QUANTRONICS LABORATORY
Department of Applied Physics
Yale University

Whispering Gallery Mode in a Parallel Plate Ring Resonator

Zlatko Minev

Michel H. Devoret

Ioan Pop

Nick Masluk

Archana Kamal

Thanks to:
Teresa Brecht
Matt Reagor
Yehan Liu
Uri Vool
QuLab
RSL Lab

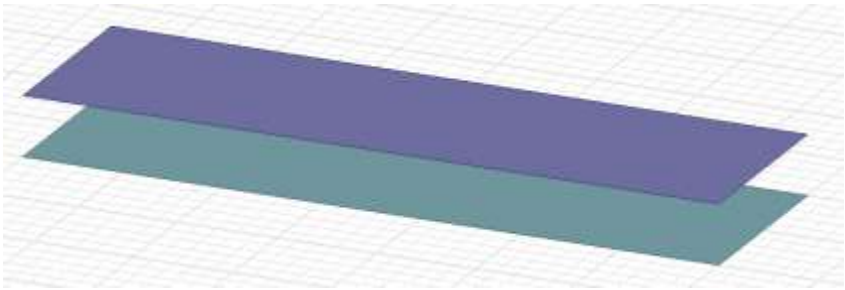
Desired Goals

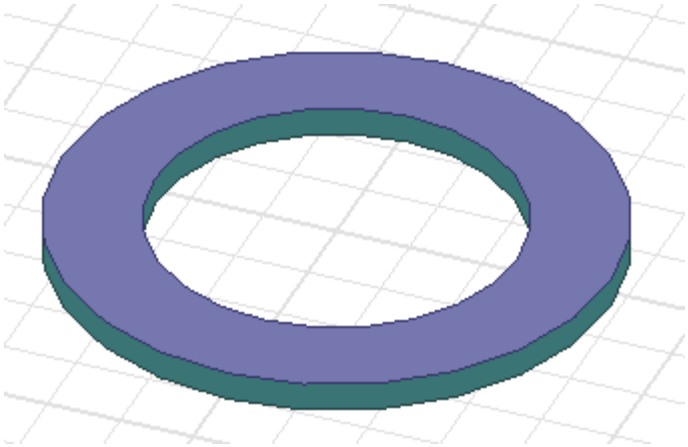
- ‘Wafer-Scalable‘ Circuit QED architecture
- Allow flux bias, copper cavity
- Study superconducting thin film quality factor

Means:

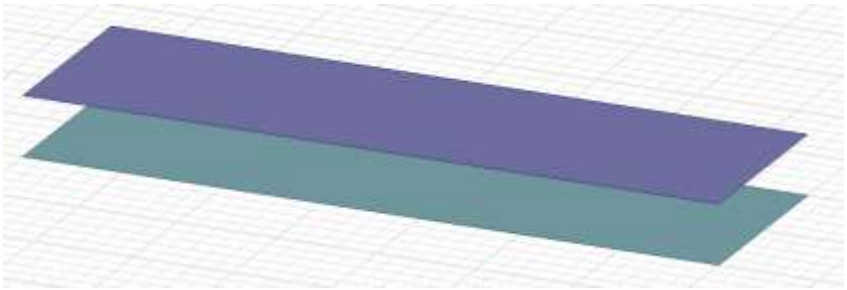
- Confine EM Waves in vacuum between patterned Aluminum films
  - Keep fields away from lossy dielectric and copper walls
  - Mode control
- Simple, robust geometry

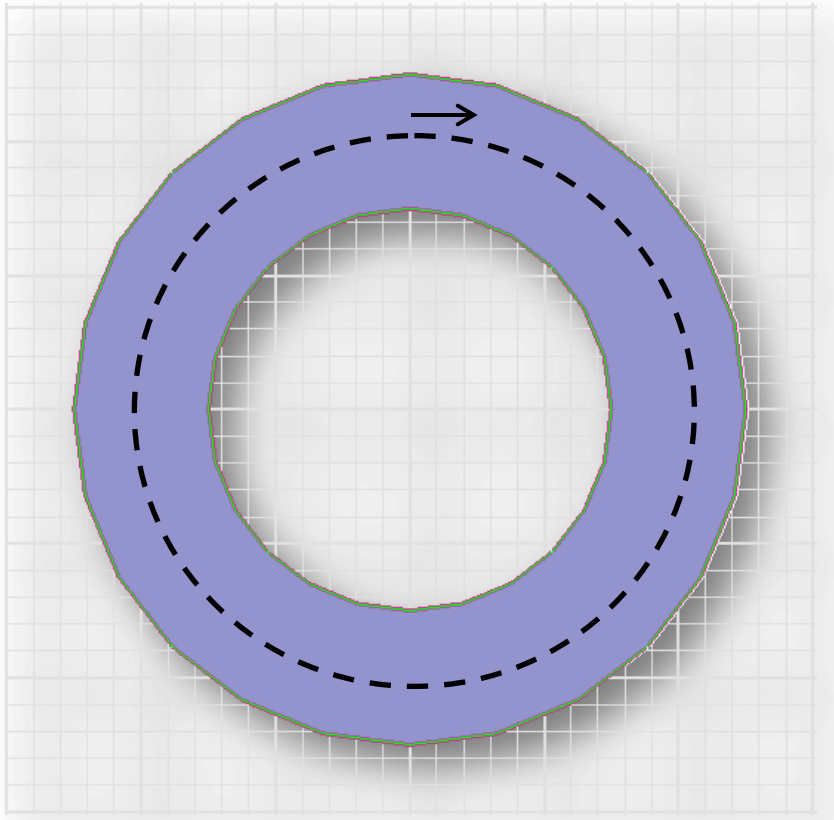
Transmission Line Ring



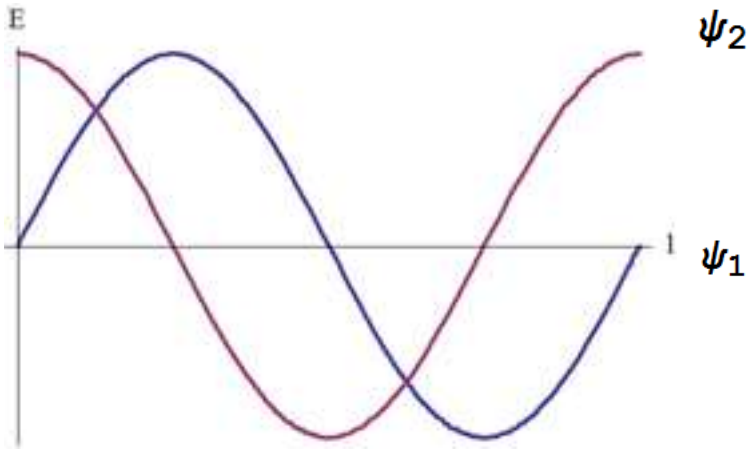


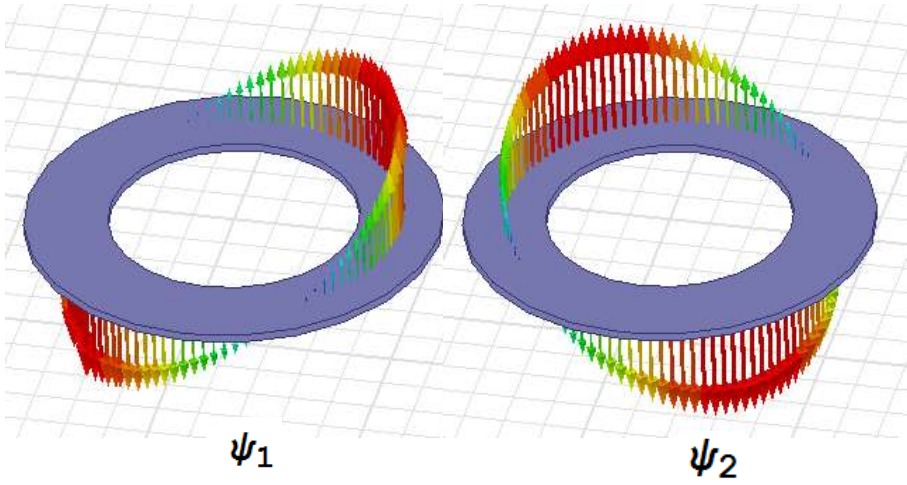
1D Description – 2 Degenerate Ground Modes



