Superconducting Parallel-Bar Deflecting/Crabbing Cavity Development and its Applications

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OLD DOMINION UNIVERSITY

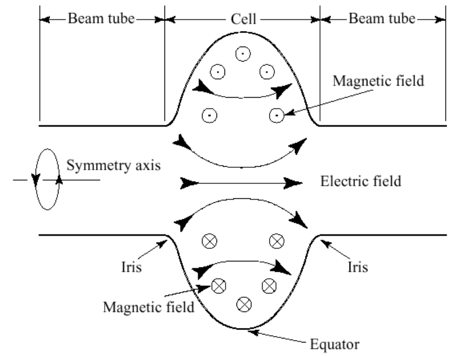
Jefferson Lab

Outline

- Deflecting and Crabbing Concept
- Type of Deflecting/Crabbing Cavities
  - TM type cavities
  - TEM type cavities
  - TE type cavities
- Parallel-Bar Cavity
  - Geometry and Design Parameters
  - Field Profile
  - Design Optimization
- Parallel-Bar Cavity Applications
  - Deflecting Cavity for Jefferson Lab 12 GeV Upgrade
  - Crabbing Cavity for LHC Luminosity Upgrade

Deflecting / Crabbing Concept

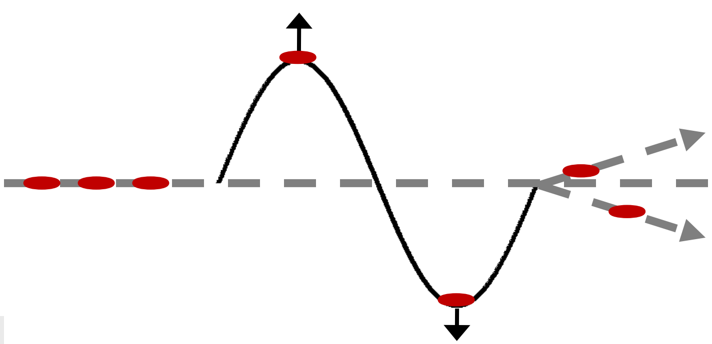
ACCELERATING CAVITIES

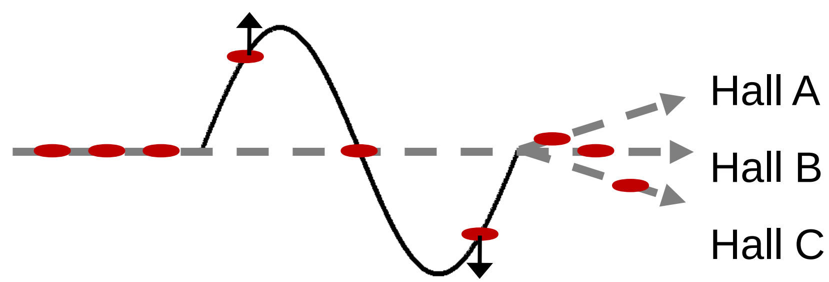


- Design structure is the same for both deflecting and crabbing of particle beams
- Only depends on the application

DEFLECTING CAVITIES

- Separation of bunches into multiple beams
- A transverse force is applied to the center of the bunch



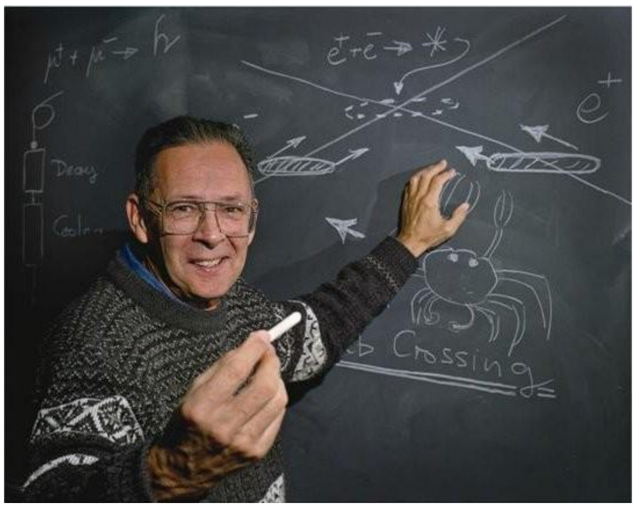


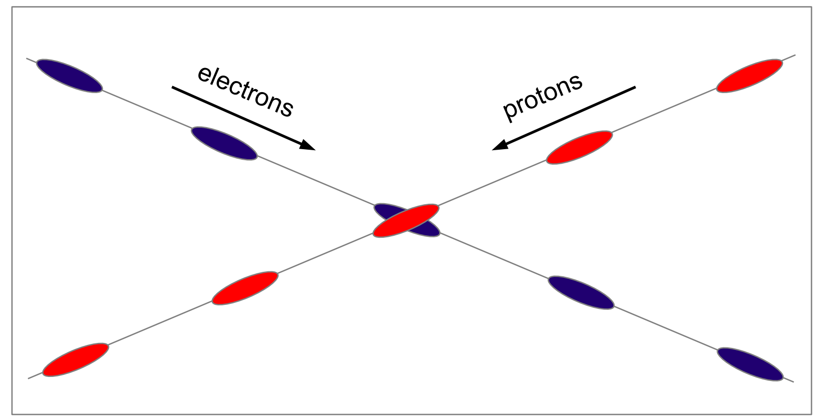
JLab Beam Separation

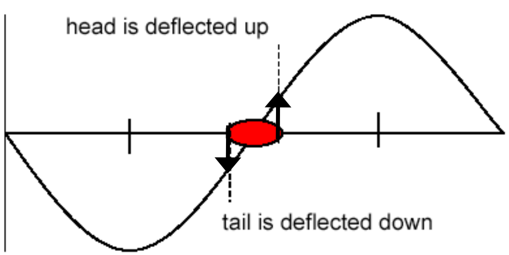
Deflecting / Crabbing Concept

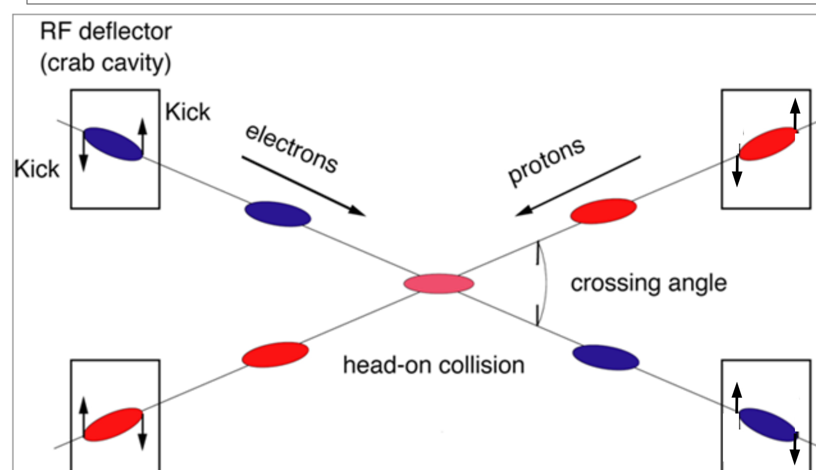
CRABBING CAVITIES

- Rotation of bunches* for head on collision of bunches → To increase the luminosity
- Rotated by applying a transverse force to the head and tail of each bunch in opposite direction









*R. Palmer, SLAC-PUB-4707 (1988).

Transverse Force

- A transverse force must be applied to either deflect or rotate the bunch around the center
- Lorentz Force $\vec{F} = \frac{d\vec{p}}{dt} = q[\vec{E} + \vec{v} \times \vec{B}]$
- Transverse Voltage experienced by a particle

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

- Panofsky Wenzel Theorem*

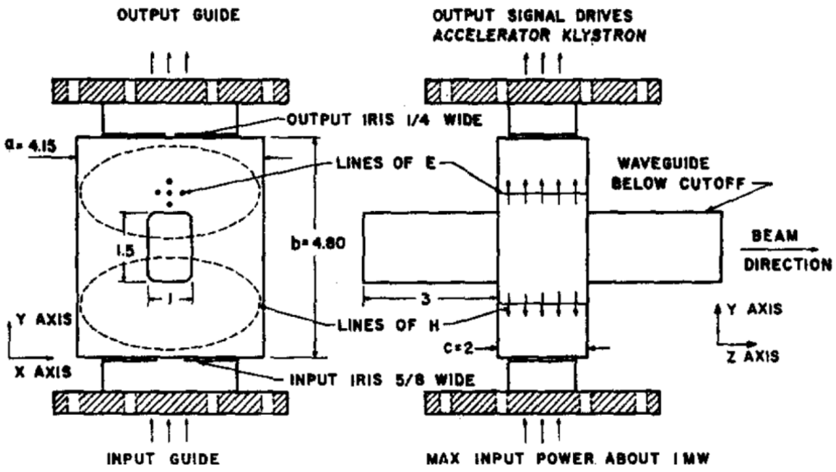
$$V_T = \frac{-i}{\omega / c} \nabla_T V_Z = \frac{-i}{\omega / c} \frac{1}{r_0} \left| \int_{-\infty}^{\infty} \vec{E}_Z(r_0, z) e^{\frac{i\omega z}{c}} dz \right|$$

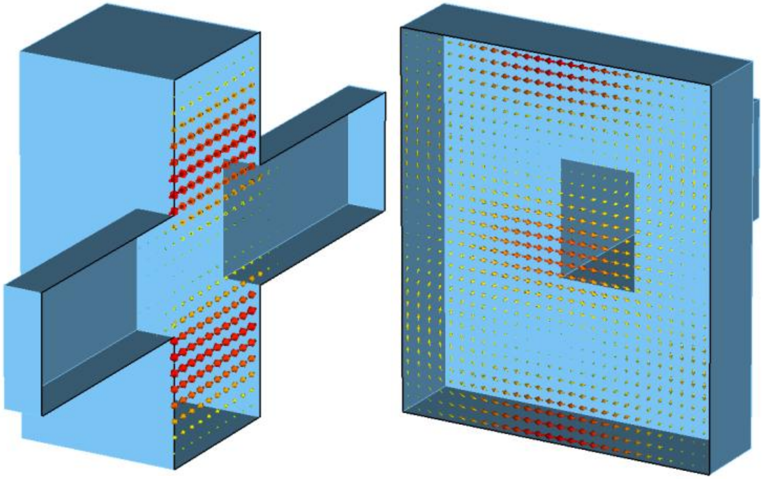
- Particles can be deflected both by magnetic field and electric field
  - TM type cavities: With transverse magnetic field
  - No pure TE type cavities: Contribution from the electric field is cancelled by the corresponding contribution from the magnetic field
  - TEM type cavities: With transverse electric and/or magnetic field

* W.K.H. Panofsky and W.A. Wenzel, "**Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields**," *Review of Scientific Instruments*, November 1956, p. 967.

TM Type Cavities

- The very first deflecting cavity* at High-Energy Physics Laboratory, Stanford University in 1960
  - Operates in TM_{110} mode @ 2.856 GHz
  - Successfully deflected an e- beam of 150 MeV with a deflection of 0.75 inches peak to peak





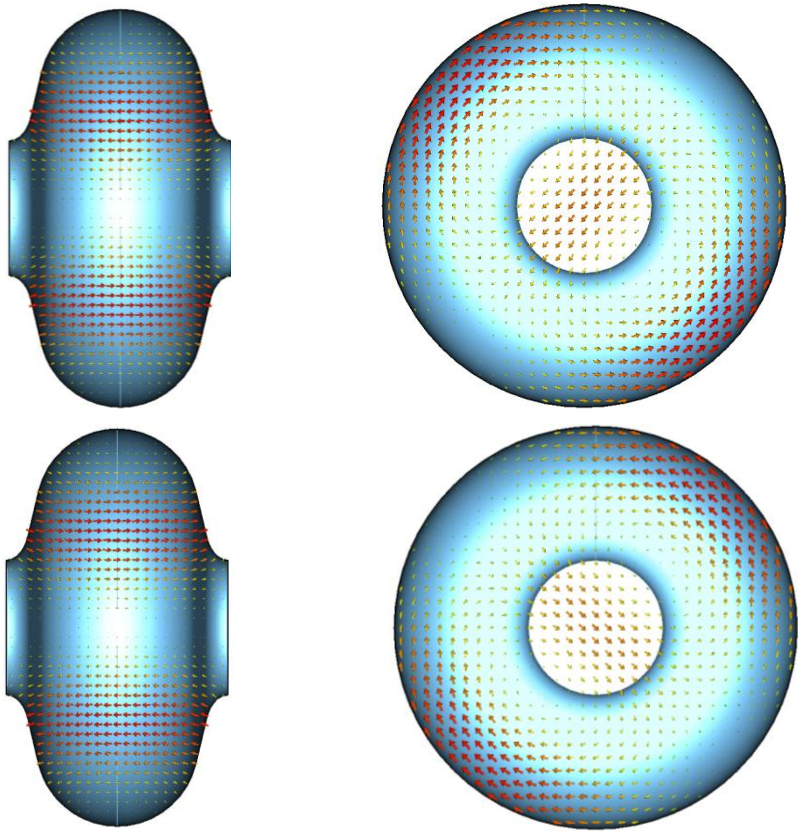
* P. R. Phillips, "**Microwave Separator for High Energy Particle Beams**", *Review of Scientific Instruments*, **32**, 13 (1961)

TM Type Cavities

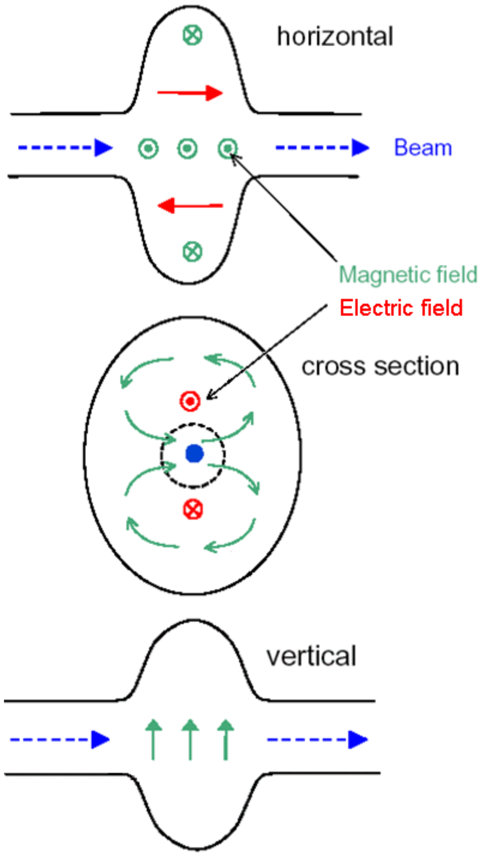
- Current designs operates in TM_{110} mode
  - Cavity designs have a squashed elliptical geometry
  - Magnetic field contributes to the transverse force

E Field

H Field



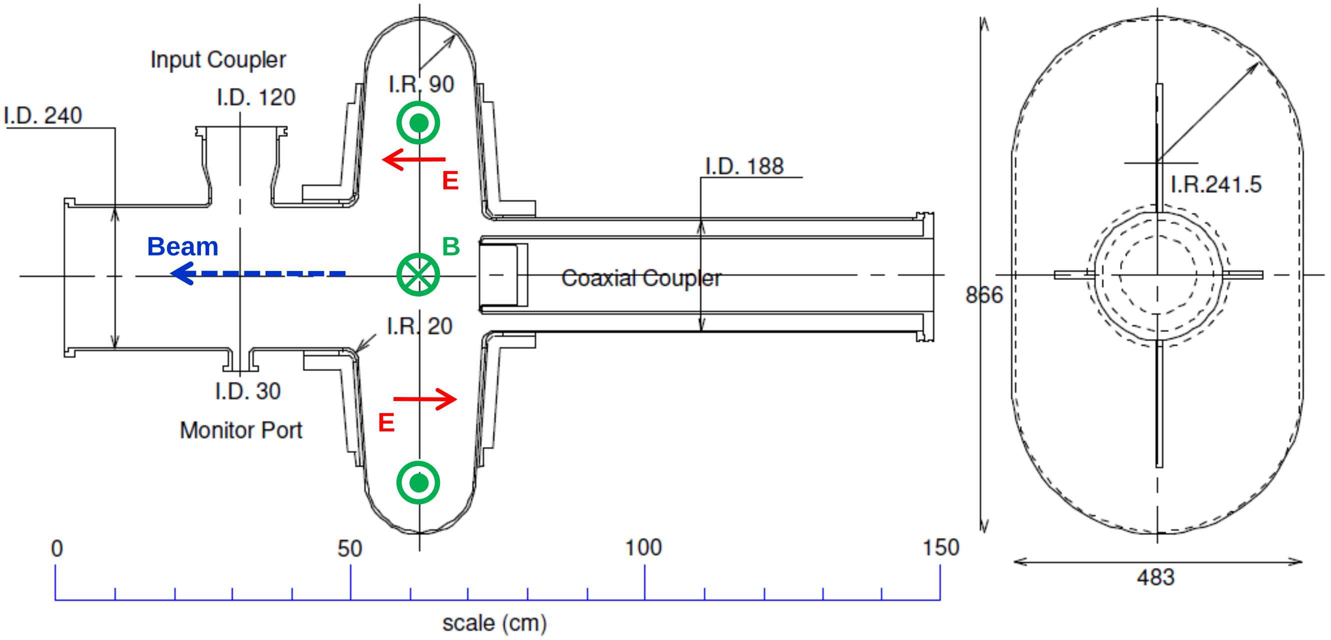
Two TM_{110} modes with same frequency



* P. R. Phillips, "**Microwave Separator for High Energy Particle Beams**", *Review of Scientific Instruments*, **32**, 13 (1961)

