COMPACT SUPERCONDUCTING CRABBING AND DEFLECTING CAVITIES

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Introduction

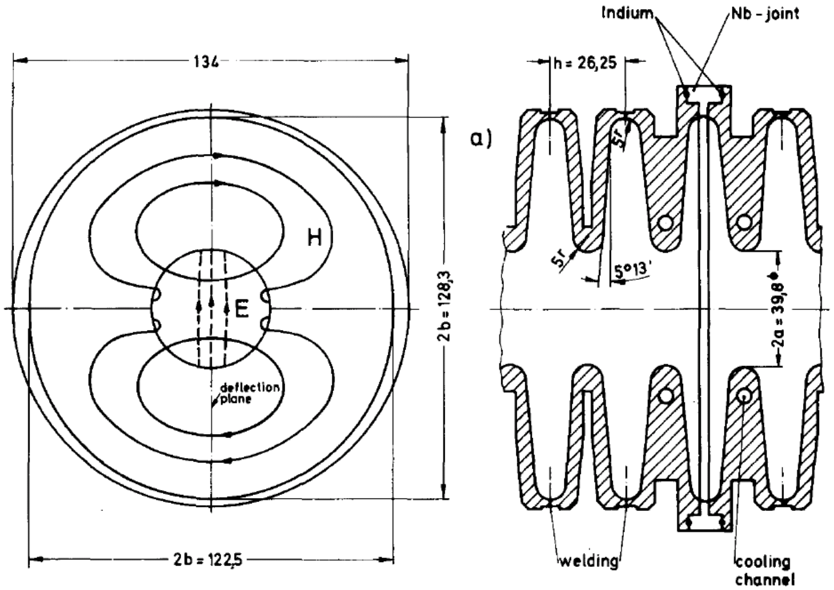
- New geometries for compact superconducting crabbing and deflecting cavities have been developed

- They have significantly improved properties over those of the standard TM_{110}–type cavities
  - They are smaller
  - Have low surface fields
  - High shunt impedance
  - Some of the designs have no lower-order-mode with a well-separated fundamental mode

Crabbing/Deflecting Cavity Applications

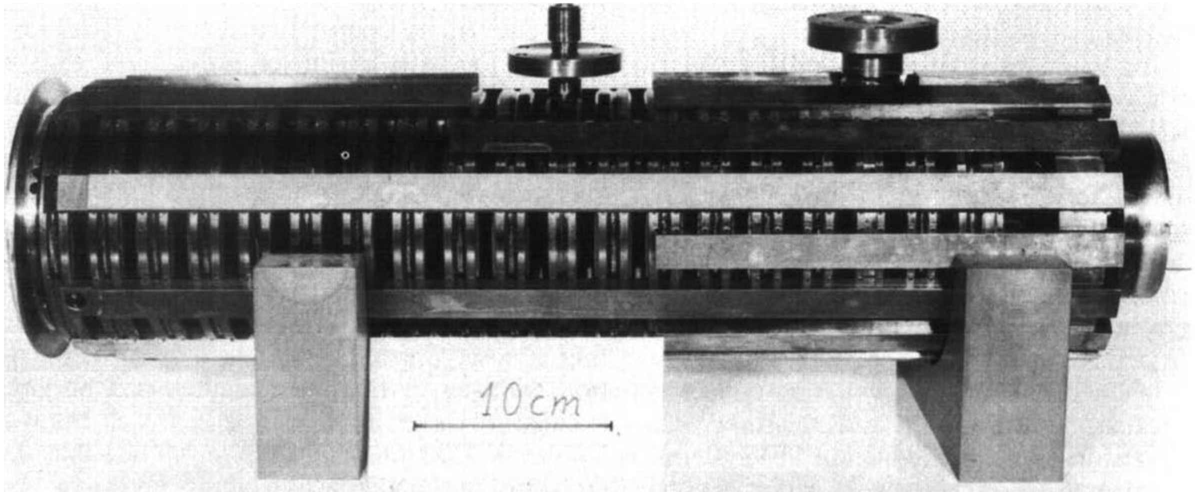
- Luminosity management in linear or circular colliders
- Separation or merge of multiple beams
- Emittance exchange in beams
- X-ray pulse compression
- Beam diagnostics

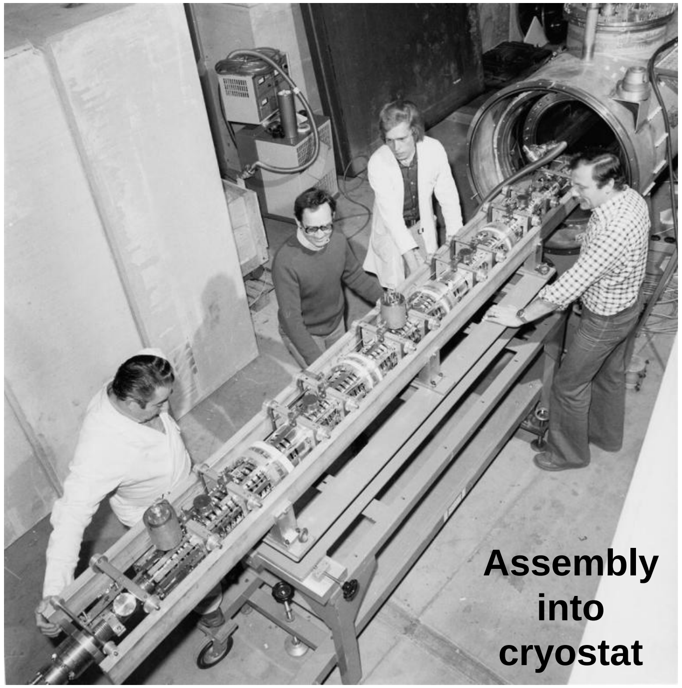
The 1st Superconducting RF Deflecting Cavity



2.865 GHz Karlsruhe/CERN RF Separator*

- Designed 1970, operated 1977-1981
- 104 cells
- At IHEP since 1998
- Operating mode: bi-periodic TM_{110} mode





Assembly into cryostat

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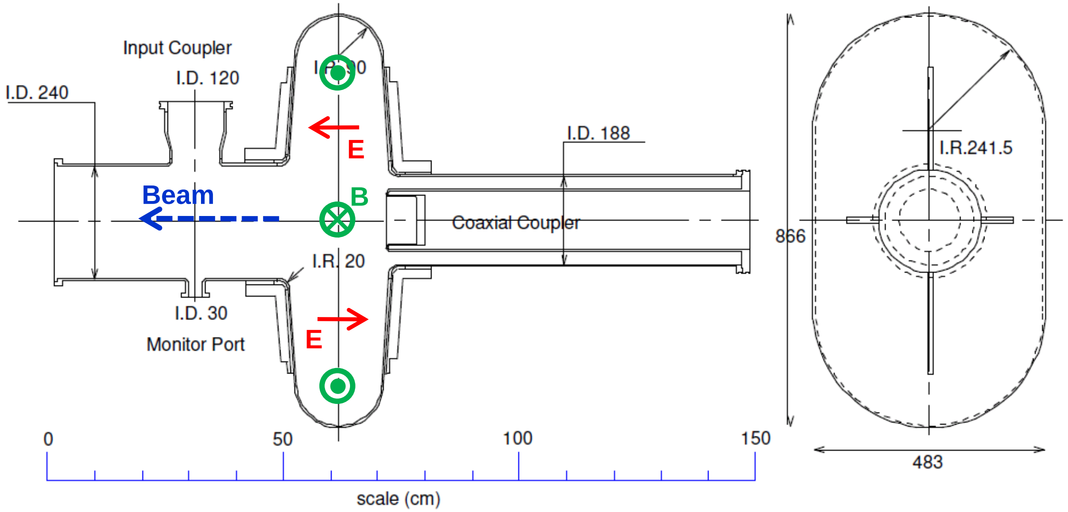
* A. Citron et al., NIM 164, 31-55, (1979)

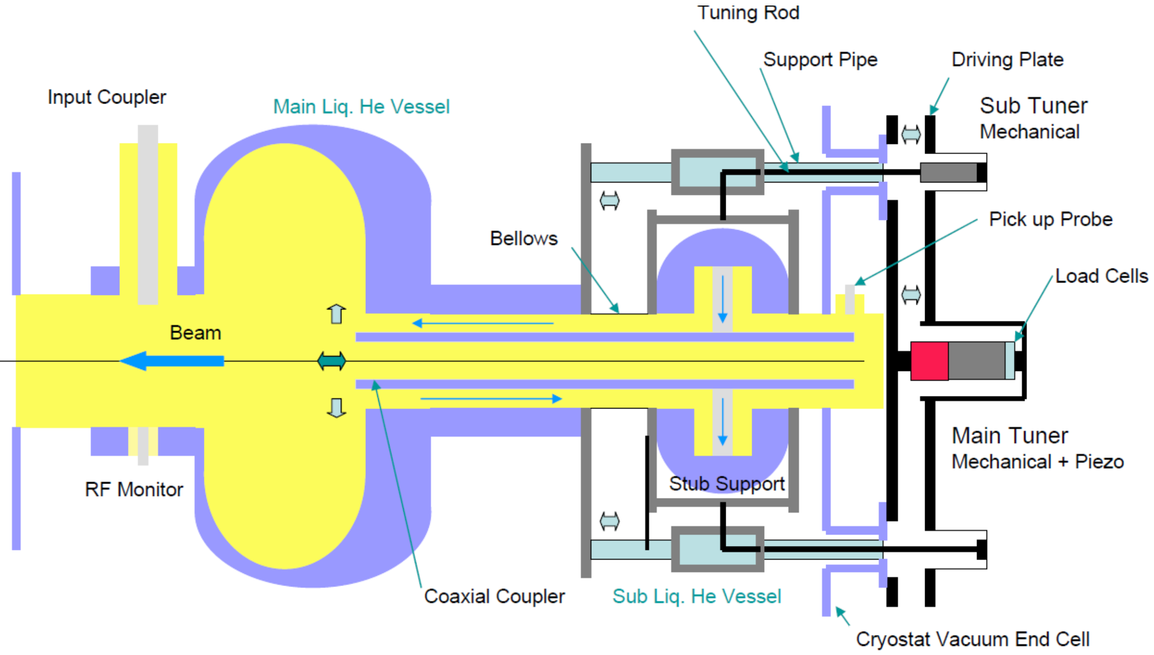
The 1st Superconducting Crabbing Cavity



KEK Crabbing Cavity*

Frequency	**508.9**	**MHz**
LOM	410.0	MHz
Nearest HOMs	630.0, 650.0, 680.0	MHz
E_p^*	4.24	MV/m
B_p^*	12.23	mT
B_p^*/E_p^*	2.88	mT/(MV/m)
$[R/Q]_T$	48.9	Ω
Geometrical Factor (G)	227.0	Ω
$R_T R_S$	1.11×10^4	Ω^2
At E_T^* = 1 MV/m		

- Operating mode: TM$_{110}$ mode
- Required transverse deflection: 1.44 MV
- Operation: 2007-2010



Complex HOM Damping Scheme

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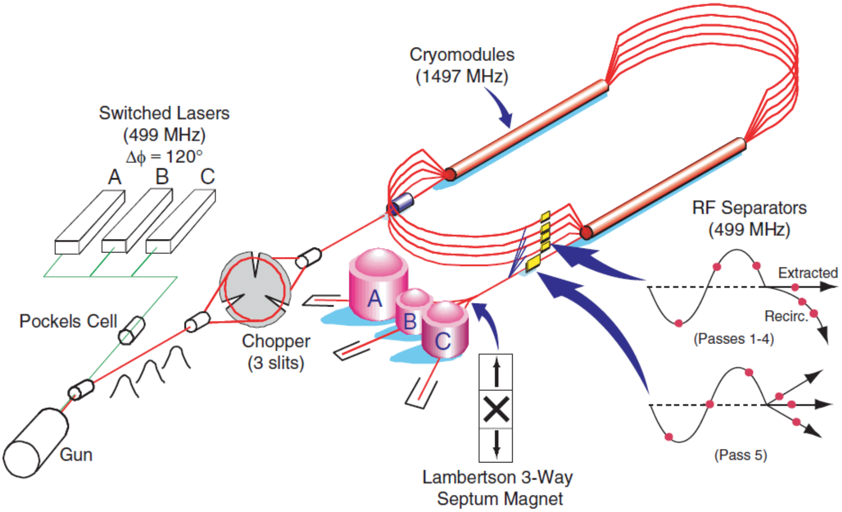
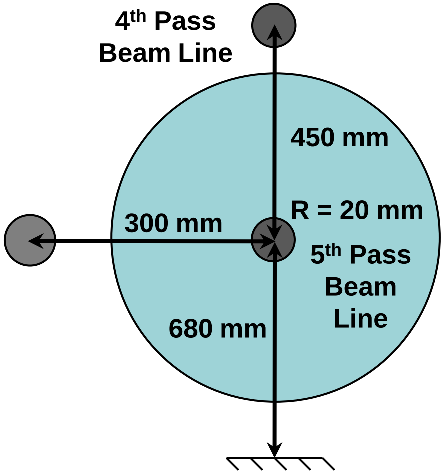
*K. Hosoyama et al, "Crab Cavity for KEKB", Proc. of the 7th Workshop on RF Superconductivity, p.547 (1998)

Potential Applications of Compact Superconducting Deflecting/Crabbing Cavities

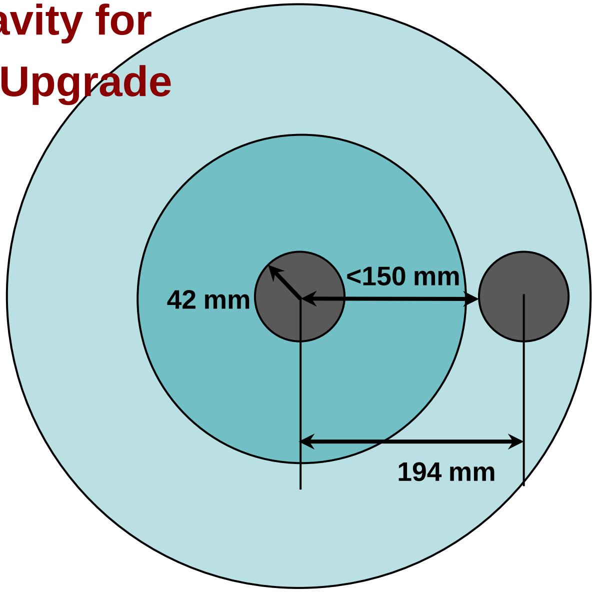
499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade



