XV Mexican School of Particles and Fields

# RADIO FREQUENCY CRABBING SYSTEM FOR AN ELECTRON-ION COLLIDER

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September 13th 2012

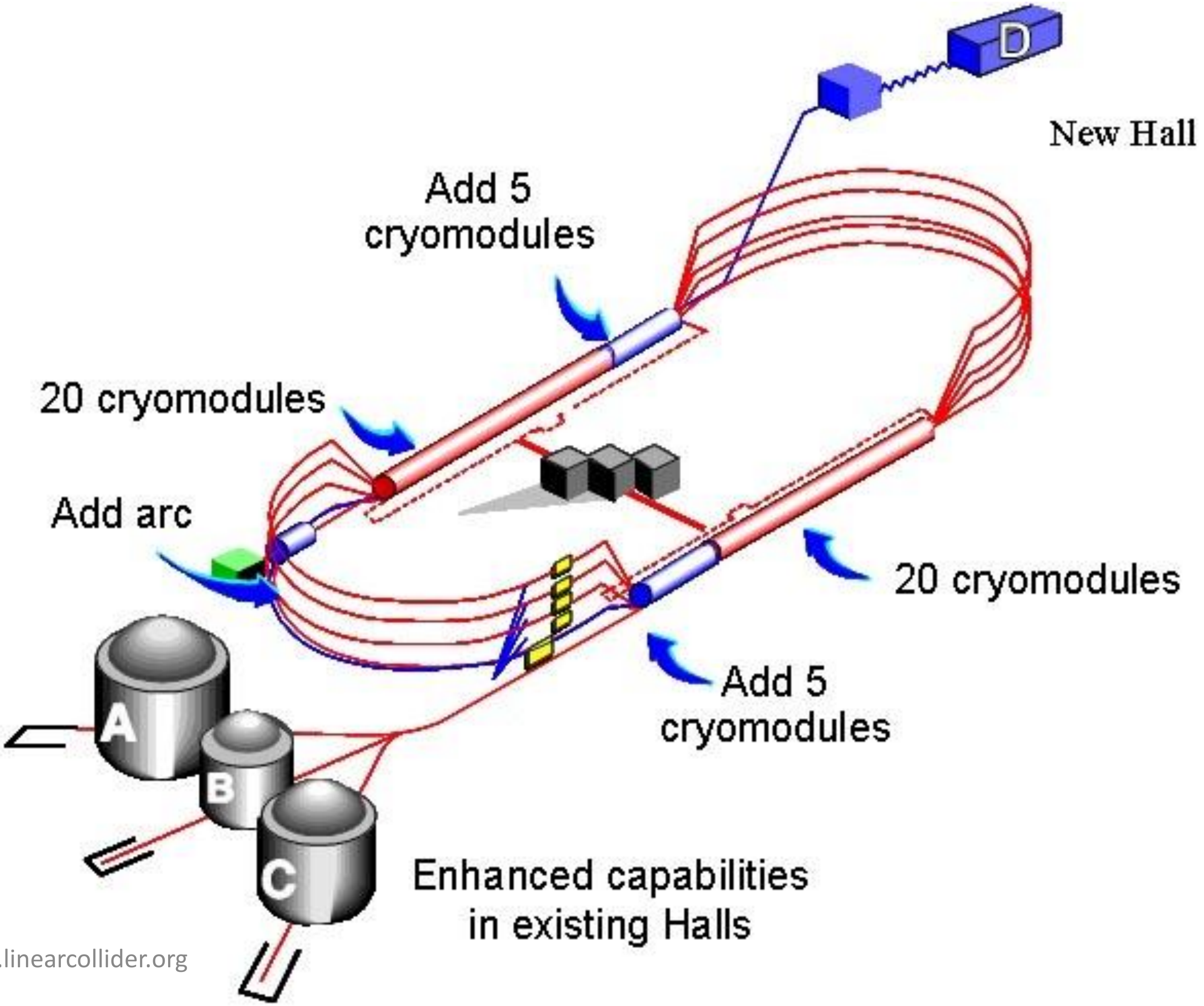
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Department of Physics

# Outline

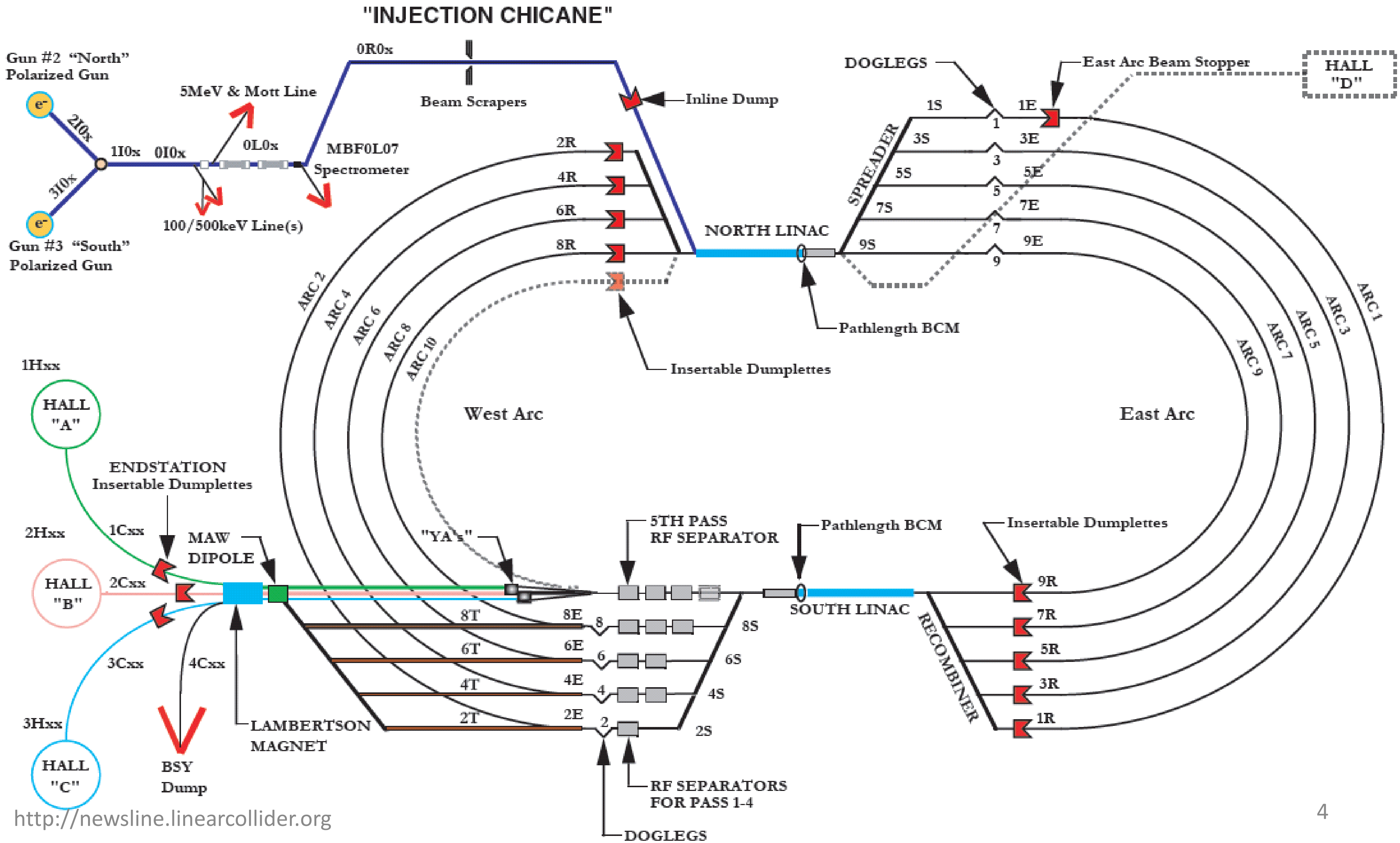
- **Thomas Jefferson National Laboratory:**
  - JLab and the 12 GeV Upgrade.
  - The Medium-energy Electron-Ion Collider.
- **Improving Luminosity on Colliders (Crabbing):**
  - The Idea behind Radio-Frequency Crabbing Systems.
  - Our Design.
- **Next Generation X-Ray Sources:**
  - Inverse Compton Scattering.
  - Cubix (MIT/Jlab).

# JLab 12 GeV Upgrade

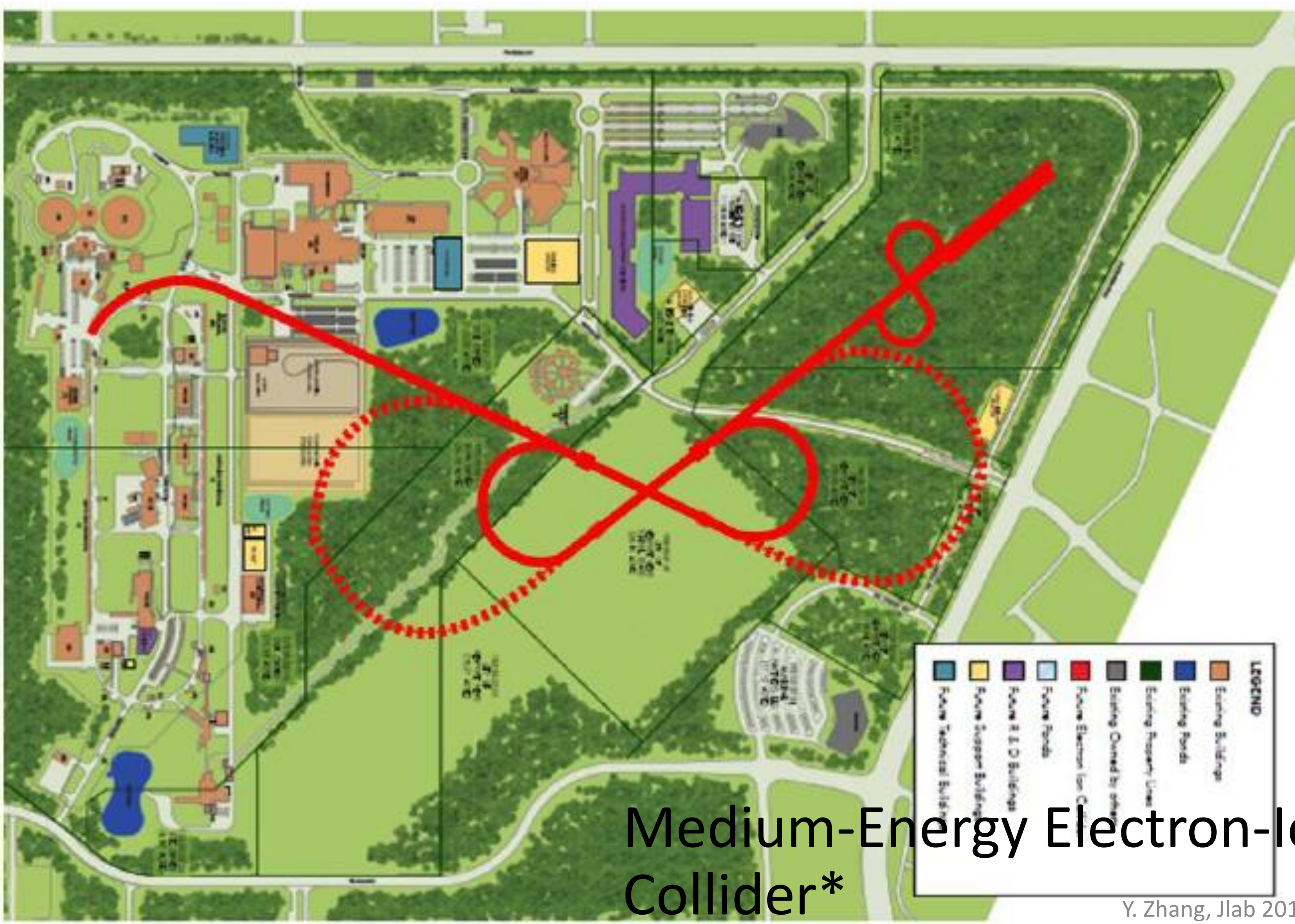



http://newsline.linearcollider.org

# JLab 12 GeV Upgrade



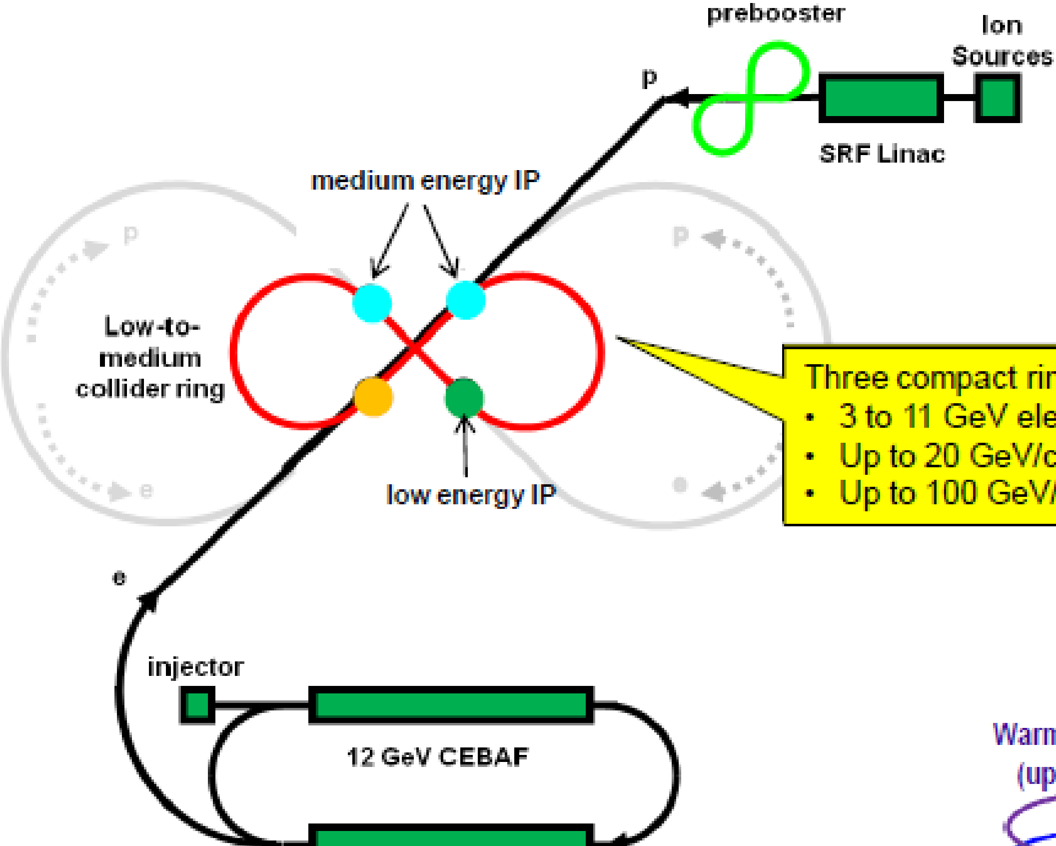
# Jlab 12 GeV Upgrade and the MEIC*



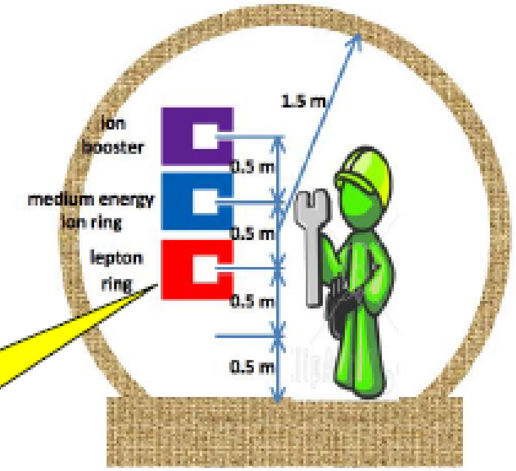

Medium-Energy Electron-Ion Collider*

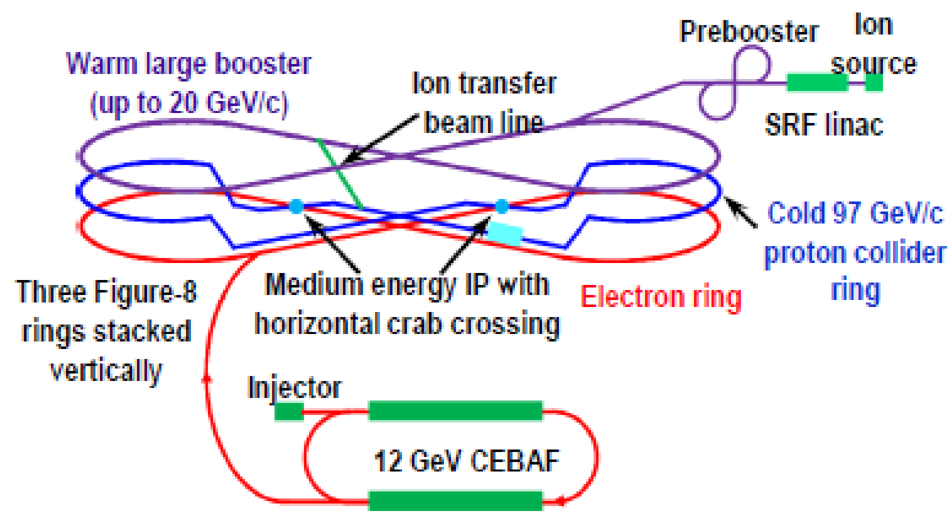
Y. Zhang, Jlab 2012.

# Jlab 12 GeV Upgrade and the MEIC*




Three compact rings:
- 3 to 11 GeV electron
- Up to 20 GeV/c proton (warm)
- Up to 100 GeV/c proton (cold)

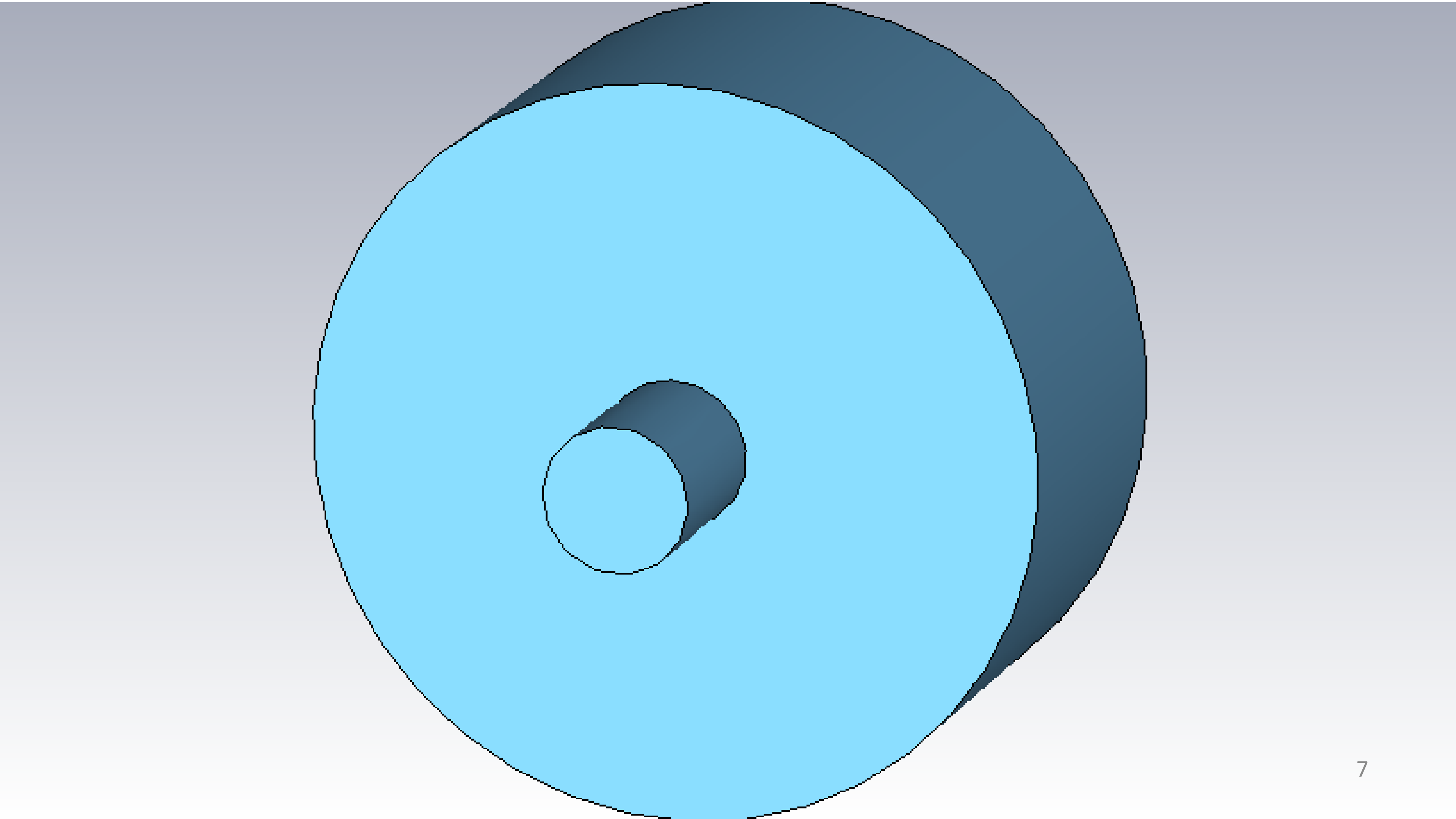



*Y. Zhang, Jlab 2012.

