Multiphysics Analysis of Crab Cavities for High Luminosity LHC Upgrade

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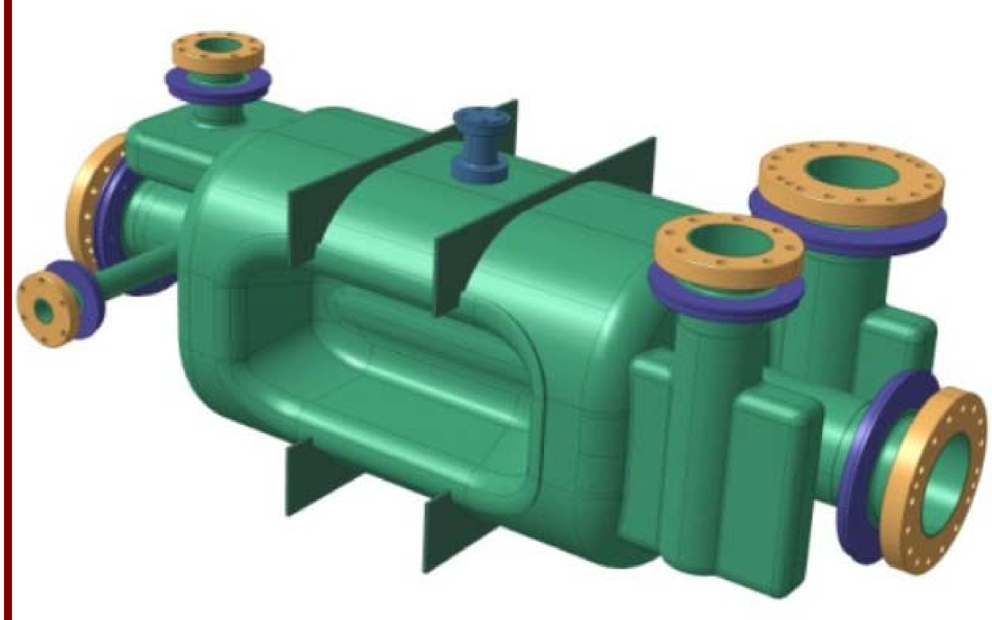
Motivation

- The High-Luminosity LHC project aims to broaden the machine potential after 2025
- The superconducting crab cavities will be used for maximizing and leveling luminosity beyond the LHC design value
- One of the major operational concerns of the beam crabbing scheme is the RF field stability that is sensitive to Lorentz force and external loads
- The relevant electro-mechanical coupling parameters must be determined for beam dynamics and cavity performance analysis

DQW and RFD Baseline Cavity Designs

DQW and RFD cavity designs are now under development* to demonstrate the beam crabbing scheme for high-luminosity LHC.

DQW

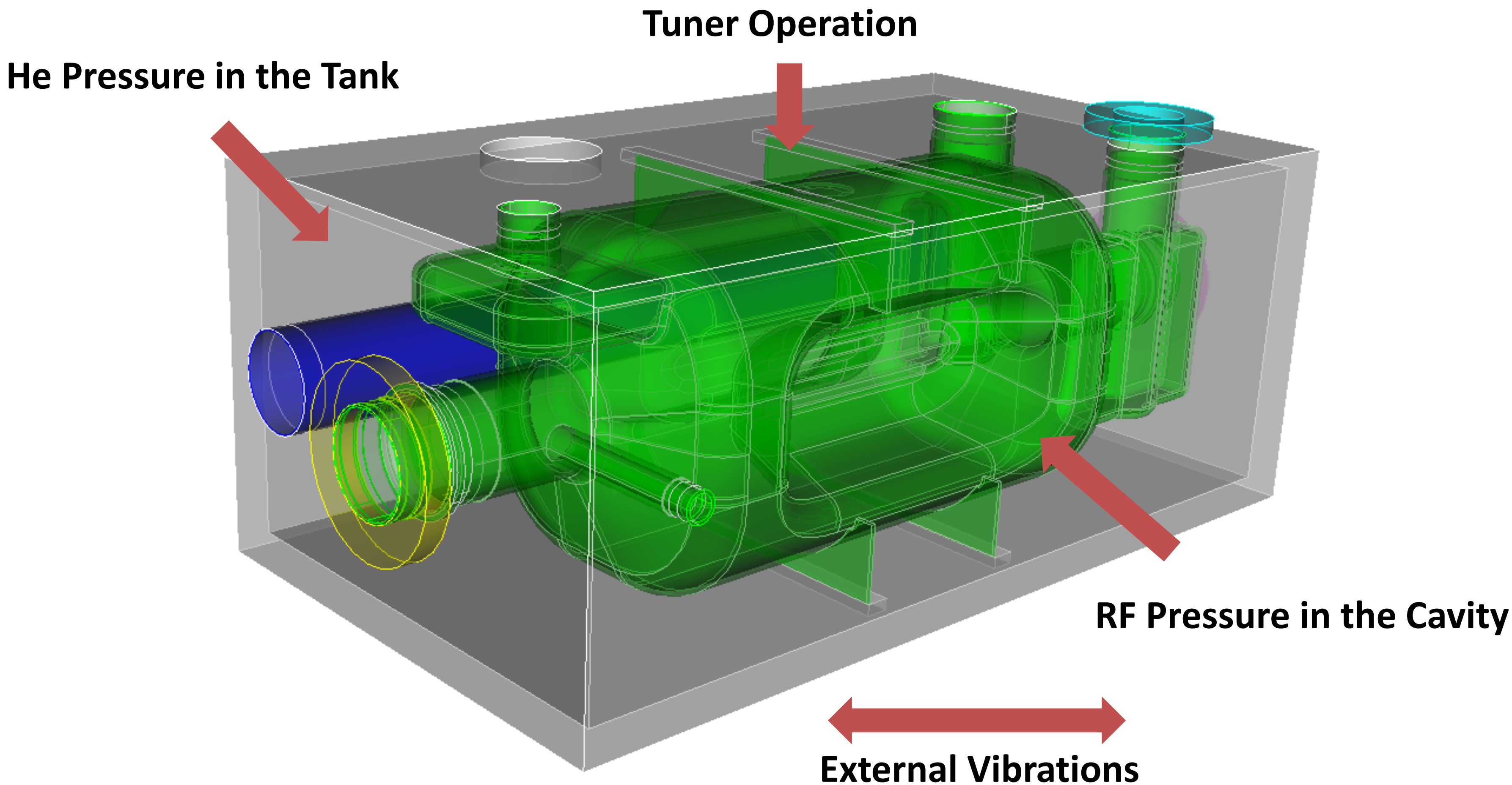


RFD

*High-Luminosity Large Hadron Collider (HL-LHC). Preliminary Design Report, edited by G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont, L. Rossi, CERN–2015–XXX (CERN, Geneva, 2015), DOI: http://dx.doi.org/10.5170/CERN-2015-XXX

Sources of RF Detuning

RF field stability is sensitive to Lorentz force and external loads. Most of these multiphysics effects can now be studied with the massively parallel SLAC's ACE3P simulation suite.