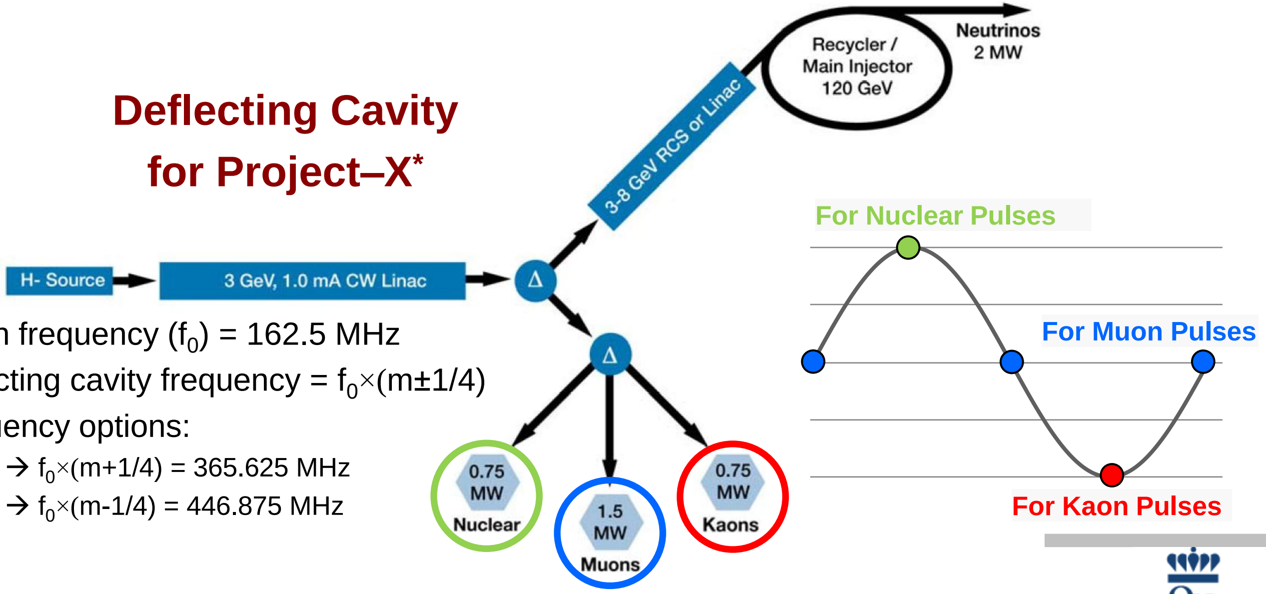


400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

- Requires a crabbing system at two interaction points (IP1 and IP5)
  - Vertical crossing at IP1
  - Horizontal crossing at IP5



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

*V. Yakovlev and M. Champion, "A Beam Splitter for the Project-X", LHC-CC11, (2011)

How To Achieve Compact Designs

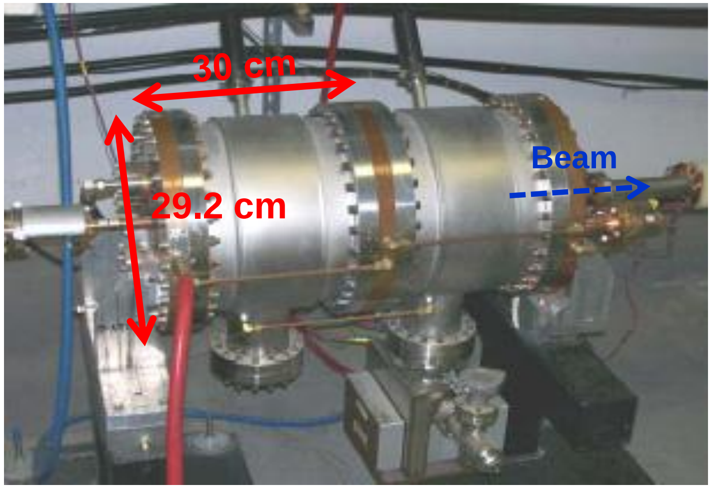
- Karlsruhe/CERN deflector and KEK crabbing cavity used magnetic field
  - Operating in TM_{110} mode which is not the lowest mode
- Current compact designs use electric field or both electric and magnetic fields
  - TEM-like designs
  - TE-like designs

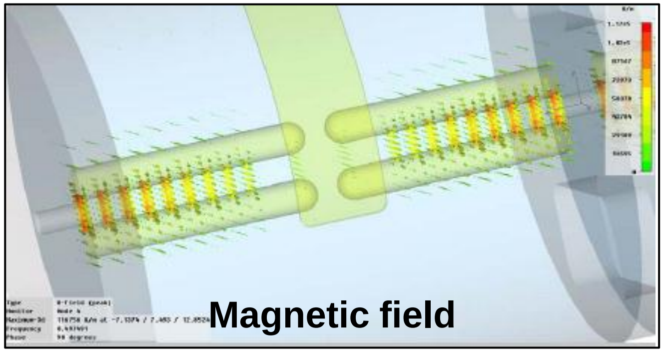
- Compact superconducting crabbing/deflecting cavity designs
  - University of Lancaster / Jefferson Lab – 4-Rod Cavity
  - BNL – Quarter Wave Cavity
  - ODU/SLAC – Parallel-Bar Cavity and RF-Dipole Cavity

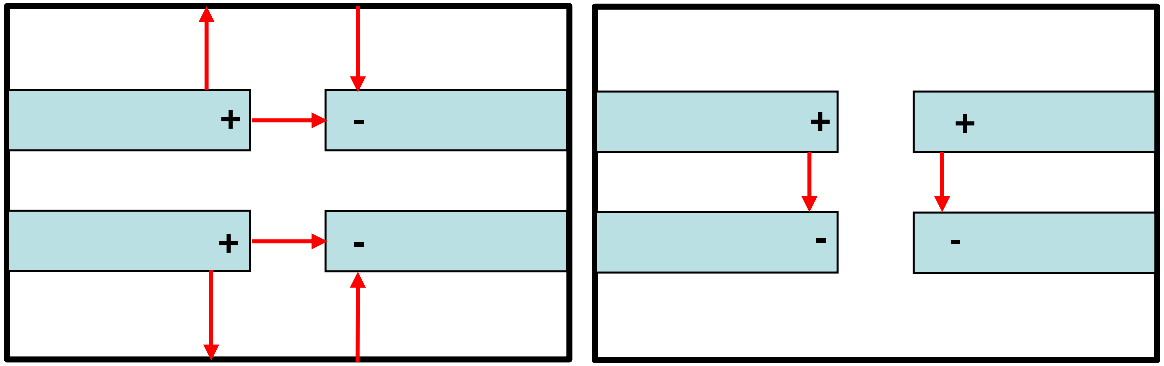
4-Rod Cavity

- 499 MHz normal conducting rf separator* at Jefferson Lab
- High shunt impedance

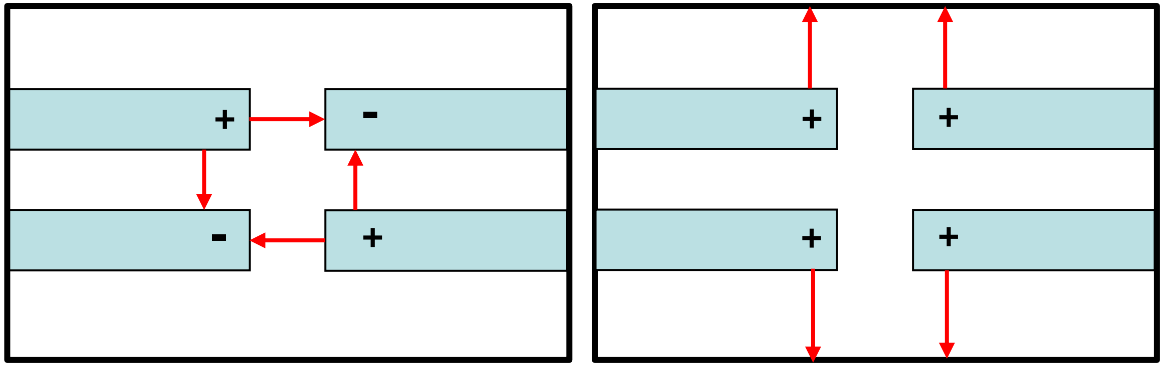
- Operates in a TEM-like mode
  - Uses both electric field and magnetic field
  - Deflecting mode is not the lowest mode




Magnetic field



Accelerating lower order mode

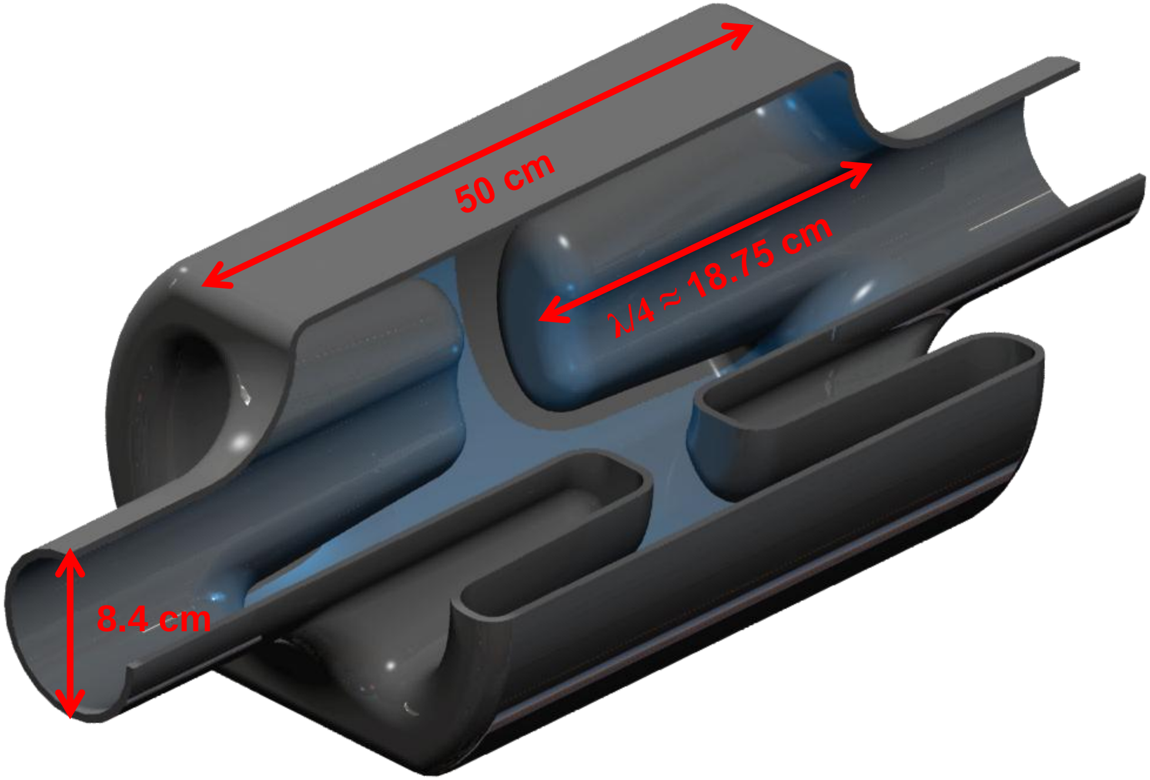


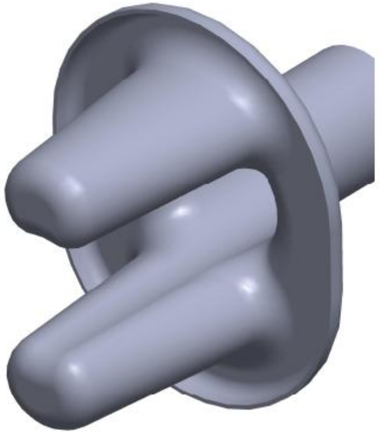
Fundamental deflecting mode

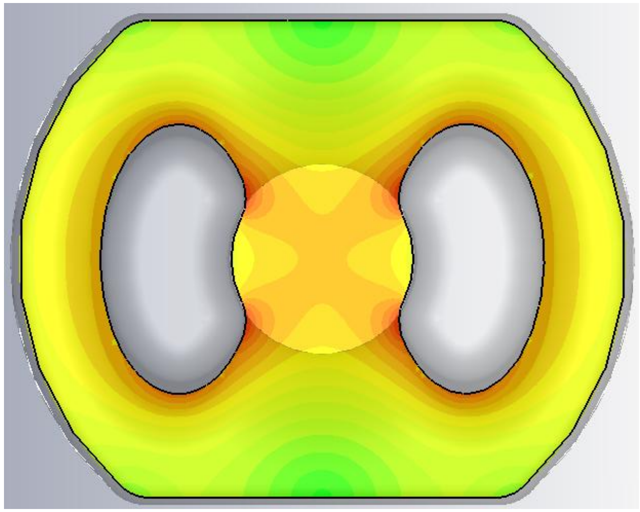
*C. Leemann and C.G. Yao,
“A Highly Effective Deflecting Structure”,
Proc. of the 1990 LINAC, p.232-234, (1991)

4-Rod Cavity (U. Lancaster/Jefferson Lab)

- 400 MHz superconducting 4-rod cavity*
- Rod shaping
  - To reduce surface electric and magnetic fields
  - To reduce offset field non-uniformities

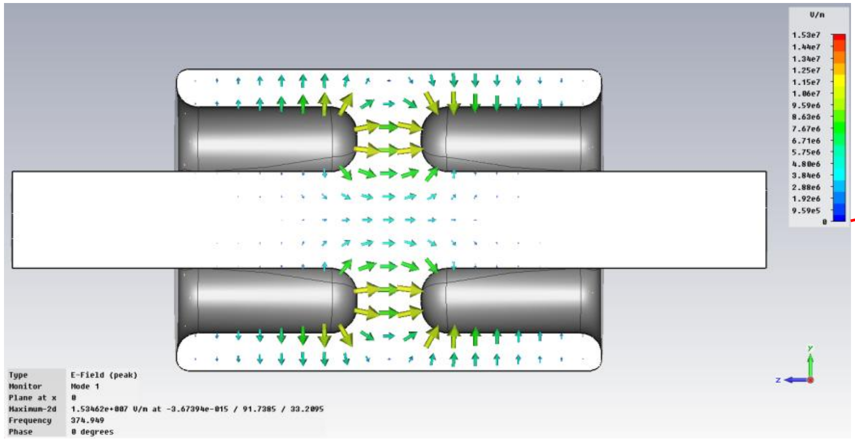






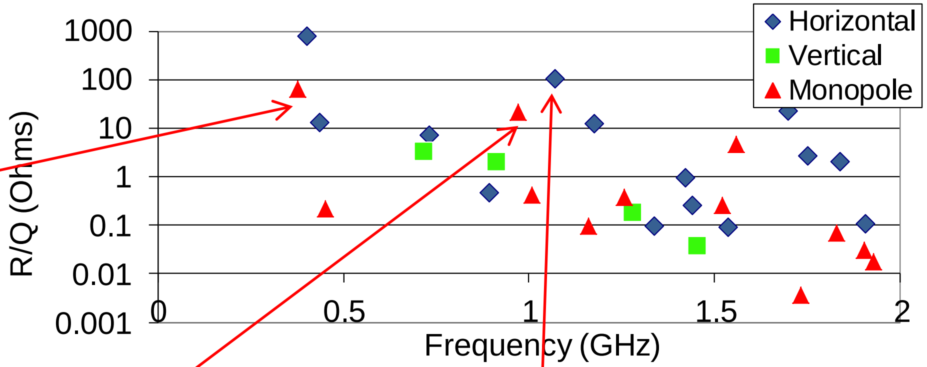
*B. Hall, “LHC-4R Crab Cavity”, EUCARD SRF Annual Review, March 2012