# Electromagnetic Resonators

- **Perfect conductor: Pillbox.**



# Electromagnetic Resonators

**Electric field**

$$\nabla \times \left(\nabla \times \vec{E}\right) = i\omega\nabla \times \vec{B}$$

$$\nabla\left(\nabla \cdot \vec{E}\right) - \nabla^2\vec{E} = \mu\epsilon\omega^2\vec{E}$$

$$\nabla \times \vec{B} = -i\mu\epsilon\omega\vec{E}$$

$$\nabla \cdot \vec{E} = 0$$

$$\nabla^2\vec{E} + \mu\epsilon\omega^2\vec{E} = 0$$

**Magnetic field**

$$\nabla \times \left(\nabla \times \vec{B}\right) = -i\mu\epsilon\omega\nabla \times \vec{E}$$

$$\nabla\left(\nabla \cdot \vec{B}\right) - \nabla^2\vec{B} = \mu\epsilon\omega^2\vec{E}$$

$$\nabla \times \vec{B} = -i\mu\epsilon\omega\vec{E}$$

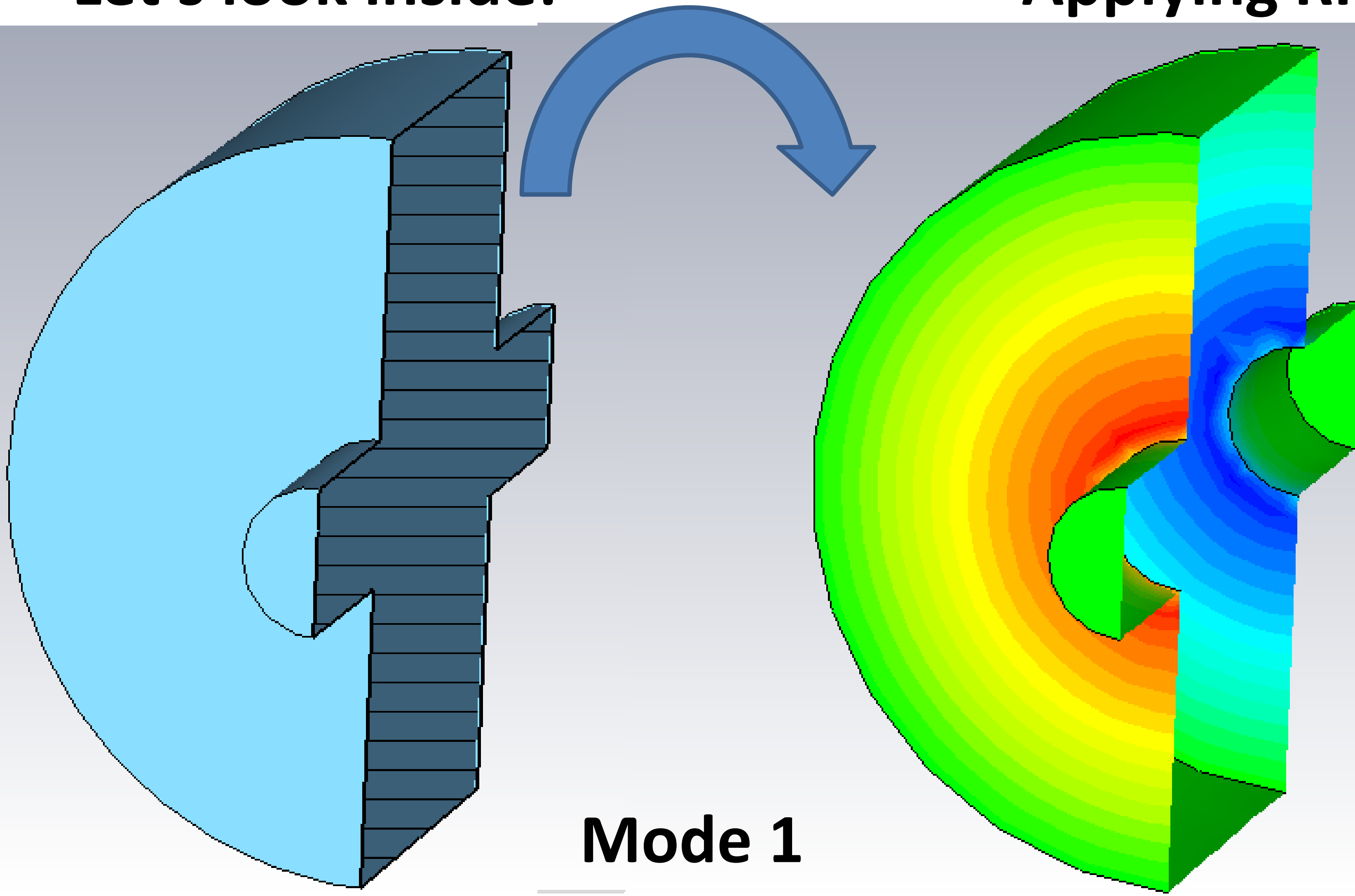
$$\nabla \cdot \vec{E} = 0$$

$$\nabla^2\vec{B} + \mu\epsilon\omega^2\vec{B} = 0$$

Helmholz equations.

# Electromagnetic Resonators

- **Let’s look inside:**
- **Applying RF:**

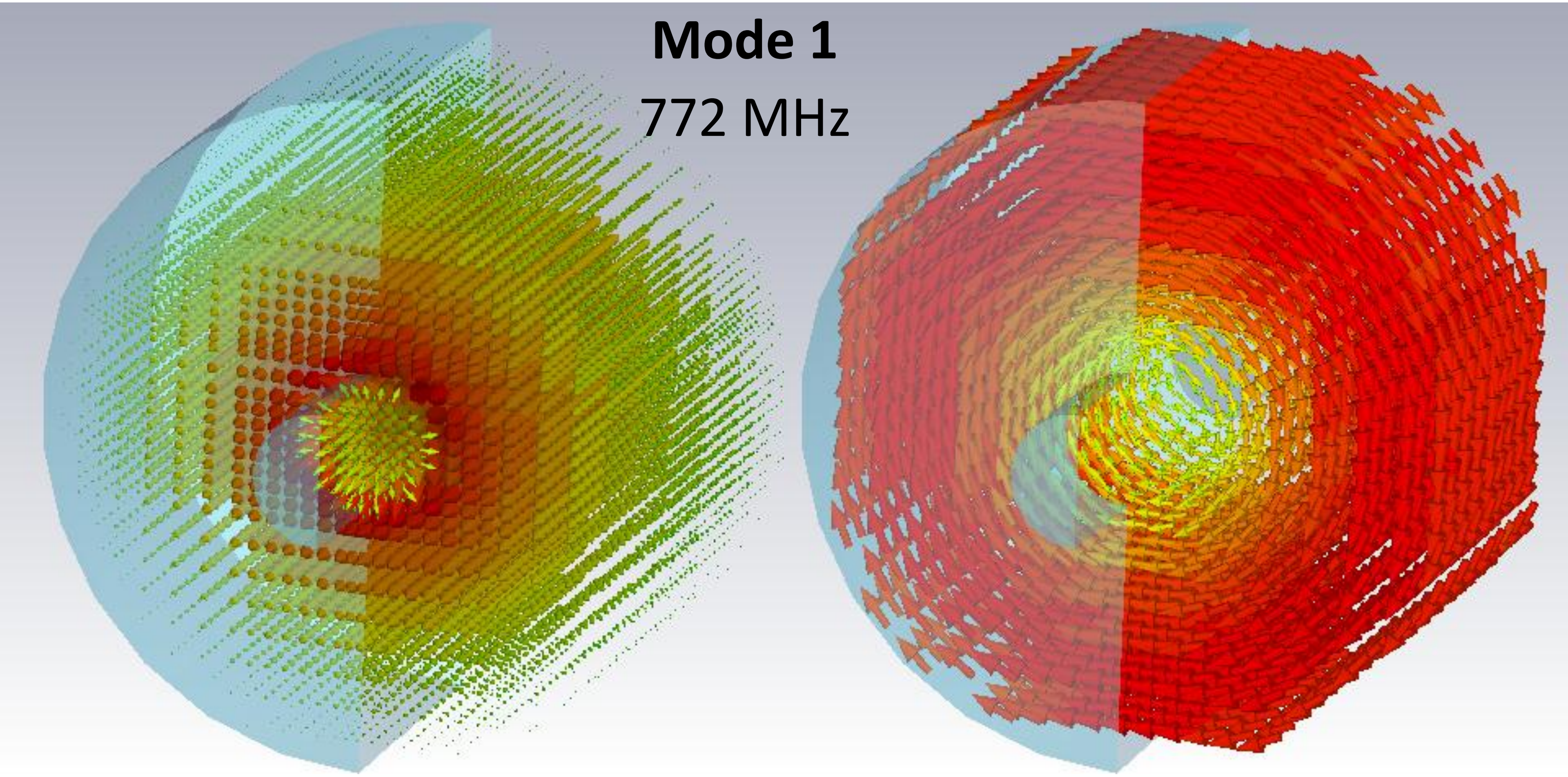


**Mode 1**

# Electromagnetic Resonators

**Mode 1**

772 MHz



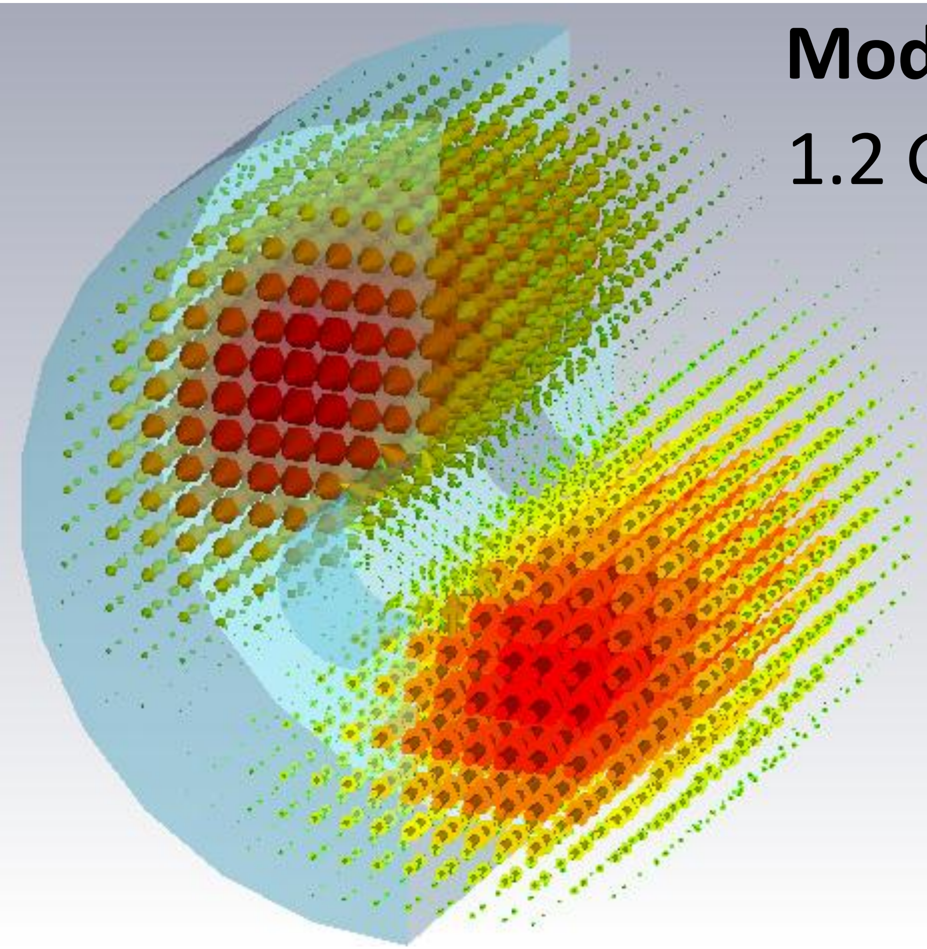
– Electric Field

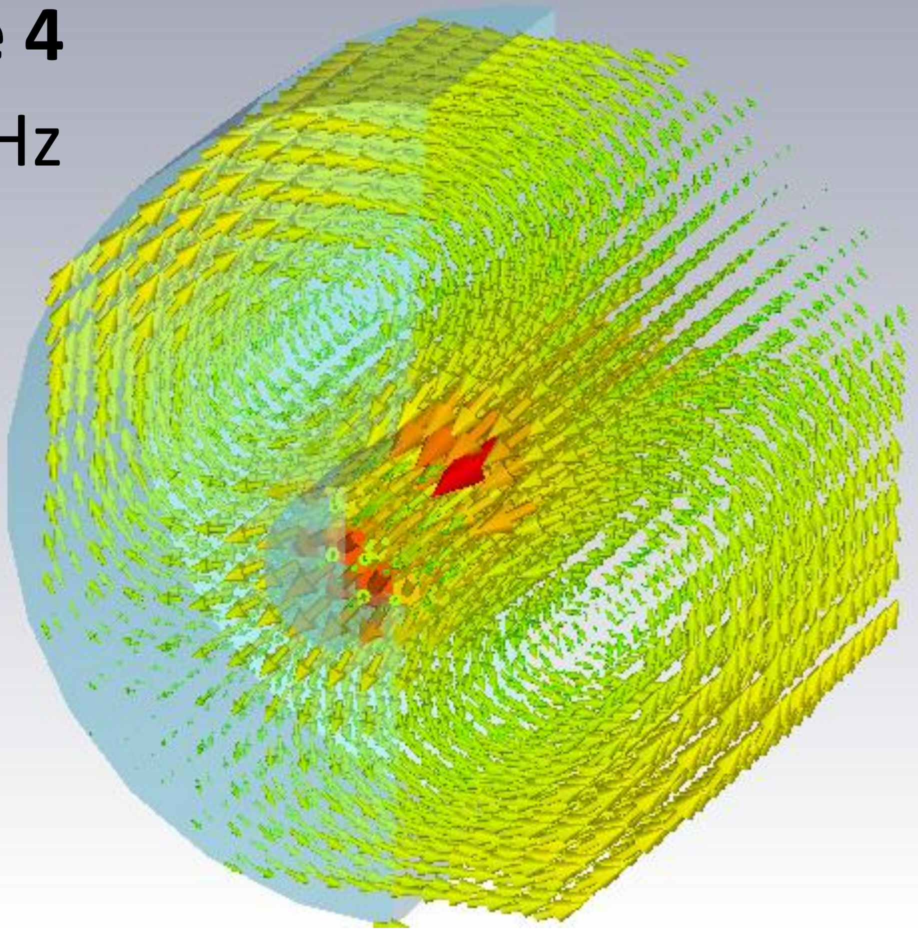
– Magnetic Field

# Electromagnetic Resonators

**Mode 4**

1.2 GHz





– Electric Field

– Magnetic Field

# Particle Accelerators

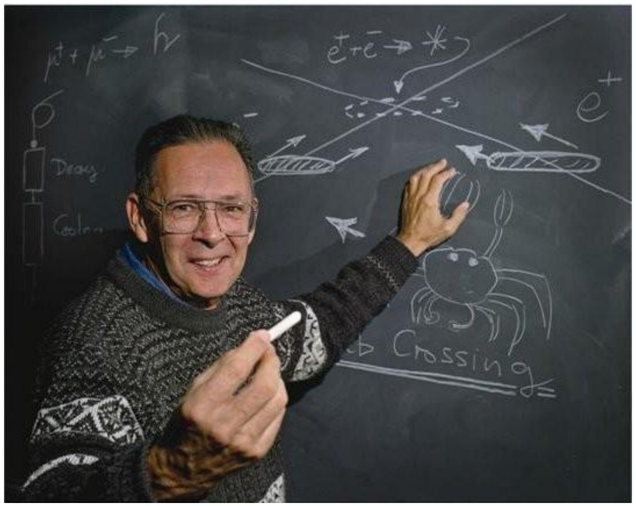
- Particle accelerators propel charged particles using electromagnetic fields.
- Lorentz Force: $\vec{F} = \frac{d\vec{p}}{dt} = q[\vec{E} + \vec{v} \times \vec{B}]$
  - Electric field for acceleration.
  - Magnetic field for bending and focusing.
- Transverse force due the fields as well:

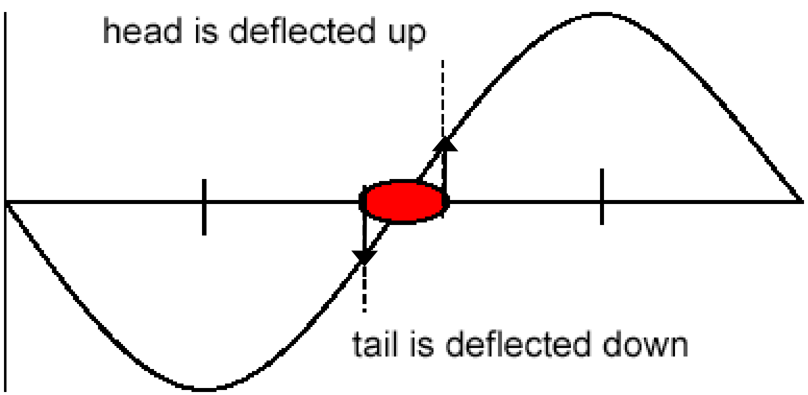
$$V_T = \left| \int_{-\infty}^{\infty} [\vec{E}_T(z) + i\left(\vec{v} \times \vec{B}(z)\right)_T] e^{\frac{i\omega z}{c}} dz \right|$$

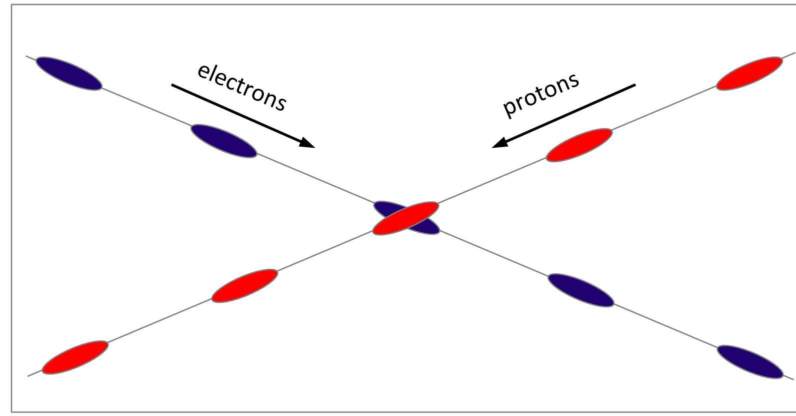
$$V_T = \frac{-i}{\omega / c} \nabla_T V_Z = \frac{-i}{\omega / c} \frac{1}{r_0} \left| \int_{-\infty}^{\infty} \vec{E}_Z(r_0, z) e^{\frac{i\omega z}{c}} dz \right|$$

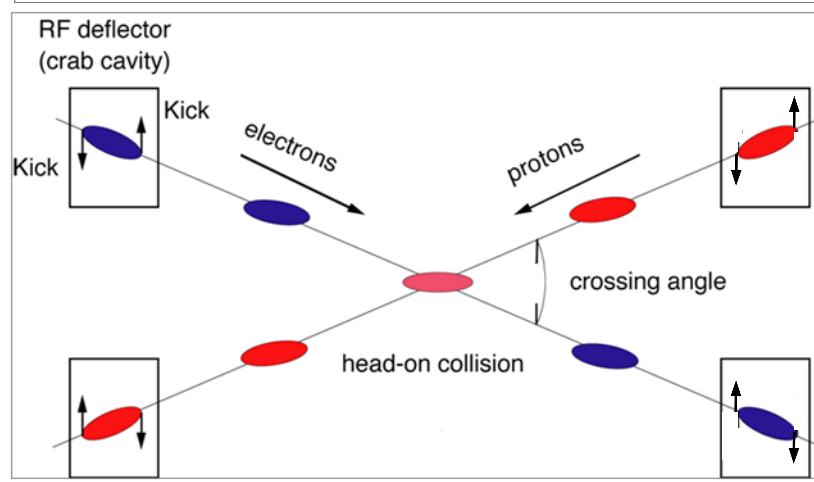
* W.K.H. Panofsky and W.A. Wenzel, "**Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields**," *Review of Scientific Instruments*, November 1956, p. 967.

# Crabbing Concept






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

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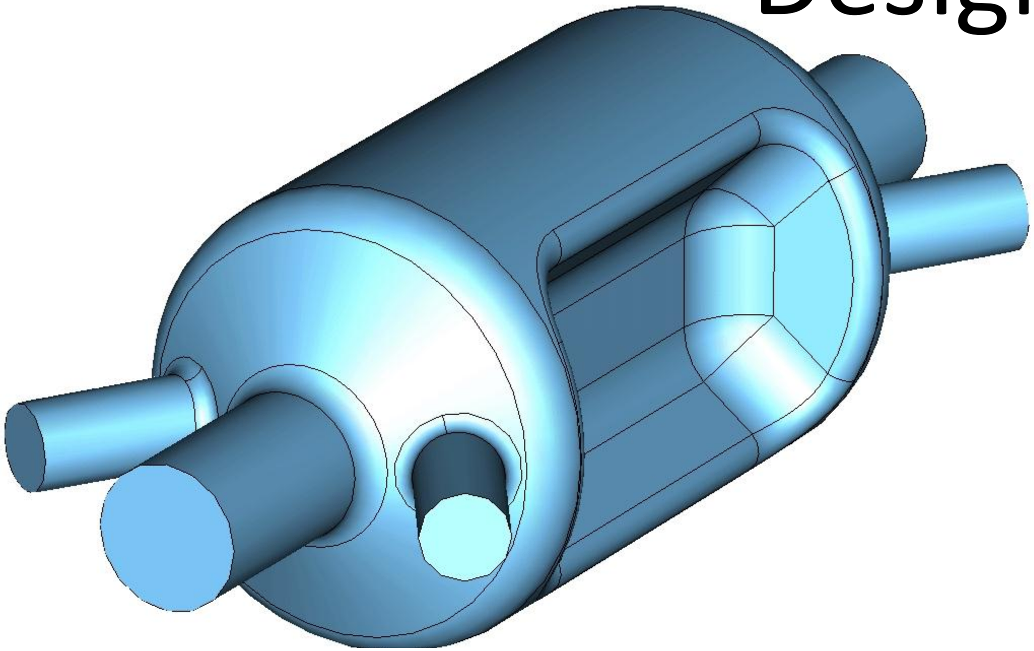
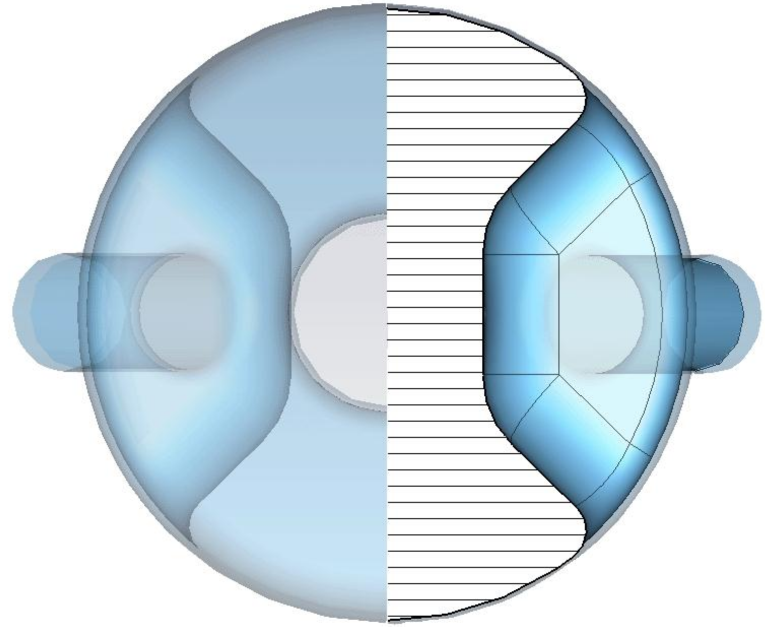
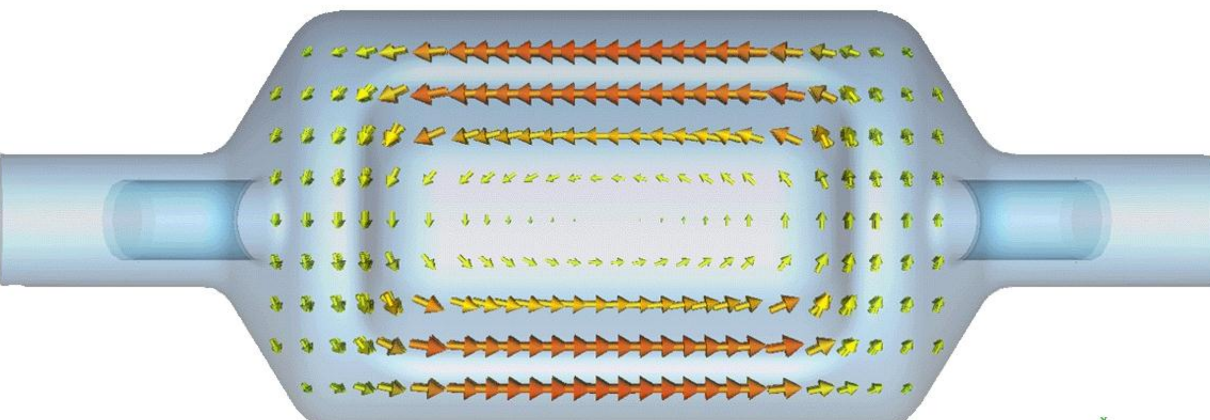
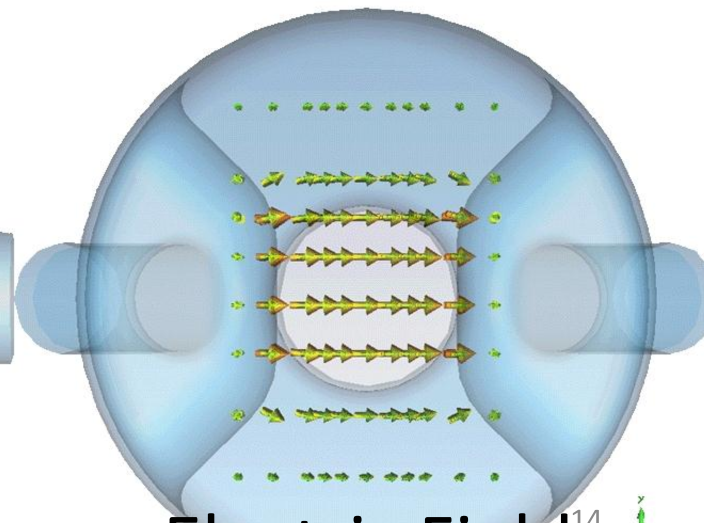
# Design







