Parallel-bar TEM-type Cavities

Jean Delayen
Subashini de Silva

Center for Accelerator Science
Old Dominion University
and
Thomas Jefferson National Accelerator Facility

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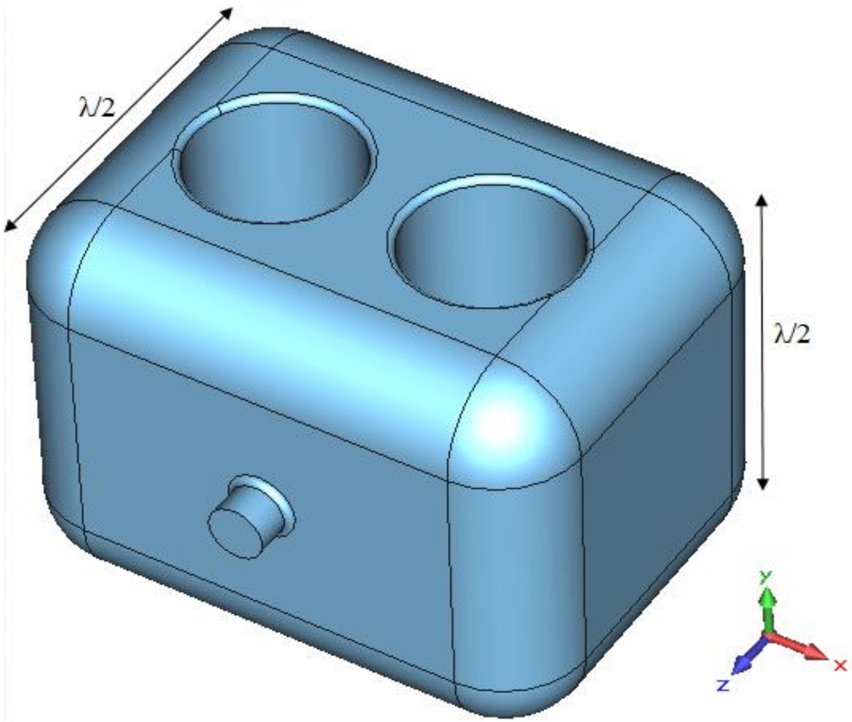
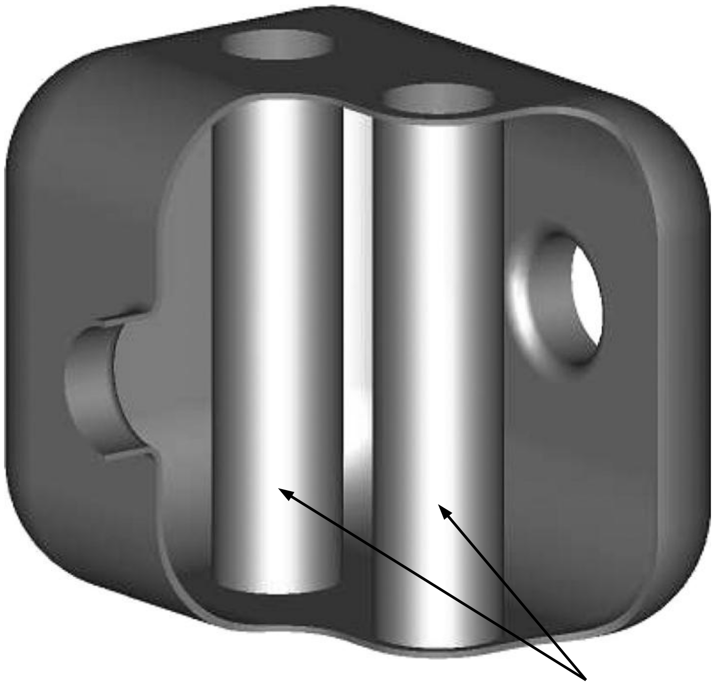
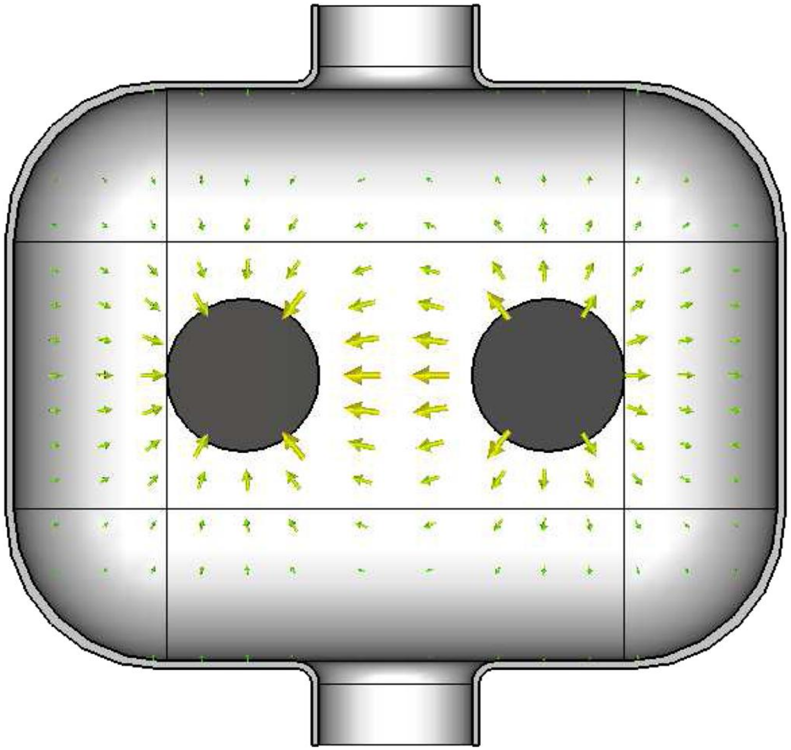
Parallel Bar Cavity Concept



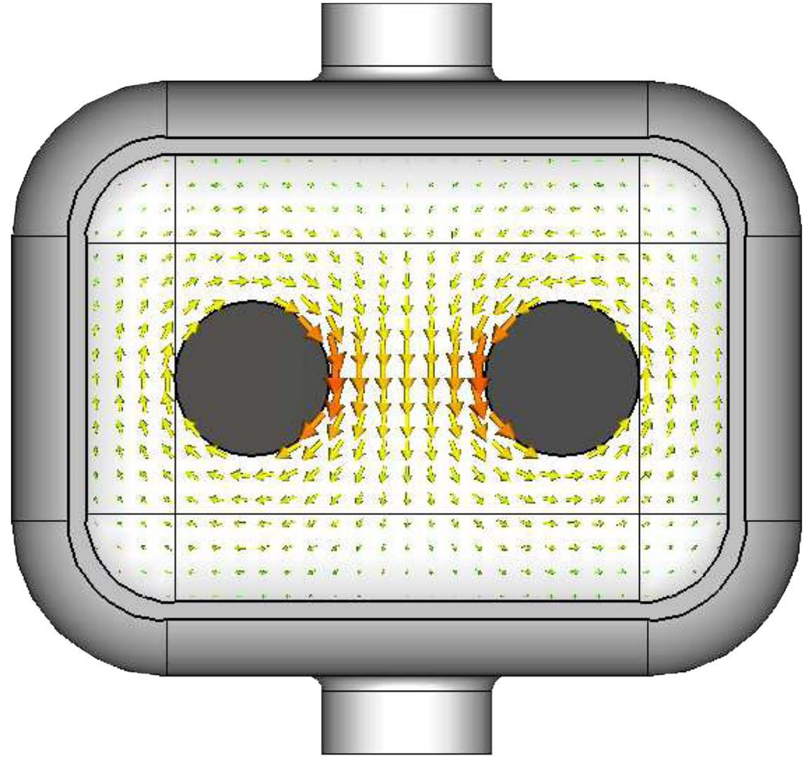


- **Compact design supports low frequencies**
- For deflection and crabbing of particle bunches
- Cavity design – Two Fundamental TEM Modes
  - 0 mode :- Accelerating mode
  - π mode :- Deflecting or crabbing mode

Parallel Bar Cavity Concept



E field on mid plane
(Along the beam line)



B field on top plane

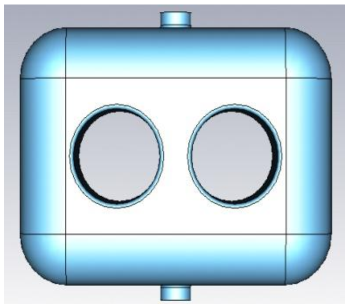
Deflection is due to the interaction with the Electric Field

Parallel Bar Cavity Applications

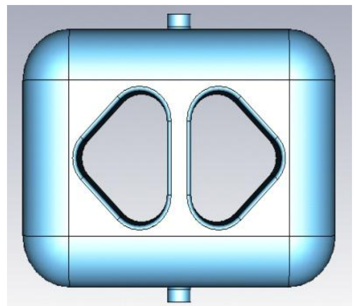
- **Deflecting Cavity** – Jefferson Lab 12 GeV Upgrade (499 MHz)
  - supported by DOE ARRA to JLab and STTR Phase I to Niowave, (Delayen PI)
- **Crab Cavity**
  - LHC IR Upgrade (400 MHz)
    - supported by Phase I STTR to Niowave (Delayen PI)
  - Jefferson Lab EIC (500 MHz)
- **Advantages**
  - Compact size
  - Lower Frequencies
  - Fundamental mode with lowest frequency
  - Low surface fields
  - Higher shunt impedances

Parallel Bar Cross Sections

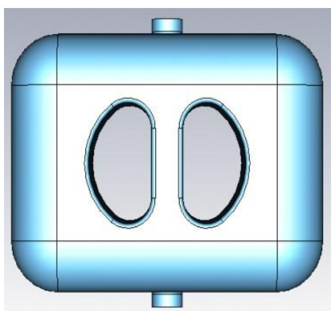
Optimizing condition – Obtain a higher deflection with lower surface fields



(a)



(b)



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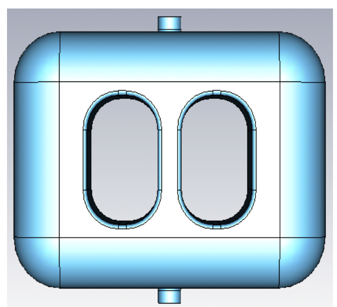


(d)

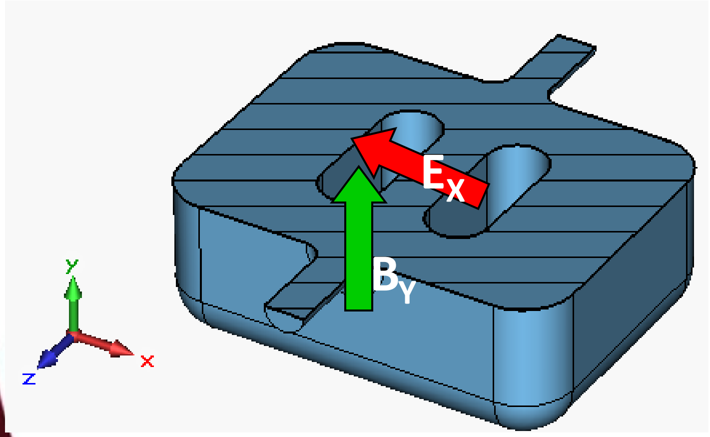
Peak Surface Fields

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		

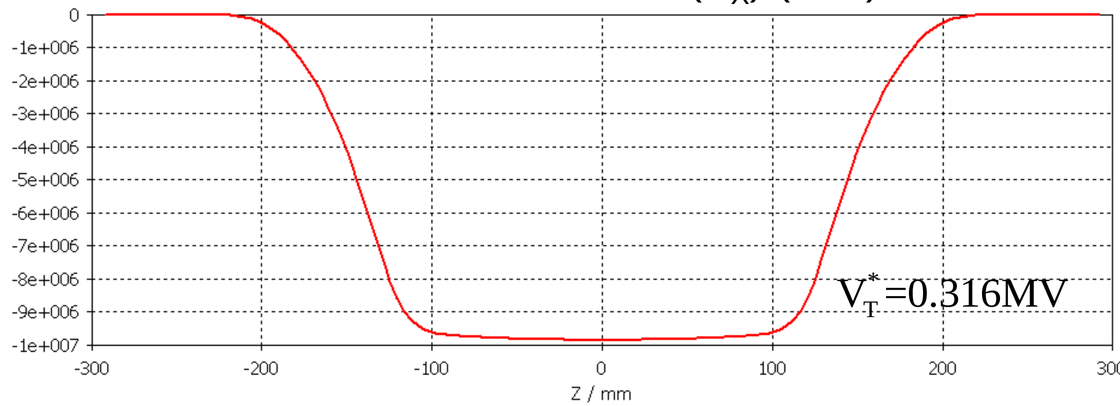
- Increasing effective deflecting length along the beam line increases net transverse deflection seen by the particle
- Racetrack shaped structure (d) has better performance with higher deflection for lower surface fields

Transverse Deflection

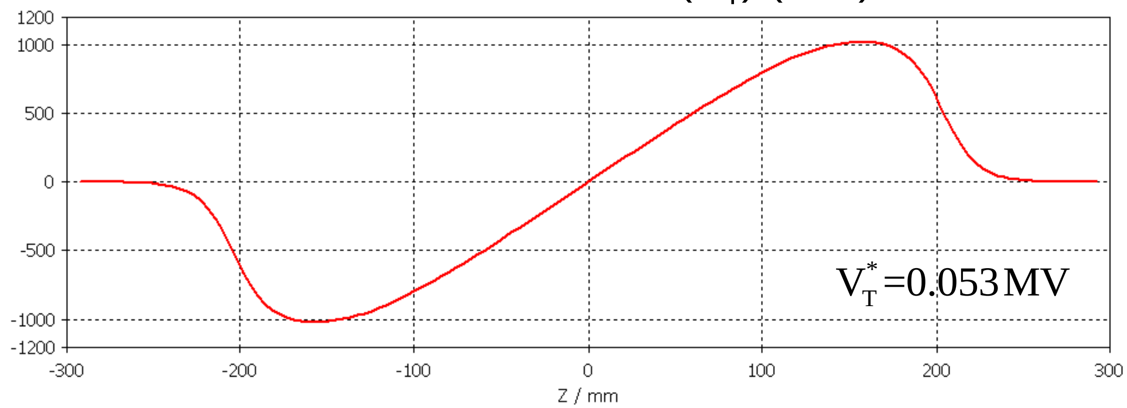
$$\vec{V}_T = \int_{-\infty}^{+\infty} \left[\vec{E}_x(z) + \vec{v} \times \vec{B}_y(z) \right] e^{j\frac{\omega z}{c}} dz$$



