

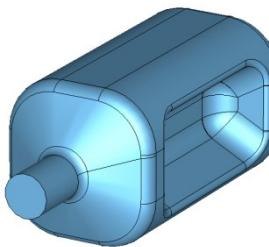
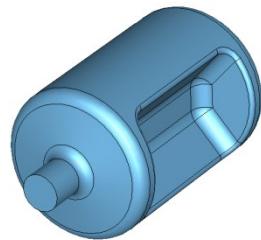
# **SUPERCONDUCTING RF-DIPOLE DEFLECTING AND CRABBING CAVITIES**

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

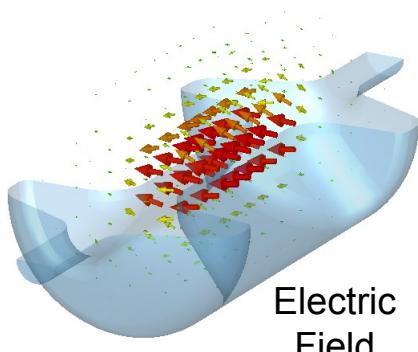
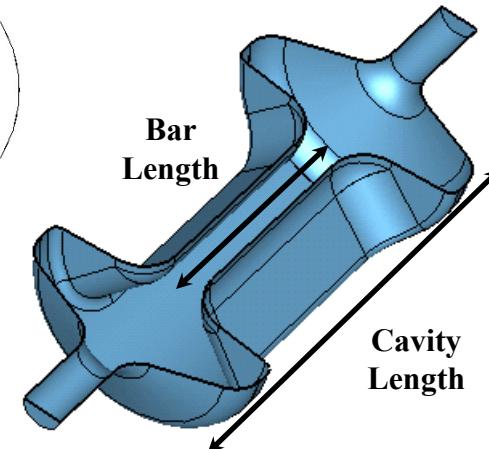
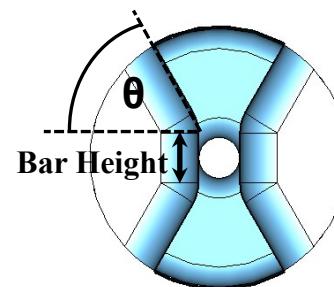
# RF-Dipole Design

- 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

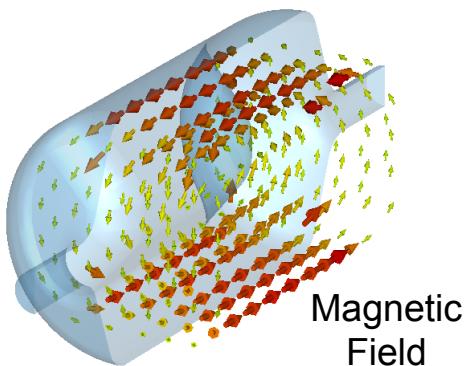


Properties depend on a few parameters

- Frequency determined by diameter of the cavity design
- Bar Length  $\sim \lambda/2$
- Bar height and aperture determine  $E_p$  and  $B_p$
- Angle determines  $B_p/E_p$



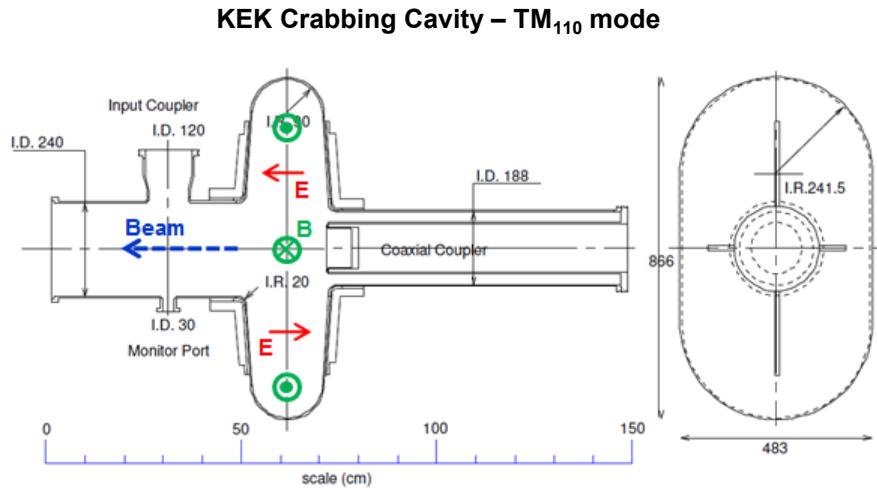
Electric Field



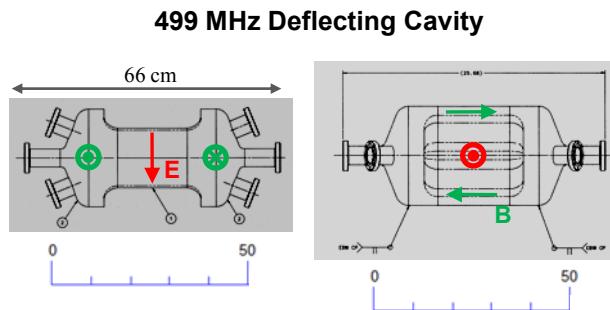
Magnetic Field

# Deflecting and Crabbing Cavities

- TM<sub>110</sub> type cavities



- RF-Dipole Cavity



	KEK Crabbing Cavity	RF- Dipole Cavity	Units
Frequency	<b>508.9</b>	<b>499.0</b>	<b>MHz</b>
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	$\Omega$
Geometrical Factor	227.0	105.9	$\Omega$
$R_T R_S$	$1.1 \times 10^4$	$1.0 \times 10^5$	$\Omega^2$
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

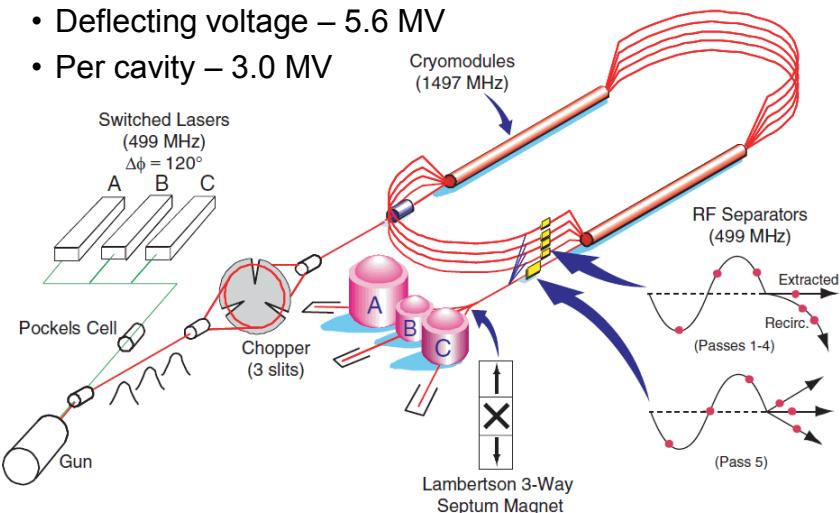
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- Luminosity management in linear or circular colliders
- Separation or merge of multiple beams
- Emittance exchange in beams
- X-ray pulse compression
- Beam diagnostics

# Current and Proposed Applications of RF Dipole Cavity

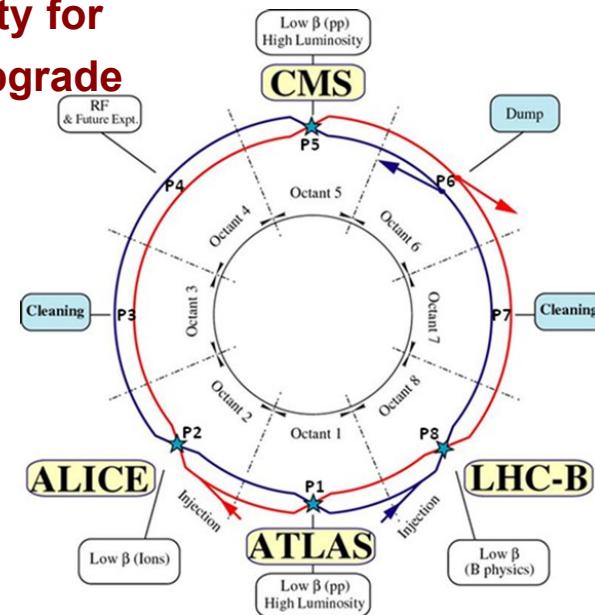
## 499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade

