Application of the Bead Perturbation Technique to a Study of a Tunable 5 GHz Annular Cavity

Nicholas Rapidis

UC Berkeley

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Outline

- ADMX-HF brief overview
- Cavity Characteristics
- Cavity study at Berkeley
- Future work
- Conclusion and summary

Collaboration

Yale University (experiment site)

Steve Lamoreaux, Ling Zhong, Ben Brubaker, Sid Cahn, Kelly Backes

UC Berkeley

Karl van Bibber, Maria Simanovskaia, Samantha Lewis, Jaben Root, Saad Al Kenany, Nicholas Rapidis, Isabella Urdinaran

CU Boulder/JILA

Konrad W. Lehnert, Daniel Palken, William F. Kindel, Maxime Malnou

LLNL

Gianpaolo Carosi, Tim Shokair

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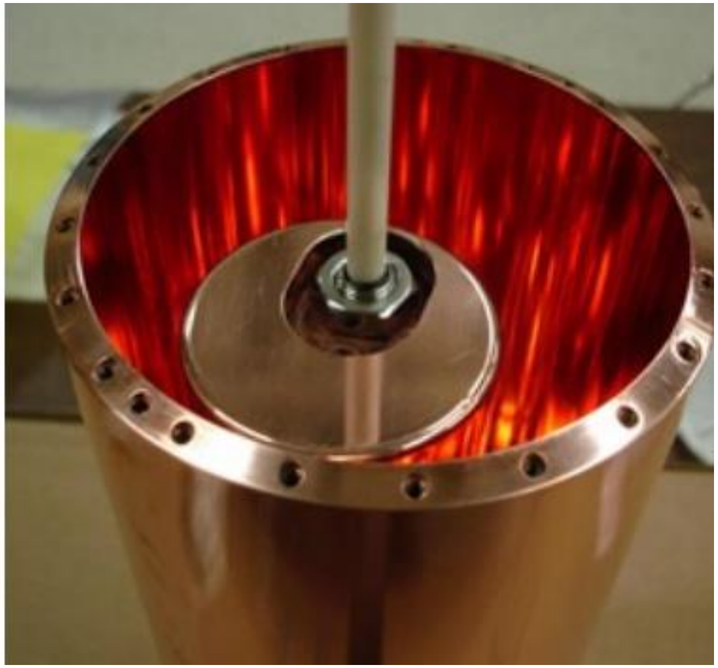
Experiment at Yale

- Cu Cavity with off-axis tuning rod
- 9 T magnet
- Dilution refrigerator T~100 mK
- Josephson Parametric Amplifier, tunable from 4.4-6.4 GHz
- First data run (2016) in 5.75 GHz range (~24 μeV)

$$\mathrm{P}_{signal} \propto \mathrm{B}^2\mathrm{VQ}C_{mnl}$$



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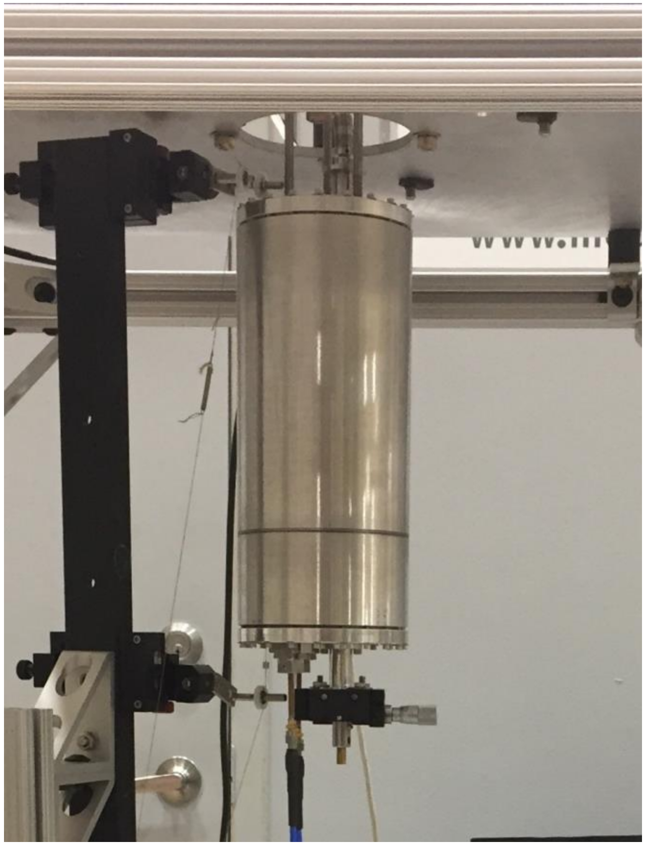
Desired Cavity Characteristics

- Large Volume ~2 L
  - 25.4 cm height
  - 10.2 cm diameter

  Use of 5.1 cm diameter copper rod
- Large dynamic frequency range
  - 3.4 – 5.8 GHz



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Desired Cavity Characteristics

- High Quality factor, Q

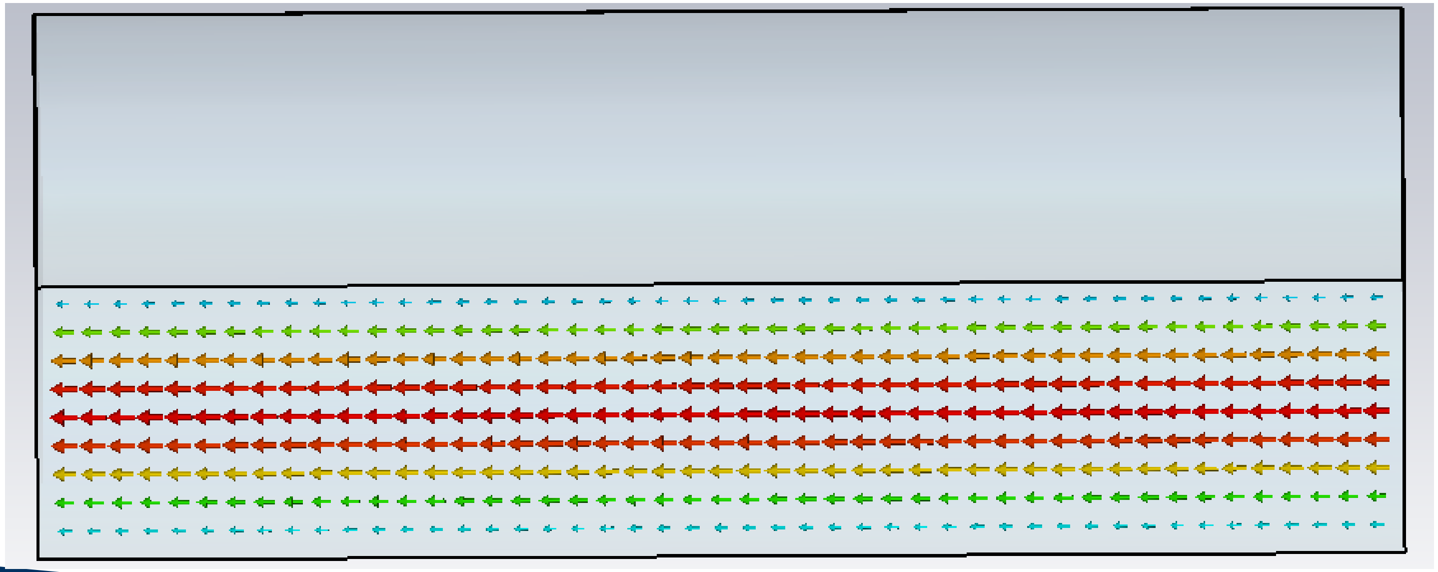
$$Q \propto \frac{(\text{Mode}-\text{dependent constant of order 1}) * (\text{Volume})}{(\text{Surface area}) * (\text{Skin Depth})}$$

  – Increases at lower temperature
  – Affected by rod position, coupling, intruder modes