Transverse E Field (E_X) (V/m)



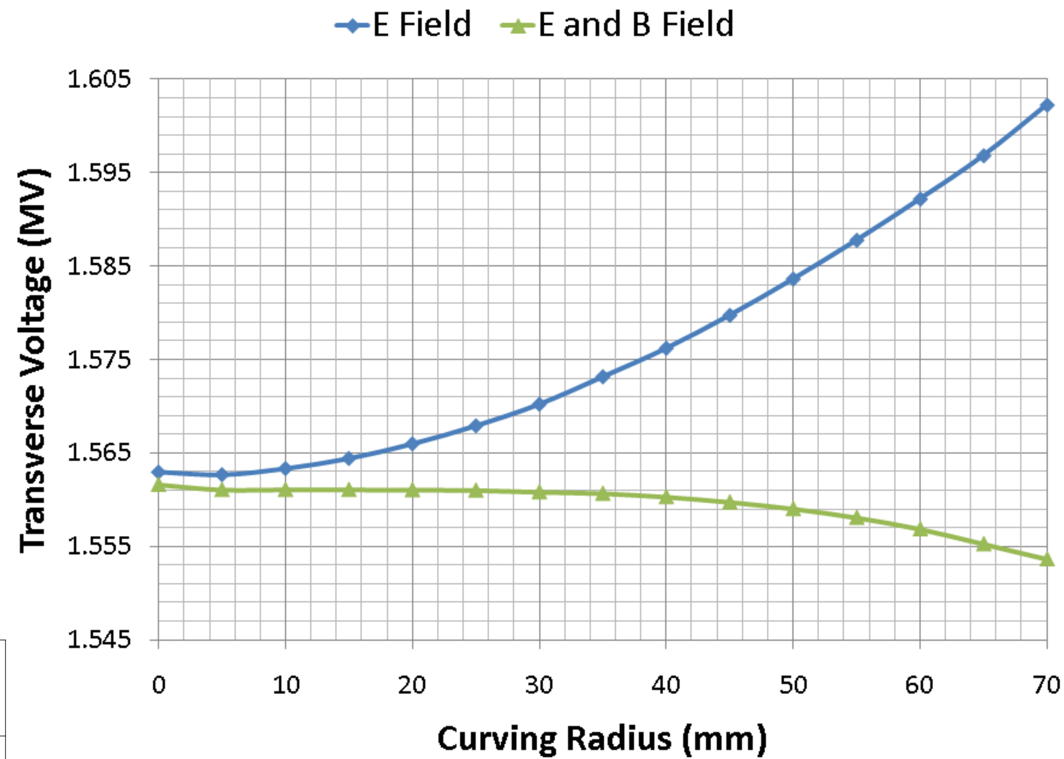
Transverse H Field (H_Y) (A/m)



Resultant V_T^* = 0.3 MV
At E_T^* = 1 MV/m

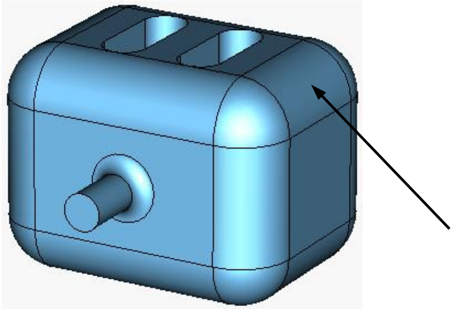
Transverse Deflection

- Transverse deflecting voltage (V_T) for a single cell cavity (At E_T = 1 MV/m) is 0.3 MV
- Achievable transverse deflection per cavity at 499 MHz
  - For a surface electric field of E_P = 40 MV/m, V_T = 5.84 MV
  - For a surface magnetic field of B_P = 100 mT, V_T = 4.58 MV



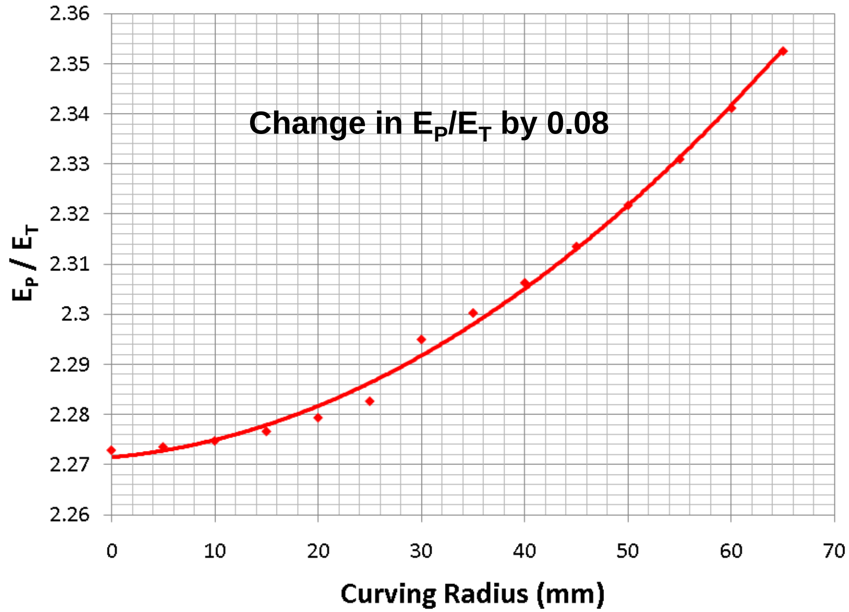
Design Parameters	Value (mm)
Cavity reference length	300.4
Cavity height	300.4
Cavity width	400.0
Bar width	60.0
Bar length	160.0
Beam aperture	40.0

