Parallel Bar Crabbing Cavity Option for ELIC

Subashini De Silva

Jean Delayen

Center for Accelerator Science

Old Dominion University

and

Thomas Jefferson National Accelerator Facility

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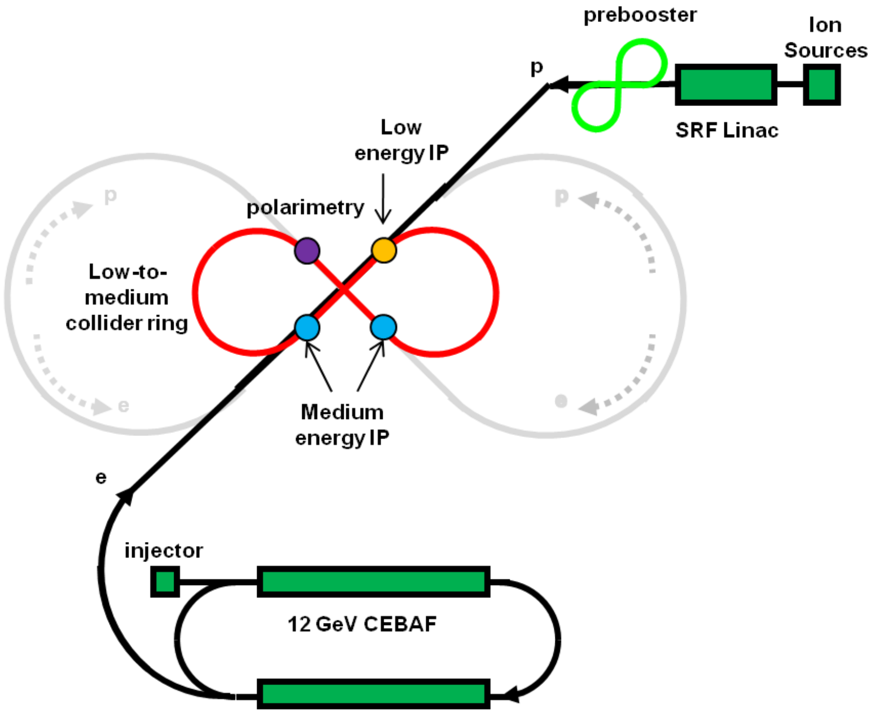
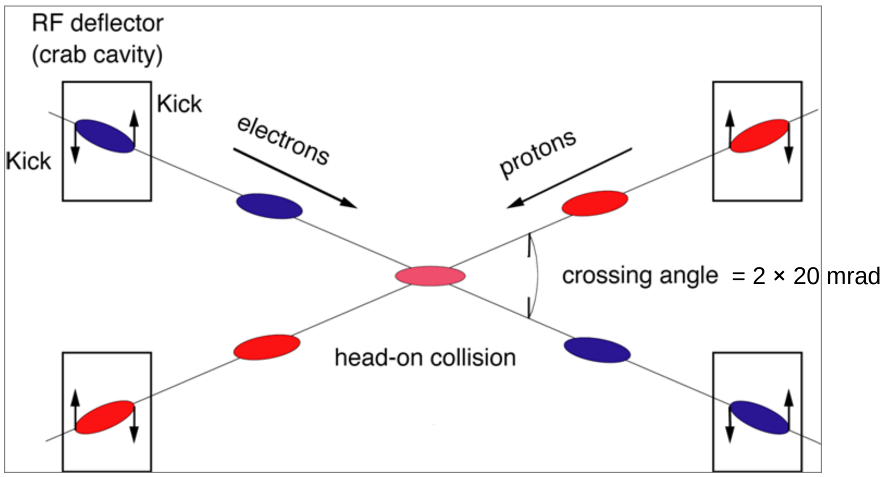
Outline

- ELIC Crab Cavity Requirements
- Parallel Bar Crab Cavity Structure
- Design Optimization
- Cavity Properties
  – Cavity Geometry
  – Field Orientation
  – Higher Order Modes
- Summary

Electron Ion Collider (ELIC)



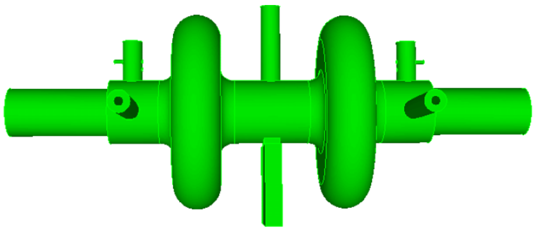


Stage	Beam Energy (GeV/c)	Integrated Deflecting Voltage (MV)
Electron	10	~ 1
Proton	12	~ 1
Proton	60	10

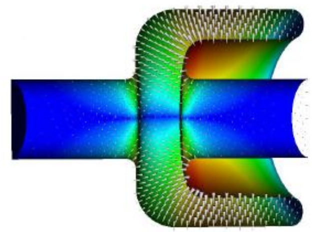
Requirements

- Crab cavities are needed to restore head-on collision and avoid luminosity reduction
- ELIC crossing angle ~ 2x20 mrad (6+6 m IR)
- Total deflection required for protons – 10 MV
- RF frequency – 500 MHz
- Beam aperture diameter – 40 mm