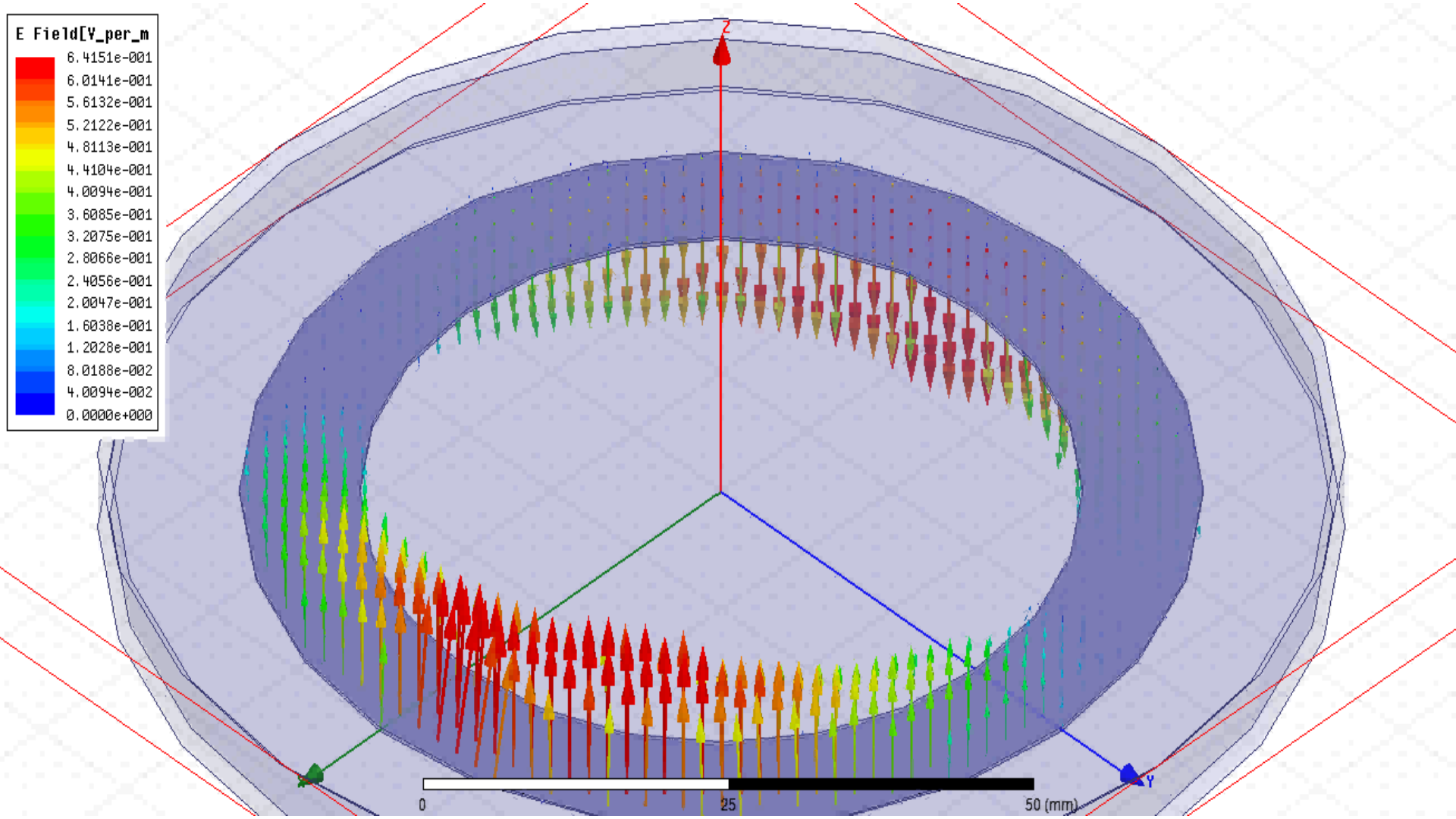


$$\nabla^2\psi + \frac{w^2}{c^2}(1 + \Delta n(x)^2)\psi = 0$$

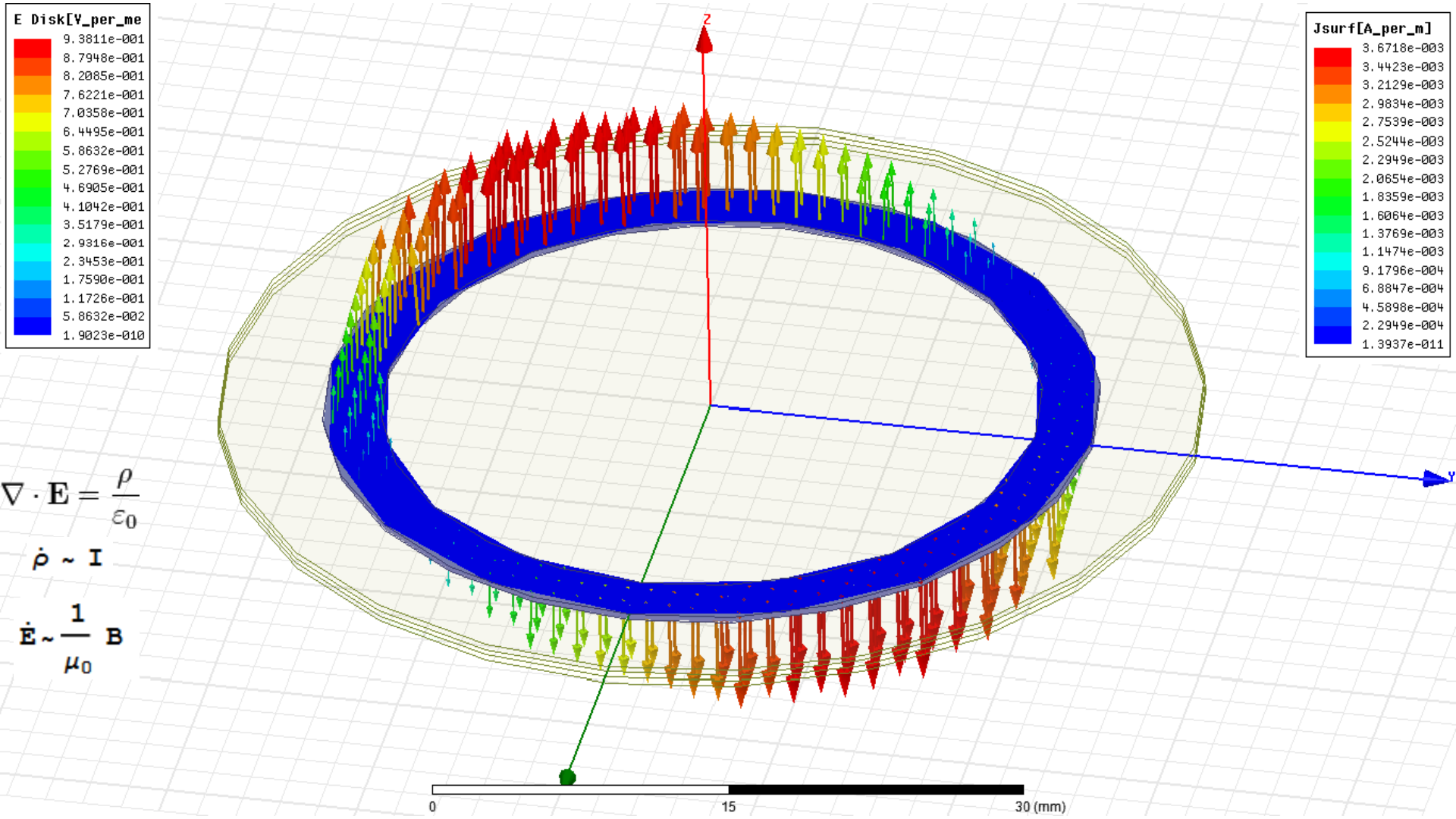




Whispering Gallery Mode



E & Current on Ring



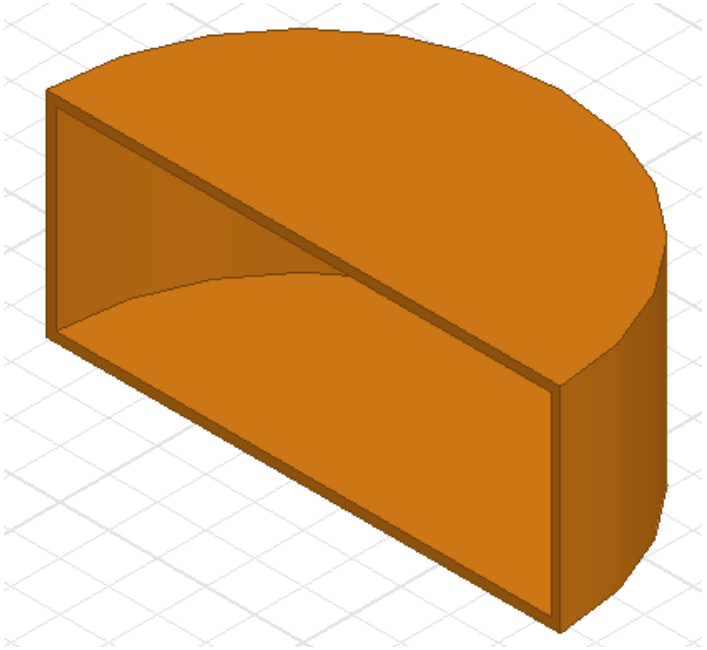
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\dot{\rho} \sim \mathbf{I}$$

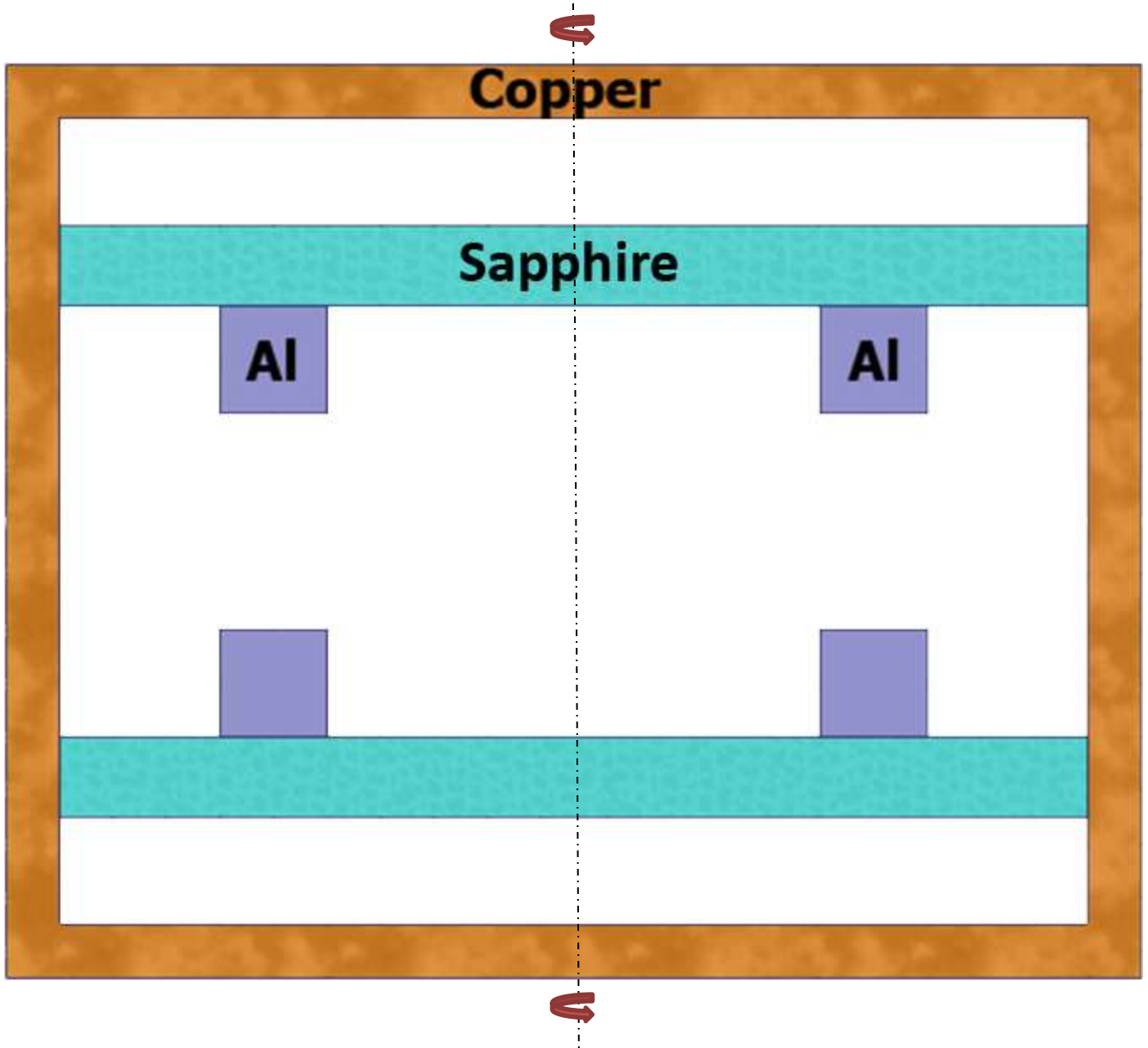
$$\dot{\mathbf{E}} \sim \frac{1}{\mu_0} \mathbf{B}$$