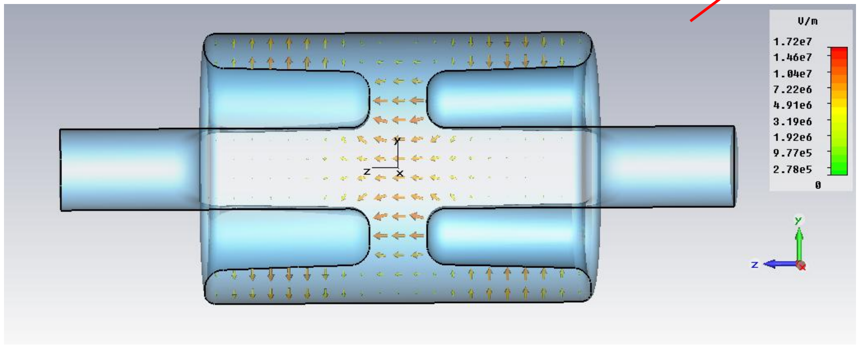
Lower and Higher Order Modes of the 4-Rod Cavity



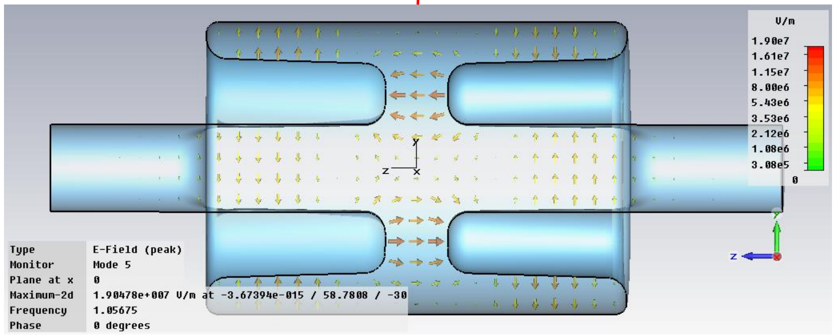
Type E-Field (peak)
Monitor Mode 1
Plane at x 0
Maximum-2d 1.53462e+007 V/m at -3.67394e-015 / 91.7385 / 33.2095
Frequency 374.949
Phase 0 degrees

Lower Order Monopole Mode – 374.9 MHz





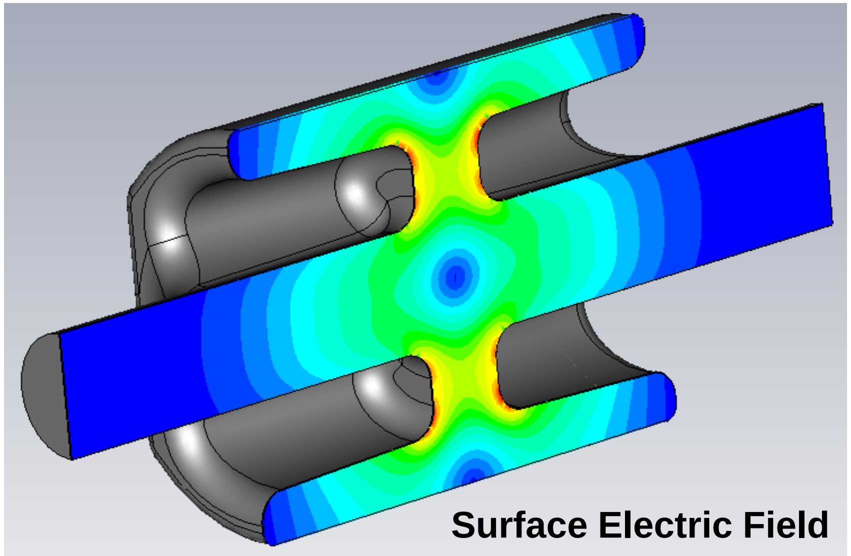
3π/4 Higher Order Monopole Mode



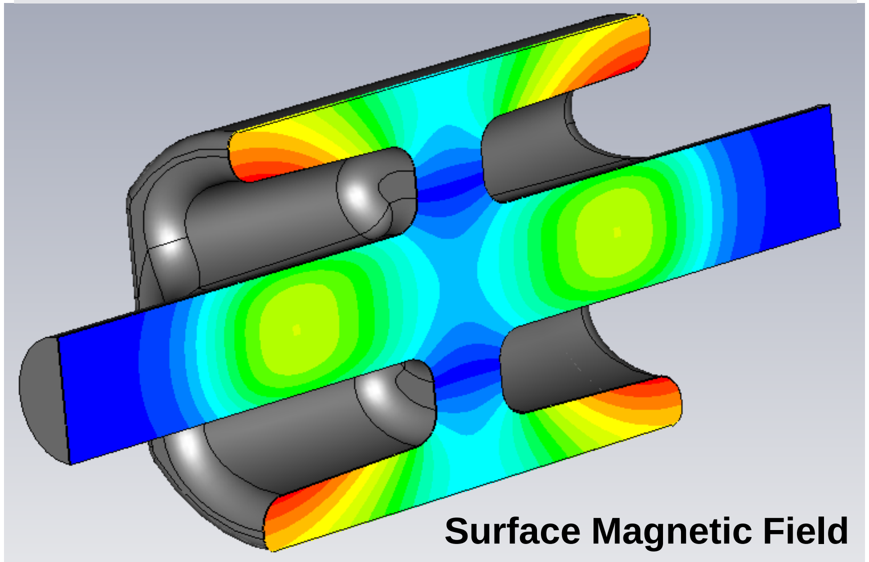
Type E-Field (peak)
Monitor Mode 5
Plane at x 0
Maximum-2d 1.90478e+007 V/m at -3.67394e-015 / 58.7808 / -30
Frequency 1.05675
Phase 0 degrees

3π/4 Higher Order Dipole Mode

4-Rod Cavity Properties



Surface Electric Field



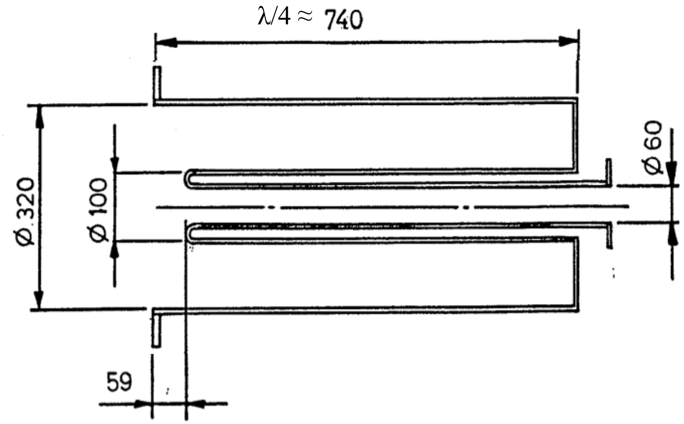
Surface Magnetic Field

Frequency	**400.0**	**MHz**
LOM	375.2	MHz
Nearest HOMs	436.6, 452.1	MHz
E_p^*	4.0	MV/m
B_p^*	7.56	mT
B_p^*/E_p^*	1.89	mT/(MV/m)
$[R/Q]_T$	915.0	Ω
Geometrical Factor (G)	70.35	Ω
$R_T R_S$	6.4×10^4	Ω^2
At $E_T^* = 1$ MV/m		

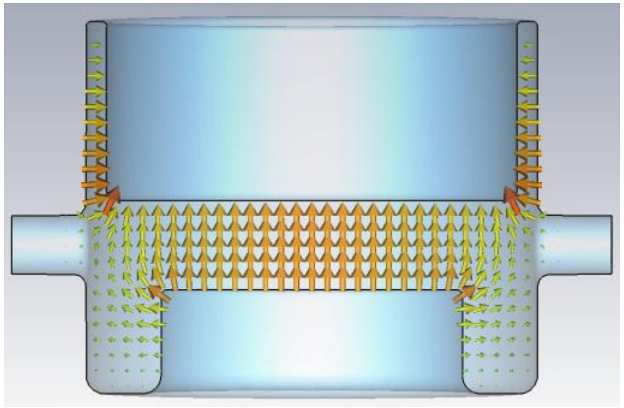
Quarter-Wave Cavity (BNL)

100 MHz
¼-Wave Cavity*

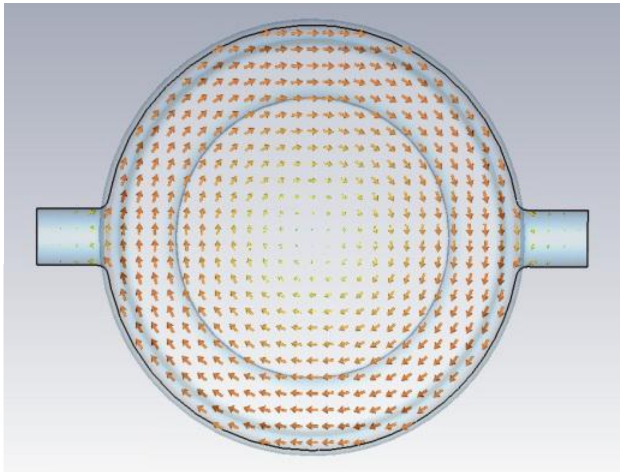
- Attractive at low frequencies
- Strong reentrant form makes the field pattern at the outer radius predominately TEM



181 MHz ¼-wave cavity for eRHIC#

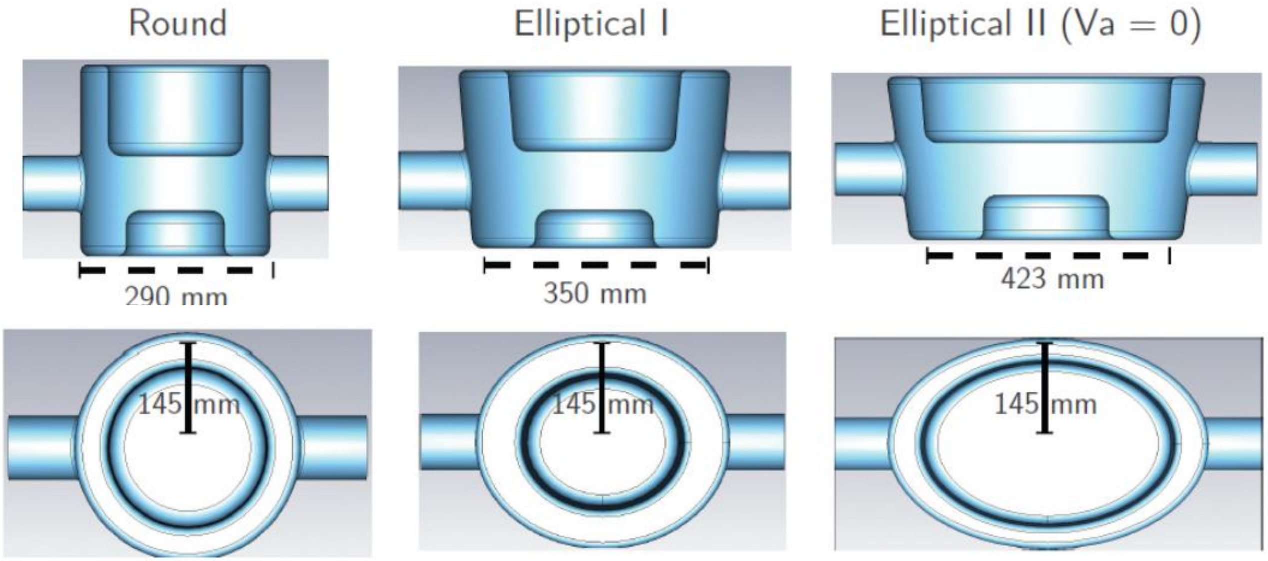


Electric Field



Magnetic Field

400 MHz superconducting asymmetric ¼-wave cavity



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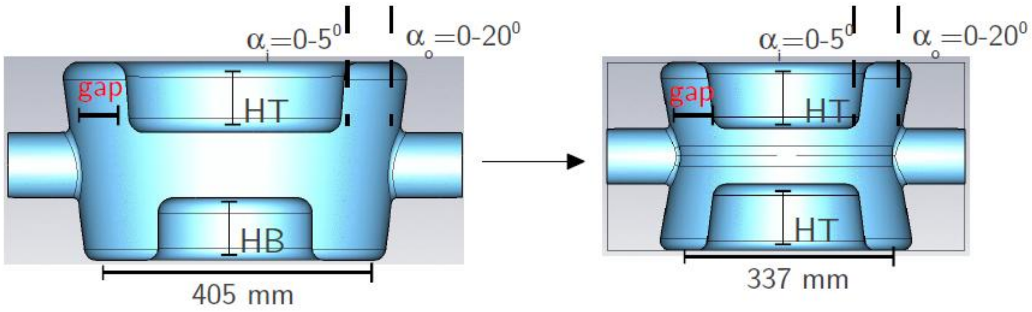
*E. Haebel, "Superconducting Cavities and Minimum RF Power Schemes for LHC", CERN/EF/RF 84-4

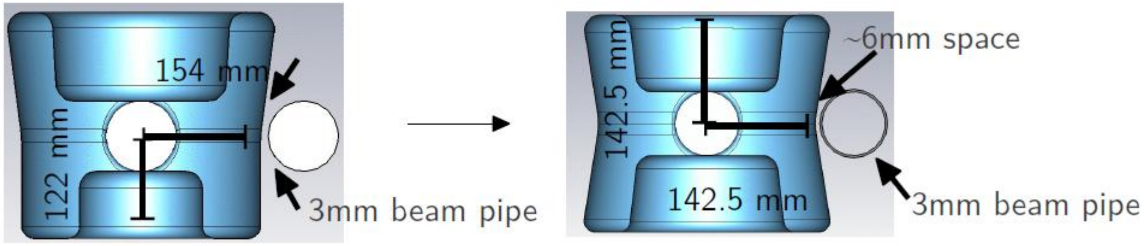
#Q. Wu et al., "Novel Deflecting Cavity Design for eRHIC", Proc. of the15th International Conference on RF Superconductivity, p.707, (2011)

Quarter-Wave Cavity

- Two design options at 400 MHz
- Asymmetric cavity*
  - V_{acc} = 0.12 MV at V_t = 3.0 MV
  - Higher mode separation between fundamental mode and nearest HOM
- Symmetric cavity (similar to rf-dipole cavity)
  - V_{acc} = 0 V
  - Better field non-uniformity

	Asymmetric Cavity	**Symmetric Cavity**	
LOM	None	None	MHz
Nearest HOM	657	582	MHz
E_p^*	5.38	4.04	MV/m
B_p^*	7.6	7.2	mT
B_p^*/E_p^*	1.42	1.77	mT/(MV/m)
$[R/Q]_T$	344.0	401.1	Ω
Geometrical Factor (G)	131.0	82.4	Ω
$R_T R_S$	4.5×10^4	3.3×10^4	Ω^2
At E_T^* = 1 MV/m			





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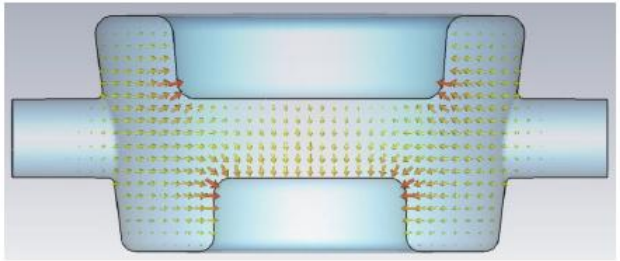
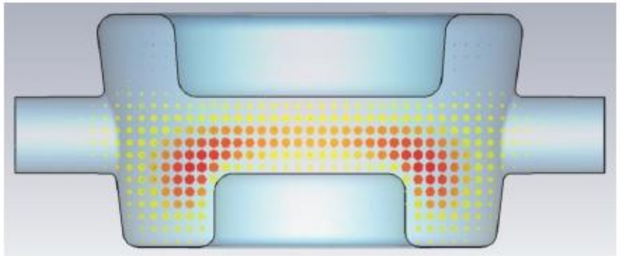
*R. Calaga et.al., in Proceedings of the 3rd IPAC, New Orleans, Louisiana (2012), p. 2260.