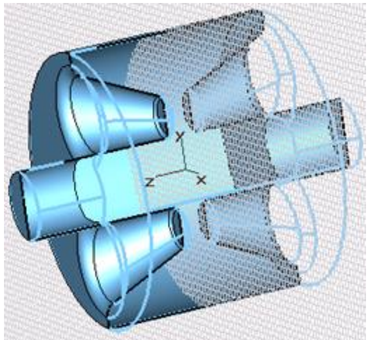
Crab Cavity Structures



SLAC 800 MHz Coaxial Cavity



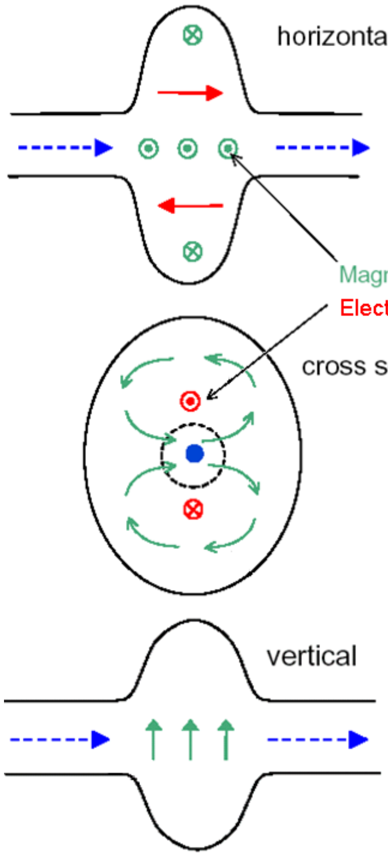
SLAC 400 MHz Half Wave Resonator

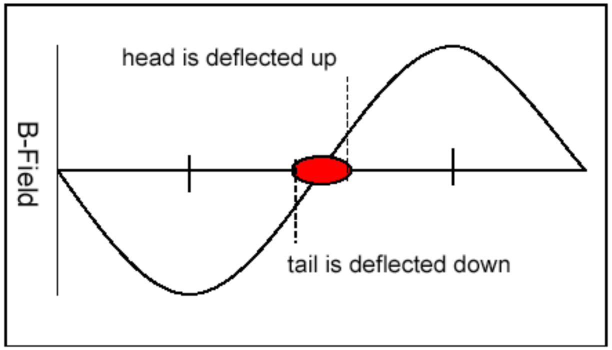


JLab 400 MHz Modified Separator Cavity

KEK 508 MHz Elliptical Cavity

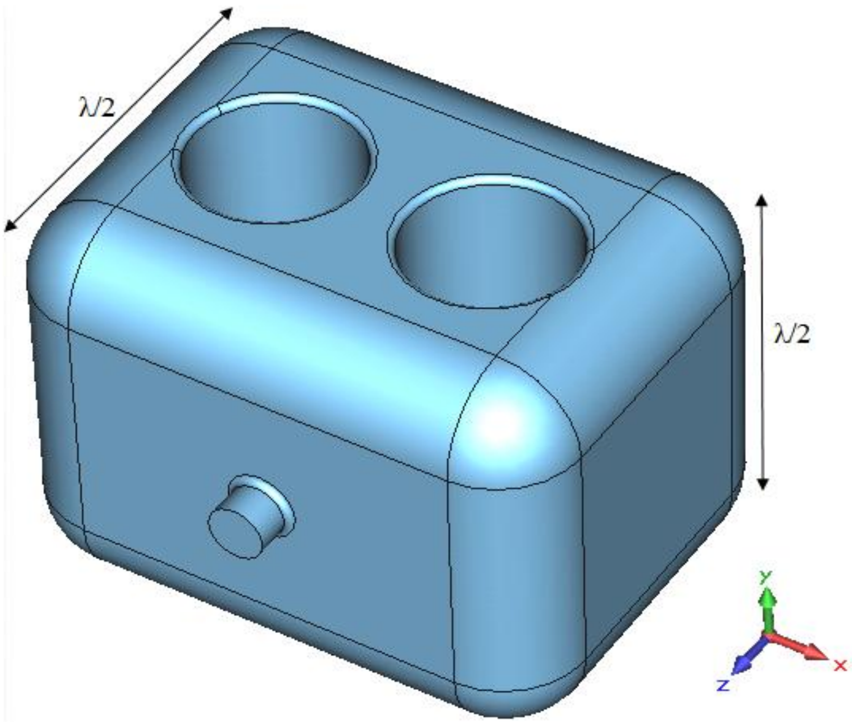
For TM_{110} Mode

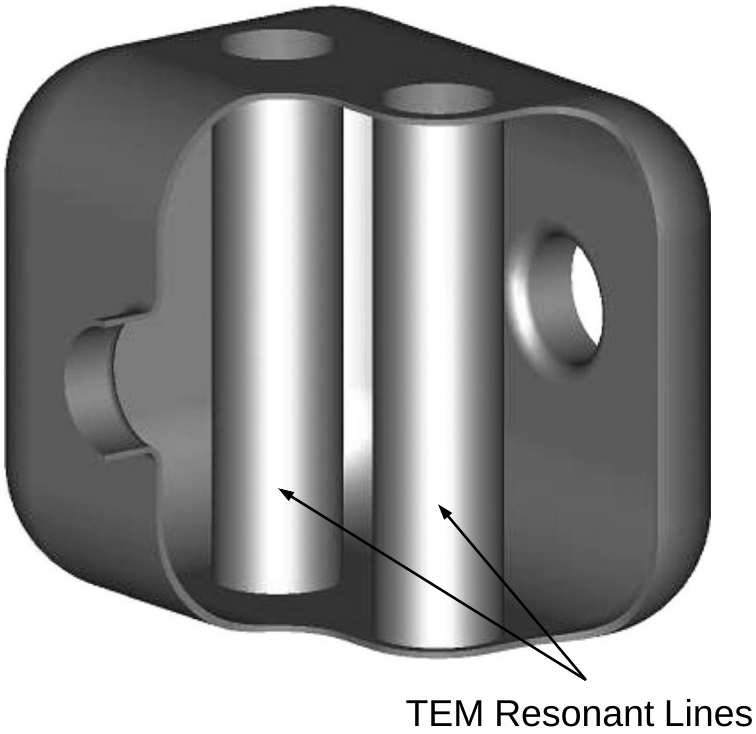




- Imparts a transverse momentum to the bunch
- Transverse deflection is due to the Magnetic Field
- Rotate the bunch without deflecting the bunch

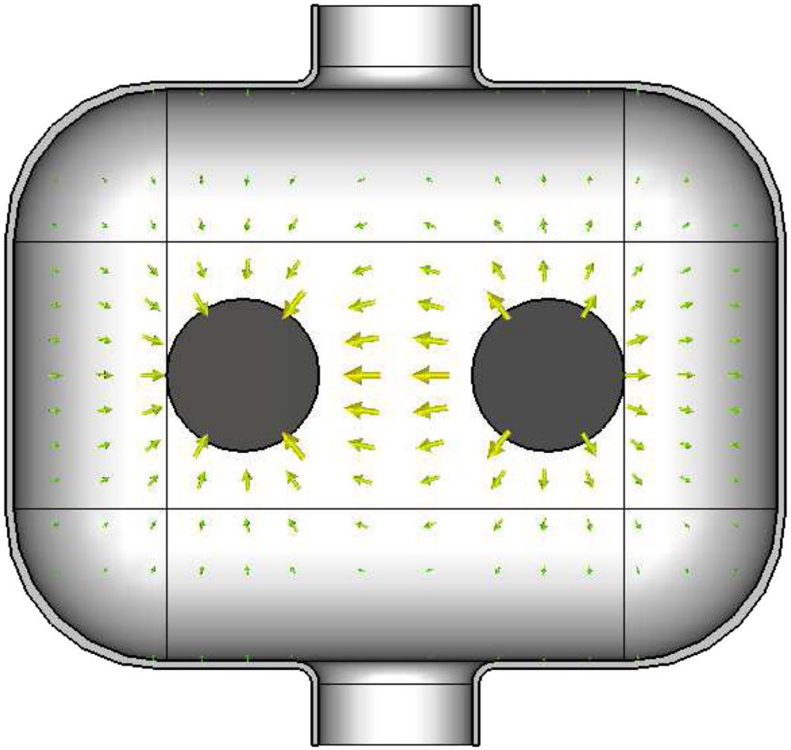
Parallel Bar Cavity Concept



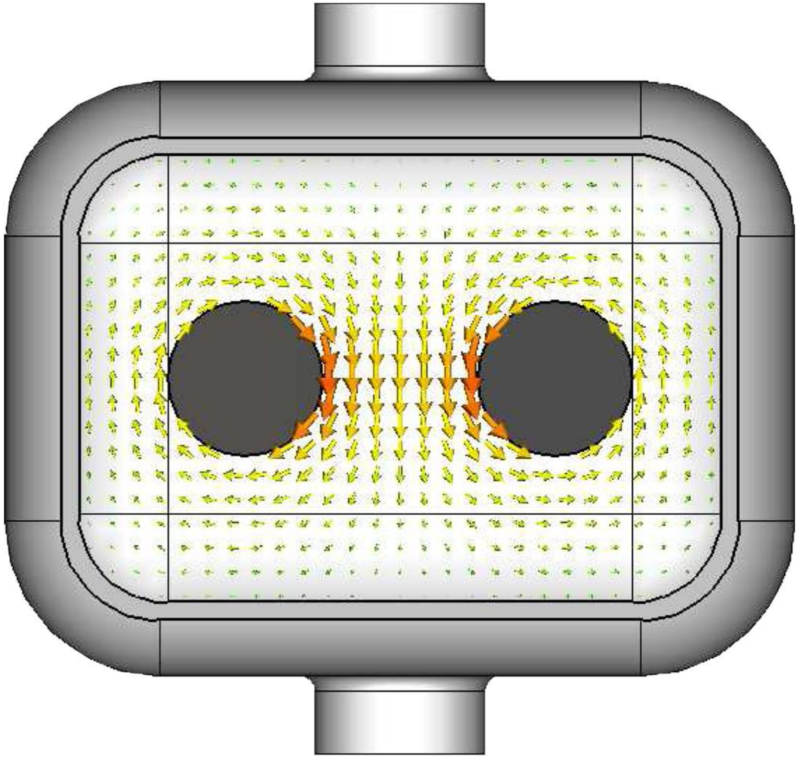


- **Compact design supports low frequencies**
- For deflection and crabbing of particle bunches
- Cavity design – Two Fundamental TEM Modes
  - 0 mode :- Accelerating mode
  - π mode :- Deflecting or crabbing mode

