RF DIPOLE DEFLECTING/CRABBING CAVITIES

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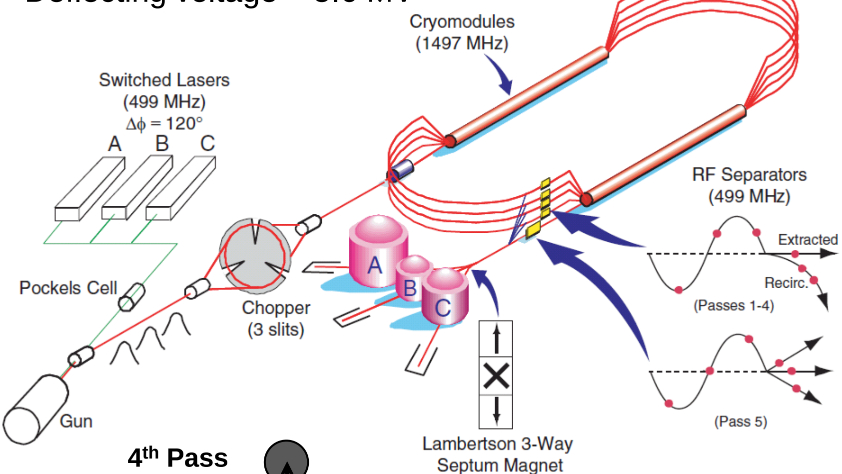
Compact Deflecting/Crabbing Designs

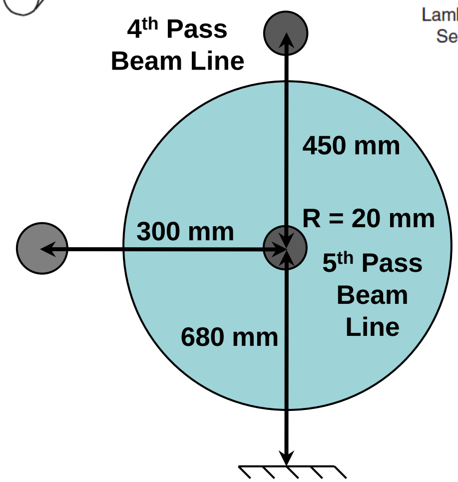
- Operate in TE-like or TEM-like modes
  - 4-Rod Cavity (University of Lancaster / Jefferson Lab)
  - Parallel-Bar / RF-Dipole Cavity (ODU / SLAC)
  - Quarter Wave Cavity (BNL)
- RF Dipole design has
  - Low surface fields and high shunt impedance
  - Good balance between peak surface electric and magnetic field
  - No LOMs
  - Nearest HOM is widely separated (~ 1.5 fundamental mode)
  - Good uniformity of deflecting field due to high degree symmetry

Current Applications of RF Dipole Cavity

499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade

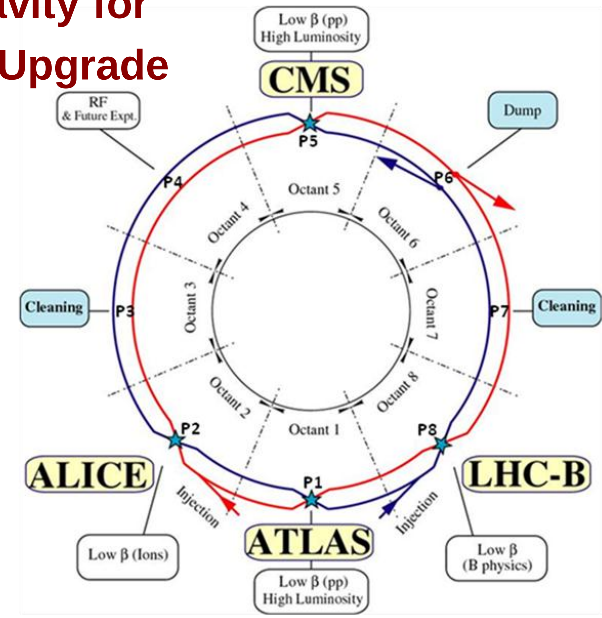
Deflecting voltage – 5.6 MV



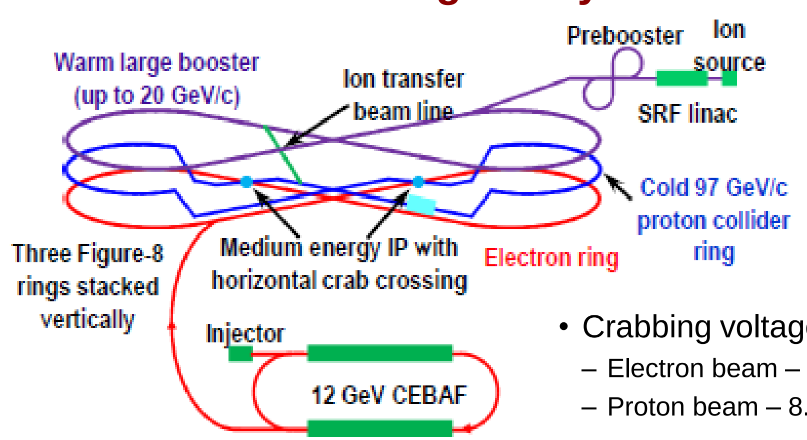


400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

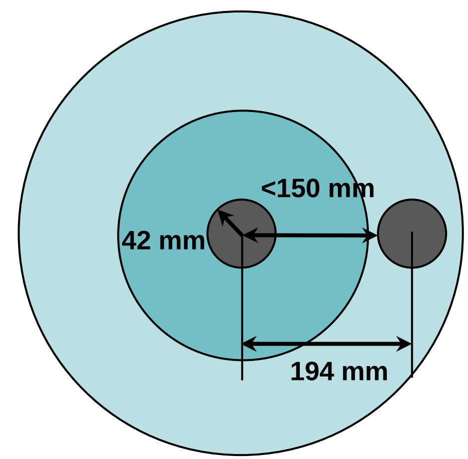
- Crabbing voltage – 10 MV per beam per side
- Requires a crabbing system at two interaction points (IP1 and IP5)
  - Vertical crossing at IP1
  - Horizontal crossing at IP5



750 MHz Crabbing Cavity for MEIC*



- Crabbing voltage
  - Electron beam – 1.5 MV
  - Proton beam – 8.0 MV

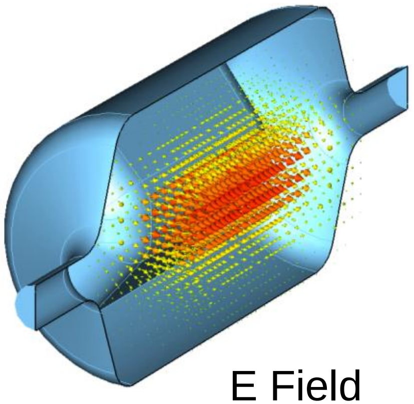


*A. Castilla et.al., in Proceedings of the 3rd IPAC, New Orleans, Louisiana (2012), p. 2447.

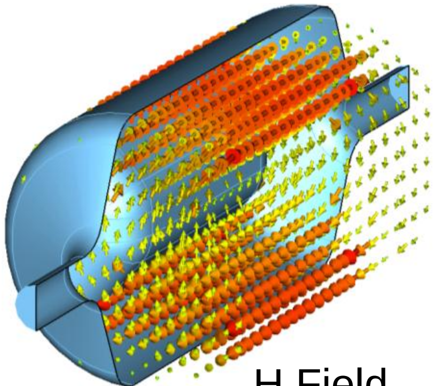
RF Dipole Cavity

- Operates in a TE-like mode (cannot be a pure TE mode – Panofsky Wenzel Theorem)
- Deflecting/Crabbing mode is the lowest operating mode
- Net deflection is mainly due to the transverse electric field
- Transverse voltage

$$V_t = \int_{-\infty}^{+\infty} \left[E_x(z) \cos\left(\frac{\omega z}{c}\right) + cB_y \sin\left(\frac{\omega z}{c}\right) \right] \mathrm{d}z.$$