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

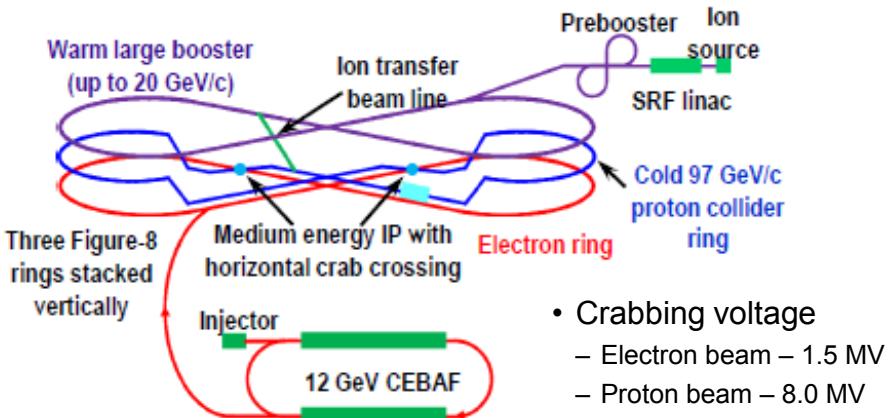


## 400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

- 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\*



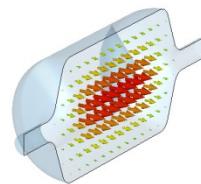
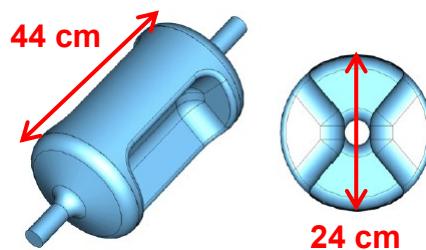
- Crabbing voltage
  - Electron beam – 1.5 MV
  - Proton beam – 8.0 MV

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

# Properties of Proof of Principle Cavities

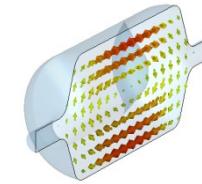
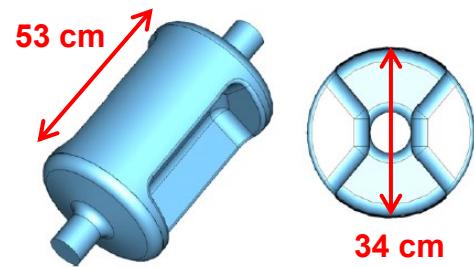
Frequency	499.0	400.0	MHz
Aperture Diameter (d)	40.0	84.0	mm
d/(λ/2)	0.133	0.224	
V <sub>T</sub> <sup>*</sup>	0.3	0.375	MV/m
E <sub>p</sub> <sup>*</sup>	<b>2.86</b>	<b>4.02</b>	MV/m
B <sub>p</sub> <sup>*</sup>	<b>4.38</b>	<b>7.06</b>	mT
B <sub>p</sub> <sup>*</sup> /E <sub>p</sub> <sup>*</sup>	1.53	1.76	mT/(MV/m)
U*	0.029	0.195	J
[R/Q] <sub>T</sub>	982.5	287.0	Ω
Geometrical Factor (G)	105.9	140.9	Ω
R <sub>T</sub> R <sub>S</sub> = [R/Q] <sub>T</sub> G	<b>1.0×10<sup>5</sup></b>	<b>4.0×10<sup>4</sup></b>	Ω <sup>2</sup>
At E <sub>T</sub> <sup>*</sup> = 1 MV/m			
V <sub>T</sub>	<b>5.6</b>	<b>5.0</b>	MV
E <sub>p</sub>	<b>54</b>	<b>54</b>	MV/m
B <sub>p</sub>	<b>82</b>	<b>95</b>	mT

499 MHz Deflecting Cavity

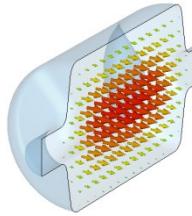


E field

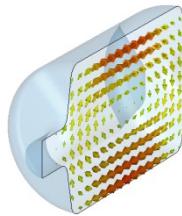
400 MHz Crabbing Cavity



H field



E field

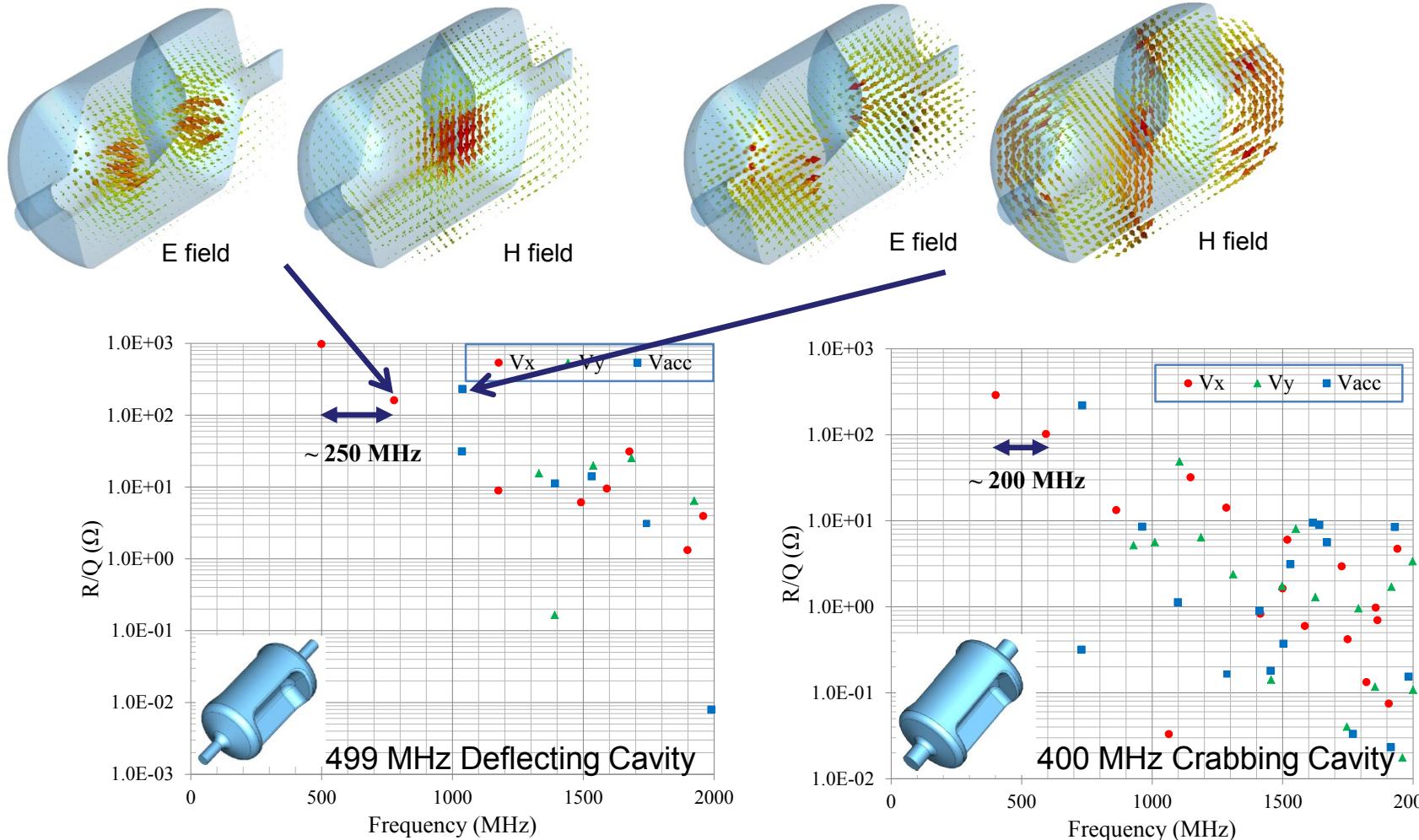


H field

- 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  $\mu\text{m}$
- Average removal
  - 499 MHz  $\rightarrow$  108  $\mu\text{m}$
  - 400 MHz  $\rightarrow$  85  $\mu\text{m}$
- Heat Treatment  $\rightarrow$  H<sub>2</sub> degassing at 600°C – 10 hours
- Light BCP – Removal of 10  $\mu\text{m}$  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

