Tuning Cavity Arrays with Non-Linear Dielectrics

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Slow Progress Towards Cavity Arrays

- Arrays of up to 1000 cavities proposed 25 years ago or more.
- Largest prototype system used 4 cavities (Kinion, 2004)
- Al experiments done to-date used only a single cavity.

From "A Proposed Search for Dark Matter Axions in the 0.6-16 μeV Range", K. van Bibber et al., 1991.

Number of cavities	Arrangement	Tuning Range MHz	T_n K	Q_w	$\frac{1}{f}\frac{df}{dt}$ %/wk	Time weeks
1	○	148–233	6	530000	1.3	36
2	⊖	233–325	6	370000	1.4	23
4	⊕	325–488	6	300000	1.9	24
8	○×8	488–770	5	280000	1.8	27
16	⊖×8	770–1070	5	190000	1.9	17
32	⊕×8	1070–1350	5	160000	2.1	11
128	∘×64 × 2	1350–1880	6	150000	2.0	16
512	∘×128 × 4	1880–2620	7	130000	1.8	18
1024	∘×256 × 4	2620–3900	9	100000	1.7	24

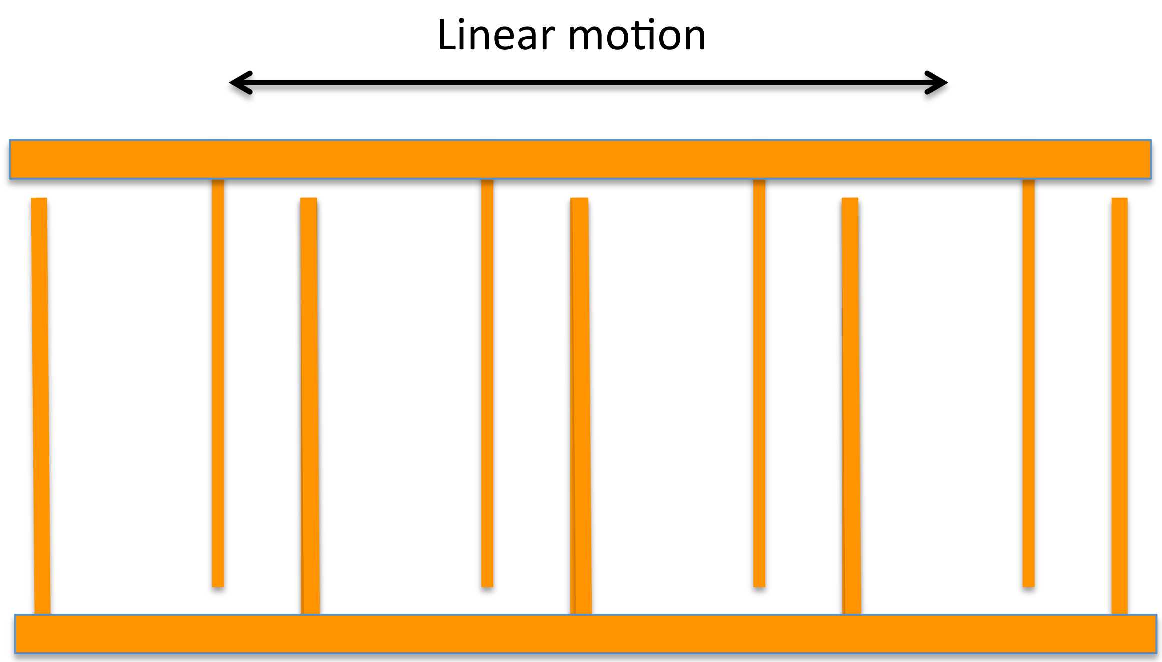
Table II. Search rate of the proposed experiment. Rate and time estimates were made with under the condition that a DFSZ axion would be seen with (s/n) = 4, and presumes the intrinsic cavity quality factors and effective total noise temperatures as shown.

Why Such Slow Progress?

- Tuning mechanisms for multiple cavities are mechanically complex, space in cryostat is limited.
- Power budget is very limited at mK temperatures.
- Cryogenic piezo mechanisms seem to have performance and reliability problems.
- …?