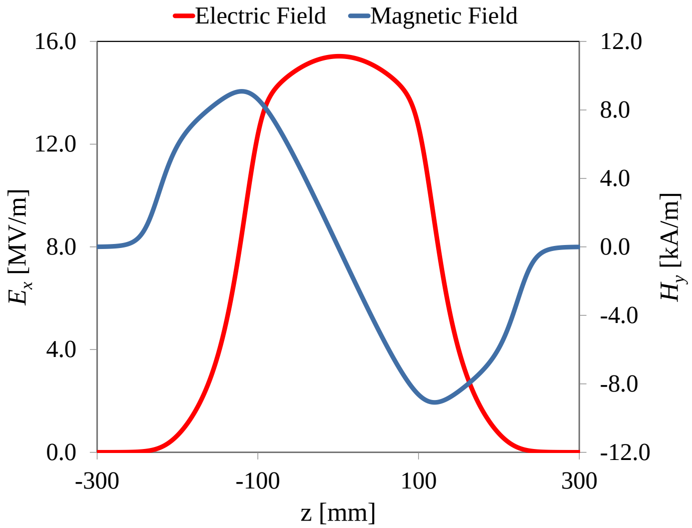


E Field



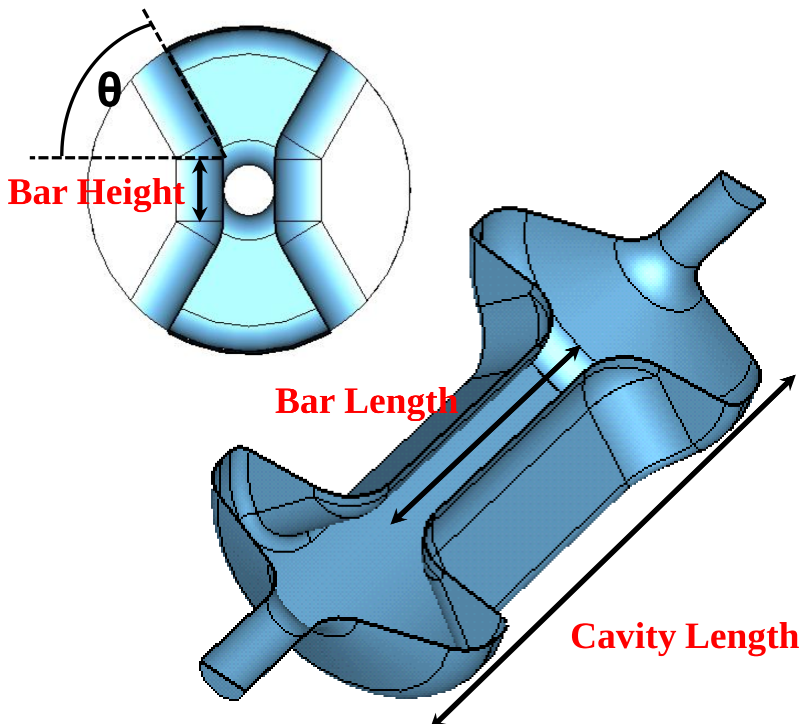
H Field

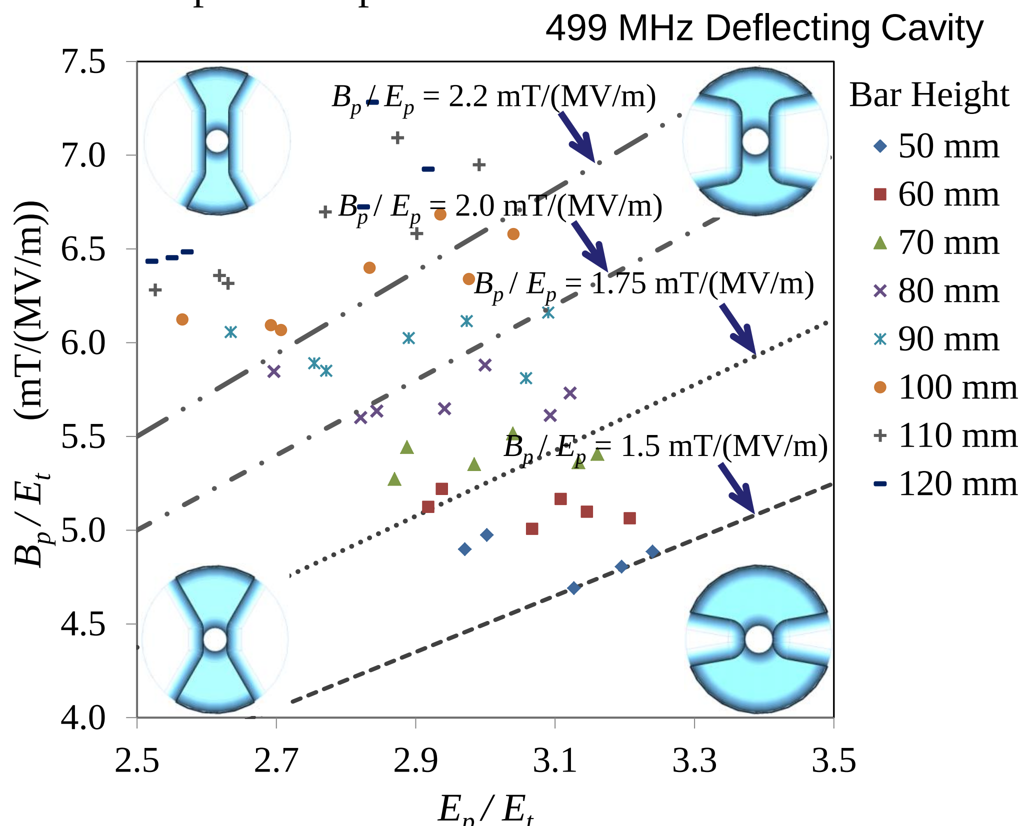
Field on axis



Characteristics of the RF-Dipole Cavity

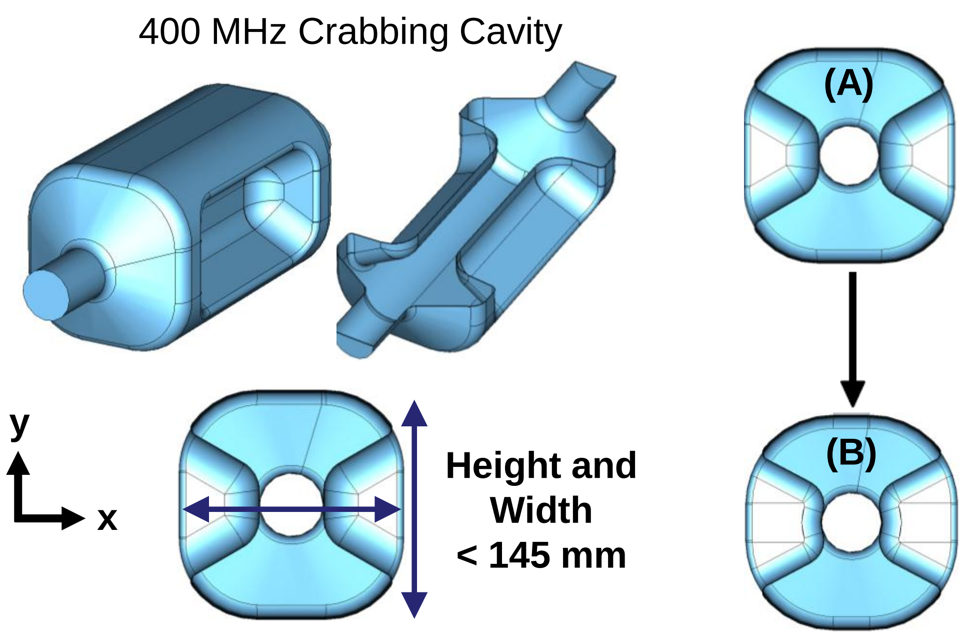
- Properties depend on a few parameters
  - Frequency determined by diameter of the cavity design
  - Bar Length ~λ/2
  - Bar height and aperture determine E_P and B_P
  - Angle determines B_P/E_P



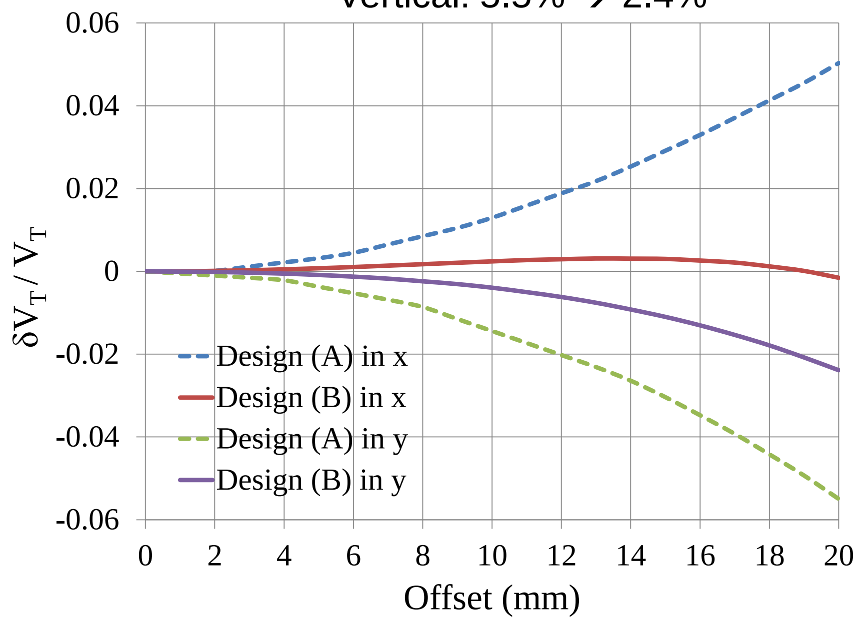


RF-Dipole Square Cavity Options

- Square-type rf-dipole cavity to further reduce the transverse dimensions
- Frequency is adjusted by curving radius of the edges
- RF-dipole cavity with modified curved loading elements across the beam aperture to reduce field non-uniformity



