HiLumi HL-LHC PROJECT

COMSOL CONFERENCE 2018 LAUSANNE

Numerical evaluation of the tuning, pressure sensitivity and Lorentz force detuning of RF superconducting crab cavities

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CERN

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COMSOL CONFERENCE – LAUSSANE – 22/10/2018

Outline

- Introduction
- Numerical model
- Results
  - Overall results
  - Tunability
  - Pressure sensitivity
  - Lorentz force detuning
- Conclusions

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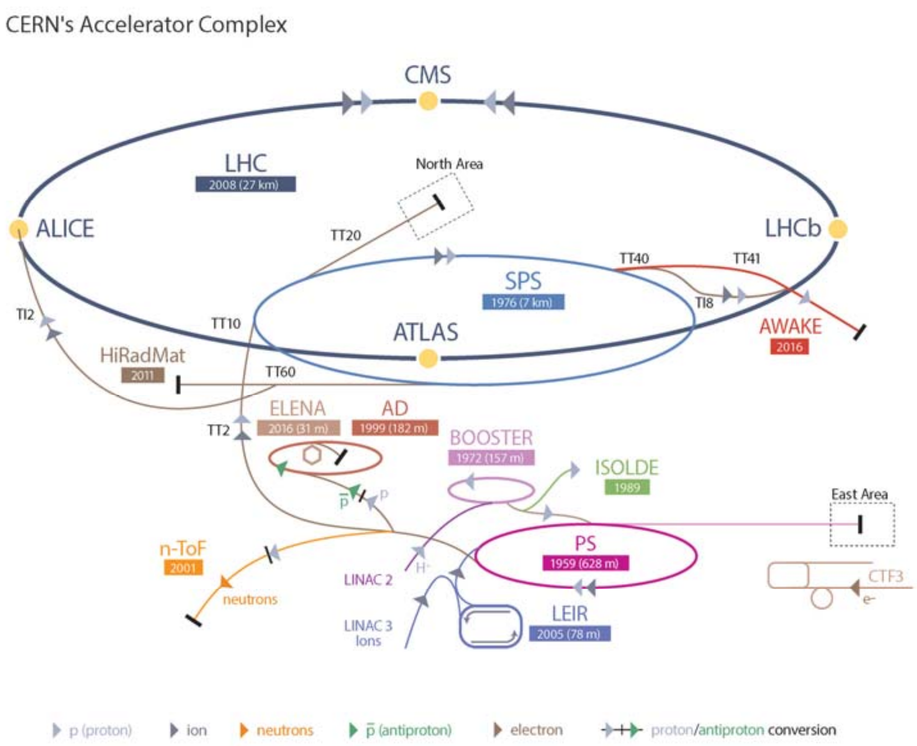
Introduction - CERN



- CERN accelerator complex is the largest in the world
- LHC is the last stage and CERN's flagship
- **27 km** underground tunnel
- **2** counter-rotating **proton beams**
- **Collisions** (**experiment** location) which generate other particles

- **Radio Frequency System** (Acceleration)
- **Superconducting magnets** (bend trajectory)
- **2 Collimation Regions** (Beam Cleaning and Machine Protection)

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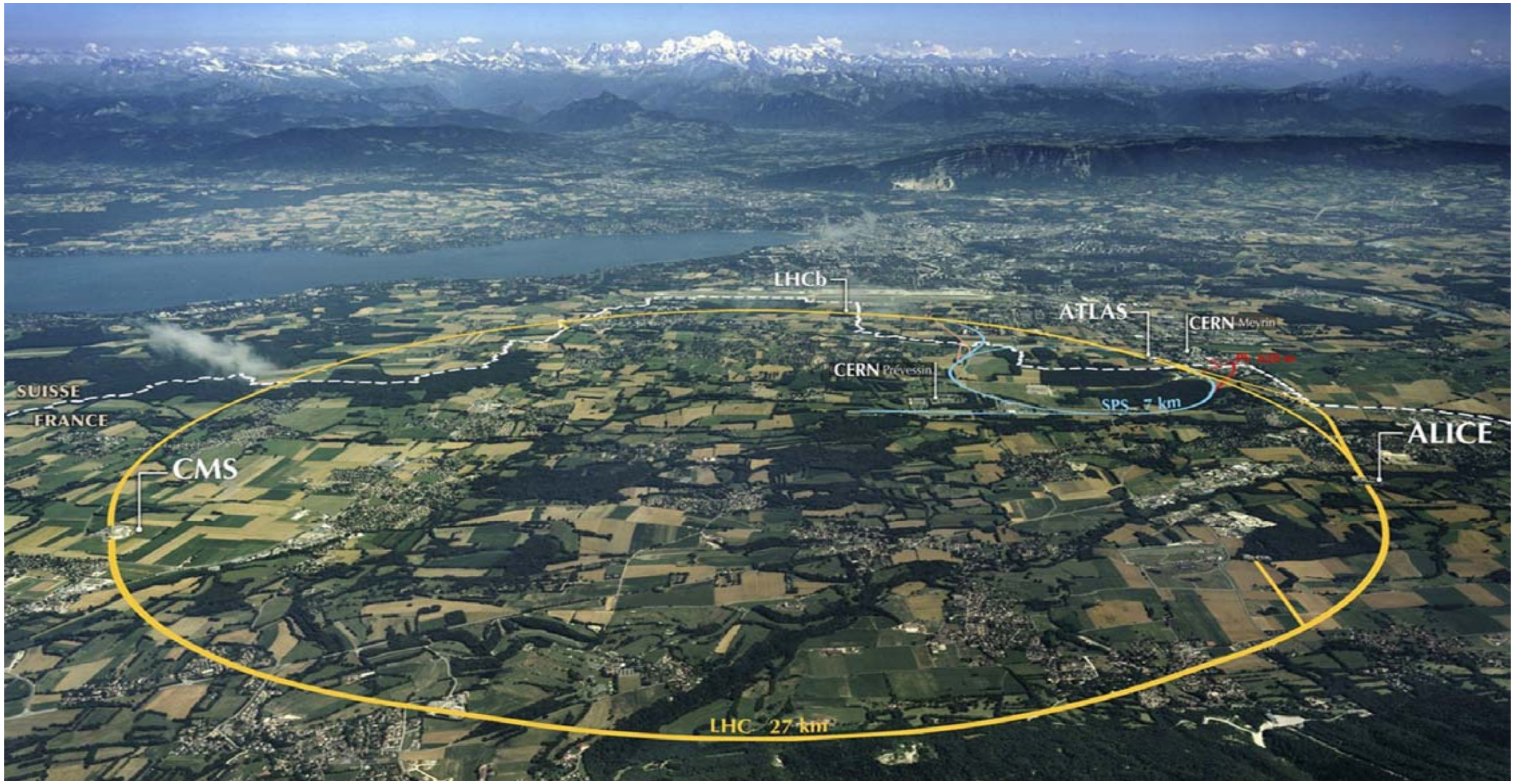

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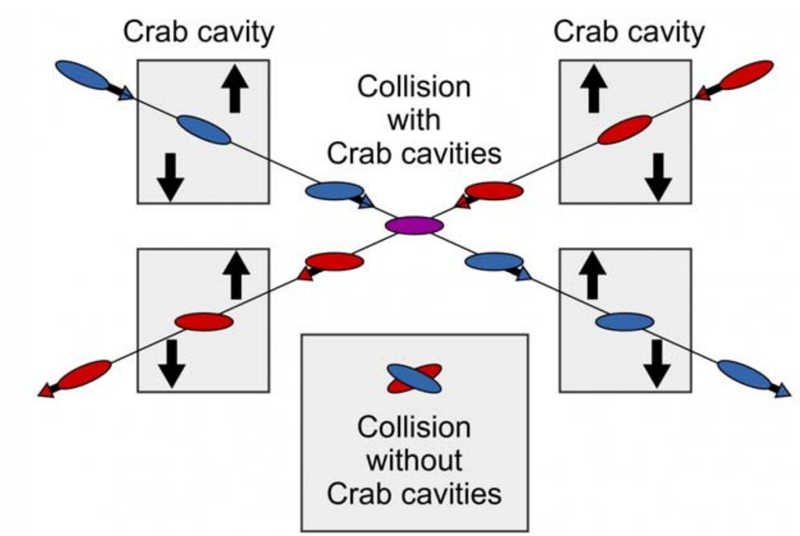
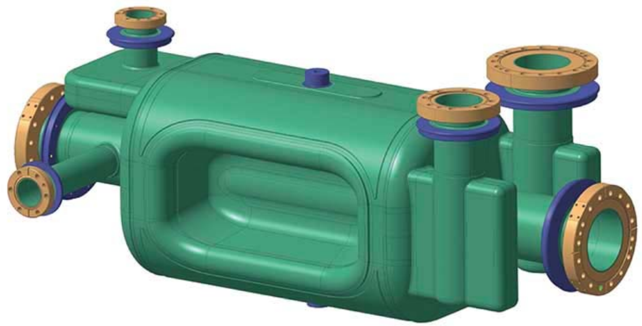
Introduction - HL-LHC

- Peak luminosities a factor of five larger than LHC
- Update on **superconducting magnets**, **high-power superconducting links** with zero energy dissipation. New demands on **vacuum, cryogenics** and **machine protection**, and will require new concepts for **collimation** and **diagnostics**.
- **Crab cavities.** Transverse deflection of particle bunches.



