Tuning Axion Detectors With Nonlinear Dielectrics

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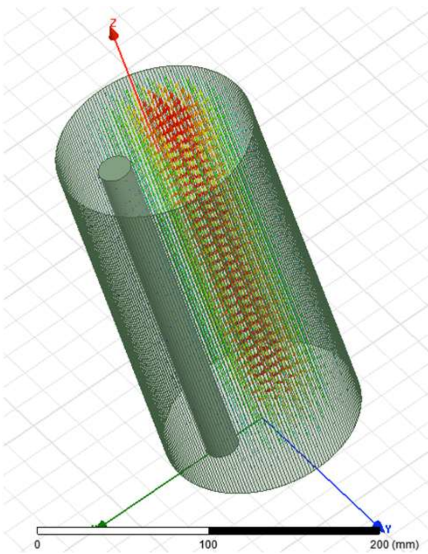
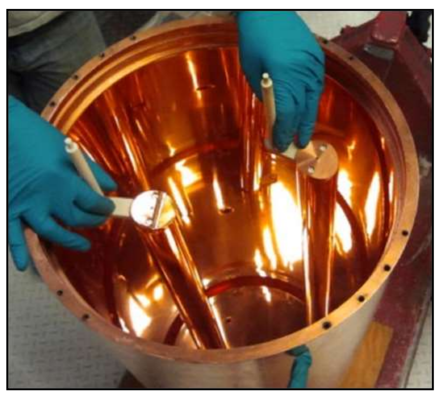
Problem: Current Axion Detector Mechanical Tuning Technique Doesn't Scale to High Axion Mass and Frequency.

- Number of resonator cells required goes as $1/\lambda^3$, with λ Compton wavelength of axion.
- Need large numbers of tuning rods and motors operating at millikelvin temperatures

TM010 Resonance Modified With Tuning Rod



ADMX Single Cavity Resonator, 0.5-1.5 GHz (2017-2019)



4- Cavity Array, 1.5- 2.2 GHz (2020-2021)

14- Cavity Array 2.2-2.4 GHz (2022-2024)

Fermilab

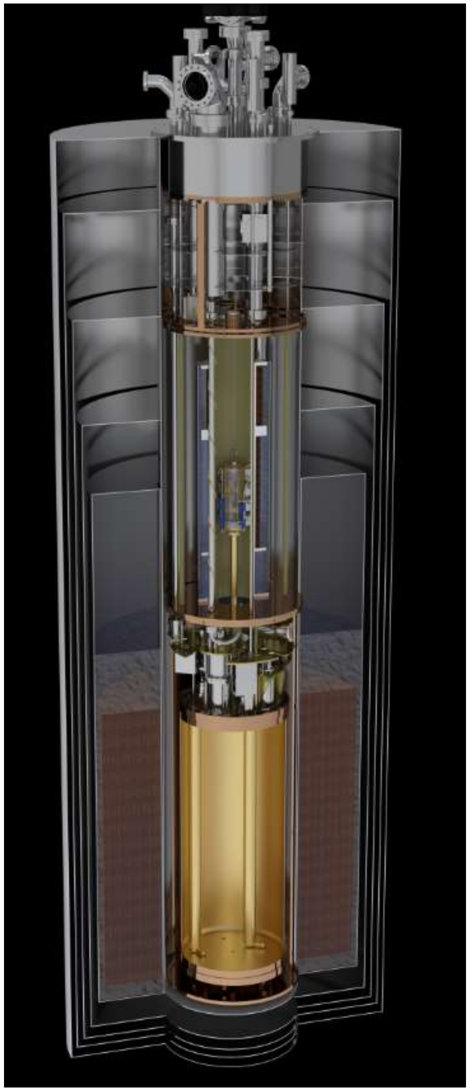
Scan Rate Vs Frequency & other parameters

$$\frac{df}{dt} \approx 1.68\ \text{GHz/year}\ \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \text{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \text{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \text{T}}\right)^4 \left(\frac{V}{100\text{l}}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2$$