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

Transverse Deflection

- Transverse Voltage

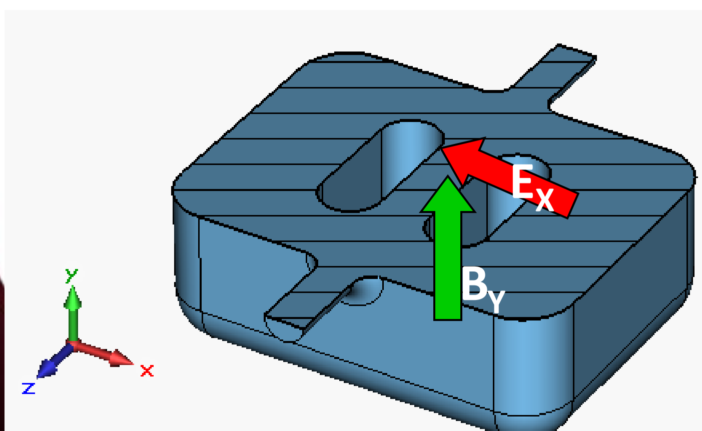
$$\vec{V}_T = \int_{-\infty}^{+\infty} \left[\vec{E}_x(z) + \left(\vec{v} \times \vec{B}_y(z) \right) \right] e^{j\frac{\omega z}{c}} dz$$

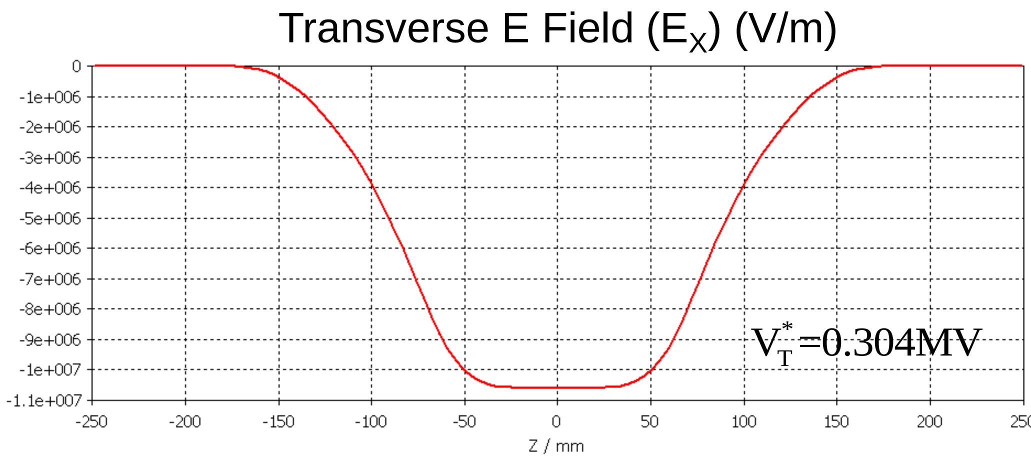
- Transverse Electric Field

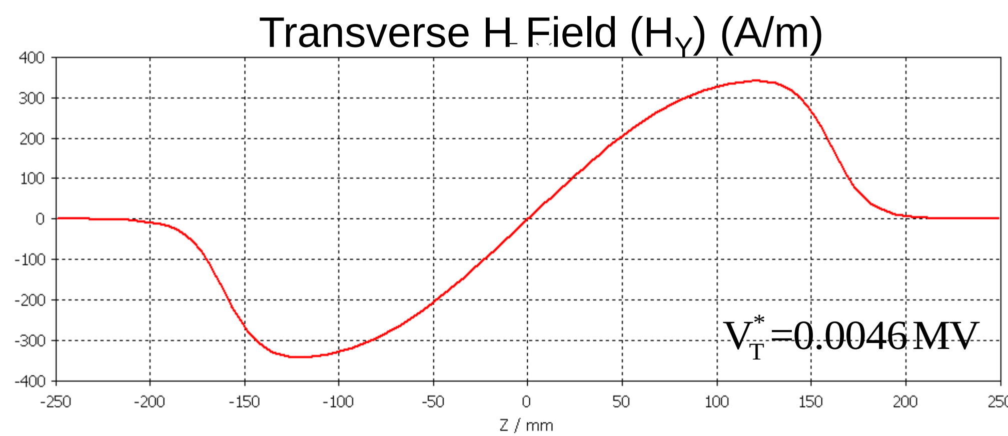
$$E_T = \frac{V_T}{\lambda / 2}$$

- Transverse Shunt Impedance

$$\frac{R_T}{Q} = \frac{V_T^2}{\omega U}$$





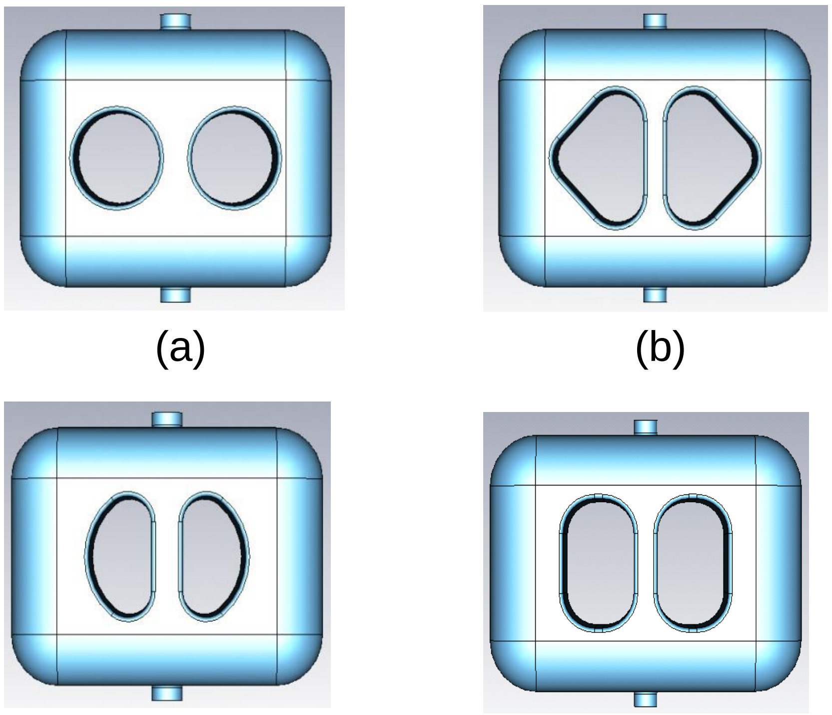


At $E_T^* = 1$ MV/m

Resultant $V_T = 0.2998$ MV
Drop of $V_T = 1.55$ %

Parallel Bar Cross Sections

Optimizing condition – Obtain a higher deflection with lower surface fields



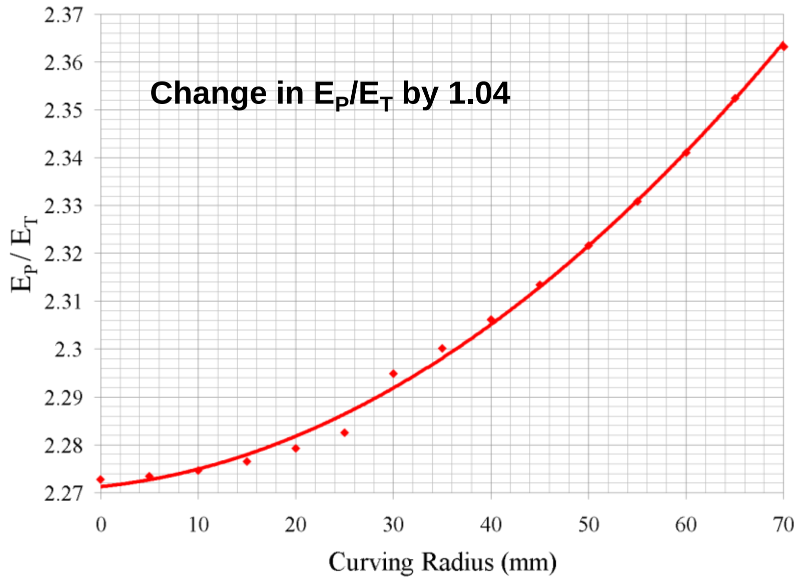
(a) (b) (c) (d)