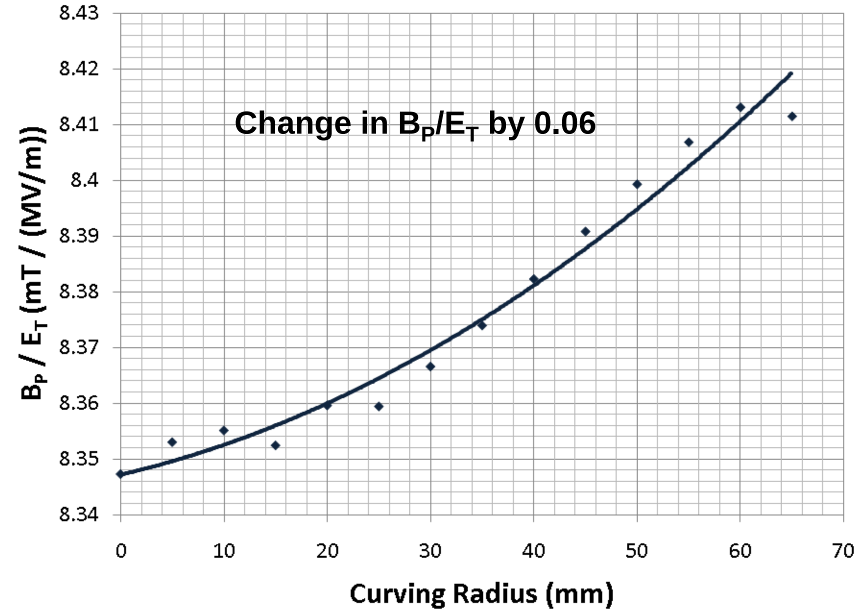
f = 499 MHz

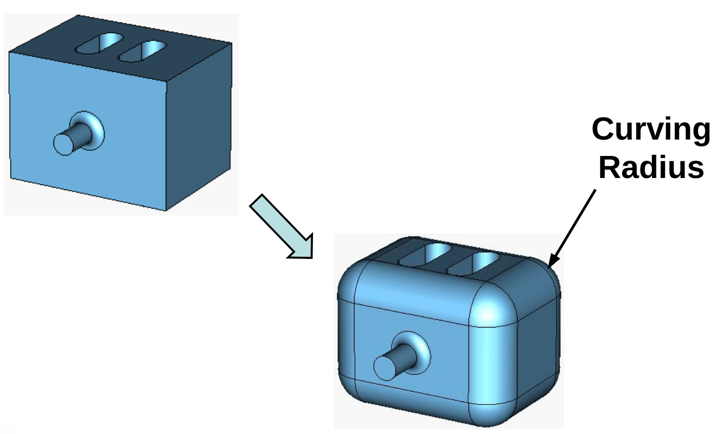


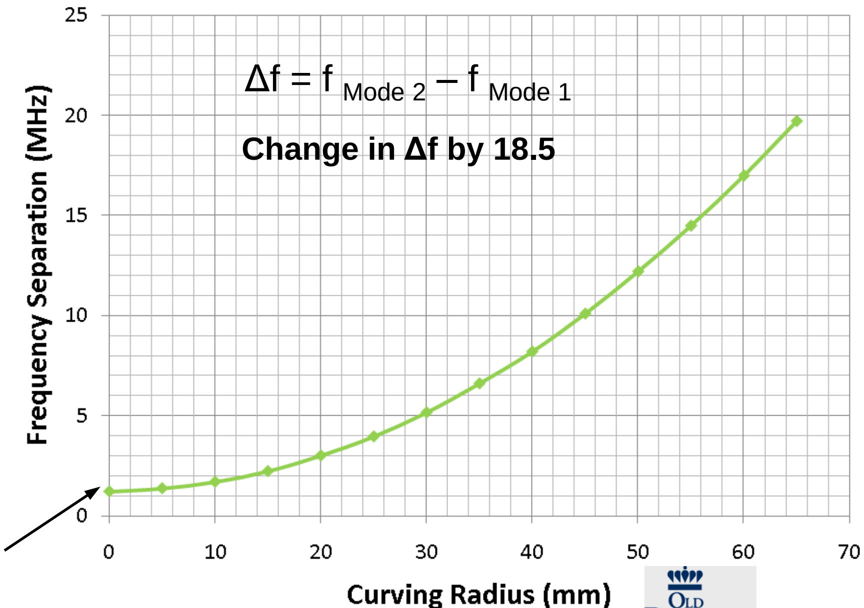
Curving Radius

Mode Separation by Rounding Edges



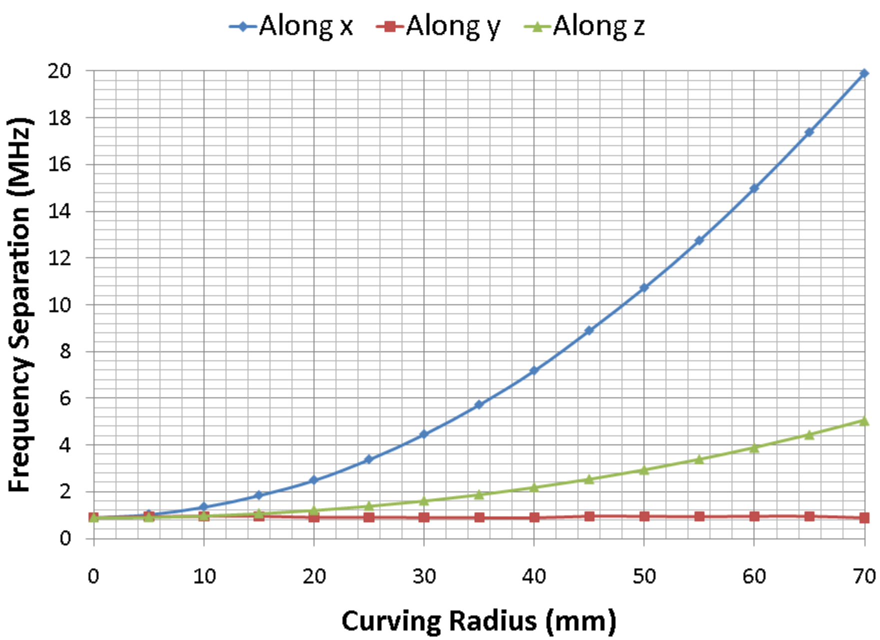


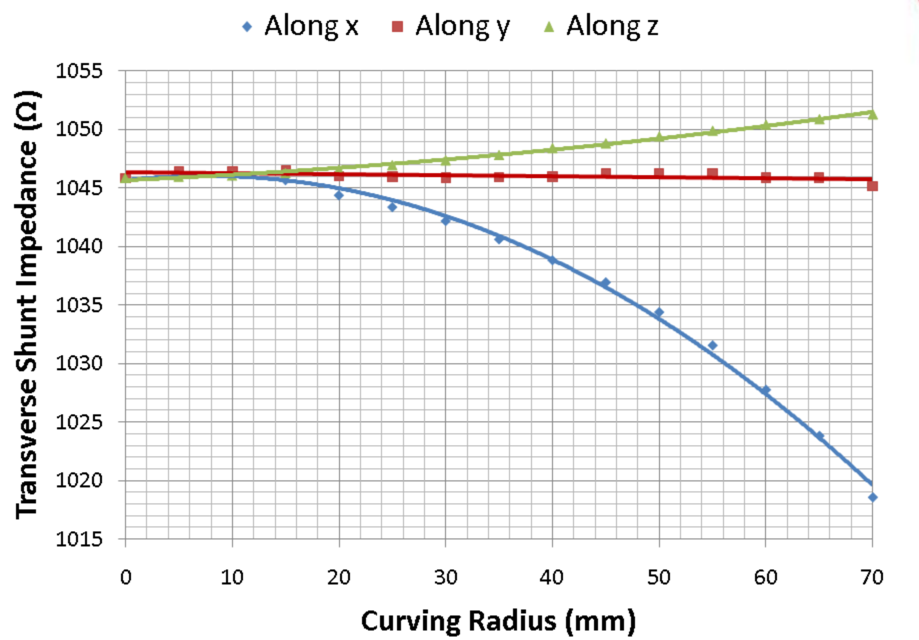


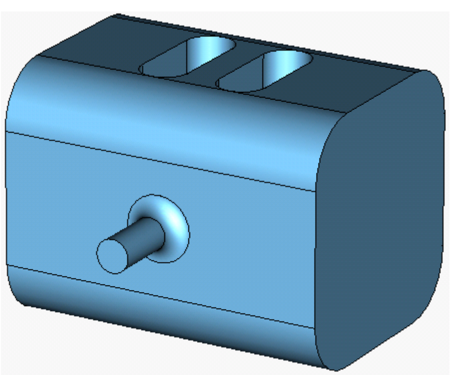


Frequency separation due to beam pipe = 1.21 MHz

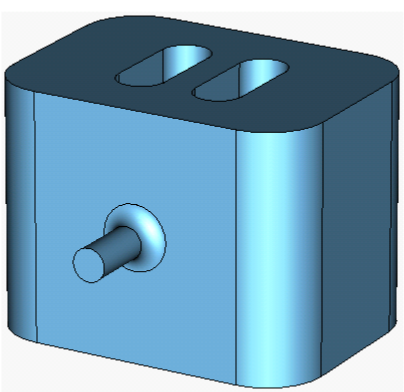
Design Sensitivities – Rounding Edges



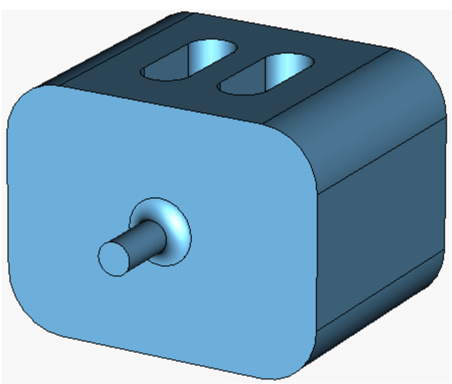




Along x

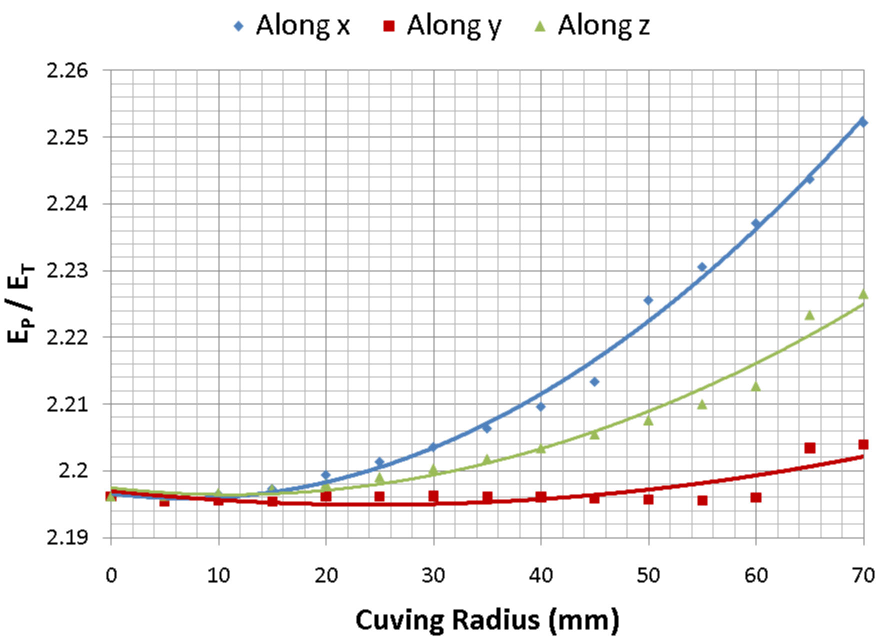


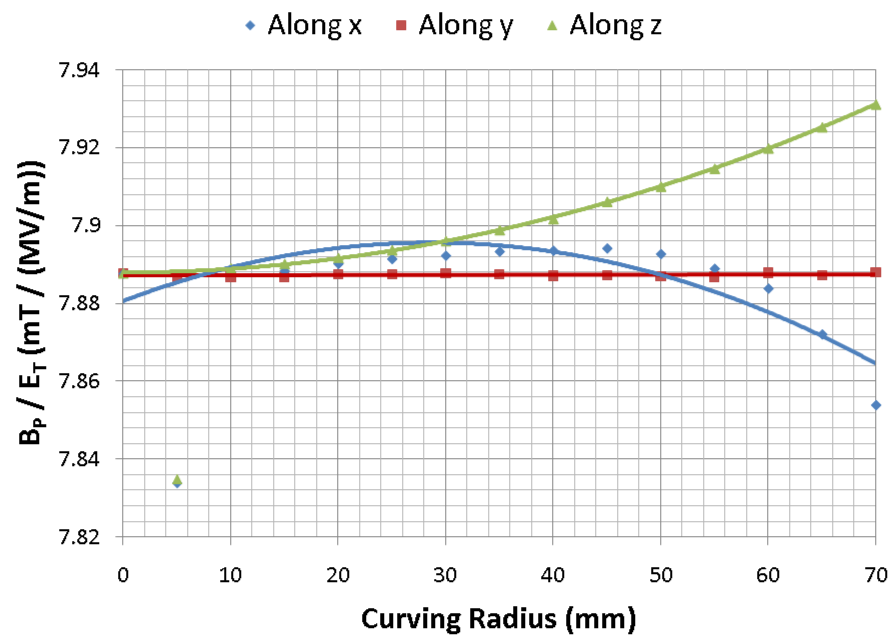
Along y

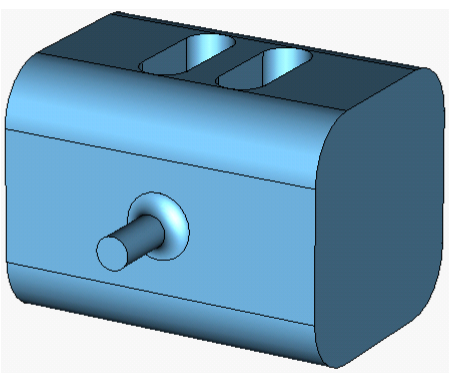


Along z

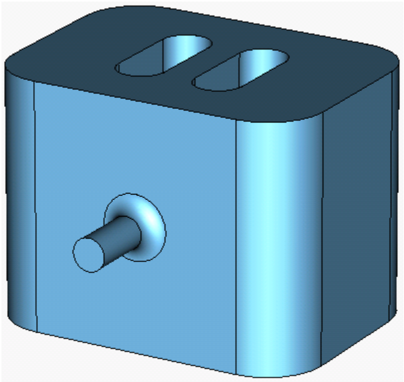
Design Sensitivities – Rounding Edges



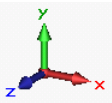


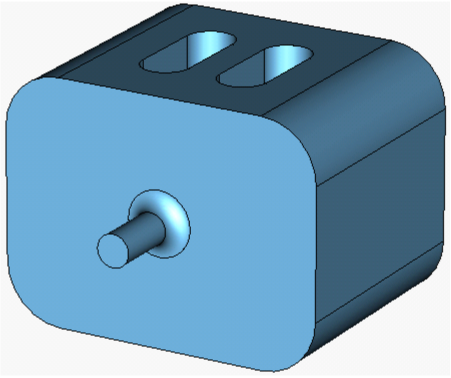


Along x



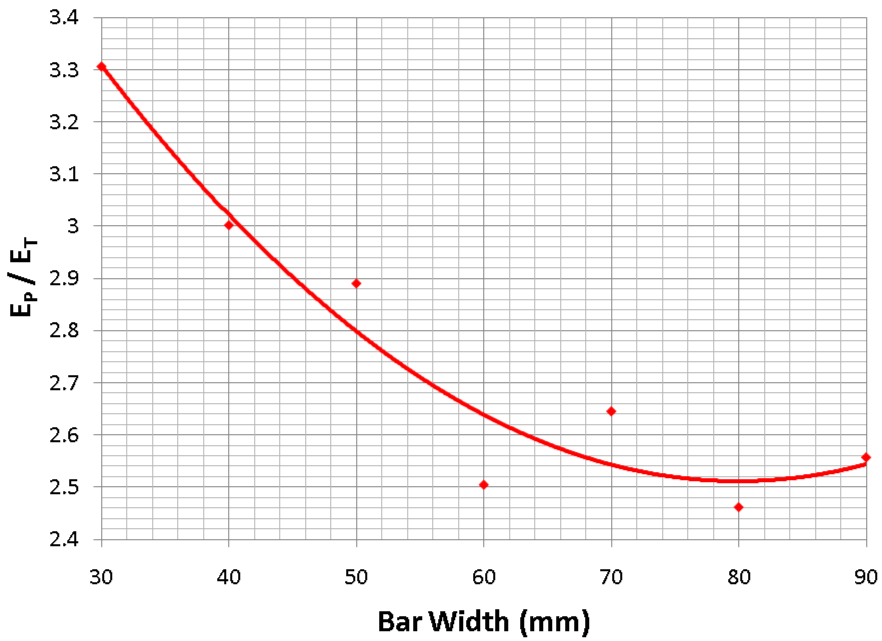
Along y

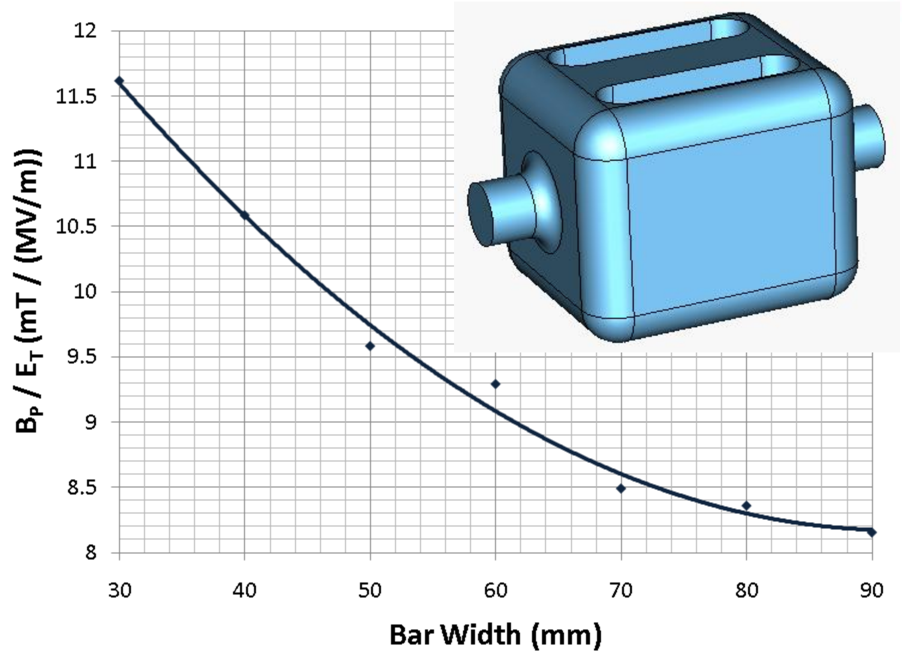




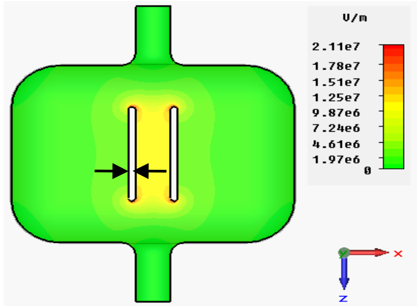
Along z

Optimization of Bar Width – 400 MHz

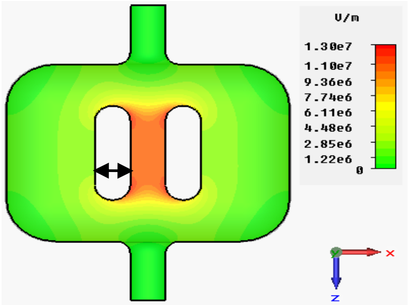




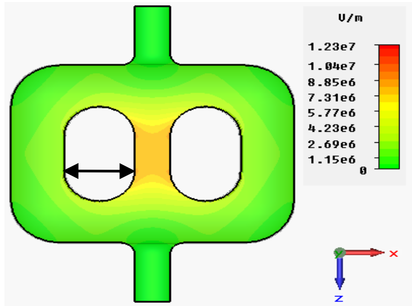
Design Parameters	Value (mm)
Cavity reference length	374.7
Cavity height	374.7
Cavity width	400.0
Bar width	85.0
Bar length	250.0
Beam aperture	100.0