Higher Magnetic Field Increases Signal

Arrays of Cryogenic RF Resonators Increase Volume

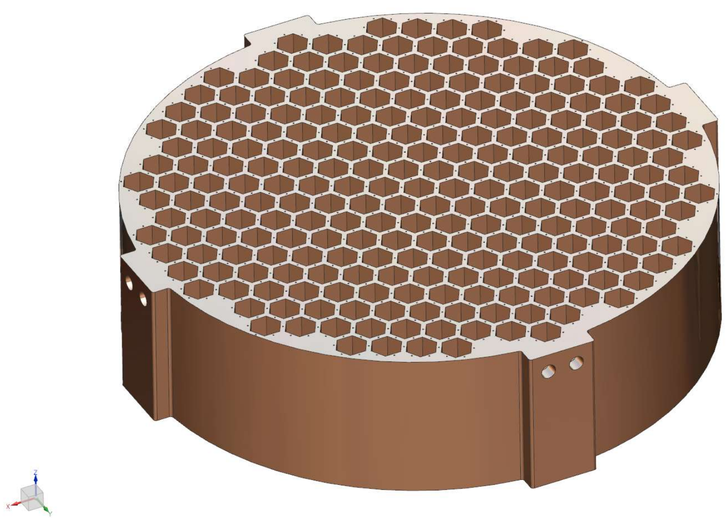
Quantum Sensors Reduce Noise (qubits, etc.)

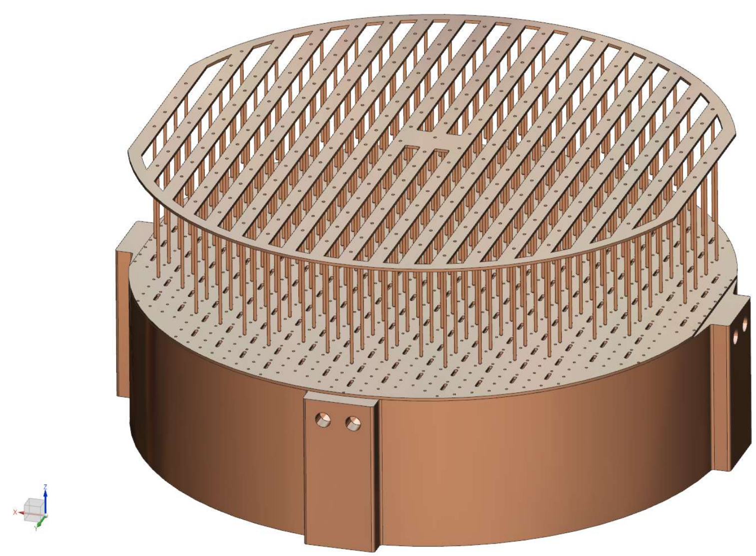


Large High Frequency Arrays for 4-10 GHz Range

- High frequency search will need hundreds of cavities.
- Common mode coarse tuning.
- Fine tuning at 0.1% level to lock all cavities to a common frequency.

1 meter

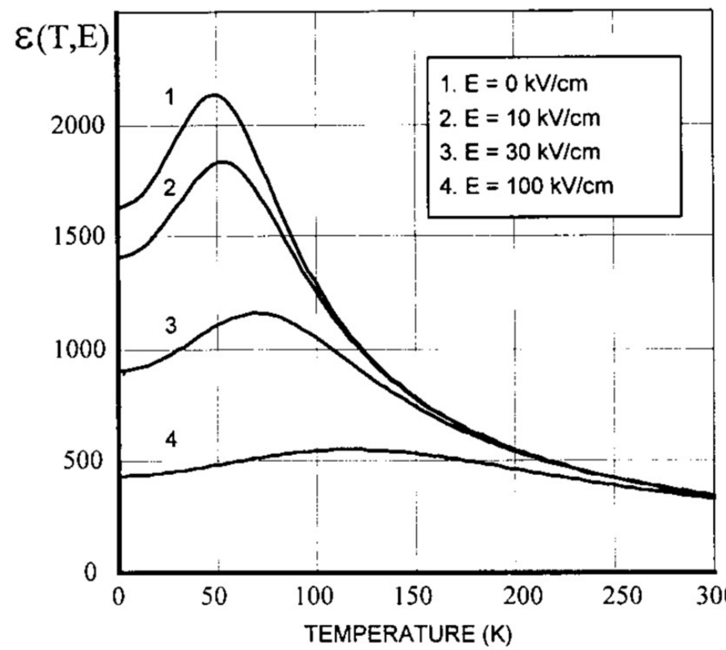




Proposed Solution: Electronic Tuning of Cavities with Non-Linear Dielectrics Such as Strontium Titanate

- Resonant frequency of detector cavities can be shifted using dielectric films.
- Non-linear dielectrics exhibit change in effective AC dielectric constant due to DC bias field.
- Effect can be remarkably large at low temperatures in some materials (SrTiO3 Strontium Titanate is best studied)