Desired Cavity Characteristics

- High Form Factor, C_{mnl}

$$C_{mnl} \equiv \frac{\left(\int d^3x \;\hat{z} \cdot \mathbf{e}^*_{mnl}(\mathbf{x})\right)^2}{V \int d^3x \;\epsilon(\mathbf{x}) \left|\mathbf{e}^*_{mnl}(\mathbf{x})\right|^2} \quad \text{in our case } \epsilon(\mathbf{x}) = 1$$



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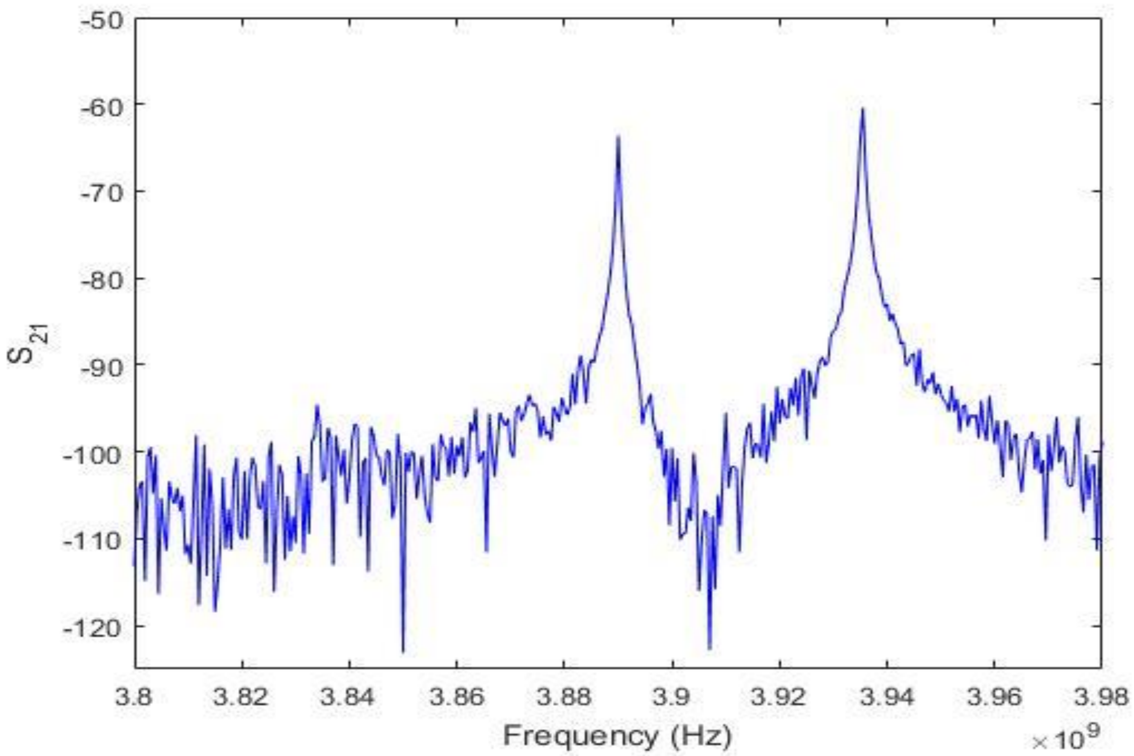
Non-uniformities in the cavity will cause mode localization thus deteriorating the form factor

Desired Cavity Characteristics

- Freedom from mode crossings



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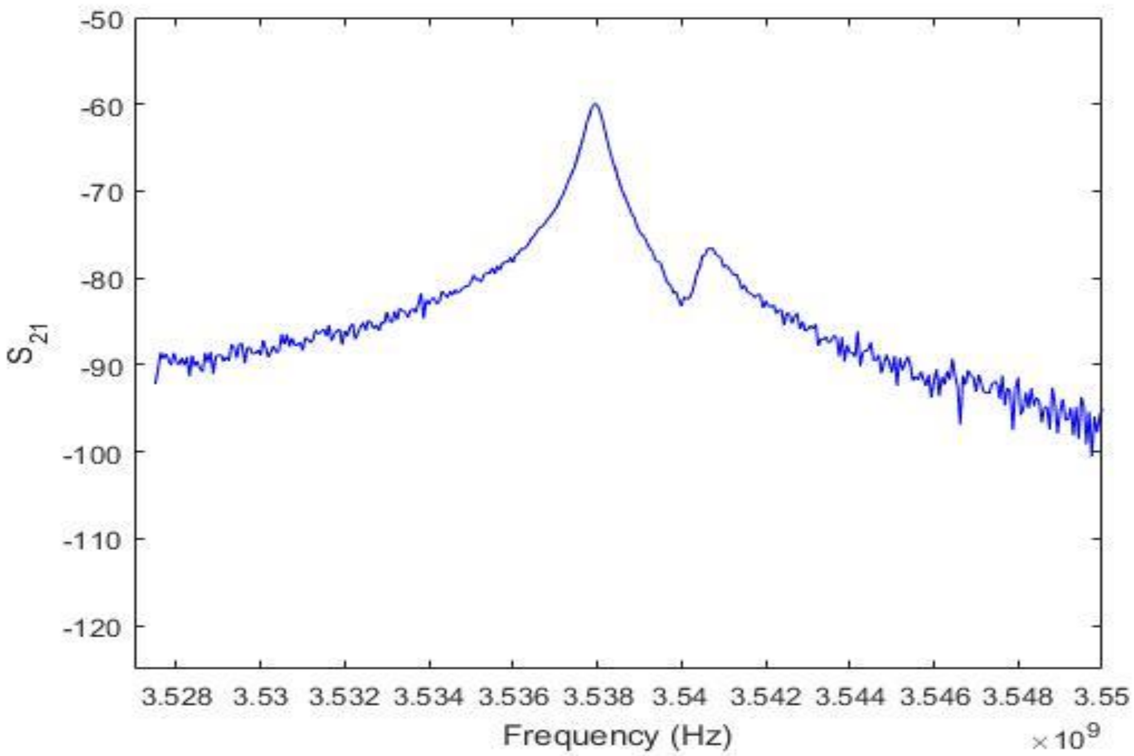
Desired Cavity Characteristics

- Freedom from mode crossings

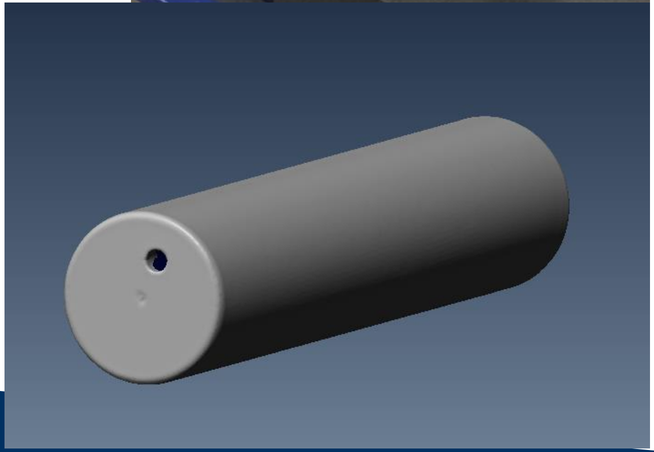


Detailed Cavity Study at Berkeley

- Precision metrology on current apparatus
- High Fidelity Simulations
- Precision Field Mapping using Bead-Perturbation Technique

Detailed Cavity Study at Berkeley

- Precision metrology on central rod
  - Alignment of rod axis w.r.t. tubes holding it in place in the cavity
  - Better understanding of mode localization when misaligned in cavity
- Precision metrology on cavity
  - Allows for more accurate future simulations