TM Type Cavities

- KEK Cavity* is the only currently operating superconducting crab cavity



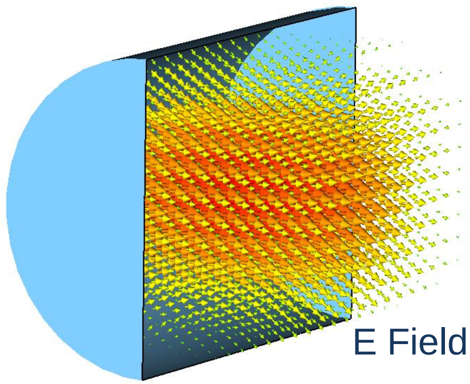
- Operates in TM_{110} mode at 508.9 MHz
- Squashed elliptical geometry is to separate the degeneracy in TM_{110} modes → Shifted to 700 MHz
- Maximum transverse voltage is 1.4 MV

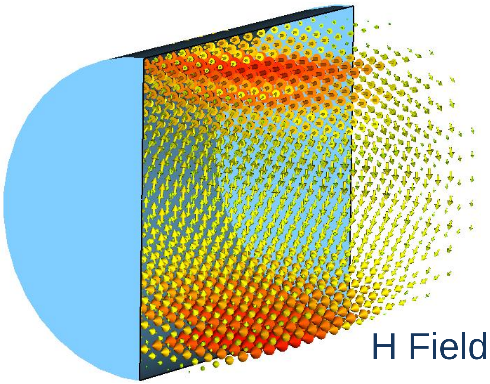
* K. Hosoyama et al, "**Crab cavity for KEKB**", Proc. of the 7th Workshop on RF Superconductivity, p.547 (1998)

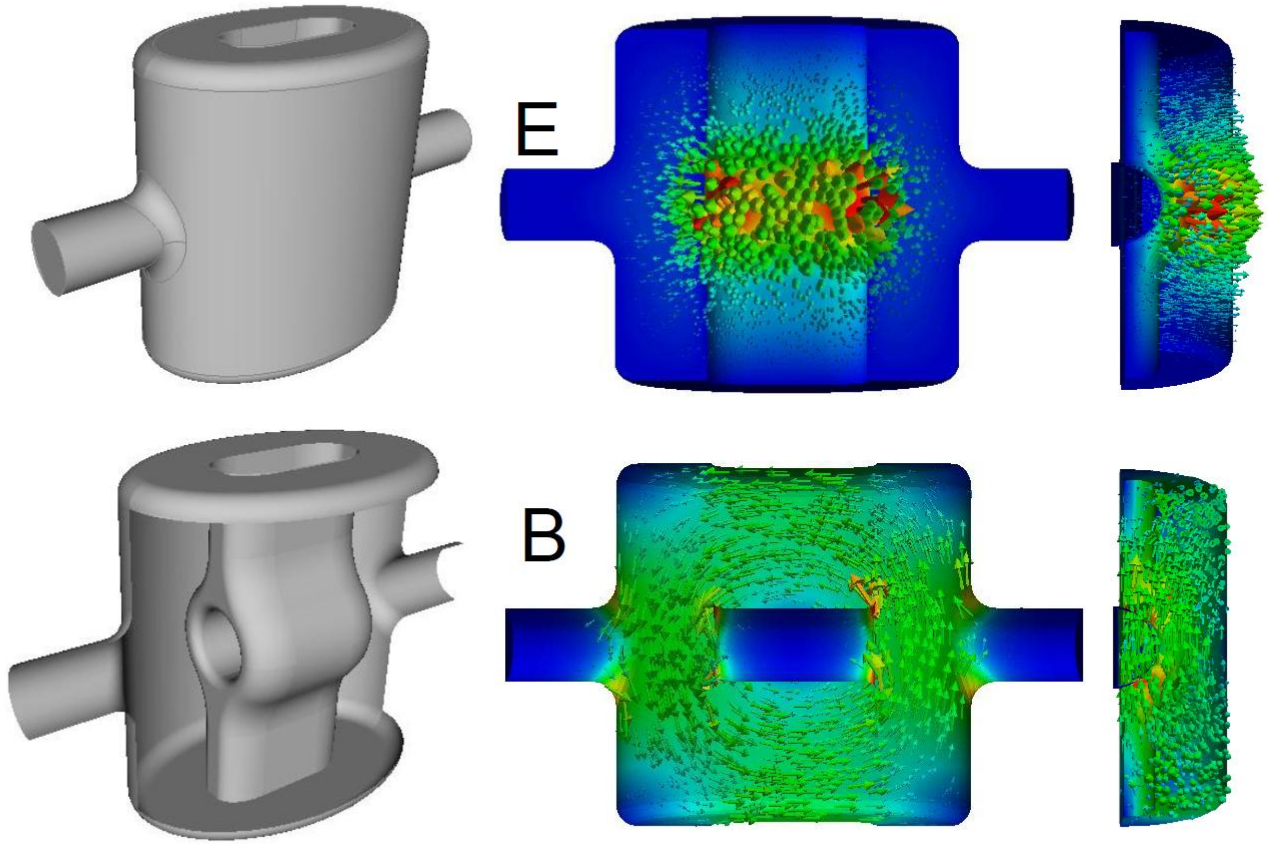
TE Type Cavities

- SLAC 400 MHz half wave spoke resonator
- Operates in TE_{11}–like mode
- Design frequency determined by the longitudinal and vertical dimensions

Pure TE_{111} mode



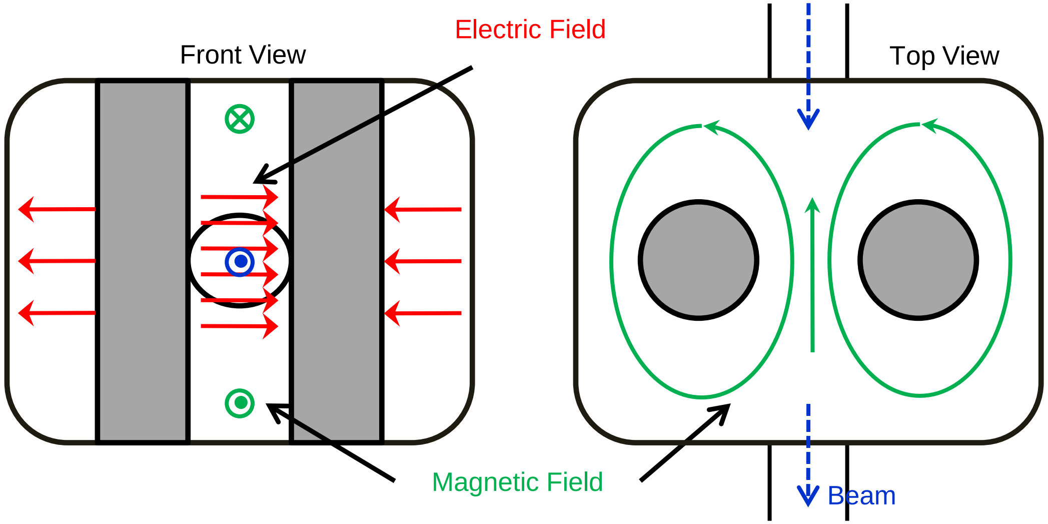


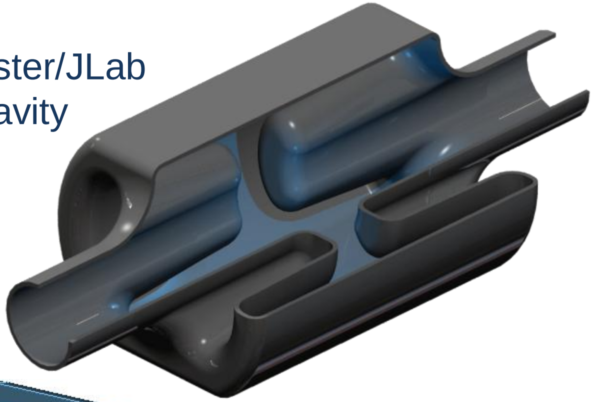


TEM Type Cavities

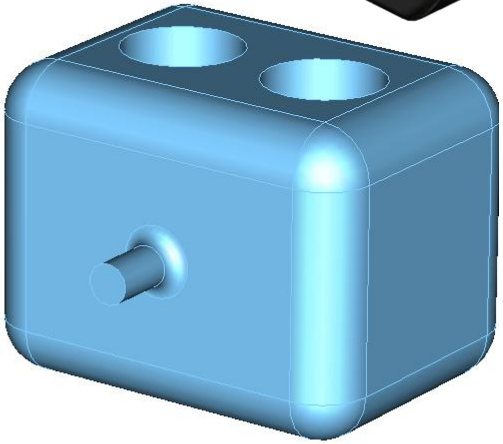
- TEM Type Cavities
  - Electric field contributes to the transverse force
    - E.g. Jefferson Lab 4-Rod Cavity
    - E.g. U. Lancaster/JLab 4-Rod Cavity
    - E.g. Parallel-Bar Cavity

