Advanced Materials for Accelerator Technologies in Euclid's R&D Program

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On behalf of the Euclid's team

FRIB/MSU APES

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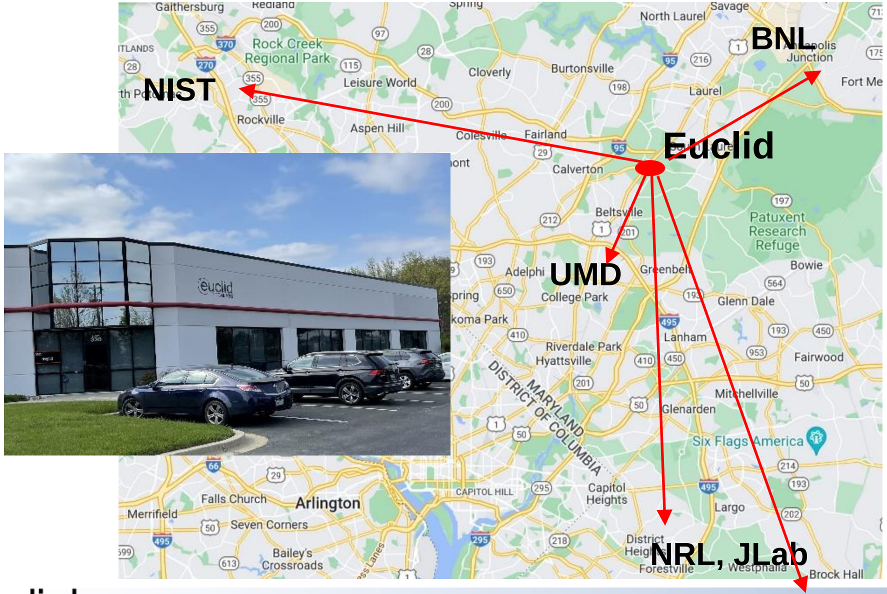
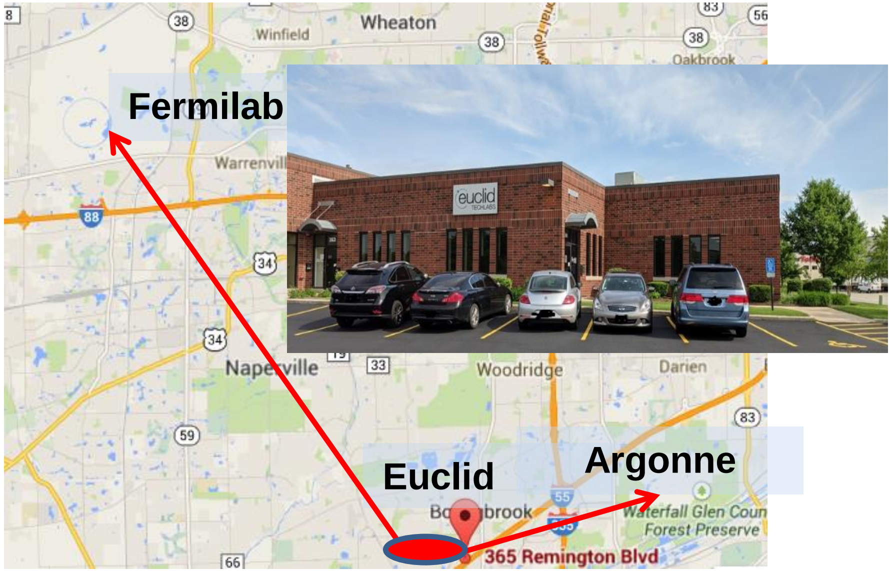
Outline

- Introduction Euclid Techlabs and Euclid Beamlabs
- Ferroelectric material and Ferroelectric Fast Reactive Tuners (F-FRT)
- Conductive Microwave Ceramic and New High Power RF Windows
- High Purity Diamond Growth for X-ray Optics
- Summary

Euclid Techlabs/Euclid Beamlabs

Euclid Techlabs, LLC is a research and development company specializing in linear particle accelerators, ultrafast electron microscopy, and advanced material technologies. The company was formed in 2003. Euclid Beamlabs LLC, formed in the winter of 2014, is a sister (spin-off) company of Euclid Techlabs LLC, particularly to commercialize industrial accelerator and related advanced material technologies developed at Euclid Techlabs. Euclid has developed expertise and products in several innovative technologies: time-resolved ultra-fast electron microscopy; ultra-compact linear accelerators; electron guns with thermionic, field emission or photo-emission cathodes; fast tuners for SRF cavities; advanced dielectric materials; HPHT and CVD diamond growth and applications; thin-film for accelerator technologies;





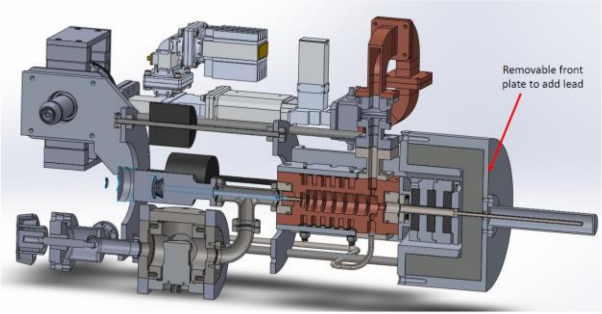
Products & Capabilities Snapshot

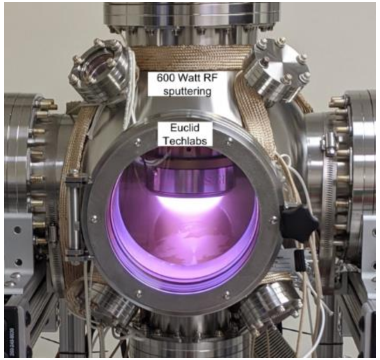
Products

- UltraFast Pulser (UFP^{TM}) for TEM
- Compact X-Ray Source
- L-band High Peak Current Linac
- RF high power windows
- Fast reactive tuners for SRF
- BPMs other accelerator components
- CVD and HPHT diamonds,
- Electron sources and cathodes

Capabilities

- Femtosecond Laser Ablation System
- Thin Film Deposition Lab
- TEM Testing Lab
- Radiation Shielding/Testing Lab
- Diamond Growth Lab
- Photocathode Lab
- Ceramic/ferroelectric Lab





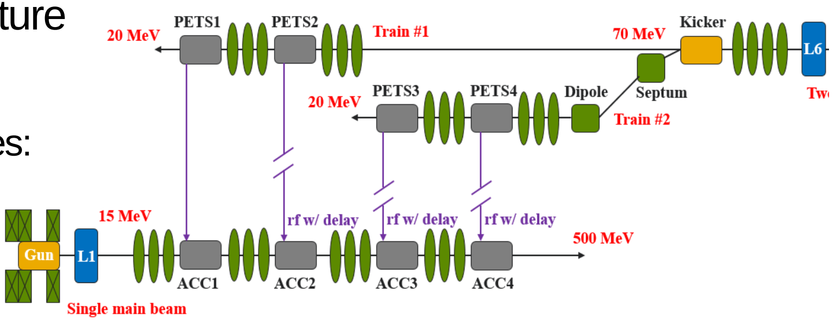
Advanced Acceleration for Future Linear Colliders
In collaboration with ANL/AWA

Euclid actively participates in HEP Snowmass’22 process. We are leading authors for the White paper of the Structure Wakefield Accelerator and coauthors for many others

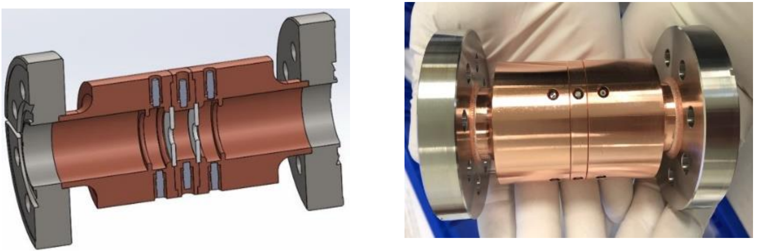
Euclid is developing critical components for two SWFA milestones:

1. 0.5GeV demonstrator at Argonne National Laboratory
2. Collinear wakefield accelerator energy doubler

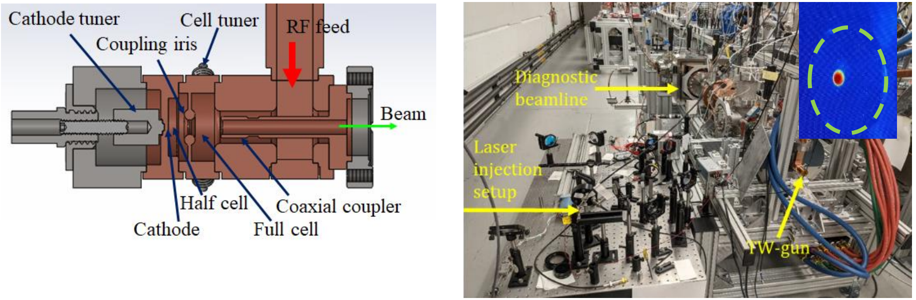
0.5GeV Demonstrator



Novel Dielectric Disk Accelerator, first time demonstrated 100MV/m, multipactor free.

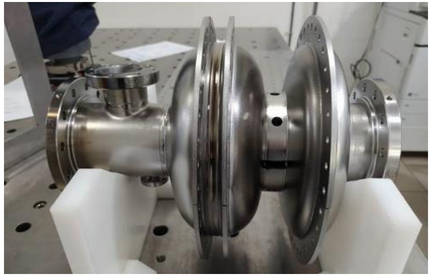


Novel short pulse traveling wave photogun, record high gradient: 400MV/m, and insignificant dark current

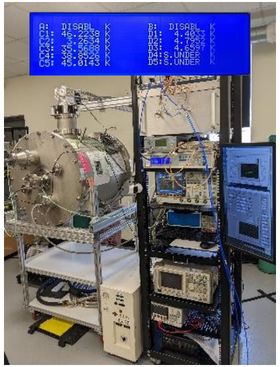


SRF Technologies for Big Science and Industrial Accelerators

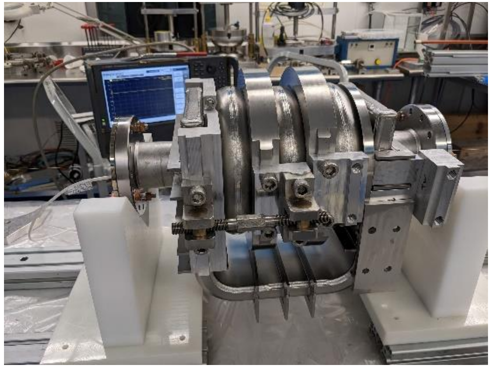
Development of MeV-range ultrafast electron diffraction/microscopy (UED and UEM) is a priority for the DOE. Euclid is developing the **SRF photocathode gun** that is a promising candidate to produce highly stable electrons for UEM/UED applications



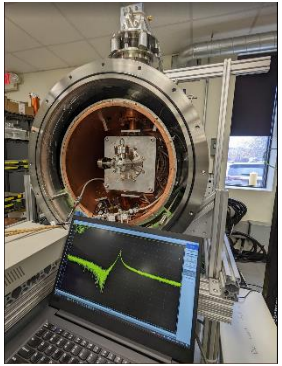
1.3 GHz SRF Photogun



Design optimization of **TW SRF structure**. It is shown that a TW structure can have an accelerating gradient that is about 1.5 times higher than contemporary SW SRF structures with the same magnetic field.



3-Cell Traveling Wave Cavity



Euclid's Conduction Cooled Cryomodule

Euclid is developing SRF technology for conduction cooled industrial Nb3Sn accelerator: **cold spray copper on Nb.**

(in collaboration with FNAL, BNL and Jlab)

1 MeV Mini-linac based Electronic Brachytherapy Cancer Radiotherapy

In 2021 Euclid was awarded the NNSA Phase III (all-metal EB) and NIH NCI (dielectric EB) contracts for development of the compact Electronic Brachytherapy (EB) accelerator for cancer radiotherapy.

The purpose of this effort is to deliver a prototype High Dose Rate (HDR) Electronic Brachytherapy (EB) machine to replace the radioactive sources, e.g., Ir-192, that are commonly used in brachytherapy.

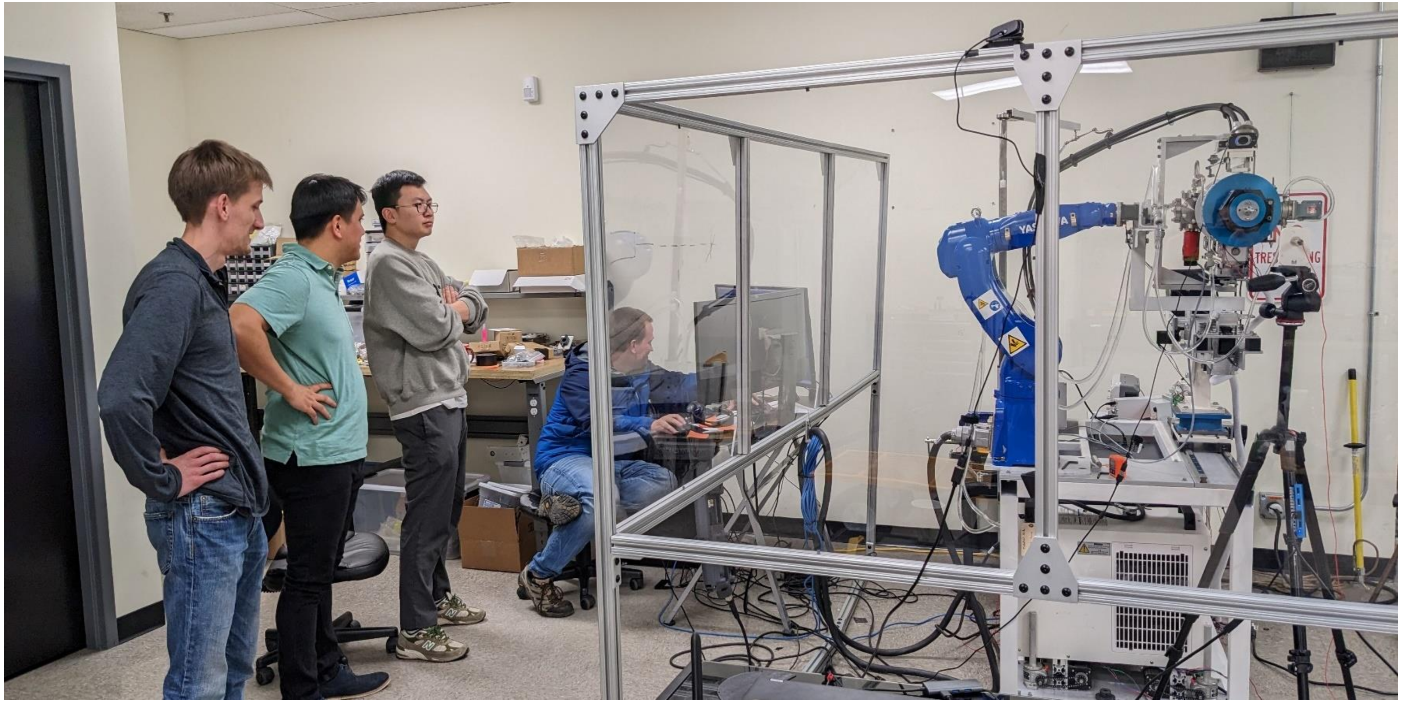
Features

- Table top robotic arm with IMWS (independent mobile weight system)
- Rotational waveguide system to minimize the weight of radiation head
- 3D vision system to automatic find the applicator and insert.

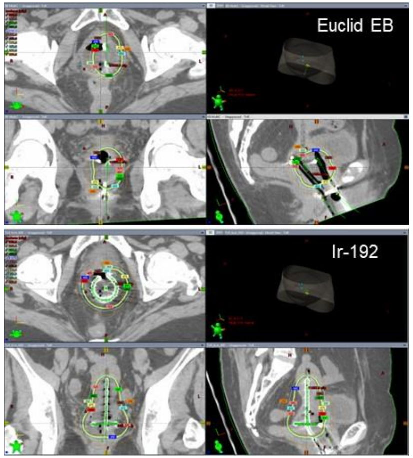
In collaboration with Northwestern Medicine Proton Center (Chicago, IL)

Electronic Brachytherapy – First Prototype

We thank ARDAP provided funds for the “hot” integration test using AWA facility!