Double Quarter Wave

RF Dipole

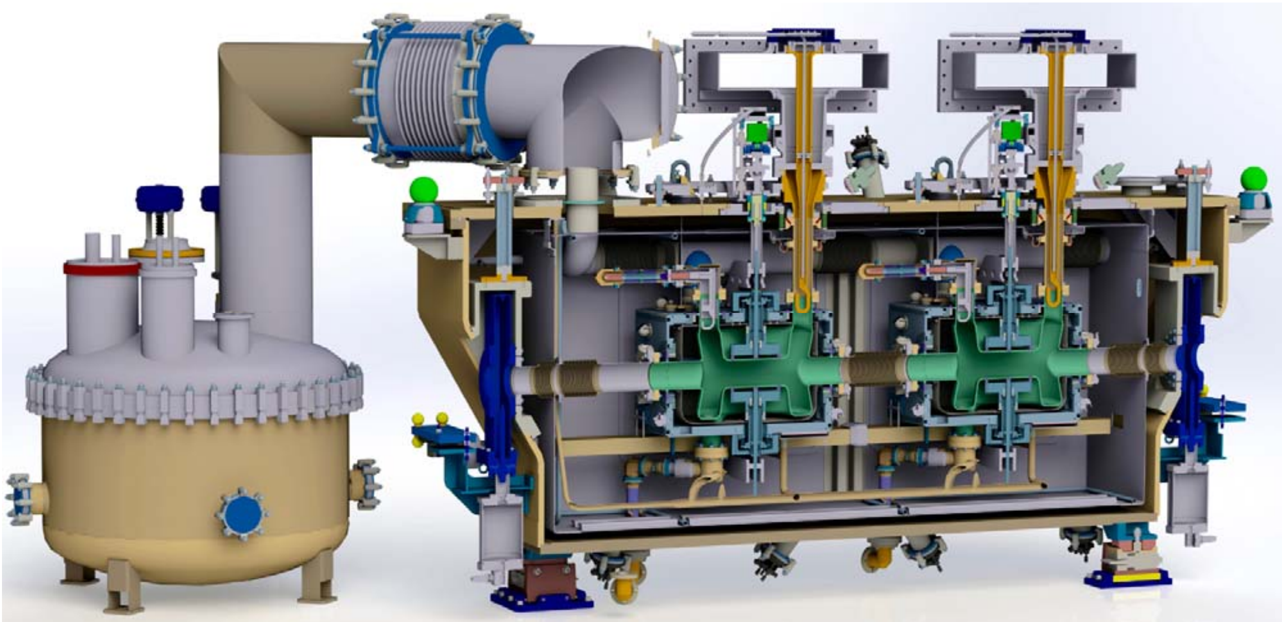


Introduction - Crab cavities

Double Quarter Wave (DQW)

RF Dipole (RFD)

- Operated at **2 K**



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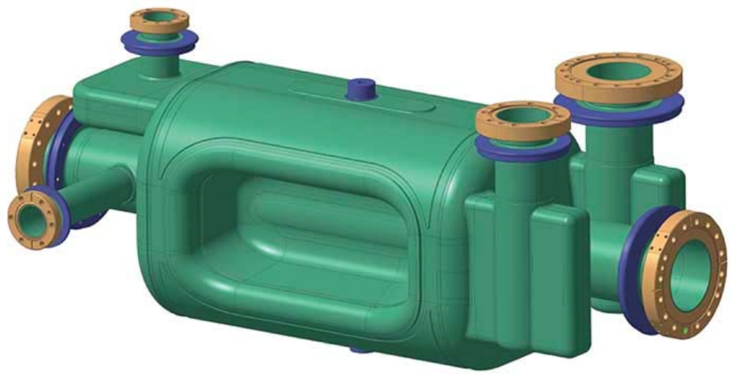
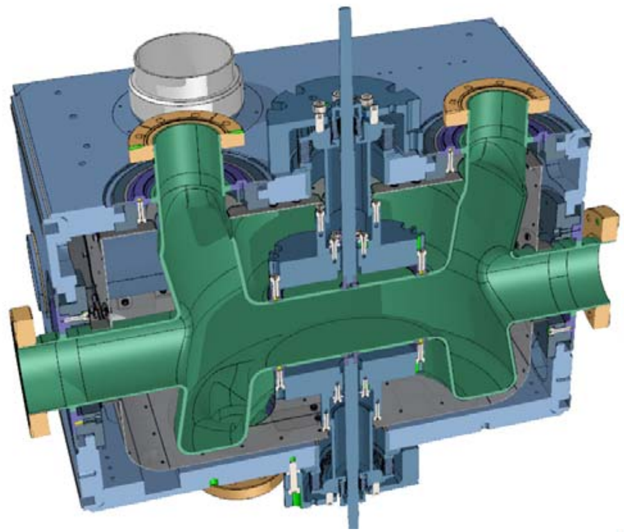


- Operated at **2 K**
- **3.4 MV** deflecting kick
- **400.79 MHz** fundamental frequency. **Tuning system**



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Introduction - Crab cavities

Double Quarter Wave (DQW)

RF Dipole (RFD)

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- **Pressure sensitivity** requirements. Changes of the cavity fundamental frequency due to pressure fluctuations of the cold He bath.
- **Lorentz force detuning** requirements. Change of the cavity fundamental frequency due to radiation forces.

Introduction - Crab cavities

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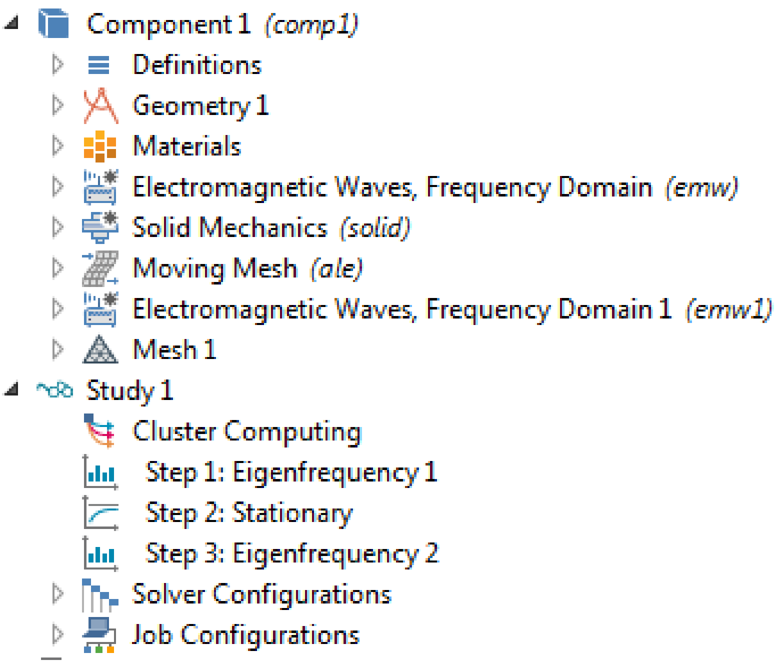
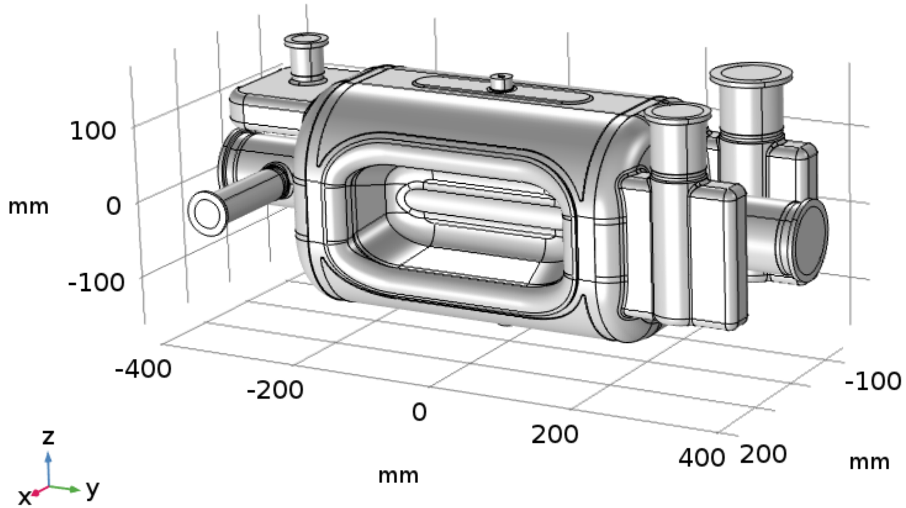
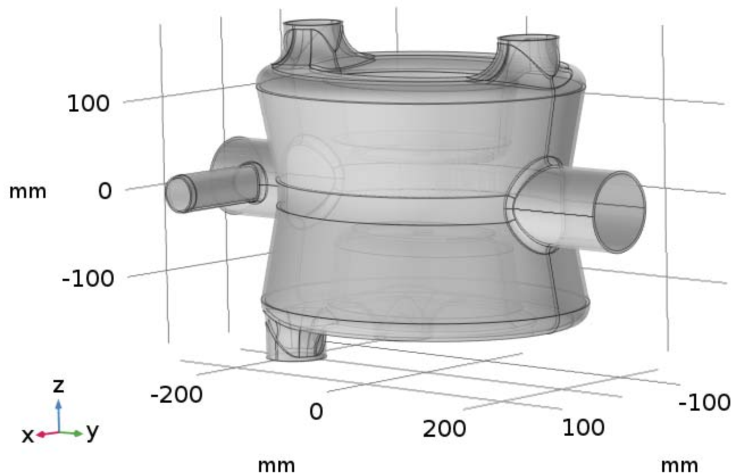
Numerical model



