TEM – Type Cavities

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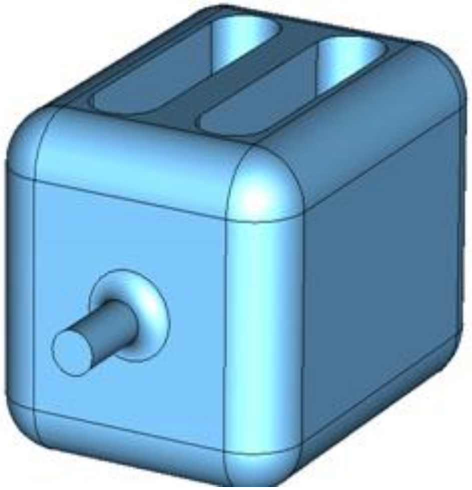
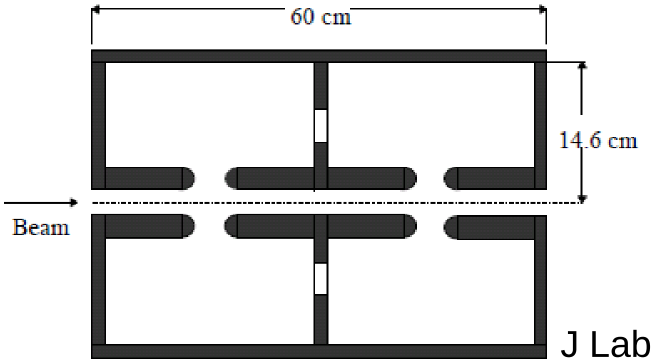
ICFA Beam Dynamics Mini-Workshop on Deflecting/Crabbing Cavity Applications in Accelerators
1 – 3 September, 2010

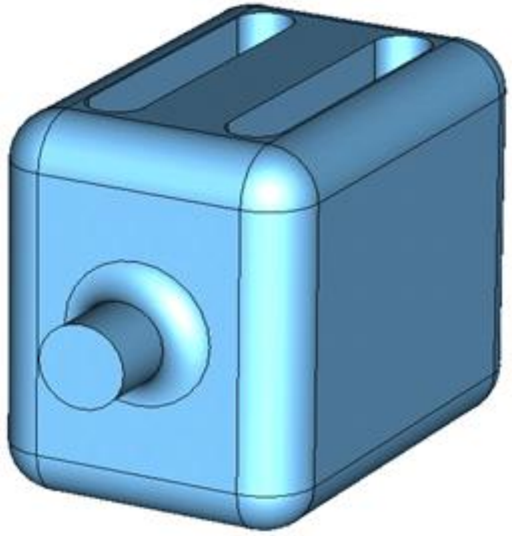
TEM-Type Deflecting/Crabbing Cavities



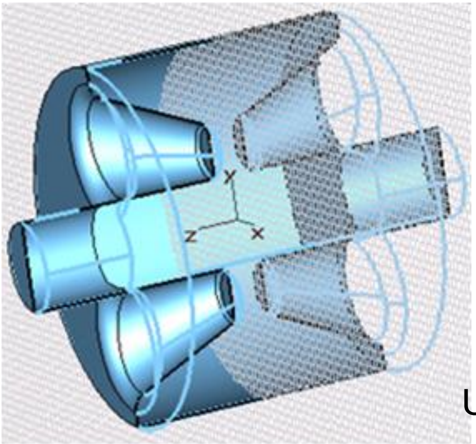
J Lab-ODU-Niowave
499 MHz
Parallel-Bar Cavity



J Lab 499 MHz
Normal Conducting
4 – Rod
Separator Cavity



ODU-Niowave
400 MHz
Parallel-Bar Cavity



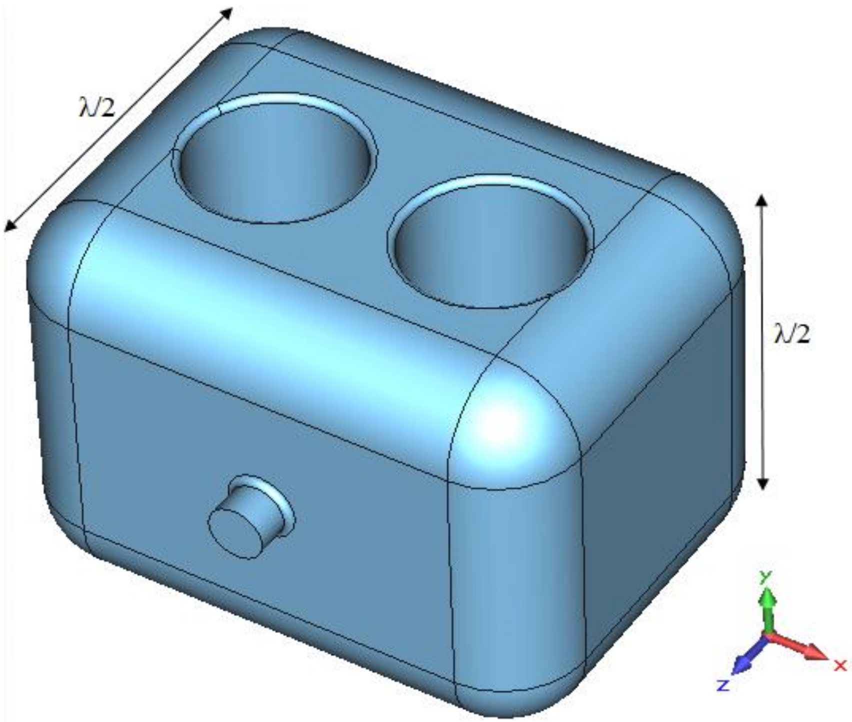
UK-J Lab 400 MHz
Superconducting
4 – Rod Cavity

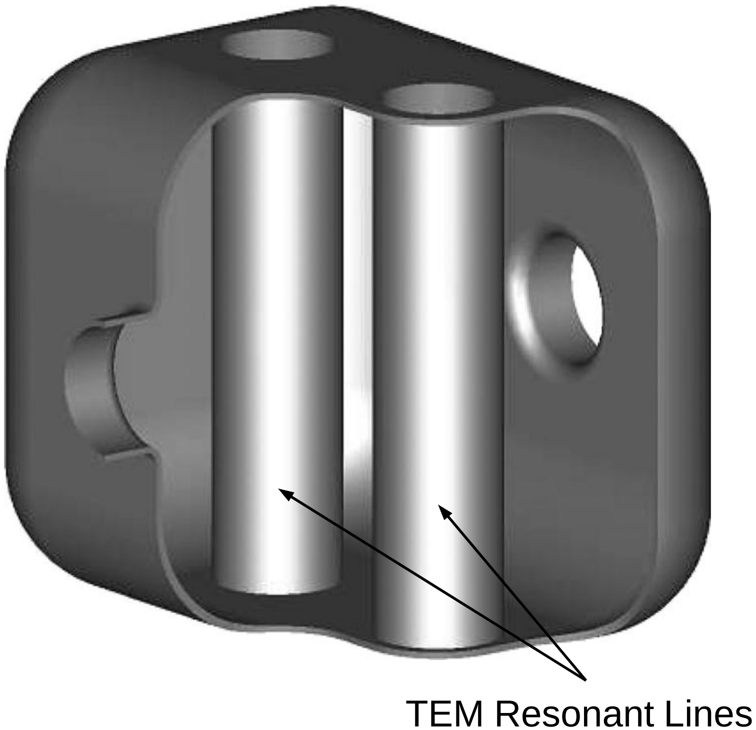
Parallel Bar Cavity Applications

- **Deflecting Cavity**
  - Jefferson Lab 12 GeV Upgrade (499 MHz) (DOE-NP, ODU-Niowave P1 STTR)
  - *Project-X* (400 MHz) (ODU-Niowave P1 STTR)
- **Crab Cavity**
  - LHC Luminosity Upgrade (400 MHz) (ODU-Niowave P2 STTR)
  - *Jefferson Lab ELIC* (500 MHz) (ODU-Niowave P1 STTR)

- **Design Properties**
  - Compact designs (Supports low frequencies)
  - Fundamental deflecting / crabbing mode has the lowest frequency → No LOMs
  - Low surface fields and high shunt impedance

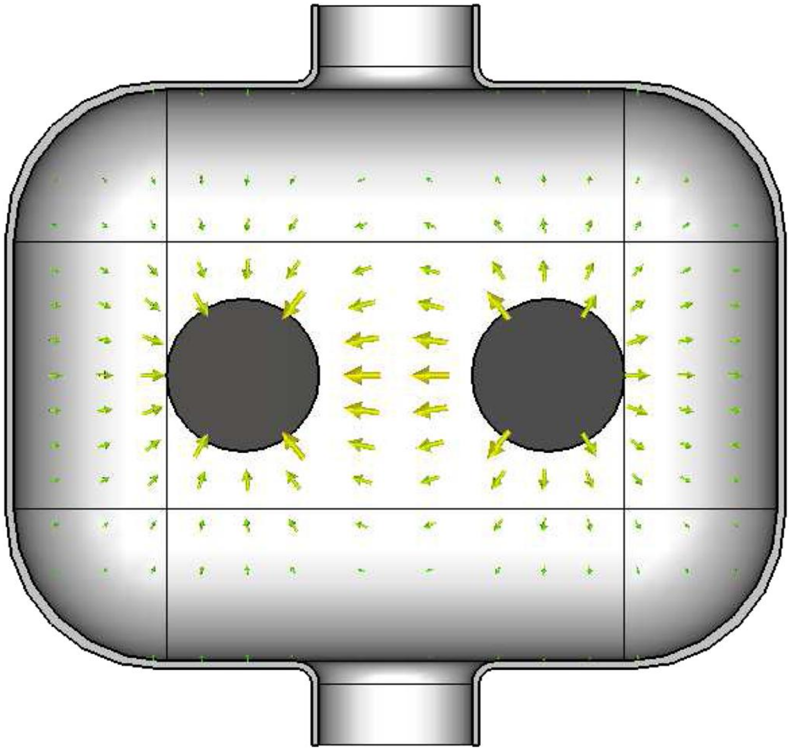
Parallel Bar Cavity Concept



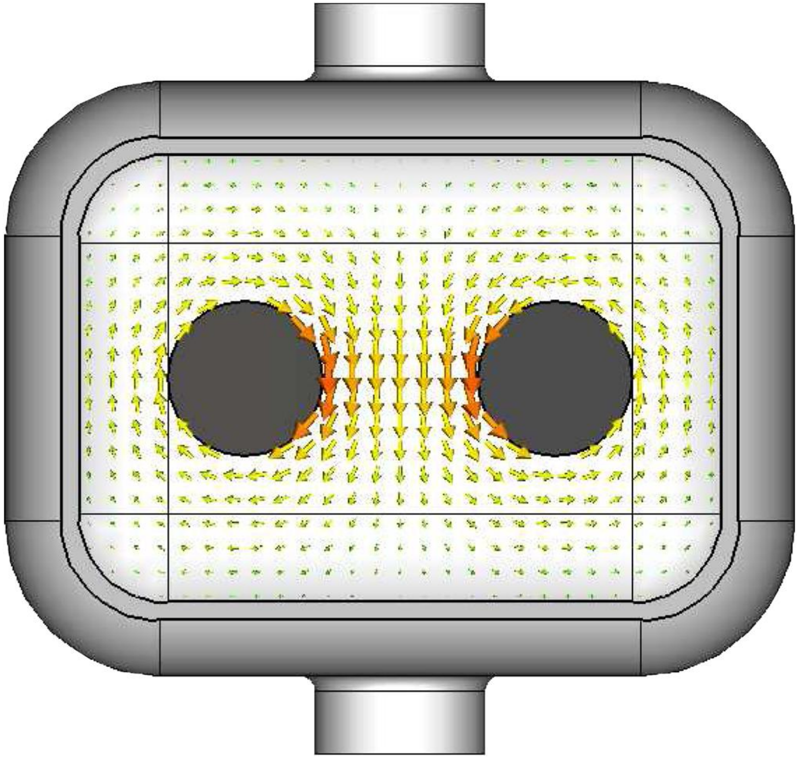


- **Compact design supports low frequencies**
- For deflection and crabbing of particle bunches
- Cavity design – Two Fundamental TEM Modes
  - 0 mode :- Accelerating mode
  - π mode :- Deflecting or crabbing mode

Parallel Bar Cavity Concept



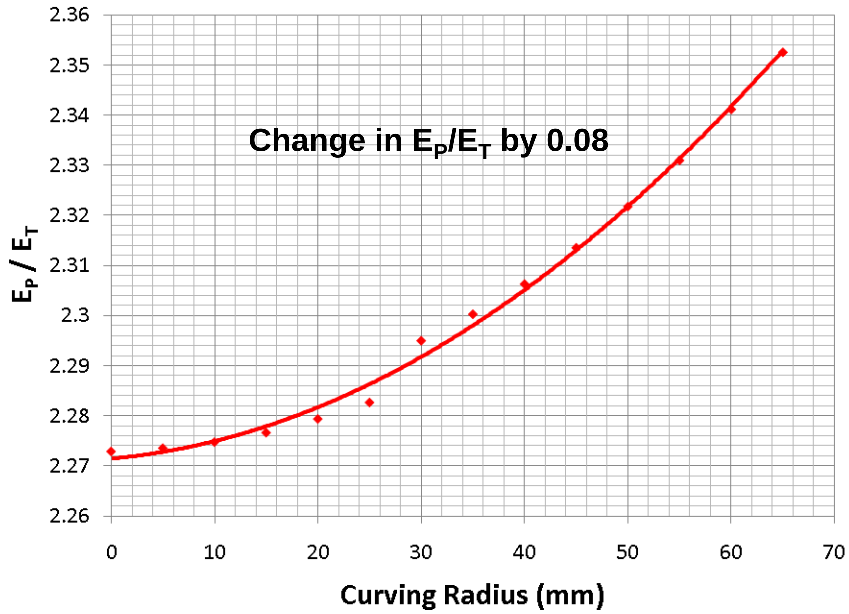
E field on mid plane
(Along the beam line)