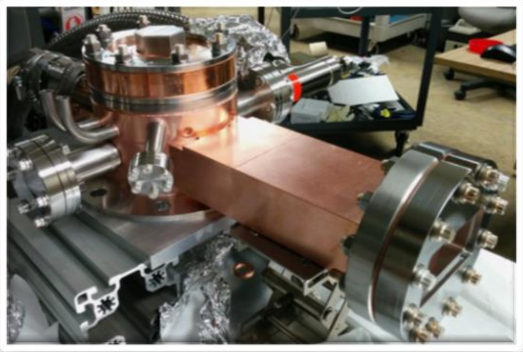


- Tight engagement with Chicago Proton Center oncologists.
- Contact with FDA.
- Established the expertise in radiation simulation and dosimetry measurement.

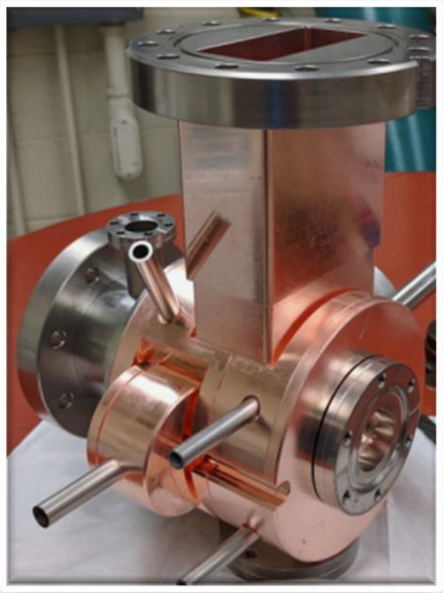


Commercial products: Electron Sources for Accelerators

S-band 1000 pps Photogun



S-band 100MV/m Photogun



S-band Thermionic RF gun

L-band 100nC Photogun

1.3GHz SRF Photogun

Advanced Electron Beam Emitters & Instrumentation

Ultra-high brightness electron sources
- ultrafast electron microscopy
- high-energy x-ray free electron lasers (e.g., SLAC's LCLS-II-HE).

Highly spin-polarized electron beams (>85%)
- nuclear physics experiments (e.g. JLab's CEBAF, and positron drivers).

Longer-lived photocathodes
- future colliders (e.g. BNL's EIC).

Demonstrated novel spin filters and GaAs nanoarrays.

First-ever diamond Mott spin analyzer (5 MeV, CEBAF).

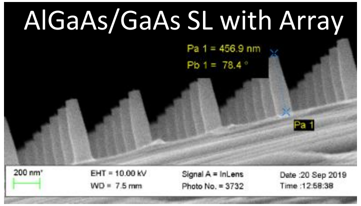
Atomically smooth, high-quantum-efficiency cathodes on conductive substrates, with Arizona State University.

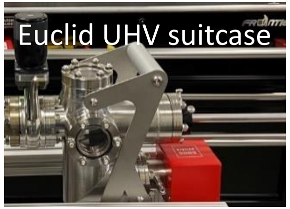
Photocathode factory and cleanroom.

Protective thin films of 2D material: front page-attention at BNL's website; for high current applications.

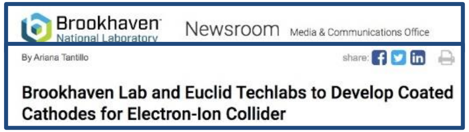
Heusler Spin Filter

Superlattice Nanoarray





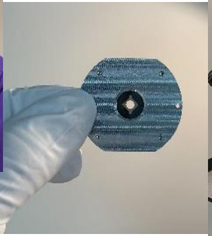
Front page BNL News!



By Ariana Tantillo

Brookhaven Lab and Euclid Techlabs to Develop Coated Cathodes for Electron-Ion Collider

Eric with Joe Grames at JLab



Diamond Mott Target

New Cleanroom, future MBE Cathode Factory

Euclid Plays an essential role in critical components assembly for ANL-SLAC Cavity-based FEL Experiment at LCLS-II

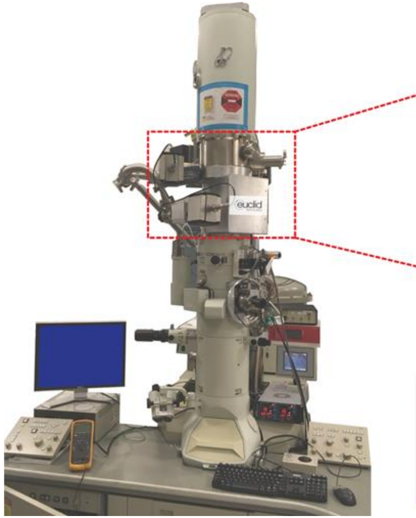
- The X-ray FEL oscillator (XFELO) and the X-ray regenerative amplifier FEL (XRAFEL) concepts use this technique
- Both schemes require a high repetition rate electron beam, an undulator to provide FEL gain, and an X- ray cavity to recirculate and monochromatize the radiation.
- A joint Argonne National Laboratory (ANL) and SLAC National Laboratory (SLAC) collaboration aimed at enabling these schemes at LCLS-II.
- Euclid has been actively participating this project by assembling, testing, and QA all critical components in Euclid Class10k cleanroom at Euclid West facility.

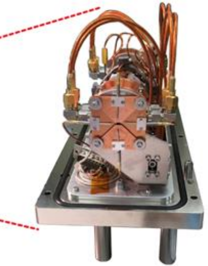
Clean room facility at Bolingbrook IL

Ultrafast Pulser for Transmission Electron Microscopy (in collaboration with BNL, NIST)

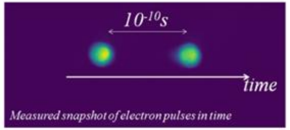
2019 R&D 100 WINNER

As a successful result of the DoE SBIR "Stroboscopic TEM Pulser" project, Euclid was awarded a Phase III contract for Transmission Electron Microscope (TEM) modification at NIST in 2016-2018. The NIH and Chan-Zuckerberg awards started in 2021. Currently Euclid is installing the UltraFast Pulser at California Institute of Technology (Caltech) as part of the NIH project.



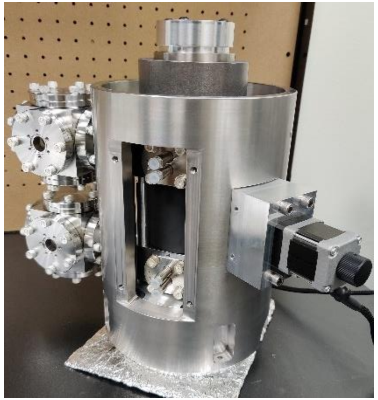


(G1)

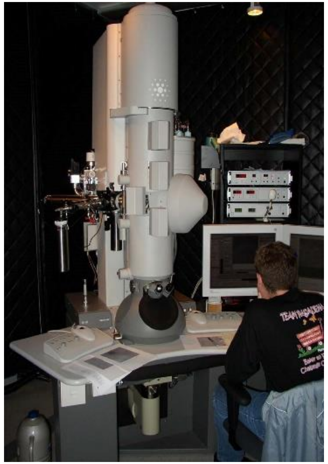


Measured snapshot of electron pulses in time

Euclid's' Commercialization. Ultrafast Pulser (UFP) for TEM



Euclid
UFP^{TM} G2



Commercial sale and NIH Grant to Caltech, 2022

The installations for 2022 include CalTech and Jülich (Germany) to be completed by the end of 2023.

These two installations introduce the UFP technology to the life sciences market and upper echelon laboratories in Europe.

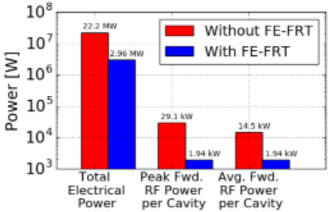
Both of these installations are on ThermoFisher instruments, the largest EM supplier in the world.

Commercial sales to Jülich, Germany, 2022

Material Science ➡ for Accelerators

FERROELECTRIC CERAMIC

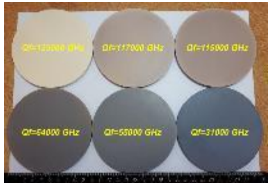
Ferroelectric ceramic with low loss tangent at RF allow development of DC biased tuners with extremely fast switching times (τ<30 ns).



These tuners reduce the RF power for SRF and NC accelerators, LHeC case study – factor of ~15.

LOW LOSS CONDUCTIVE CERAMIC

a new ceramic material with a finite DC electrical conductivity combined with a low RF loss tangent for use at high power RF



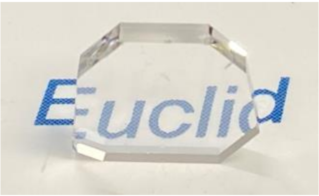
5x10^-6 – 2x10^-5
at 650 MHz
conductivity is up 4
orders !
(10^-13 -10^-9) S/m

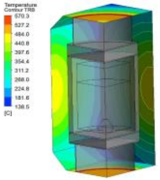
This ability to tune the conductivity allows one to effectively discharge any charge deposited on the ceramic.

DIAMONDS FOR X-RAY OPTICS

HPHT and CVD diamonds are grown by Euclid.

High crystallinity HPHT substrates, quantum CVD



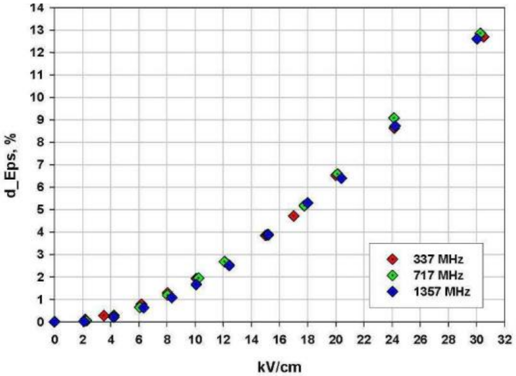


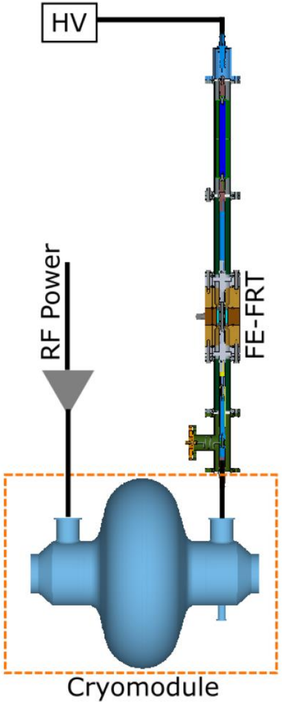
X-ray optics requires ultrahigh purity, no dislocation, stress-free single crystal diamonds

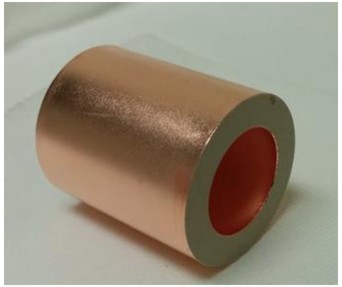
Motivation Fast Ferroelectric Tuner

- Ferroelectrics have unique intrinsic properties that make them extremely attractive for high-energy accelerator applications. Their response time is ≈ 10^{-10} s for ceramic compounds which make ferroelectric promising candidates for the tuning and switching RF devices.
- A fast controllable tuners would allow microphonics compensation for the SRF accelerator with low beam loading.

- 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 is used to cause a phase change of a propagating rf signal or change the resonant frequency of a cavity. The key was the development of a low loss highly tunable ferroelectric material.



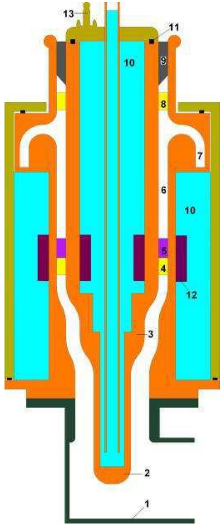




Courtesy of N. Shipman, CERN

Collaboration with BNL, Jlab, FNAL and CERN

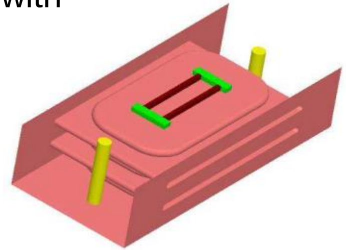
History of the Fast Ferroelectric Tuner Development



Ferroelectric phase and amplitude control was developed during the 1990's[1], in 2003 V. Yakovlev proposed RF switching by changing the frequency of a 'switching cavity' containing ferroelectric material[2]. In 2006 Ilan Ben-Zvi initiated F-FRT research at BNL whereby the frequency of a cavity would be controlled by an external ferroelectric tuner

Initial project to develop an ultra-fast (~1us) phase shifter/tuner using ferroelectric was carried out in collaboration with Omega-P/Yale University (V. Yakovlev, S. Kazakov) and BNL (I. Ben-Zvi) in 2004-2010[3]. The phase shifter/tuner was intended to control of coupling of accelerating structures (phase/amplitude), and to tune resonance frequency of the cavity. With this project, Euclid developed a ferroelectric material with dielectric constant $\varepsilon \sim 500$, $\tan\delta \sim 2\times10^{-3}$ at 1.3GHz but low tuning range $\partial\varepsilon/\partial E_{\text{bias}}$ ~2/ kV/cm[3,4].

In 2013, I. Ben-Zvi (BNL) proposed a new topic for the DOE SBIR/STTR program on the ferroelectric fast reactive tuner (F-FRT) development for microphonics compensation. It allowed Euclid to develop a new improved ferroelectric ceramic (parameters formulated by V. Yakovlev) with $\varepsilon \sim 150$, $\tan\delta < 1\times10^{-3}$ at 1.3GHz and the tuning range up to $\Delta\varepsilon/\varepsilon \sim 10\%$ at 15 kV/cm[5].



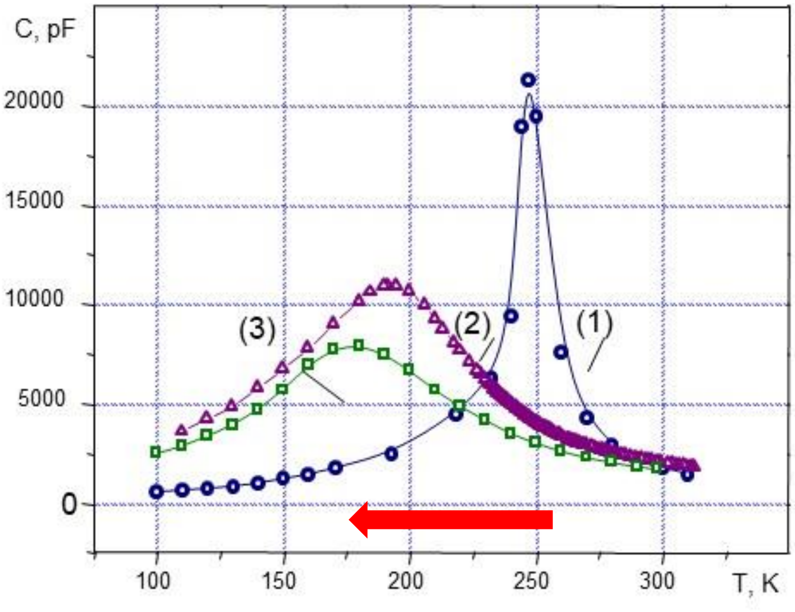
A new, simple coaxial tuner design (S. Kazakov) for the F-FRT became feasible[5], and the 400 MHz tuner prototype was fabricated by Euclid and tested at CERN in 2019 with the 400 MHz SRF cavity[6].