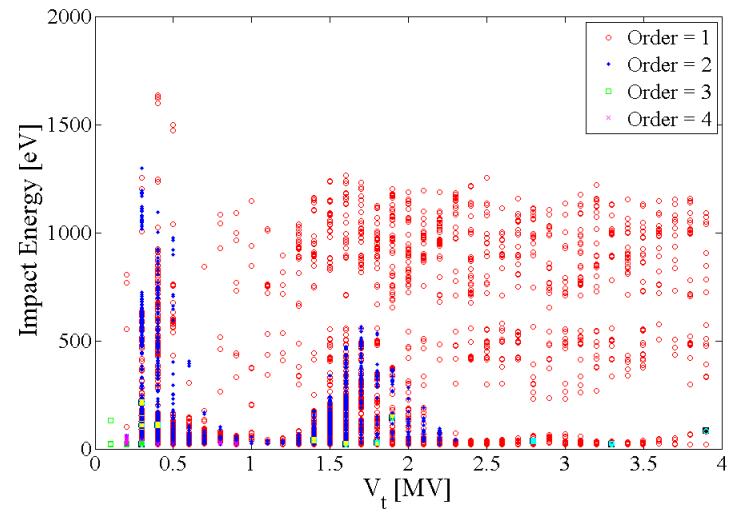
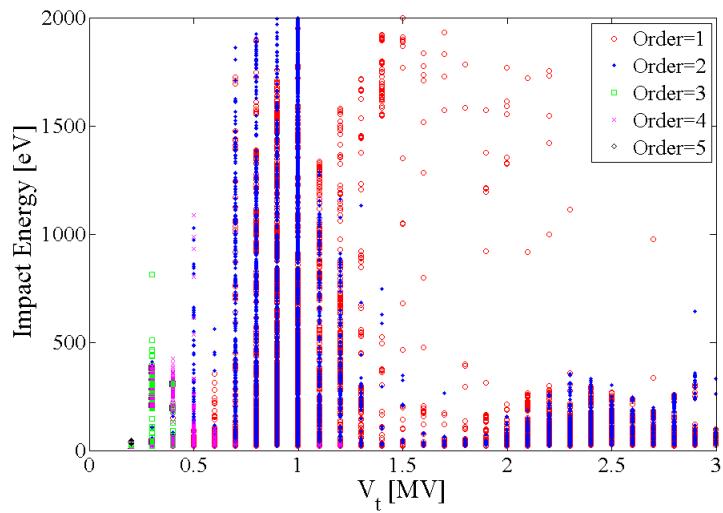
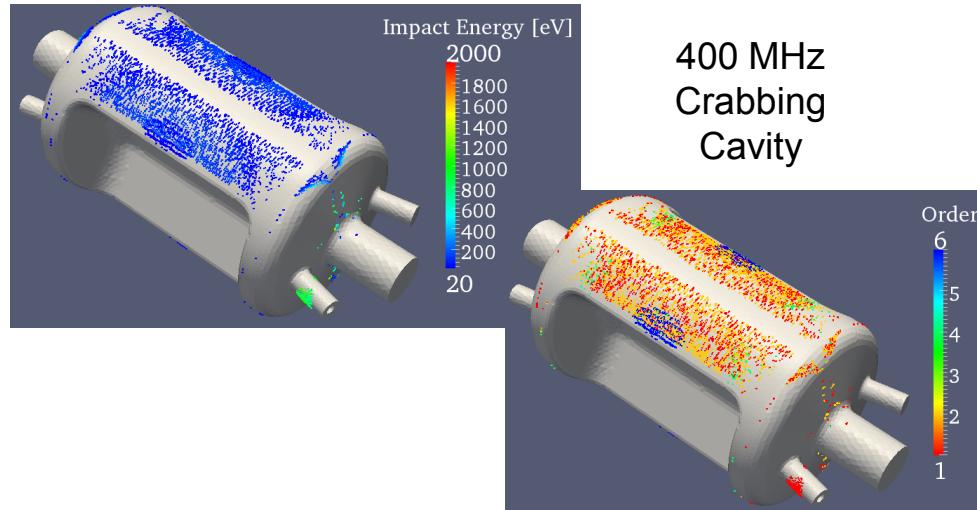
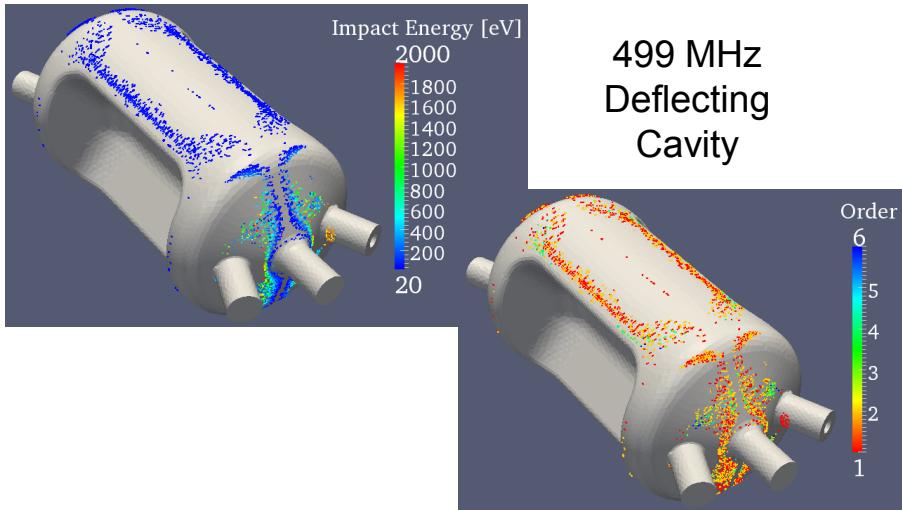
400 MHz  
Crabbing  
Cavity