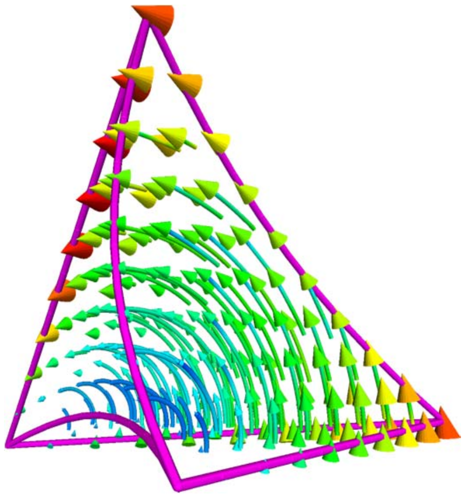


ACE3P Simulation Suite

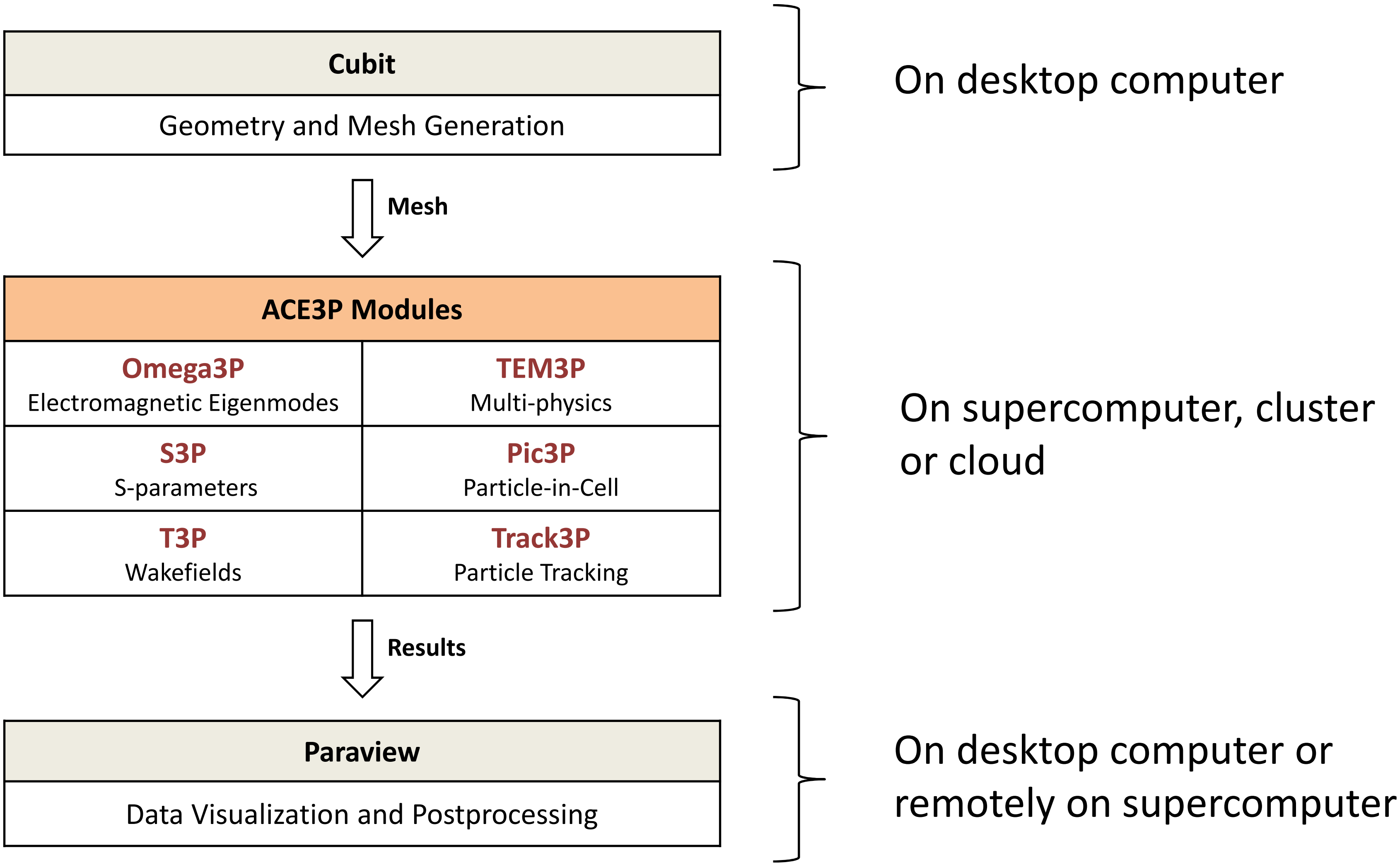
ACE3P is a 3D massively parallel finite-element simulation suite developed at SLAC for integrated electromagnetic, thermal and mechanical analysis of accelerators.

ACE3P electro-mechanical multiphysics capabilities include:

- •Lorentz force (LF) detuning
- •static structural analysis
- •mechanical eigenmodes
- •spatial mode decomposition
- •response to external vibrations
  - RF detuning due to modes or loads
  - …

