability to change the cavity fundamental frequency by locally deforming its shape.
- *Pressure sensitivity (PS)* – Variation of the cavity fundamental frequency due to external pressure fluctuations, $P_{PS}$.
- *Lorentz force detuning (LFD)* – Variation of the cavity fundamental frequency due to radiation pressure, $P_{LFD}$ [1,2].

$$P_{LFD} = \frac{1}{4}(\mu_0 H^2 - \varepsilon_0 E^2)\left(\frac{V_{T,nominal}}{V_T}\right)^2$$

$$V_T = \left| \int E_x \cos\left(\frac{\omega y}{c}\right) dy + \int \mu_0 c \cdot H_z \cdot \sin\left(\frac{\omega y}{c}\right) dy \right|$$

**Table 1**. Calculation of cavity tunability, PS and LFD

| Tunability [kHz/mm] | PS [Hz/mbar] | LFD [Hz/MV$^2$] |
|---|---|---|
| $\frac{f_1 - f_0}{\lvert v_{s1}\rvert + \lvert v_{s2}\rvert}$ | $\frac{f_1 - f_0}{P_{PS}}$ | $\frac{f_1 - f_0}{V_{T,nominal}^2}$ |

**COMPUTATIONAL METHODS**:

- Coupled RF-structural simulations (*emw, solid, ale*).
- Cavity and vacuum meshes deformed according to structural loads (*solid, ale*).
- Niobium cavity solid domain, vacuum domain inside the cavity.
- Integration in COMSOL® of the cavity deflecting kick, $V_T$.
- Mesh sensitivity analysis in the high deformation regions. Choice of a 2 mm mesh.