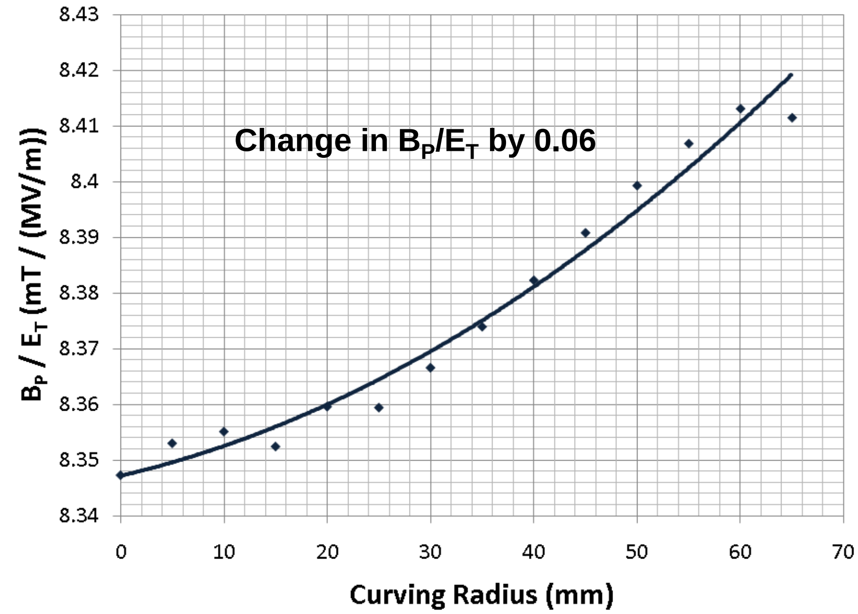


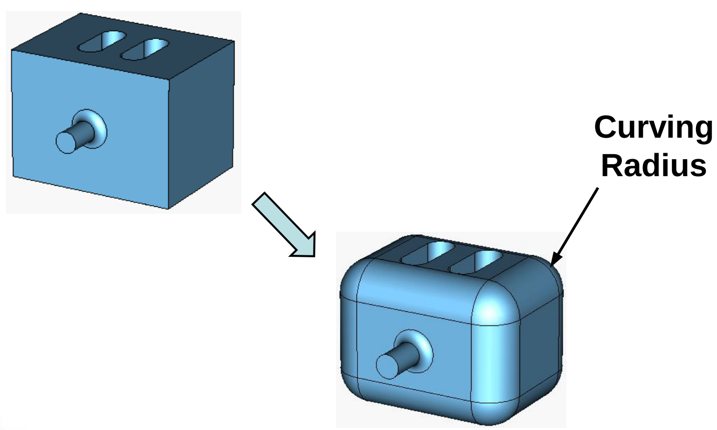
B field on top plane

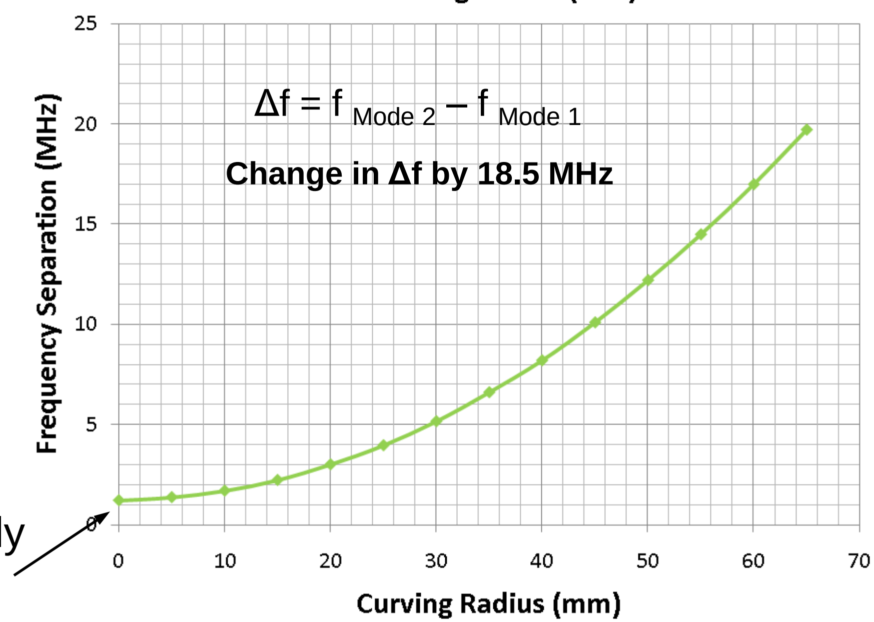
Deflection is due to the interaction with the Electric Field

Separation of Modes by Curved Edges



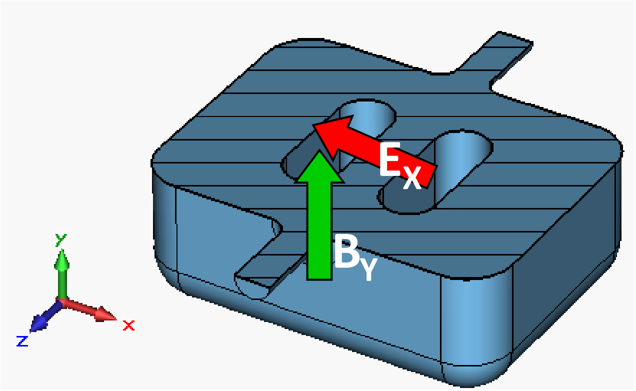






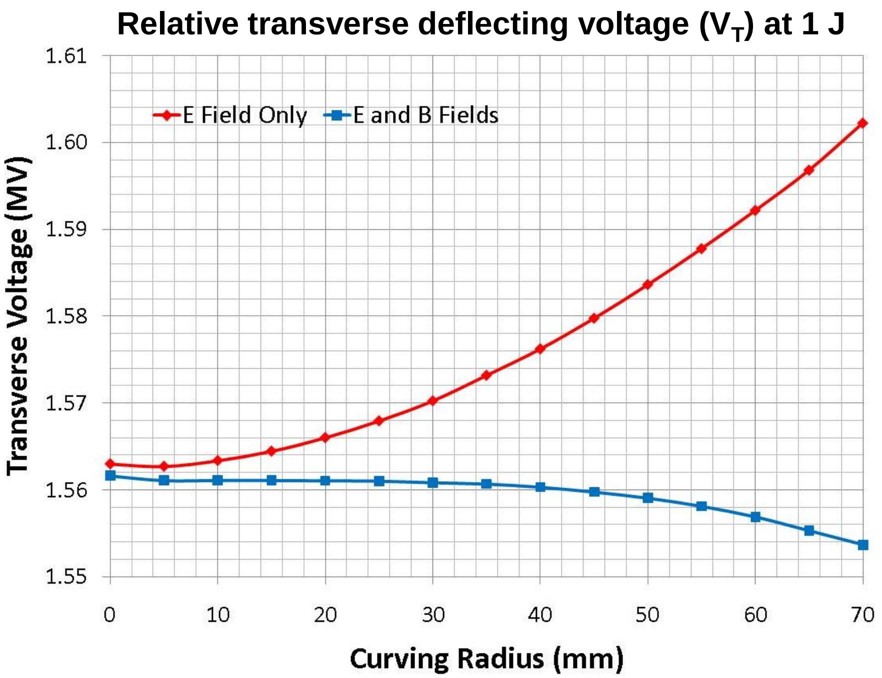
Frequency separation only due to beam pipe = 1.21 MHz

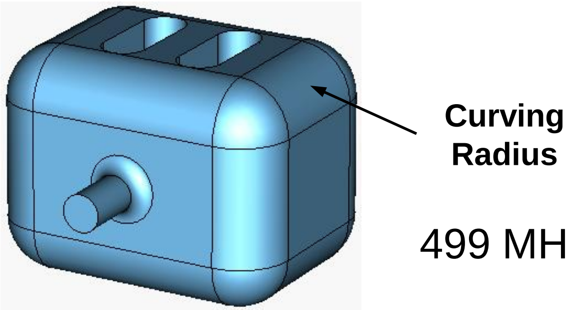
Transverse Deflection



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

- Curved cavity edges introduce a small vertical magnetic field in the gaps
- Maximum change in transverse deflecting voltage ~ 3% →Resultant contribution to the net deflection is small

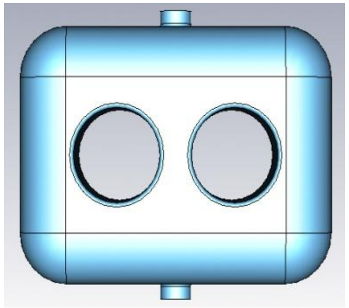




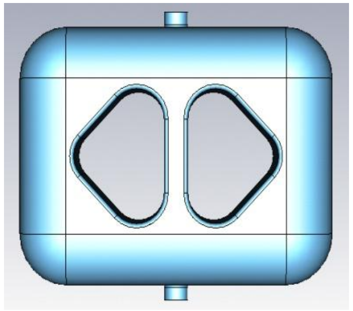
499 MHz

Parallel Bar Cross Sections

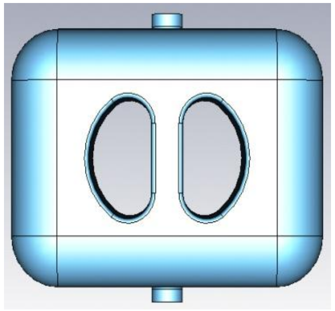
Optimizing condition – Obtain a higher deflection with lower surface fields



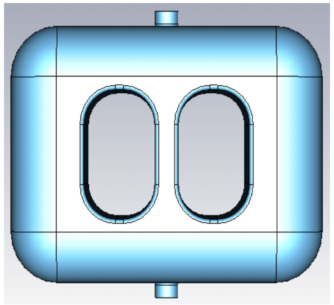
(a)



(b)



(c)



(d)

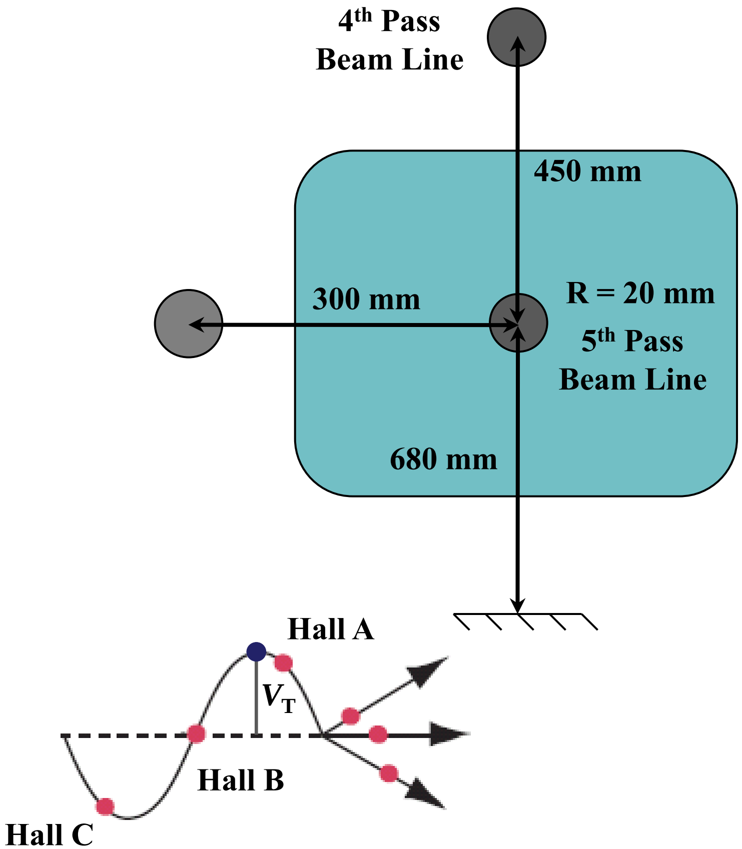
Peak Surface Fields

Design Structure	E_P/E_T^*	B_P/E_T^* (mT / MV/m)
(a)	3.30	11.54
(b)	2.80	10.31
(c)	2.61	8.86
(d)	2.31	8.16
At $E_T^* = 1$ MV/m		

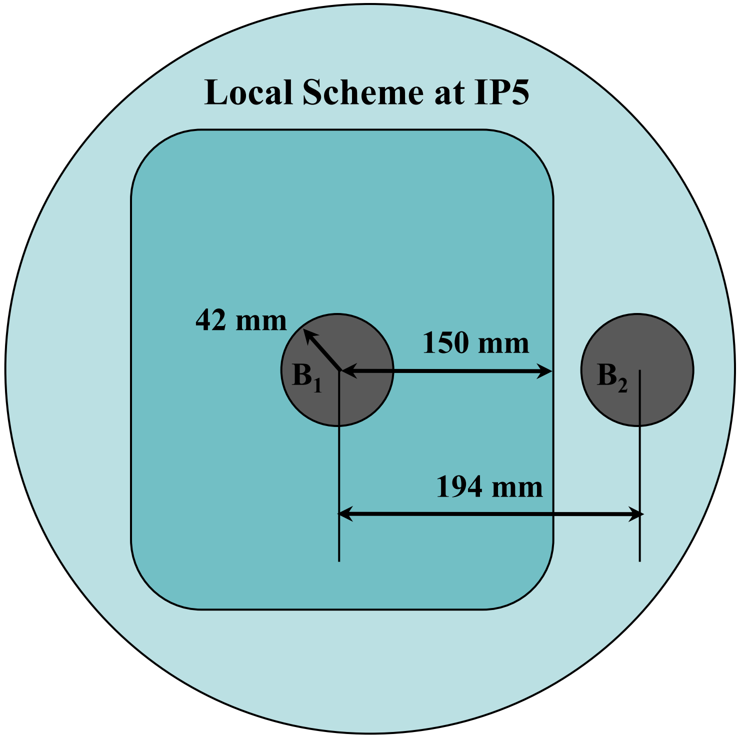
- Increasing effective deflecting length along the beam line increases net transverse deflection seen by the particle
- Racetrack shaped structure (d) has better performance with higher deflection for lower surface fields