RF Dipole



Double Quarter Wave



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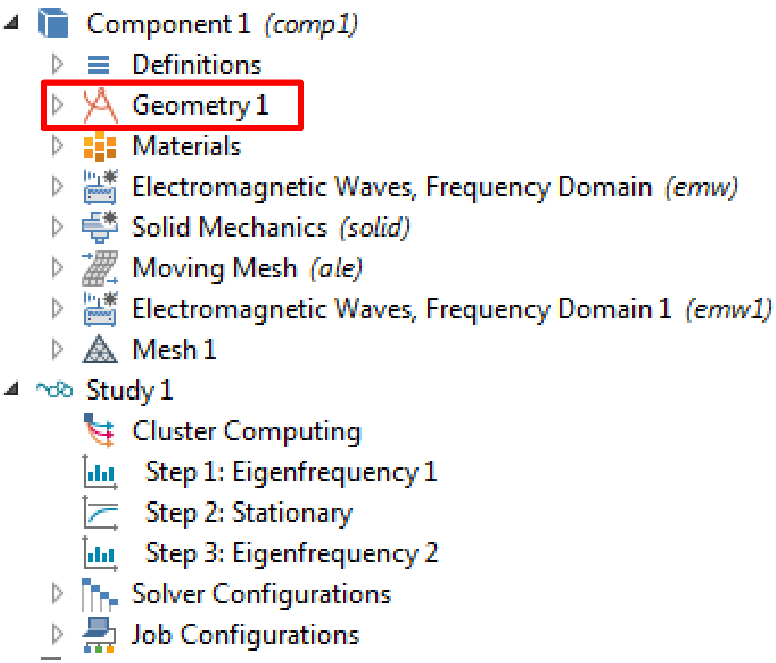
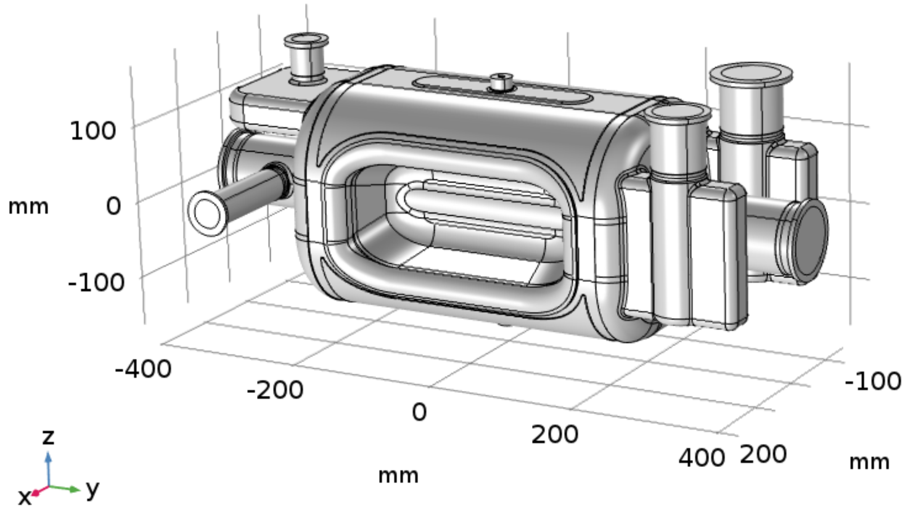


- Two models:
- DQW for tunabilty, validation and mesh sensitivity
- RFD for pressure sensitivity (PS), Lorentz force detuning (LFD) and design optimization

RF Dipole



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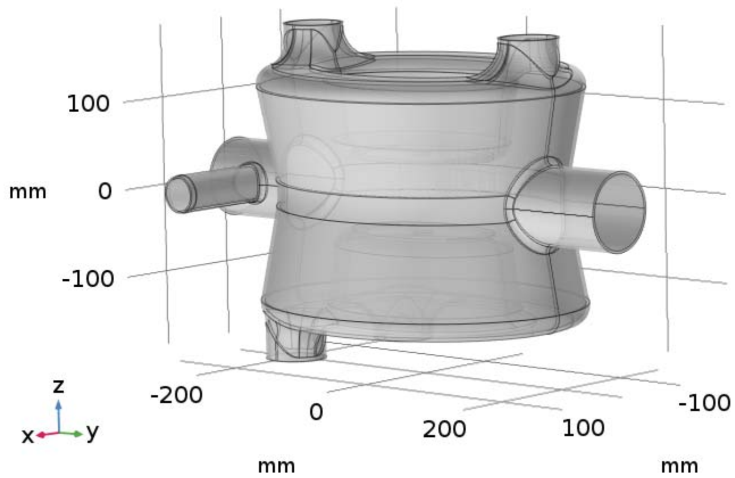
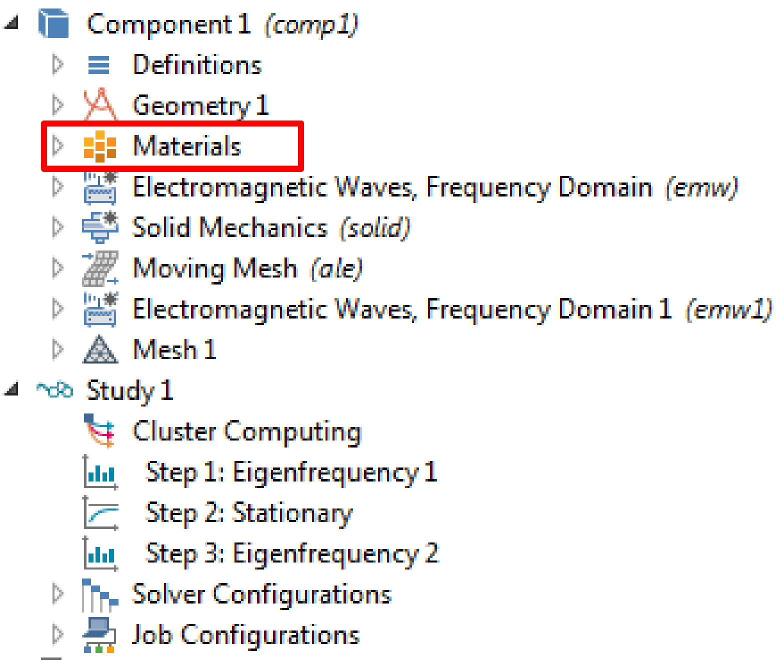


Numerical model



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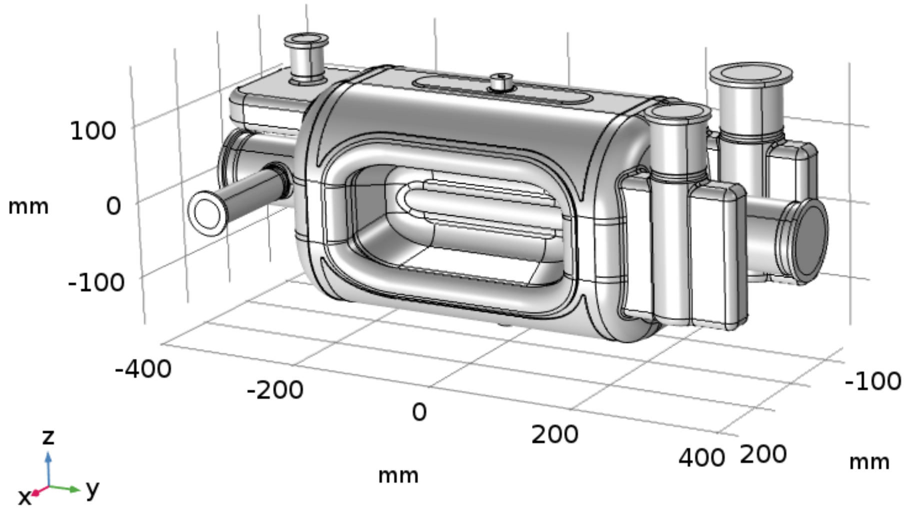