Jefferson Lab 4-Rod Cavity



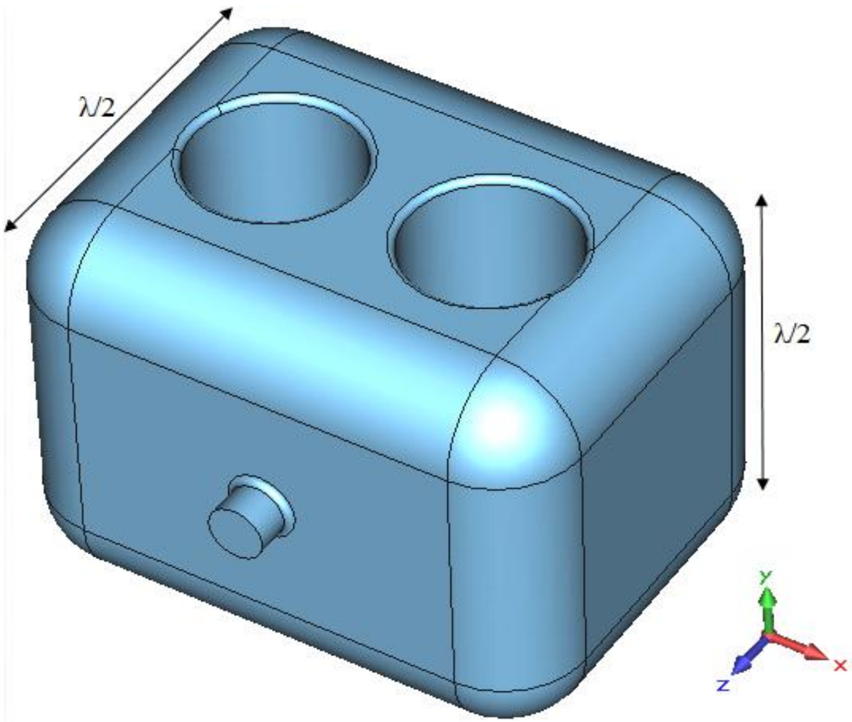


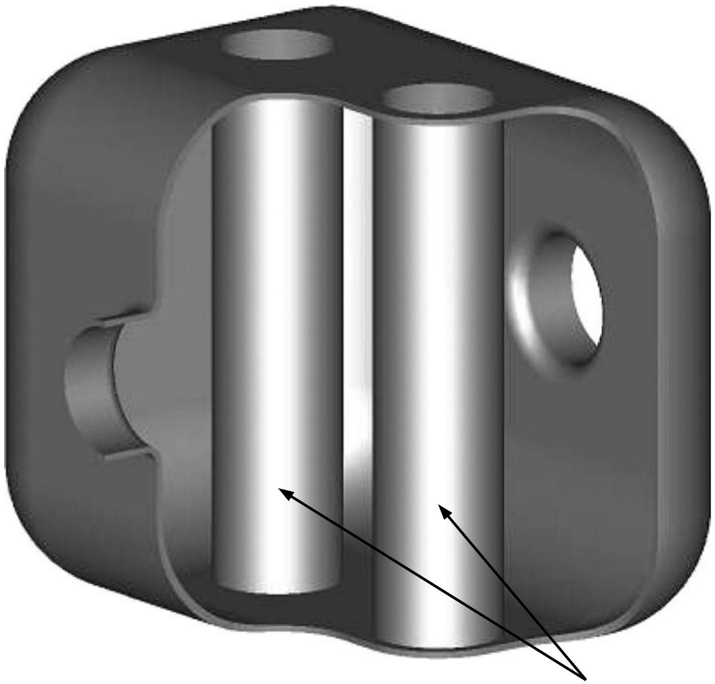
U. Lancaster/JLab 4-Rod Cavity



Parallel-Bar Cavity

TEM Type Cavities - Parallel Bar Cavity

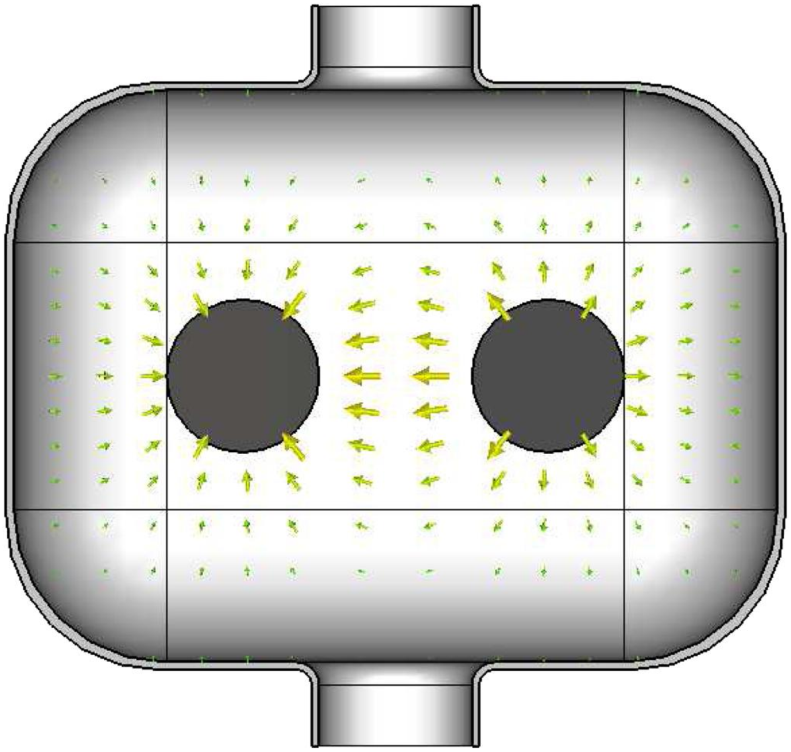




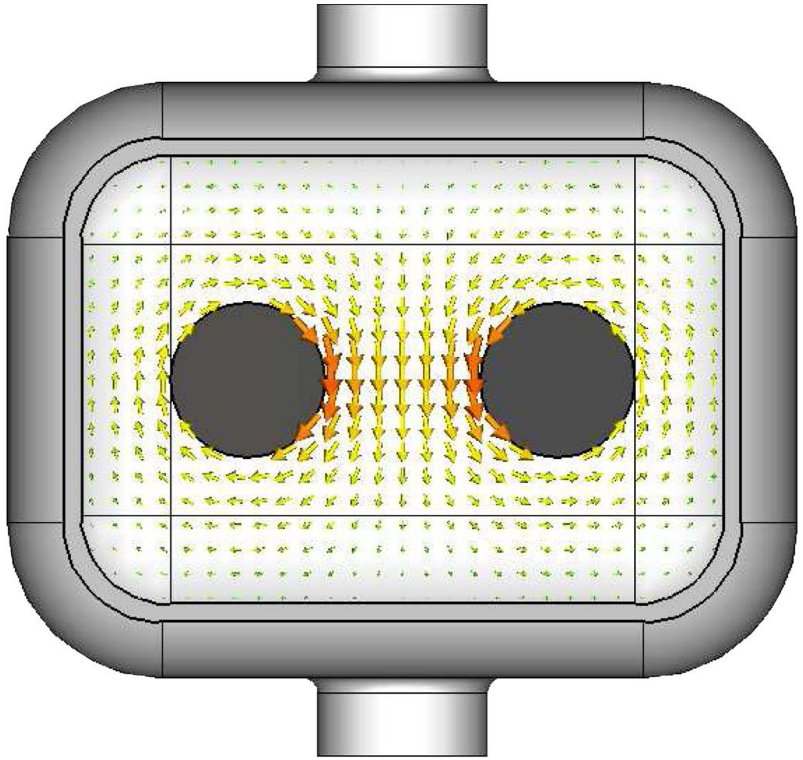
TEM Resonant Lines

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

Parallel Bar Cavity Field Profile



E field on mid plane

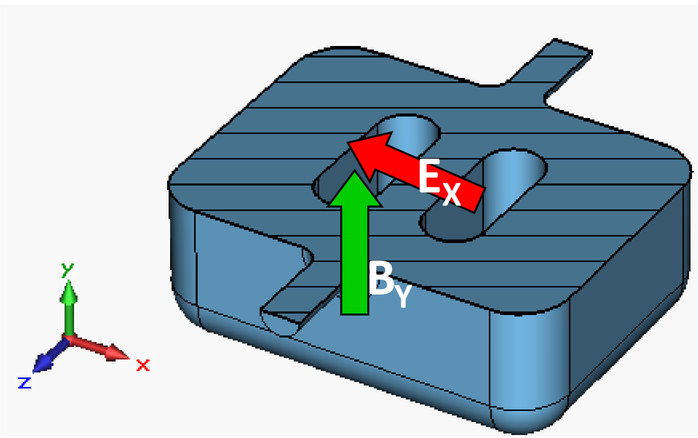


B field on top plane

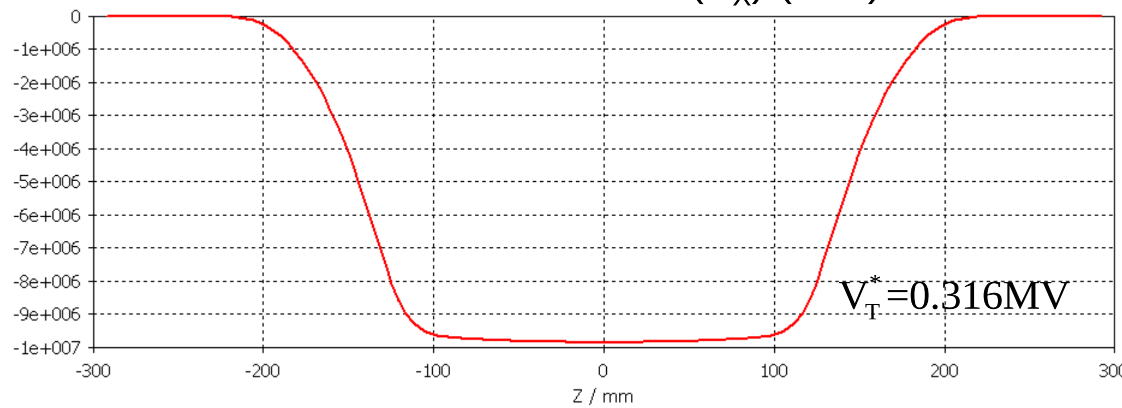
Deflection is mainly due to the interaction with the Electric Field

Transverse Deflection

Transverse Voltage : $$V_T = \int_{-\infty}^{+\infty} \left[E_x(z)\cos\left(\frac{\omega z}{c}\right) + cB_y(z)\sin\left(\frac{\omega z}{c}\right) \right] dz$$



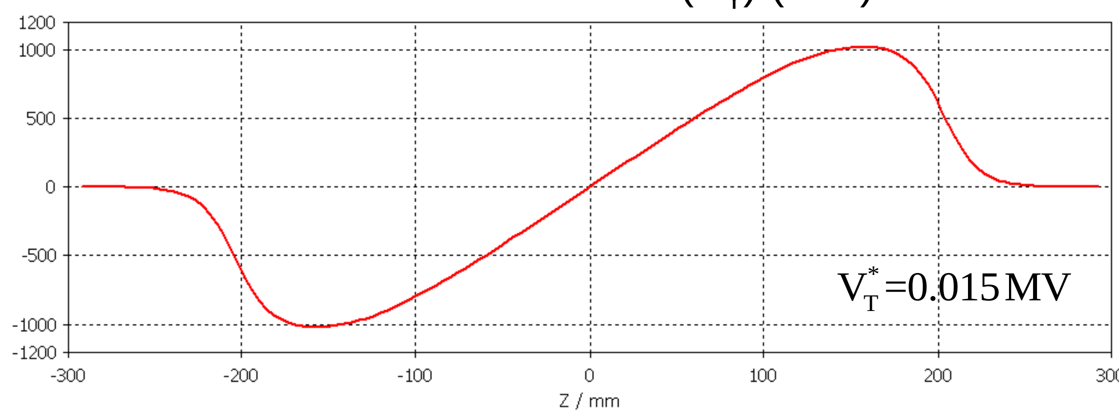
Transverse E Field (E_X) (V/m)



Transverse Electric Field :

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

Transverse H Field (H_Y) (A/m)



Resultant $V_T^* = 0.3$ MV

At $E_T^* = 1$ MV/m

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Design Optimization Parameters

- Minimize fields on the surface
  - Peak Surface Electric Field (E_P)
    - Technical Limit ~ 40-50 MV/m
    - Due to field emission
  - Peak Surface Magnetic Field (B_P)
    - Theoretical Limit ~ 180 mT
    - Critical magnetic field limit for Nb
    - Technical Limit ~ 80-100 mT
    - Due to quenching of the cavity
- Maximize Shunt Impedance (R_{sh})
  - Shunt Impedance $$R_{sh} = \frac{V_T^2}{P_{diss}}$$
  - Transverse [R/Q] $$\left[\frac{R}{Q}\right]_T = \frac{V_T^2}{\omega U}$$
  - To achieve a higher transverse voltage with low power loss

Optimizing Parameters

$$\frac{E_P}{E_T} \text{ and } \frac{B_P}{E_T}$$

Balanced Peak Fields

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

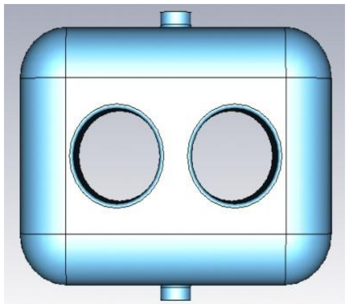
Peak Fields

$$E_P < 35 \text{ MV/m}$$

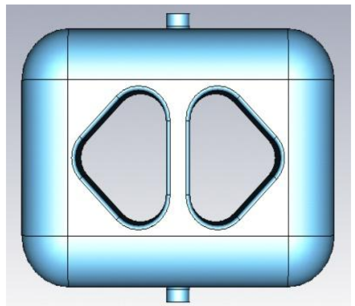
$$B_P < 70 \text{ mT}$$

Parallel Bar Cross Sections

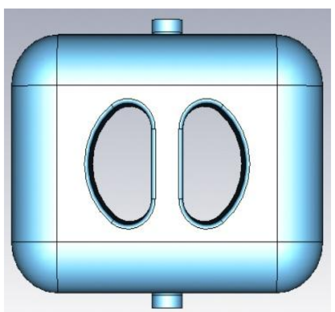
Optimizing condition – Obtain a higher deflection with lower surface fields



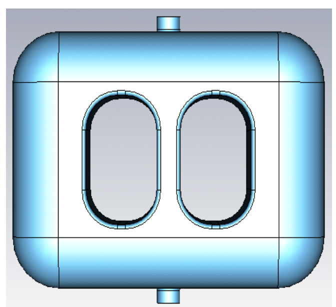
(a)



(b)



(c)



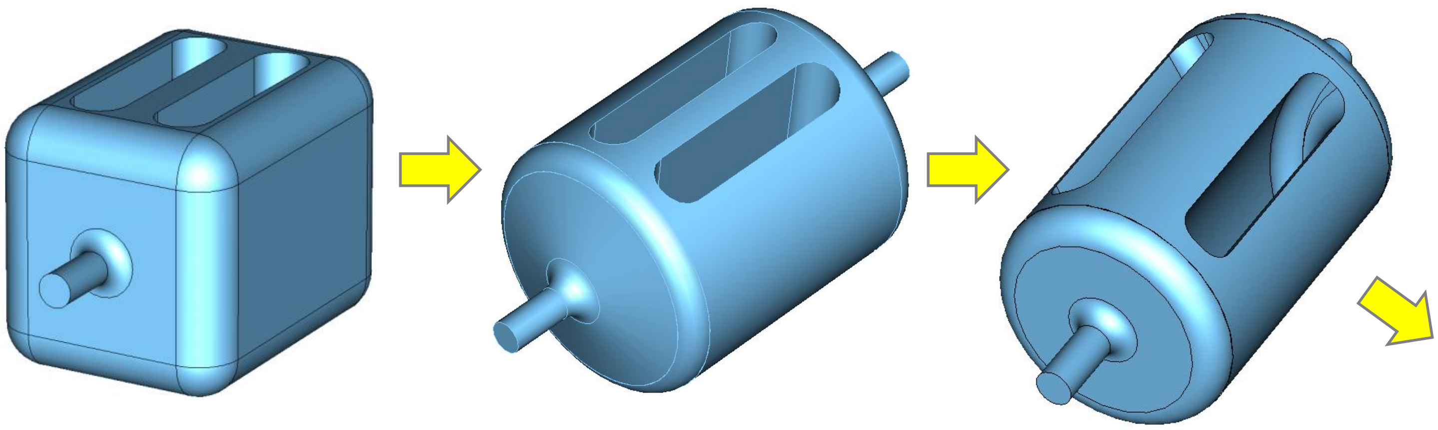
(d)

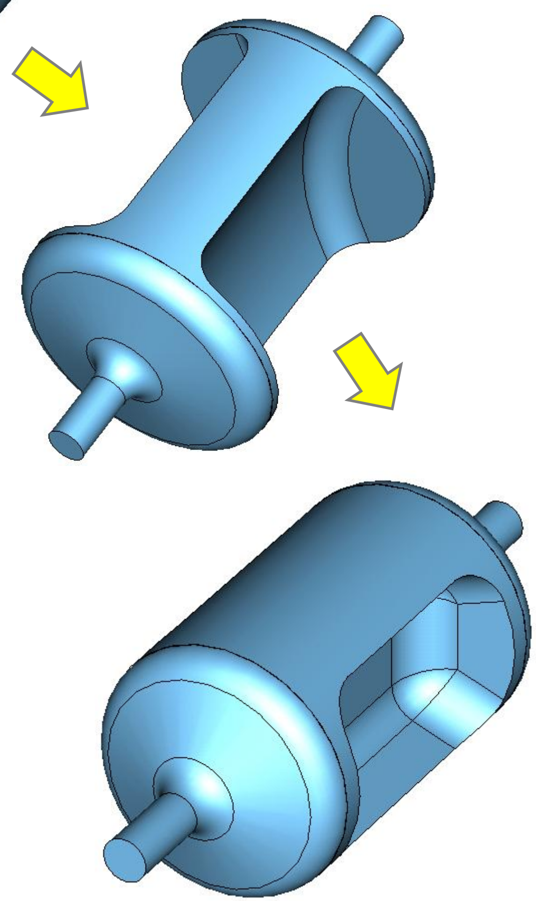
Peak Surface Fields

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

Design Optimization





- Aspects of optimization
  - Lower and balanced peak surface fields
  - Stability of the design
    - Cylindrical shape is preferred to reduce flat surfaces
  - Cavity processing
    - Curved end plates for cleaning the cavity
  - Wider separation in Higher Order Mode (HOM) spectrum
  - Multipacting

- Optimizing parameters of the structures
  - Cavity length
  - Cavity cross section → Height and Width / Diameter
  - Bar shape → Width, Length, Curvature
  - Proper curving of edges

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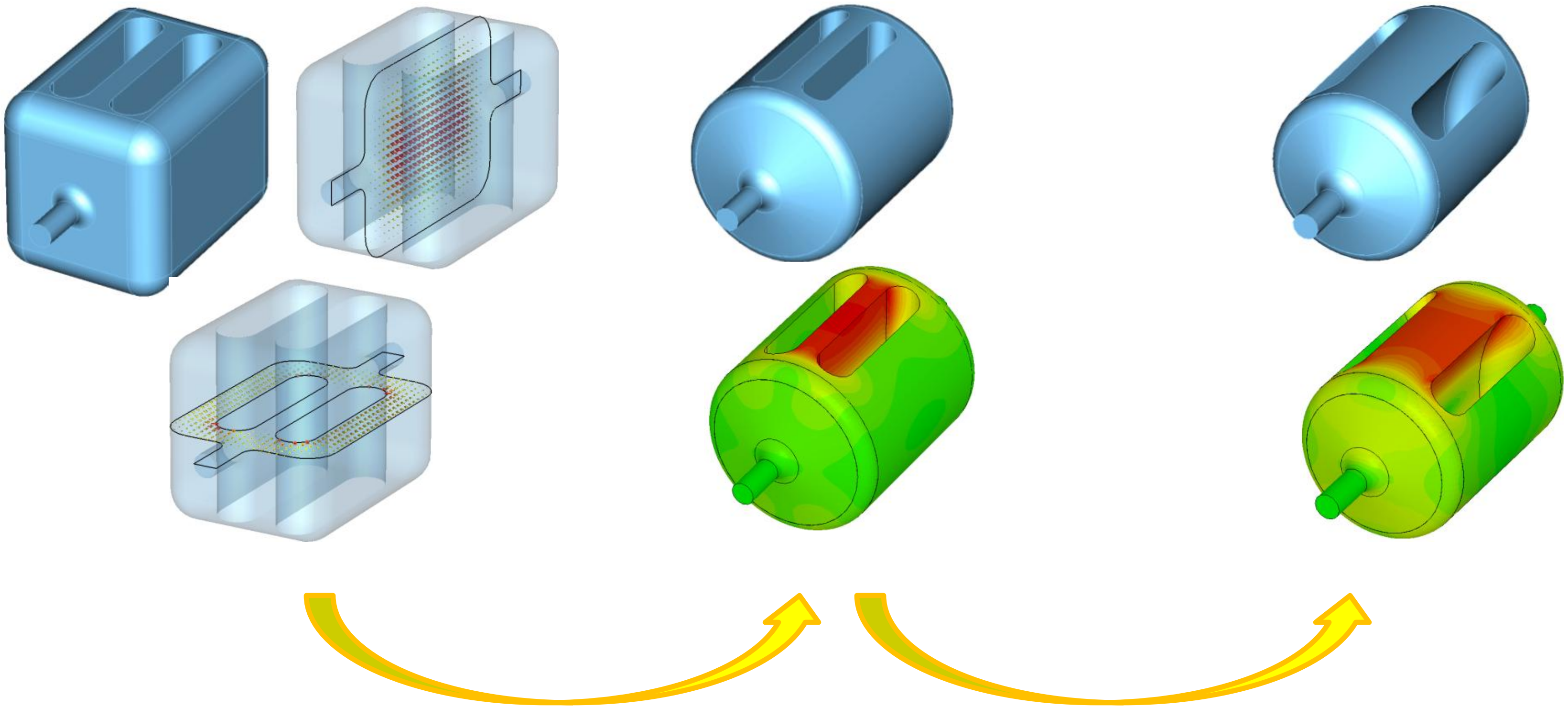
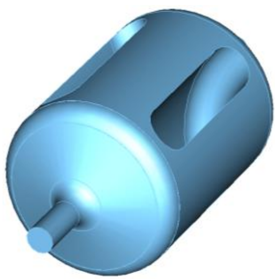
Design Evolution