Dimensional Constraints

499 MHz Deflecting Cavity for JLab Upgrade



400 MHz Crabbing Cavity for LHC



Global scheme :
Separation between beam pipes – 420 mm

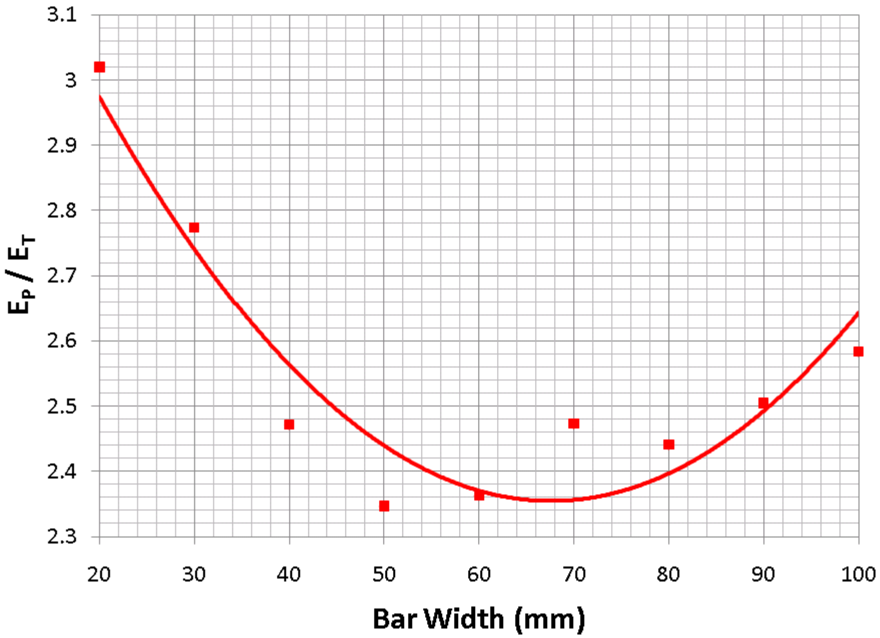
No dimensional constraints in Project-X
and ELIC deflecting/crabbing designs

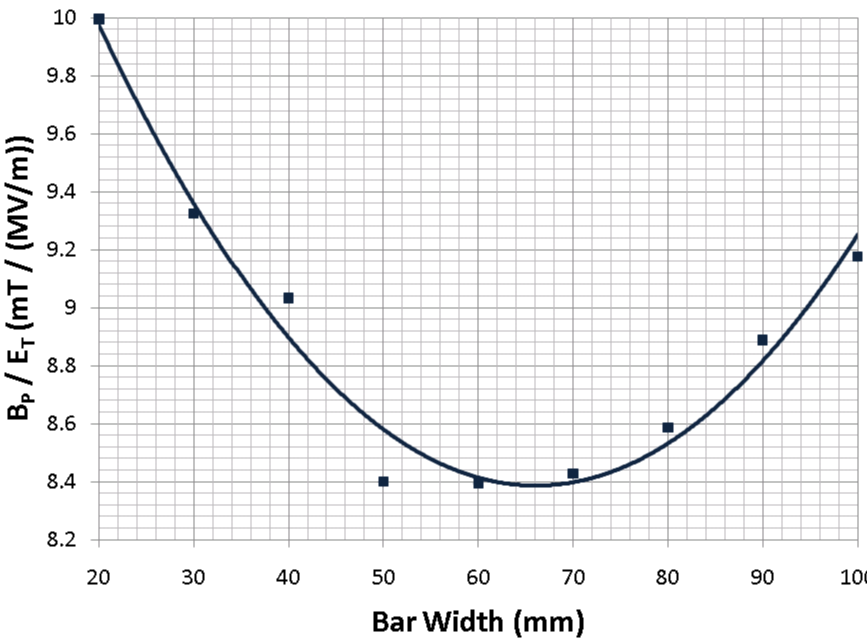
Jefferson Lab

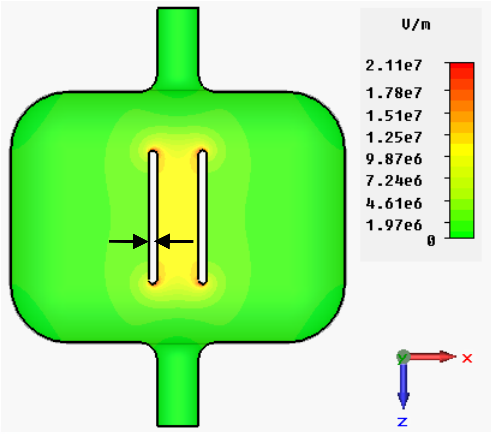
Old Dominion University

JSA

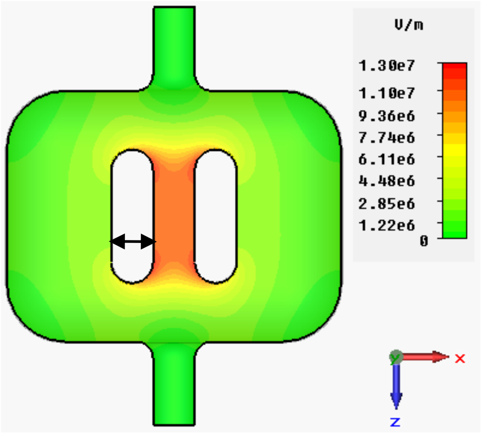
Optimization of Bar Width – 499 MHz



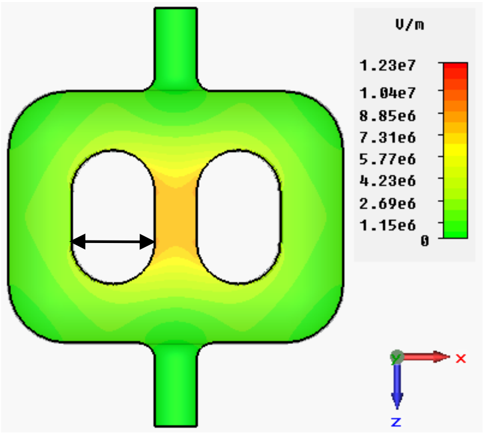




Bar Width = 10 mm

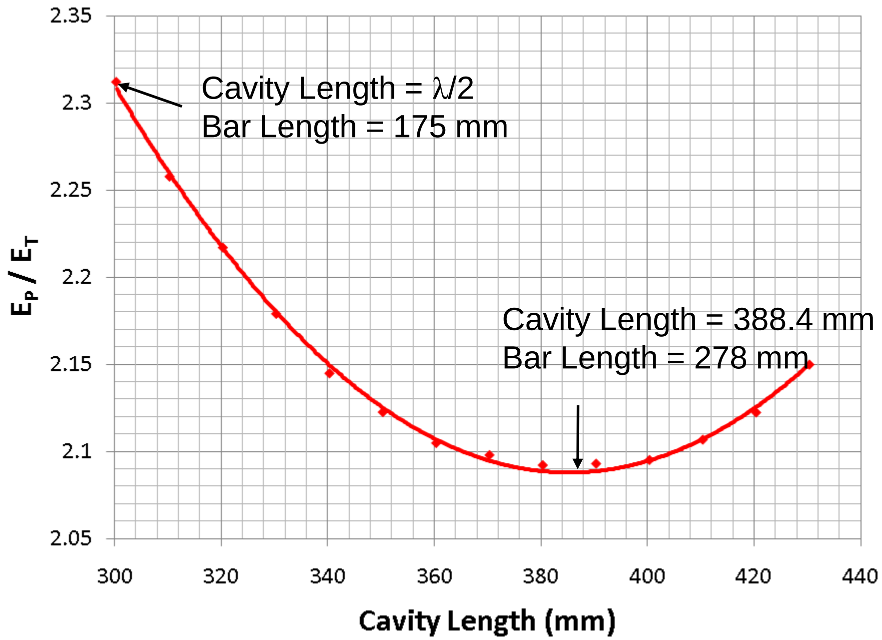


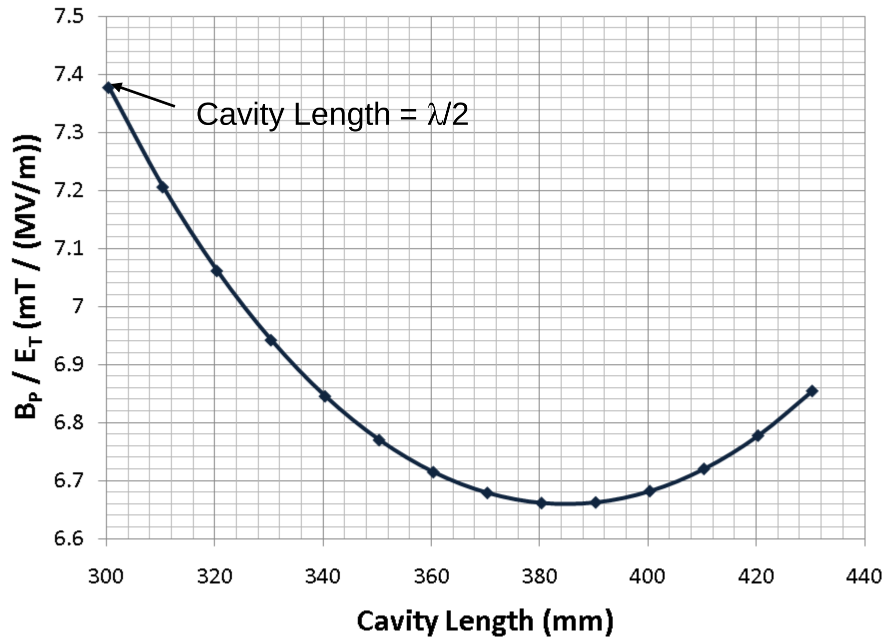
Bar Width = 50 mm



Bar Width = 100 mm

Optimization of Bar and Cavity Length – 499 MHz

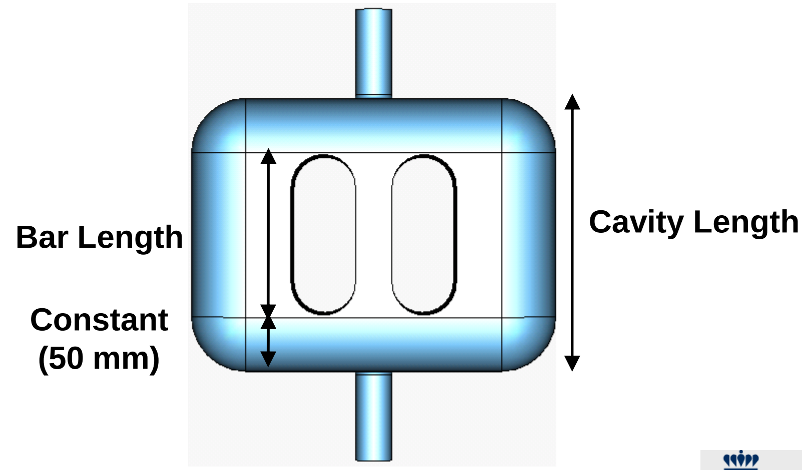




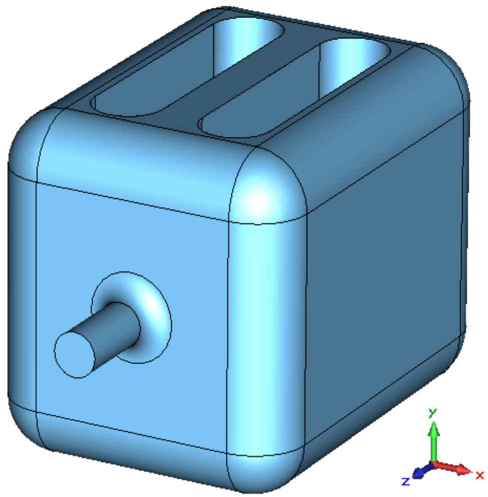
- Increase bar and cavity length simultaneously with a constant rounded edge
- Increase in bar length and cavity length increases the net deflection
- Optimized bar length ~ λ/2

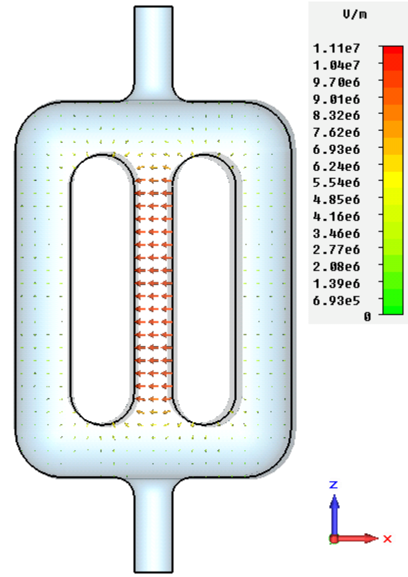
f = 499 MHz

λ/2 = 300.4 mm

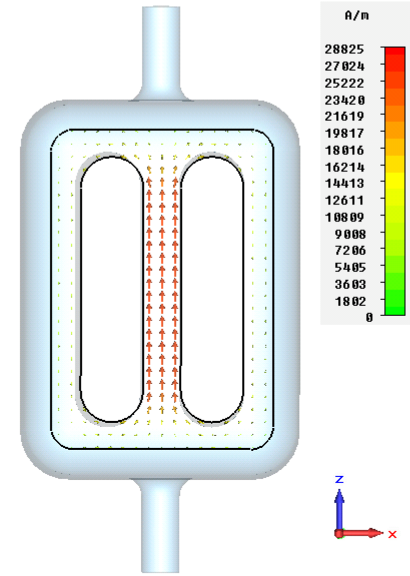


Optimized Cavity Geometry and Field Profiles – 499 MHz



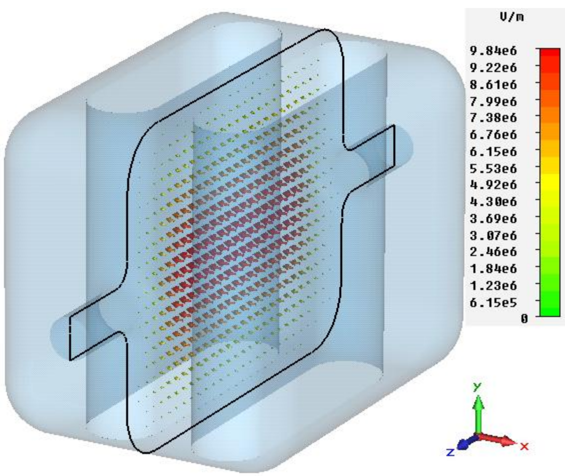


E field on mid plane

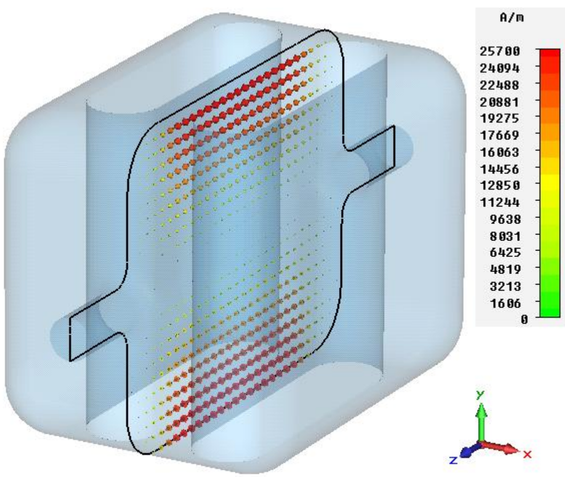


B field on top plane

Compact Design Dimensions	Value (mm)
Cavity reference length	394.4
Cavity height	304.8
Cavity width	290.0
Bar width	67.0
Bar length	284.0
Beam aperture	40.0

