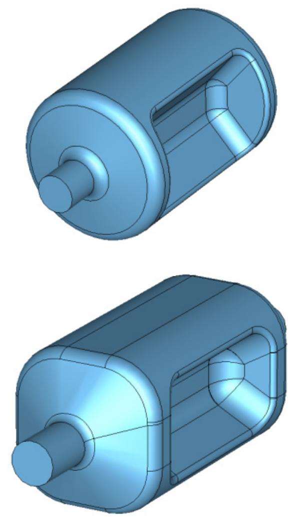
SUPERCONDUCTING RF-DIPOLE DEFLECTING AND CRABBING CAVITIES

Subashini De Silva

Center for Accelerator Science
Department of Physics, Old Dominion University
and
Thomas Jefferson National Accelerator Facility

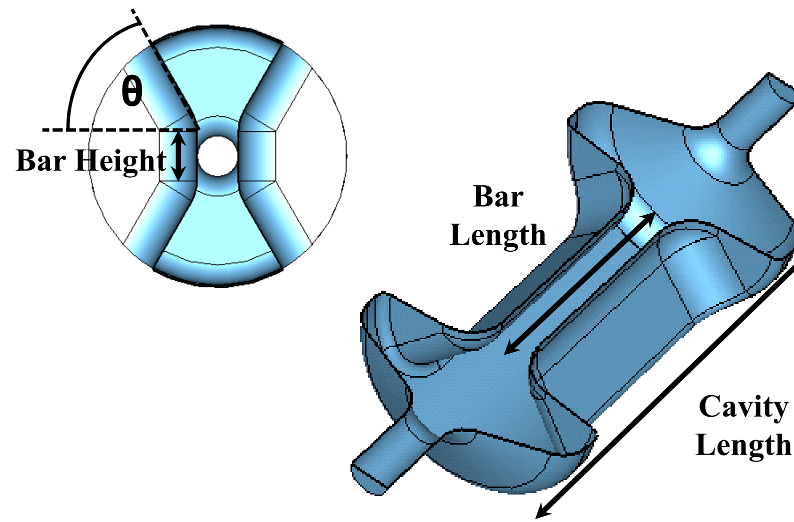
RF-Dipole Design

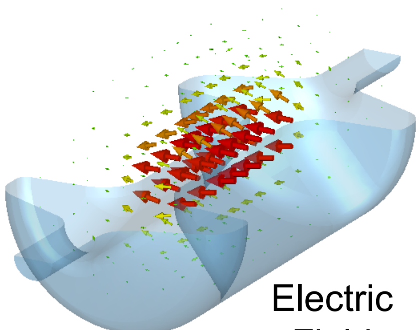
- Small size
- Square shape for additional compactness
- Lower and balanced peak surface fields
- High shunt impedance
- Wider separation in HOM spectrum and no LOMs
- Multipacting processes easily
- Cavity processing – Curved end plates for cleaning the cavity



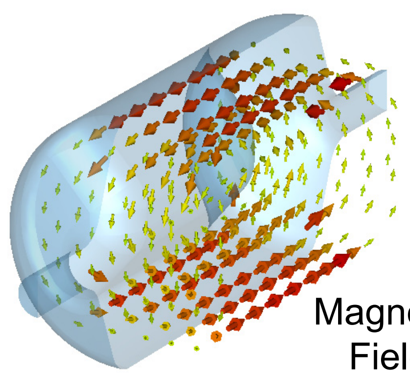
Properties depend on a few parameters

- 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





Electric Field

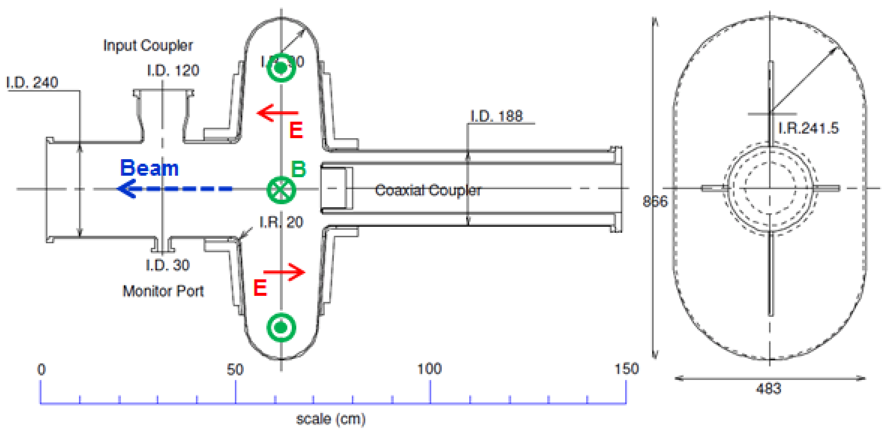


Magnetic Field

Deflecting and Crabbing Cavities

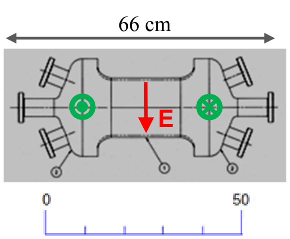
- TM$_{110}$ type cavities

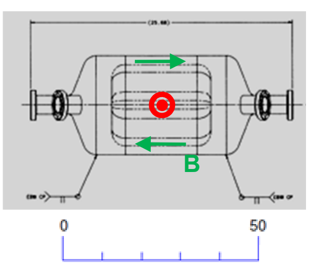
KEK Crabbing Cavity – TM$_{110}$ mode



- RF-Dipole Cavity

499 MHz Deflecting Cavity





	KEK Crabbing Cavity	RF-Dipole Cavity	Units
Frequency	**508.9**	**499.0**	**MHz**
LOM	410.0	None	MHz
Nearest HOM	630.0	777.2	MHz
Aperture Diameter	100.0	40.0	mm
Cavity width	48.3	24.0	cm
Cavity height	86.6	24.0	cm
Cavity length	~150	66	cm
V_T^*	0.295	0.3	MV
E_p^*	4.24	2.86	MV/m
B_p^*	12.23	4.38	mT
B_p^*/E_p^*	2.88	1.53	mT/ (MV/m)
$[R/Q]_T$	48.9	982.5	Ω
Geometrical Factor	227.0	105.9	Ω
$R_T R_S$	1.1×10^4	1.0×10^5	Ω^2
At $E_T^* = 1$ MV/m			

*K. Hosoyama et al, "Crab Cavity for KEKB", Proc. of the 7th Workshop on RF Superconductivity, p.547 (1998)

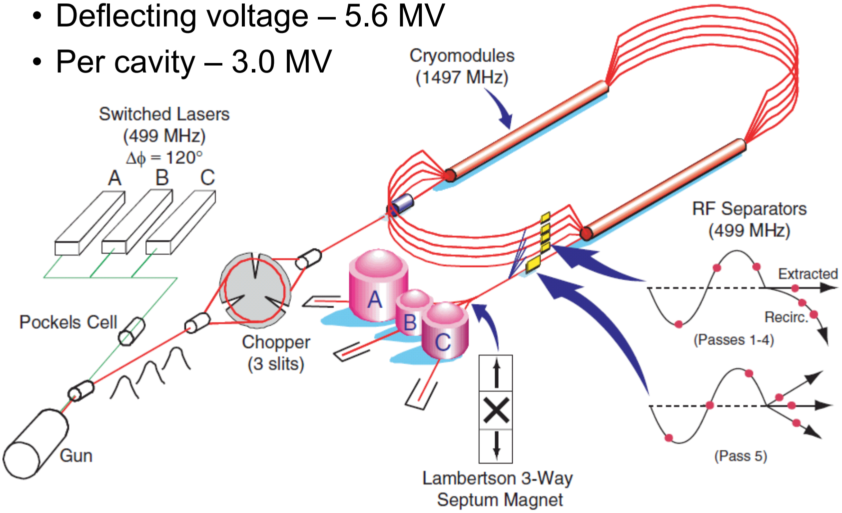
Crabbing/Deflecting Cavity Applications

- Luminosity management in linear or circular colliders
- Separation or merge of multiple beams
- Emittance exchange in beams
- X-ray pulse compression
- Beam diagnostics

Current and Proposed Applications of RF Dipole Cavity

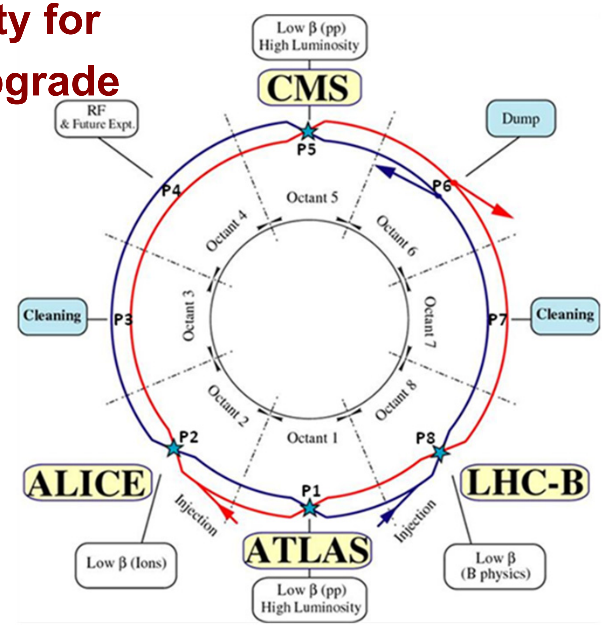
499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade