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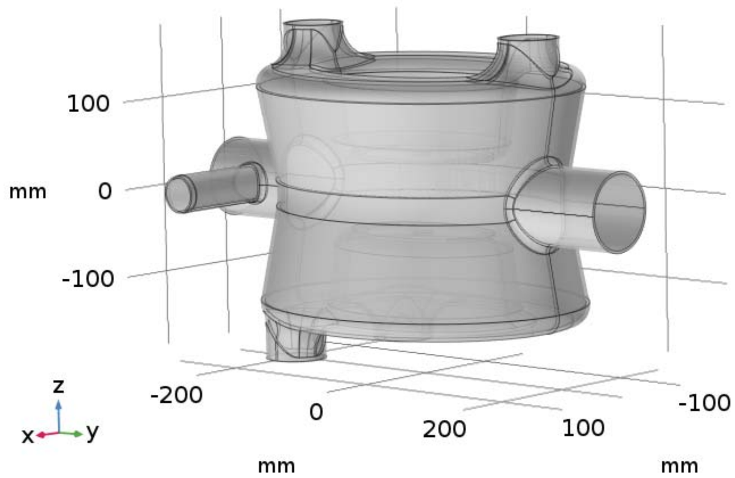

- Niobium RRR300 for the cavities
- 55Ti45Nb for the tuning interfaces
- Vacuum volume inside the cavity

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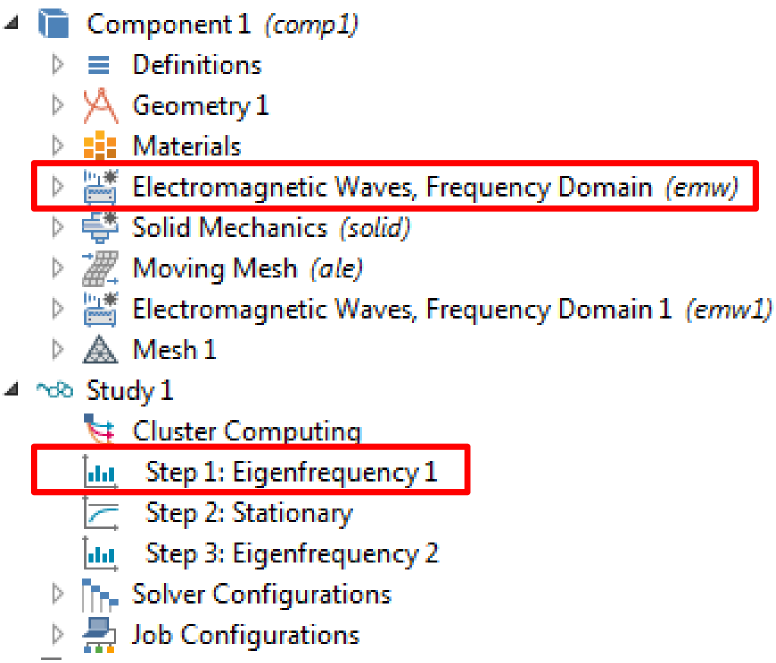
Numerical model



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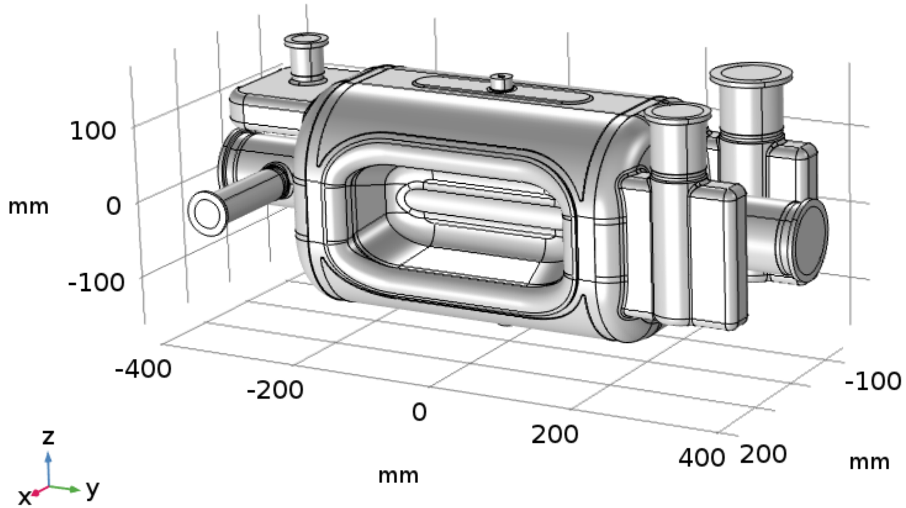

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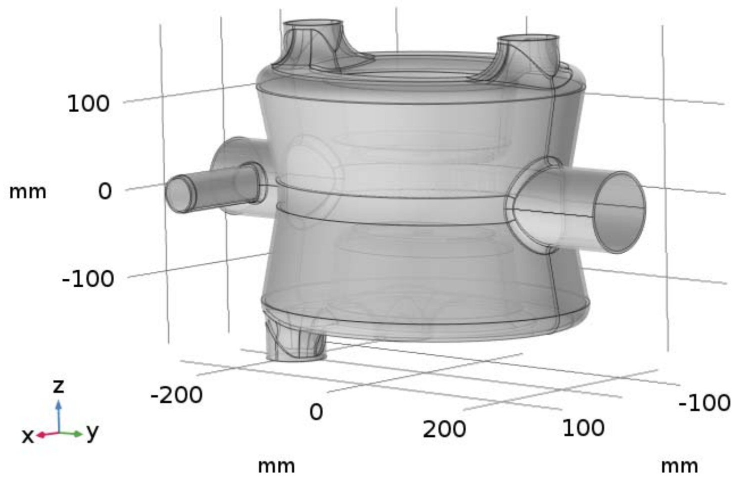
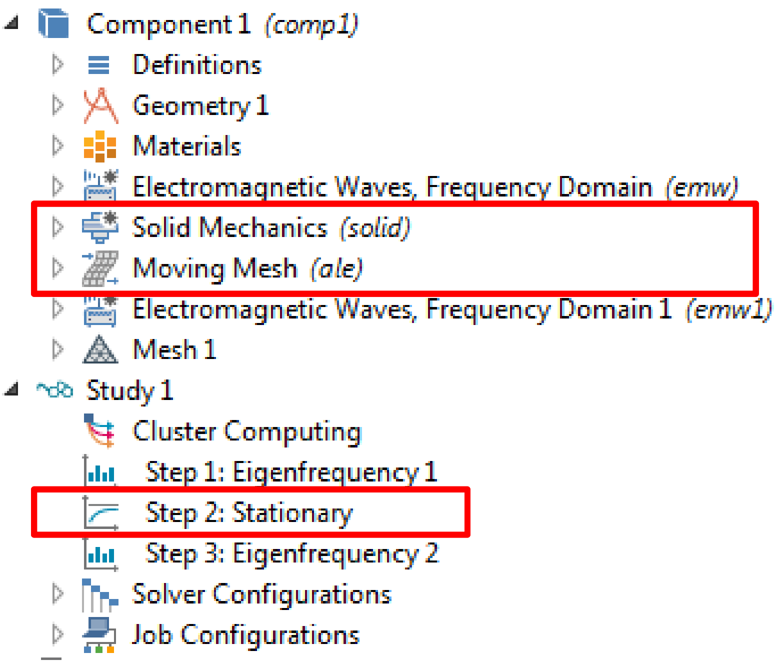


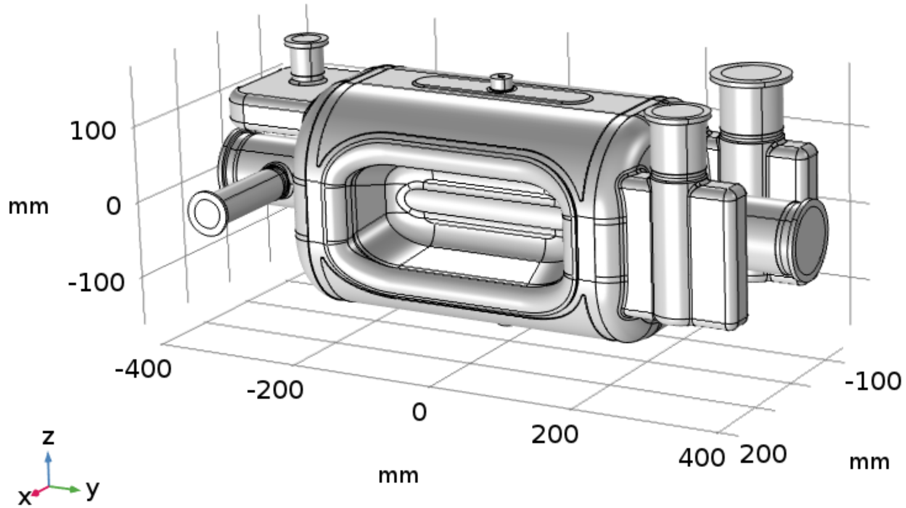
- Fundamental frequency of the cavity without any imposed load

Numerical model



- Structural & moving mesh coupled simulation to capture the cavity and vacuum volume deformation.