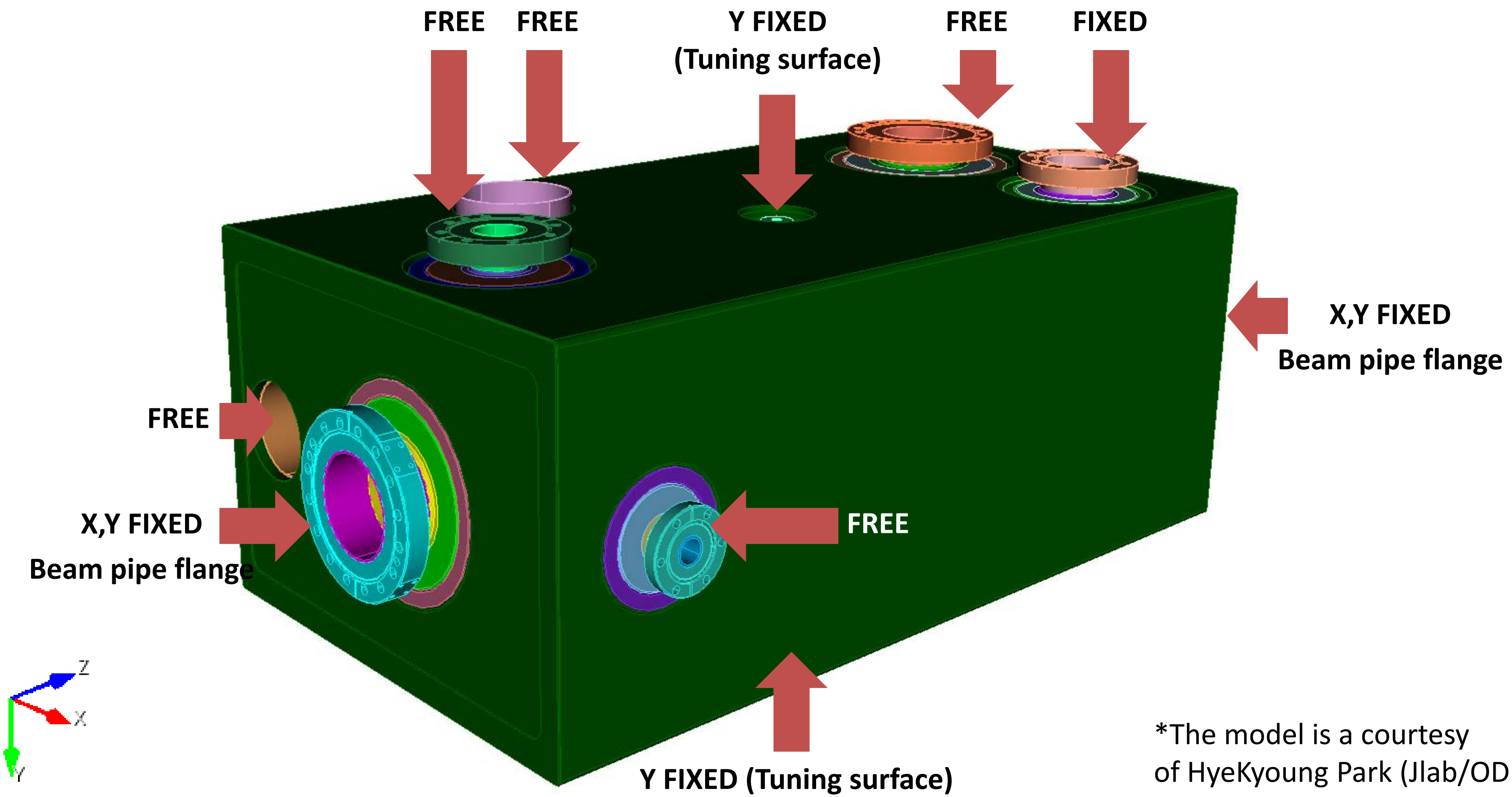


ACE3P Simulation Workflow



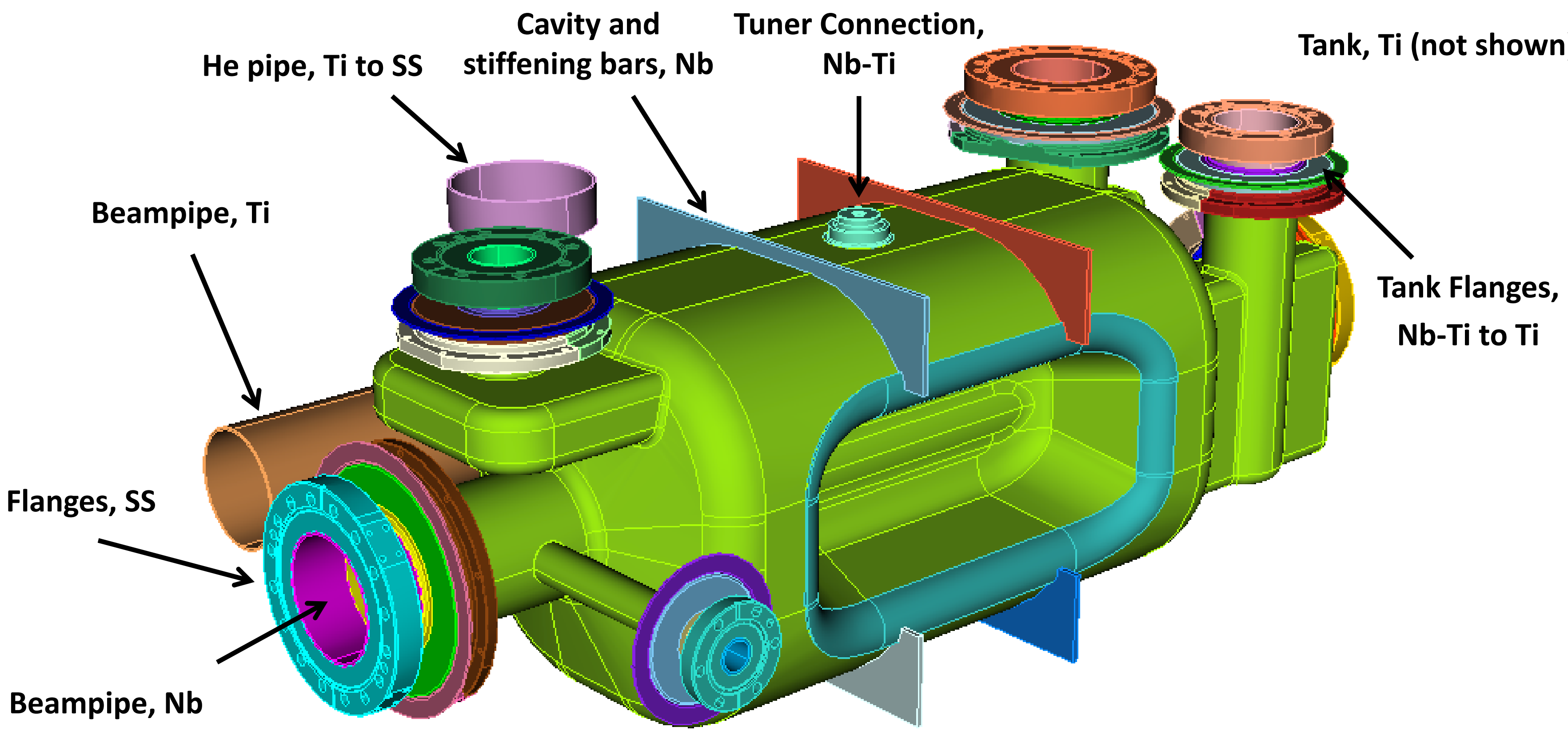
Structural Model* of the RFD Cavity

Since the supporting geometry was not fully designed at the time of the simulations, the boundary conditions are therefore a simplification, aimed at preserving the modes of the cavity inside the helium tank.