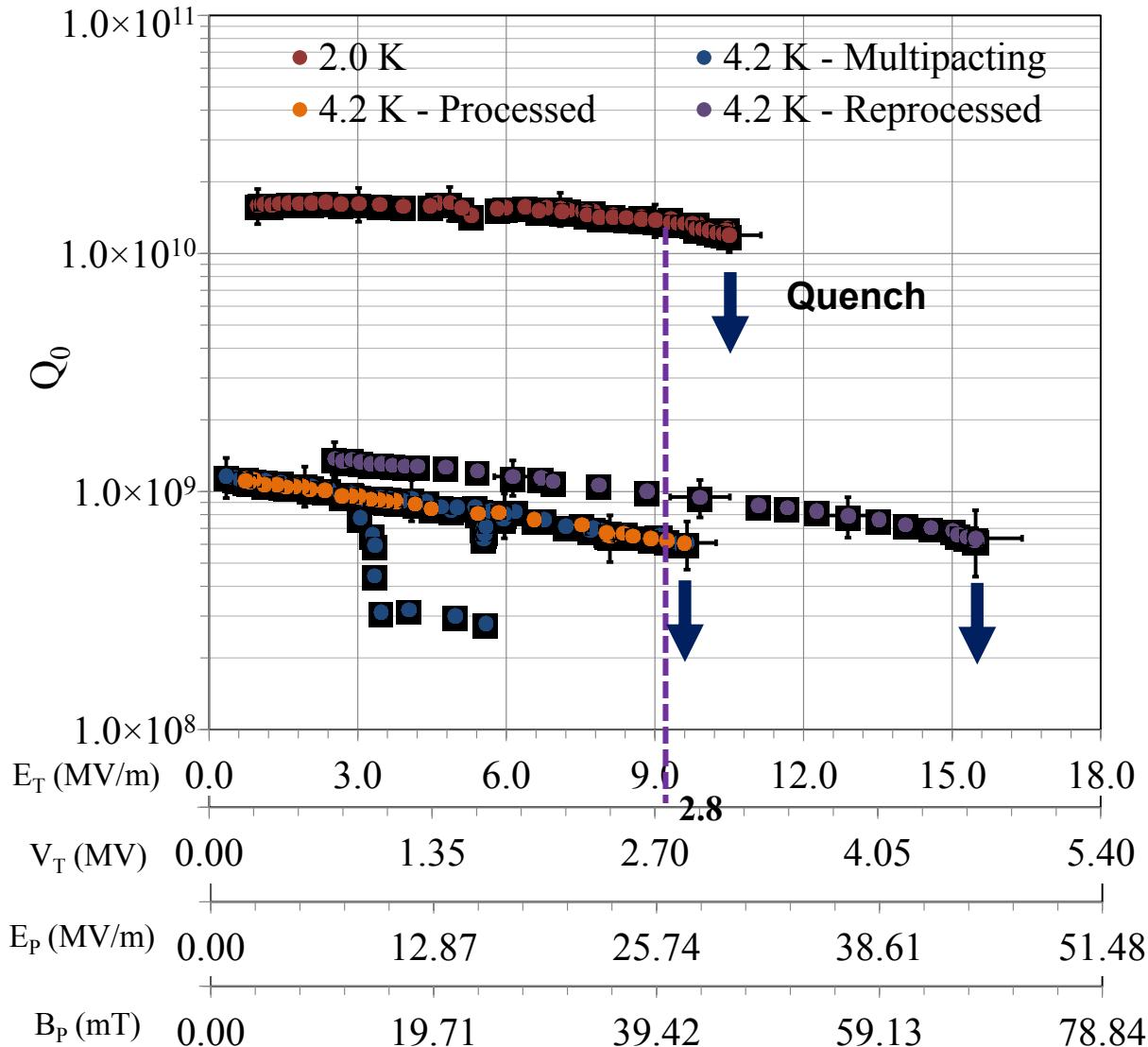
499 MHz  
Deflecting  
Cavity

# Multipacting Analysis

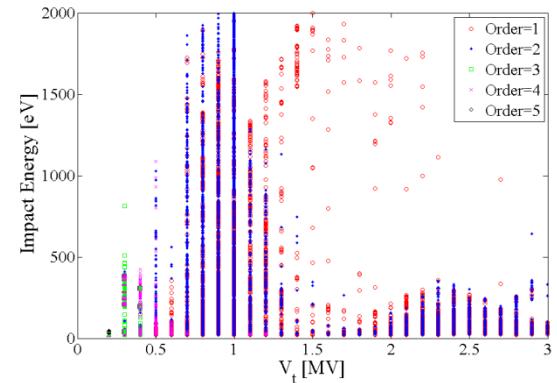
Track3P – Resonant particle tracking code in SLAC ACE3P suite



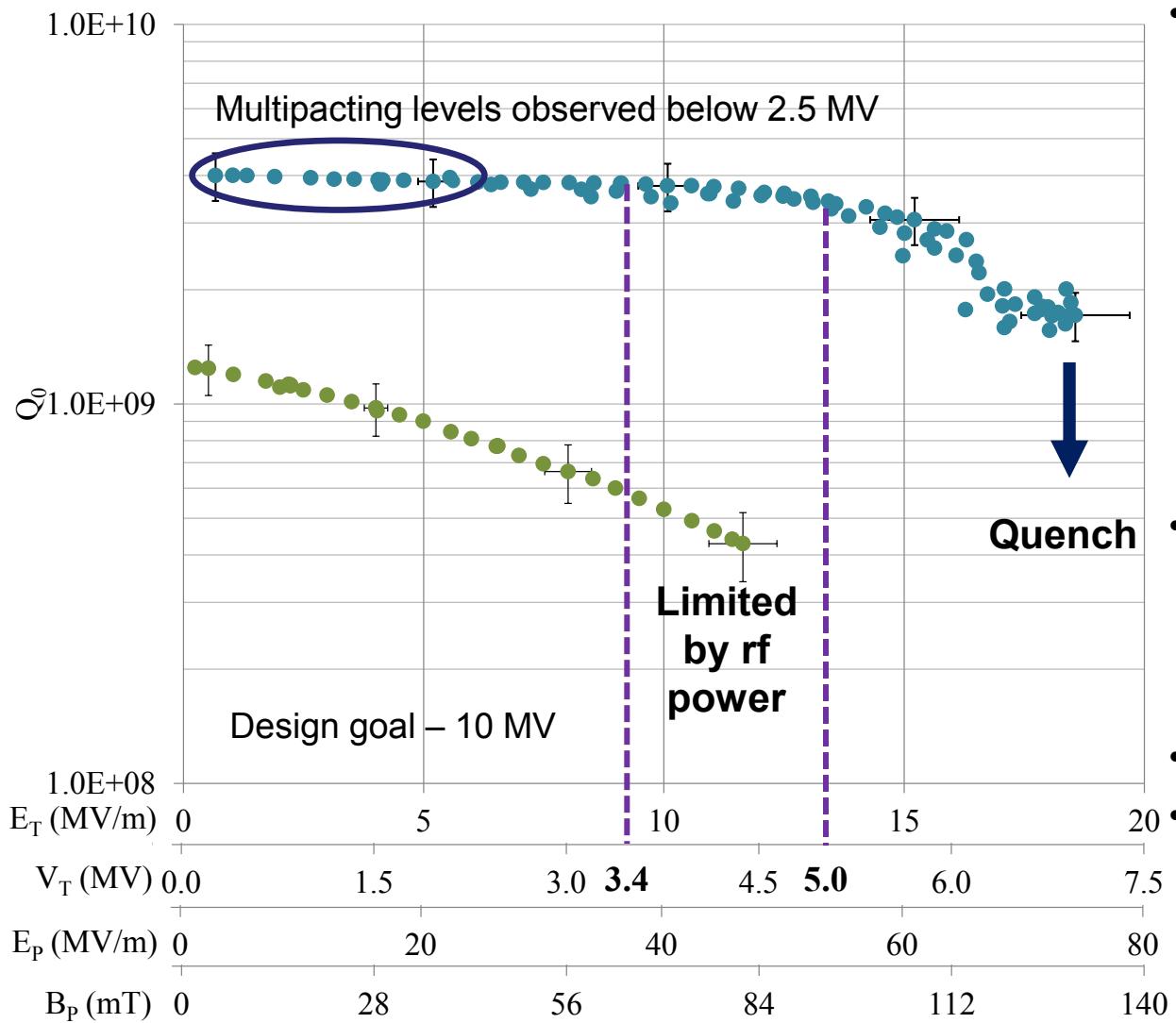
# 4.2 K and 2 K Test Results – 499 MHz



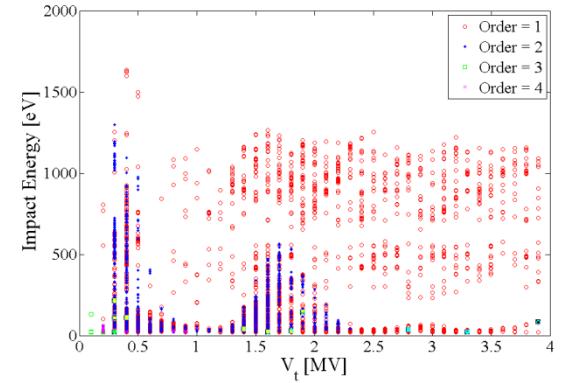
- Multipacting was easily processed during the 4.2 K rf test
- Design requirement of 5.6 MV can be achieved with 2 cavities
- Reprocessed cavity achieved fields at 4.2 K
  - $E_T = 15.5$  MV/m
  - $V_T = 4.65$  MV
  - $E_P = 44.3$  MV/m
  - $B_P = 67.9$  mT