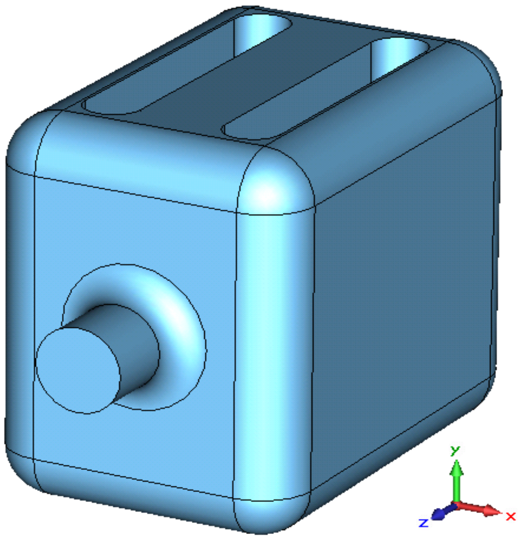


Transverse E Field

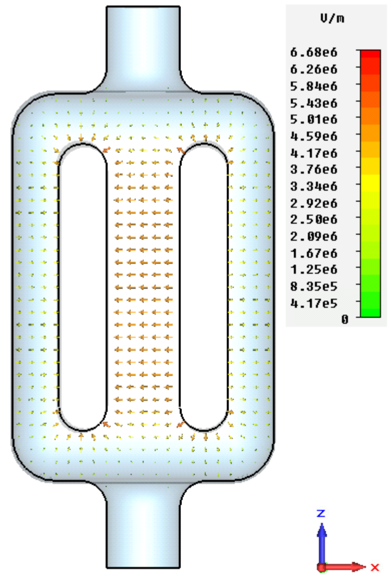


B Field

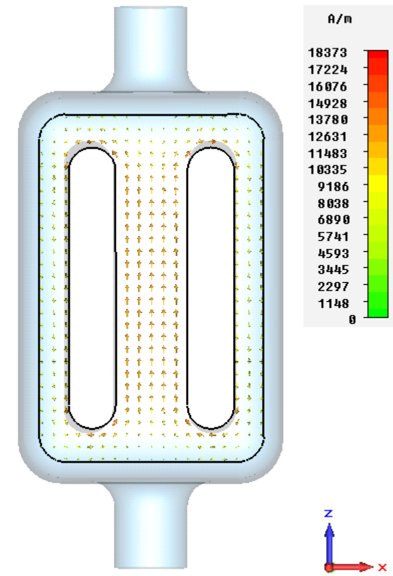
Optimized Cavity Geometry and Field Profiles – 400 MHz



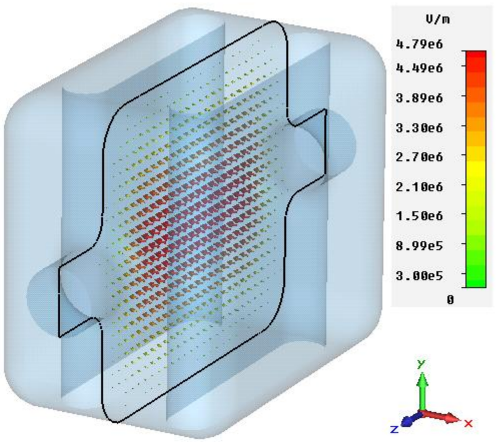
Compact Design Dimensions	Value (mm)
Cavity reference length	444.7
Cavity height	383.2
Cavity width	300.0
Bar width	55.0
Bar length	330.0
Beam aperture	84.0



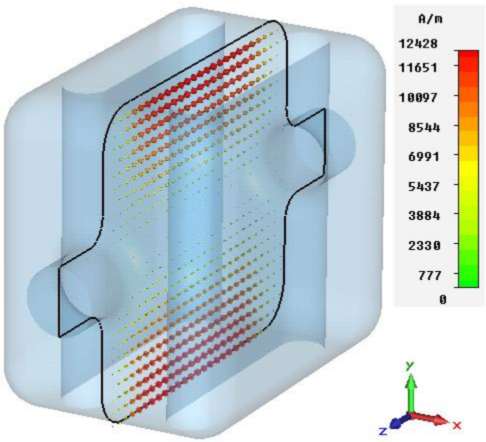
E field on mid plane



B field on top plane



Transverse E Field

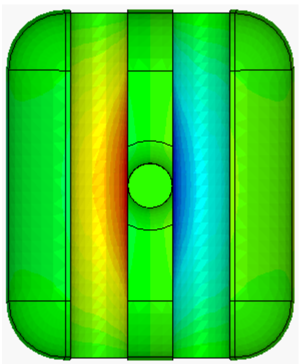


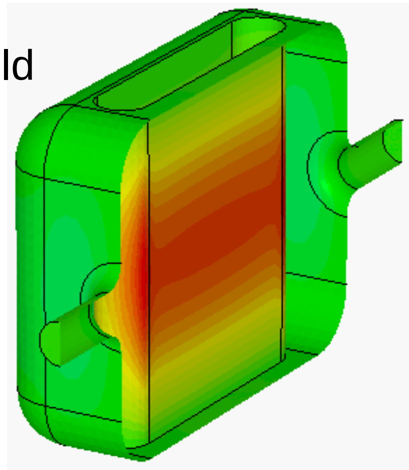
B Field

Surface Fields

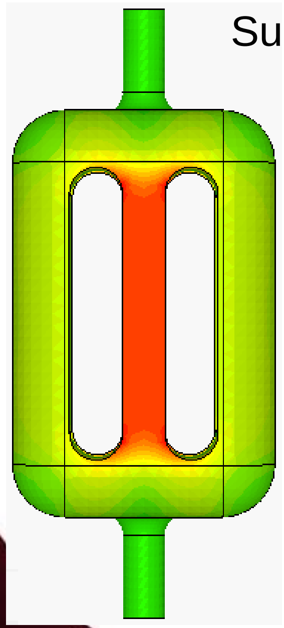
499 MHz

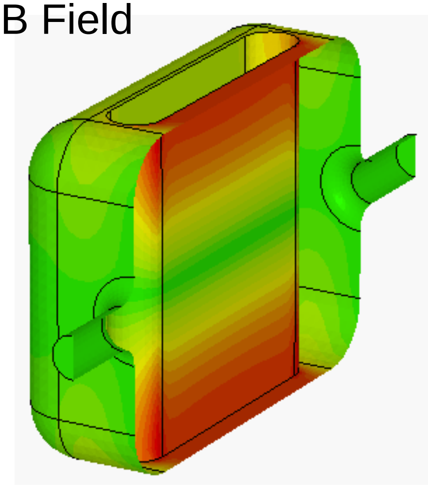
Surface E Field





Surface B Field



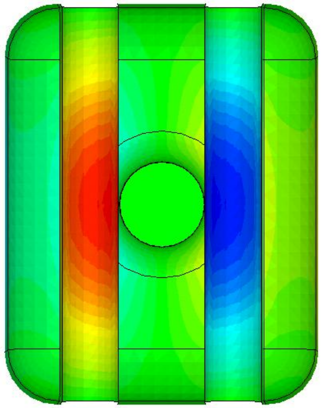


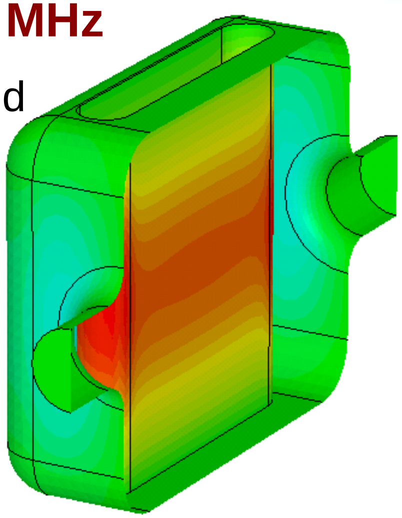
$$\frac{E_P}{E_T} = 1.85$$

$$\frac{B_P}{E_T} = 6.69 \text{ mT/(MV/m)}$$

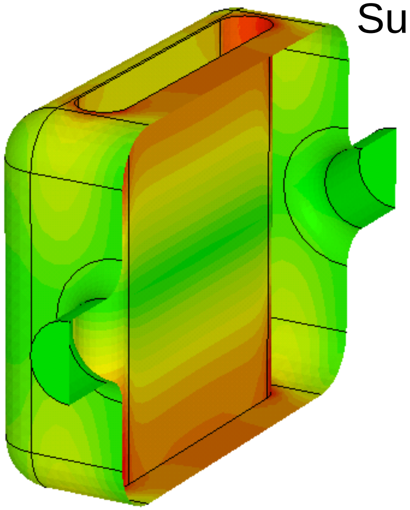
400 MHz

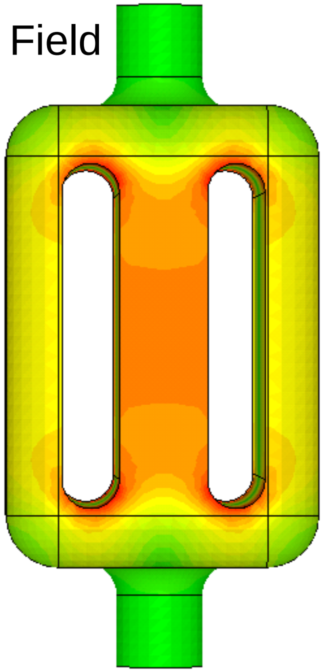
Surface E Field





Surface B Field





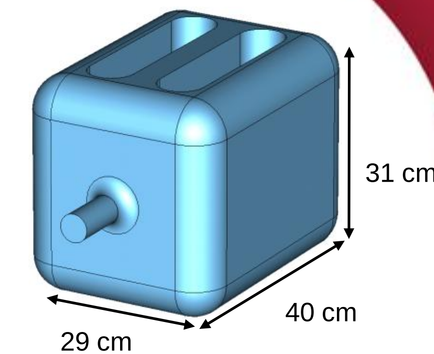
$$\frac{E_P}{E_T} = 2.2$$

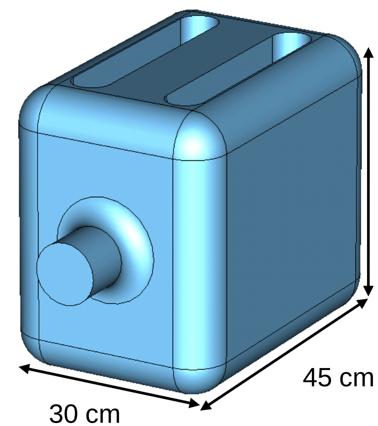
$$\frac{B_P}{E_T} = 7.9 \text{ mT/(MV/m)}$$

Cavity Properties

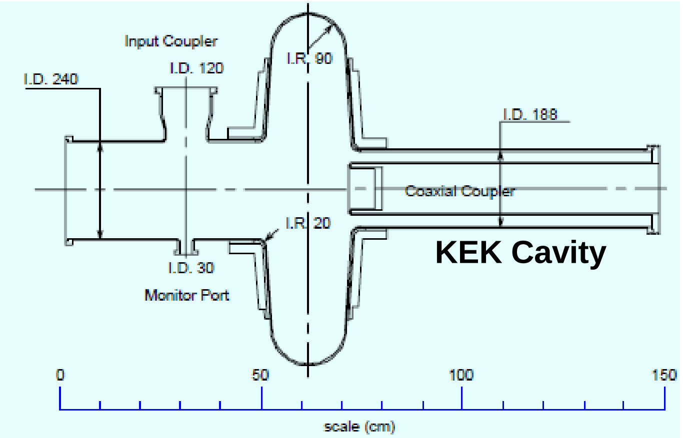
Parameter	499 MHz	400 MHz	400 MHz #	KEK Cavity ŧ	Unit
Frequency of π mode	499.2	400.7	400.0	501.7	MHz
$\lambda/2$ of π mode	300.4	374.7	374.7	299.8	mm
Frequency of 0 mode	517.8	413.05	411.0	~ 700	MHz
Cavity reference length	394.4	456.7	444.7	299.8	mm
Cavity width	290.0	400.0	300.0	866.0	mm
Cavity height	304.8	384.4	383.2	483.0	mm
Bars length	284.0	332.0	330.0	–	mm
Bars width	67.0	85.0	55.0	–	mm
Aperture diameter	40.0	100.0	84.0	130.0	mm
Deflecting voltage (V_T^*)	0.3	0.375	0.375	0.3	MV
Peak electric field (E_P^*)	1.85	2.18	2.2	4.32	MV/m
Peak magnetic field (B_P^*)	6.69	7.5	7.9	12.45	mT
B_P^* / E_P^*	3.62	3.44	3.6	2.88	mT / (MV/m)
Geometrical factor ($G = QR_S$)	67.96	83.9	74.09	220	Ω
$[R/Q]_T$	933.98	317.92	413.34	46.7	Ω
$R_T R_S$	6.3 10^4	2.67 10^4	2.06 10^4	1.03 10^4	Ω^2
At E_T^* = 1 MV/m			# For Current LHC Specifications		

499 MHz





400 MHz



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

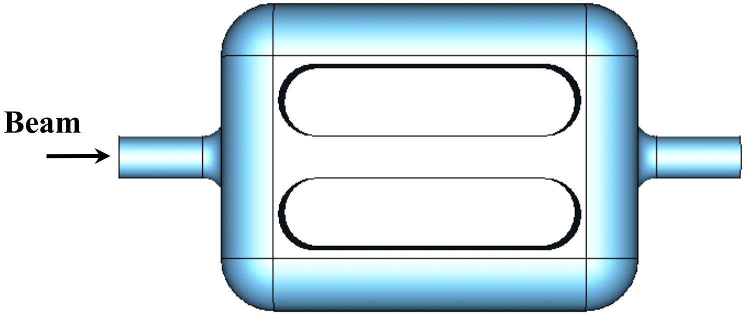
Cavity Requirements

- Required net deflection
  - JLab – 499 MHz : 5.6 MV
  - LHC – 400 MHz : 8.0 MV

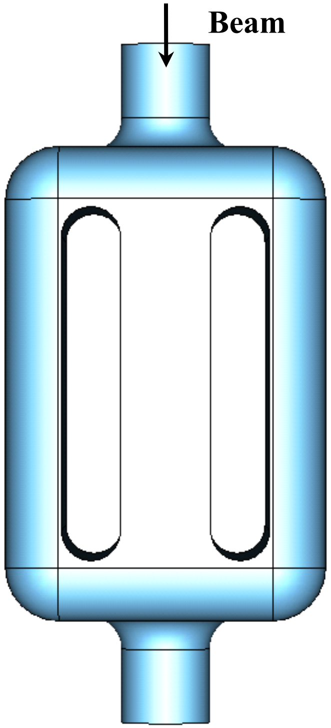
- At E_T = 1 MV/m
  - JLab – 499 MHz geometry V_T = 0.3 V
  - LHC – 400 MHz geometry V_T = 0.375 V