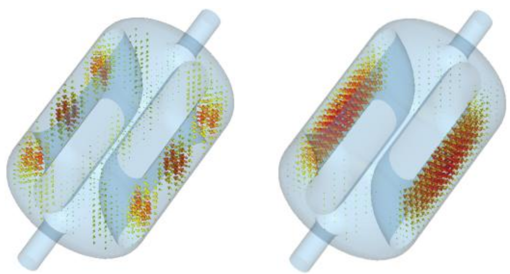


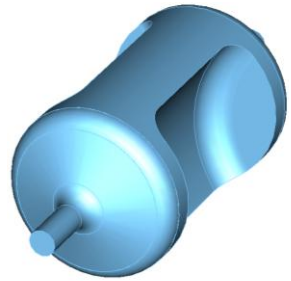
- To increase mode separation between fundamental modes
- ~18 MHz → ~ 130 MHz
- To improve design rigidity → Less susceptible to mechanical vibrations and deformations

- To lower peak magnetic field
- Reduced peak magnetic field by ~20%

Design Evolution

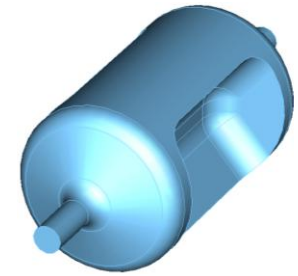






Balanced Peak Field Ratio

$$\frac{B_P}{E_P} = 2.06\ \text{mT/(MV/m)}$$



Balanced Peak Field Ratio

$$\frac{B_P}{E_P} = 1.53\ \text{mT/(MV/m)}$$

- 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 = 1.5 mT/(MV/m)

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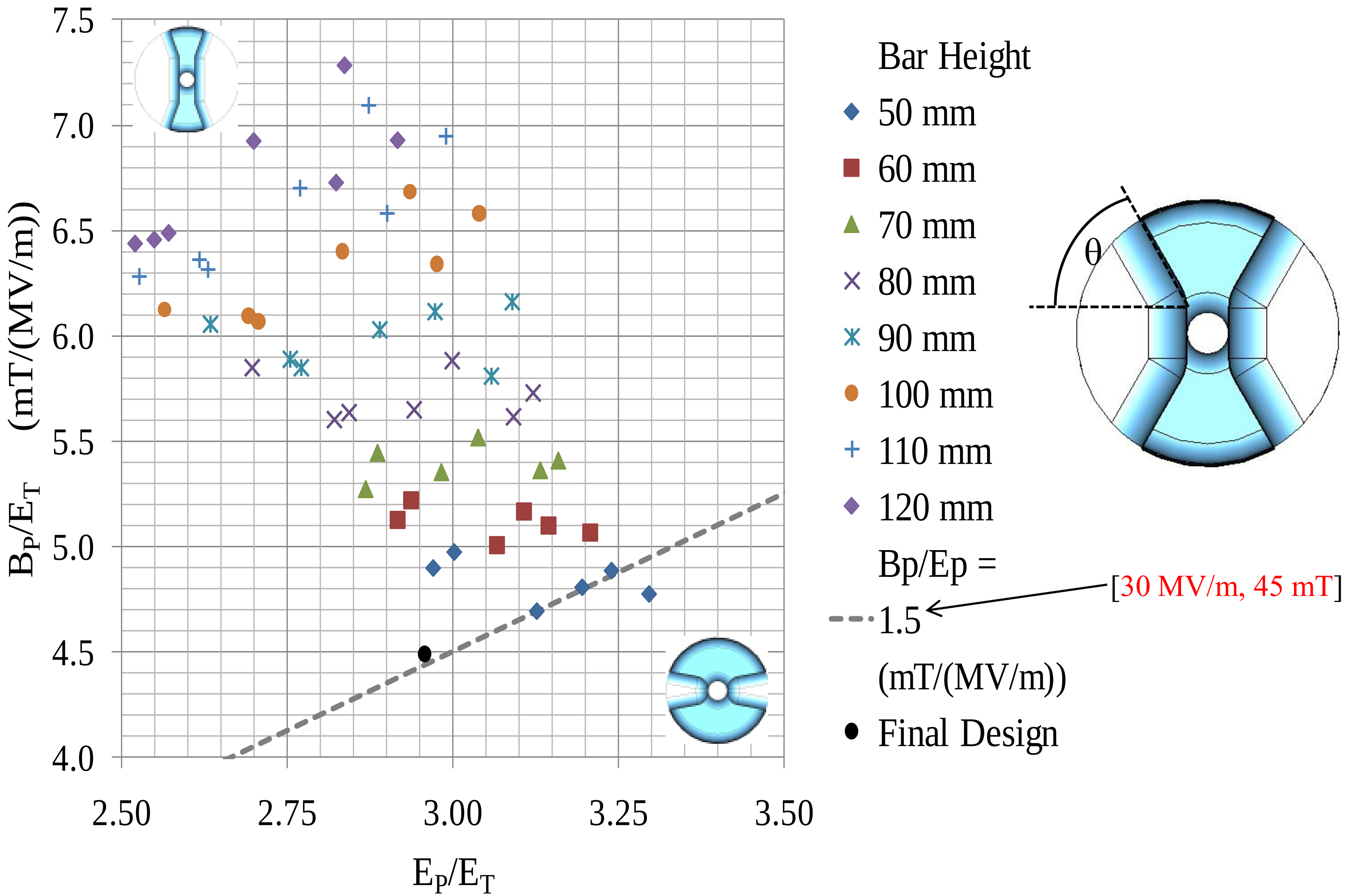
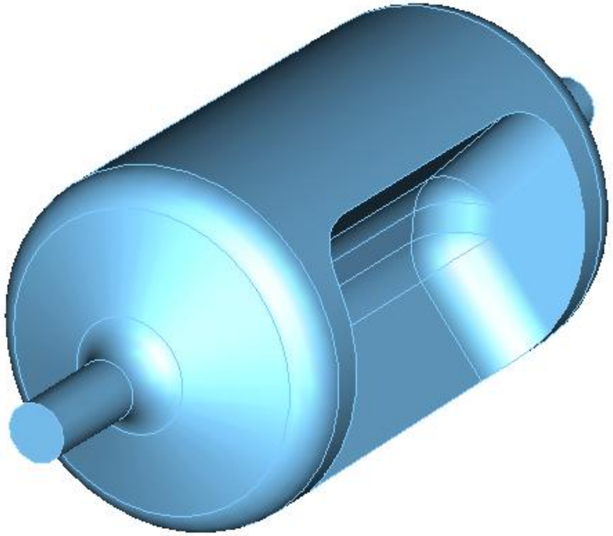
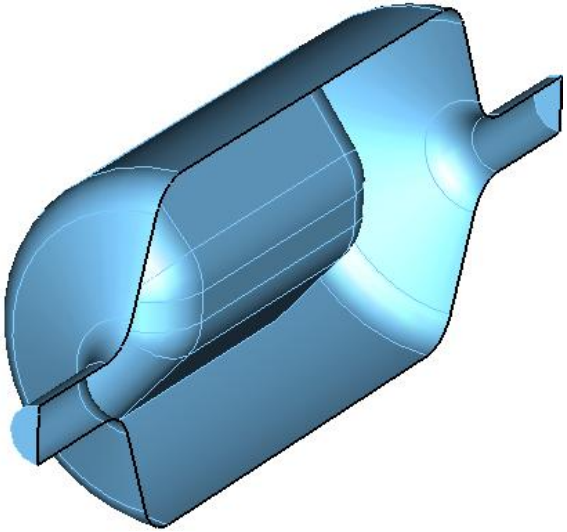
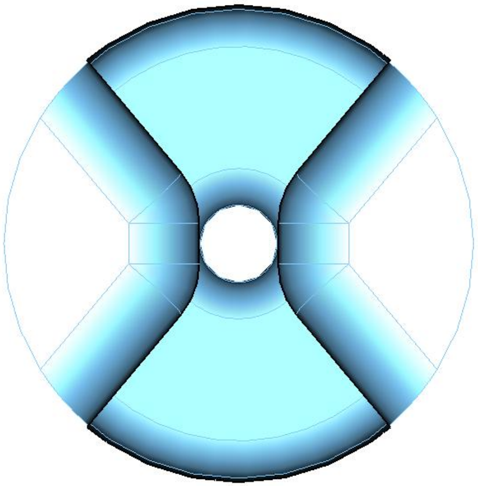
Optimization of Bar Shape

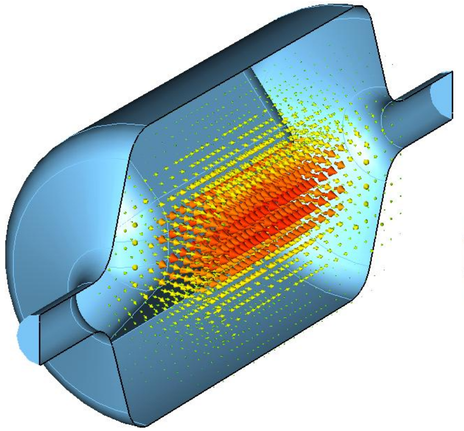


Cylindrical Parallel-Bar Cavity

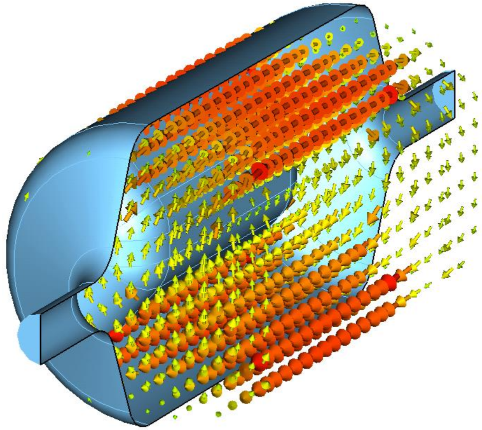




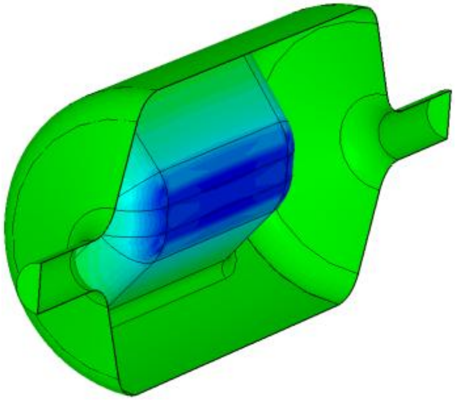




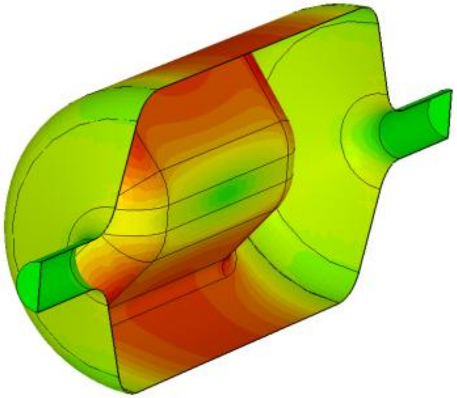
E Field



H Field

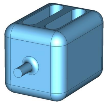
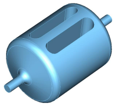
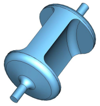
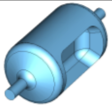


Peak E Field



Peak H Field

Comparison of Design Structures

Parameter						Units
Frequency of π mode	499.0	499.0	499.0	499.0	499.0	MHz
λ/2 of π mode	300.0	300.0	300.0	300.0	300.0	mm
Frequency of 0 mode	518.4	629.3	887.0	983.7	1036.1	MHz
Frequency of near neighbour mode	518.4	629.3	758.0	745.0	777.0	MHz
Cavity length	394.4	437.8	415.0	492.0	440.0	mm
Cavity diameter / width	290.0	316.7	266.7	260.9	241.2	mm
Cavity height	305.1	-	-	-	-	mm
Bars width at waist	67.0	60.0	-	-	-	mm
Bars length	284.0	277.8	265.0	292.0	260.0	mm
Bars height	305.1	256.0	-	-	50.0	mm
Angle	-	-	-	-	50.0	deg
Aperture diameter	40.0	40.0	40.0	40.0	40.0	mm
Deflecting voltage (V_T^*)	0.3	0.3	0.3	0.3	0.3	MV
Peak electric field (E_P^*)	1.86	2.11	2.57	2.65	2.86	MV/m
Peak magnetic field (B_P^*)	6.29	6.47	5.4	5.46	4.38	mT
B_P^* / E_P^*	3.39	3.06	2.1	2.06	1.53	mT/(MV/m)
Energy content (U^*)	0.031	0.033	0.033	0.035	0.029	J
Geometrical factor	66.2	66.2	89.9	92.9	105.9	Ω
$[R/Q]_T$	932.3	879.8	873.6	817.9	982.5	Ω
$R_T R_S$	6.2×10^4	5.8×10^4	7.9×10^4	7.6×10^4	1.0×10^5	Ω^2

At $E_T^* = 1$ MV/m

Higher Order Modes

- Higher Order Modes (HOMs) – Parasitic modes present in a cavity other than the fundamental mode of operation
- For a beam passing through the cavity, one or more of these modes gets activated due to the interaction with the charged particles, generating wake fields that act upon the beam in return

- Longitudinal [R/Q]

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

- Transverse [R/Q]
  - Direct Integral Method

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

  - Using Panofsky Wenzel Theorem (x_0=5 mm)

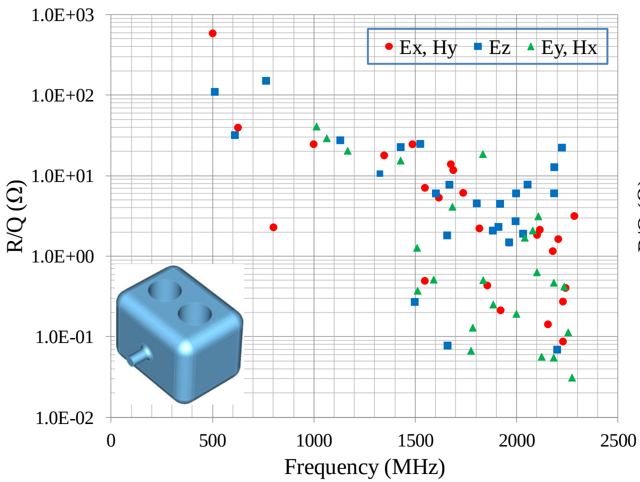
$$\left[\frac{R}{Q}\right]_T = \frac{|V_Z(x=x_0)|^2}{\omega U}\frac{1}{\left(kx_0\right)^2} = \frac{\left|\int_{-\infty}^{+\infty} E_z\left(z, x=x_0\right) e^{\frac{j\omega z}{c}} dz\right|^2}{\left(kx_0\right)^2 \omega U}, \qquad k = \frac{\omega}{c}$$

