DESIGNING, PROTOTYPING AND TESTING OF SUPERCONDUCTING RF-DIPOLE DEFLECTING/CRABBING CAVITIES

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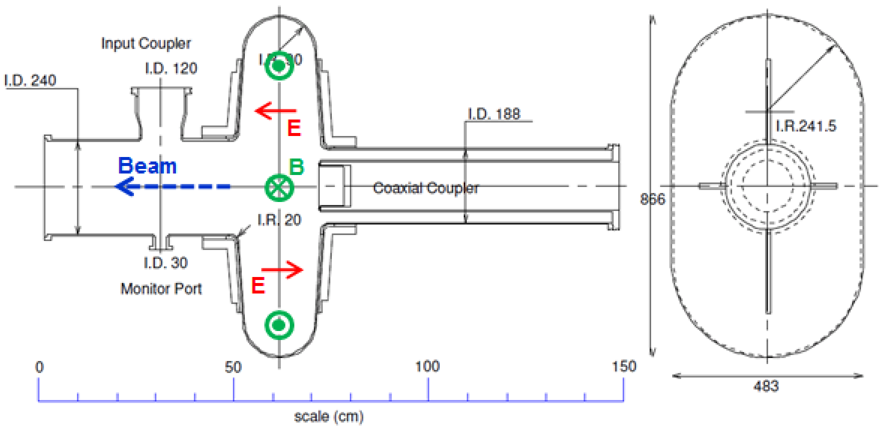
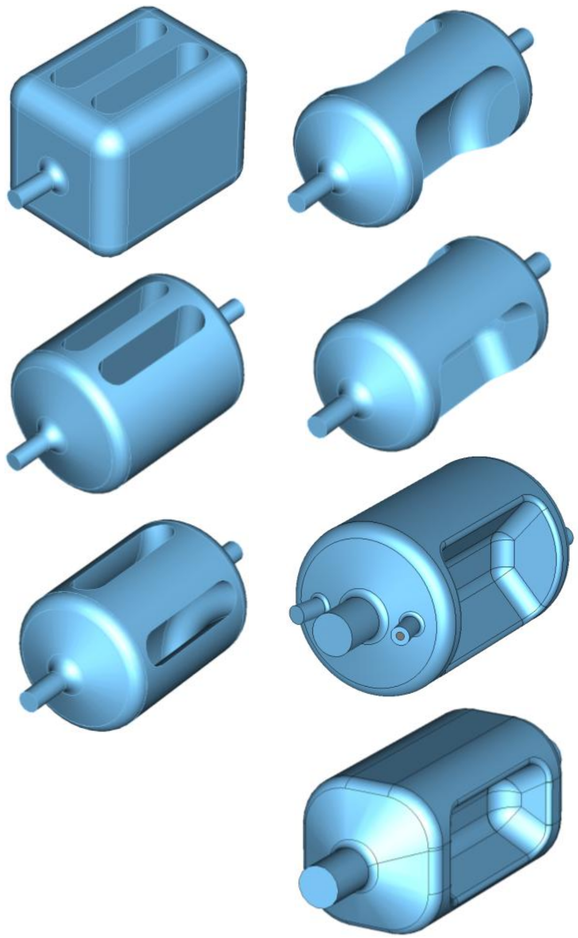
Motivation

Design superconducting compact deflecting and crabbing cavities at lower frequencies

KEK Crabbing Cavity – TM_{110} mode

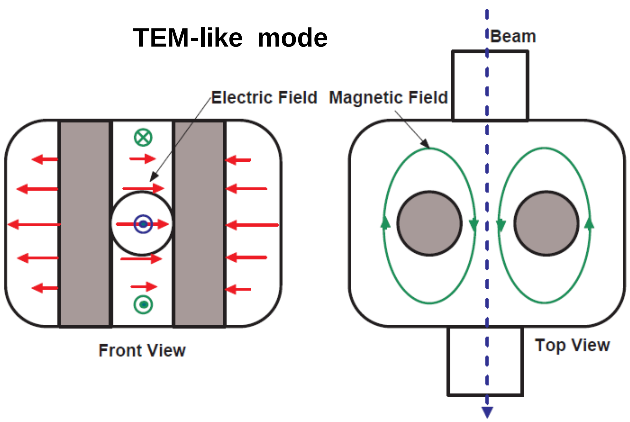


TEM-like Designs **TE-like Designs**



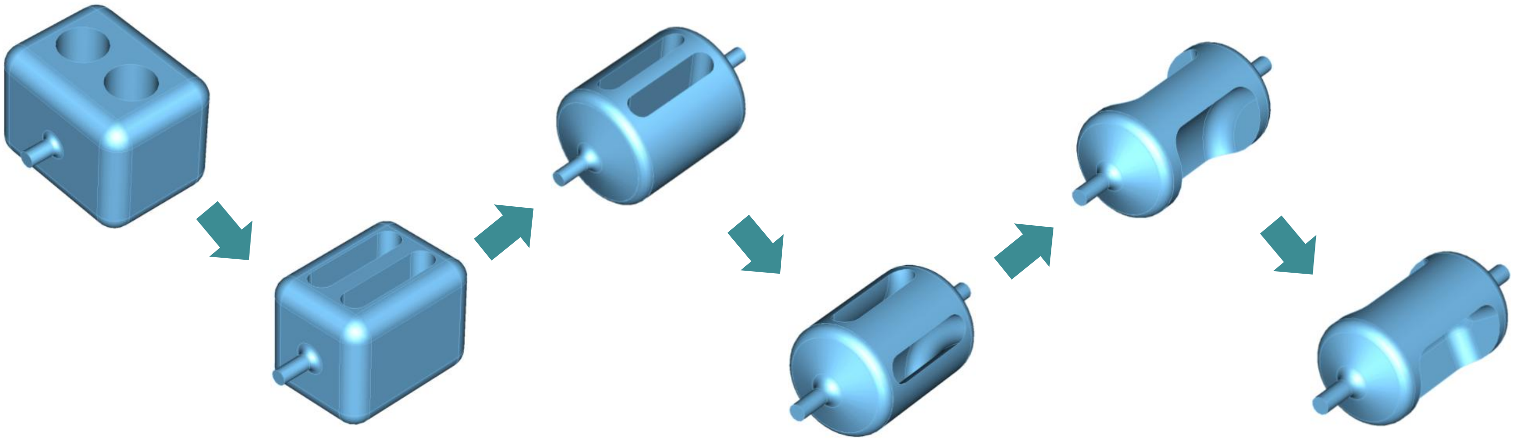
- Operating mode: TEM-like or TE-like modes
  - Net deflection is due to the transverse electric mode
- Cannot be a pure TE mode – Panofsky Wenzel Theorem

TEM-like mode



Design Evolution from Parallel-Bar to RF-Dipole

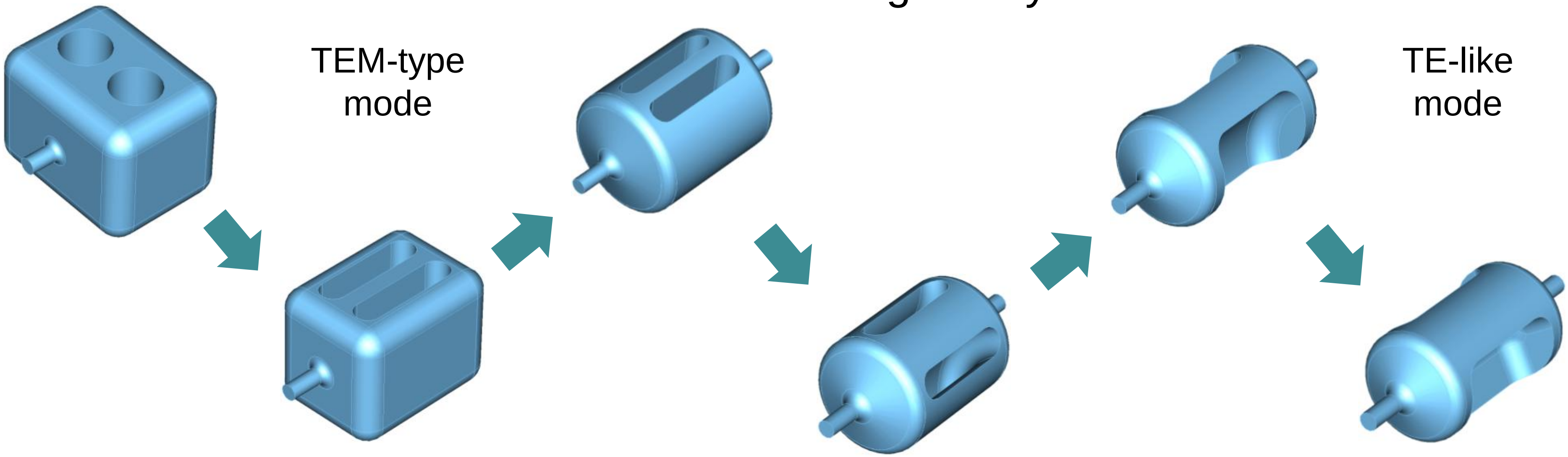
- Aspects of optimization
  - Lower and balanced peak surface fields
  - Stability of the design
    - Cylindrical shape is preferred to reduce flat surfaces
  - Cavity processing
    - Curved end plates for cleaning the cavity
  - Multipacting
  - Wider separation in Higher Order Mode (HOM) spectrum

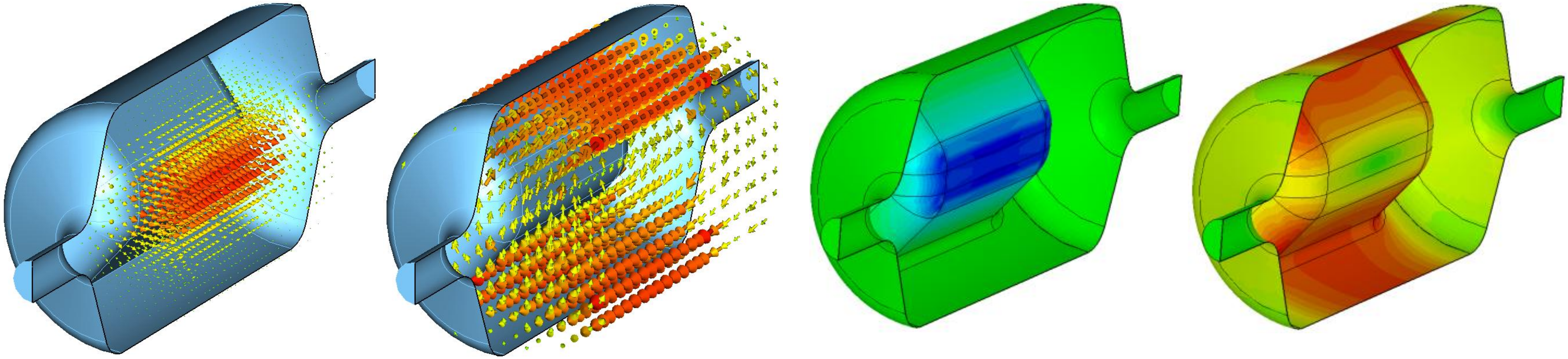


499 MHz Deflecting Cavity

Design Evolution from Parallel-Bar to RF-Dipole

499 MHz Deflecting Cavity*

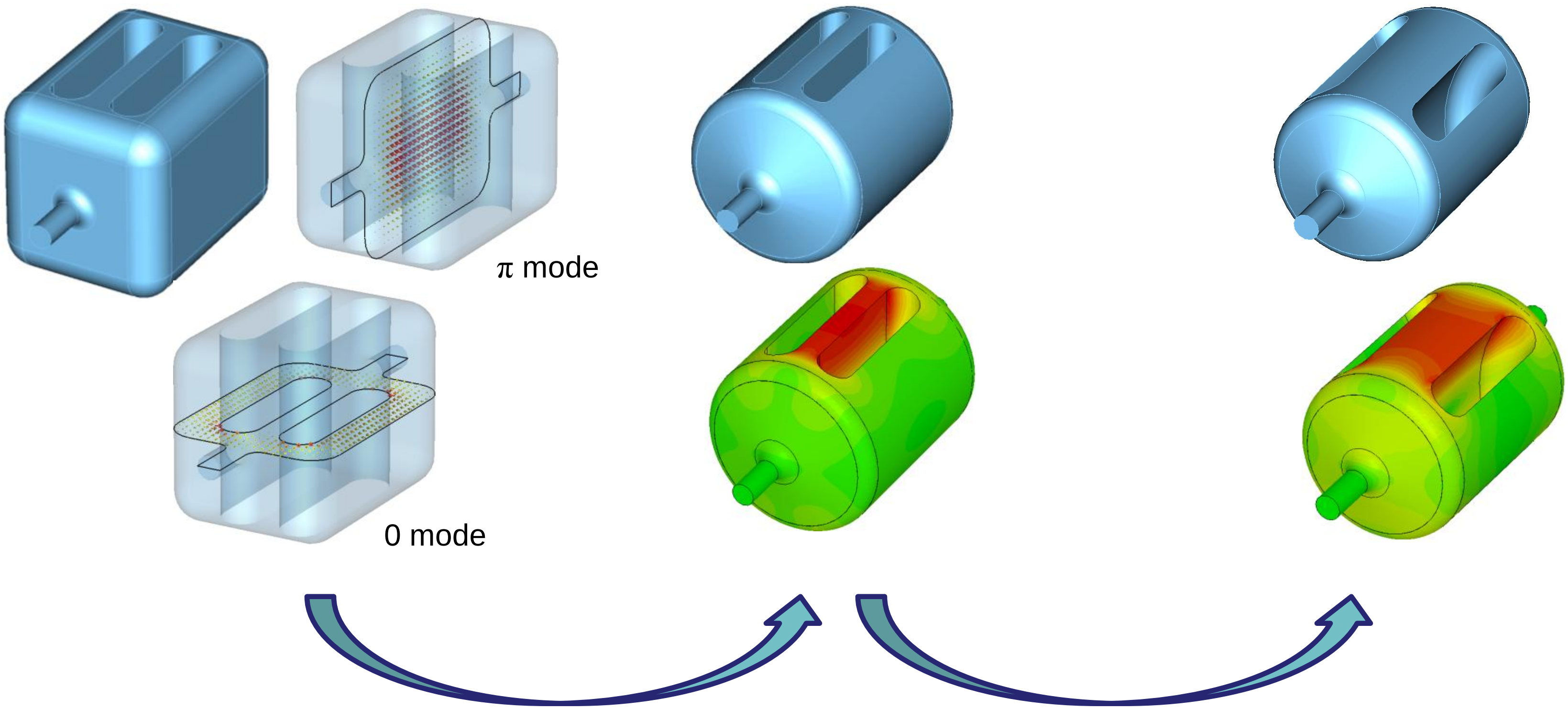




E Field H Field Surface E Field Surface H Field

*J.R. Delayen, S.U. De Silva, “Designs of Superconducting Parallel-Bar Deflecting Cavities for Deflecting/Crabbing Applications”, Proc. of the15th International Conference on RF Superconductivity, p.219, (2011)

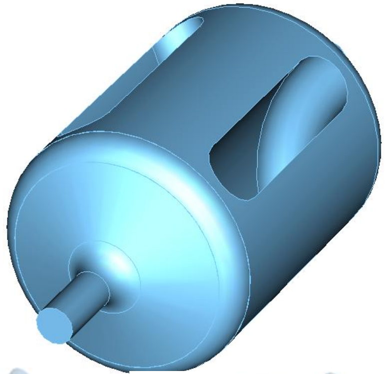
Design Evolution from Parallel-Bar to RF-Dipole

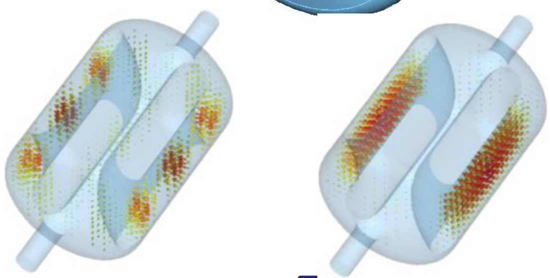


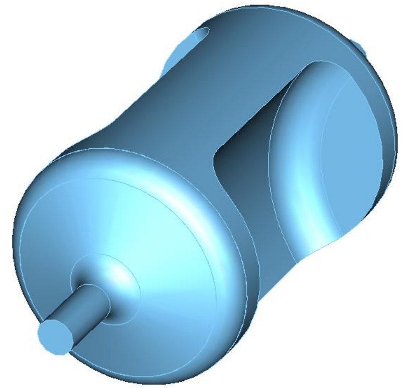
- To increase mode separation between fundamental modes
- ~18 MHz → ~ 130 MHz
- To improve design rigidity → Less susceptible to mechanical vibrations and deformations

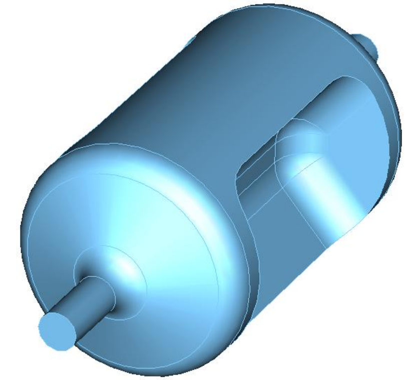
- To lower peak magnetic field
- Reduced peak magnetic field by ~20%

Design Evolution from Parallel-Bar to RF-Dipole









Balanced Peak Fields

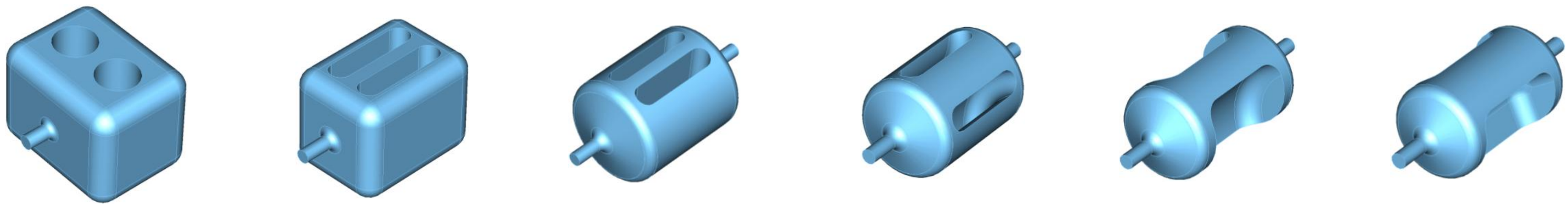
$$\frac{B_P}{E_P} \leq 2.0 \text{ mT/(MV/m)}$$

- 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)

Design Evolution from Parallel-Bar to RF-Dipole

499 MHz Deflecting Cavities



10.7 MHz | 18.4 MHz | 127.1 MHz | 264.5 MHz | 255.3 MHz | 278.0 MHz

Balanced surface field ratio

[–]