Cylindrical Sample Box (Cavity)

- Wafer imposed
  - Keep the lossy walls as far away as possible
- Cleaner machining
- Demonstrated high Q
- Simple mode structure



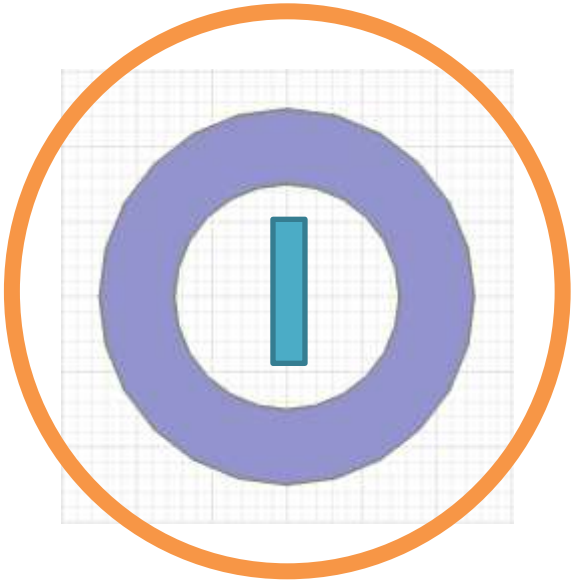
Geometry

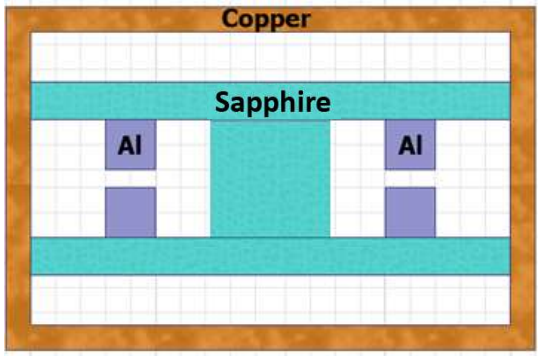


Not To Scale

Wafer Separation

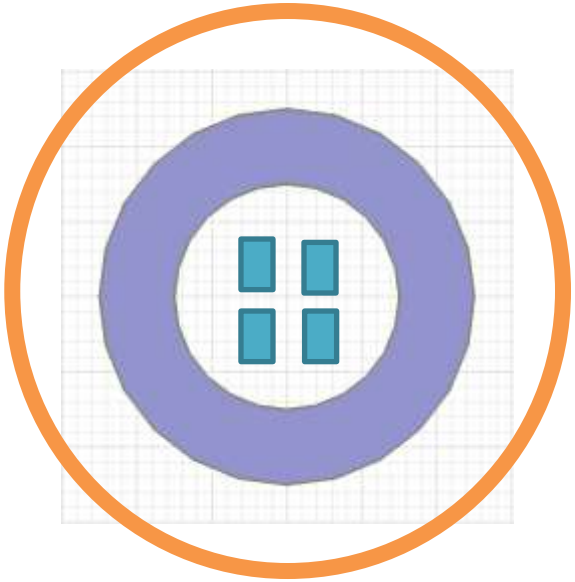
Sapphire Wafer Bits

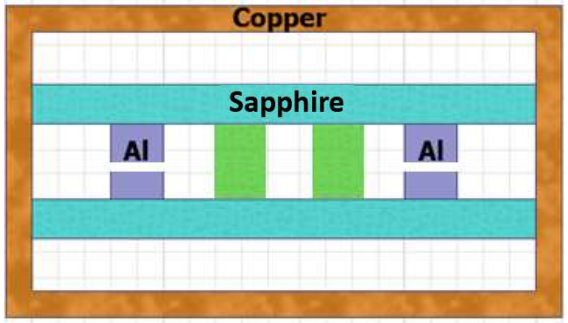




300um

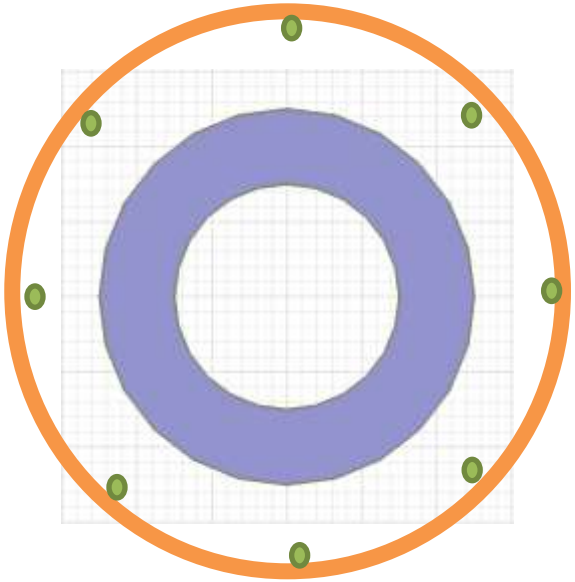
Resist & Newton Rings





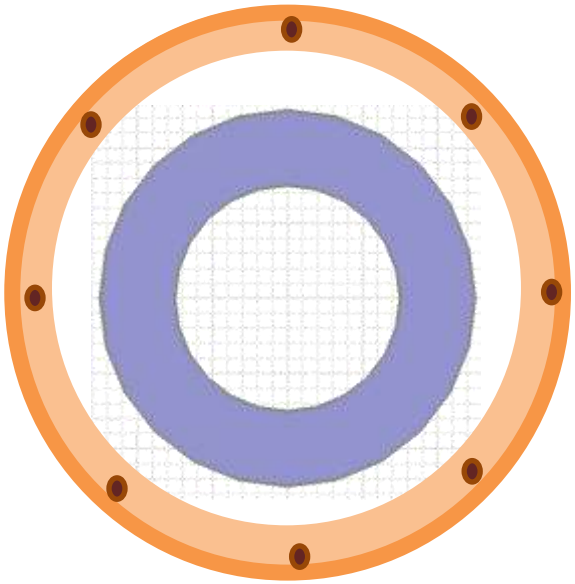
1-10um

Resist Spun Dots



1-10um

Harnessing Wafer in Cylinder with Springs



- Copper-Beryllium spring - Cryo-safe
- Indium Seal - good electrical contact between two halves

Physical Considerations

- Thermalizing Al
  - Reduce quasiparticles
  - Backing Aluminum with Copper film
- Dissipation via magnetic vortices
  - Chicken wire ring
- Alignment and tolerances
- Wafer separation
- Differential thermal contraction