RF Dipole



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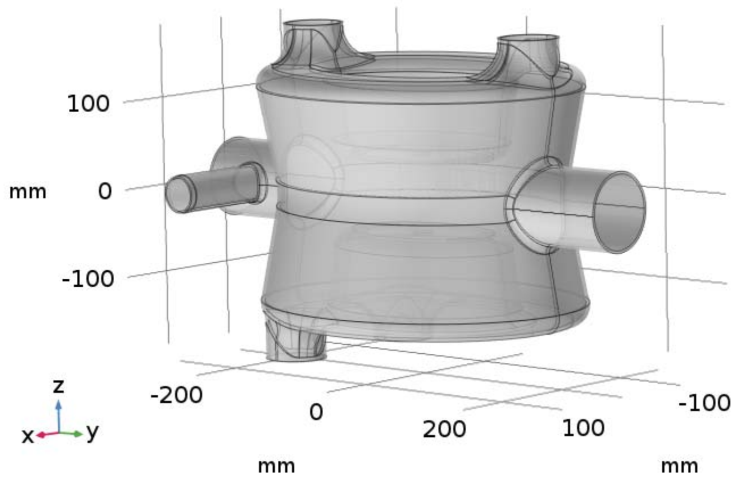

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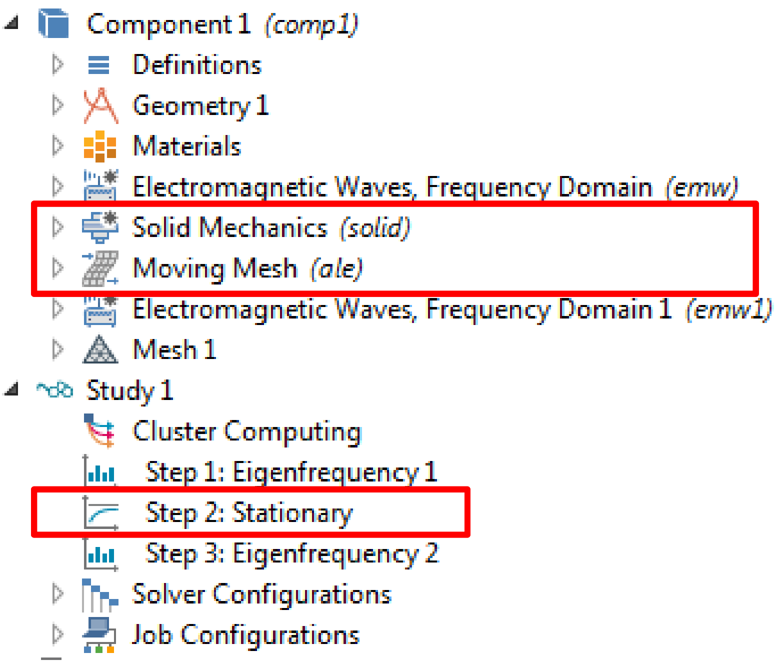

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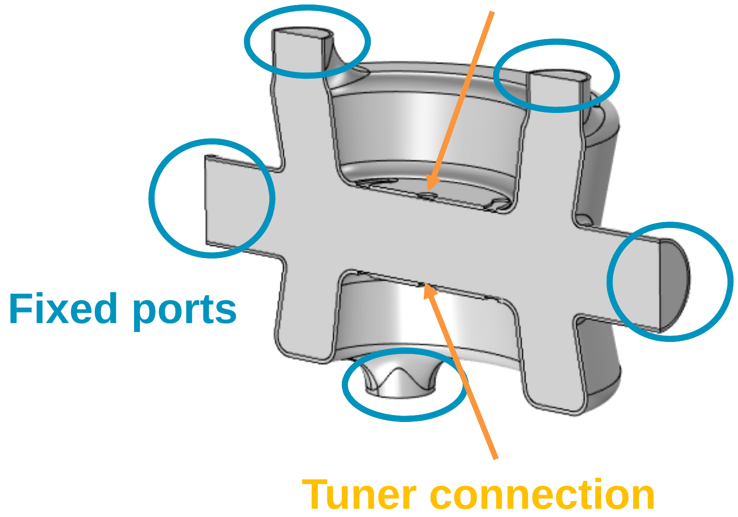

- Boundary conditions:
  - Symmetry
  - Fixed ports
  - DQW: **imposed displacement** in the tuners

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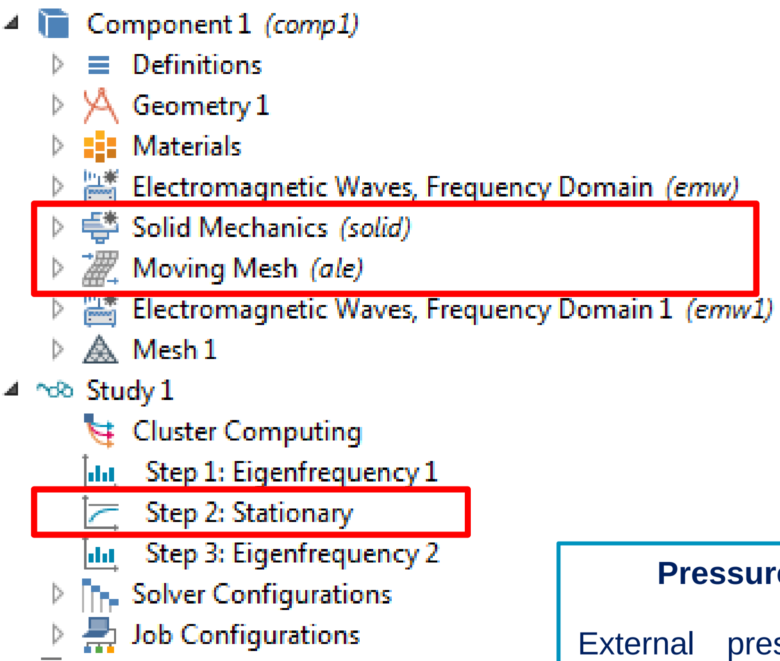
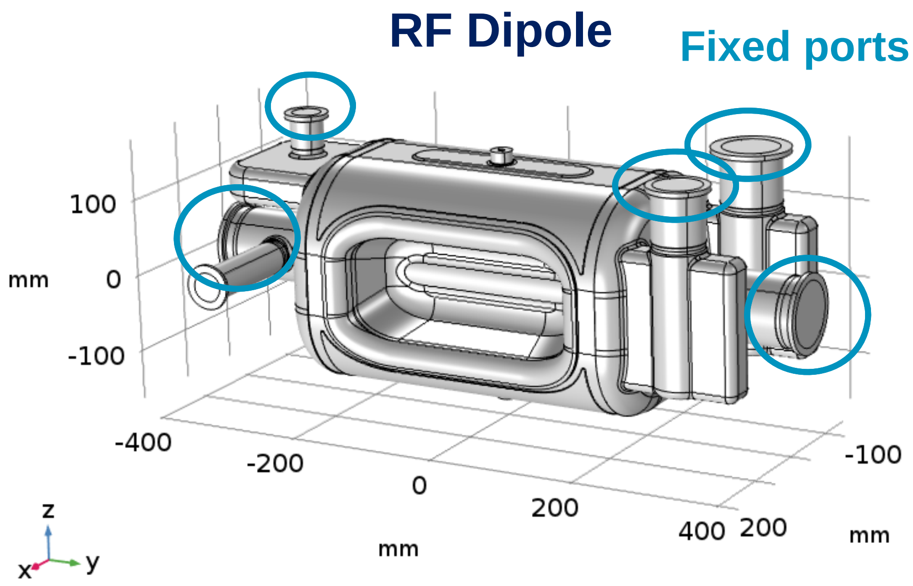
Numerical model





