FERROELECTRIC BASED HIGH POWER COMPONENTS FOR L-BAND ACCELERATOR APPLICATIONS

Supported by the DOE SIR DE-SC0007630, Phase II

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On behalf of Euclid Techlabs/BNL/FNAL collaboration

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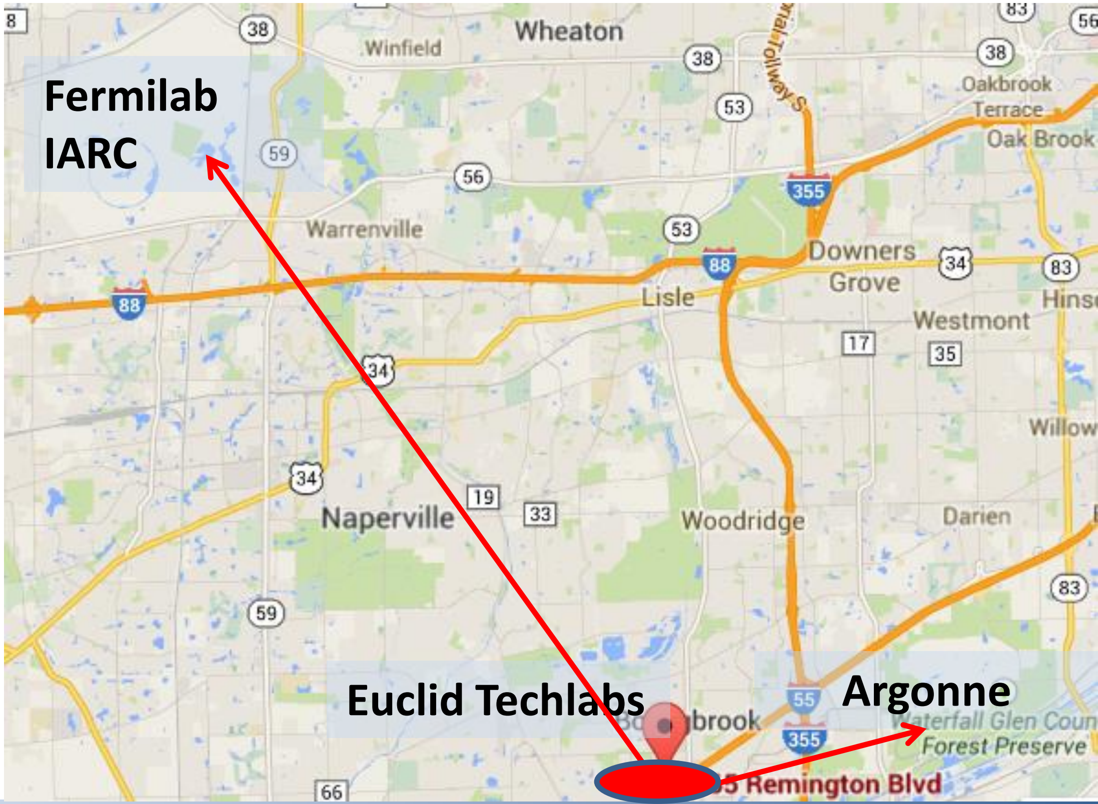
Euclid Techlabs LLC

Euclid TechLabs LLC, founded in 1999 is a company specializing in the development of advanced materials and new designs for beam physics and high power/high frequency applications. Additional areas of expertise include dielectric structure based accelerators and "smart" materials technology and applications.

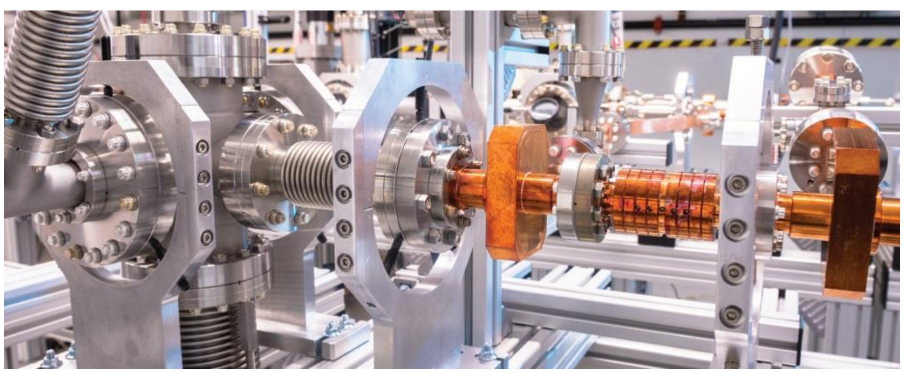
- 20 people, 17 research staff including 14 PhDs.
- 2 offices: Bolingbrook, IL (lab) and Gaithersburg MD (administrative).
- Tight collaborations with National Labs: Argonne, Fermi, BNL, LBNL, LANL.
- Actively participate in Accelerator Stewardship DOE Program
- Joined Fermi/IARC lately



NEW LAB FACILITY IN BOLINGBROOK IL

- Compact electron accelerator test facility (bunker)
- Time resolved TEM beamline
- Clean room/magnetron sputtering (TiN, copper, dielectrics)
- Field Emission cathode DC test stand
- Femtosec laser
- RF lab
- …other beam physics related equipment - www.beamphysics.com

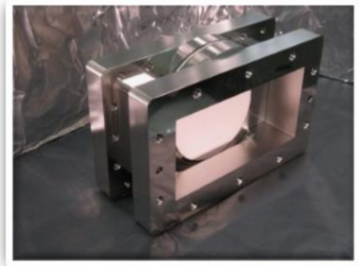
8000 sq. ft. - total
1000 sq.ft. – office
7000 sq.ft. - lab



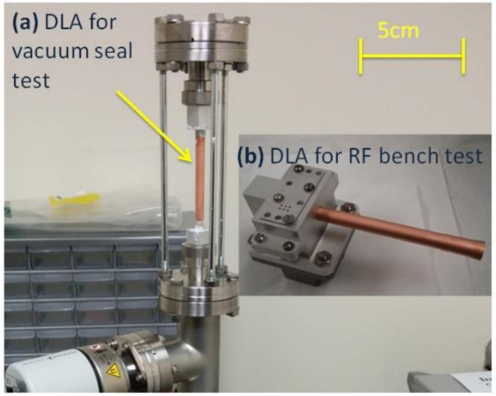
ANL/AWA accelerator, ANL/CNM - FE UNCD,
ANL/APS- diamond based X-ray optics
Fermi: SRF tests

Products and Projects

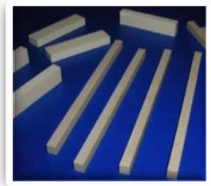
L-band high peak current LINAC



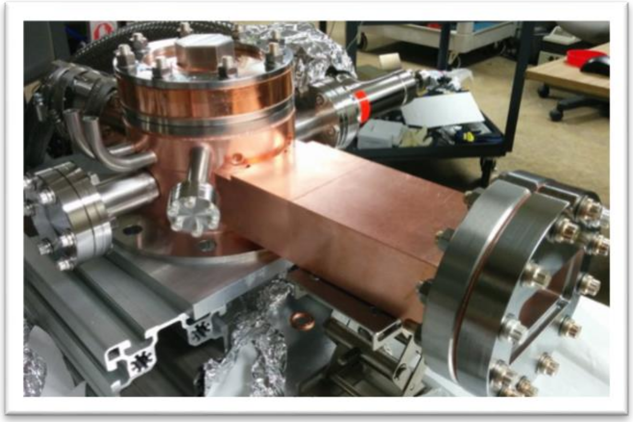
UHV L-band RF window



Compact dielectric accelerator

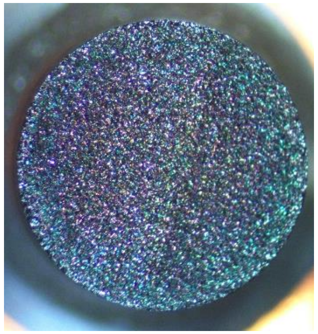


Linear and non-linear ceramics low loss; various form factors

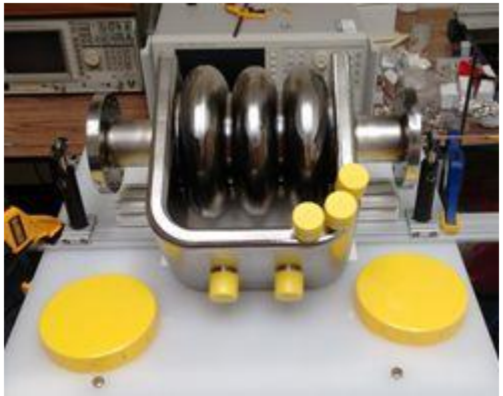


Photoinjectors:

- L-band high peak current
- S-band (high brightness)
- S-band (high rep rate)

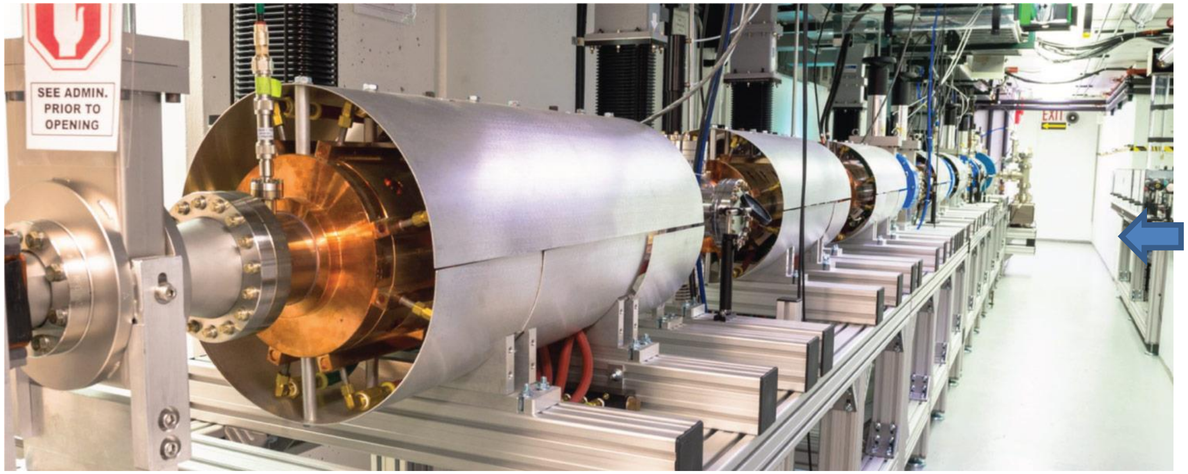


UNCD diamond cathode



3 Cell Traveling Wave SRF cavity (joint project with FNAL)

Research on Dielectric Wake Field Accelerating (DWFA) structures



Experiments with DWFA were done by Euclid Techlabs at Argonne,

- Externally powered dielectric structure: Naval Research Lab

- designs: 7-26 GHz
- scalable to THz

Brookhaven, SLAC

History: Tunable Dielectric-Based Accelerator

PRL **106,** 164802 (2011) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2011