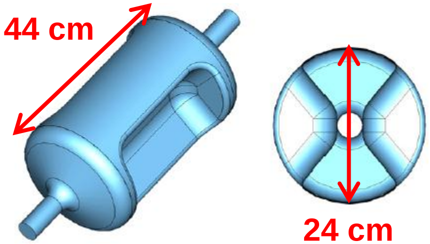
- Voltage deviation at 20 mm
  - Horizontal: 5.0% → 0.2%
  - Vertical: 5.5% → 2.4%



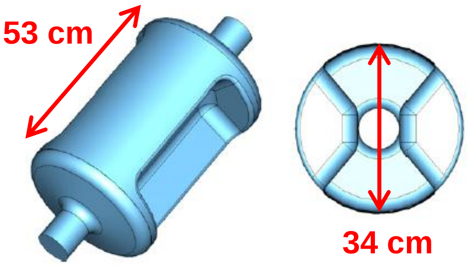
RF-Dipole Cavity Designs

Frequency	499.0	400.0	750.0*	MHz
Aperture Diameter (d)	40.0	84.0	60.0	mm
d/(λ/2)	0.133	0.224	0.3	
LOM	None	None	None	MHz
Nearest HOM	777.0	589.5	1062.5	MHz
E_p^*	2.86	3.9	4.29	MV/m
B_p^*	4.38	7.13	9.3	mT
B_p^*/E_p^*	1.53	1.83	2.16	mT/(MV/m)
$[R/Q]_T$	982.5	287.2	125.0	Ω
Geometrical Factor (G)	105.9	138.7	136.0	Ω
$R_T R_S$	1.0×10^5	4.0×10^4	1.7×10^4	Ω^2
At $E_T^* = 1$ MV/m				

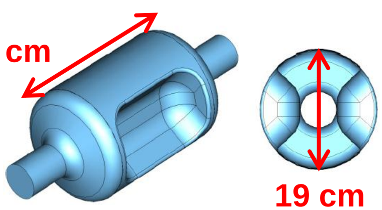
499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade



400 MHz Crabbing Cavity for LHC High Luminosity Upgrade



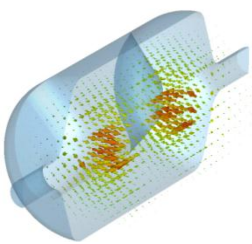
750 MHz Crabbing Cavity for MEIC at Jefferson Lab



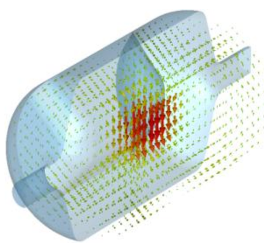
*** Alex Castilla (ODU)**

HOM Properties of the RF-Dipole Cavity

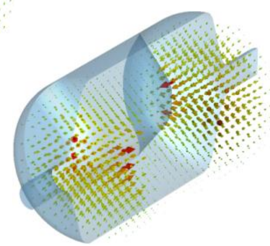
- Widely separated Higher Order Modes
- No Lower Order Modes