[1] R. Babbitt et al., 1994. "US Patent, US5334958A, 1993.
[2] V. Yakovlev et al. AIP Conf.Proc. 691,187, 2003.
[3] S. Kazakov et al. PRAB 13, 113501, 2010
[4] A. Kanareykin et al. Proc. EPAC 2006, 3251, 2006.
[5] A. Kanareykin et al. Proc. IPAC2013, 2486, 2014.
[6] N.Shipman et al. Proc. SRF2019, Dresden,WETEB7, 2019.

Fast tuning ferroelectric elements

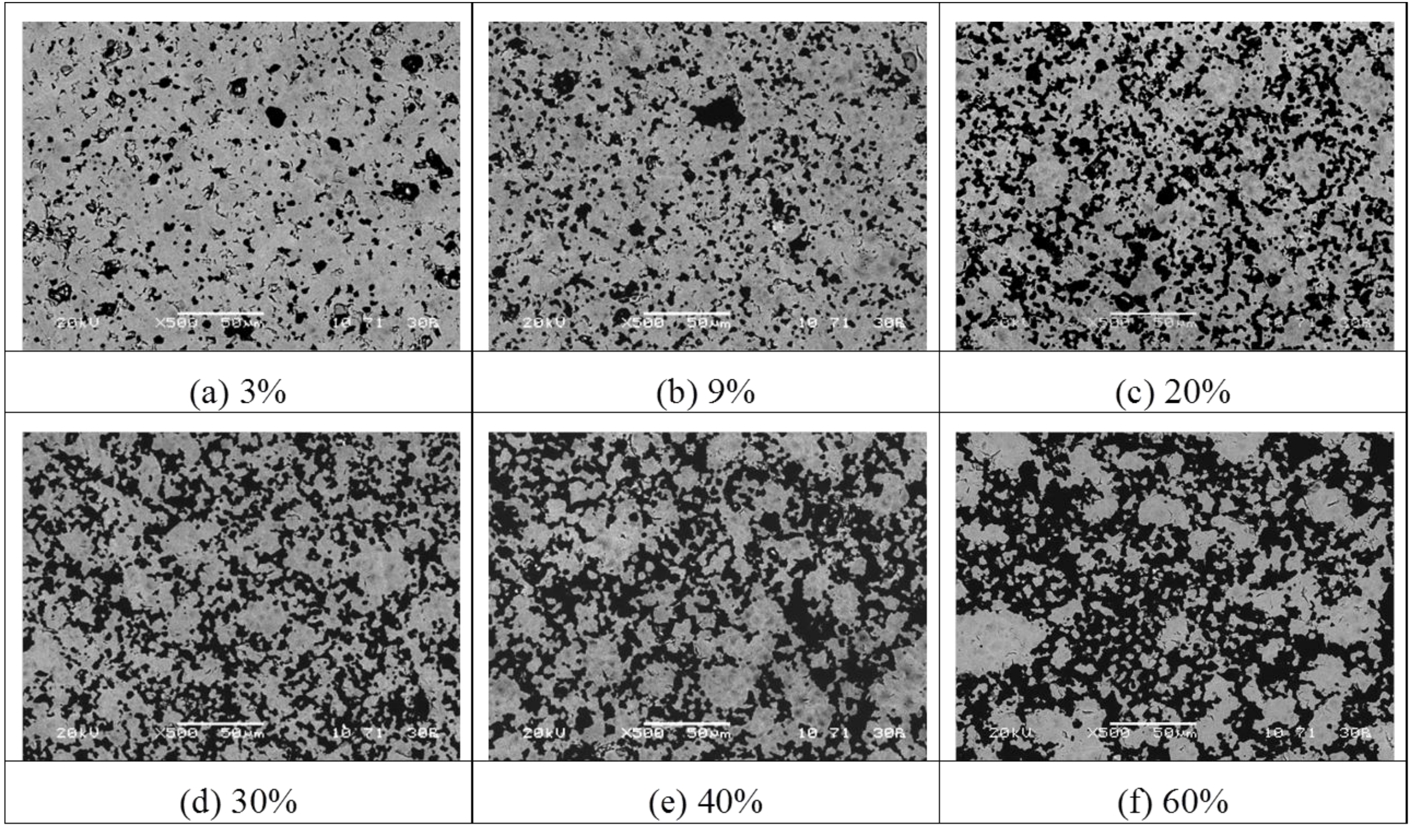
- **Dielectric constant** has to be low (~ 100-150)
- **Loss factor** has to be low ~ 1x10^{-3} at 1 GHz and ~1x10^{-4} at 100 MHz
- **Tuning range** has to be high ~ 6-8% at 15kV/cm
- Can be done with **(Ba, Sr)TiO$_4$+Mg oxides**

Dielectric constant of pure BST ~ 1000, and it's lossy. To reduce both eps and tanδ, one has to develop a mixture (solid solution) of BST ferroelectric and low loss linear ceramic



Curie temperature dependence on Mg-oxide content.
Curie temperature shift with Mg based oxide increase

BST(M) Microstructure vs. Mg oxide-based content

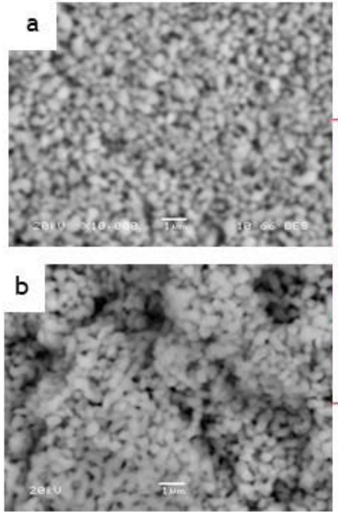


(a) 3%
(b) 9%
(c) 20%
(d) 30%
(e) 40%
(f) 60%

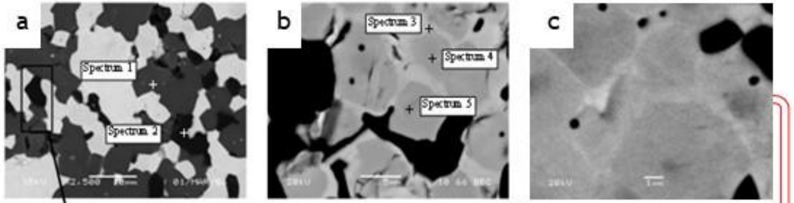
- SEM image of the BST/Mg-oxide compo-site material with increased Mg-oxide content from 3% up to 60%.
- Grain boundary interface area is growing with % of oxide increase

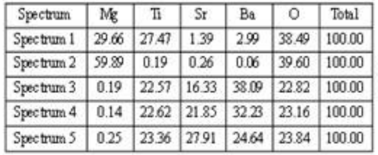
Ferroelectric composite materials

Powders ⇒ Ceramics



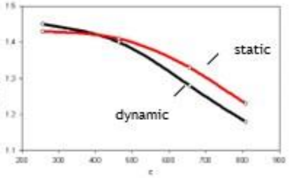
SEM-image of the initial powders of barium titanate (a) and strontium titanate (b).





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).

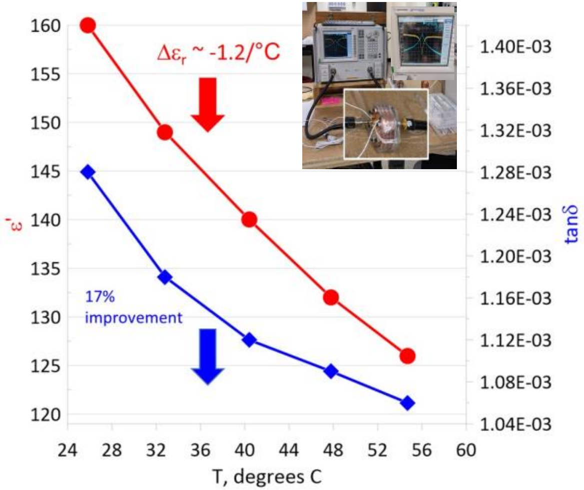


Static and dynamic tunability as a function of the permittivity

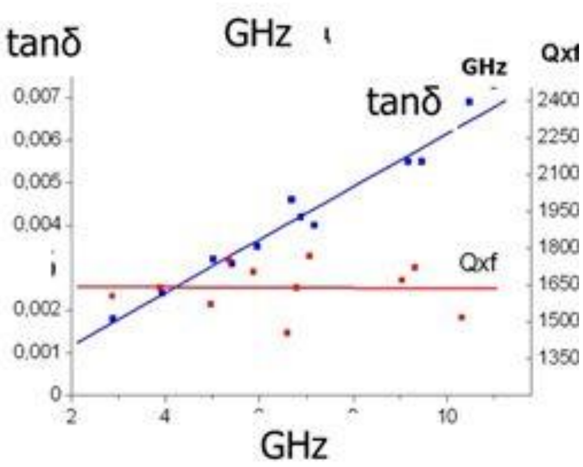
- It was demonstrated recently that by introducing a linear (non-tunable) Mg-based ceramic component into the BST solid solution one can enhance the tunability factor of the composition while keeping tanδ<10^{-3} at L-band.
- This counter-intuitive property (by increasing the non-tunable ceramic content of the ferroelectric-ceramic mixture one can enhance the tunability of the resulting material) opens new possibilities in tuning at low magnitude biasing fields.

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

ε and tanδ vs. temperature and frequency



Dielectric constant and tanδ measurements in the temperature range $T=20^0C-60^0C$ at 400 MHz for the BST(M) ferroelectric material: $\tan\delta=1.3\times10^{-3}$ $T=22^0C$ and ~ 17% improvement at $T=55^0C$.



- Dielectric constant weakly depends on the frequency
- Loss tangent increase linearly with frequency

- For lower dielectric constant, tanδ is significantly reduced.

Q×f (GHz)=const

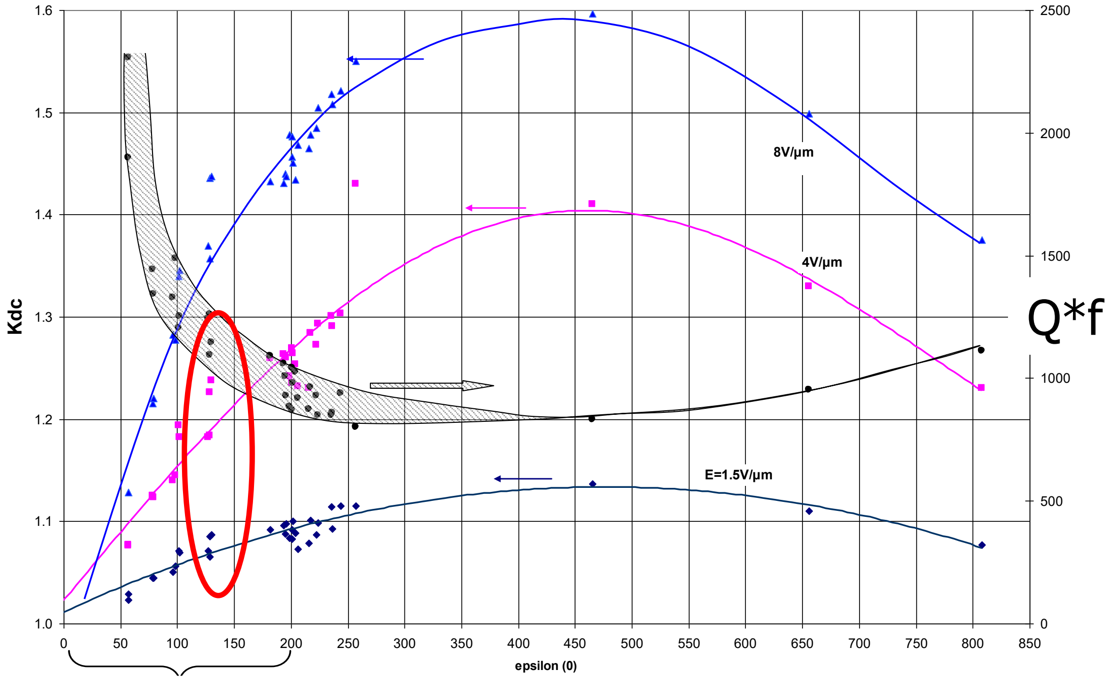
tanδ=1/Q

for ~1 GHz and ε~150

Q×f~1,000, $\tan\delta\sim1\times10^{-3}$

Progress on BST Material Development

$(Ba, Sr)TiO_4$+Mg oxides



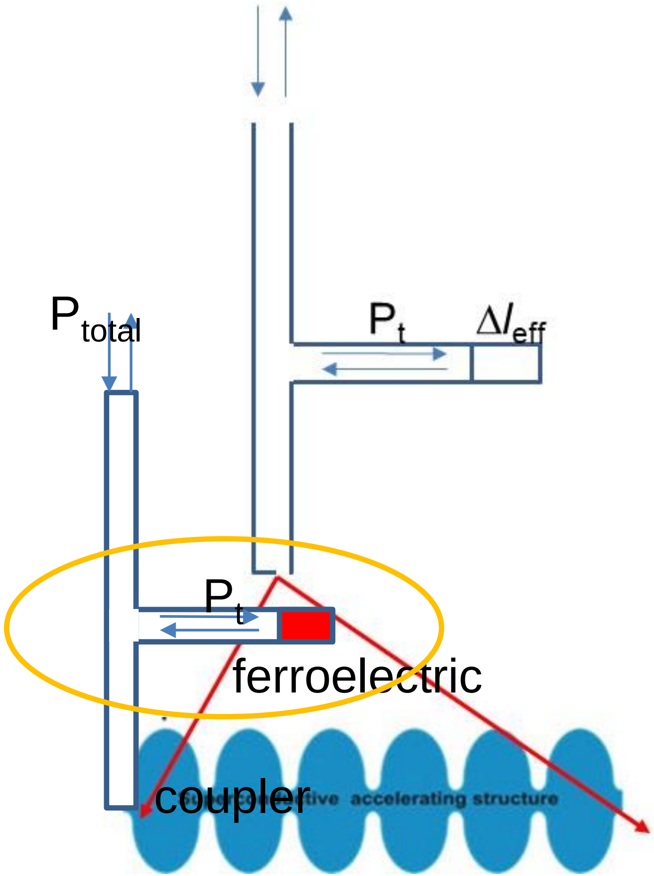
BST(M),
ε~50-150

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	~150
tunability, $\Delta\varepsilon$	~ 10% at $15\text{kV}\cdot\text{cm}^{-1}$ of the bias field
response time	< 10 ns
loss tangent at 1.3 GHz, $\tan\delta$	$\sim 1\times10^{-3}$
breakdown limit	200 kV/cm
thermal conductivity, K	7.02 W/m-K
specific heat, C	0.605 kJ/kg-K
density, ρ	$4.86\ \text{g/cm}^3$
coefficient of thermal expansion	$10.1\times10^{-6}\ \text{K}^{-1}$
temperature tolerance, $\partial\varepsilon/\partial T$	(1-2 units) K^{-1}

Ferroelectric Tuner Requirements (1)



$\delta\omega/\omega = \Delta W/W$ – relative frequency shift due to tuner,
W – is a full stored energy in a cavity.

$P_t = (\delta\omega/\omega)\times\omega\times W/\Delta\varphi$ - power circulating at tuner waveguide.

$\Delta\varphi = k\Delta l_{eff}$ – phase shift provided by tuner.

$P_{loss} = P_t\times 2kl_F\varepsilon^{1/2}\tan\delta$ - losses in ferroelectric.

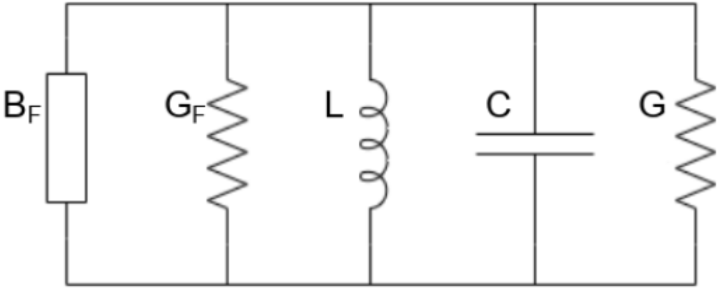
$\Delta W = Pt\frac{\Delta l_{eff}}{c}$ – change of energy caused by tuner, Δl_{eff} – is an effective change of waveguide length.