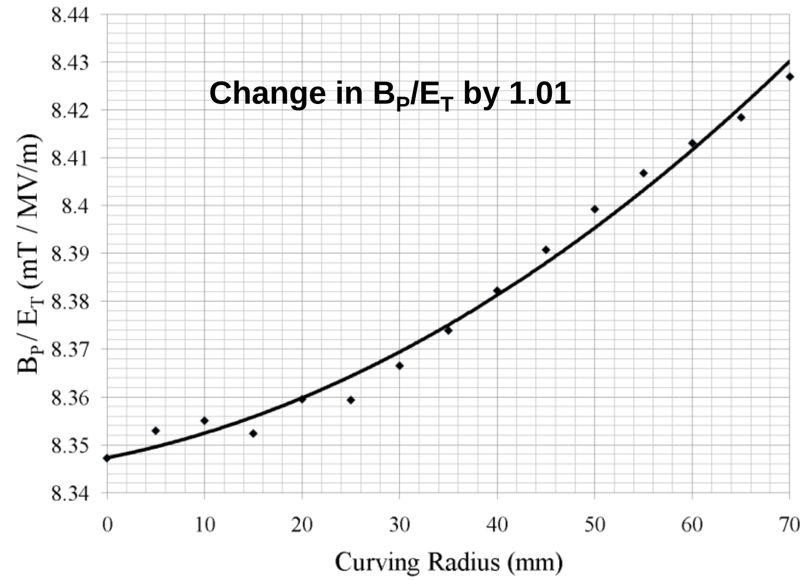
Peak Surface Fields

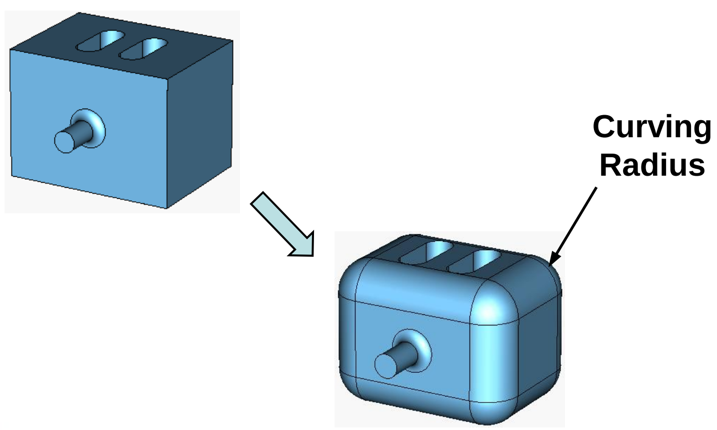
Design Structure	E_P/E_T^*	B_P/E_T^* (mT / MV/m)
(a)	3.30	11.54
(b)	2.80	10.31
(c)	2.61	8.86
(d)	2.31	8.16
At E_T^* = 1 MV/m		

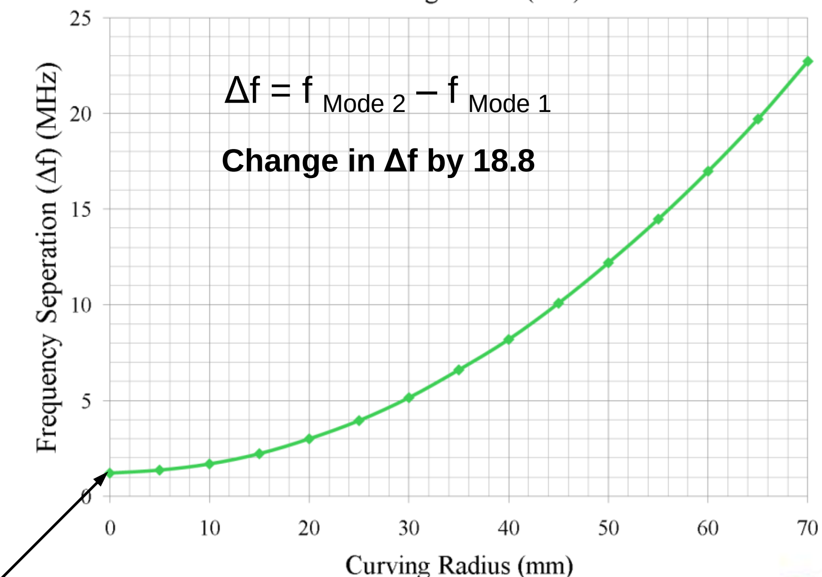
- Increasing effective deflecting length along the beam line increases net transverse deflection seen by the particle
- Racetrack shaped structure (d) has better performance with higher deflection for lower surface fields