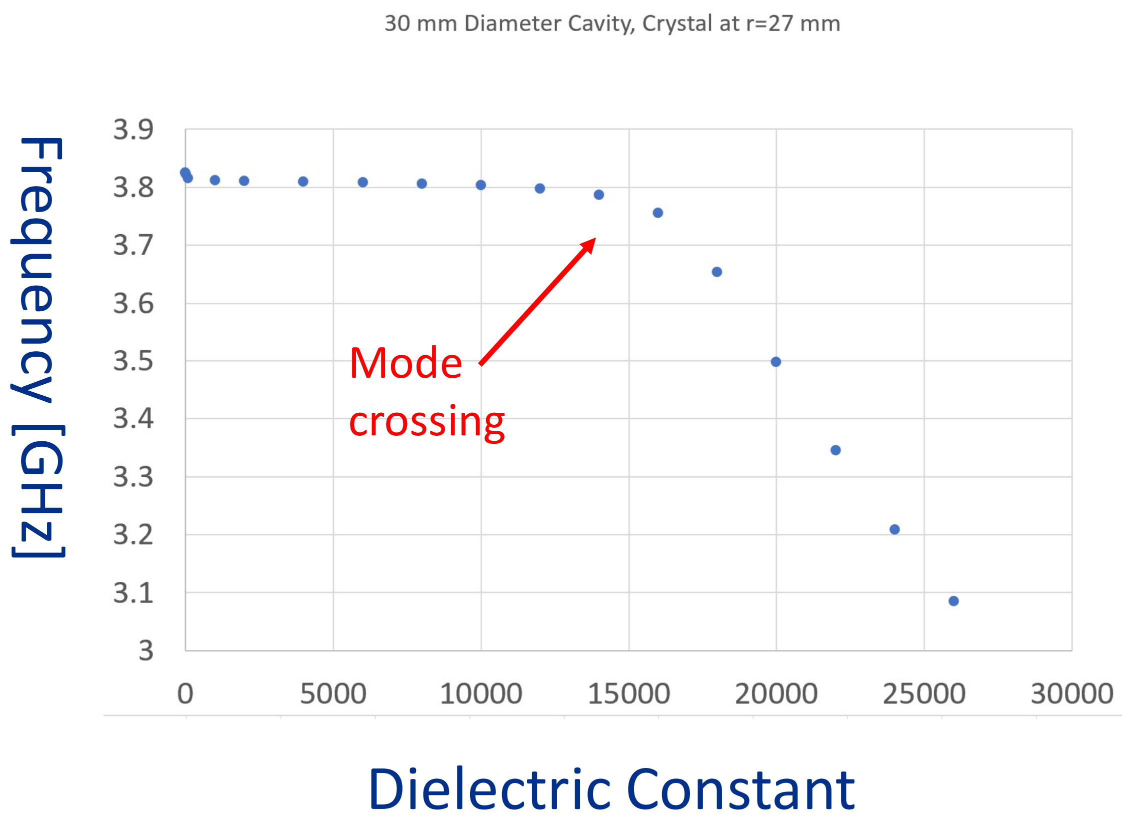
Strontium Titanate Microwave Dielectric Constant With DC Bias Field

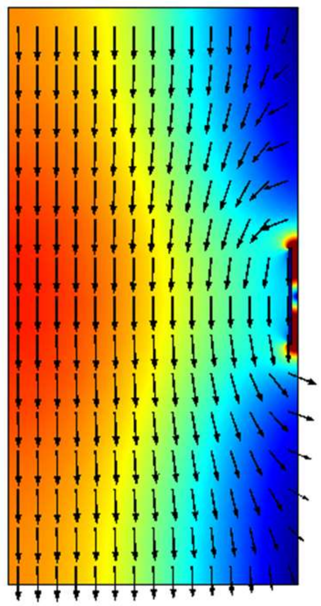


Vendik et al., 1999.