For a typical ferroelectric tuner needed for SRF cavity excitation, on need ferroelectric material having the tunability of >6% and loss tangent of ~10^{-4} 10^{-3} in the 100 MHz- 1 GHz range.

Ferroelectric Tuner Requirements (2)

- Tuning Range
  - $\Delta\omega_F = \dfrac{\omega_0 \Delta B_F \sqrt{L/C}}{2}$
- Increase in Bandwidth
  - $\sigma = \dfrac{G_F}{C}$

σ_1 and σ_2 –increase in bandwidth at zero and maximum applied voltage



Equivalent Circuit Model

- Figure of Merit
  - $\text{FoM} = \dfrac{\Delta\omega_F}{\sqrt{\sigma_1\sigma_2}}$ ⇒ $\text{FoM} = \dfrac{\Delta\mathcal{P}}{2\sqrt{P_1 P_2}}$ ⇒ $\text{FoM} = \dfrac{\Delta\omega_F}{\omega_0}\sqrt{Q_1^{FRT} Q_2^{FRT}}$ $\quad Q_i^{FRT} = \dfrac{\omega_i U}{P_i}$

reactive power

ω_i resonant frequency, U- stored energy
P_i- dissipated power

- B_F and G_F depend on:
  - FE-FRT
  - Transmission Line
  - Antenna/Coupling

FoM value required for various applications has to be in the range FoM>30 (microphonics), FoM~70 (*f* switching) and transient detuning FoM>100 (? TBD, I. Ben-Zvi et al. arXiv:2109.06806v3).

N. Shipman, et al., IPAC’21, 1305, 2021 ⇐

A new type of tuner*

Table: Material Properties at $\approx 800\,\mathrm{MHz}$

Parameter	**Value**
Max. ϵ_r	140
Min. ϵ_r	131.6
$\tan\delta$	9.1×10^{-4}
$\frac{\Delta\epsilon_r}{E}$	$0.6\ \mathrm{kV}^{-1}\mathrm{cm}$
τ	$< 10\,\mathrm{ns}$

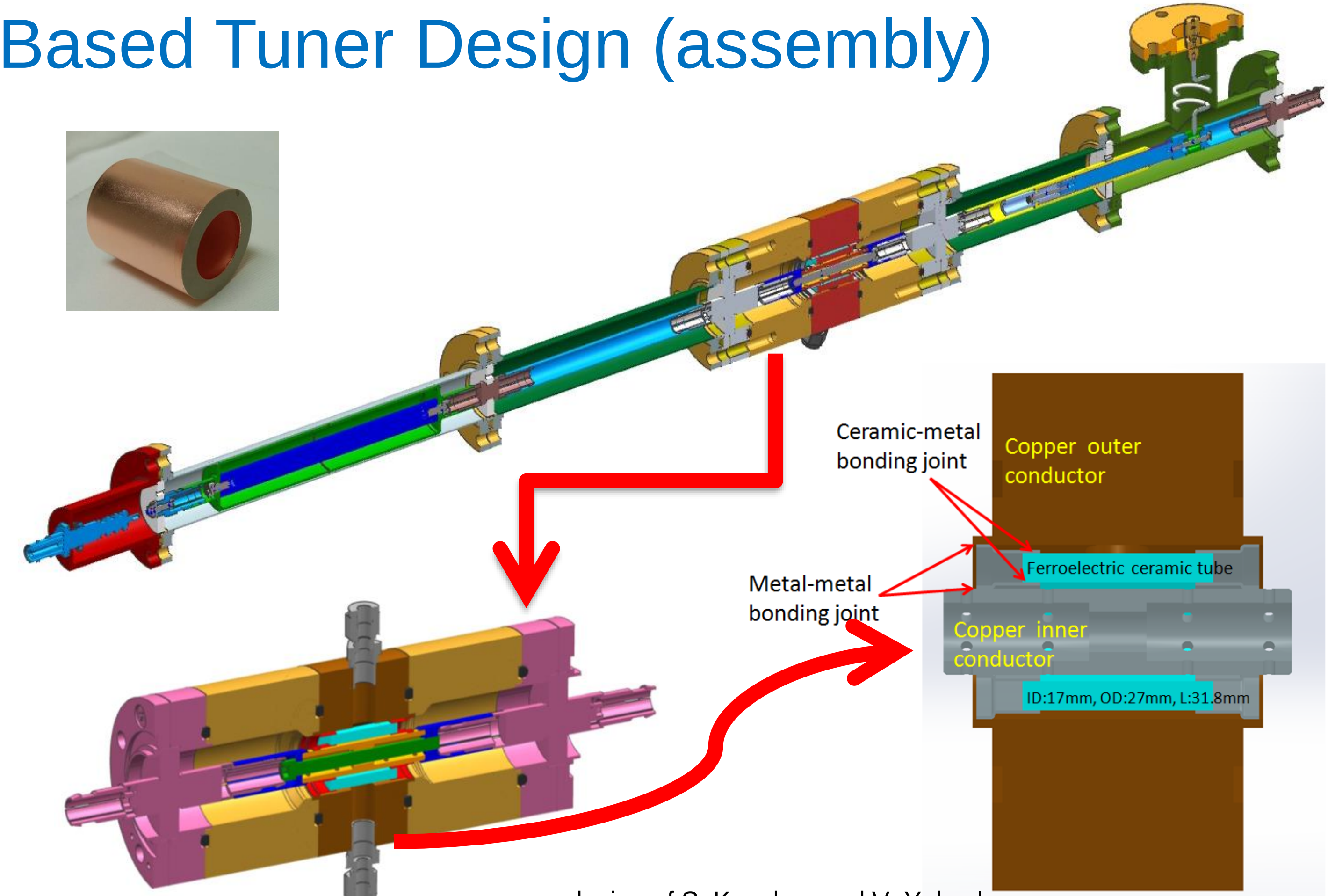
- New class of tuner.
- Fast (really fast).
- No moving parts.
- Low losses.
- Outside cryomodule.

- Eliminate microphonics.
- Reduce power.
- ERLs.
- Heavy Ion.
- $\mathrm{Nb_3Sn}$/New Materials.
- No need to generate a large magnetic field
- Intrinsic speed $< 10\,\mathrm{ns}$[1]

- $\mathrm{BaTiO_3}$ - $\mathrm{SrTiO_3}$ solid solution (BST)
- Added linear (non-tunable) Mg-based ceramic component[3]
- Enhanced tunability with low losses

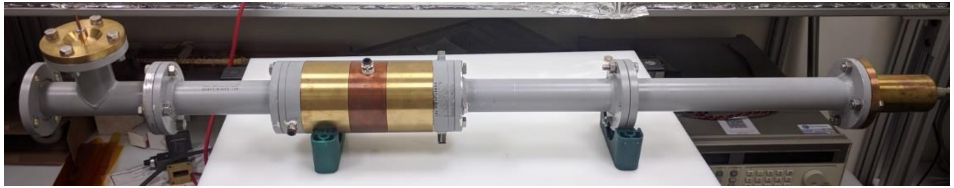
*N. Shipman. SRF'19

BST Based Tuner Design (assembly)

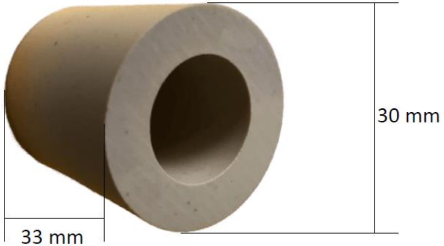


design of S. Kazakov and V. Yakovlev

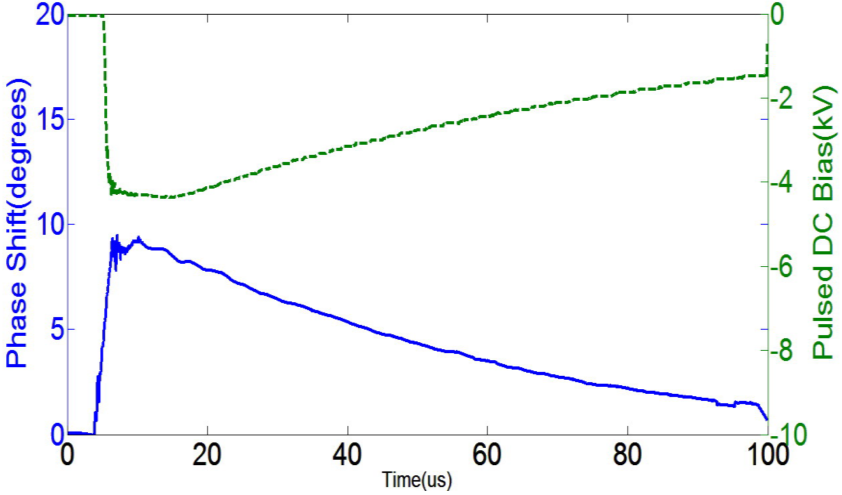
F-FRT low power tests at Euclid at CERN



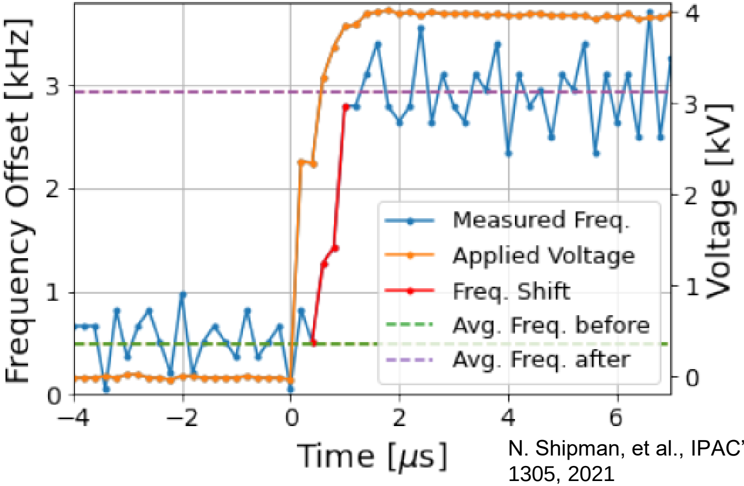
Assembled F-FRT



Ferroelectric element before metallization



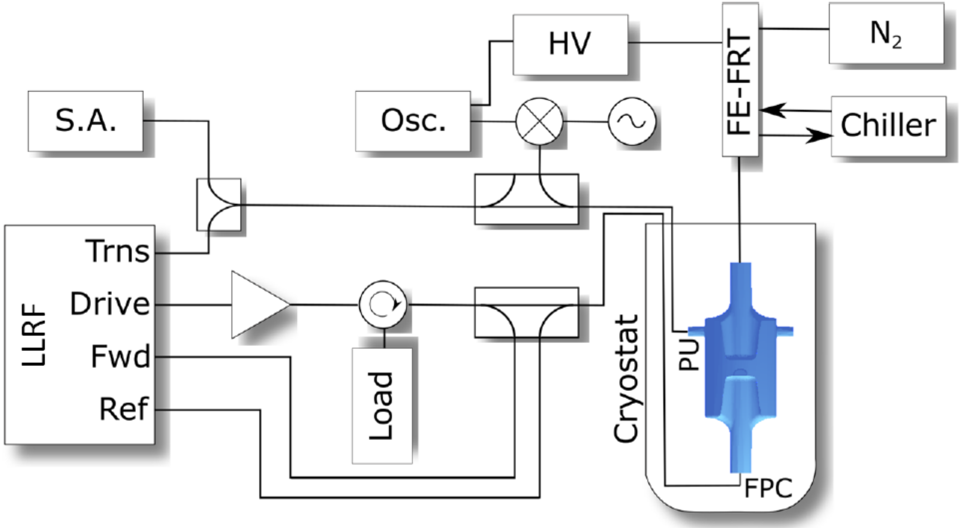
Measured at Euclid phase shift vs. time at biasing voltage applied (~ μs range response time)



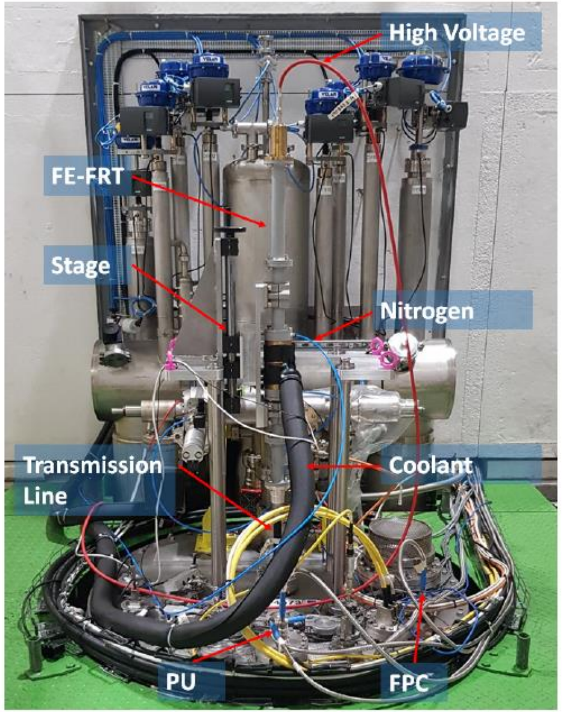
N. Shipman, et al., IPAC'21, 1305, 2021

Measured at CERN frequency response at 600 ns of a cavity to a 4 kV high voltage pulse (orange) applied to the connected FE-FRT.

F-FRT test with SRF Cavity at CERN



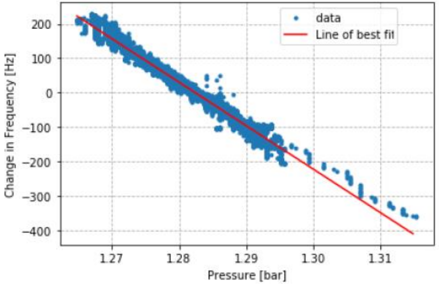
Experimental Setup



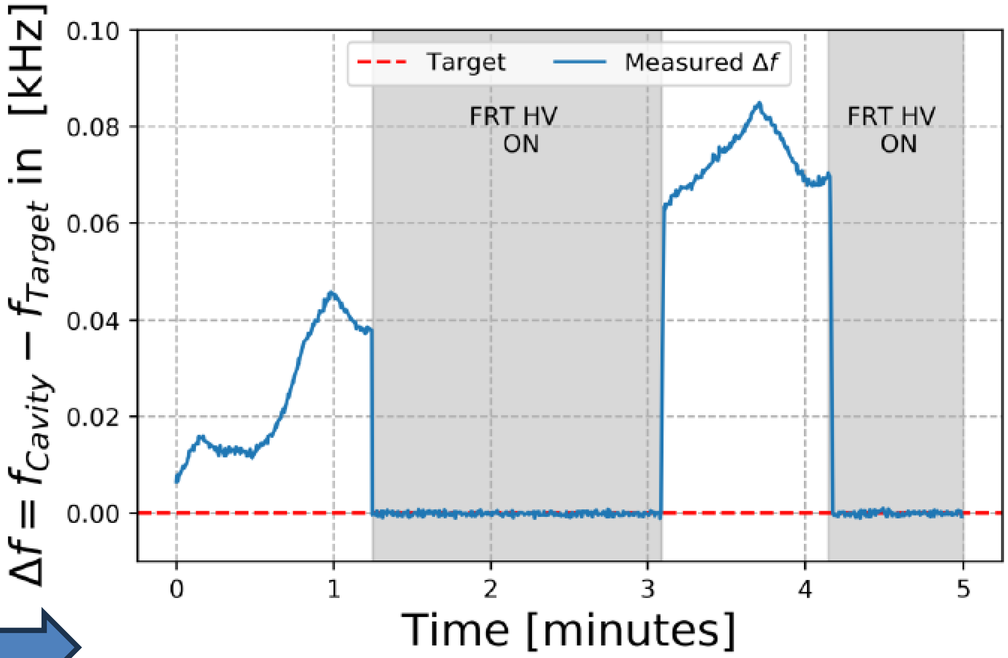
FE-FRT mounted on cryostat.

N. Shipman, et al., SRF'19, WETEB7

Slow Tuning



Slow frequency changes caused by variation in cryostat pressure.