Higher Order Modes of the ¼-Wave Cavity

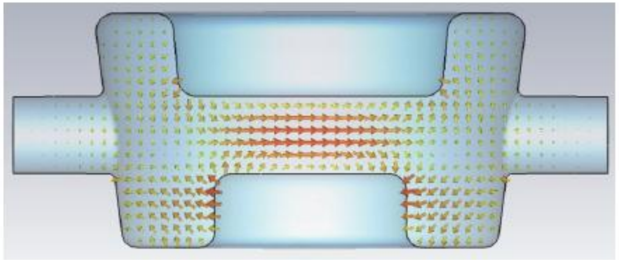
Electric field



deflection mode

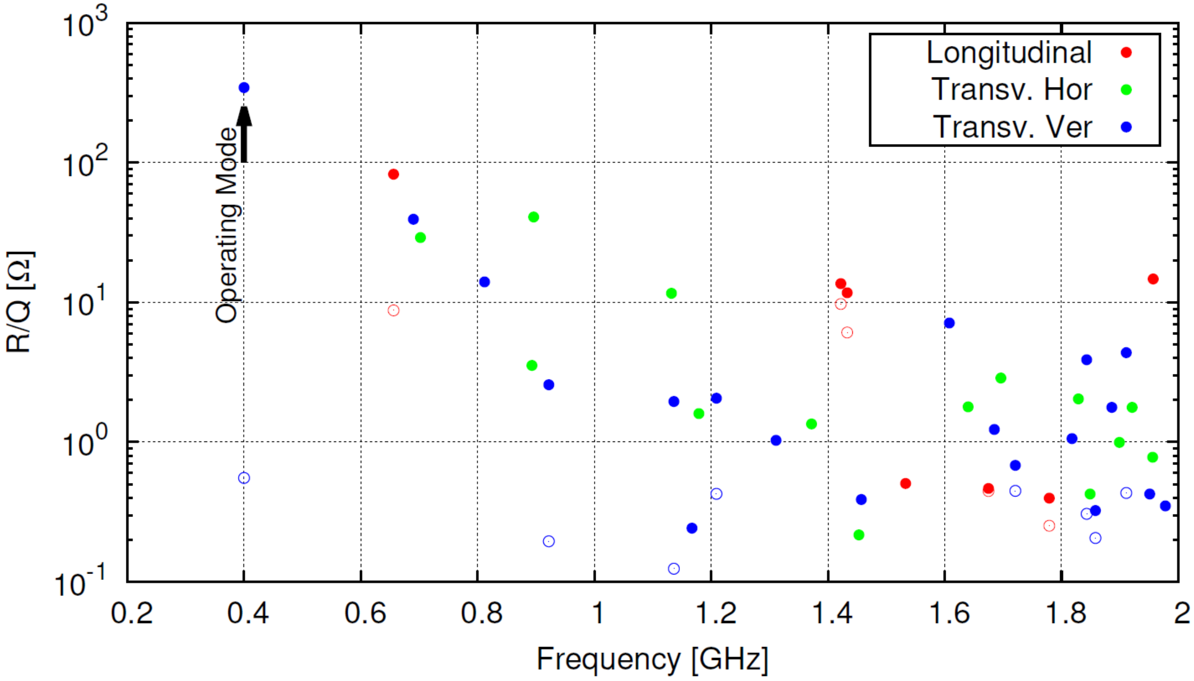


horizontal mode



longitudinal mode

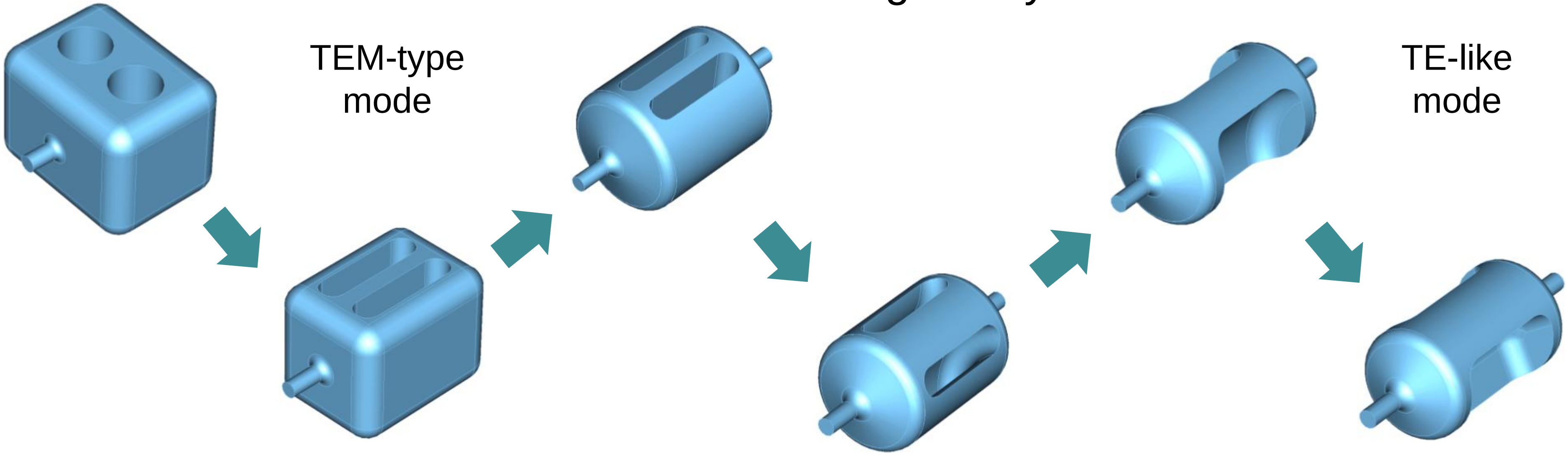
- No Lower Order Modes
- Hybrid modes with both deflection and acceleration

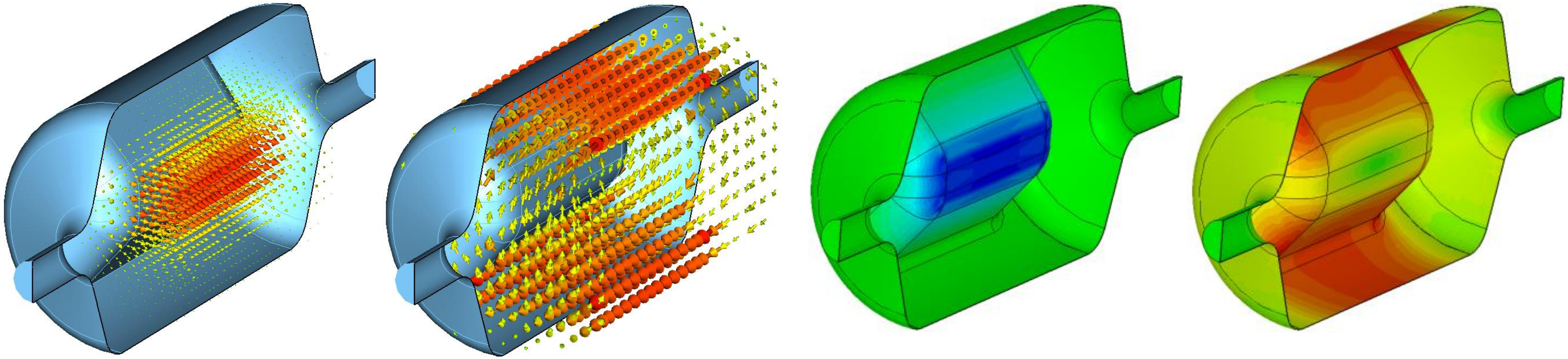


*R. Calaga et.al., in Proceedings of the 3rd IPAC, New Orleans, Louisiana (2012), p. 2260.

Parallel-Bar Cavity to RF-Dipole Cavity (ODU)

499 MHz Deflecting Cavity*





E Field H Field Surface E Field Surface H Field

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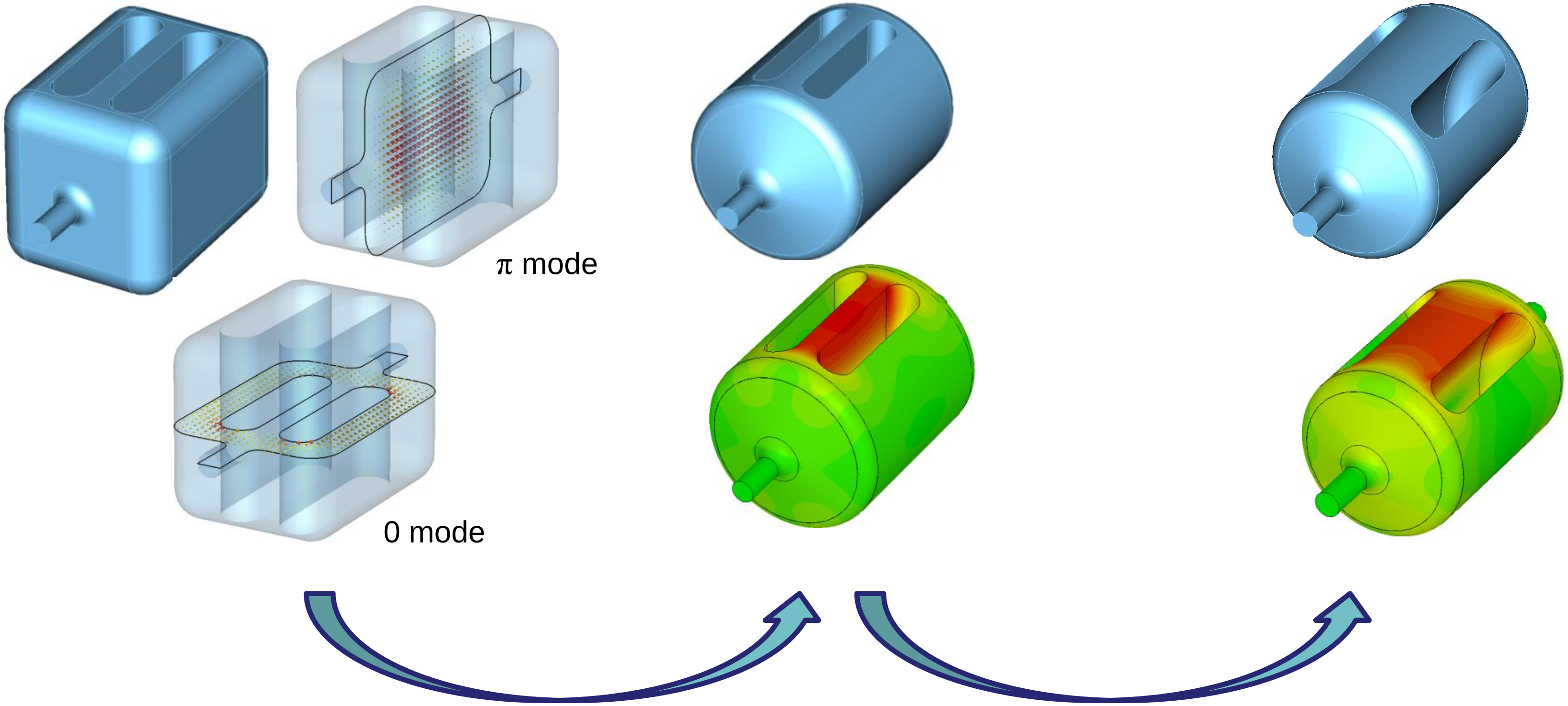
*J.R. Delayen, S.U. De Silva, "Designs of Superconducting Parallel-Bar Deflecting Cavities for Deflecting/Crabbing Applications", Proc. of the15th International Conference on RF Superconductivity, p.219, (2011)

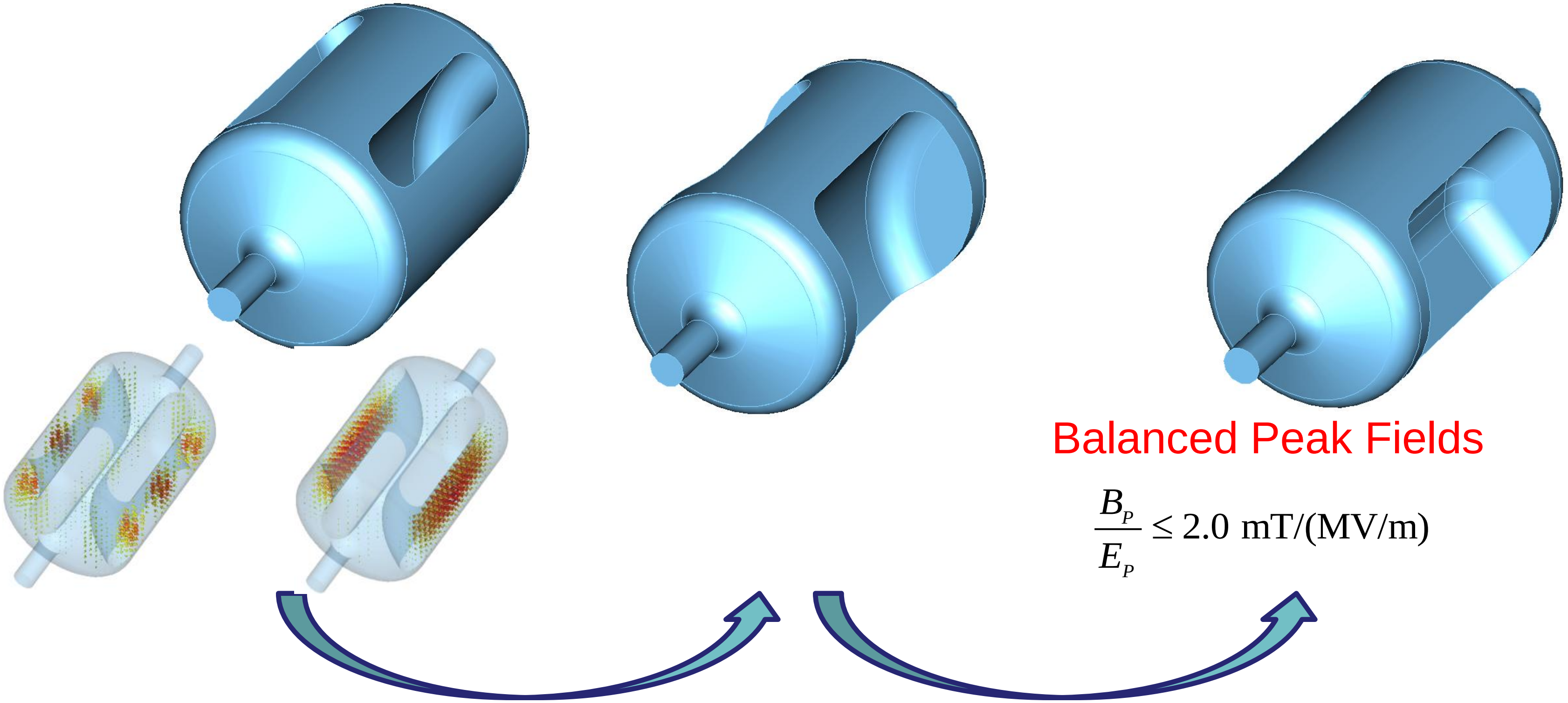
Design Evolution of the 499 MHz Deflecting Cavity