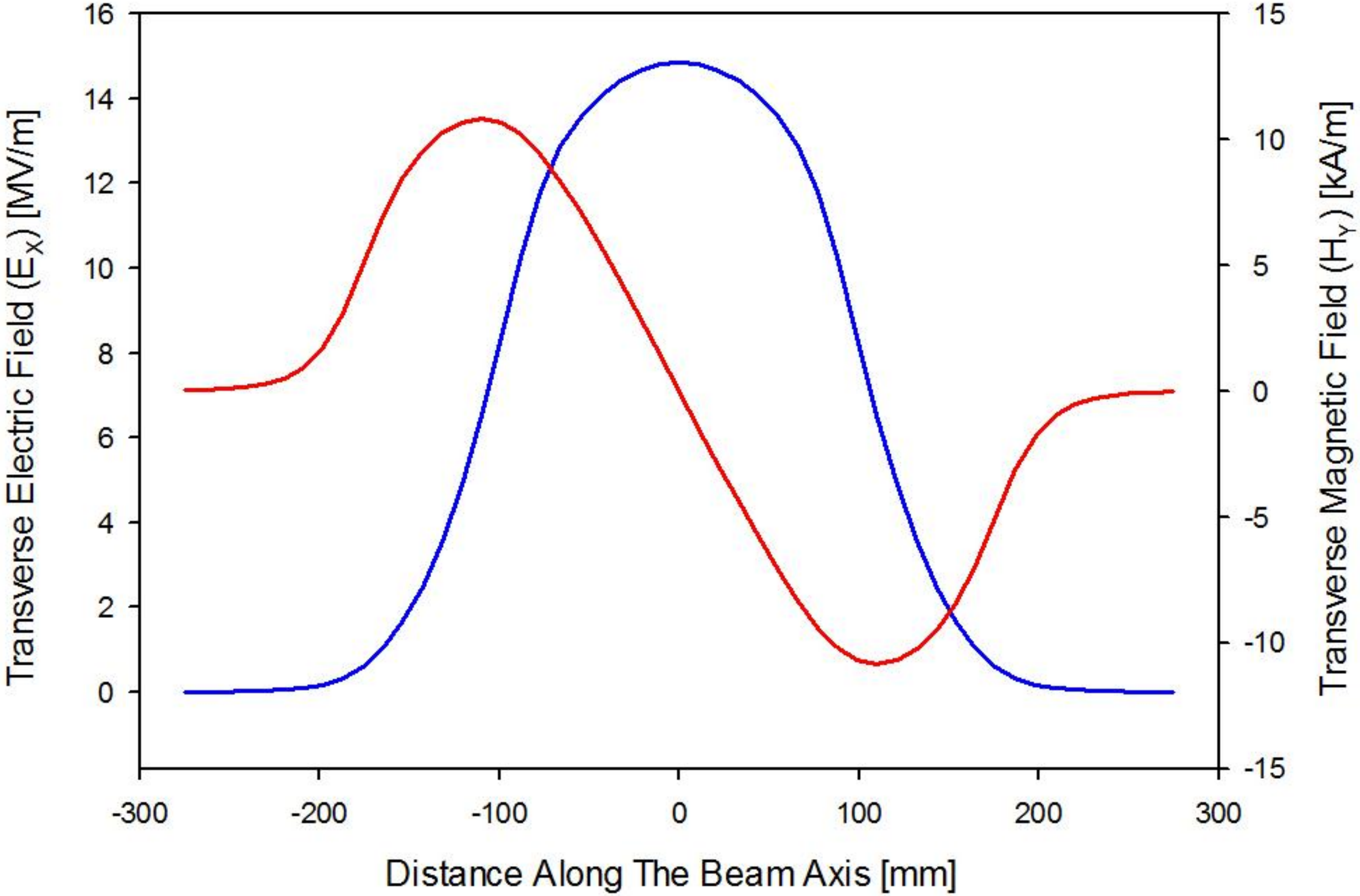
Magnetic Field



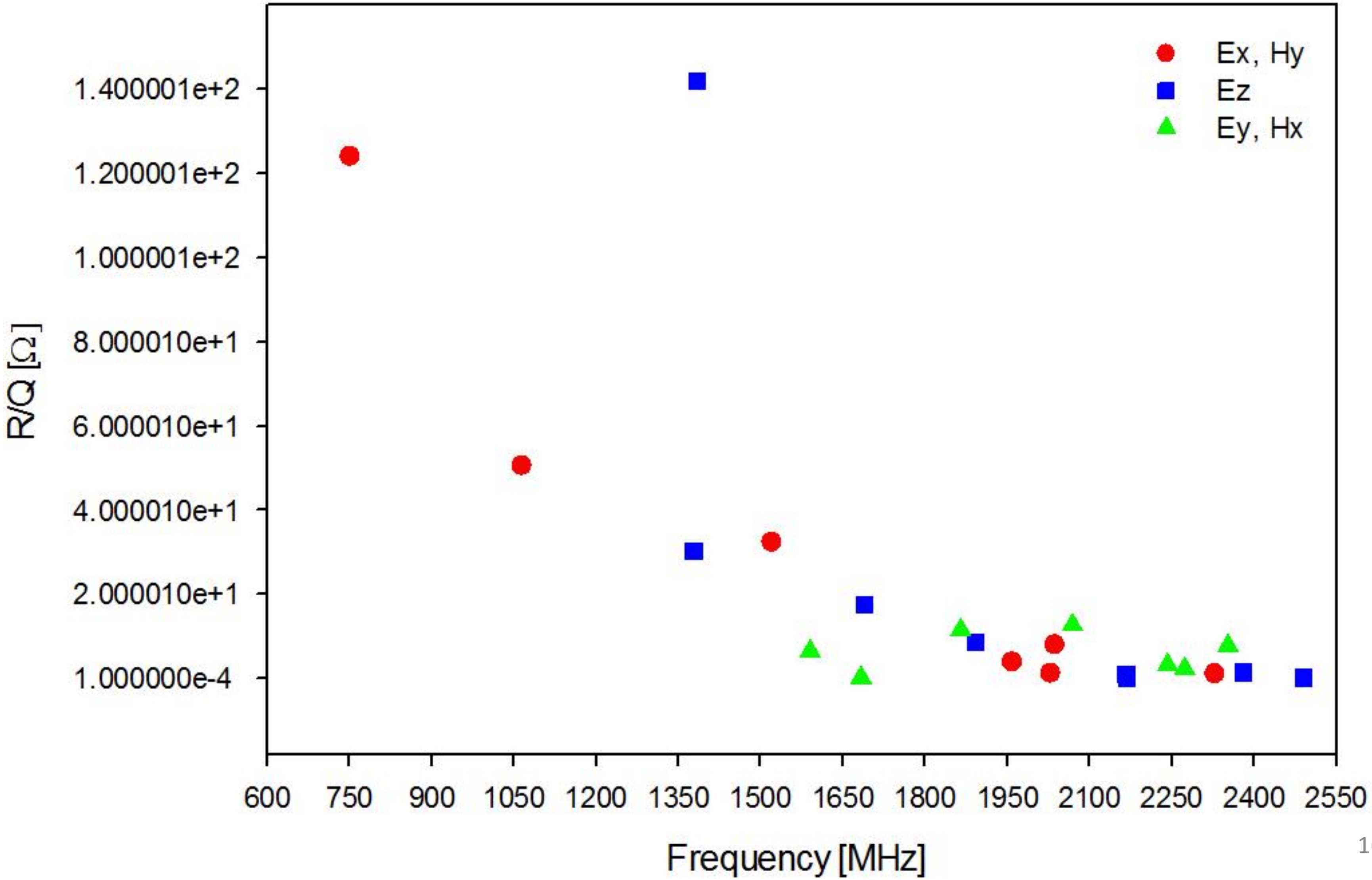
Electric Field

# Transverse Fields

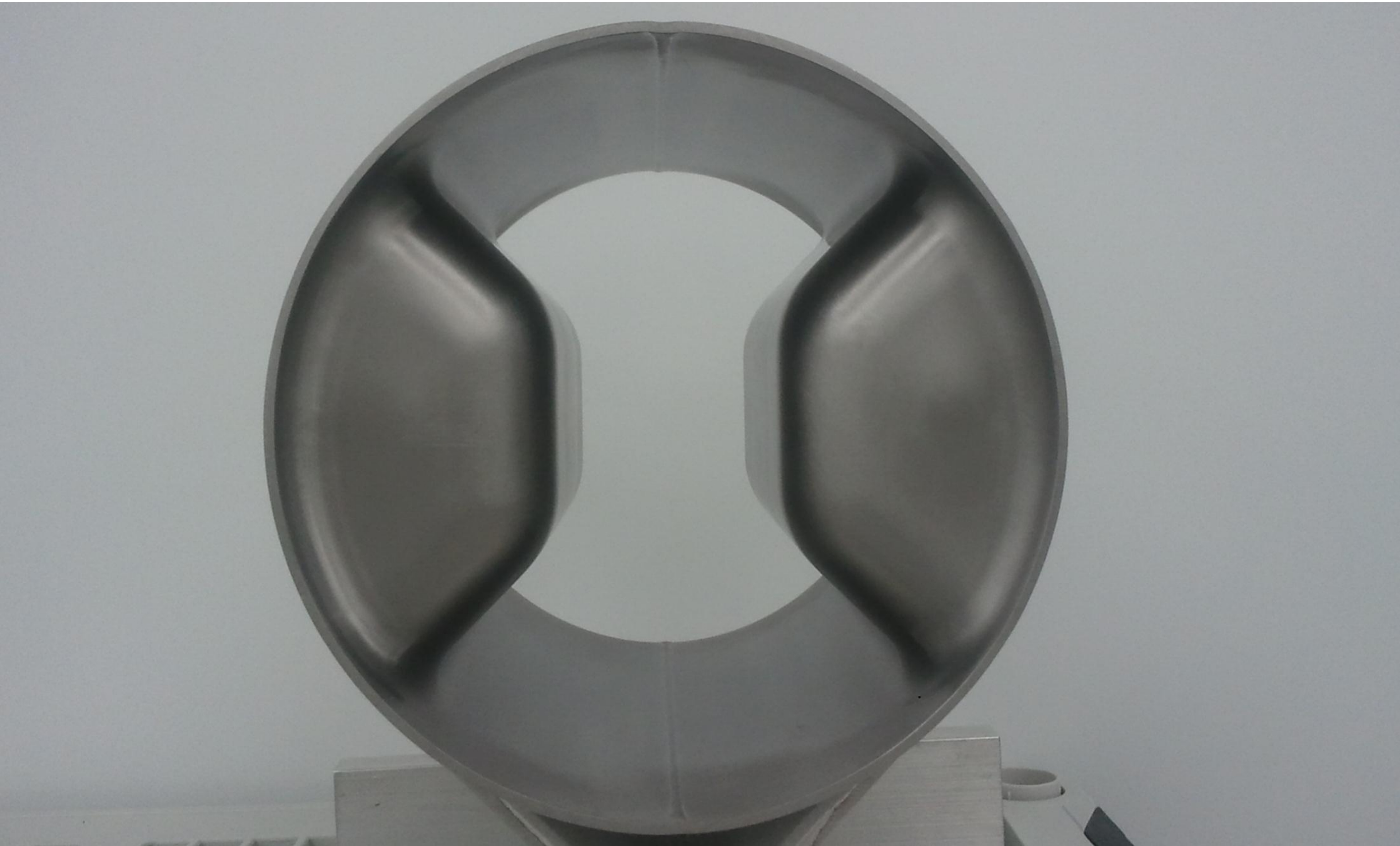
(Fundamental Mode)



# Higher Order Modes



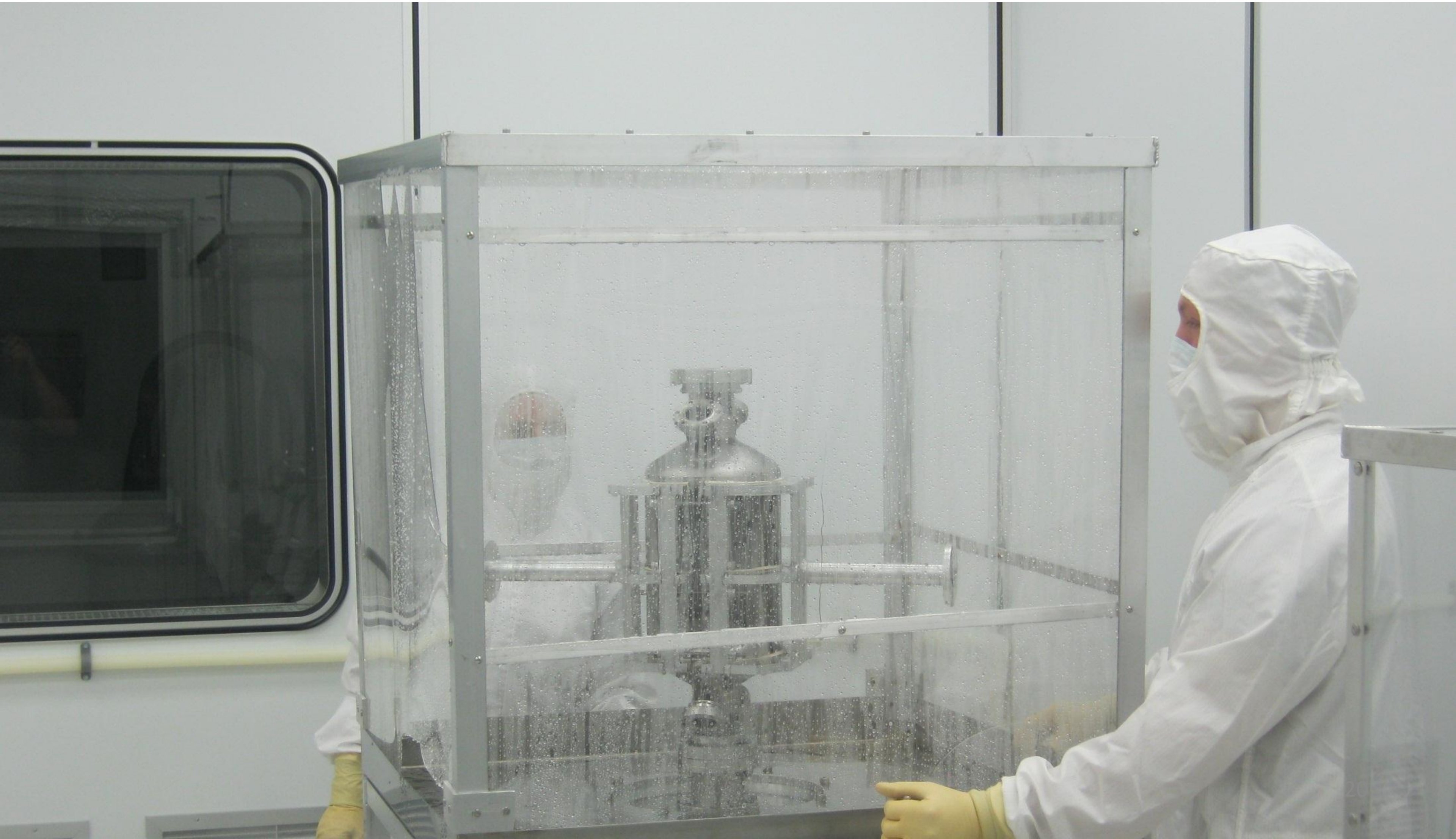
# Assembling



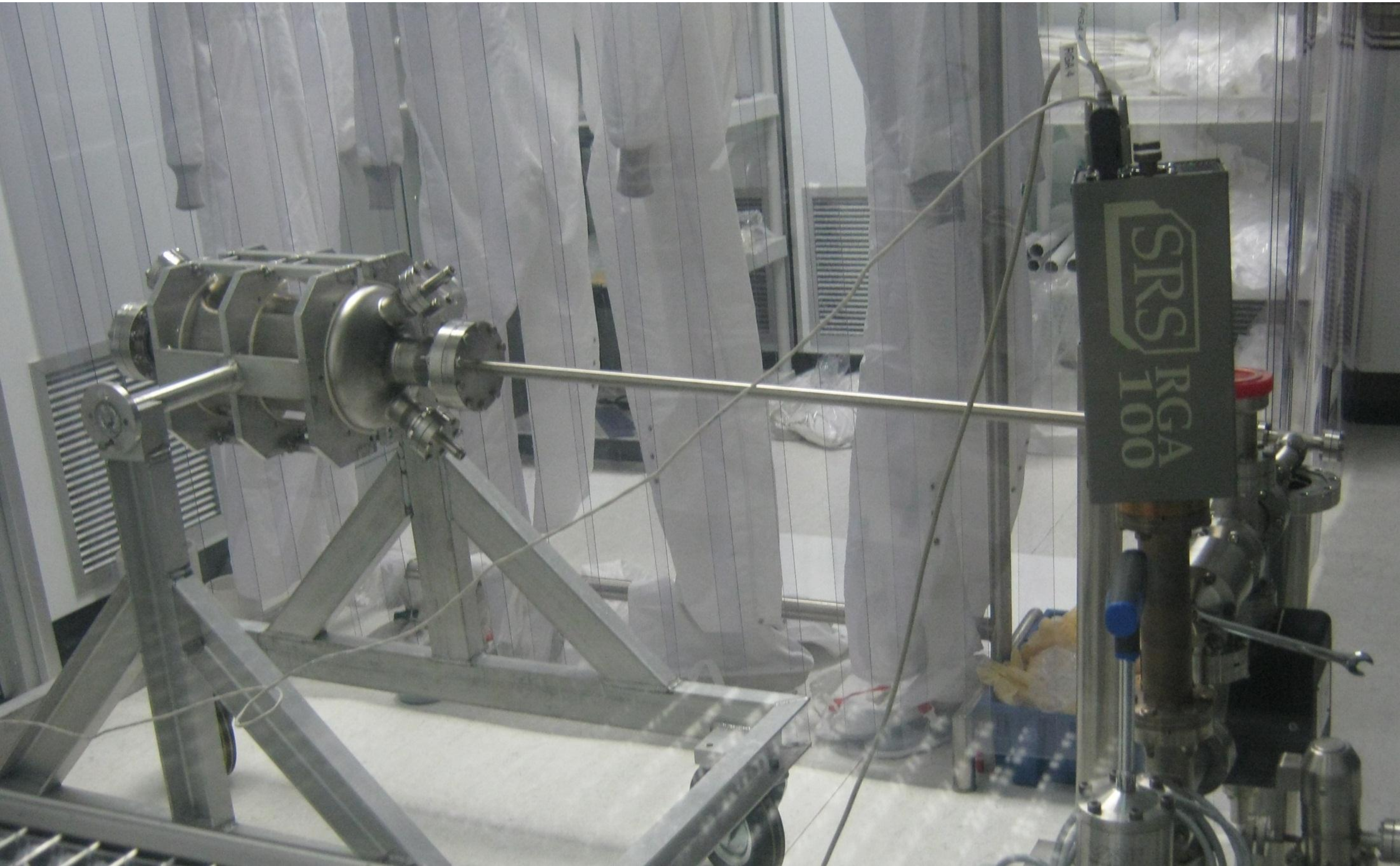
# For Electron-Welding

# Buffer Chemical Polishing

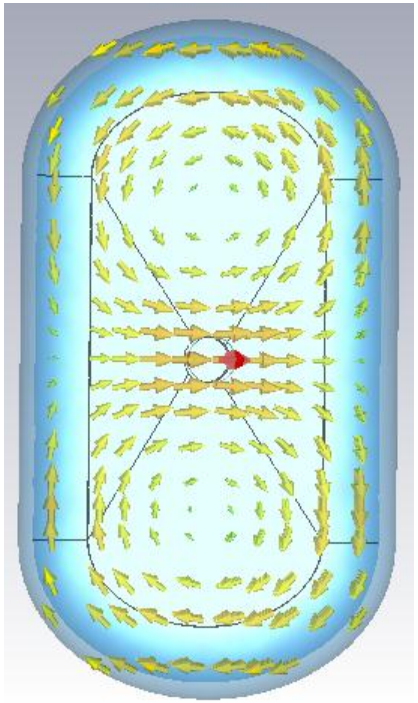
# High Pressure Rinsing



# Vacuum Pumping



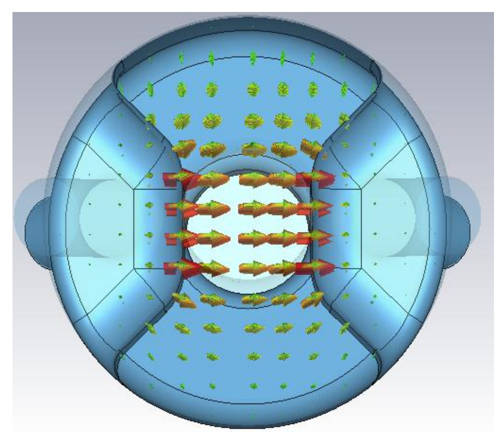
# Comparing Crabs



KeK

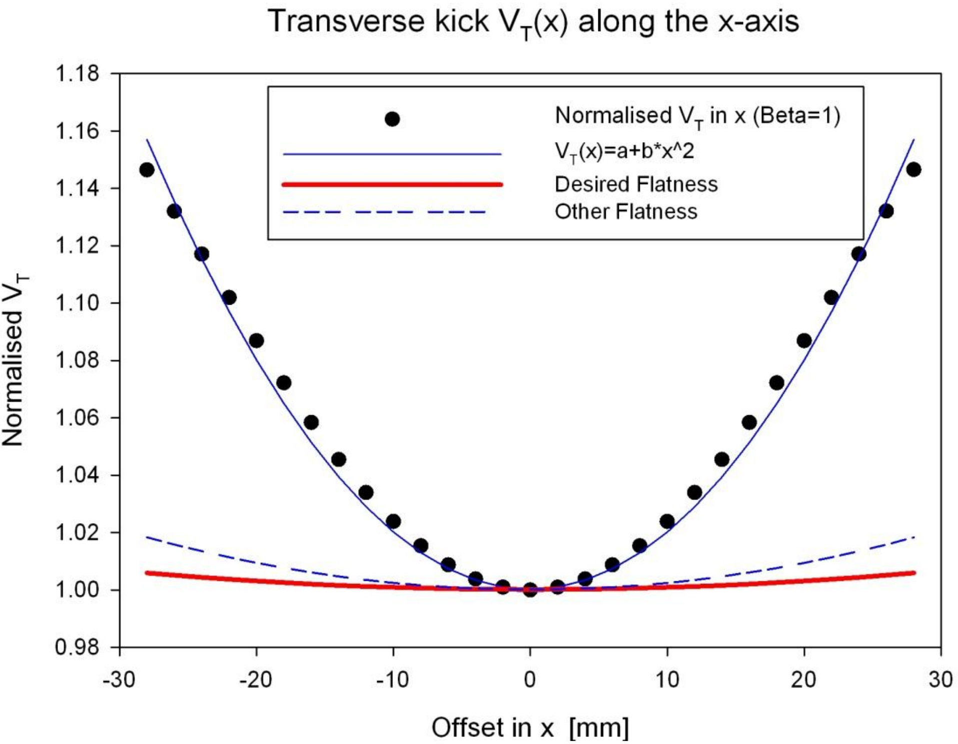
| Parameter | 750 MHz | KEK[4] MHz | Units |
|---|---|---|---|
| Freq. of π mode | 750.1 | 501.7 | MHz |
| λ/2 of π mode | 200.0 | 299.8 | mm |
| Freq. of 0 mode | 1350.6 | ~700.0 | MHz |
| Cavity length | 300.0 | 299.8 | mm |
| Cavity width | 190.1 | 866.0 | mm |
| Cavity height | 190.1 | 483.0 | mm |
| Bars width | 67.0 | - | mm |
| Angle | 45 | - | deg |
| Aperture diameter | 60.0 | 130.0 | mm |
| Deflecting voltage ($V_T$*) | 0.200 | 0.300 | MV |
| Peak electric field ($E_P$*) | 4.45 | 4.36 | MV/m |
| Peak magnetic field ($B_P$*) | 9.31 | 12.45 | mT |
| Geometrical factor | 131.4 | 220 | Ω |
| $[R/Q]_T$ | 124.15 | 46.70 | Ω |
| $R_T R_S$ | $1.65\times10^4$ | $1.03\times10^4$ | $\Omega^2$ |