Experimental Demonstration of Wakefield Acceleration in a Tunable Dielectric Loaded Accelerating Structure

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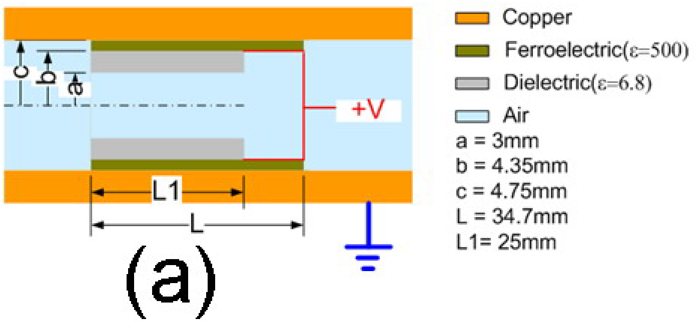
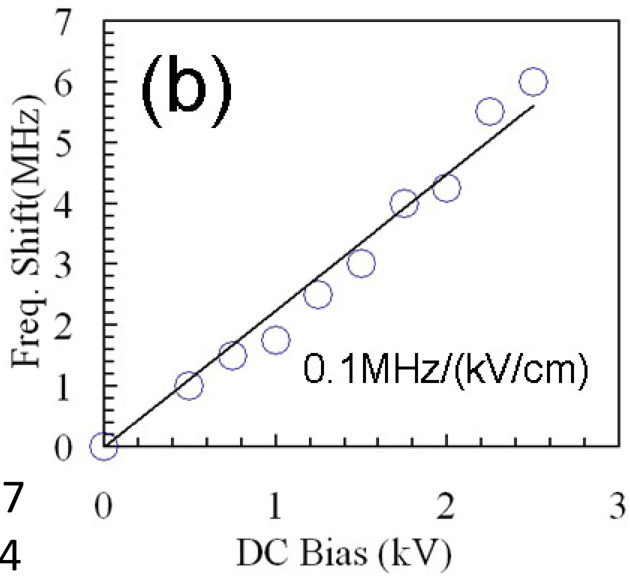
(Received 28 January 2011; published 21 April 2011)

We report on a collinear wakefield experiment using the first tunable dielectric loaded accelerating structure. By introducing an extra layer of nonlinear ferroelectric, which has a dielectric constant sensitive to temperature and dc bias, the frequency of a dielectric loaded accelerating structure can be tuned. During





ε(E) for ferroelectric dielectric composite

NONLINEAR CERAMIC

US patent 7,768,187
US patent 8,067,324

Ferroelectric Based Tuner (Ultrafast Phase Shifter) for SRF Accelerator Operation

Motivation

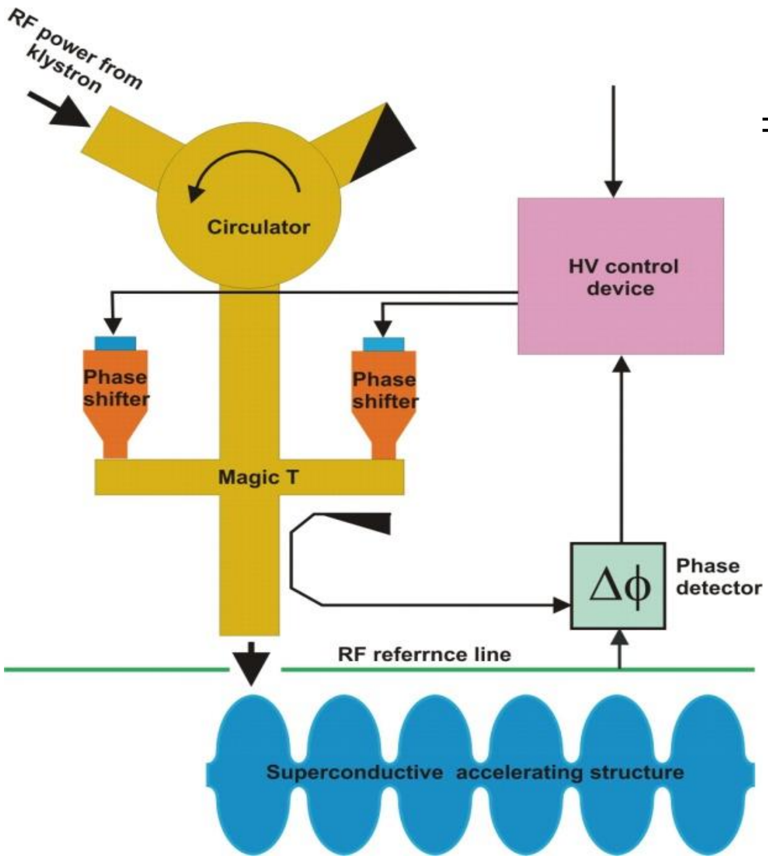
- A fast controllable phase shifter would allow microphonics compensation for CW SRF accelerators supporting ERLs and FEL.

- Nonlinear ferroelectric microwave components can control the tuning or the input power coupling for rf cavities. Applying a bias voltage across a nonlinear ferroelectric changes its permittivity. This effect can be used to cause a phase change of a propagating rf signal or change the resonant frequency of a cavity. The key is the development of a low loss highly tunable ferroelectric material.

- Topic was suggested by BNL (I.Ben-Zvi) for eRHIC cavity tuning

Tuner Requirements

$$P_g = P_{loss} + \omega W / Q_0 \quad \Delta\omega = 2Q_0 / \omega. \quad P_{g,\max} = W\delta\omega$$



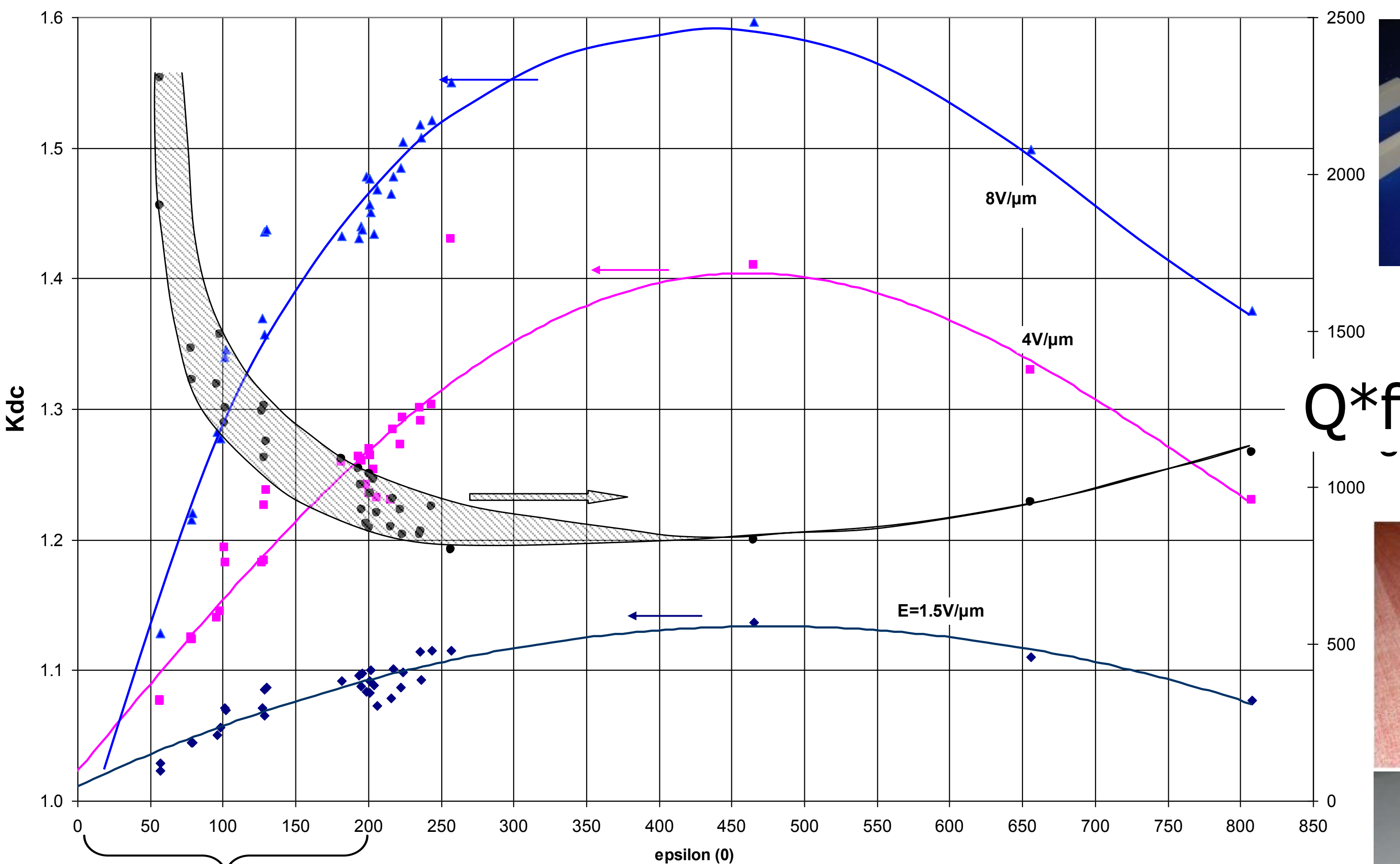
$$= P_g / P_{g,\max} = \delta\omega / \Delta\omega \left(1 - 4tn\delta \frac{\eta(\varphi_0)\varepsilon}{\Delta\varepsilon}\right).$$

for BNL ERL and the tuner described in the Euclid Proposal ($\Delta\varepsilon/\varepsilon$=0.2 and φ_0= 135°)

For a typical ferrolectric tuner needed for ERL SC cavity excitation, on need ferroelectric material having the tunability of 0.06 and loss tangent of ~0.001.