Tuning Multiple Cavities with A Single Mechanical Motion

- Idea: Tune many cavities to a common frequency with a single mechanical degree of freedom. Only 1 piezo actuator for entire array.
- Problem: cavities will all be at slightly different frequencies due to mechanical inaccuracies.
- We need some way to "trim" the cavities so they are all at the same frequency, at the level of a few parts per million for $Q \sim 10^5$



Tunable Dielectrics

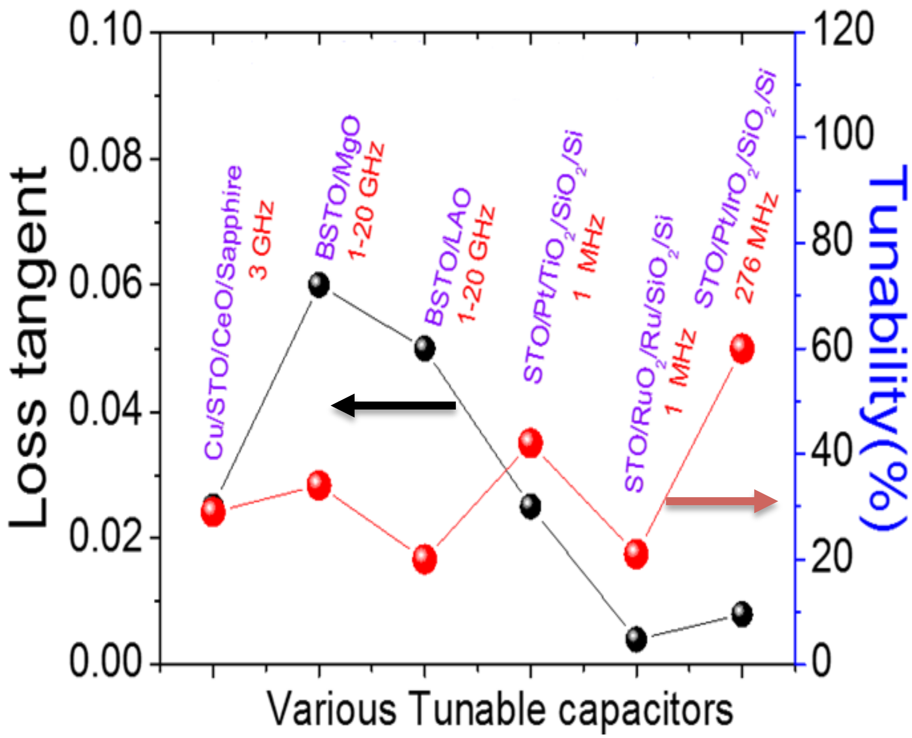
- In the limit where backreaction of an inserted dielectric object on fields is small, change in cavity frequency is simply:

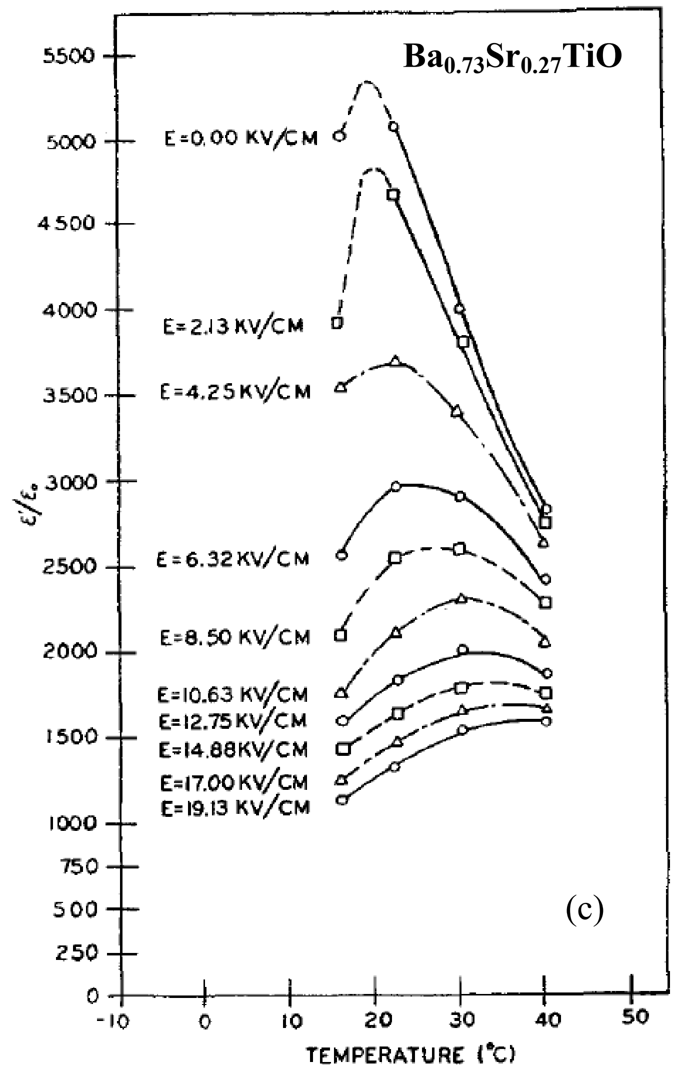
$$\frac{\omega - \omega_0}{\omega_0} \simeq \frac{-\int_{V_0}(\Delta\epsilon|\bar{E}_0|^2 + \Delta\mu|\bar{H}_0|^2)dv}{\int_{V_0}(\epsilon|\bar{E}_0|^2 + \mu|\bar{H}_0|^2)dv}$$