Bar Width = 10 mm

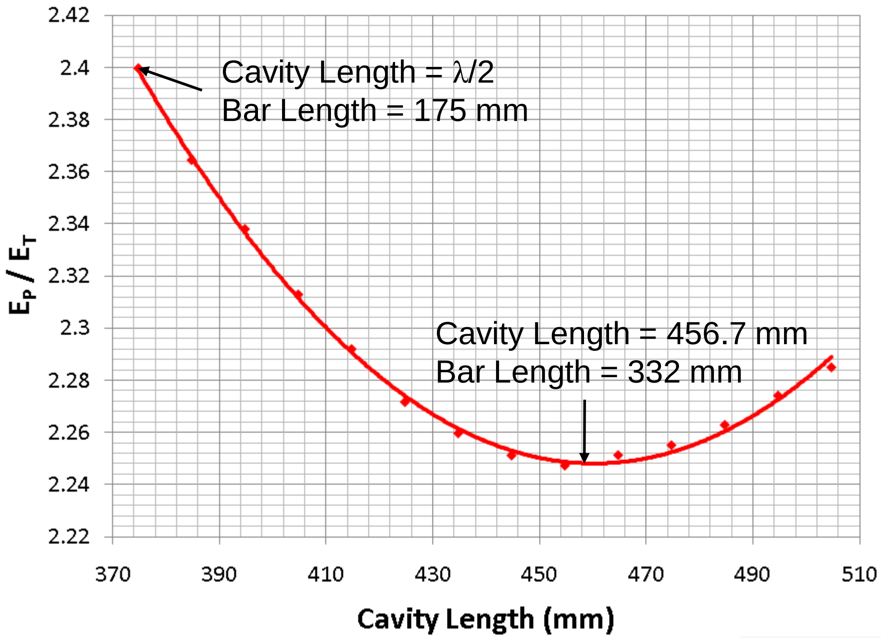


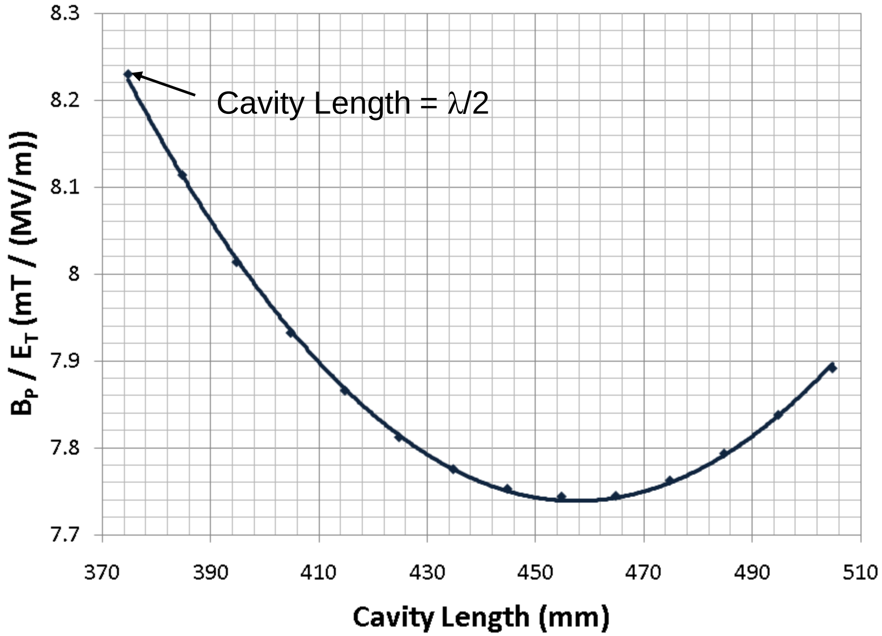
Bar Width = 50 mm

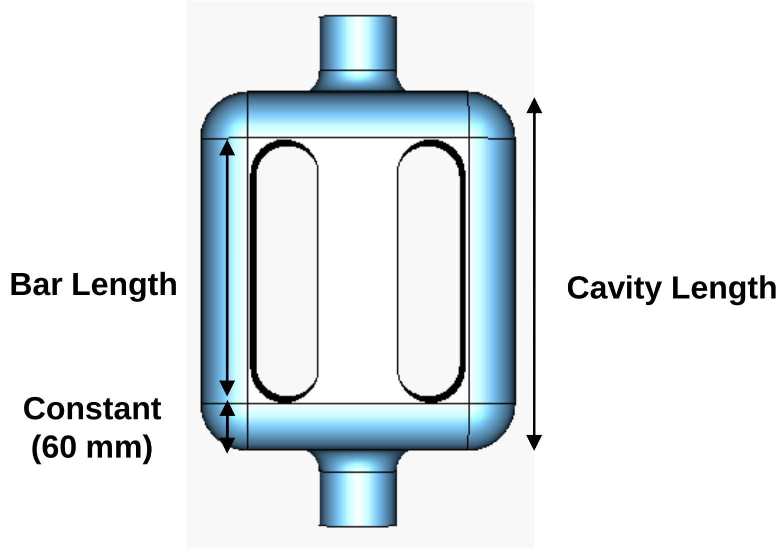


Bar Width = 100 mm

Optimization of Bar and Cavity Length – 400 MHz

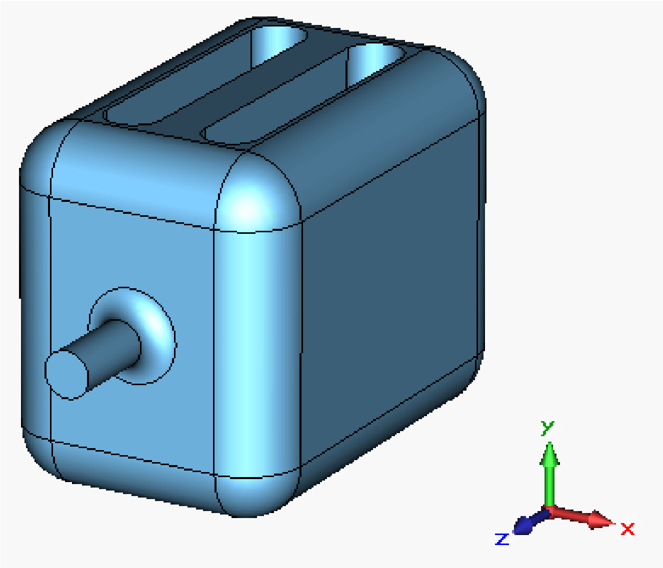


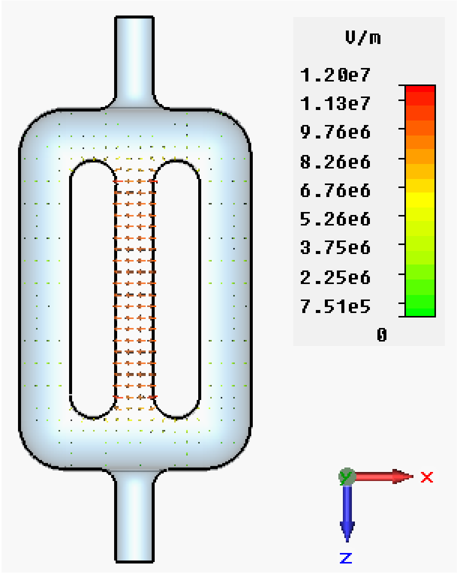




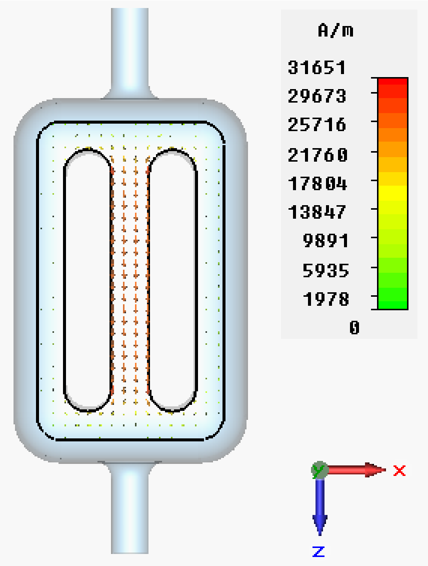
f = 400 MHz
$\lambda/2$ = 374.7 mm

Optimized Cavity Geometry and Field Profiles – 499 MHz



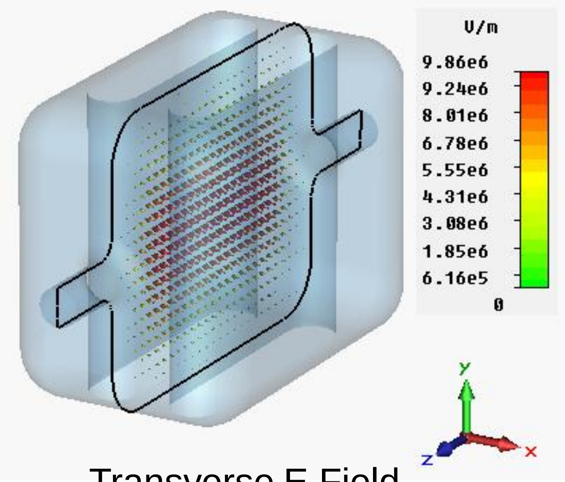


E field on mid plane

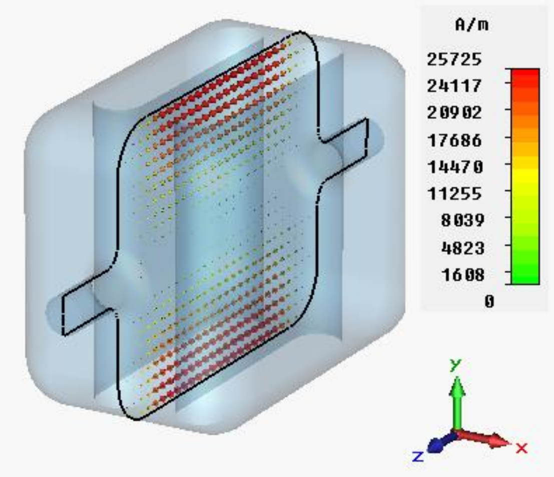


B field on top plane

Compact Design Dimensions	Value (mm)
Cavity reference length	388.4
Cavity height	305.0
Cavity width	250.0
Bar width	50.0
Bar length	278.0
Beam aperture	40.0

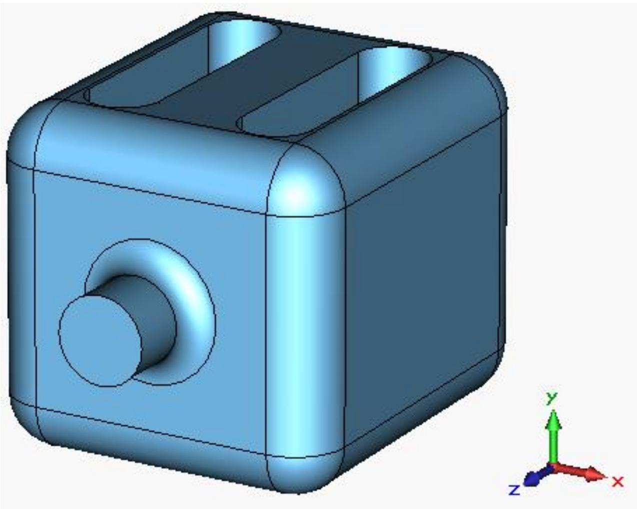


Transverse E Field

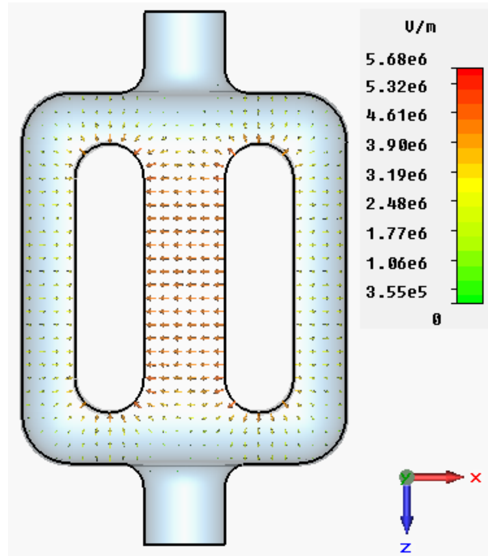


B Field

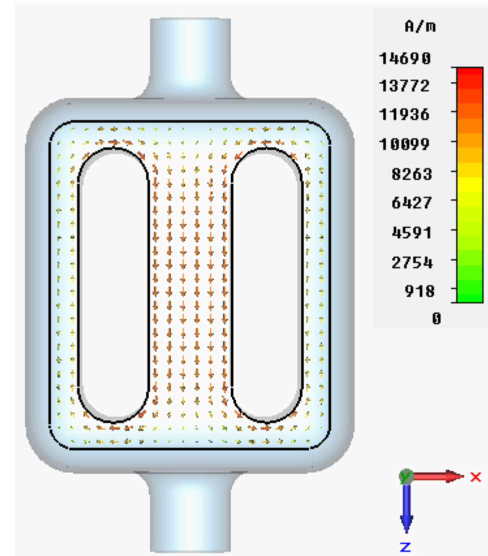
Optimized Cavity Geometry and Field Profiles – 400 MHz



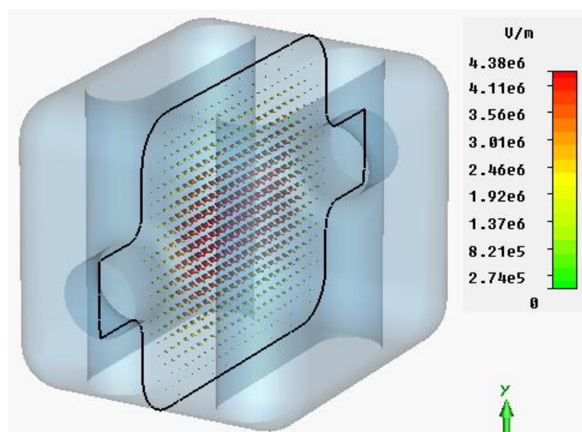
Compact Design Dimensions	Value (mm)
Cavity reference length	456.7
Cavity height	384.4
Cavity width	400.0
Bar width	85.0
Bar length	332.0
Beam aperture	100.0