*The model is a courtesy of HyeKyoung Park (Jlab/ODU)

Structural Model: Materials at 2K



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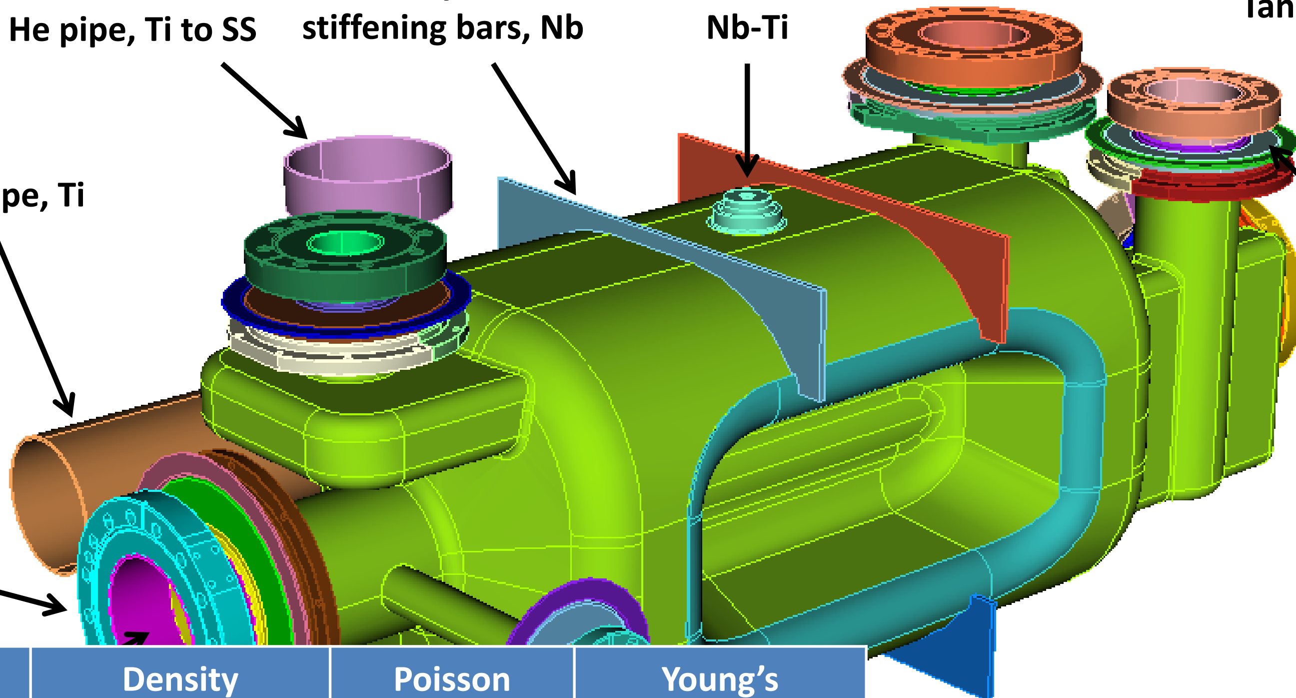
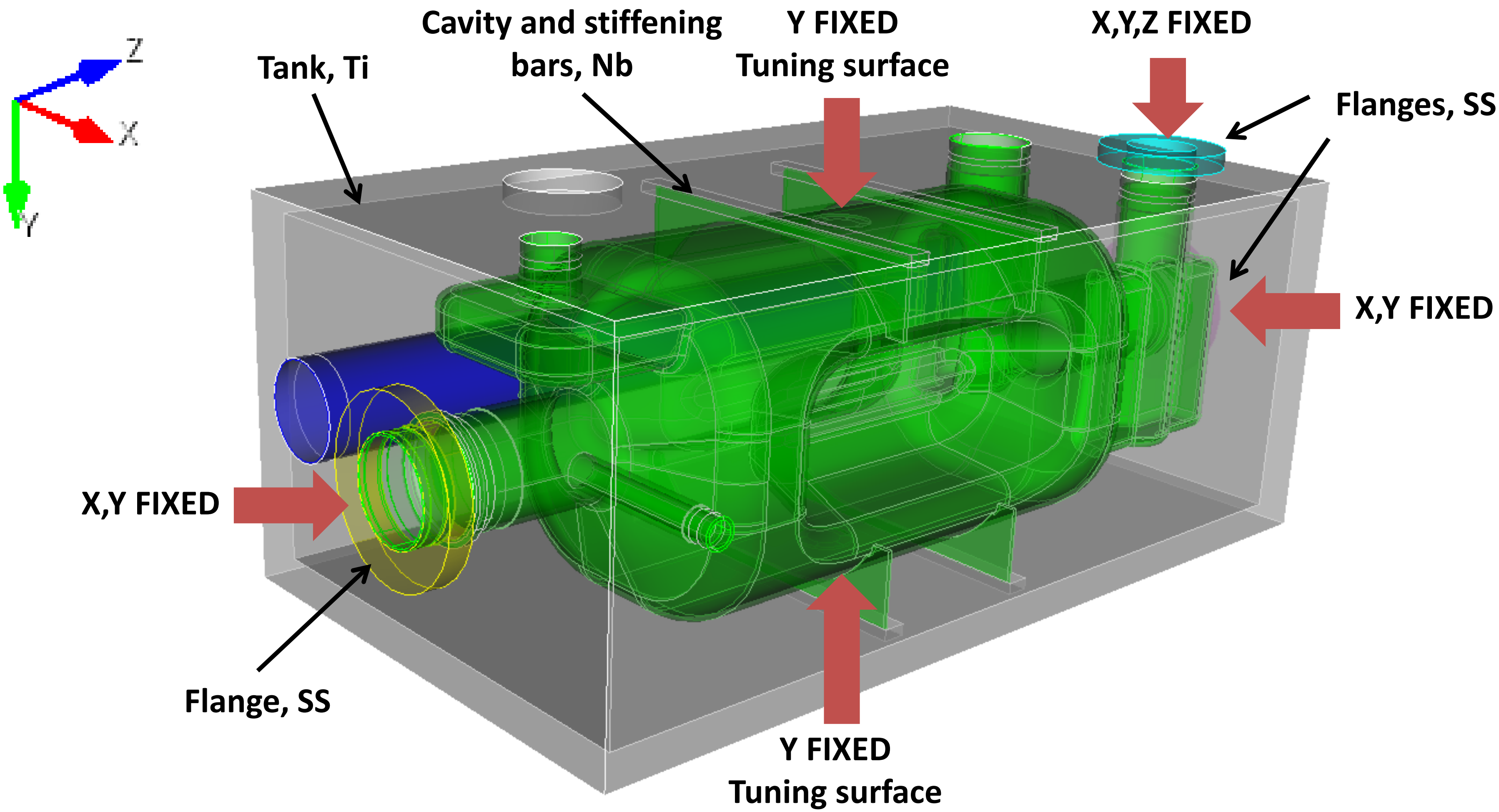


