FERROELECTRIC BASED HIGH POWER COMPONENTS FOR L-BAND ACCELERATOR APPLICATIONS

Supported by the DOE SIR DE-SC0007630, Phase II

Chunguang Jing, Euclid Techlabs LLC

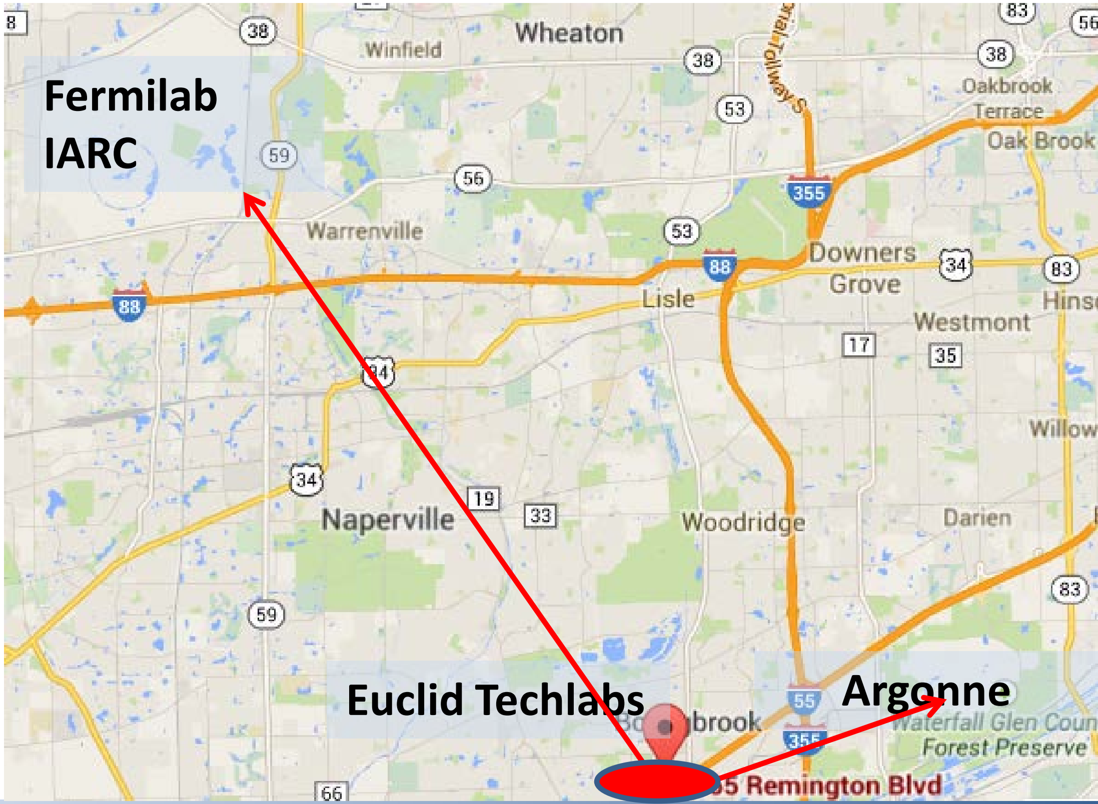
On behalf of Euclid Techlabs/BNL/FNAL collaboration

8/06/2015

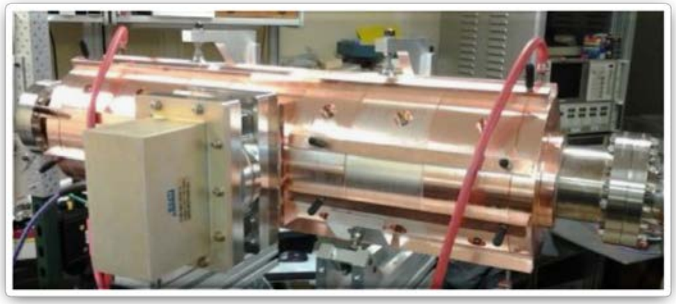
Euclid Techlabs LLC

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

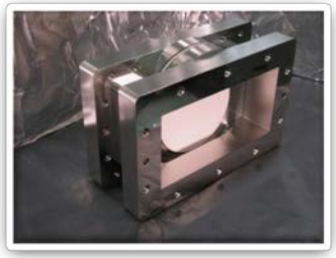
- 2014: 12 people research staff and 3 administrative,
- 2 offices: Bolingbrook, IL (lab) and Gaithersburg MD (administrative).
- Tight collaborations with National Labs: Fermi, Argonne, BNL, Berkely.
- Joined Fermi/IARC lately.



Products and Projects



L-band high peak current LINAC

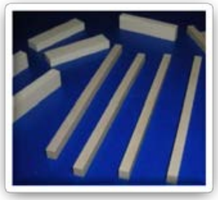


UHV L-band RF window

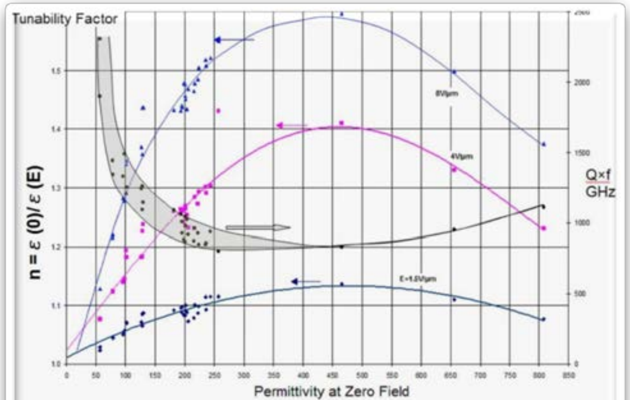
BPM compact readout

Photoinjectors:

- L-band high peak current AWA-style
- S-band (LCLS-style)



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



Tunability factor *n* and figure of merit *Q×f = f/tan δ* dependences on the permittivity for BST (M) ceramics. Data based on Euclid Techlabs research.

Compact, detachable coaxial coupler for SRF cavity (joint project with FNAL)

euclid TECHLABS

Research on dielectric loaded accelerating structures (DLA)

- designs: 7-26 GHz
- scalable to THz

Experiments with DLA were done by Euclid Techlabs at:

Argonne, Naval Research Laboratory, Brookhaven, SLAC

- S. Antipov, et. al, Phys. Rev. Lett. 112, 114801 (2014)
- S. Antipov, et. al, Phys. Rev. Lett. 111, 134802 (2013)
- S. Antipov, et. al, RSI 84 (2) (2013)
- S. Antipov, et. al, Phys. Rev. Lett. 108, 144801 (2012)
- S. Antipov, et. al, Appl. Phys. Lett. 100 132910 (2012)
- C. Jing, et. al, PRSTAB, v14(2) (2011)
- C. Jing, et. al, Phys. Rev. Lett. 106, 164802 (2011)
- C. Jing, et. al, IEEE Trans. Plasma Sc. 1354-60 (2010)

