# FERROELECTRIC BASED HIGH POWER COMPONENTS FOR L-BAND ACCELERATOR APPLICATIONS

Supported by the DOE SIR DE-SC0007630, Phase II

**A.Kanareykin E,Nenasheva, Y.Xie, C,Jing, S.Baryshev, A.Kozyrev, I.Ben-Zvi, V.Yakovlev, N.Solyak.**

**Euclid Techlabs/BNL/FNAL collaboration**

# Outline

- Company introduction
- BST(M) material development and initial experiments
- BST(M) ferroelectric properties; low permittivity BST(M)
- Sputtering system development; metallization technology and RTZ measurements;
- Bulk ferroelectric fabrication, HV contacts deposition;
- RF characterization of the bulk ferroelectric elements;
- Ferroelectric based tuner design

# Company introduction

Euclid TechLabs LLC, founded in 1999 is a company specializing in the development of advanced designs and new dielectric materials for particle accelerator and other microwave applications. Additional areas of expertise include superconducting accelerating structure design; dielectric structure based accelerator development; theoretical electromagnetics; "smart" materials technology and applications; and software development.

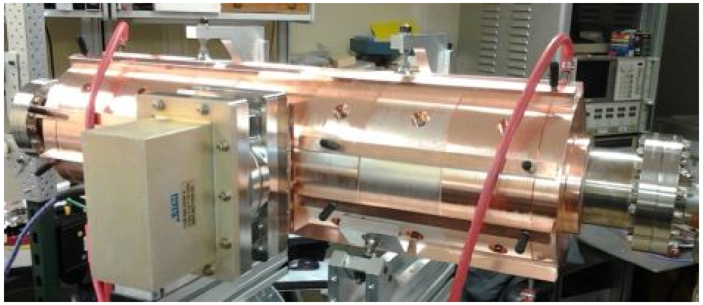
Euclid collaborates with ANL, BNL and FNAL in engineering development and experimental demonstration of normal conducting and SRF cavities, high gradient accelerating structures and other accelerator components.

Research team: 10 PhDs in beam physics, material science and engineering.

**www.euclidtechlabs.com**

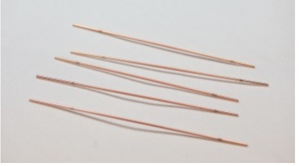
Offices:
Bolingbrook, IL (lab); Solon, OH;
and Gaithersburg, MD

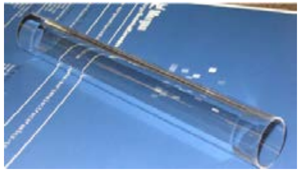
# Facility and Commercial Products
## www.euclidtechlabs.com

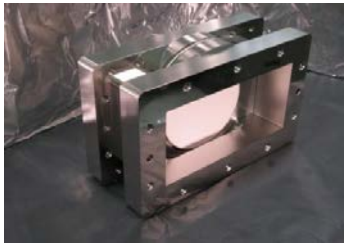


### Our lab is in Bolingbrook, IL

RF lab, machine shop, dielectric components machining, sputtering system, metallization.

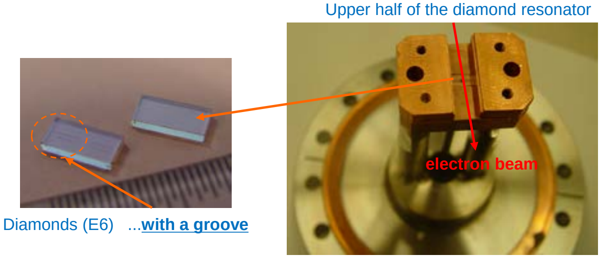


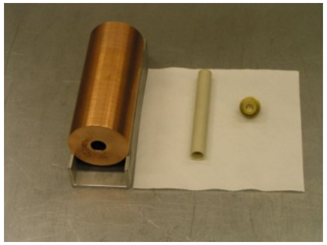


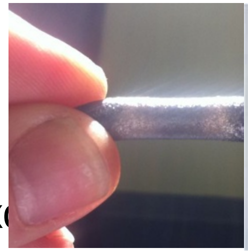


### Commercial products:

- ➢ low energy compact X-band accelerators,
- ➢ photoinjectors
- ➢ accelerating structures,
- ➢ rf windows, rf loads,
- ➢ THz components
- ➢ ceramic, quartz and diamond elements.
- ➢ software (SLANS, BBU'3000)

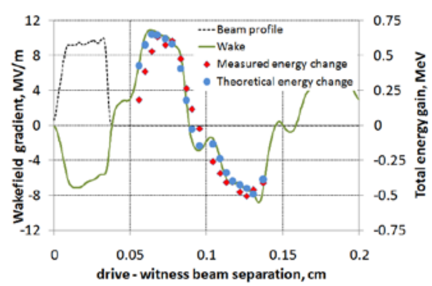


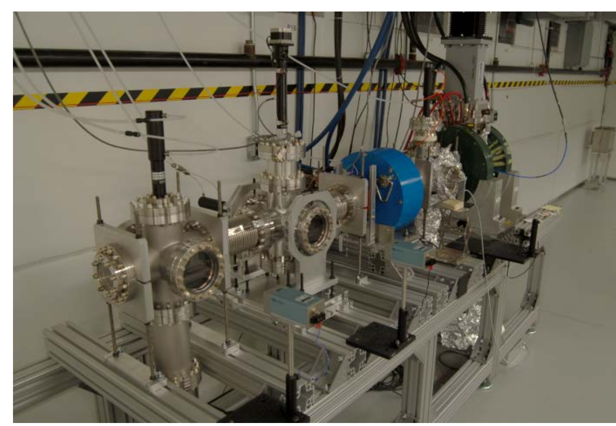





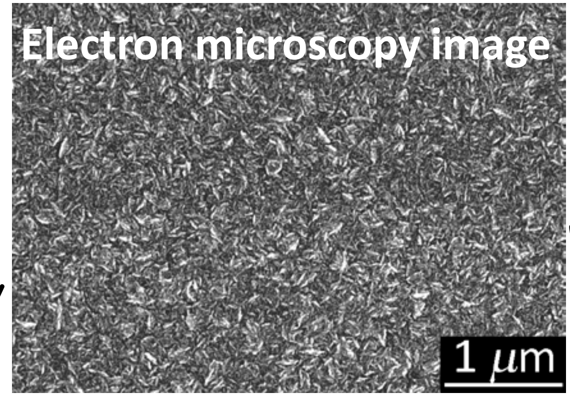
# Research

- Dielectric based wakefield acceleration (ANL/AWA)
- High repetition rate dielectric based FEL linac (ANL/APS)
- FEL beam chirp correction (ANL/APS)
- SRF components for ERLs, LCLS-II and ILC (FNAL/BNL)
- THz generation and beam manipulation (BNL/ANL)
- Diamond capillary for LWFA (LBNL)
- Diamond Field Emission Cathode



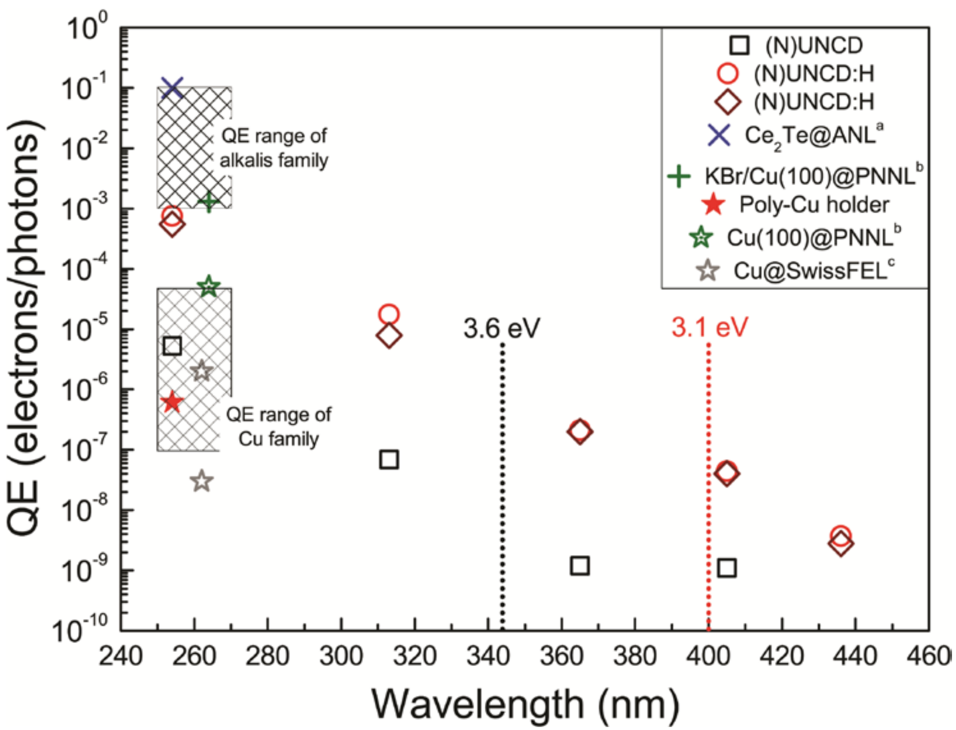



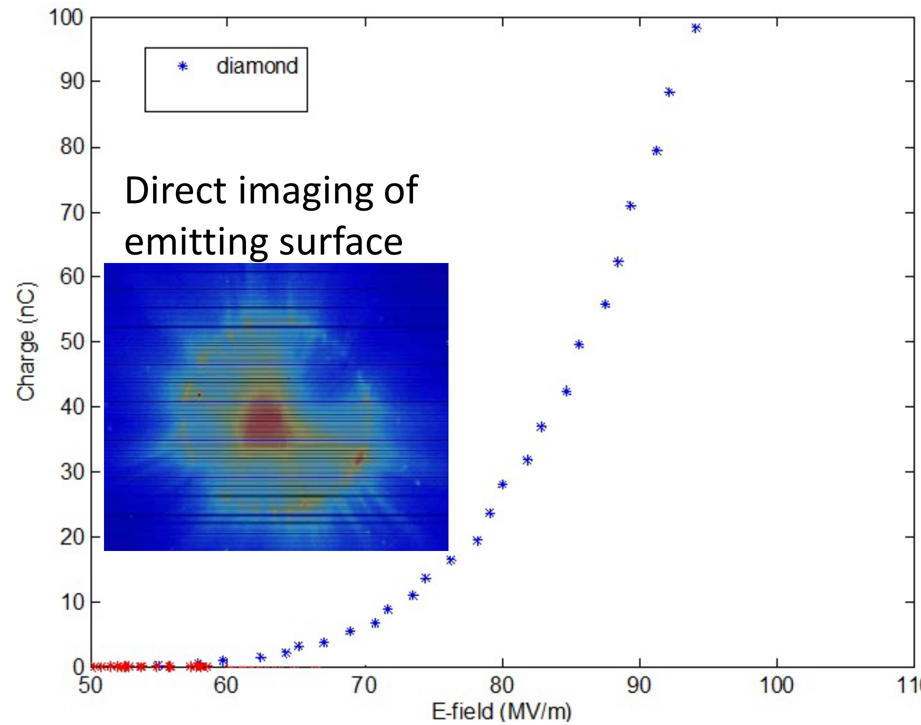
# Flat thin film synthetic diamond electron emitters