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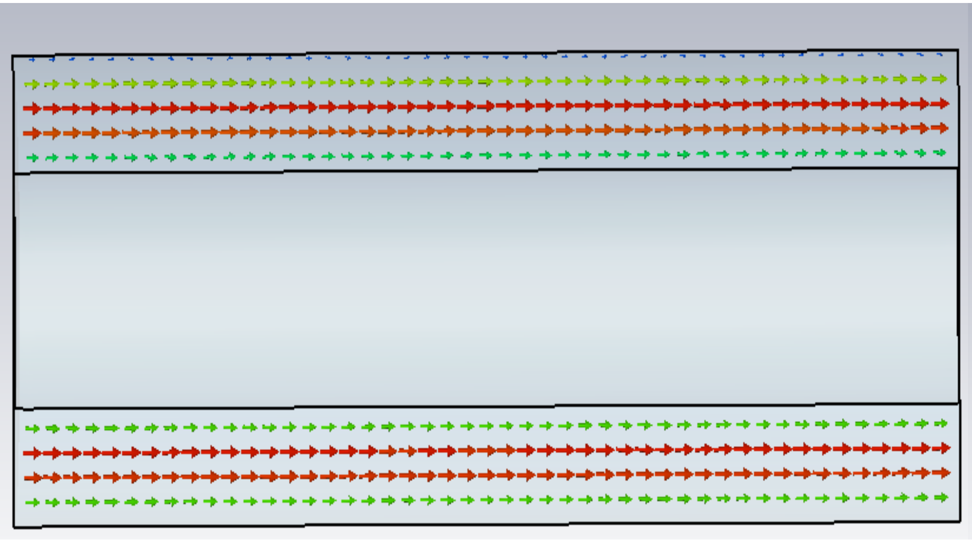
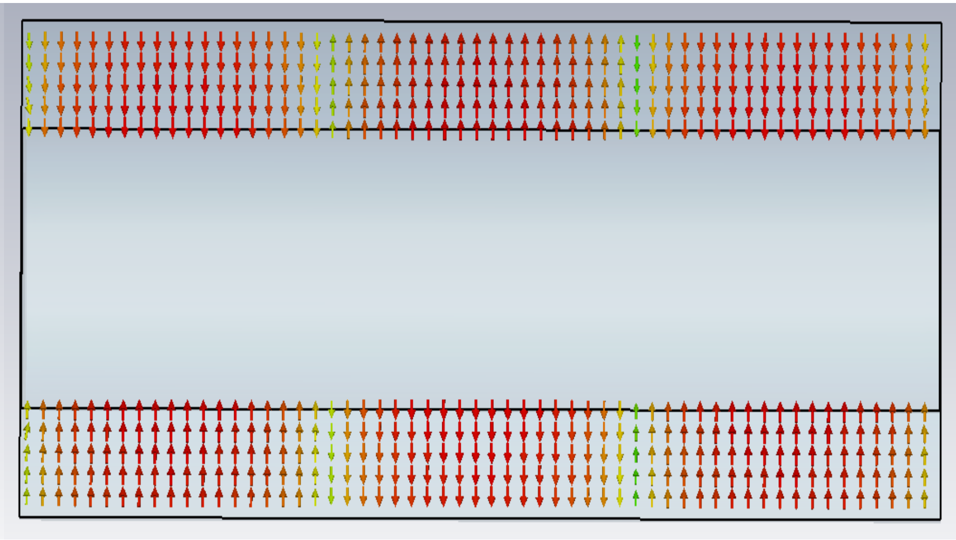
Detailed Cavity Study at Berkeley

- High Fidelity Simulations



TM_{010}



TE

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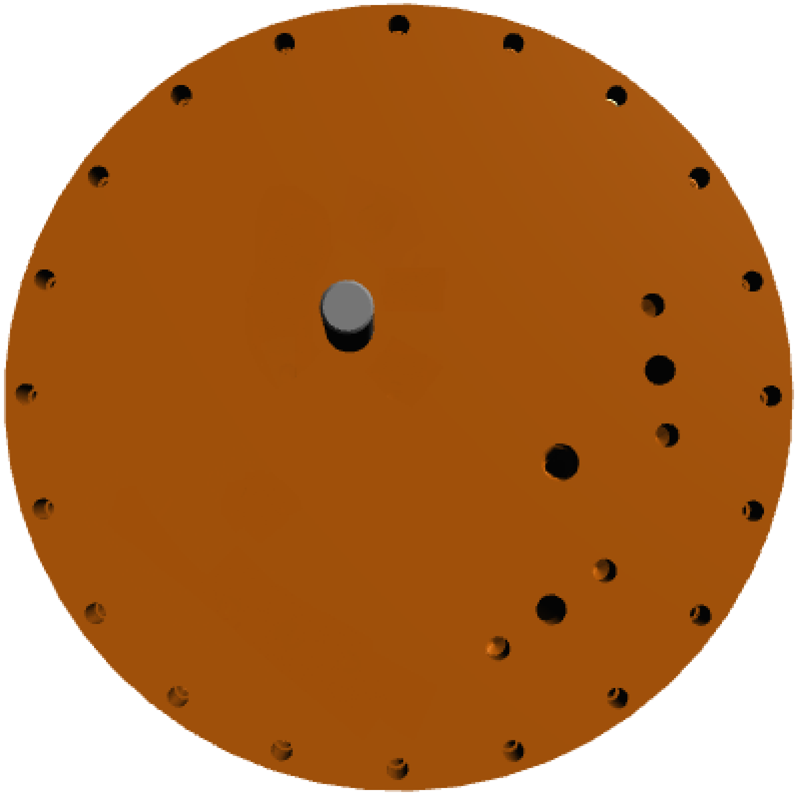
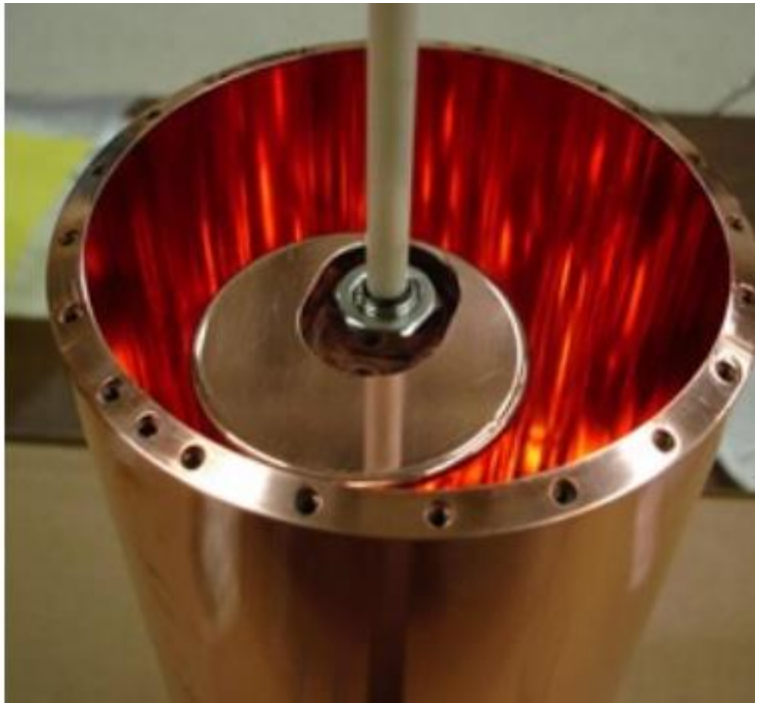
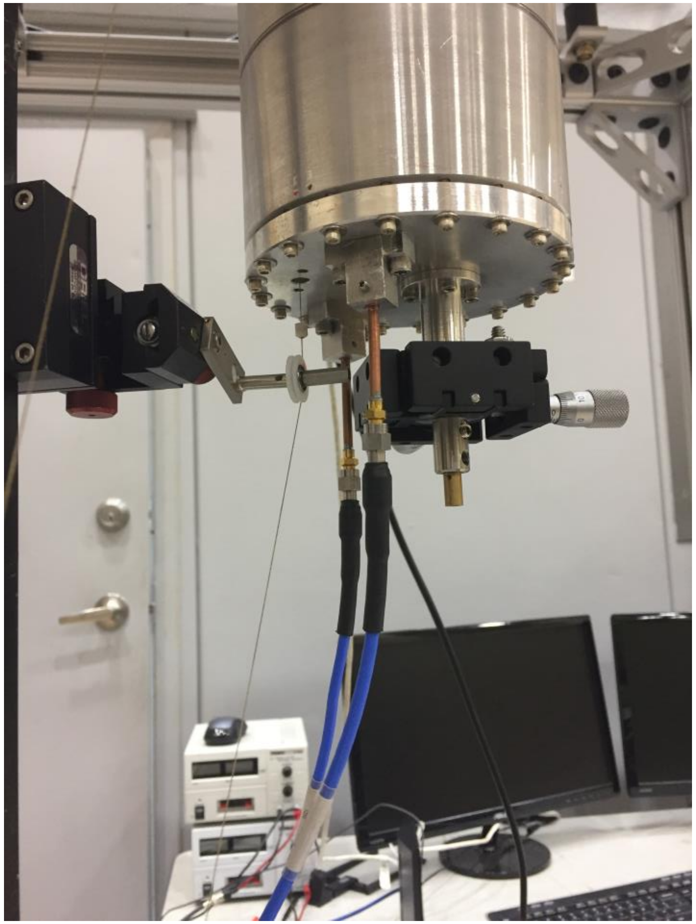
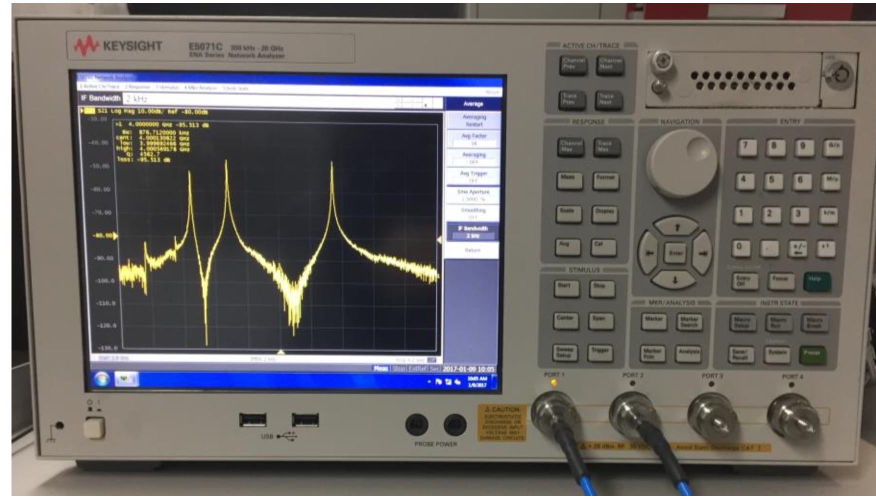
Detailed Cavity Study at Berkeley