- 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 of the 499 MHz Deflecting Cavity



Balanced Peak Fields

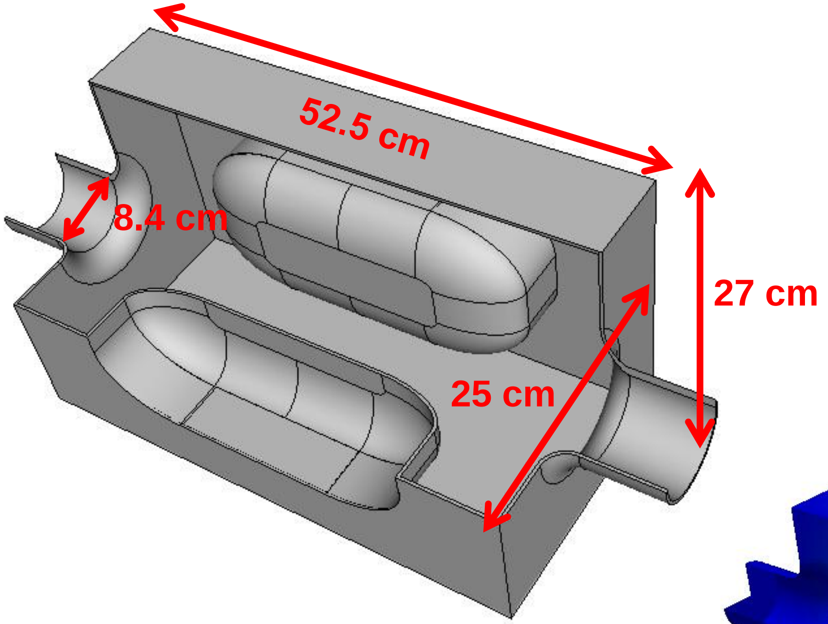
$$\frac{B_P}{E_P} \le 2.0 \text{ mT/(MV/m)}$$

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

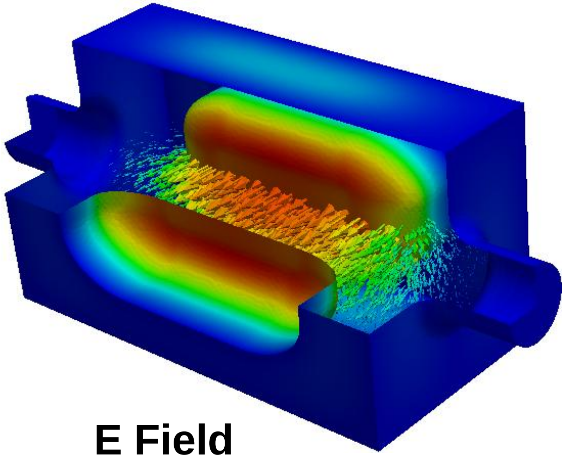
- To lower peak magnetic field
- Reduced peak magnetic field by ~25%
- To achieve balanced peak surface fields
- $B_P/E_P \approx 1.5$ mT/(MV/m)

Ridged Waveguide Cavity (SLAC)

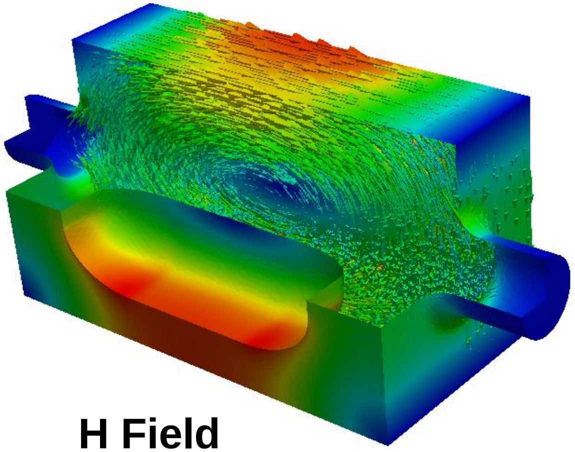
- 400 MHz Crabbing Cavity*
- Operating at a TE_{11}-like mode



Frequency	**400.0**	**MHz**
LOM	None	MHz
Nearest HOM	617.0	MHz
E_p^*	3.38	MV/m
B_p^*	7.05	mT
B_p^*/E_p^*	2.09	mT/(MV/m)
$[R/Q]_T$	330.0	Ω
At $E_T^* = 1$ MV/m		



E Field



H Field

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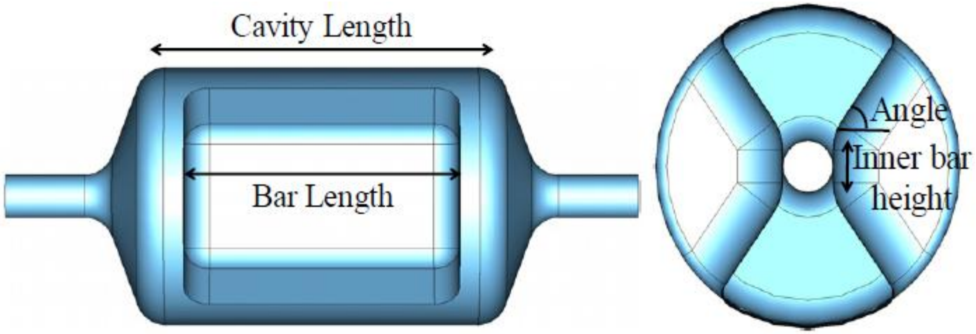
*Z. Li and L. Ge, "Compact Crab Cavity Design and Modeling Using Parallel Code ACE3P", LHC-CC11, (2011)

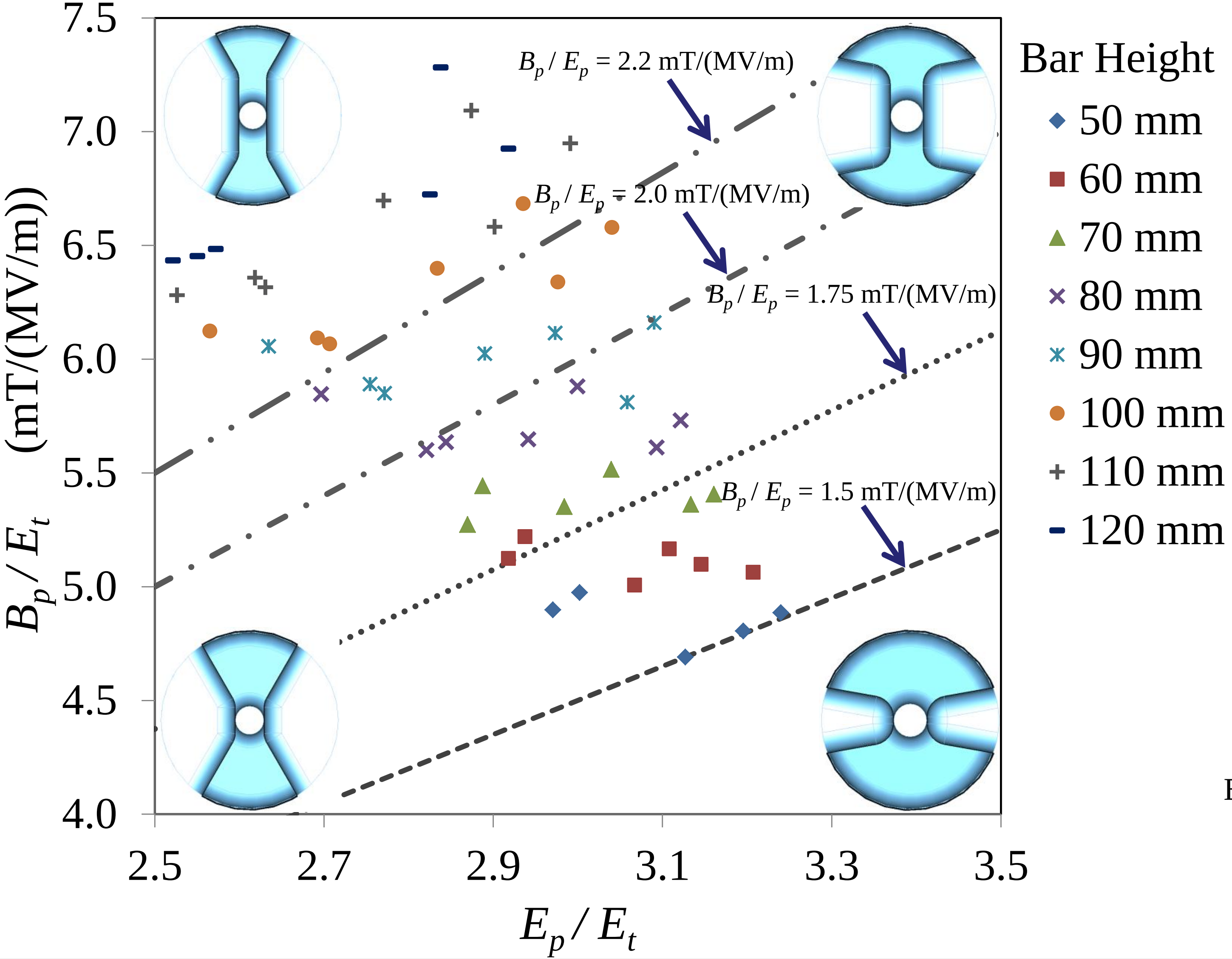
Characteristics of the RF-Dipole Cavity

- 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

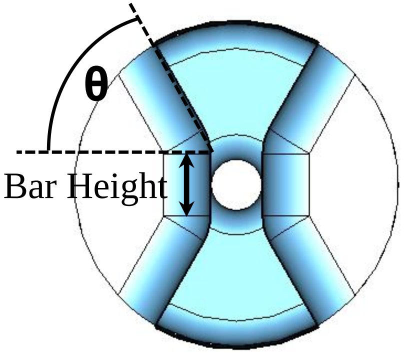


- RF-Dipole design has
  - Low surface fields and high shunt impedance
  - Good balance between peak surface electric and magnetic field
  - No LOMs
  - Nearest HOM is widely separated (~ 1.5 fundamental mode)
  - Good uniformity of deflecting field due to high degree symmetry

Optimization of Bar Shape of the RF-Dipole Cavity



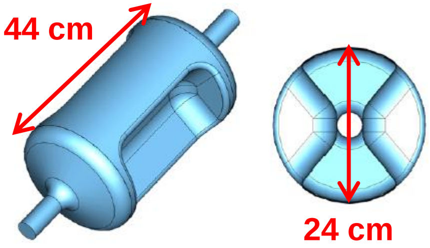
499 MHz
Deflecting
Cavity



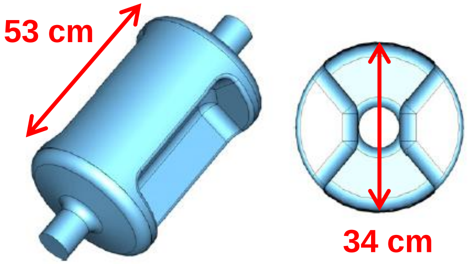
RF-Dipole Cavity Designs

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				

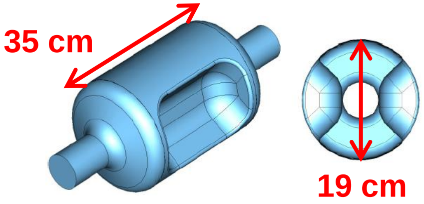
499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade



400 MHz Crabbing Cavity for LHC High Luminosity Upgrade



750 MHz Crabbing Cavity for MEIC at Jefferson Lab[*]



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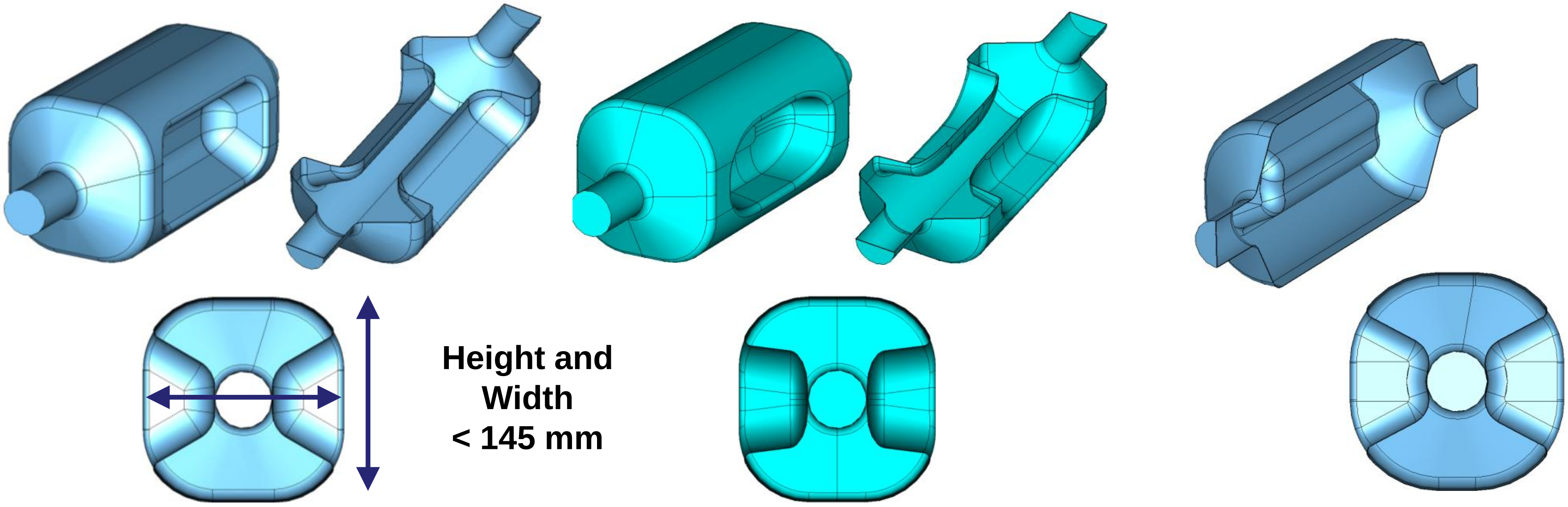
[*] A. Castilla et.al., in Proceedings of the 3rd IPAC, New Orleans, Louisiana (2012), p. 2447.