Air resistant photocathode
with high quantum efficiency
~ 0.1% in near UV@254 nm
~ $10^{-5}$% in visible@405 nm

Flat field emission cathode
useful for SRF technology
with peak current (per $inch^2$)
~ 4 mA@60MV/m
~ 40 mA@70MV/m
~ 400 mA@100MV/m



# History: Tunable DLA Beam Test

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

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

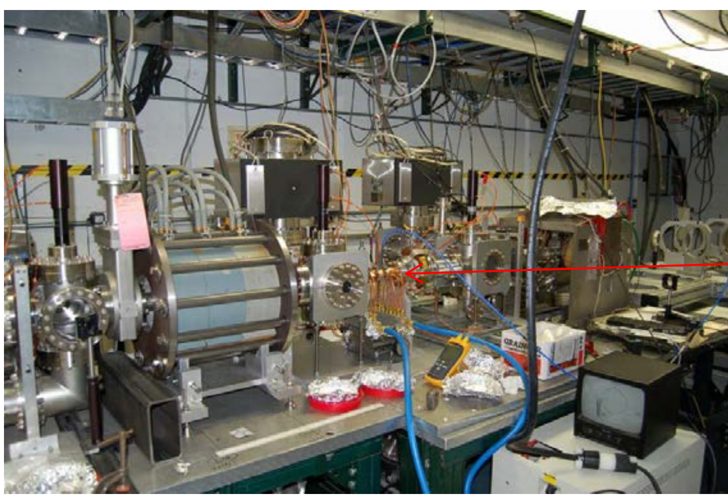
C. Jing,[1,2] A. Kanareykin,[1] J. G. Power,[2] M. Conde,[2] W. Liu,[2] S. Antipov,[1,2] P. Schoessow,[1] and W. Gai[2]

[1]*Euclid Techlabs, LLC, 5900 Harper Road, Solon, Ohio 44139, USA*

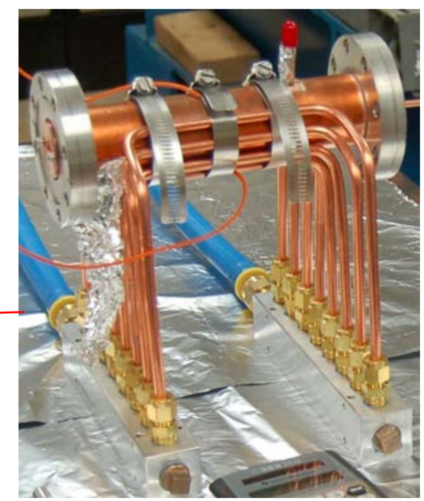
[2]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

(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



Picture of the wakefield acceleration experiment setup.



Apparatus to tune the temperature of the tunable standing wave DLA structure.

# Motivation

A fast controllable phase shifter would allow microphonics compensation for CW SRF accelerators supporting NP, 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.

# CW Accelerating Cavity Issues

**Proposed accelerators:**
**Modest gradient • Low beam loading • CW operation**

- * Loaded Q: Optimized for beam loading: Nuclear Physics < 1 mA, ERLs close to zero net current; Light Sources - 10's of μA to 100 μA
- Microphonics & Lorentz Detuning: Determined by cavity/cryomodule design and background environment.
  - Effects are driven by $Q_L$ and the available rf source power

*Tom Powers/Curt Hovater. RF Control of CW Superconducting Cavities. CW SCRF 2012 .

# Cavity tuner : design to minimize microphonics; Active microphonic compensation by ferroelectric.

- Specific features of ERLs accelerator technology and the challenges of ERL designs for X-ray light sources are the high magnitude and phase stability of its operations, in the range of $3\times10^{-4}$ and 0.06 degree respectively.
- Mechanical vibrations (microphonics) contaminate the resonator frequency with characteristic frequencies in the range of 100 Hz. Ferroelectric tuners have demonstrated extremely high tuning speeds and this concept is promising for accelerator systems where high frequency tuning is an ultimate goal. The ERL technology requires exactly the same type of fast tuner.

# Microphonics and Low Bandwidth

Mechanical oscillations change cavity resonance
Mechanical noise couples directly to the beam through the cavities
XFEL : Net beam loading 200 kW; Bandwidth ~400 Hz
CW ERL Linac Net beam loading<0.1 kW; Bandwidth~20Hz

*To compensate the RF source must provide additional power: $\Delta P_g$

$$\Delta P_g = \frac{V_c^2}{R/Q} \frac{f_{1/2}}{f_0} \times \left( \frac{\Delta f}{f_{1/2}} \right)^2$$

**$\Delta f$= microphonics**

**$f_{1/2}$ = bandwidth**

*O.Kugeler, J.Knobloch. CW for LINAC based accelerators. 2009.

# Microphonics Compensation

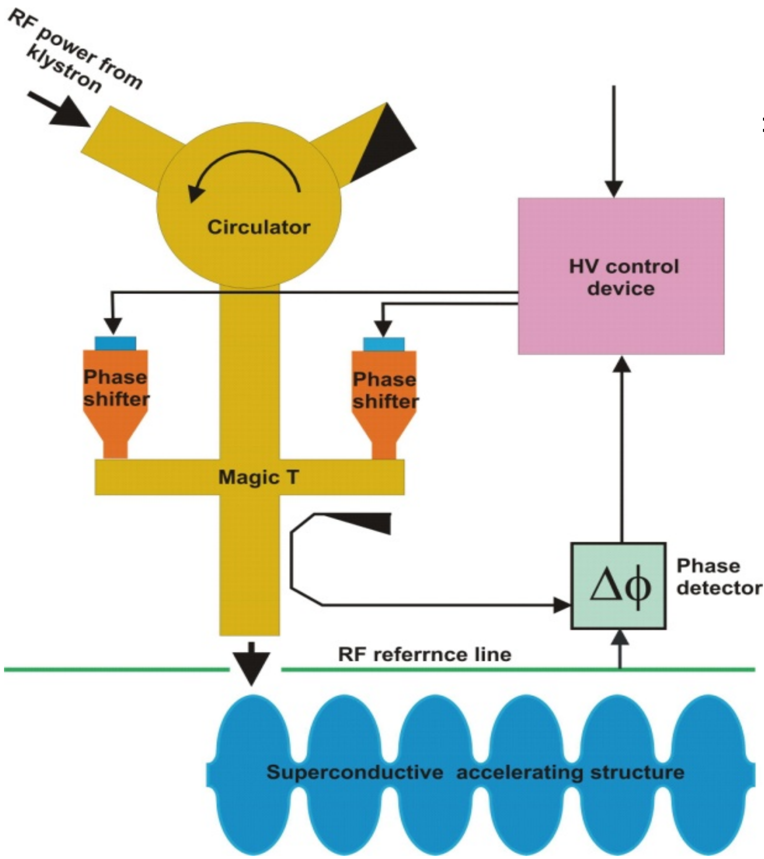
*How does one limit microphonics?

- Ensure stable helium system, low pressure fluctuations (0.01 mbar)
- Design the cryostat not to transmit mechanical vibrations to the cavity
- Ensure your system is stiff and mechanical resonances are at high frequencies (e.g., stiff cavity)
- Active control with the tuner. Originally developed for LF detuning in pulsed machines

*O.Kugeler, J.Knobloch. CW for LINAC based accelerators. 2009.