# 4.2 K and 2 K Test Results – 400 MHz

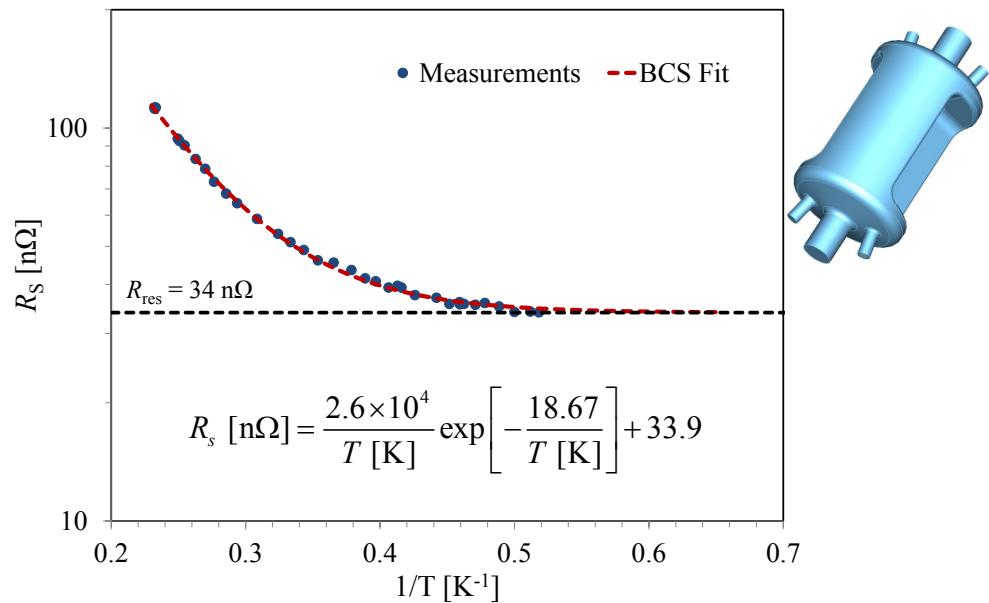
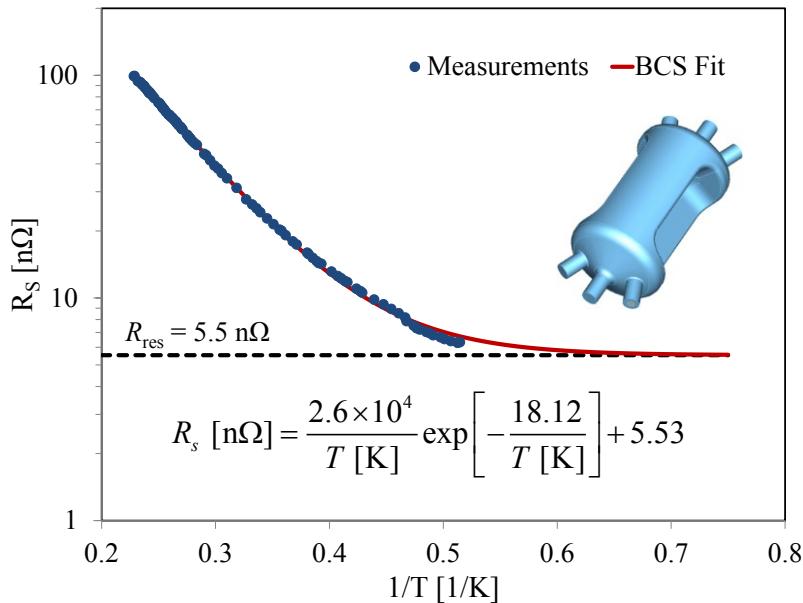


- Multipacting levels were easily processed



- 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

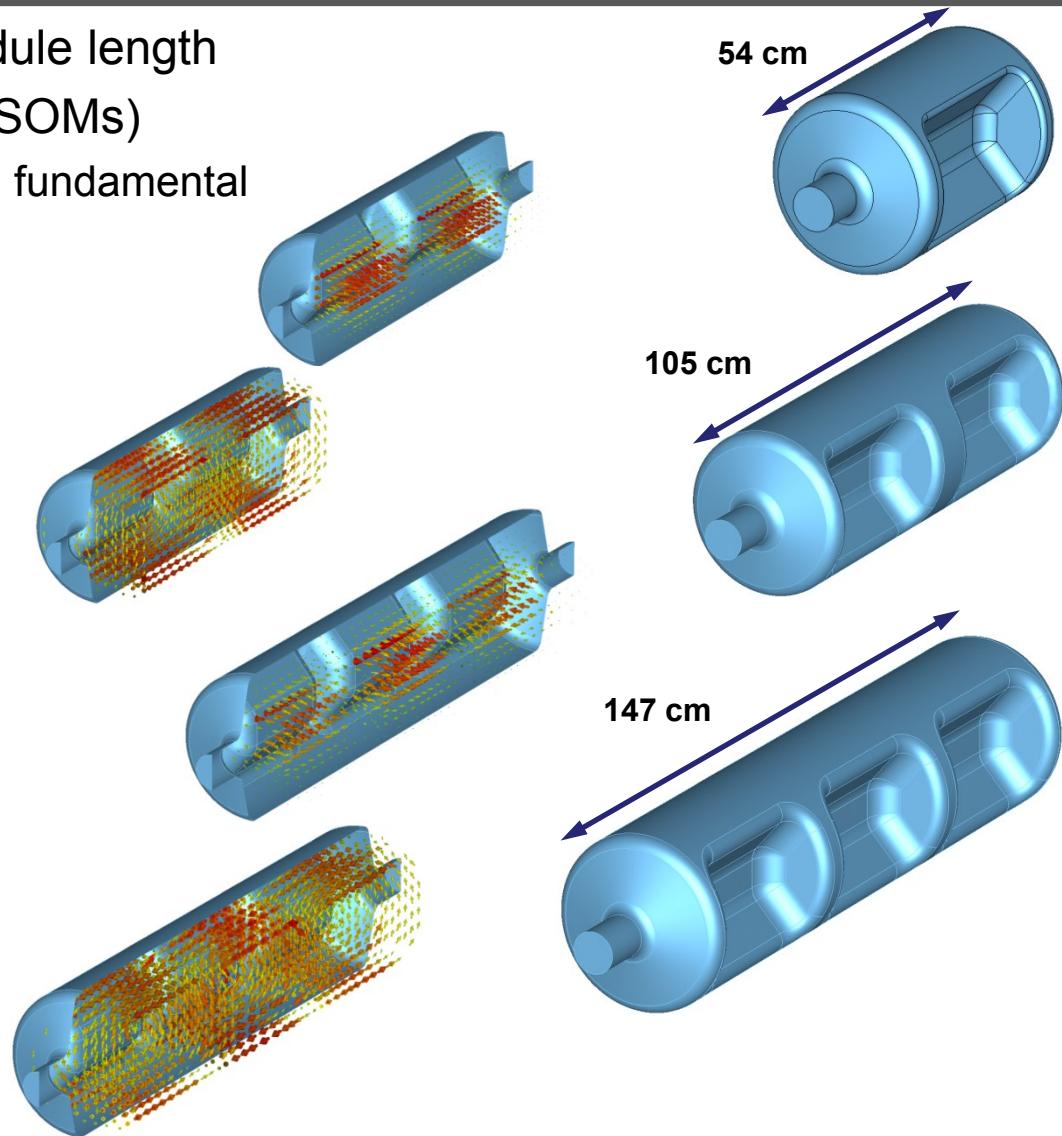


- 499 MHz Cavity
  - $R_{BCS} = 1.3 \text{ n}\Omega$  at 2.0 K
  - $R_{\text{res}} = 5.5 \text{ n}\Omega$
- 400 MHz Cavity
  - $R_{BCS} = 2.0 \text{ n}\Omega$  at 2.0 K
  - $R_{\text{res}} = 34 \text{ n}\Omega$
  - Measured  $Q_0$  at 2.0 K =  $4.0 \times 10^9$
  - $Q_0$  due to power loss at the beam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