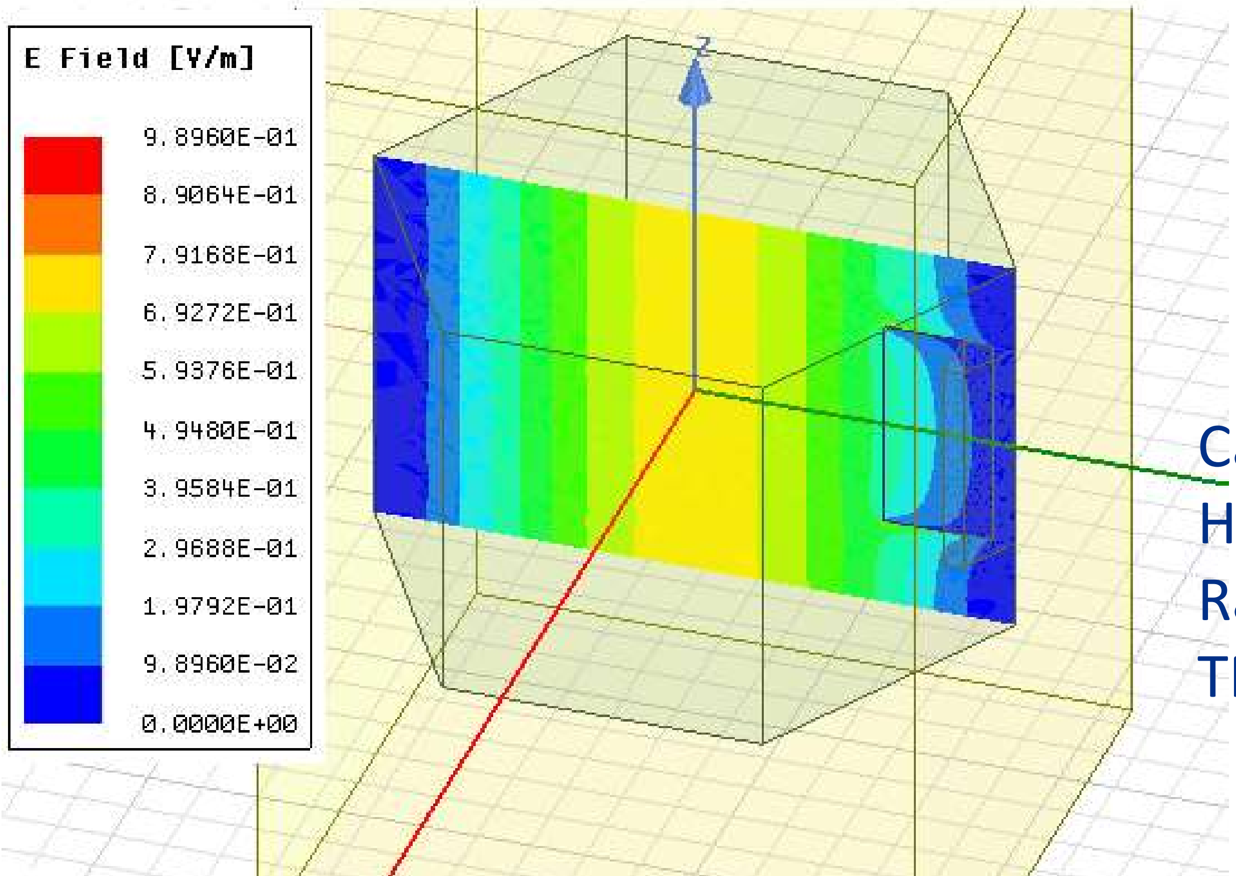
Frequency Shift Vs. Dielectric Constant

- Knee in frequency shift due to crossing of cavity and crystal modes- mode is mixed above the knee.
- For axion search, useful tuning range will be near the knee where fields resemble empty cavity TM_{010} modes.