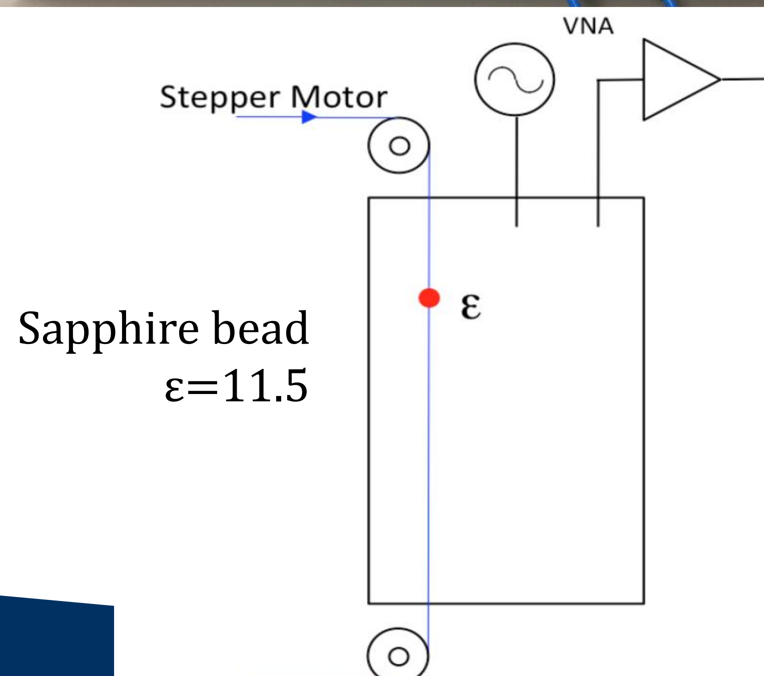




Detailed Cavity Study at Berkeley







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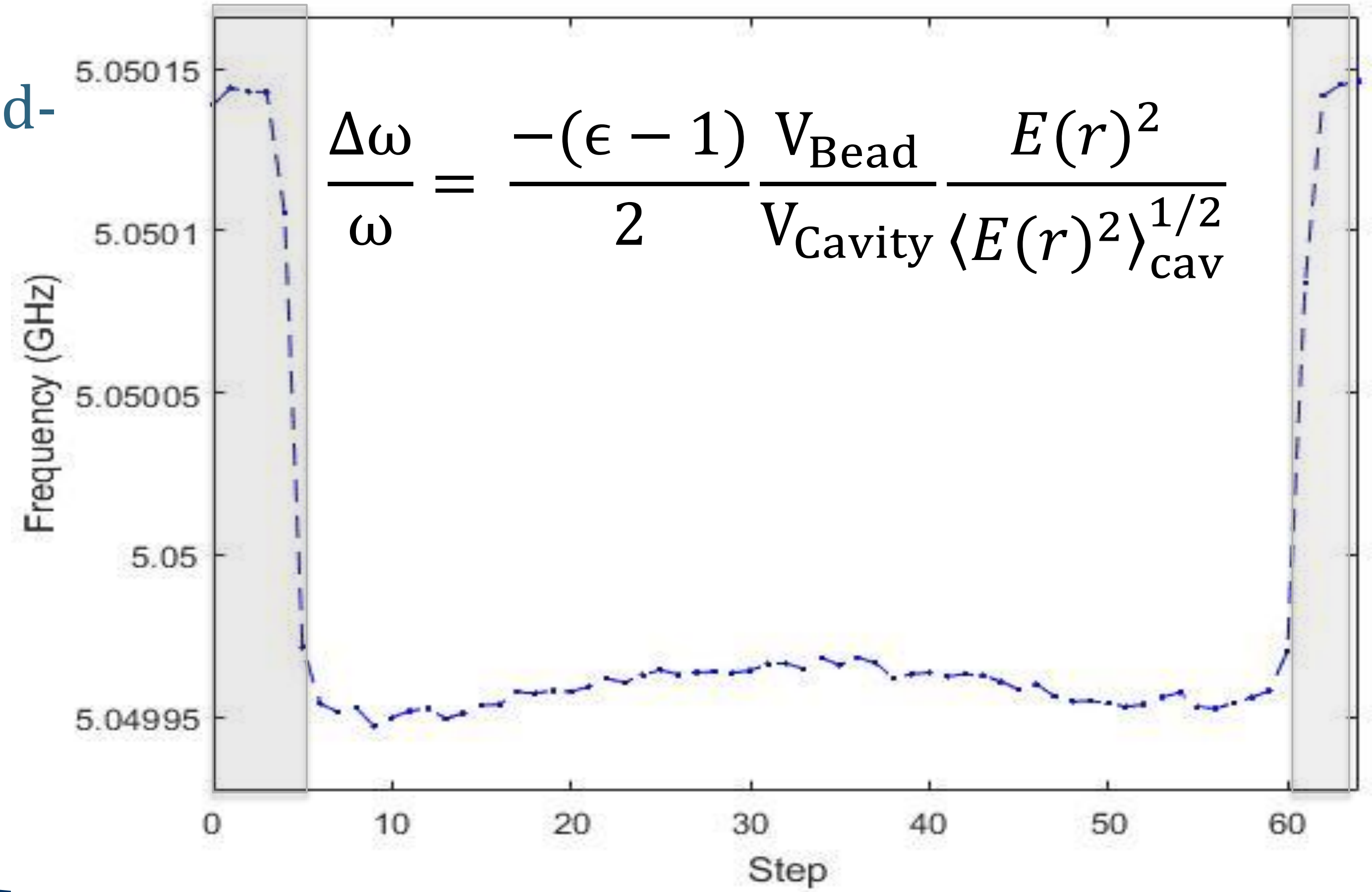
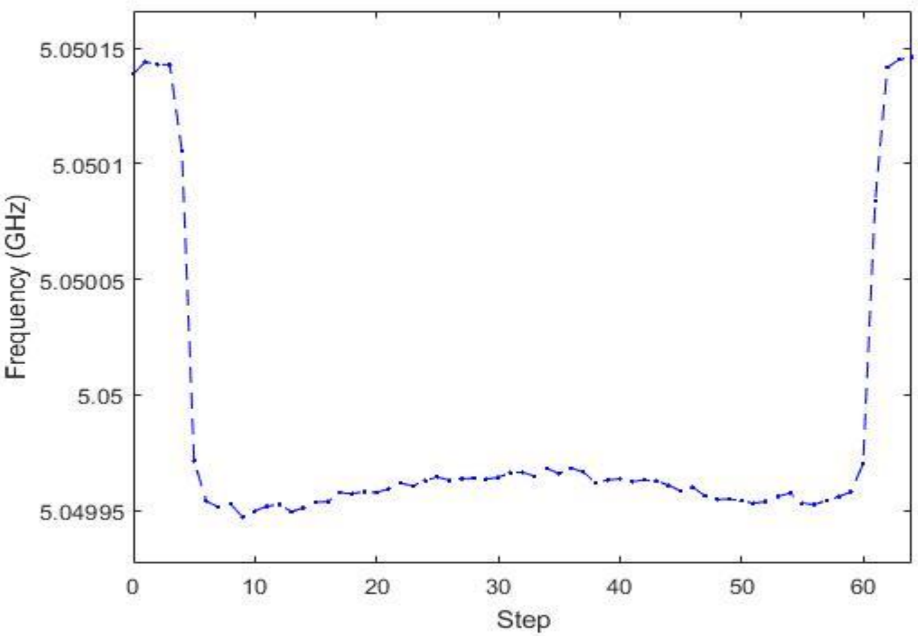
Detailed Cavity Study at Berkeley