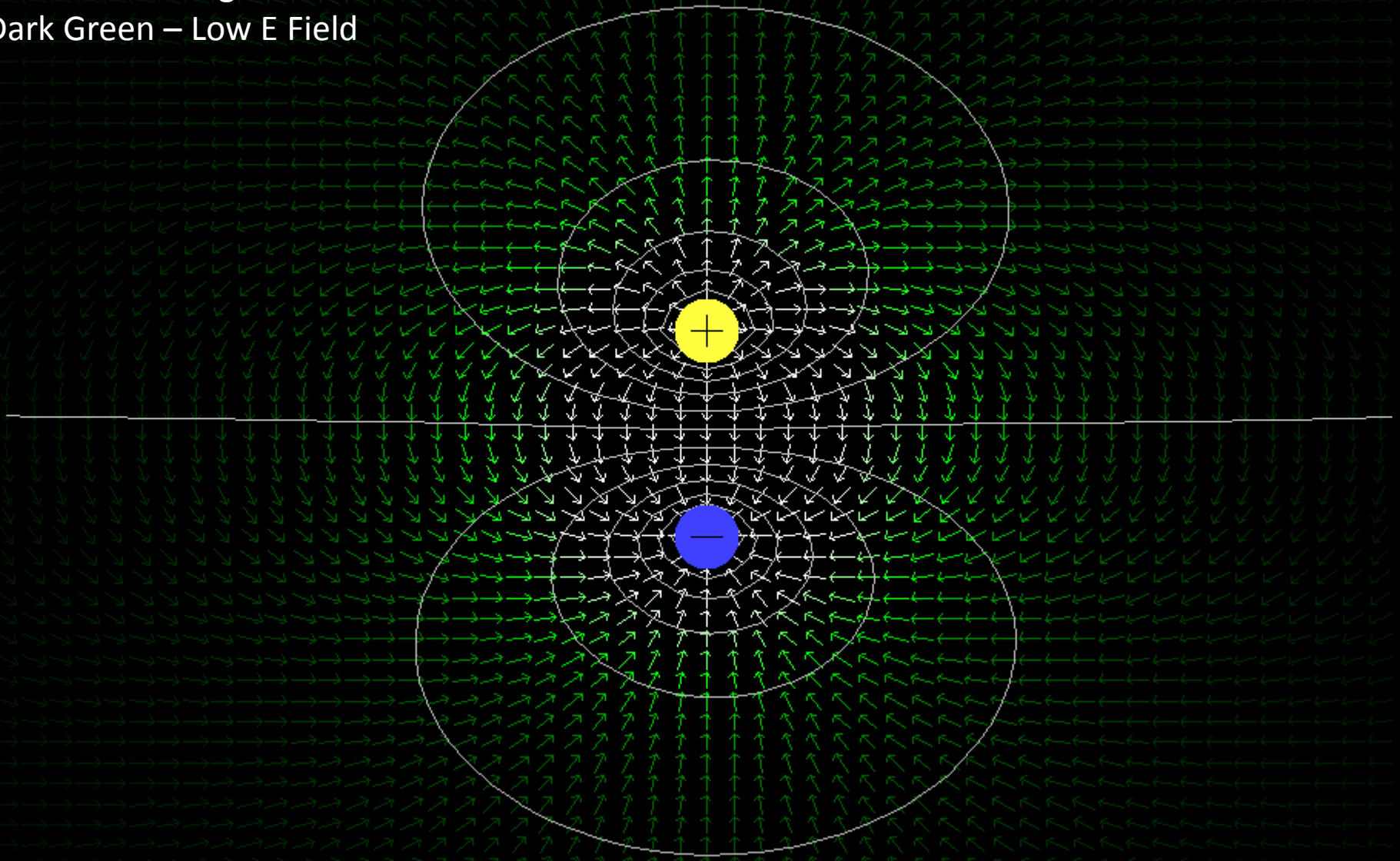
- Dielectric -
Simple Physical Picture

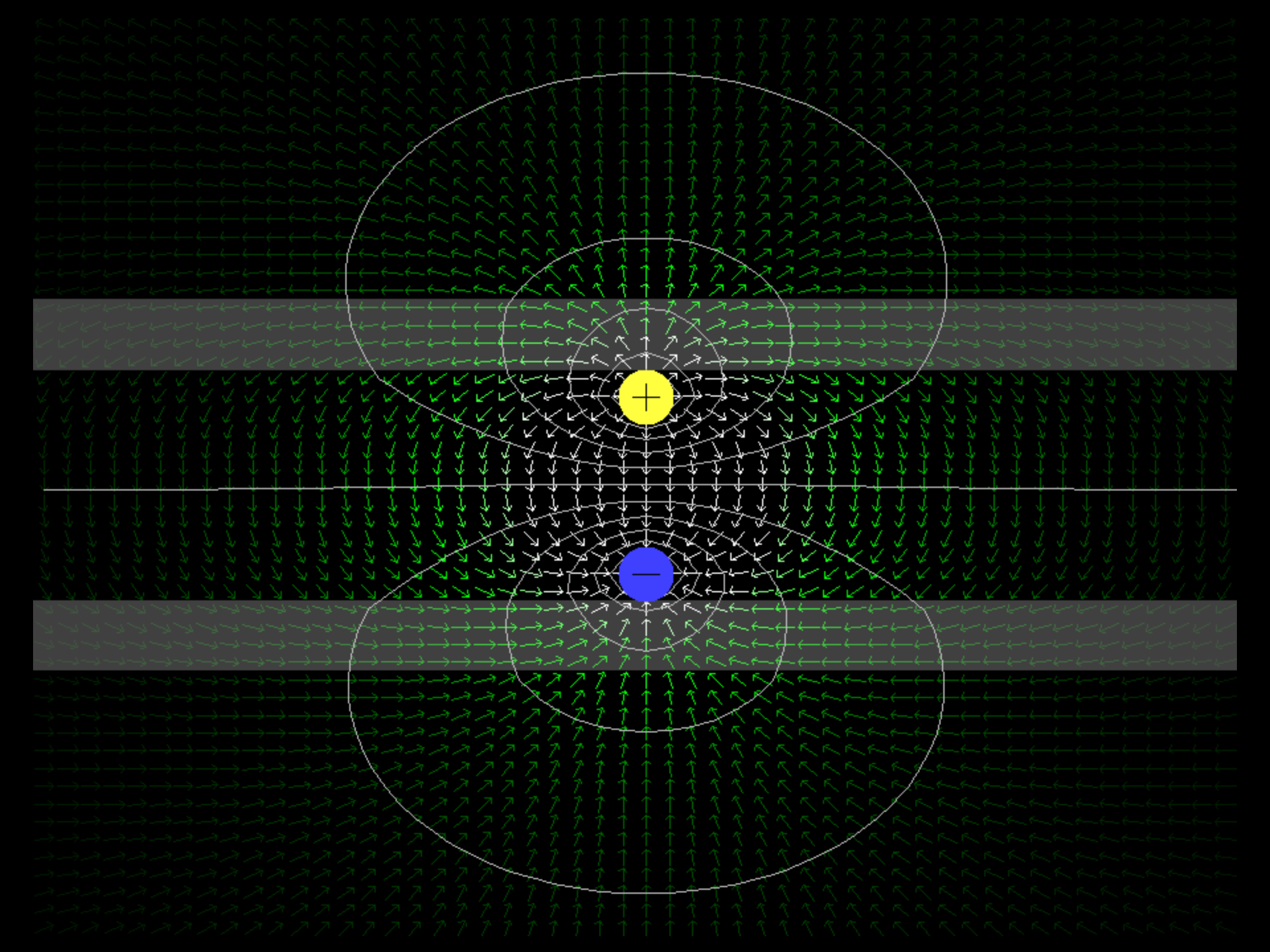
Yellow – Positive Charge

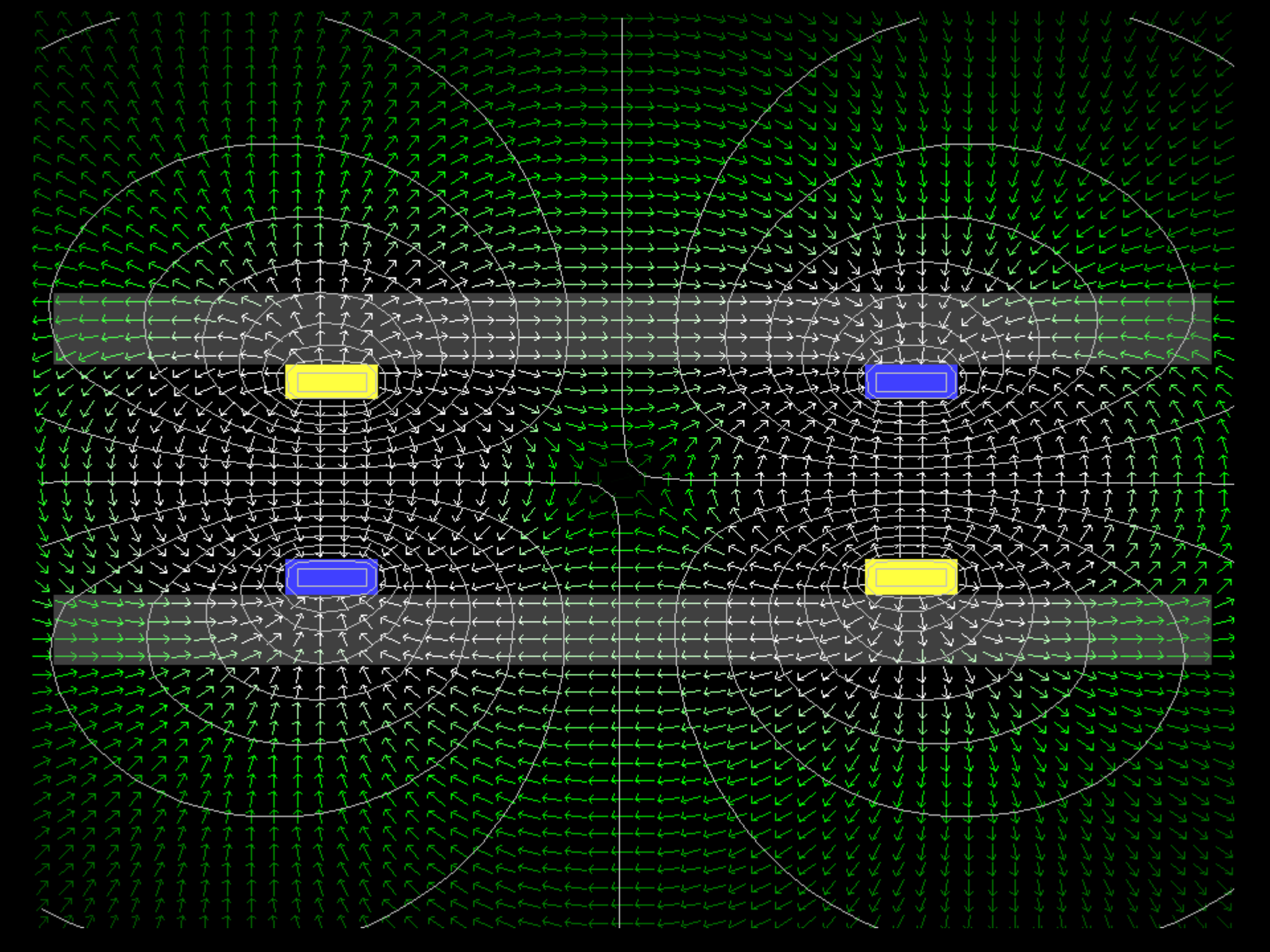
Blue – Negative Charge

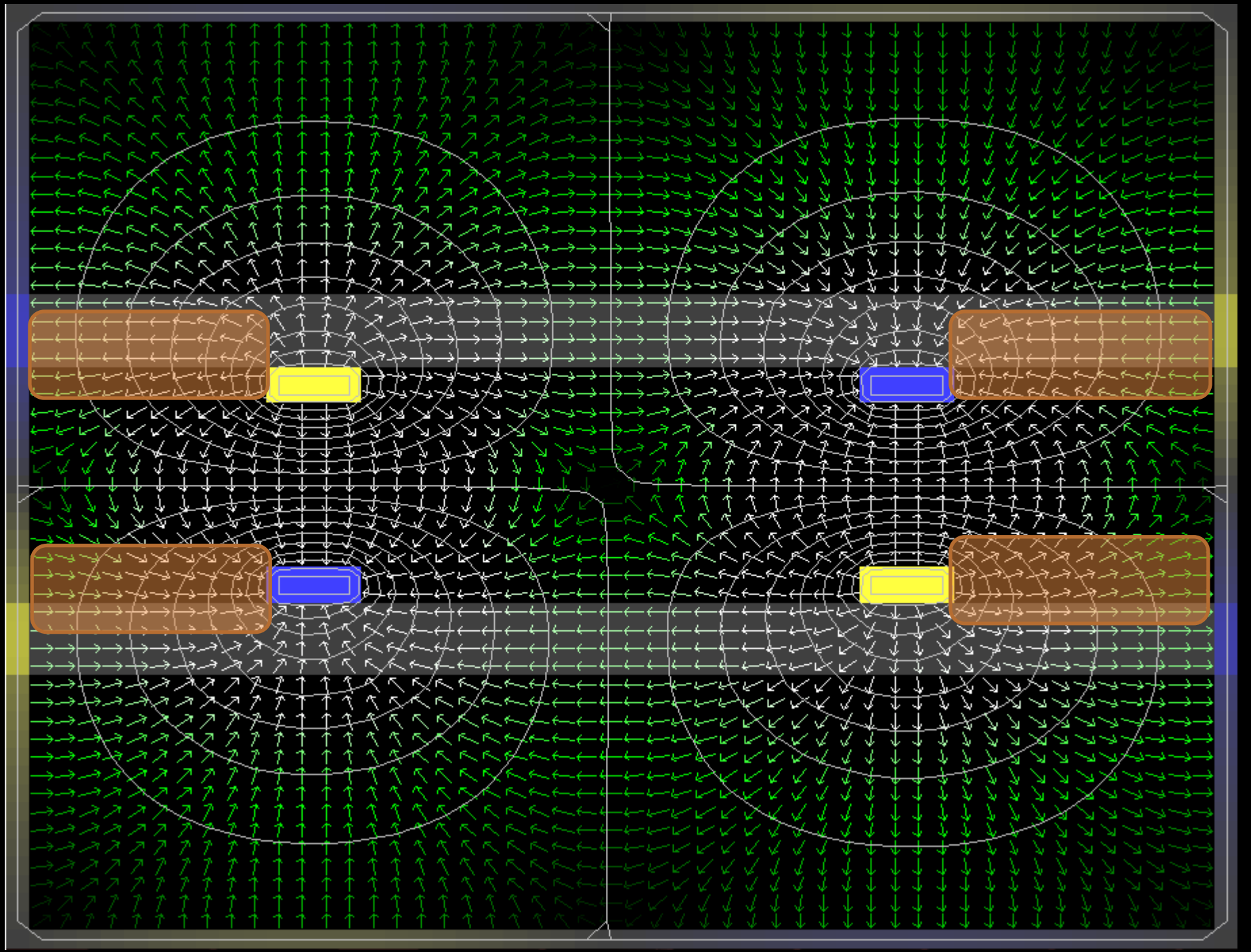
White – High E Field

Dark Green – Low E Field

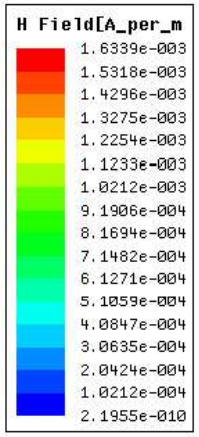








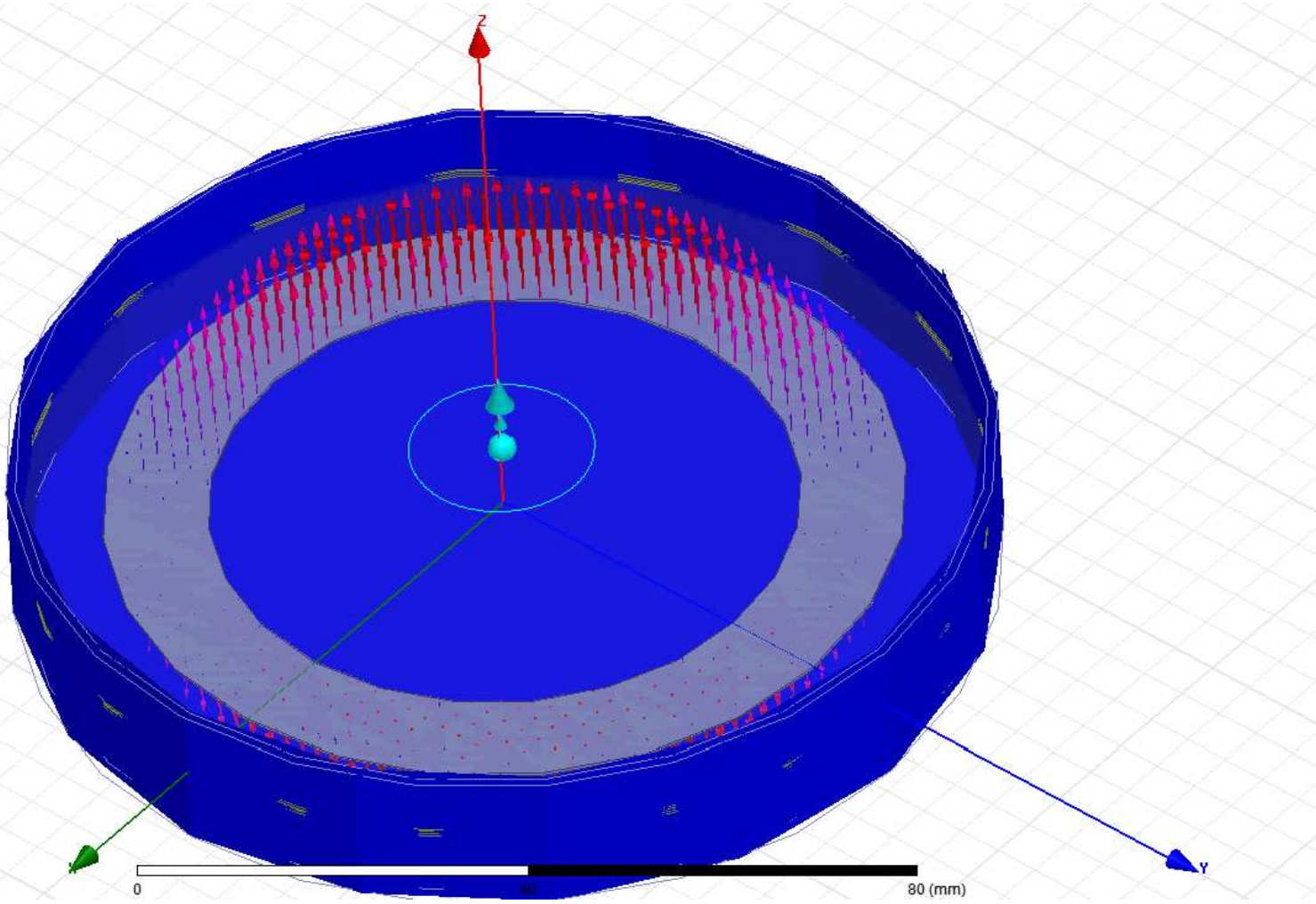
Currents Induced on Cylinder by Whispering Mode