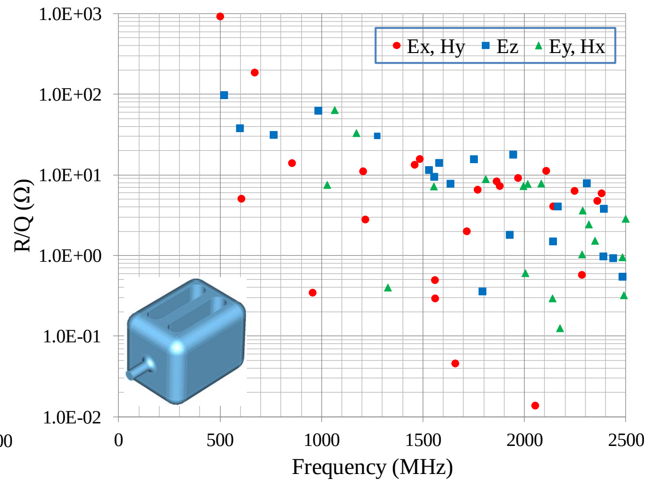
Types of Modes

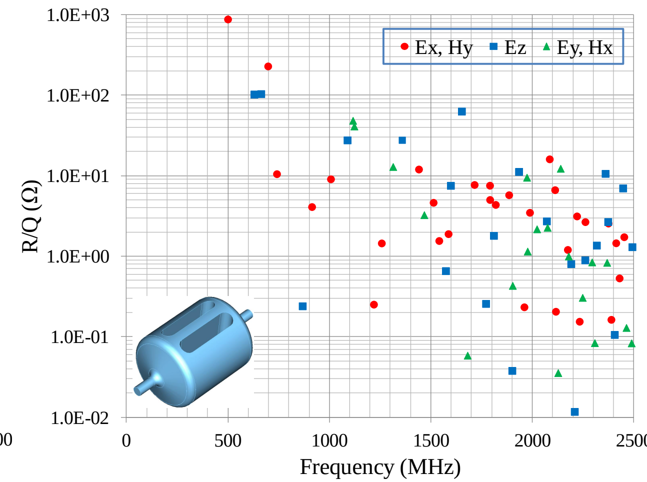
Field on Beam Axis	Type of Mode
E_x, H_y	Deflecting
E_z	Accelerating
E_y, H_x	Deflecting
H_z	Does not couple to the beam

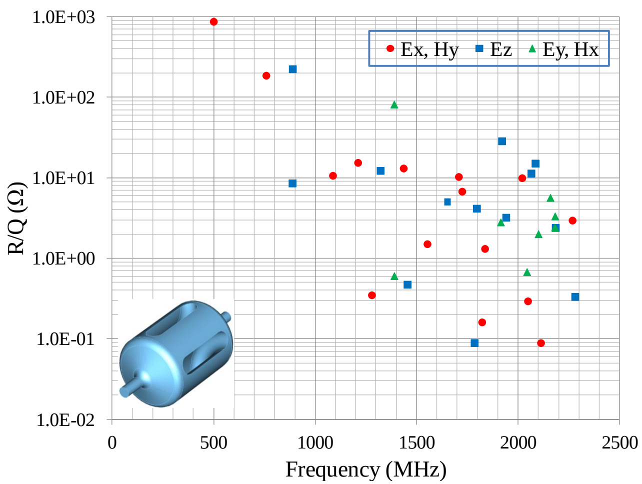
No Lower Order Modes

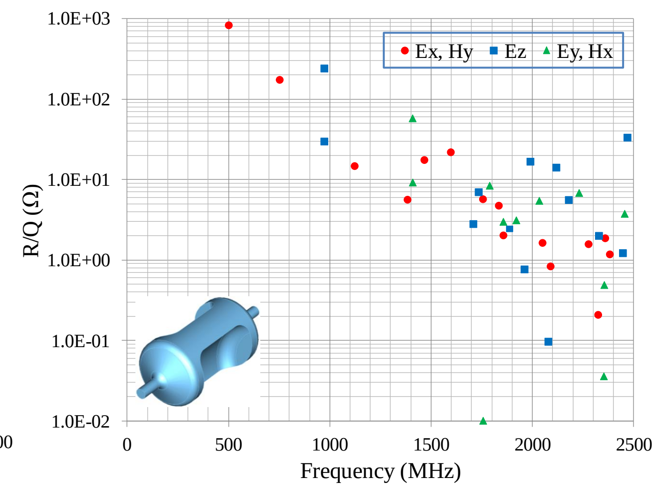
Higher Order Mode Comparison

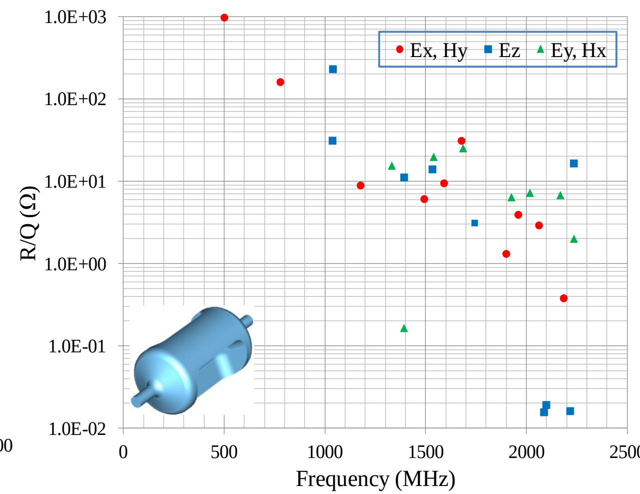








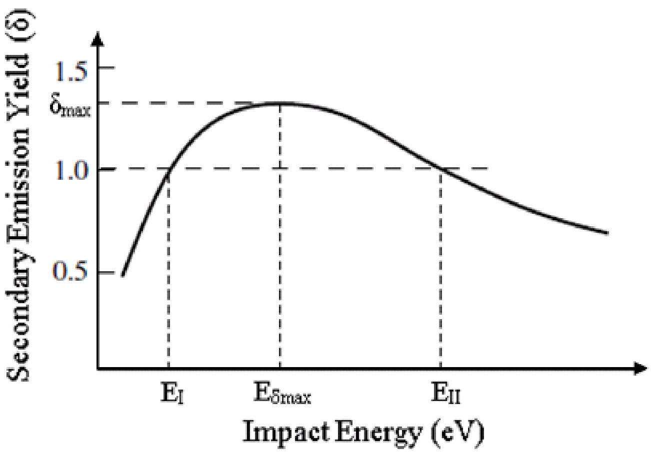




No Lower Order Modes

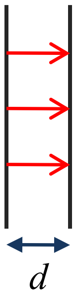
Multipacting Analysis

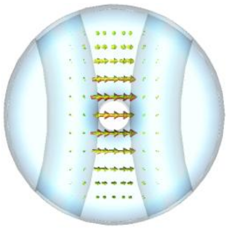
- Multipacting condition – A large amount of secondary electrons are emitted from the cavity surface by the incident primary electrons
- Resonant condition
  - The secondary electrons have localized and sustainable resonant trajectories with the cavity rf fields
  - Impact energies corresponds to a secondary emission yield (SEY) greater than one



For Nb: $E_I > 150\,eV$ $E_{II} < 2000\,eV$

For a parallel plate geometry





Resonant Voltage

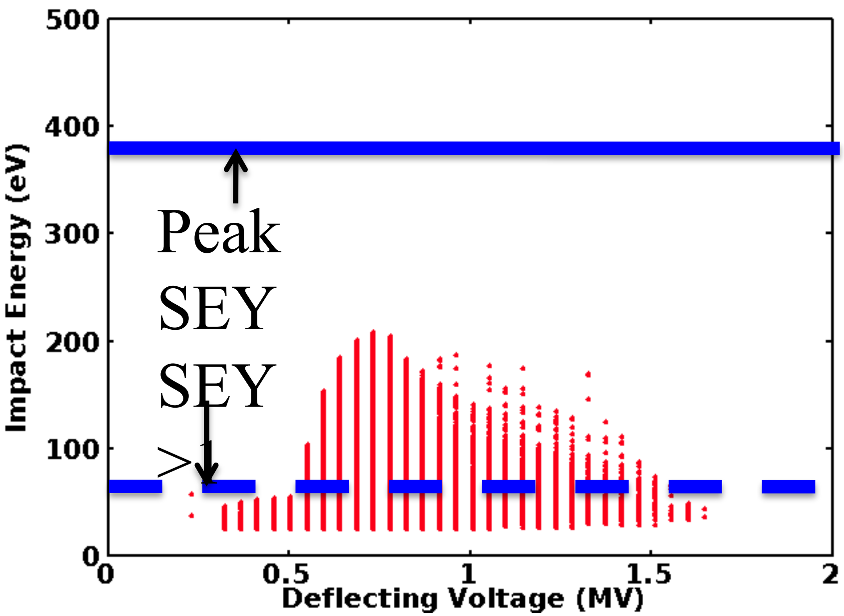
$$V_n = \frac{m\omega^2 d^2}{(2n-1)\pi e}$$

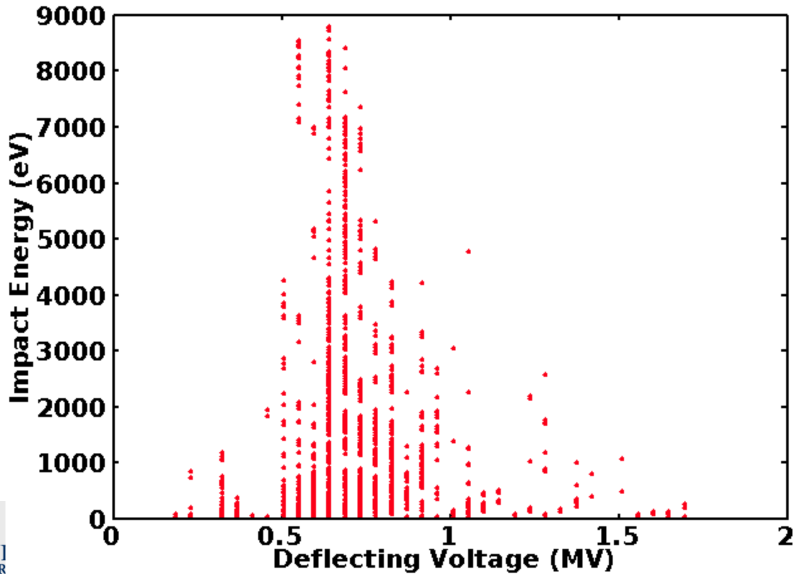
Impact Energy

$$E_n = \frac{2m\omega^2 d^2}{(2n-1)^2 \pi^2}$$

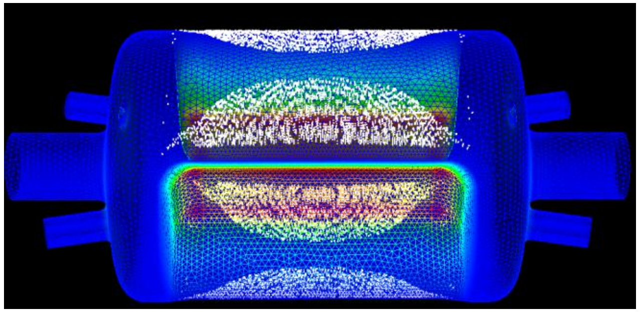
n – Order of multipacting

Resonant Particles in Cavity





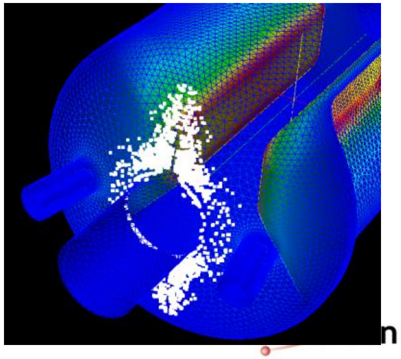
- Multipacting analysis – Track3P in SLAC ACE3P
- One point first order
- Impact energy below the peak value
- Large enhancement counter region: 0.6MV ~1.0MV



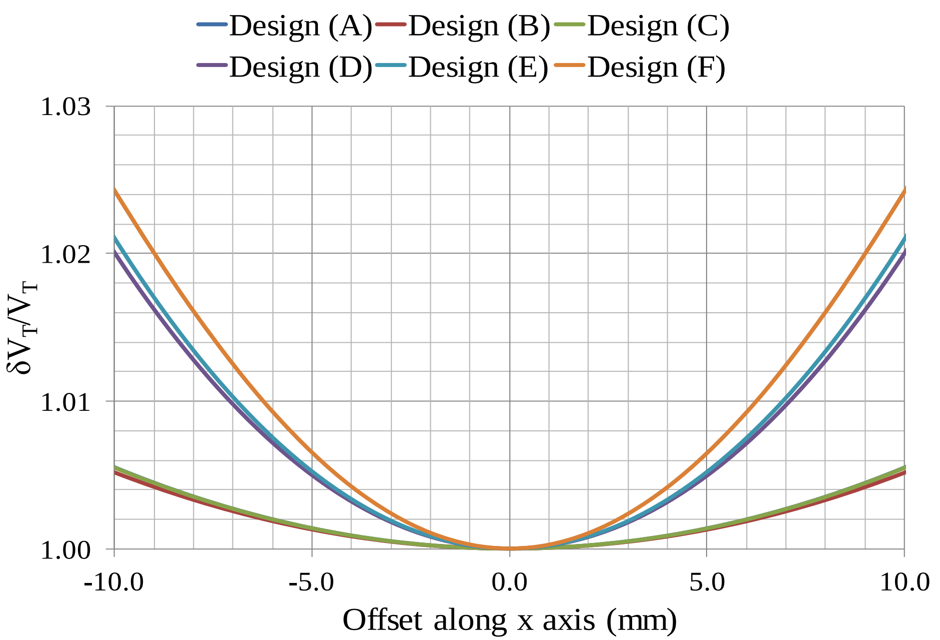
Resonant Particles Distribution at 0.6MV

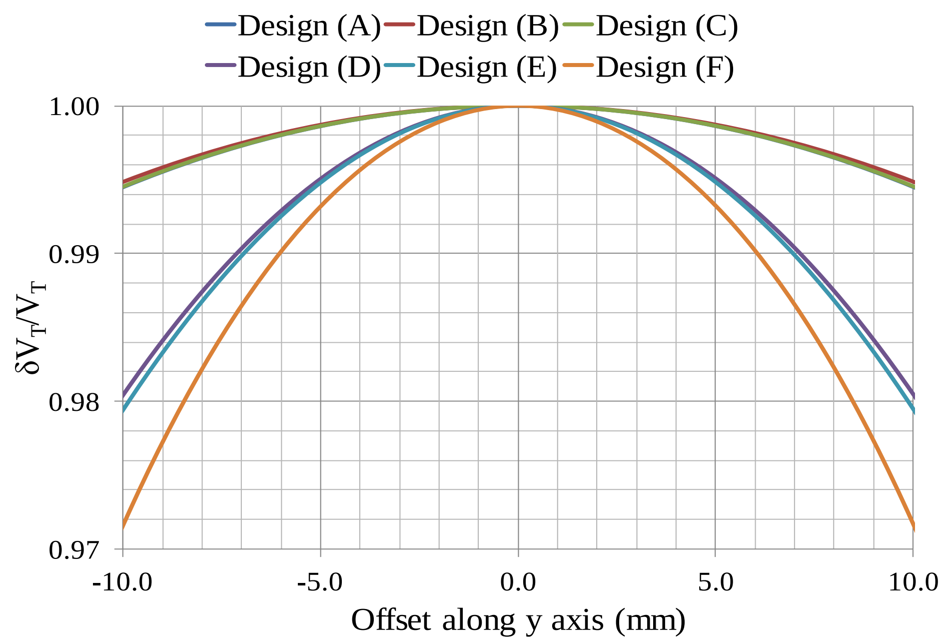
- Peak enhancement happens between 0.65 MV and 0.85 MV

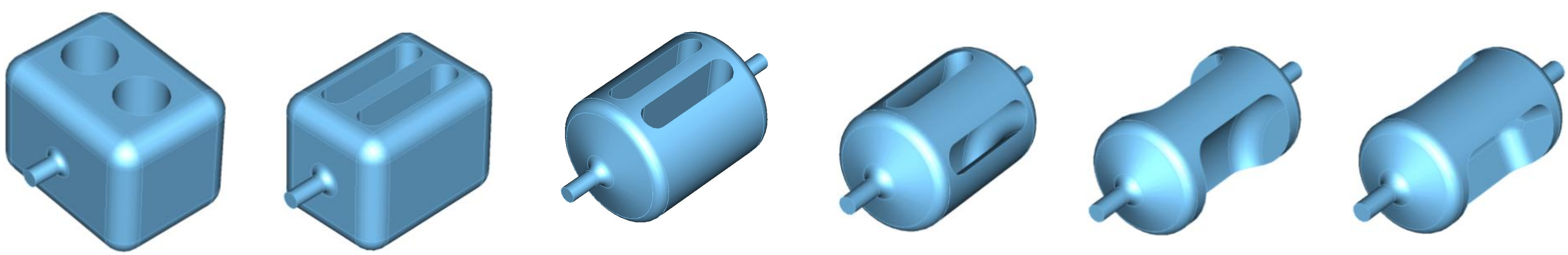
Resonant Particles Distribution at 0.7MV