Mode Separation by Rounding Edges



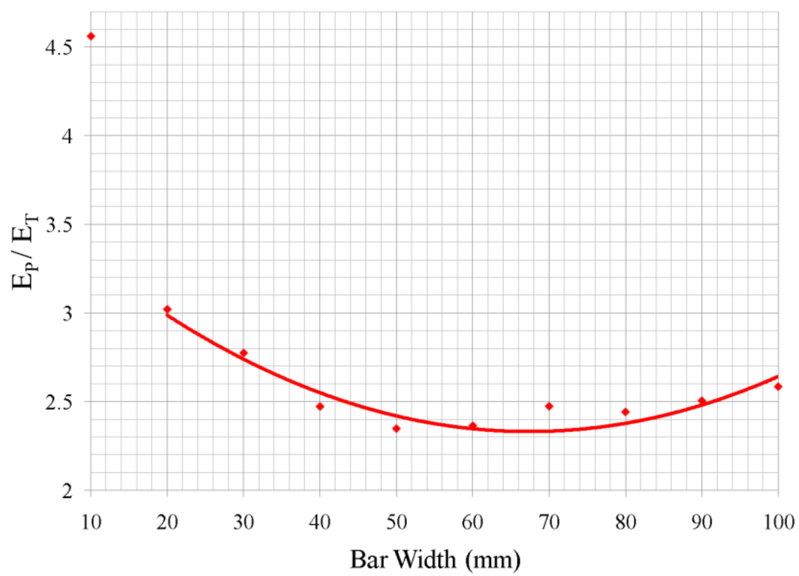


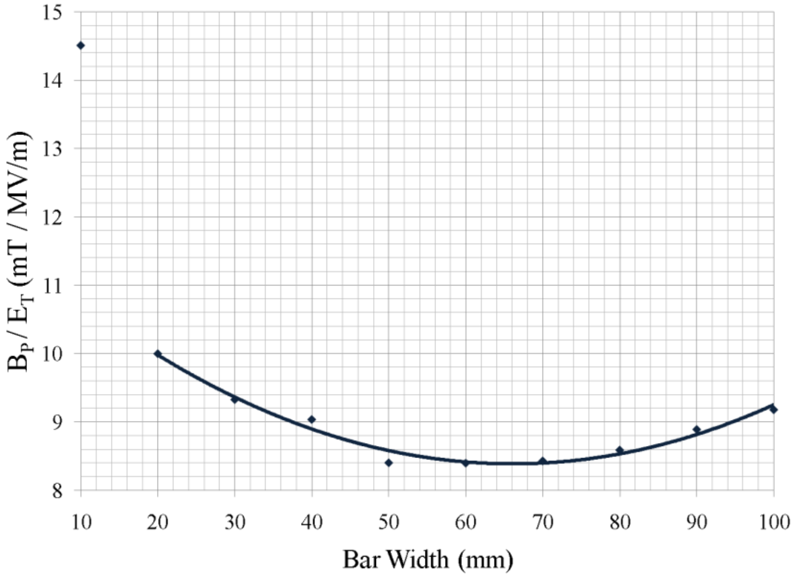


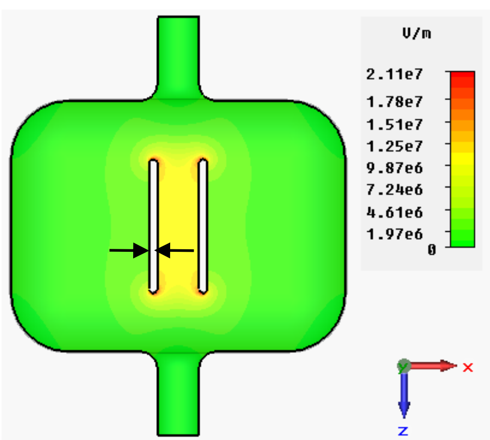


Frequency separation due to beam pipe = 1.21 MHz

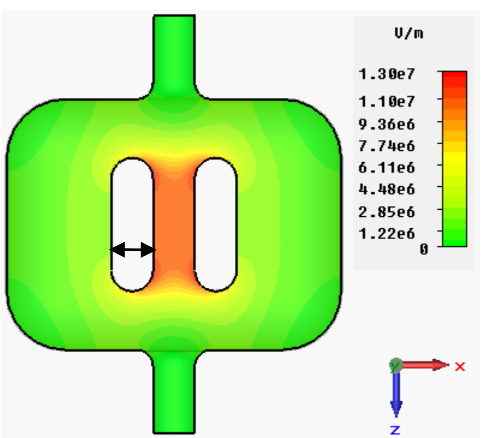
Optimization of Bar Width



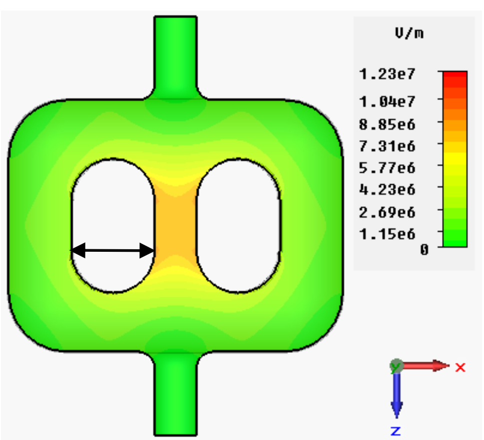




Bar Width = 10 mm

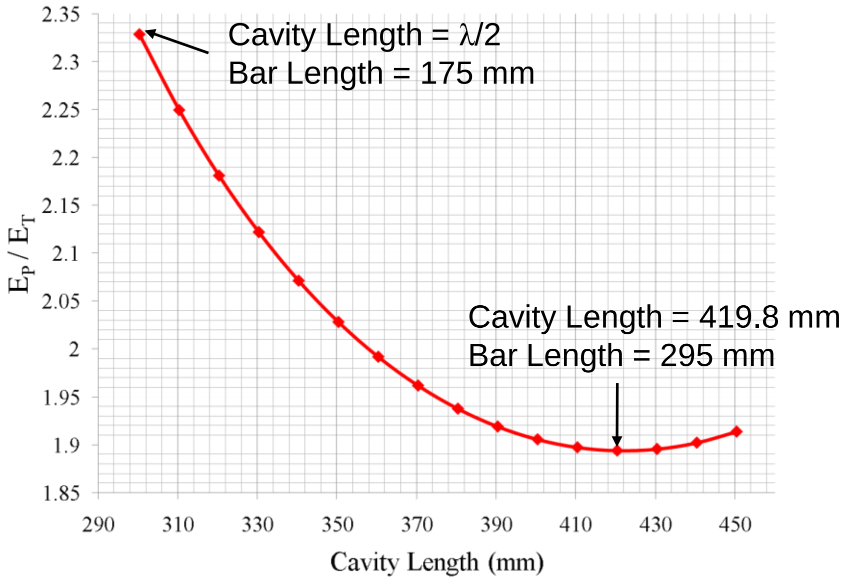


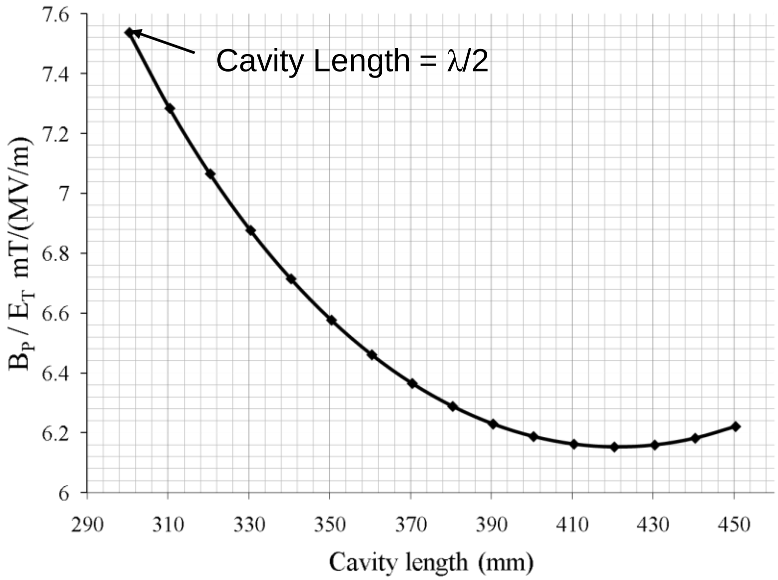
Bar Width = 50 mm



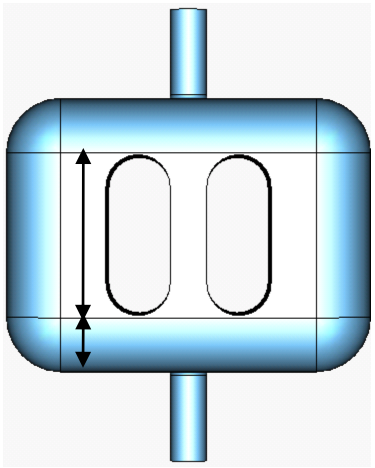
Bar Width = 100 mm

Optimization of Bar and Cavity Length



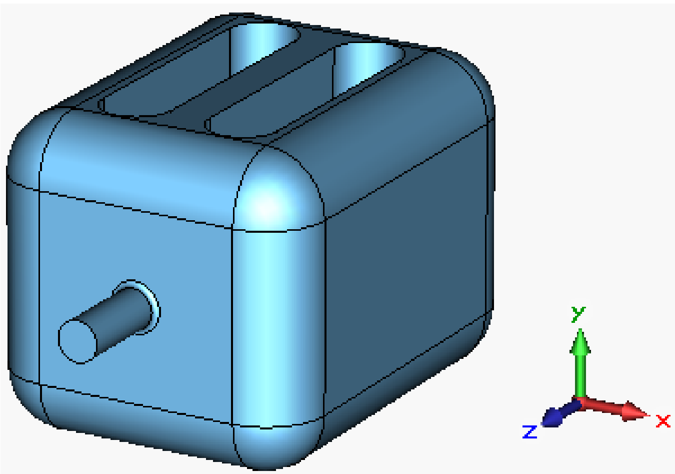


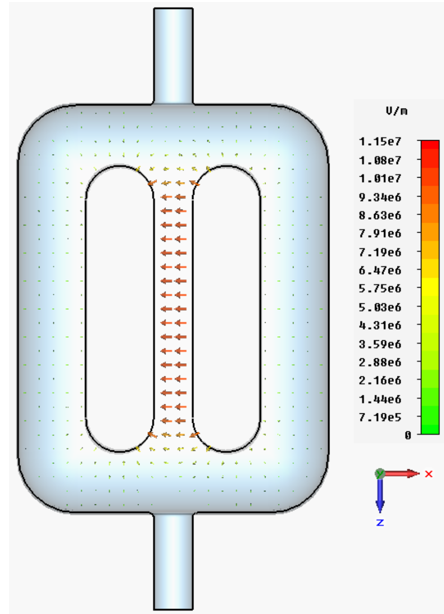
- Increase bar and cavity length simultaneously with a constant rounded edge
- Increase in bar length and cavity length increases the net deflection
- Optimizes the bar length to λ/2