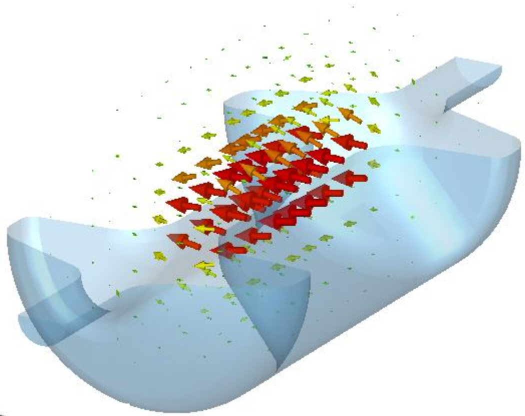
Deflecting Voltage (V_t[a])	0.30	0.30	0.30	0.30	0.30	0.30	MV
Peak Electric Field (E_p[a])	3.45	1.83	2.08	2.55	2.85	2.86	MV/m
Peak Magnetic Field (B_p[a])	11.47	6.05	6.47	5.42	5.12	4.38	mT
B_p/E_p	3.33	3.30	3.12	2.12	1.80	1.53	mT/(MV/m)
Energy Content (U[a])	0.049	0.030	0.032	0.033	0.036	0.029	J
Geometrical Factor (G)	80.9	67.0	67.4	87.7	94.2	105.9	Ω
$[R/Q]_t$	591.7	935.9	887.3	866.8	807.7	982.5	Ω
R_tR_s	4.8×10^4	6.3×10^4	6.0×10^4	7.6×10^4	7.6×10^4	1.0×10^5	Ω^2

[a] At E_t = 1 MV/m

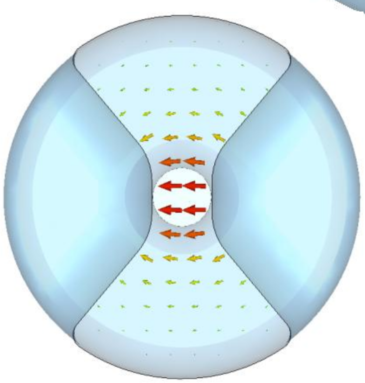
RF-Dipole Design

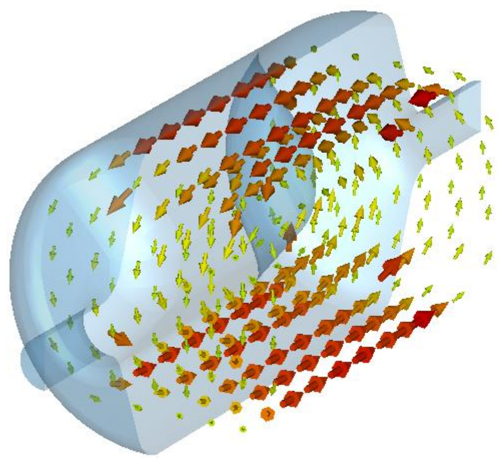
- Properties depend on a few parameters
  - Frequency determined by diameter of the cavity design
  - Bar Length ~$\lambda/2$
  - Bar height and aperture determine E_P and B_P
  - Angle determines B_P/E_P

499 MHz Deflecting Cavity

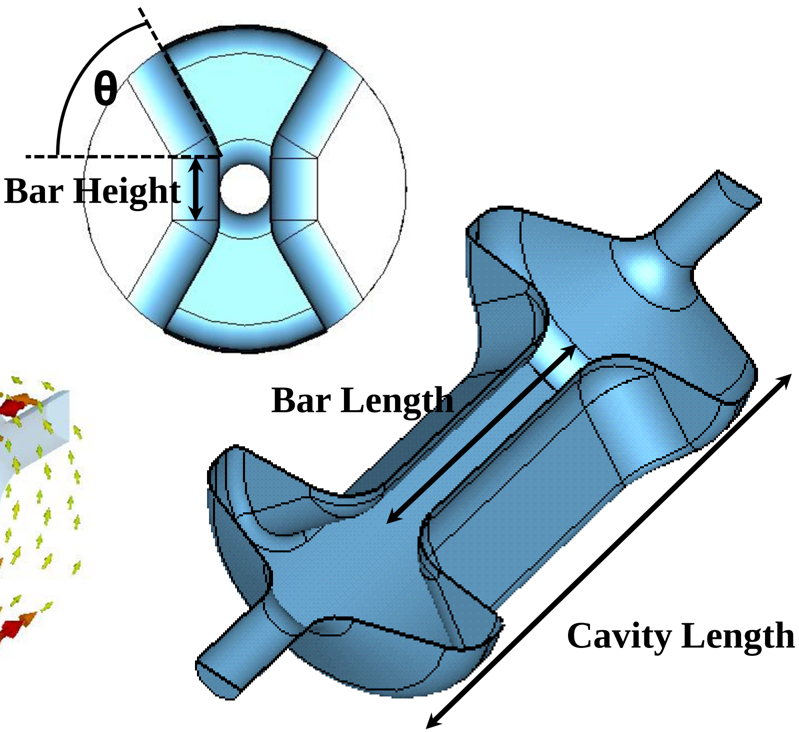


Electric Field





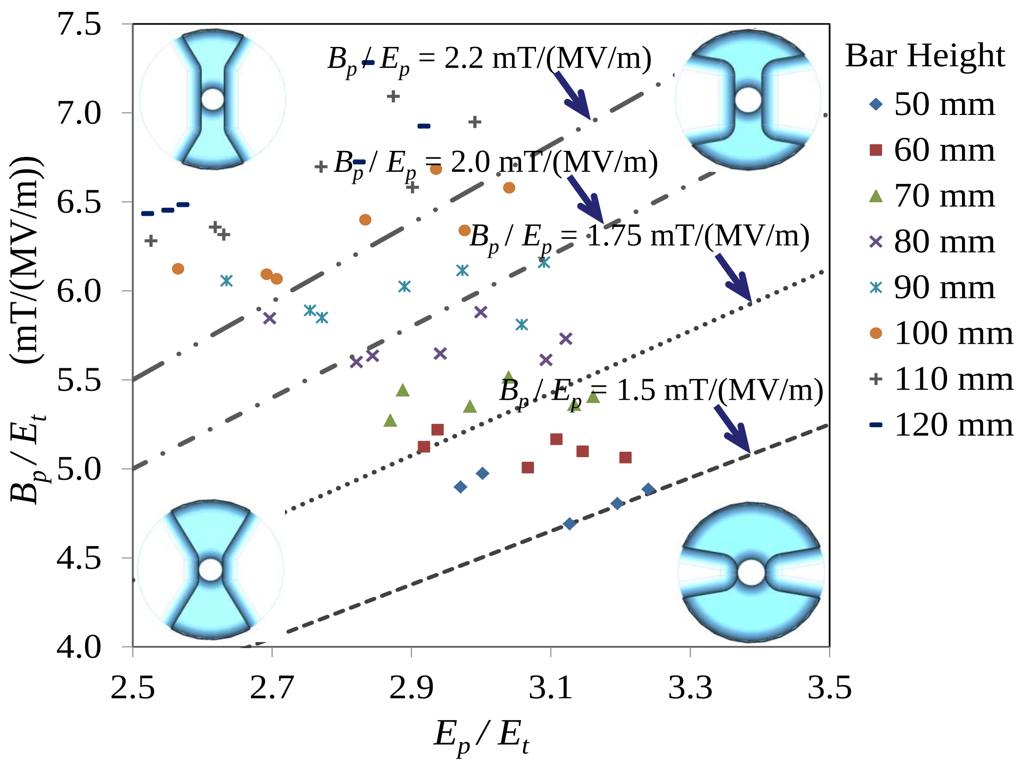
Magnetic Field

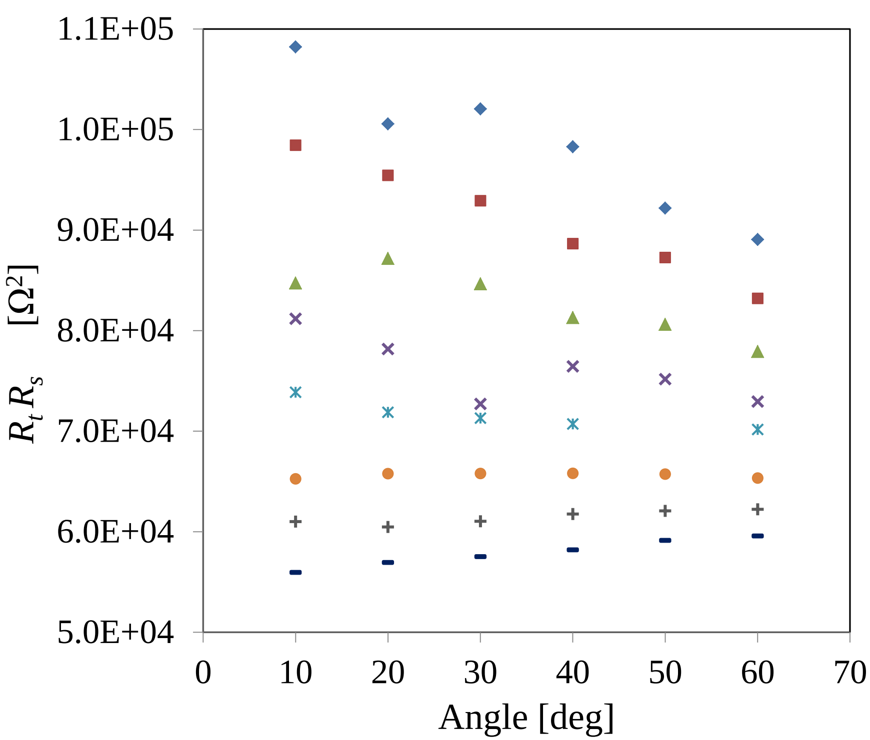


Design Optimization

- For superconducting rf cavities
  - Minimize E_P/E_T and B_P/E_T
  - Maximize $R_T R_S$

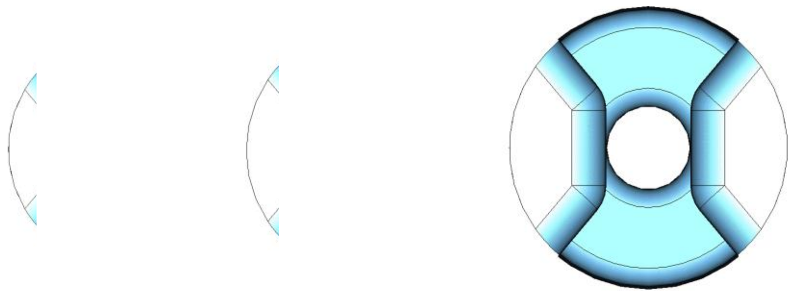
499 MHz Deflecting Cavity

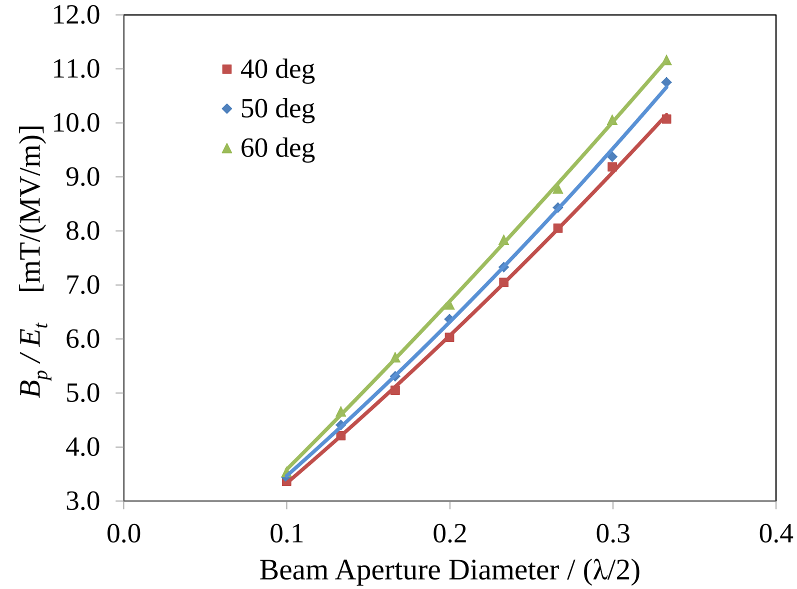


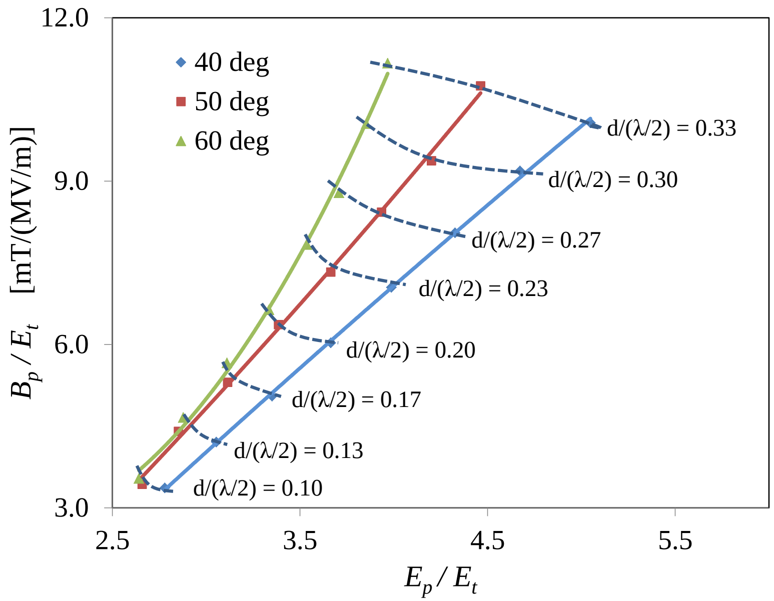


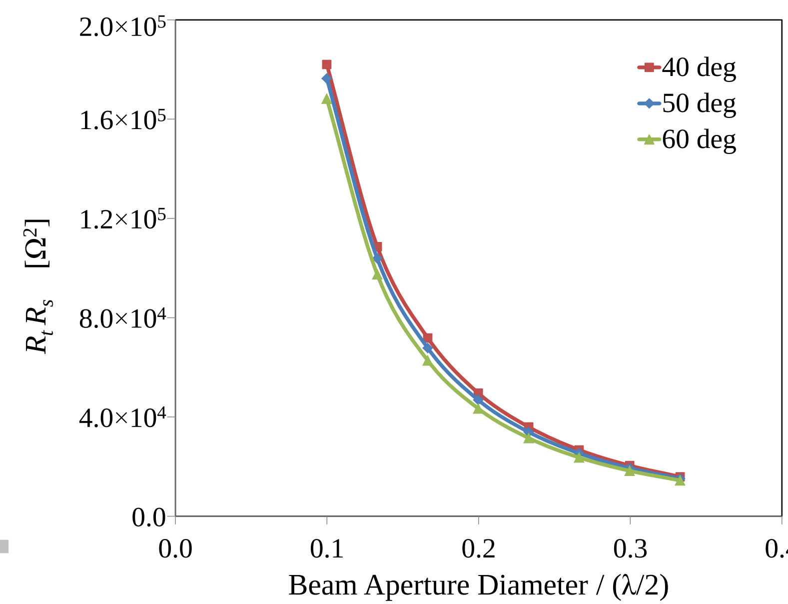
Beam Aperture Dependence

- At 499 MHz varying beam aperture from 30 – 100 mm





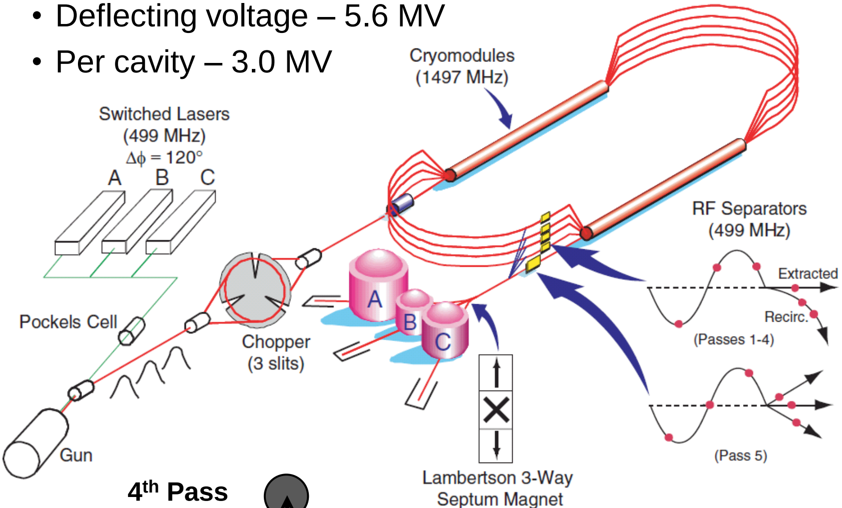


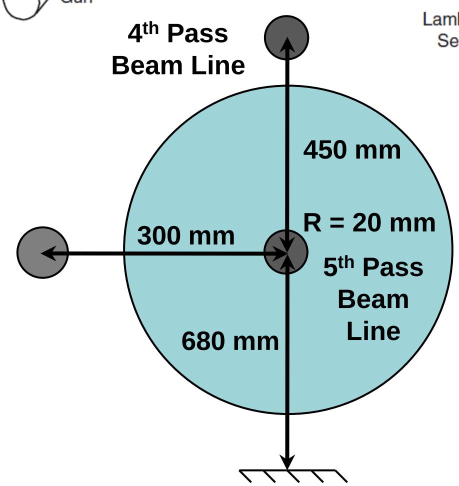


Current Applications of RF Dipole Cavity

499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade

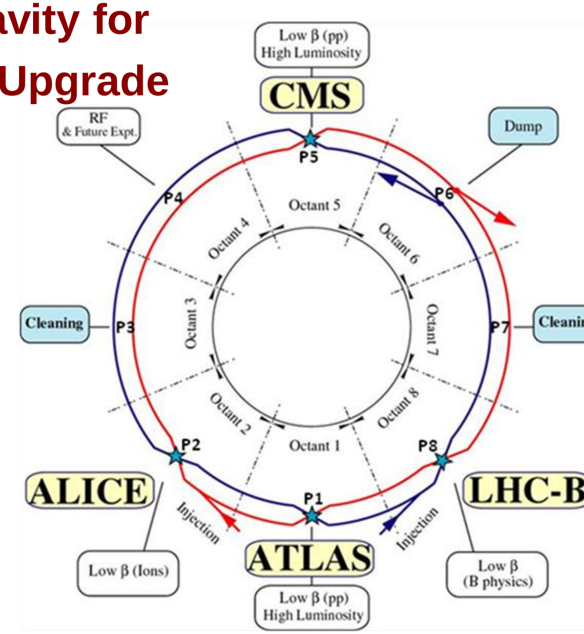
- Deflecting voltage – 5.6 MV
- Per cavity – 3.0 MV