- Frequency change is proportional to change in dielectric constant.

- With non-linear dielectric response, effective small signal AC dielectric constant is affected by a DC field.

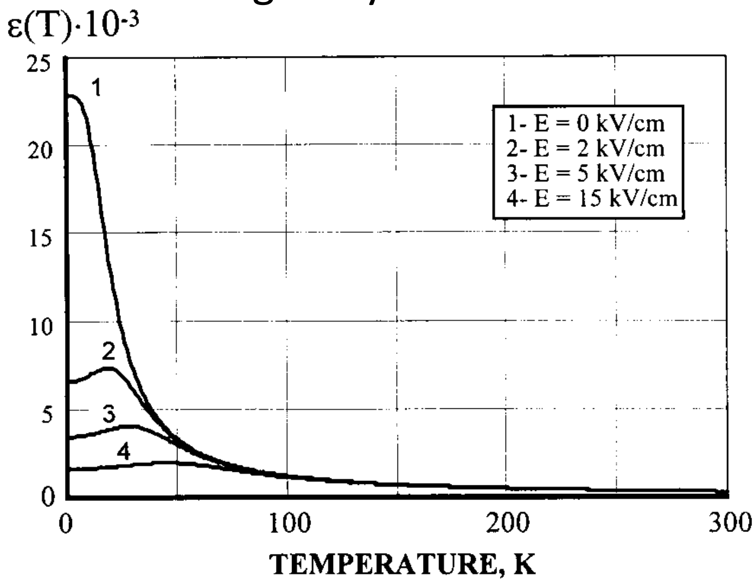
Tunable Dielectrics



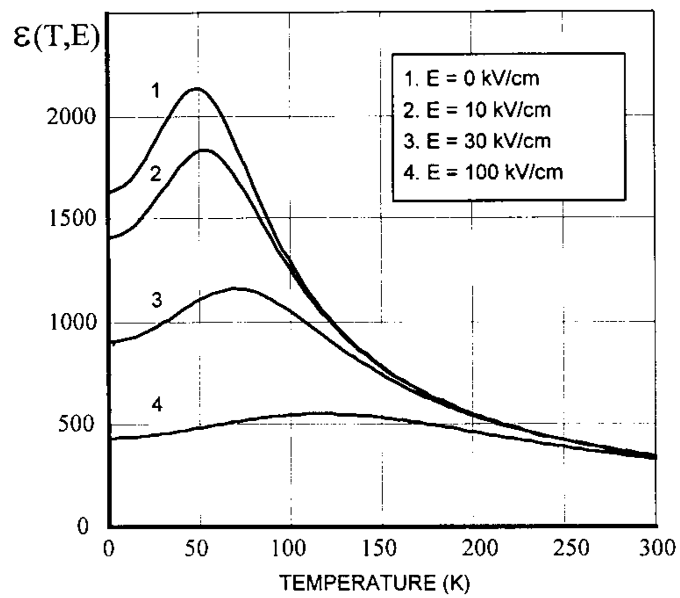