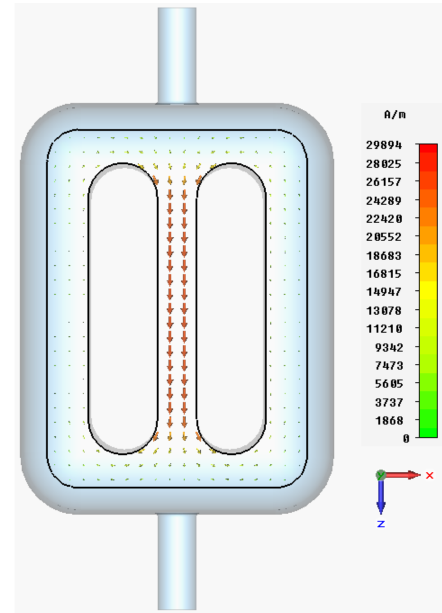
f = 500 MHz
λ/2 = 299.8 mm

Optimized Cavity Geometry and Field Profiles



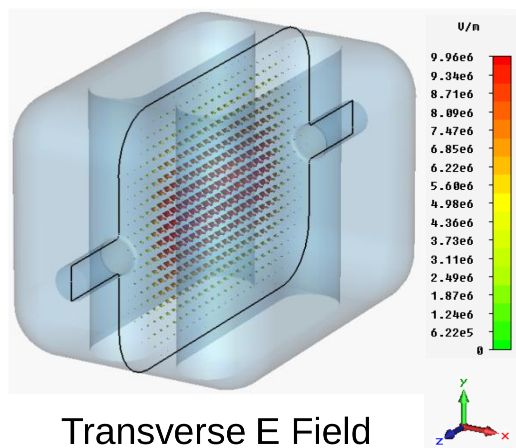


E field on mid plane

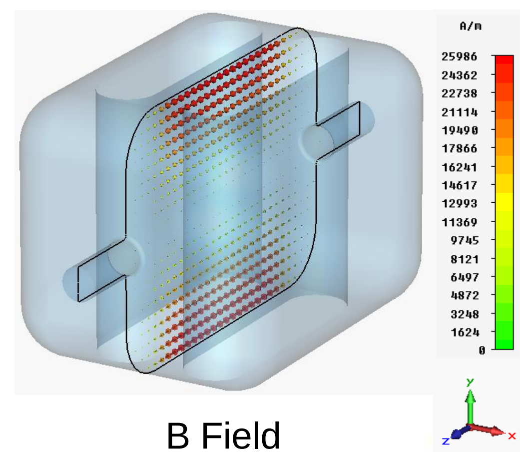


B field on top plane

Compact Design Dimensions	Value (mm)
Cavity reference length	419.8
Cavity height	304.5
Cavity width	320.0
Bar width	70.0
Bar length	295.0

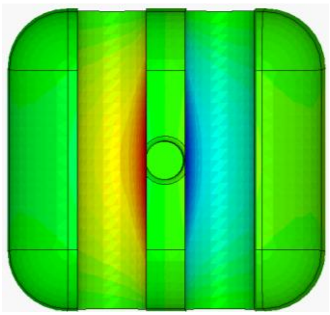


Transverse E Field

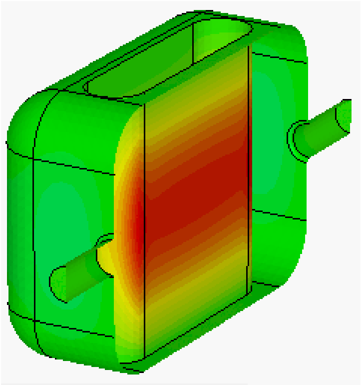


B Field

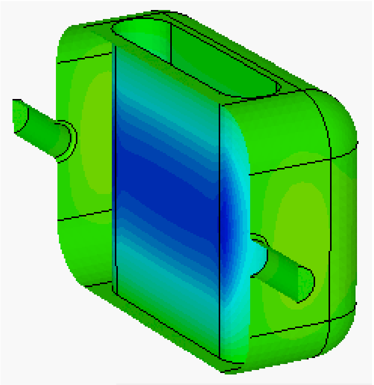
Surface Fields



Surface E Field



Surface E Field
on left bar

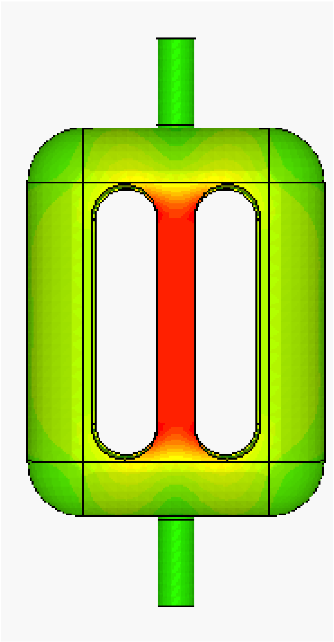


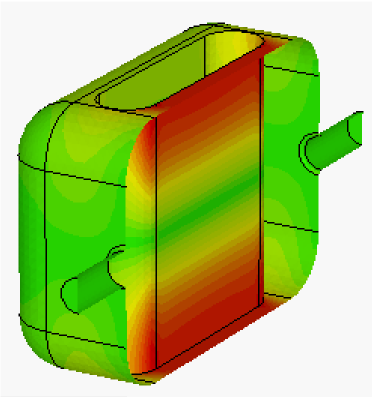
Surface E Field
on right bar

- Surface fields are localized between the bars
- Cavity size is made more compact by reducing the width

$$\frac{E_P}{E_T} = 2.02$$

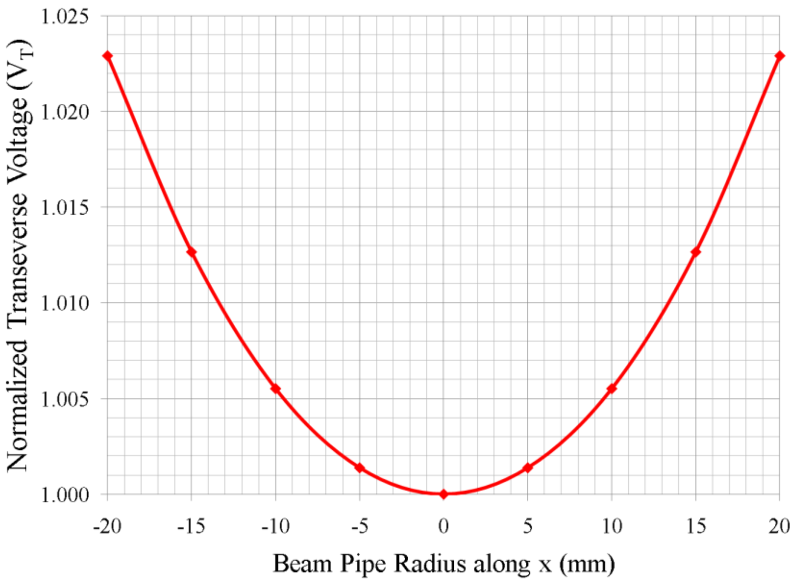
$$\frac{B_P}{E_T} = 6.58 \text{ mT/(MV/m)}$$