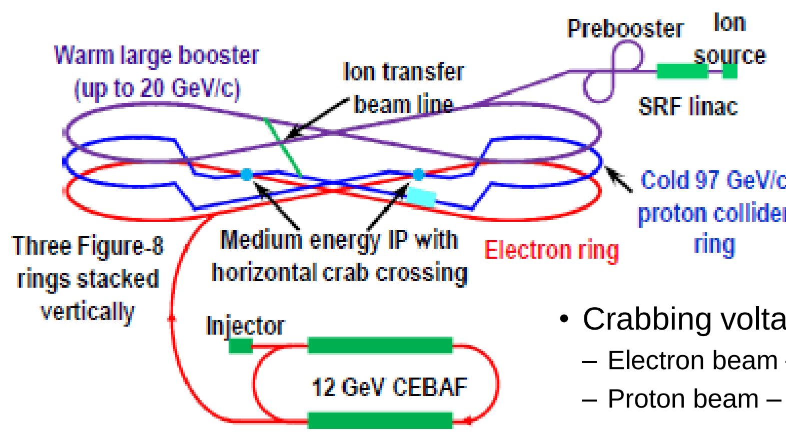


400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

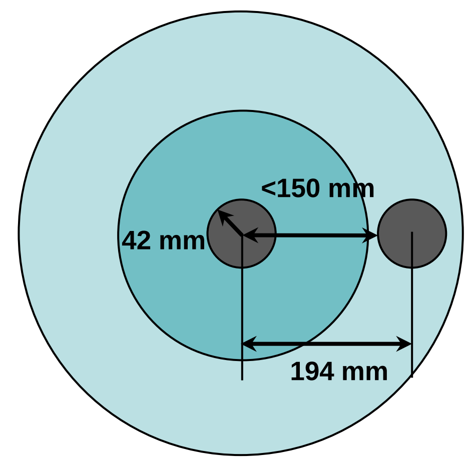
- Crabbing voltage – 10 MV per beam per side
- Per cavity – 3.4 MV
- Requires a crabbing system at two interaction points (IP1 and IP5)
  - Vertical crossing at IP1
  - Horizontal crossing at IP5



750 MHz Crabbing Cavity for MEIC*



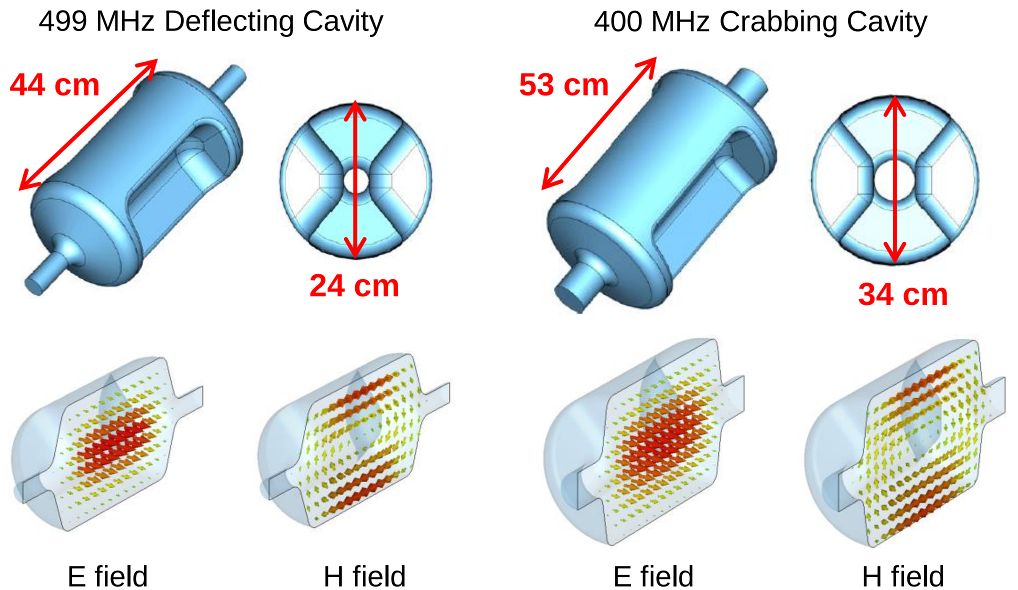
- Crabbing voltage
  - Electron beam – 1.5 MV
  - Proton beam – 8.0 MV



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

Properties of Proof of Principle Cavities

Frequency	**499.0**	**400.0**	**MHz**
Aperture Diameter (d)	40.0	84.0	mm
d/(λ/2)	0.133	0.224	
V_T^*	0.3	0.375	MV/m
E_p^*	2.86	4.02	MV/m
B_p^*	4.38	7.06	mT
B_p^*/E_p^*	1.53	1.76	mT/ (MV/m)
U^*	0.029	0.195	J
$[R/Q]_T$	982.5	287.0	Ω
Geometrical Factor (G)	105.9	140.9	Ω
$R_T R_S$	$1.0\ \ 10^5$	$4.0\ \ 10^4$	Ω^2
At $E_T^* = 1$ MV/m			
V_T	3.0 / 5.6	3.4 / 5.0	MV
E_p	28.6 / 53.4	36.5 / 53.6	MV/m
B_p	43.8 / 81.8	64.0 / 94.2	mT

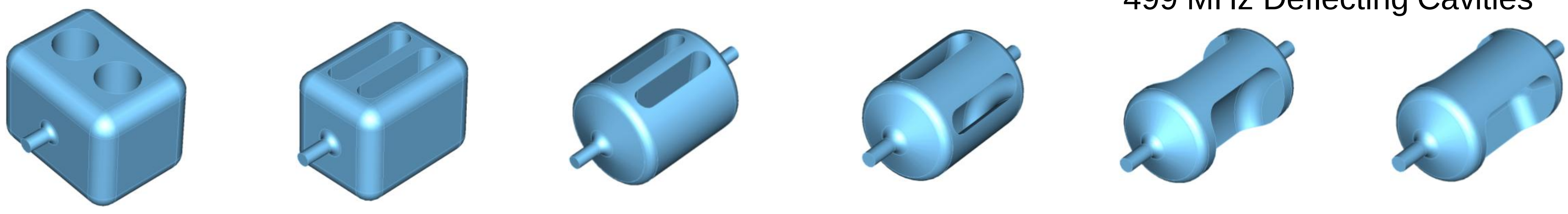


Frequency	**499.0**		**400.0**		**MHz**
T	2.0	4.2	2.0	4.2	K
R_{BCS}	1.3	70.0	2.0	110.0	nΩ
R_{res}	20.0		20.0		nΩ
R_s	21.3	90.0	22.0	130.0	nΩ
Q_0	4.8	0.9	6.7	1.6	10^9

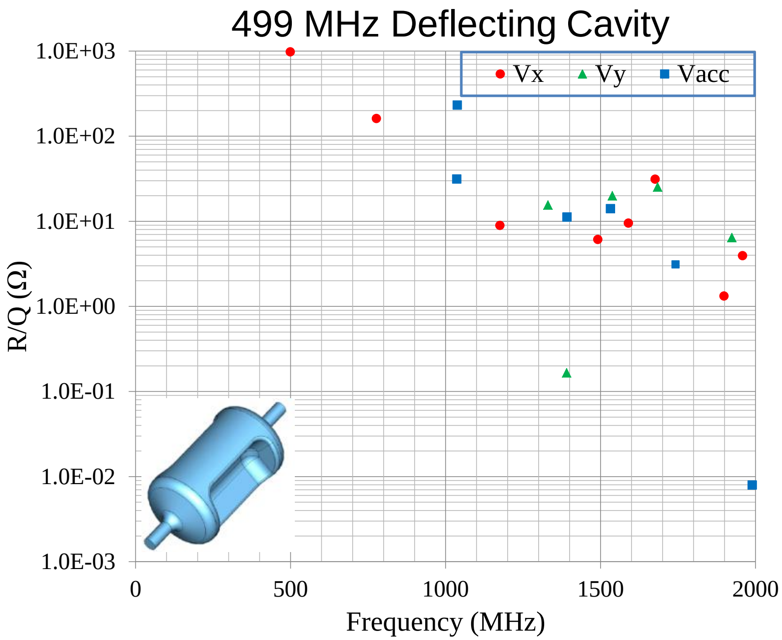
Higher Order Mode Properties

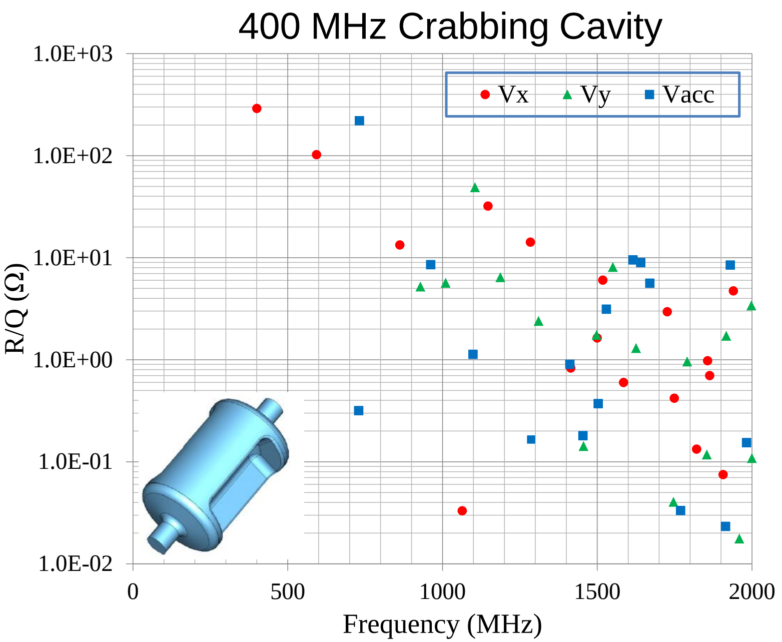
- Widely separated Higher Order Modes
- No Lower Order Modes

499 MHz Deflecting Cavities



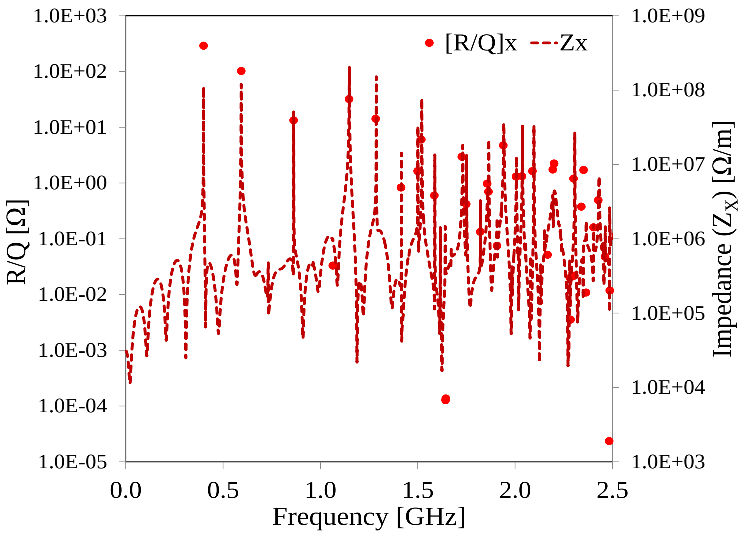
10.7 MHz **18.4 MHz** **127.1 MHz** **264.5 MHz** **255.3 MHz** **278.0 MHz**





Wakefield Analysis

T3P – Time domain wakefield and transient solver in the SLAC ACE3P suite

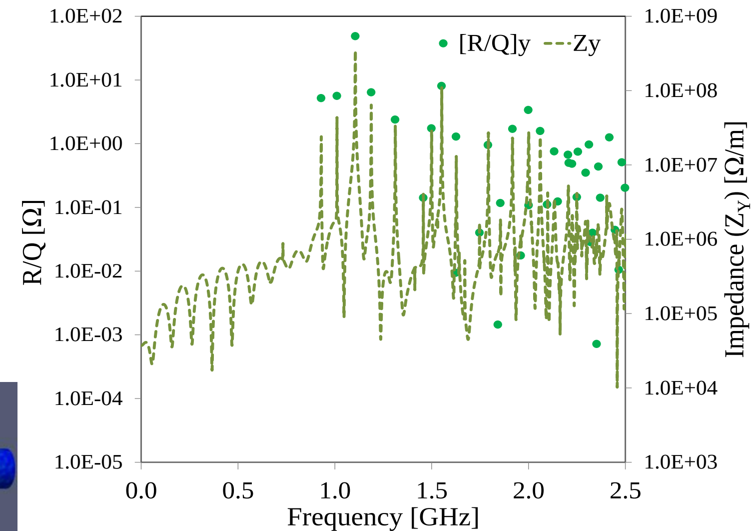


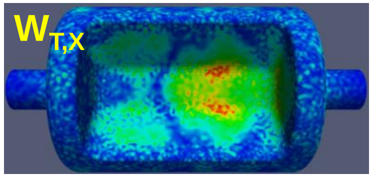
400 MHz

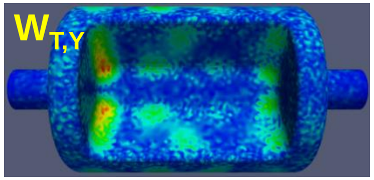
Crabbing Cavity

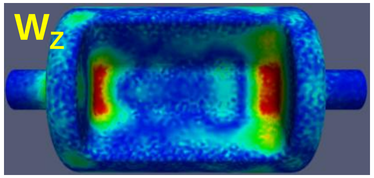
For a Gaussian bunch of

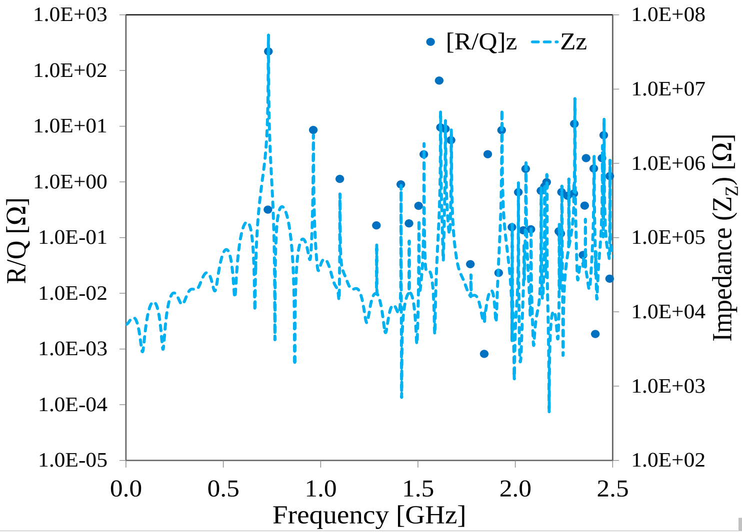
σ_{z_rms} = 0.5 cm

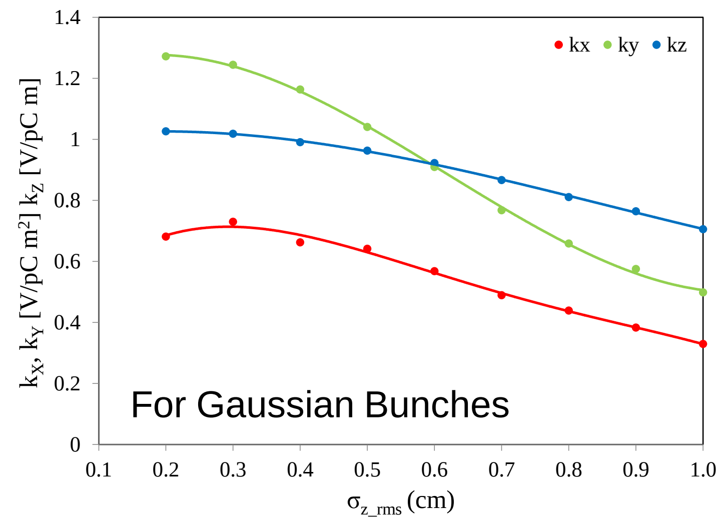






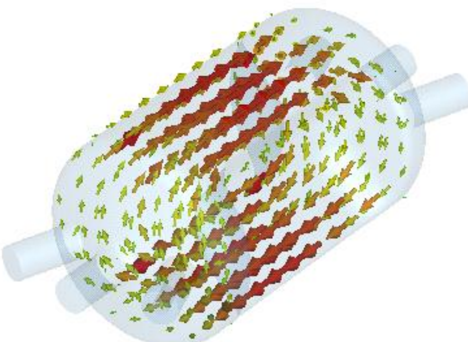


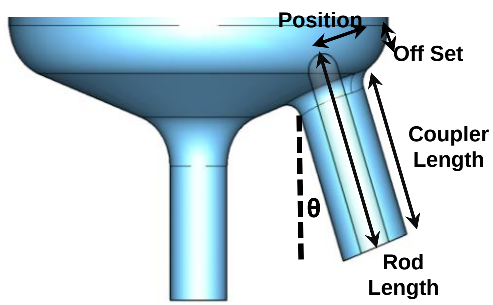


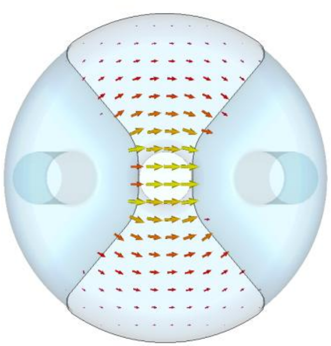


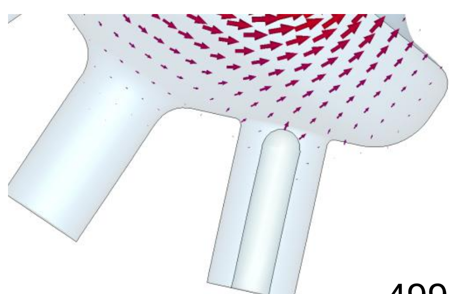
RF Coupling

- Possible coupling: Both electric and magnetic coupling
- Coupled to the transverse electric field to reduce field enhancement
- Four coupling ports to avoid asymmetry and to cancel the on-axis longitudinal electric field