	Density [kg/m³]	Poisson Ratio	Young's Modulus [GPa]
Nb	8700	0.38*	118
Nb-Ti	5700	0.33	68
Ti	4540	0.37	117
SS	8000	0.29*	193

*Material properties for engineering analyses of SRF cavities. Fermilab specification: ED0371110

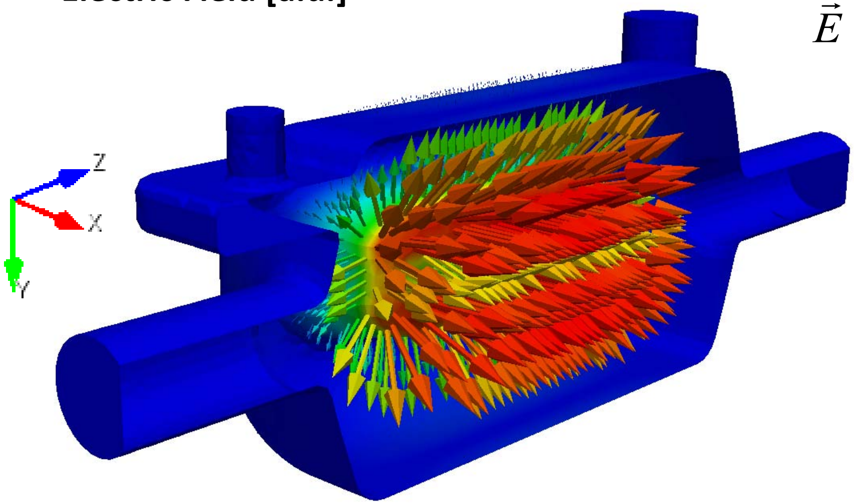
Simplified Simulation Model

The complicated tank shell structure has been replaced with the solid one having the same mass and external dimensions. Flanges are removed on the free boundaries, tuner is attached and constrains the cavity vertically.

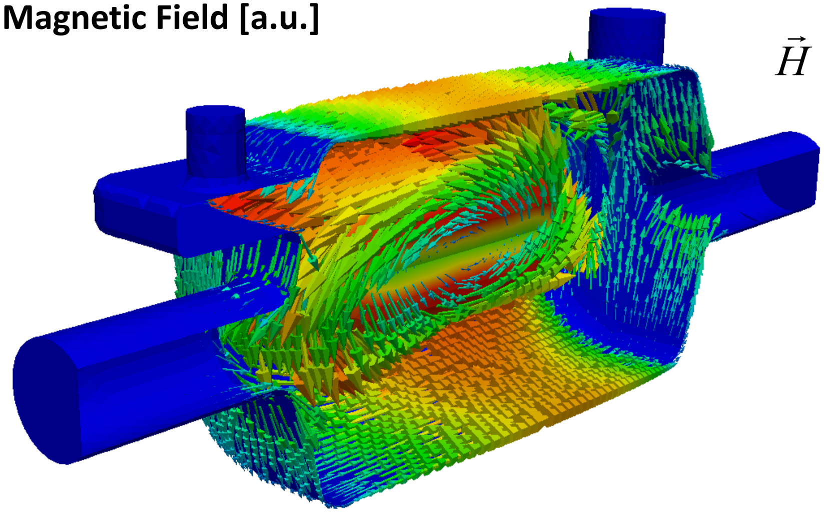


Vacuum Model of the RFD Cavity

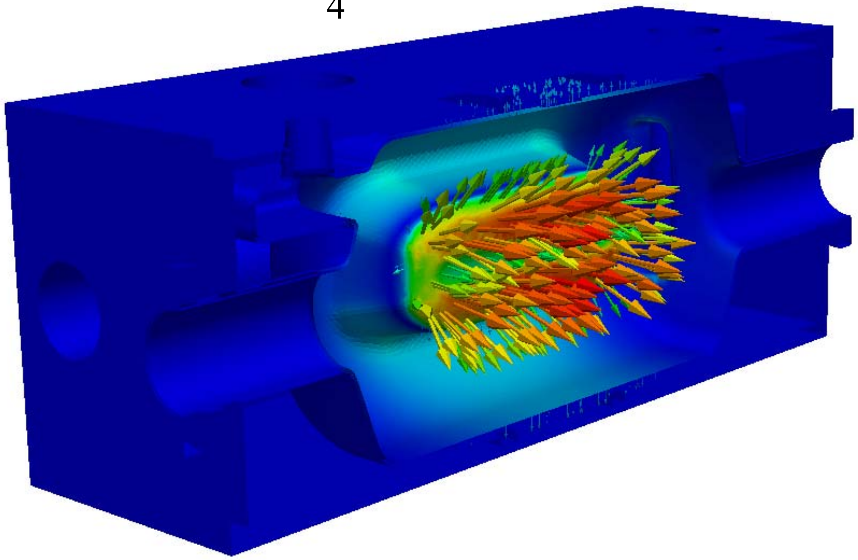
Electric Field [a.u.]



Magnetic Field [a.u.]