# Tuner Requirements

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



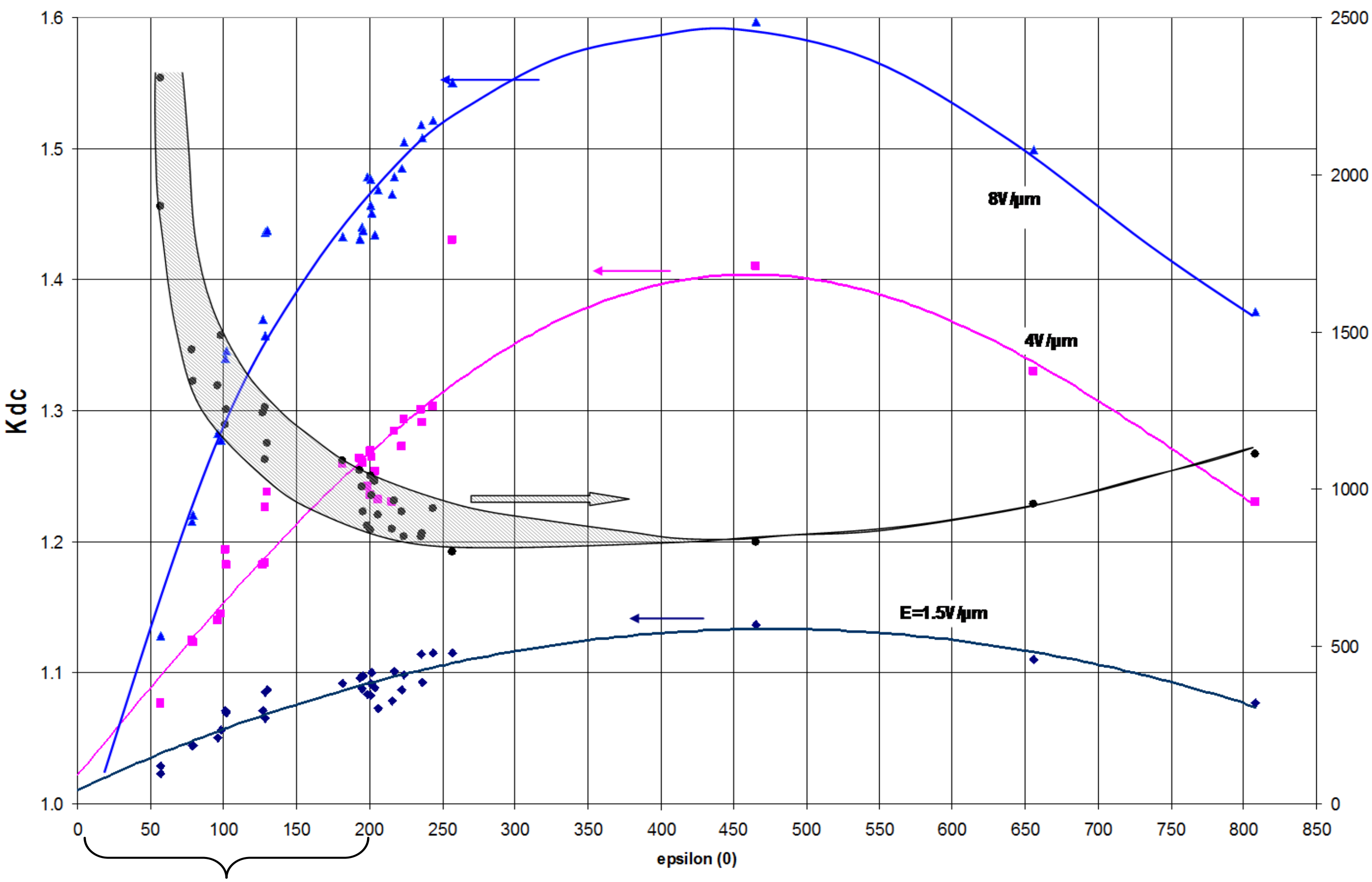

$$= P_g / P_{g,\max} = \delta\omega / \Delta\omega \left(1 - 4tn\delta \frac{\eta(\varphi_0)\varepsilon}{\Delta\varepsilon}\right).$$

for BNL ERL and the tuner described in the Euclid Proposal ($\Delta\varepsilon/\varepsilon$=0.2 and $\phi_0$= 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.

# Tunable Ferroelectric Ceramics for Microwave Devices

# Progress on Nonlinear BST Material Development




BST(M), ε~50-150

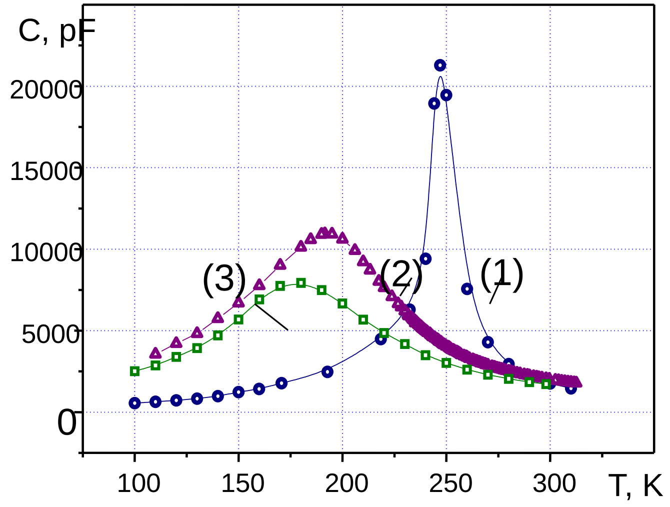
record low values of dielectric constant and loss tangent at relatively high tunability level required for high power bulk tuner operating in air (< 30 kV/cm) and in vacuum ( up to 80 kV/cm).

# Ferroelectric ceramic properties

| | |
|---|---|
| dielectric constant, $\varepsilon$ | 50-450 |
| tunability, $\Delta\varepsilon$ | >30@15kV·cm$^{-1}$ of the bias field |
| response time | < 10 ns |
| loss tangent at 1.3 GHz, tan$\delta$ | ~$1\times10^{-3}$ |
| breakdown limit | 200 kV/cm |
| thermal conductivity, $K$ | 7.02 W/m-K |
| specific heat, $C$ | 0.605 kJ/kg-K |
| density, $\rho$ | 4.86 g/cm$^3$ |
| coefficient of thermal expansion | $10.1\times10^{-6}$ K$^{-1}$ |
| temperature tolerance, $\partial\varepsilon/\partial T$ | (1-3) K$^{-1}$ |

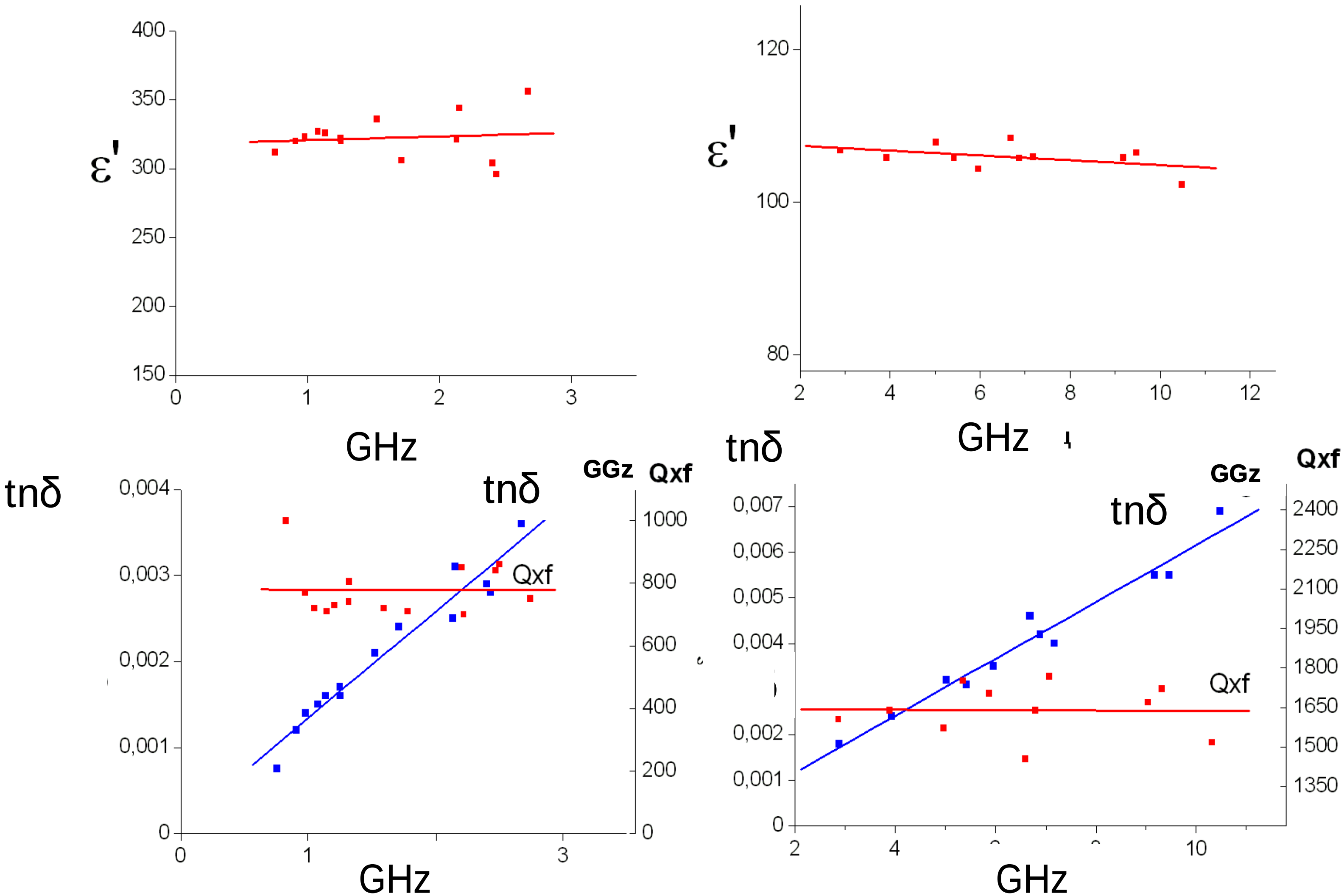
# Issues with the ferroelectric elements

- 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

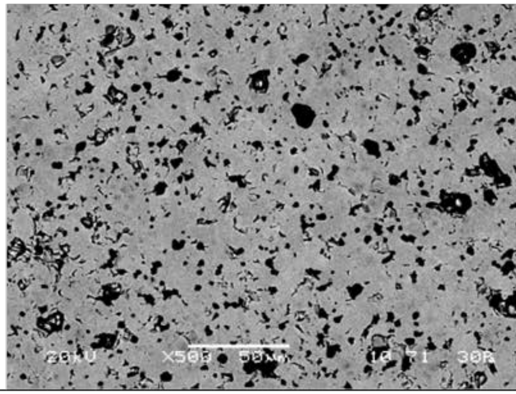



(Ba, Sr)$TiO_4$+Mg oxides

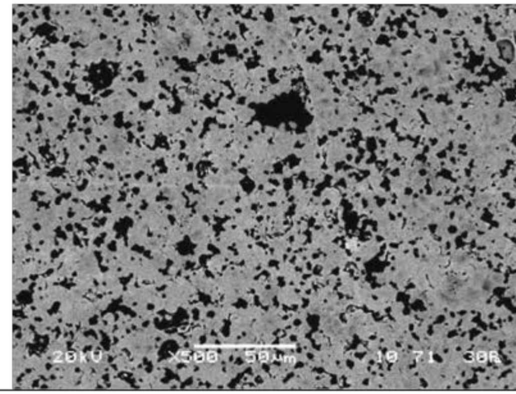
# Frequency dependence of ε and tnδ for the ferroelectrics with low permittivity