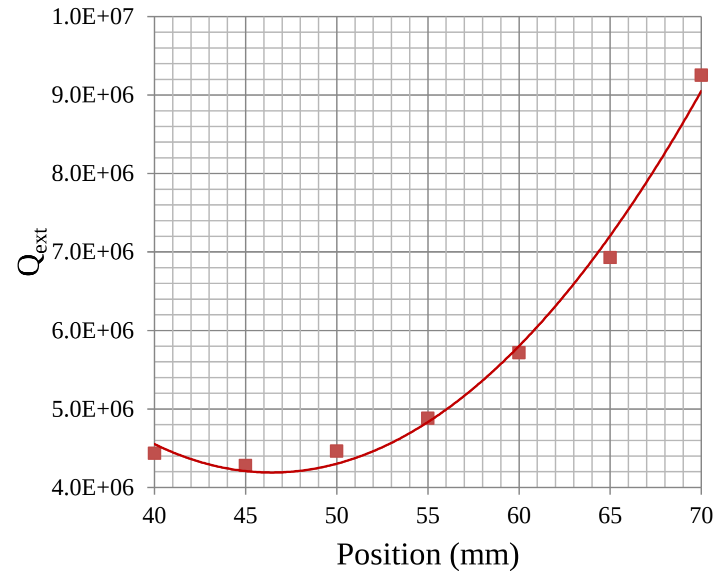


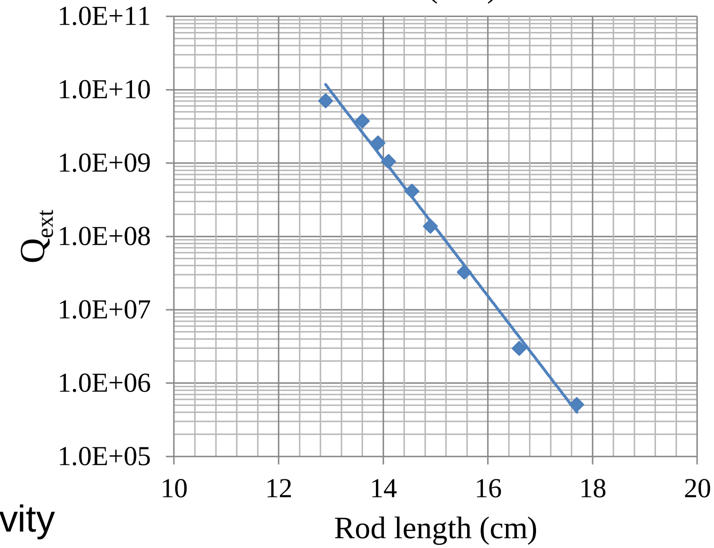






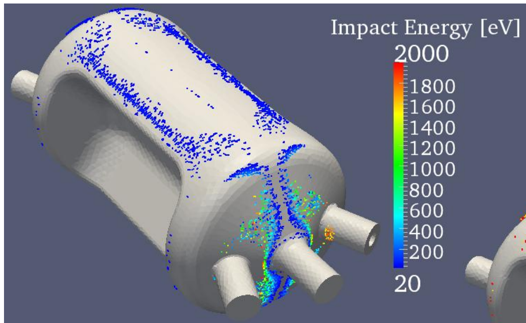
499 MHz Deflecting Cavity



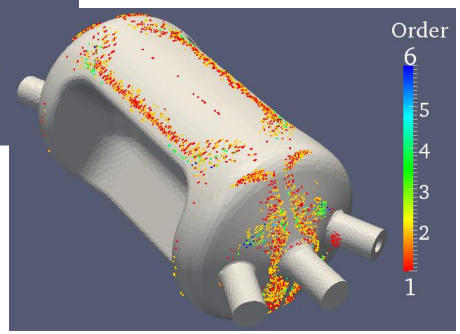


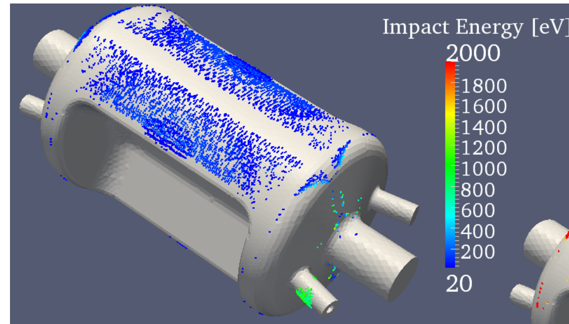
Multipacting Analysis

Track3P – Resonant particle tracking code in SLAC ACE3P suite

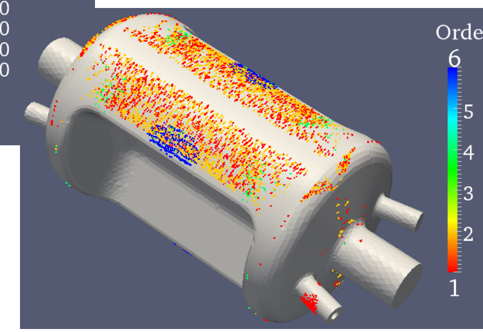


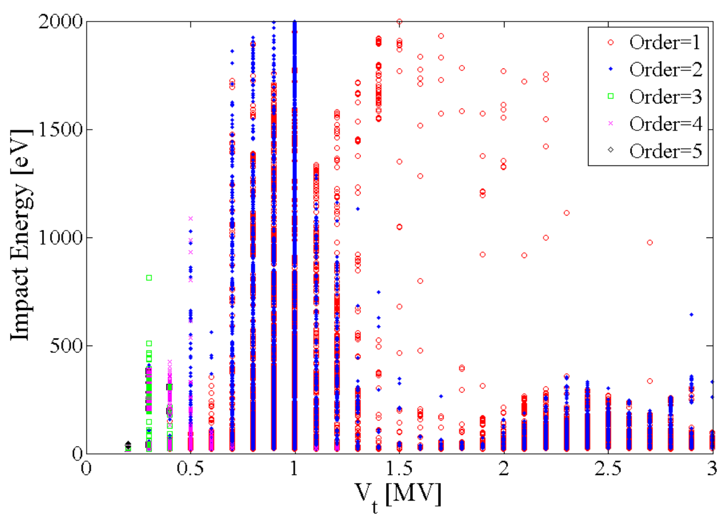
499 MHz
Deflecting
Cavity

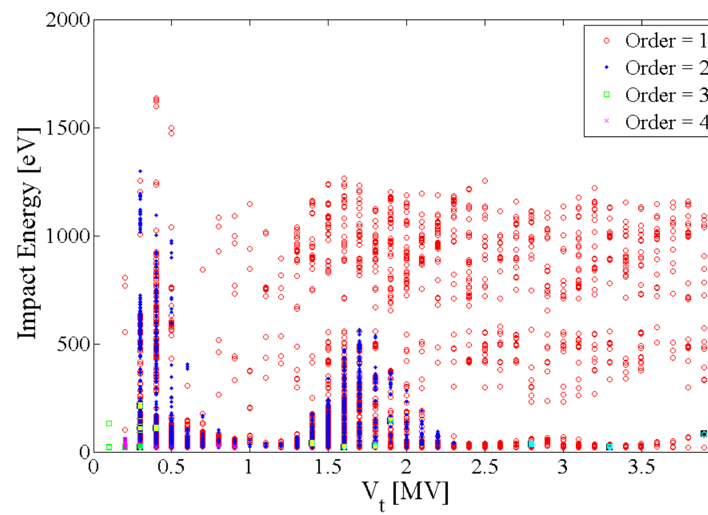




400 MHz
Crabbing
Cavity

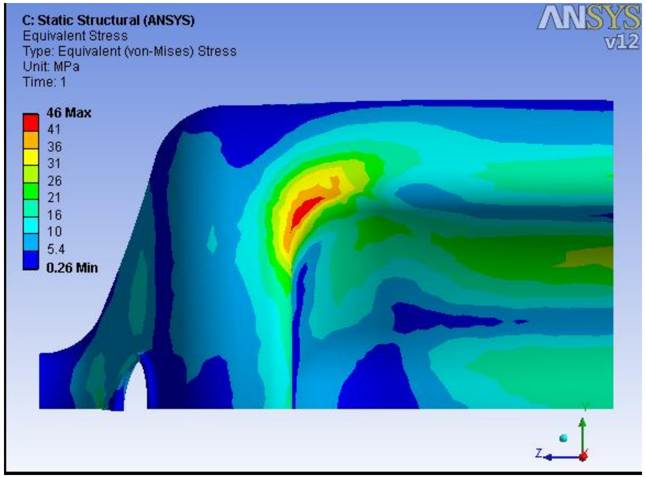




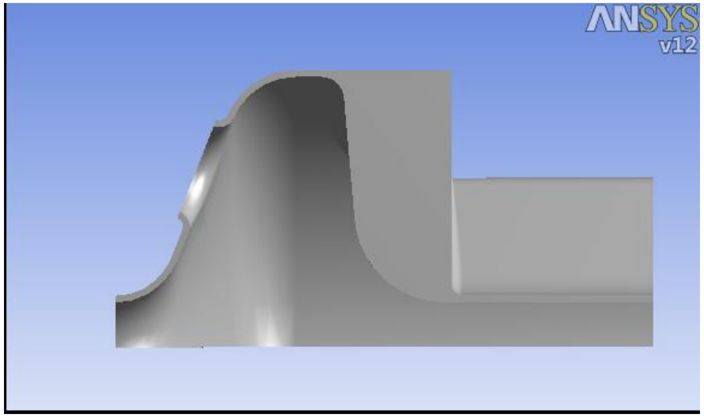


Mechanical Analysis (HyeKyoung Park)

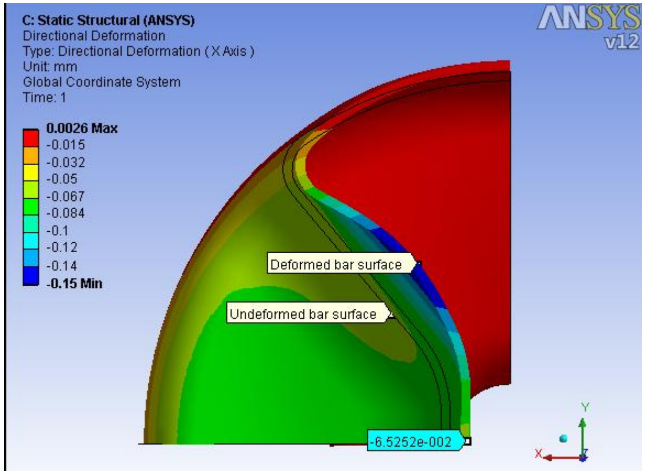
Cavity with 3 mm uniform thickness at 1atm



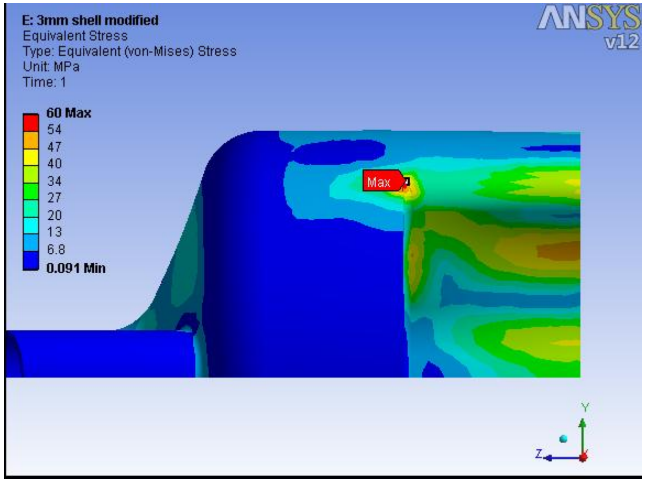
499 MHz Deflecting Cavity



Deformation under vacuum load



Stresses of the modified geometry



Add HK's paper

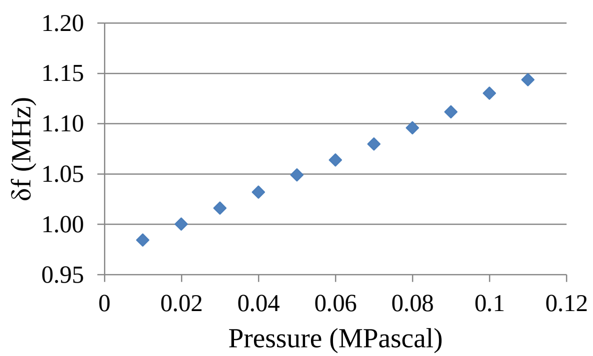
*H. Park et.al., in Proceedings of the SRF Conference, Chicago (2011), p. 188.

Mechanical Analysis (HyeKyoung Park)

- Without any kind of stiffening or pressure sensitivity optimization for 499 MHz cavity

Pressure

- Pressure sensitivity - 212 Hz/torr



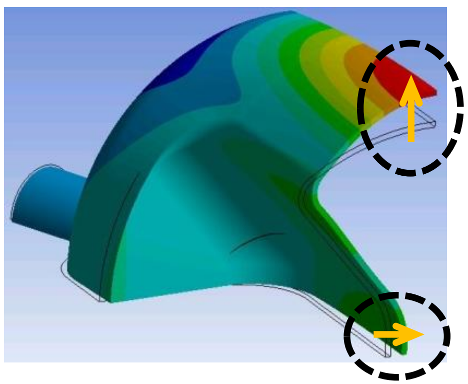
Lorentz Detuning

Room temperature cavity with a uniform 3 mm thickness

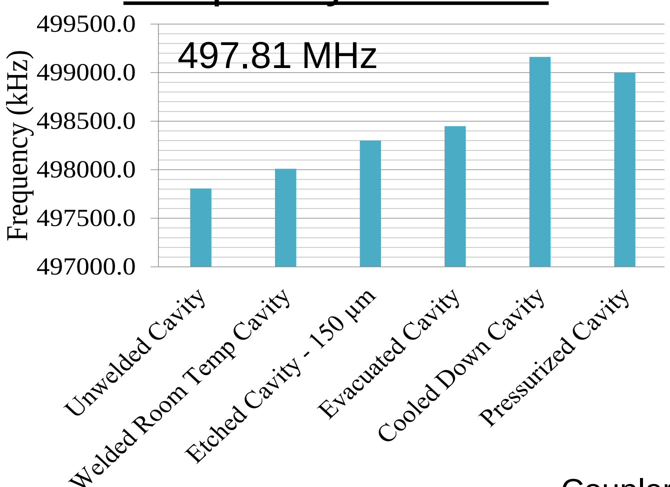
- Δf = 6.15 kHz @ V_T = 3.0 MV
- k_L = 61.54 Hz/(MV/m)^2

Fabricated cavity at 4 K

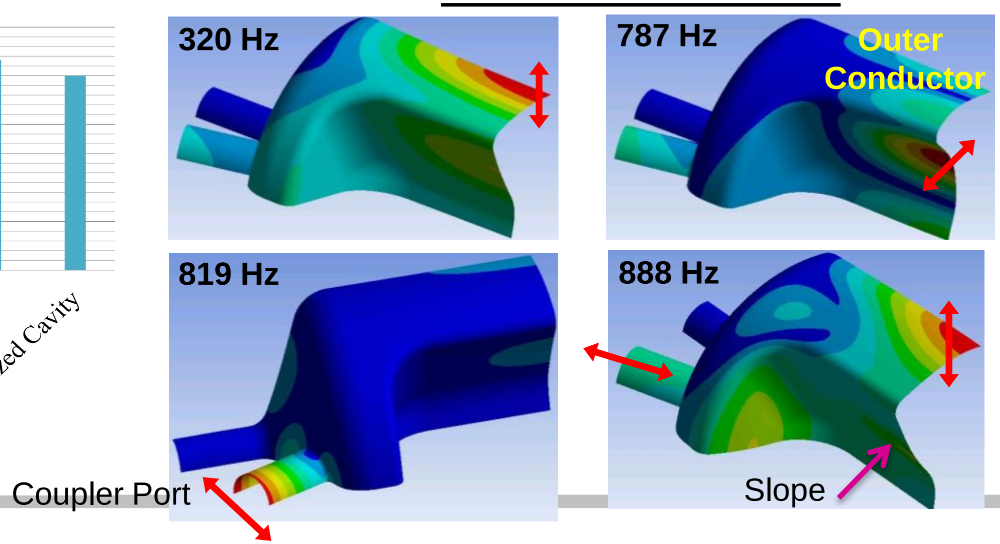
- Δf = 4.93 kHz @ V_T = 3.0 MV
- k_L = 49.27 Hz/(MV/m)^2
- Deformation = 1.2 μm



Frequency Variation



Mechanical Modes

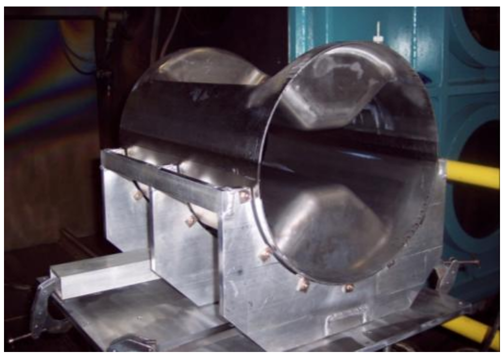


- Cavity with a 3 mm uniform thickness
- At room temperature and under vacuum

Fabrication

400 MHz Crabbing Cavity

Fabricated at Niowave Inc.