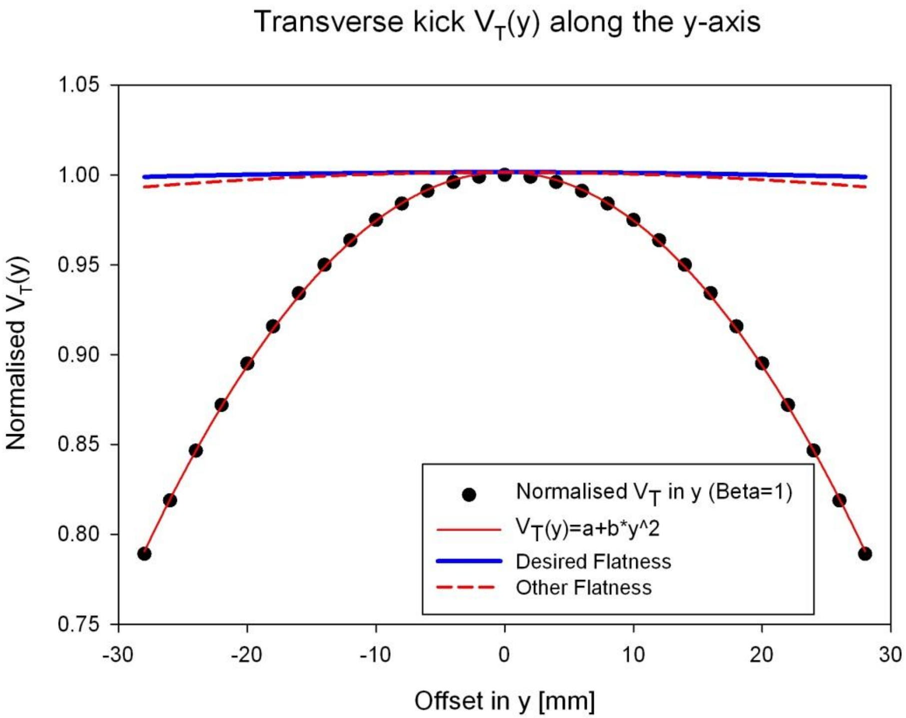
At $E_T^* = 1$ MV/m



ODU-JLab

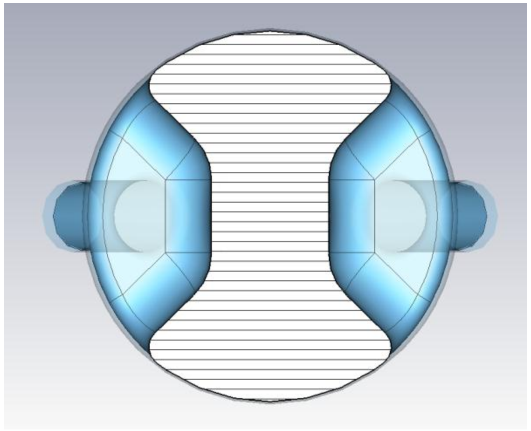
# Field Uniformity and Emittance



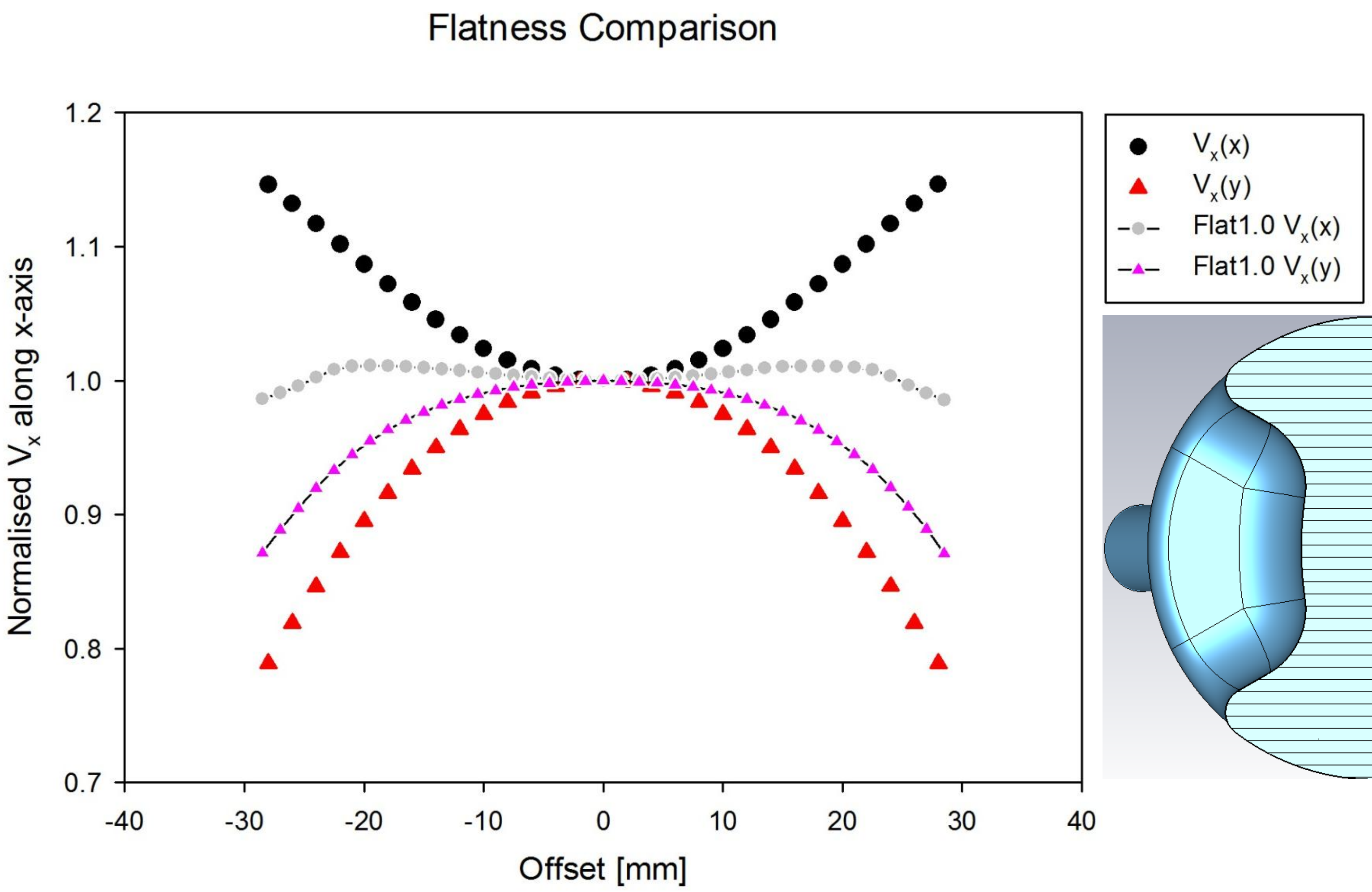



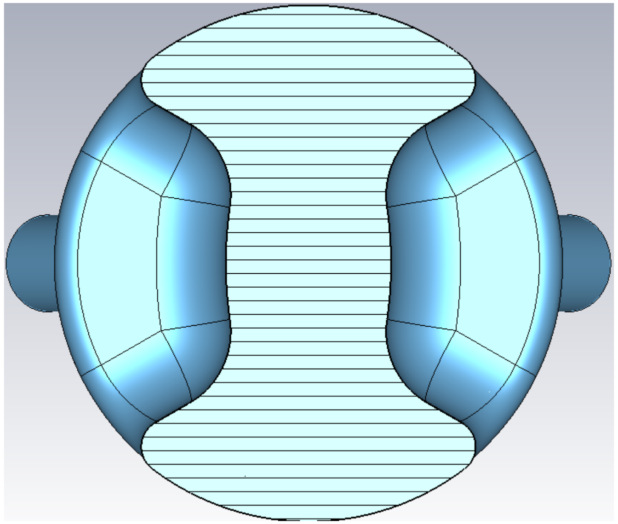

$$\epsilon_{n,rms}^2 \equiv \epsilon_{0n,rms}^2 + \frac{x_{0,rms}^2(\overline{\Delta p_x^2} - \overline{\Delta p_x}^2)}{m^2c^2}.$$

Therefore, if the proton beam enters the crab cavity with $\epsilon_{0n,rms}(x) = 0.35\,\mu m - rad$ then comes out of the cavity with $\epsilon_{n,rms}(x) = 0.36\,\mu m - rad$ after 1 pass. While for the $y$ direction if $\epsilon_{0n,rms}(y) = 0.07\,\mu m - rad$ then comes out of the cavity with $\epsilon_{n,rms}(x) = 0.13\,\mu m - rad$ after 1 pass, both considering *zero* offset.

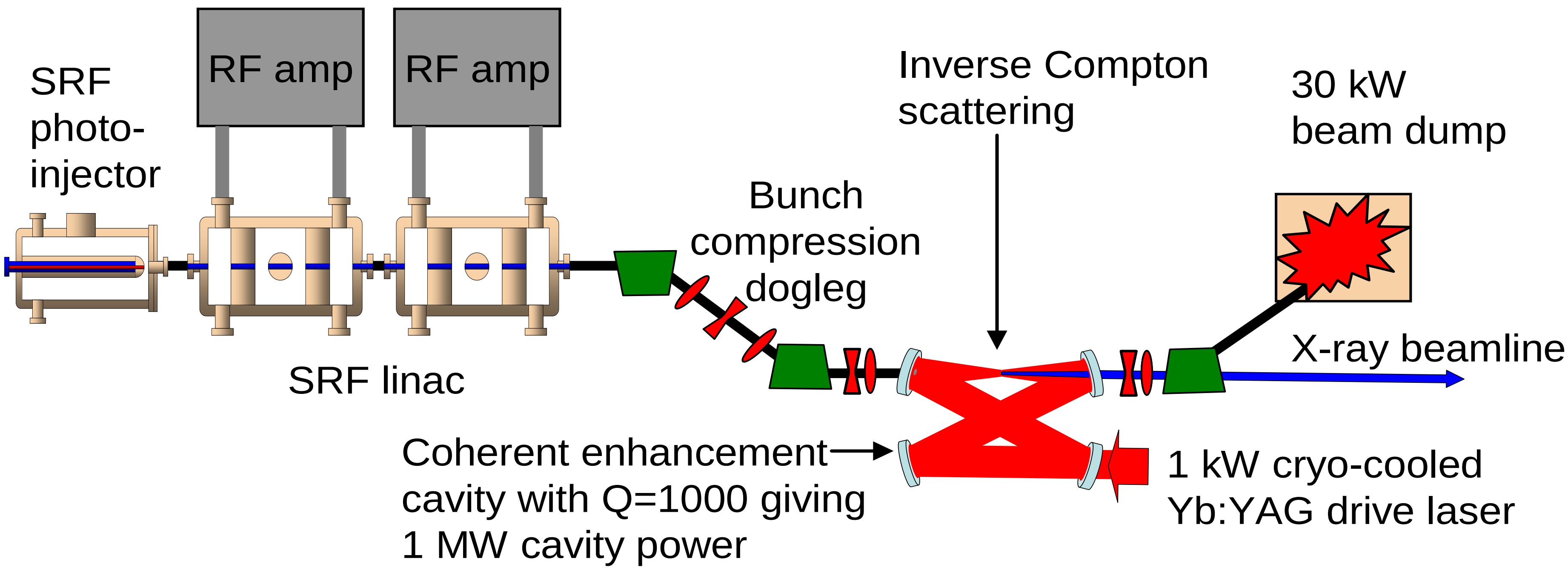


# Correcting Field Non-Uniformity



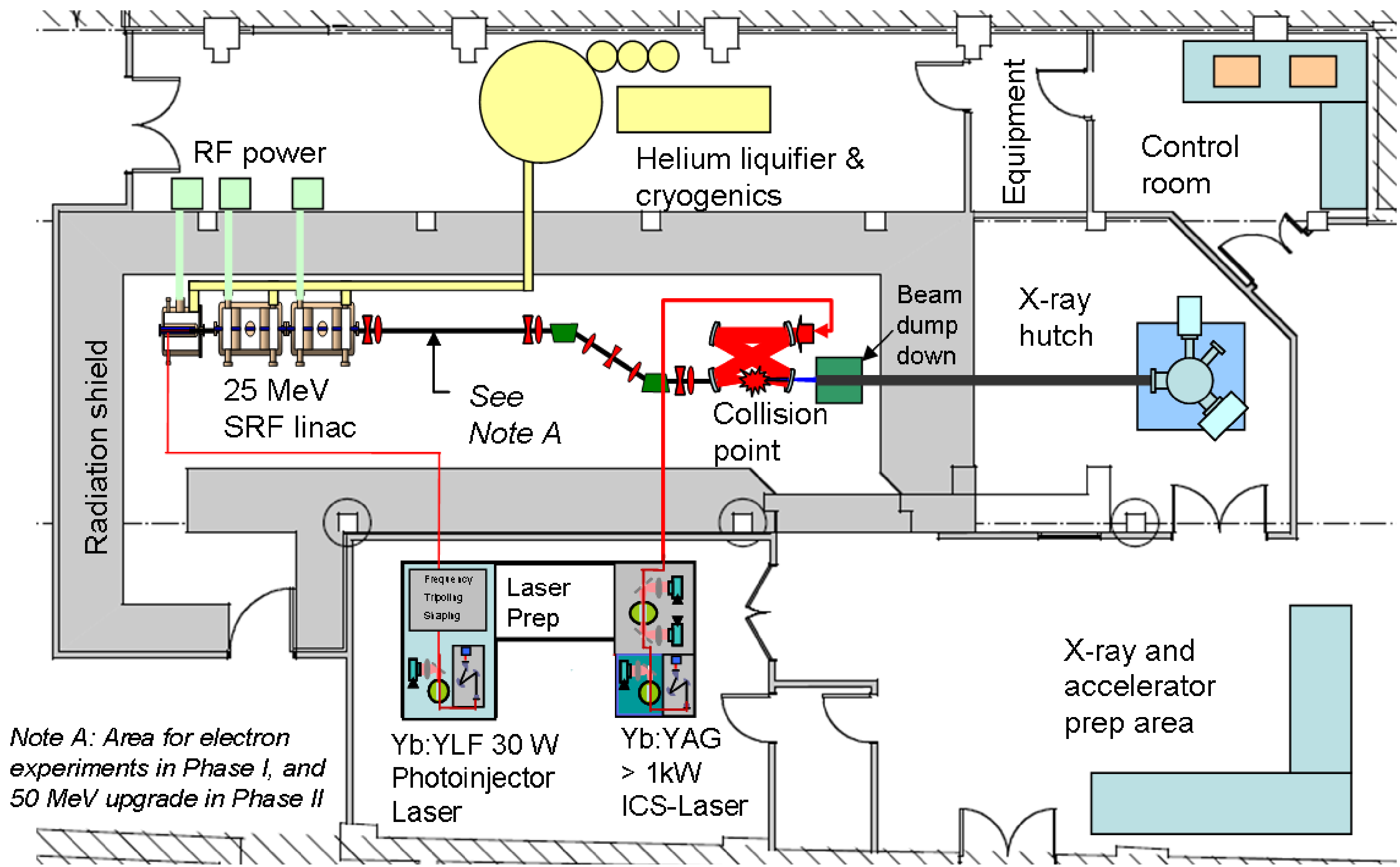



# 4rd Generation X-Ray Source




*Goeff Kraft, Jlab 2011.

# 4rd Generation X-Ray Source




*Goeff Kraft, Jlab 2011.

# 4rd Generation X-Ray Source

- **What do we want?**

-X-Ray specs

| Parameter | Quantity | Unit |
|---|---|---|
| X-ray energy | Up to 12 | keV |
| Photons/bunch | $1.6\times10^{6}$ | |
| Flux | $1.6\times10^{14}$ | photon/sec |
| Average Brilliance | $1.5\times10^{15}$ | photon/(sec mm$^2$ mrad$^2$ 0.1%BW) |

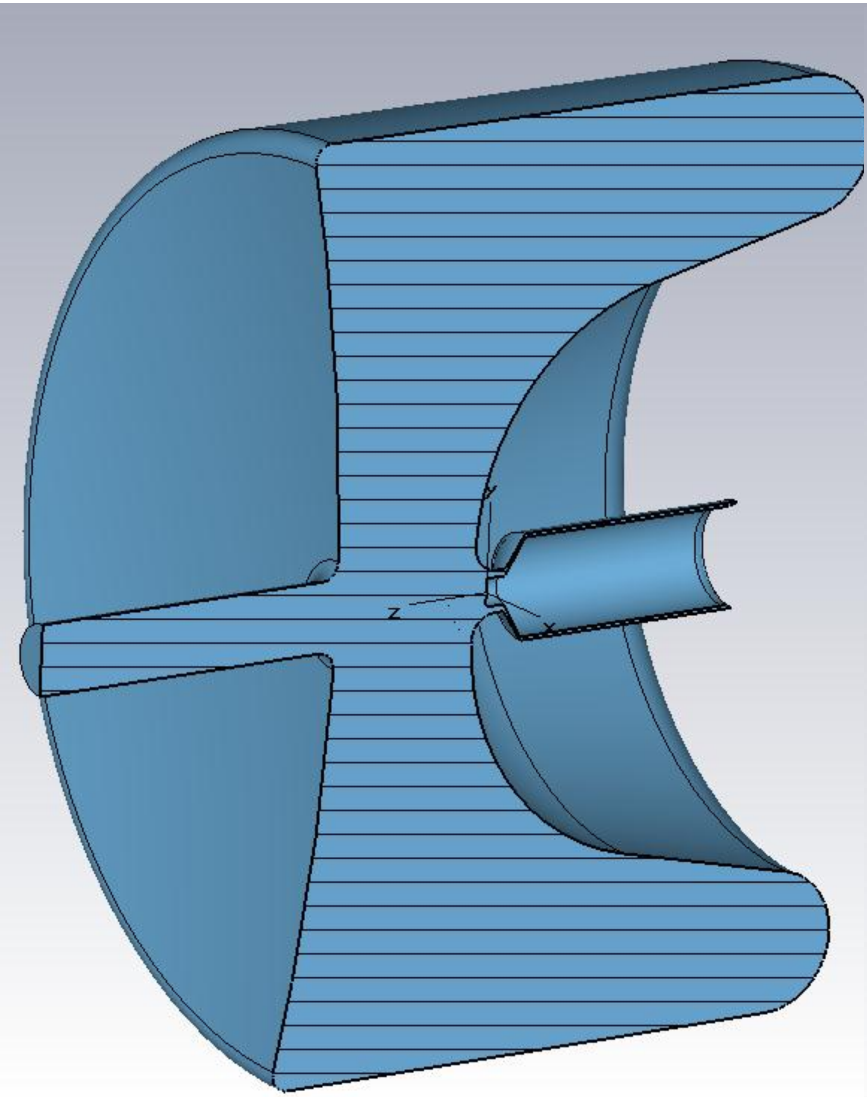
- **What do we need?**

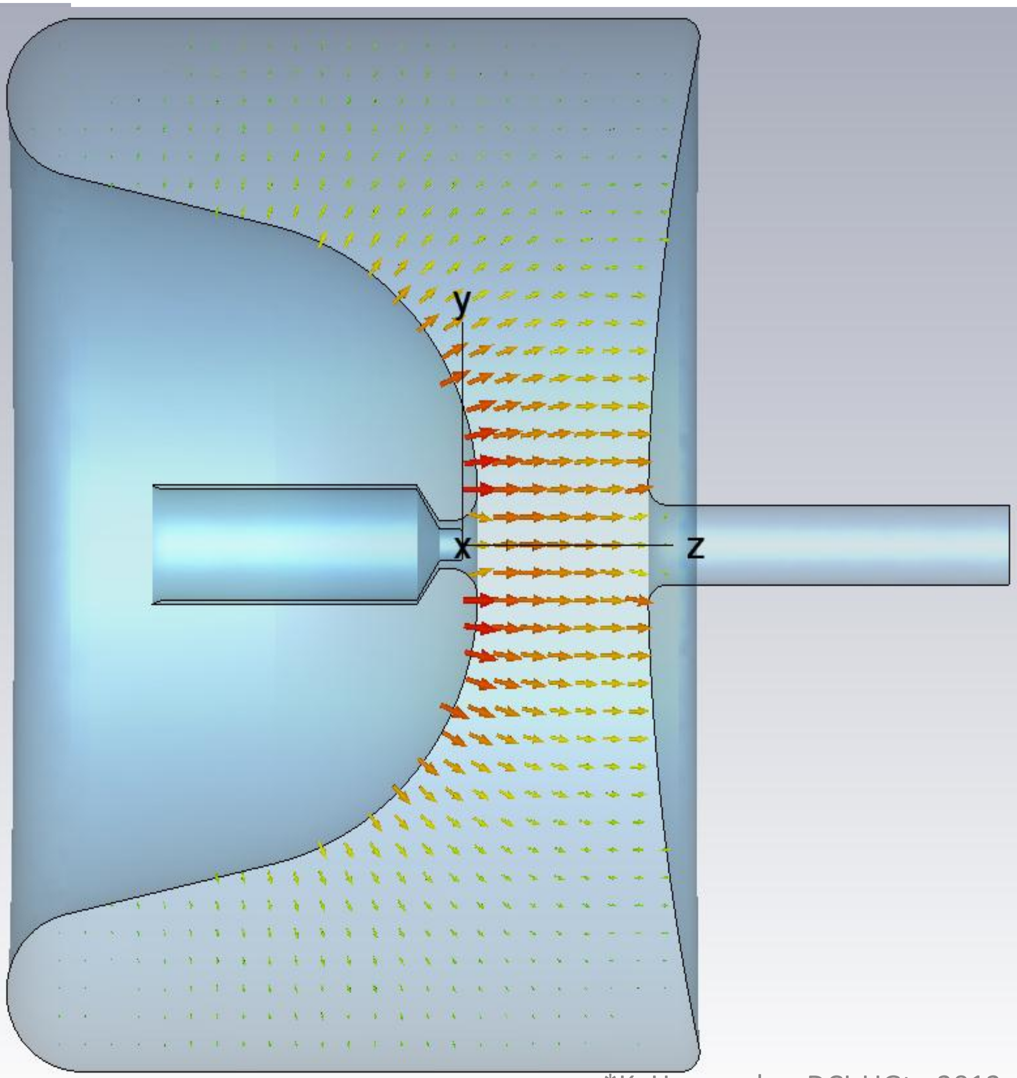
-Beam specs

| Parameter | Quantity | Unit |
|---|---|---|
| Energy | 25 | MeV |
| Bunch charge | 10 | pC |
| Repetition rate | 100 | MHz |
| Average current | 1 | mA |
| Normalized emittance | 0.1 | mm-mrad |
| $\beta$ | 5 | mm |
| FWHM bunch length | 3.0(0.9) | psec(mm) |
| RMS energy spread | 7.5 | keV |

*Goeff Kraft, Jlab 2011.