Precision Field Mapping using Bead-Perturbation technique

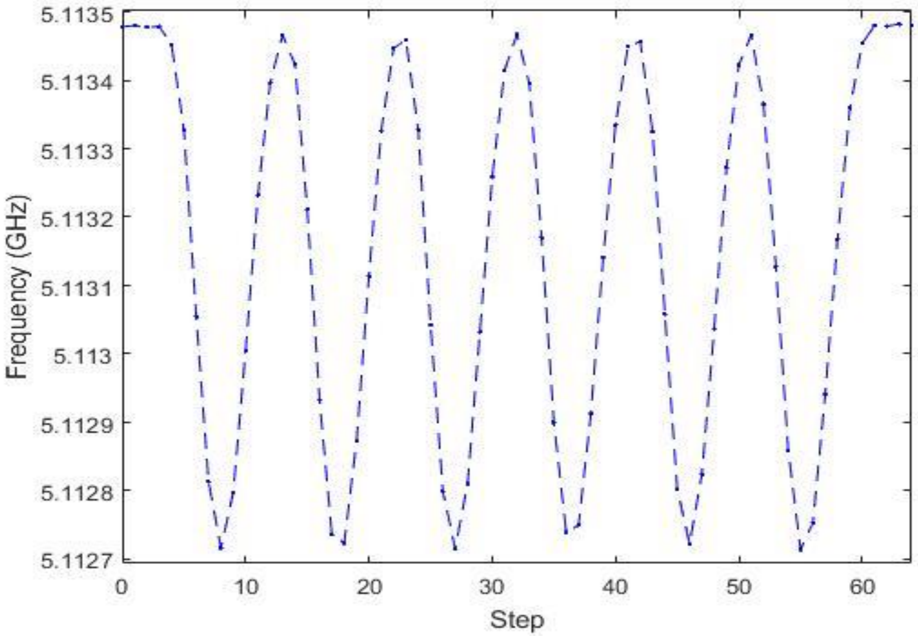
$$\frac{\Delta\omega}{\omega} = \frac{-(\epsilon - 1)}{2} \frac{V_{Bead}}{V_{Cavity}} \frac{E(r)^2}{\langle E(r)^2 \rangle_{cav}^{1/2}}$$



Determining mode type using bead pull



TM_{010}



TE_{050}

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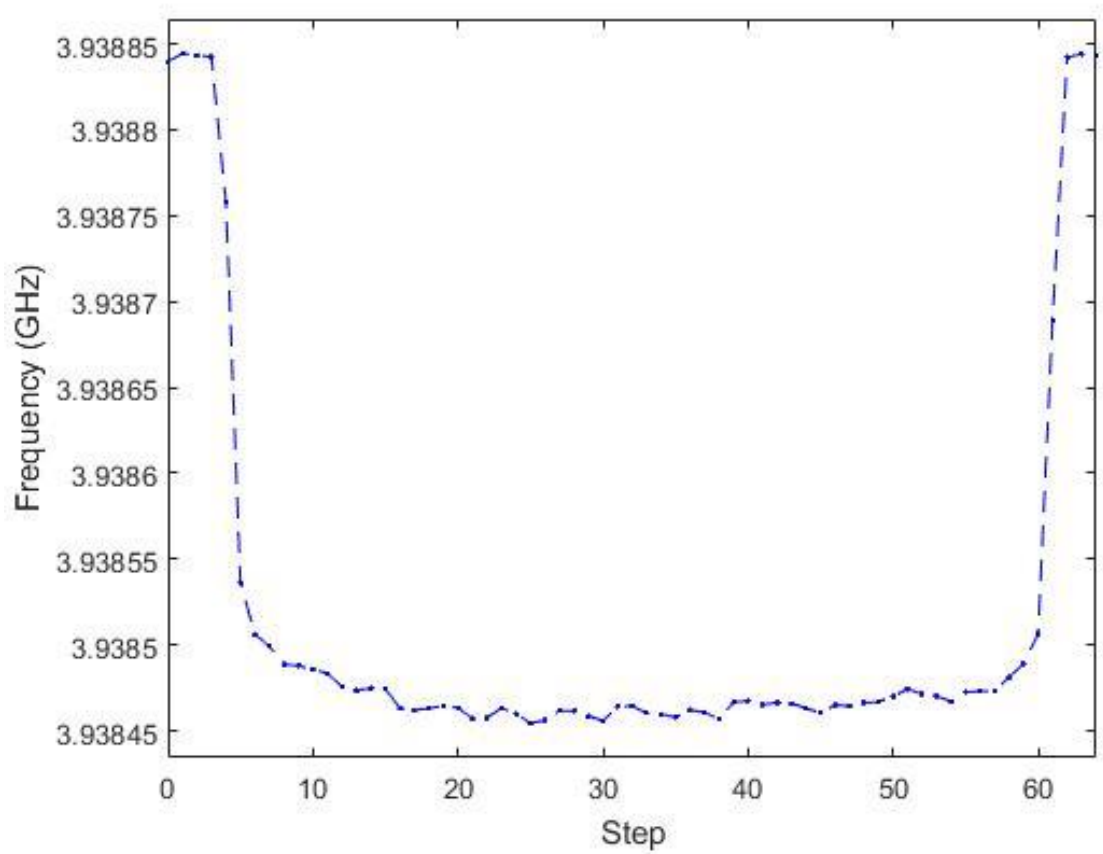
Misalignment Measurements