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

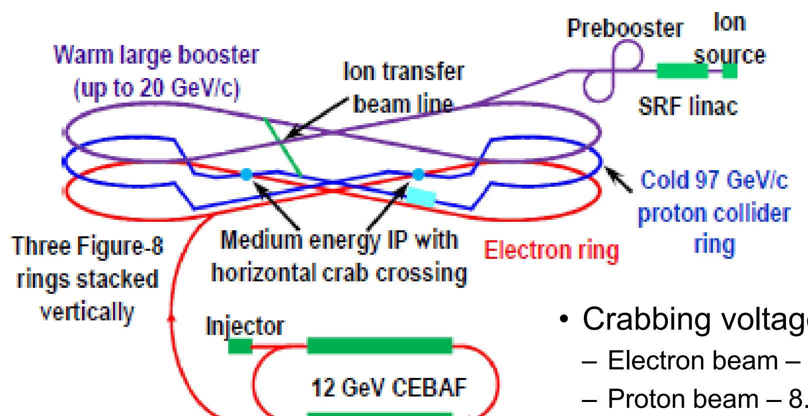


400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

- 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



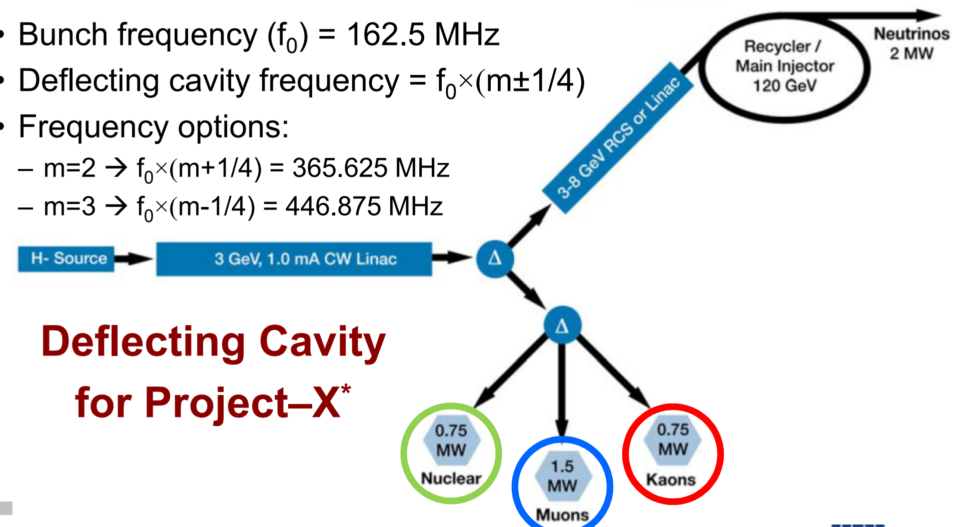
750 MHz Crabbing Cavity for MEIC*



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

Deflecting Cavity for Project–X*

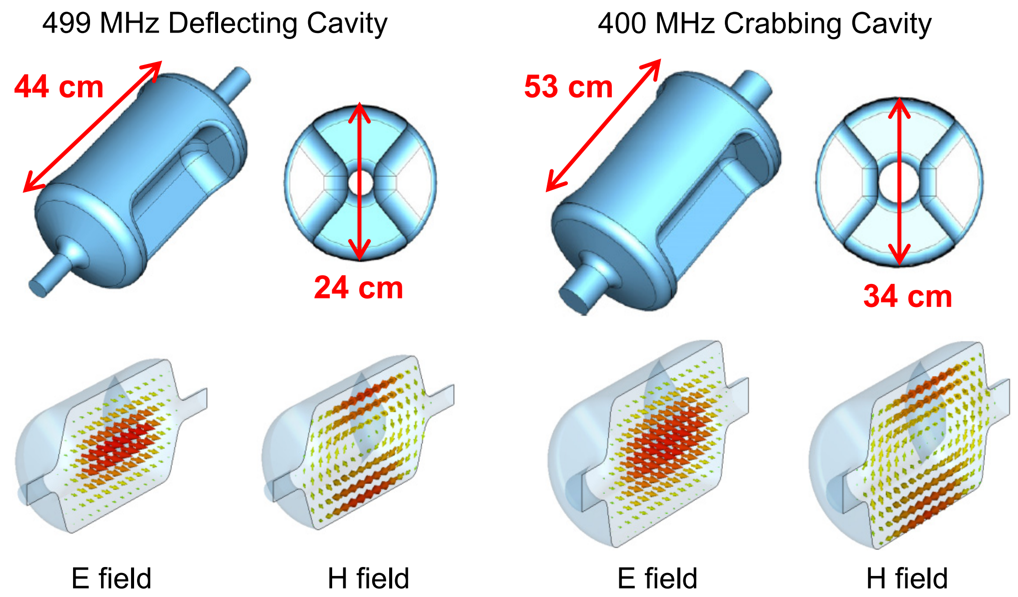
- Bunch frequency (f_0) = 162.5 MHz
- Deflecting cavity frequency = $f_0 \times (m \pm 1/4)$
- Frequency options:
  - m=2 → $f_0 \times (m+1/4)$ = 365.625 MHz
  - m=3 → $f_0 \times (m-1/4)$ = 446.875 MHz



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

Properties of Proof of Principle Cavities

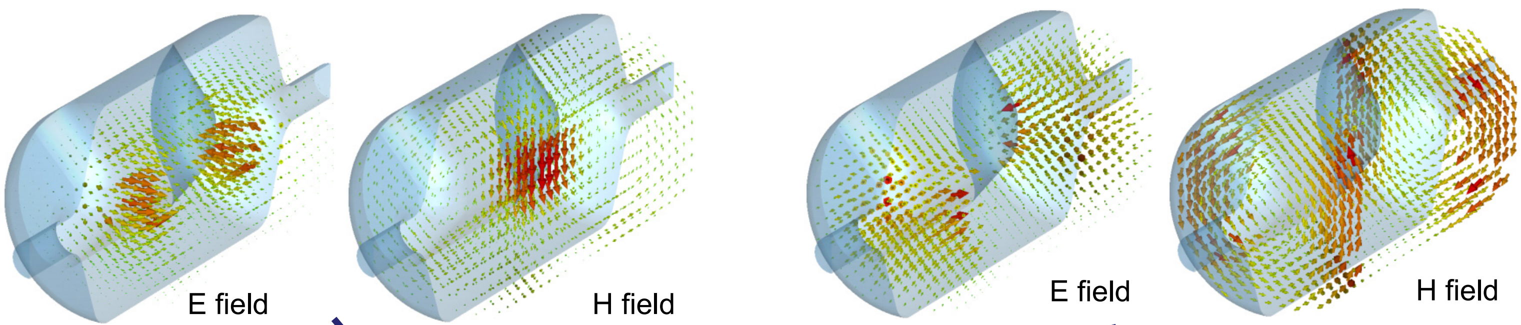
Frequency	499.0	400.0	MHz
Aperture Diameter (d)	40.0	84.0	mm
d/(λ/2)	0.133	0.224	
V_T^*	0.3	0.375	MV/m
E_p^*	**2.86**	**4.02**	MV/m
B_p^*	**4.38**	**7.06**	mT
B_p^*/E_p^*	1.53	1.76	mT/ (MV/m)
U^*	0.029	0.195	J
$[R/Q]_T$	982.5	287.0	Ω
Geometrical Factor (G)	105.9	140.9	Ω
$R_T R_S = [R/Q]_T G$	**1.0×10^5**	**4.0×10^4**	Ω^2
At $E_T^* = 1$ MV/m			
V_T	**5.6**	**5.0**	MV
E_p	**54**	**54**	MV/m
B_p	**82**	**95**	mT