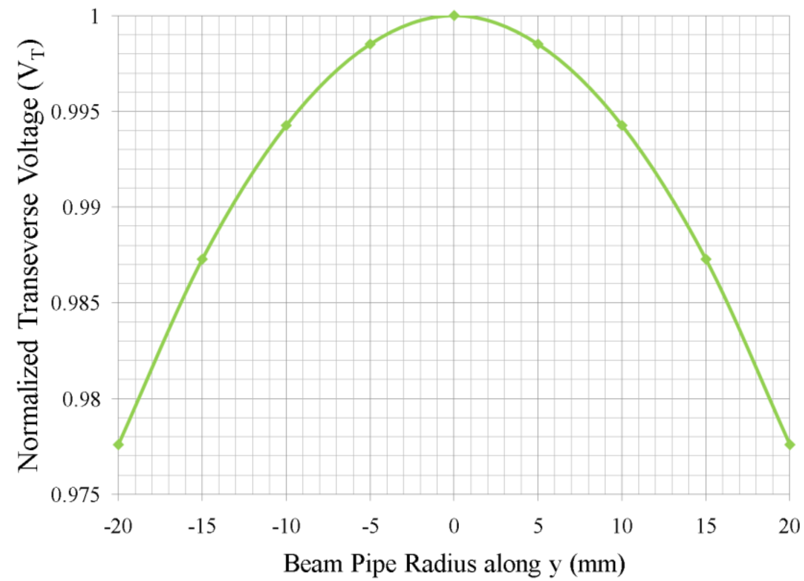




Surface B Field

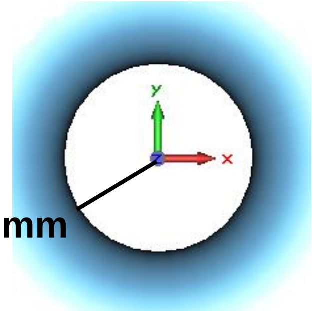
Transverse Deflecting Voltage along Beam Line Cross Section





$$\frac{V_T}{V_T(r=0)} = 6.0\times10^{-5}\Delta x^2 + 1.0$$

$$\frac{V_T}{V_T(r=0)} = -6.0\times10^{-5}\Delta y^2 + 1.0$$

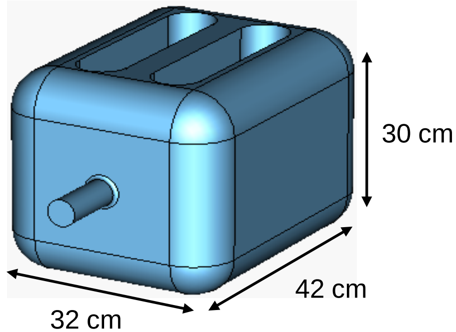


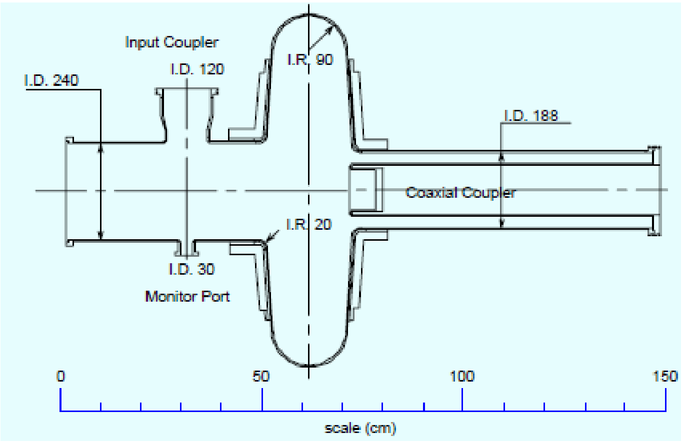
R = 20 mm

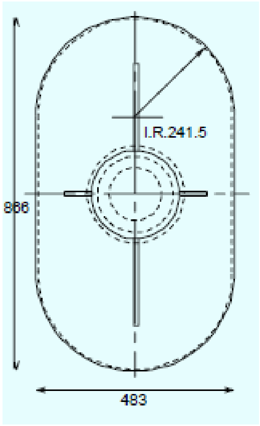
Direction	$\Delta V_T/V_T$ (At R = 20 mm)
x	2.29 %
y	2.24 %

Cavity Properties

Parameter	Parallel Bar Structure	KEK Cavity *	Unit
Frequency of π mode	500.31	501.7	MHz
$\lambda/2$ of π mode	299.8	299.8	mm
Frequency of 0 mode	524.39	~ 700 MHz	MHz
Cavity reference length	419.8	299.8	mm
Cavity width	320.0	866.0	mm
Cavity height	304.5	483.0	mm
Bars length	295.0	–	mm
Bars width	70.0	–	mm
Aperture diameter	40.0	130.0	mm
Deflecting voltage (V_T^*)	0.3	0.3	MV
Peak electric field (E_T^*)	2.02	4.32	MV/m
Peak magnetic field (B_T^*)	6.58	12.45	mT
Geometrical factor ($G = QR_S$)	67.11	220	Ω
$[R/Q]_T$	926.67	46.7	Ω
$R_T R_S$	6.22×10^4	1.03×10^4	Ω^2
At E_T^* = 1 MV/m			





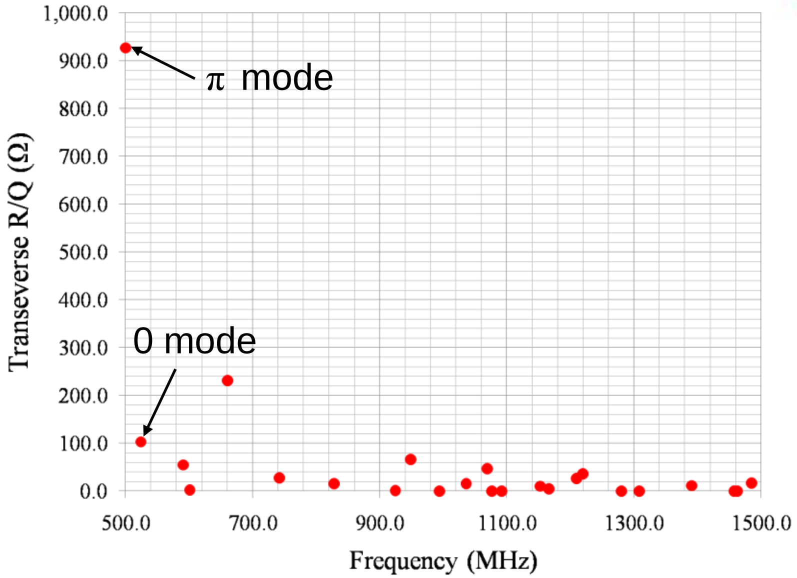


* K. Hosoyama et al, “Crab cavity for KEKB”, Proc. of the 7th Workshop on RF Superconductivity, p.547 (1998)

Jefferson Lab

Higher Order Modes

Mode	Frequency (MHz)	Mode of Operation	Field direction on beam axis		$[R/Q]_T$ (Ω)	
			E	B	Direct Integral Method	Using Panofsky Wenzel Theorem
						(r_0 = 5 mm)
1	500.32	Deflecting	x	y	926.67	928.16
2	524.39	Accelerating	z		102.81	
3	590.80	Accelerating	z		54.71	
4	601.29	Deflecting	x	y	2.346	2.35
5	660.46	Deflecting	x	y	230.84	231.06
6	742.10	Accelerating	z		27.98	
7	828.44	Deflecting	x	y	15.44	15.43
8	924.69	Deflecting	x	y	1.25	1.249
9	948.75	Accelerating	z		66.53	
10	994.08			z	0.0	
11	1036.12	Deflecting	y	x	15.19	15.17
12	1069.49	Deflecting	y	x	46.78	46.79
13	1076.42			z	0.0	
14	1091.90			z	0.0	
15	1152.82	Deflecting	x	y	10.27	10.25
16	1166.42	Deflecting	y	x	4.59	4.62
17	1166.49	Deflecting	x	y	4.44	4.38
18	1209.64			z	26.32	
19	1219.86	Accelerating	z		36.29	
20	1280.60			z	0	