RF Pressure [a.u.] $P = \frac{1}{4}(\mu_0 H^2 - \varepsilon_0 E^2)$

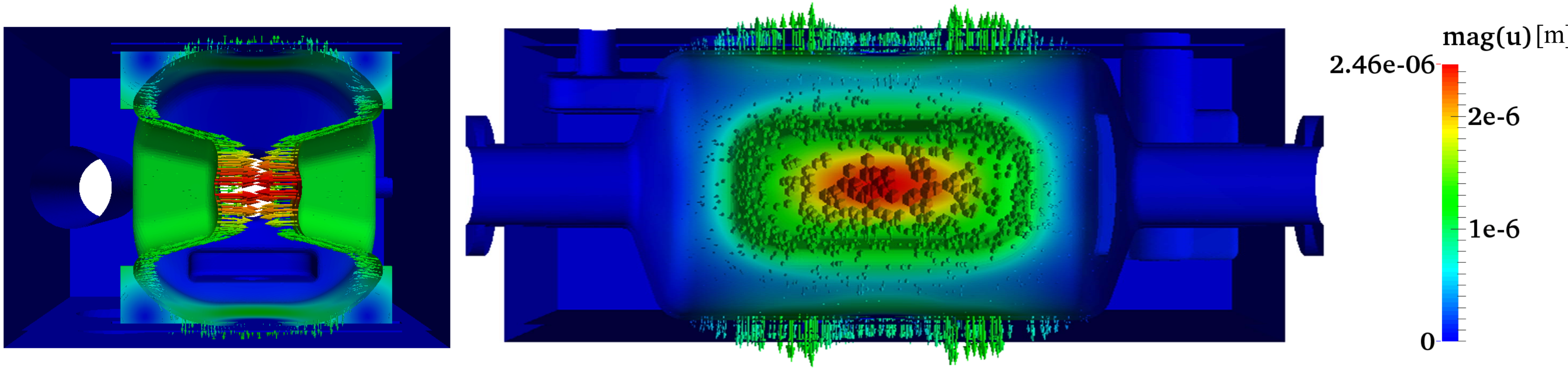


Parameter	Value
Frequency [MHz]	400
V_T [MV]	3.34
V_L at x = 0.02 m [MV]	0.56

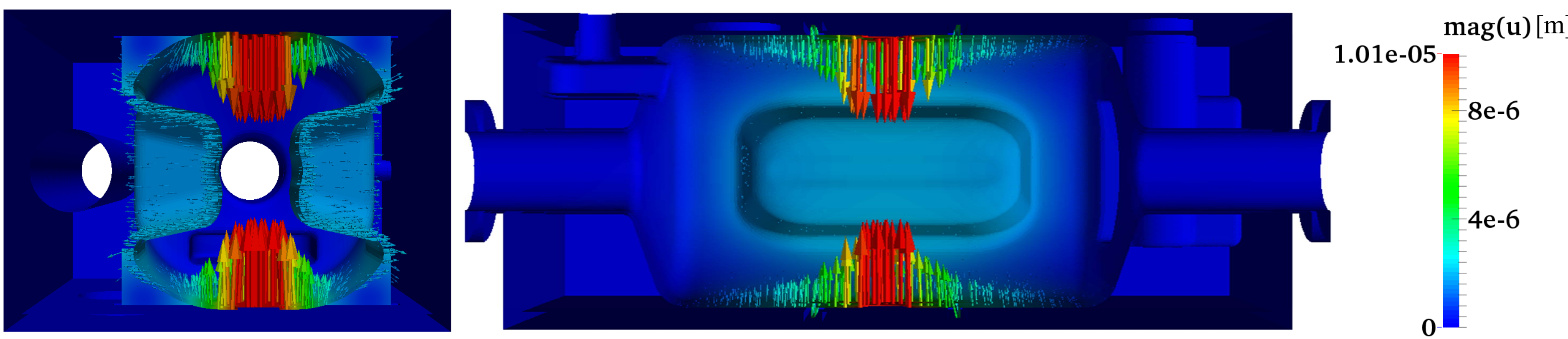
Panofsky-Wenzel Theorem $V_T = -\frac{icV_L}{\omega r}$

RF Detuning: Lorentz Force vs Tuner

Lorentz force detuning is determined to be **-6 639 Hz** per **3.34 MV**, i.e. k_{LF} = **-595.1** Hz/MV^2

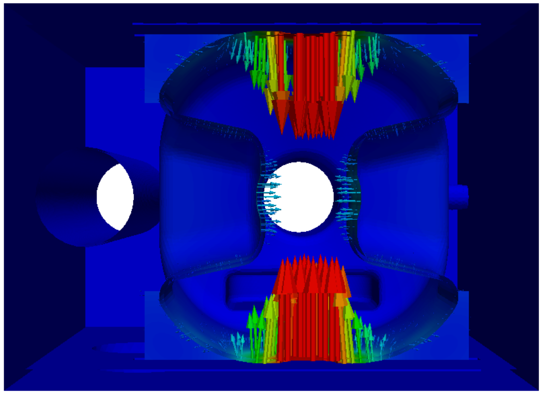


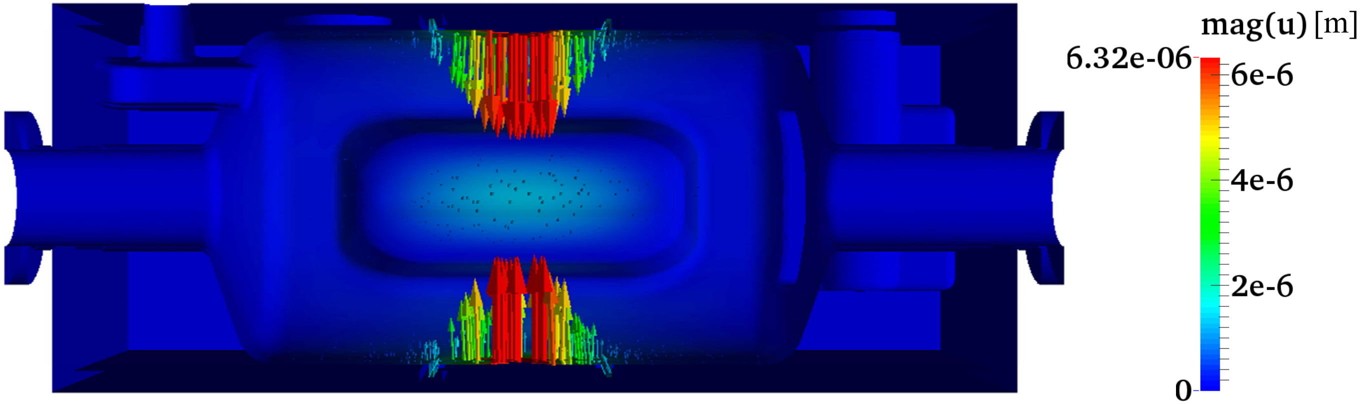
Tuner sensitivity is calculated to be **10 594 Hz** per **10 um**, i.e. $k_T = \Delta f_T / (2*dy)$) = **529.5 Hz/um**



↕LF Compensation: Residual Deformation and Von Mises Stress

The tuner displacement $dy = \Delta f_{LF} / (2^* k_T) \approx$ **6.3 um** compensates for the detuning due to LF