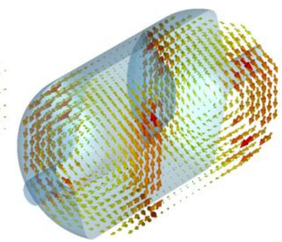
E field



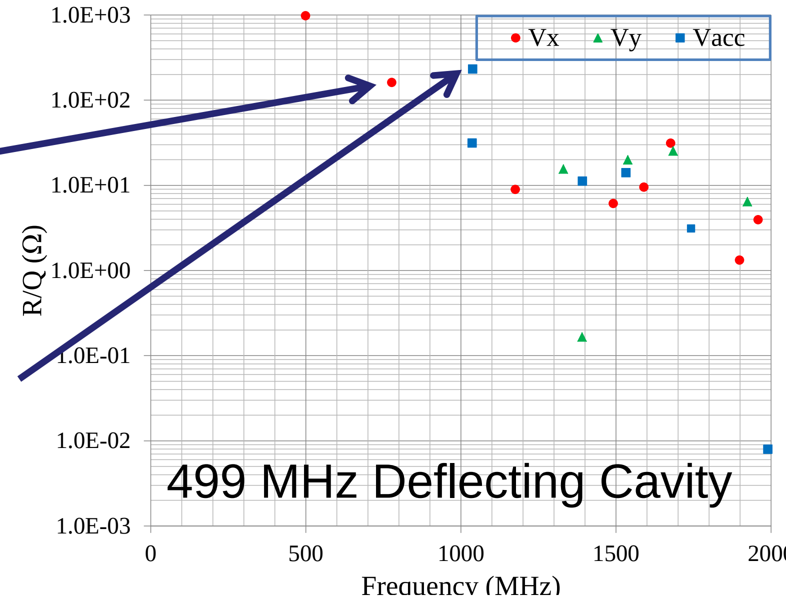
H field

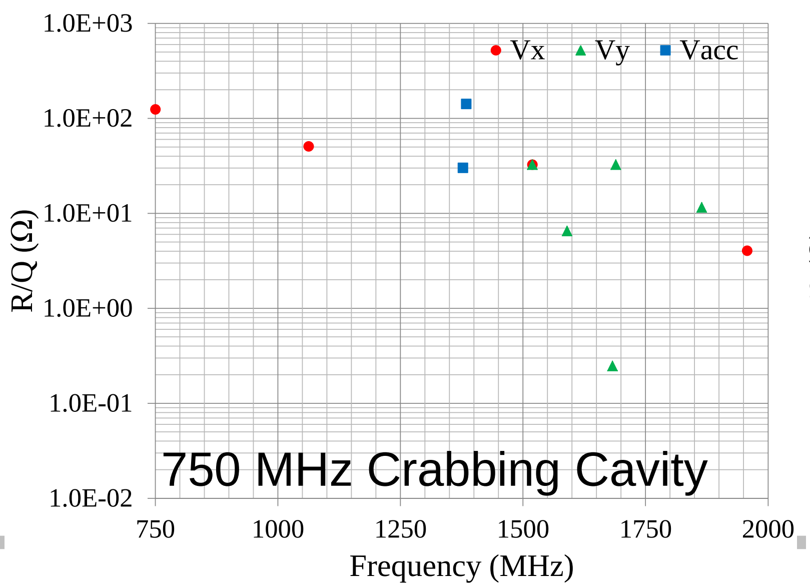


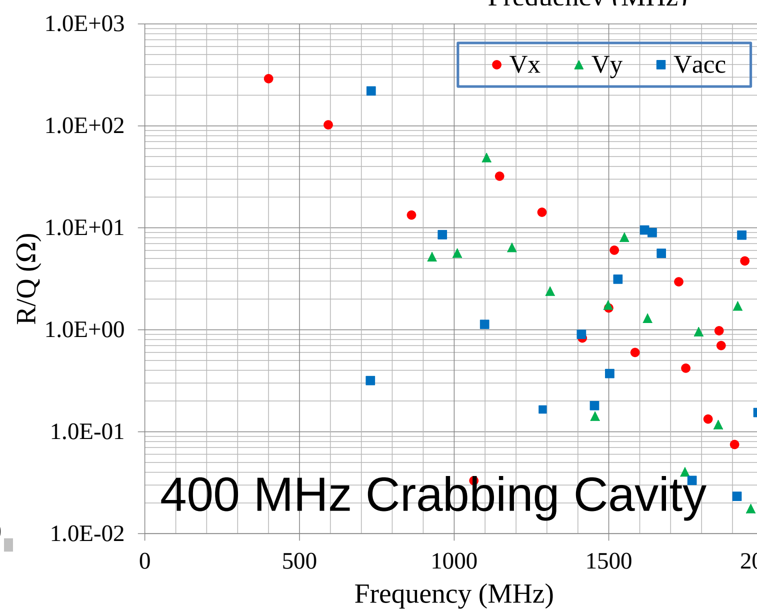
E field



H field



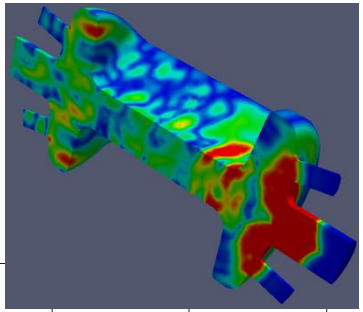


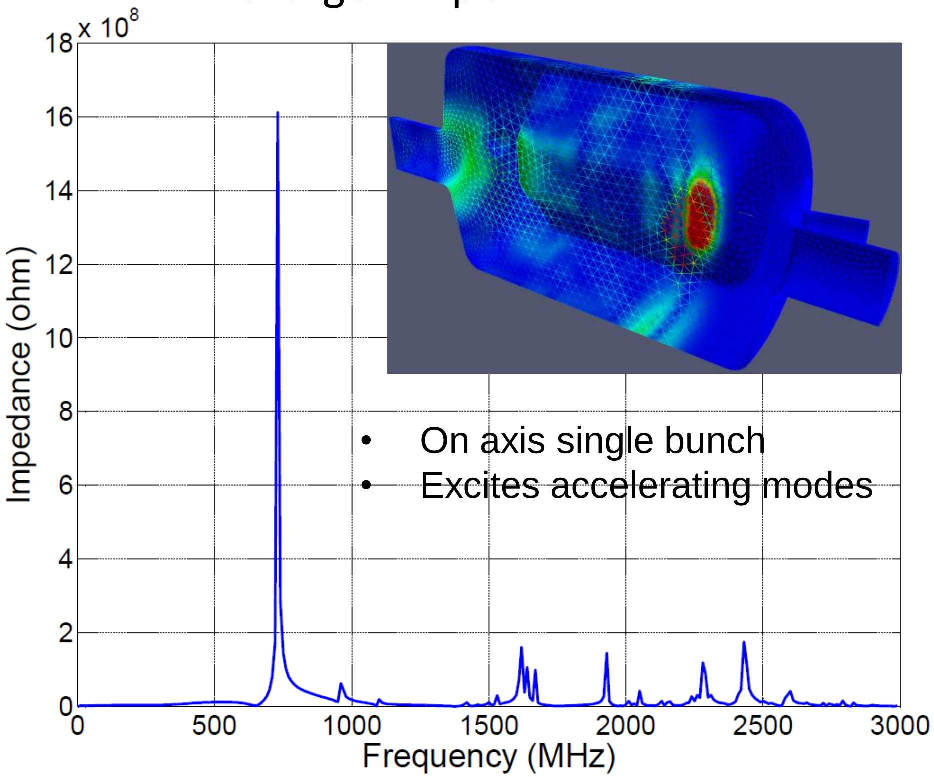


Wakefield and Impedance

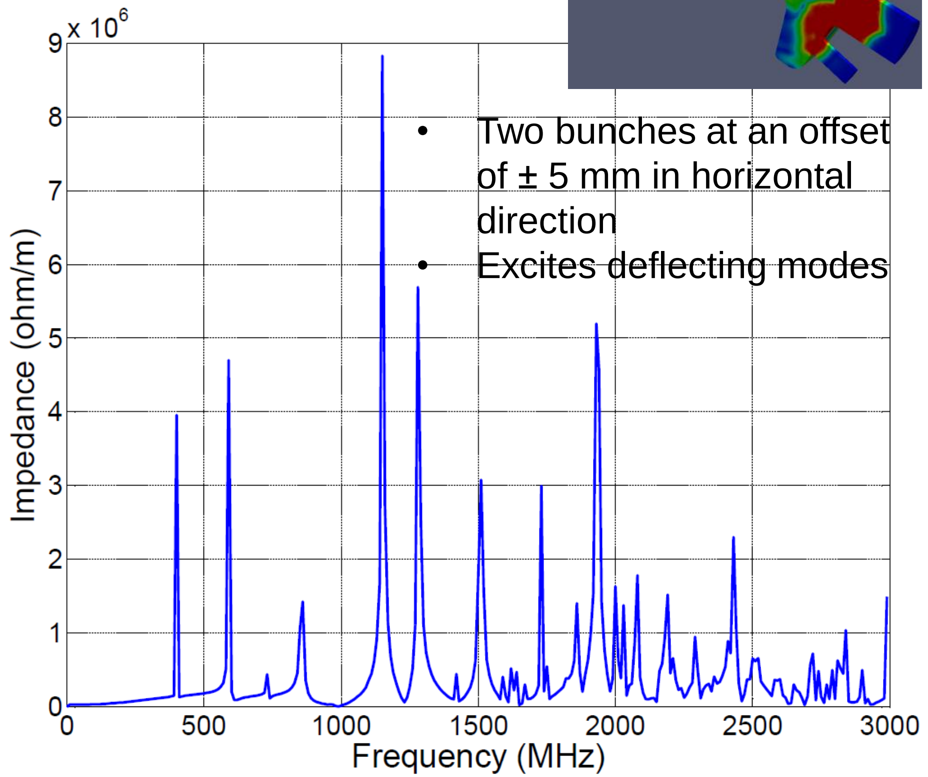
- T3P – EM Time Domain Solver in the SLAC ACE3P Suite
- For the 400 MHz crabbing cavity
- Bunch Parameters
  - σ = 1.4 cm
  - charge = 1 pC

$$\lambda(s) = \frac{1}{\sigma\sqrt{2\pi}} \exp[-\frac{(s-s_0)^2}{2\sigma^2}]$$





- On axis single bunch
- Excites accelerating modes



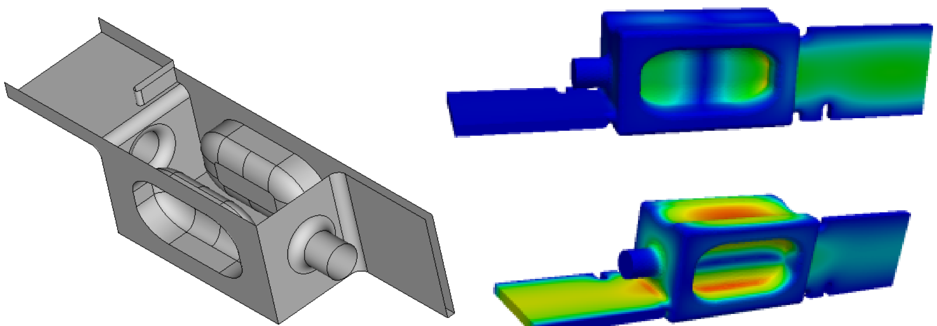
- Two bunches at an offset of ± 5 mm in horizontal direction
- Excites deflecting modes

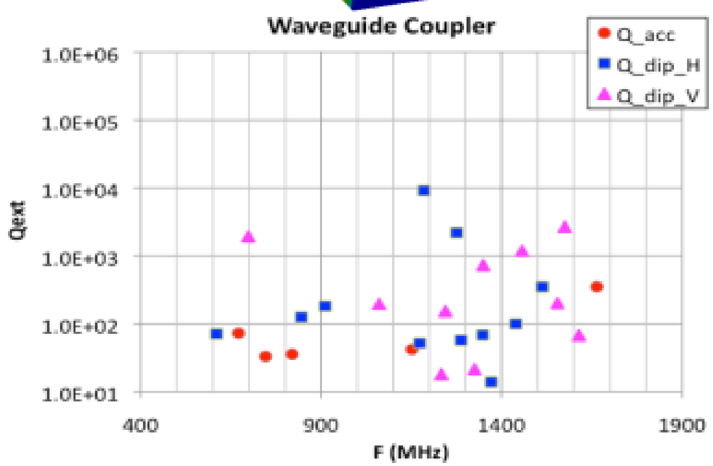
HOM Damping

- Widely separated HOMs from the operating mode allows more options in the design of damping schemes

Waveguide Damping

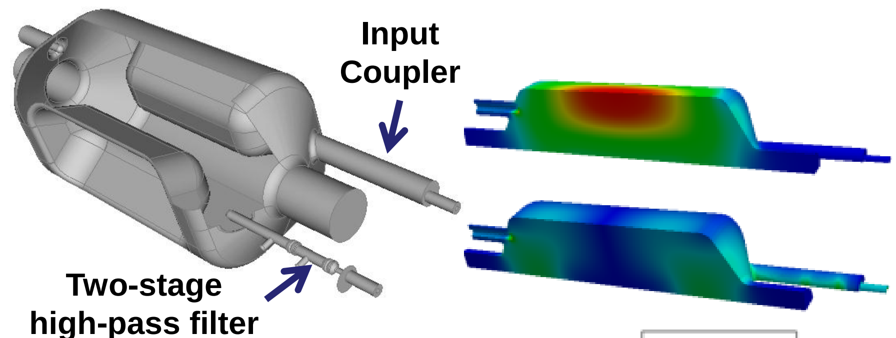
- Strong damping was achieved with waveguide couplers