Fundamental Mode Separation = 24.1 MHz

Longitudinal Shunt Impedance

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

Direct Integral

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

Using Panofsky Wenzel Theorem

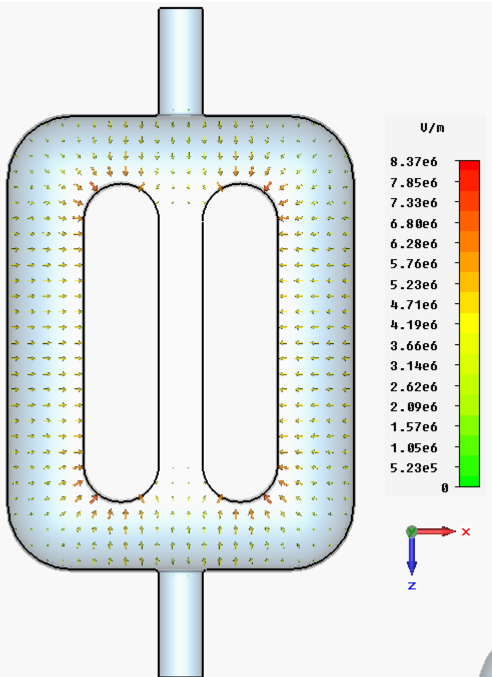
$$\left[\frac{R}{Q}\right]_T = \frac{|V_Z(r = r_0)|^2}{\omega U} \frac{1}{(kr_0)^2} = \frac{\left|\int_{-\infty}^{+\infty} E_z(z, r = r_0) e^{\frac{j\omega z}{c}} dz\right|^2}{(kr_0)^2 \omega U}$$

$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$$

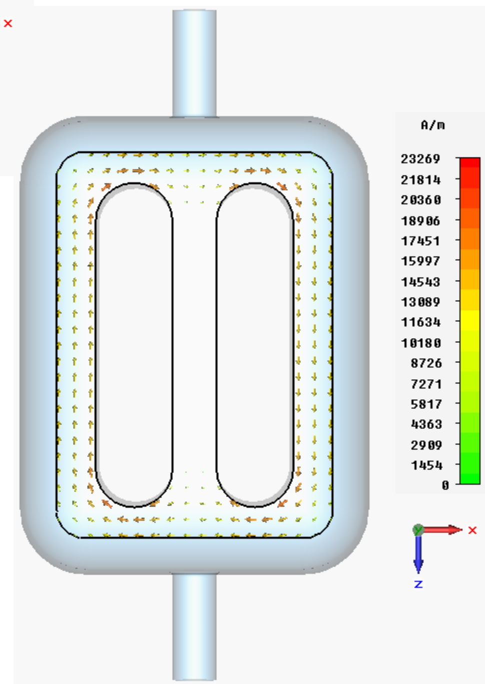
Transverse Shunt Impedance

Modes of Interest

Mode 2



E field on mid plane

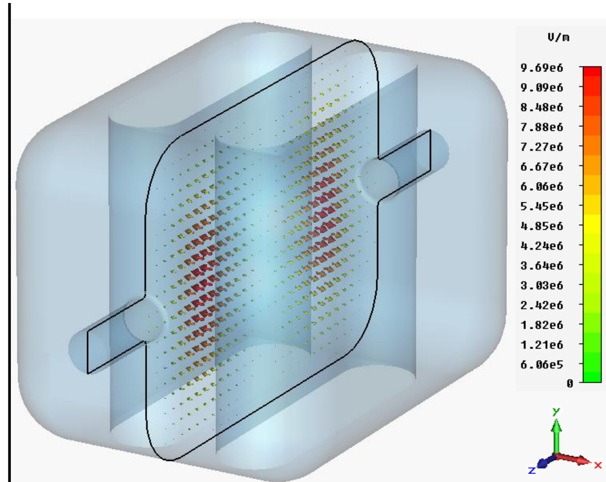


B field on top plane

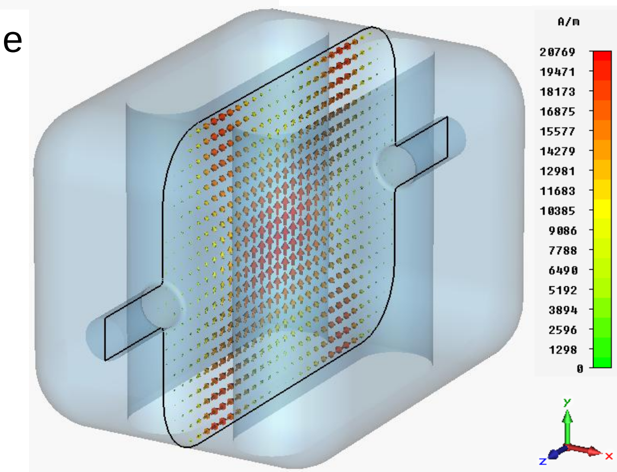
Frequency = 524.39 MHz
Mode of Operation – Accelerating

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

Mode 6



E field on mid plane



B field on mid plane

Frequency = 660.46 MHz
Mode of Operation – Deflecting

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

Crab Cavity for ELIC

- 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 500 MHz
  - For a surface electric field of E_P = 40 MV/m, V_T = 5.94 MV
  - For a surface magnetic field of B_P = 100 mT, V_T = 4.56 MV

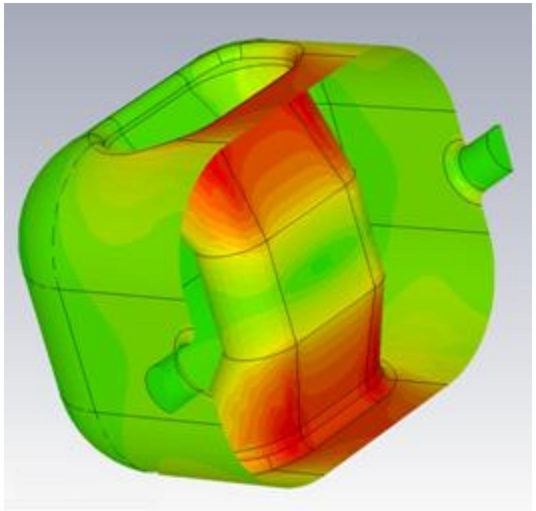
The design satisfies the current needs of the ELIC crab cavity requirements

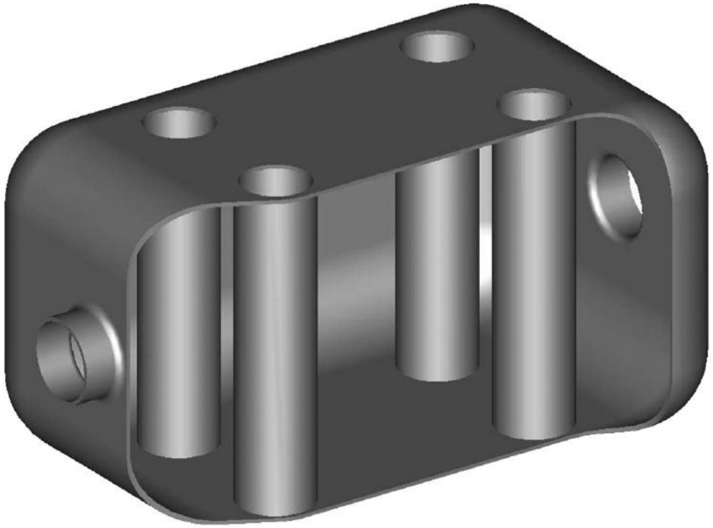
- **Can achieve the required deflecting voltage of 10 MV using 3 cavities (with B_P = 100 mT)**
- **Required resultant cavity reference length = 3 x 42 cm = 126 cm**
- **KEKB Squashed Cell Crab Cavity Operating in TM_{110} Mode**

  Crossing angle = 2 x 11 mrad

  V_T=1.4 MV, E_P= 21 MV/m

Other Parallel Bar Cavity Options





Summary

- **Parallel bar crab cavity structure provides the required deflection of 10 MV for protons of 60 GeV with 3 cavities**
- Structure is capable of generating higher transverse deflection with very lower surface fields and higher shunt impedance compared to other crabbing structures
- Supports very low frequencies of operation
- Compact design occupies less free space

Future Work

- Further optimization as needed by the ELIC design
- Analysis of Multipacting effects on cavity
- Further study of HOMs and designing of couplers to damp HOMS
- Analysis of Microphonic effects and RF Control