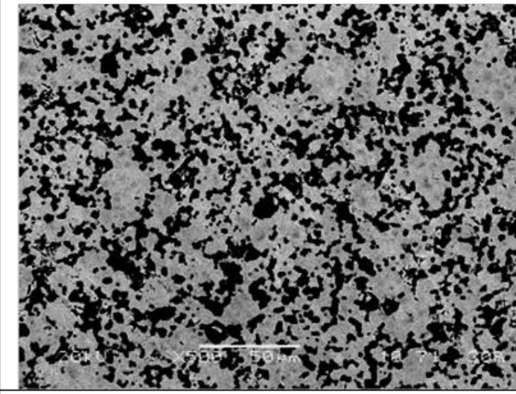
# BST(M) Microstructure vs. Mg based content



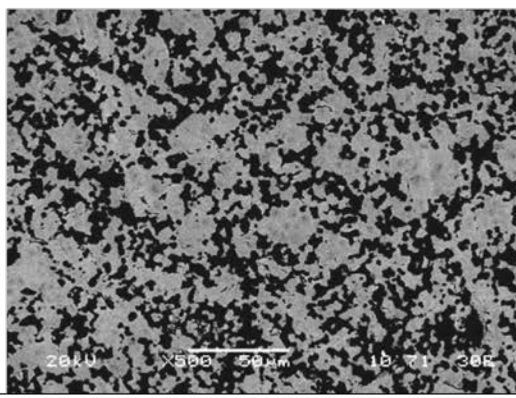
(a) 3%



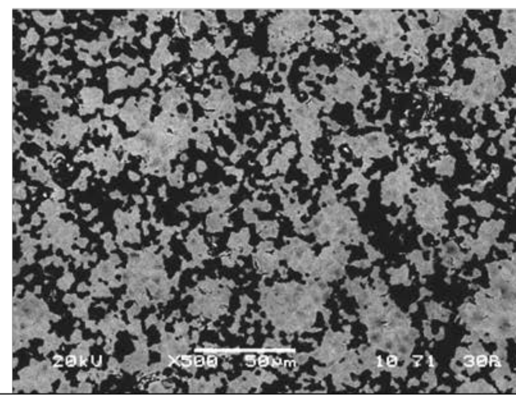
(b) 9%



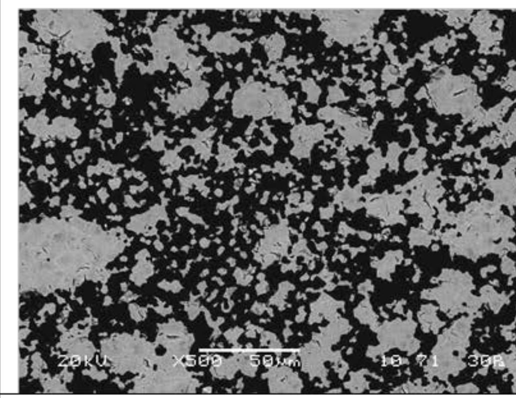
(c) 20%



(d) 30%



(e) 40%

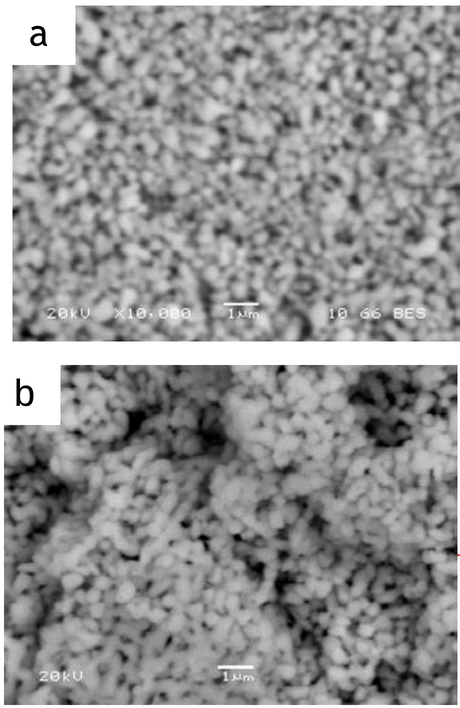


(f) 60%

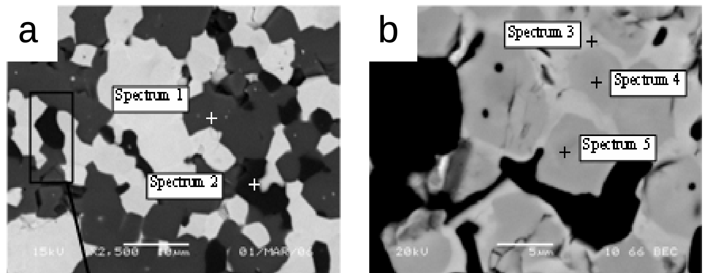
# Ferroelectric composite materials

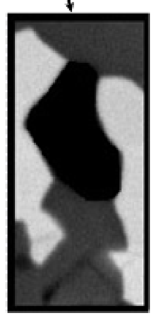
*Patent US 8,067,324 B2, Nov. 29, 2011*

## Powders ⇒ Ceramics



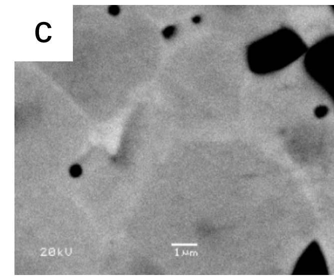
**SEM-image of the initial powders of barium titanate (a) and strontium titanate (b).**

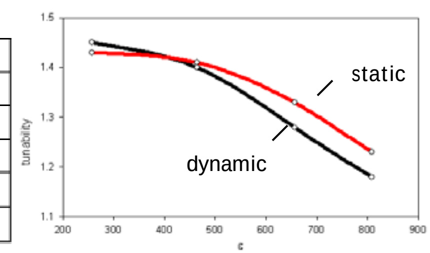




| Spectrum | Mg | Ti | Sr | Ba | O | Total |
|---|---|---|---|---|---|---|
| Spectrum 1 | 29.66 | 27.47 | 1.39 | 2.99 | 38.49 | 100.00 |
| Spectrum 2 | 59.89 | 0.19 | 0.26 | 0.06 | 39.60 | 100.00 |
| Spectrum 3 | 0.19 | 22.57 | 16.33 | 38.09 | 22.82 | 100.00 |
| Spectrum 4 | 0.14 | 22.62 | 21.85 | 32.23 | 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).**

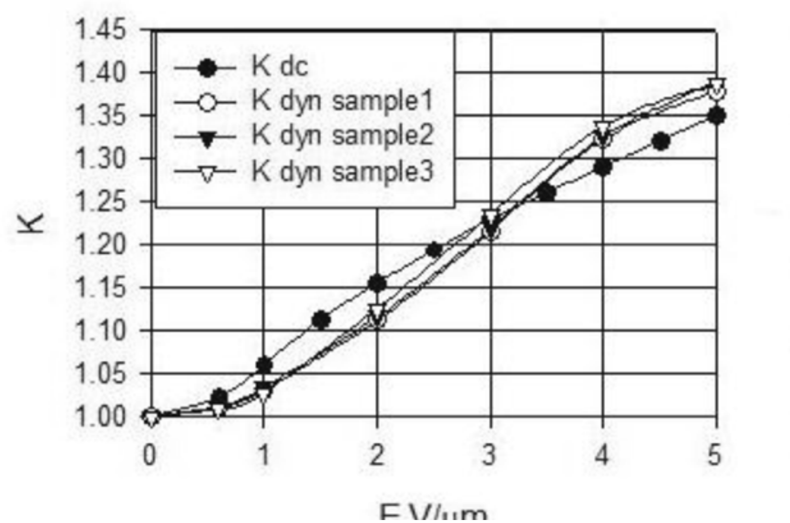


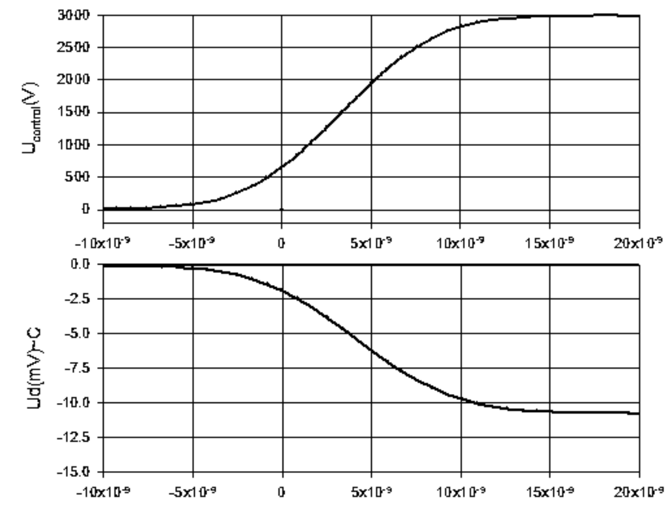


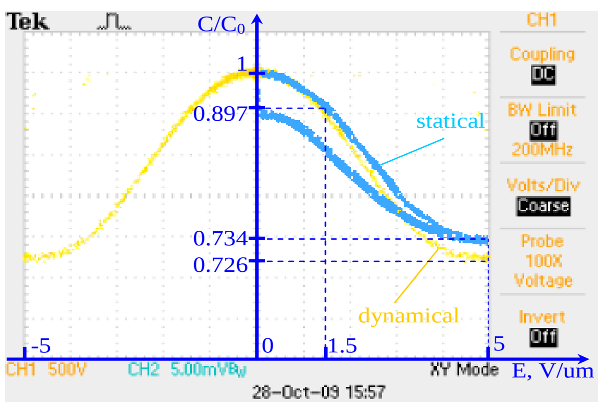

**Static and dynamic tunability as a function of the permittivity**

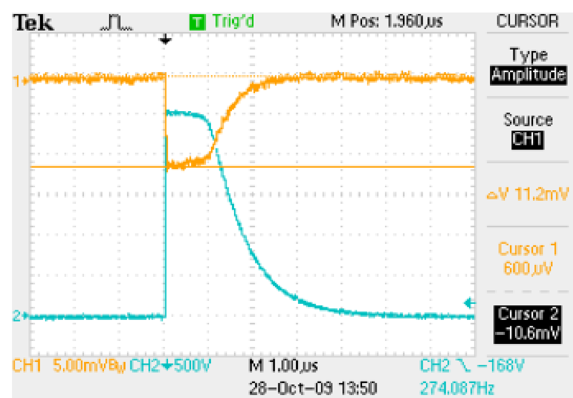
SEM image of the boundary interface region in between the grains of the $BST-MgO-Mg_2TiO_4$ composite material.