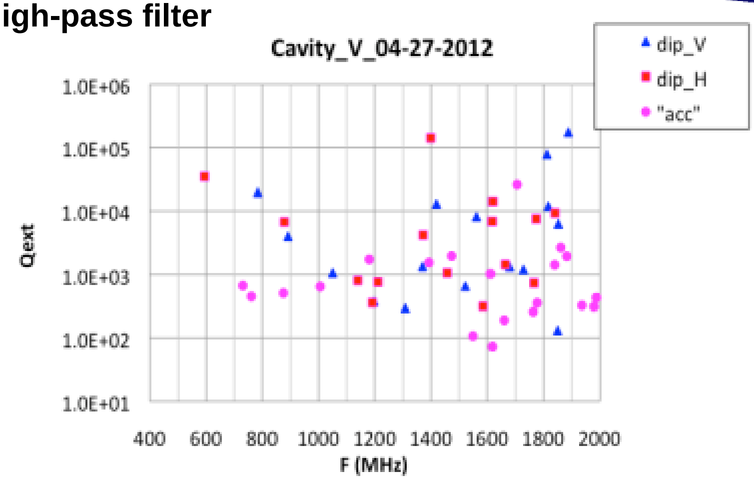




Coaxial Coupling

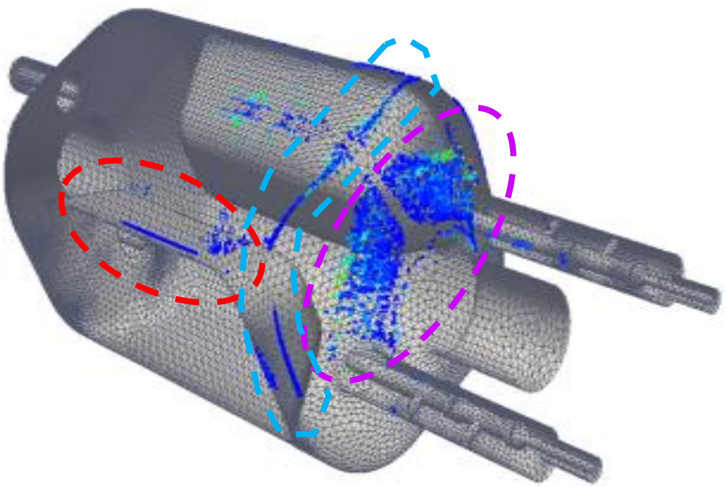
- A high pass coaxial couplers to exclude the operating mode

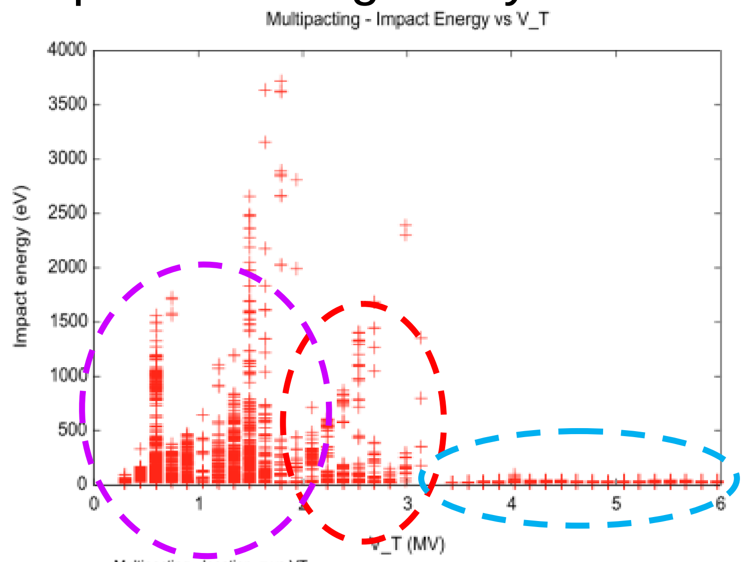




Multipacting Analysis

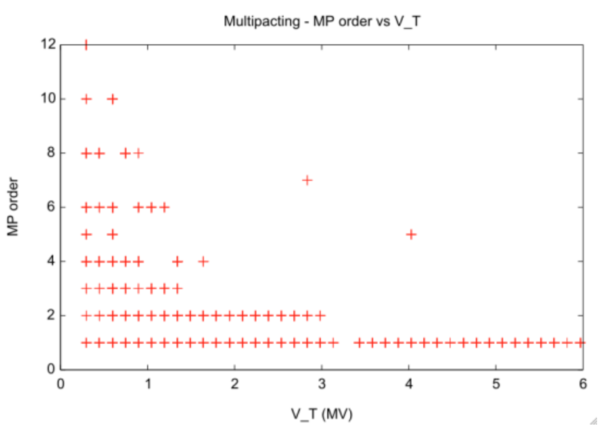
- Track3P – Particle tracking code in the SLAC ACE3P Suite
- For the 400 MHz square-shaped crabbing cavity

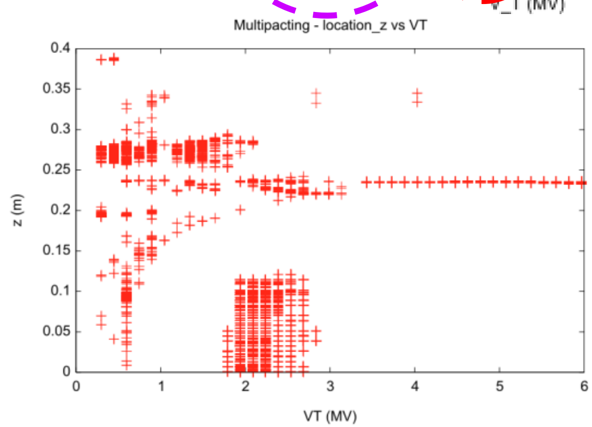


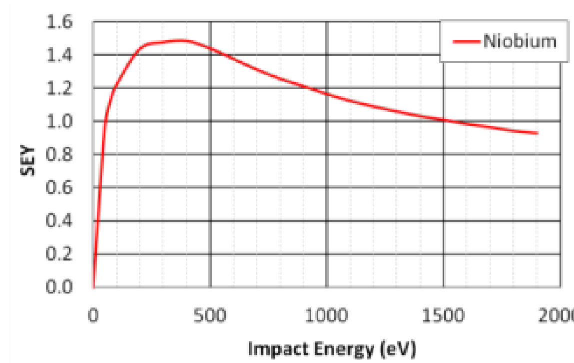


Deflecting Voltage

- *0.5MV to 2.6 MV*
- *1.8 MV to 2.8MV*
- *3.0 MV to 6.0 MV*







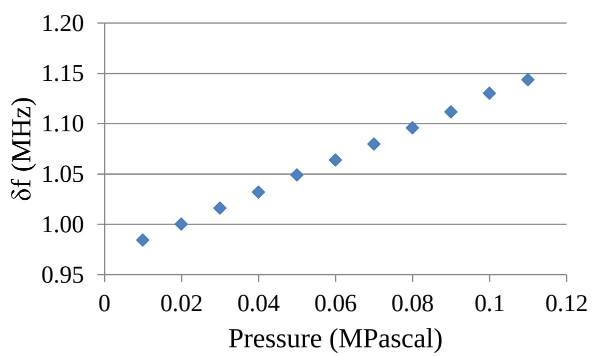
Z. Li et.al., in Proceedings of the 3rd IPAC, New Orleans, Louisiana (2012), p. 2185

Mechanical Analysis – 499 MHz Cavity

- Without any kind of stiffening or pressure sensitivity optimization

Pressure

- Pressure sensitivity - 212 Hz/torr



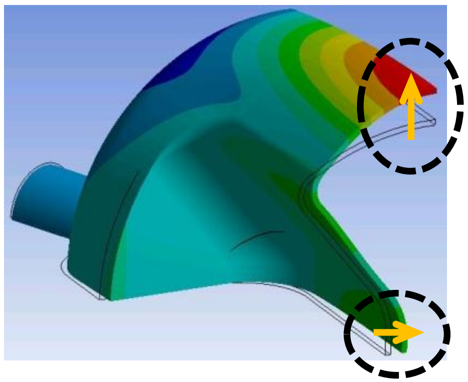
Lorentz Detuning

Room temperature cavity with a uniform 3 mm thickness

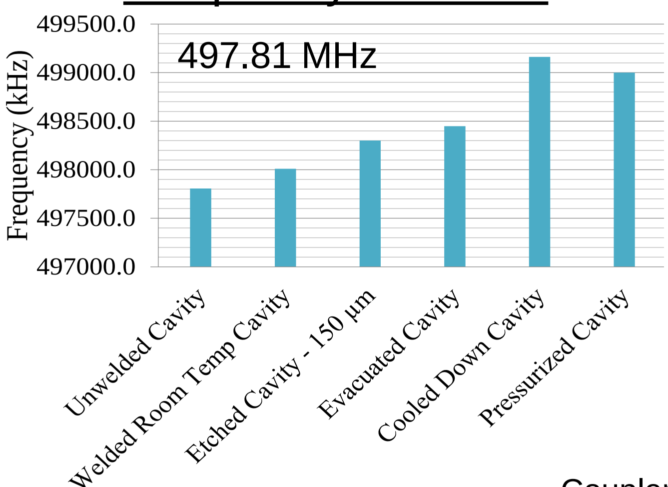
- Δf = 6.15 kHz @ V_T = 3.0 MV
- k_L = 61.54 Hz/(MV/m)^2