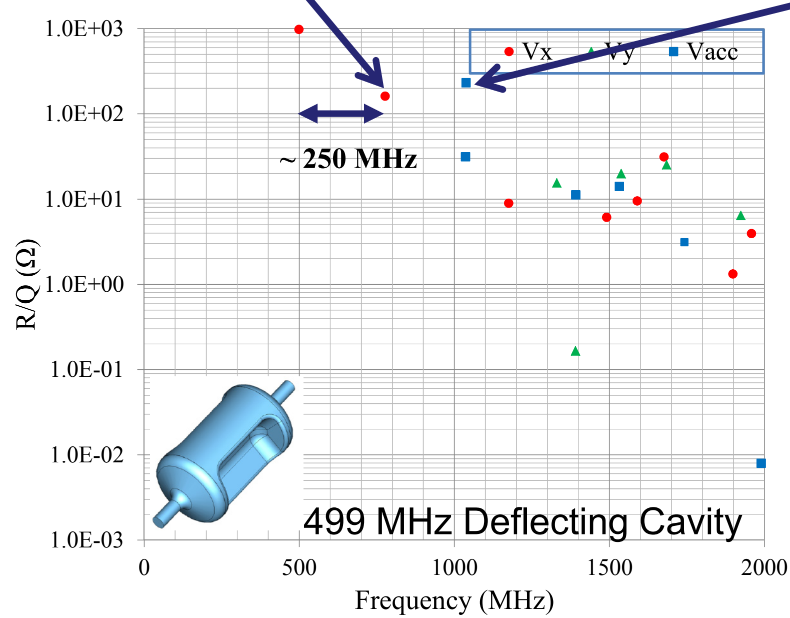


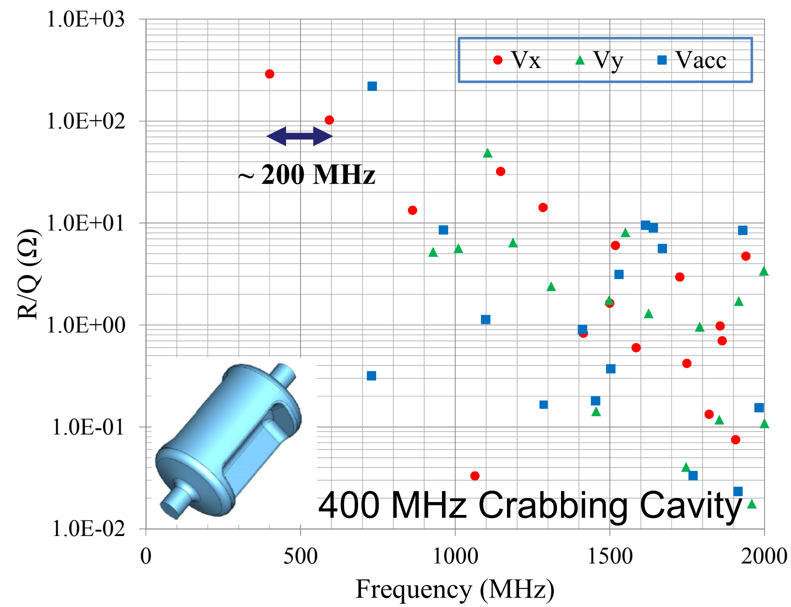
- Dependence of beam aperture ($d/(\lambda/2)$)
  - Peak surface fields (B_P/E_T and E_P/E_T) increase
  - Shunt impedance ($R_T R_S$) drops

Higher Order Mode Properties

- Widely separated Higher Order Modes
- No Lower Order Modes





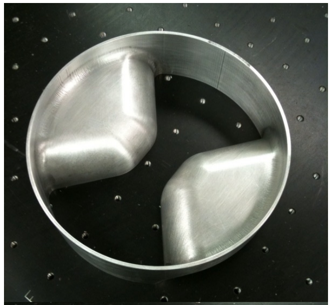


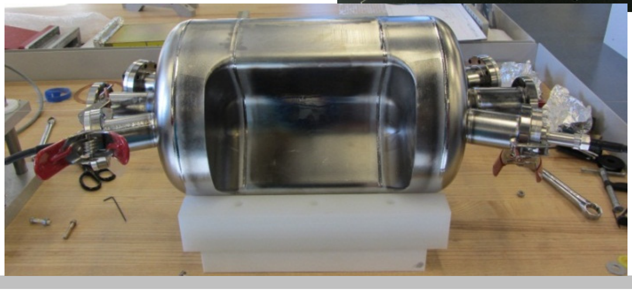
Fabrication

- Cavity thickness = 3mm
- Frequency adjustment by trimming the center shell

499 MHz Deflecting Cavity

Fabricated at Jefferson Lab

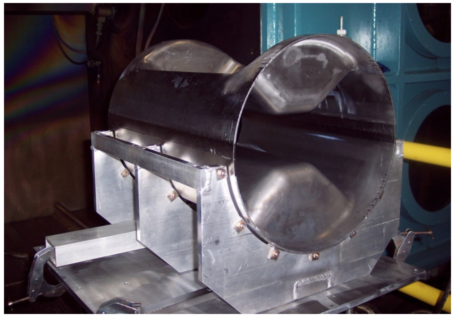



400 MHz Crabbing Cavity

Fabricated at Niowave Inc.






Surface Treatment

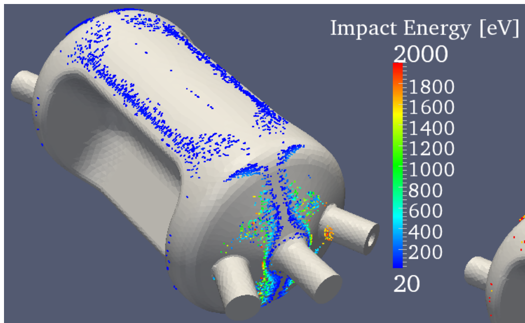
- Bulk BCP of ~150 μm
- Average removal
  - 499 MHz → 108 μm
  - 400 MHz → 85 μm
- Heat Treatment → H_2 degassing at 600^0C – 10 hours
- Light BCP – Removal of 10 μm after heat treatment
- High pressure rinsing in 3 passes
- Assembly – with fixed coupling
- No He processing
- No in-situ baking
- Tests performed
  - 4 K high power test
  - 4 K to 2 K low power test
  - 2 K high power test