Progress on BST Material Development

$(Ba, Sr)TiO_4$+Mg oxides



BST(M),
ε~50-150

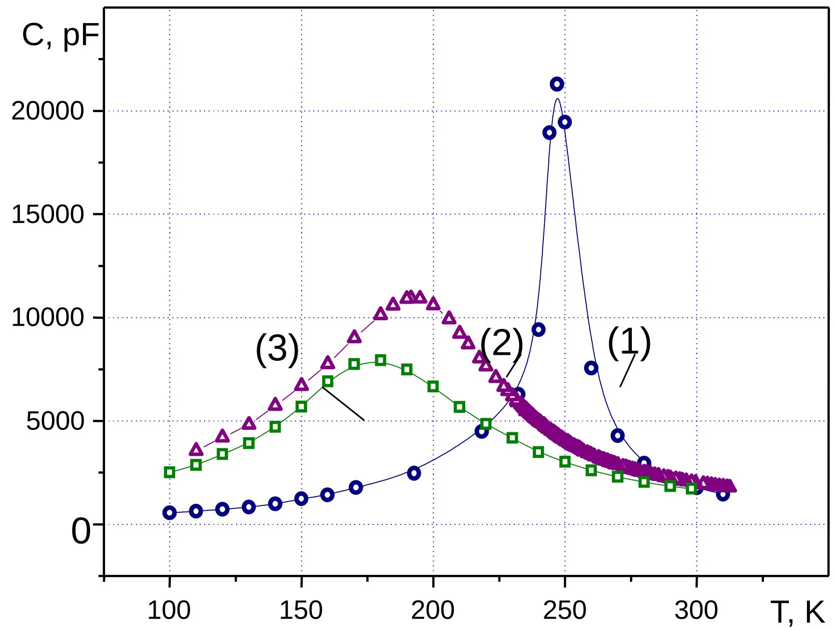
record low values of dielectric constant and loss tangent at relatively high tunability level required for high power bulk tuner operating in air (< 30 kV/cm) and in vacuum (up to 80 kV/cm).

Ferroelectric ceramic properties

Parameters	Value
dielectric constant, ε	50-450
tunability, $\Delta\varepsilon$	>30@15kV·cm^{-1} of the bias field
response time	< 10 ns
loss tangent at 1.3 GHz, tanδ	~1×10^{-3}
breakdown limit	200 kV/cm
thermal conductivity, K	7.02 W/m-K
specific heat, C	0.605 kJ/kg-K
density, ρ	4.86 g/cm^3
coefficient of thermal expansion	10.1×10^{-6} K^{-1}
temperature tolerance, $\partial\varepsilon/\partial T$	(1-3) K^{-1}

Issues with the ferroelectric elements

- Dielectric constant has to be low (~ 100)
- Loss factor has to be low ~ 1.0×10^{-3} at 1 GHz
- Tuning range has to be high ~ 6-8% at 20kV/cm
- Residual effects have to be mitigated



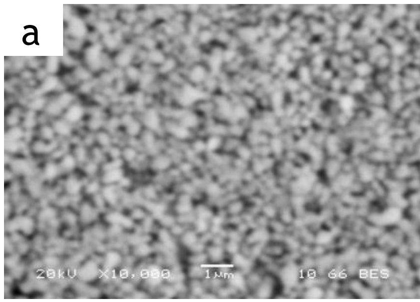
(Ba, Sr)TiO_4+Mg oxides

Ferroelectric composite materials

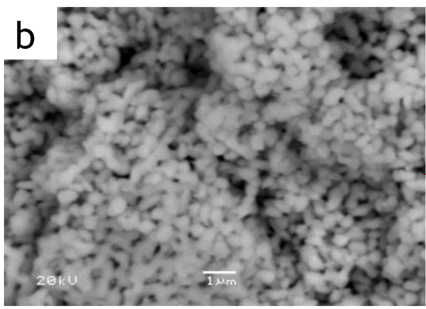
Patent US 8,067,324 B2, Nov. 29, 2011

Powders → Ceramics

a

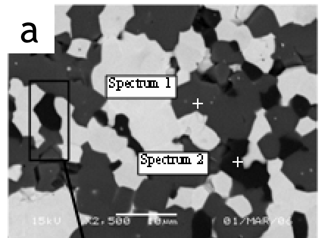


b

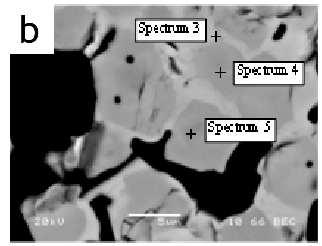


SEM-image of the initial powders of barium titanate (a) and strontium titanate (b)

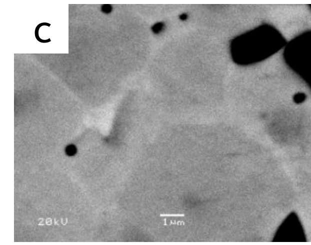
a

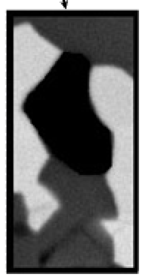


b

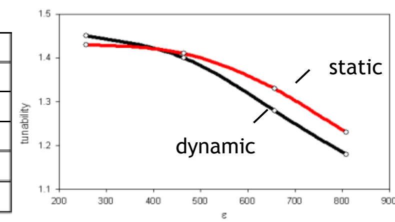


c





Spectrum	Mg	Ti	Sr	Ba	O	Total
Spectrum 1	29.66	27.47	1.39	2.99	38.49	100.00
Spectrum 2	59.89	0.19	0.26	0.06	39.60	100.00
Spectrum 3	0.19	22.57	16.33	38.09	22.82	100.00
Spectrum 4	0.14	22.62	21.85	32.23	23.16	100.00
Spectrum 5	0.25	23.36	27.91	24.64	23.84	100.00

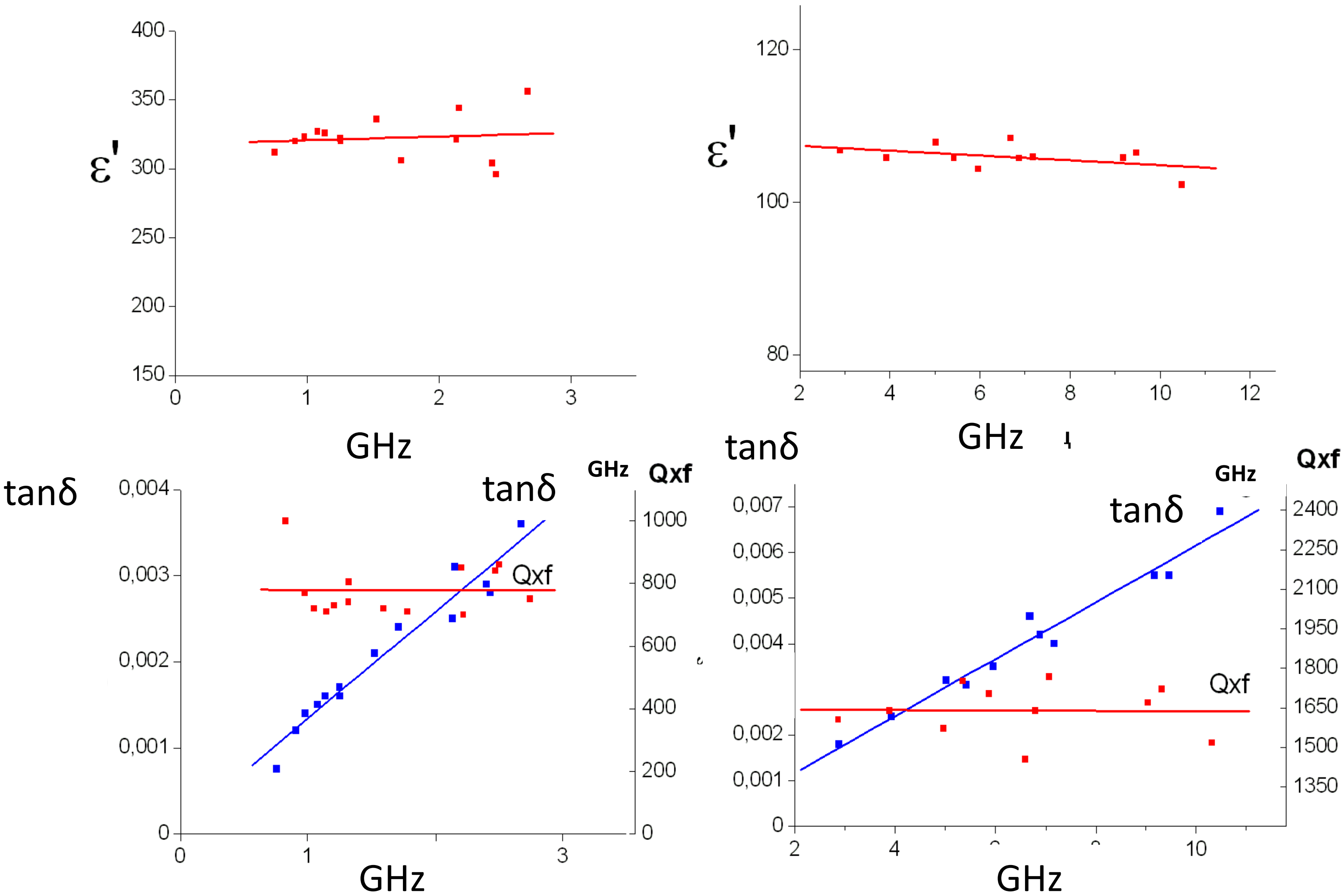


SEM images and EDS data of the sample on the basis of BST ferroelectric with linear Mg - containing additive (T = 1420 ° C) (a, b) and (T = 1400 ° C) (c).

Static and dynamic tunability as a function of the permittivity

SEM image of the boundary interface region in between the grains of the BST-MgO-Mg_2TiO_4 composite material.