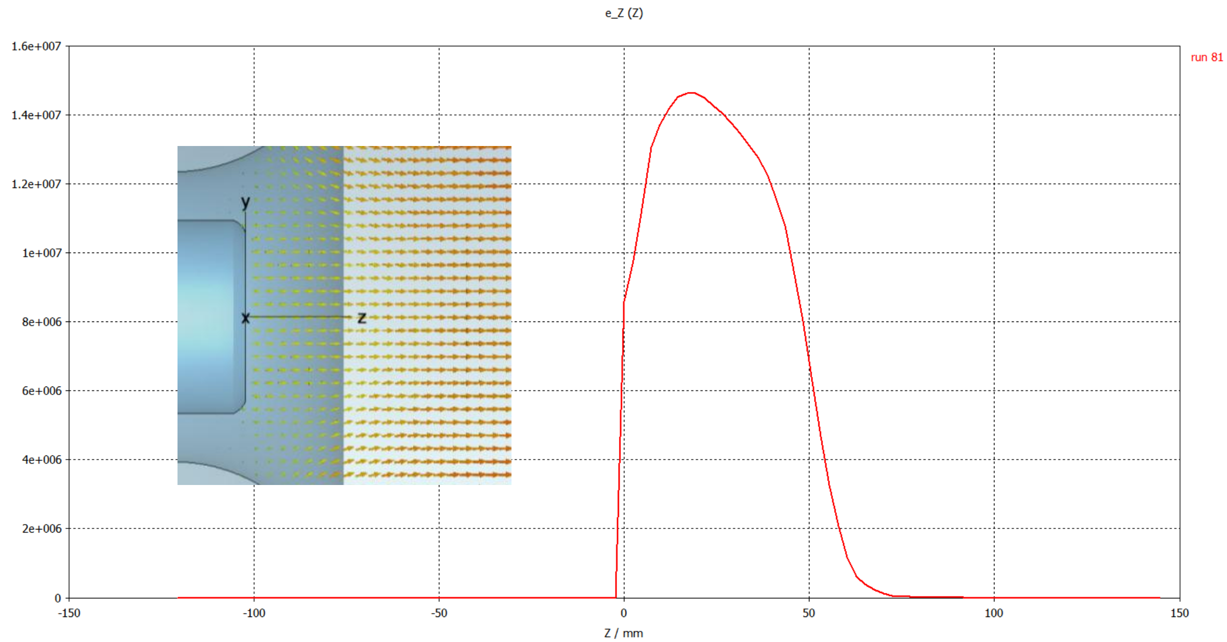
# 4rd Generation X-Ray Source

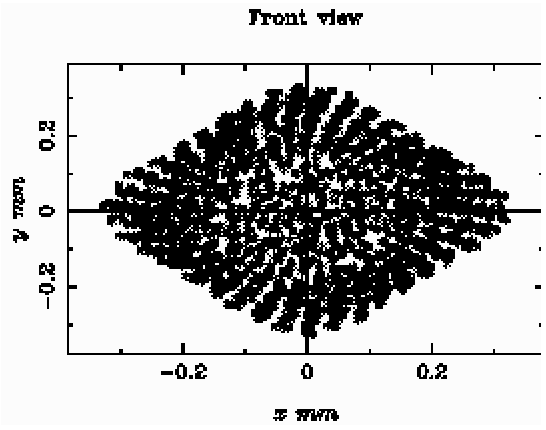


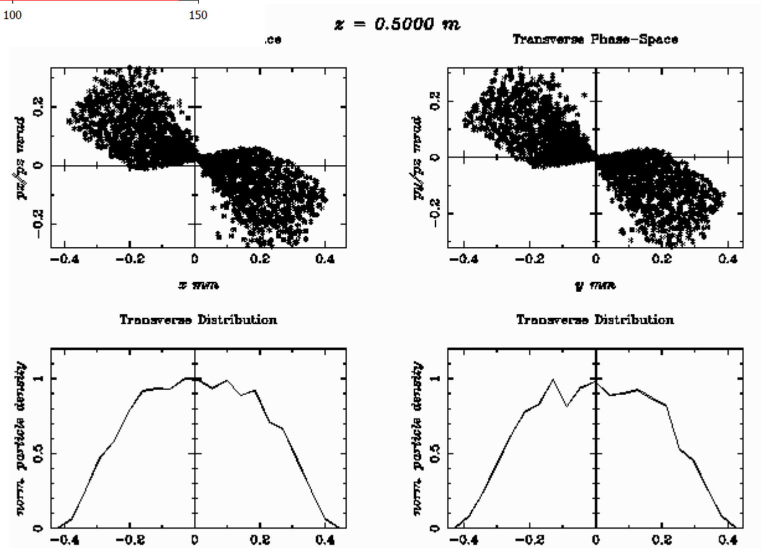




*K. Hernandez, DCI-UGto 2012.

# 4rd Generation X-Ray Source



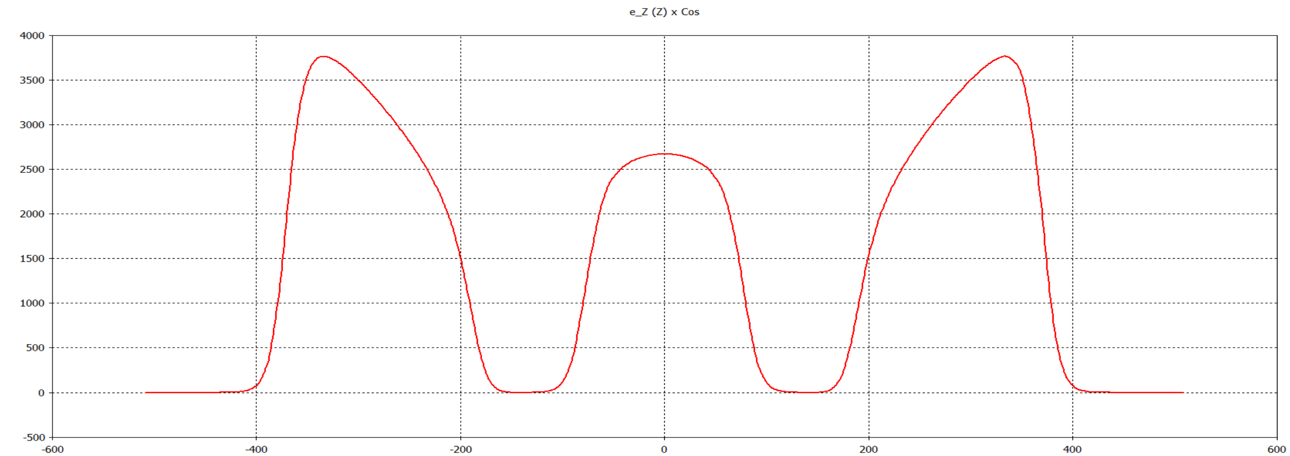



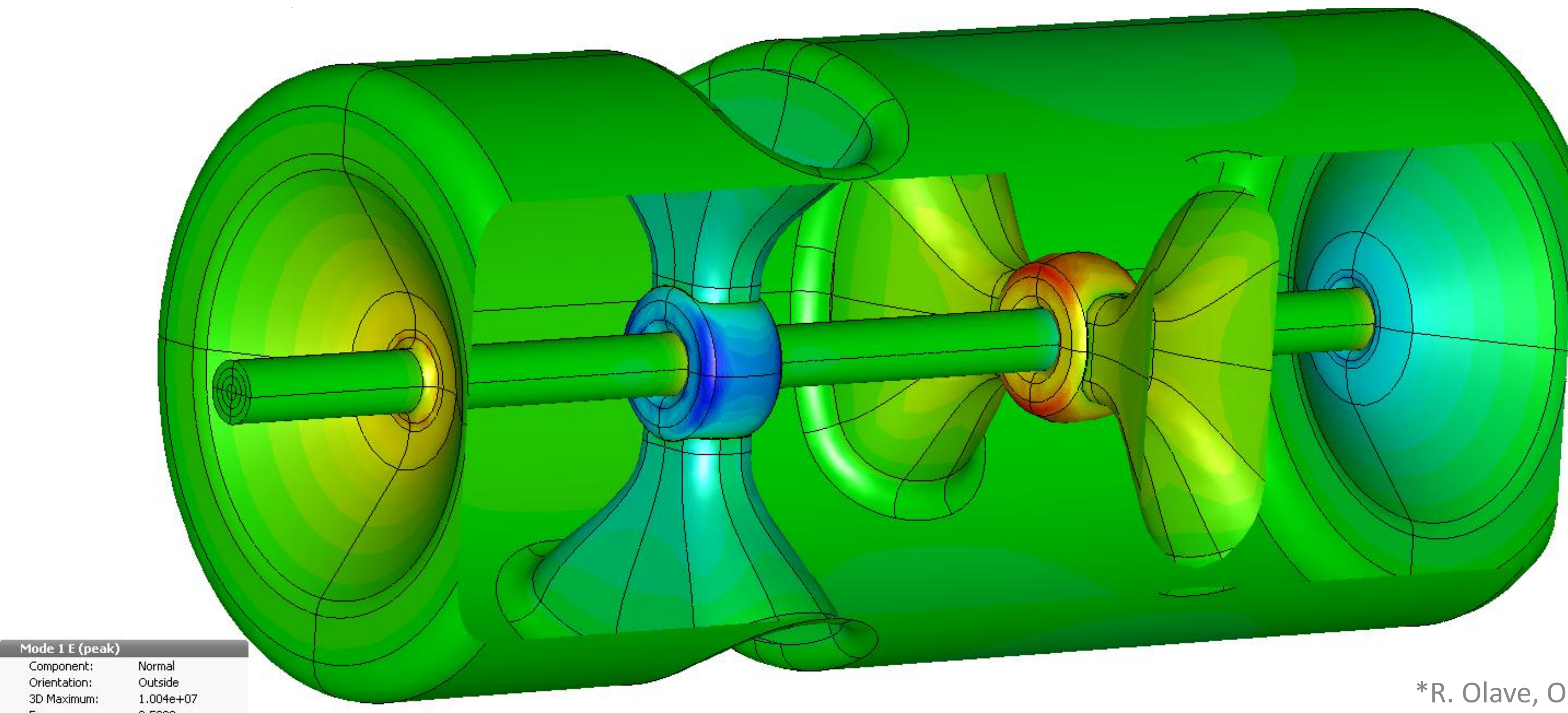

| Vacc | Eacc | Ep over Eacc | Bp over Eacc (mT over Mv over m) |
|---|---|---|---|
| 575863 | 3.84445e+0( | 5.01414 | 10.9625 |

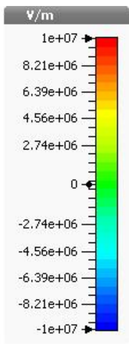
| Bp over Ep | R over Q | G | (R over Q) times (G) |
|---|---|---|---|
| 2.18631 | 105.483 | 64.7645 | 6831.56 |

*K. Hernandez, DCI-UGto 2012.

# 4rd Generation X-Ray Source

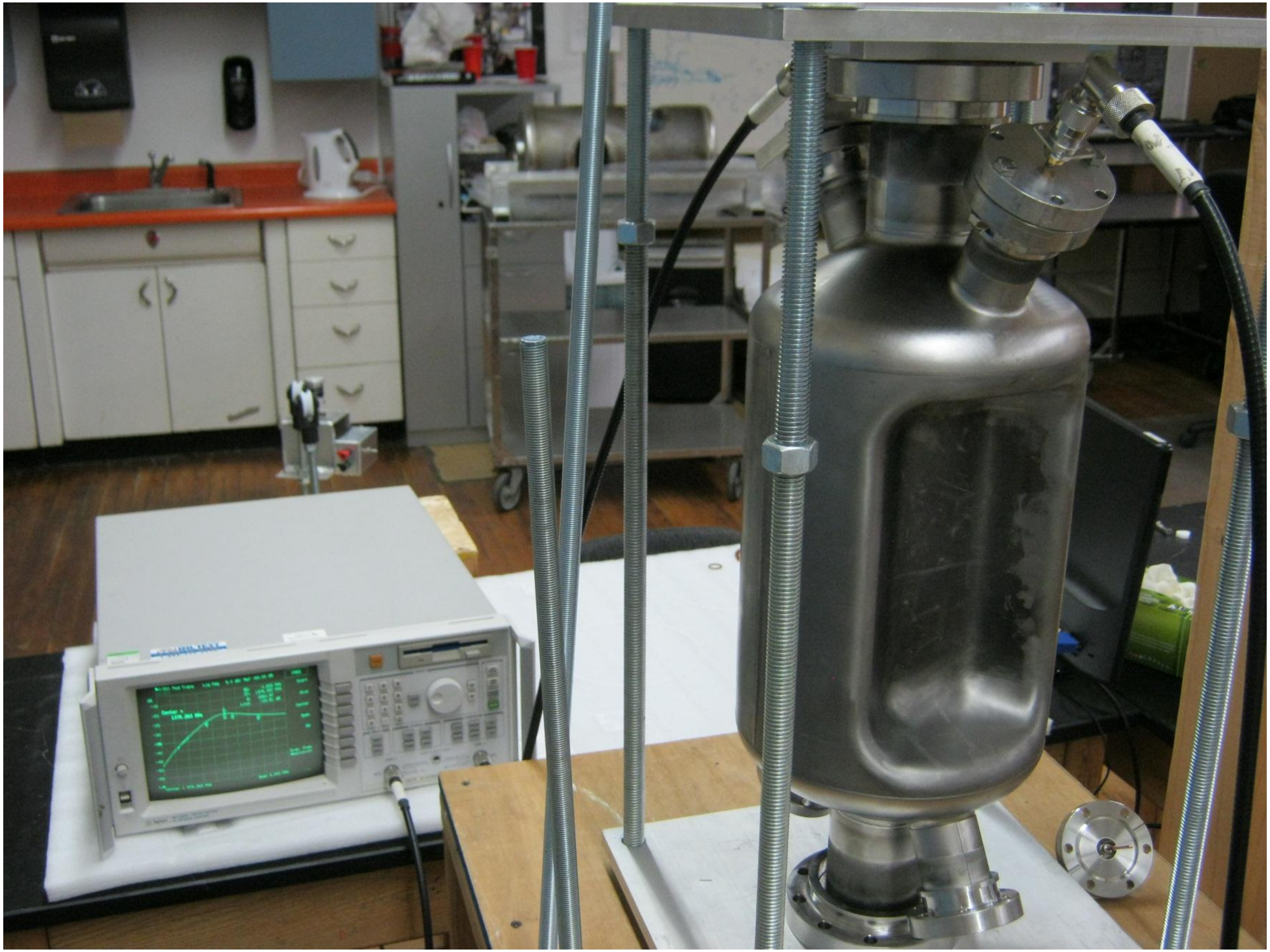



*R. Olave, ODU 2012.

# Thank you



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  - Beam Dynamics Studies for Transverse Electromagnetic Mode-type RF Deflectors – Phys. Rev. ST Accel. Beams **15**, 022001 (2012) - S. Ahmed, et.al.
- PAC 2011 – NewYork, USA
  - Design of Superconducting Parallel-bar Deflecting/Crabbing Cavities with Improved Properties – J.R. Delayen, S.U. De Silva
  - Fundamental and HOM Coupler Design for the Superconducting Parallel-Bar Cavity – S.U. De Silva, J.R. Delayen
  - Multipacting Analysis of the Superconducting Parallel-bar Cavity – S.U. De Silva, J.R. Delayen
  - Beam Dynamics Studies of Parallel-Bar Deflecting Cavities – S. Ahmed, et.al.
- SRF 2011 – Chicago, USA
  - Compact Superconducting Cavities for Deflecting and Crabbing Applications – J.R. Delayen – Inivted Talk
  - Designs of Superconducting Parallel-Bar Deflecting Cavities for Deflecting/Crabbing Applications – J. R. Delayen, S.U. De Silva
  - Analysis of HOM Properties of Superconducting Parallel-Bar Deflecting/Crabbing Cavities – S.U. De Silva, J.R. Delayen
  - Mechanical Study of Superconducting Parallel-Bar Deflecting/Crabbing Cavities – H. Park, S.U. De Silva, J. R. Delayen
- IPAC 2011 – San Sebastián, Spain
  - Design of Superconducting Parallel-bar Deflecting/Crabbing Cavities – J.R. Delayen, S.U. De Silva
  - Crab Crossing Schemes and Studies for Electron Ion Collider – S. Ahmed, et.al.

# References

- PRST-AB
  - Evolution and Properties of Parallel-Bar Deflecting/Crabbing Cavities – S.U. De Silva, J.R. Delayen
- IPAC 2012 – New Orleans, USA
  - Design and Development of Superconducting Parallel-bar Deflecting/Crabbing Cavities – S.U. De Silva, J.R. Delayen
  - Characteristics and Fabrication of a 499 MHz Superconducting Deflecting Cavity for the Jefferson Lab 12 GeV Upgrade – H. Park, S.U. De Silva, J. R. Delayen
  - Engineering of a Superconducting 400 MHz Crabbing Cavity for the LHC HiLumi Upgrade – D. Gorelov, T. Grimm (Niowave, Inc., Lansing, Michigan), S.U. De Silva, J.R. Delayen
  - RF Modeling Using Parallel Codes ACE3P for the 400-MHz Parallel-Bar/Ridged-Waveguide Compact Crab Cavity for the LHC HiLumi Upgrade – Z. Li, L. Ge (SLAC, Menlo Park, Ca*li*fornia), J.R. Delayen, S.U. De Silva
  - Simulation of a TEM-mode Crab Cavity in the SPS – H.J. Kim, T. Sen (Fermilab, Batavia), K. Li (Stony Brook University, Stony Brook)
  - Impedance Budget for MEIC Electron Ring – S. Ahmed et.al.
- LINAC 2012 – Tel Aviv, Israel
  - Compact Superconducting Crabbing and Deflecting Cavities – S.U. De Silva – Invited Talk
  - Multipole Field Effects of Parallel-Bar Deflecting/Crabbing Cavities – S.U. De Silva, J.R. Delayen

# Acknowledgements

- Terry Grimm (Niowave)
- Dmitry Gorelov (Niowave)
- Goeffrey Kraft (JLab)
- Todd Satogata (JLab)
- Jean Delayen (ODU/JlLab)
- Subashini de Silva (ODU/JLab)
- Rocío Olave (ODU)
- Christopher Hopper (ODU)
- Kirsten Deitrick (ODU)
- Randika Gamage (ODU)
- **Karim G. Hernández (DCI-Ugto)**

# Extras

# Preliminary Tests

- For the cavity after removing *150 μm* etch with standard BCP solution:

$$Q_0 = \frac{G}{R_s} \approx 3 \times 10^8$$ (measured 4K)

- Geometrical factor:

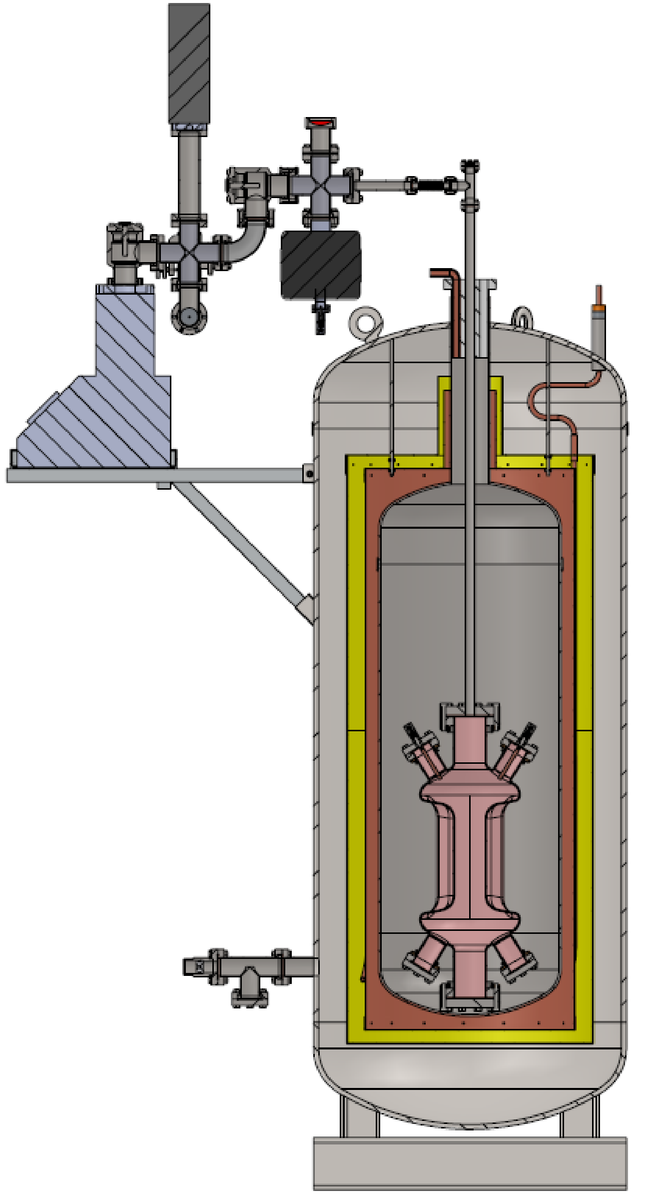
$$G = 131.4\ \Omega$$ (design)

- Now, for the shunt impedance:

$$R_s = 438\ n\Omega$$

- For the power dissipated:

$$P_{dis} = 10\ W$$ (measured 4K)