400 MHz Crabbing Cavity

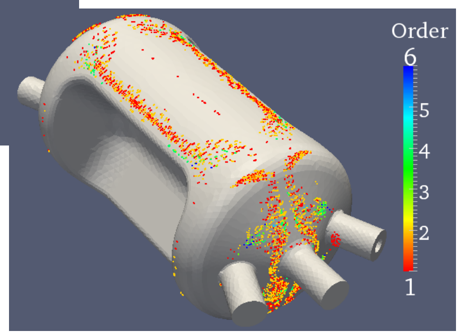
499 MHz Deflecting Cavity

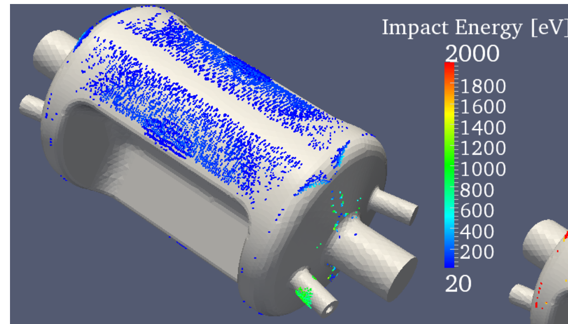
Multipacting Analysis

Track3P – Resonant particle tracking code in SLAC ACE3P suite

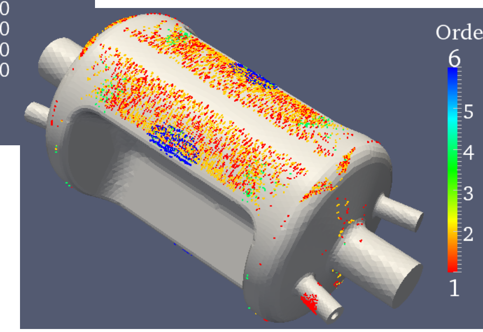


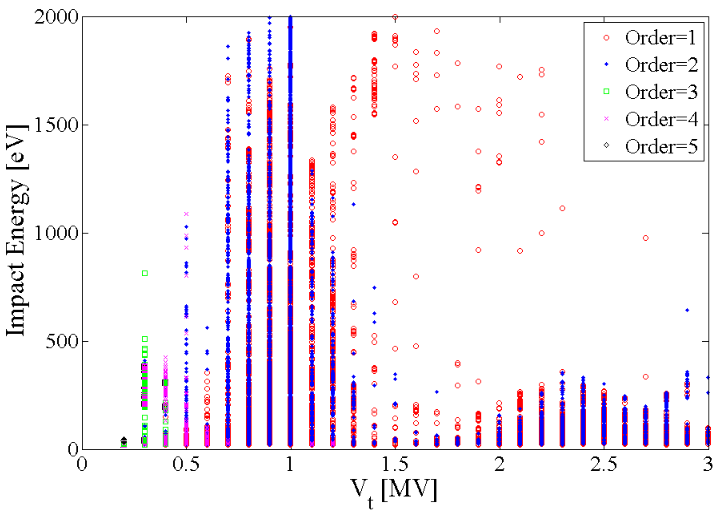
499 MHz
Deflecting
Cavity

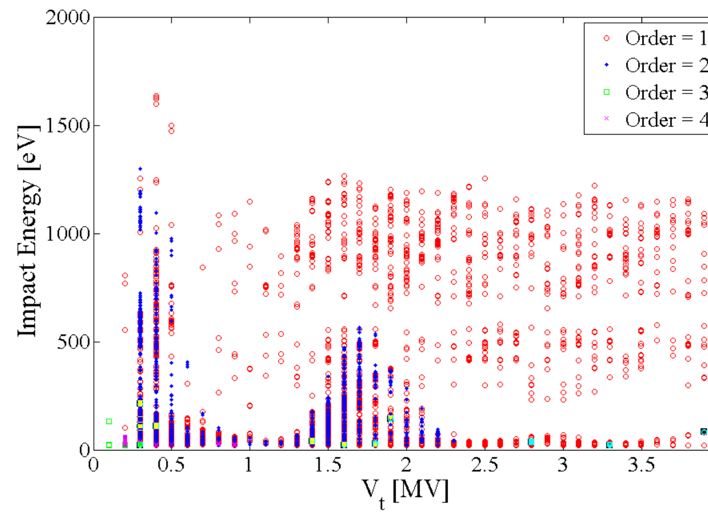




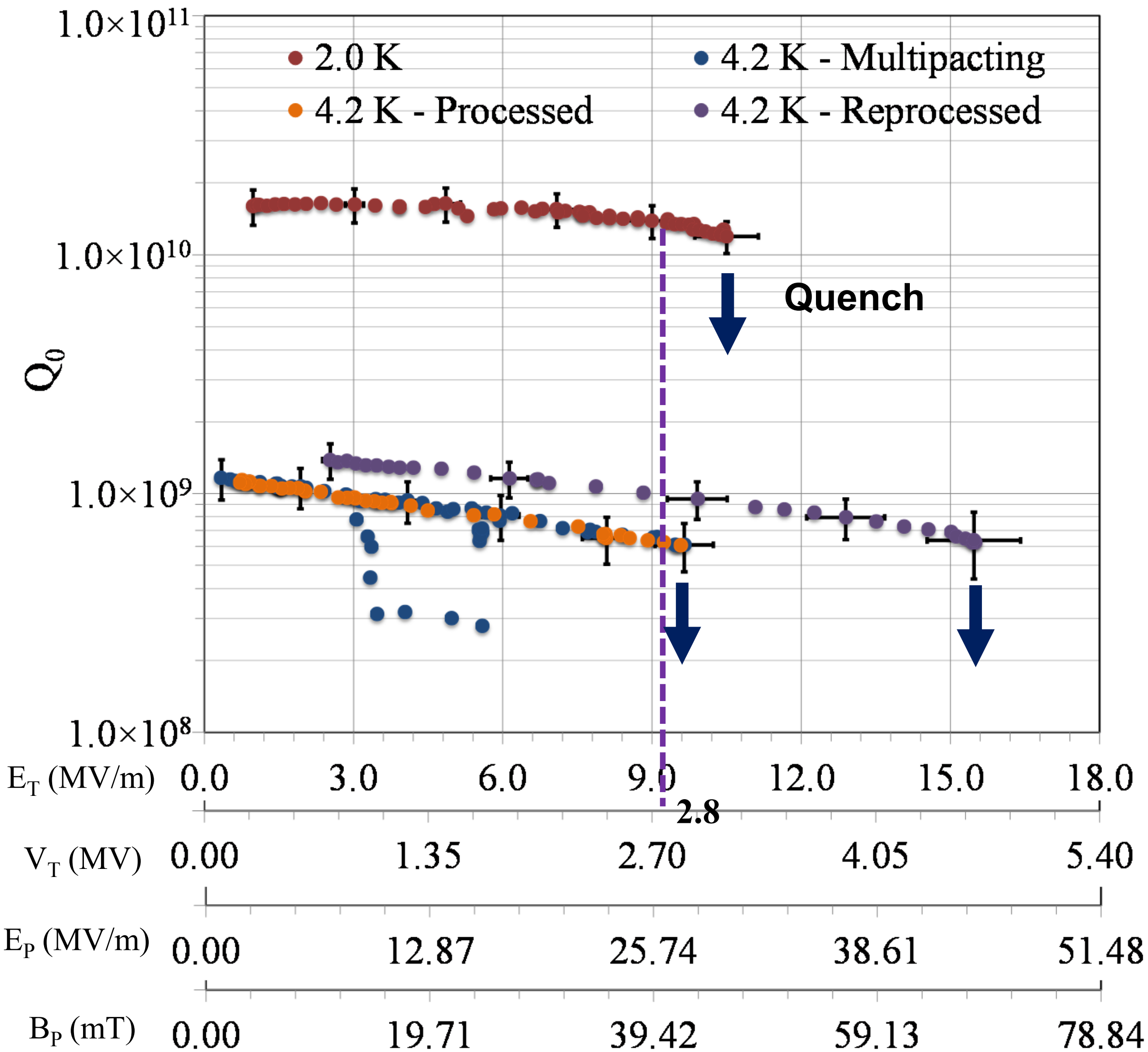
400 MHz
Crabbing
Cavity



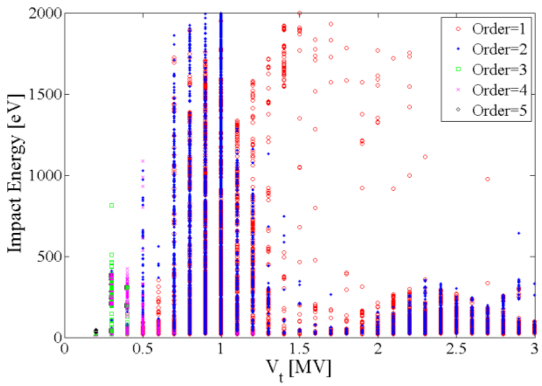




4.2 K and 2 K Test Results – 499 MHz



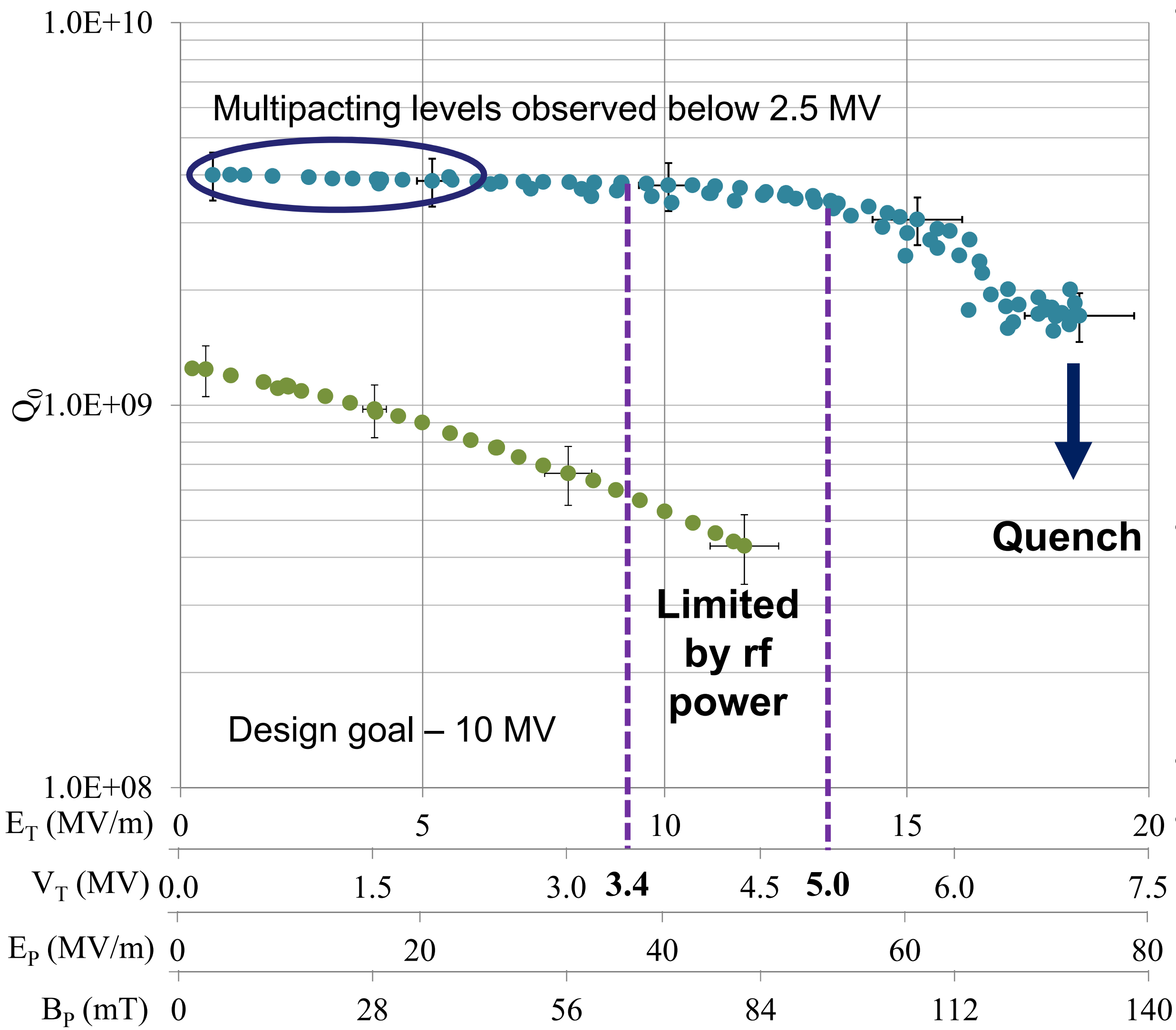
- Multipacting was easily processed during the 4.2 K rf test