Strontium Titanate (STO) Field- Dependent Dielectric Constant at Low Temperature

Single Crystal

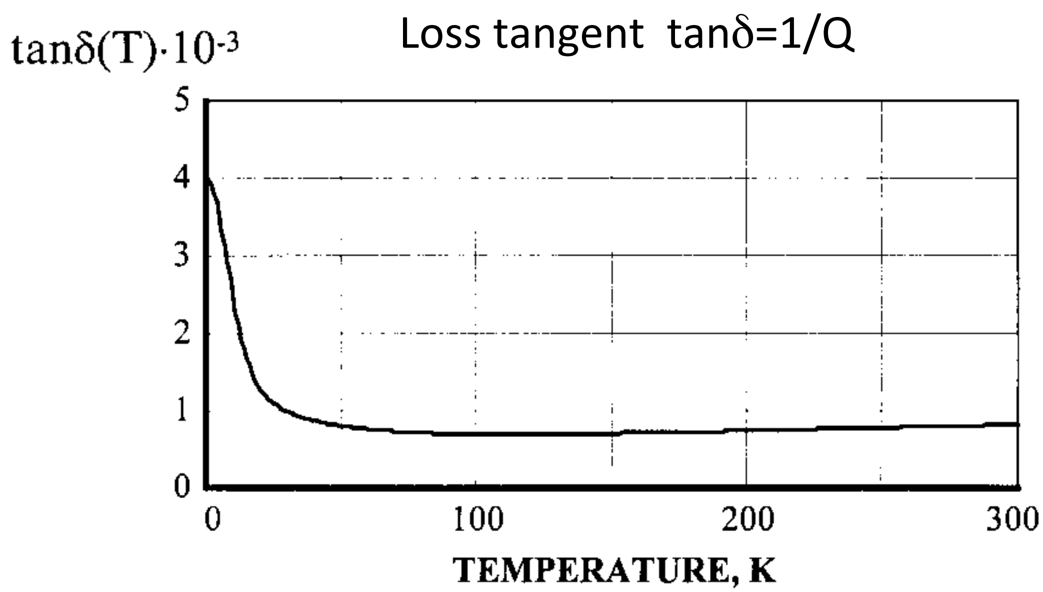


Thin Amorphous Film



Vendik et al., 1999.

Strontium Titanate Dielectric Losses at 10 GHz



Vendik et al., 1999.

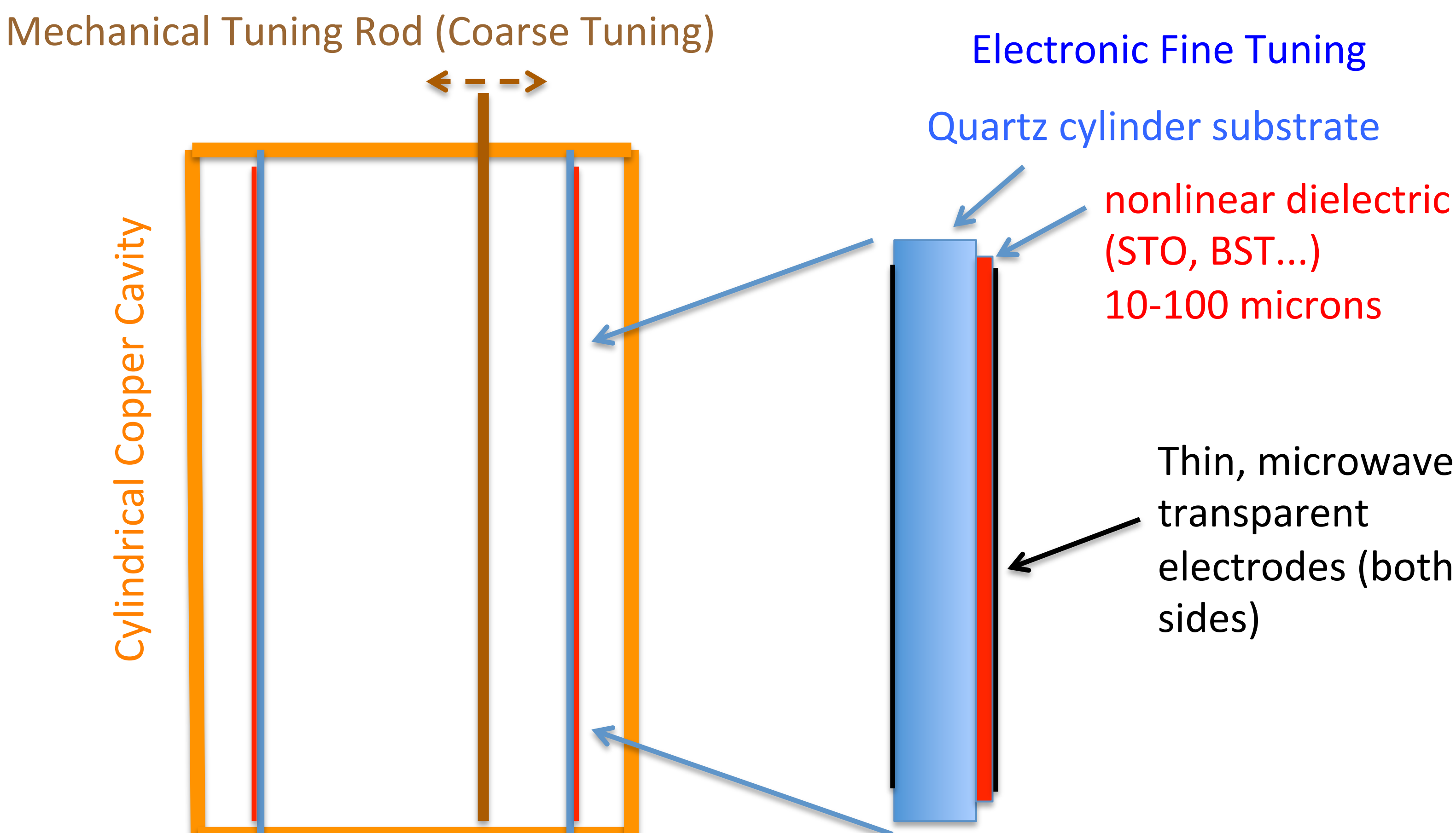
- Intrinsic Q factor is $1/\tan\delta \sim 250$ below 4 K.