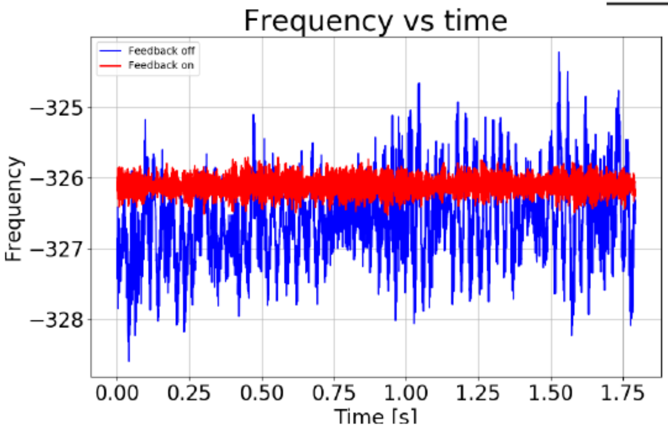
Demonstration of Slow Tuning

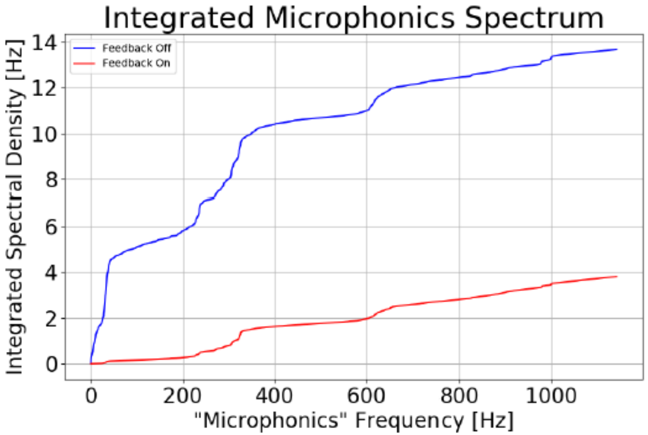
- First tuning test
  - Does it work at all?
- Aim: correct slow frequency variations
  - Due to helium bath pressure fluctuations
- Frequency quickly corrected to target

N. Shipman, et al., IPAC'21,

Microphonic Suppression (1)

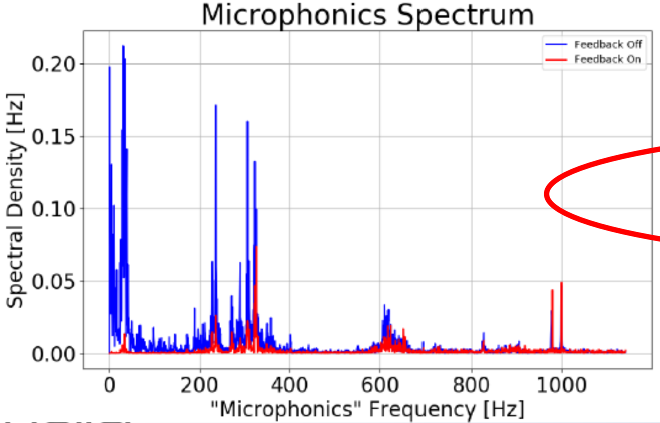
Vibration Generator Off





No correction

With correction



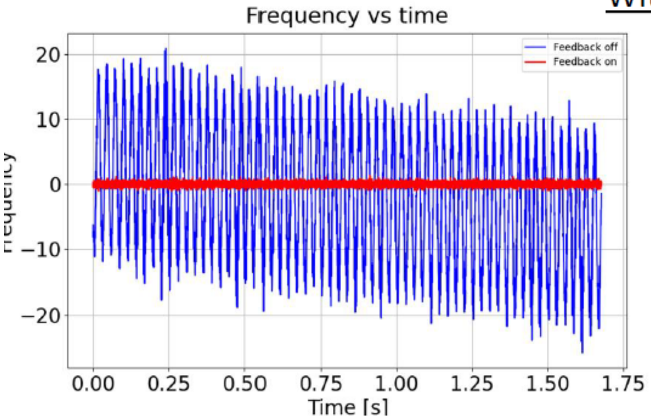
- Stiff cavity => Very low levels of microphonics
- Integrated microphonics spectral density up to 1kHz reduced by factor ~4
- More reduction at lower frequencies
- Peak deviation with correction $< \pm 0.5\mathrm{Hz}$

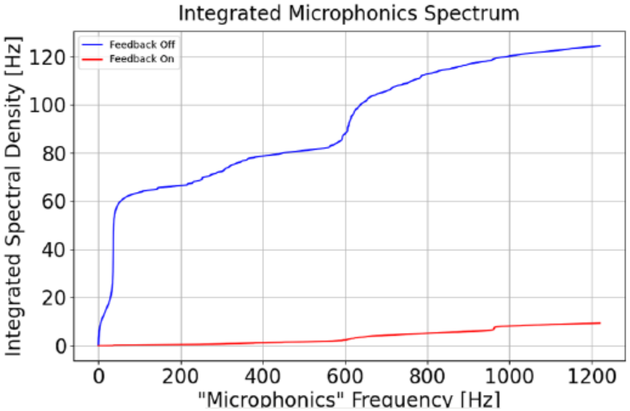
N. Shipman, et al., IPAC’21,

- First ever Ferroelectric Fast Reactive Tuner (FE-FRT) test with a superconducting cavity

Microphonic Suppression (2)

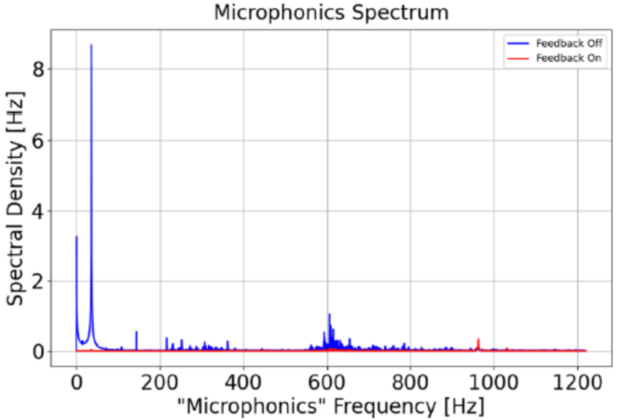
With Vibration Generator @ 37Hz





▬ No correction

▬ With correction



- Vibration generator set to 37Hz
- Integrated microphonics spectral density up to 1kHz reduced by factor ~14
- Greater reduction with more microphonics.
- Peak deviation with correction $< \pm 1.2\text{Hz}$

N. Shipman, et al., IPAC'21,

Summary of F-FRT Testing at CERN

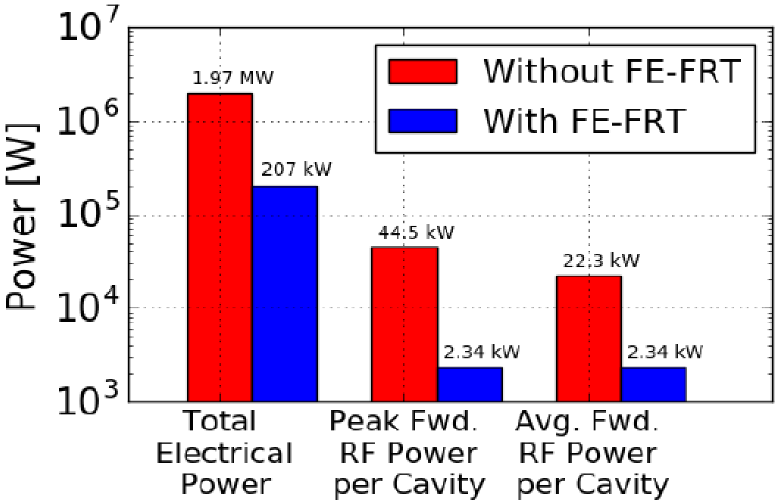
- Tested an FE-FRT with SC RF Cavity: World First!
- Ferroelectric parameters are excellent, no further material development needed.
- Eliminate microphonics, drastically reducing power requirements for low beam loading machines.
- Outside cryomodule, no moving parts → easy maintenance and high reliability
- Ease design and reduce cost of:
  - Power Couplers
  - Cryomodules
  - Cavities
  - RF power sources

N. Shipman, et al., IPAC'21,

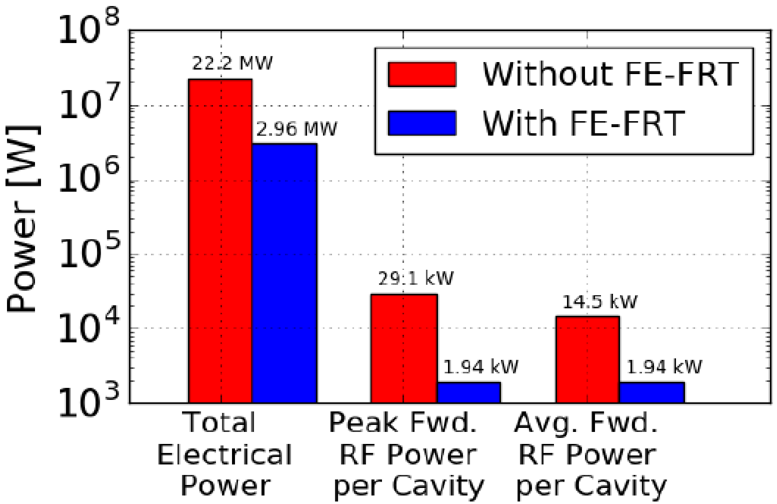
- Microphonics suppression
  - Very simple feedback algorithm
  - >10x reduction in integrated microphonics up to $1\ \mathrm{kHz}$
  - Residual deviations $< 0.5\ \mathrm{Hz}$
- Slow Tuning
  - Reliable continuous operation
- Very fast freq. switching $\leq 600\ \mathrm{ns}$
  - Limited by external circuit
- Tuning Range $> 12\ \mathrm{kHz}$
  - At limited stored energy

*N. Shipman. SRF'19

…and Case Studies (1)



Power savings with FE-FRT use for eRHIC.



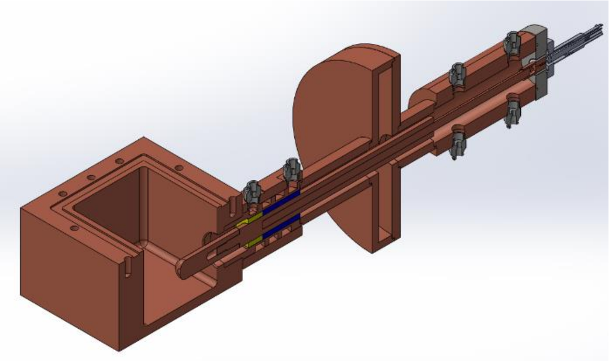
Power savings with FE-FRT use for LHeC.

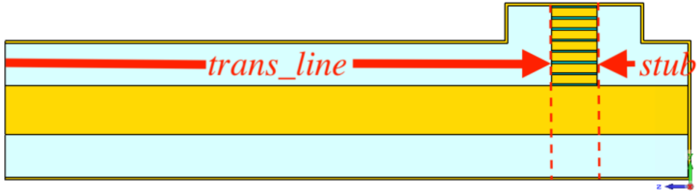
By using an FE-FRT, peak power is reduced by a factor ≈ 19, and average powers by a factor ≈ 9.

For both PERLE and LHeC, peak power is reduced by afactor ≈ 15 and average power by a factor ≈ 7.5.

N. Shipman. ERL’19, TUCOZBS02

Fast Ferroelectric Tuner (F-FRT) for SRF. What's Next ?





CEBAF

Euclid's recently developed fast SRF cavity tuning design for the nuclear physics accelerator facility that is currently in operation (CEBAF). Funding from the NP DOE is pending.

HL-LHC and EIC

F-FRT is fast enough to change frequency during beam gaps- enormous reduction in power requirements.

For HL-LHC the peak power needs during injection could be reduced by 50% by the rapid cavity tuning. Potential power reduction for the HL-LHC operational scenario from 275 kW to 30-140 kW with FE-FRT[*].

[*] I. Ben-Zvi et al. High-Power Ferro-Electric Fast Reactive Tuner. arXiv:2109.06806v3.

Horizon Europe – iSAS and bERLinPro

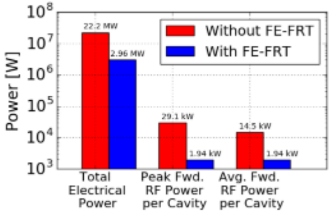
Recently, Helmholtz-Zentrum Berlin (HZB Berlin) announced a plan to use an FE-FRT for microphonics compensation in a main 1.3 GHz SRF cavity (1J energy, 150 Hz range). Euclid Techlabs plans to design and fabricate the FE-FRT prototype and test it at the ERL machine of HZB Berlin.

Horizon Europe - iSAS (Innovate for Sustainable Accelerating Systems): the concept of "From Grid to Beam," which involves the integration of Ferroelectric FRT to promote energy conservation.

Material Science ➡ for Accelerators

FERROELECTRIC CERAMIC

Ferroelectric ceramic with low loss tangent at RF allow development of DC biased tuners with extremely fast switching times (τ<30 ns).



These tuners reduce the RF power for SRF and NC accelerators, LHeC case study – factor of ~15.

LOW LOSS CONDUCTIVE CERAMIC

a new ceramic material with a finite DC electrical conductivity combined with a low RF loss tangent for use at high power RF

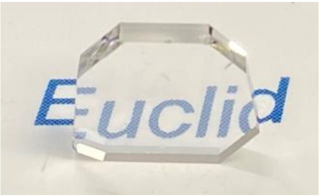
5x10^-6 – 2x10^-5
at 650 MHz
conductivity is up 4 orders !
(10^-13 -10^-9) S/m

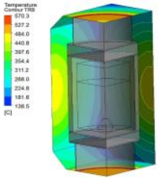
This ability to tune the conductivity allows one to effectively discharge any charge deposited on the ceramic.

DIAMONDS FOR X-RAY OPTICS

HPHT and CVD diamonds are grown by Euclid.