$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\dot{\rho} \sim \mathbf{I}$$

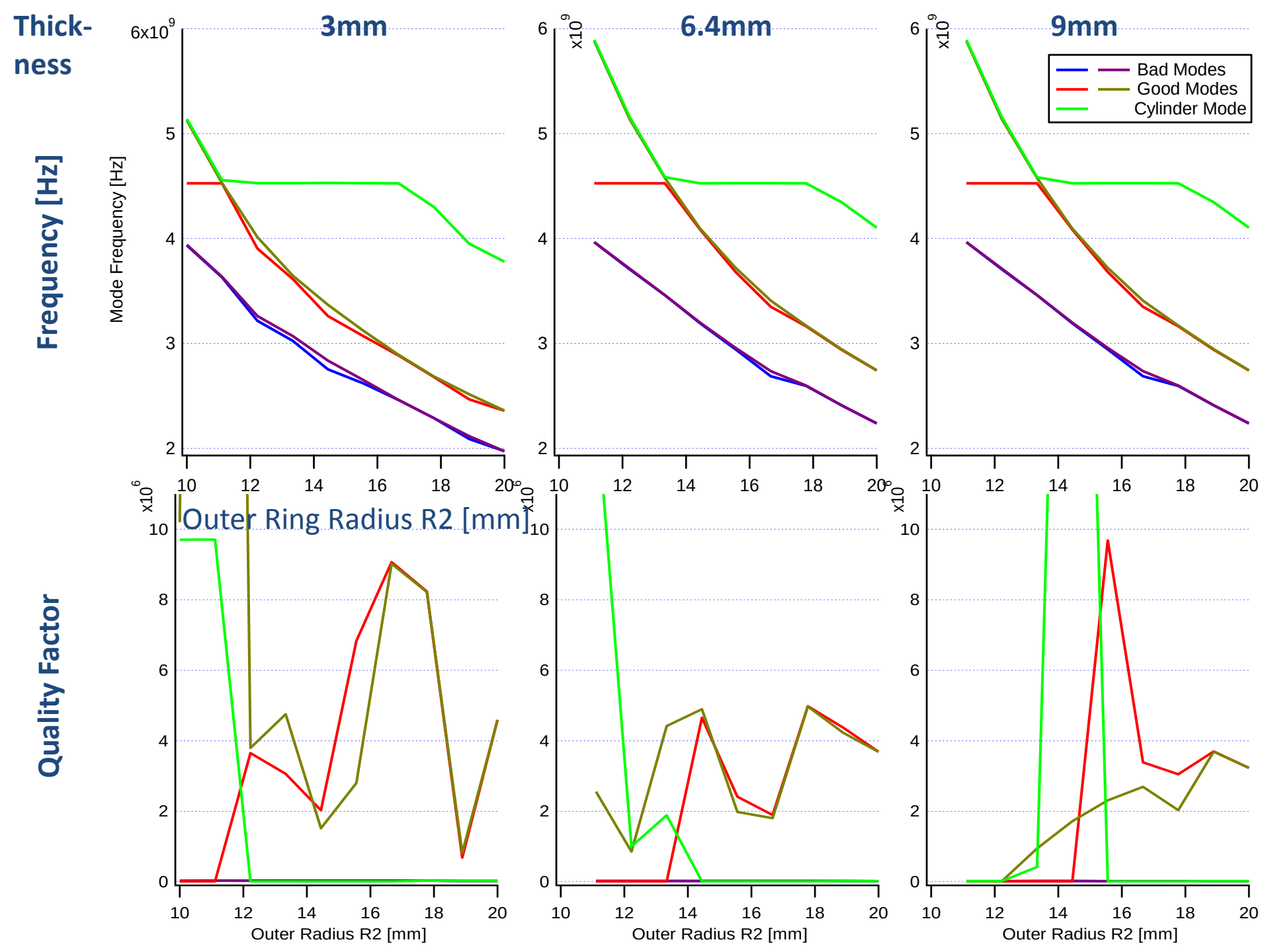
$$\dot{\mathbf{E}} \sim \frac{1}{\mu_0} \mathbf{B}$$



F, Q vs Outer Radius and Ring Thickness

- F as a function of Outer Radius [R_{outer}]
  - How does the thickness affect the mode frequency
- Does Q depend on the thickness?
- How much does Q depend on the outer radius?
- What is the scaling $Q \sim R_{outer}/R_{wafer}$