- Achievable transverse deflection per cavity,

Geometry	E_P/ E_T	B_P/ E_T mT/ (MV/m)	V_T (MV)	
			@ E_P = 35 MV/m	@ B_P = 80 mT
499 MHz	1.85	6.69	5.7	3.6
400 MHz	2.2	7.9	6.0	3.8

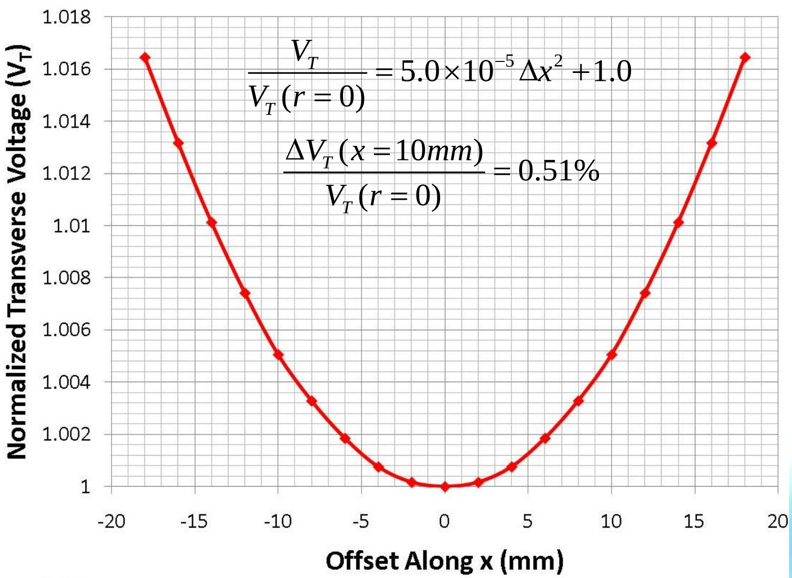


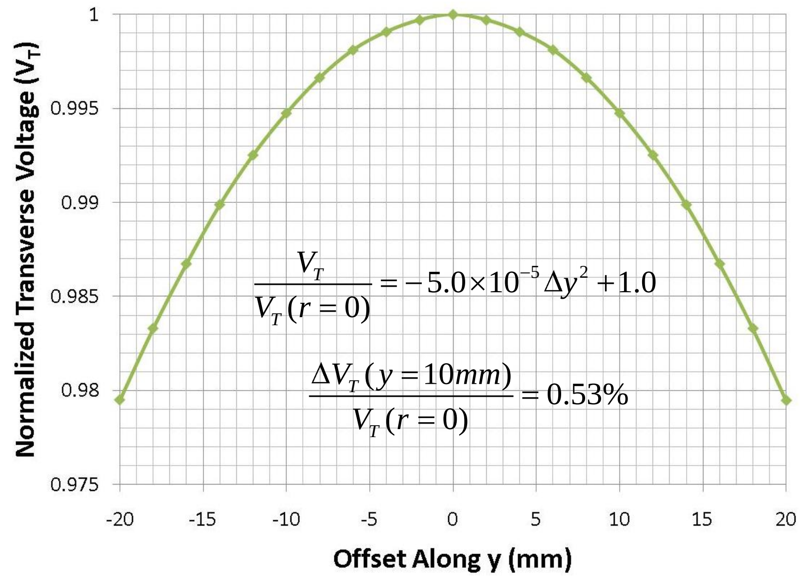
499 MHz
Vertical Deflection



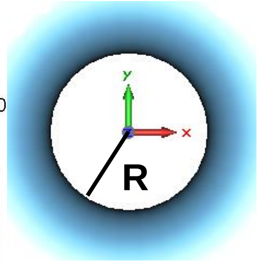
400 MHz
Horizontal Deflection

Transverse Deflecting Voltage along Beam Line Cross Section

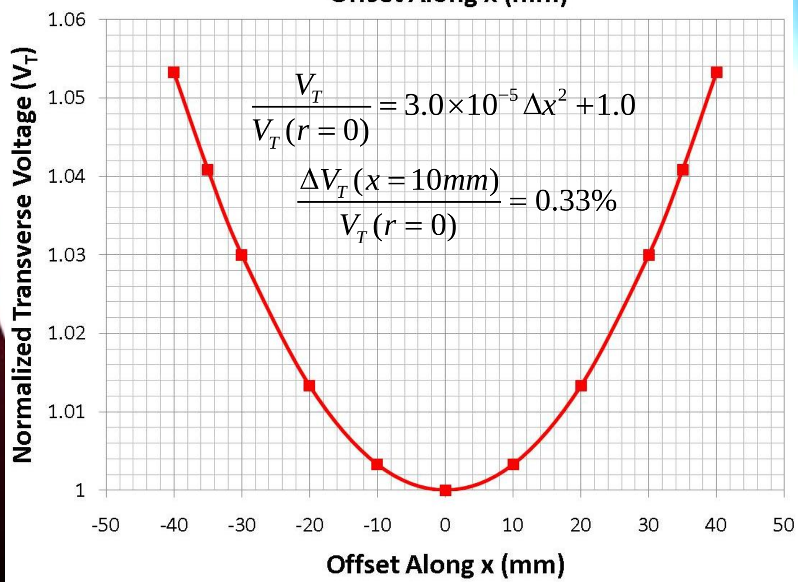


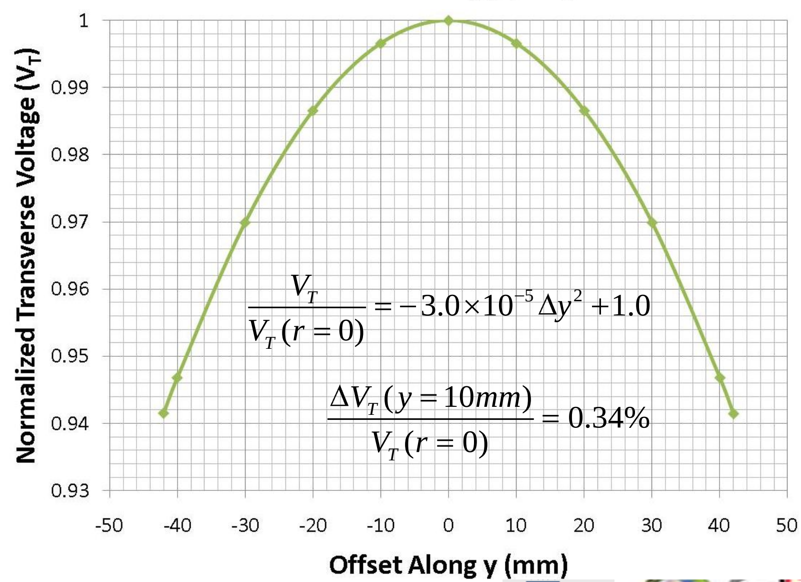


499 MHz
R = 20 mm



400 MHz
R = 42 mm





Higher Order Modes

- Longitudinal [R/Q]

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

- Transverse [R/Q]
  - Direct Integral Method

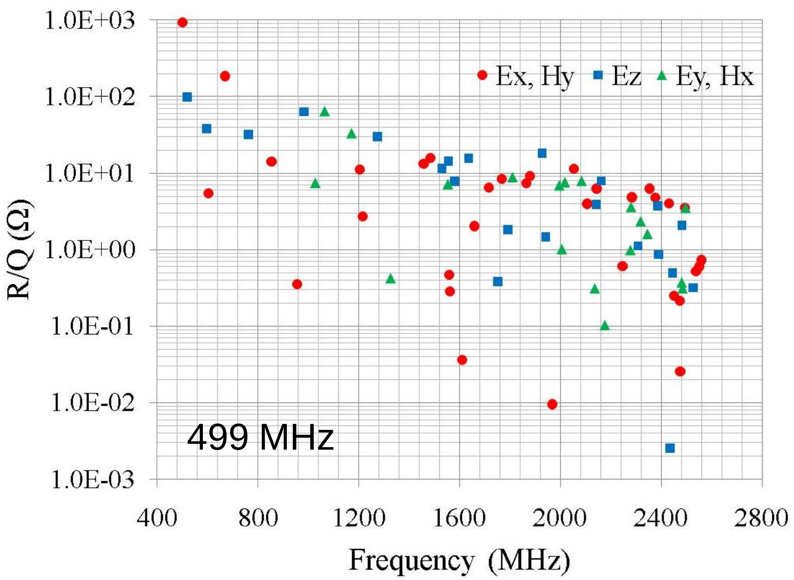
$$\left[\frac{R}{Q}\right]_T = \frac{|V_T|^2}{\omega U} = \frac{\left|\int_{-\infty}^{+\infty} \left[\vec{E}_x(z, x=0) + j\left(\vec{v} \times \vec{B}_y(z, x=0)\right)_T\right] e^{-\frac{j\omega z}{c}} dz\right|^2}{\omega U}$$

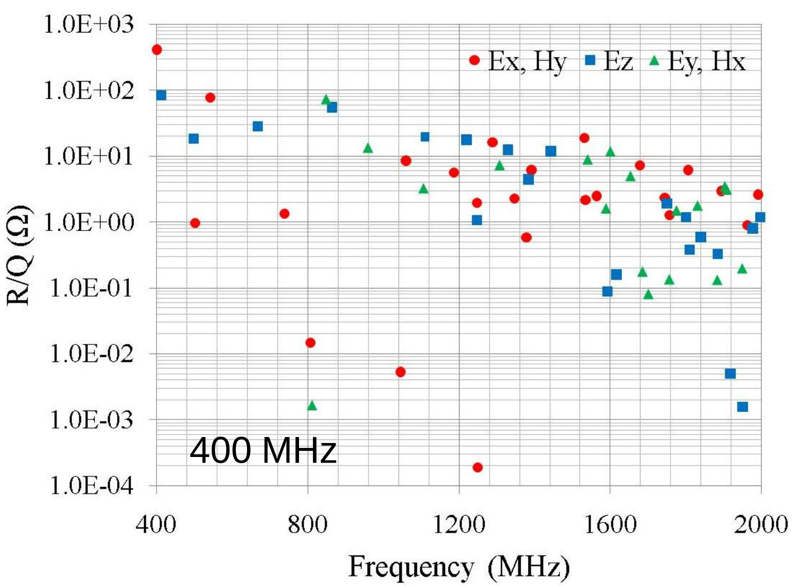
  - Using Panofsky Wenzel Theorem (x_0=5 mm)

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

  - Values are < 1% in agreement

Field on Beam Axis	Type of Mode
E_x, H_y	Deflecting
E_z	Accelerating
E_y, H_x	Deflecting
H_z	Does not couple to the beam