Field Non-Uniformity







(A) (B) (C) (D) (E) (F)

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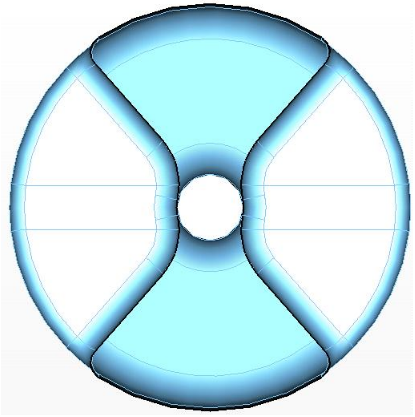
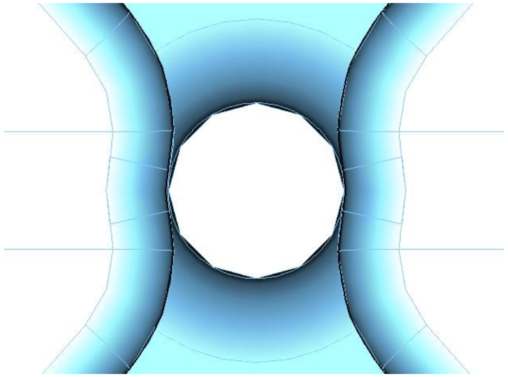
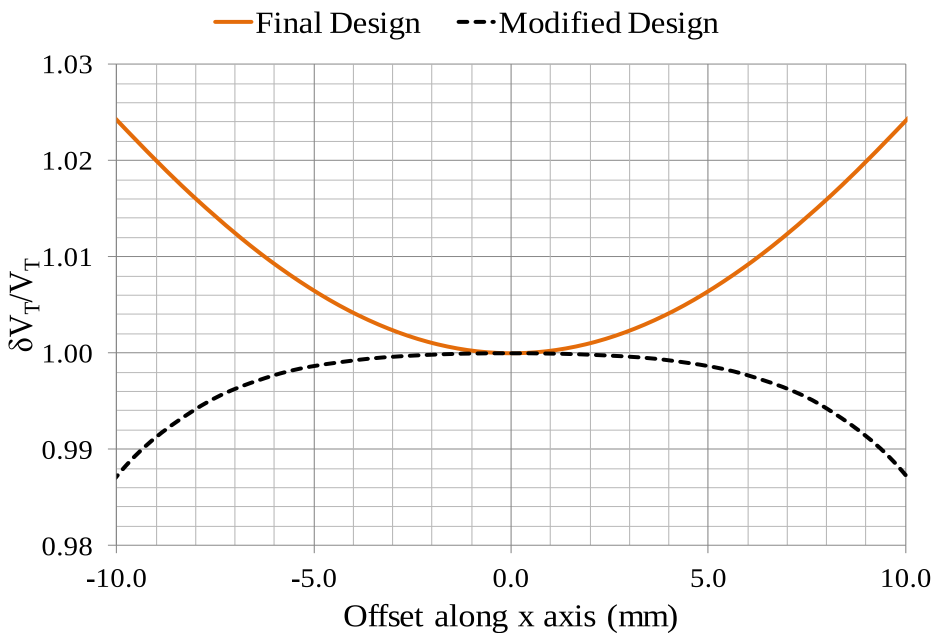
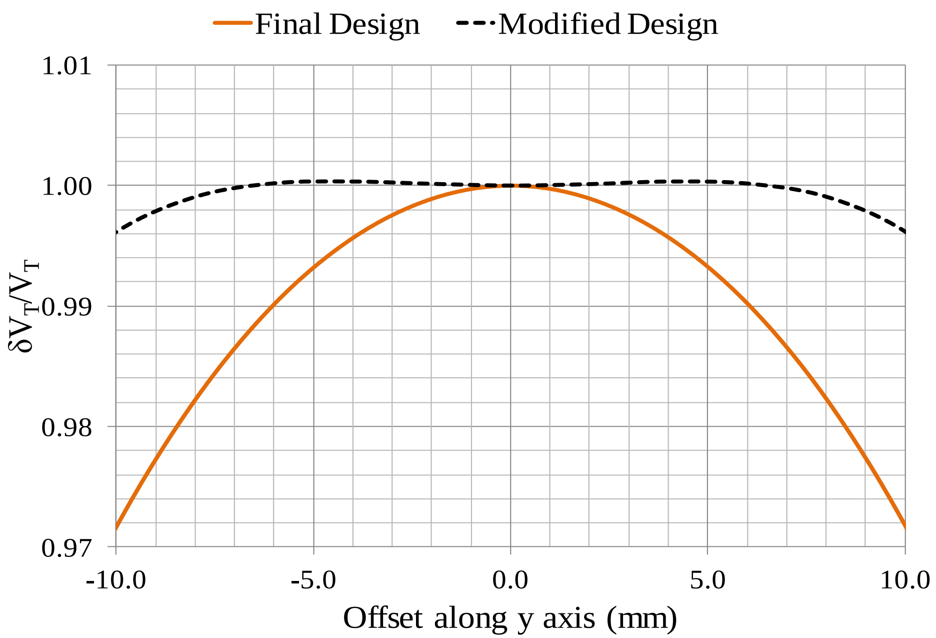
Field Non-Uniformity Compensation







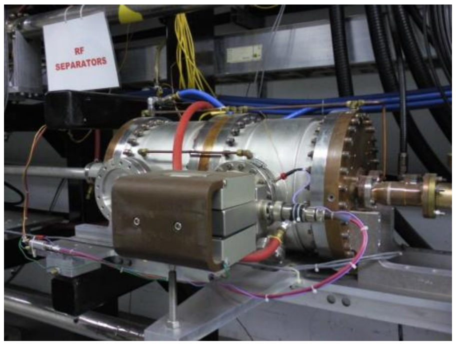


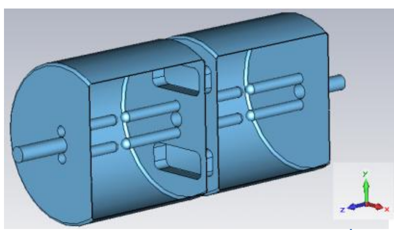
Parallel Bar Cavity Applications

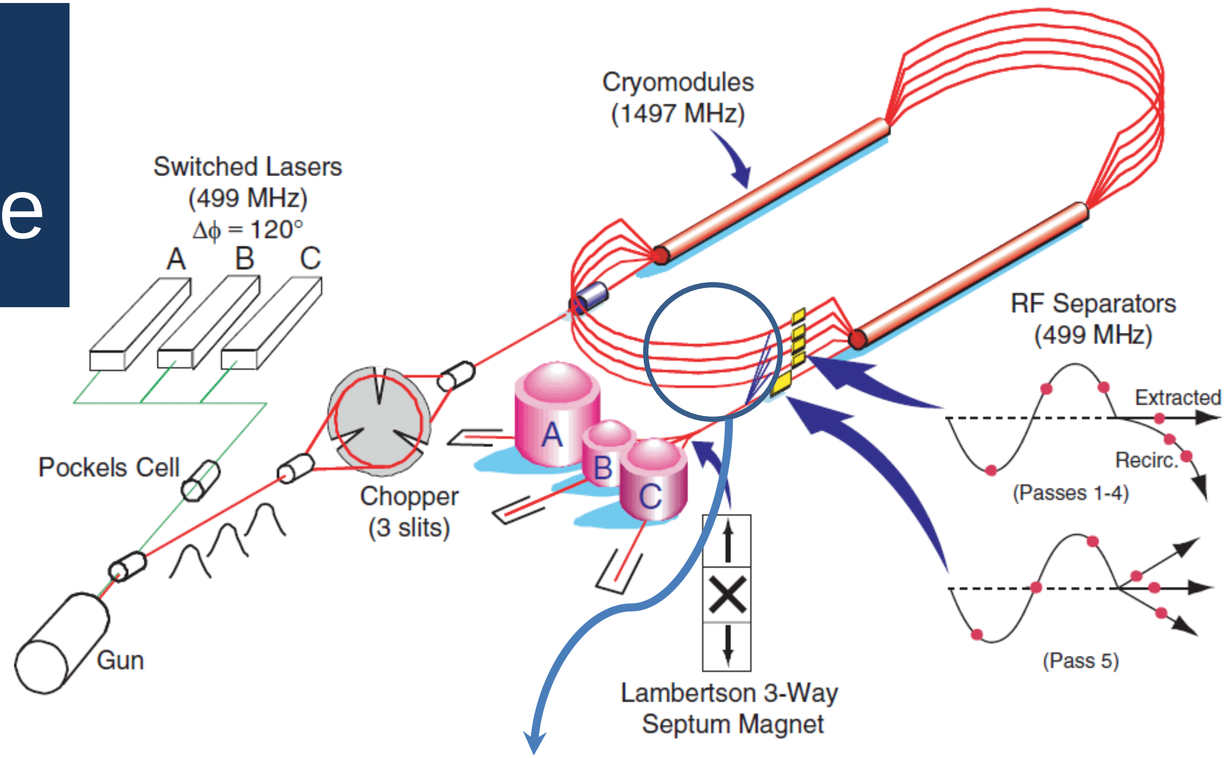
- **Deflecting Cavity**
  - Jefferson Lab 12 GeV Upgrade (499 MHz)
    (DOE-NP, ODU-Niowave P1 STTR Completed)
  - *Project-X* (365.6 MHz)
    (ODU-Niowave P1 STTR Completed, P2 Submitted)

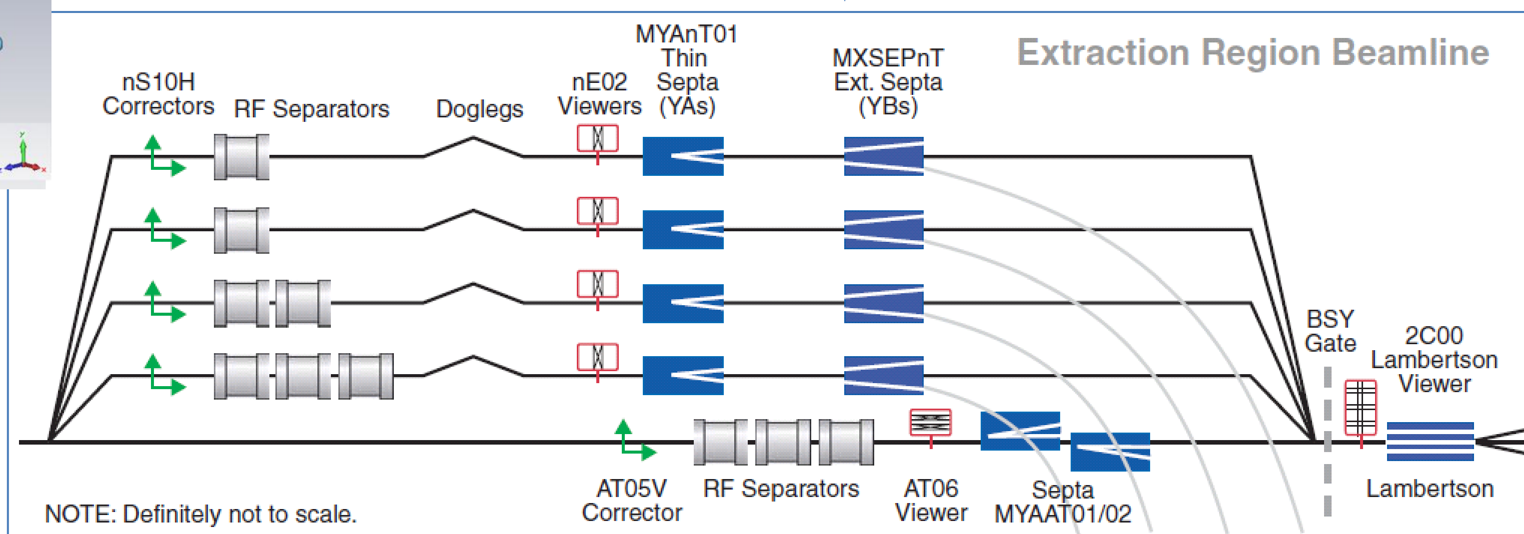
- **Crab Cavity**
  - LHC Luminosity Upgrade (400 MHz)
    (LARP, ODU-Niowave P2 STTR)
  - *Electron-Ion Collider* (750 MHz)
    (ODU-Niowave P1 STTR Completed, P2 Submitted)