Figure of Merit for Tunable Dielectrics

Figure of Merit* K = *Tunability*Q = $(\varepsilon_{v0}-\varepsilon_{v1})/\ \varepsilon_0 \tan\delta$, where ε_{v0} is zero field dielectric constant and ε_{v1} is in maximum bias field.

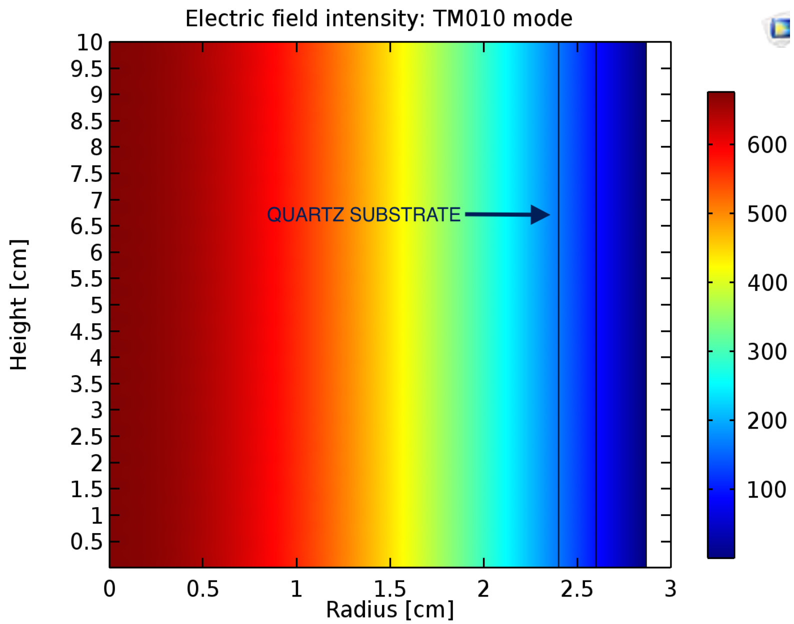
- For strontium titanate at cryogenic temperatures and GHz frequencies, K≈200
- With a partially filled resonator, it's possible to adjust tunability and Q as long as the product K remains constant
  - For example, $K=10^{-3} * 10^{5}=100$
  - It should be possible to build a resonator with 10^{-3} tunability and $Q \sim 10^5$