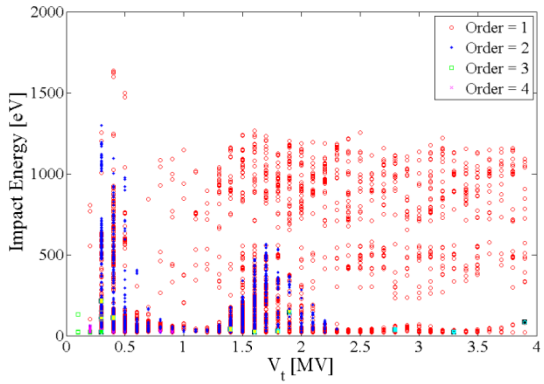
- Design requirement of 5.6 MV can be achieved with 2 cavities

- Reprocessed cavity achieved fields at 4.2 K
  - E_T = 15.5 MV/m
  - V_T = 4.65 MV
  - E_P = 44.3 MV/m
  - B_P = 67.9 mT

4.2 K and 2 K Test Results – 400 MHz

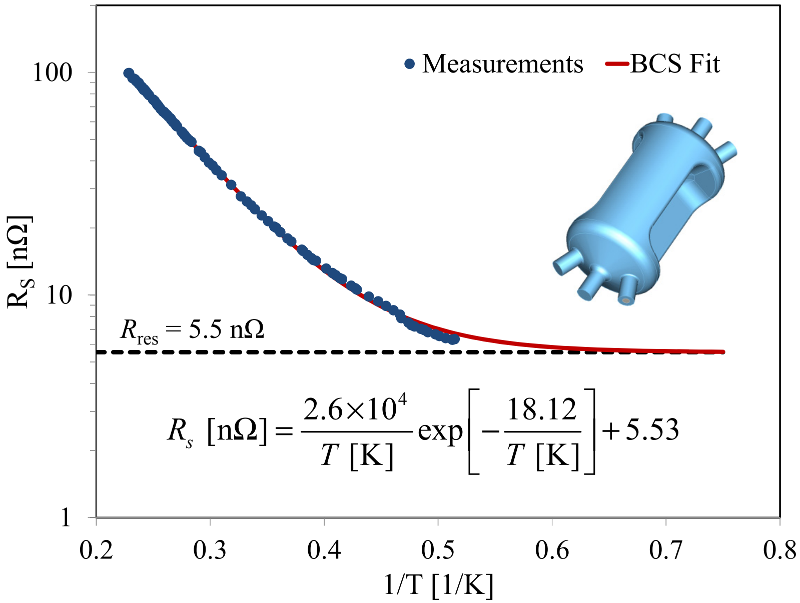


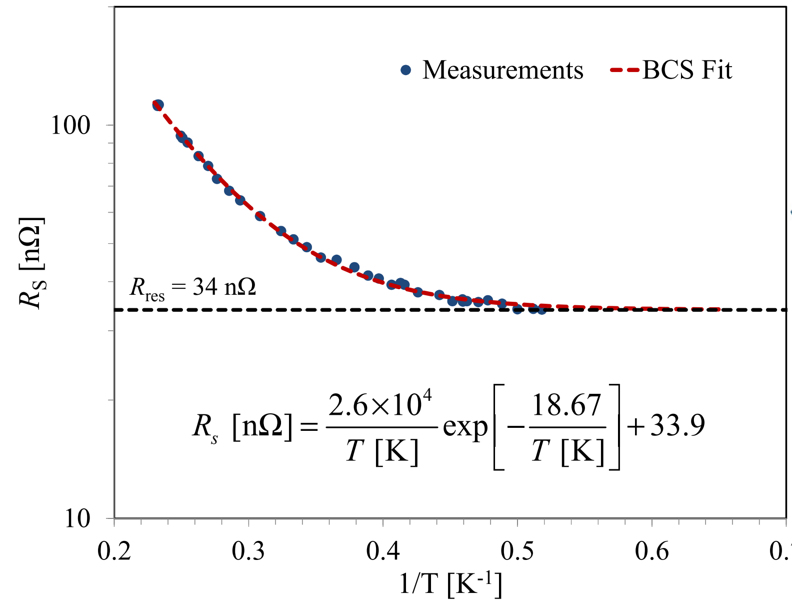
- Multipacting levels were easily processed

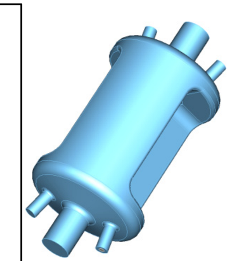


- Achieved fields at 4.2 K
  - E_T = 11.6 MV/m
  - V_T = 4.35 MV
  - E_P = 47 MV/m
  - B_P = 82 mT
- Limited by rf power at 4.2 K
- Achieved fields at 2.0 K
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT

Surface Resistance





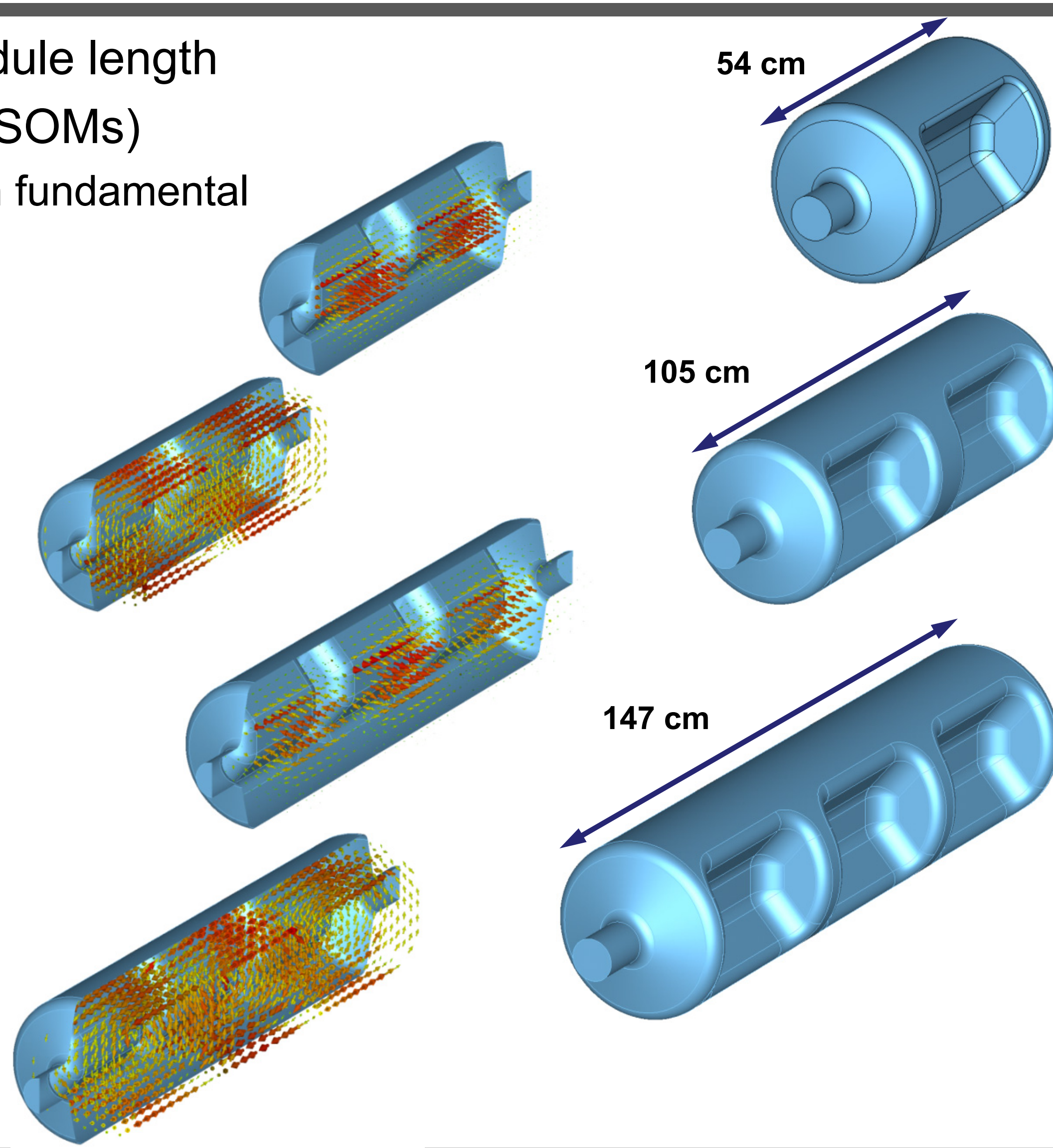


- 499 MHz Cavity
  - R_{BCS} = 1.3 nΩ at 2.0 K
  - R_{res} = 5.5 nΩ
- 400 MHz Cavity
  - R_{BCS} = 2.0 nΩ at 2.0 K
  - R_{res} = 34 nΩ
  - Measured Q_0 at 2.0 K = 4.0×10^9
  - Q_0 due to power loss at the beam ports flanges→ 3.8×10^9