Pressure sensitivity

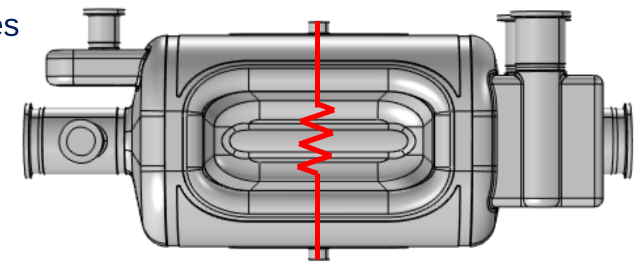
External pressure of 1 bar (negative internal pressure)

- Boundary conditions:
  - Fixed ports
  - Internal pressure
  - Tuning interfaces

Spring between the tuning interfaces

$$F_{s1} = k_s(v_{s2} - v_{s1})$$

$$F_{s2} = k_s(v_{s1} - v_{s2})$$



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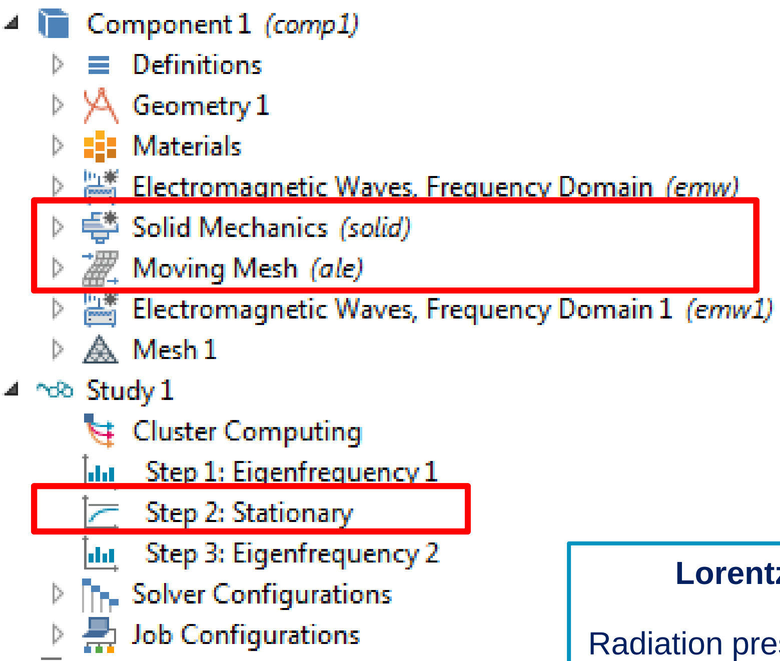

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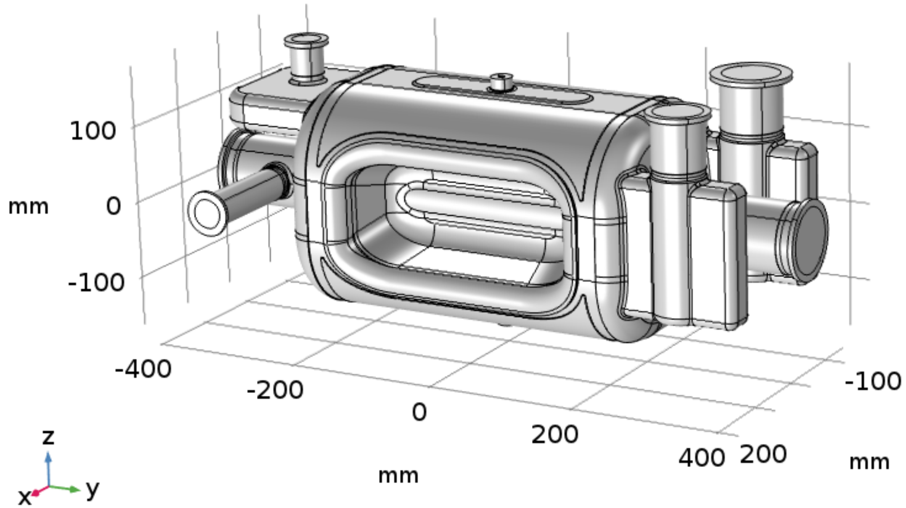


- Boundary conditions:
  - Fixed ports
  - Internal pressure
  - Tuning interfaces

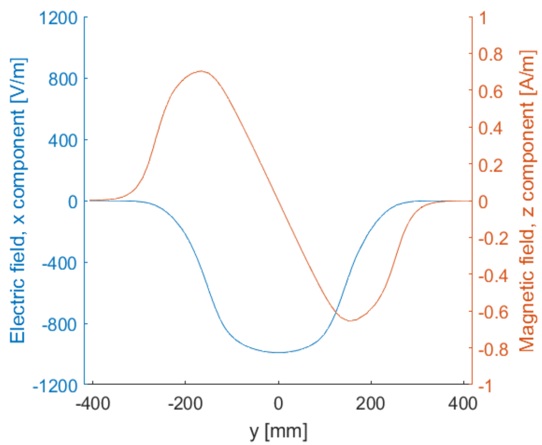
Lorentz force detuning

Radiation pressure

$$P = \frac{1}{4}(\mu_0 H^2 - \varepsilon_0 E^2) \cdot SF$$

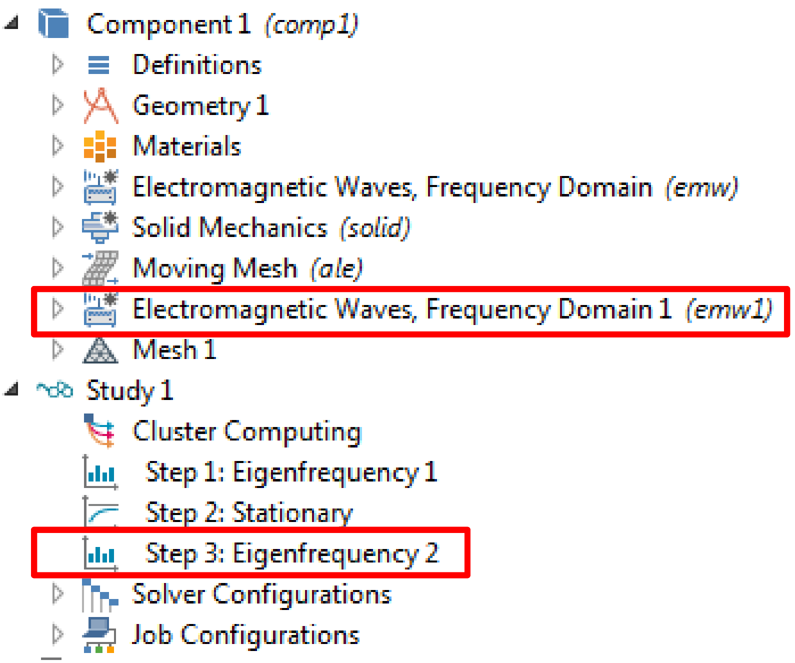
Integration of beam kick along the axis

$$SF = \left(\frac{V_{T,nominal}}{V_{T,COMSOL}}\right)^2$$



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

Numerical model



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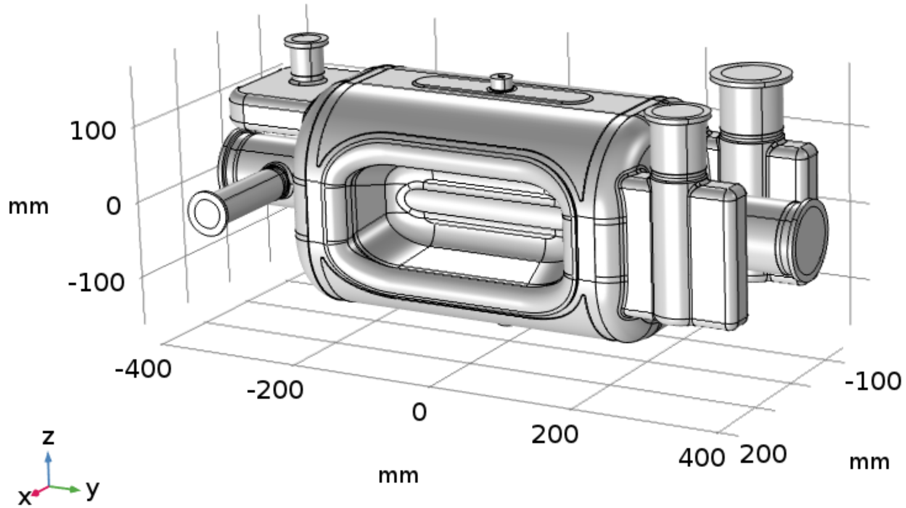