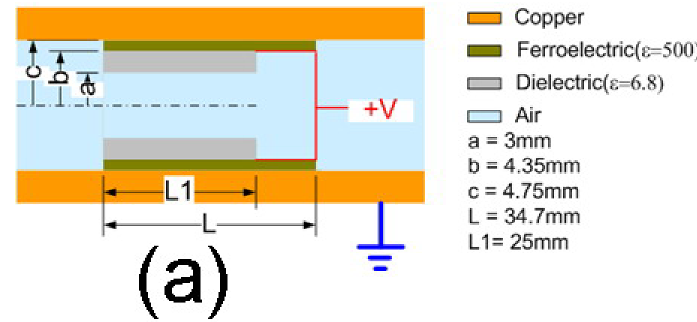
History: Tunable Dielectric-Based Accelerator

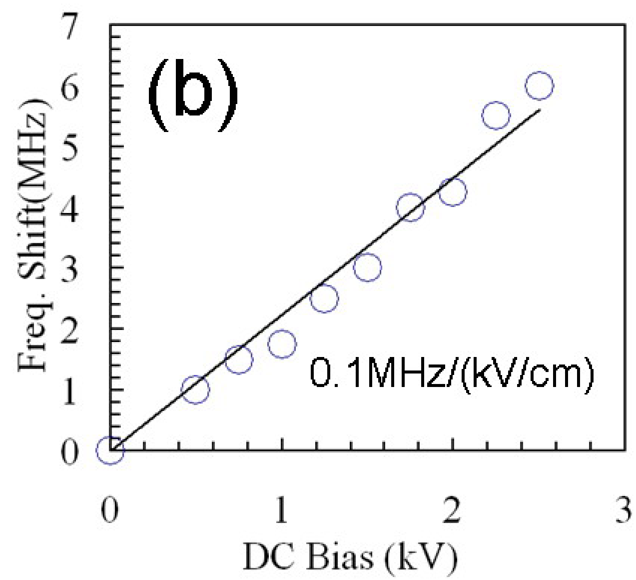
PRL 106, 164802 (2011) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2011

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

C. Jing,[1,2] A. Kanareykin,[1] J. G. Power,[2] M. Conde,[2] W. Liu,[2] S. Antipov,[1,2] P. Schoessow,[1] and W. Gai[2]
[1]*Euclid Techlabs, LLC, 5900 Harper Road, Solon, Ohio 44139, USA*
[2]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
(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

Ferroelectric Based Tuner (ultrafast phase shifter) for SRF Accelerator Operation

Motivation

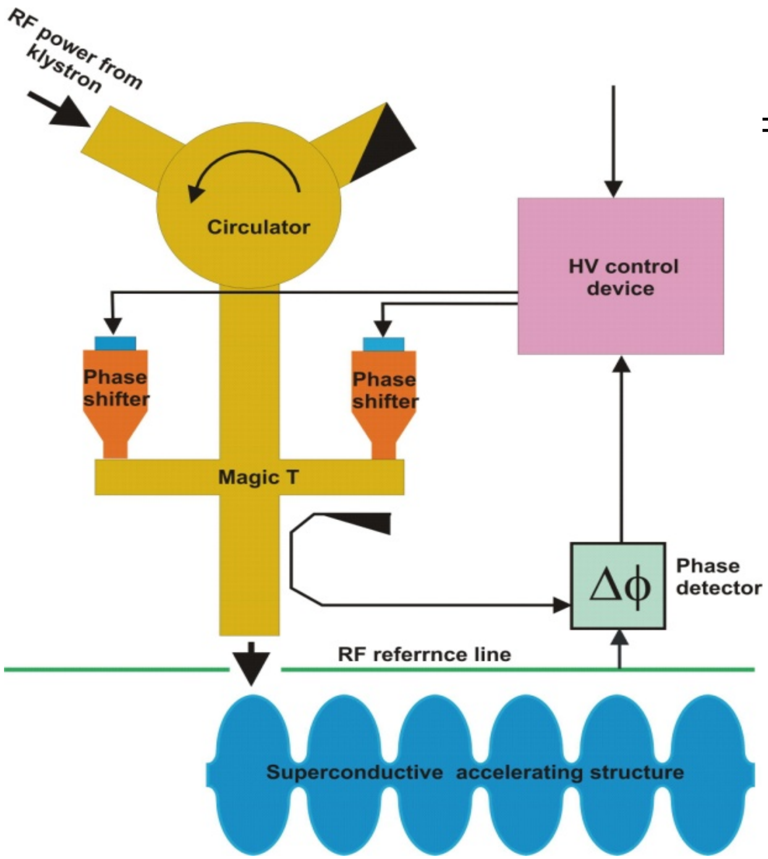
- A fast controllable phase shifter would allow microphonics compensation for CW SRF accelerators supporting ERLs and FEL.

- 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 (Ilan Ben-Zvi)

Tuner Requirements

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



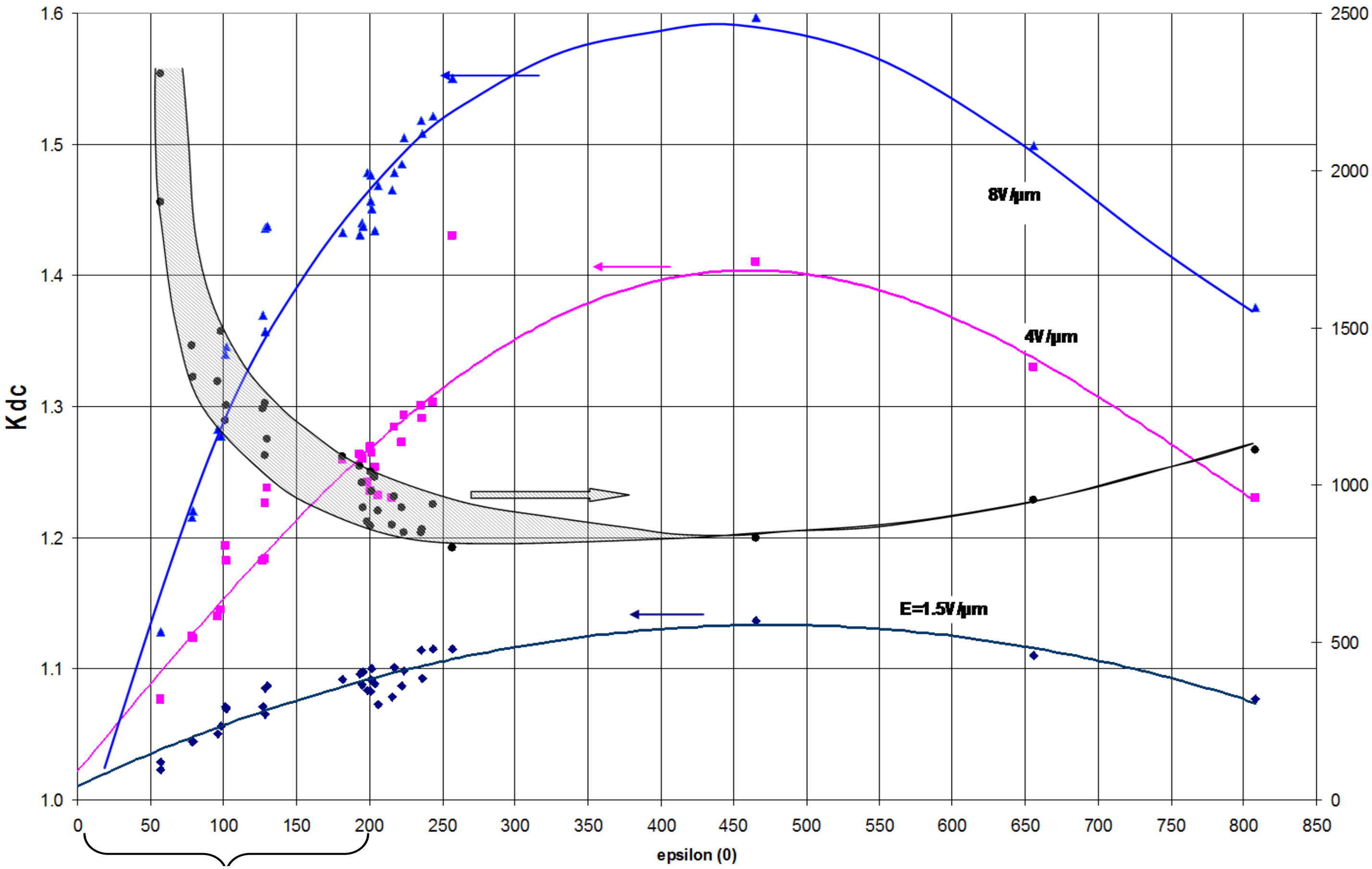
$$= P_g / P_{g,\max} = \delta\omega / \Delta\omega \left(1 - 4tn\delta \frac{\eta(\varphi_0)\varepsilon}{\Delta\varepsilon} \right).$$