High crystallinity HPHT substrates, quantum CVD

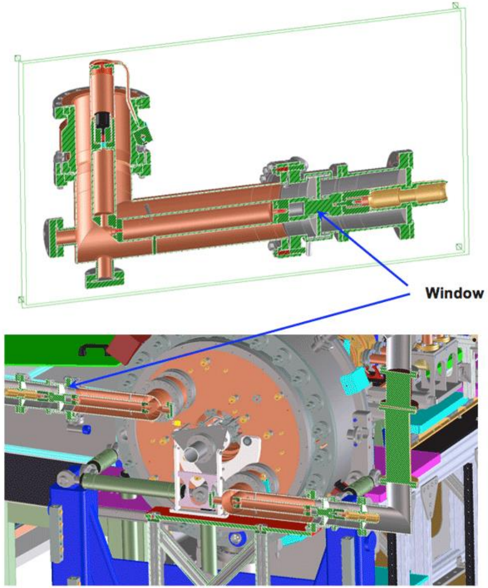




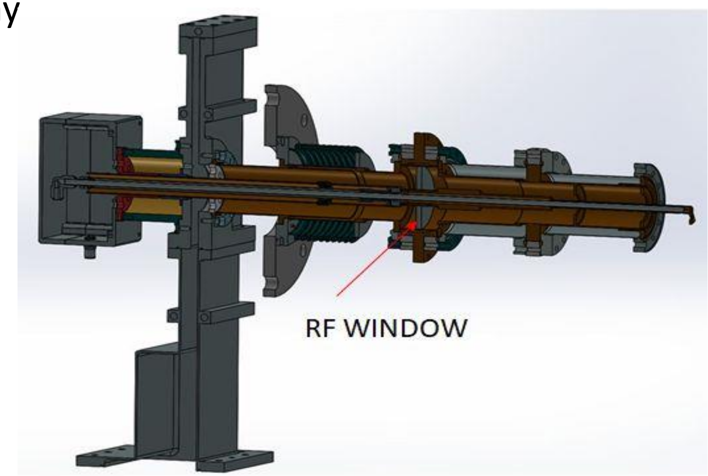
X-ray optics requires ultrahigh purity, no dislocation, stress-free single crystal diamonds

RF Windows Charging

- High power RF couplers connect transmission lines to cavities, providing power used to accelerate particle beam
- Coupler also provides vacuum barrier for beam vacuum via RF windows
- RF windows experience breakdown at much lower voltages than comparable insulators in DC fields
- For large voltages, electron emission from "triple junction" and multipacting lead to window failure due to arching and/or thermal runaway



- These processes are major problem for RF windows and couplers; responsible for damage and lost beam time in SRF cavity and cryomodule operation



- Example: the Advanced Photoinjector Experiment's VHF gun and in the LCLS-II injector
- Window was broken: charging because of the direct line of sight for the beam
- A new 90-degree coupler will keep ceramic vacuum window out of harm's way

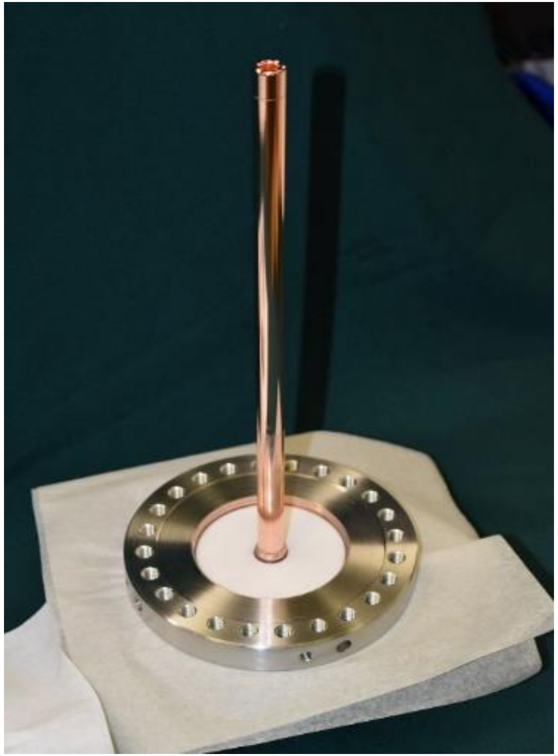
Collaboration with Jlab and FNAL

A Solution - Conductive Ceramic

Mitigate charge accumulation on RF windows by using a ***conductive ceramic*** *(V. Yakovlev)*

- What is new: a ceramic material with a finite DC electrical conductivity and low loss tangent that can be incorporated into high power couplers

- Why it is important: the electrical conductivity will drain the induced and built-up charge away. The low loss tangent will allow for high efficiency RF power transmission.



Loss vs. Conductivity at Microwaves

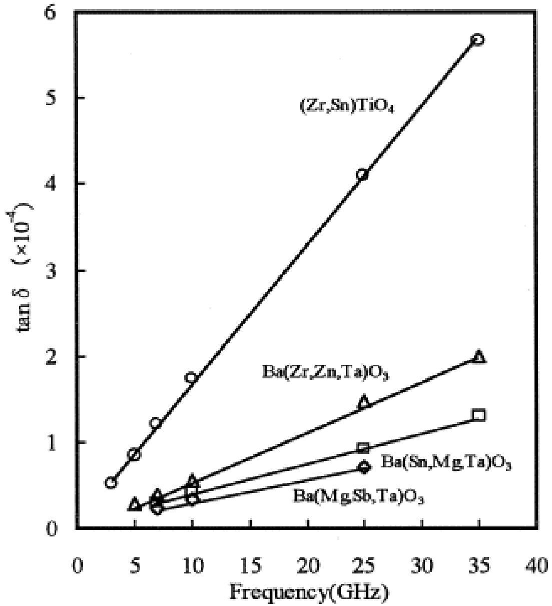
$$\tan\delta = \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'}.$$

- Dielectric loss of a material with conductivity and relaxation polarization depend on frequency, tanδ~f, or Q×f(GHz)=const.
- at GHz range, loss factor is defined by both fundamental phonon loss mechanisms and extrinsic mechanisms (coupling of the microwave field with defects). A.Tagantsev et al. Journal of Electroceramics, 11, 5, 2003

ε’>>ε” low loss dielectric

ε’>>σ/ω low loss conductor

ε“/ε’>>σ/ω

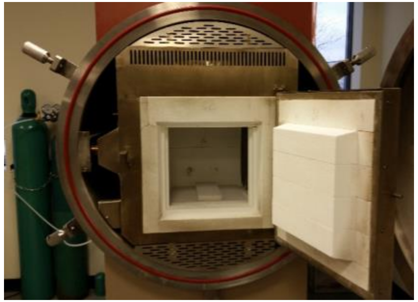


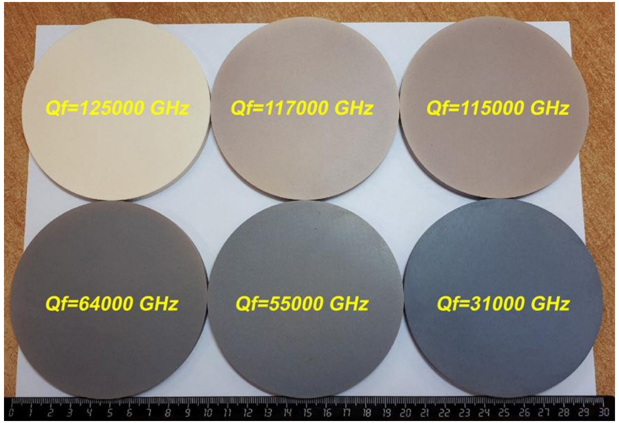
Example of tanδ vs. frequency for oxide ceramic, tanδ~f (GHz)

The goal was to decrease resistivity 2-3 orders (release carriers density inside ceramic) in the range 10^8 -10^9 Ω·m, initial resistivity was in the range ~ 10^{11}- 10^{12} Ω·m but to control the loss tangent at tanδ~10^{-5} at 650 MHz.

Fabrication and Sintering of Conductive Ceramic

- Euclid fabricated the MgTi ceramic elements with
  - Increased conductivity from 10^{-12} to 10^{-8} S/m
  - Relative dielectric constants ε_r=15
  - Figures of merit, Q×f, in the range 30,000–60,000 GHz, providing tan δ ~ 10^{-5} @ 650 MHz
- Electrical and microwave properties of ceramic window components optimized using procedure developed procedure



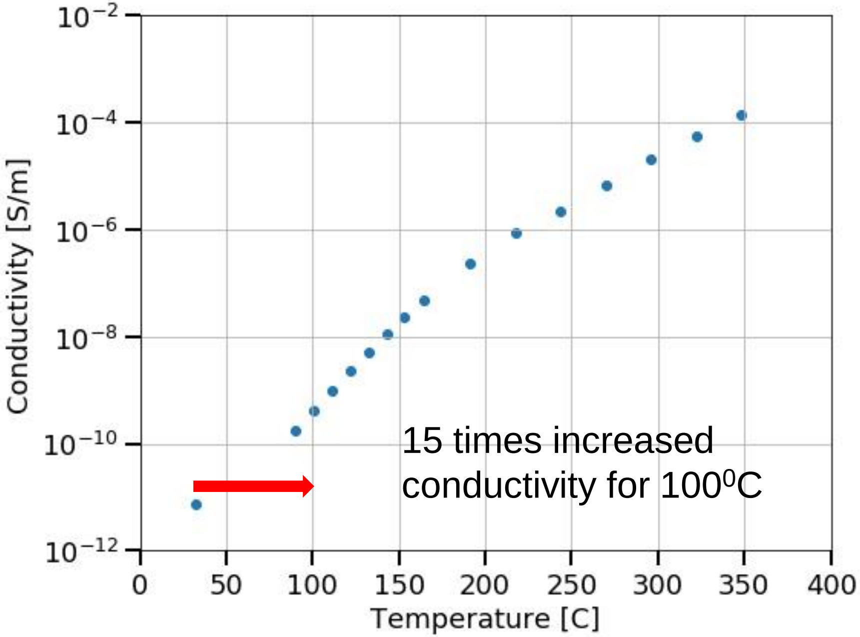


5.2x10^-6	5.5x10^-6	5.6x10^-6
1.0x10^-5	1.9x10^-5	2.1x10^-5

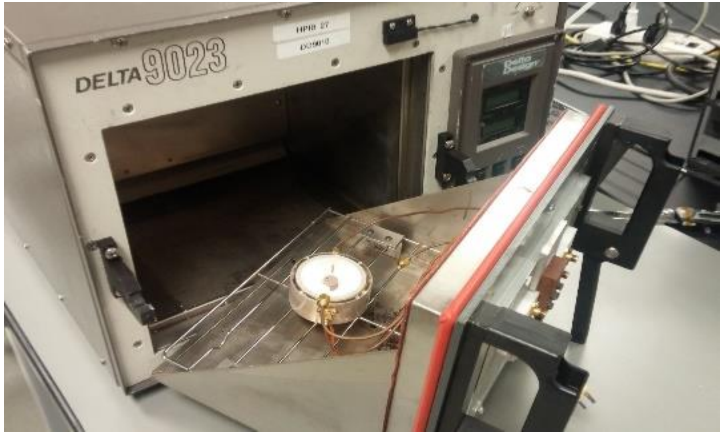
tan δ at 650 MHz

Conductivity - Temperature Dependence

- Conductivity and loss tangent measured over wide temperature range
- Conductivity increased >100x between room temperature and 100°C
- Loss tangent decreased only 20%
- *Natural benefit of temperature rise during operation is increased conductivity*

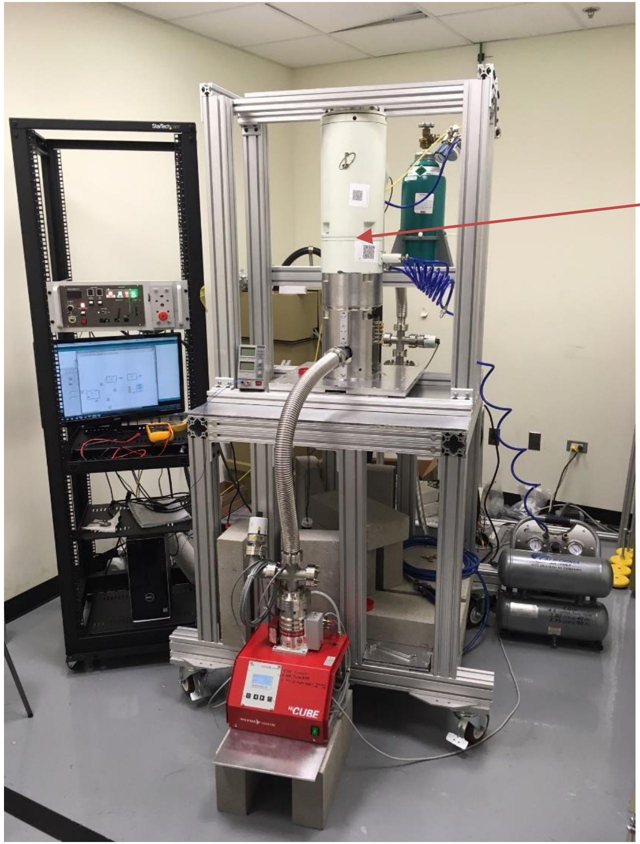


15 times increased conductivity for 100^0C

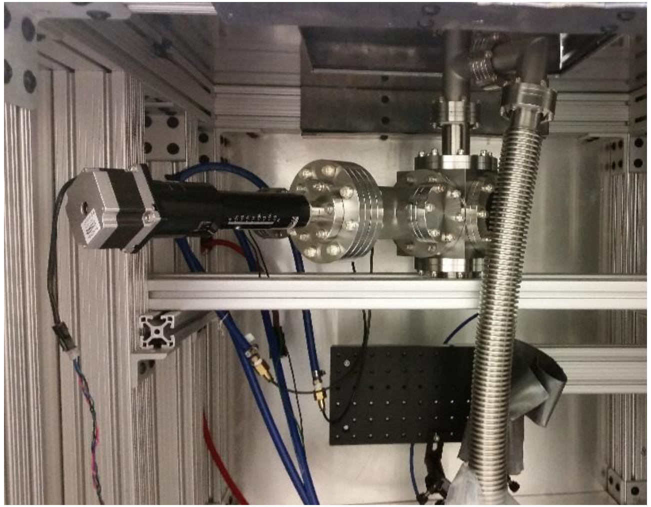


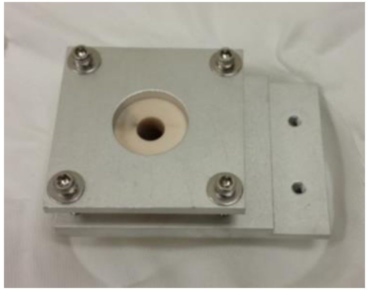
Beam Charging Test of Conductive Ceramic

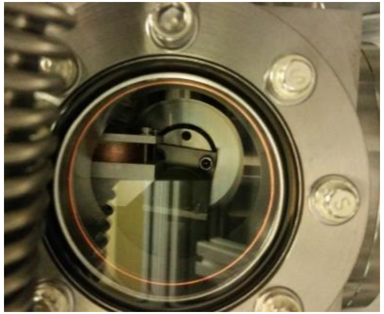
- Charging/discharging of both conductive and non-conductive ceramic measured with DC electron beam



TEM gun



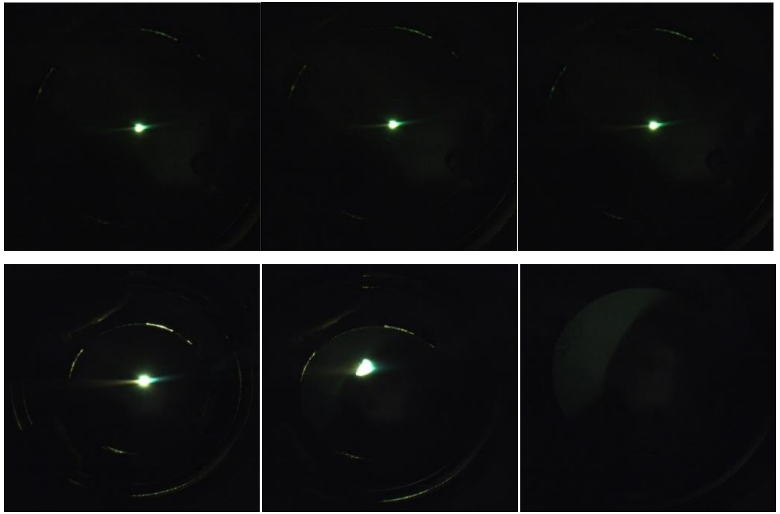




Beam Charging Results

- Ceramics subject to DC electron beam for 2.5 hours
- *Conductive ceramic effectively discharges DC electron beam directly impinging on surface*

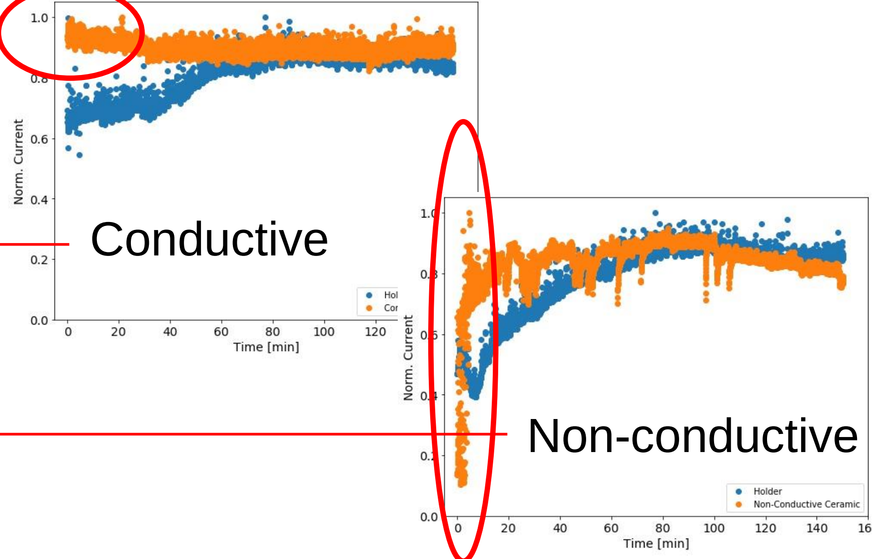
For conductive window, the current is stable from the beginning