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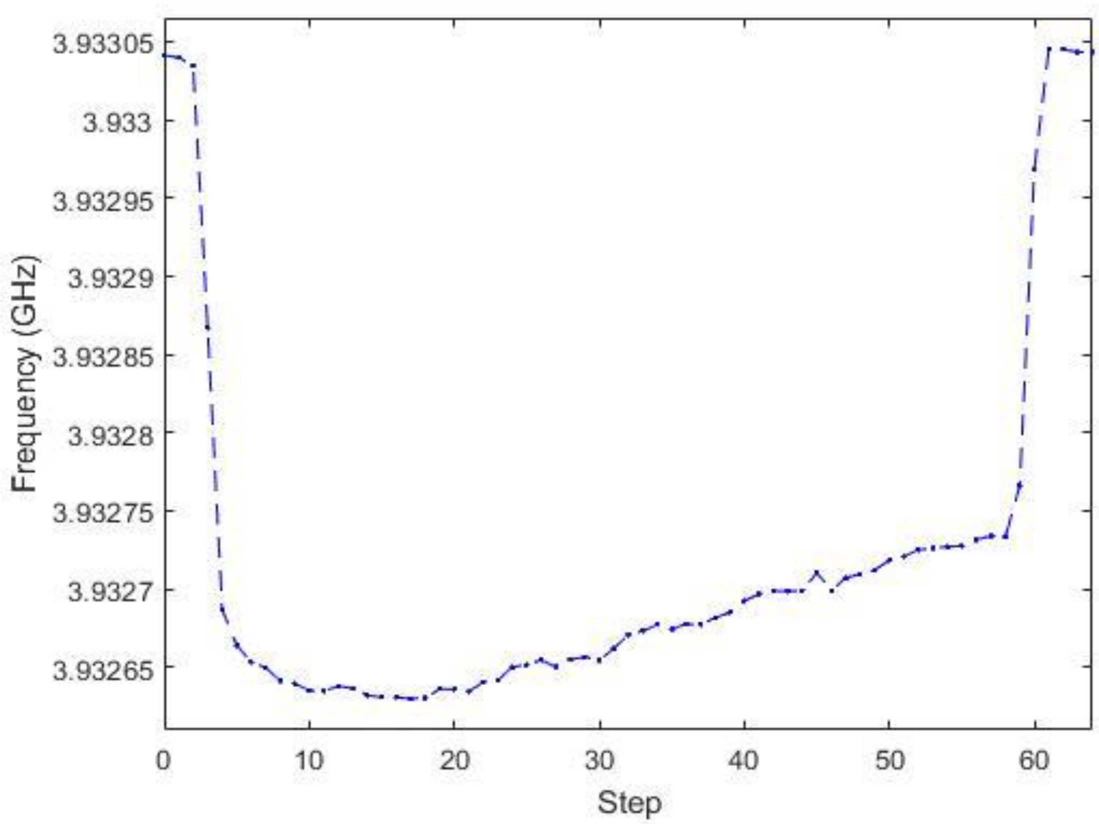
Misalignment Measurements



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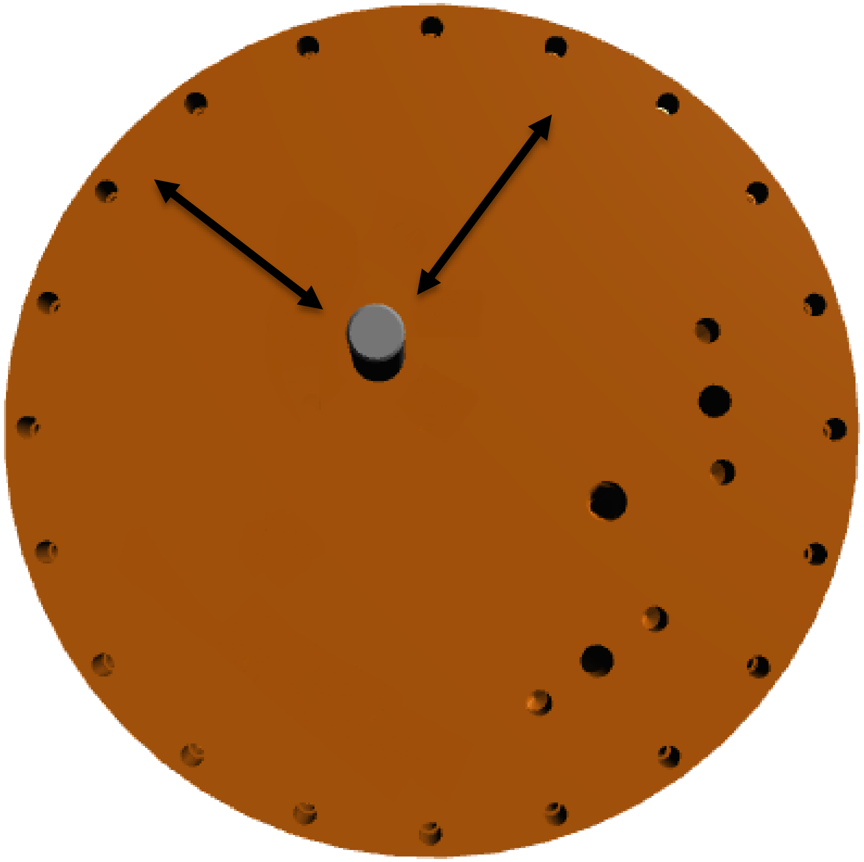
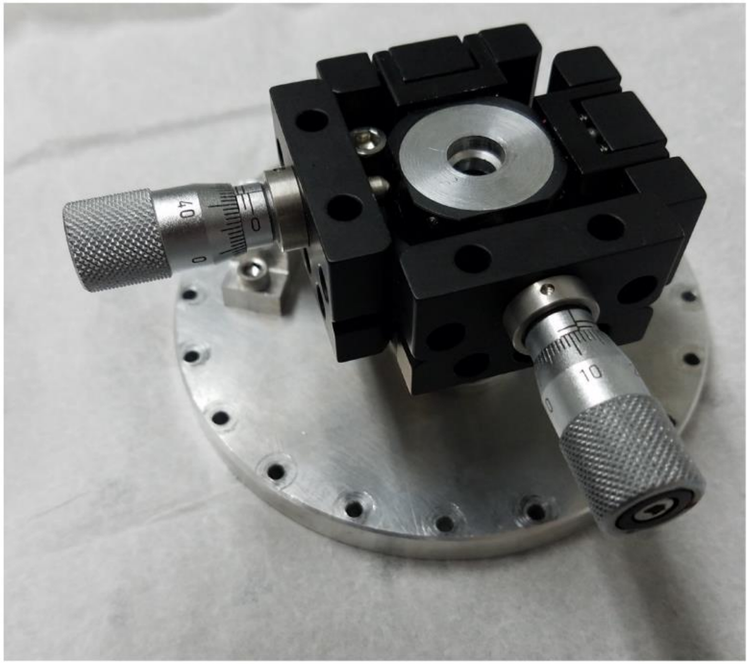
Misalignment Measurements





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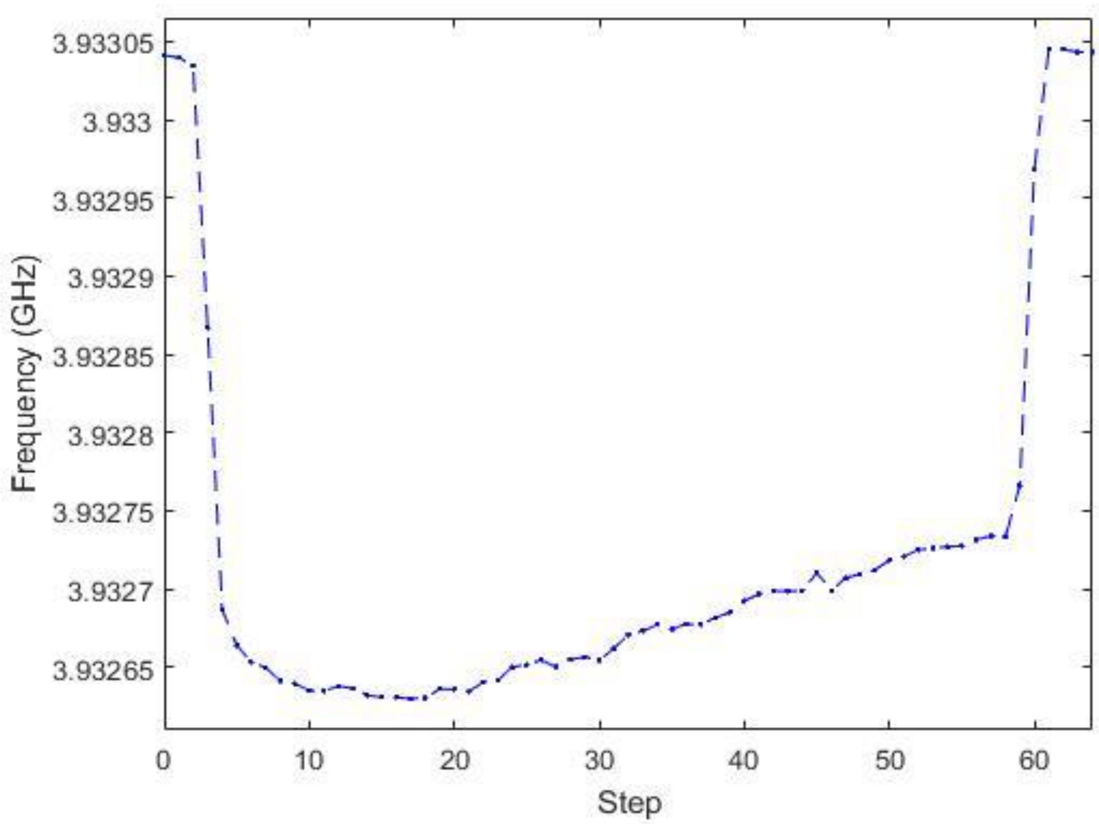
Misalignment Measurements