Fabricated cavity at 4 K

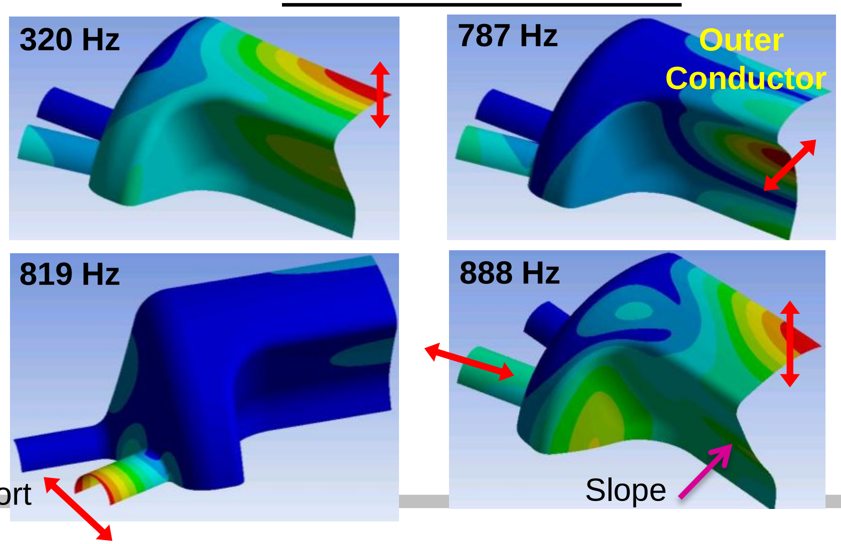
- Δf = 4.93 kHz @ V_T = 3.0 MV
- k_L = 49.27 Hz/(MV/m)^2
- Deformation = 1.2 μm



Frequency Variation



Mechanical Modes

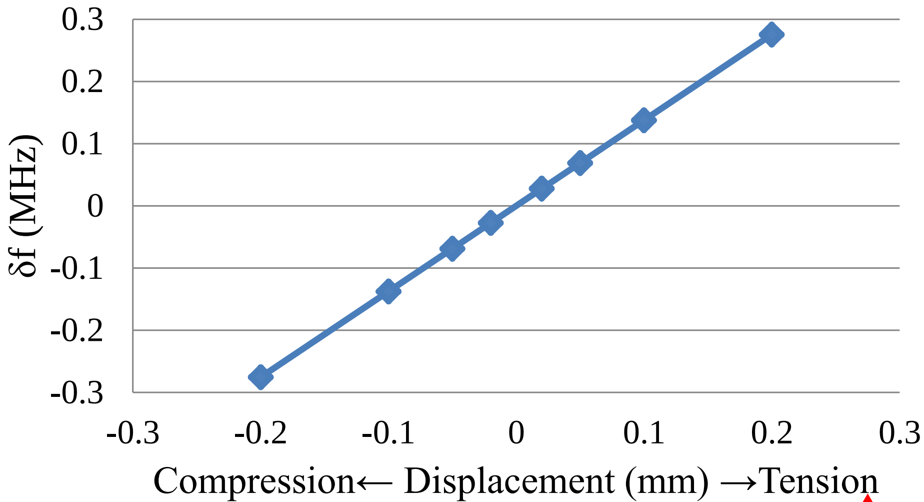


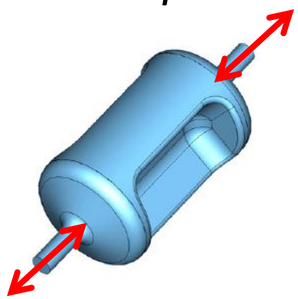
Coupler Port

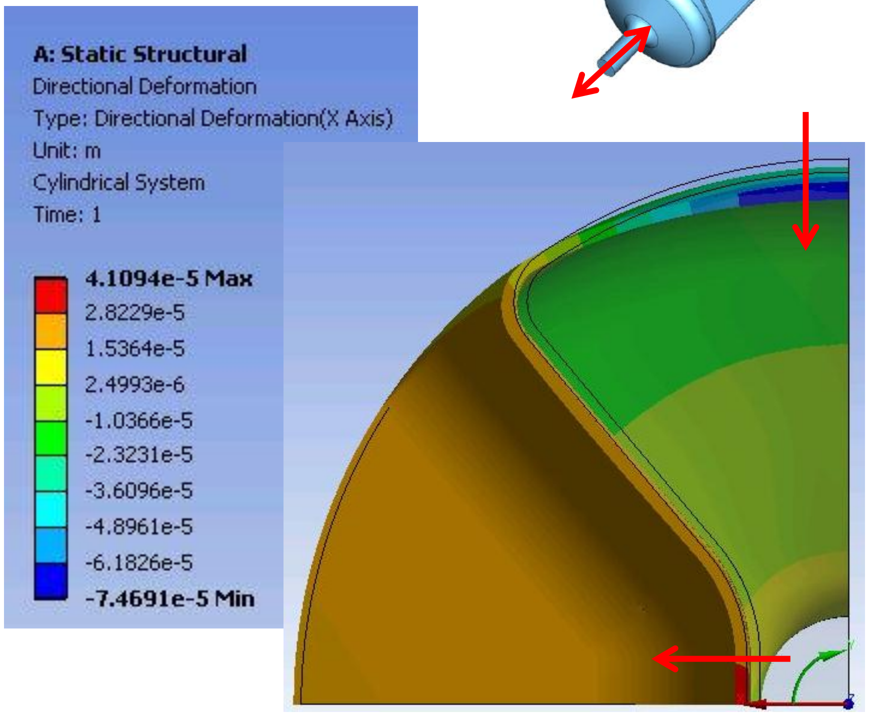
- Cavity with a 3 mm uniform thickness
- At room temperature and under vacuum