30 sec

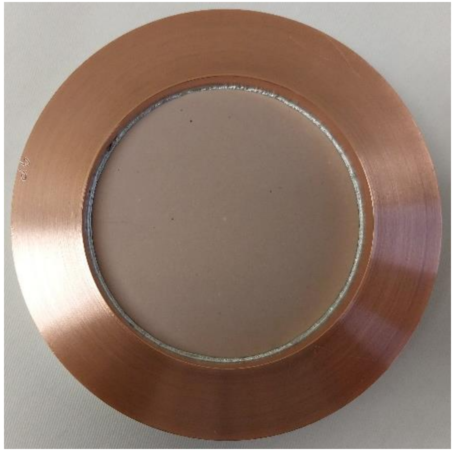
60 sec

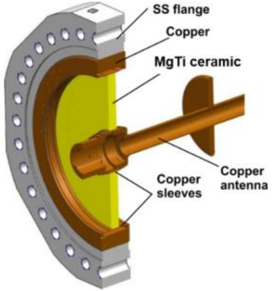
90 sec

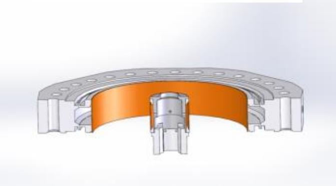


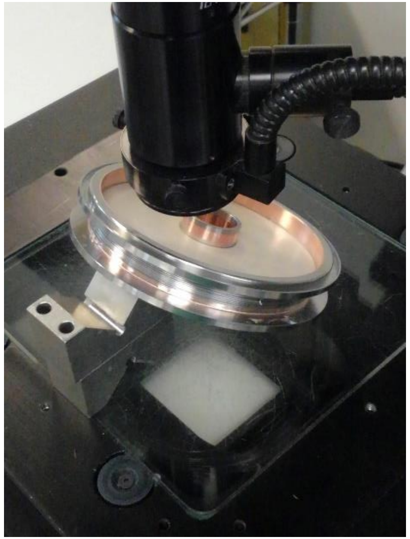
DC electron beam was deflected in 90 sec

Brazing Technology Development









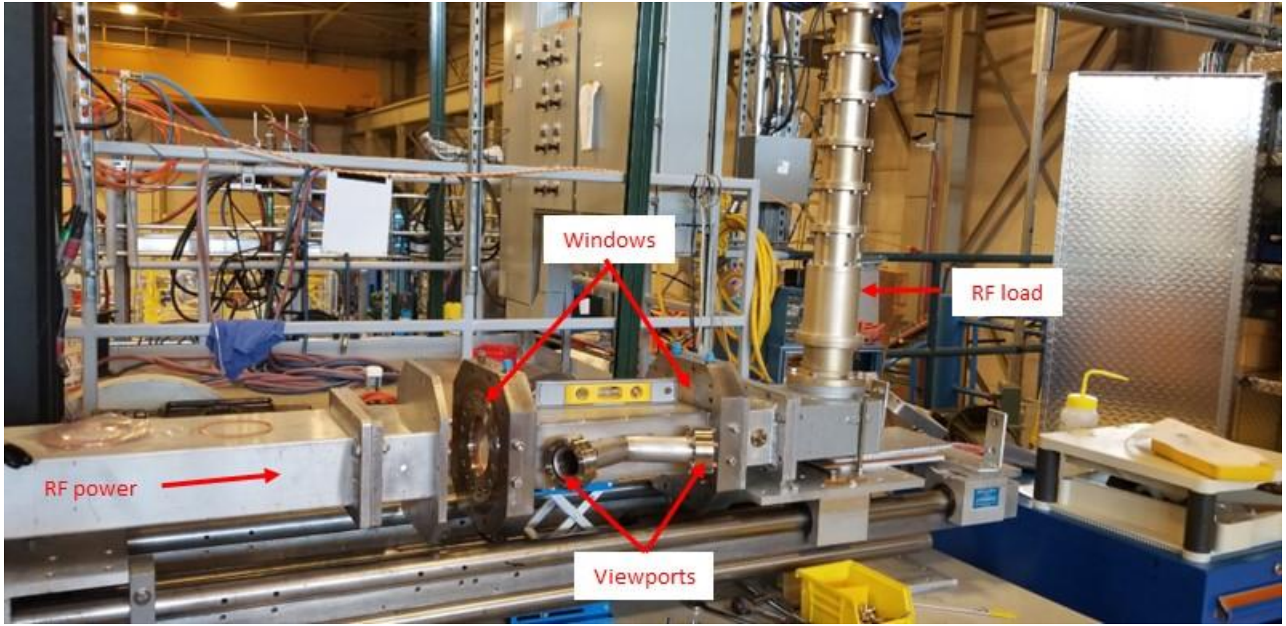
1.3 GHz waveguide window, Jlab

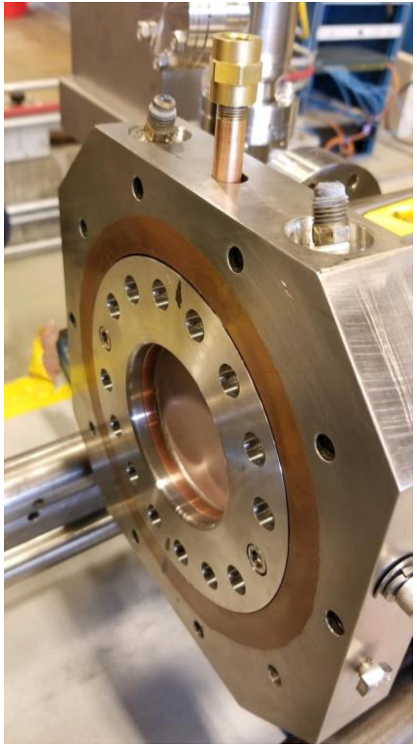
650 MHz coaxial window for Fermilab

- Lower temperature ABA (≈740°C) using MgTi windows
- Cu sputtering/electroplating
- S-Bond solder, 250°C

High-Power Test Stand at JLab

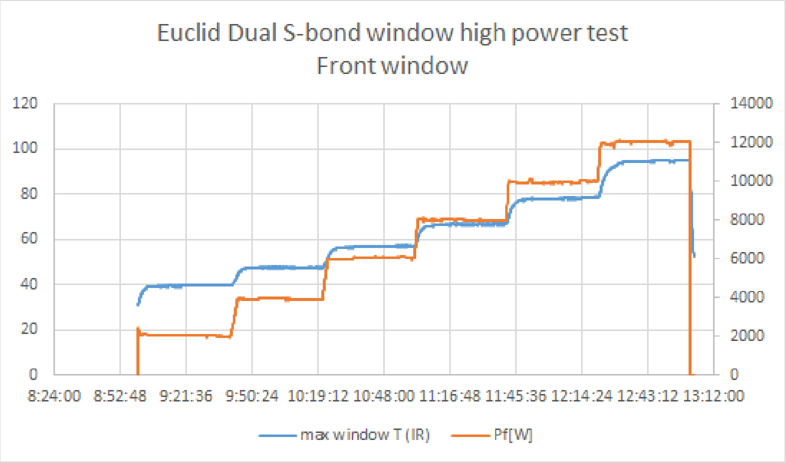
- Two high-power tests: Two windows in vacuum & single window in air
  - Water cooled
- 1.3 GHz CW RF power up to 12 kW, TW
- IR cameras pointed at both windows

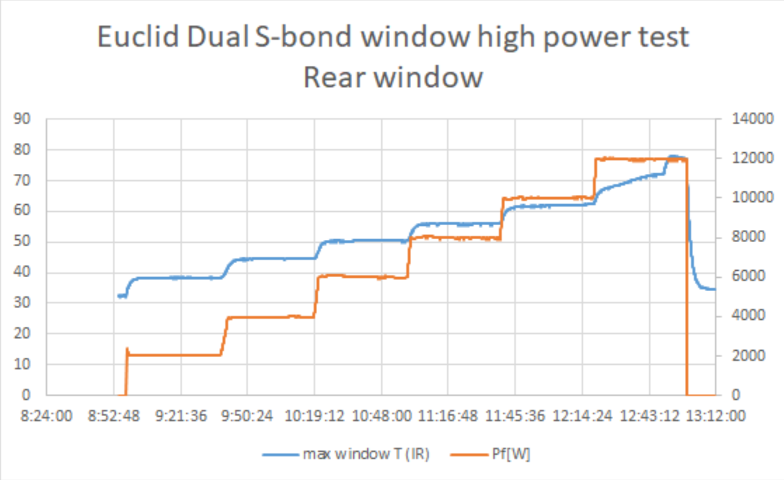




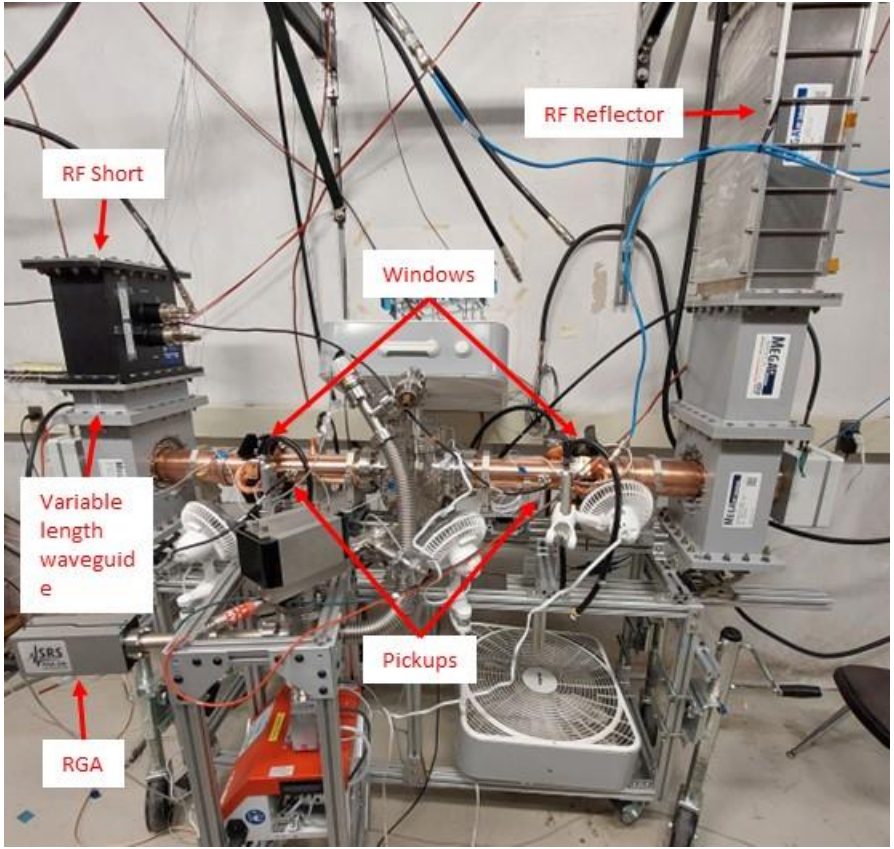
High Power Test at JLab

- Dual soldered window assemblies tested in vacuum
- *Achieved 12 kW CW TW*
  - Limited by available TW power
  - No negative behavior (electron activity) observed
  - Thermal stability reached
    - 95°C front window, 78 °C rear window





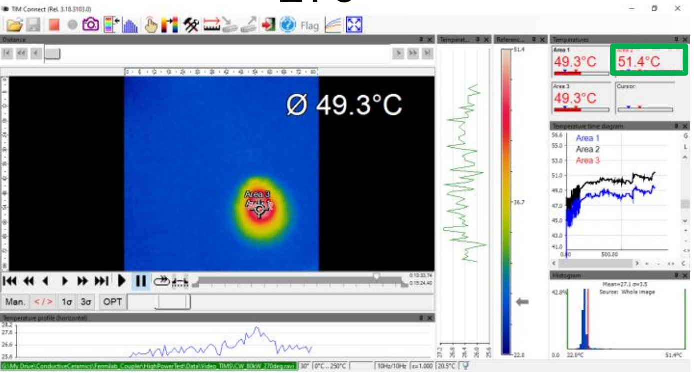
High-Power 650 MHz Test Stand at Fermilab

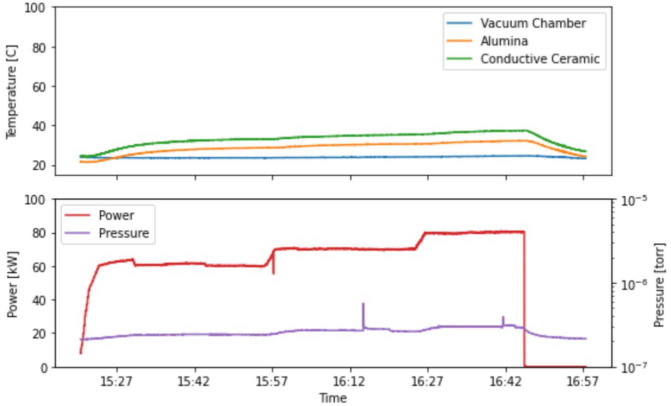


- One conductive ceramic and one alumina window tested together
- 650 MHz CW RF power up to 100 kW, SW
- Test stand allows change position of E field maxima & increase power over what klystron could normally provide
  - Four phases tested (designated 0, 90, 180 & 270°)
- Temperatures measured:
  - Thermocouples placed on window flanges & vacuum chamber
  - IR camera pointed at conductive ceramic window
- Electric pickups near each window
- Residual gas analyzer installed

High-Power Test at Fermilab – I

270°

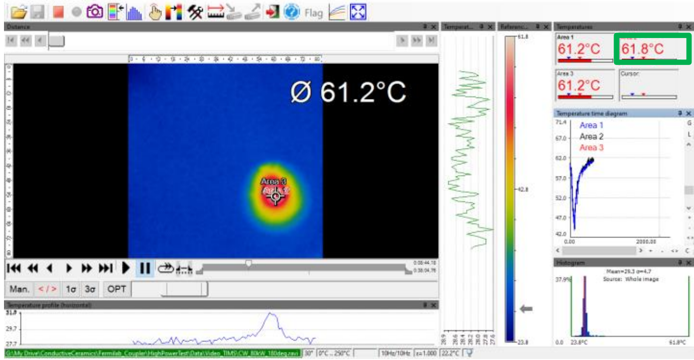


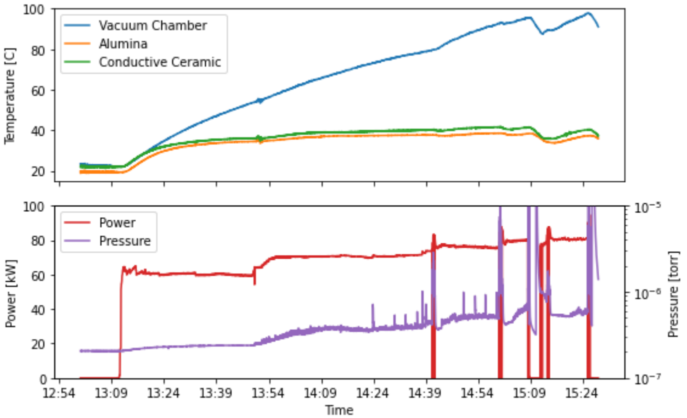


- *80 kW CW reached for two phases*
  - Not fundamental limit, only hesitant to damage window
- Max. temp. on flanges:
  - Left:
    - Conductive Ceramic = 41.8 C
    - Alumina = 38.7 C
  - Right:
    - Conductive Ceramic = 37.5 C
    - Alumina = 32.3 C