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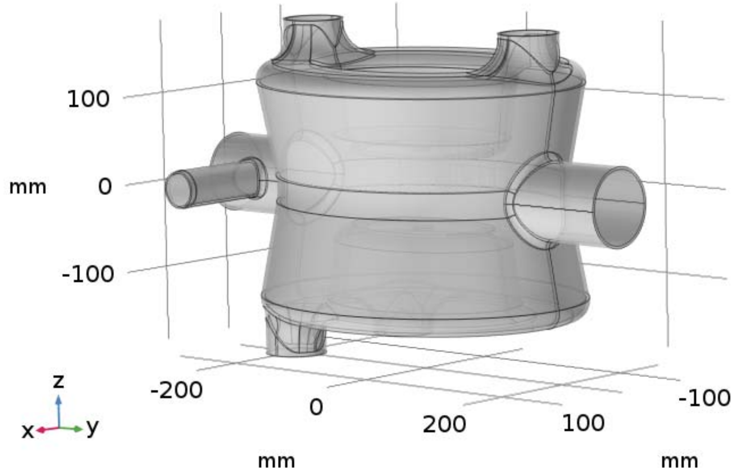

- Fundamental frequency of the deformed cavity

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

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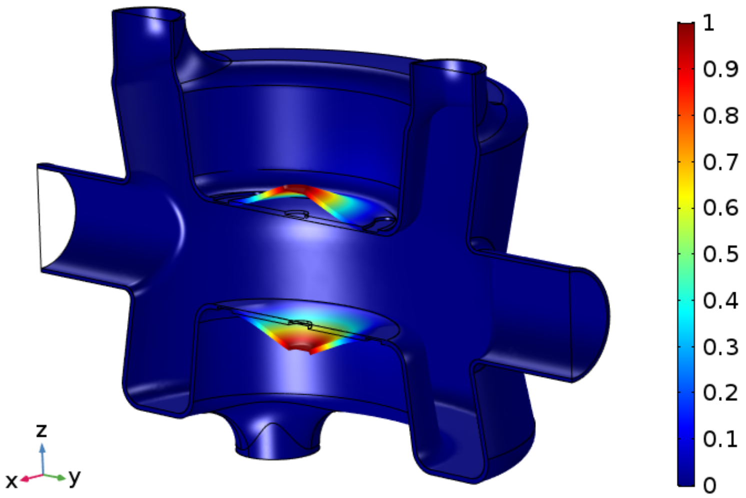
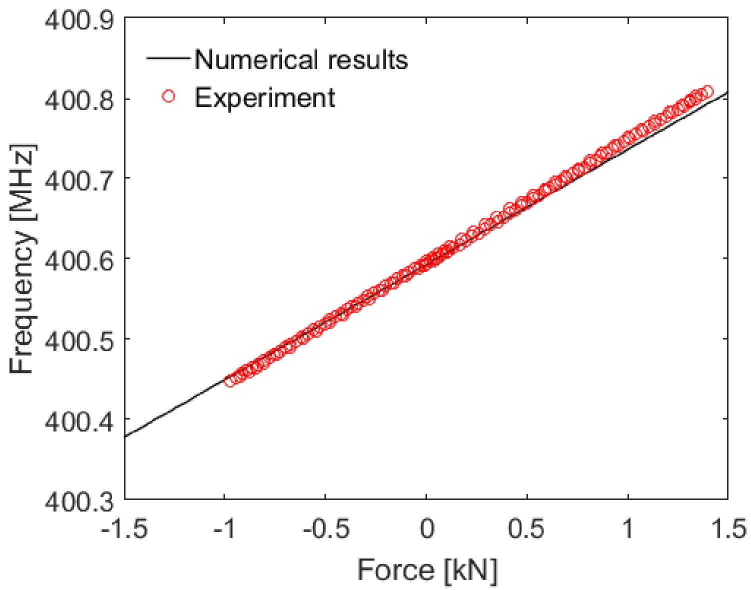
Results – DQW cavity

- Comparison with **experimental results** of the cavity cooldown at CERN at the end of 2017.
- **Very good agreement** between numerical and experimental results.
- Cavity tunability = $\frac{f_1 - f_0}{|v_{s2}| + |v_{s1}|}$ = 315.5 kHz/mm, well in line with expected values.
- **Incertitude** associated to COMSOL and the transformation from displacement to force in the tuning system.

Cavity displacement (mm)

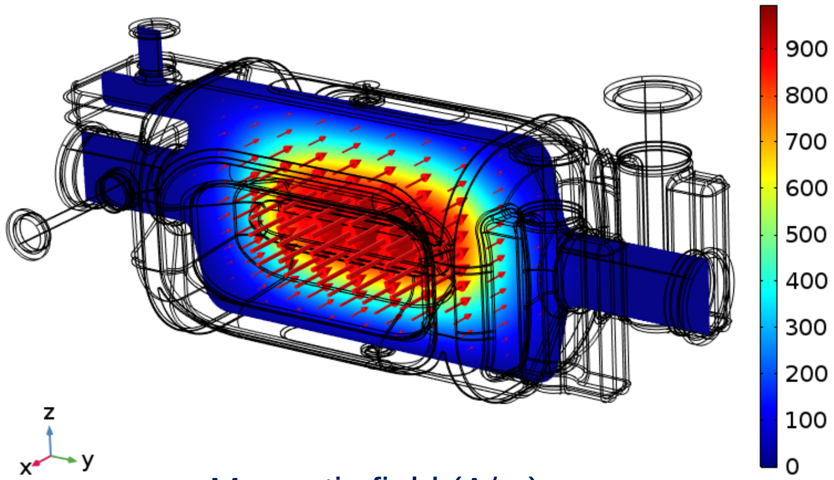


Cavity fundamental frequency vs. force on the tuning system

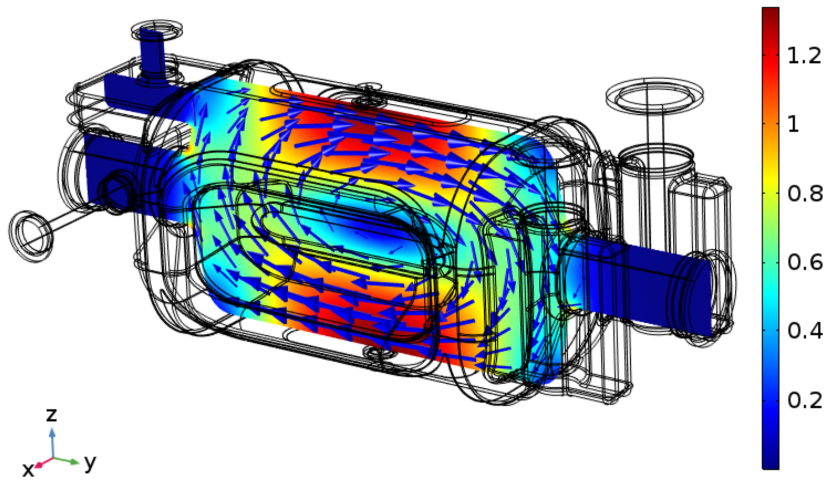


Results – RFD cavity

Electric field (V/m)



Magnetic field (A/m)



Overall results

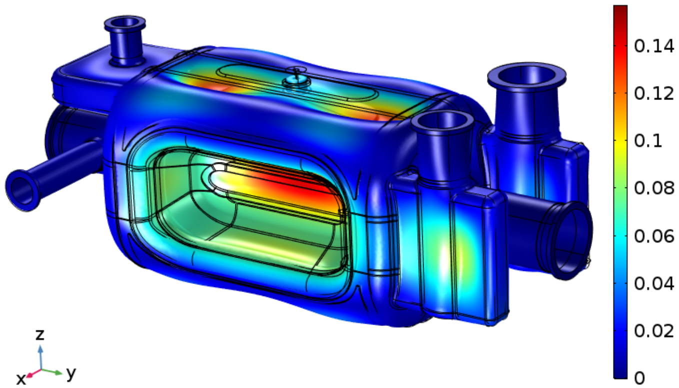
Energy stored in the cavity for 3.4 MV deflecting kick **= 10.7 J**

Scaling Factor for radiation pressure, SF=$7.086 \cdot 10^8$

Pressure sensitivity

$$\frac{f_1 - f_0}{P_{PS}} = 244\ \mathrm{Hz/mbar}$$

Cavity deformation (mm)



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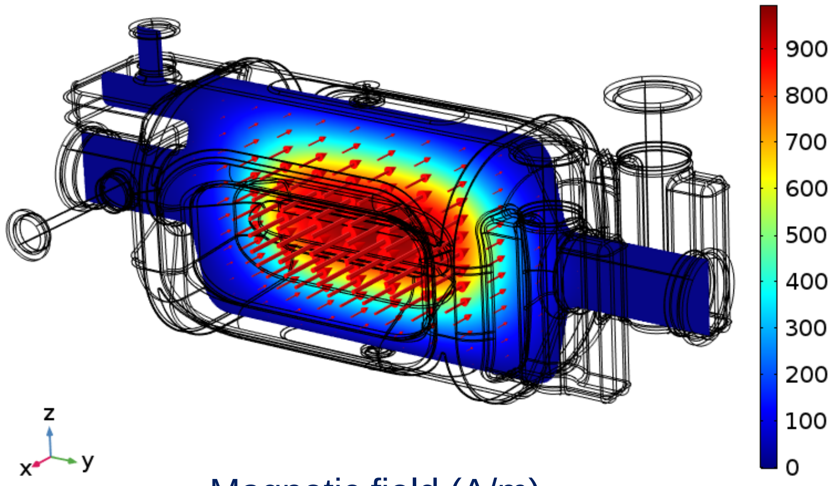