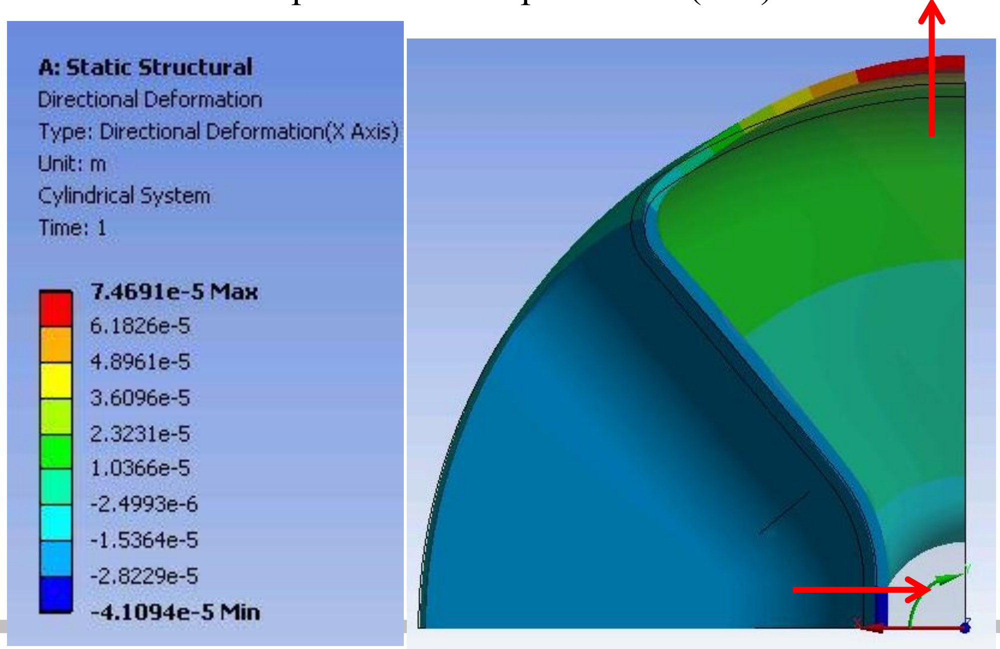
Tuning Sensitivity – 499 MHz Cavity

- Cavity as fabricated at 4 K under vacuum
- Tuning sensitivity – 1.4 kHz/μm

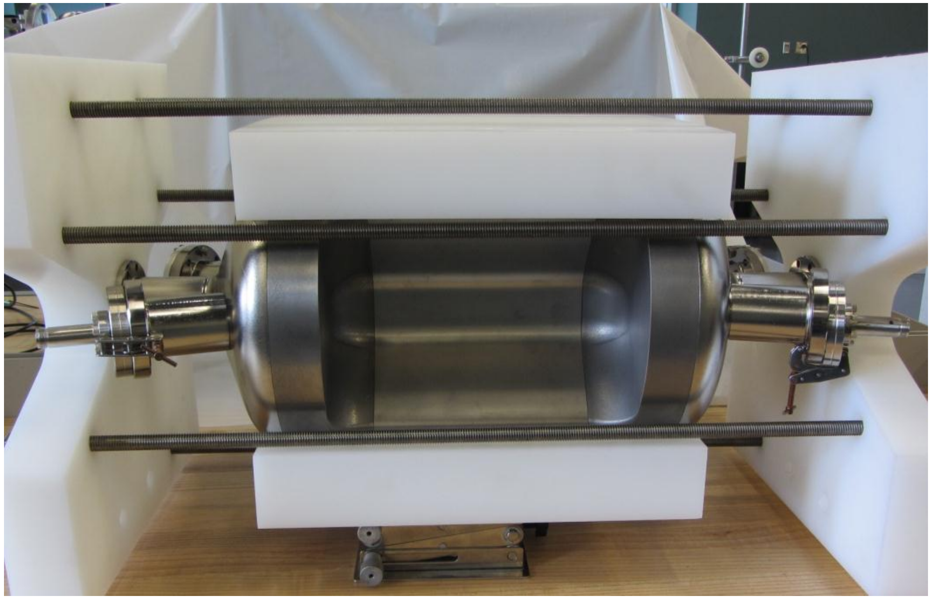


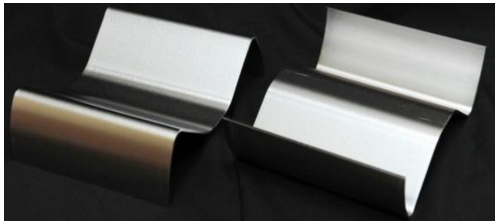


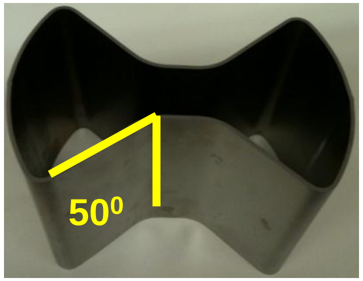




499 MHz RF-Dipole Cavity Fabrication

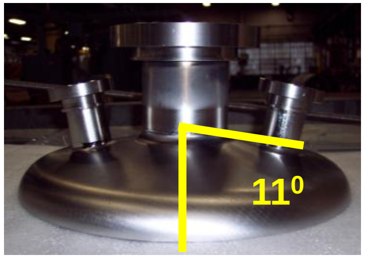


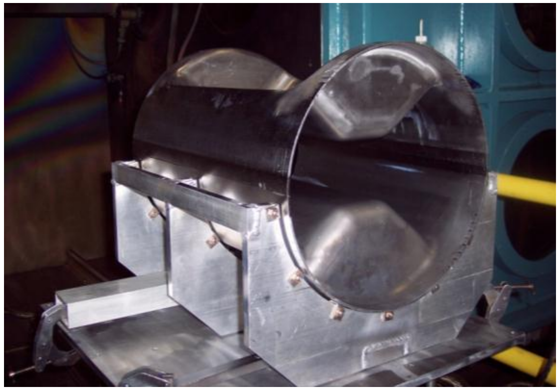




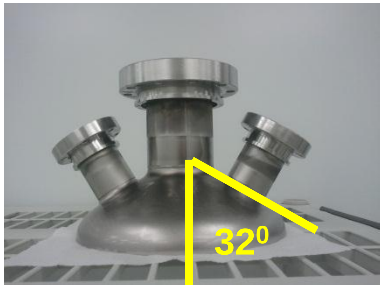
400 & 750 MHz RF-Dipole Cavity Fabrication

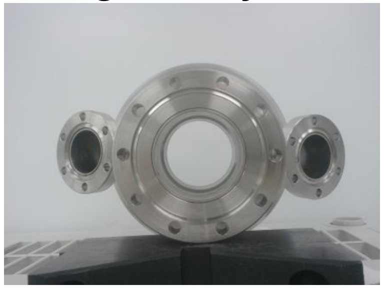
400 MHz Crabbing Cavity



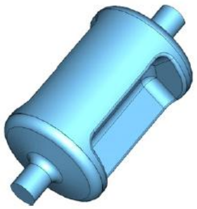
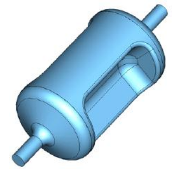
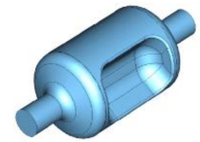


750 MHz Crabbing Cavity





Properties of Cavities Under Development

Parameter					 Alex Castilla (ODU)				Unit
Frequency	400.0		499.0		750.0				MHz
Particle	p		e^-		e^-		p		
Deflecting voltage (V_T^*)	0.375		0.3		0.2				MV
Peak electric field (E_P^*)	3.9		2.86		4.29				MV/m
Peak magnetic field (B_P^*)	7.13		4.38		9.3				mT
Required transverse voltage per beam	10.0		5.6		1.5		8.0		MV
No. of cavities	3		2		1		4		
Transverse voltage per cavity	3.4		3.0		1.5		2.0		MV
Peak magnetic field (B_P)	64.7		43.8		69.8		93.0		mT
Peak electric field (E_P)	35.4		28.6		32.2		42.9		MV
$R_T R_S$	3.7×10^4		3.6×10^4		3.7×10^4				Ω^2
Operating temperature	2.0	4.0	2.0	4.0	2.0	4.0	2.0	4.0	K
Surface Resistance (R_S)**	11.3	70.0	12.0	100.0	14.0	200.0	14.0	200.0	nΩ
Power dissipation per cavity **	3.6	21.9	3.0	25.0	0.9	12.2	1.6	21.7	W

At E_T^* = 1 MV/m ** Estimated

Summary

- Development of compact deflecting/crabbing cavities was in response to the strict dimensional requirements in some current applications

- Compact rf-dipole design has
  - Low and balanced surface fields
  - High shunt impedance
  - Has no lower-order-mode with a well-separated fundamental mode