Frequency dependence of ε and tanδ for the ferroelectrics with low permittivity



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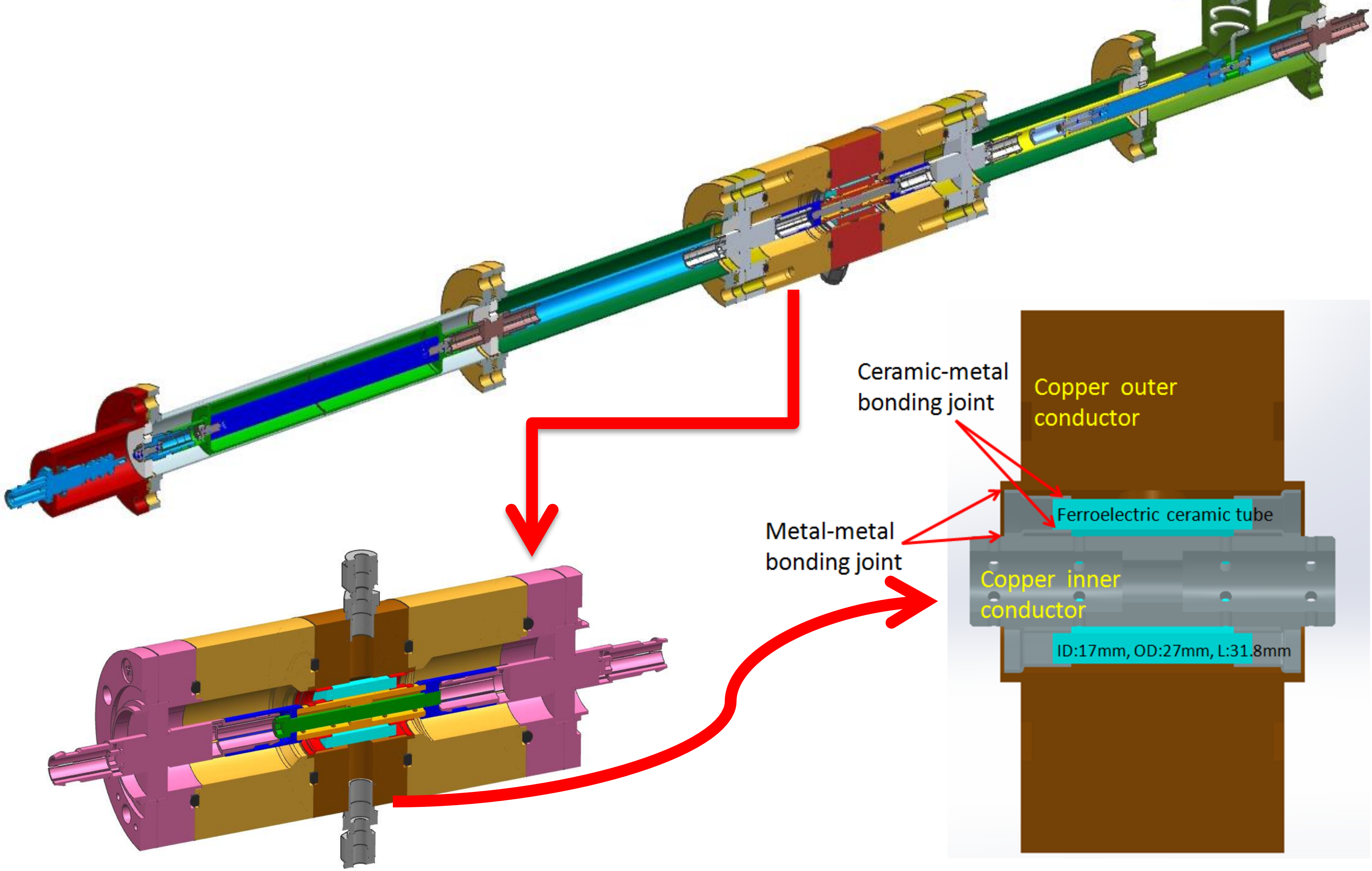
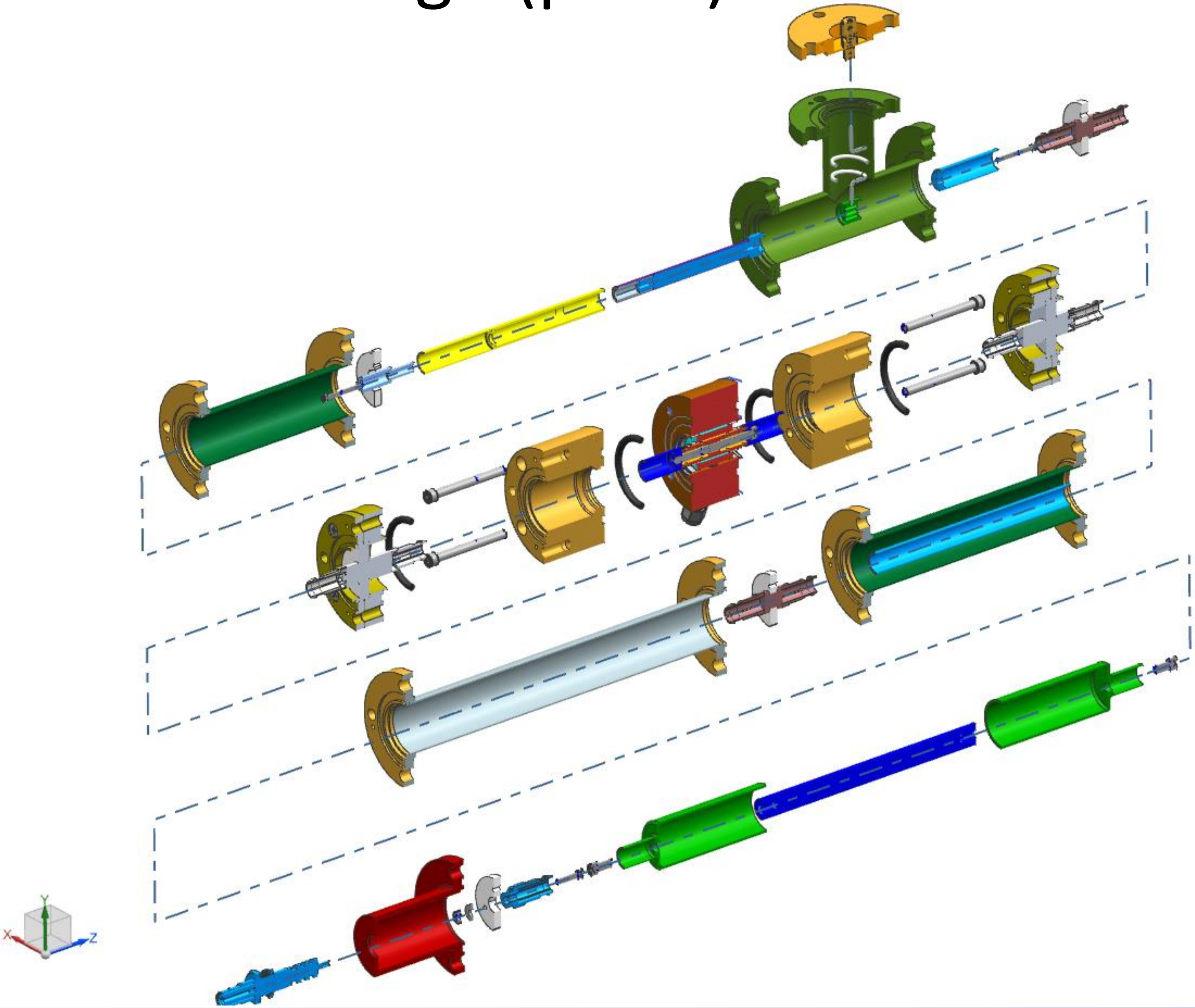
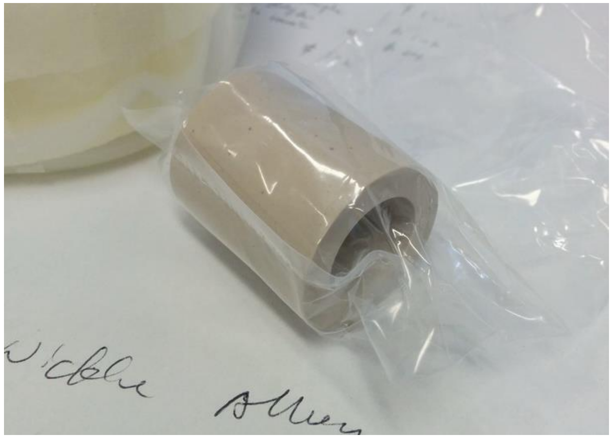
BST Based Tuner Design (assembly)

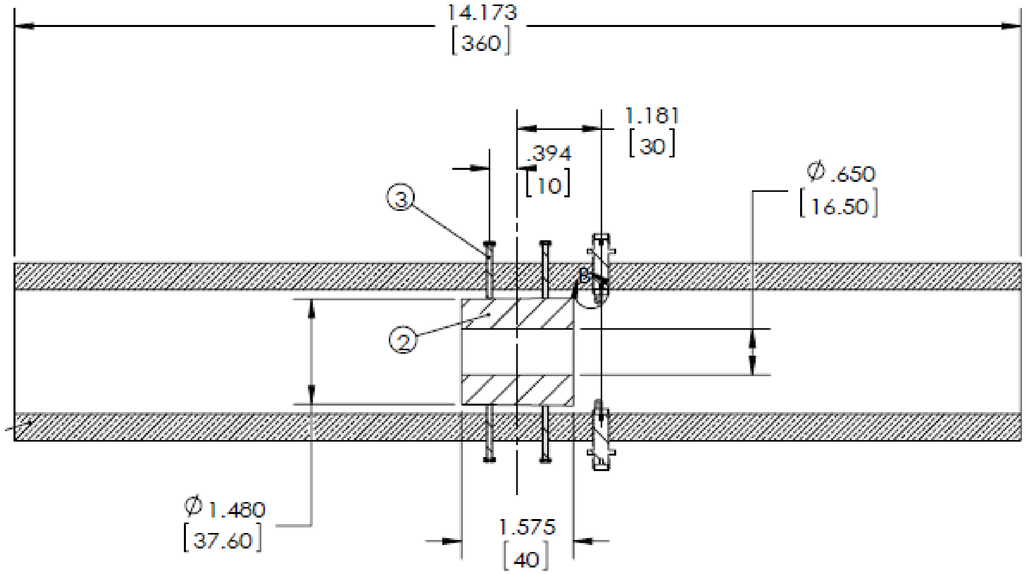


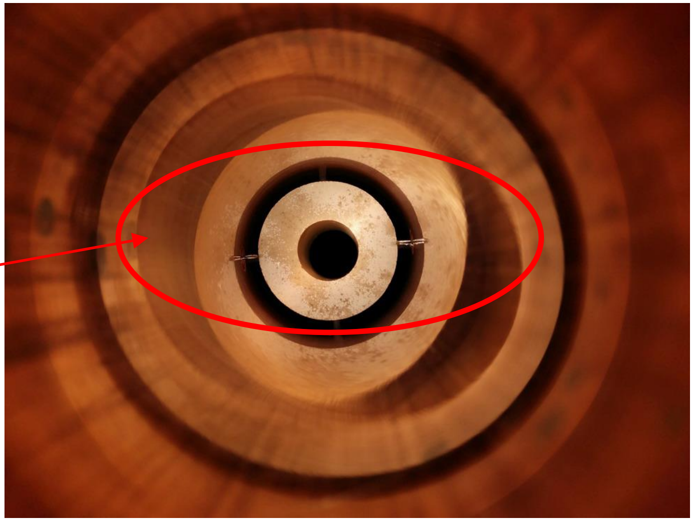
BST Based Tuner Design (parts)