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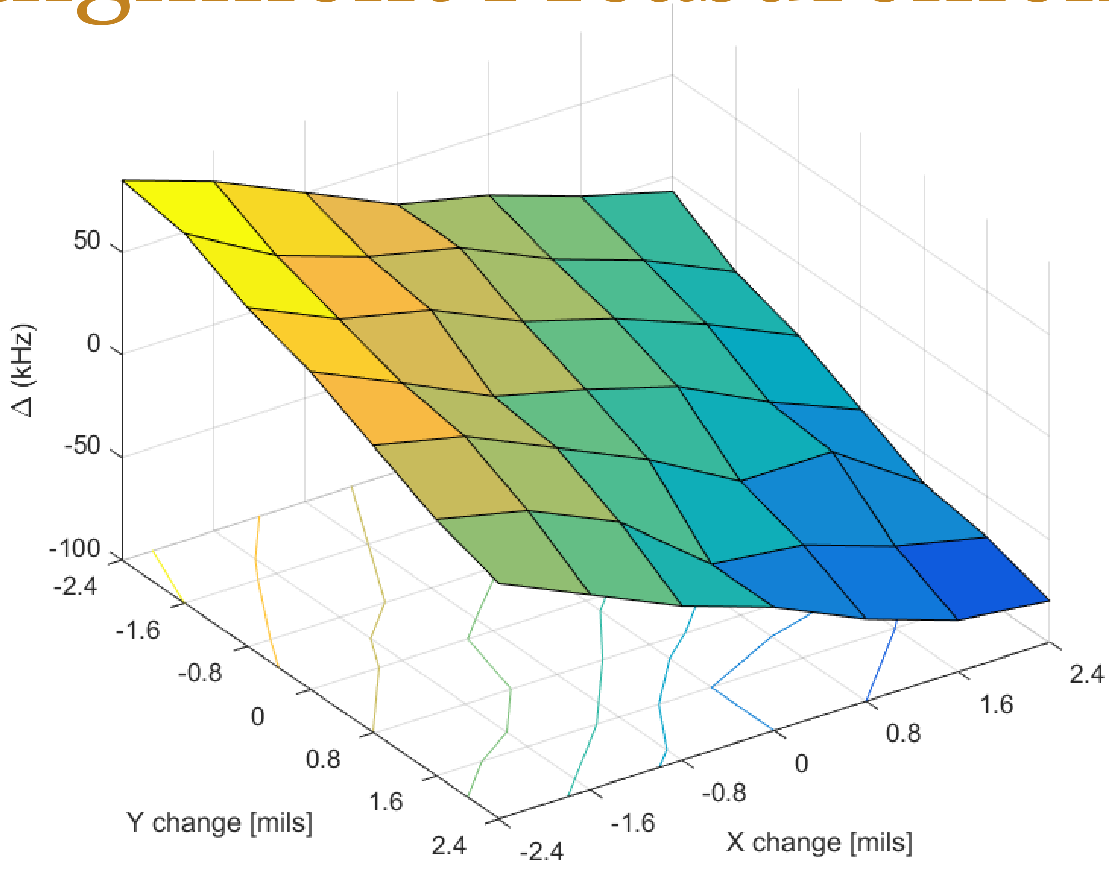
Misalignment Measurements



Each step corresponds to an angle shift of 1.5 mrad

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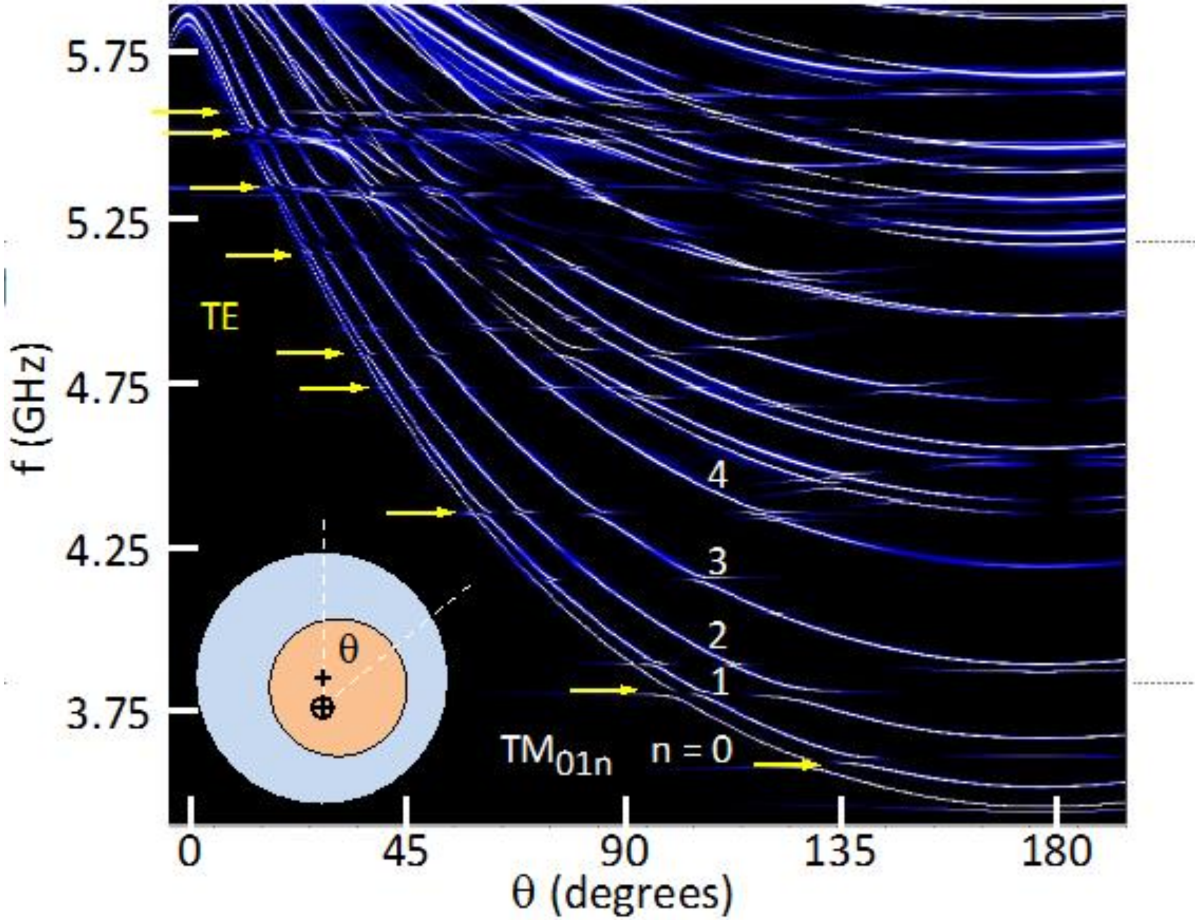
Mode Crossings