# 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

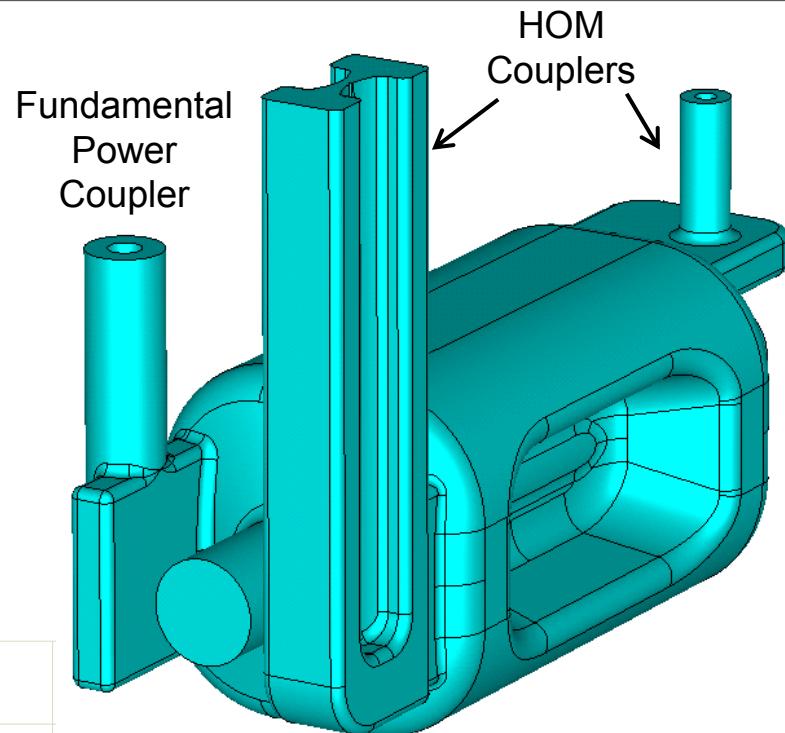
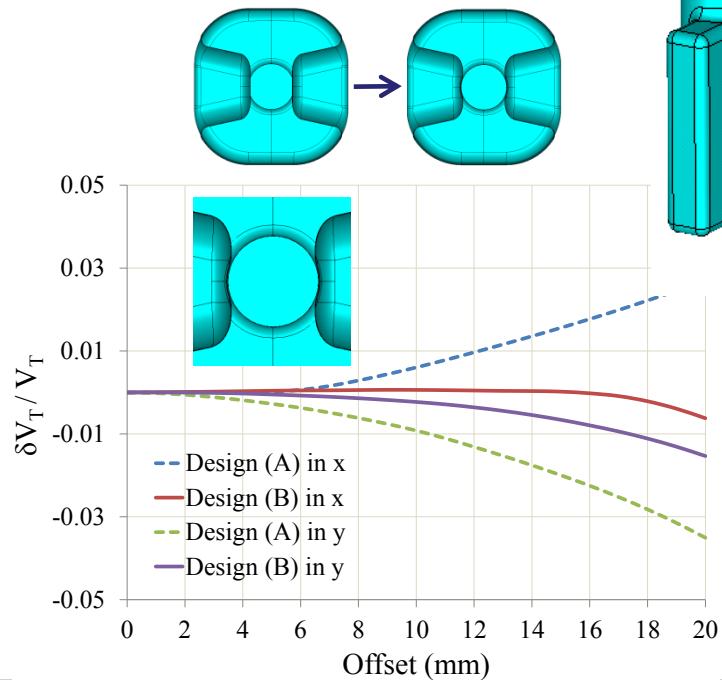
	2 cell	3 cell	
Frequency	400	400	MHz
SOMs	374.5	351.6 / 376.8	MHz
Aperture	84	84	mm
Cavity length	105	147	cm
Cavity diameter	34.5	35.4	cm
$V_T^*$	<b>0.375</b>	<b>0.375</b>	MV
$E_p^*$	<b>4.26</b>	<b>4.75</b>	MV/m
$B_p^*$	<b>7.4</b>	<b>7.77</b>	mT
$[R/Q]_T$	488.4	708.1	$\Omega$
Geometrical Factor ( $G$ )	127.8	131.8	$\Omega$
$R_T R_S$	$6.2 \times 10^4$	$9.3 \times 10^4$	$\Omega^2$
At $E_T^* = 1$ MV/m			



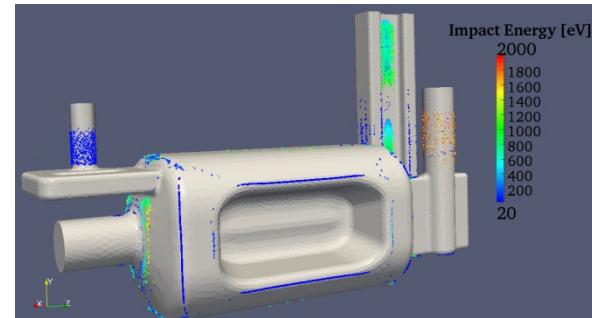
# 400 MHz Crabbing Cavity Prototype

- 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	$\Omega$
Geometric al Factor ( $G$ )	106.2	$\Omega$
$R_T R_S$	$4.6 \times 10^4$	$\Omega^2$

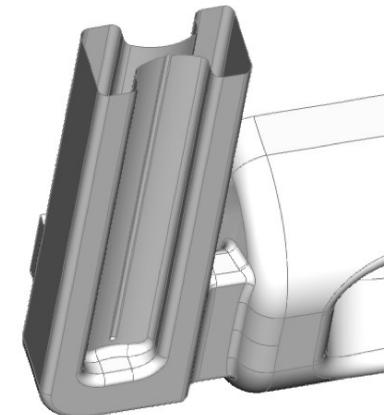


Improved multipacting levels

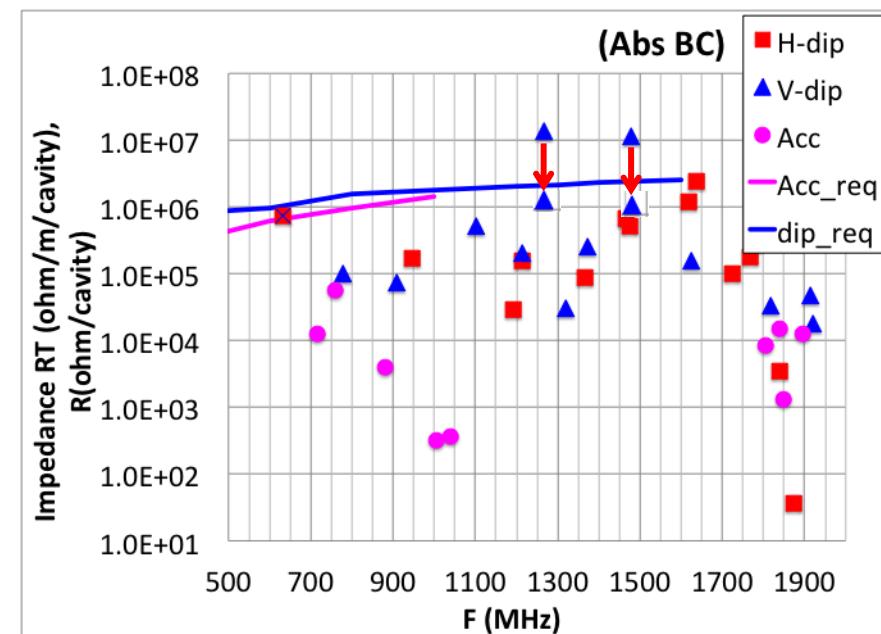
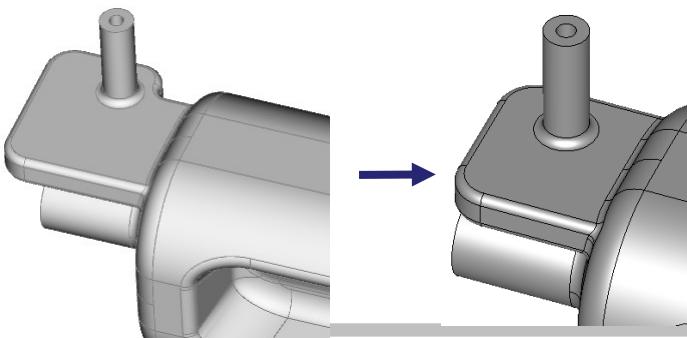


# Damping of Higher Order Modes

- 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.