Jefferson Lab 6 GeV Beam Line

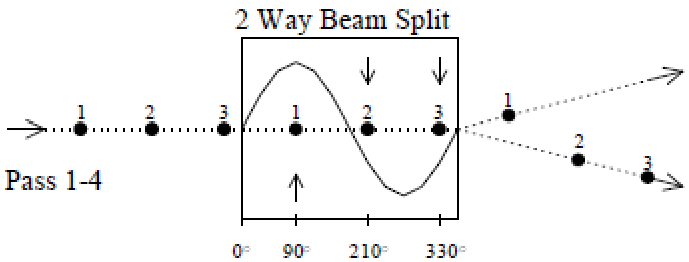


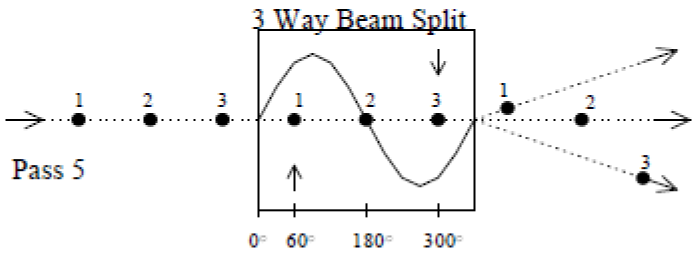


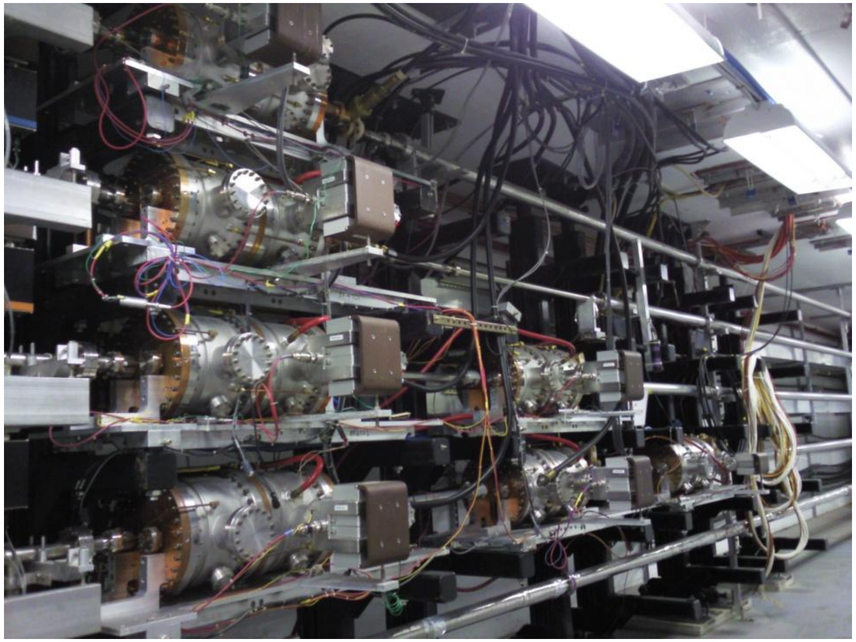


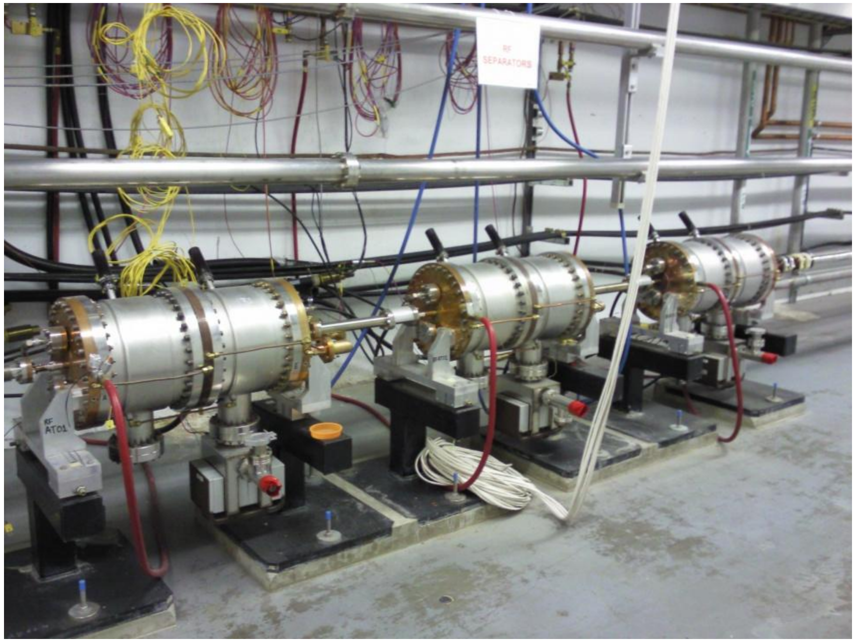


Horizontal and Vertical Separation



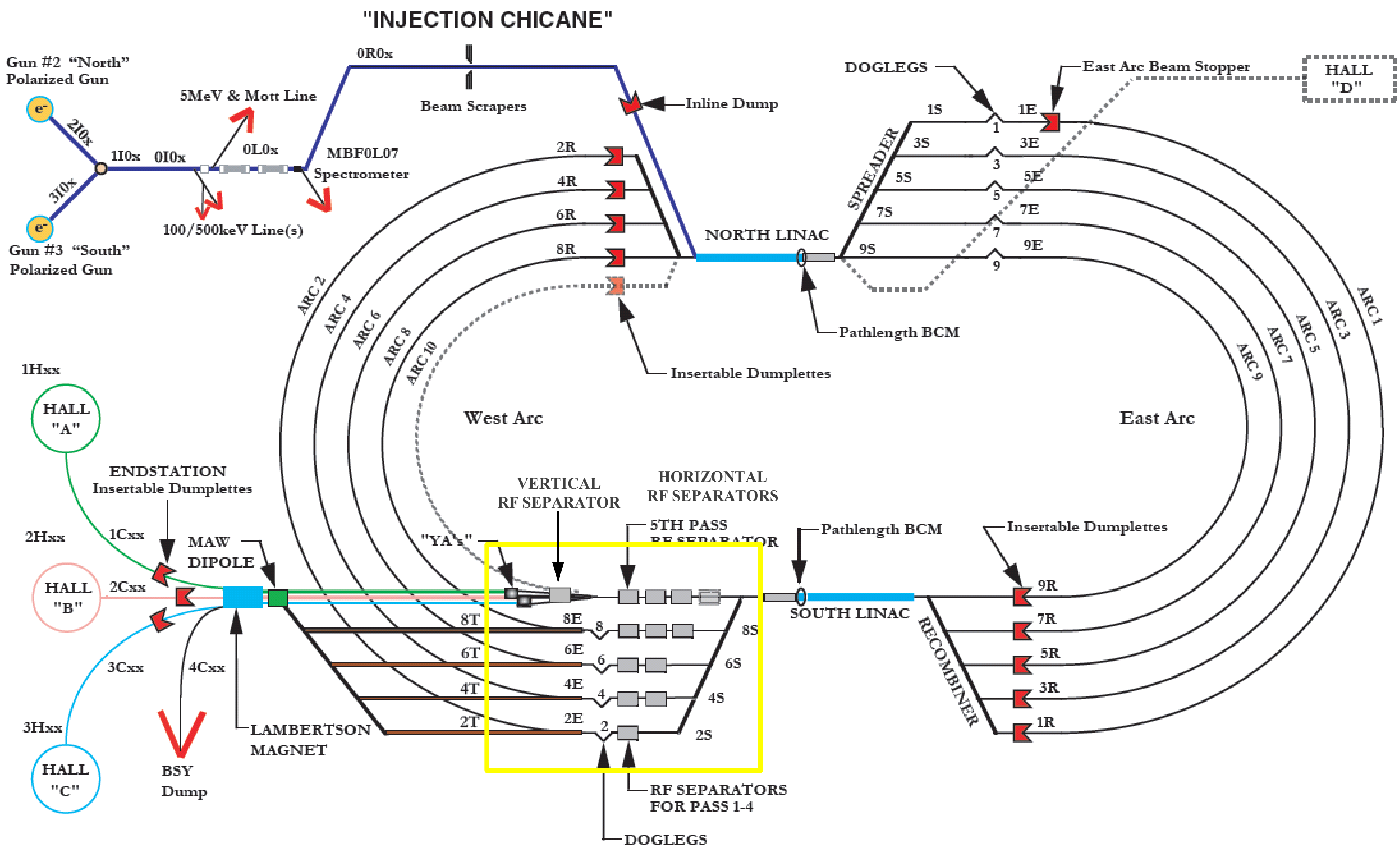






The CEBAF RF Separator System, C. Hovator et al., LINAC 96

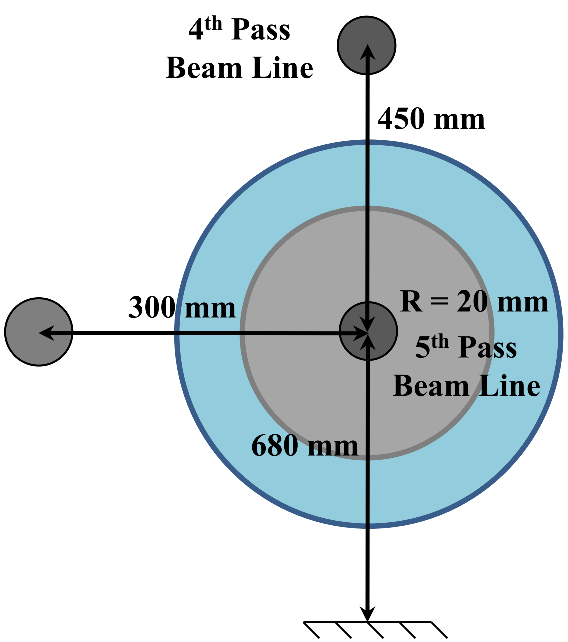
Jefferson Lab 12 GeV Beam Line



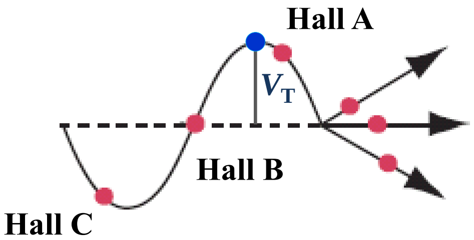
RF Separator Requirements

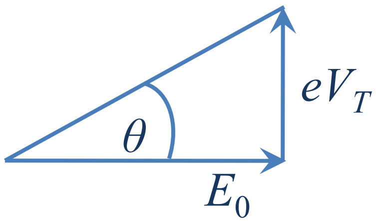
- Operating RF Frequency – 499 MHz
- Design Options
  - Normal conducting 4-rod cavity
    - Requires 6 cavities
  - Superconducting parallel-bar cavity
    - Requires 2 cavities

Dimensional Constraints



Transverse Voltage Requirement





$E_0 = 11.023\ GeV$

$V_T = E_0\ eV\ \ \theta\ rad$

Deflecting Angle:

6 cavities $\theta_{NC} = 521\ \mu\text{rad}$

2 cavities $\theta_{SC} = 504\ \mu\text{rad}$

V_T at peak:

6 cavities $V_T = 5.8\,\text{MV}$

2 cavities $V_T = 5.6\,\text{MV}$

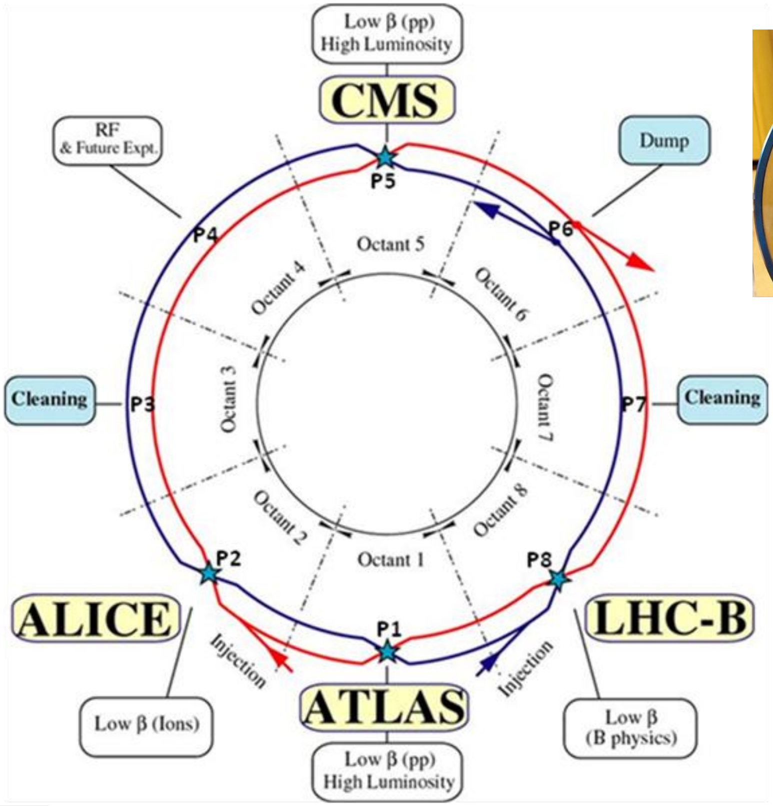
V_T per cavity:

6 cavities $V_T = 0.97\,\text{MV}$

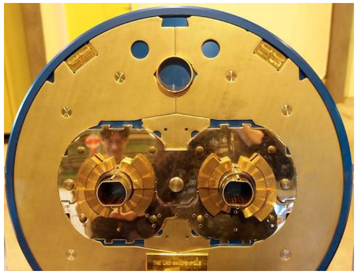
2 cavities $V_T = 2.8\,\text{MV}$

RF Crab Cavity Requirements

- Local scheme requires crab cavities on either side of the interaction point (IP)
- Requires vertical and horizontal crabbing at the two interaction points (IP1 and IP5)
- Operating rf frequency – 400 MHz
- Transverse voltage requirement - 10 MV per beam per side

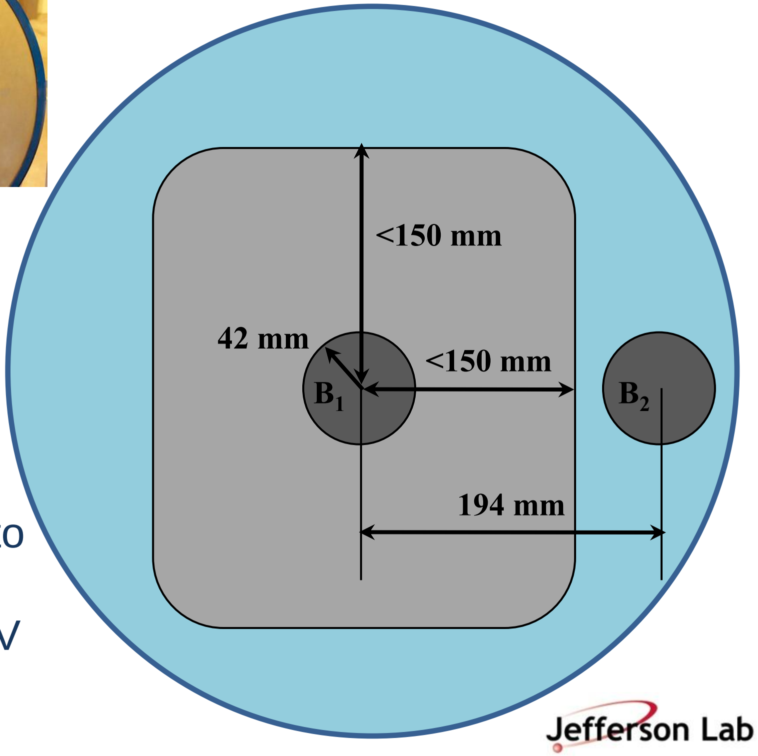


L. Rossi, LHC-CC 10



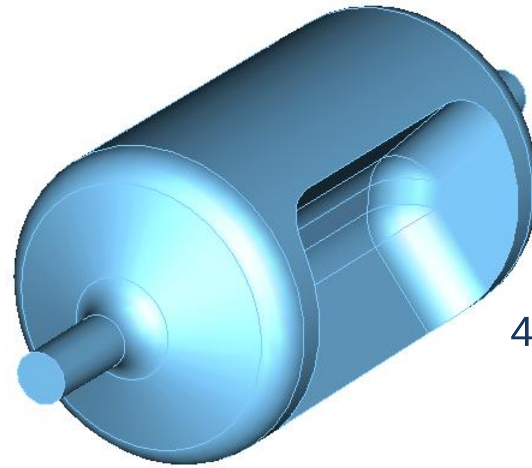
27 km @1.9K to accelerate protons to 7TeV

Dimensional Constraints

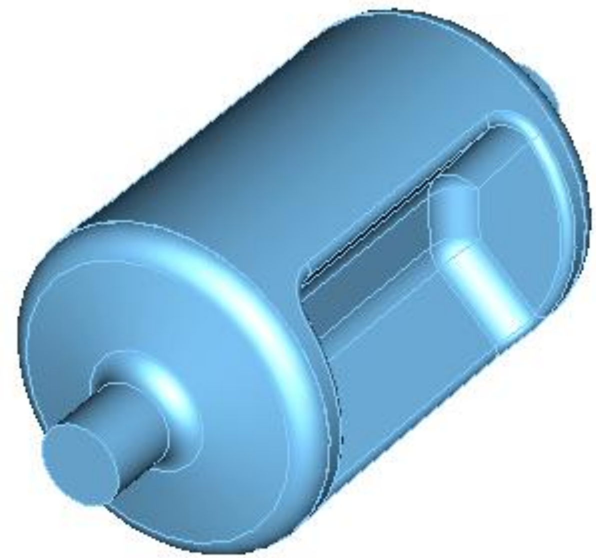


Final Cavity Properties

Parameter	**499 MHz**	**400 MHz**	**Unit**
Frequency of π mode	499.0	400.0	MHz
λ/2 of π mode	300.0	375.0	mm
Frequency of 0 mode	1036.1	729.5	MHz
Nearest mode to π mode	777.0	593.4	MHz
Cavity reference length	440.0	520.0	mm
Cavity diameter	241.2	339.8	mm
Bars length	260.0	345.0	mm
Bars height	50.0	80.0	mm
Angle	50.0	50.0	deg
Aperture diameter	40.0	84.0	mm
Deflecting voltage (V_T^*)	0.3	0.3	MV
Peak electric field (E_P^*)	2.86	3.82	MV/m
Peak magnetic field (B_P^*)	4.38	7.09	mT
B_P^* / E_P^*	1.53	1.86	mT / (MV/m)
Geometrical factor ($G = QR_S$)	105.9	119.7	Ω
$[R/Q]_T$	982.5	312.2	Ω
$R_T R_S$	1.0 10^5	3.7 10^4	$Ω^2$
At E_T^* = 1 MV/m			