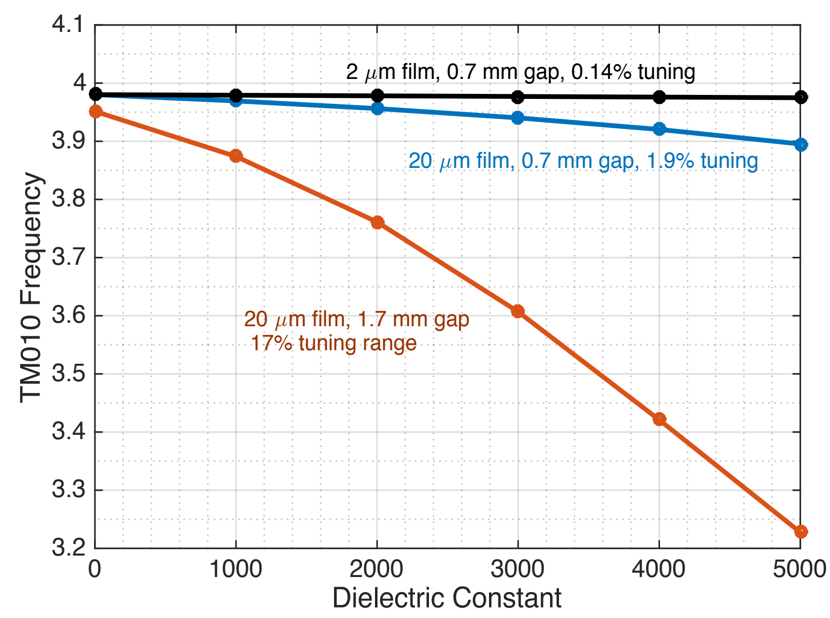
Electronic Fine Tuning With Nonlinear Dielectrics



COMSOL Simulations

- Studied tuning effect of dielectric film on a cylindrical quartz substrate.
- Tuning depends on film thickness, dielectric constant and radial position.
- For typical STO amorphous film properties, thickness will need to be ~ 1 micron and gap to wall ~ 1 mm.





Fermilab LDRD Proposal 2015

In collaboration with Daniel Bowring (Fermilab, Accelerator Division) and Shashank Priya (Virginia Tech, Dept of Mechanical Engineering)

1. Measure tunability and loss tangent of dielectric samples in fields up to 10 Tesla at 2 K, using coplanar resonator technique. Materials to explore: $Ba(Zr_xTi_{1-x})O_3$ and $(Sr,Bi)TiO_3$ Films will be deposited on quartz substrates at Virginia Tech.
2. Test tuning of 4 GHz cavity with BST dielectric at room temperature. Goal is to demonstrate 0.1% tuning without significant deterioration of Q.
3. Test cavity tuning at 2 K using optimized film.

Fermilab Test Facility for Conductor and Inserts

	Oxford Teslatron #1	Oxford Teslatron #2	Oxford Teslatron #3	Oxford Teslatron #4
Bz_max	15 T (4.2K) 17 T (2.2K)	14 T (4.2K) 16 T (2.2K)	Not equipped with solenoid for external field generation.	8.5 T (4.2K) 10 T (2.2K)
External Nb3Sn/ NbTi Fully SC Magnet Geometry	Cold Bore: **68 mm** OD: 192 mm Height: 167 mm	Cold Bore: **77 mm** OD: 218 mm Height: 180 mm	Max Magnet OD: **253 mm** (accommodates up to 4 DP helical units)	Cold Bore: **147 mm** OD: 224 mm Height: 240 mm

2 kA power supply (5 kA on order), data acquisition for quench monitoring and cryogenic monitoring

Other R&D Topics

- Tuning large arrays of cavities would be easy if we could achieve mechanical precision at the level of 1/Q~10^{-5}~(1 micron/ 10 cm). *This may or may not be possible.*

- R&D to investigate limits of mechanical precision would be useful.

- If the necessary degree of mechanical precision is impossible, common mechanical coarse tuning could be combined with electronic fine tuning of individual cavities. A modest degree of fine tuning would be required ~0.1% at the most.

- Possible fine tuning mechanisms:
  - Tunable dielectric films
  - Varactor-loaded cavities
  - Feedback
  - Short stroke piezo actuators
  - Others?