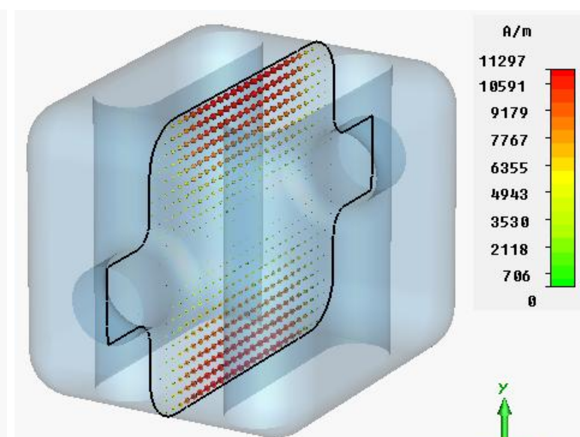
E field on mid plane



B field on top plane



Transverse E Field

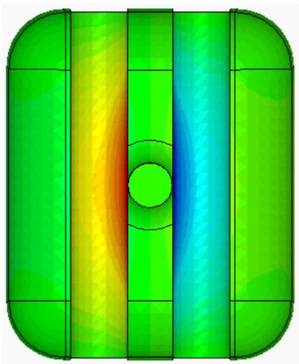


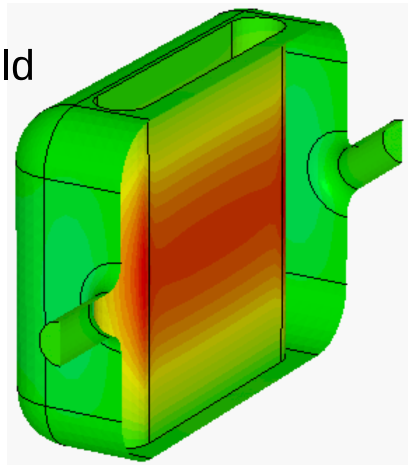
B Field

Surface Fields

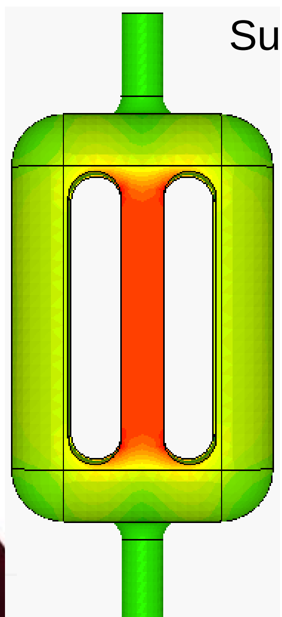
499 MHz

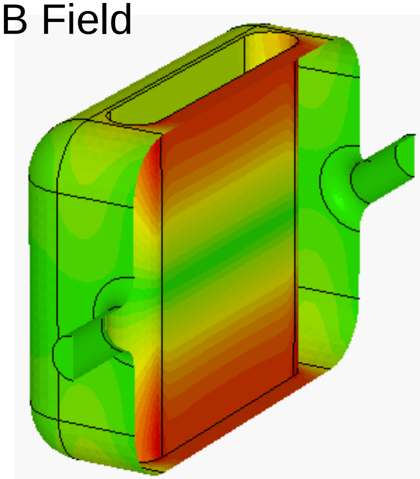
Surface E Field





Surface B Field



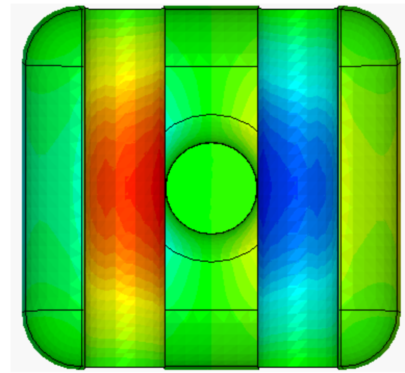


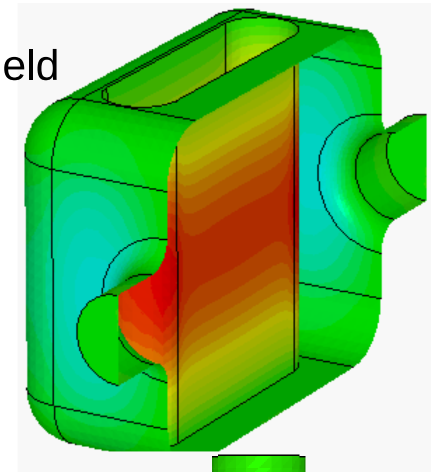
$$\frac{E_P}{E_T} = 2.06$$

$$\frac{B_P}{E_T} = 6.54\ \mathrm{mT/(MV/m)}$$

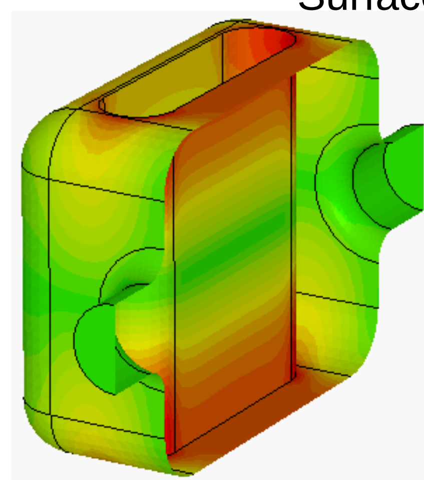
400 MHz

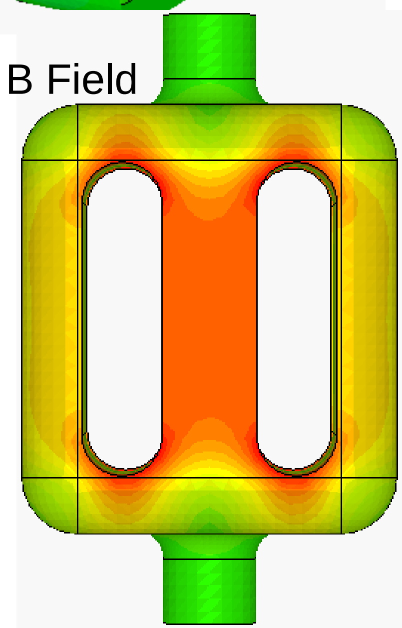
Surface E Field





Surface B Field

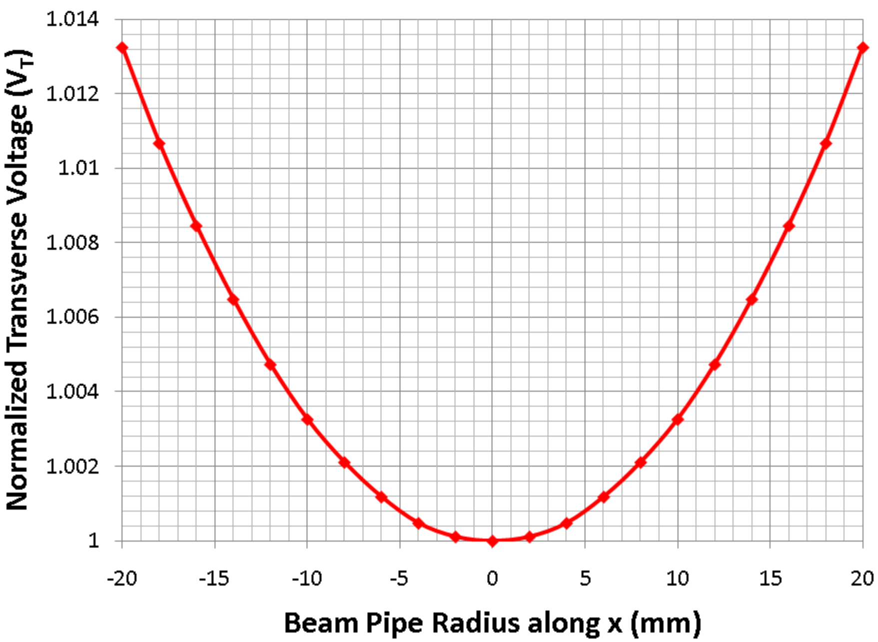


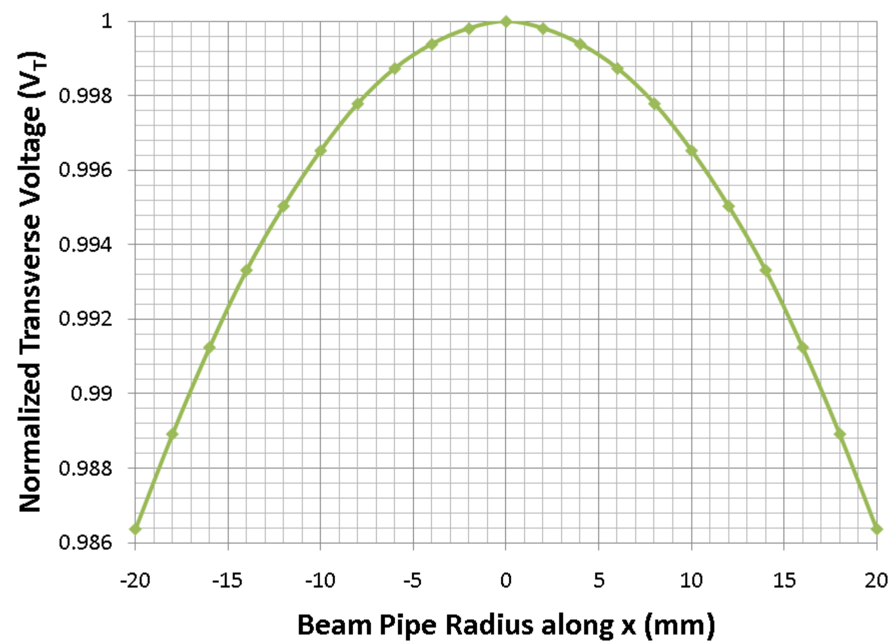


$$\frac{E_P}{E_T} = 2.18$$

$$\frac{B_P}{E_T} = 7.5\ \mathrm{mT/(MV/m)}$$

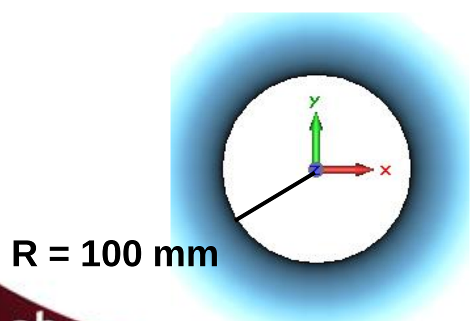
Transverse Deflecting Voltage along Beam Line Cross Section – 400 MHz





$$\frac{V_T}{V_T(r=0)} = 3.0\times10^{-5}\Delta x^2 + 1.0$$

$$\frac{V_T}{V_T(r=0)} = -3.0\times10^{-5}\Delta y^2 + 1.0$$

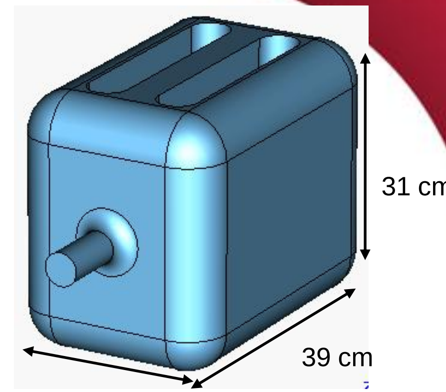


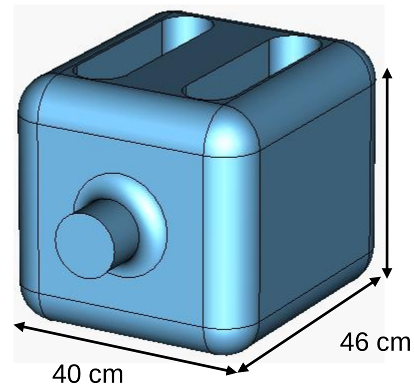
Direction	$\Delta V_T/V_T$ (At R = 50 mm)
x	1.33 %
y	1.46 %

Cavity Properties

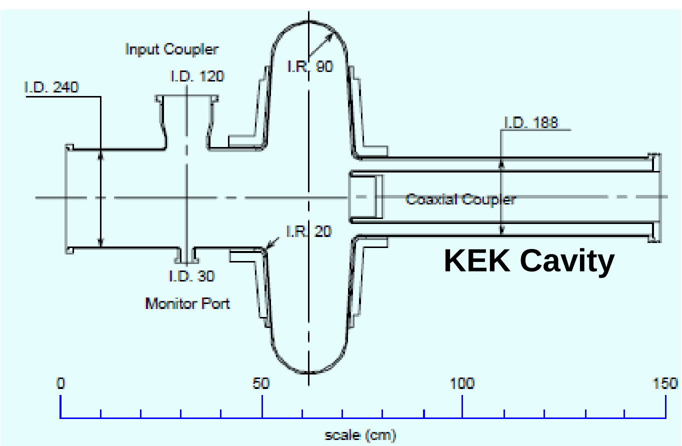
Parameter	499 MHz [1]	499 MHz	400 MHz	KEK Cavity *	Unit
Frequency of π mode	499.4	499.2	400.7	501.7	MHz
$\lambda/2$ of π mode	300.4	300.4	374.7	299.8	mm
Frequency of 0 mode	519.9	517.8	413.05	~ 700 MHz	MHz
Cavity reference length	388.4	394.4	456.7	299.8	mm
Cavity width	250.0	290.0	400.0	866.0	mm
Cavity height	305.0	304.8	384.4	483.0	mm
Bars length	278.0	284	332.0	–	mm
Bars width	50.0	67.0	85.0	–	mm
Aperture diameter	40.0	40.0	100.0	130.0	mm
Deflecting voltage (V_T^*)	0.3	0.3	0.375	0.3	MV
Peak electric field (E_T^*)	2.06	1.85	2.18	4.32	MV/m
Peak magnetic field (B_T^*)	6.54	6.69	7.5	12.45	mT
Geometrical factor ($G = QR_S$)	64.7	67.96	83.9	220	Ω
$[R/Q]_T$	942.75	933.98	317.92	46.7	Ω
$R_T R_S$	6.1 10^4	6.3 10^4	2.67 10^4	1.03 10^4	Ω^2
At E_T^* = 1 MV/m					

499 MHz [1]





400 MHz

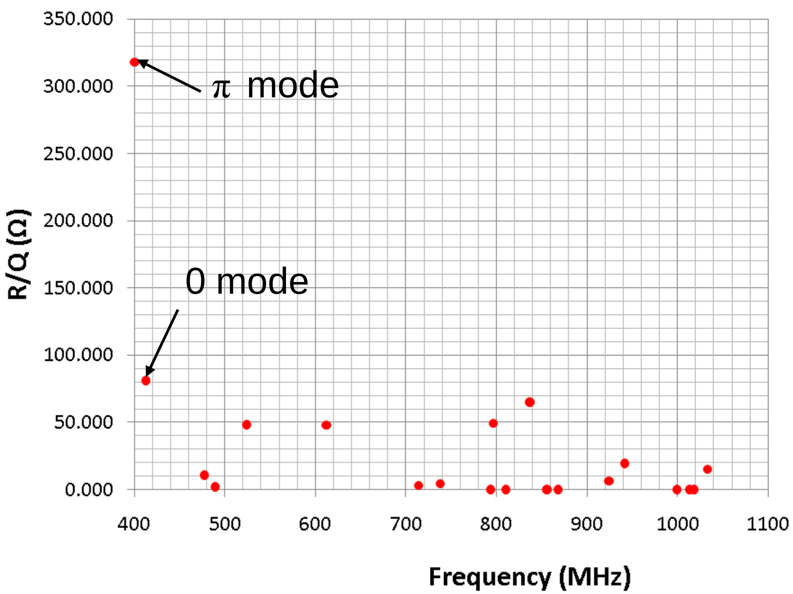


KEK Cavity

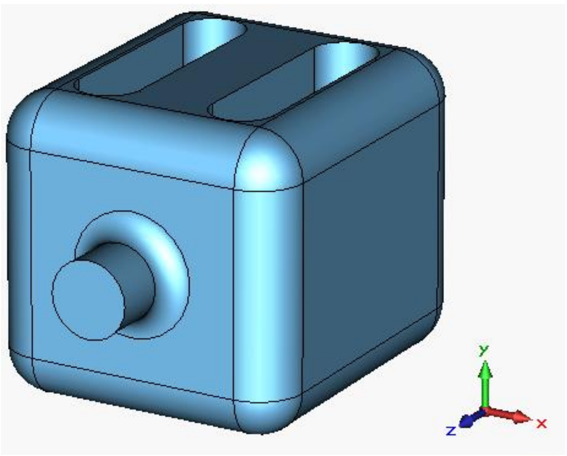
* K. Hosoyama et al, "Crab cavity for KEKB", Proc. of the 7th Workshop on RF Superconductivity, p.547 (1998)