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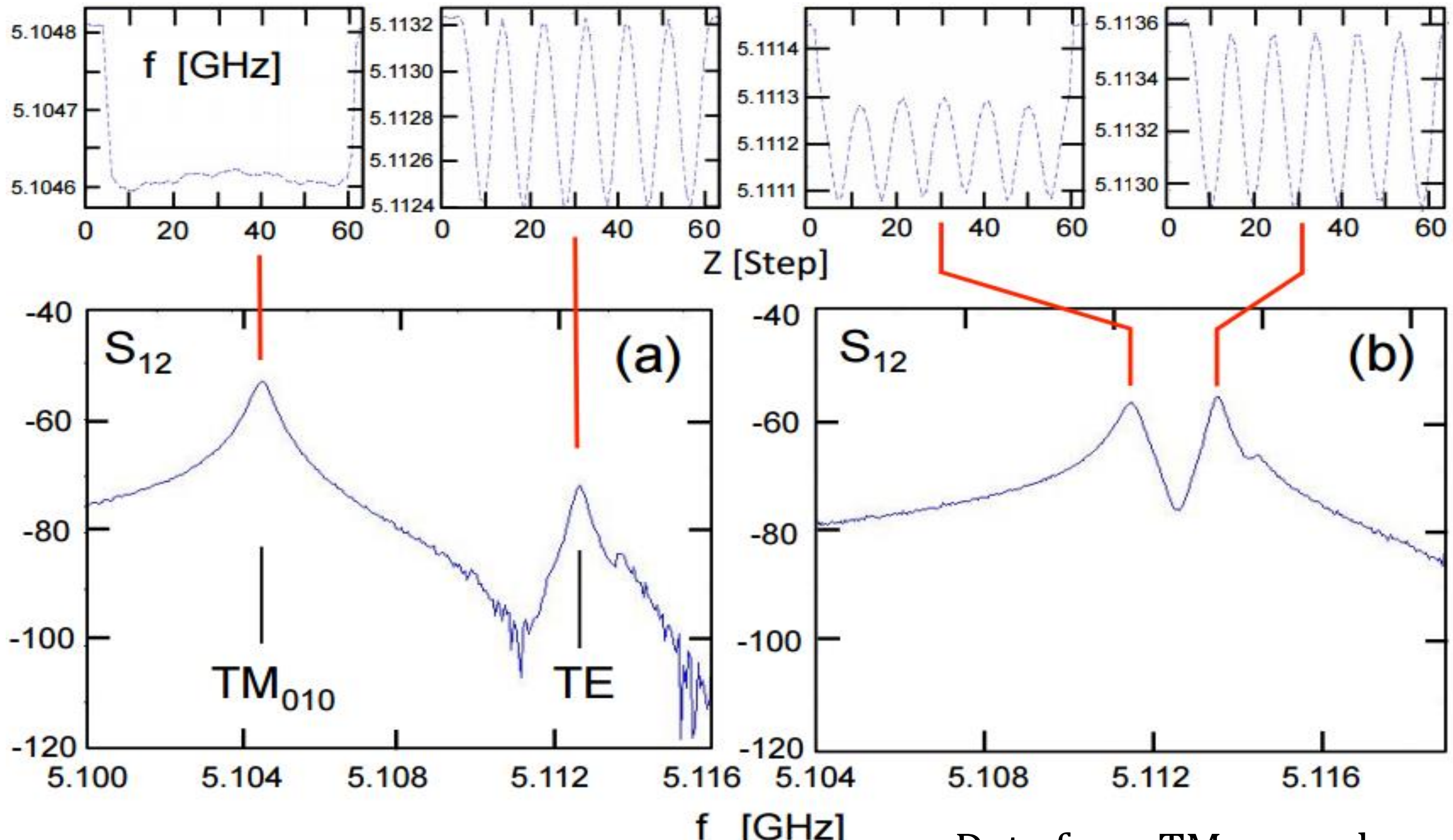
Mode Crossings



Data from TM_{010} mode no longer useful when mode is within ~3 MHz of TE mode

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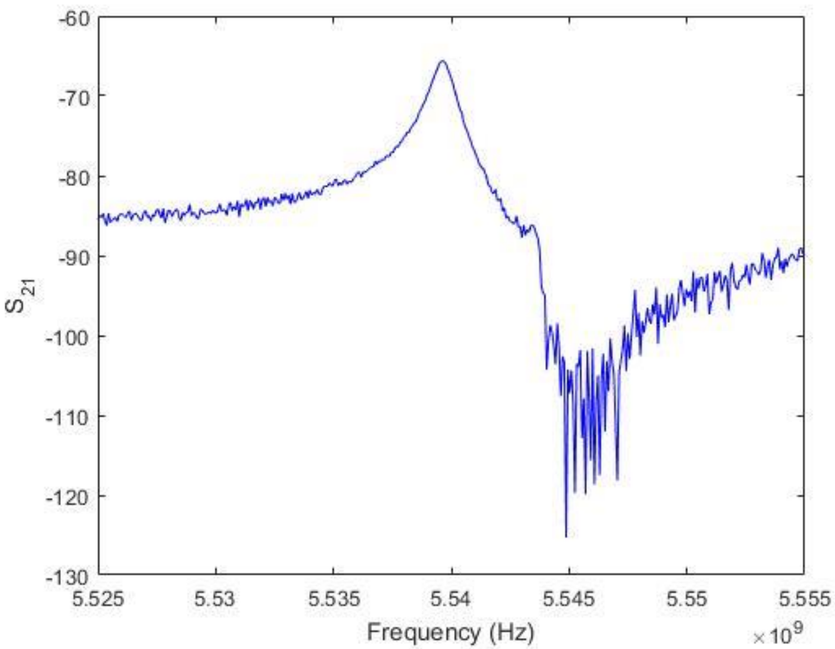
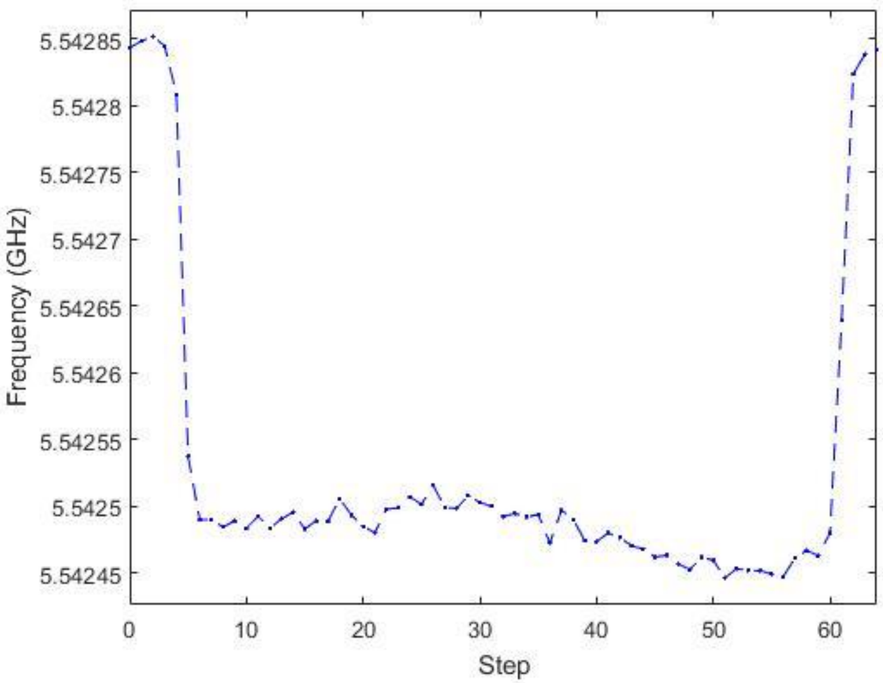
Mode crossings





Other noticeable mode crossings have no significant effect on TM_{010} mode

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Future work

- Bead pull study on actual cavity
  - Determining usable/unusable frequencies and impact of intruder modes
  - Ultimately, *in situ* bead-pull for real time characterization of the cavity and mode during the run.

- Full 3D mapping of cavity

- Simulations confirming behavior and studying further aspects of cavity
  - Free frequency ranges
  - New designs, e.g. Photonic Band Gap Cavities

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Conclusion

- Can determine type of each mode in spectrum using bead pull
- Good understanding of sensitivity to rod misalignments
- Ability to determine strength of mode crossings and determine effect on data taking

Thank you!

Questions?

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