# Preliminary Tests

- And so, for $R_T = \frac{{V_T}^2}{P_{dis}}$ (deflecting voltage):

$$R_T R_s = 1.65 \times 10^4\ \Omega^2 \text{ (design)}$$

$$R_T = 37.67 \times 10^9\ \Omega$$

- We can estimate the deflecting Voltage:

$$\boldsymbol{V \sim 0.6\ MV}$$

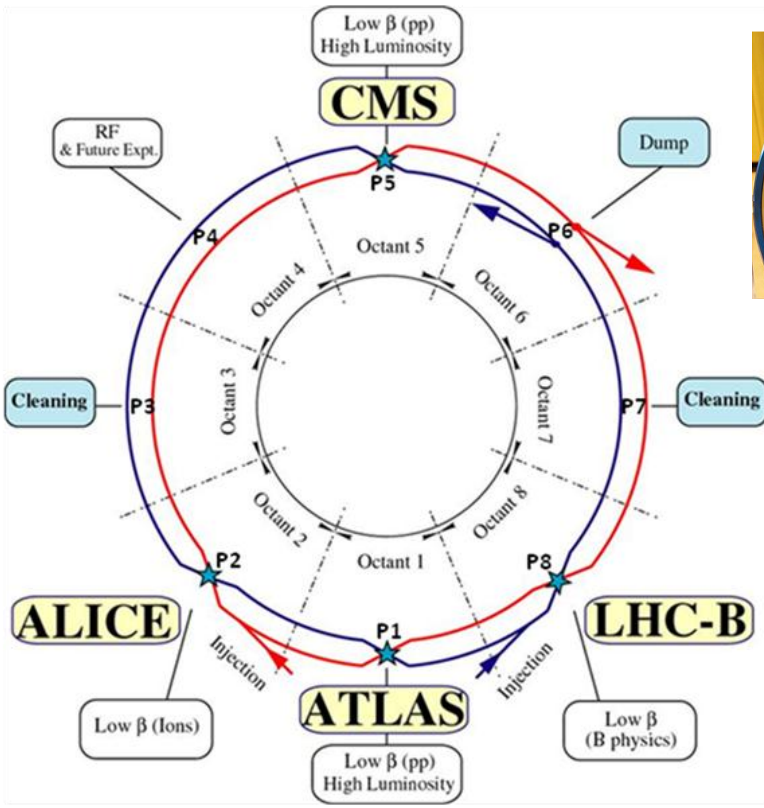
- Using this we recalculate:

$$E_p = 13.35\ {}^{\text{MV}}/_{\text{m}}$$

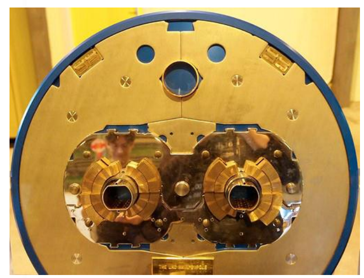
$$B_p = 27.93\ \text{mT}$$

# RF Crab Cavity Requirements

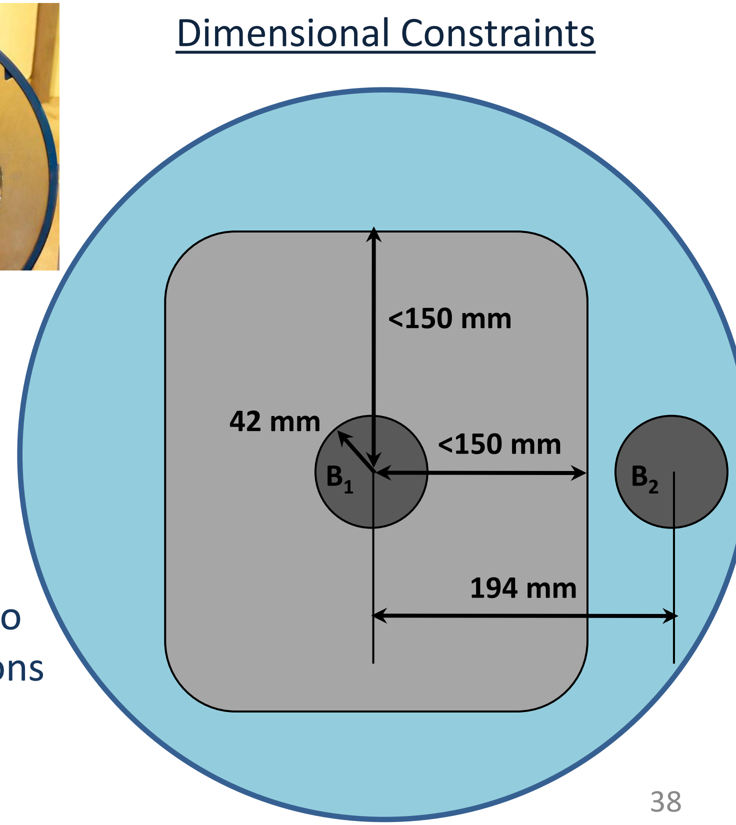
- Local scheme requires crab cavities on either side of the interaction point (IP)
- Requires vertical and horizontal crabbing at the two interaction points (IP1 and IP5)
- Operating rf frequency – 400 MHz
- Transverse voltage requirement - 10 MV per beam per side




L. Rossi, LHC-CC 10

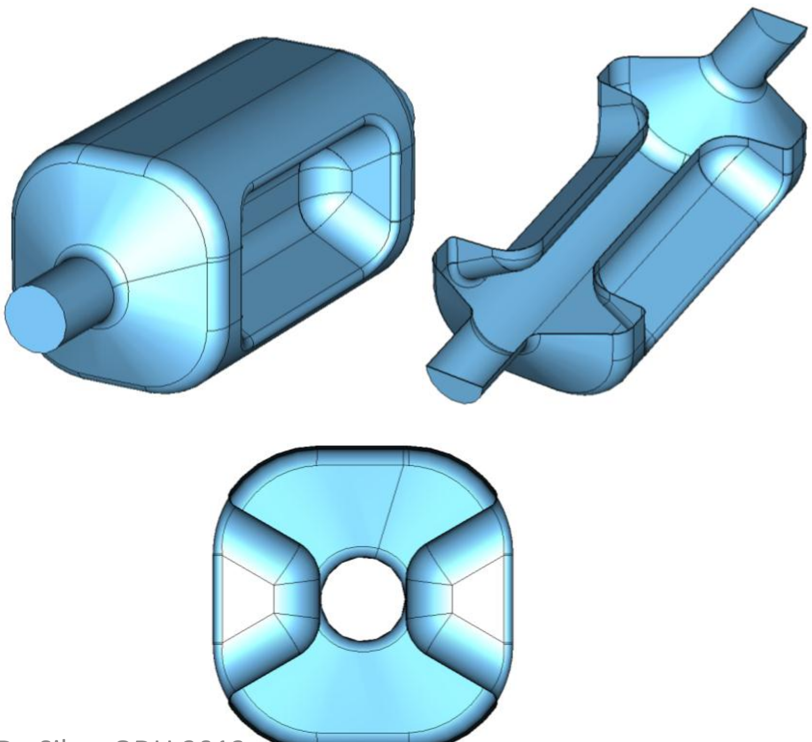


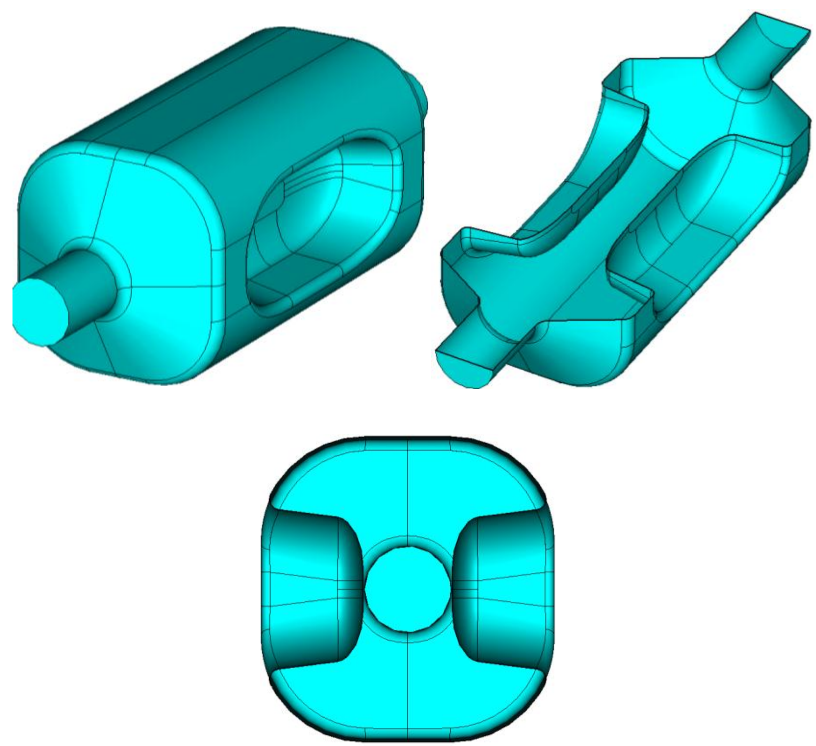
27 km @1.9K to accelerate protons to 7TeV



# ODU/SLAC 400 MHz Square Cavity Options

- Designs are fairly similar in structure and properties
- Final design depends on final specifications
  - Field uniformity
  - Impedance budget

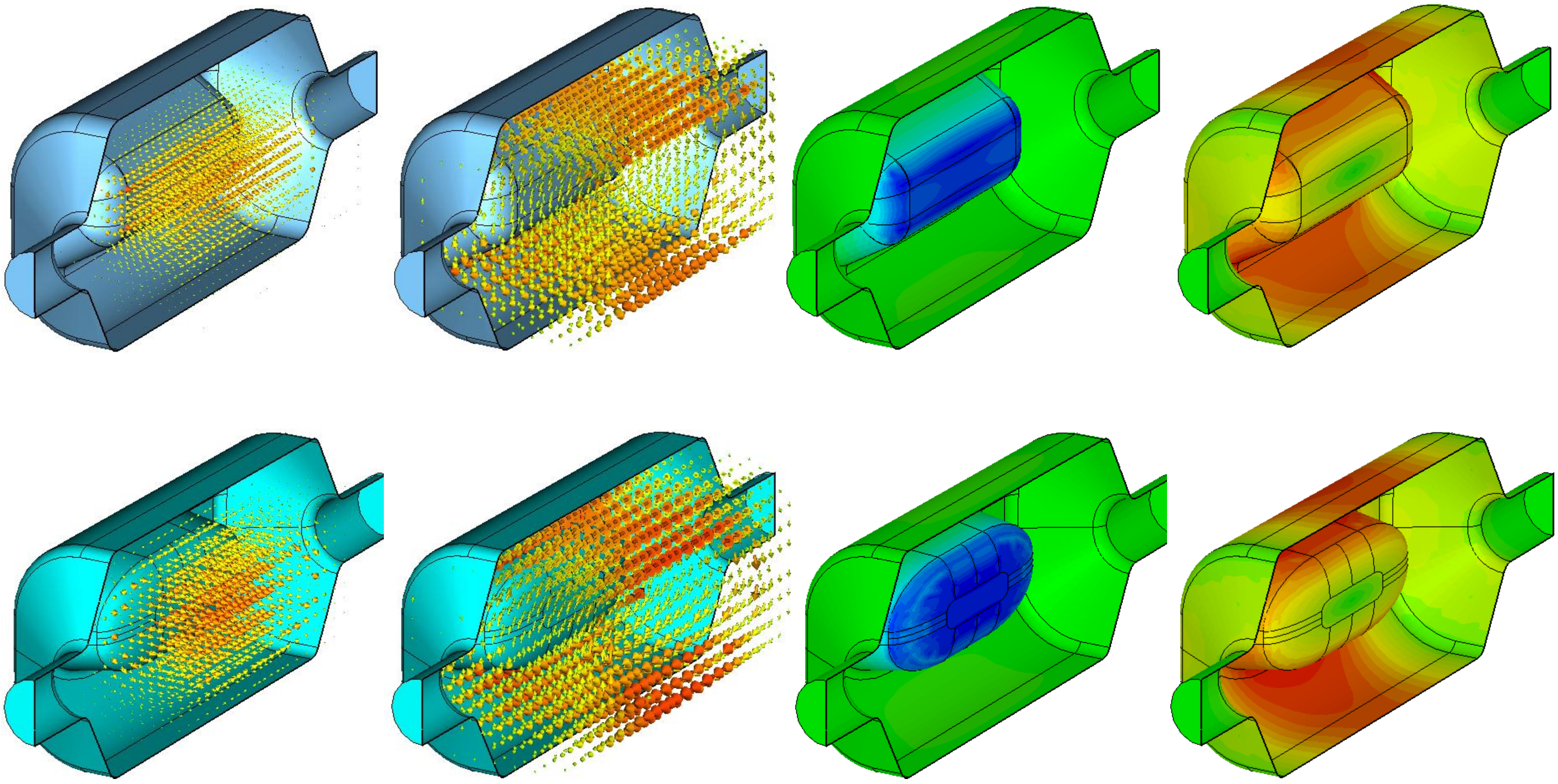




*S. De Silva, ODU 2012.

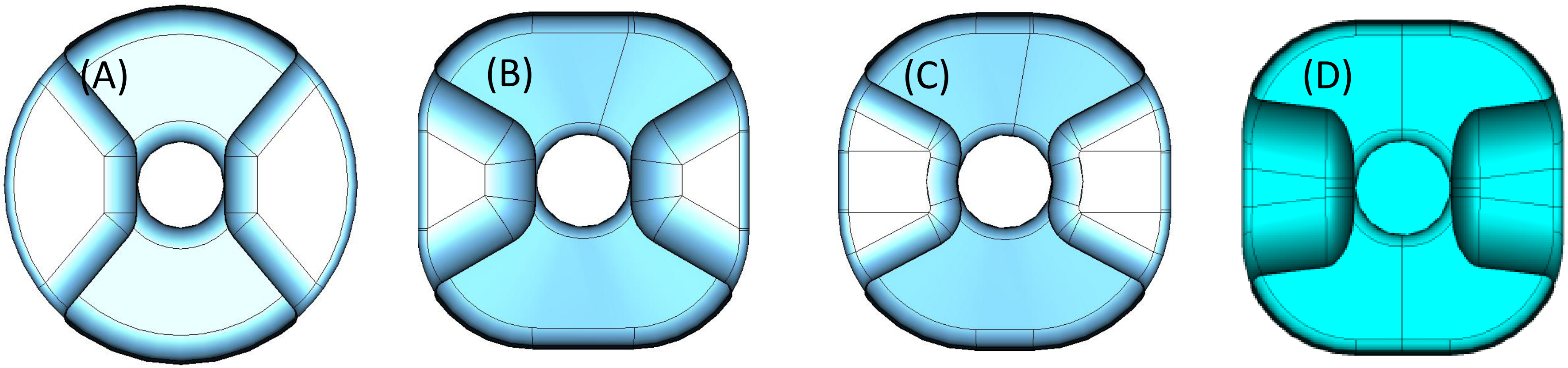
# Field Distribution / Surface Fields

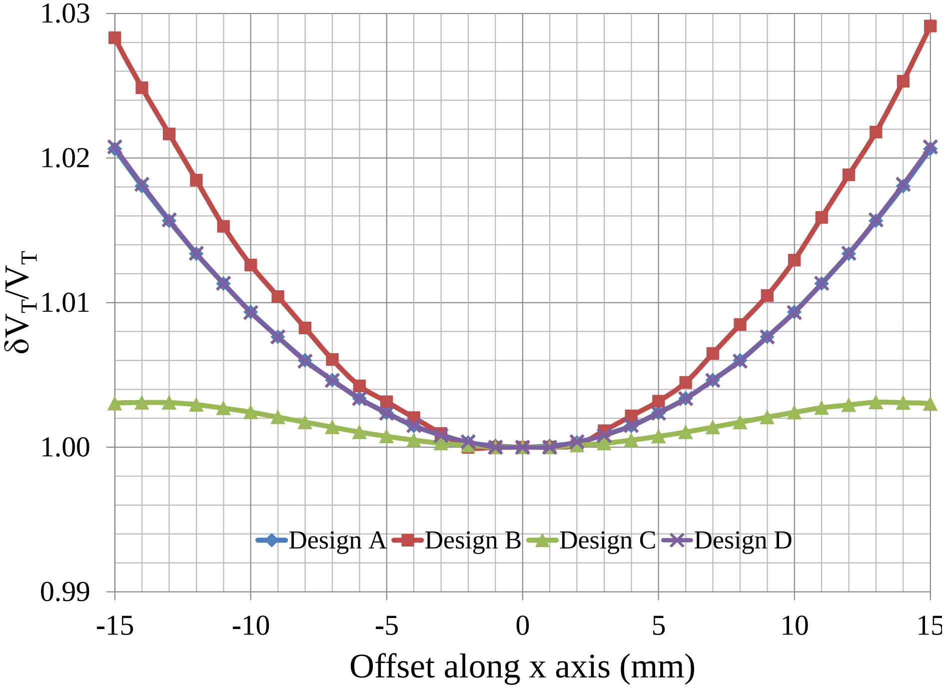
E Field | H Field | Peak E Field | Peak H Field

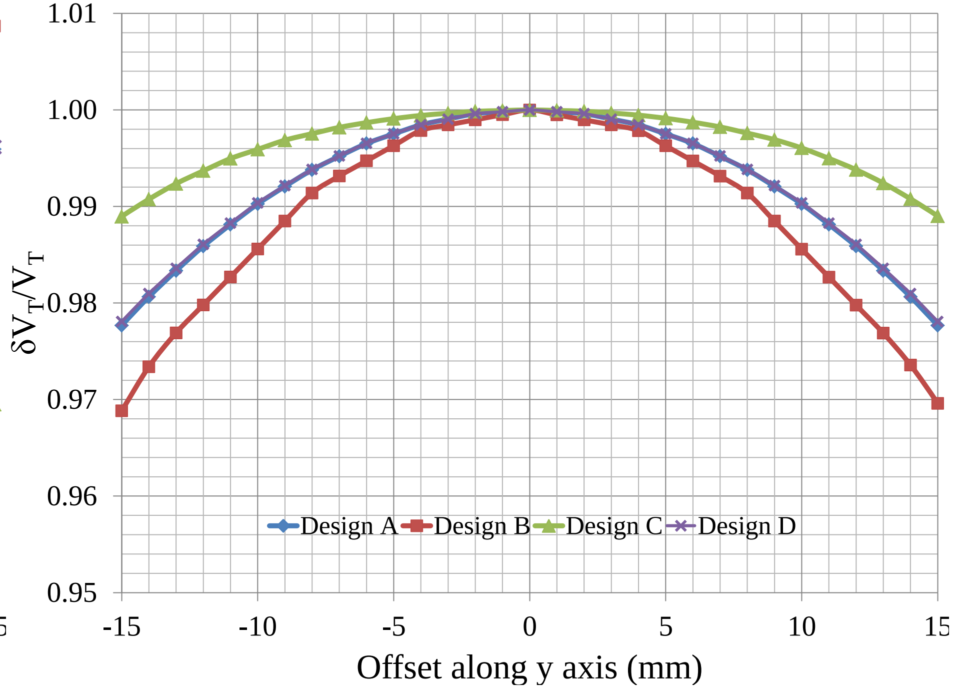


*S. De Silva, ODU 2012.

# Field Non-Uniformity



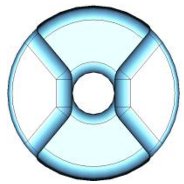
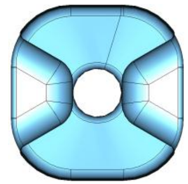
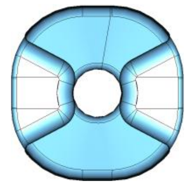
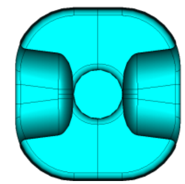




*S. De Silva, ODU 2012.

# Power Dissipation

- Surface resistance of Nb at 400 MHz
  - 4.5K: 95 nΩ→105 nΩ
  - 2K: 1.3 nΩ→10 nΩ

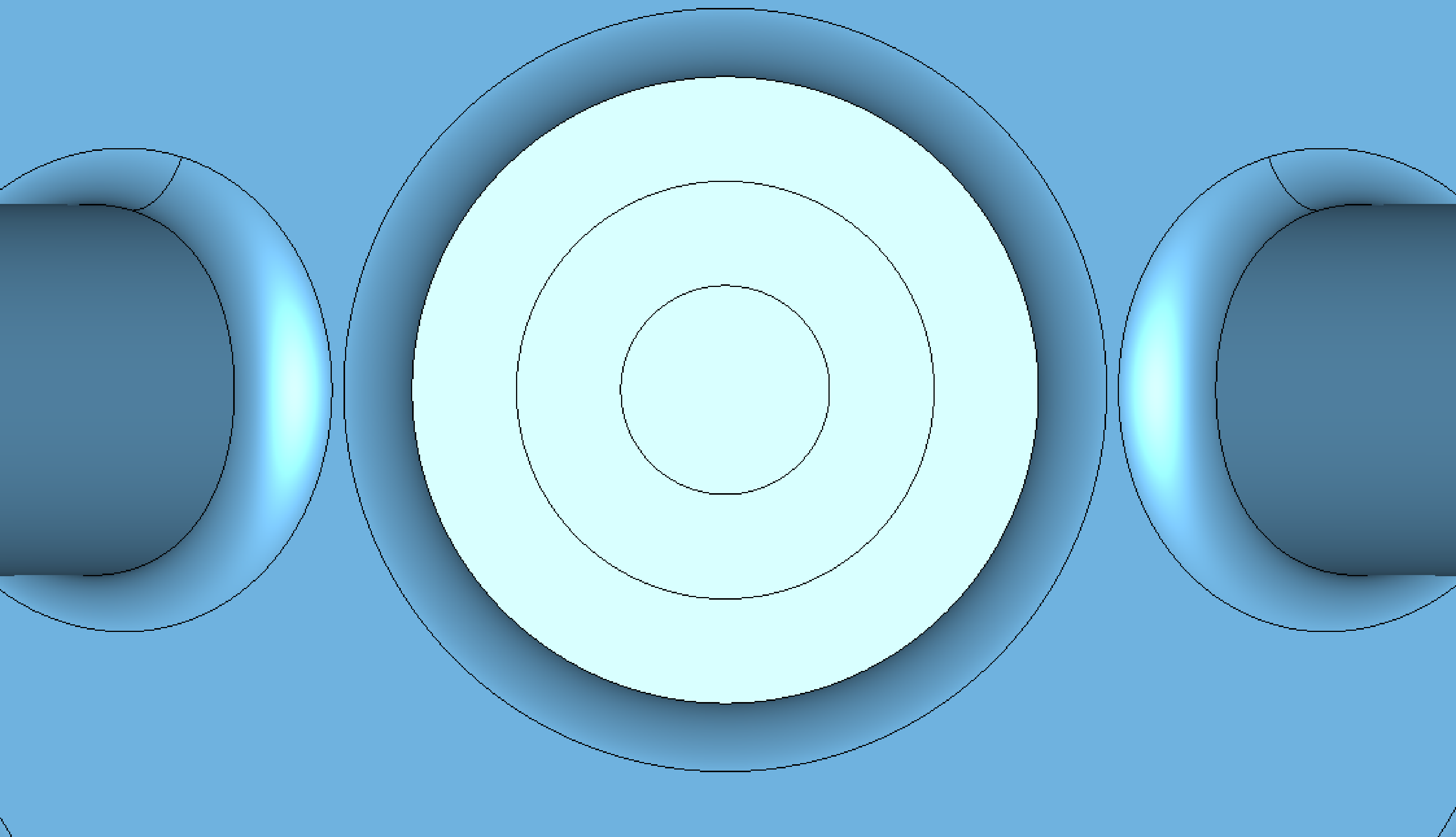
$$P = \frac{V^2}{(QR_s)(R/Q)} R_s$$

| **Parameter** |  |  |  |  | **Unit** |
|---|---|---|---|---|---|
| Deflecting voltage ($V_T^*$) | 0.375 | 0.375 | 0.375 | 0.375 | MV |
| Peak electric field ($E_P^*$) | 3.82 | 3.86 | 4.23 | 3.75 | MV/m |
| Peak magnetic field ($B_P^*$) | 7.09 | 6.9 | 7.69 | 6.85 | mT |
| $B_P^* / E_P^*$ | 1.86 | 1.79 | 1.82 | 1.83 | mT / (MV/m) |
| $E_P$ at 3 MV | 30.6 | 30.9 | 33.8 | 30.0 | MV |
| $B_P$ at 3 MV | 56.7 | 55.2 | 61.5 | 54.8 | mT |
| $E_P$ at 5 MV | 51.3 | 51.5 | 56.4 | 50.0 | MV |
| $B_P$ at 5 MV | 94.5 | 92.0 | 102.5 | 91.3 | mT |
| $R_T R_S$ | $3.7\times10^4$ | $3.6\times10^4$ | $3.7\times10^4$ | $5.1\times10^4$ | $\Omega^2$ |
| $P$ at 4.5K at 3 MV / 5 MV | 25.5 / 70.9 | 26.3 / 72.9 | 25.5 / 70.9 | 18.5 / 51.5 | W |
| $P$ at 2K at 3 MV / 5 MV | 2.4 / 6.8 | 2.5 / 6.9 | 2.4 / 6.8 | 1.8 / 4.9 | W |
| At $E_T^*$ = 1 MV/m | | | | | |