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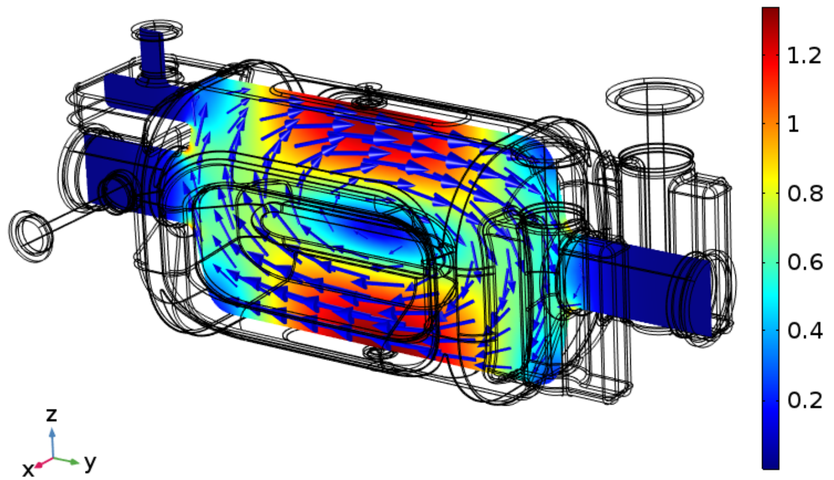
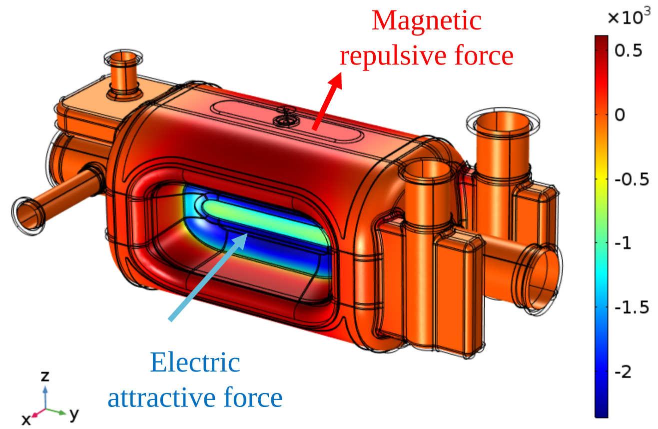


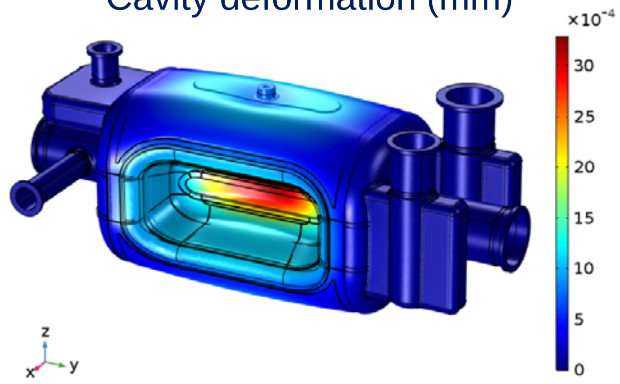
Lorentz force detuning

Radiation pressure (Pa)



$$\frac{f_1 - f_0}{{V_{T,nominal}}^2} = 659\ \mathrm{Hz/MV^2}$$

Cavity deformation (mm)



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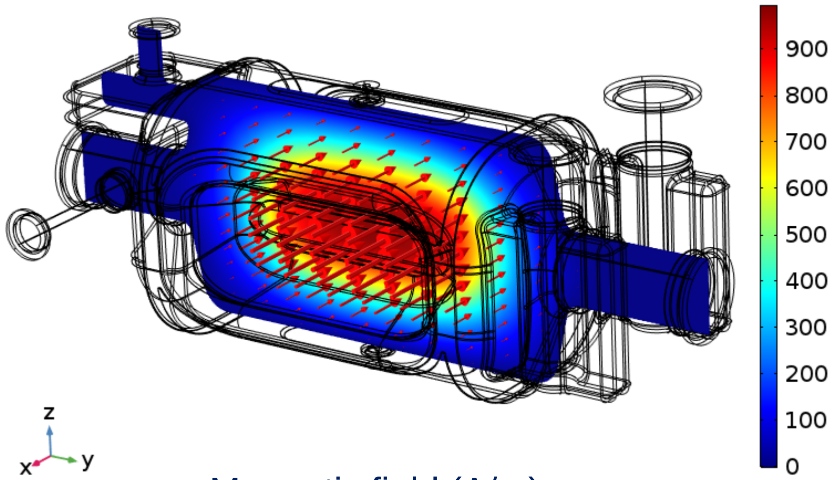

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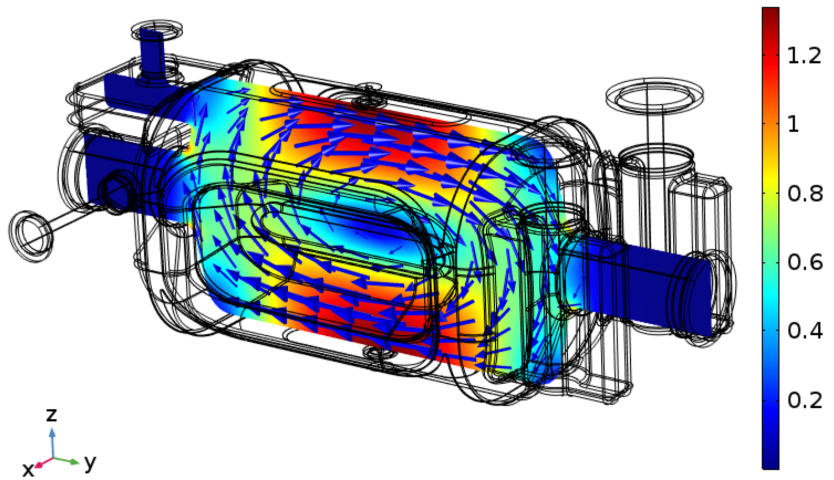
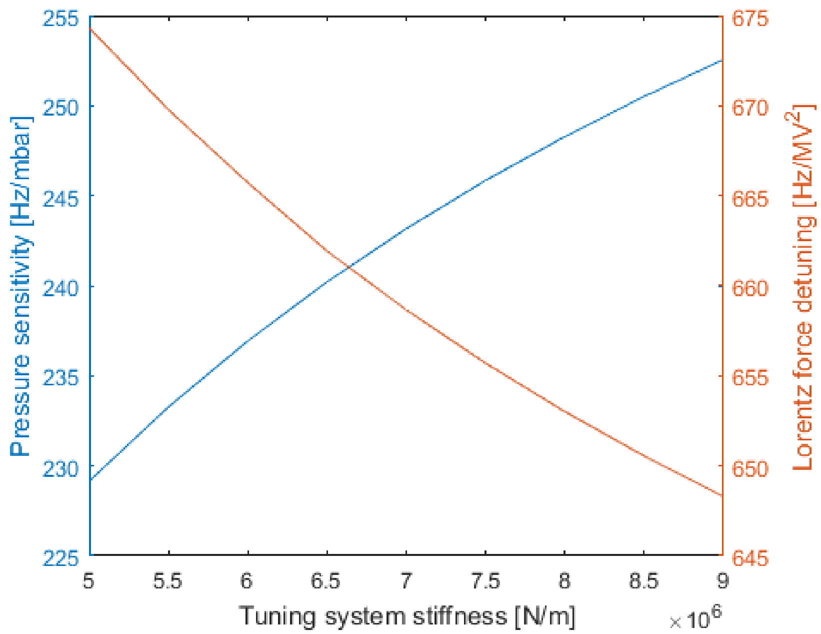


Tuning stiffness

- Tuning stiffness, k_s, parametric analysis.
- **Counteracting effects** of deformation in the pole and tuning regions.



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- **Tunability, pressure sensitivity** and **Lorentz force detuning** of SRF Crab cavities were numerically evaluated using COMSOL.
- The numerical predictions of the DQW cavity tunability **matched very well** the experimental results.
- Pressure sensitivity and Lorentz force detuning values were used **during the design** stage of the **RFD cavity body**.
- Parametric study on the tuning stiffness is used for the **design of the tuning system**.
- COMSOL is a **very powerful tool** for the RF-Structural evaluation of crab cavities during the validation and design stages.

Thank you for your attention!