Higher Order Modes – 400 MHz

Mode	Frequency (MHz)	Mode of Operation	Field direction on beam axis		[R/Q] (Ω)	
			E	B	Direct Integral Method	Using Panofsky Wenzel Theorem
						(r_0 = 5 mm)
1	400.60	Deflecting	x	y	317.98	317.16
2	412.94	Acclerating	z		81.12	-
3	477.76	Acclerating	z		10.64	-
4	489.70	Deflecting	x	y	2.124	2.13
5	524.13	Deflecting	x	y	48.24	48.42
6	612.03	Accelerating	z		47.89	-
7	713.89	Deflecting	x	y	2.85	2.6
8	737.67	Deflecting	x	y	4.2	3.5
9	793.85			z	0.0	0.0
10	796.26	Acclerating	z		49.3	-
11	810.72	Deflecting	y	x	0.0199	0.0043
12	836.70	Deflecting	y	x	65.04	62.51
13	855.67			z	0.0	0.0
14	868.28			z	0.0	0.0
15	924.27	Deflecting	y	x	6.29	6.87
16	941.54	Deflecting	x	y	19.53	16.87
17	999.08			z	0.0	0.0
18	1013.13	Deflecting	x	y	0.0144	0.00761
19	1018.24			z	0.0	0.0
20	1032.98	Accelerating	z		15.0	-

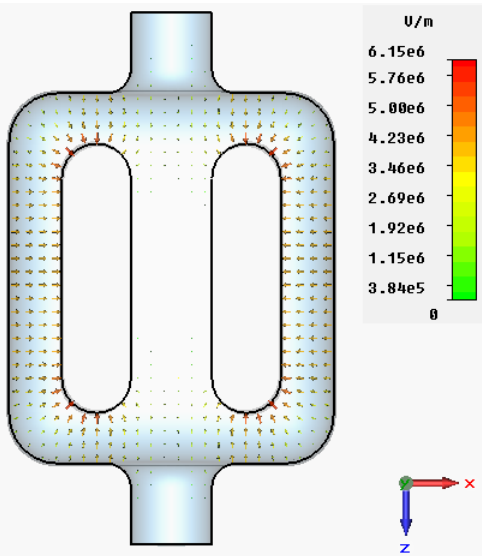


Fundamental Mode Separation = 12.3 MHz



Modes of Interest – 400 MHz

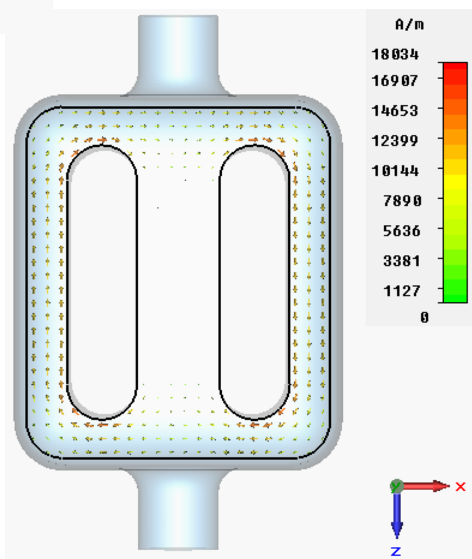
Mode 2



E field on mid plane

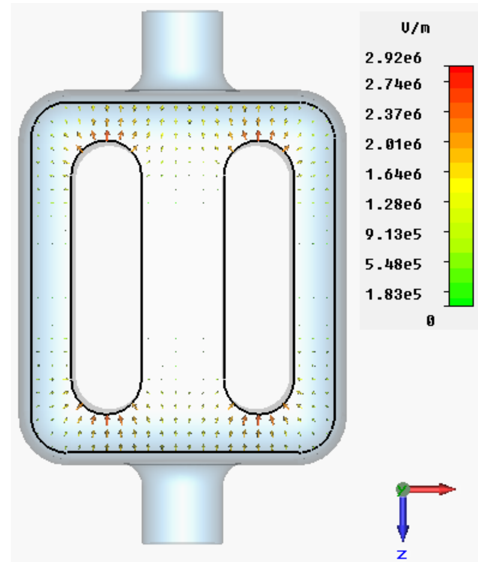
Frequency = 412.94 MHz
Mode of Operation – Accelerating

$$\left[\frac{R}{Q}\right] = 102.81$$



B field on top plane

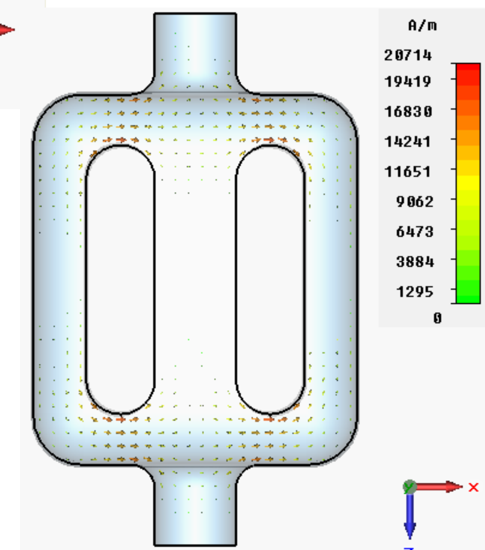
Mode 12



E field on mid plane

Frequency = 836.70 MHz
Mode of Operation – Deflecting

$$\left[\frac{R}{Q}\right]_T = 230.84$$

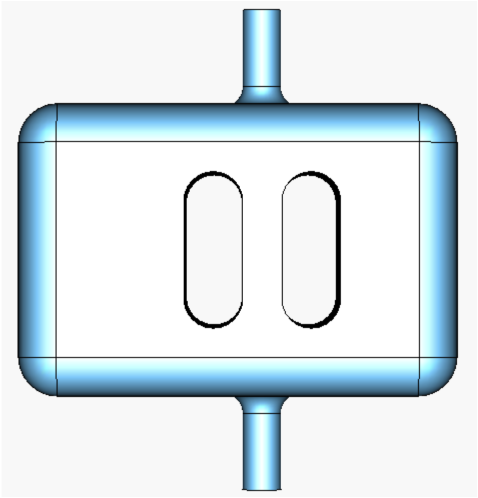


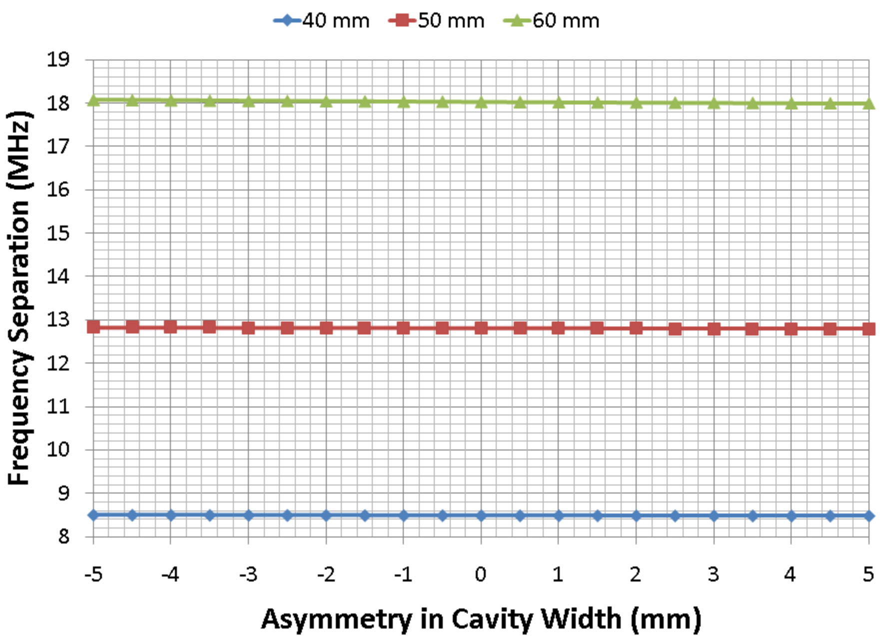
B field on top plane

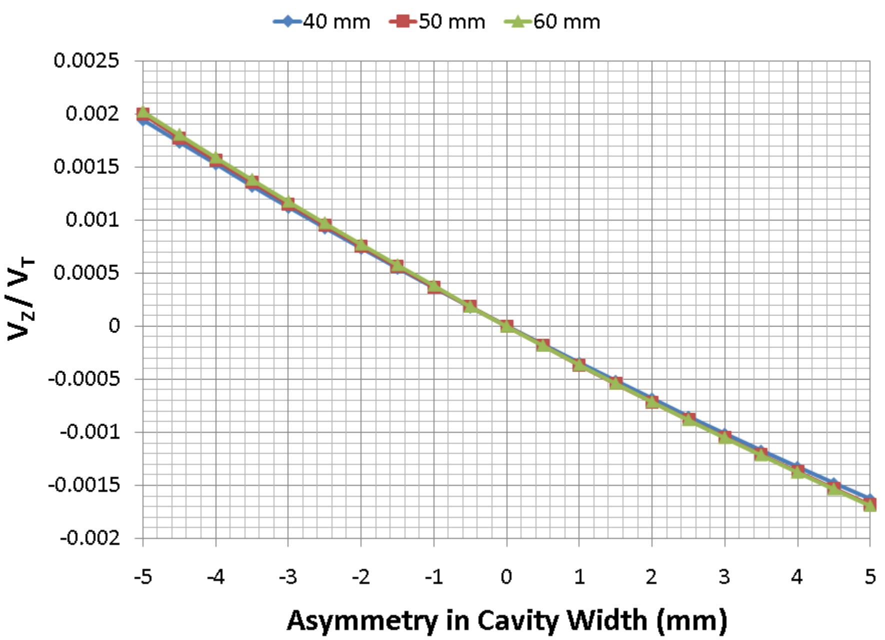
Asymmetry Study – 499 MHz

- Study of mixing in transverse and longitudinal voltage along the beam line at the fundamental mode, due to asymmetry in
  - Cavity Width
  - Cavity Edge Radius
  - Bar Width
  - Bar Length
  - Bar Separation