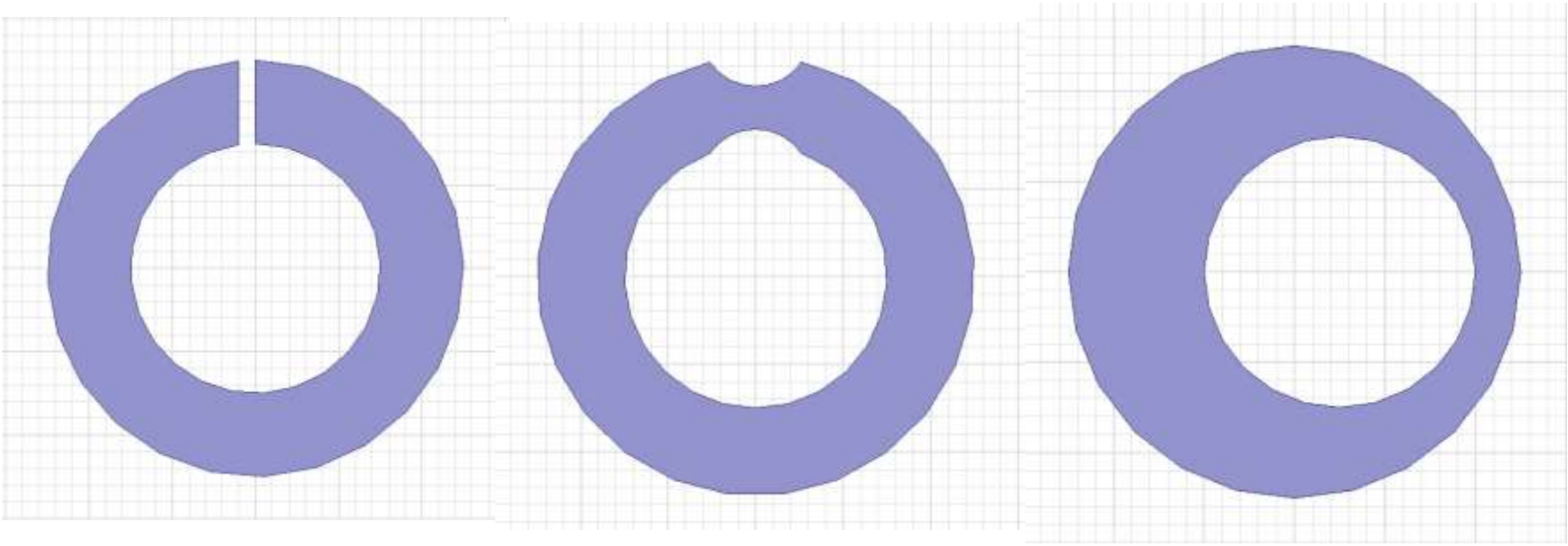
- Simulation Parameters:
  - 300 um separation of rings
  - 12 mm cylinder height
  - 2in (50.8mm) wafer, 300 um thick


Thick-ness
3mm
6.4mm
9mm
Frequency [Hz]
Mode Frequency [Hz]
6x10^9
x10^9
Bad Modes
Good Modes
Cylinder Mode
Outer Ring Radius R2 [mm]
Quality Factor
x10^6
Outer Radius R2 [mm]

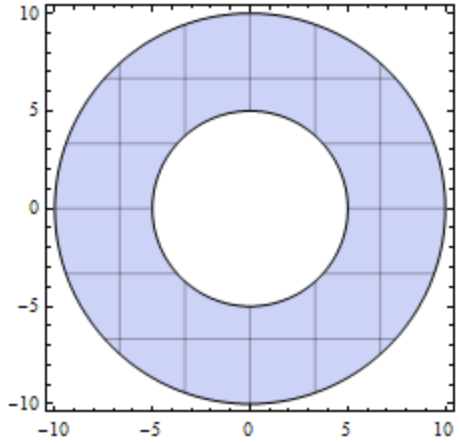
Observations

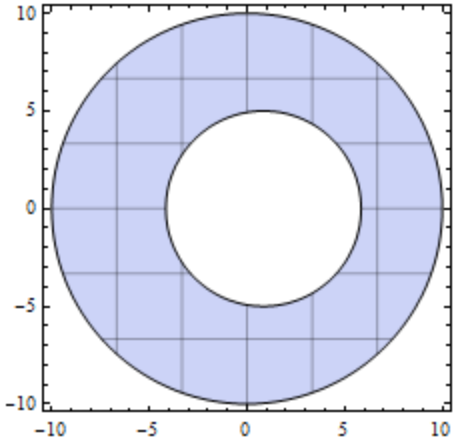
- Good frequency separation between the good whispering gallery modes and the cylinder or parasitic whispering gallery modes. (~500 MHz)
  - Bad Modes Q ~> 10,000, small line width (< few MHz)
- Q is safely & easily in millions, but is sensitive to other modes
- Can tune the Frequency from 1 to 4 GHz
  - Highest frequency is limited to ~ 4 GHz by cylinder radius. (in principle can go higher)
- Too thick a ring will perturb the modes, and couple to the top walls more, lowering the Q (within a factor of 3)
- Degeneracy of good mode