**RESULTS**: DQW tunability value is 315.5 kHz/mm, which is in fair agreement with experimental measurements.

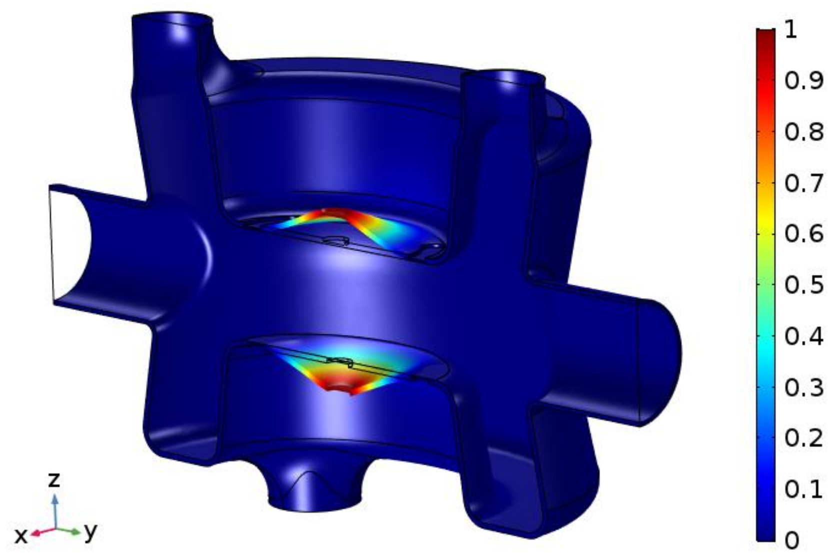

**Figure 2**. DQW deformation (mm). Tuning pull

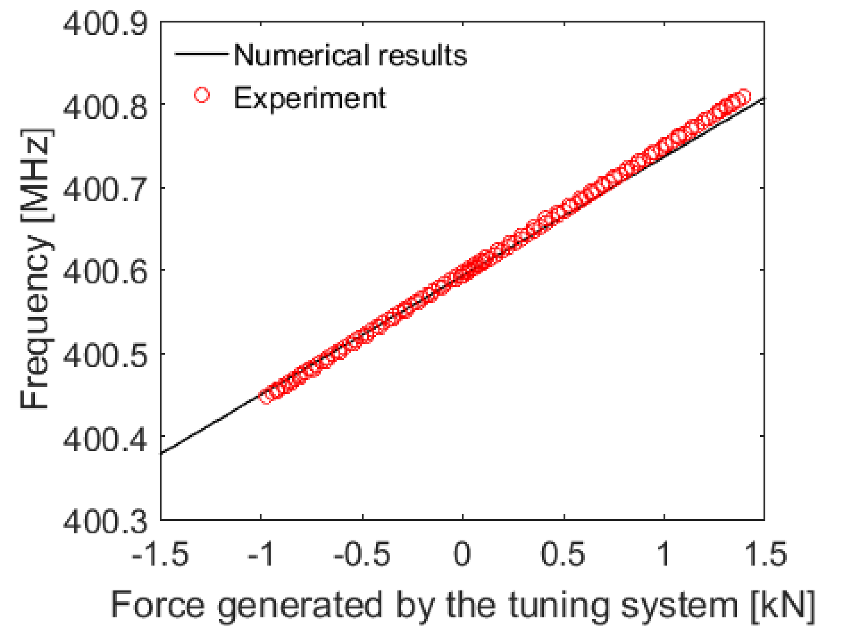


**Figure 3**. Experimental vs. numerical results of tuning frequency shift

PS and LFD results were used to optimize the RFD cavity design. *PS*=244 Hz/mbar, *LFD*=659 Hz/MV$^2$.