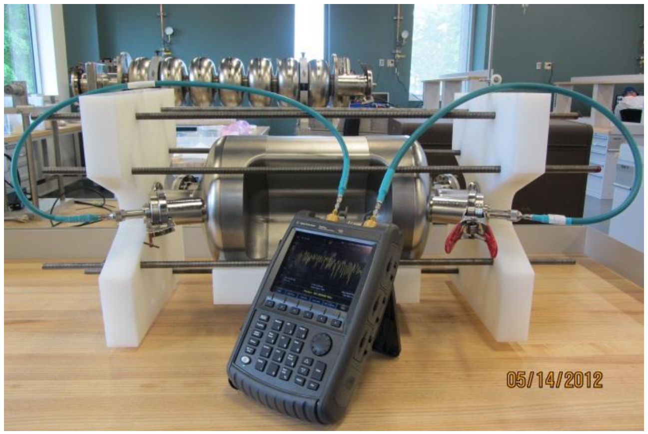
499 MHz Deflecting Cavity

Fabricated at Jefferson Lab

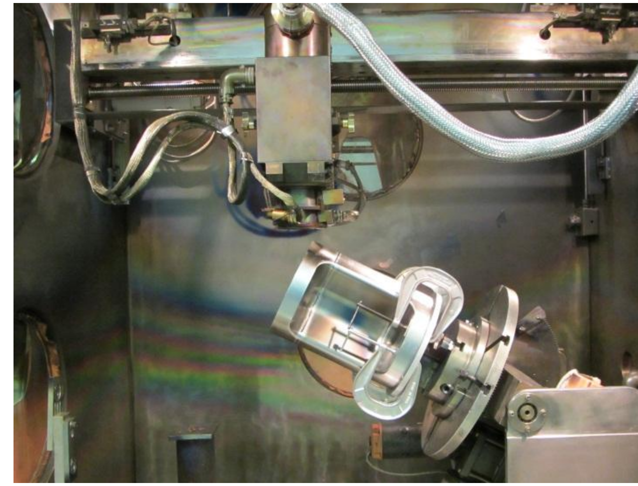
Cavity thickness = 3mm

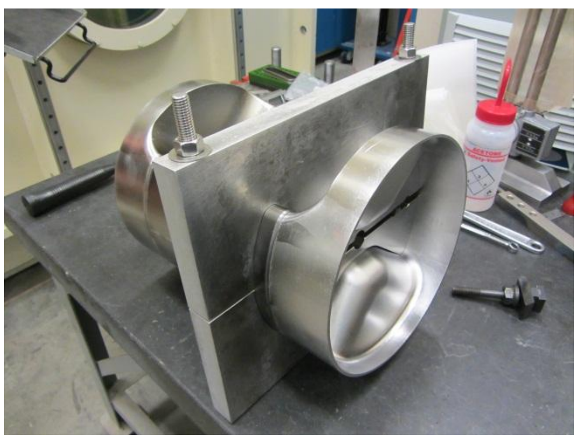
Fabrication

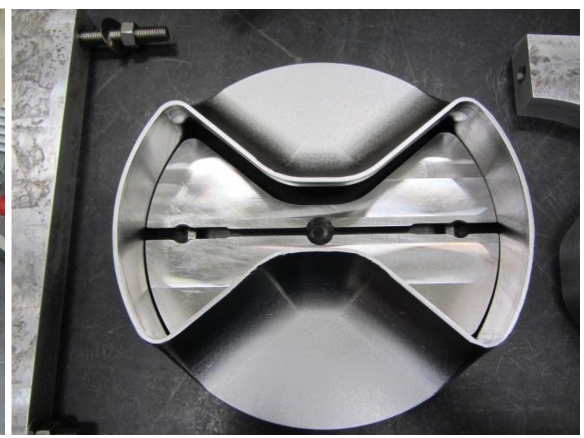
- Frequency adjustment by trimming the center piece



499 MHz Deflecting Cavity





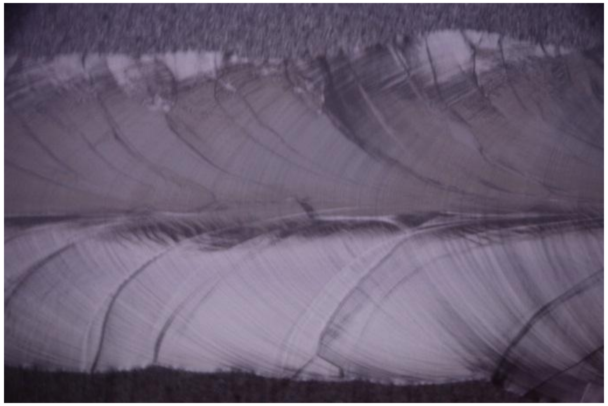


Optical Inspection

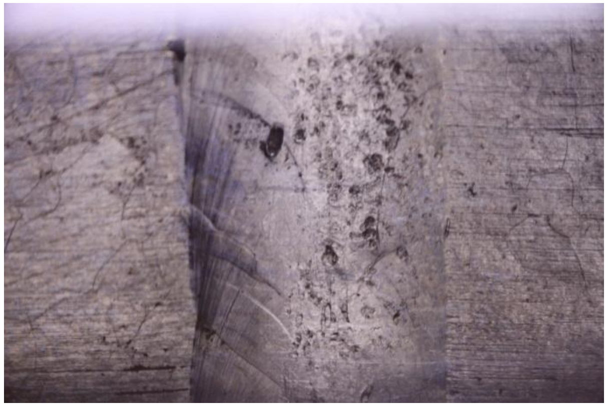
400 MHz Crabbing Cavity

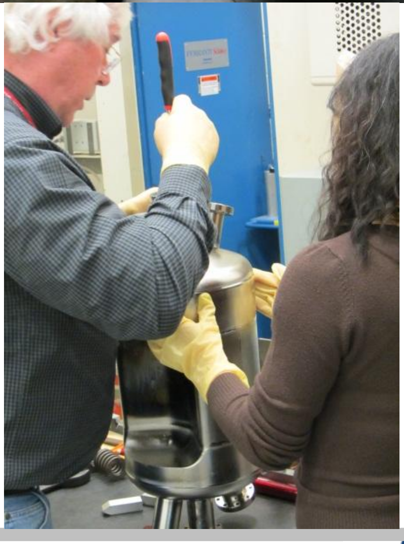
499 MHz Deflecting Cavity

Weld seam at equator



Weld seam at beam pipe

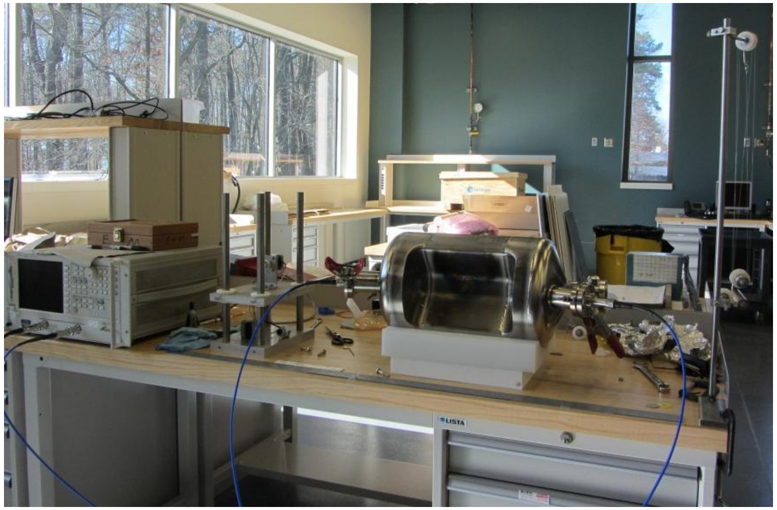




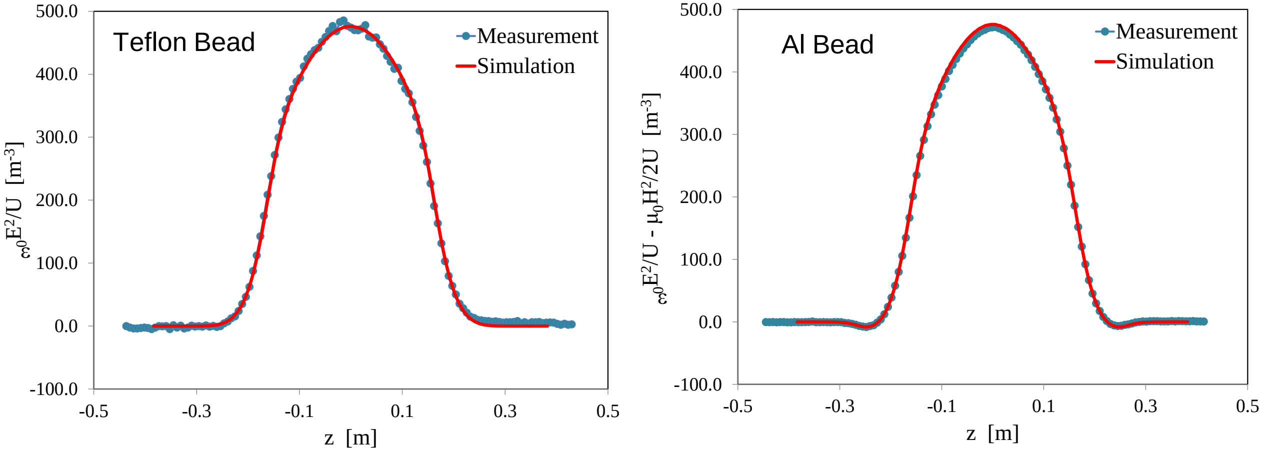
Bead Pull Study

- On axis fields were measured for both
  - 499 MHz deflecting cavity
  - 400 MHz crabbing cavity
- Measured components
  - On–axis transverse electric field: Using a Teflon bead
  - Both on–axis transverse electric and magnetic fields: Using an Al bead

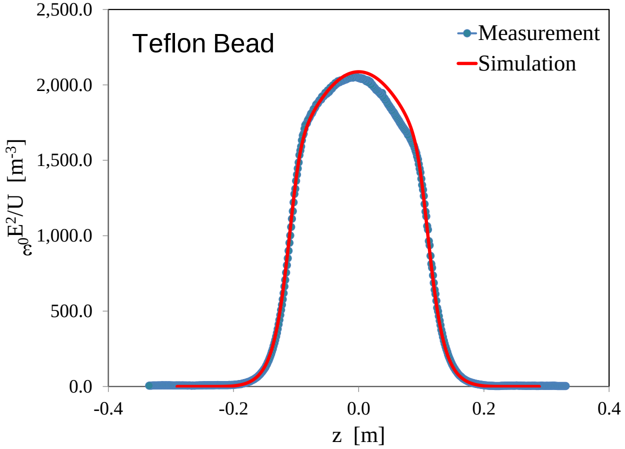
Bead Pull Set UP



400 MHz Crabbing Cavity

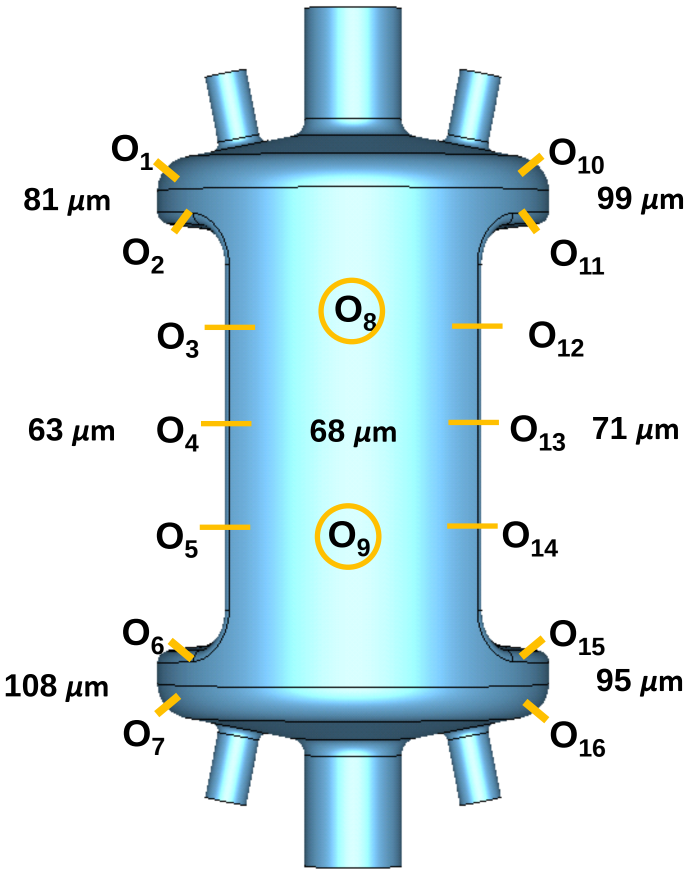


499 MHz Deflecting Cavity

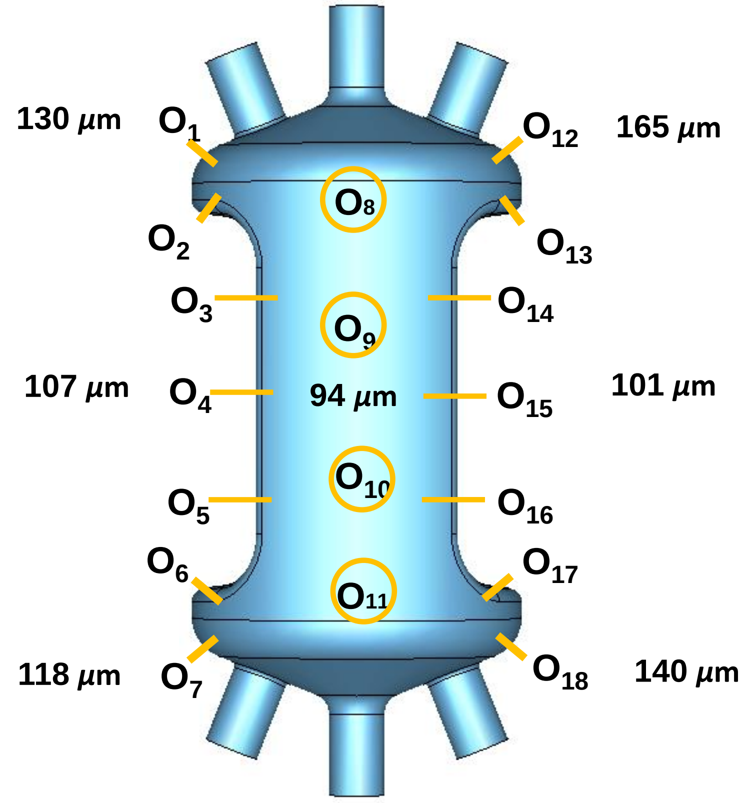


Surface Treatment – Bulk BCP

- Reduced etch rate from 2.7-2.8 µm /min to 1.8 µm/min due to contaminated acid mixture (with glycol)
- Average removal 85 μm



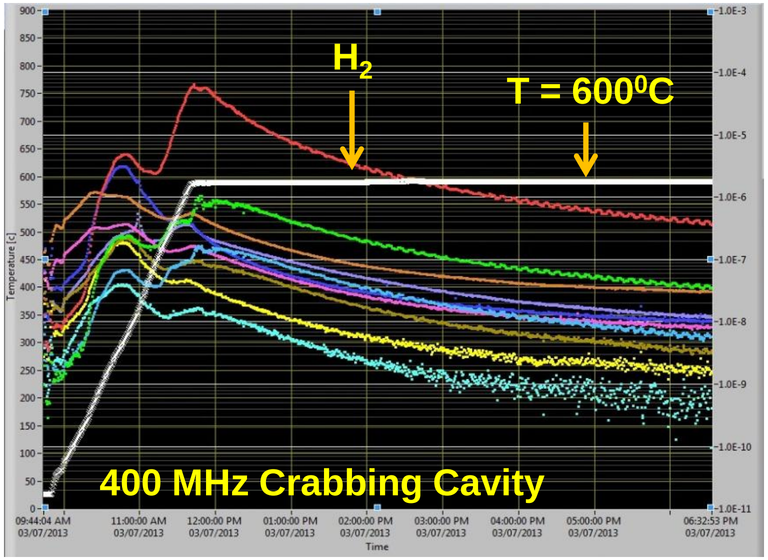
- Etch rate: 1.78 μm/min
- Average removal 108 μm

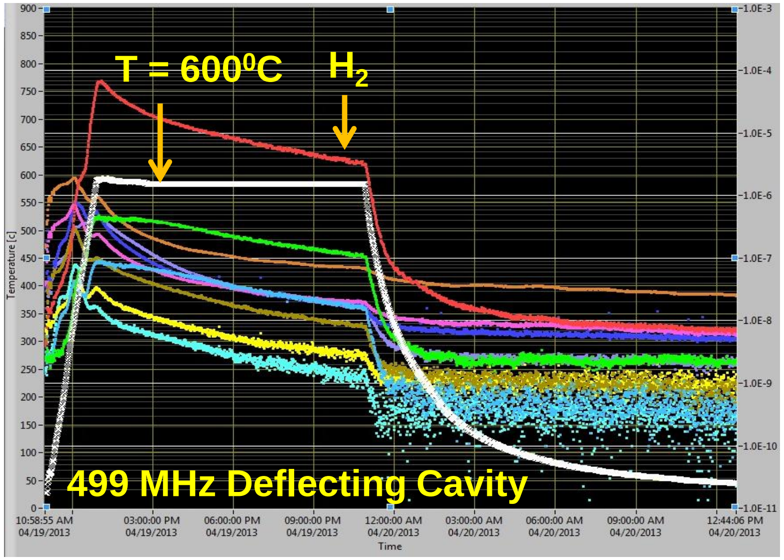


Average of O_{19}, O_{20}, O_{21} and O_{22} – 99 μm

Surface Treatment

- Heat Treatment
  - For H_2 degassing at 600^0C – 10 hours





- Light BCP – Removal of 10 μm after heat treatment
  - Completed for 400 MHz cavity and in progress for 499 MHz cavity

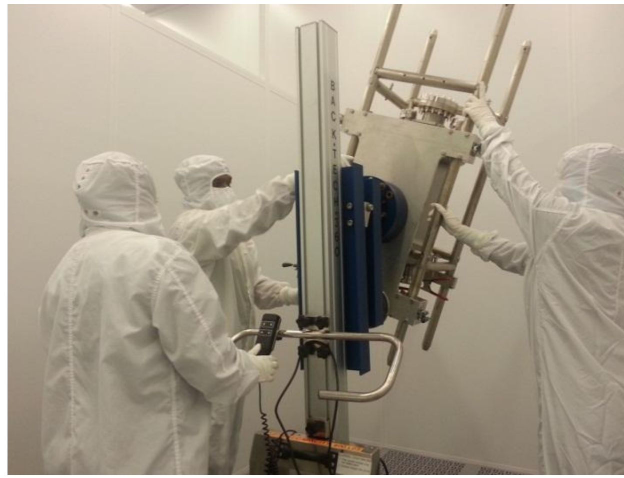
- High pressure rinsing in 3 passes
  - Completed for 400 MHz cavity