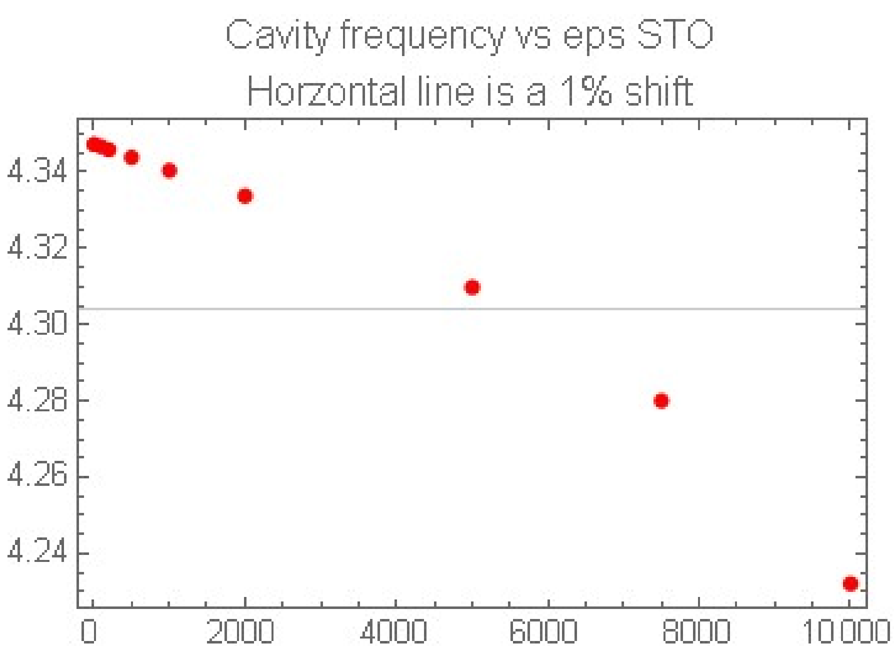


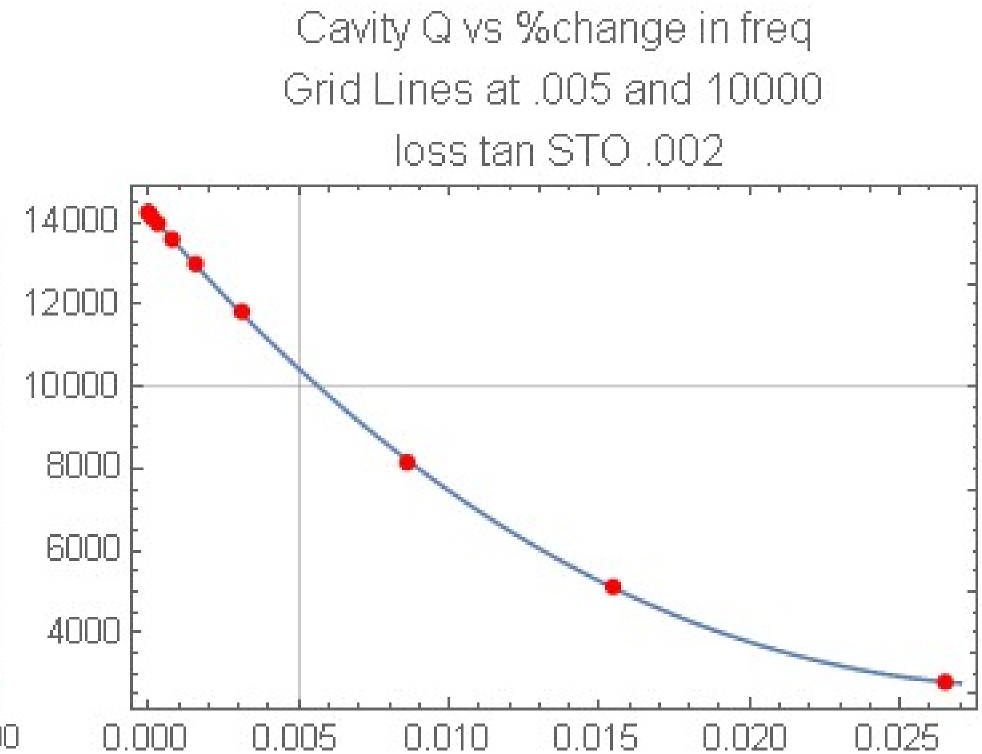
Simulation used: Hex cavity with a 2 x 1 x 0.5 cm quartz Plate with a 5 micron STO film on one side. The cavity is resonant at 4.34 ghz. The Ez is plotted in color.



Cavity
Height 1.5”
Radius 1”
TM010 mode

The Ez field is shown. It bisects the STO film. The BC at a dielectric Boundary are Et1 = Et2 and En1 = eps En2