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

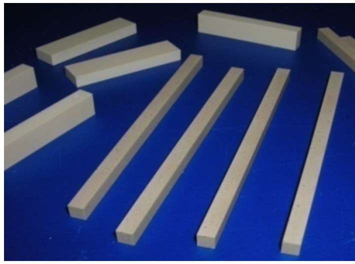
For a typical ferrolectric tuner needed for ERL SC cavity excitation, on need ferroelectric material having the tunability of 0.06 and loss tangent of ~0.001 in order to get the power gain of 12-15.

Progress on BST Material Development

(Ba, Sr)TiO_4+Mg oxides



Q*f



BST(M), ε~50-150

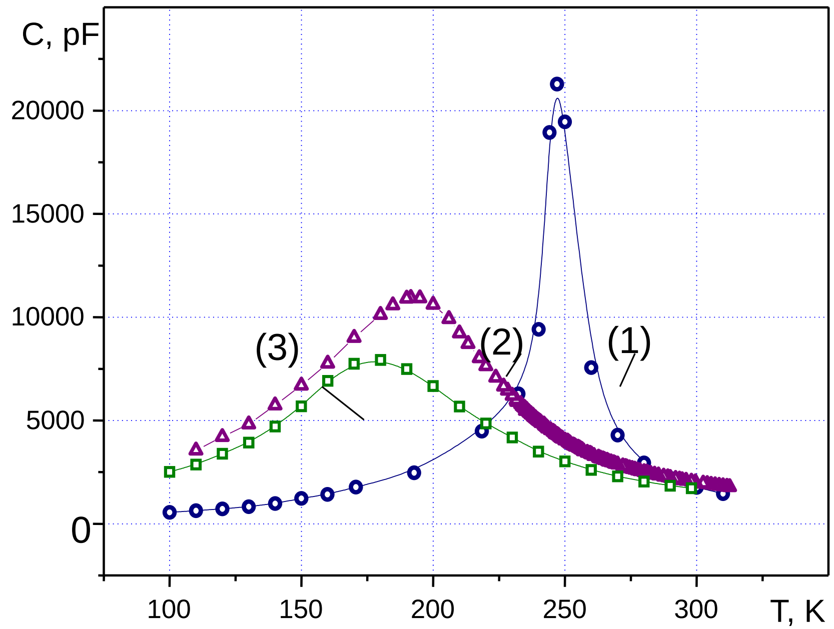
record low values of dielectric constant and loss tangent at relatively high tunability level required for high power bulk tuner operating in air (< 30 kV/cm) and in vacuum (up to 80 kV/cm).

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$\times$10^{-3}
breakdown limit	200 kV/cm
thermal conductivity, K	7.02 W/m-K
specific heat, C	0.605 kJ/kg-K
density, ρ	4.86 g/cm^3
coefficient of thermal expansion	10.1$\times$10^{-6} K^{-1}
temperature tolerance, $\partial\varepsilon/\partial T$	(1-3) K^{-1}