Cavity Assembly

- Preparation of hardware and assembly in clean room

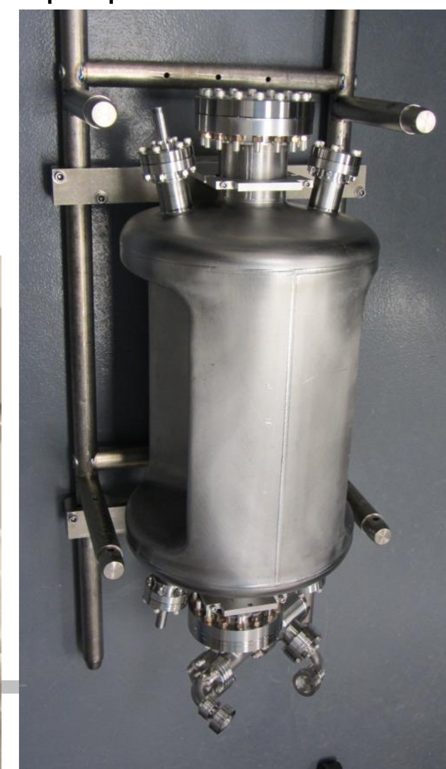
Leak test

Assembly in clean room



Ultrasonic degreased hardware

Assembled cavity with input and output probes and relief valves



Transport to clean room

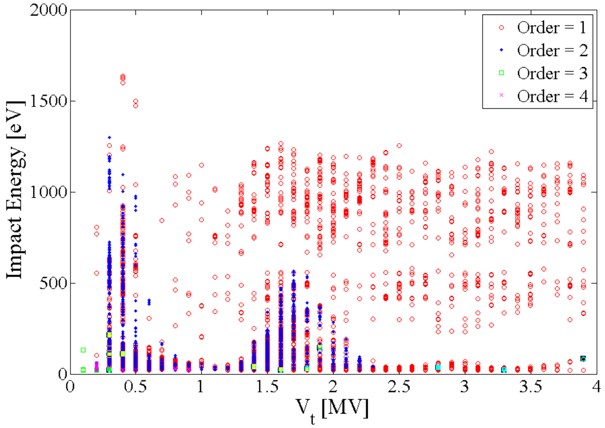
Preparation for Testing



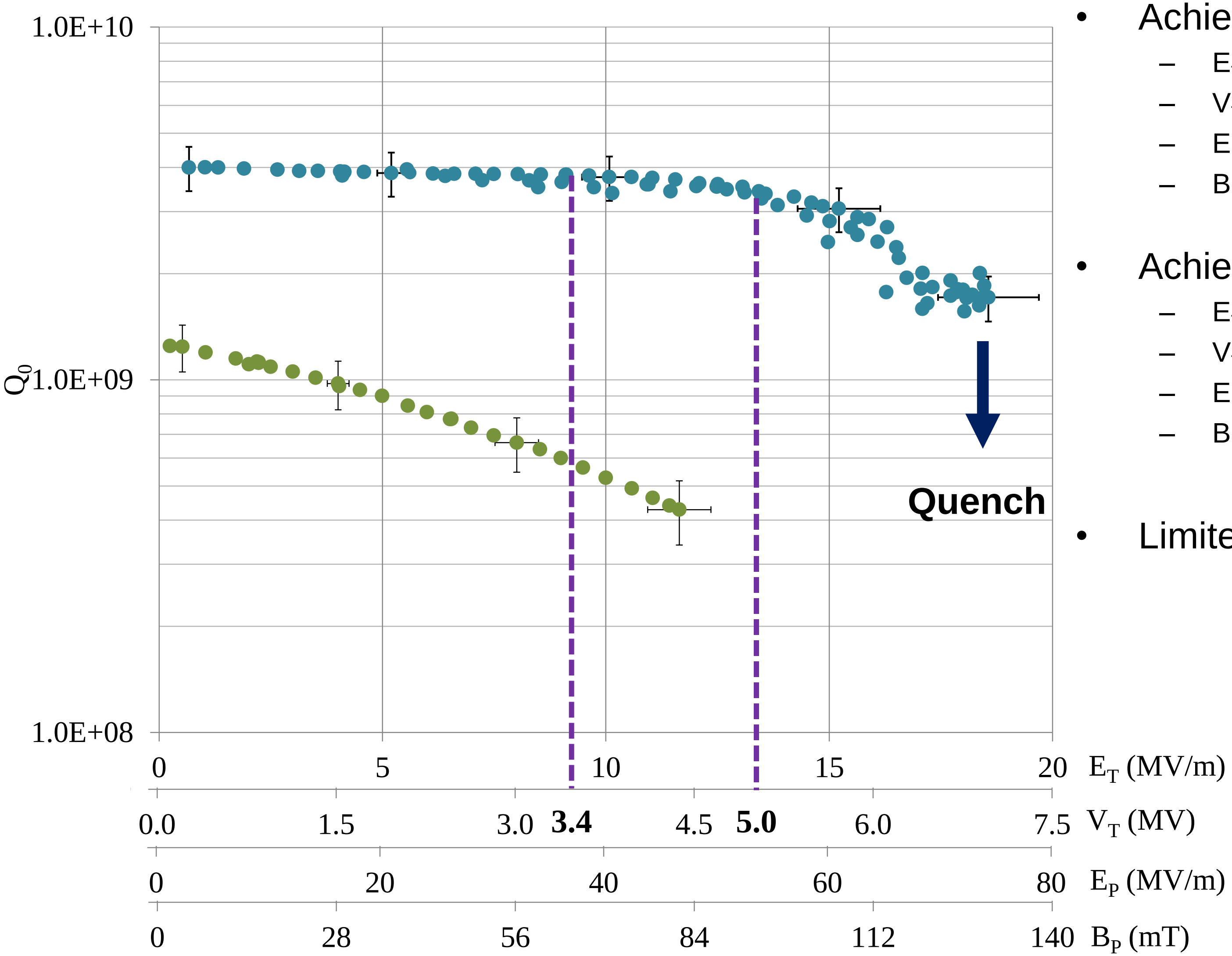

RF Testing

- Input and pick up probe calibration
  - Calibrated Q → Measured Q
  - $Q_1 = 2.76\ 10^9 \rightarrow 3.0\ 10^9$
  - $Q_2 = 8.62\ 10^{10} \rightarrow 1.1\ 10^{11}$
- Tests performed
  - 2 K high power test
  - Cavity warmed up to 4 K
  - 4 K high power test
  - Cavity cooled down to 2 K
  - 2 K high power test
- Multipacting
  - A multipacting barrier was observed in the first 2 K test at very low fields
  - Increasing the power processed the cavity and no multipacting was observed in the following 4.2 K and 2 K tests

What is the V_T ?

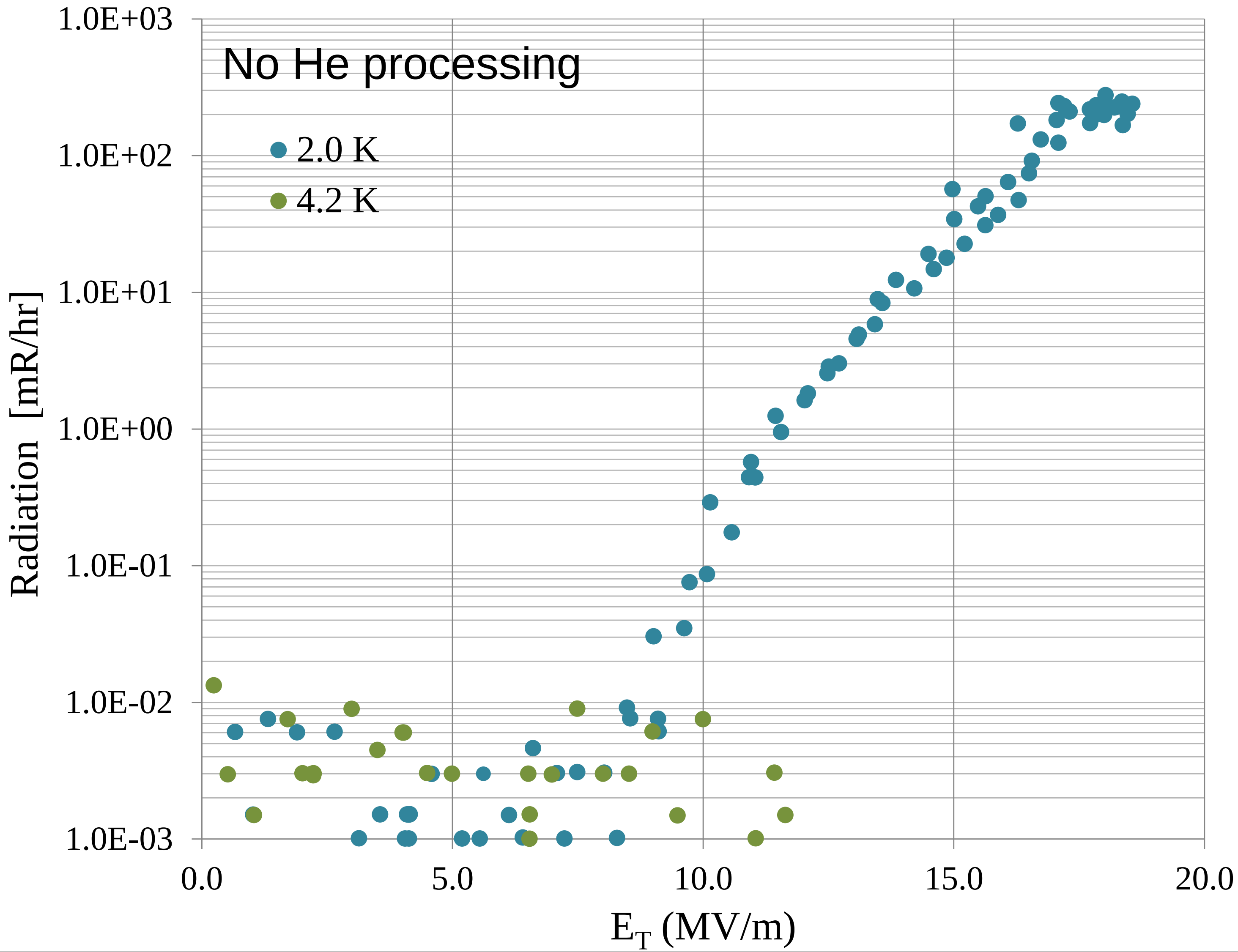


4.2 K and 2 K Test Results

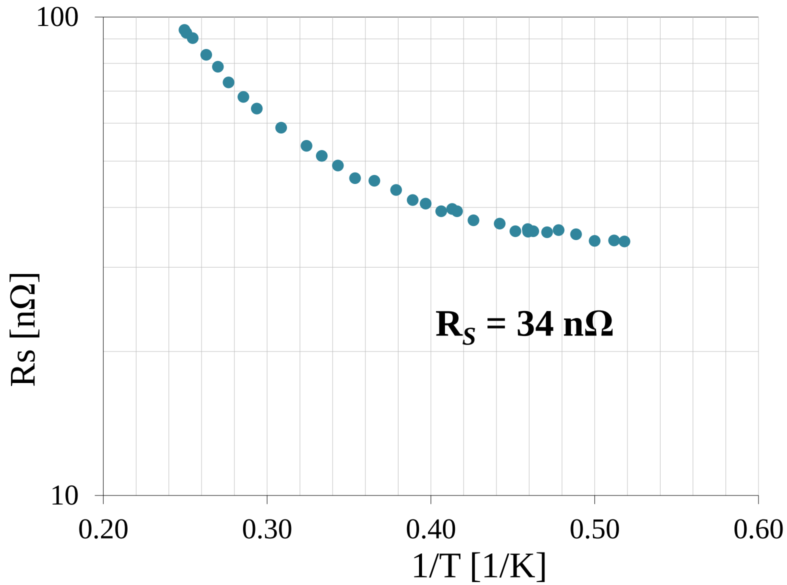


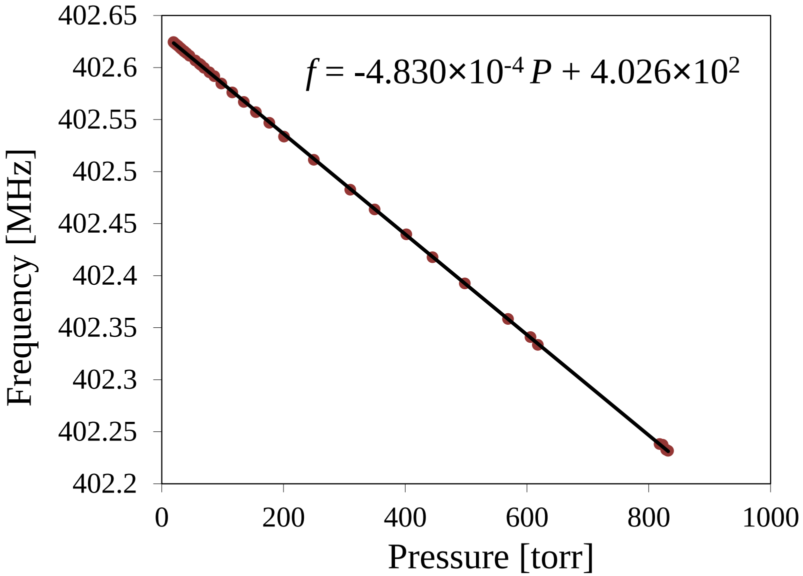
- Achieved fields at 4.2 K
  - E_T = 11.6 MV/m
  - V_T = 4.35 MV
  - E_P = 47 MV/m
  - B_P = 82 mT
- Achieved fields at 2.0 K
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT
- Limited by rf power at 4.2 K

Field Emission

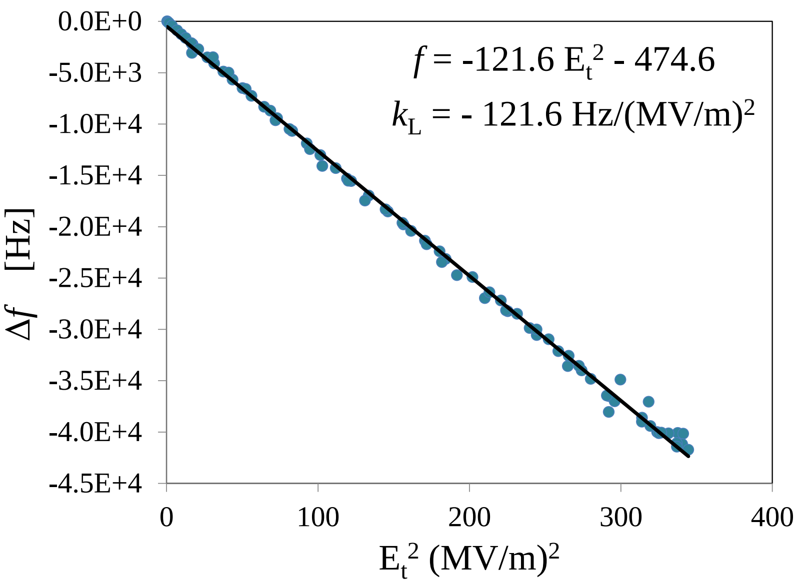


RF Testing





- Frequency deviations
  - Room temperature f : 402.0 MHz
  - After bulk BCP : Δf = – 51.1 kHz
  - After bake : Δf = – 30.2 kHz
  - Under vacuum : Δf = 318.5 kHz
  - At 2 K : Δf = 365.3 kHz

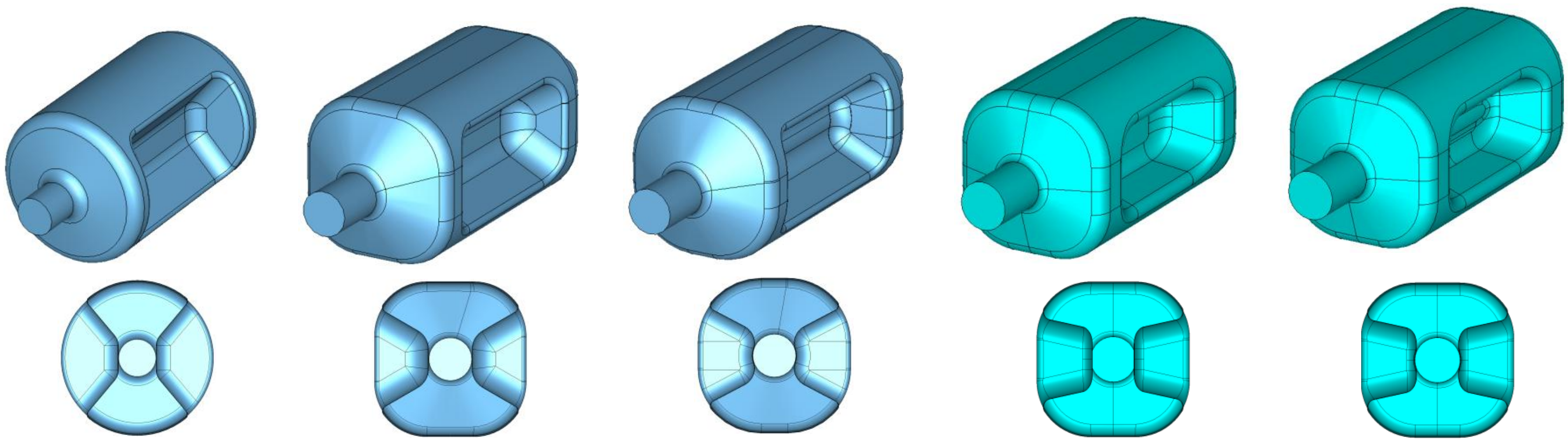


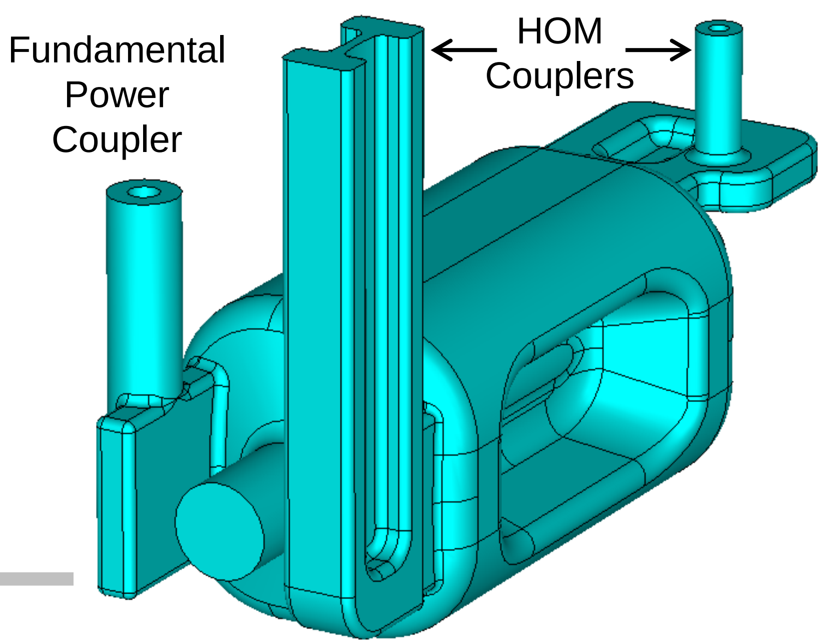
Current Status and Next Steps

- Proof-of-Principle 400 MHz cavity achieved 7 MV deflecting voltage cw (Twice design voltage)
- Residual surface resistance a little high (34 nΩ)
  - Possibly due to contaminated acid, not enough Nb removed
  - Losses at possibly steel flanges, copper probes
- Multipacting quickly processed and did not reoccur
- Proof-of-Principle cavity has achieved its purpose
- Now moving on to the prototype cavity to be tested with beam at CERN-SPS
- Reasonably confident that 10 MV can be achieved with 2 cavities