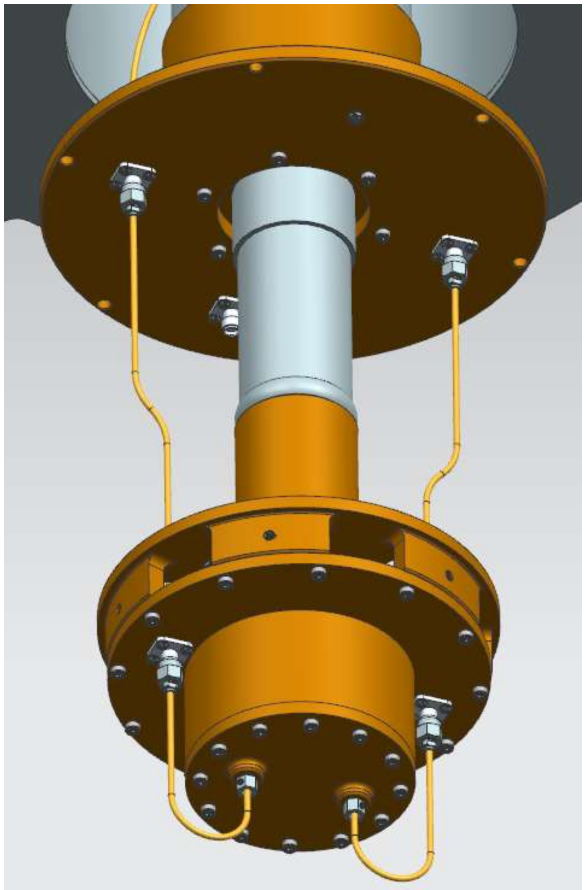
Freq vs eps STO 5 micron film

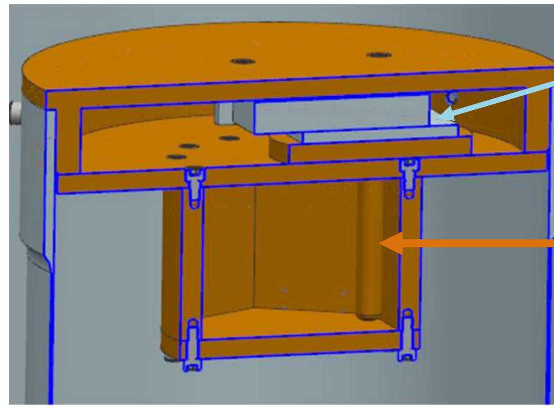
Cavity Q vs delta F/F

Unfortunately the STO dielectric has losses that lowers the Q . Loss tan = 1/Qd where Qd is the dielectric Q and is the energy stored / cycle over the energl loss per cycle. STO films have loss tan between .001 and 0.5.

The loss tan can limit the available frequency sweep!

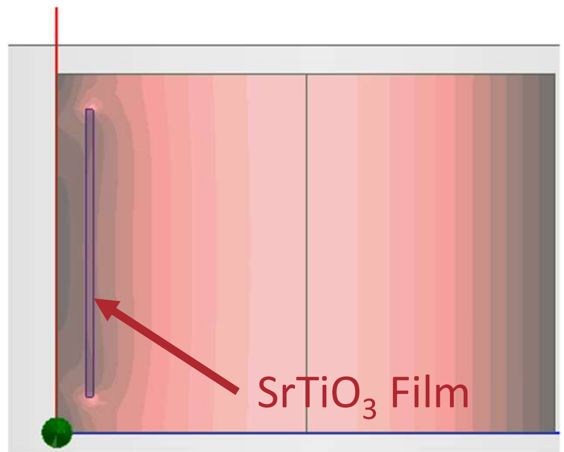
3D Hexagonal Resonator Design With Mechanical Coarse Tuning & Electronic Fine Tuning