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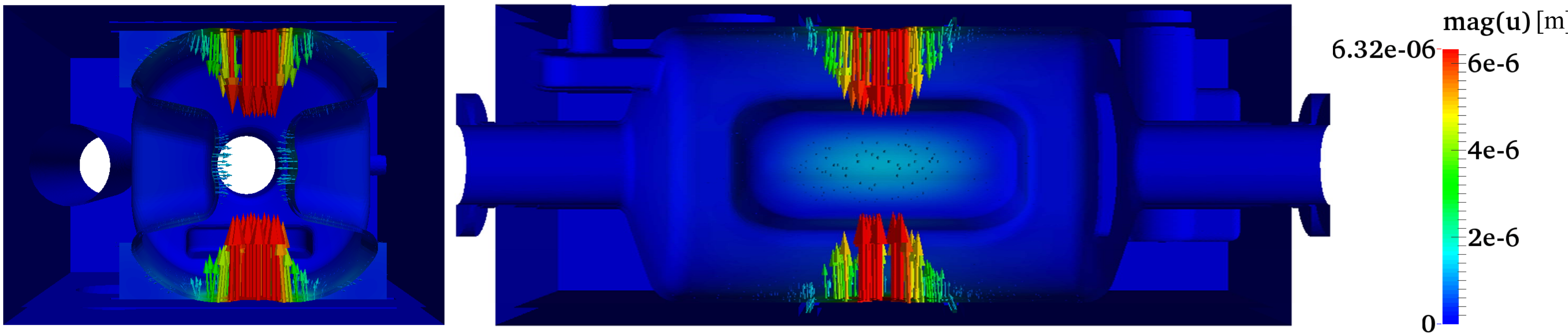
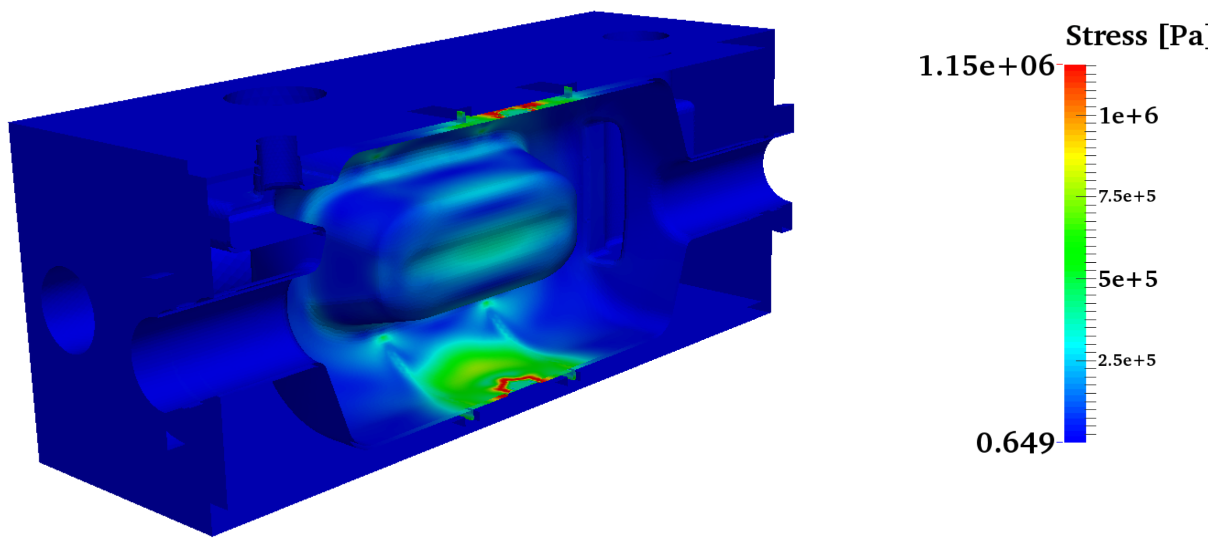


As expected, most of the stress (Von Mises) is concentrated around the tuning surfaces



Electro-Mechanical Cavity Model*

The displacements due to the external forces are expanded as a set of the mechanical eigenmodes resulting in the mode equations for the unknown spatial decomposition coefficients q:

$$\vec{u}(x,y,z)=\sum_{\mu=0}^{\infty} q_\mu \vec{u}_\mu(x,y,z)$$

$$\ddot{q}_\mu + \frac{2}{\tau_\mu}\dot{q}_\mu + \Omega_\mu^2 q_\mu = \frac{\Omega_\mu^2}{c_\mu} F_\mu$$

$$\vec{F}(x,y,z)=\sum_{\mu=0}^{\infty} F_\mu \vec{u}_\mu(x,y,z)$$

Based on the mechanical mode decomposition, **the total RF detuning is a sum over all the modes** and the corresponding equation determines the RF detuning as a function of time:

$$\Delta\omega = \sum_{\mu=0}^{\infty} \Delta\omega_\mu$$

$$\Delta\omega_0 = \sum_{\mu=0}^{\infty} \Delta\omega_{0\mu} = -G^2 \sum_{\mu=0}^{\infty} k_\mu$$

$$k = \sum_{\mu=0}^{\infty} k_\mu$$

$$\Delta\ddot{\omega}_\mu + \frac{2}{\tau_\mu}\Delta\dot{\omega}_\mu + \Omega_\mu^2 \Delta\omega_\mu = -k_\mu \Omega_\mu^2 G^2 + n_\mu$$

Measurements (τ_μ)

ACE3P (Ω_μ^2, k_μ, Ω_μ^2, n_μ)

*J. Delayen, Ponderomotive instabilities and microphonics - a tutorial, Proc. 12th Int. Workshop on RF Superconductivity, Ithaca, New York, USA, Jul 2006, pp. 1-6.