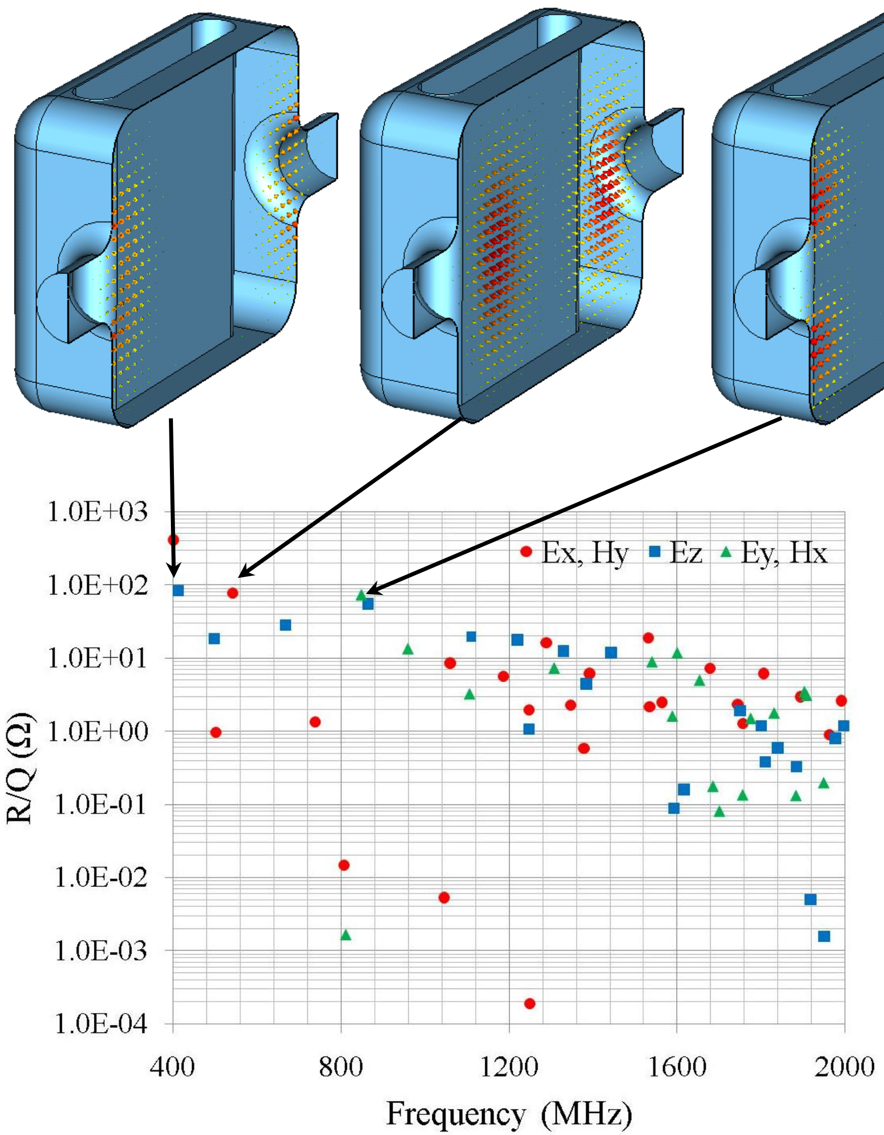




No Lower Order Modes

Modes of Interest – 400 MHz

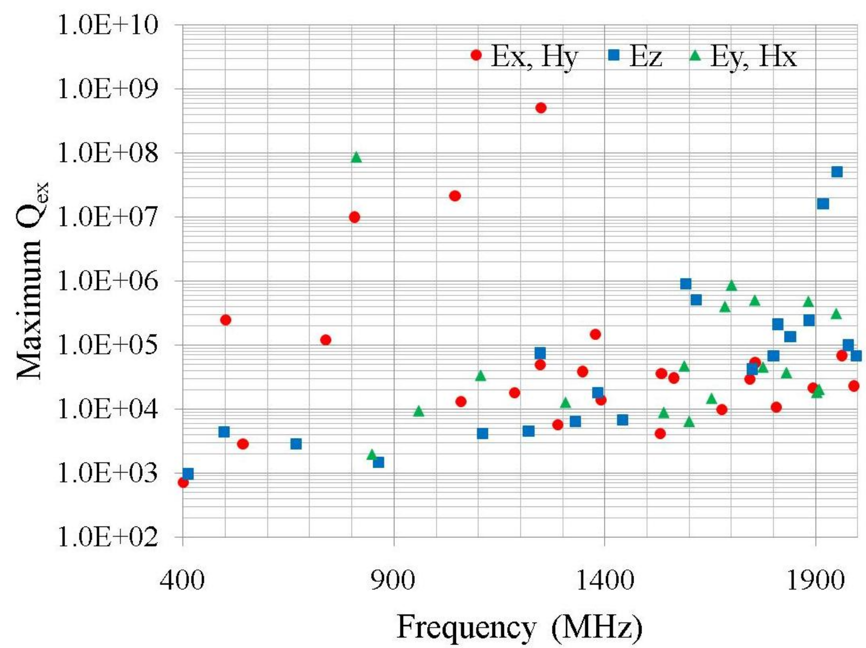
E Field Profiles



Frequency (MHz)	Type of Mode	[R/Q] (Ω)
411.0	E_z	82.7
541.8	E_x, H_y	77.1
847.6	E_y, H_x	72.4
863.7	E_z	54.9

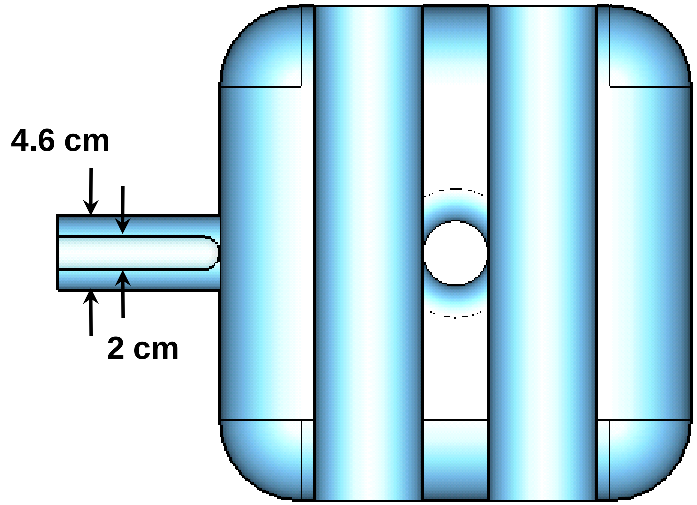
* Longitudinal Impedance: 80 kΩ

* Transverse Impedance: 2.5 MΩ/m

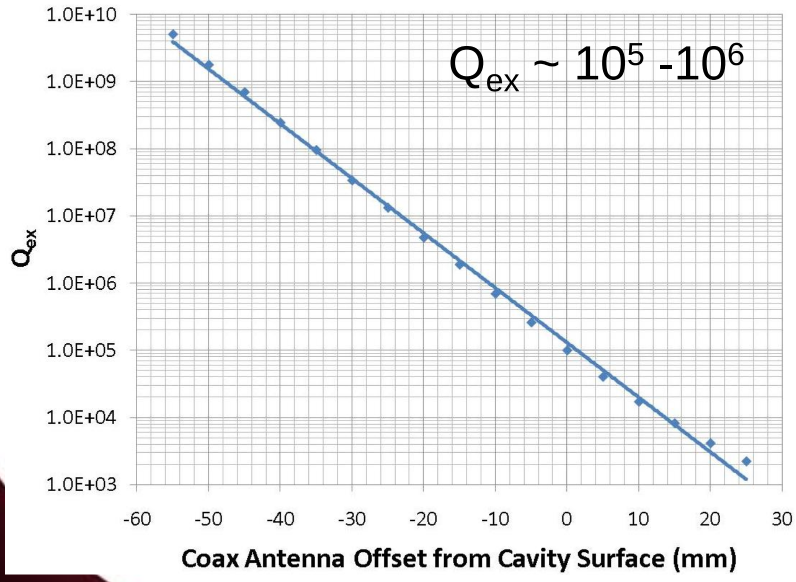


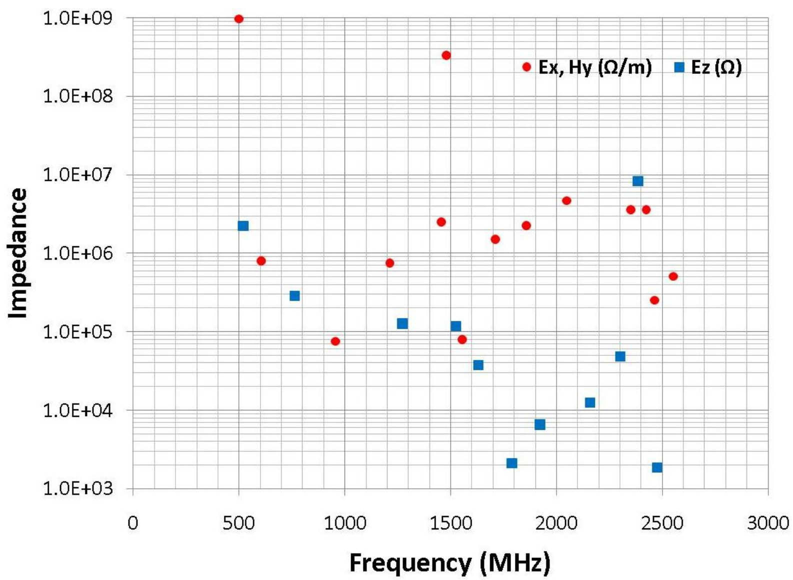
*** E. Shaposhnikova – LHC-CC09**

Fundamental Power Coupler – 499 MHz

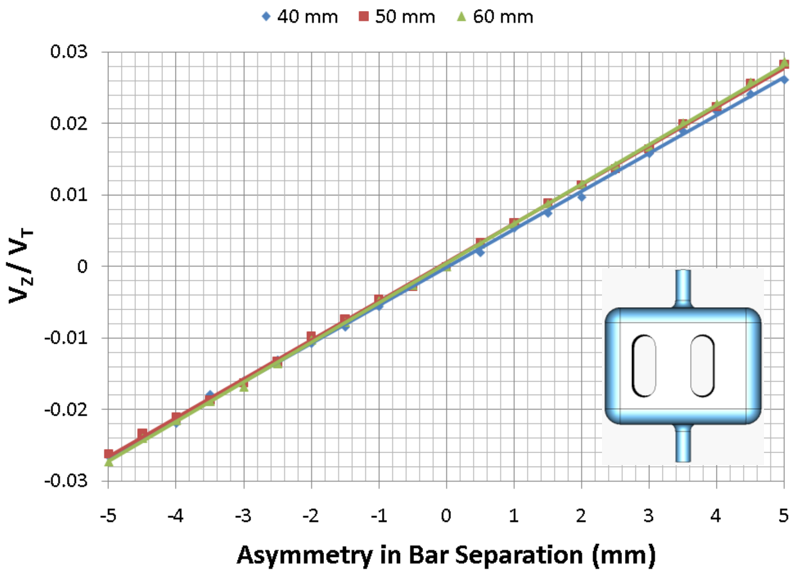


- 50 Ω coaxial variable input coupler on the side wall
- Impedance
  - Longitudinal modes: $Z_Z = \left[\frac{R}{Q}\right] Q_{L,n}$
  - Transverse modes: $Z_T = \frac{\omega}{c}\left[\frac{R}{Q}\right]_T Q_{L,n}$
- E_y, H_x (vertical deflecting) modes do not couple to the input coupler

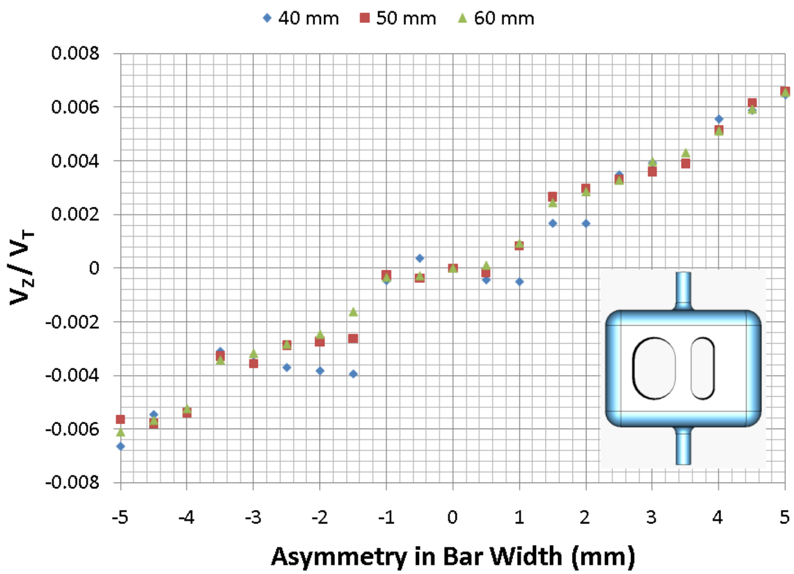


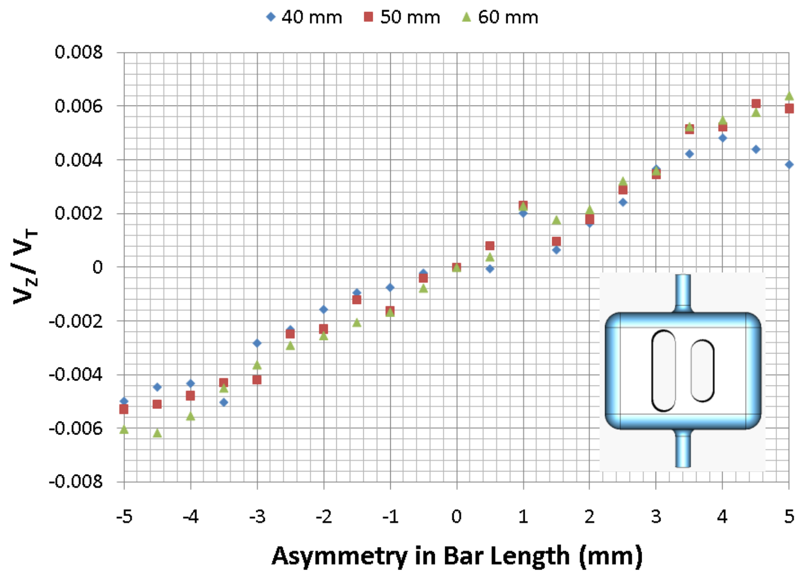


Asymmetry Study – 499 MHz



- Mixing in transverse and longitudinal modes caused by the asymmetries in,
  - Width of the bars
  - Length of the bars
  - Separation between the bars
- Asymmetry in separation between the bars results a higher longitudinal field
- Change in frequency separation of the fundamental modes < 1 MHz



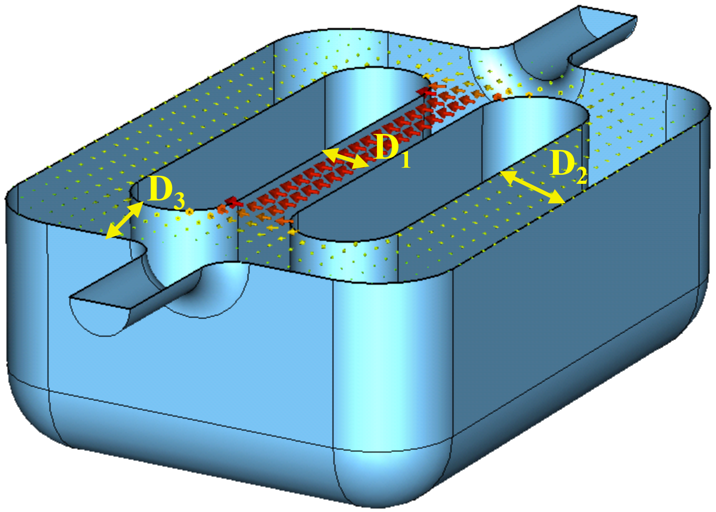


In all cases the amount of mixing is small

Preliminary Multipacting Analysis

- Multipacting was analyzed for the fundamental deflecting mode
- Gaps in the mid plane of the cavity were analyzed for possible **Two Point Multipacting**
- Gap Voltage: $V_n = \frac{m\omega^2 D^2}{(2n-1)\pi e}$ Impact Energy: $K_n = \frac{2m\omega^2 D^2}{(2n-1)^2 \pi^2}$

	Gap Width (cm)	1st Order Resonance (kV)	Impact Energy (keV)
D_1	4.0	28.5	18.1
D_2	5.8	59.8	38.1
D_3	5.52	54.2	34.5