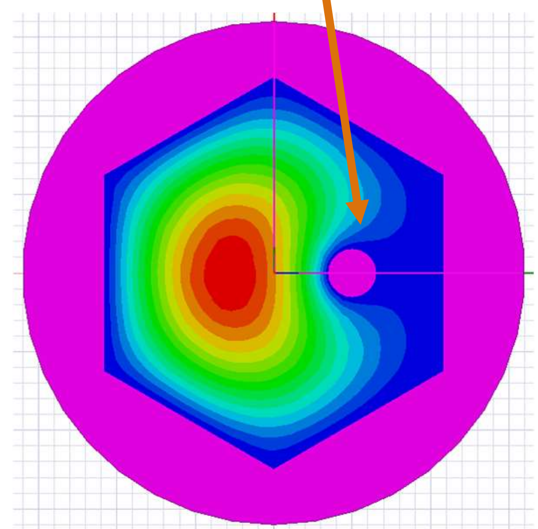


Piezoelectric linear actuator

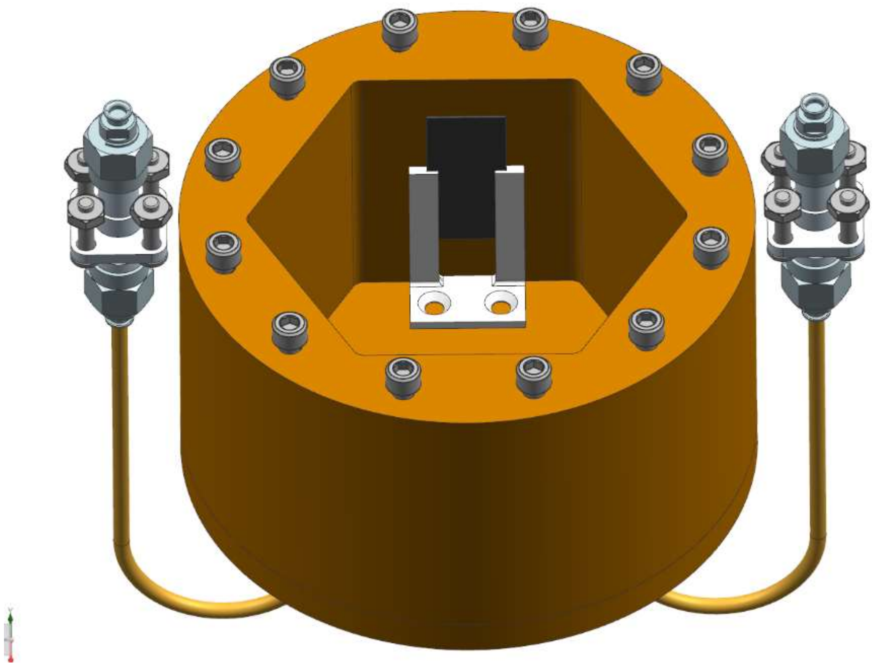
Tuning rod

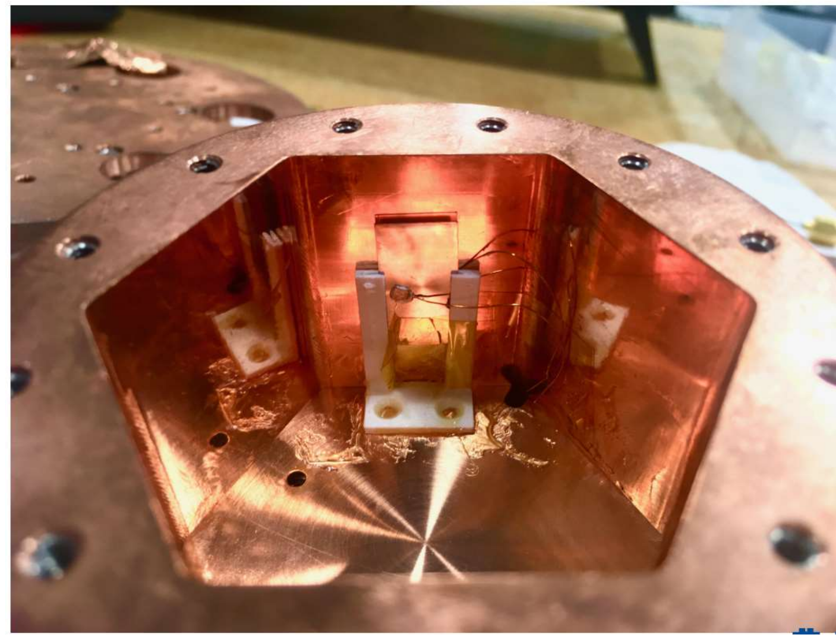


Electronic Fine Tuning



Mechanical Coarse Tuning

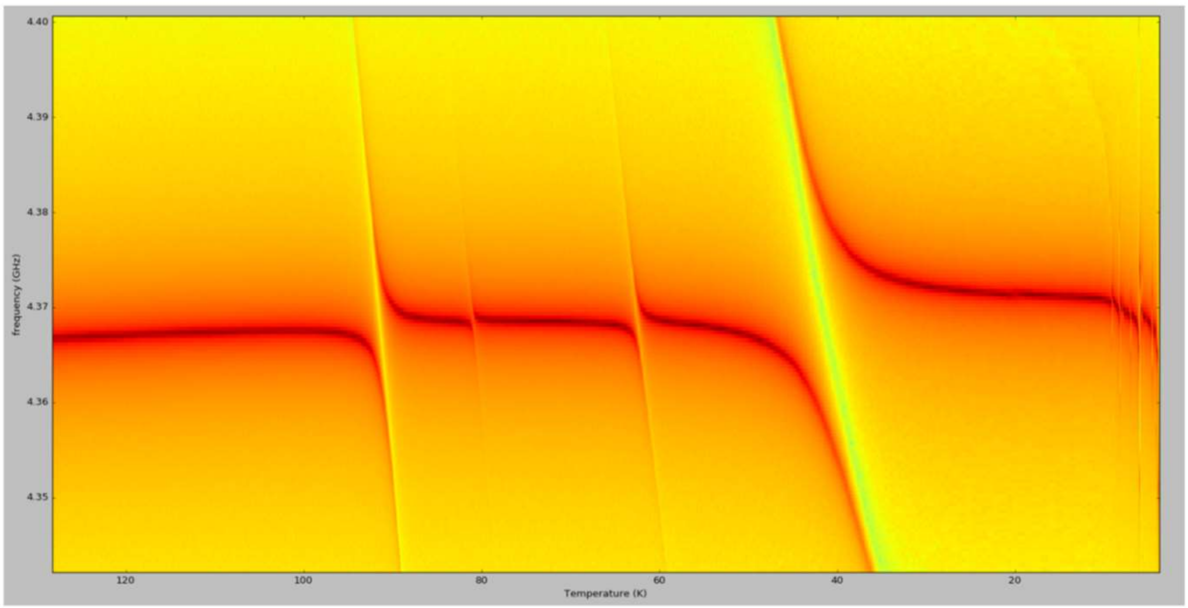




Initial Measurements of Coupled Crystal & Cavity

- Measure transmission between two antennas as crystal cools from room temp to 4 K.
- Dielectric constant increases from 300 (room temp) to 25,000 at 4K