Multicell RF-Dipole Designs

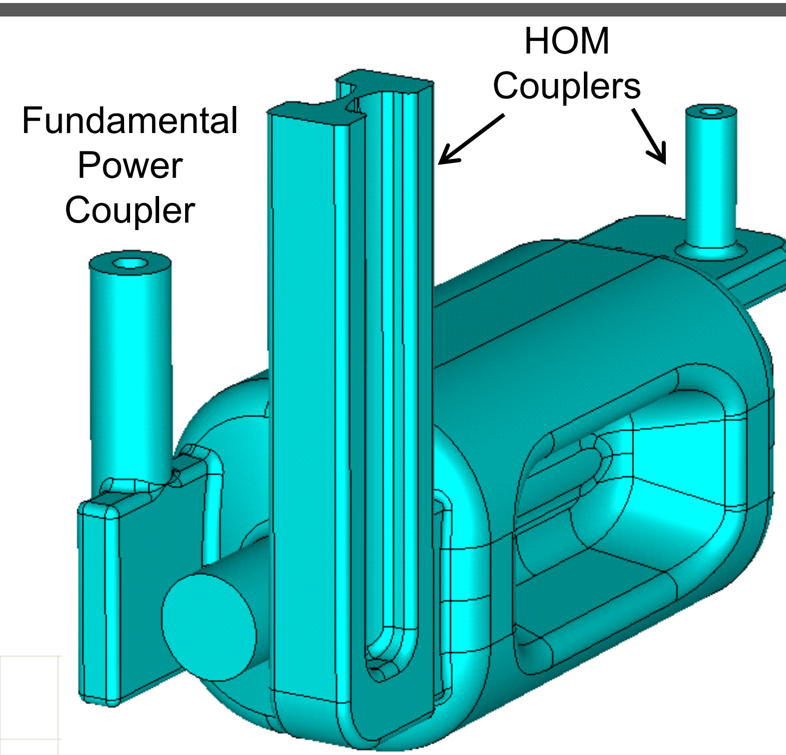
- Reduced total cavity and cryomodule length
- Existence of same order modes (SOMs)
  - SOMs have lower frequency than fundamental
  - No. of SOMs = No. of cells

	2 cell	**3 cell**	
Frequency	400	400	MHz
SOMs	374.5	351.6 / 376.8	MHz
Aperture	84	84	mm
Cavity length	105	147	cm
Cavity diameter	34.5	35.4	cm
V_T^*	**0.375**	**0.375**	MV
E_p^*	**4.26**	**4.75**	MV/m
B_p^*	**7.4**	**7.77**	mT
$[R/Q]_T$	488.4	708.1	Ω
Geometrical Factor (G)	127.8	131.8	Ω
$R_T R_S$	**6.2×10⁴**	**9.3×10⁴**	Ω²
At $E_T^* = 1$ MV/m			

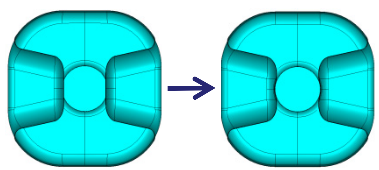


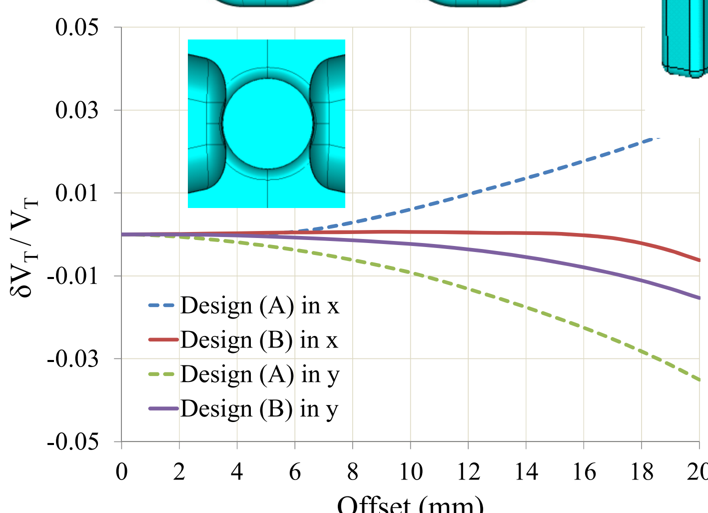
400 MHz Crabbing Cavity Prototype

- Work done in collaboration with Zenghai Li at SLAC
- 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
- Requires to deliver vertical and horizontal crabbing

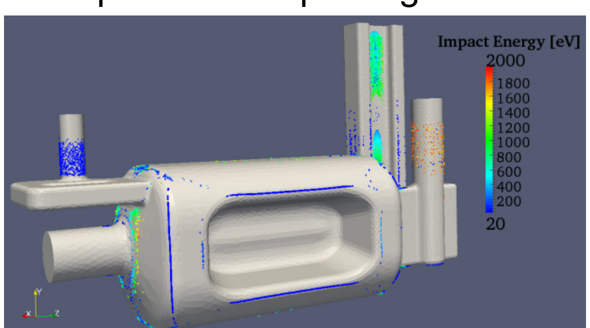


Frequency	**400.0**	**MHz**
Aperture Diameter	84.0	mm
V_T	5.0	MV/m
E_p	49	MV/m
B_p	82	mT
$[R/Q]_T$	429.0	Ω
Geometrical Factor (G)	106.2	Ω
$R_T R_S$	4.6×10^4	Ω^2



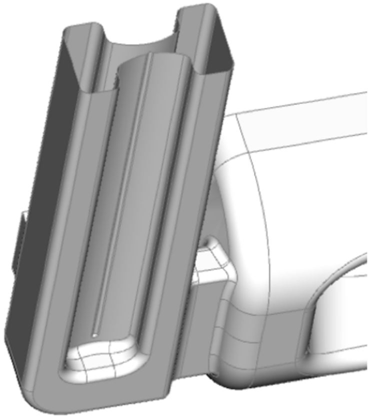


Improved multipacting levels

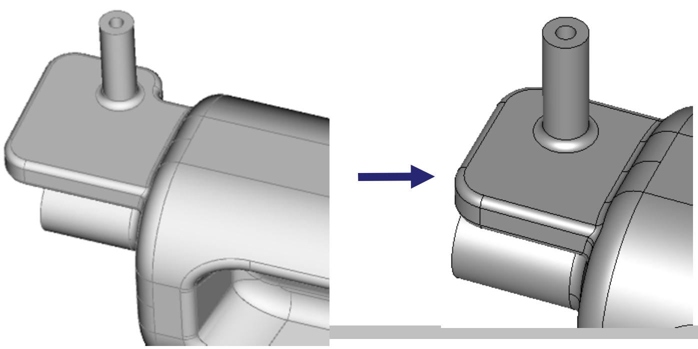


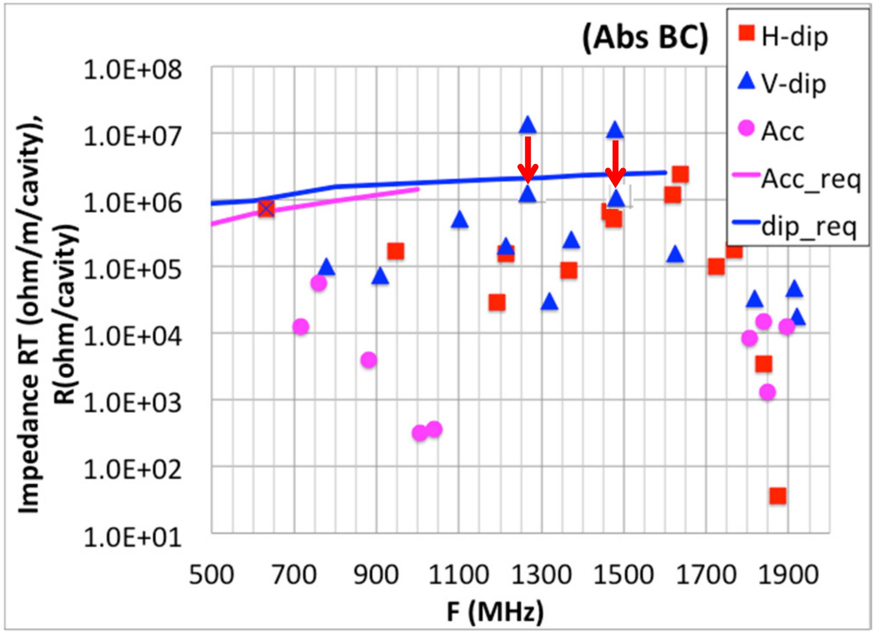
Damping of Higher Order Modes

- Horizontal HOM Coupler
  - Ridged waveguide coupler
  - Operating mode below cutoff – naturally reject operating mode
  - Couple to both horizontal dipole and accelerating HOM modes
  - Groove reduces multipacting levels at the waveguide



- Vertical HOM coupler
  - Selective WG-stub-coaxial coupler, does not couple to operating mode - no filter needed
  - Damps both vertical HOM and accelerating HOM modes
  - Asymmetric probe position to couple to higher HOMs (e.g. quad, etc)