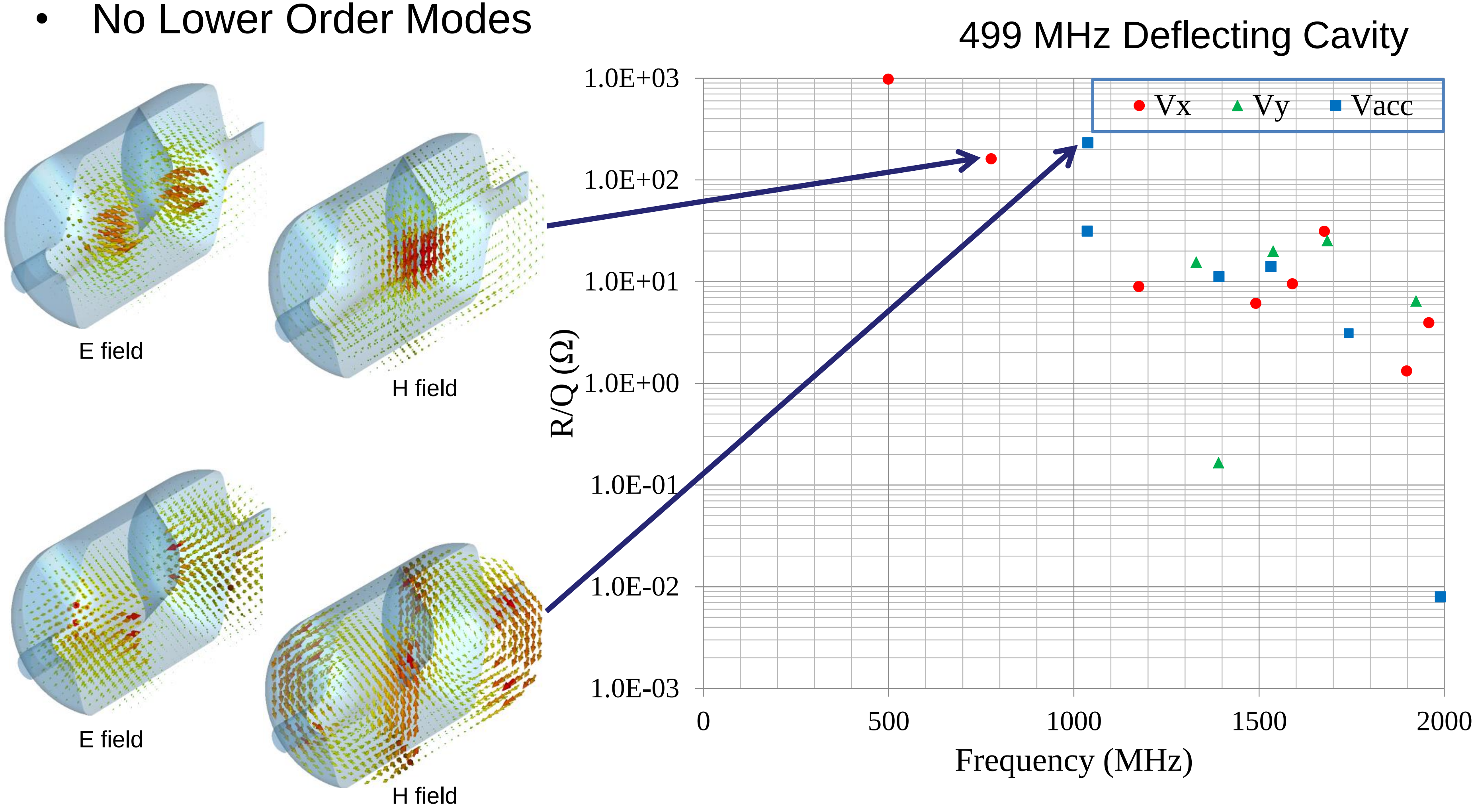
RF-Dipole Square Cavity Options

- 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



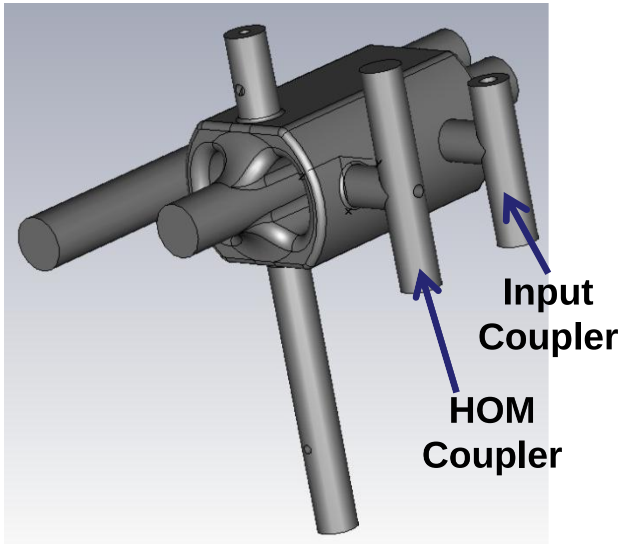
HOM Properties of the RF-Dipole Cavity

- Widely separated Higher Order Modes
- No Lower Order Modes



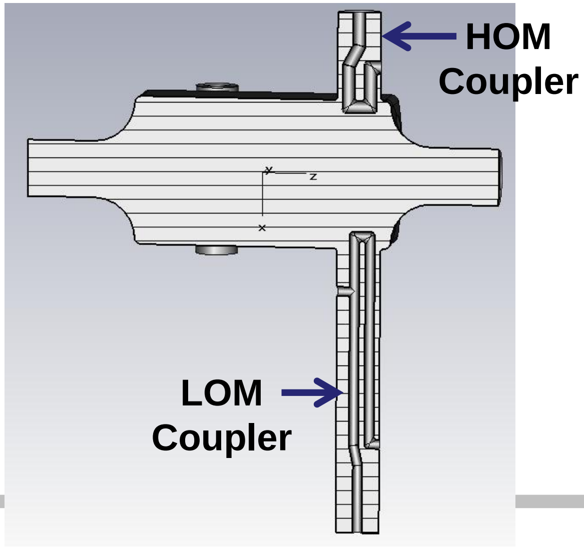
LOM and HOM Damping

4-Rod Cavity[*]



Input Coupler

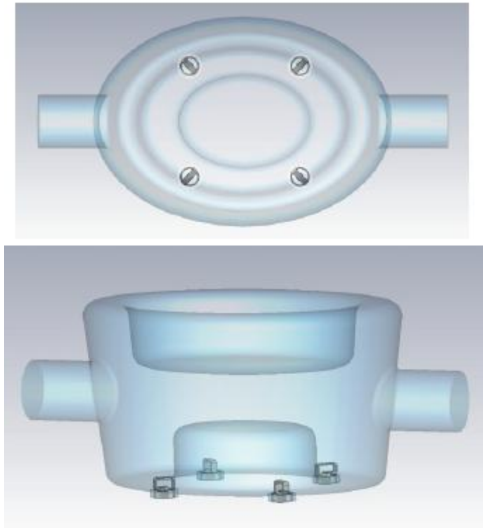
HOM Coupler



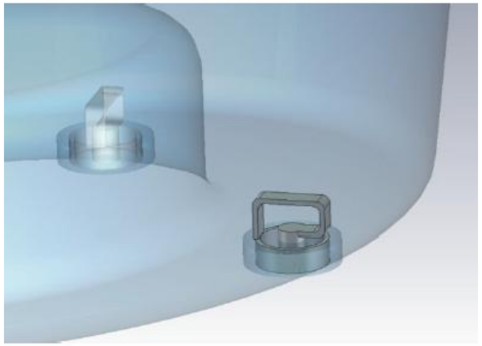
HOM Coupler

LOM Coupler

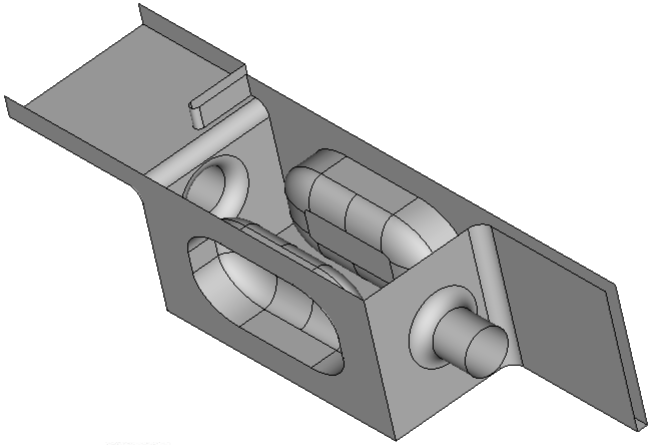
¼-Wave Cavity[*]

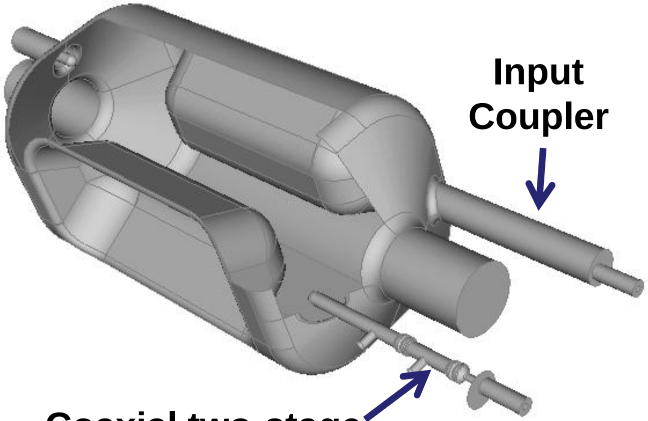


Magnetic loop-type HOM couplers



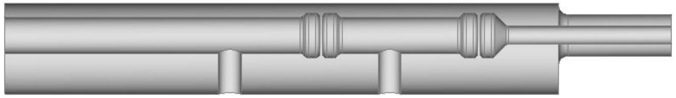
RF-Dipole Cavity[*]





Input Coupler

Coaxial two-stage high-pass filter coupler



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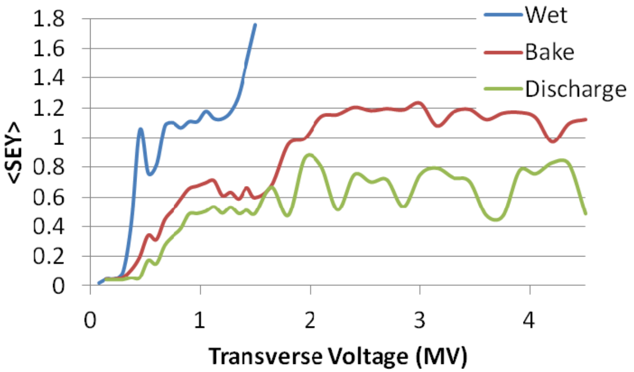
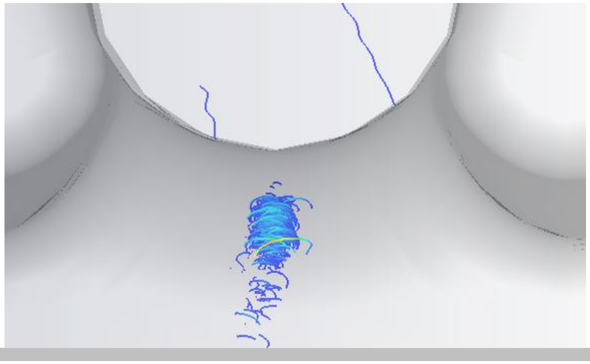
[*] Presented at LARP CM 18 / HiLumi LHC Meeting, Fermilab, May 2012

Multipacting Analysis

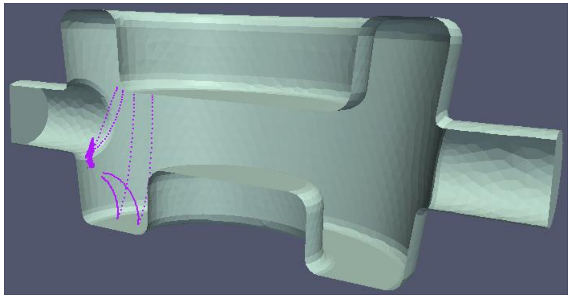
4-Rod Cavity*

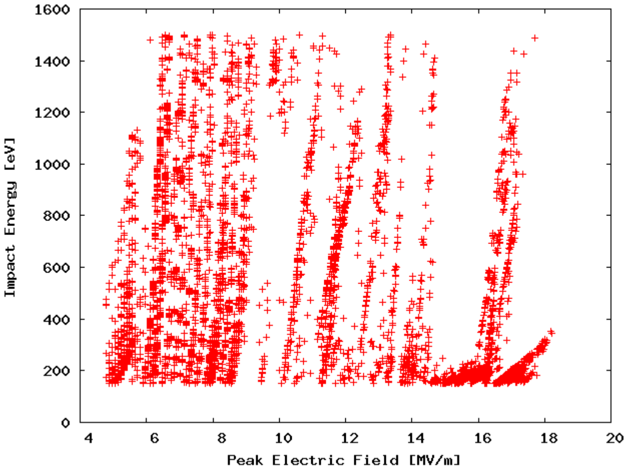


- Soft multipactor barriers were found in the cavity above 0.5 MV
- No Hard barriers were found
- Multipacting on the beam pipe was found on the beam pipe at ~1.6MV

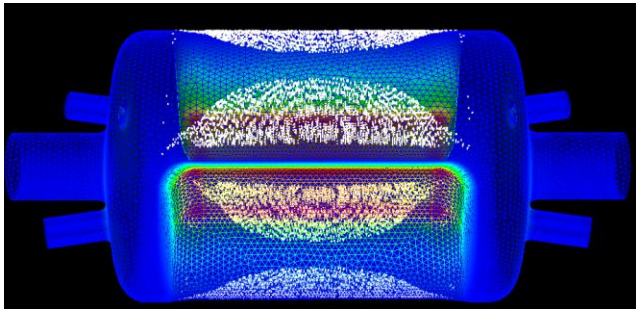


¼-Wave Cavity*

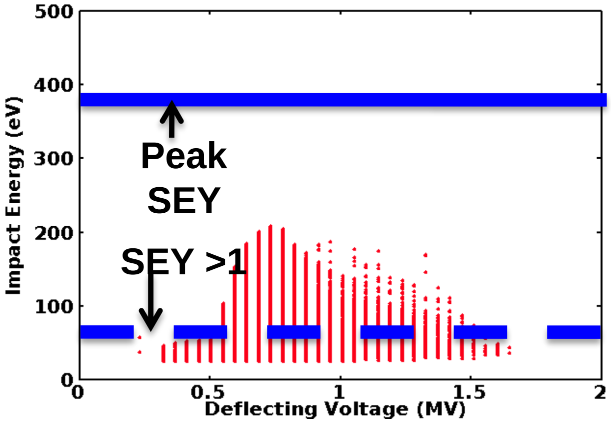


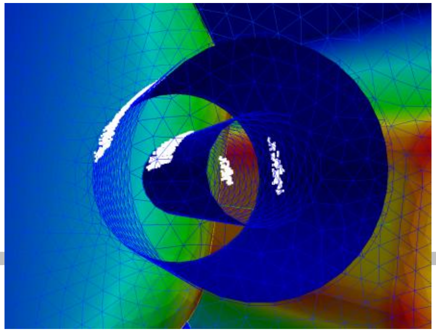


RF-Dipole Cavity*



Resonant Particles Distribution at 0.6MV





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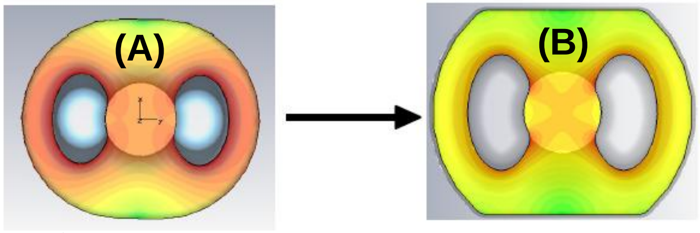
*Presented at LARP CM 18 / HiLumi LHC Meeting, Fermilab, May 2012