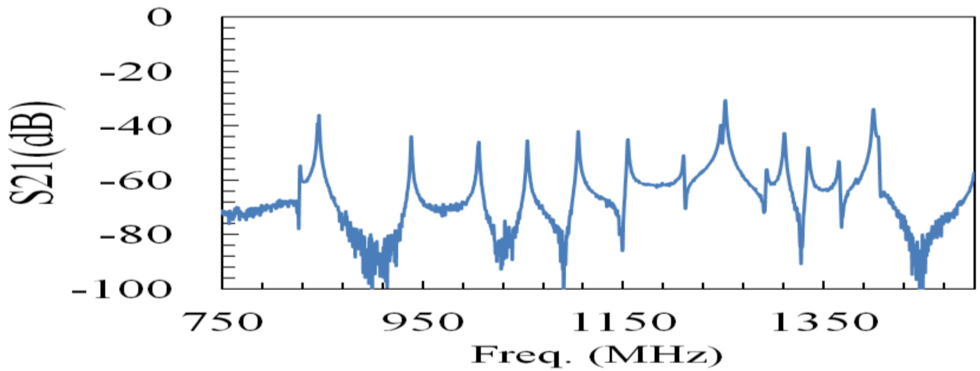
Ferroelectric Characterization

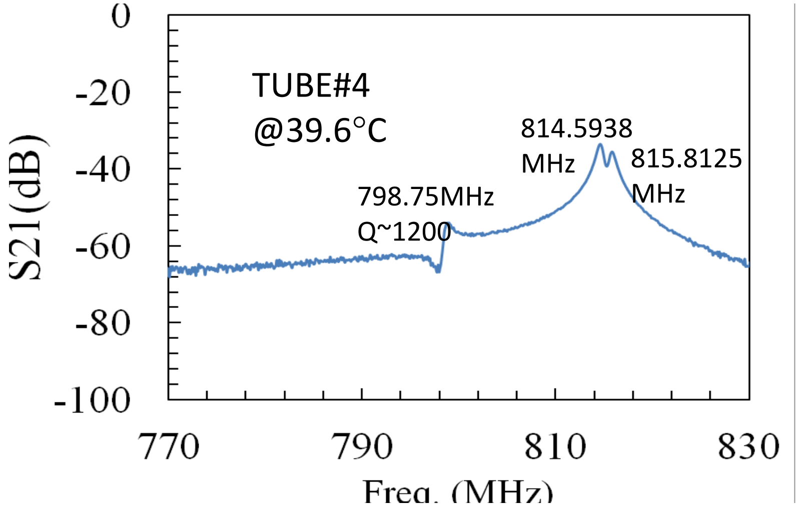






Material Characterization Results





Tube	ID(mm)	OD(mm)	L(mm)	T(°C)	f_{TE01}(MHz)	Eps	Eps (22.1C)
0	16.42-16.64	37.6-38.3	45.82	22.1	767.475	149.2	149.2
1	15.9-16.46	36.7-37.85	46	23.5	743.88	159.1	160.6
2	16.02-16.44	37-37.87	45.82	24.3	744.94	158.5	160.7
3	16-16.4	36.83-37.79	46.16	24	744.76	158.6	160.6
4	16.02-16.47	36.91-37.8	45.81	24.4	746.3825	158.2	160.6
5	15.93-16.4	36.81-37.65	45.95	25.3	750.3575	156.5	159.9
6	15.93-16.35	36.94-37.7	47.93	25.8	750.175	155.2	159.1

Ferroelectric #4: Eps(@39.6C)=138.1; Loss tan (@ 39.6C) ~ 8E-4

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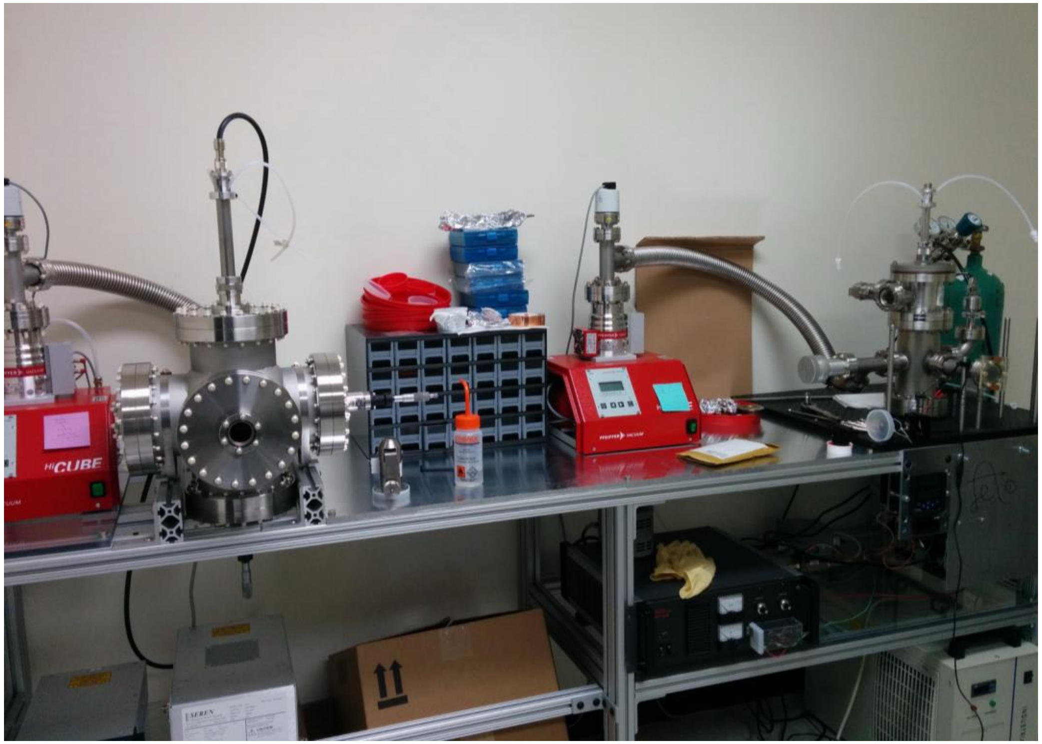
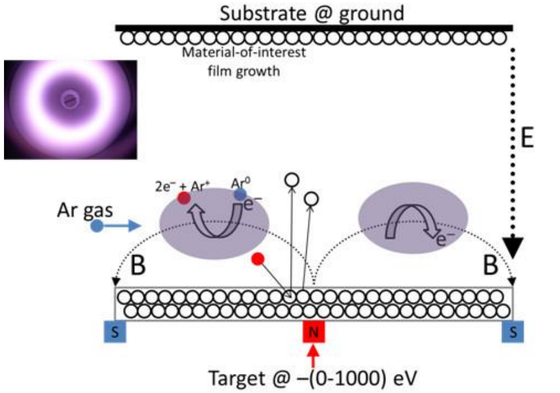
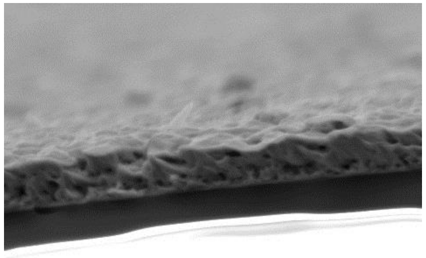
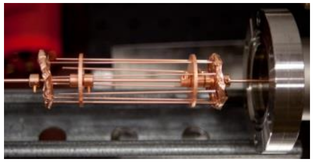
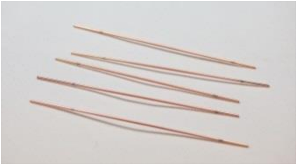
Euclid's Sputtering System, Bolingbrook IL







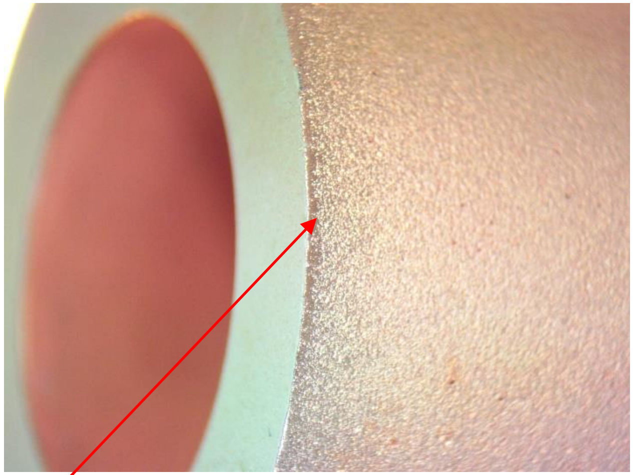


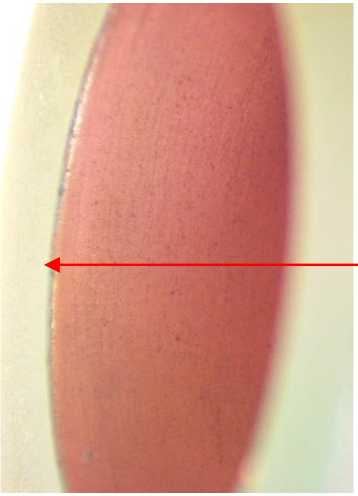


Euclid has developed a sputtering system for depositing of a variety of metallization and dielectric deposition applications.