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

Summary

- Proof-of-Principle 499 MHz and 400 MHz cavities were tested
  - 499 MHz cavity achieved a low surface resistance and high fields
  - 400 MHz cavity achieved high surface fields (7 MV deflecting voltage cw which is twice design voltage)
    - High residual losses due losses at the stainless steel flanges

- In both cavities multipacting quickly processed and did not reoccur

- RF Dipole cavity has attractive properties compared to TM_{110} Cavity
  - Small size
  - Low surface fields
  - No lower-order modes
  - Widely separated higher-order modes
  - Disadvantage: due to its small size, probably could not be used at as high a frequency and large aperture

Acknowledgements

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

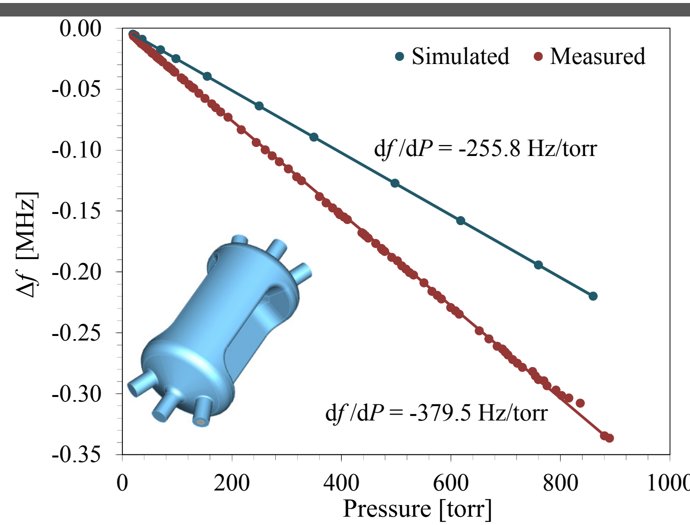
- ODU
  - Chris Hopper
  - Alex Castilla
  - HyeKyoung Park
  - Rocio Olave

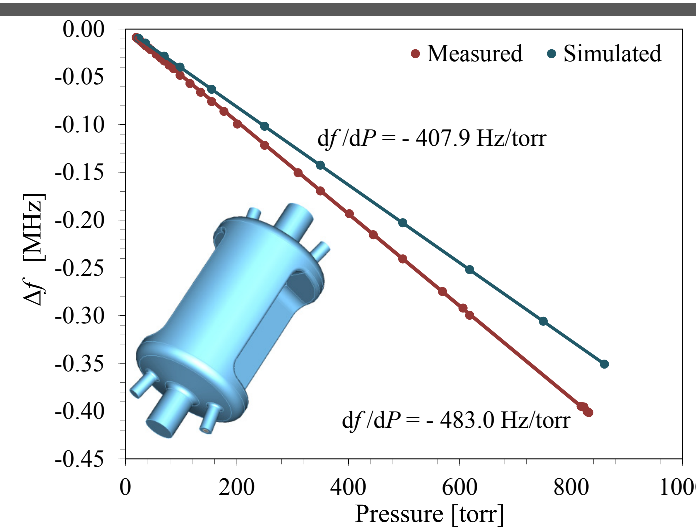
- SLAC
  - Zenghai Li

- Niowave
  - Terry Grimm
  - Dmitry Gorelov
  - Chase Boulware
  - Nick Miller

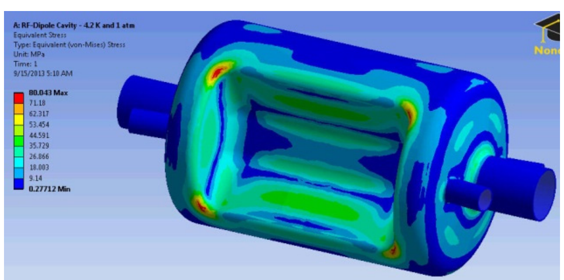
- JLab
  - HyeKyoung Park
  - Peter Kneisel
  - Rongli Geng
  - Haipeng Wang
  - Joe Preble
  - Tony Reilly
  - Tom Powers
  - Kirk Davis
  - Pete Kushnick
  - Dave McCay
  - Casy Apeldoorn
  - Danny Forehand and his team
  - Steve Castagnola and his team

Pressure Sensitivity



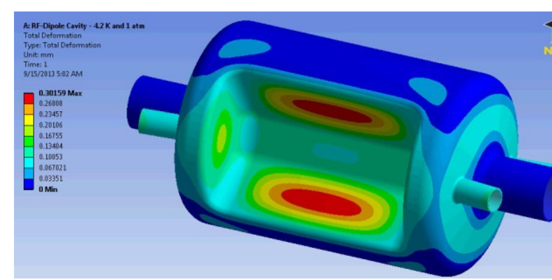


- Simulated in ANSYS with 3 mm uniform thickness
- Difference between simulation and measurements are possibly due to varying cavity thickness and material properties
- The edges of loading elements require reinforcement to reduces the stresses