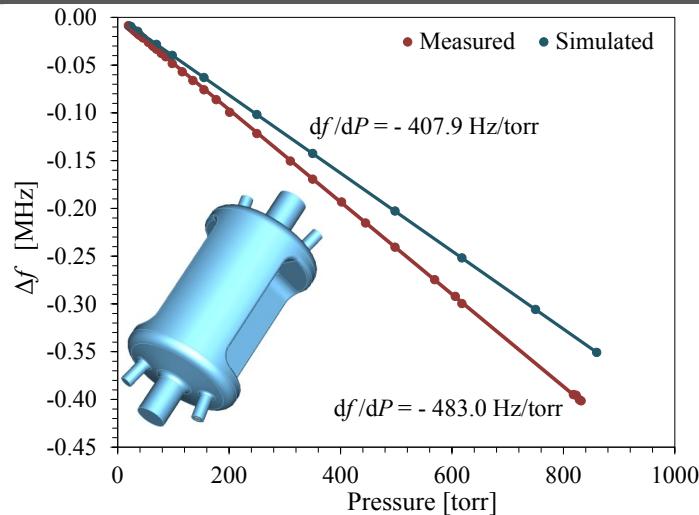
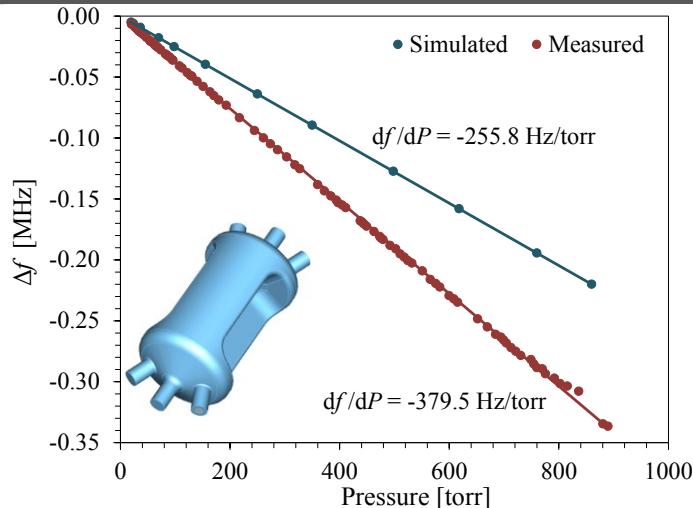
# Summary

- 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 to losses at the stainless steel flanges
- In both cavities multipacting quickly processed and did not reoccur
- RF Dipole cavity has attractive properties compared to  $\text{TM}_{110}$  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

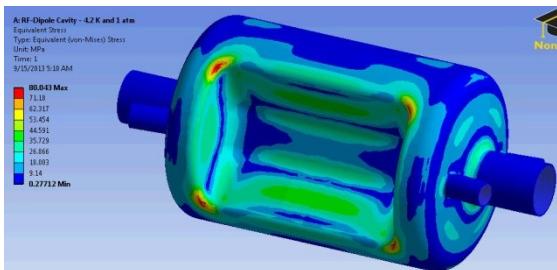
# Acknowledgements

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

# Pressure Sensitivity

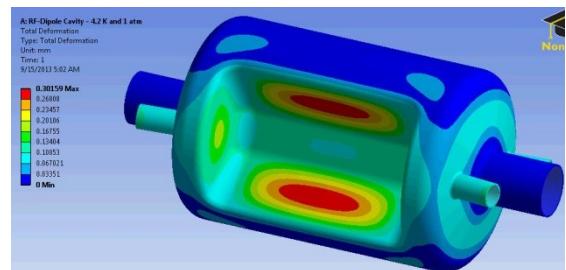


- Simulated in ANSYS with 3 mm uniform thickness
- Difference between simulation and measurements are possibly due to varying cavity thickness and material properties
- The edges of loading elements require reinforcement to reduces the stresses

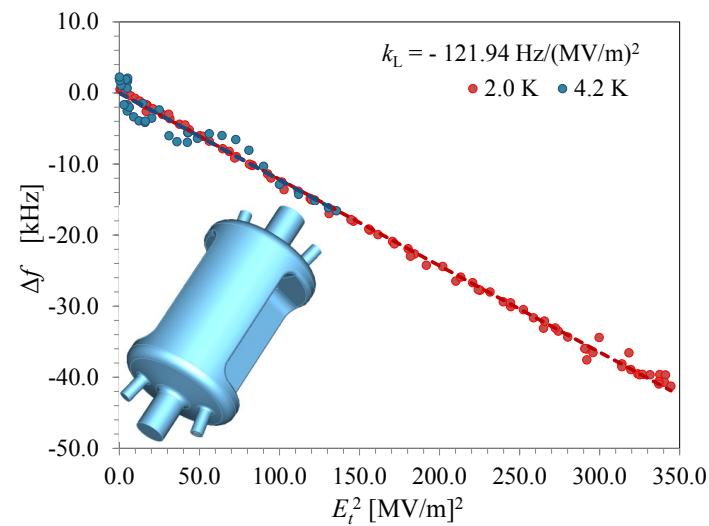
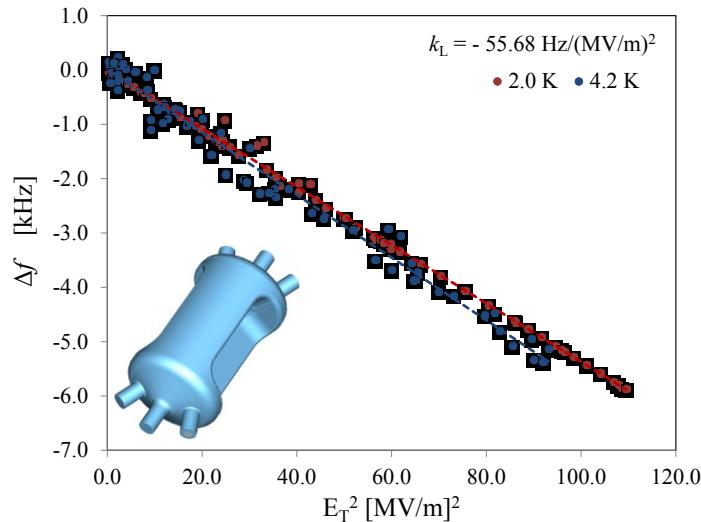


Stresses at 4 K

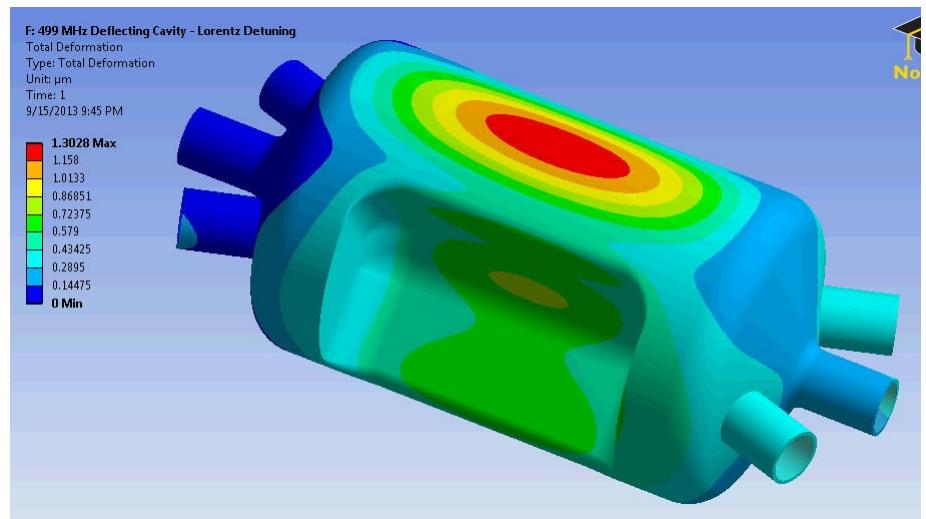
Deformation at  
4.0 K due to  
pressure of 1 atm