# *Dynamic Tunability > Static Tunability



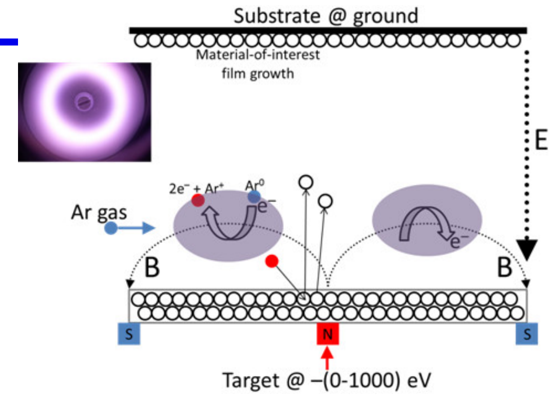



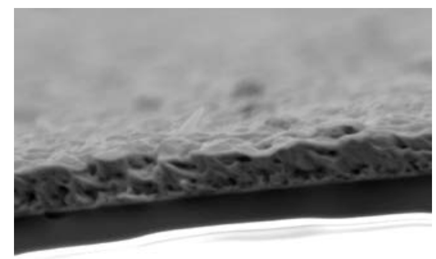



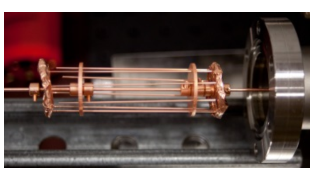



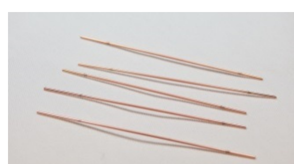

*Courtesy A.Kozyrev

# Euclid's Sputtering System, Bolingbrook IL



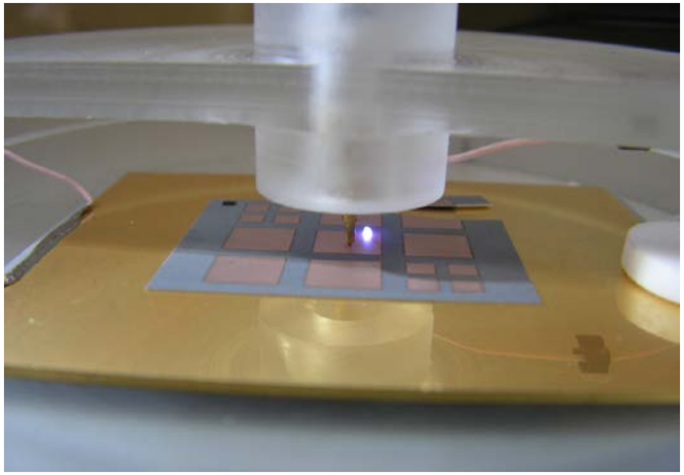



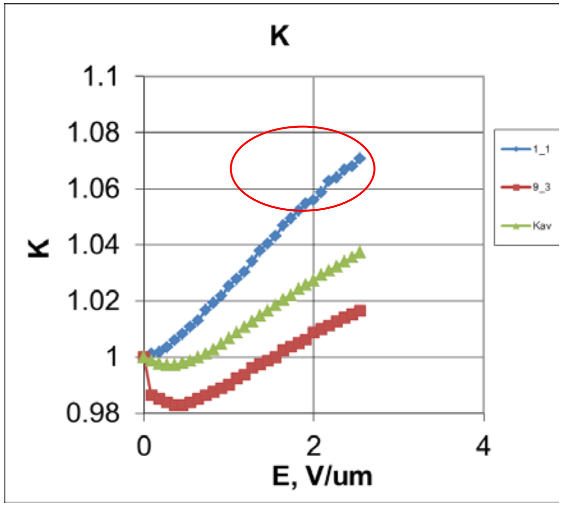




Euclid has developed a sputtering system for depositing of a variety of metallization and dielectric deposition applications.

# Tunability Measurements

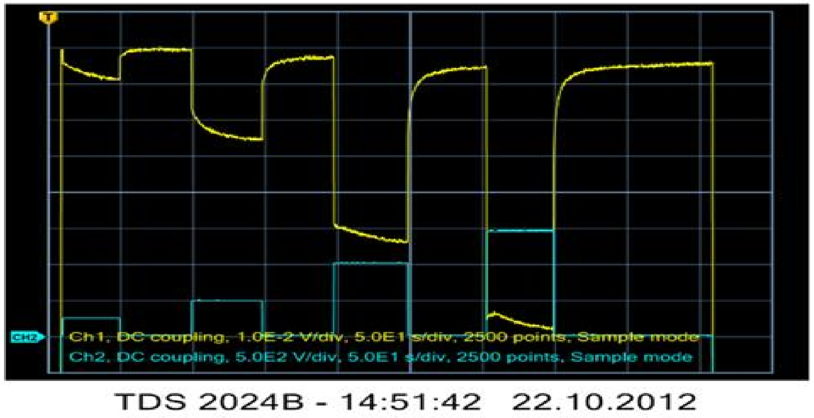


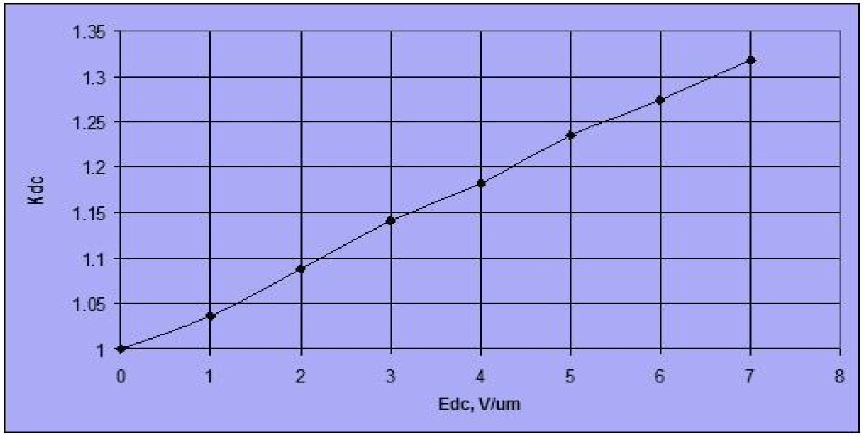



Development of a ferroelectric material having a dielectric constant in the range 80-150, tunability 5-6% at 15-20 kV/cm and a figure of merit Q×f ~ 1500-1700.

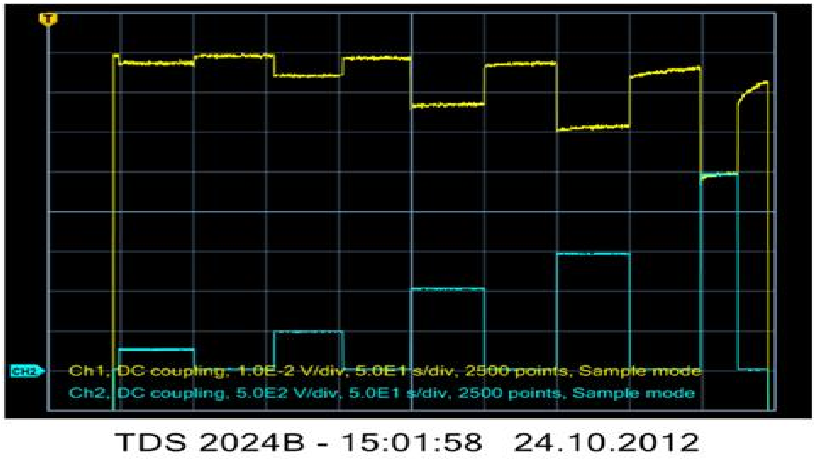
- Measuring setup with an option to apply bias voltages (up to 6 kV) using a pin-like DC electrode to the metalized ferroelectric substrate (patch) was fabricated. Ferroelectric compositions; its tunability at *K*=2V/μm bias field, RZT coefficient (%) were obtained.
- It was found three basic compositions with the tuning value of 1.06-1.08 at 2 V/μm bias voltage were selected for the tuning element of the phase shifter fabrication.