499 MHz



400 MHz

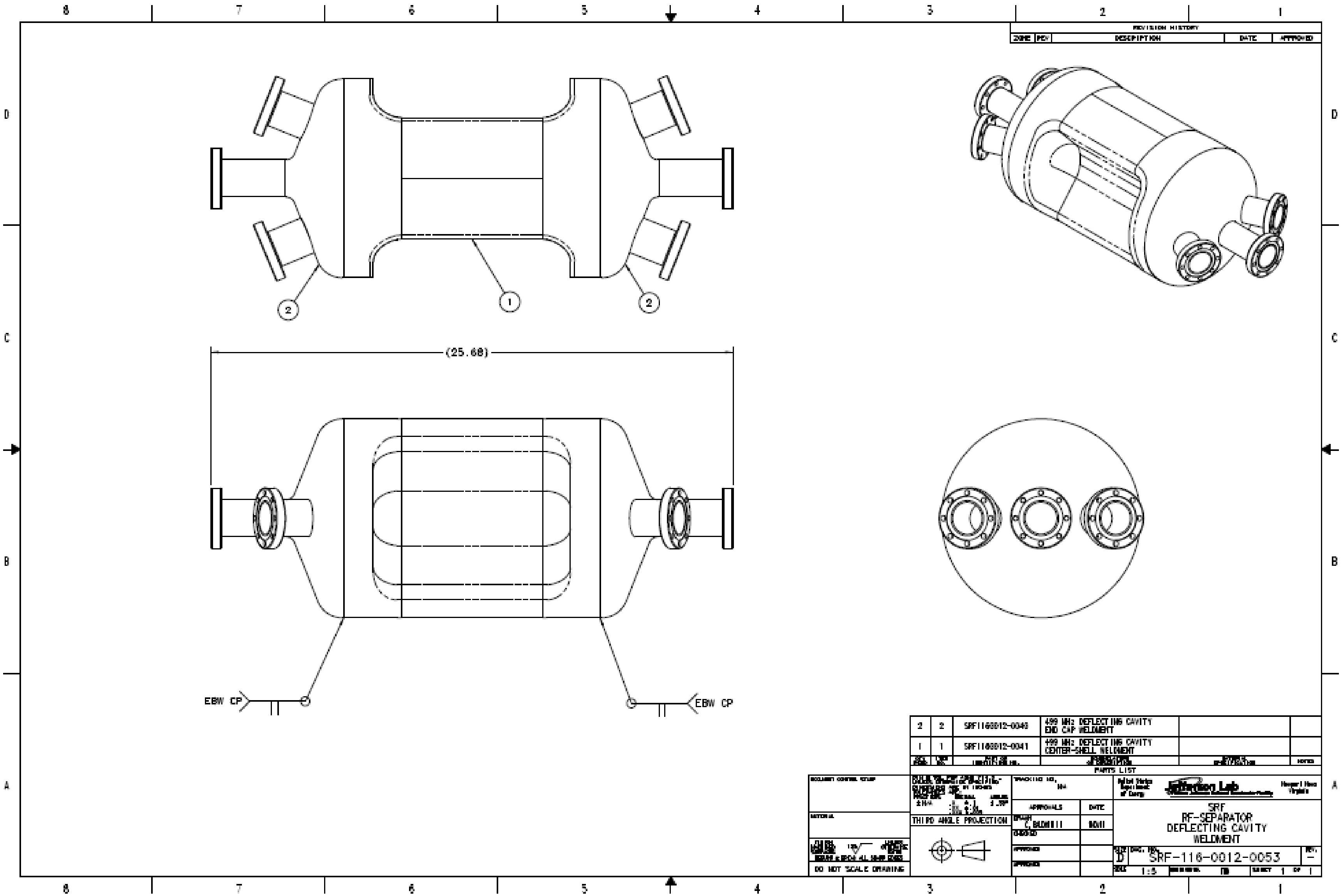
Design Summary

- Parallel-Bar Geometry
  - Is a very attractive compact design for deflecting/crabbing applications
  - Low surface fields and high shunt impedance
  - Has no lower order modes with widely separated modes
  - Good balance in peak surface fields (E_p< 35 MV/m, B_p< 70 mT)

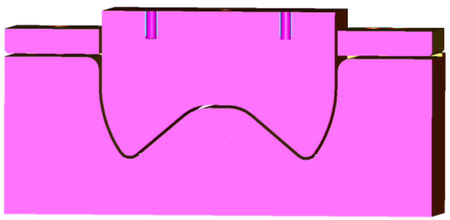
- Both 499 MHz and 400 MHz designs have improved designs to meet the
  - Required deflection
  - Low surface fields

Geometry	E_P/E_T	E_P/V_T m^{-1}	B_P/E_T mT/(MV/m)	B_P/V_T mT/MV	@ V_T = 3MV		Required V_T (MV)	No. of cavities
					E_P (MV/m)	B_P (mT)		
499 MHz	2.86	9.54	4.38	14.6	28.6	43.8	5.6	2
400 MHz	3.82	10.19	7.09	18.91	30.6	56.7	10.0	3

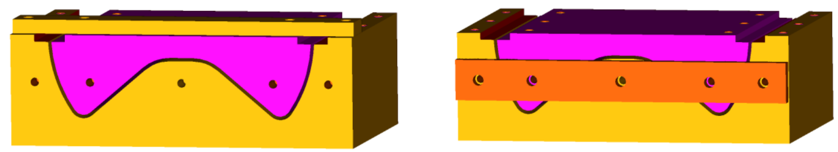
499 MHz Deflecting Cavity Fabrication



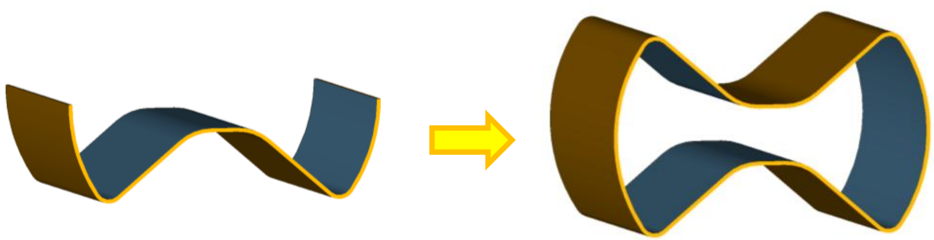
Fabrication of Center Shell



Center shell forming
(Die cross section)

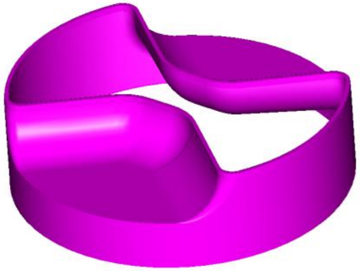


Center shell machining
Weld margin included

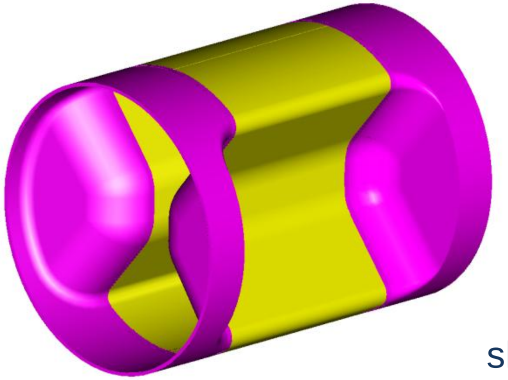


Electron
Beam Welded
Center Shell
(EBW)

Fabrication of Center Shell

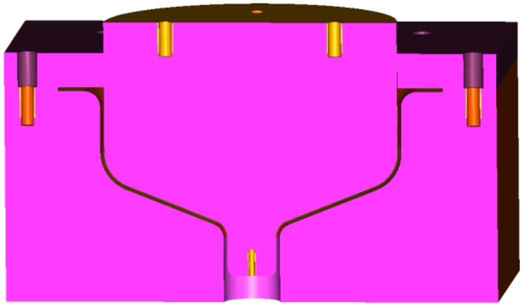


Machined cavity shoulder

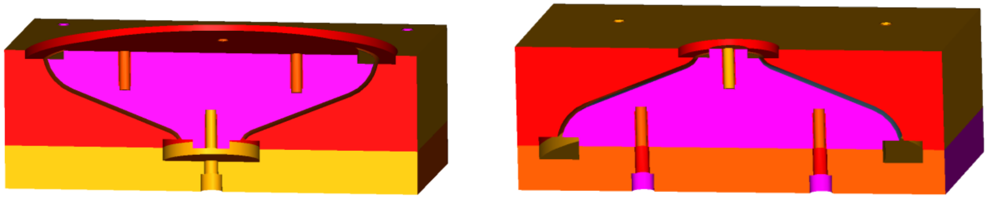


Welding cavity shoulder and center shell

End Plate Fabrication

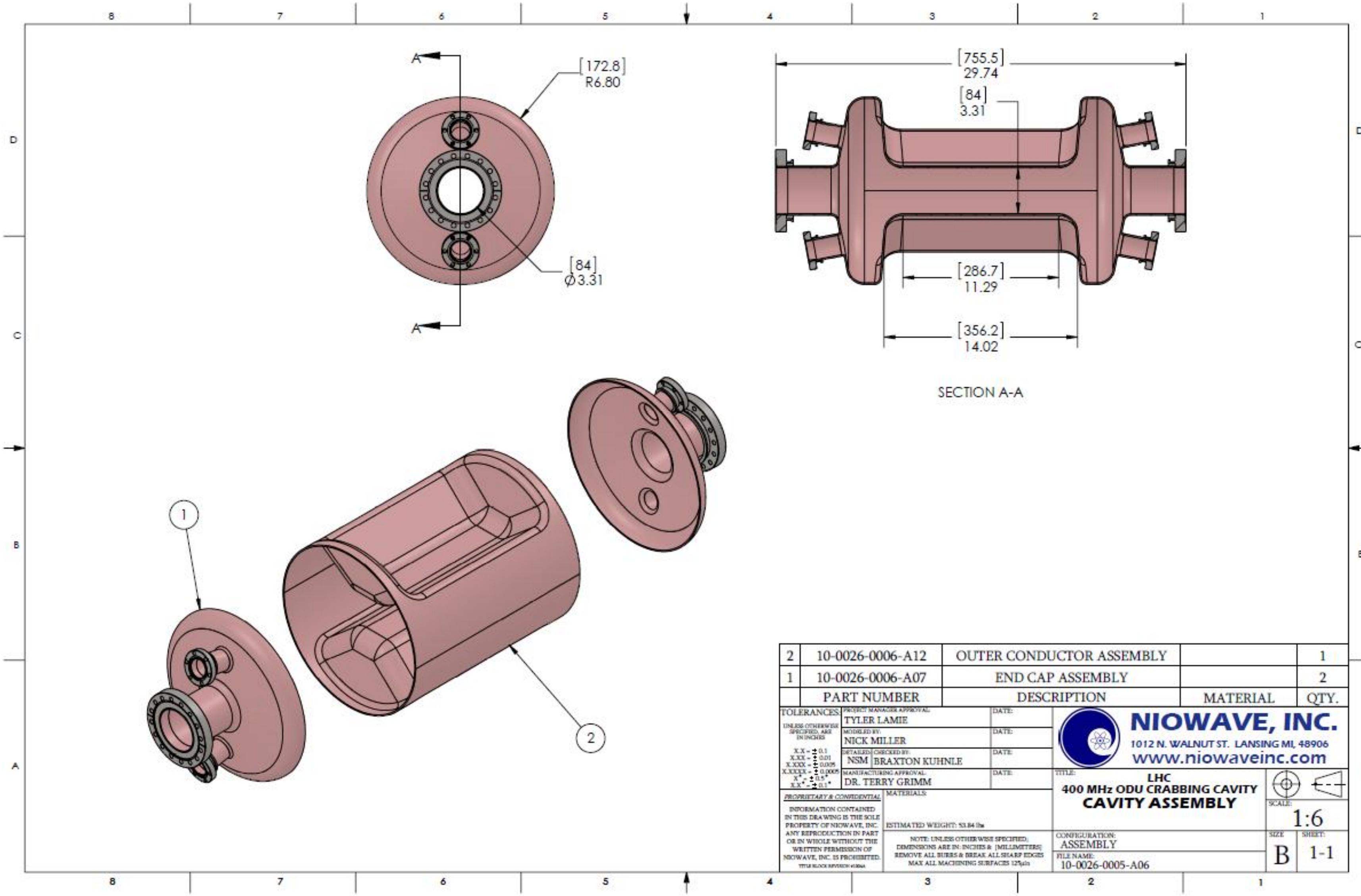


End cap forming

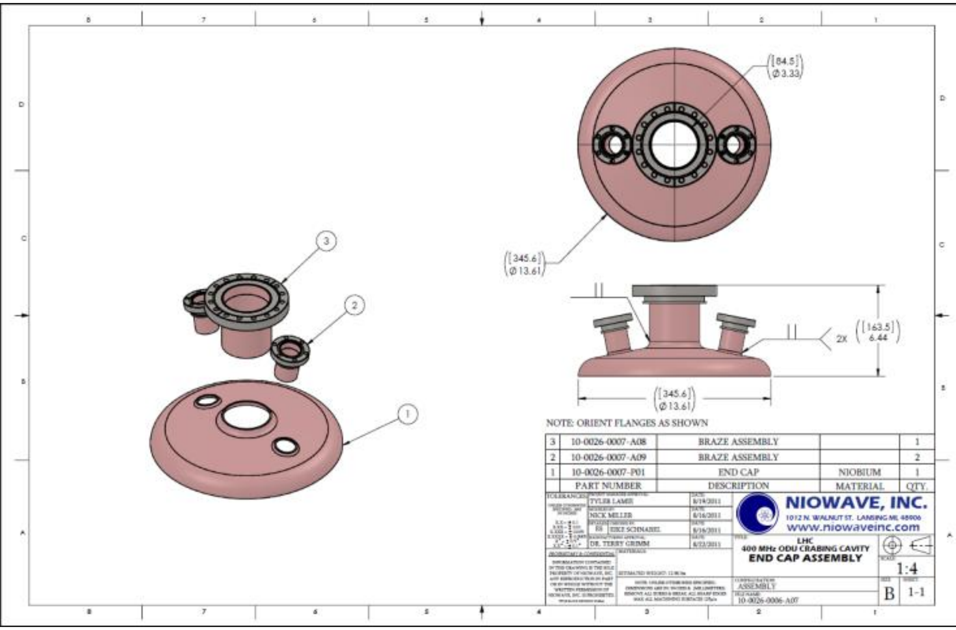


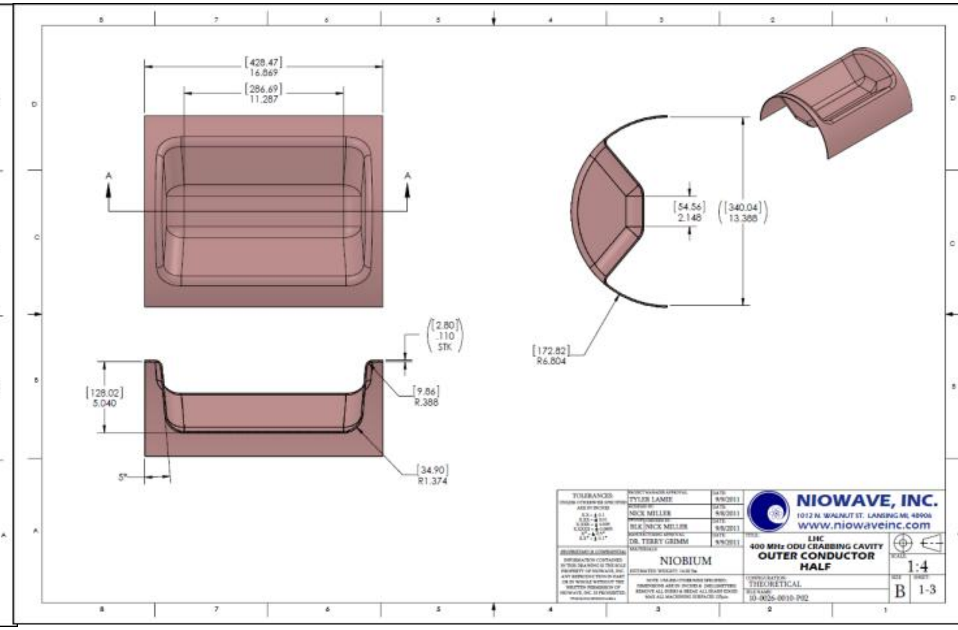
Machining (Weld and tuning margin included)

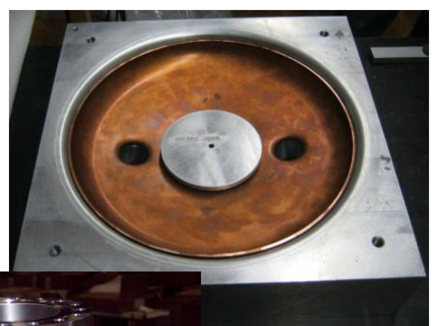
400 MHz Crabbing Cavity Fabrication



400 MHz Crabbing Cavity Fabrication







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Future Work

- 499 MHz/400 MHz Geometry
  - Surface treatment of parts
    - BCP and/or EP
  - Final Welding
  - RF Testing

499 MHz Deflecting Cavity

400 MHz Crabbing Cavity

- Thank you
  - My Advisor – Jean Delayen
  - HyeKyoung Park from the Mechanical Engineering Group