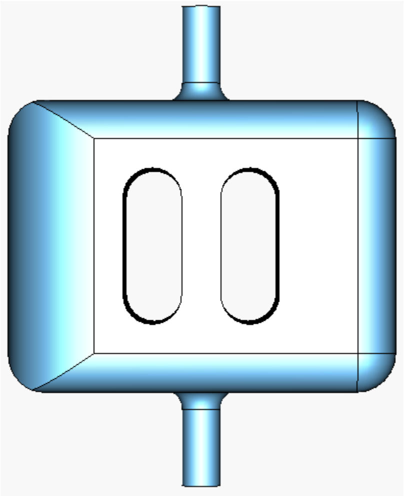
Asymmetry in Cavity Width

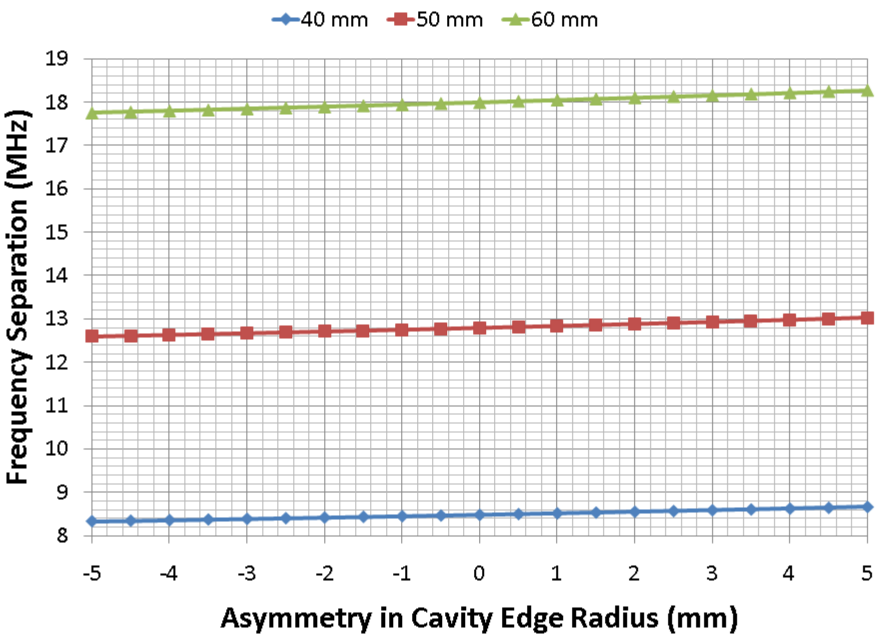


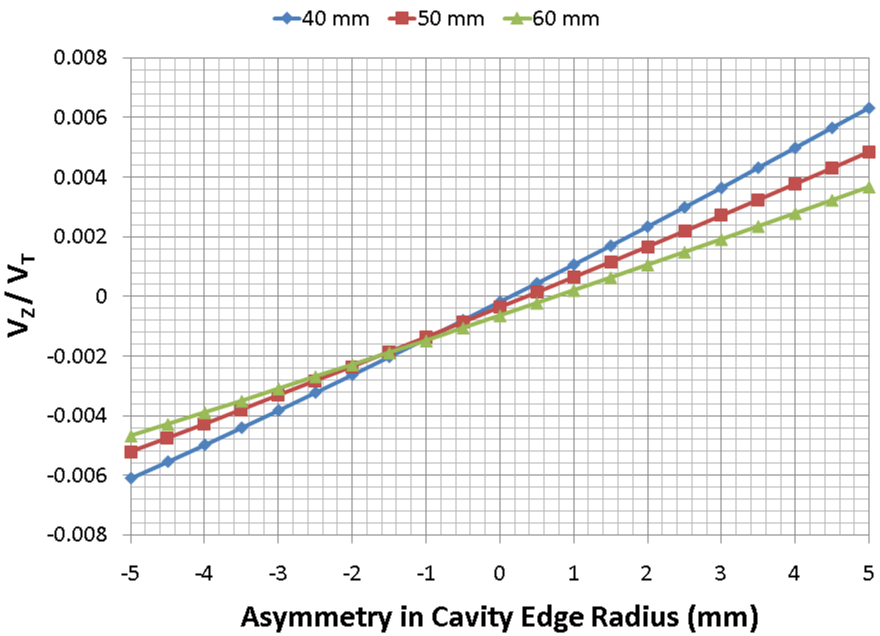




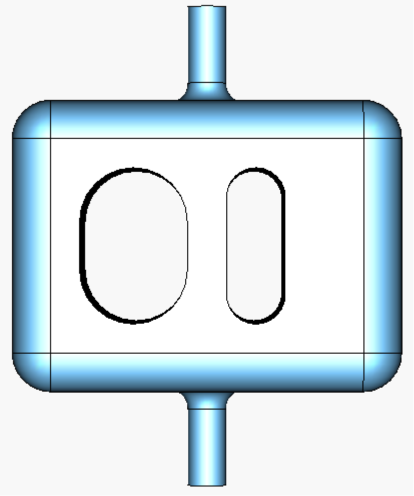
Asymmetry in Cavity Edge Radius

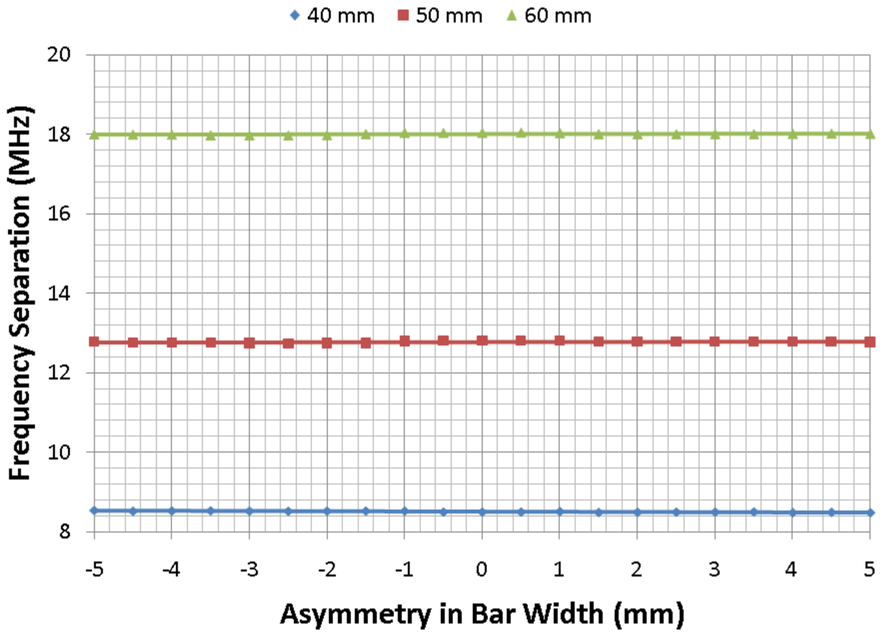


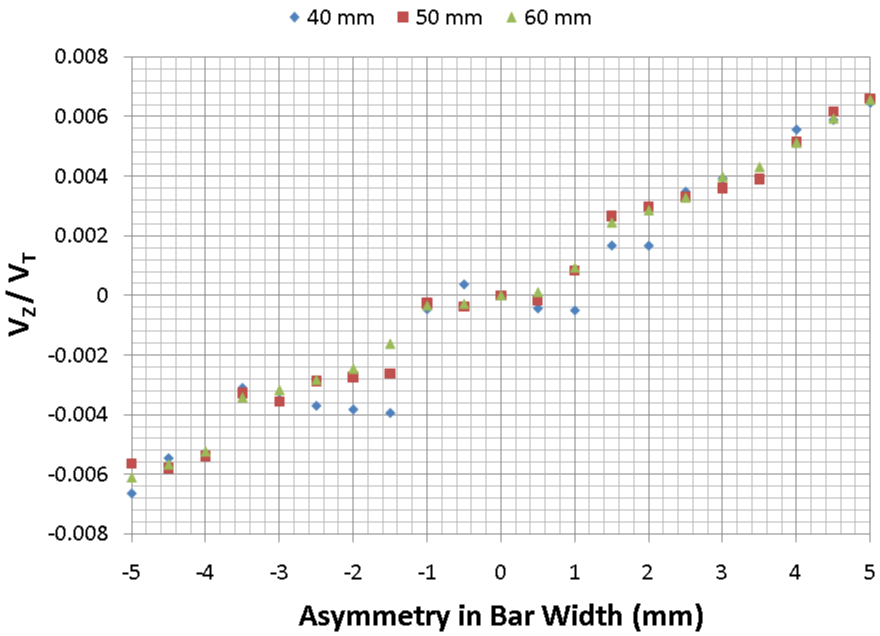




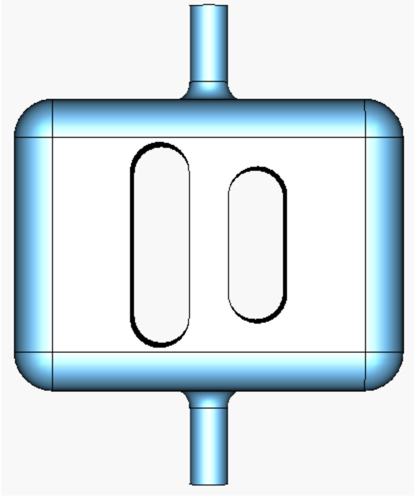
Asymmetry in Bar Width

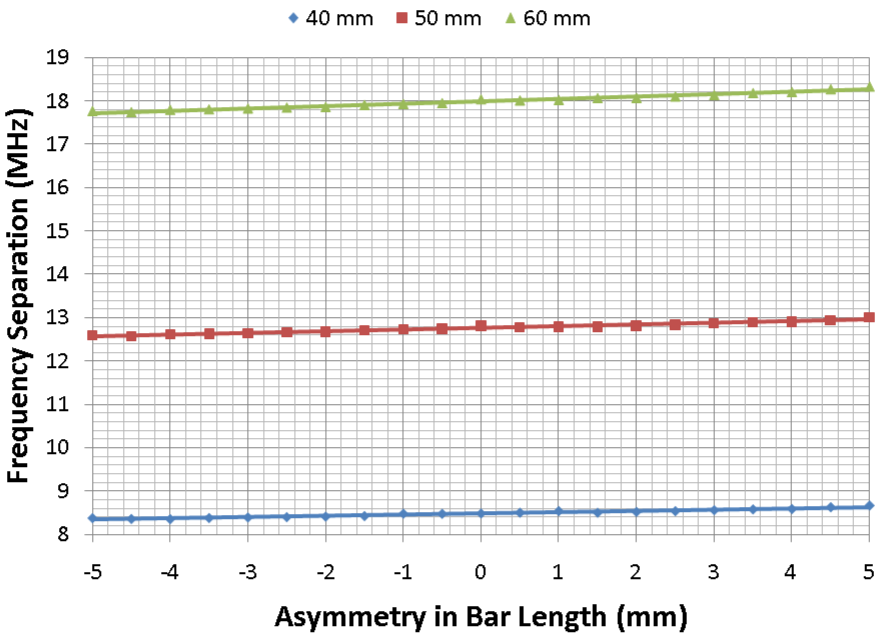


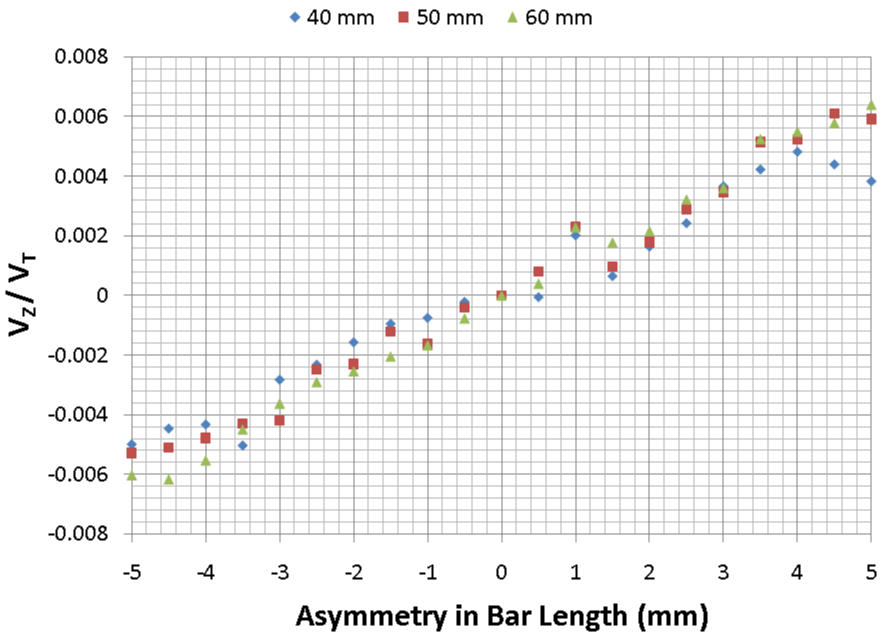




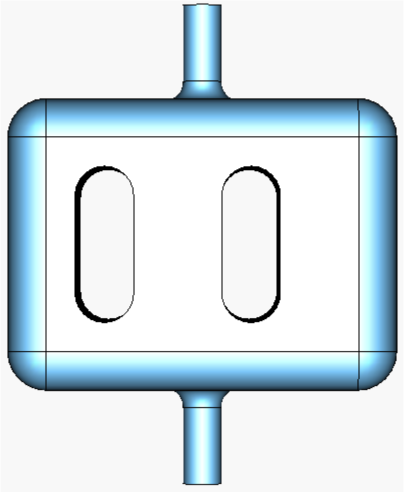
Asymmetry in Bar Length

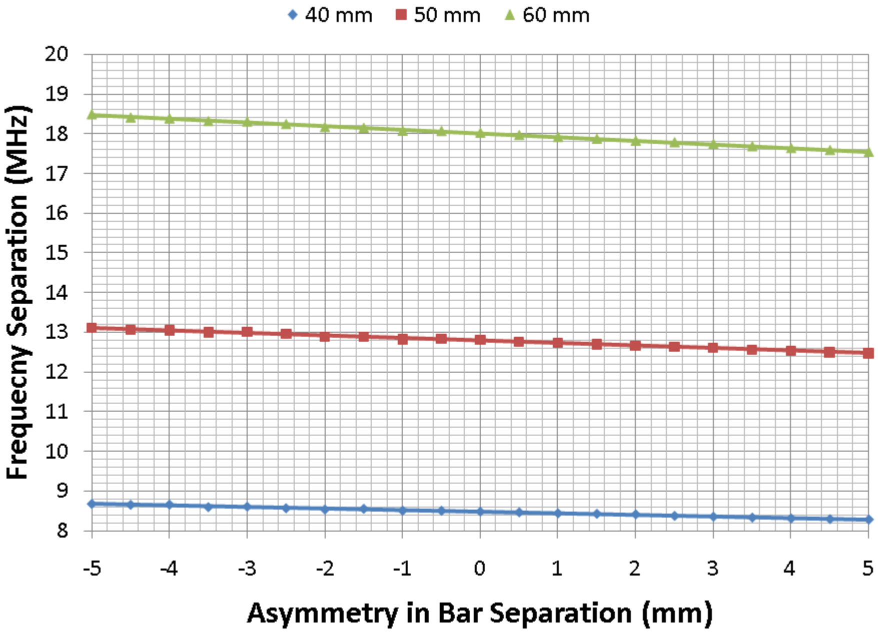


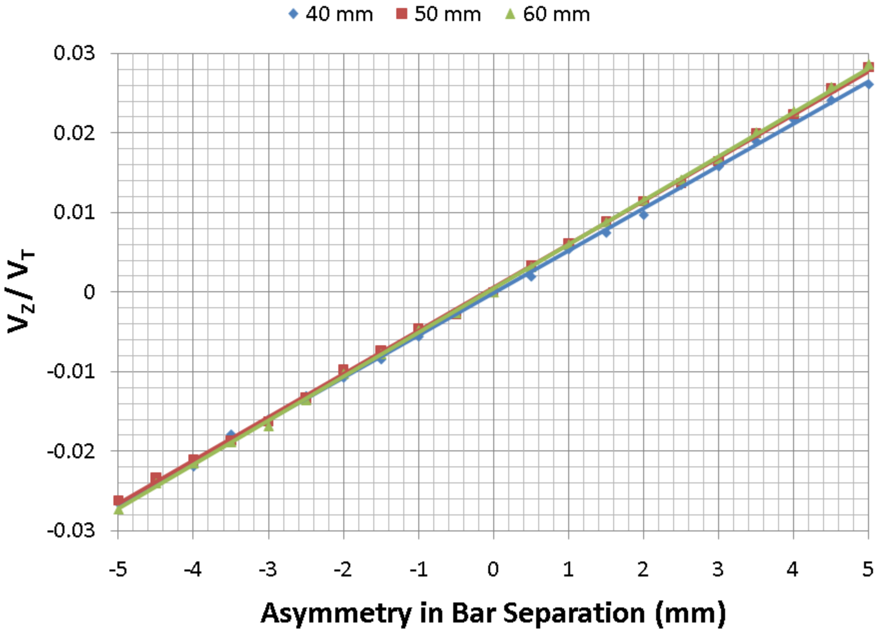




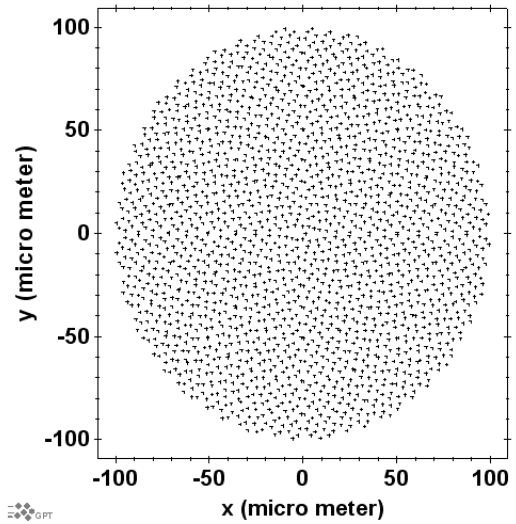
Asymmetry in Bar Separation





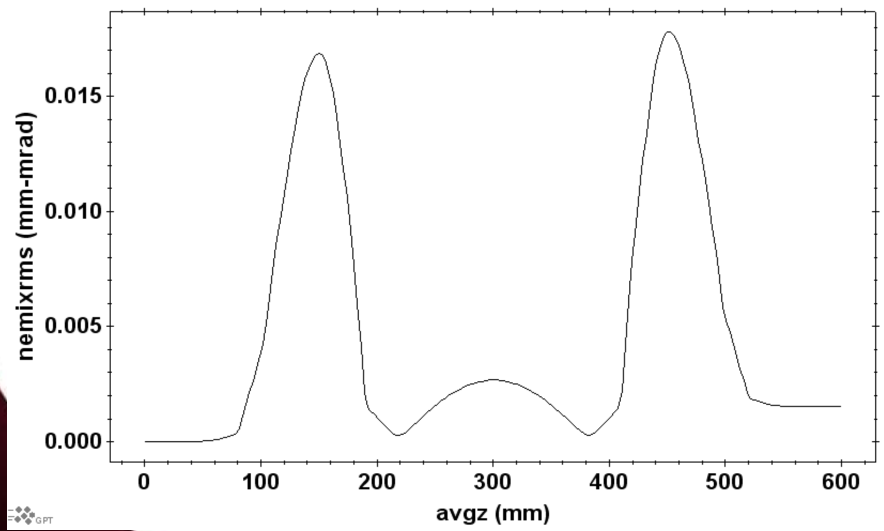


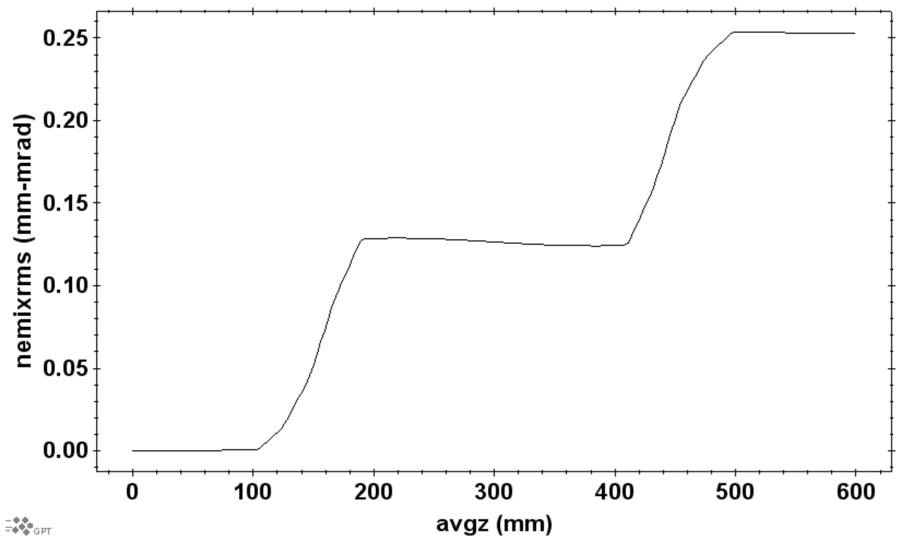
Emittance Growth



crabbing

deflecting

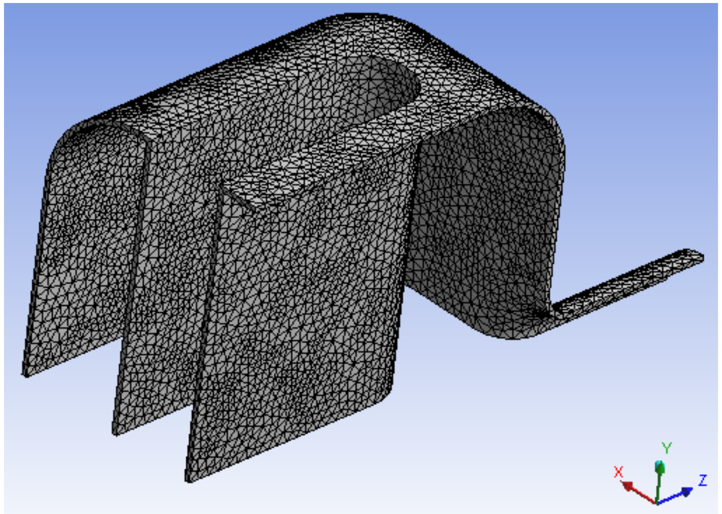




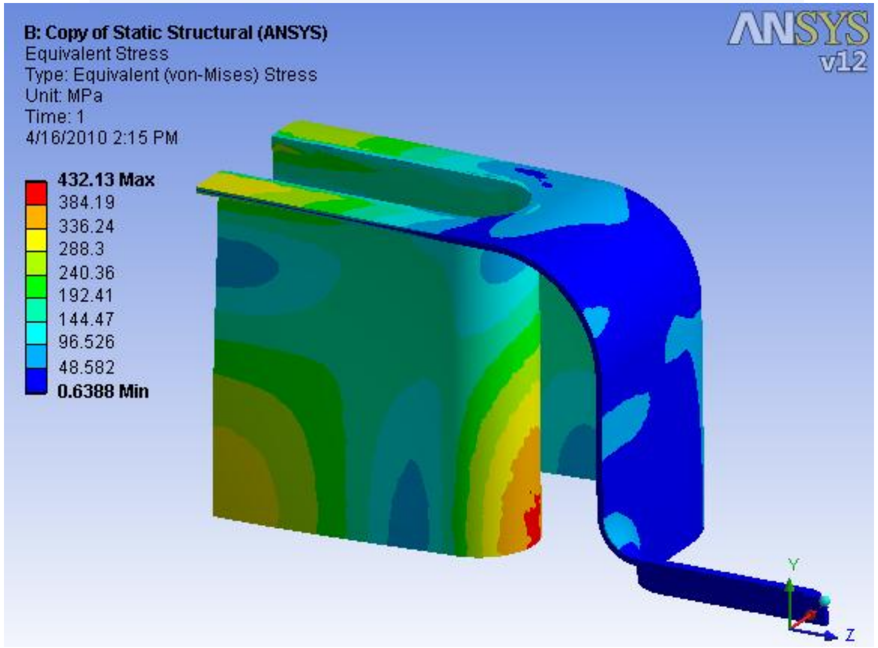