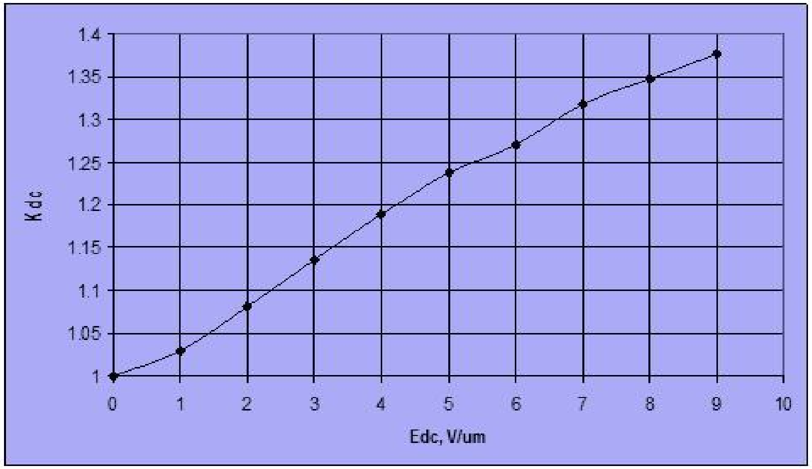
# Return-to-Zero and Deposition



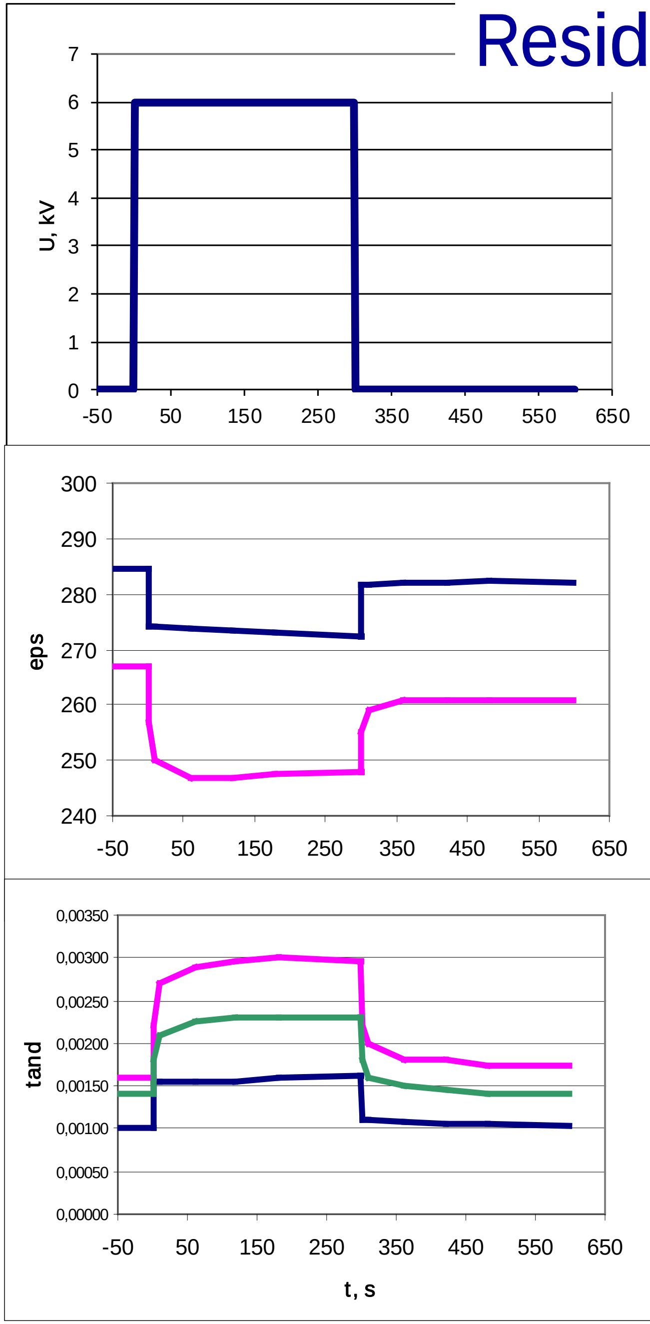

(a) (b)



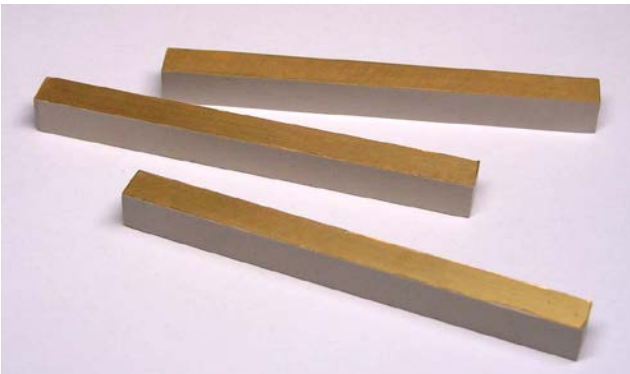

(c) (d)

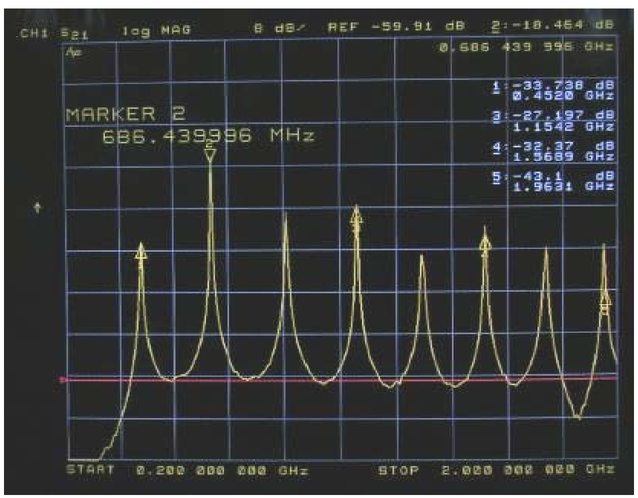
# Residual Effects Mitigation




Dielectric response measurement (permittivity and tan δ relaxation) after the dc bias pulse (a). After process improvement: (b) permittivity ε~ 230 – 270; (c) loss tangent after, ε=270 (blue); and before improvement ε=267(magenta) and 233 (green).

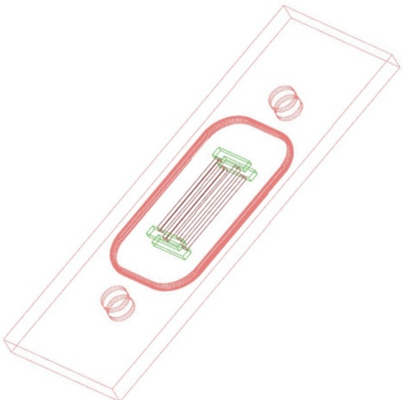
# RF measurements of the BST(M) parameters



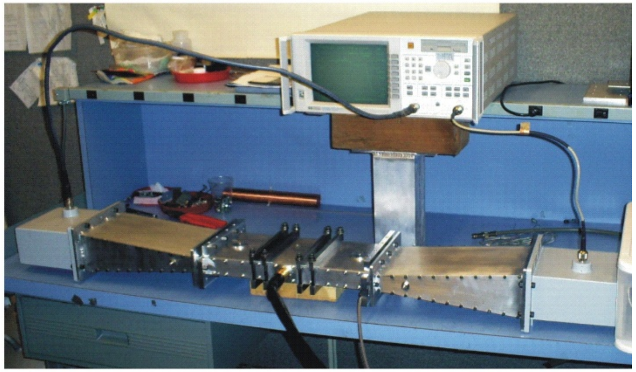



Test stand for the bulk metalized ferroelectric characterization

# *High dielectric constant ε~ 500 ferroelectric tuner cold test

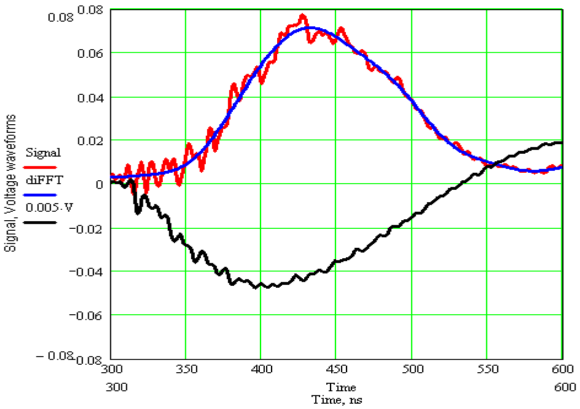


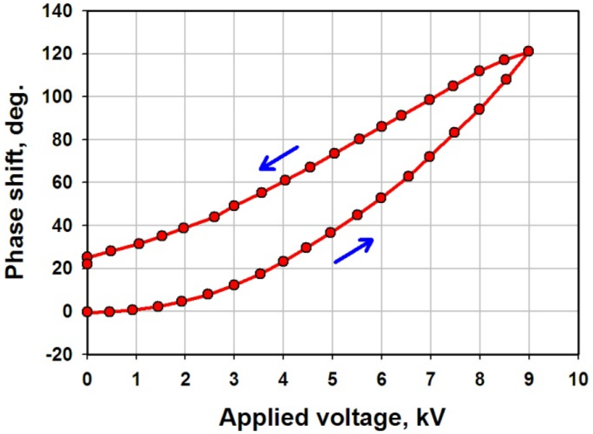
(a)



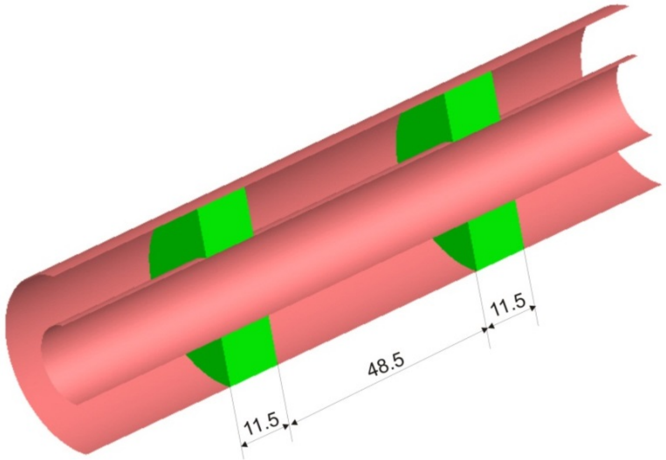
(b)

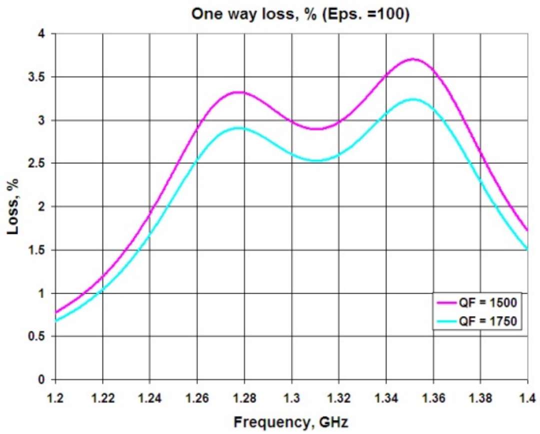
*Courtesy Omega-P, Inc.