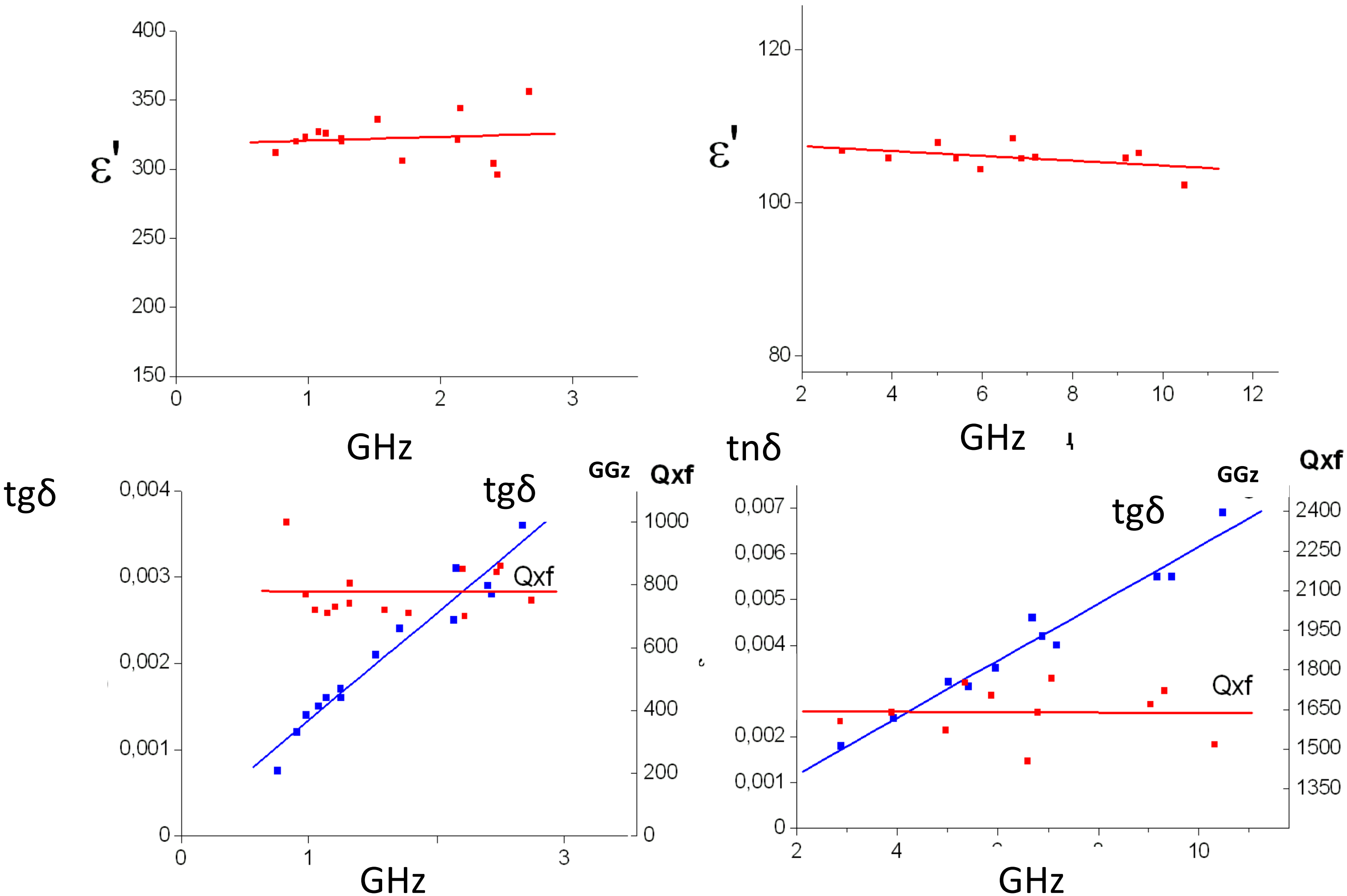
Issues with the ferroelectric elements

- Dielectric constant has to be low (~ 100)
- Loss factor has to be low ~ 1.0 ×10^{-4} 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

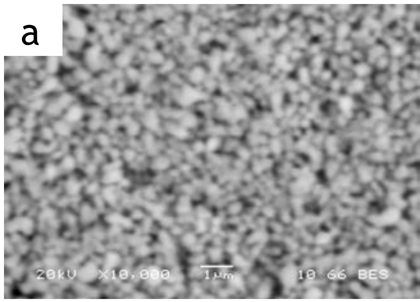
Frequency dependence of ε and tnδ for the ferroelectrics with low permittivity

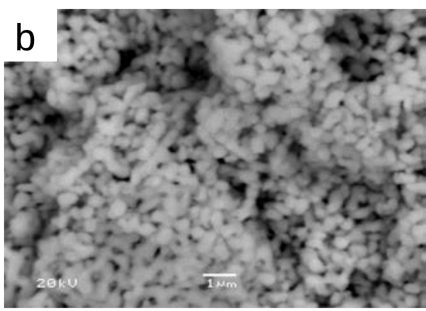


Ferroelectric composite materials

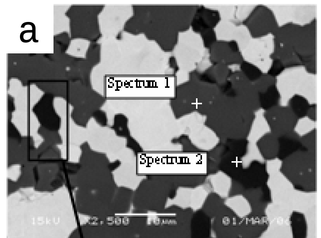
Patent US 8,067,324 B2, Nov. 29, 2011

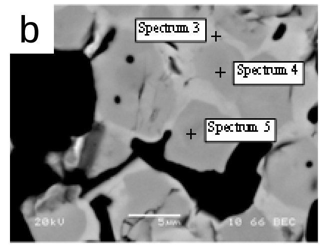
Powders ⇒ Ceramics

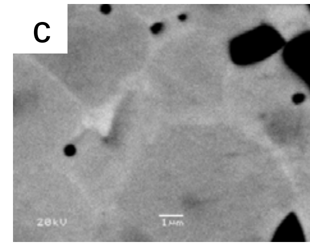


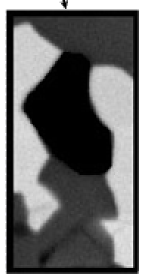


SEM-image of the initial powders of barium titanate (a) and strontium titanate (b)



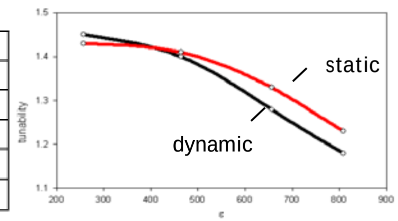






Spectrum	Mg	Ti	Sr	Ba	O	Total
Spectrum 1	29.66	27.47	1.39	2.99	38.49	100.00
Spectrum 2	59.89	0.19	0.26	0.06	39.60	100.00
Spectrum 3	0.19	22.57	16.33	38.09	22.82	100.00
Spectrum 4	0.14	22.62	21.85	32.23	23.16	100.00
Spectrum 5	0.25	23.36	27.91	24.64	23.84	100.00

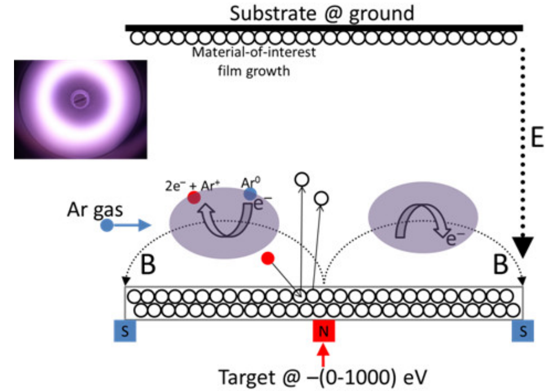
SEM images and EDS data of the sample on the basis of BST ferroelectric with linear Mg - containing additive (T = 1420 ° C) (a, b) and (T = 1400 ° C) (c).

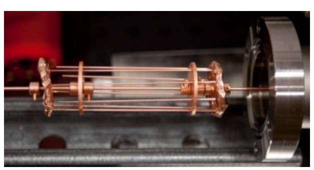


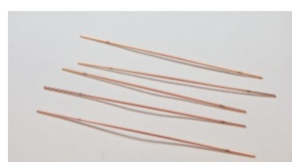
Static and dynamic tunability as a function of the permittivity

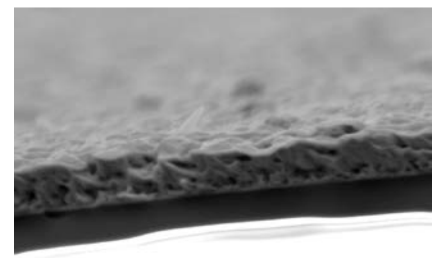
SEM image of the boundary interface region in between the grains of the BST-MgO-Mg_2TiO_4 composite material.