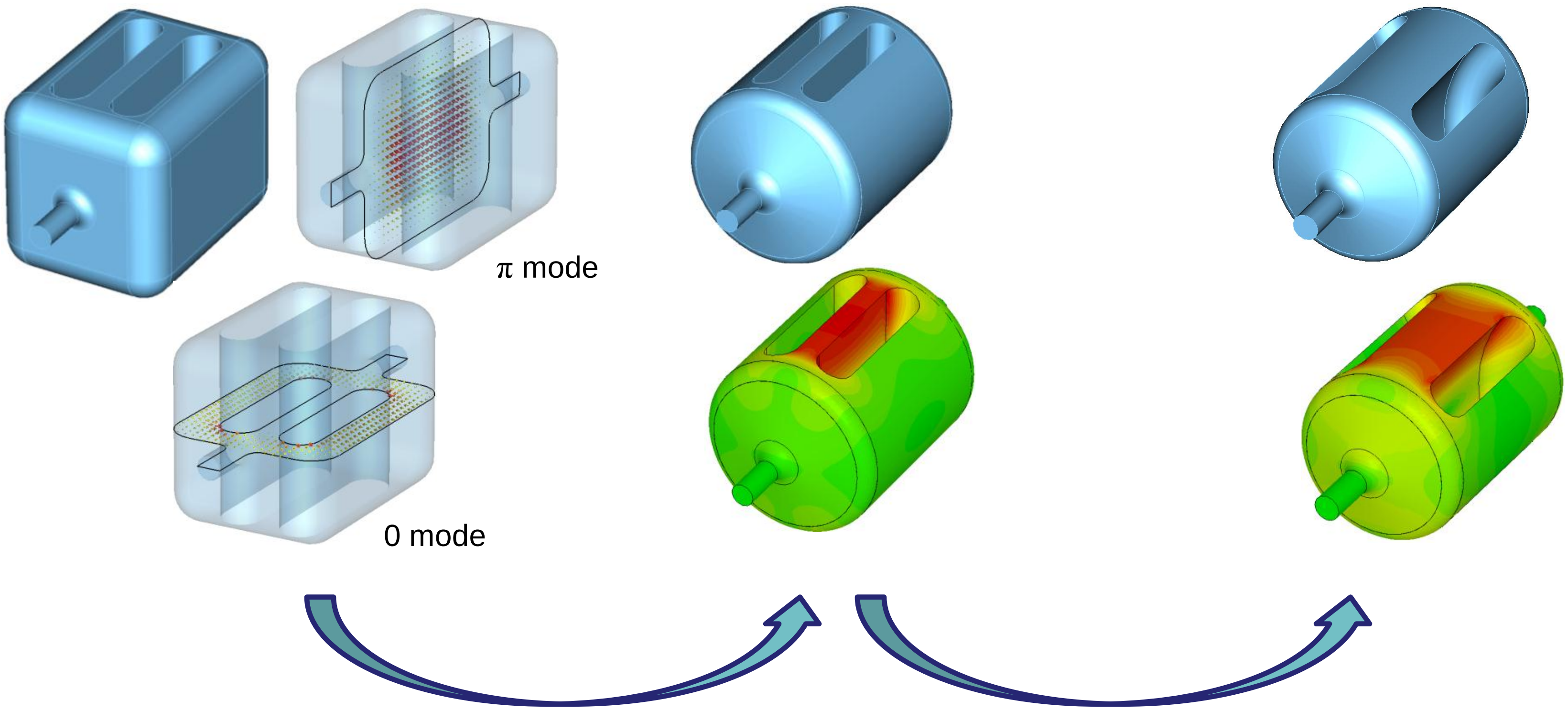
- Work in progress
  - 499 MHz deflecting cavity
    - Fabrication will be completed by Nov-Dec
  - 400 MHz crabbing cavity
    - Preparation for processing
    - Bulk BCP – Fixtures and parts are being fabricated for both cavities (Nov-Dec)
  - 750 MHz crabbing cavity
    - Cavity processed with bulk BCP of 150 μm

Acknowledgements

- Jefferson Lab
  - HyeKyoung Park
- ODU
  - Alejandro Castilla
- SLAC
  - Zenghai Li, Lixin Ge
- Niowave
  - Dmitry Gorelov, Terry Grimm

- The work done at ODU is towards my PhD carried out under the supervision of Dr. Jean Delayen

Design Evolution

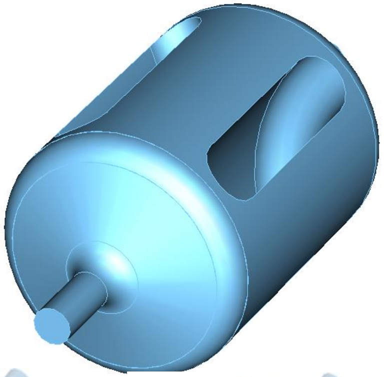


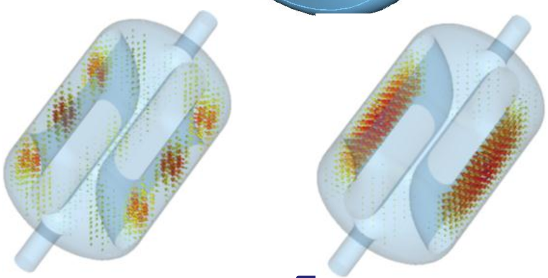
- To increase mode separation between fundamental modes
- ~18 MHz → ~ 130 MHz
- To improve design rigidity → Less susceptible to mechanical vibrations and deformations

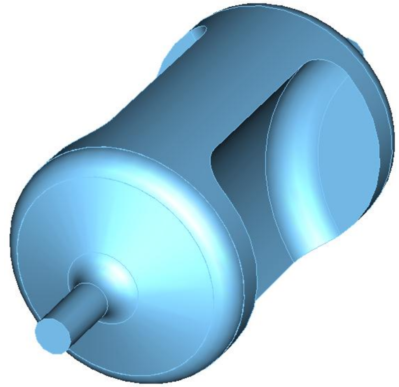
- To lower peak magnetic field
- Reduced peak magnetic field by ~20%

Design Evolution

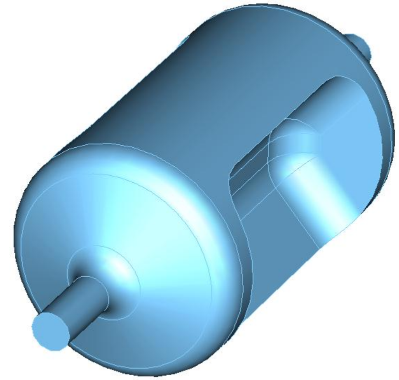
TEM-type mode







TE-like mode



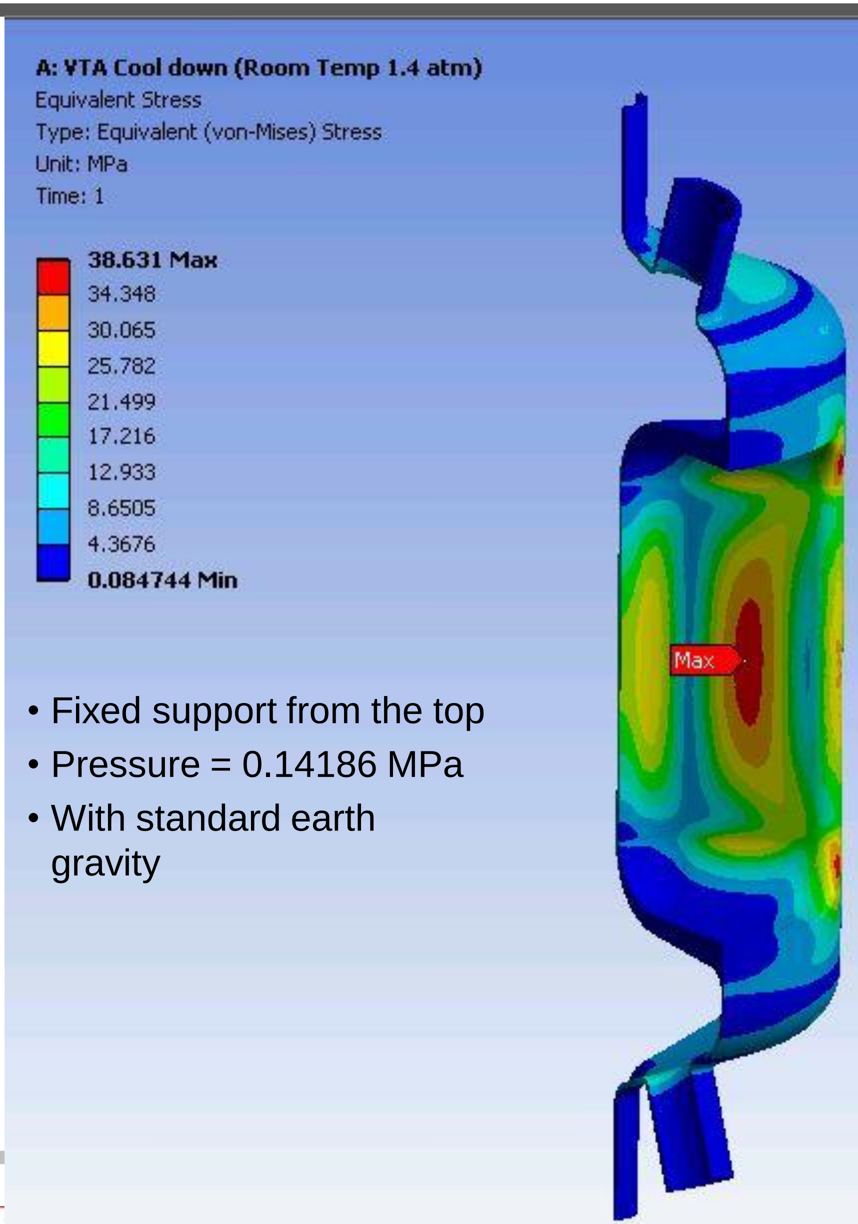
Balanced Peak Fields

$$\frac{B_P}{E_P} \leq 2.0 \ \mathrm{mT/(MV/m)}$$

- To remove higher order modes with field distributions between the cavity outer surface and bar outer surface
- Eliminate multipacting conditions

- To lower peak magnetic field
- Reduced peak magnetic field by ~25%
- To achieve balanced peak surface fields
- $B_P/E_P \approx 1.5$ mT/(MV/m)

Stress Analysis – 499 MHz Cavity



- Fixed support from the top
- Pressure = 0.14186 MPa
- With standard earth gravity