Prototype Design vs. Proof-of-Principle

- ODU/SLAC prototype design evolution

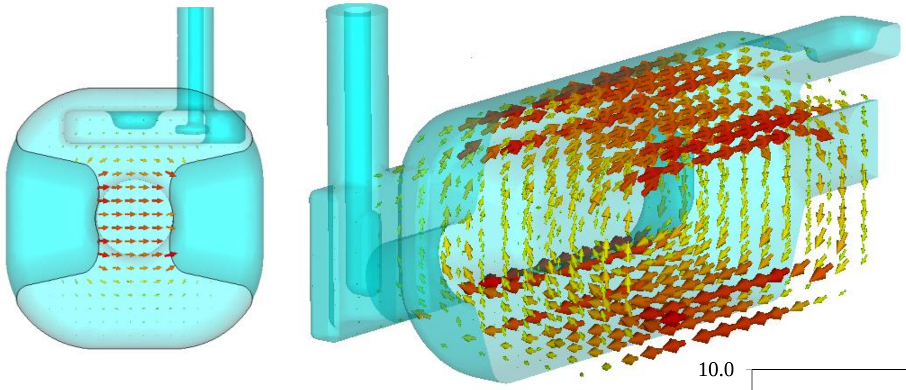


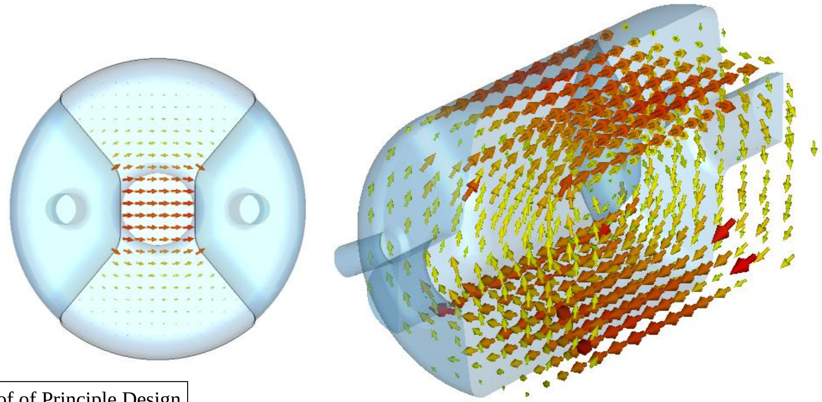


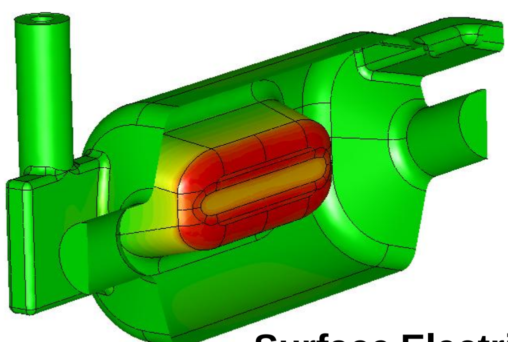
Cavity Dimensions

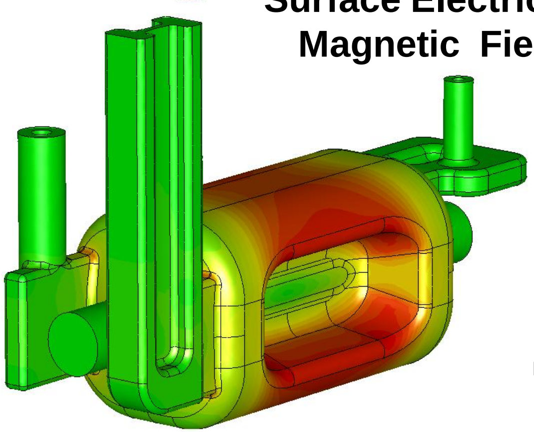
	Prototype Design	Proof of Principle Design	Units
Cavity Radius	**14.1**	17.0	cm
Cavity length	53.5	52.8	cm
Aperture diameter	4.2		cm

Prototype Design vs. Proof-of-Principle

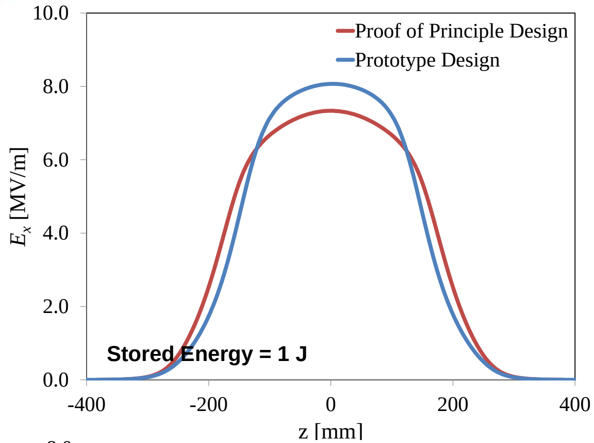


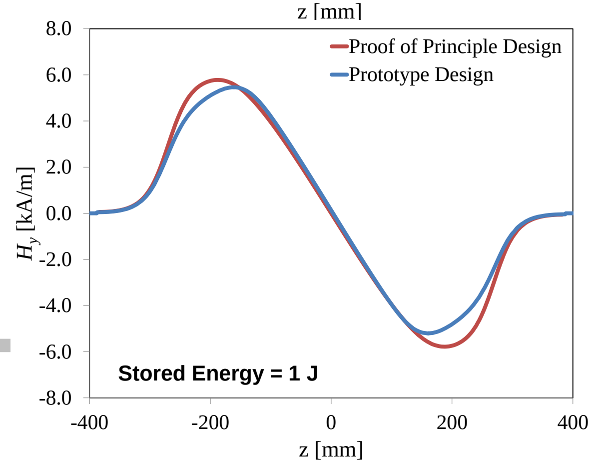


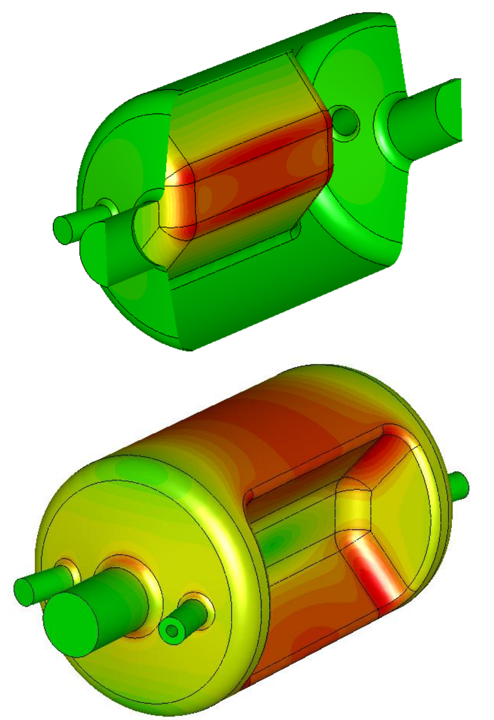




Surface Electric and Magnetic Fields

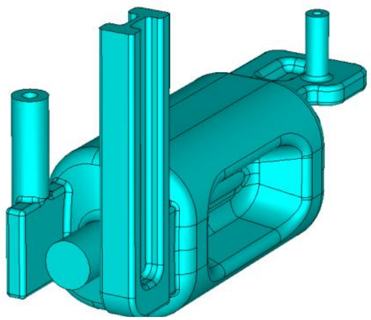


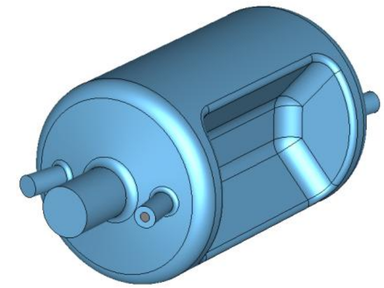


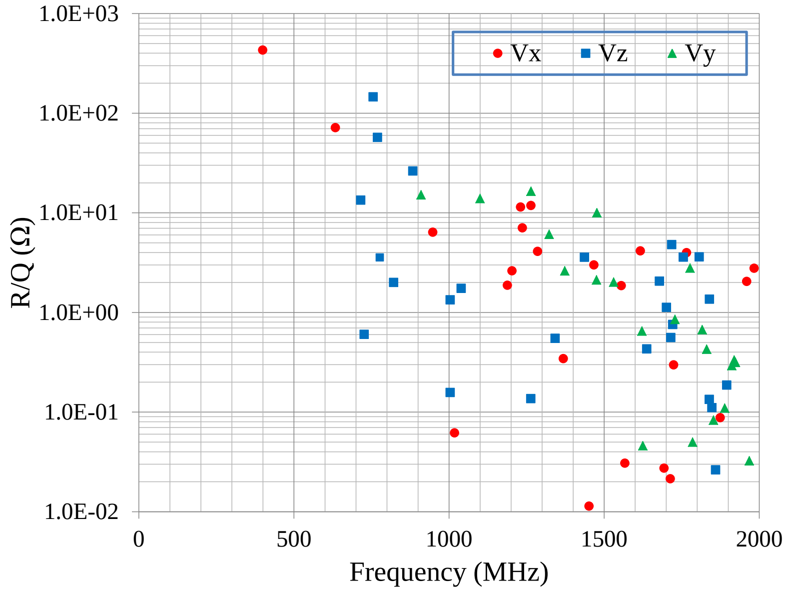


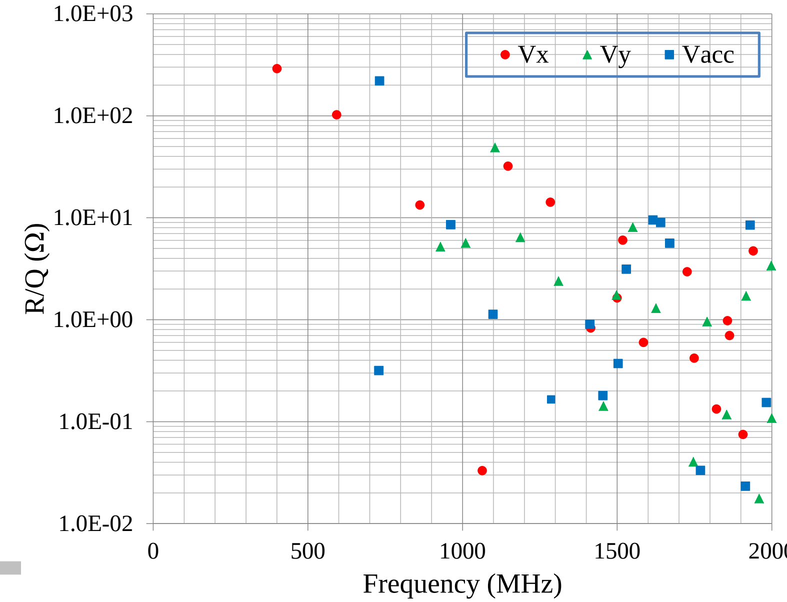
Prototype Design vs. Proof-of-Principle

- Wider frequency separation between modes
- No lower order modes
- Nearest HOM – ~190 MHz → ~230 MHz









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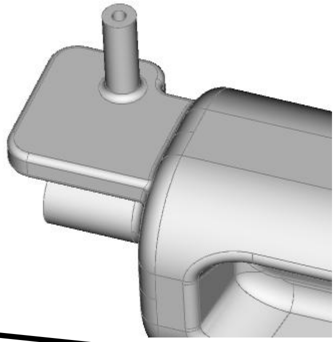
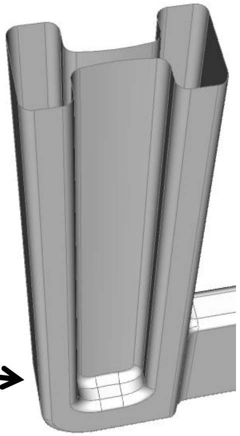
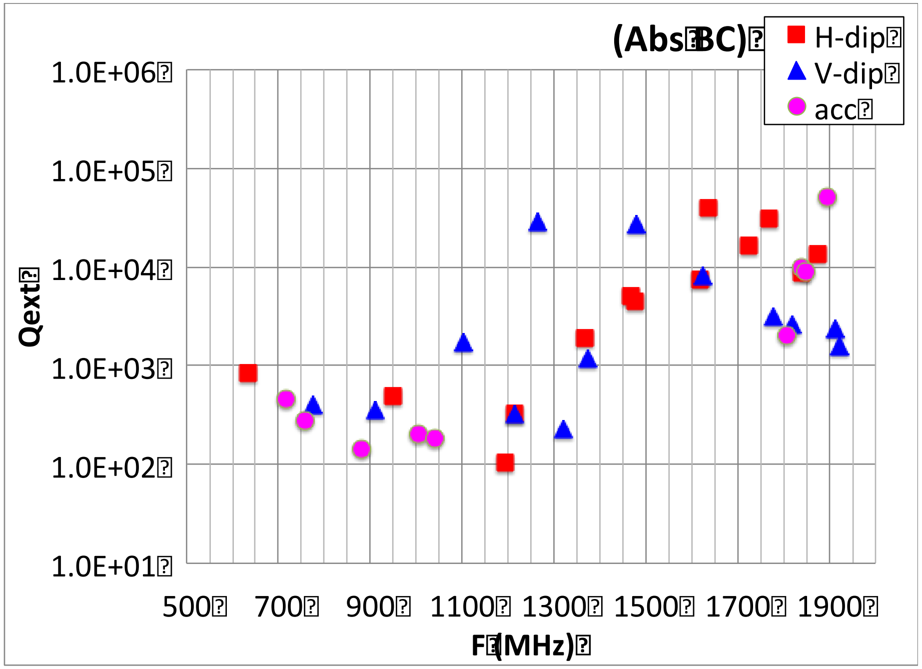
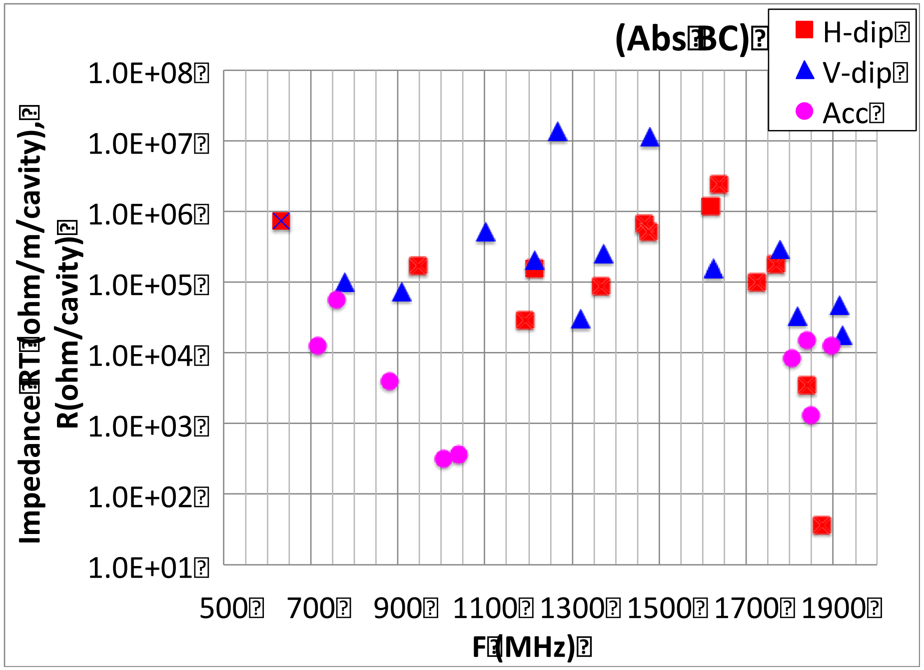
Damping of Higher Order Modes

- Work done by Zenghai Li at SLAC
- Mode coupling
  - H-HOM coupler couples to both H-dip and accelerating modes
  - V-HOM coupler couples to both V-dip and accelerating modes