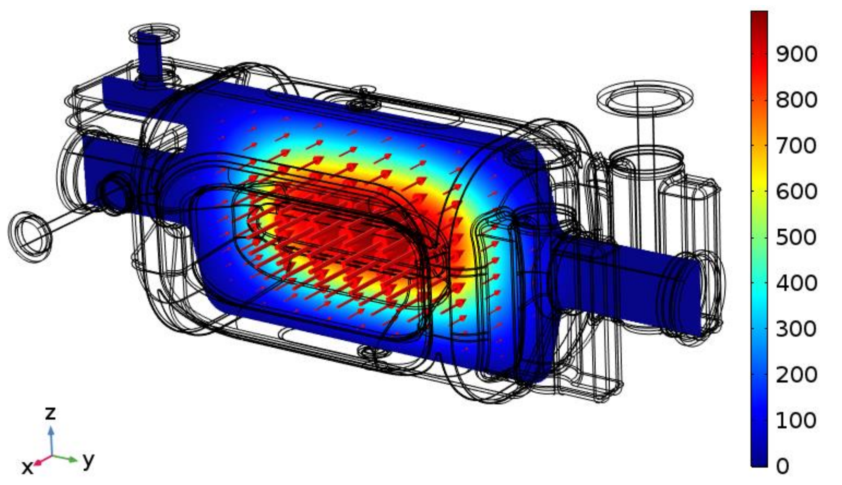

**Figure 4**. Electric field (V/m)

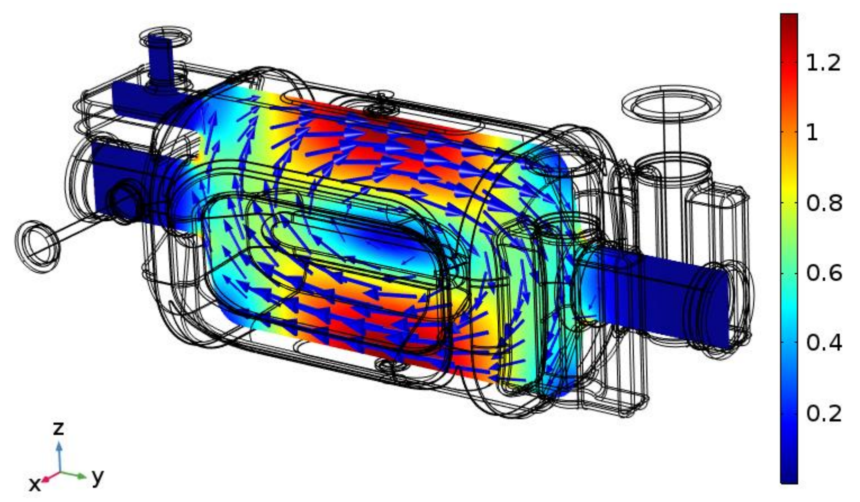

**Figure 5**. Magnetic field (A/m)

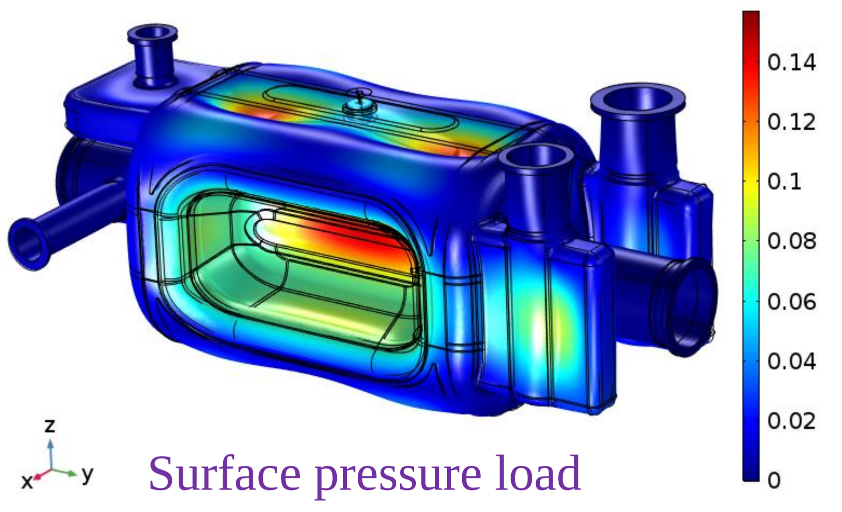


**Figure 6**. PS deformation (mm)

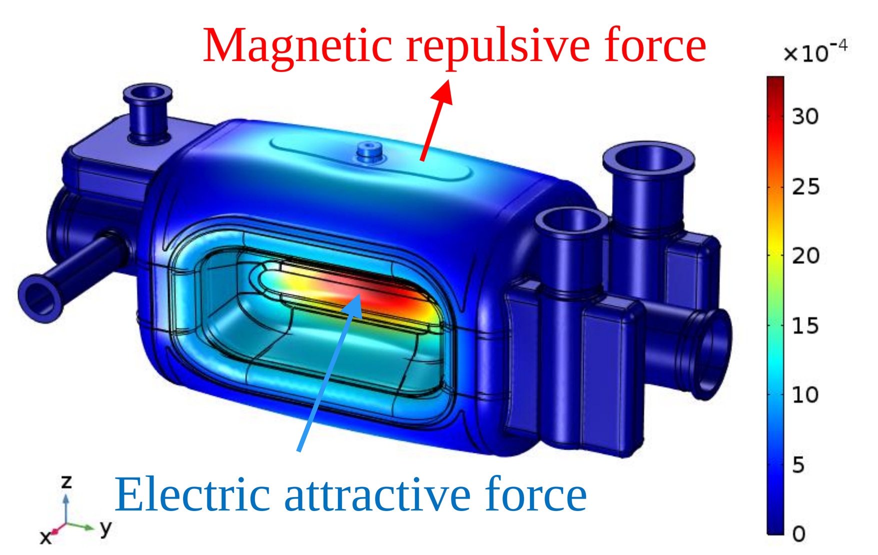


**Figure 7**. LFD deformation (mm)

Results were also used to understand the effect of the tuning system stiffness on the frequency shift and optimize its design.

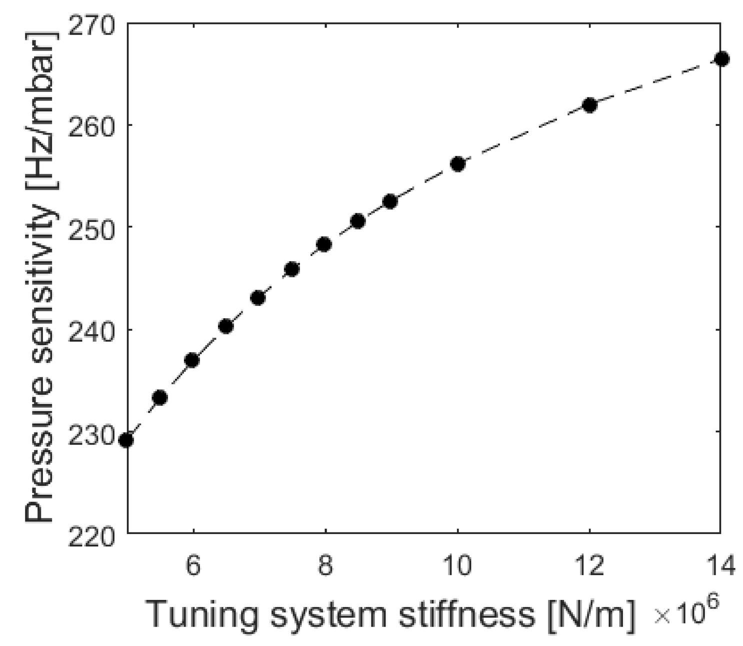


**Figure 8**. PS vs. tuner stiffness

**CONCLUSIONS**: Tunability, PS and LFD are paramount parameters in the design of SRF cavities. COMSOL® provided useful and valuable results that were used for comparison with experimental evidence of the DQW cavity and to support the design of the RFD cavity and tuning system.

**REFERENCES**:

1. R. Calaga, "Deflecting cavities," Joint Accelerator School, Japan, 2017.
2. S. Verdú-Andrés et al., "Lorentz detuning for a double-quarter wave cavity", SRF2015, Whistler, BC, Canada, 2015.