Euclid's Sputtering System, Bolingbrook IL



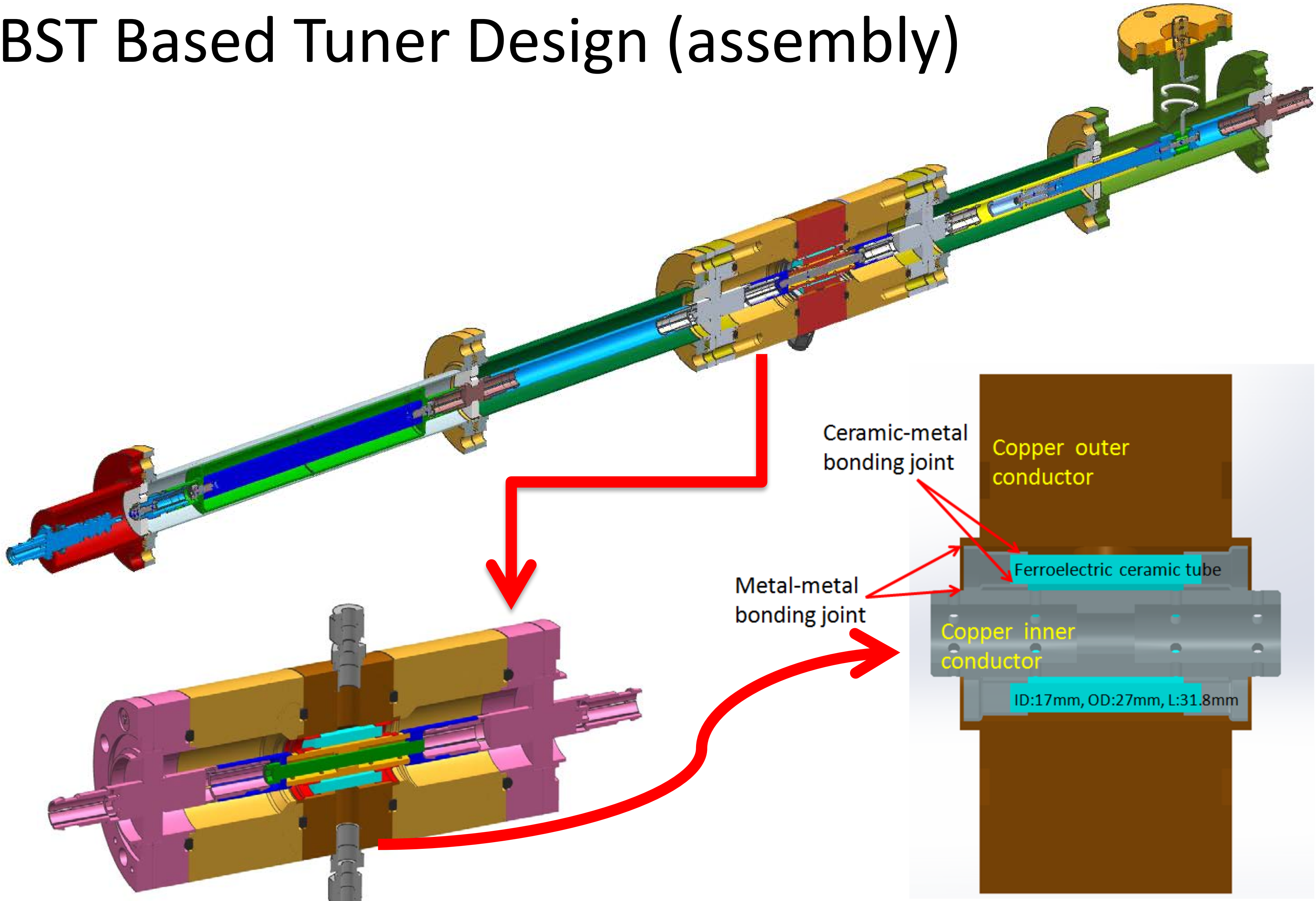




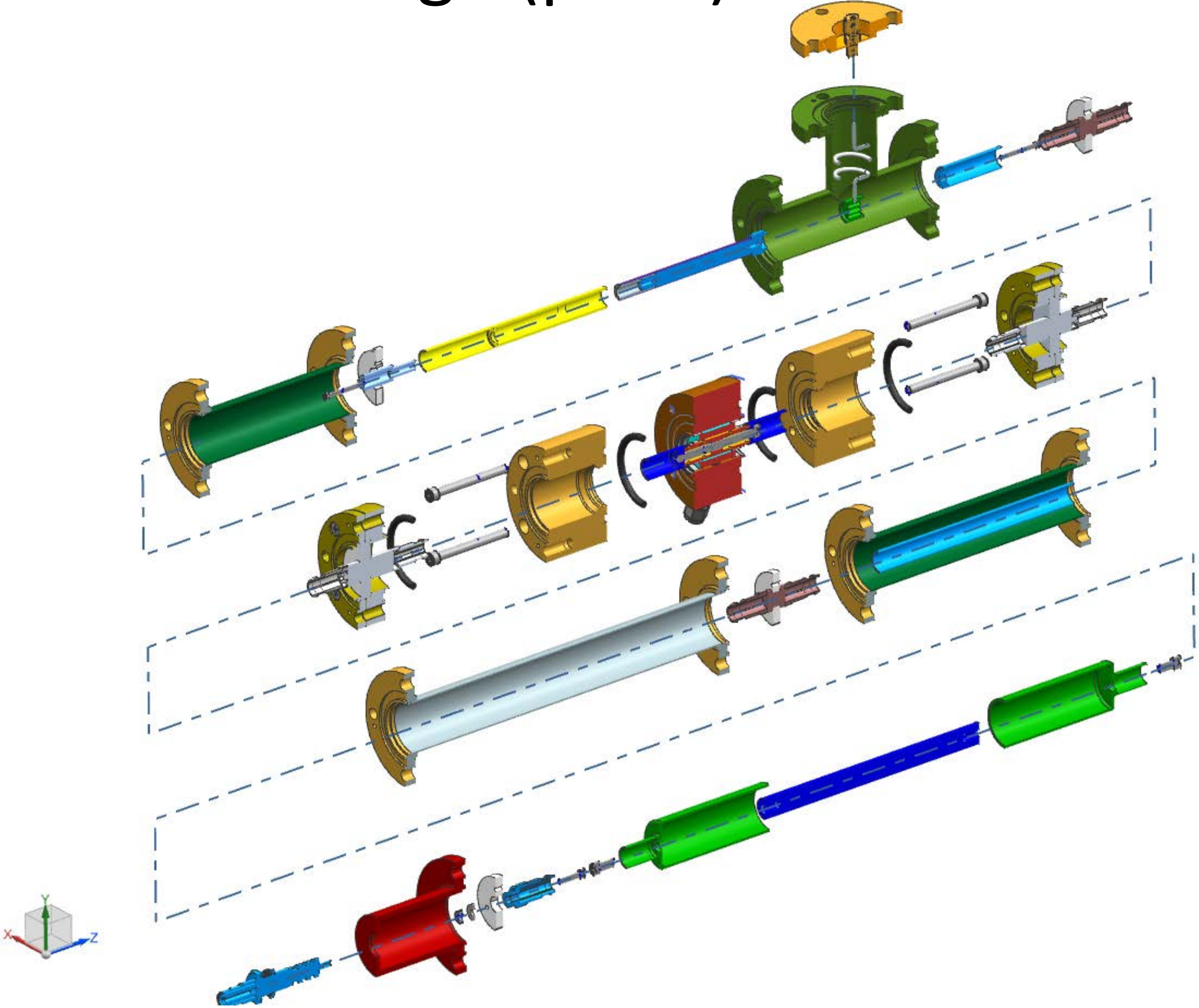


Euclid has developed a sputtering system for depositing of a variety of metallization and dielectric deposition applications.