Mechanical Eigenmode Decomposition

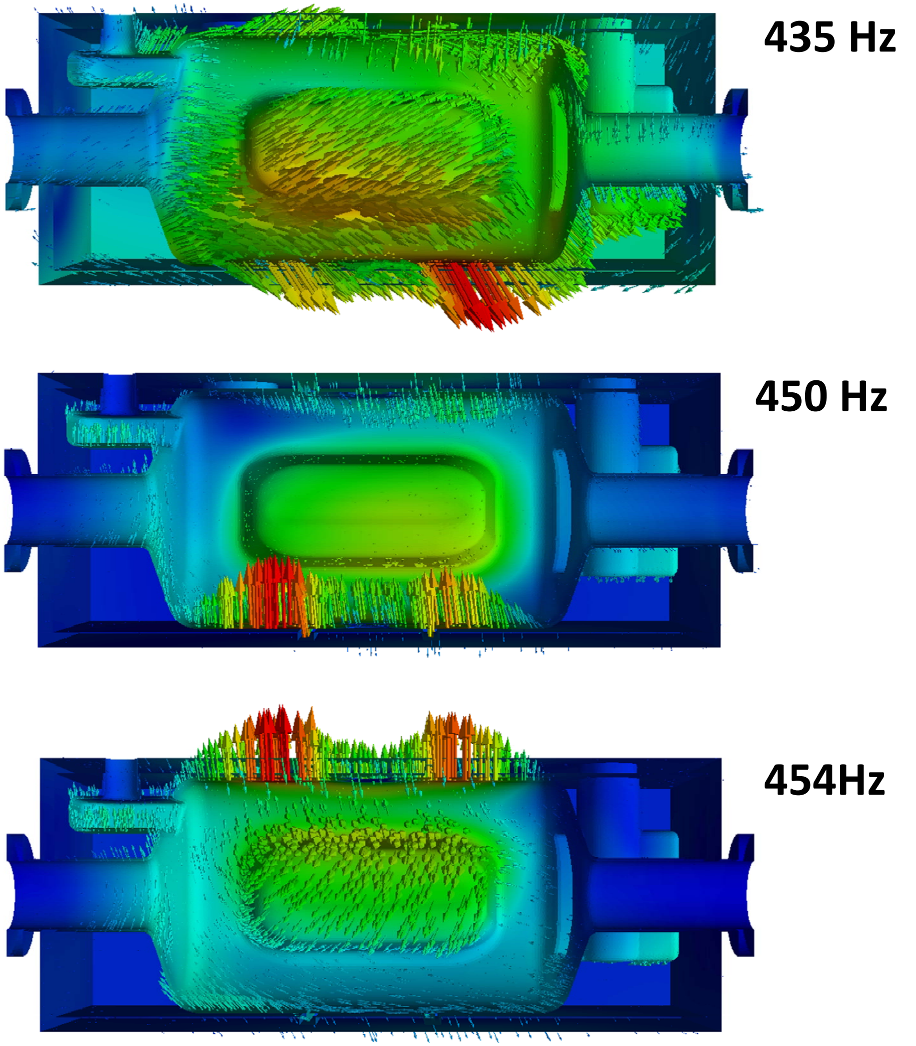
- By doing the spatial decomposition we calculate the contribution of mechanical modes to the static Lorentz force and tuner RF frequency shifts.
- Discrepancy between the modal summation and the static frequency shift is due to the finite number of mechanical modes being included. Contribution of higher frequency modes is yet to be calculated.

Mode #	Ω [Hz]	Δf_{LF} [Hz]	Δf_T [Hz]
3	274	-1	3
4	289	-1	3
5	365	-4	9
7	382	-3	6
8	388	-9	17
9	435	-394	772
10	450	-2 505	4 752
11	454	-1 305	2 455
12	496	-17	29
13	526	-2	4
…	…	…	…
Sum over 20 modes		**-4 235**	**8 039**
Static frequency shift		**-6 639**	**10 594**

Displacements of Mechanical Modes

Mode #	f [Hz]	Mode #	f [Hz]
1	175	**11***	**454**
2	220	12	496
3	274	13	526
4	289	14	570
5	365	15	575
6	375	16	587
7	382	17	590
8	388	18	620
9*	**435**	19	624
10*	**450**	20	625

* top and bottom cavity plate modes



Summary and Further Steps

- Lorentz Force effects, tuner displacement and mechanical modes have been studied for the LHC RFD crab cavity.

- It is demonstrated that the lower frequency modes have insignificant coupling to RF. However, if the top or bottom cavity plates hit the resonances at ~400 Hz this may have significant impact on detuning.

- Further steps will include refinement of the RFD model with supports and tuner frame, analysis of the DQW design, calculation of the cavity response due to external vibrations as well as their effects on deflecting voltage and RF phase.

ACE3P Code Workshop at SLAC

CW16 Accelerator Code Workshop

SLAC NATIONAL ACCELERATOR LABORATORY

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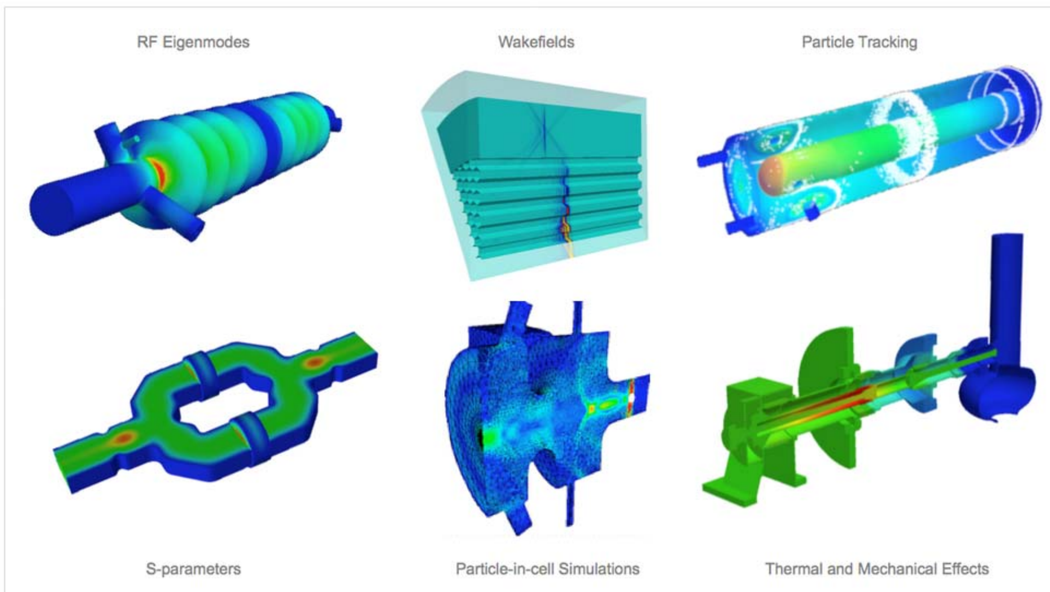
CW16 Accelerator Code Workshop

31 Oct-4 Nov, 2016
B048 Redwood Conference Rooms C&D
SLAC National Accelerator Laboratory, Menlo Park, CA
E-mail: ace3p@slac.stanford.edu



- Introduction to ACE3P
- Advanced capabilities
- User presentations
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- No registration fee
- **You're welcome!**

Website: https://portal.slac.stanford.edu/sites/conf_public/cw16/