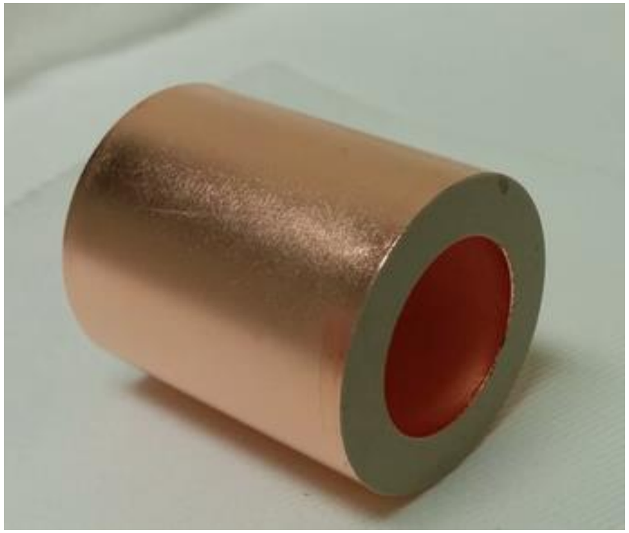
Fabrication of Ferroelectric Tuner

Machined to the dimensions

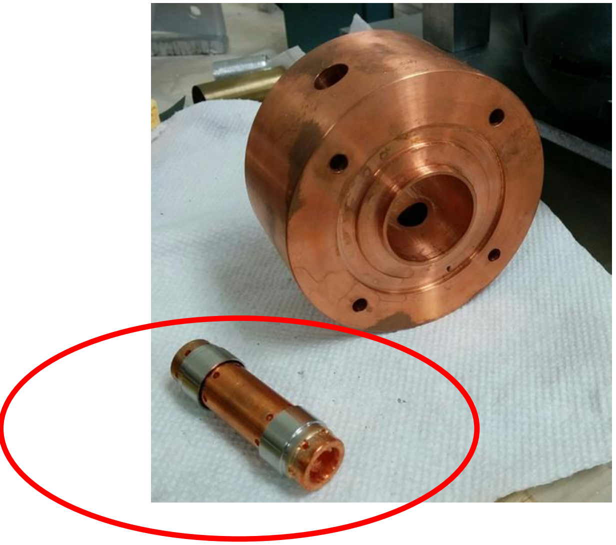




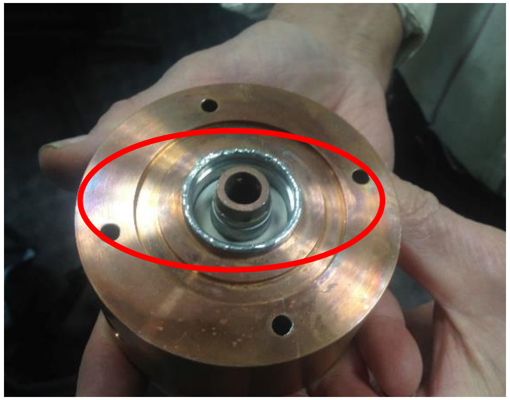
Copper deposition with sublayers



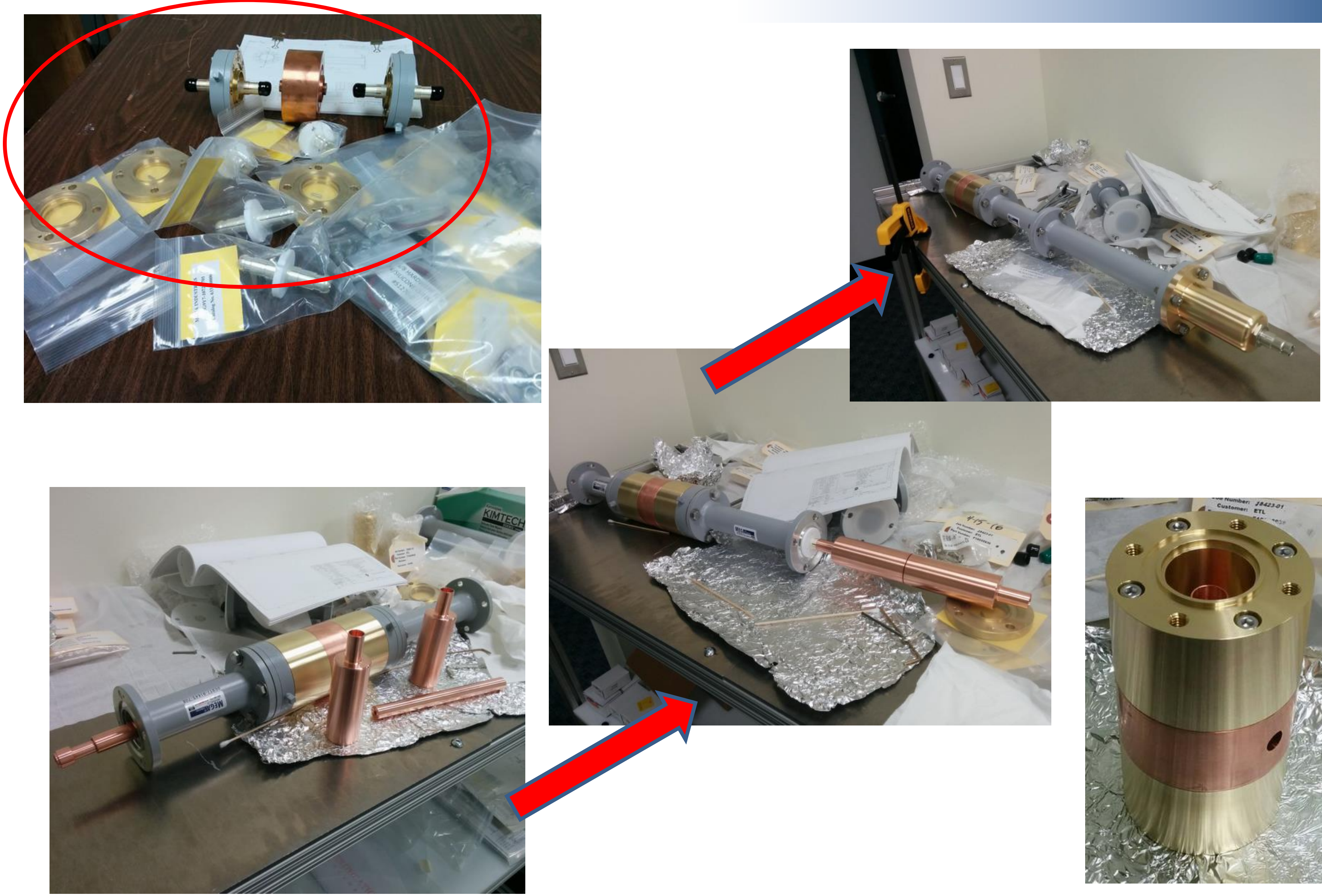
Metallization on ID and OD



Soldered Assembly

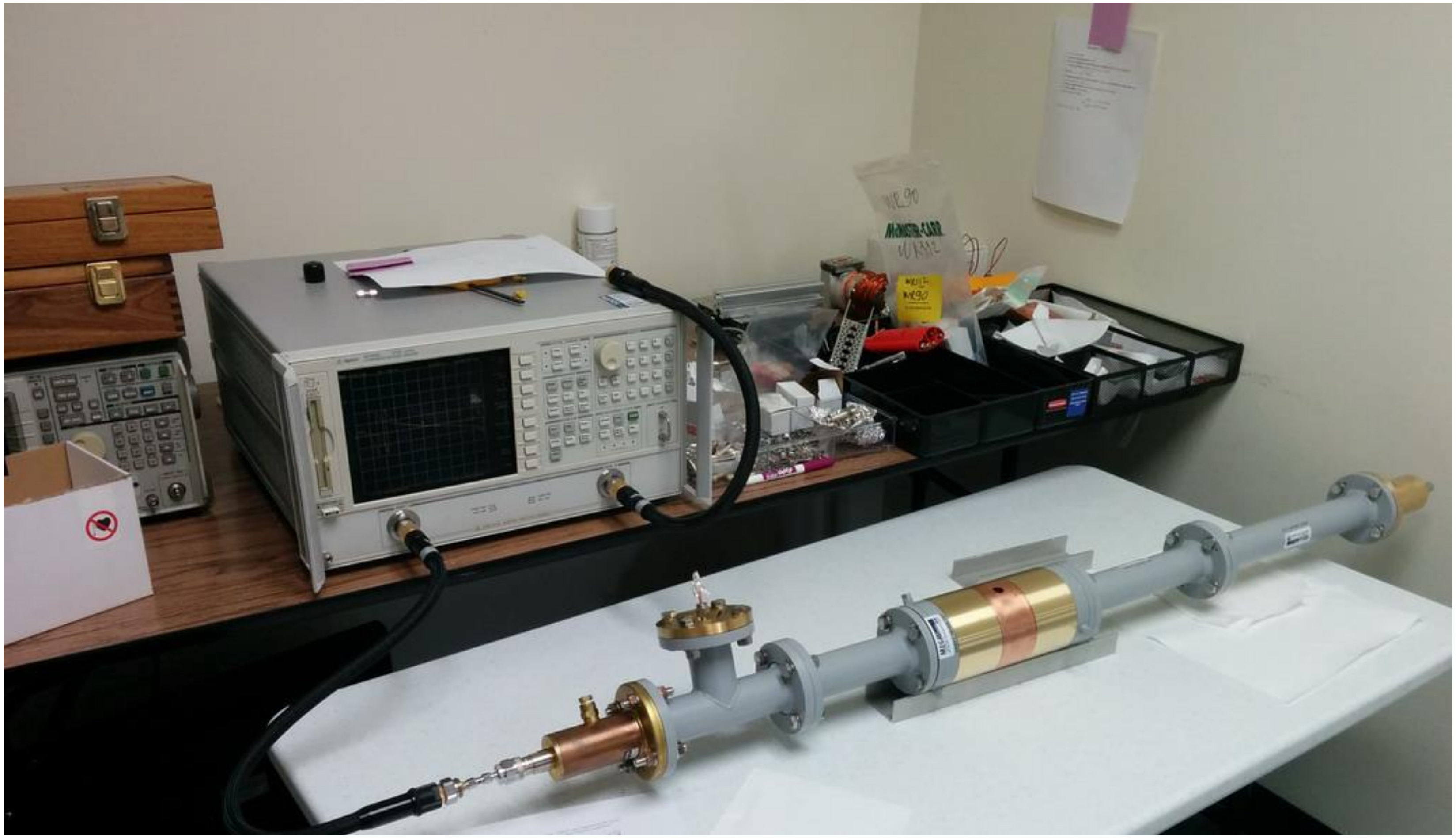


Inner and outer
jacket for applying
DC and cooling

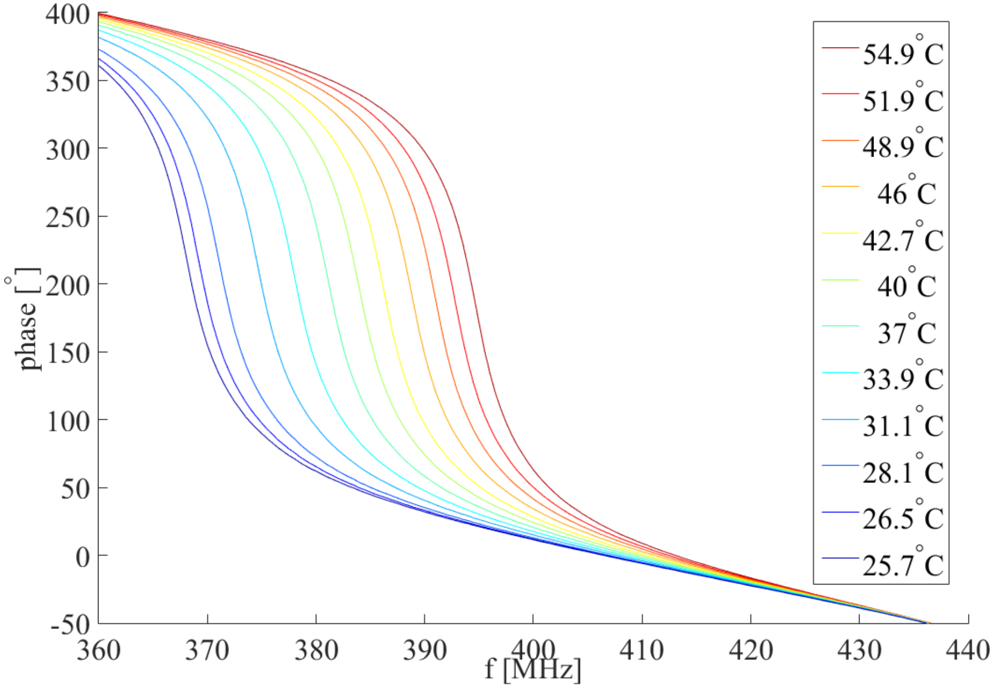


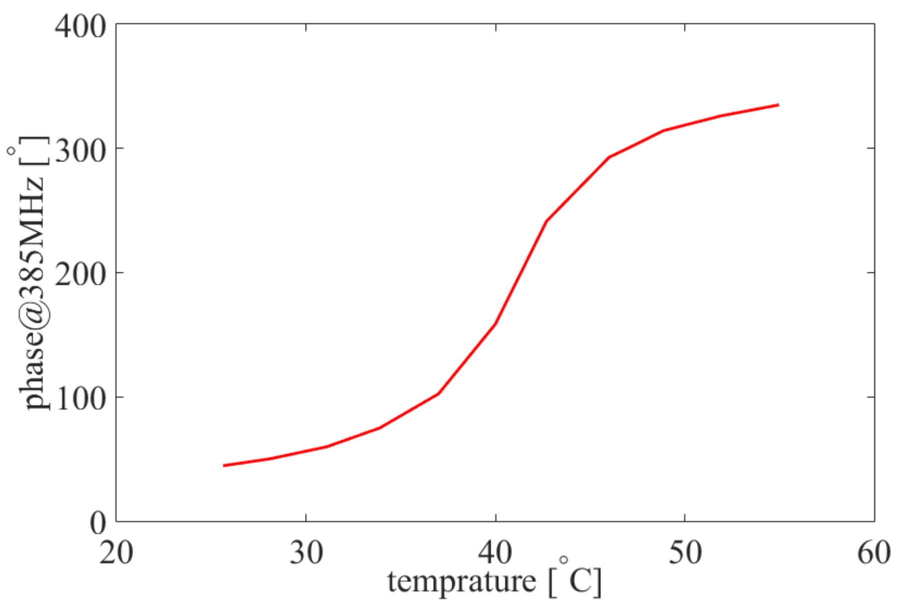
Partial assembly

Ferroelectric Tuner full assembly

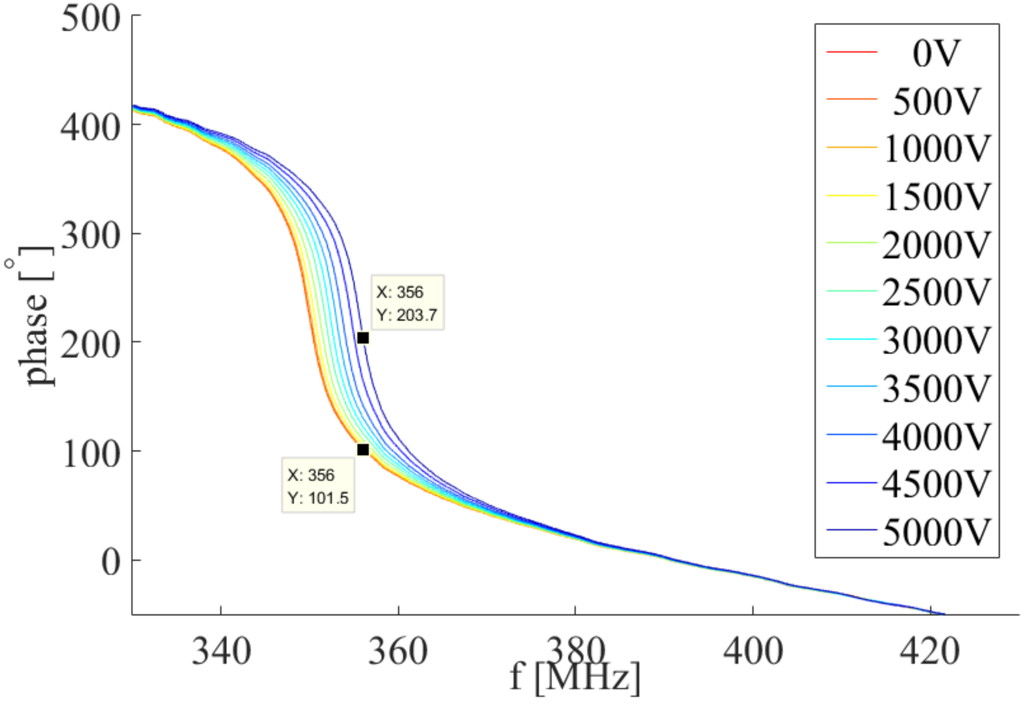


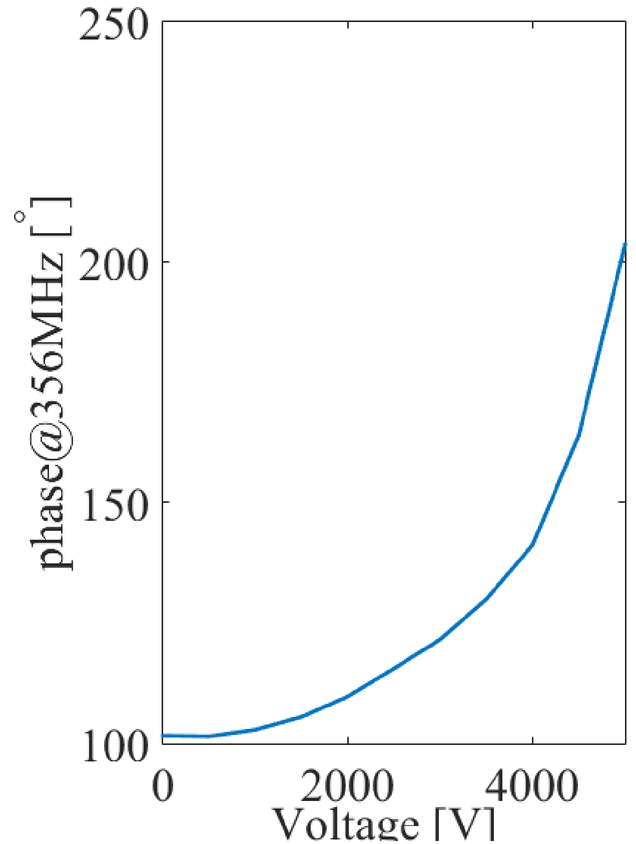
Tuning with temperature



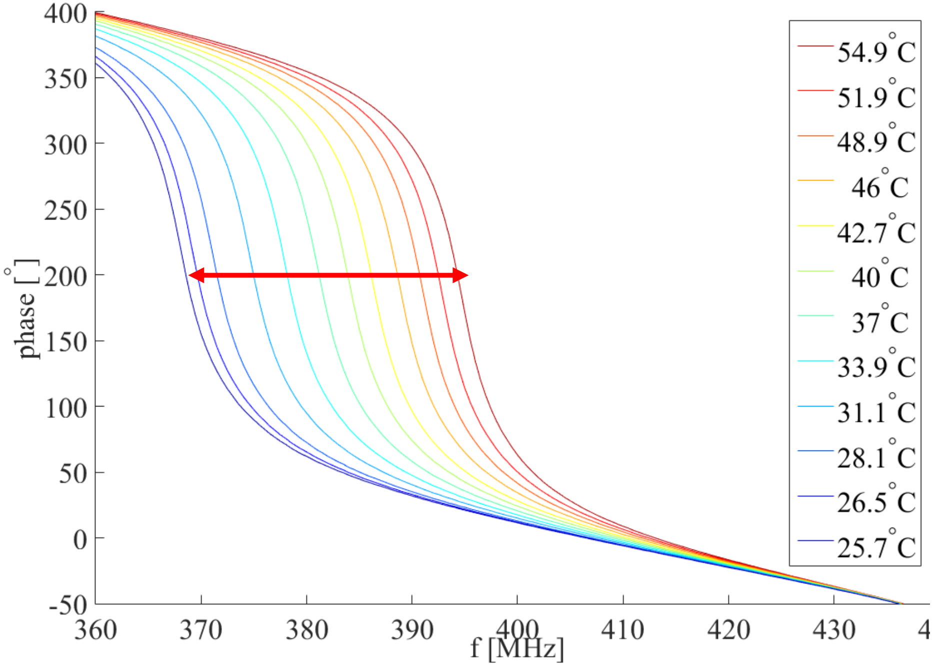


Tuning with DC bias

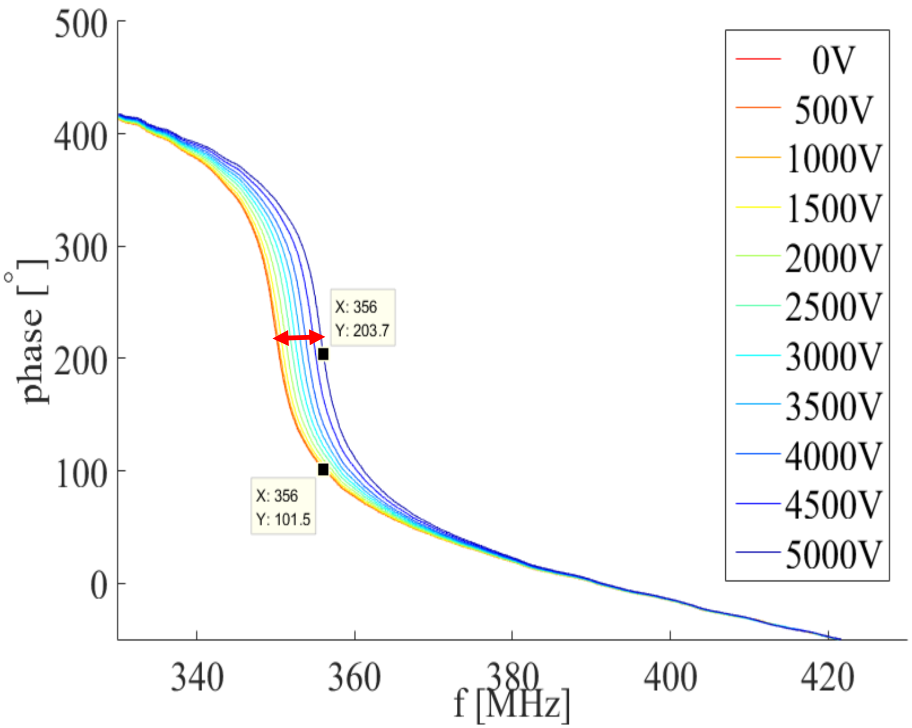




Tuning with temperature and DC bias



Temperature: slow but wide tuning range



DC voltage: fast but narrow tuning range

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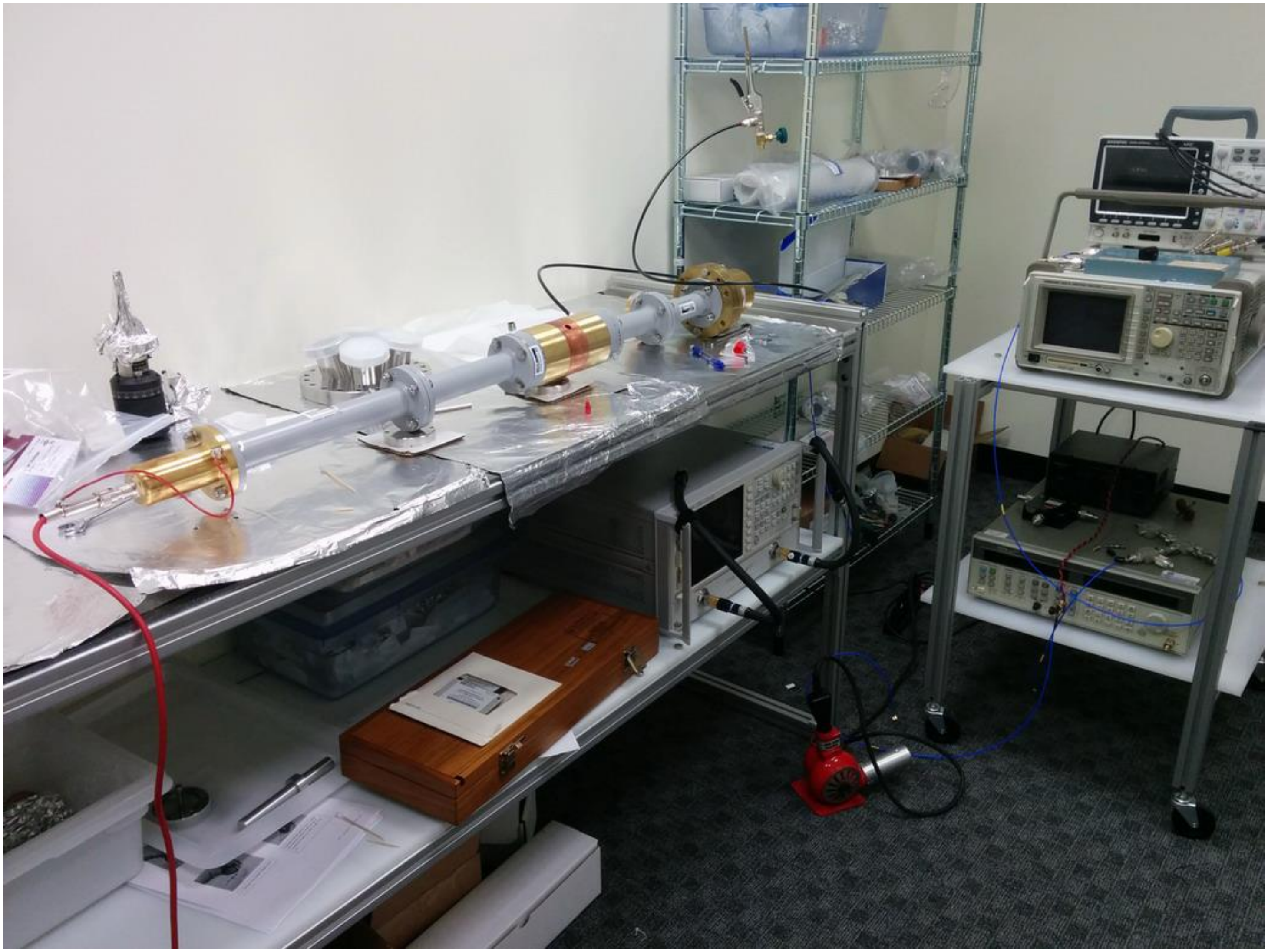
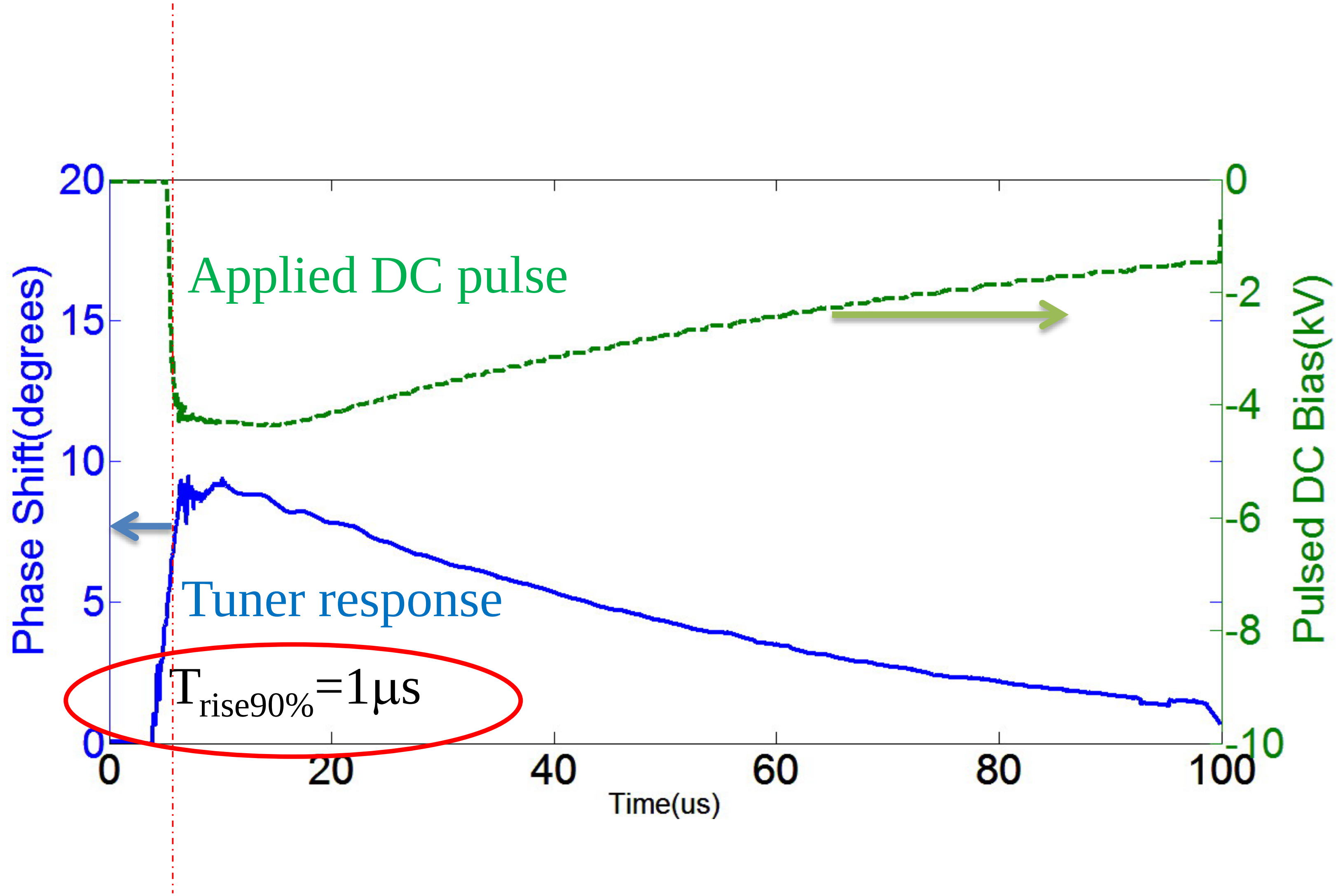
Tuning with the fast <μs range DC pulser



Tuning with fast DC pulse



Tasks