# Lorentz Detuning

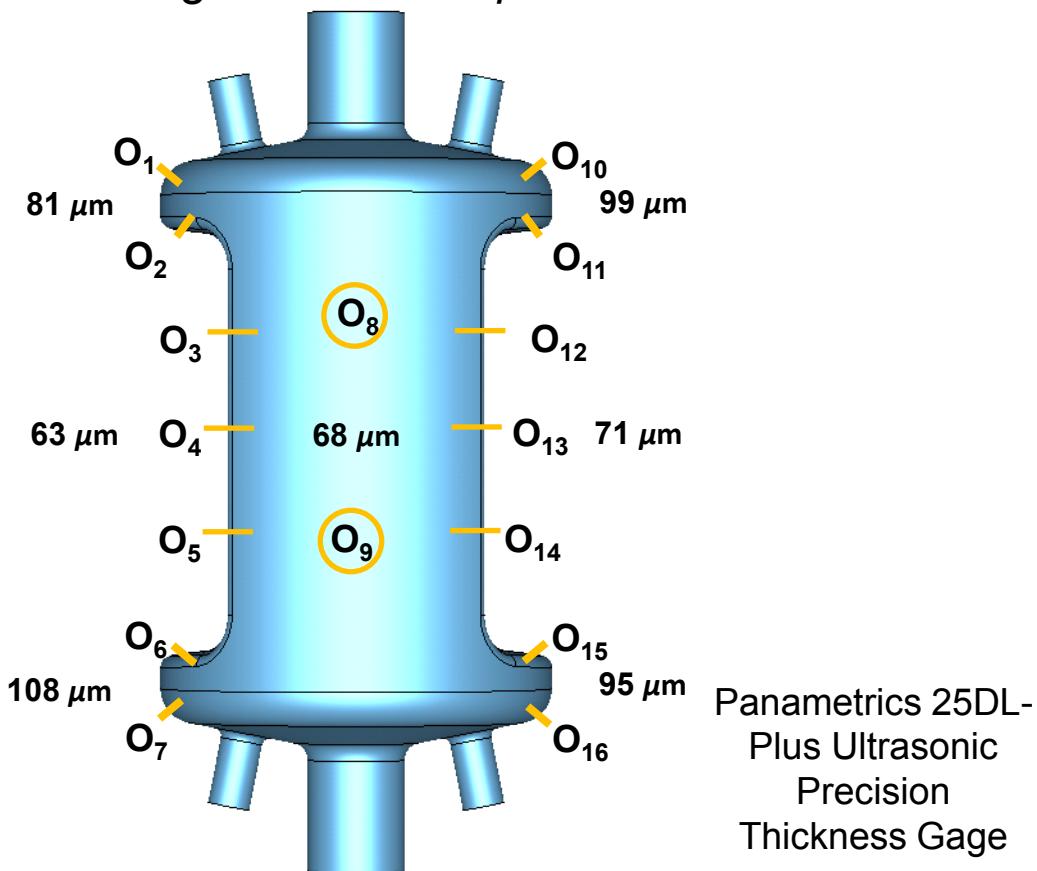


- Simulated Lorentz coefficient ( $k_L$ )
  - 499 MHz  $\rightarrow -52.4 \text{ Hz}/(\text{MV/m})^2$
  - 400 MHz  $\rightarrow -117.3 \text{ Hz}/(\text{MV/m})^2$



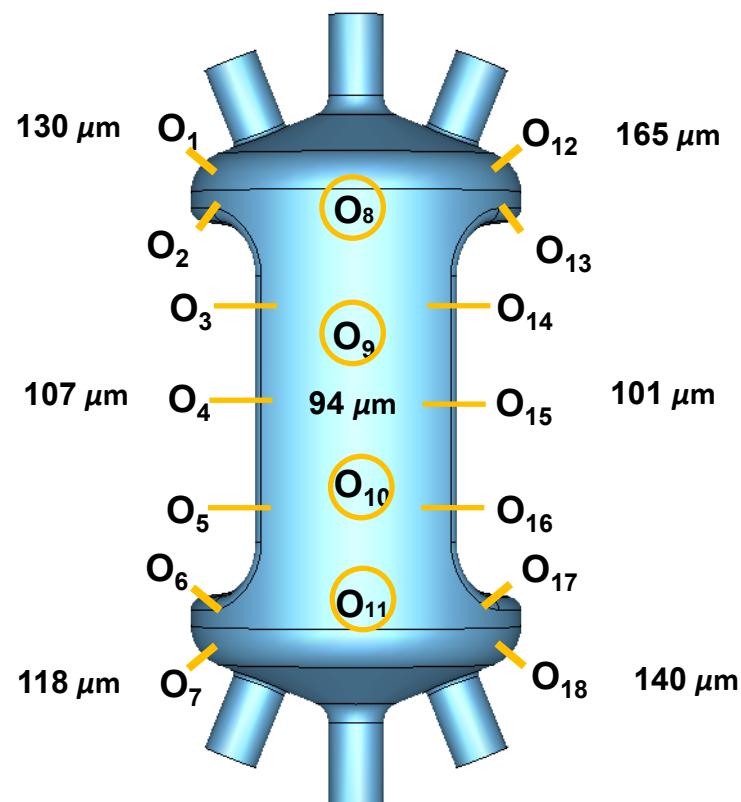
# Surface Treatment – Bulk BCP

- Reduced etch rate from 2.7-2.8  $\mu\text{m}/\text{min}$  to 1.8  $\mu\text{m}/\text{min}$  due to contaminated acid mixture (with glycol)
- Average removal 85  $\mu\text{m}$



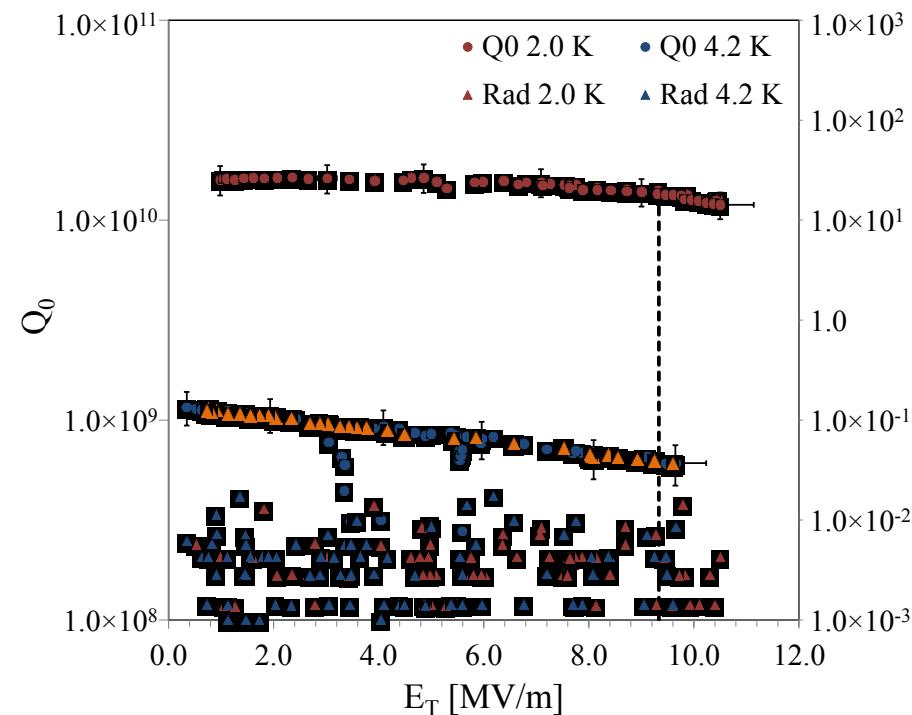
Panametrics 25DL-  
Plus Ultrasonic  
Precision  
Thickness Gage

- Etch rate: 1.78  $\mu\text{m}/\text{min}$
- Average removal 108  $\mu\text{m}$

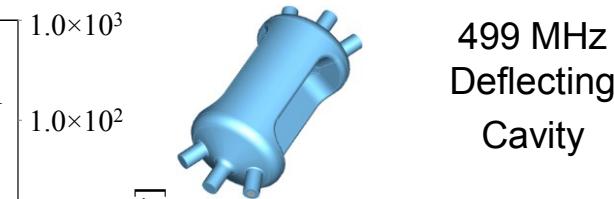


Average of O<sub>19</sub>, O<sub>20</sub>, O<sub>21</sub> and O<sub>22</sub> – 99  $\mu\text{m}$

# Field Emission



400 MHz  
Deflecting  
Cavity



499 MHz  
Deflecting  
Cavity