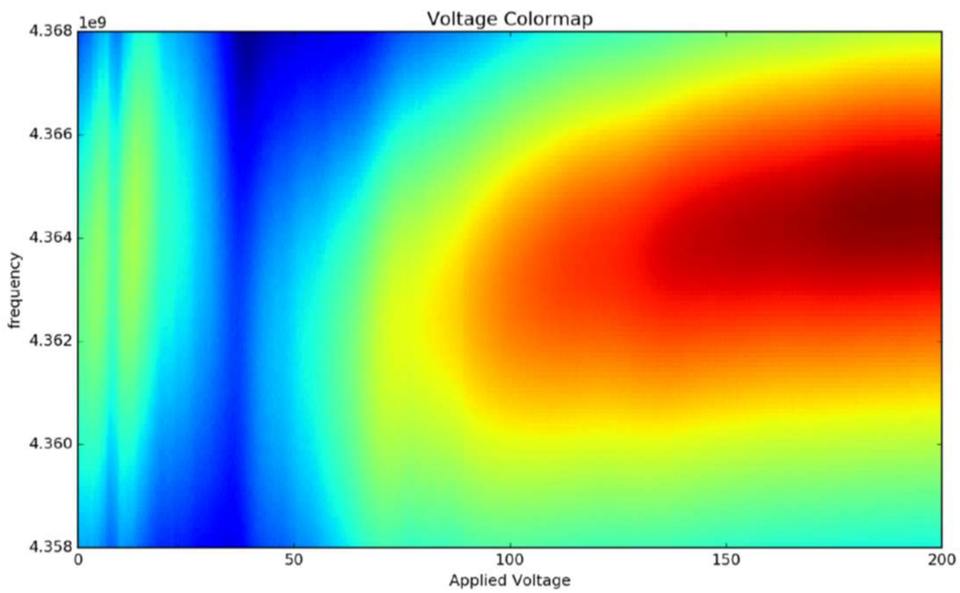
Frequency

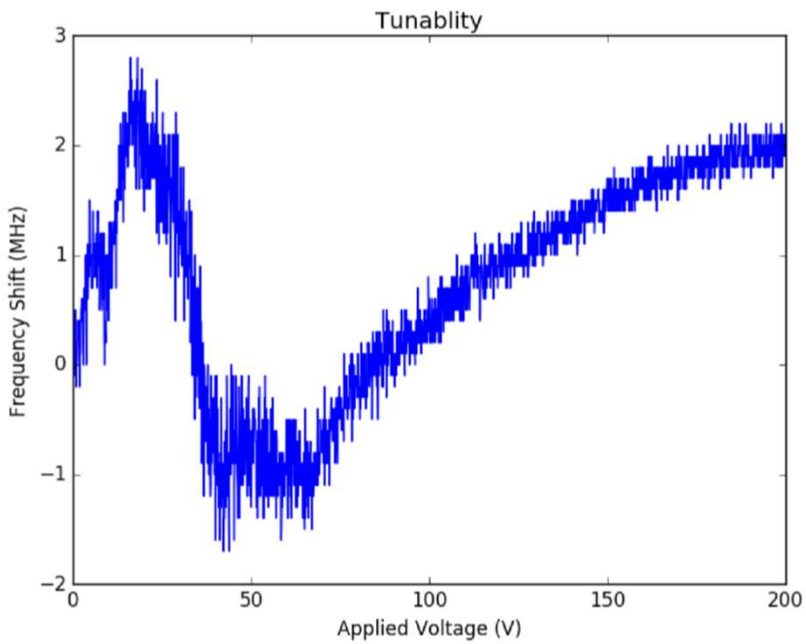


Temperature 300 -> 4 K

First Test of Electric Field Bias- August 2018

- Q is low in these initial test (~100) due to dissipation in electrode.
- Approximately 1 linewidth of tuning.





Effect of Bias Electrode Position and Resistivity

- Simulations show that bias electrodes need to be very resistive and close to cavity wall for high Q.
- E.g. 10 nm NiCr film ~ 100 Ohms/ Square