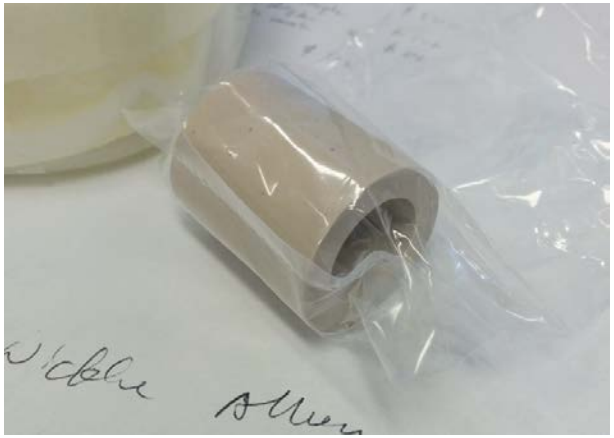
BST Based Tuner Design (assembly)

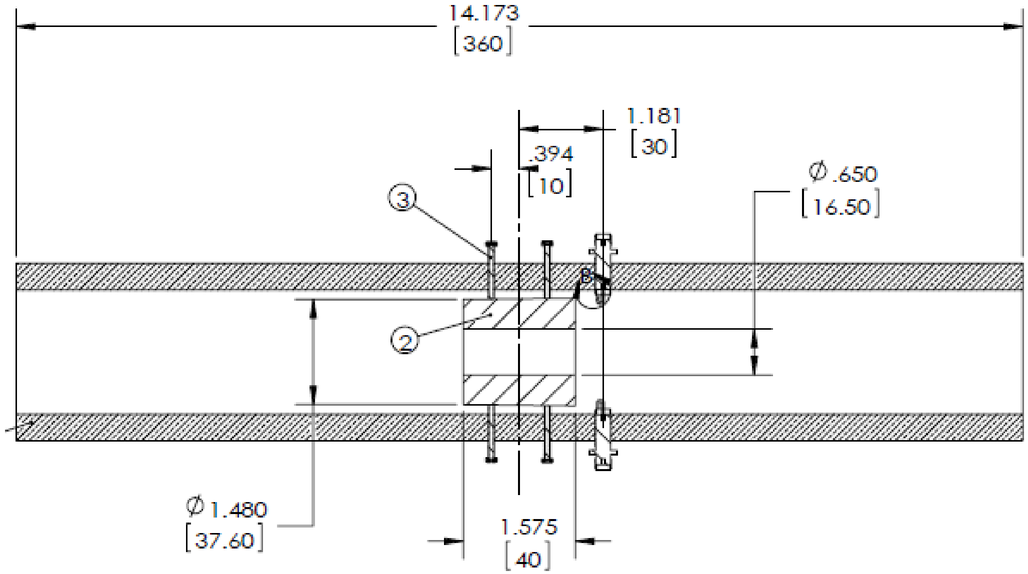


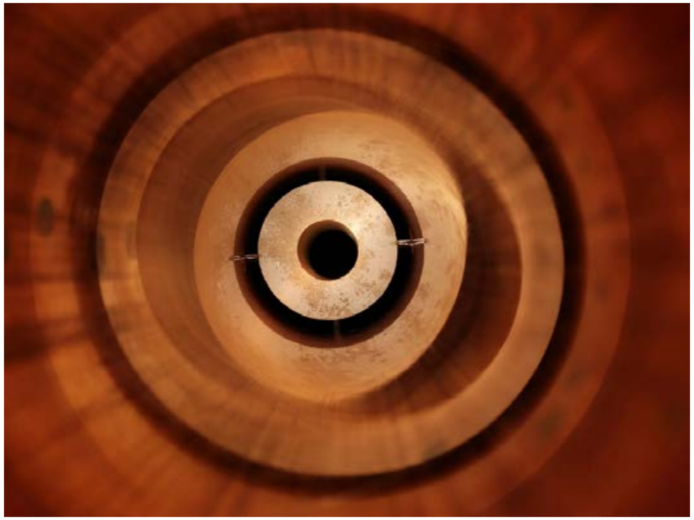
BST Based Tuner Design (parts)



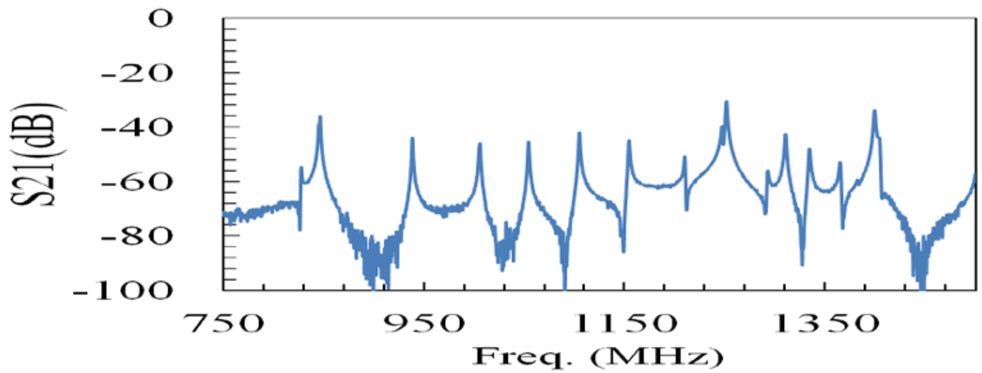
Tube Characterization

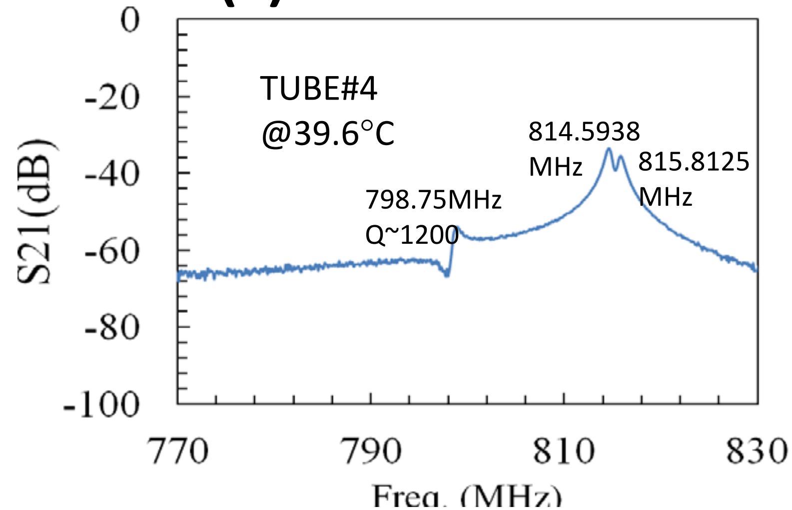






Material Characterization Results (I)