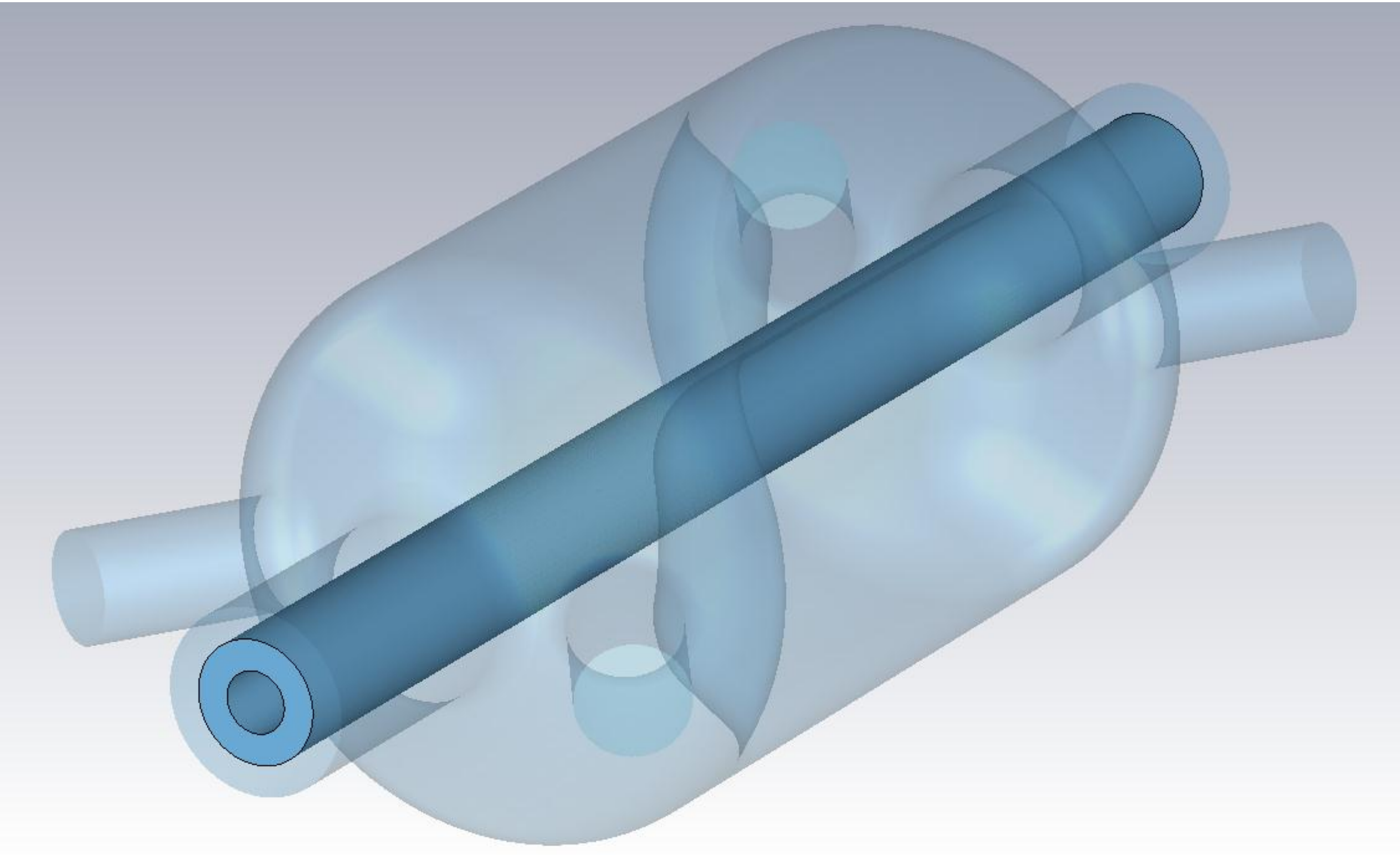
*S. De Silva, ODU 2012.

# Multipole Expansion

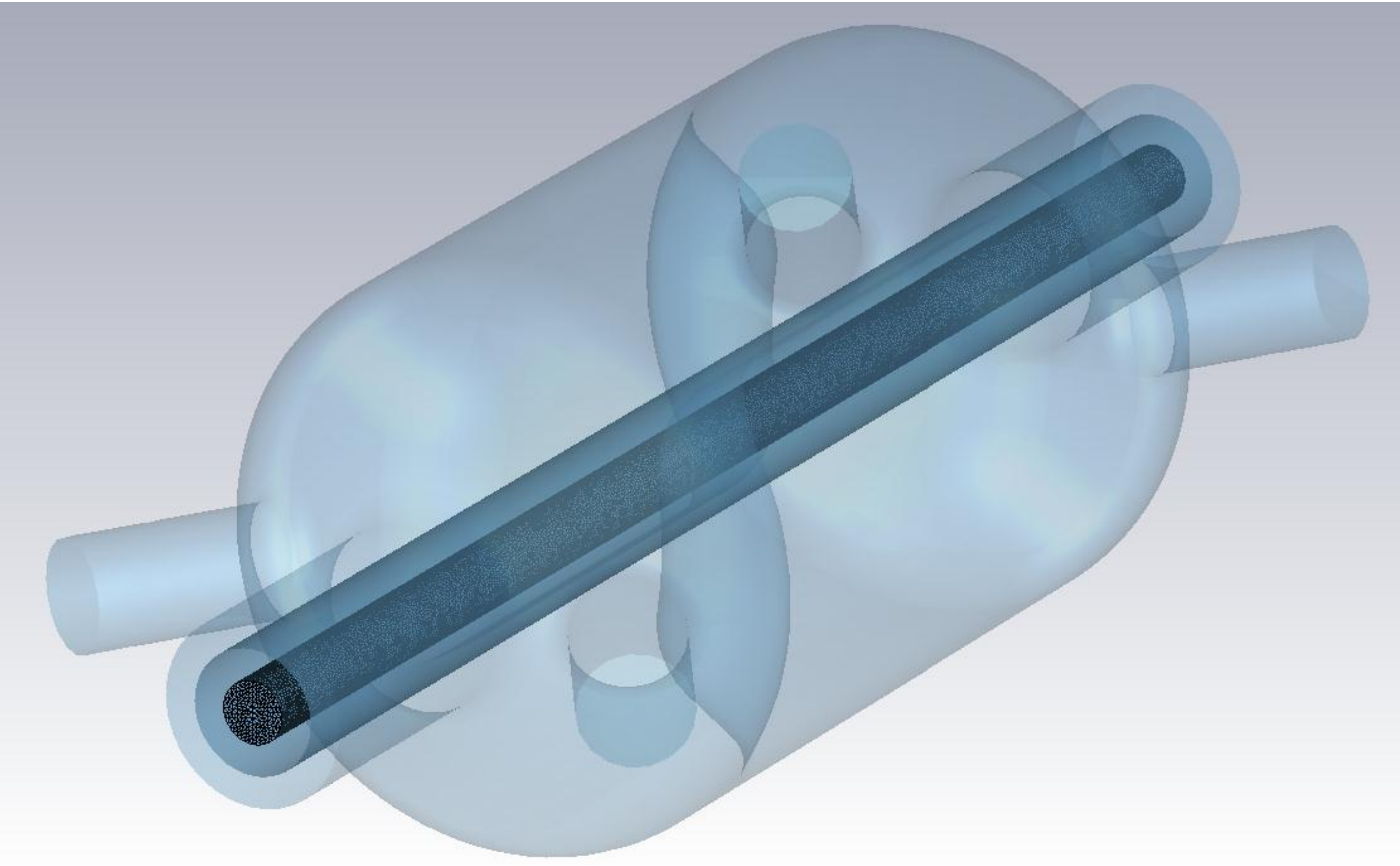
$$E(r,\phi,z) = \sum_{\mu} E_{\mu}(r,z)\cos(\mu\phi)$$



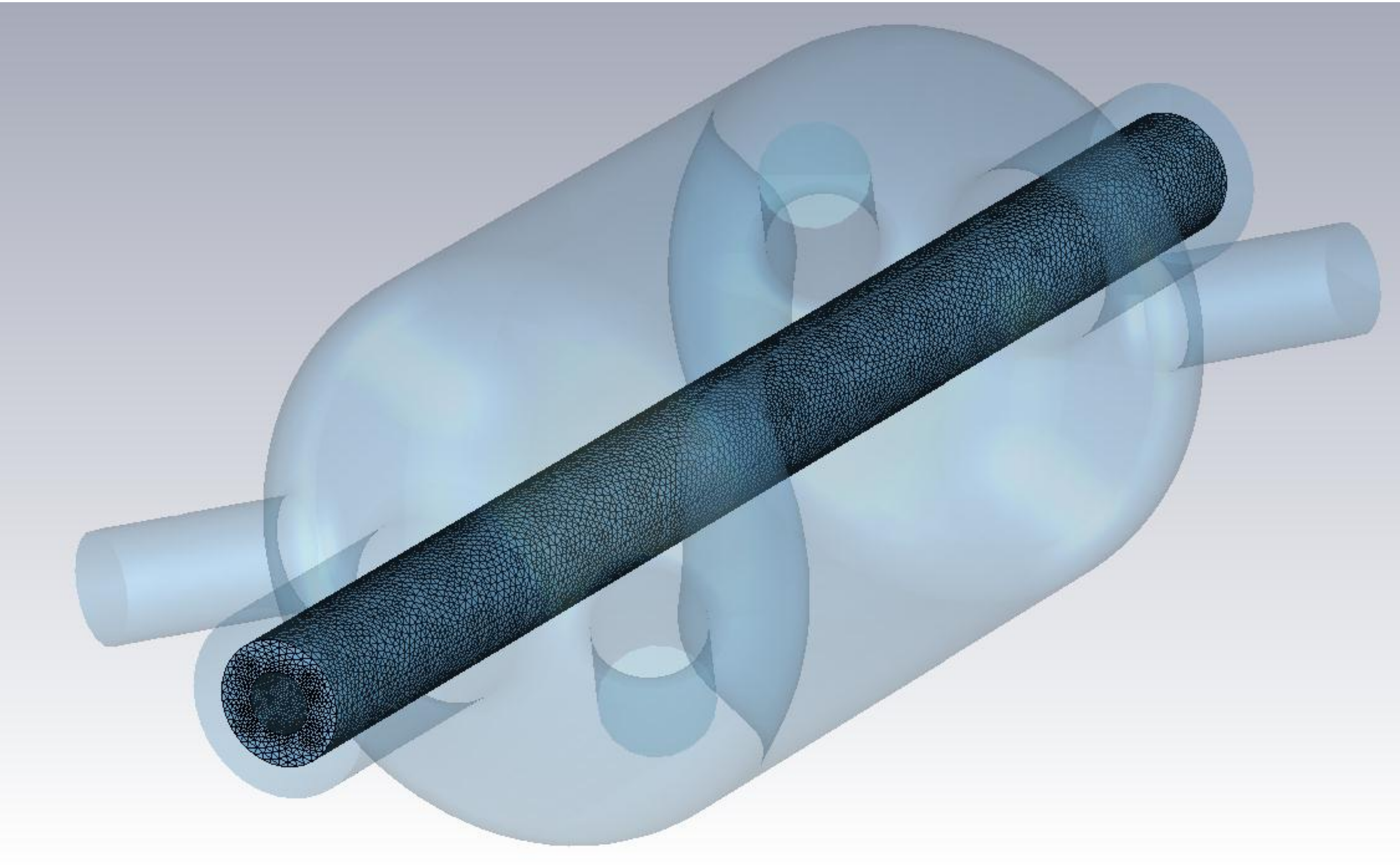
# Multipole Expansion



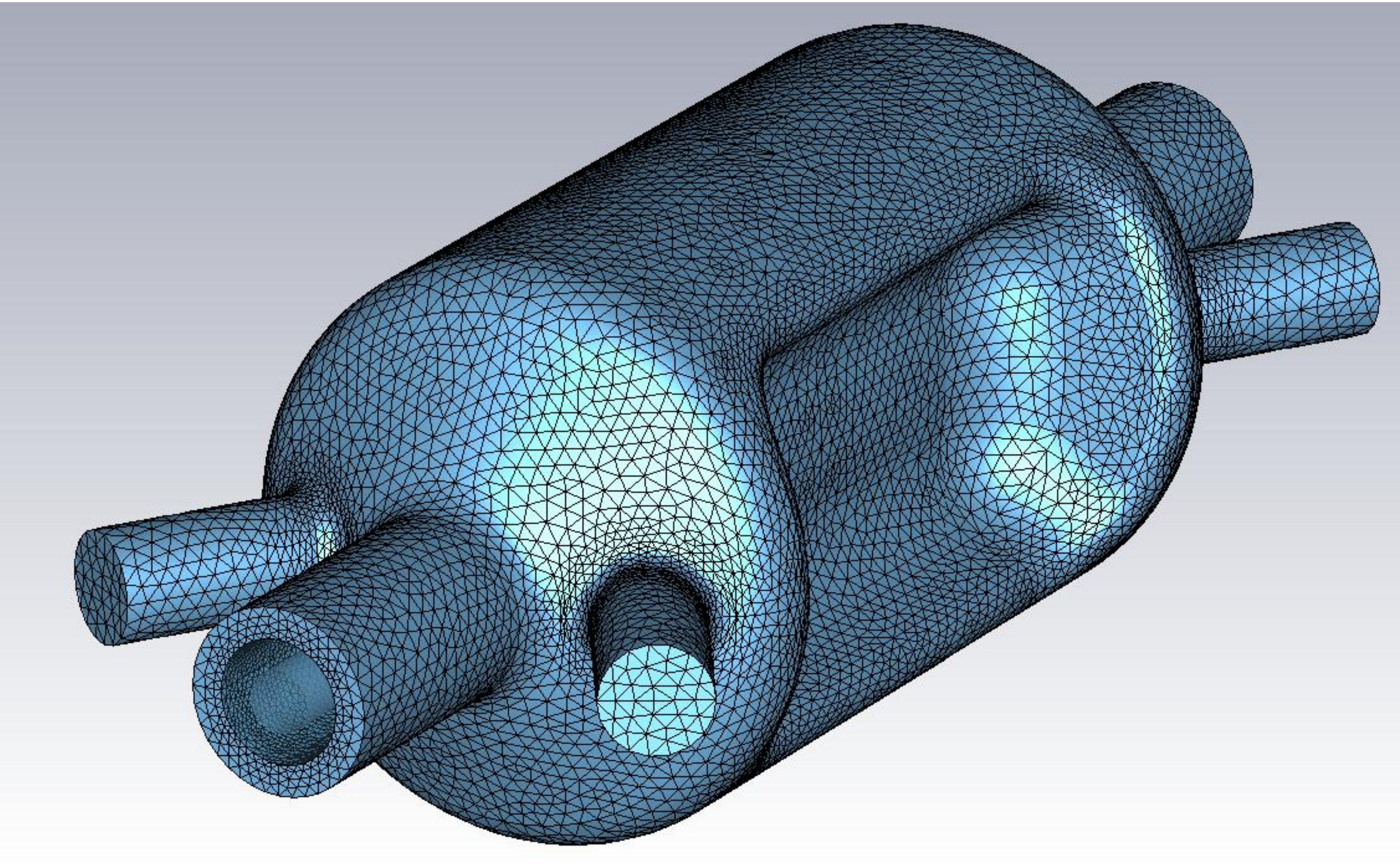
# Multipole Expansion



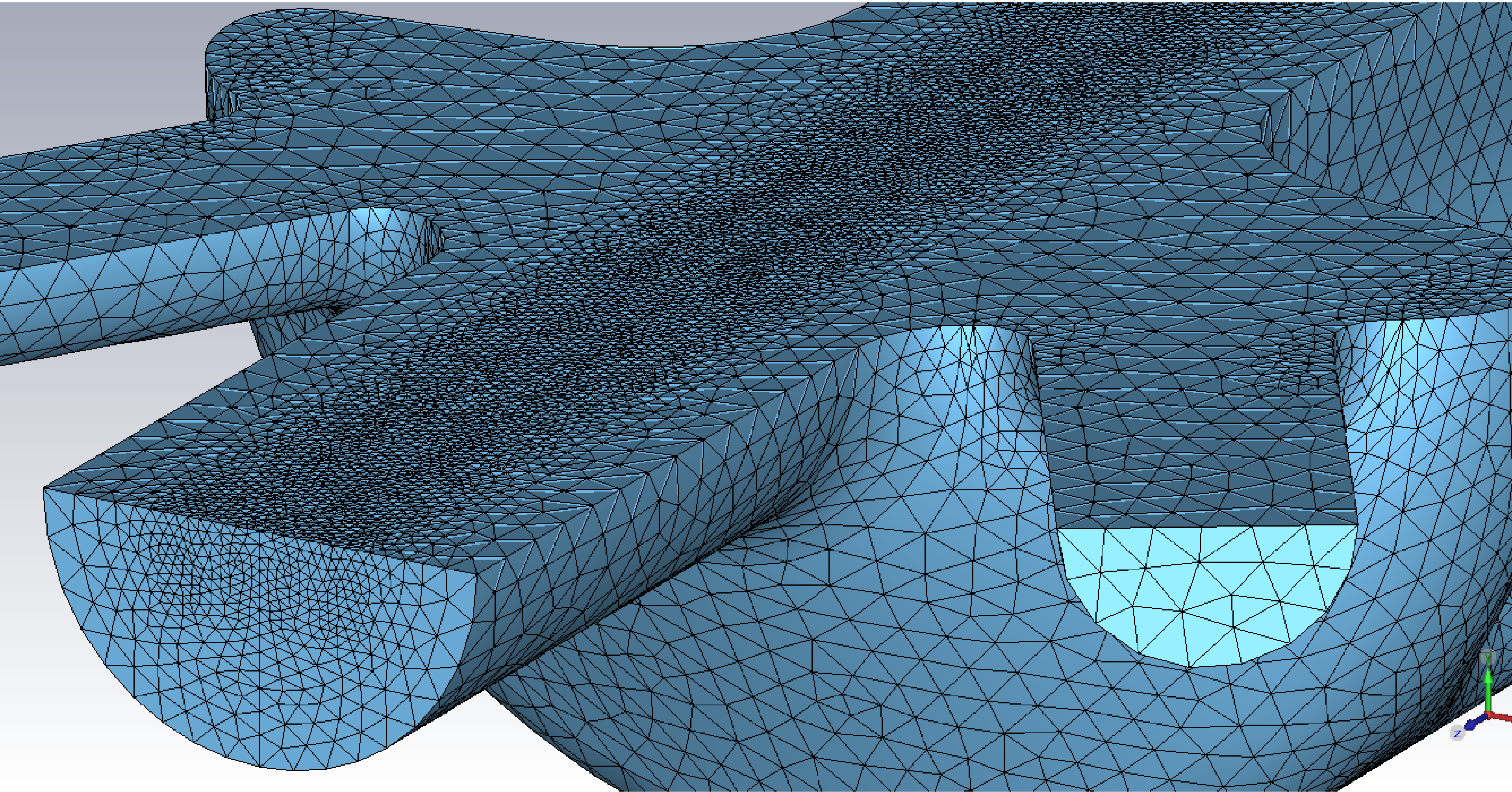
# Multipole Expansion



# Multipole Expansion

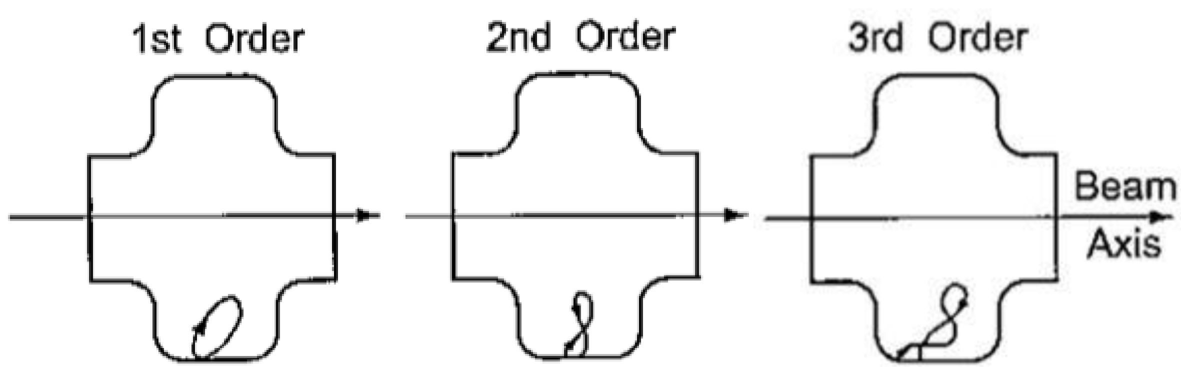


# Multipole Expansion



# Multipacting

- Multipacting mechanism:
  - Electron emitted from a surface due to: cosmic ray, photoemission, or field emission.
  - It is accelerated by the RF fields, impacts a wall again, and may produce secondary electrons.
  - Secondary electrons are accelerated and, upon impact, produce another electrons.
  - As a result, the avalanche of electrons may be generated.




*Ilkyoung Shin, Jlab 2012.

# Multipacting

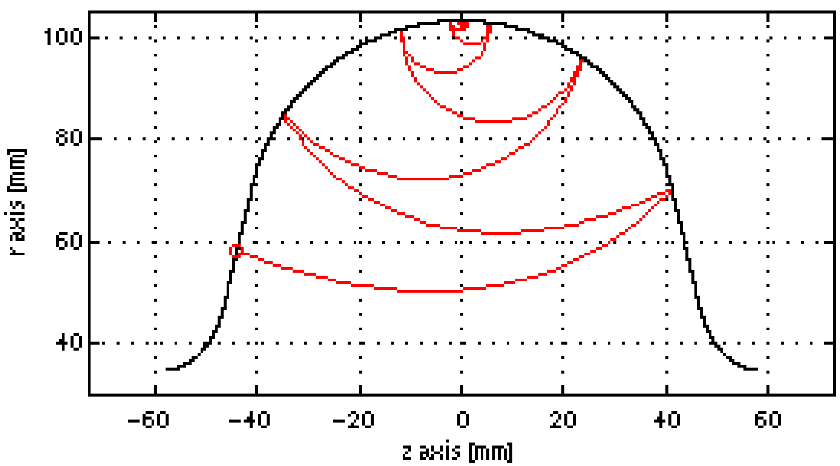
- RF power loss due to multipacting electrons
  - The undesirable multipacting electrons absorb the RF power.