Preliminary Stress Analysis

Material Properties of Nb*

Property	SI Units	English Units
Modulus - Room Temp	1.03 E+11 Pa	1.49 E+07 psi
Modulus - Cryo Temp	1.23 E+11 Pa	1.79 E+07 psi
Poisson's Ratio	0.38	
Density	8.58E-03 g/mm^3	0.31 lb/in^3
Yield - RT	4.83 E+07 Pa	7.0 ksi
Yield - Cryo	5.77 E+08 Pa	83.7 ksi

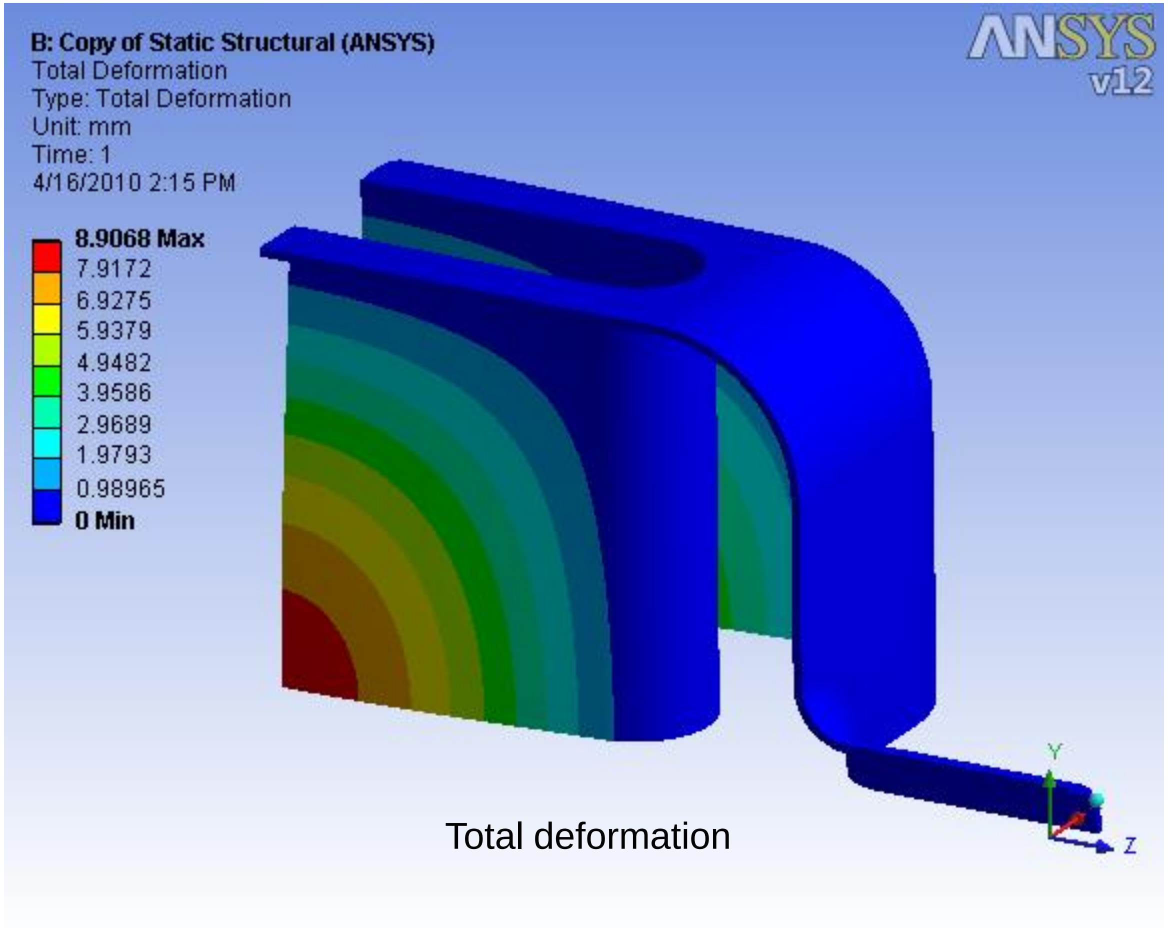


- Analysis using properties at room temperature
- Cavity wall thickness = 3 mm
- Mechanical model
  - Standard gravity = 9.806 ms^{-2}
  - Pressure normal to the cavity outer surface = 0.20265 Mpa (29.392 psi)
- Stress = 432 MPa > Yield Strength = 48 MPa



* K.M.Wilson at al. "Mechanical cavity design for 100MV upgrade cryomodule" Proceedings of PAC2003

Cavity Deformations

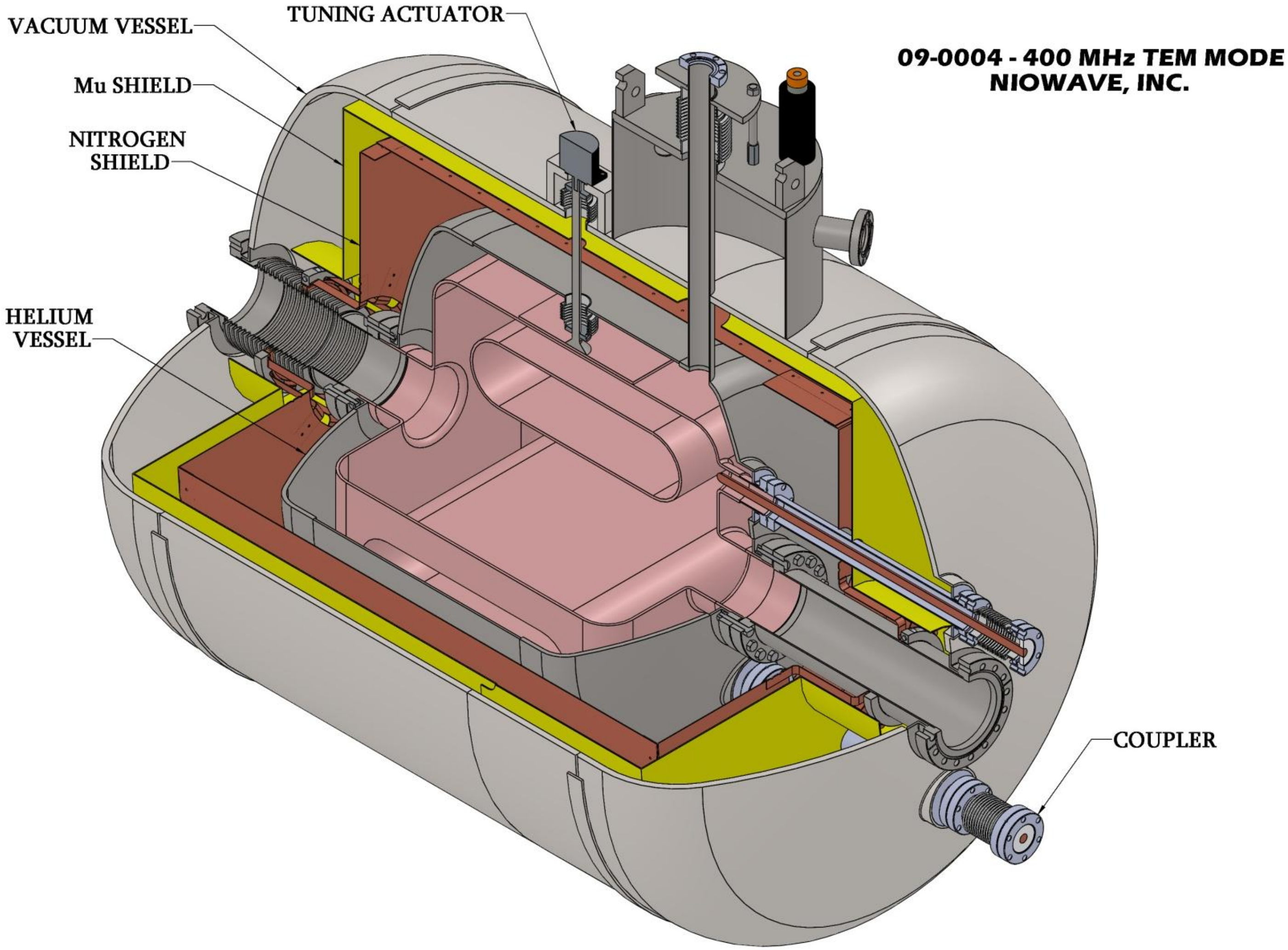


Total deformation

Directional Deformations

- x axis → 9 mm
- y axis → 0.8 mm
- z axis → 0.3 mm

Test Cryostat Concept



Test Cryostat Concept