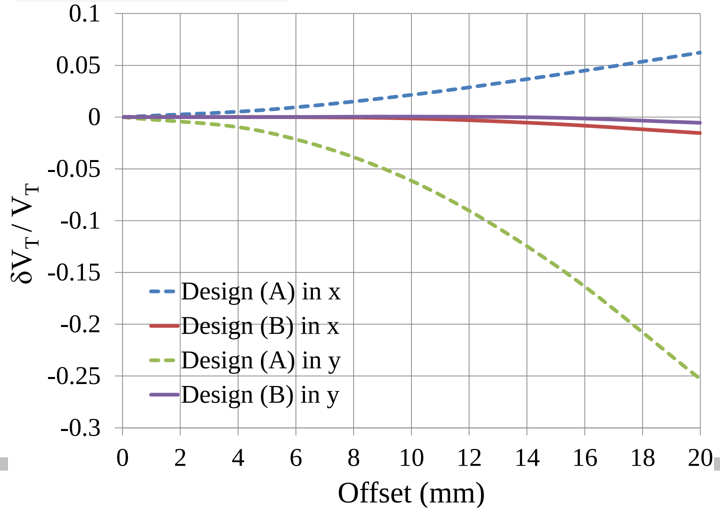
Field Non-Uniformity

- Shaped rods
  - To reduce filed non-uniformity across the beam aperture
  - Suppress higher order multipole components

4-Rod Cavity

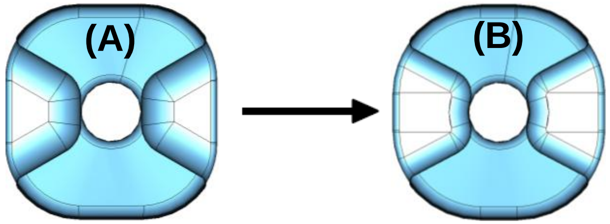
- Voltage deviation at 20 mm
  - Horizontal: 6.2 % → 1.5%
  - Vertical: 25.3% → 0.6%

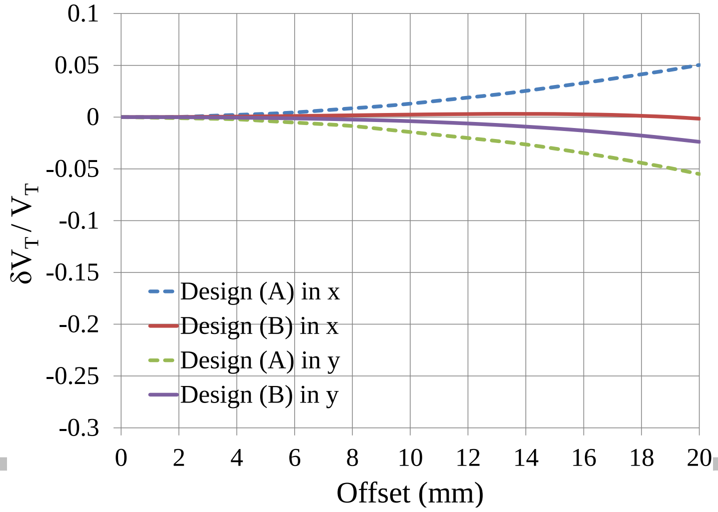




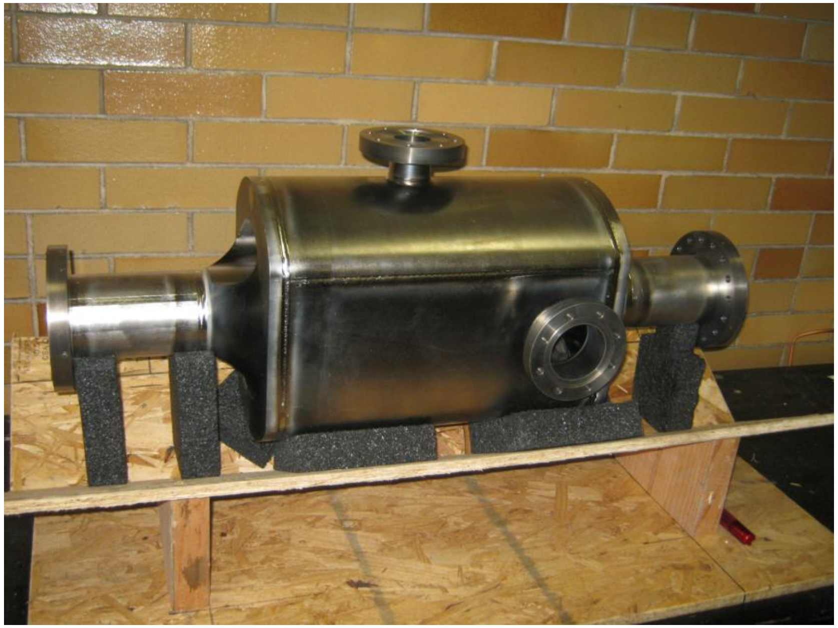
RF-Dipole Cavity

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

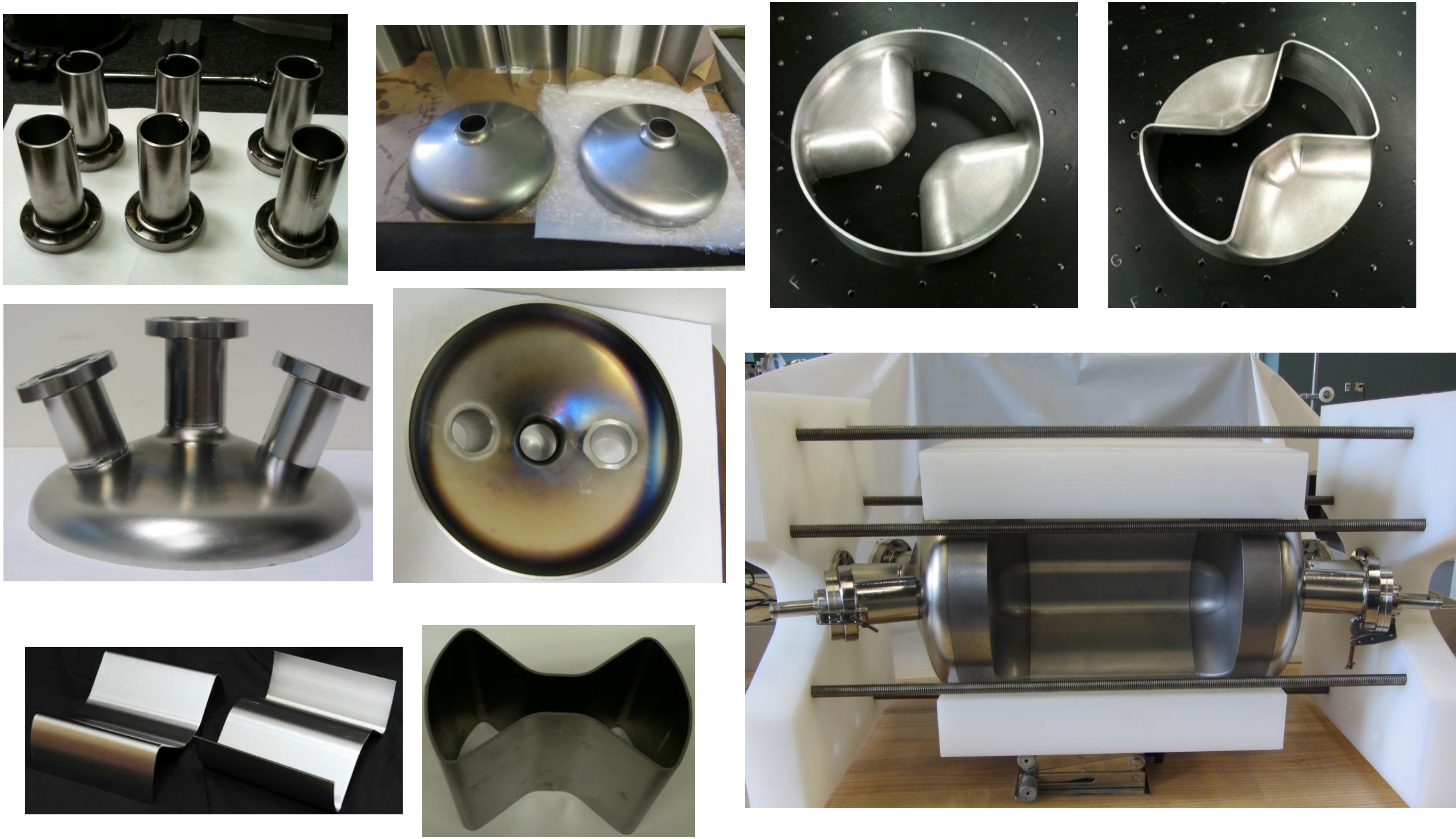




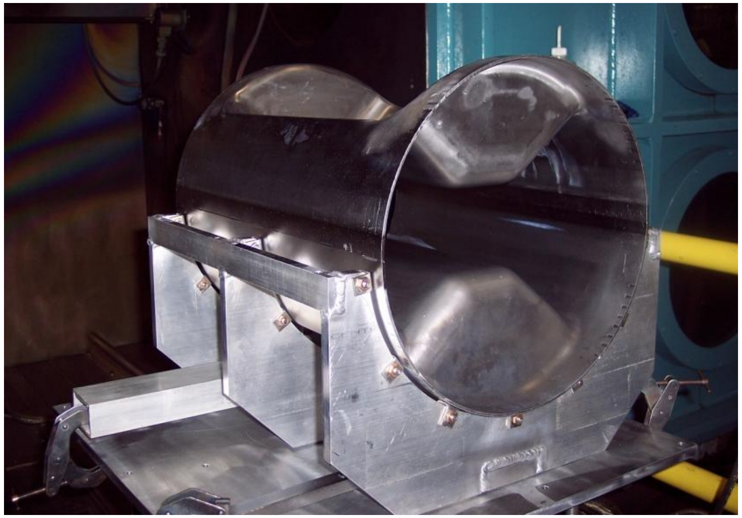
400 MHz 4-Rod Cavity Fabrication



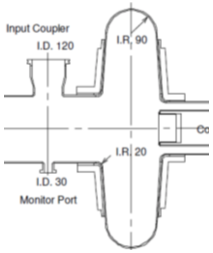
499 MHz RF-Dipole Cavity Fabrication

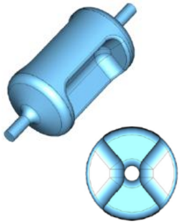


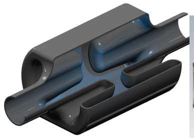
400 MHz RF-Dipole Cavity Fabrication

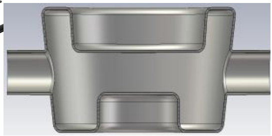


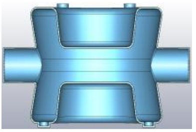
Summary











	KEK Crabbing Cavity	**RF-Dipole Cavity**	**RF-Dipole Cavity**	**4-Rod Cavity**	**Asymmetric ¼-Wave Cavity**	**Symmetric ¼-Wave Cavity**	**Units**
Frequency	**508.9**	**499.0**	**400.0**	**400.0**	**400.0**	**400.0**	**MHz**
Aperture Diameter (d)	100.0	40.0	84.0	84.0	84.0	84.0	mm
d/(λ/2)	0.34	0.13	0.22	0.22	0.22	0.22	
LOM	410.0	None	None	375.2	None	None	MHz
Nearest HOM	630.0	777.0	589.5	436.6	657.0	577.8	MHz
E_p^*	4.24	2.86	3.9	4.0	5.38	4.04	MV/m
B_p^*	12.23	4.38	7.13	7.56	7.6	7.2	mT
B_p^*/E_p^*	2.88	1.53	1.83	1.89	1.42	1.77	mT/(MV/m)
$[R/Q]_T$	48.9	982.5	287.2	915.0	344.0	401.1	Ω
Geometrical Factor (G)	227.0	105.9	138.7	70.35	131.0	82.4	Ω
$R_T R_S$	1.1×10^4	1.0×10^5	4.0×10^4	6.4×10^4	4.5×10^4	3.3×10^4	Ω^2
At $E_T^* = 1$ MV/m							

Summary

- The development of compact deflecting/crabbing cavities was in response to the strict dimensional requirements in some current applications
- All these compact designs have attractive properties in meeting the requirements
  - Low and balanced surface fields
  - High shunt impedance
  - Some of the designs have no lower-order-mode with a well-separated fundamental mode
- HOM damping, multipacting and mechanical analysis have been addressed
- Most of the compact designs are currently being fabricated and prototype testing is underway

ACKNOWLEDGEMENTS

- Jefferson Lab
  - HyeKyoung Park
- ODU
  - Alejandro Castilla
- SLAC
  - Zenghai Li, Lixin Ge
- Niowave
  - Dmitry Gorelov, Terry Grimm
- CERN
  - Rama Calaga
- University of Lancaster
  - Graeme Burt, Ben Hall
- BNL
  - Ilan Ben-Zvi, Qiong Wu

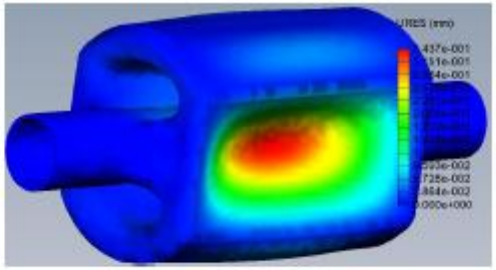
- The work done at ODU is towards my PhD carried out under the supervision of Dr. Jean Delayen

THANK YOU

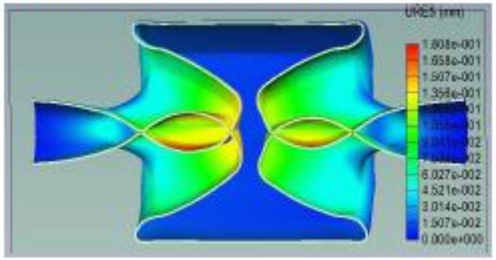
Mechanical Analysis

4-Rod Cavity*

~ 1mm displacement for 4mm thickness

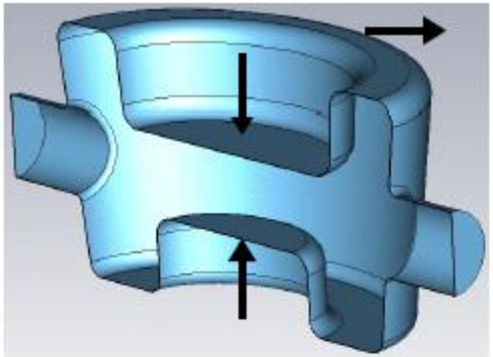


~ 0.1mm displacement for 4mm thickness



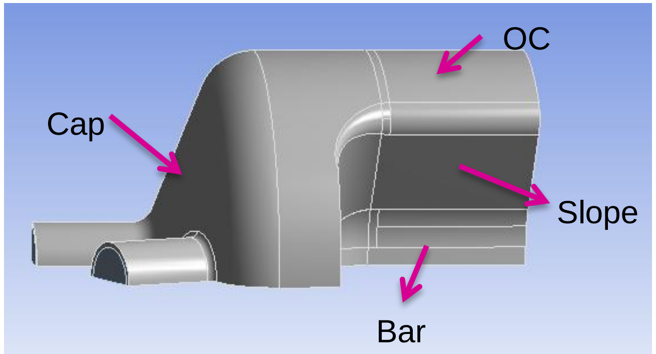
Vibrational modes are 450 Hz and above but detailed simulations underway