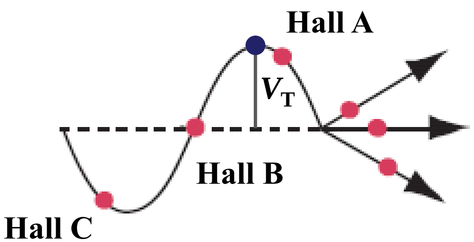


499 MHz

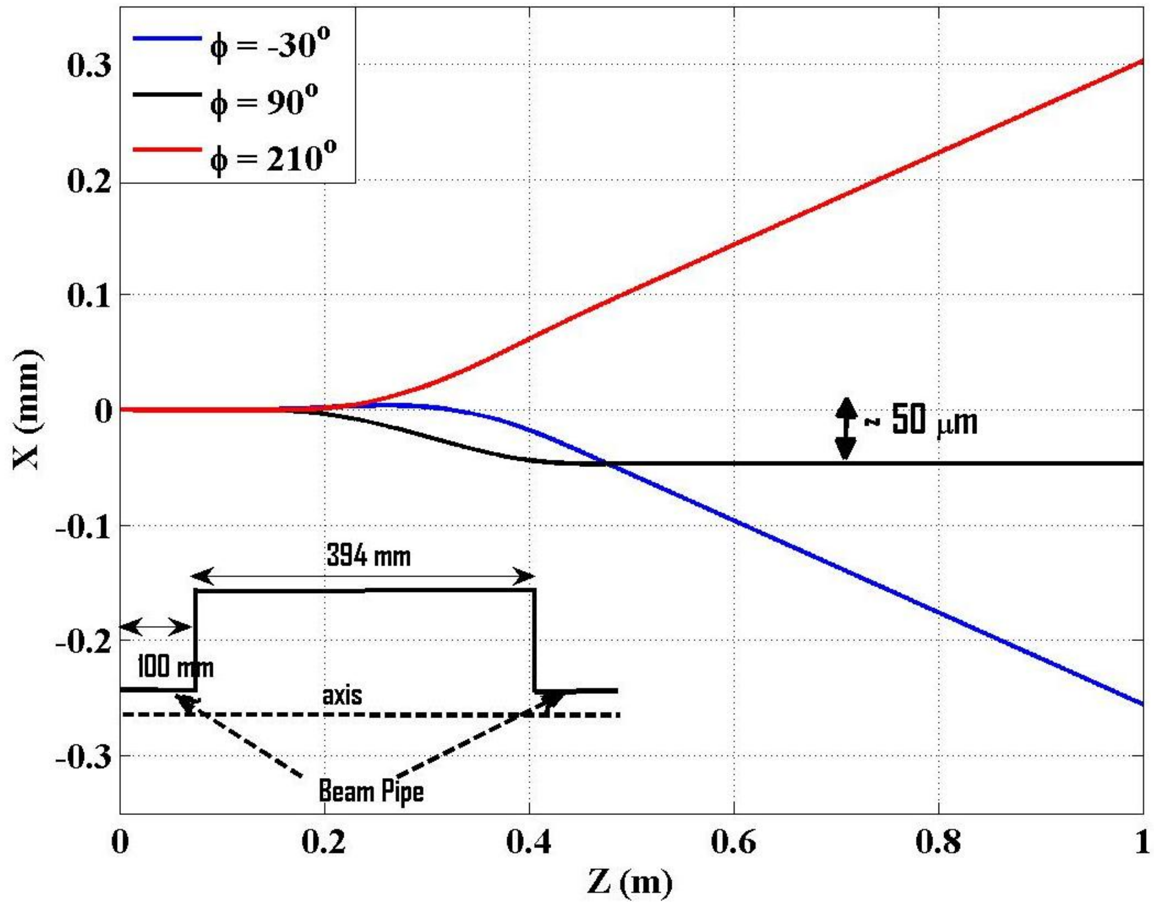
- Impact energies for the gaps >> 1 keV
- A detailed MP analysis will be done using Track3P in SLAC - ACE3P suite

Transverse Displacement

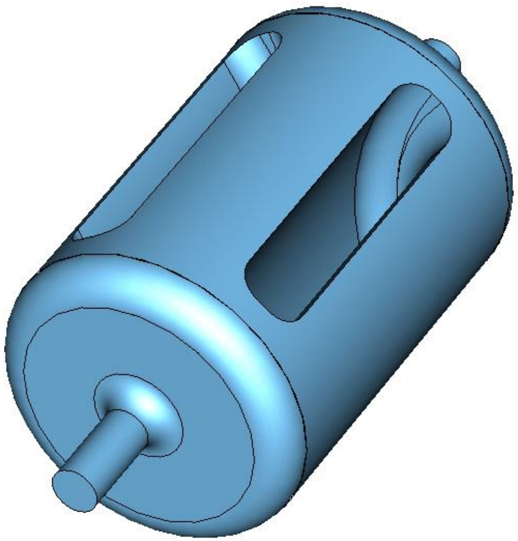
Displacement in the transverse direction is analyzed for the 499 MHz design

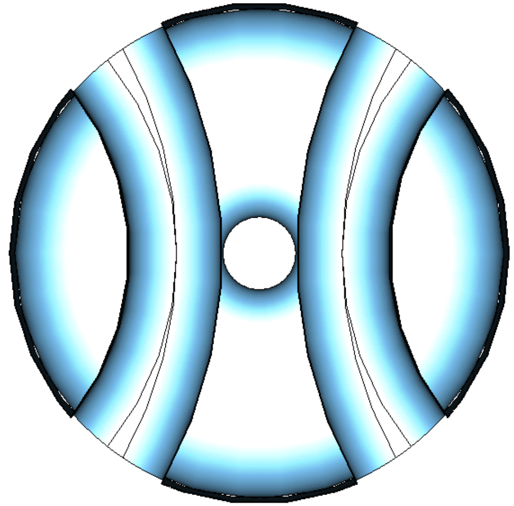


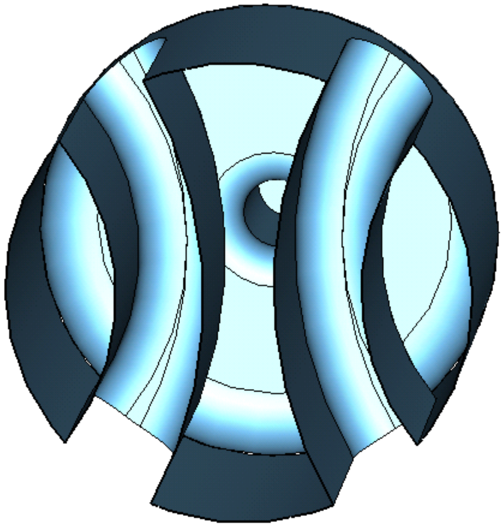
- Displacement for Halls A and C are symmetric
- Hall B has a small offset of 50 µm



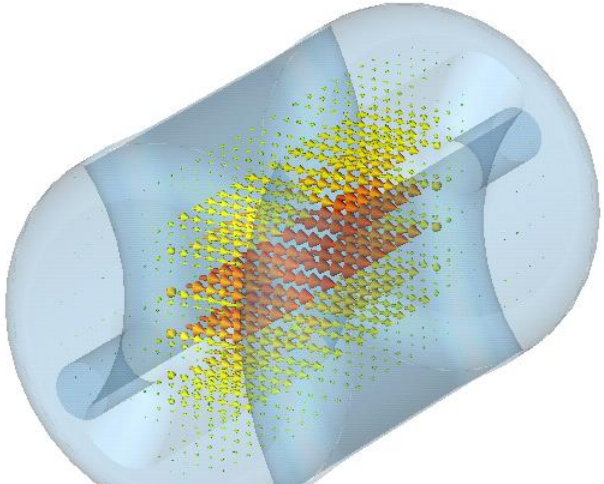
Cylindrical Parallel-Bar Cavity



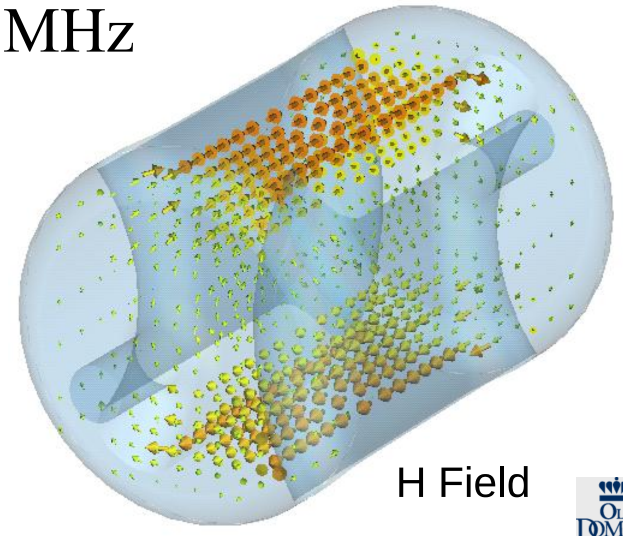




499 MHz



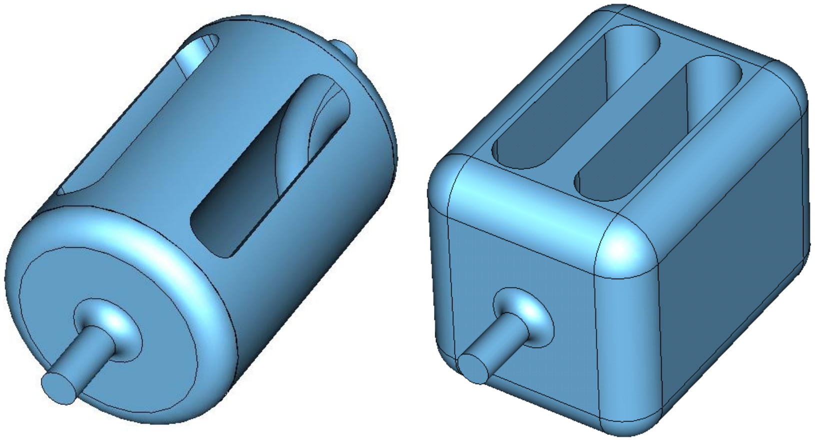
E Field



H Field

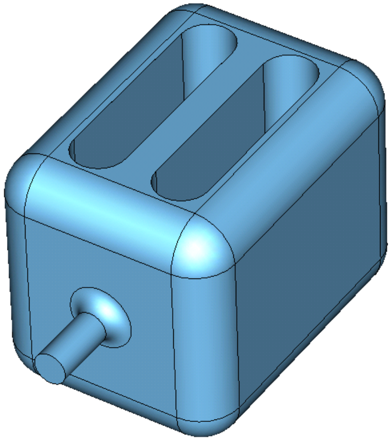
Cavity Properties – Cylindrical Design

Parameter	Rectangular Shaped	Cylindrical Shaped	Unit
Frequency of π mode	499.2	499.3	MHz
$\lambda/2$ of π mode	300.4	300.4	mm
Frequency of 0 mode	517.8	815.1	MHz
Nearest mode to π mode	517.8	720.1	MHz
Cavity reference length	394.4	394.0	mm
Cavity width / diameter	290.0	267.0	mm
Cavity height	304.8	267.0	mm
Bars length	284.0	284.0	mm
Bars width	67.0	50.0	mm
Aperture diameter	40.0	40.0	mm
Deflecting voltage (V_T^*)	0.3	0.3	MV
Peak electric field (E_P^*)	1.85	2.38	MV/m
Peak magnetic field (B_P^*)	6.69	5.33	mT
B_P^* / E_P^*	3.62	2.24	mT / (MV/m)
Geometrical factor ($G = QR_S$)	67.96	88.4	Ω
$[R/Q]_T$	933.98	886.13	Ω
$R_T R_S$	6.3 10^4	7.8 10^4	Ω^2
At E_T^* = 1 MV/m			

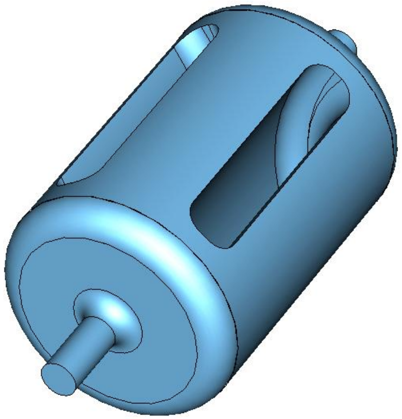


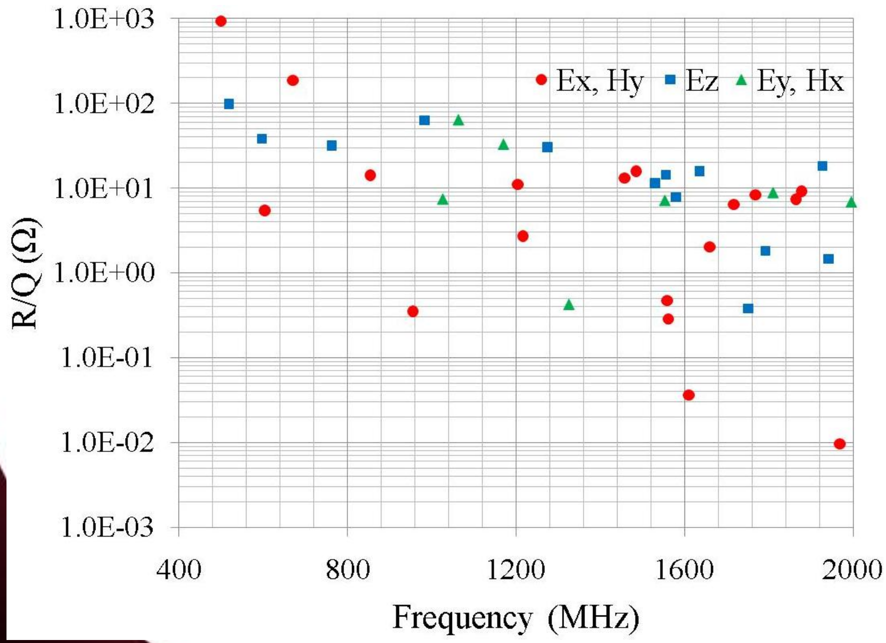
- Surface electric and magnetic fields are well balanced for E_P < 35 MV/m and B_P < 80 mT (B_P/E_P = 2.3 mT/(MV/m))
- Surface magnetic fields have improved by 20%
- Frequency separation of the first two modes ~ 220 MHz compared to 18 MHz in the rectangular design
- Reduced cavity width and no large flat surfaces (Reduce stresses)
- Higher shunt impedance