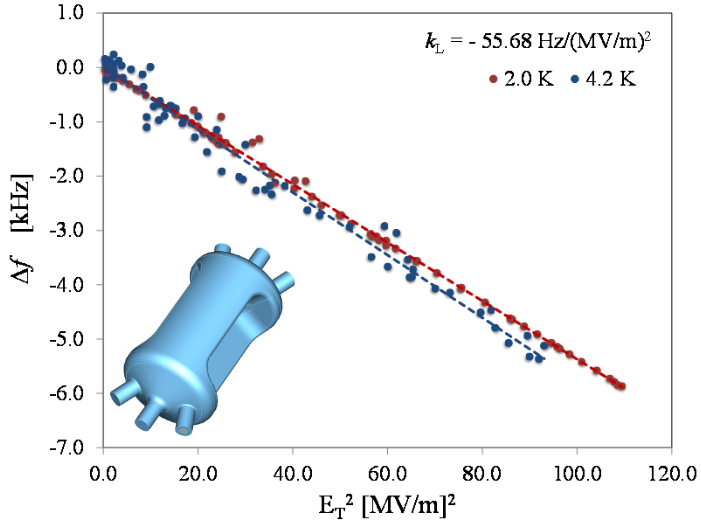


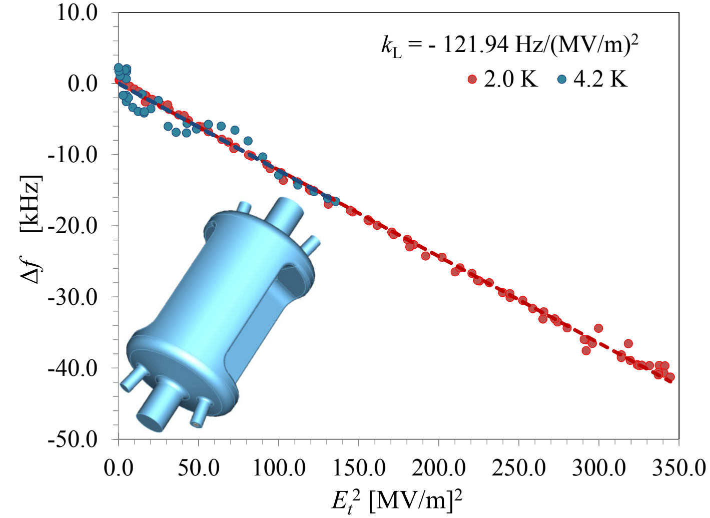
Stresses at 4 K

Deformation at 4.0 K due to pressure of 1 atm

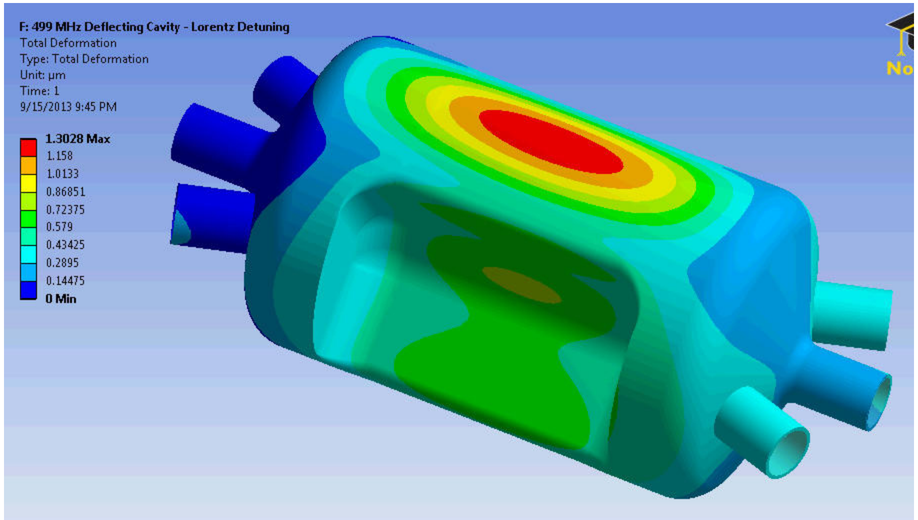


Lorentz Detuning



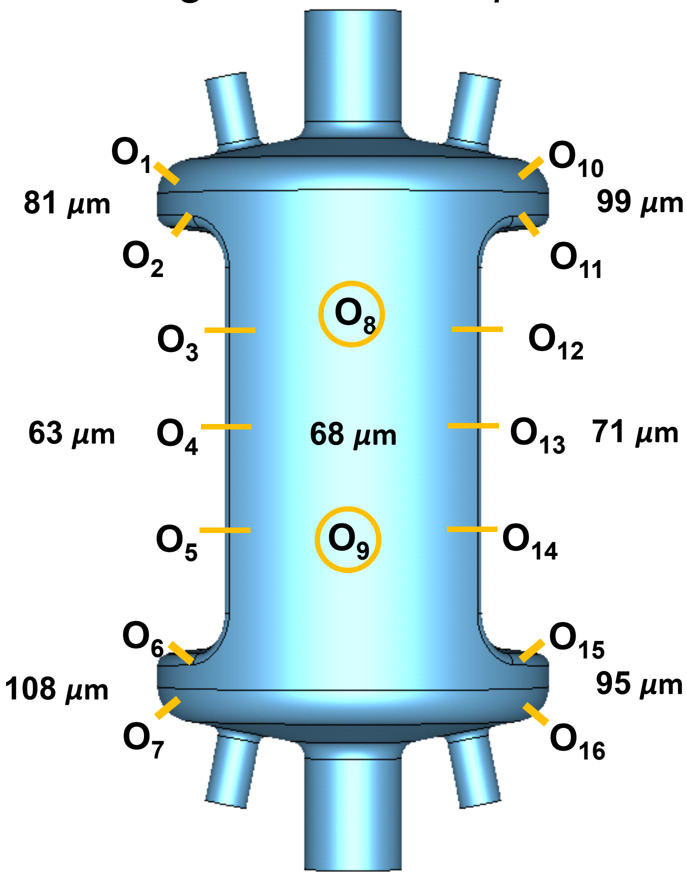


- Simulated Lorentz coefficient (k_L)
  - 499 MHz → -52.4 Hz/(MV/m)^2
  - 400 MHz → -117.3 Hz/(MV/m)^2



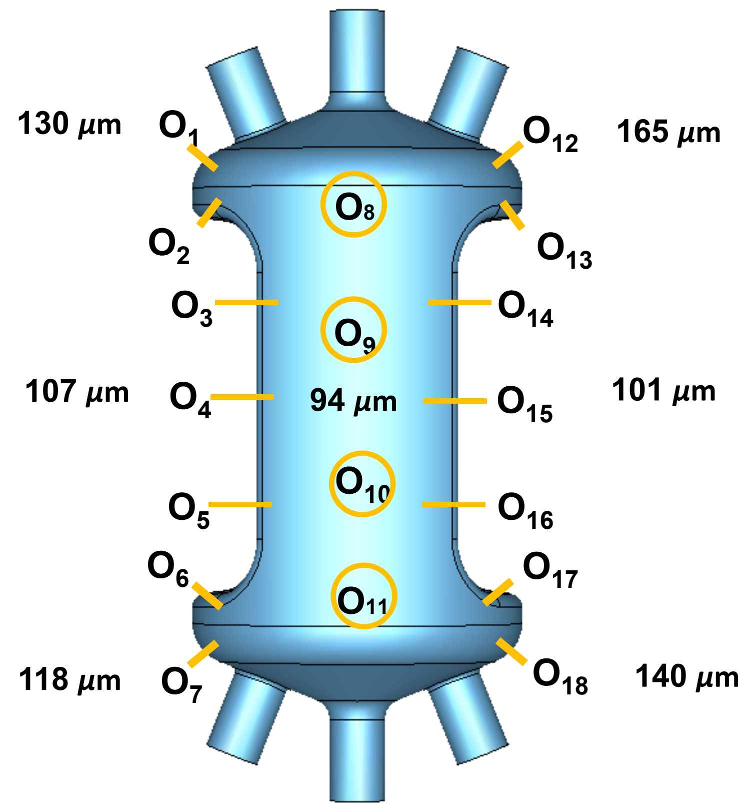
Surface Treatment – Bulk BCP

- 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 *μ*m



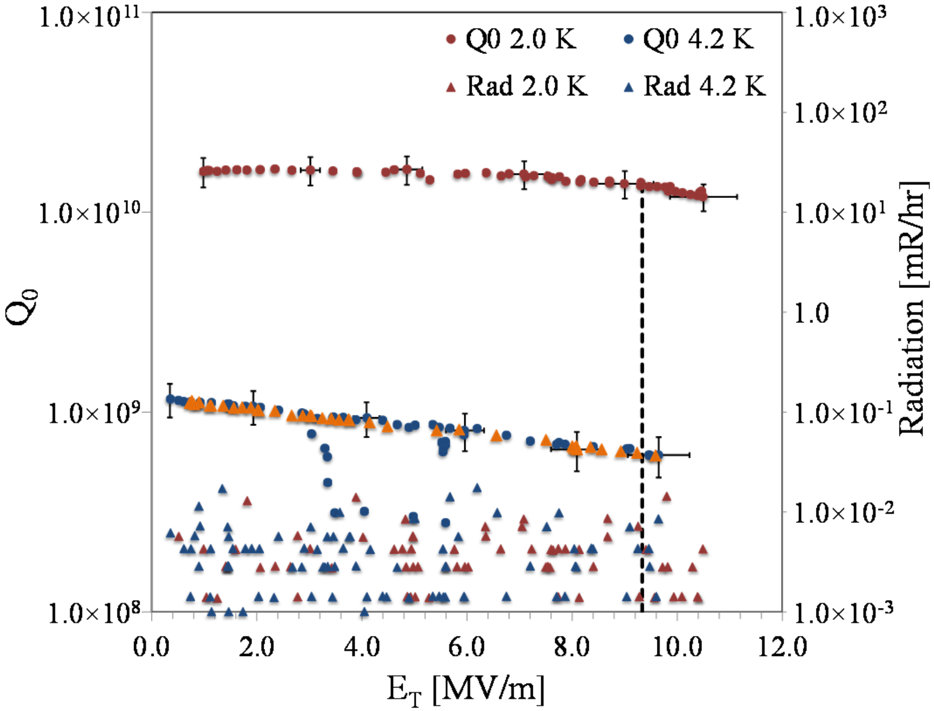
Panametrics 25DL-Plus Ultrasonic Precision Thickness Gage

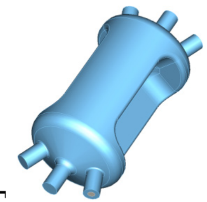
- Etch rate: 1.78 *μ*m/min
- Average removal 108 *μ*m



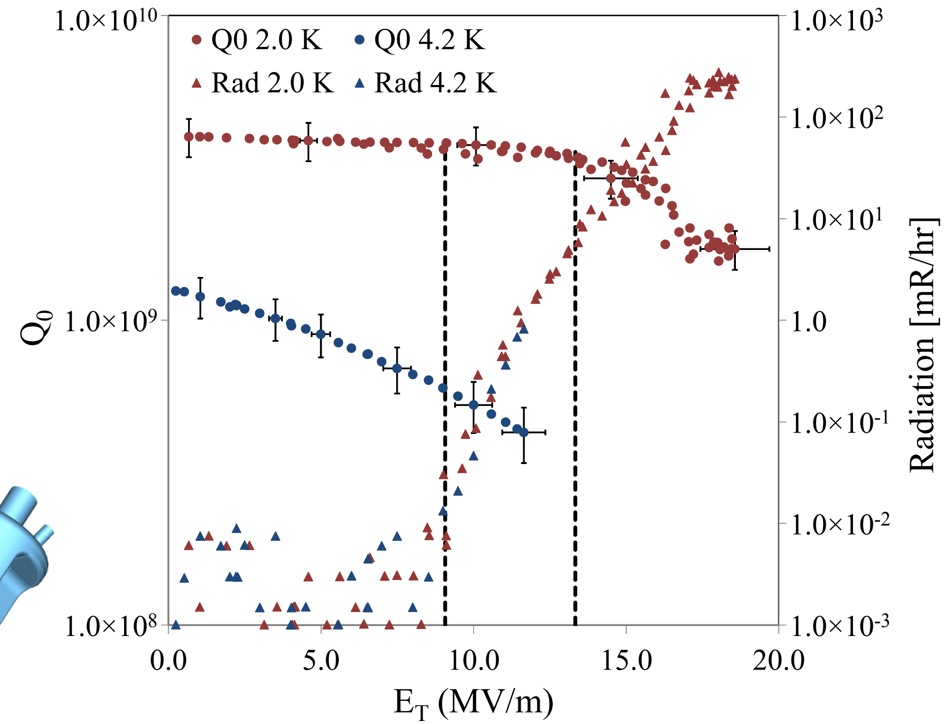
Average of O_{19}, O_{20}, O_{21} and O_{22} – 99 *μ*m

Field Emission





499 MHz Deflecting Cavity



400 MHz Deflecting Cavity