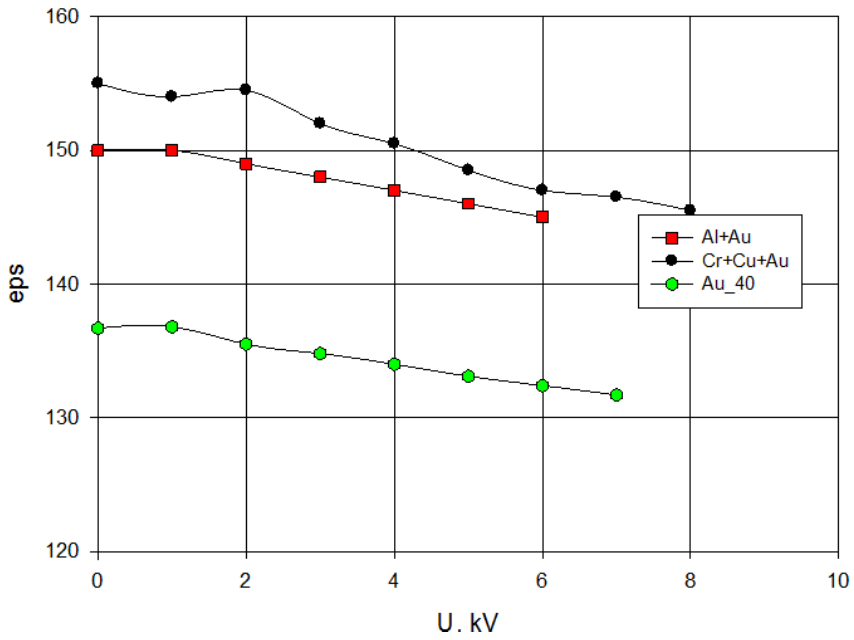


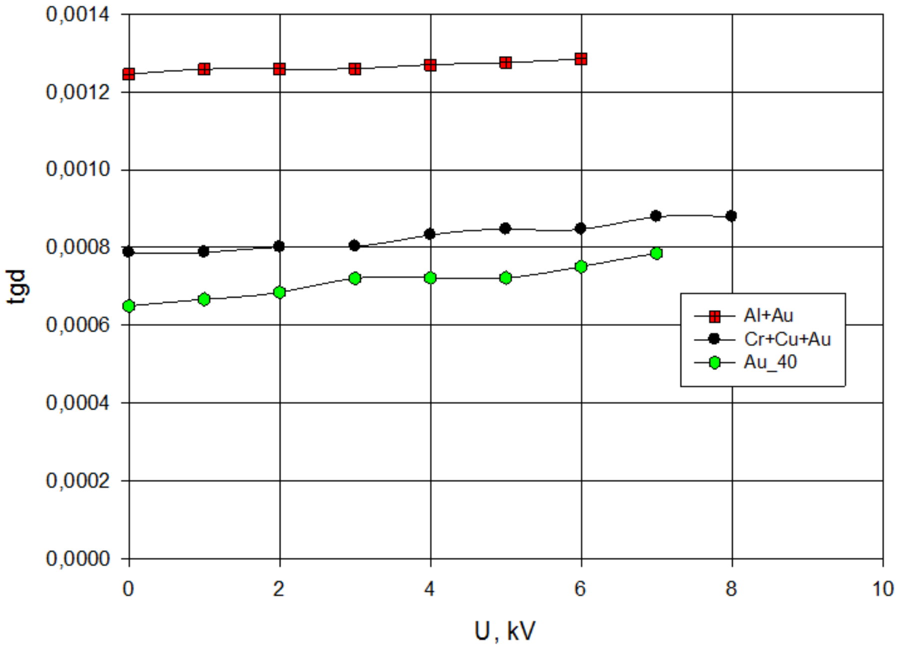
Tube	ID(mm)	OD(mm)	L(mm)	T(°C)	f_{TE01}(MHz)	Eps	Eps (22.1C)
0	16.42-16.64	37.6-38.3	45.82	22.1	767.475	149.2	149.2
1	15.9-16.46	36.7-37.85	46	23.5	743.88	159.1	160.6
2	16.02-16.44	37-37.87	45.82	24.3	744.94	158.5	160.7
3	16-16.4	36.83-37.79	46.16	24	744.76	158.6	160.6
4	16.02-16.47	36.91-37.8	45.81	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

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

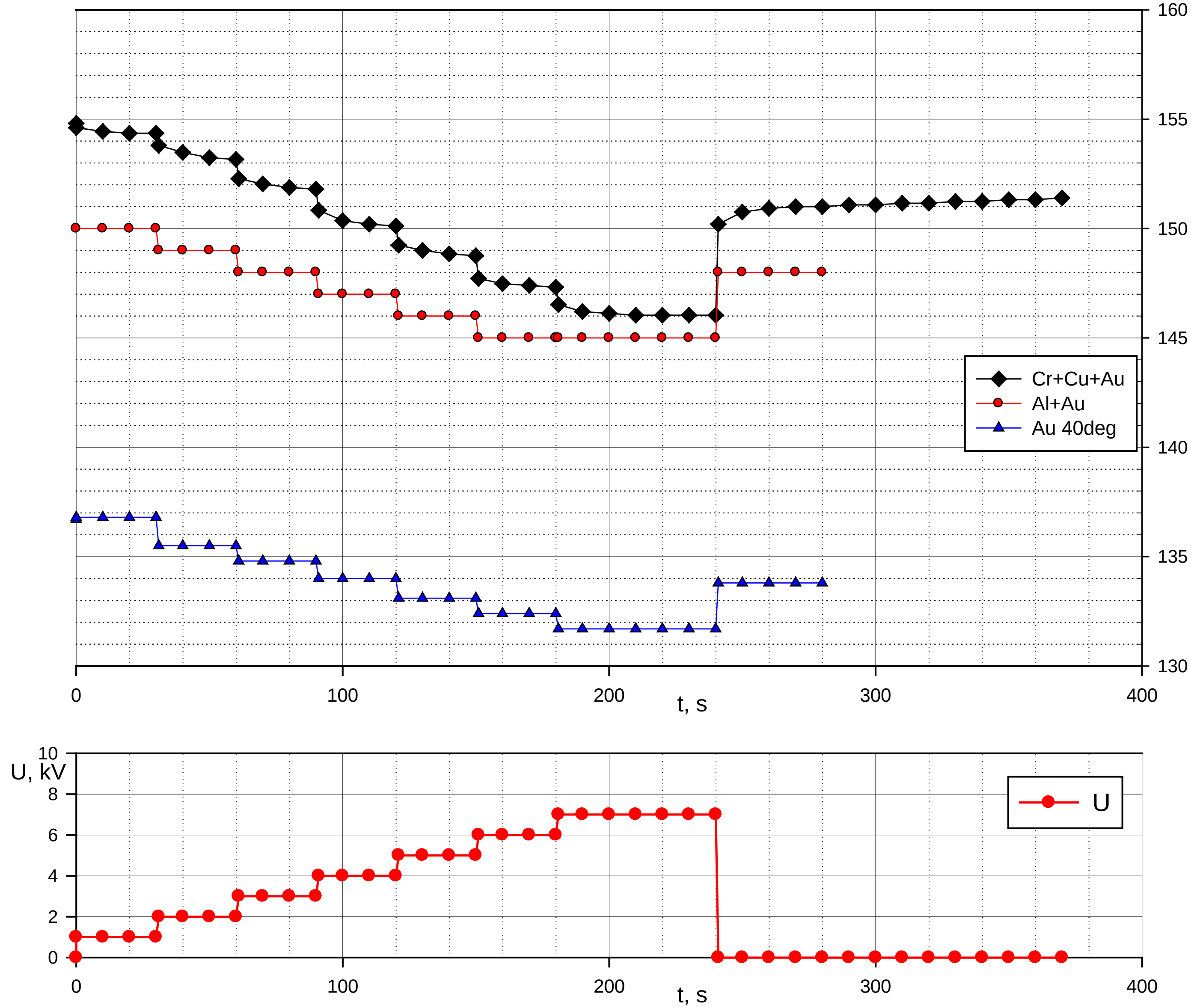
Material Characterization Results (II)