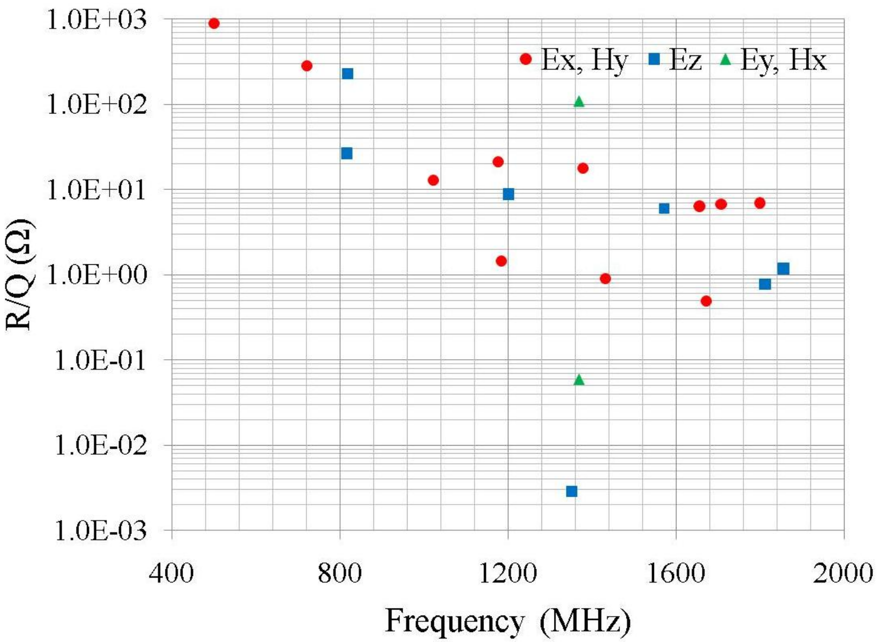
Higher Order Modes – 499 MHz



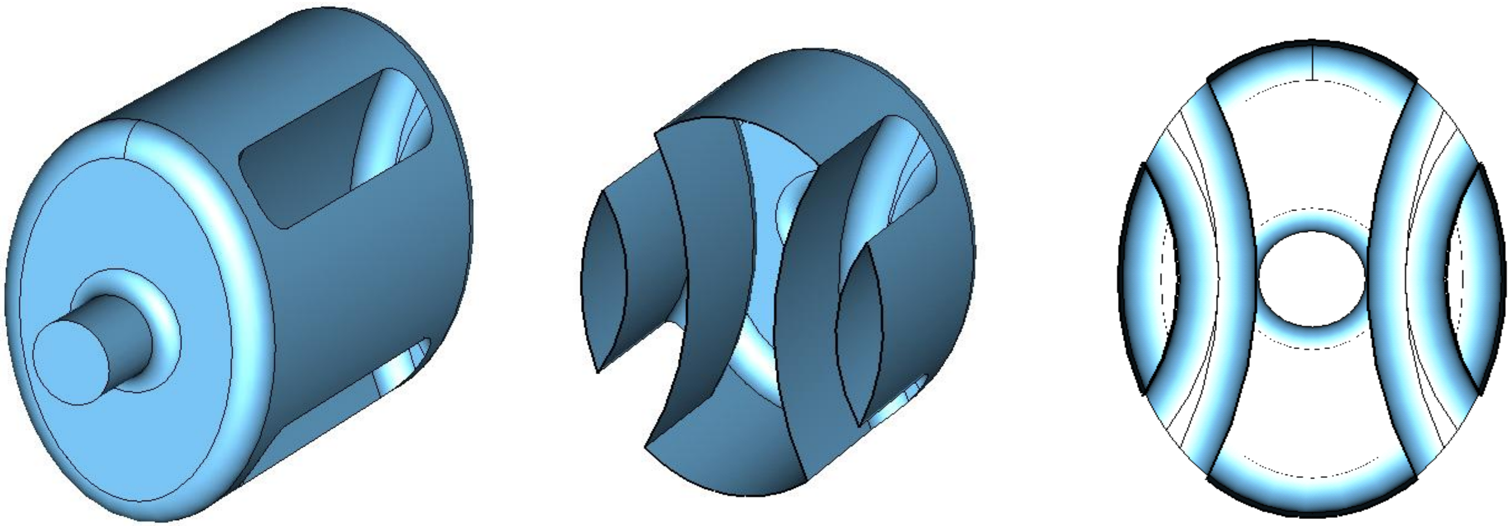
Fewer low frequency modes compared to the rectangular design with larger separation of modes



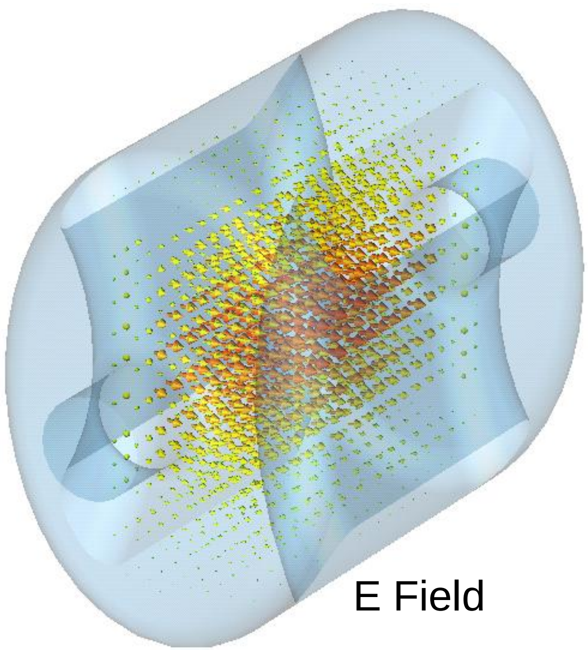




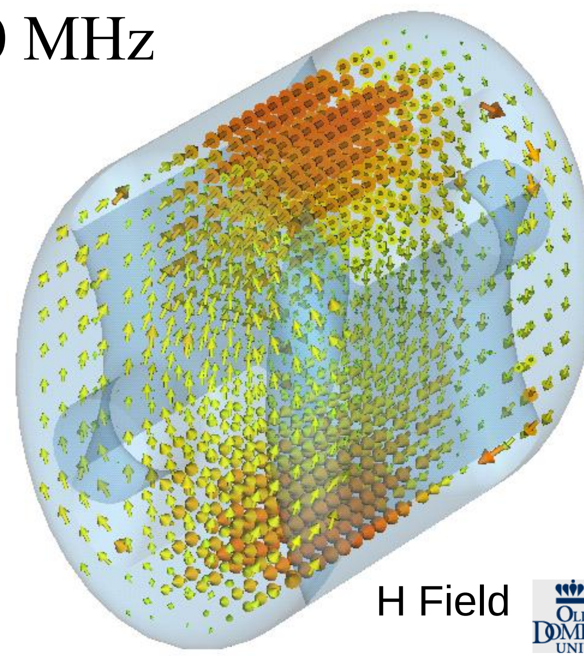
Elliptical Parallel-Bar Cavity



400 MHz



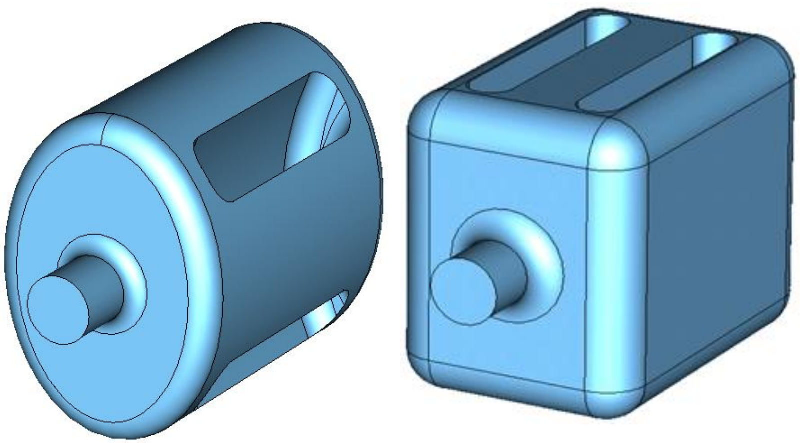
E Field



H Field

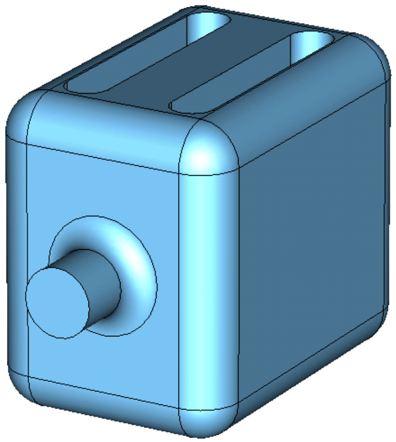
Cavity Properties – Elliptical Design

Parameter	Rectangular Shaped	Elliptical Shaped	Unit
Frequency of π mode	400.0	400.1	MHz
$\lambda/2$ of π mode	374.7	374.7	mm
Frequency of 0 mode	411.0	677.1	MHz
Nearest mode to π mode	411.0	609.2	MHz
Cavity reference length	444.7	445.0	mm
Cavity width / diameter	300.0	295.0	mm
Cavity height	383.2	406.0	mm
Bars length	330.0	330.0	mm
Bars width	55.0	60.0	mm
Aperture diameter	84.0	84.0	mm
Deflecting voltage (V_T^*)	0.375	0.375	MV
Peak electric field (E_P^*)	2.2	2.7	MV/m
Peak magnetic field (B_P^*)	7.9	6.03	mT
B_P^* / E_P^*	3.6	2.23	mT / (MV/m)
Geometrical factor ($G = QR_S$)	74.1	108.9	Ω
$[R/Q]_T$	413.34	262.63	Ω
$R_T R_S$	$3.1\ 10^4$	$2.7\ 10^4$	Ω^2
At E_T^* = 1 MV/m			

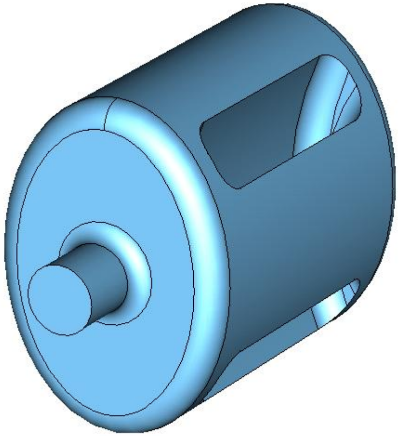


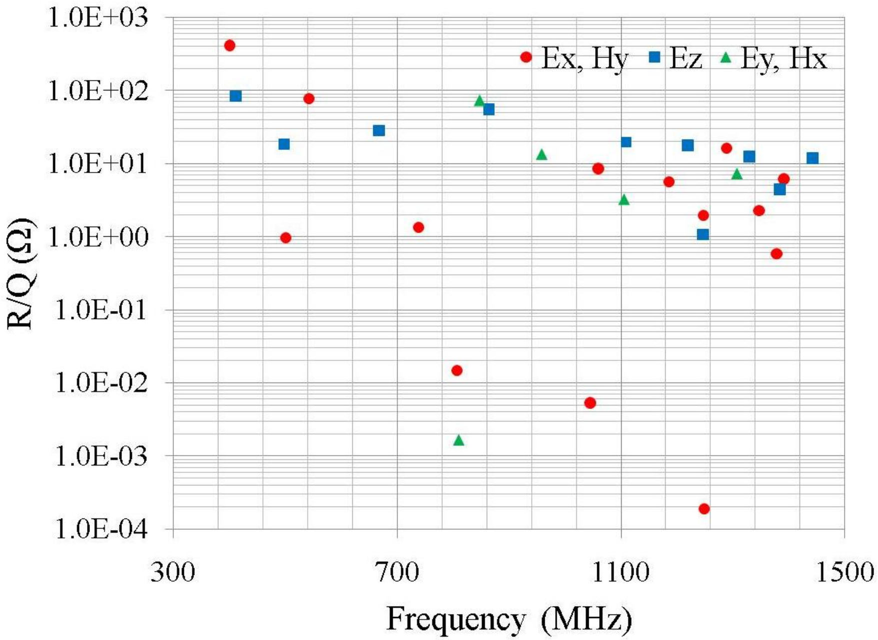
- Surface magnetic fields have improved by 24%
- Frequency separation of the first two modes ~ 209 MHz compared to 11 MHz in the rectangular design
- Reduced cavity width to meet the LHC crab cavity specifications

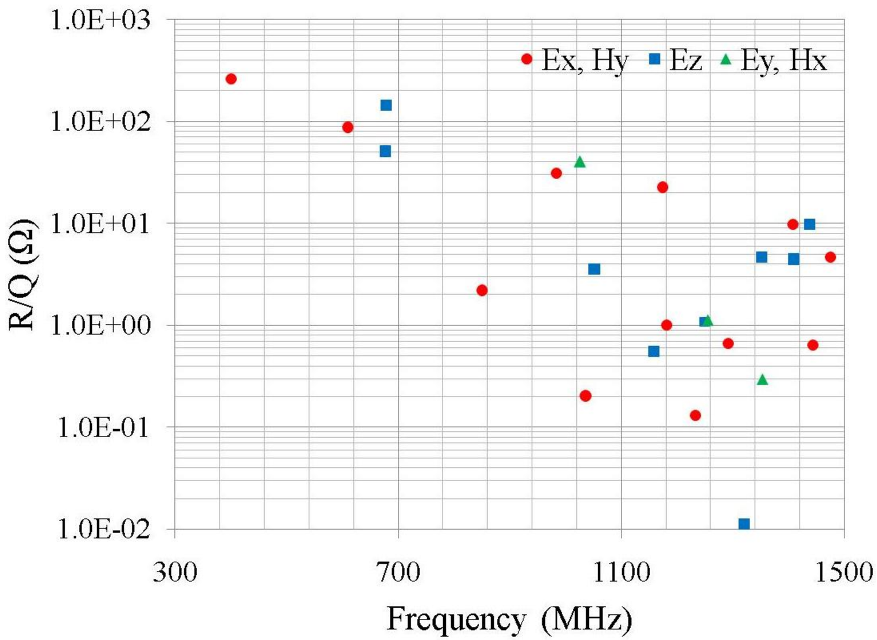
Higher Order Modes – 400 MHz



Fewer low frequency modes compared to the rectangular design with larger separation of modes







Summary

- Both 499 MHz and 400 MHz designs have been improved to meet the
  - Required deflection
  - Dimensional constraints
  - Low surface fields

Geometry	E_P/E_T	B_P/E_T mT/ (MV/m)	V_T (MV)	
			@ E_P = 35 MV/m	@ B_P = 80 mT
499 MHz (Cylindrical)	2.4	5.3	4.4	4.5
400 MHz (Elliptical)	2.7	6.0	4.9	5.0

- Properties of HOMs analyzed to determine damping thresholds
  - Detail study of HOM damping with coupler ports under way
- Preliminary multipacting analysis was completed
- Cylindrical and elliptical geometries with curved parallel bars look promising
  - Further optimization for both designs on going