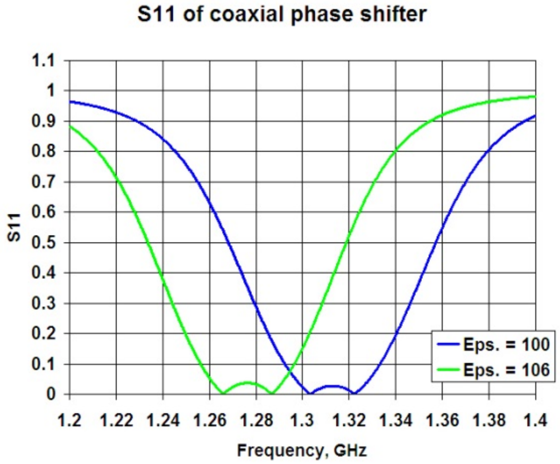


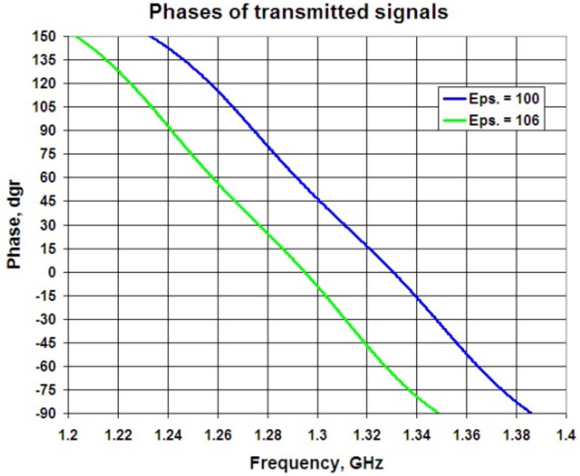



# Conceptual BST Based Tuner Design

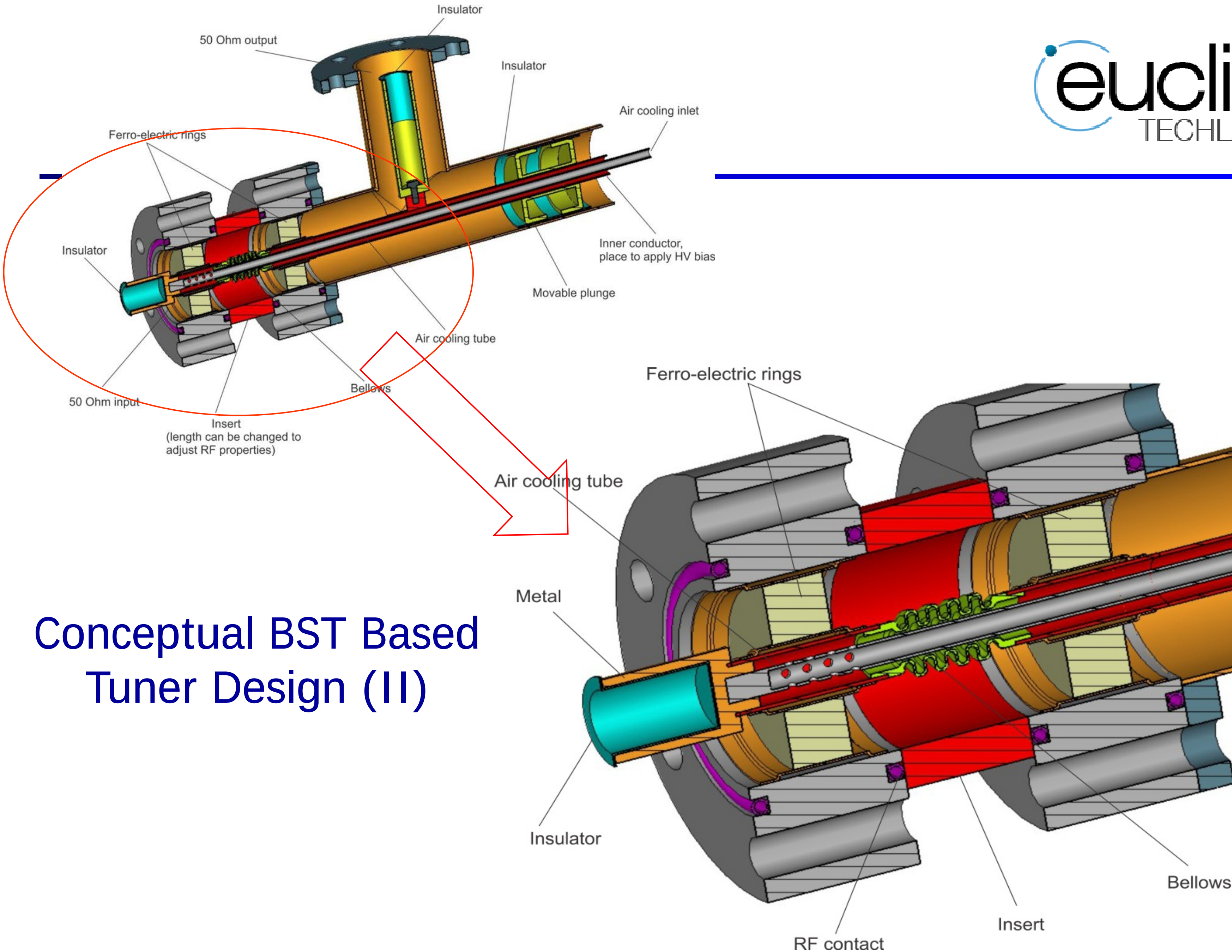


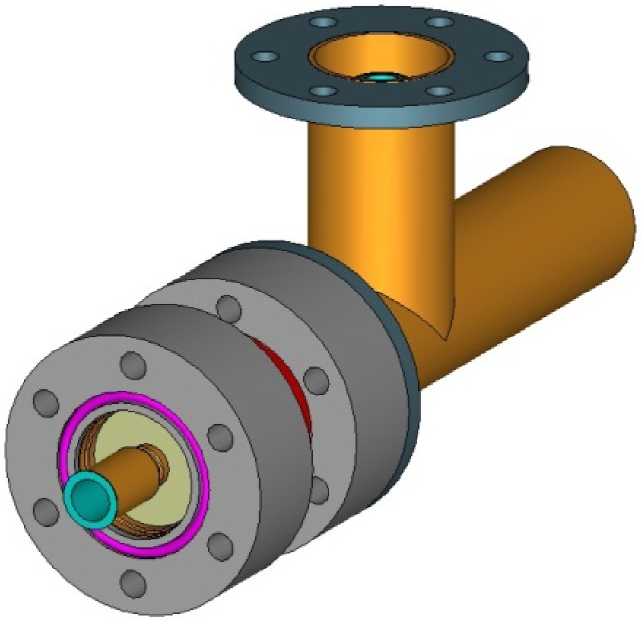



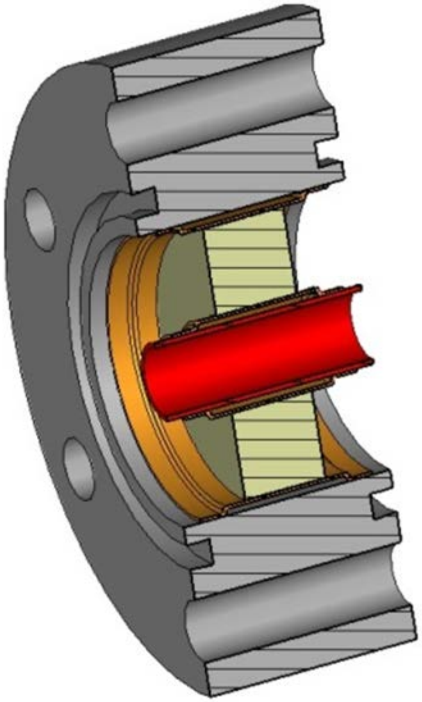



# Conceptual BST Based Tuner Design (II)



# Conceptual BST Based Tuner Design (III)

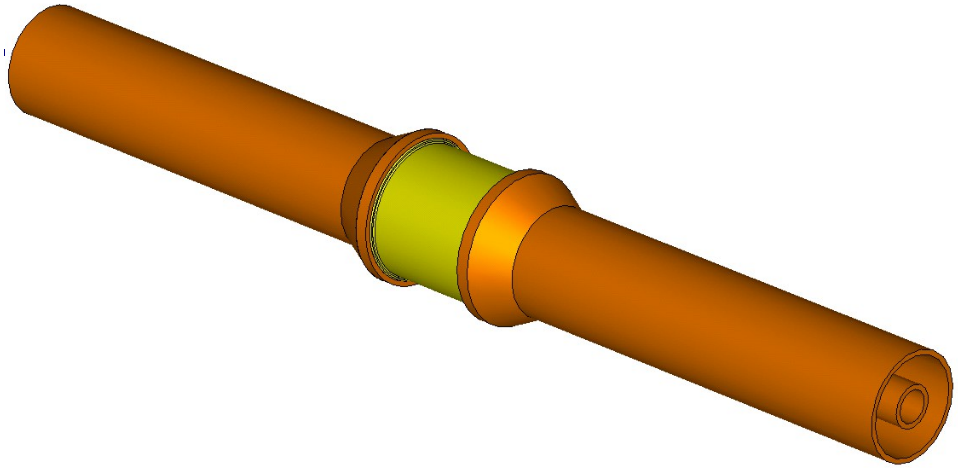


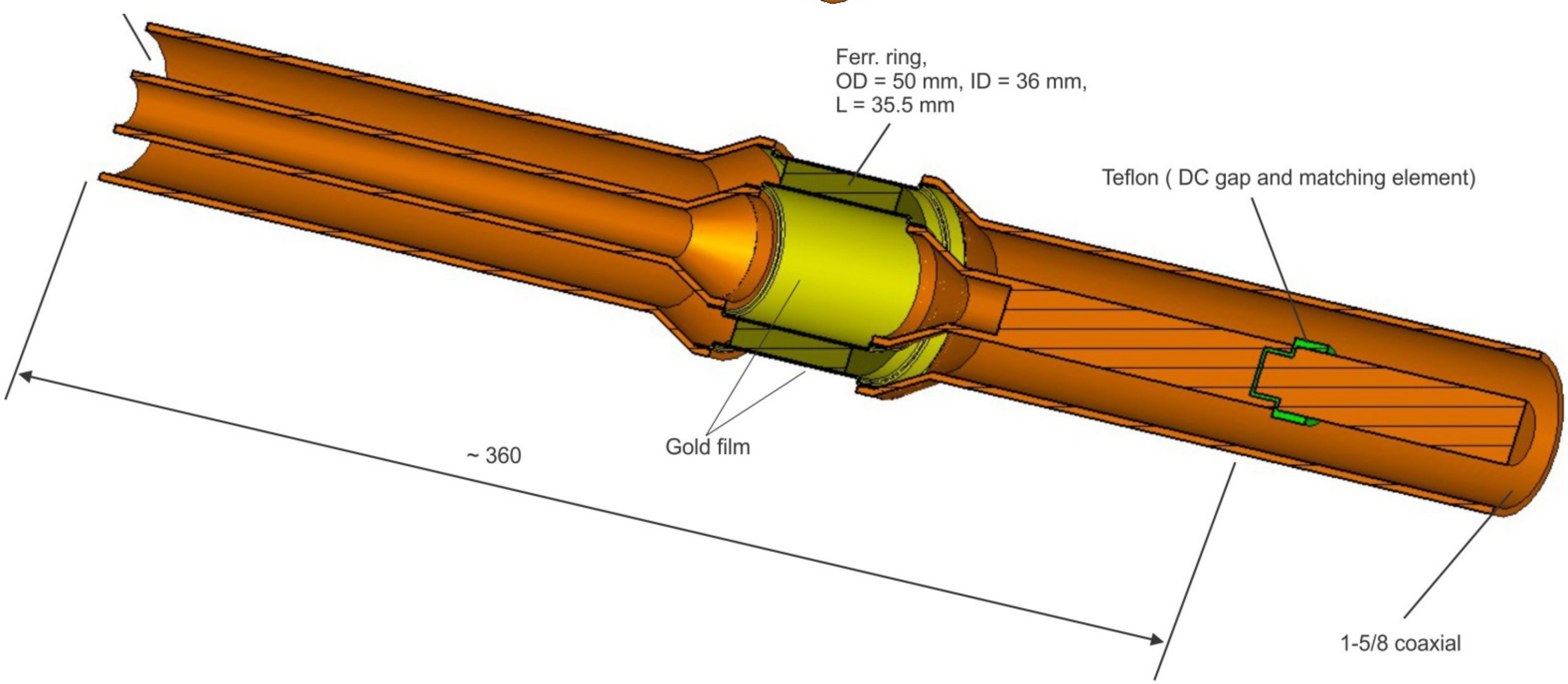


# Final Design

Total losses of 120 dgr phase shifter
(Eps. changes 107 -113)

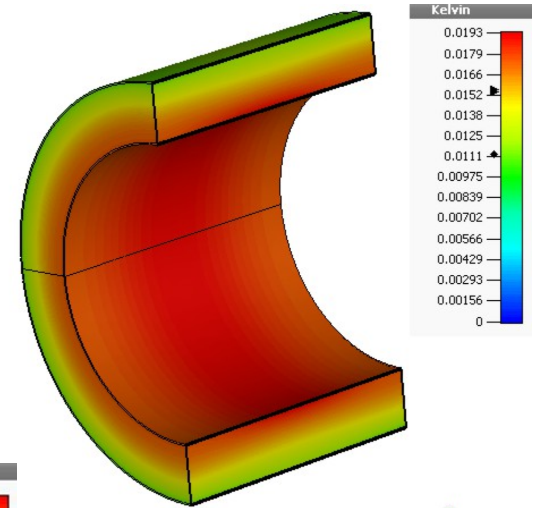
Loss tangent 0.0, losses 4.6%
Loss tangent 3.5E-4, losses 7.4%
Loss tangent 7.0E-4, losses 10.1 %
Loss tangent 1.0E-3, losses 12.4%



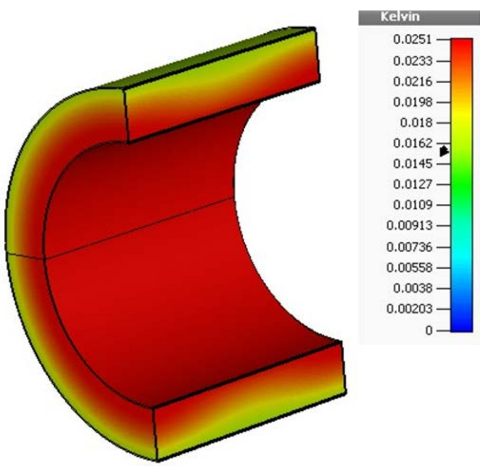


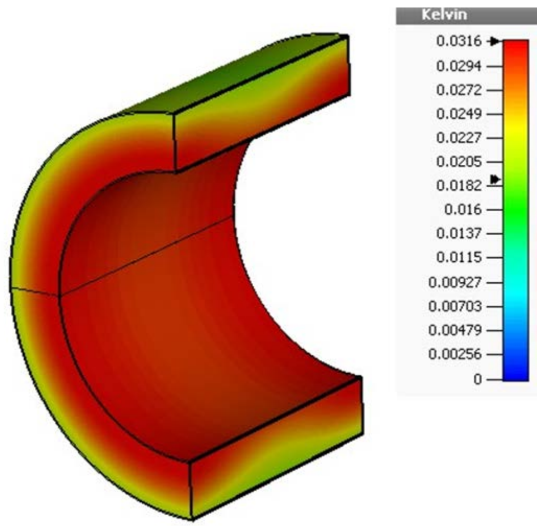