Testing of the BST (M) at 40^{0}C with 3 different metallizations (1) Al (1um)+Au (5 um), (2) Cr (50нm)+Cu (1um)+Au (5um) and (3) Au (1um+5um)

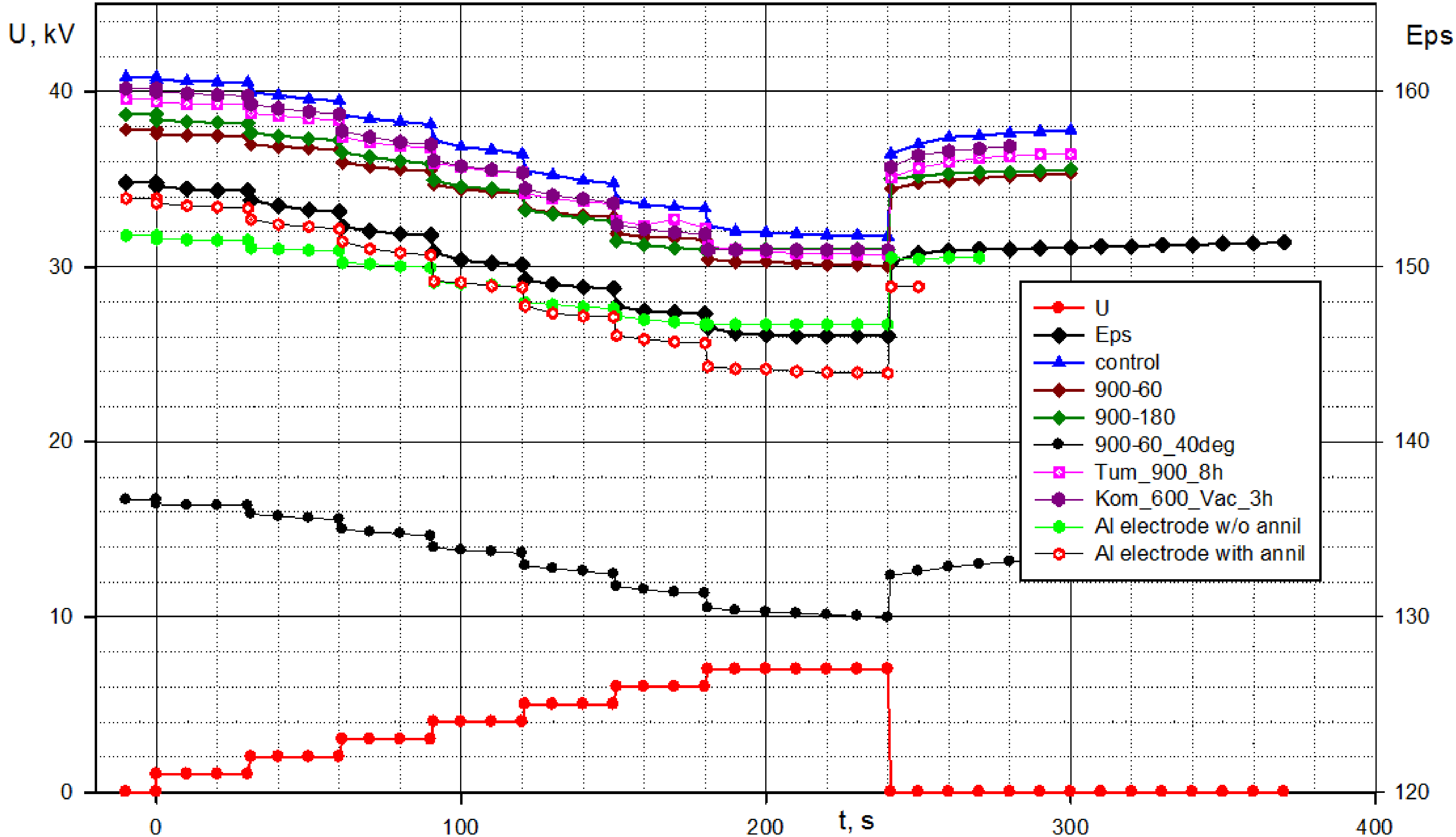




Time response measurements



Time response measurements after annealing at oxygen atmosphere



euclid TECHLABS

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 is under manufacture and assembled.
- Task 6: Low power tests of the ferroelectric phase shifter under high dc bias control voltages.
- Task 7: High-power tests and evaluation of the ferroelectric phase shifter will be carried out to study the device characteristics as functions of rf power level, HV bias level, temperature control and bandwidth.

Summary

The ultimate goal of the Phase II project regarding BST based composition development is designing a ferroelectric element based on BST(M) material with permittivity reduced to 80-150 , tunability $\Delta\varepsilon/\varepsilon$ of 1.05 -1.06 at 15-20 kV/cm bias field magnitude, and loss tangent 5-6×10-4 at 700 MHz. Currently have been demonstrated:

- Dielectric constant ~ 100-150
- Loss factor ~ 1.0 $\times 10^{-4}$ at 1 GHz
- Tuning ~ 6% at 20kV/cm
- Residual effects can be mitigated with metallization technology

Ferroelectric components have been fabricated; the tuner assembling, cold and high power testing is ongoing .