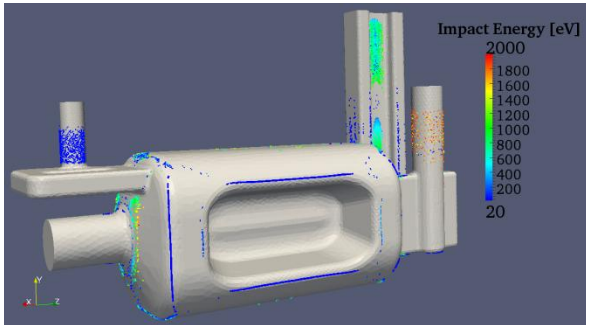


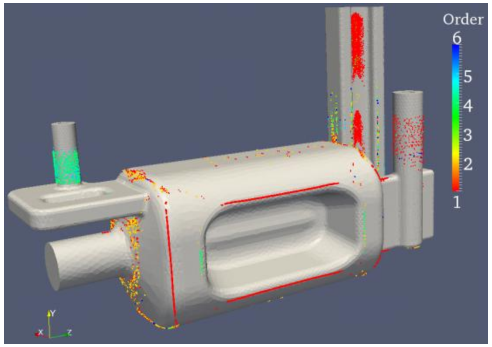


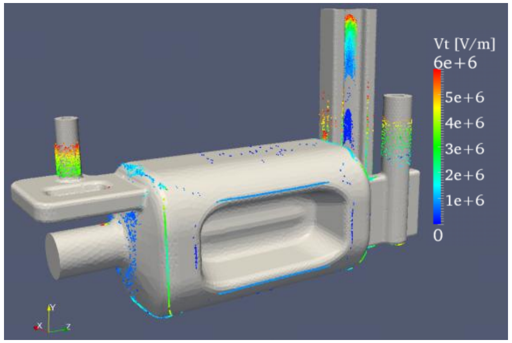


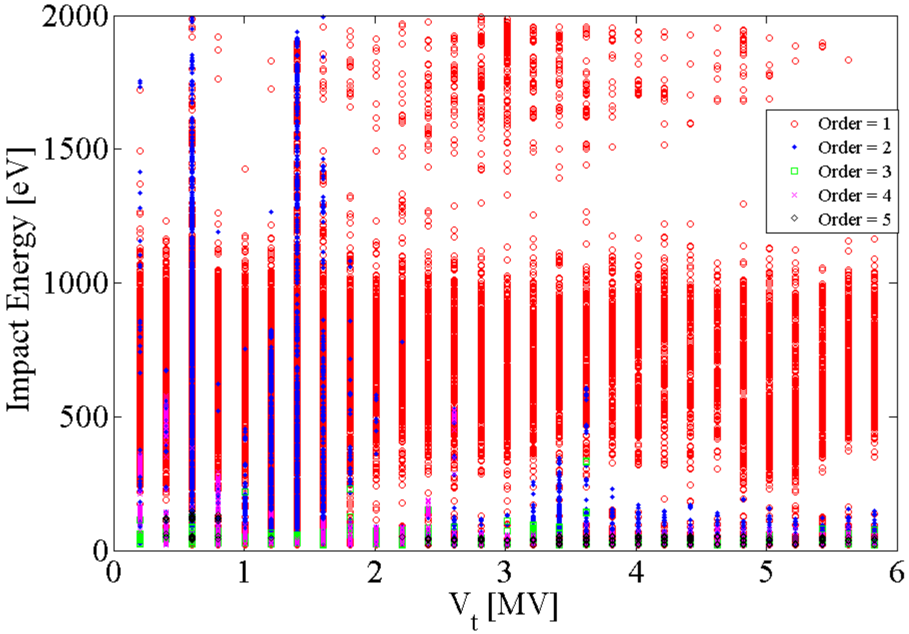


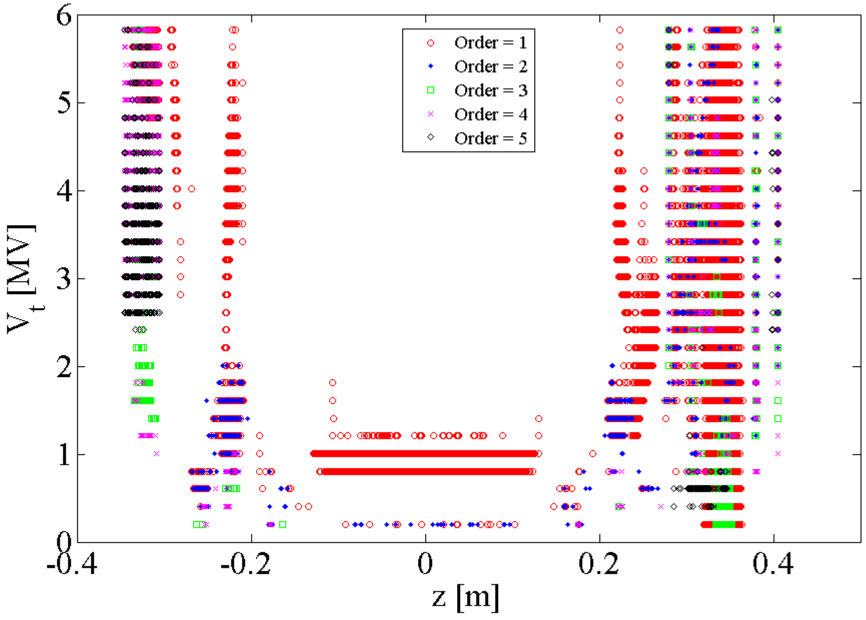
Multipacting Simulations











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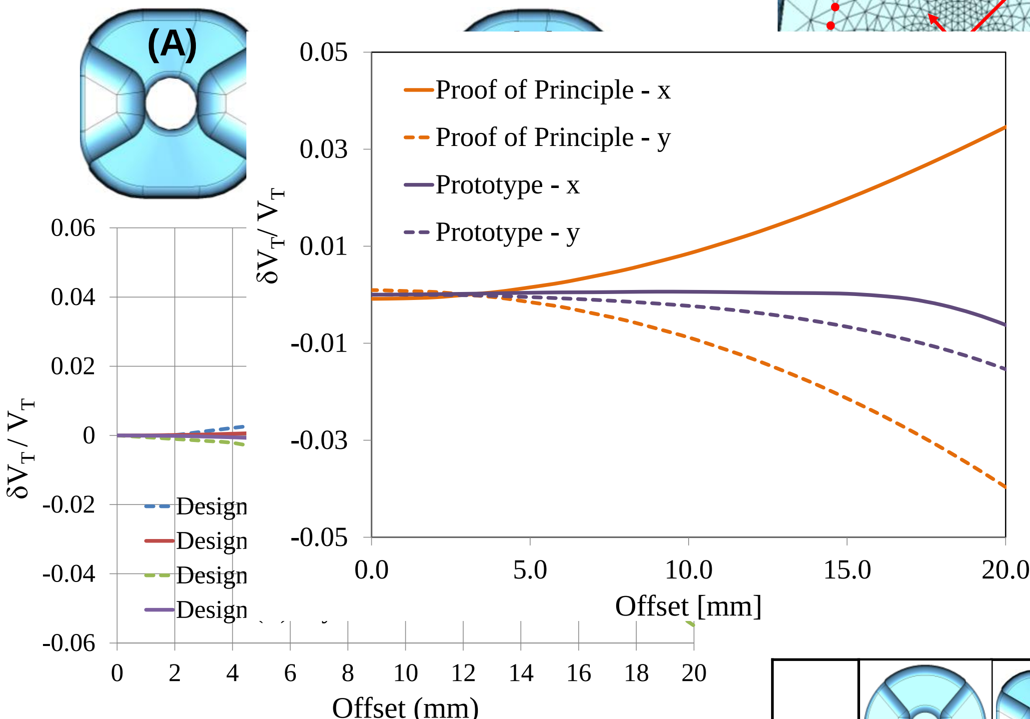
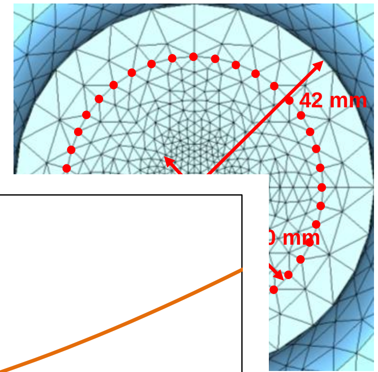
Field Non-Uniformity

400 MHz Crabbing Cavity





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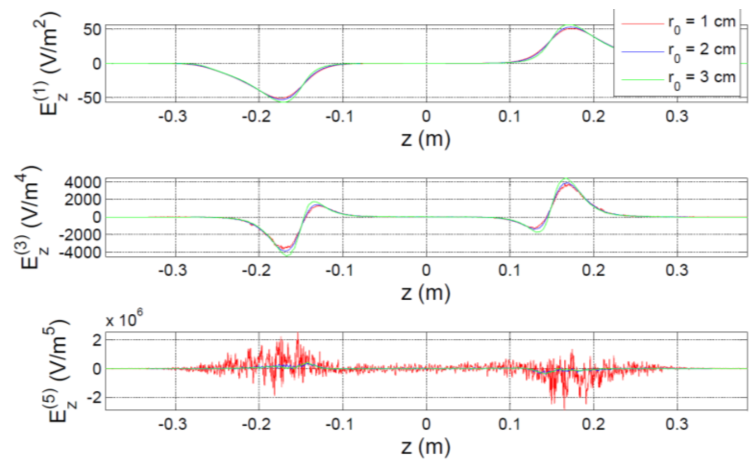
$$E_z(r,\phi,z) = \sum_{n=0}^{\infty} E_z^{(n)}(z) r^n \cos(n\phi) \quad E_{acc}^{(n)}(z) = E_z^{(n)}(z) e^{j\omega t}$$

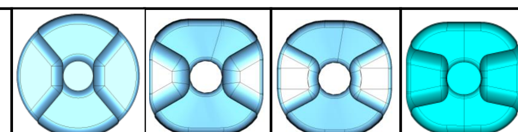
$$B^{(n)}(z) = \frac{1}{qc} F_t^{(n)}(z) = j\frac{n}{\omega} E_{acc}^{(n)}(z) \ \left[\mathrm{T/m^{n-1}}\right]$$

$$b_n = \int_{-\infty}^{\infty} B^{(n)}(z) dz \ \left[\mathrm{T/m^{n-2}}\right]$$



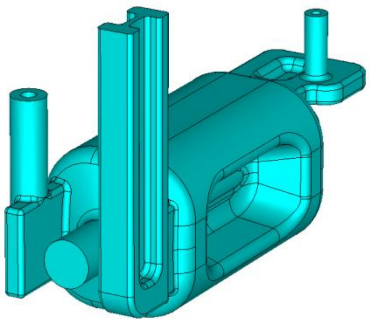
Voltage deviation at 20 mm

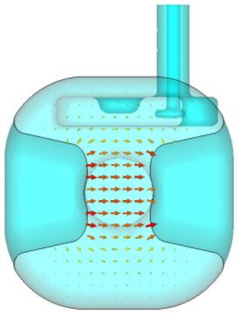
- Horizontal: 5.0% → 0.2%
- Vertical: 5.5% → 2.4%

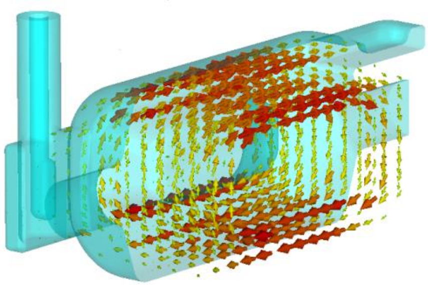


					Units
V_z	0.0	0.0	0.0	0.46	kV
V_T	1.0				MV
b_3	300	410	100	45.0	mT/m
b_4	0.0	0.0	0.0	2.5	mT/m^2
b_5	-4.6 10^4	-4.1 10^4	-2.2 10^4	-2.2 10^5	mT/m^3

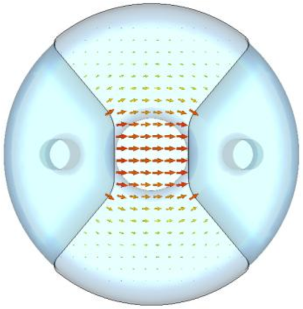
Prototype Design vs. Proof-of-Principle

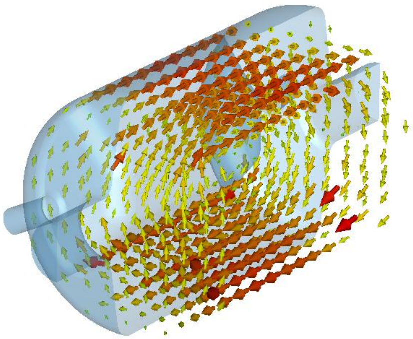






Parameters	**Prototype Design**	**Proof of Principle Design**	**Units**
Deflecting Voltage (V_T^*)	0.375	0.375	MV
Peak Electric Field (E_p^*)	3.66	4.02	MV/m
Peak Magnetic Field (B_p^*)	6.14	7.06	mT
B_p^*/E_p^*	1.67	1.76	mT/(MV/m)
Stored Energy (U^*)	0.13	0.195	J
$[R/Q]_T$	427.2	287.0	Ω
Geometrical Factor (G)	106.4	140.9	Ω
R_TR_S	$4.5\ \ 10^5$	$4.0\ \ 10^4$	Ω^2
At $E_T^* = 1$ MV/m			
V_T	3.4		MV
E_p	33.2	36.5	MV/m
B_p	55.7	64.0	mT





- Prototype is superior to Proof-of-Principle across all parameters
- Electromagnetic design is now frozen
- Multipacting studies in waveguide couplers under way

Acknowledgements

- ODU
  - Chris Hopper
  - Alex Castilla
  - HyeKyoung Park
  - Kevin Mitchell
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  - Zenghai Li
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  - Rongli Geng
  - Haipeng Wang
  - Joe Preble
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  - Pete Kushnick
  - Dave McCay
  - Casy Apeldoorn
  - Danny Forehand and his team
  - Steve Castagnola and his team

THANK YOU

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  - Chris Hopper
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  - Kevin Mitchell
- SLAC
  - Zenghai Li
- Niowave
  - Terry Grimm
  - Dmitry Gorelov
  - Chase Boulware
  - Nick Miller
- JLab
  - HyeKyoung Park
  - Peter Kneisel
  - Rongli Geng
  - Haipeng Wang
  - Joe Preble
  - Tony Reilly
  - Tom Powers
  - Kirk Davis
  - Pete Kushnick
  - Dave McCay
  - Casy Apeldoorn
  - Danny Forehand and his team
  - Steve Castagnola and his team

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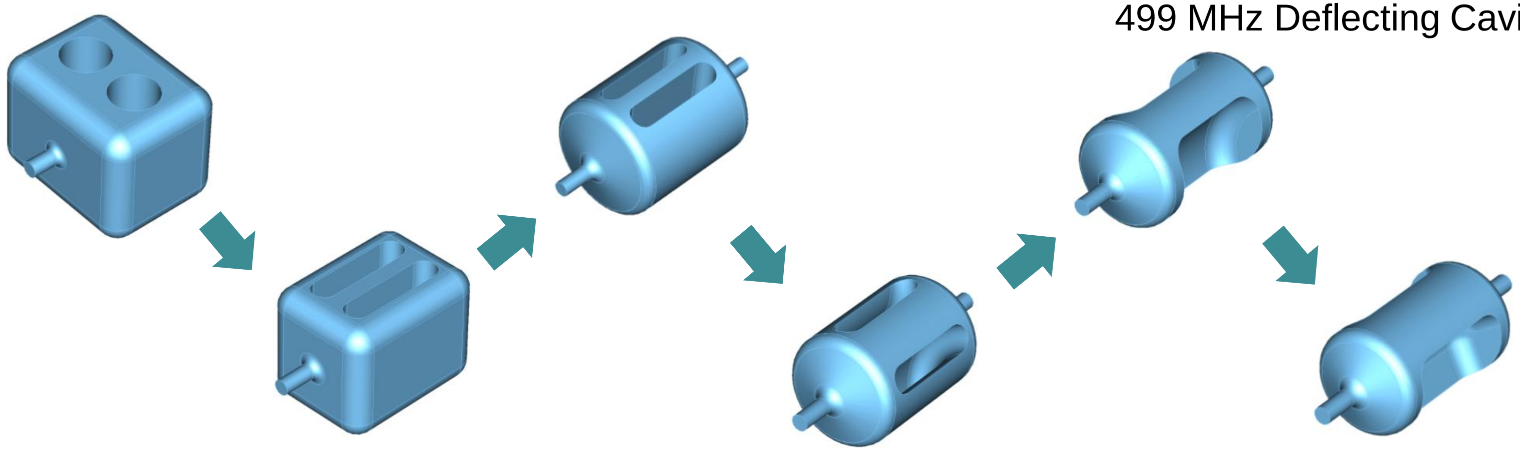
- SLAC – Zenghai Li, Lixin Ge
- Niowave – Terry Grimm, Dmitry Gorelov, Chase Boulware, Nick Miller

THANK YOU

Electromagnetic Design Evolution

- Optimization of the electromagnetic design to achieve
  - Lower and balanced surface peak surface fields at a higher net transverse voltage
  - Higher shunt impedance

499 MHz Deflecting Cavity



Balanced surface field ratio

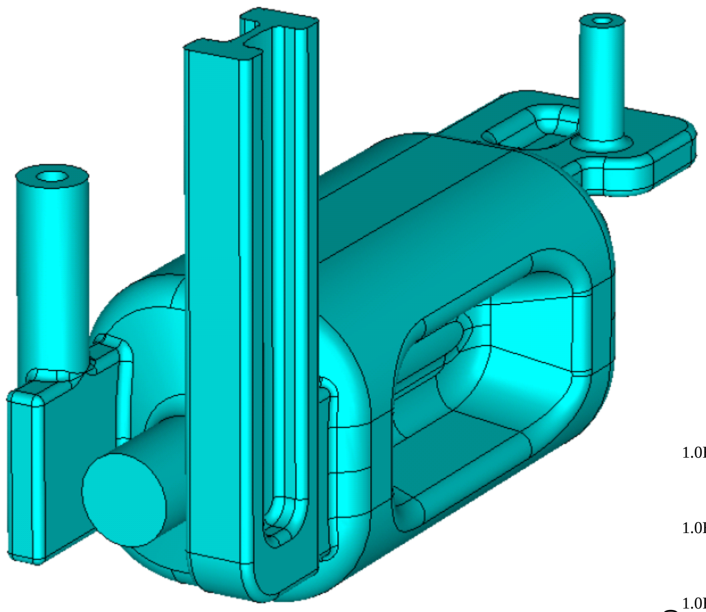
Deflecting Voltage (V_t[a])	0.30	0.30	0.30	0.30	0.30	0.30	MV
Peak Electric Field (E_p[a])	3.45	1.83	2.08	2.55	2.85	2.86	MV/m
Peak Magnetic Field (B_p[a])	11.47	6.05	6.47	5.42	5.12	4.38	mT
B_p/E_p	3.33	3.30	3.12	2.12	1.80	1.53	mT/(MV/m)
Energy Content (U[a])	0.049	0.030	0.032	0.033	0.036	0.029	J
Geometrical Factor (G)	80.9	67.0	67.4	87.7	94.2	105.9	Ω
$[R/Q]_t$	591.7	935.9	887.3	866.8	807.7	982.5	Ω
R_tR_s	4.8×10^4	6.3×10^4	6.0×10^4	7.6×10^4	7.6×10^4	1.0×10^5	Ω^2

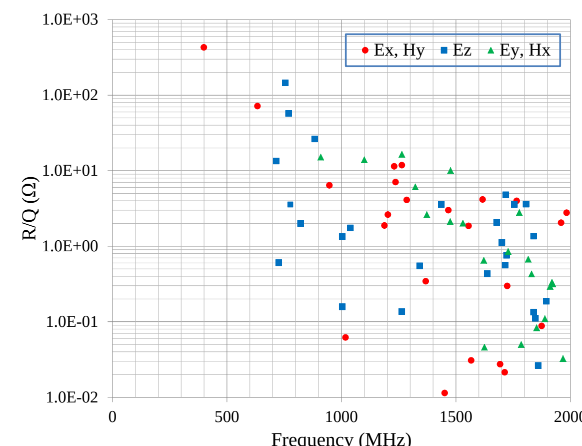
[a] At $E_t = 1$ MV/m

400 MHz Crabbing Cavity Prototype

- With the completion of the 400 MHz cylindrical rf-dipole cavity (proof of principle cavity), now focusing on the next generation of the LHC crabbing cavity design

Parameter		Unit
Frequency	399.06	MHz
Deflecting voltage (V_T^*)	0.375	MV
Peak electric field (E_P^*)	3.66	MV/m
Peak magnetic field (B_P^*)	6.14	mT
Stored Energy (U^*)	0.13	J
$[R/Q]$	427.21	Ω
Geometrical Factor (G)	106.37	Ω
$R_T R_S$	4.54×10^4	Ω^2
At $V_T = 3.4$ MV		
Peak magnetic field (B_P)	55.7	mT
Peak electric field (E_P)	33.2	MV
At $V_T = 5.0$ MV		
Peak magnetic field (B_P)	81.9	mT
Peak electric field (E_P)	48.8	MV
At $E_T^* = 1$ MV/m		





Expand
Include HOM damping detailed multipacting requirements from CERN SPStest

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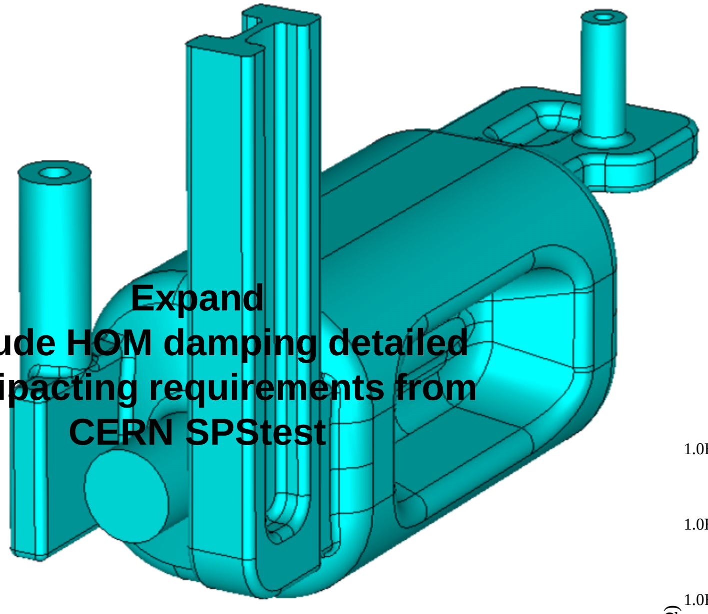
At E_T^* = 1 MV/m		



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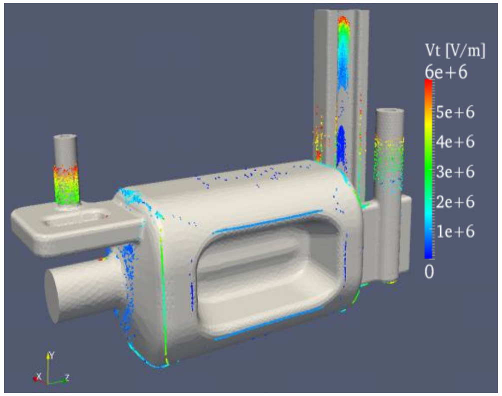

Component		Unit
V_T	10.0	MV
b_1	33.43	mT m
b_2	0.29	mT
b_3	455.25	mT/m
b_4	24.62	mT/m^2
b_5	-2.19×10^6	mT/m^3