# Ferroelectric temperature distribution

for 1W RF power.
Cooling:
outer surface 1000 W/(m2*K), water
inner surface 100 W/(m2*K), oil




Loss tng = 3.5E-4,
T avr. ~ 0.016 C



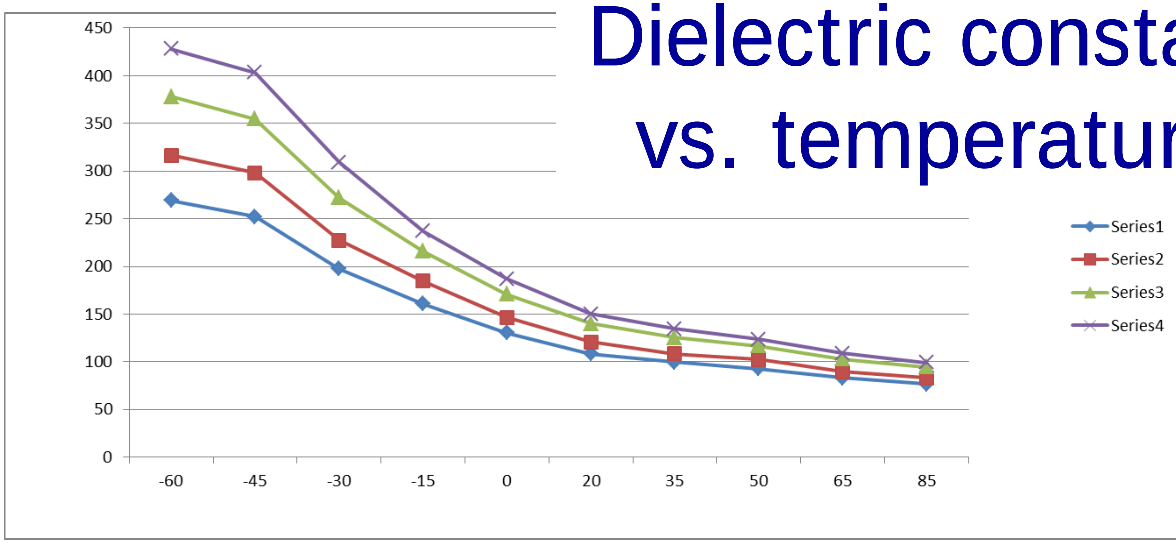



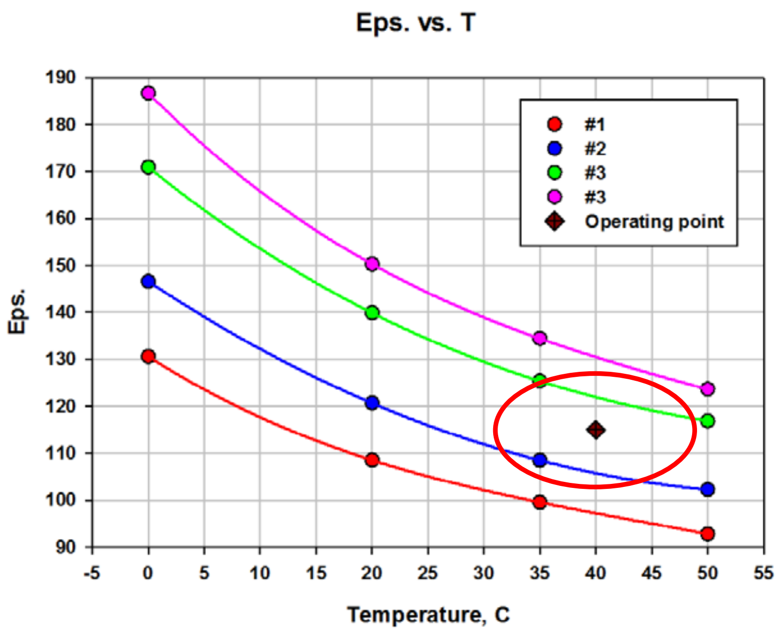

Loss tng = 7.0E-4,
T avr. ~ 0.022 C

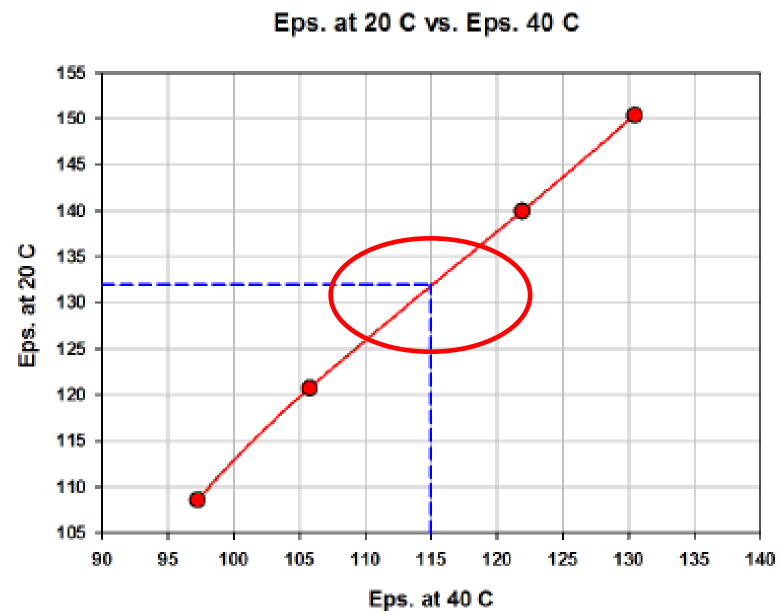
Loss tng = 1.0E-3,
T avr. ~ 0.026 C

# Dielectric constant vs. temperature

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 to be manufactured 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 $5\text{-}6\times10^{-4}$ at 700 MHz.
Currently have been demonstrated:

- Dielectric constant ~ 100-150
- Loss factor ~ $1.0\times10^{-4}$ 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 will be carried out in 2015.