- Task 1: Design simulation studies for the ferroelectric phase shifter design.
- Task 2: Development of a ferroelectric material having a dielectric constant in the range 80-150, tunability 5-6% at 15-20 kV/cm and Q×f ~ 1500-1700.
- Task 3: Final design optimization of the tuning elements to further minimize losses and to improve efficiency. A HV connector design.
- Task 4: Engineering design for the phase shifter.
- Task 5. Phase shifter manufacturing and assembling.
- Task 6: Low power tests of the ferroelectric phase shifter under temperature and high dc bias control voltages. Fast < μs switching demonstration.
- Task 7: High-power test.

Pass to the High Power Test

1. Using ANL/APS 100 kW 350 MHz Test Stand

100kW and 150kW Tests on the AFT 350MHz Fast Ferrite Cavity Tuner

- **100kW CW cavity tuning test**
  - -- maintain cavity resonance at 100kW CW cavity input power
  - -- demonstrate minimum cavity tuning range of 10kHz
  - -- limited to 100kW CW due to limit of cavity coupler
- **150kW CW power handling capability test**
  - -- Qualify operation of the fast-ferrite tuner at it's specified maximum power input

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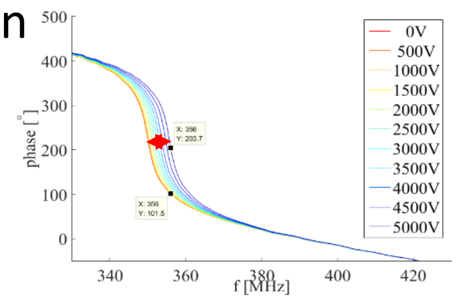
Doug Horan
Advanced Photon Source
RF Group

2. Losses control, surface DC breakdown prevention

3. Resonance frequency, operating temperature, losses and DC tuning range optimization



Summary

The ultimate goal of the Phase II project is (1) design a ferroelectric element based on BST(M) material with the required parameters; (2) development of metallization technology with no residual effects; (3) the tuner engineering design; (4) the fast tuner fabrication; (5) fast < μs switching time demonstration (6) high power testing

- Ferroelectric element has been designed and fabrication, ε ~ 100-150; loss factor ~ 1.0×10^{-3} at 700 MHz; tuning dielectric constant ~ 6% at 20kV/cm; residual effects can be mitigated with metallization technology
- the tuner assembled, bench tested, temperature (slow) tuning demonstrated with 360^0 range,
- dc voltage (fast) tuning demonstrated at < 1 μs ~100^0 range
- high power test to be carried out

***Commercialization**: high (10-100 kW) and mid (10-100 W) power fast switching RF components*

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