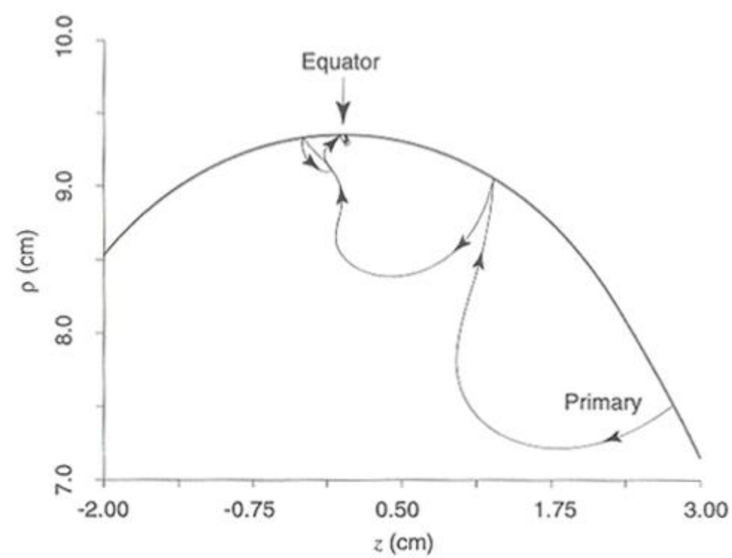
- One mechanism of thermal breakdown in superconductor
  - The electrons collide with cavity walls.
  - The collisions lead to a large temperature rise.
  - Temperature rise causes thermal breakdown in superconductor.

*Ilkyoung Shin, Jlab 2012.

# How to avoid Multipacting (Elliptical Shape)

- The multipacting electrons drift to the equator.
- At the equator, $E_\perp$ vanishes.
- The electrons do not gain any energy.

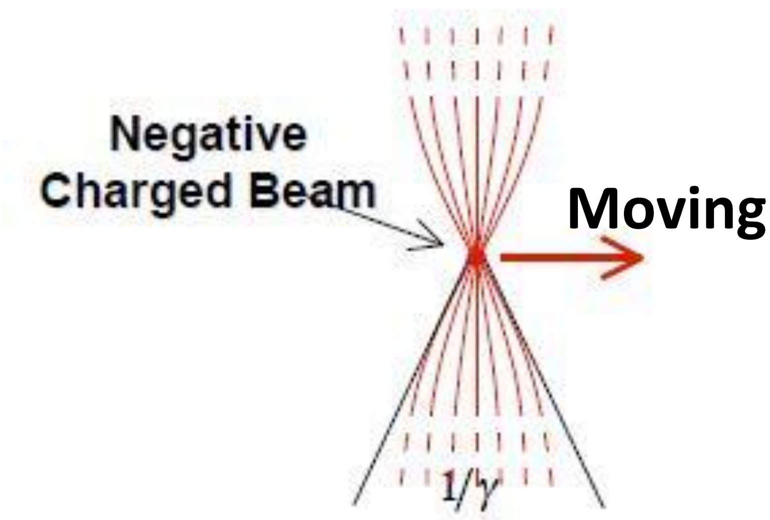


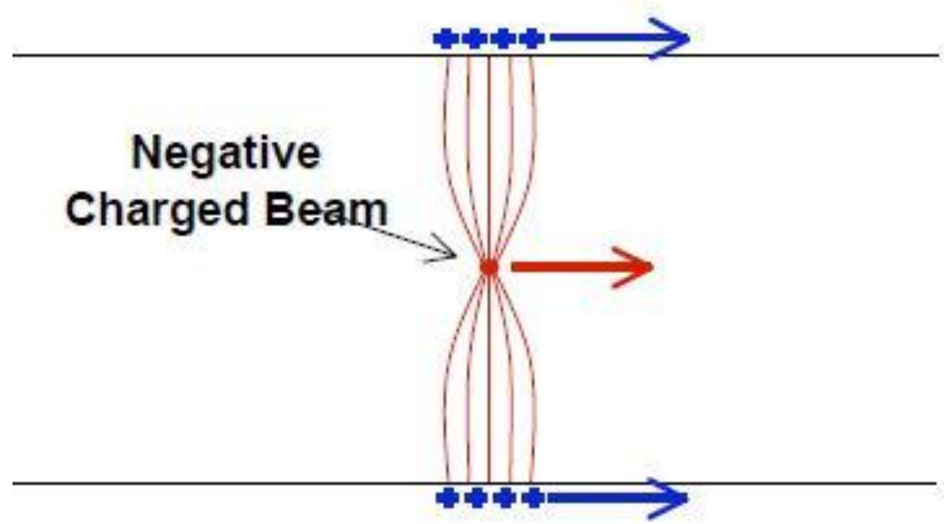

*Ilkyoung Shin, Jlab 2012.

# Wakefields

- Electromagnetic field of a relativistic particle
  - In the lab frame, the electric field of a relativistic particle is transversely confined within a cone of aperture of ~1/γ .



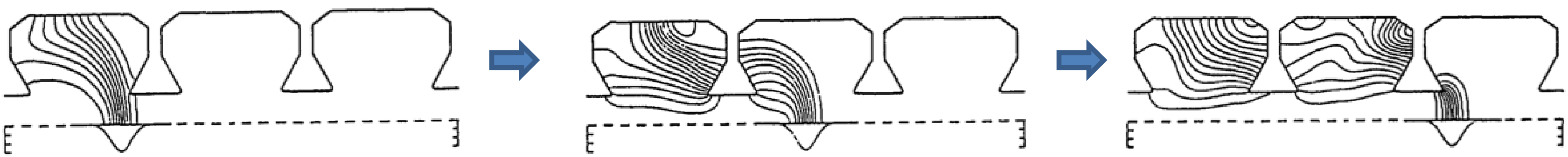

Electric Field



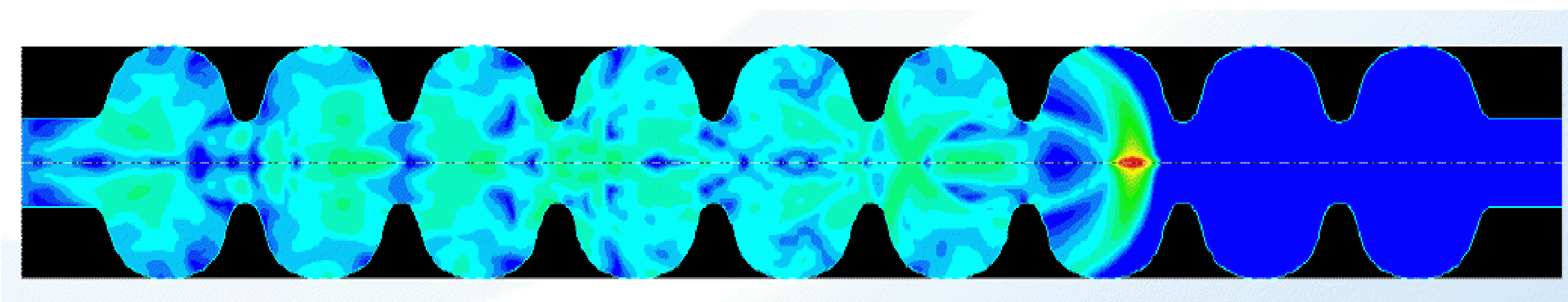

*John Byrd, Mexican Accelerator School 2011.

# Wakefields

- Wakefield: Charged particles interact with surroundings and leave wakefields behind.



Numerically calculated electric wakefields by an ultra-relativistic Gaussian bunch



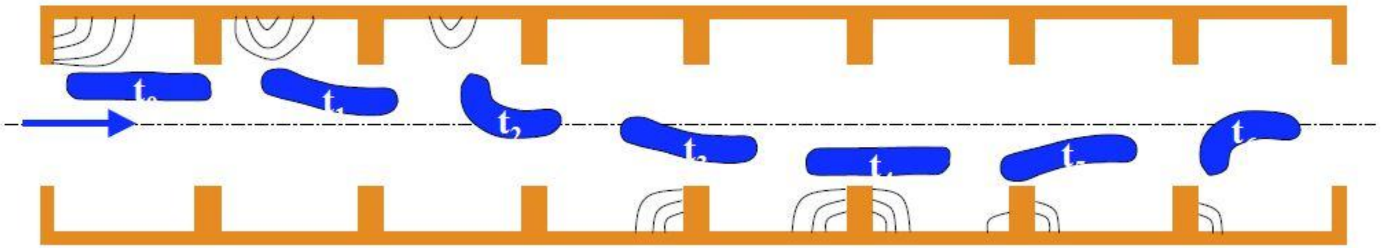
- **The wakefields manifest themselves as excitations of the resonant modes in the cavity.**



*Ilkyoung Shin, Jlab 2012.

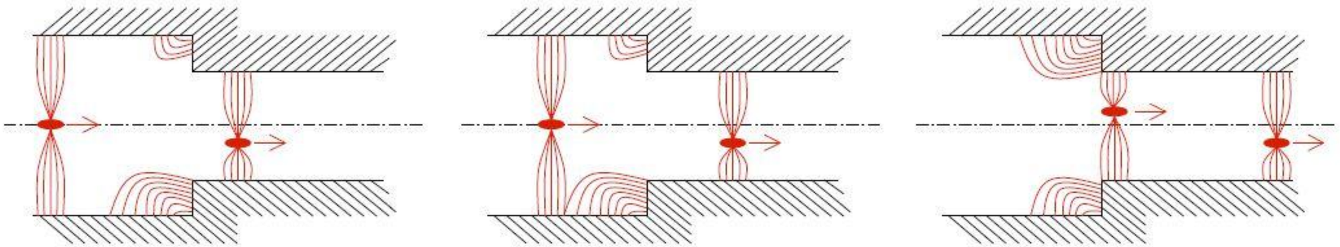
# Beam Instabilities

- Single bunch instability: Particles in the tail can interact with wakefields due to particles in the head.



Snapshots of a single bunch traversing a SLAC structure

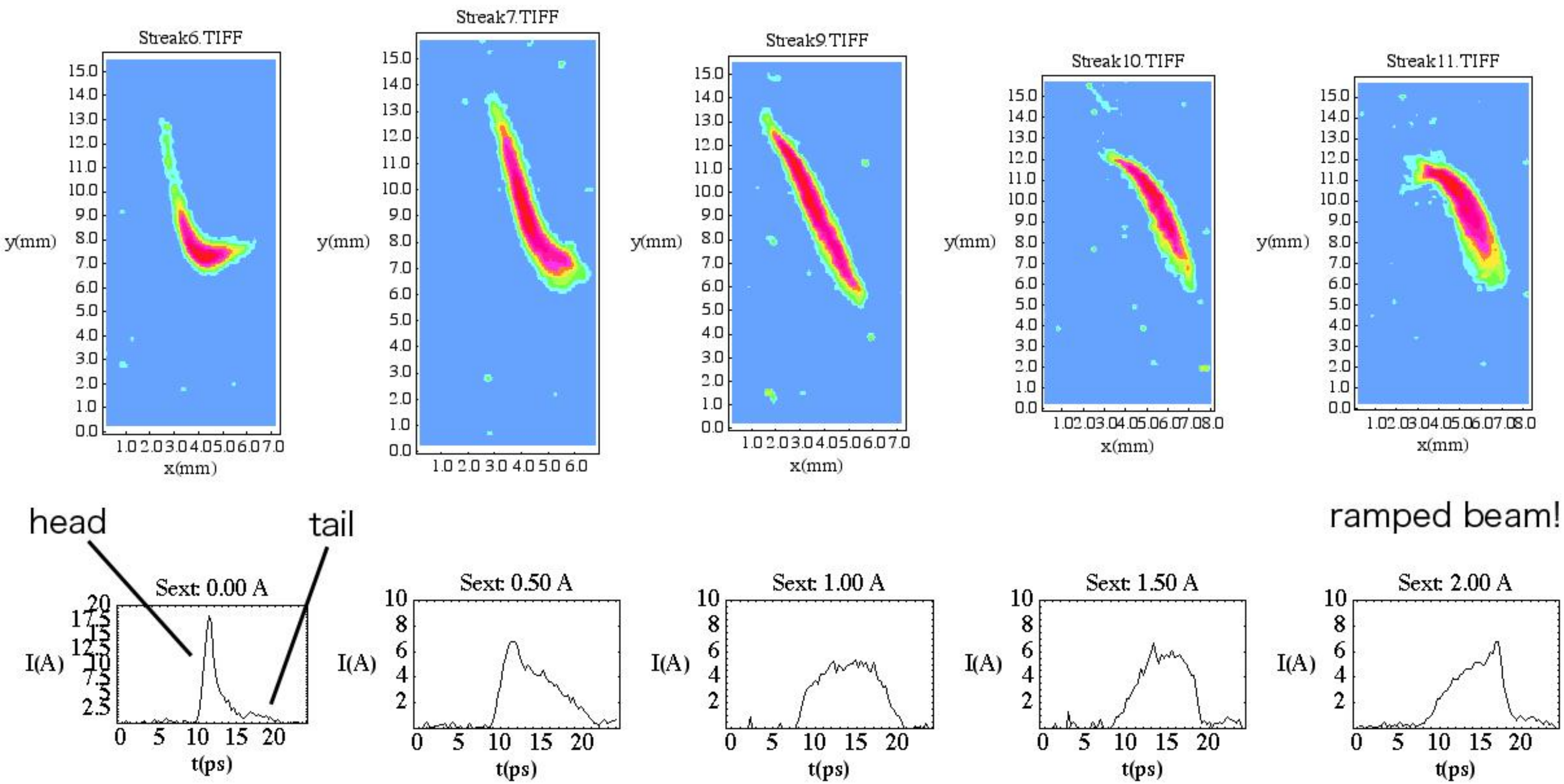
- Multibunch instability: Trailing bunches can interact with wakefields from leading bunches to generate multibunch instability.





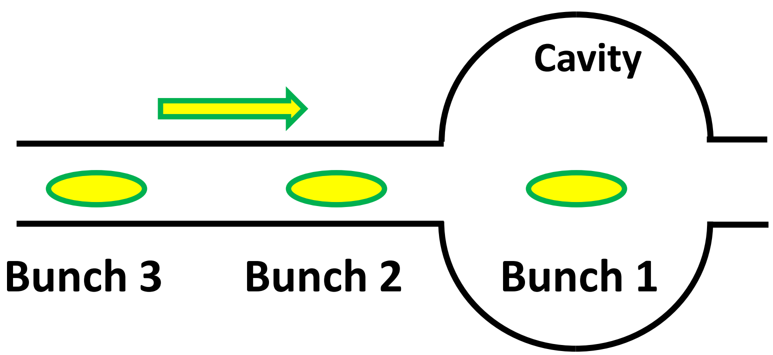
*Ilkyoung Shin, Jlab 2012.

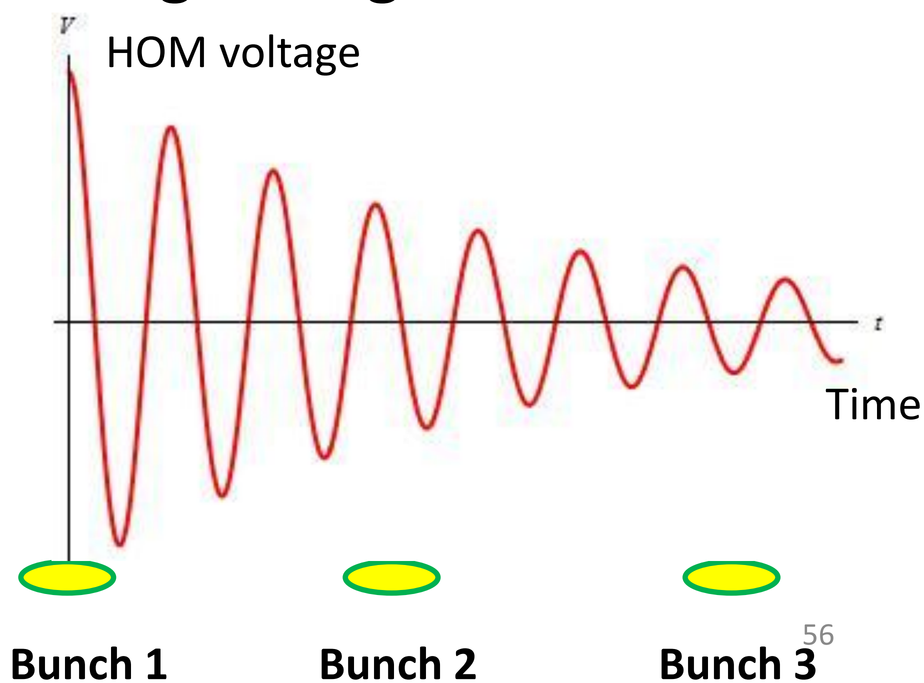
# Transversal Cross Section



# Beam Instability by HOMs

- A particle bunch excites HOMs which oscillate and decay by the cavity wall resistance.
- The trailing bunches or the same bunch on the next revolution see the HOMs oscillating in the cavity.
- The excited HOMs can be strong enough to cause instabilities on beam.

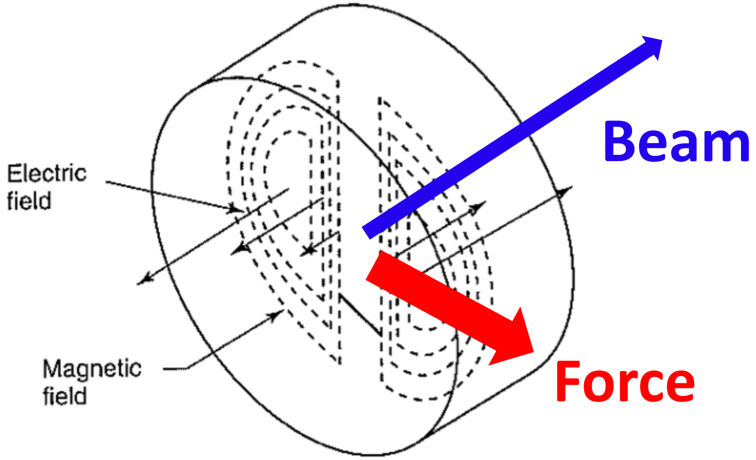


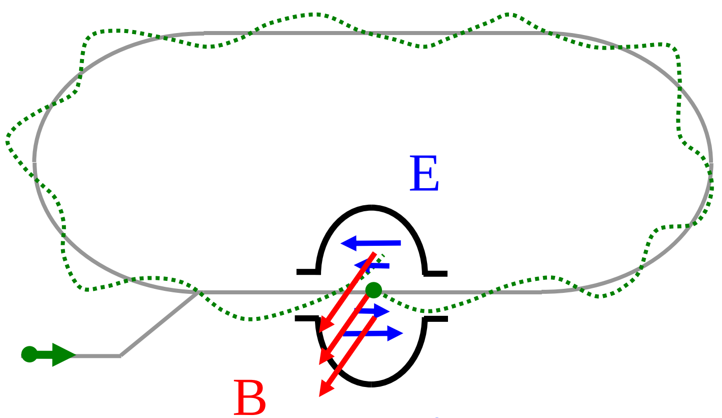

*Ilkyoung Shin, Jlab 2012.

# Multipass Beam Instability

- A positive feedback between the recirculated beam and the HOM which kicked the beam on the previous pass
  - A positive feedback enhances the HOM field.
  - The enhanced HOM kicks the next bunch harder.
- Beam breakup (BBU)
  - Exponential increase of the HOM field
  - Beam loss if transverse displacement > physical aperture




$TM_{110}$ mode



# 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]

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

- 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)

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

**Types of Modes**

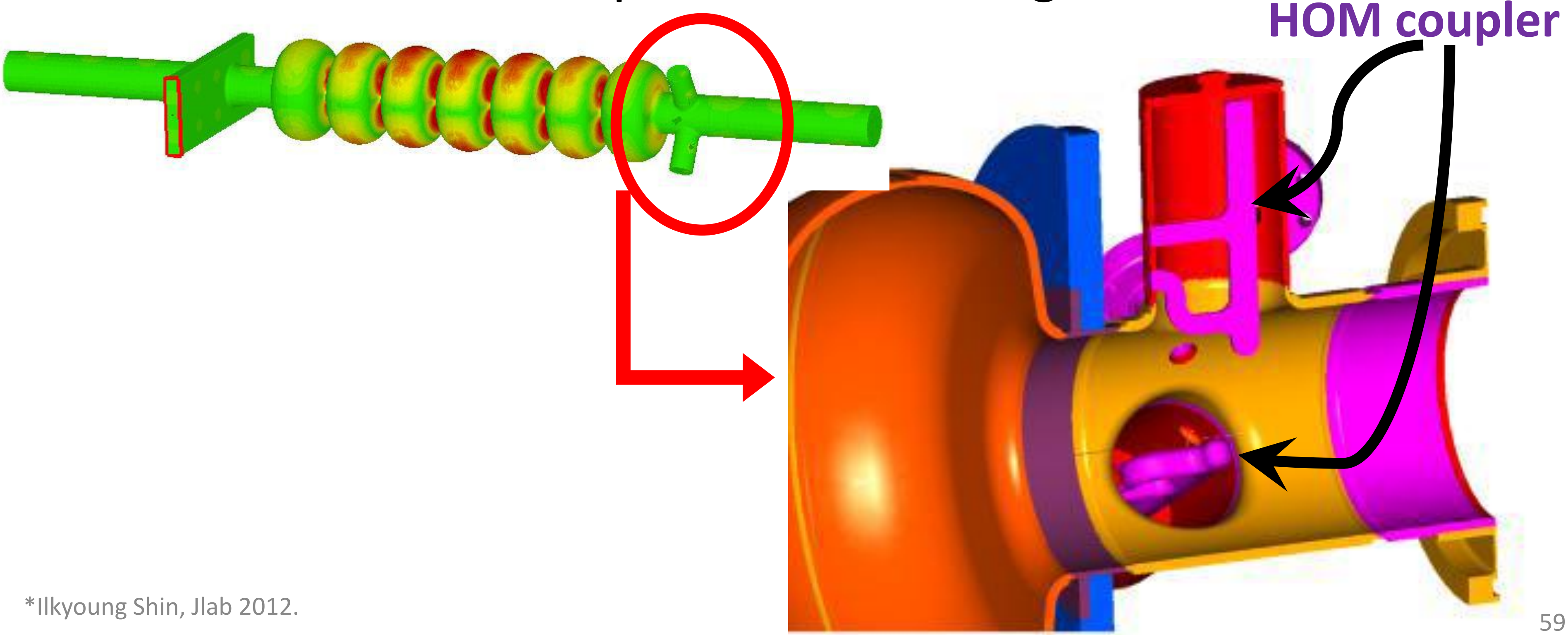
| Field on Beam Axis | Type of Mode |
|---|---|
| $E_x$, $H_y$ | Deflecting |
| $E_z$ | Accelerating |
| $E_y$, $H_x$ | Deflecting |
| $H_z$ | Does not couple to the beam |

**No Lower Order Modes**

*S. De Silva, ODU 2012.

# HOM damping

- HOM couplers
  - extract HOMs energy.
  - have to be broadband to cover the most HOMs.
  - should not damp the accelerating mode.




*Ilkyoung Shin, Jlab 2012.