¼-Wave Cavity*



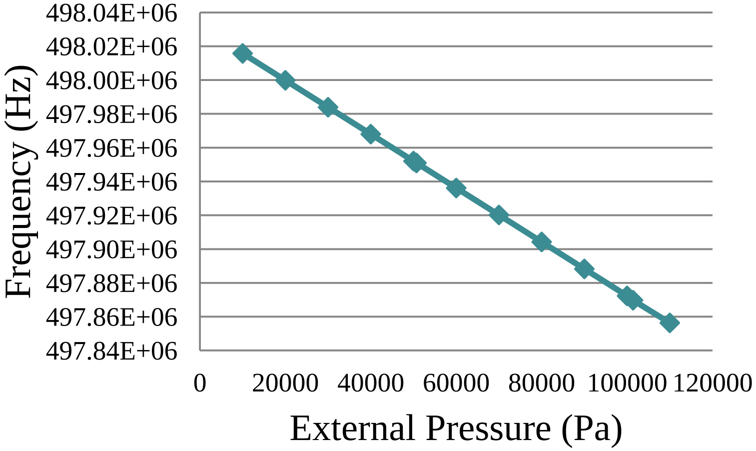
Vibration of flat surfaces and/or change in ellipticity ~MHz/mm (constrain with stiffners)

RF-Dipole Cavity*

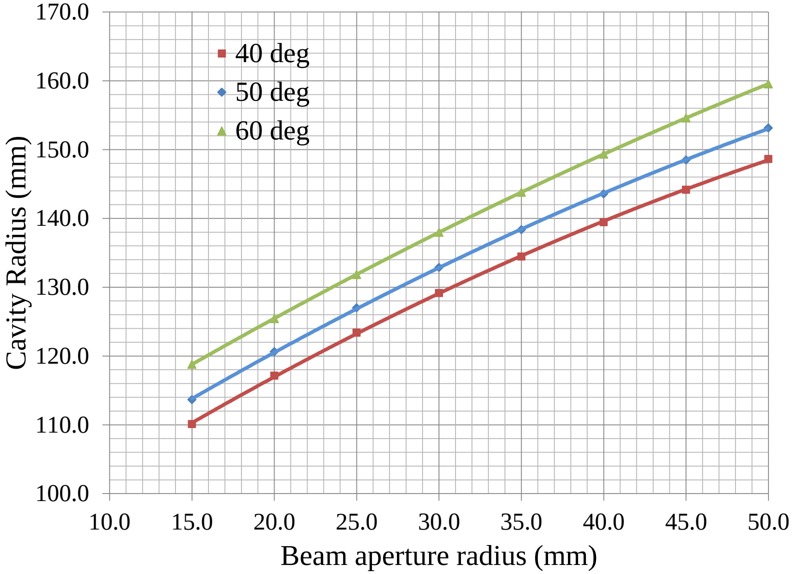


Pressure sensitivity - 212 Hz/torr

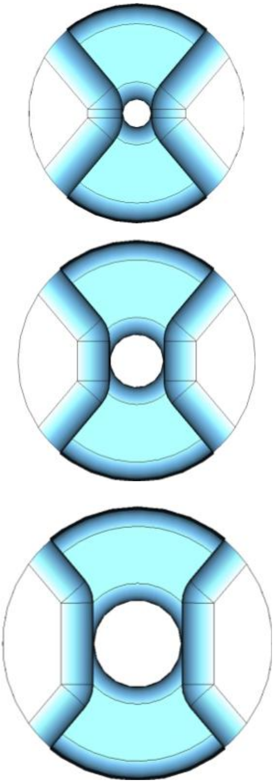
Baseline Cavity (No stiffeners)

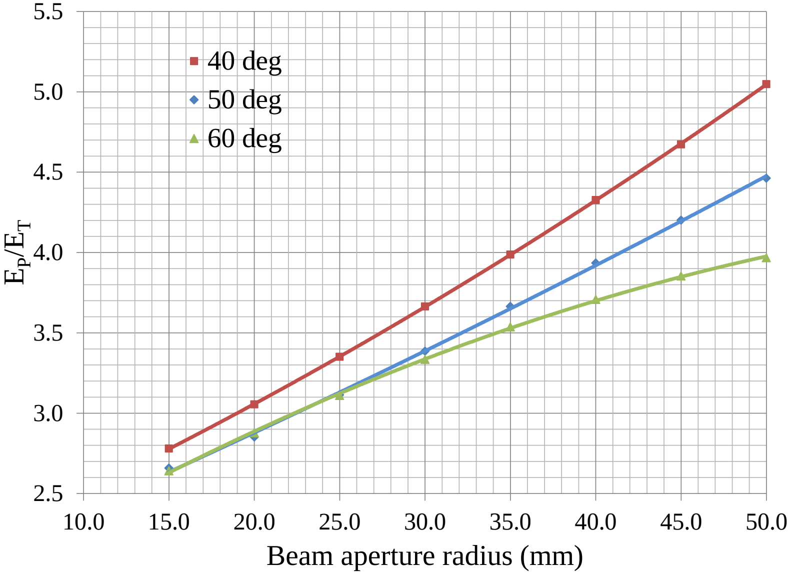


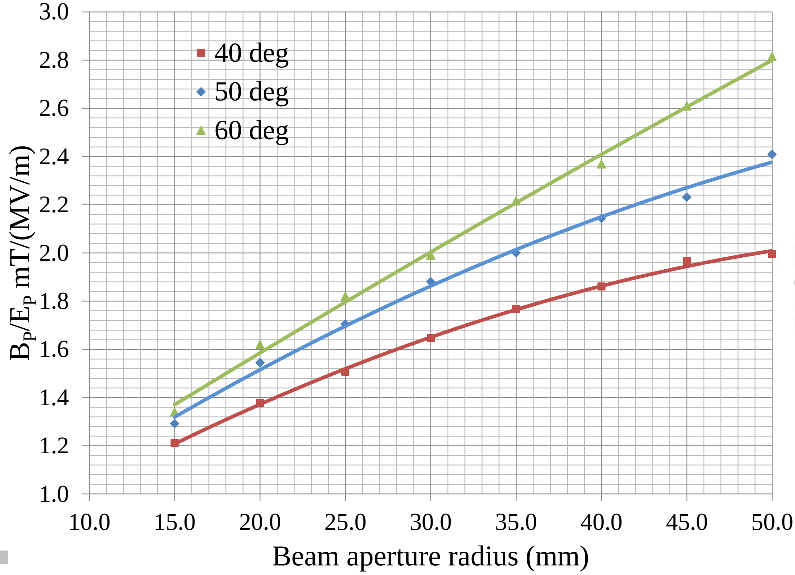
Beam Aperture Dependence

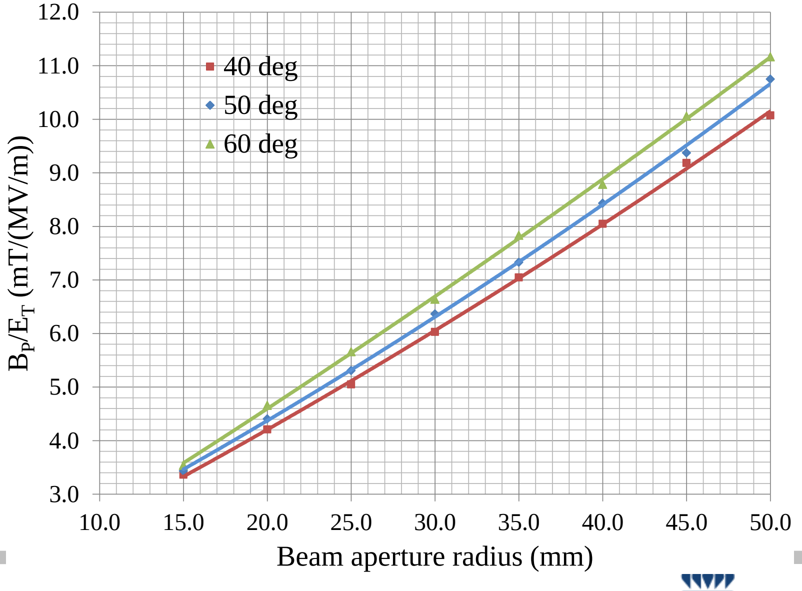


At 499 MHz

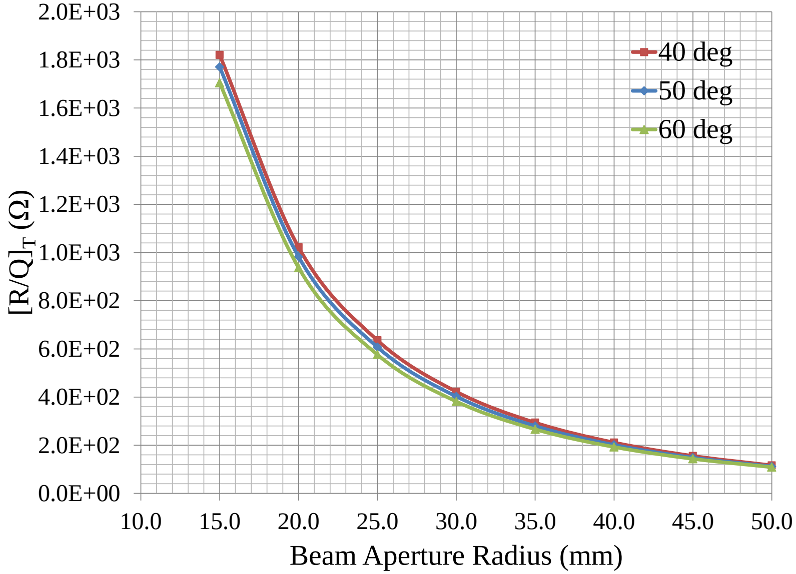




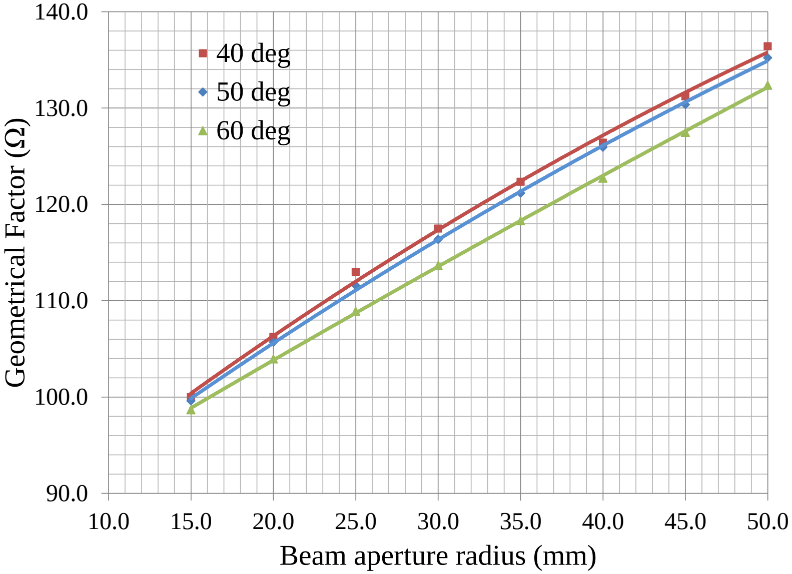




Beam Aperture Dependence

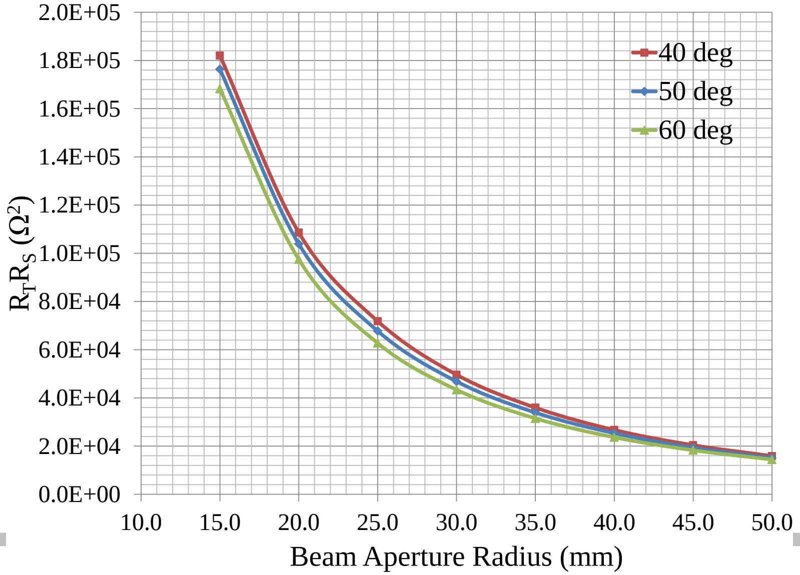


At 499 MHz



$$R_T R_S = \left[\frac{R}{Q}\right]_T Q R_S$$

$$= \left[\frac{R}{Q}\right]_T G$$



Transverse Voltage

- Lorentz Force $\vec{F} = \frac{d\vec{p}}{dt} = q[\vec{E} + \vec{v} \times \vec{B}]$
- Transverse Voltage experienced by a particle

$$V_T = \left| \int_{-\infty}^{\infty} [\vec{E}_T(z) + i\left(\vec{v} \times \vec{B}(z)\right)_T] e^{\frac{i\omega z}{c}} dz \right|$$

- Panofsky Wenzel Theorem

$$V_T = \frac{-i}{\omega / c} \nabla_T V_Z = \frac{-i}{\omega / c} \frac{1}{r_0} \left| \int_{-\infty}^{\infty} \vec{E}_Z(r_0, z) e^{\frac{i\omega z}{c}} dz \right|$$

[R/Q]

- Longitudinal [R/Q]

$$\left[\frac{R}{Q}\right]=\frac{\left|V_Z\right|^2}{\omega U}=\frac{\left|\int_{-\infty}^{+\infty}\vec{E}_z\left(z,x=0\right)e^{\frac{j\omega z}{c}}dz\right|^2}{\omega U}$$

- Transverse [R/Q]
  - Direct Integral Method

$$\left[\frac{R}{Q}\right]_T=\frac{\left|V_T\right|^2}{\omega U}=\frac{\left|\int_{-\infty}^{+\infty}\left[\vec{E}_x\left(z,x=0\right)+j\left(\vec{v}\times\vec{B}_y\left(z,x=0\right)\right)_T\right]e^{-\frac{j\omega z}{c}}dz\right|^2}{\omega U}$$

  - Using Panofsky Wenzel Theorem (x_0=5 mm)

$$\left[\frac{R}{Q}\right]_T=\frac{\left|V_Z\left(x=x_0\right)\right|^2}{\omega U}\frac{1}{\left(kx_0\right)^2}=\frac{\left|\int_{-\infty}^{+\infty}E_z\left(z,x=x_0\right)e^{\frac{j\omega z}{c}}dz\right|^2}{\left(kx_0\right)^2\omega U},\qquad k=\frac{\omega}{c}$$