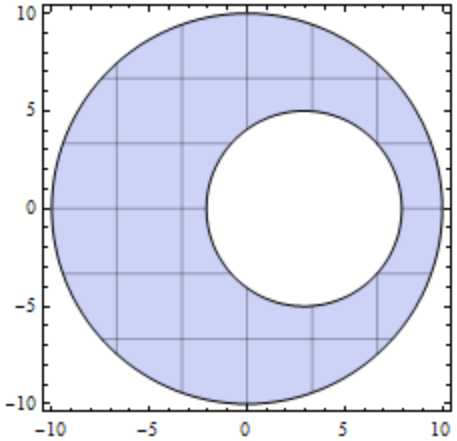
Degeneracy ⇨ Lift Modes

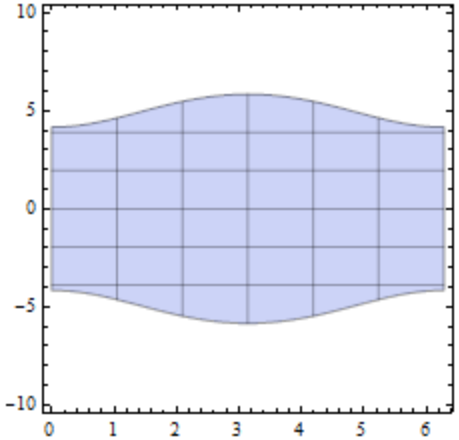


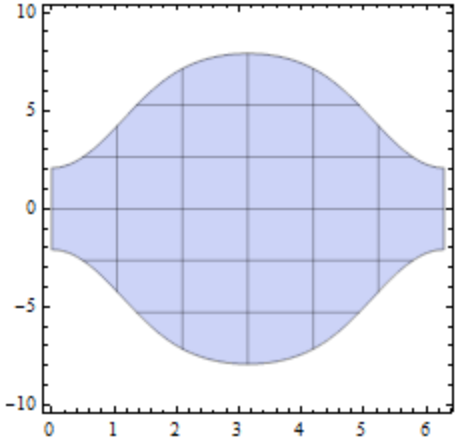
Effective 2D Potential in Space

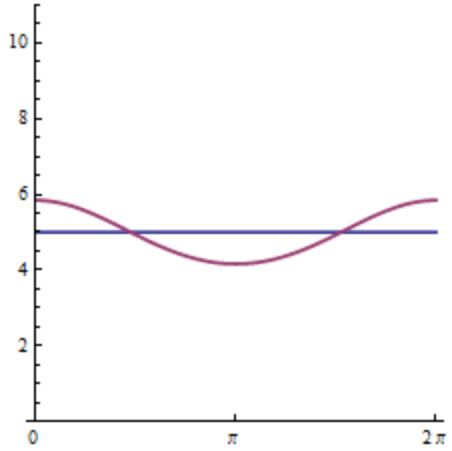


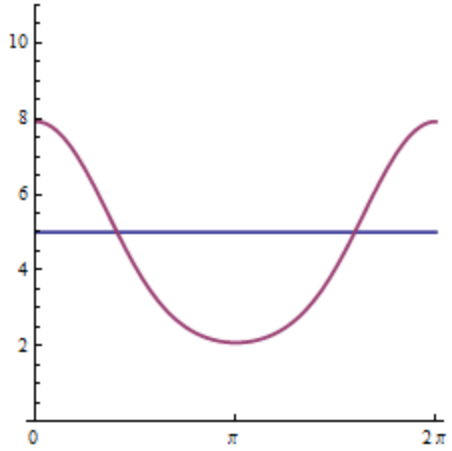








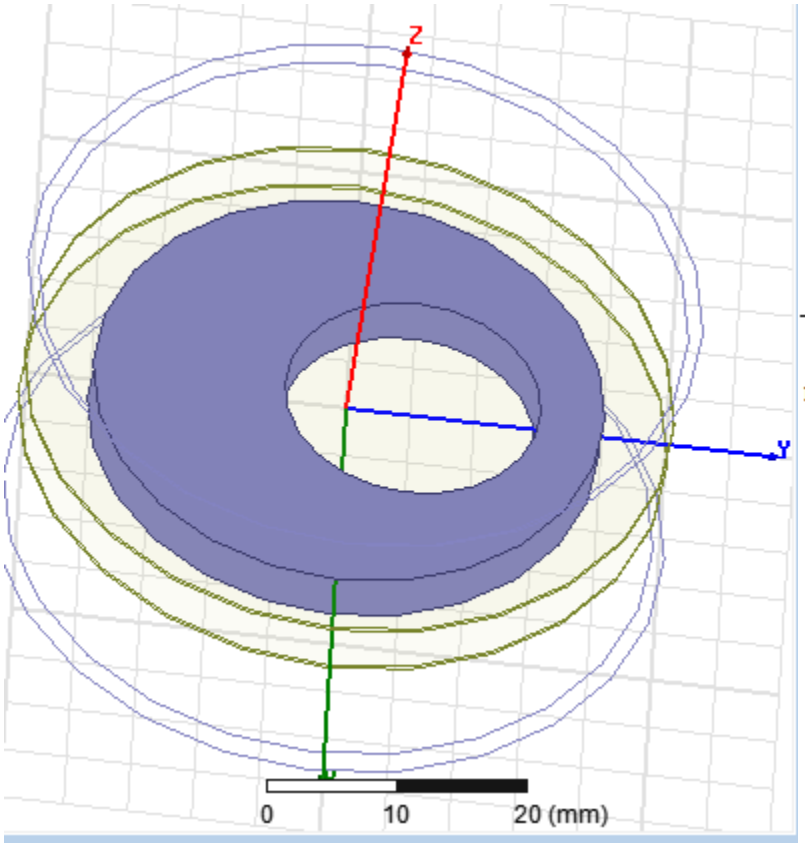


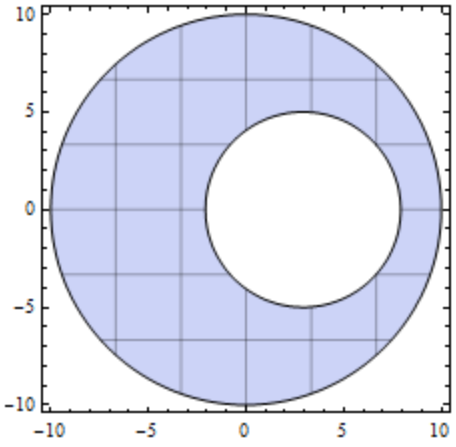


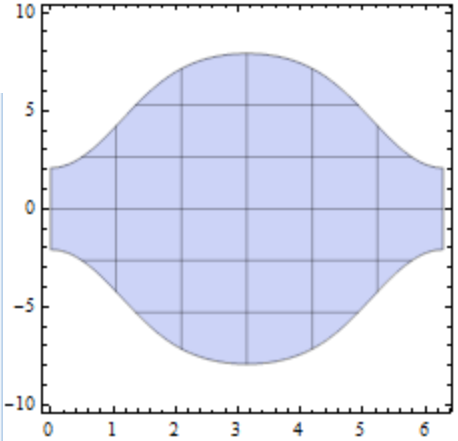
Variation in Inner Circle Position

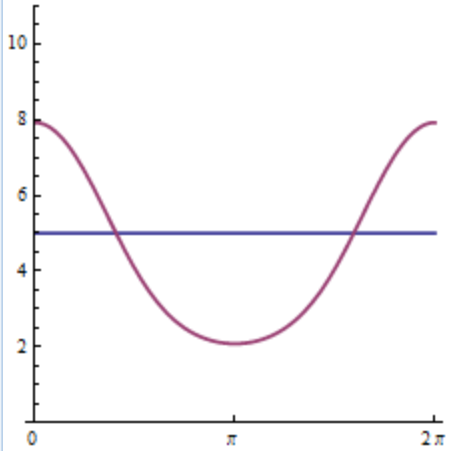
- How much is degeneracy lifted
- How much is Q affected

- Parameters:
  - Thickness
    - 6.4mm
  - Cylinder height
    - 12mm





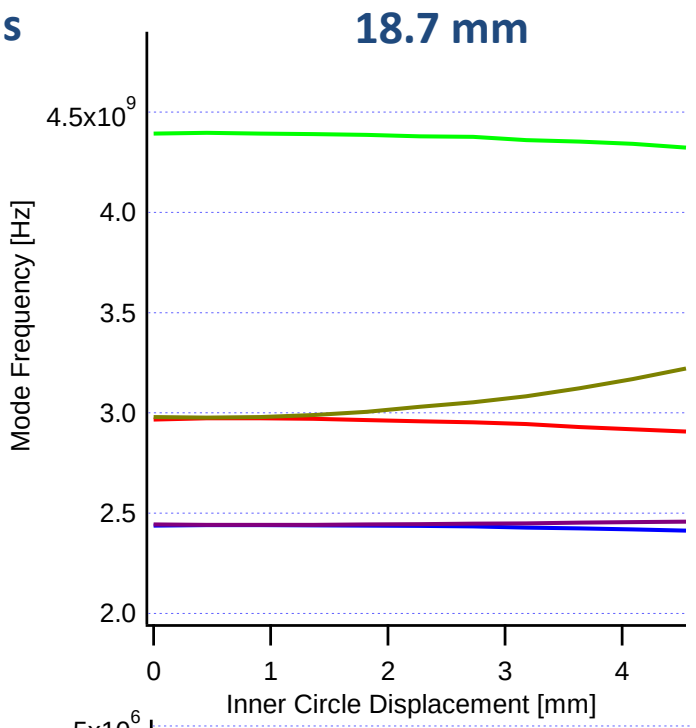


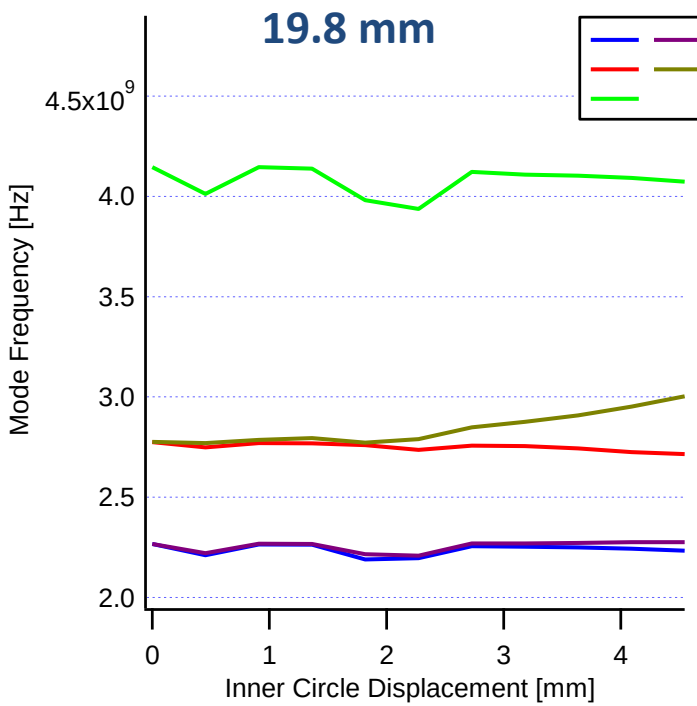


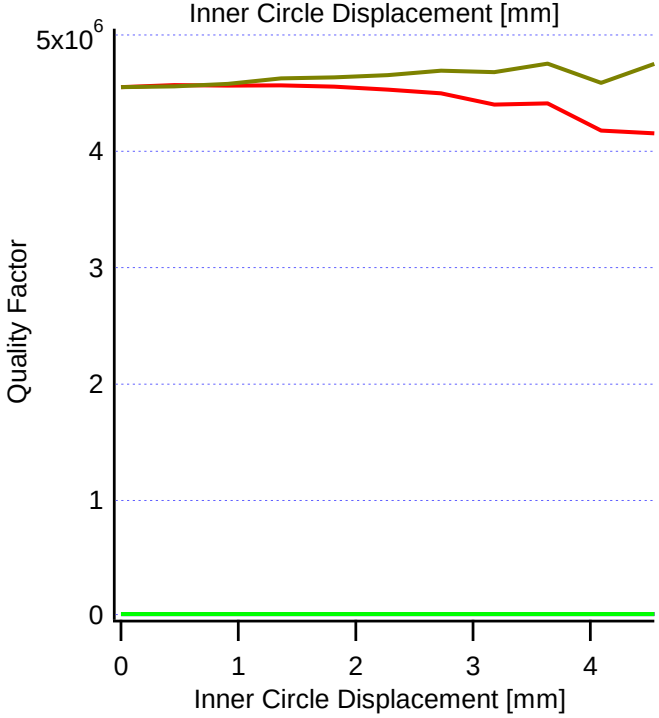
Outer Radius

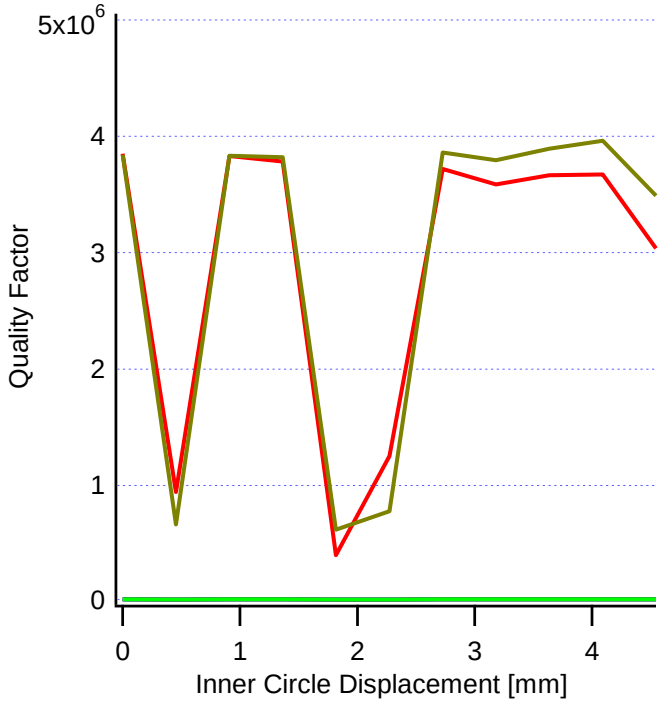
Frequency

Quality Factor









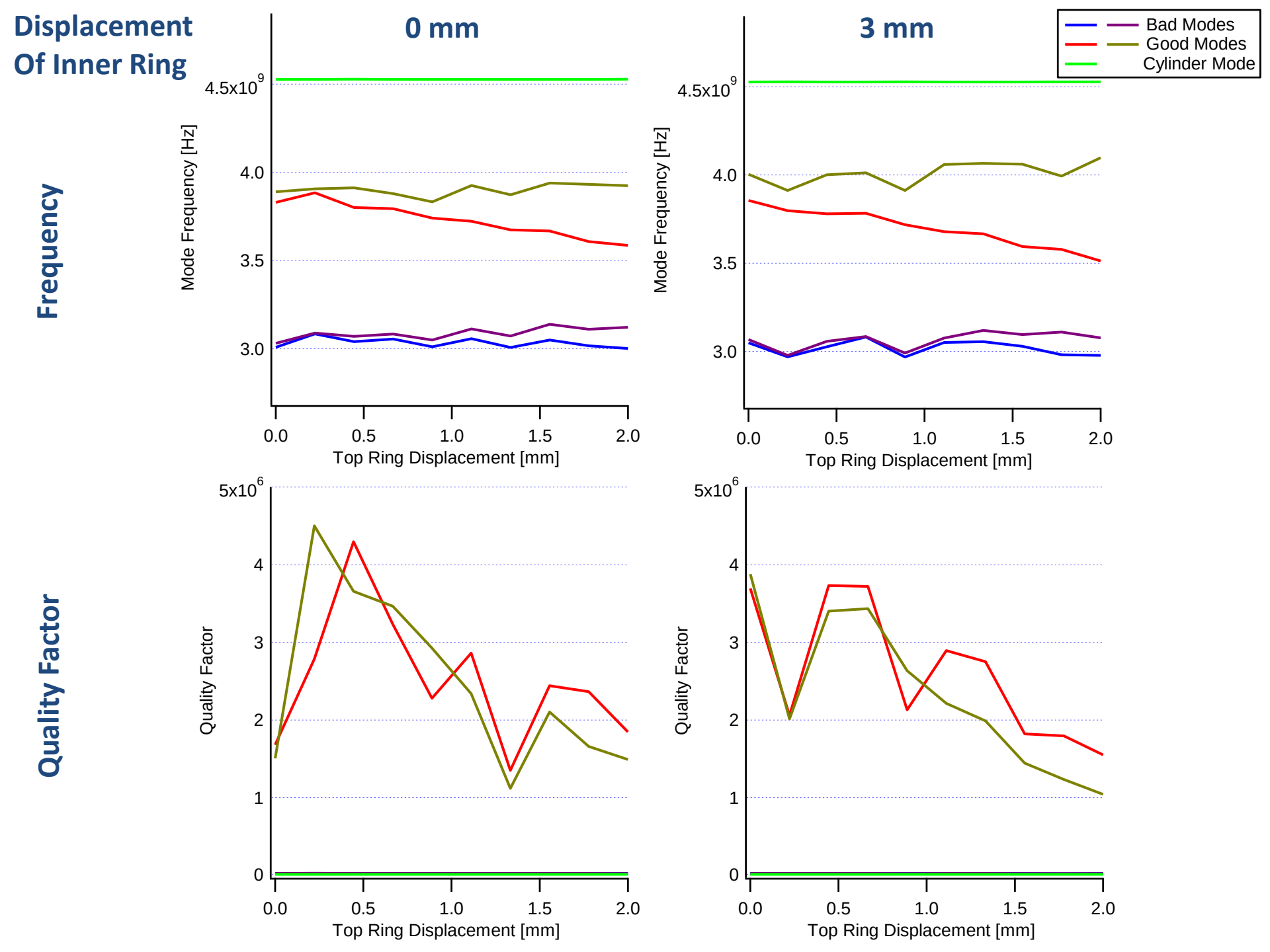
Observations

- As long as we don't hybridize the mode, we can achieve the same high Q as for concentric rings
  - Bad mode Q's still >10,000, linewidth (< few MHz)
- Can safely get 300 MHz separation for displacement of 4.5 mm
  - Separation drops with larger radius ~30 MHz/mm
  - Cannot exceed the thickness of the rings ~ 6.4mm

Alignment Tolerance

- How sensitive are Q and F to misalignment of the rings

- Note: Q goes exponentially with cylinder height


Displacement Of Inner Ring
Frequency
Quality Factor
0 mm
3 mm
Bad Modes
Good Modes
Cylinder Mode
Mode Frequency [Hz]
4.5x10^9
4.0
3.5
3.0
0.0
0.5
1.0
1.5
2.0
Top Ring Displacement [mm]
Quality Factor
5x10^6
4
3
2
1
0

Next Challenges

Coupling

Aligning

- Plating walls with Al?

Thermalizing

....

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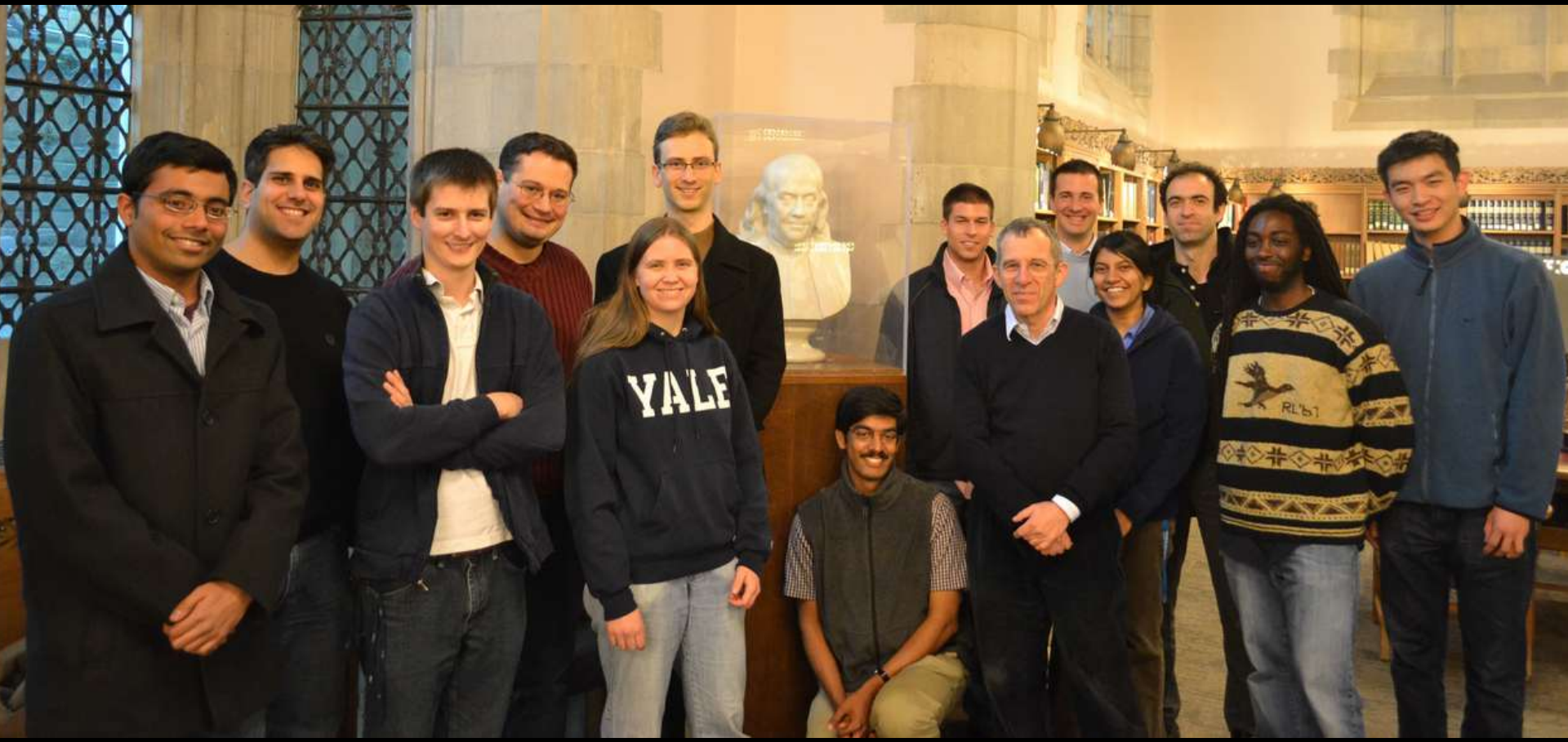
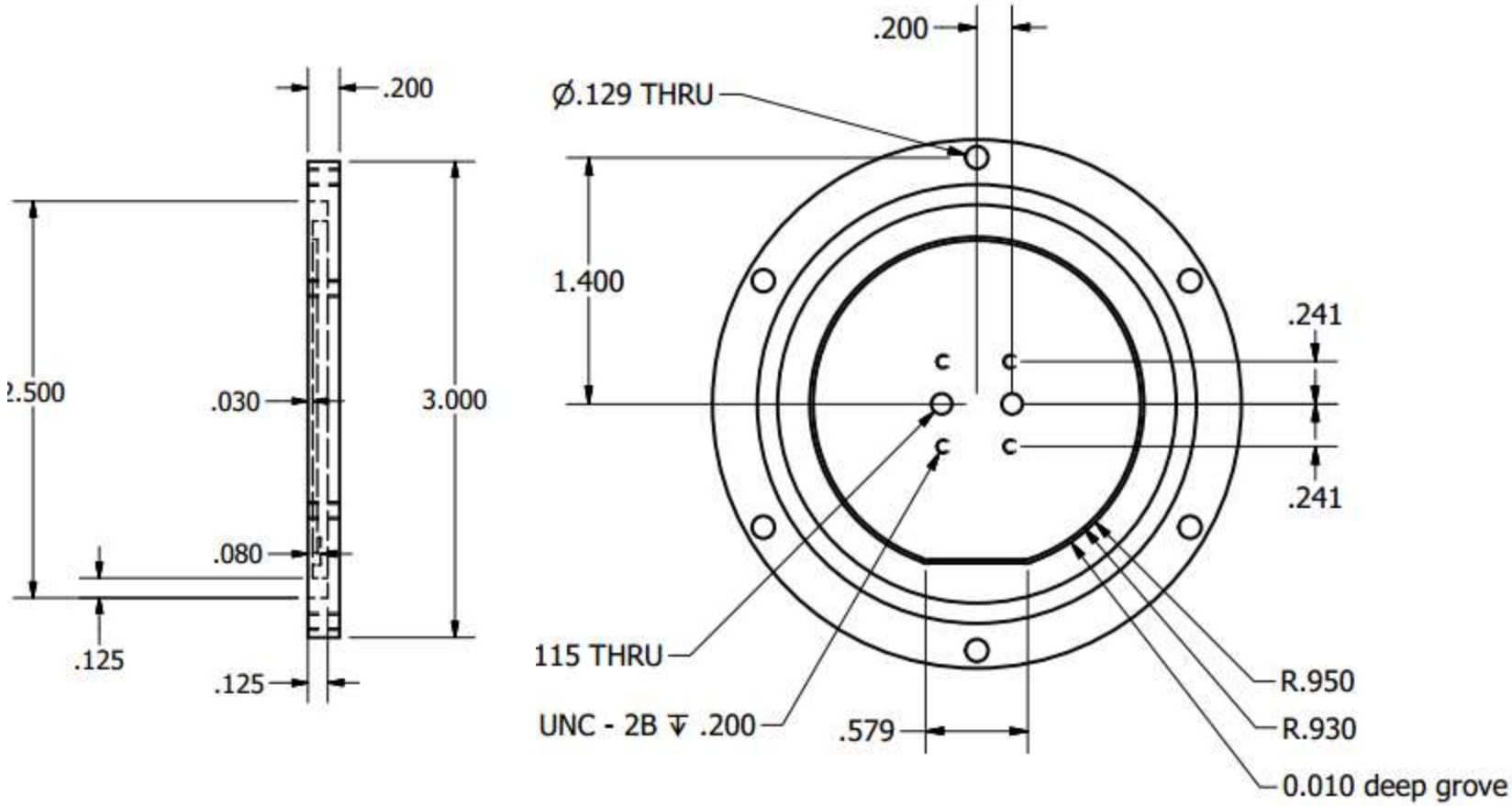
Yale University

Q LAB

LUX ET VERITAS



Chuck



Thanks Teresa