<u>Max. Conductive Ceramic window temp. 61.8 C at 80 kW!</u>

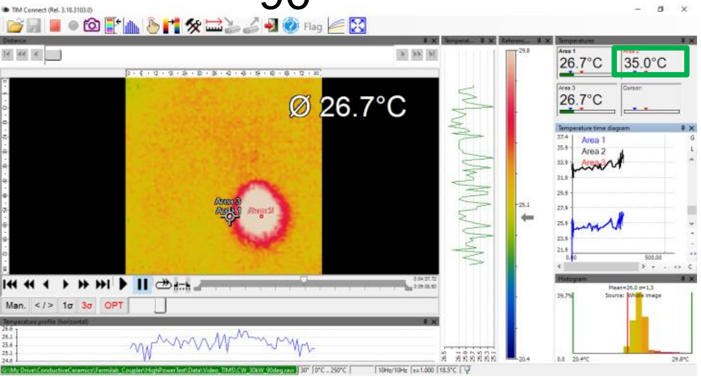
180°

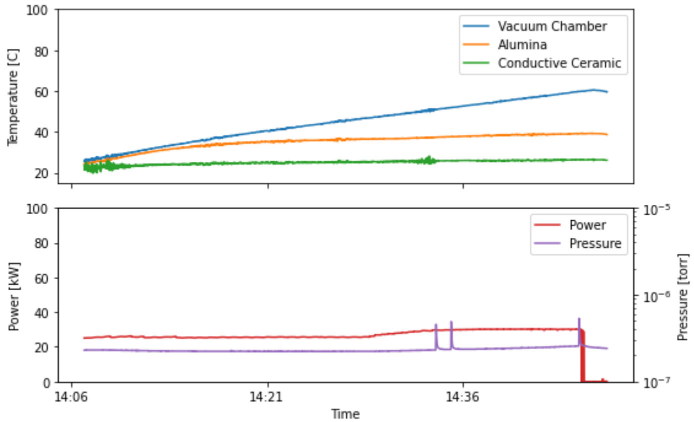




High-Power Test at Fermilab – II

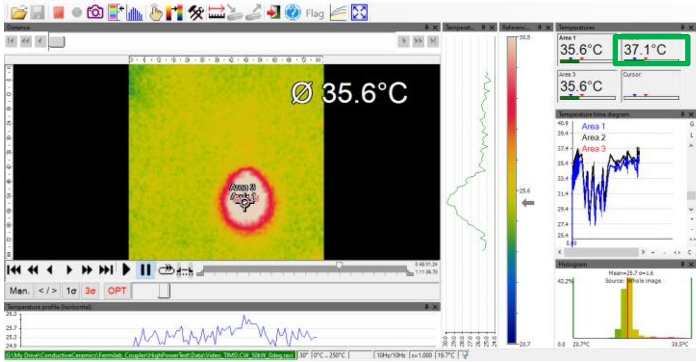
90°

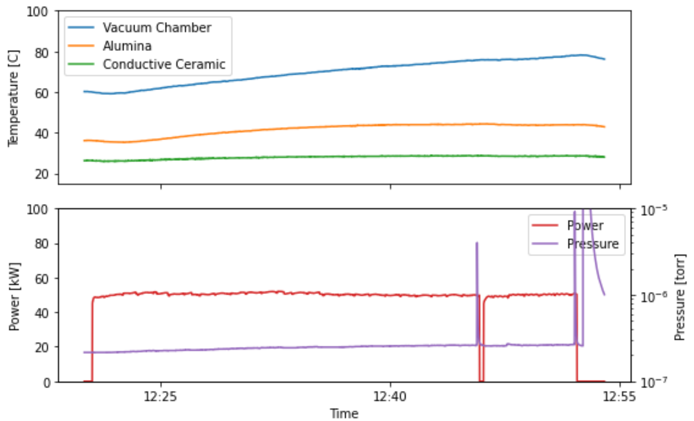




- 30 & 50 kW CW reached for other two phases
  - Limited by vacuum activity
- Max. temp. on flanges:
  - Left, 30 kW:
    - Conductive Ceramic = 28.2 C
    - Alumina = 39.3 C
  - Right, 50 kW:
    - Conductive Ceramic = 28.8 C
    - Alumina = 44.4 C

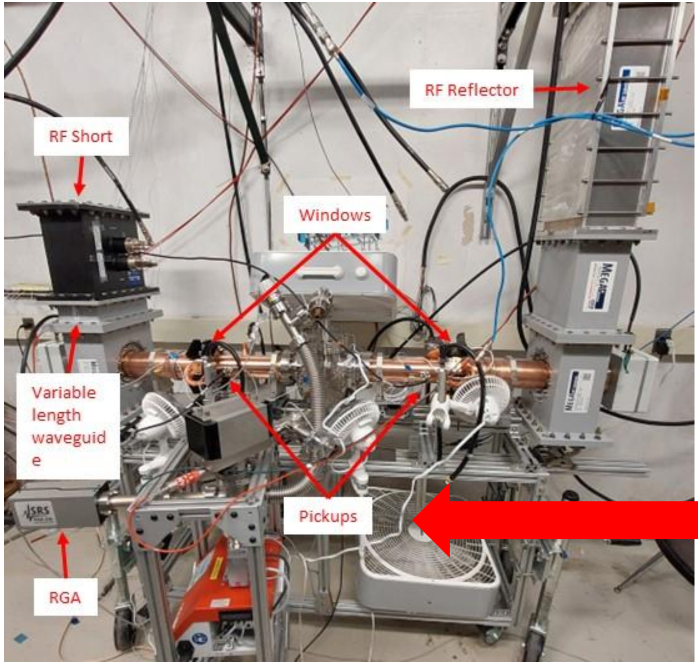
0°

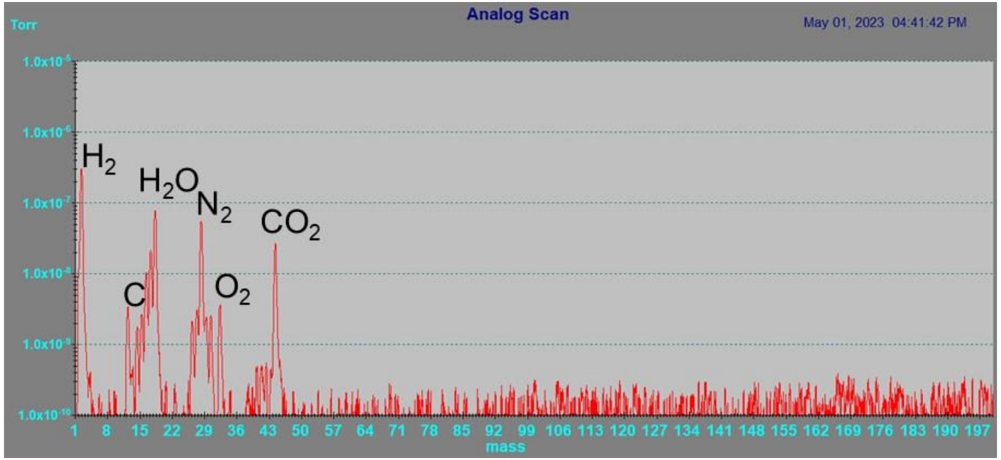




High-Power Test at Fermilab – RGA & Pickups

- RGA scan conducted at 80 kW temperature plateau shows < 10^{-9} torr partial pressure of Sn (118.7 amu), Ag (107.9 amu), Ti (47.9 amu), Mg (24.3 amu)



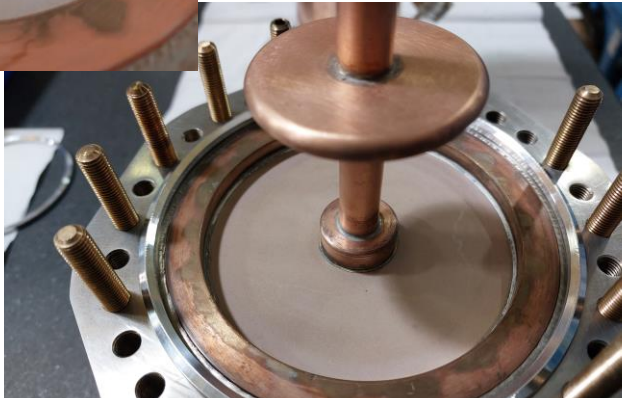


Electric pickups showed minimal activity on Conductive Ceramic window and significant activity on alumina window

High-Power Test at Fermilab Inspection

Before – Conductive Ceramic

- No visual signs of damage on conductive ceramic window after high power test



After – Conductive Ceramic

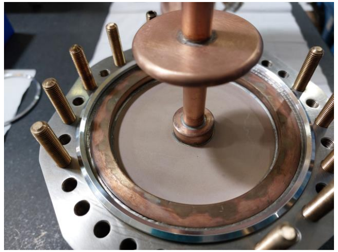
Before – Alumina

- Alumina window and antenna discolored / damaged after high power test

After – Alumina

High Power Test Summary

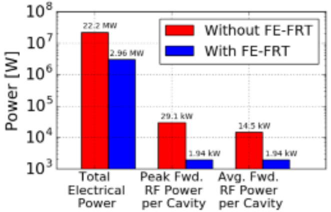
- Three windows, coaxial and waveguide, with varying conductivity & RF loss, have been tested at high power
- Waveguide window pair reached 12 kW CW TW with no observed electron activity
  - Window 1 plateaued at 78°C and Window 2 at 95°C
- Coaxial window tested in tandem with alumina window reached 80 kW CW SW
  - Conductive Ceramic window plateaued at 62°C
  - *Fundamental limit not reached*
  - Alumina window showed signs of electron activity and surface damage (conductive window overperformed it !)
  - Highest power ever achieved in Fermilab test stand



Material Science ➡ for Accelerators

FERROELECTRIC CERAMIC

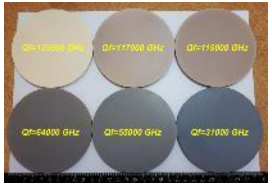
Ferroelectric ceramic with low loss tangent at RF allow development of DC biased tuners with extremely fast switching times (τ<30 ns).



These tuners reduce the RF power for SRF and NC accelerators, LHeC case study – factor of ~15.

LOW LOSS CONDUCTIVE CERAMIC

a new ceramic material with a finite DC electrical conductivity combined with a low RF loss tangent for use at high power RF



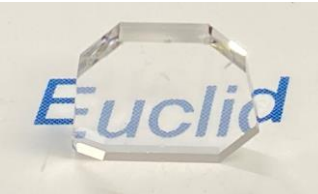
5x10^-6 – 2x10^-5
at 650 MHz
conductivity is up 4 orders !
(10^-13 -10^-9) S/m

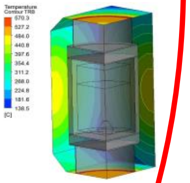
This ability to tune the conductivity allows one to effectively discharge any charge deposited on the ceramic.

DIAMONDS FOR X-RAY OPTICS

HPHT and CVD diamonds are grown by Euclid.

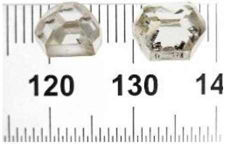
High crystallinity HPHT substrates, quantum CVD

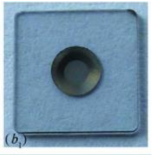




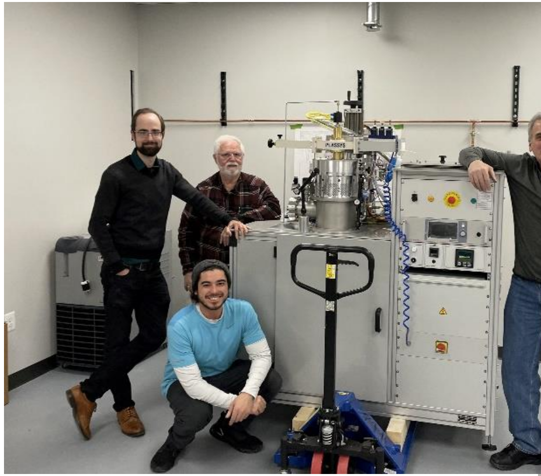
X-ray optics requires ultrahigh purity, no dislocation, stress-free single crystal diamonds

X-ray Optics for Light Sources.





Presently, there are no suppliers in the US to provide scalability and manufacturability of high-quality HPHT diamonds for the rapidly developing field of X-ray optics for the next generation X-ray sources.



Commissioning the CVD reactor in Beltsville, MD

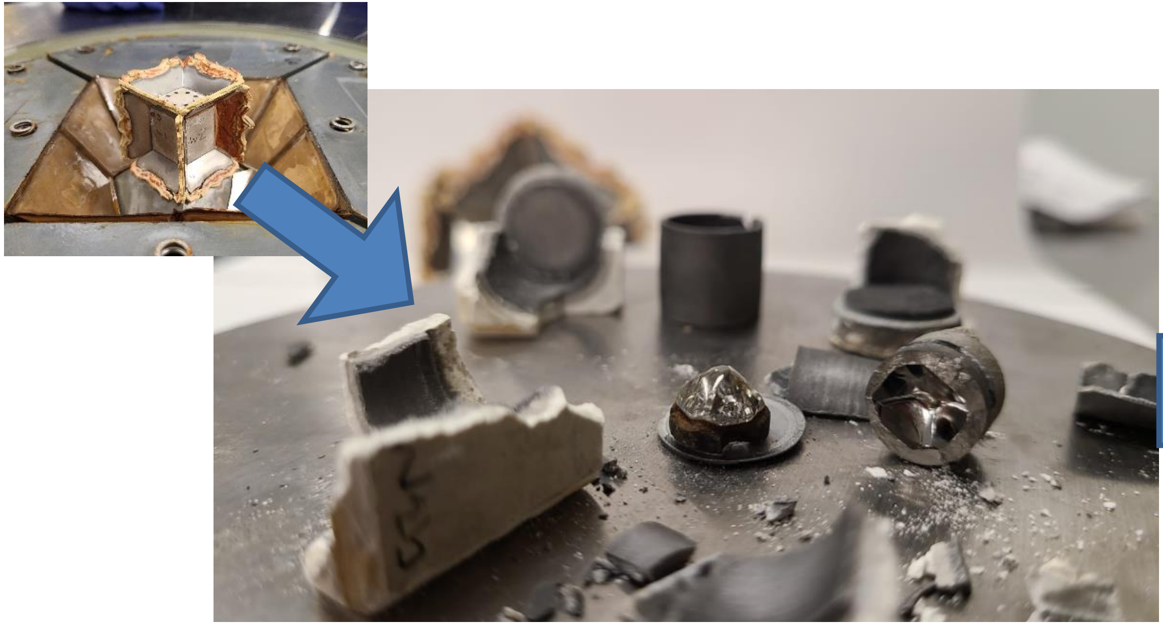
In collaboration with ANL and SLAC

HPHT diamond growth reactor at Beltsville, MD lab

With Euclid's 2021 DOE SBIR Ph2 projects, we have commissioned the first HPHT and CVD diamond growth reactor. Euclid had previously developed techniques for growing near dislocation free diffraction-grade diamonds that were characterized and highly praised by APS/ANL and SLAC

HPHT Diamond Single Crystal Synthesis.

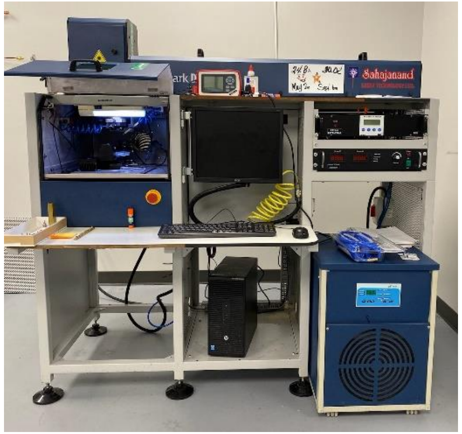
Breaking open HPHT growth cell



>4 ct Single Crystal

Post Growth Diamond Infrastructure.

Laser Cutting



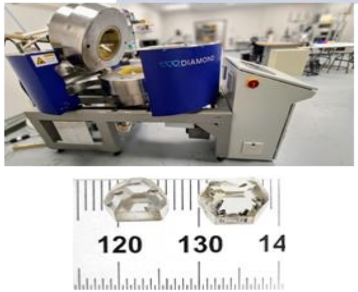
Polishing

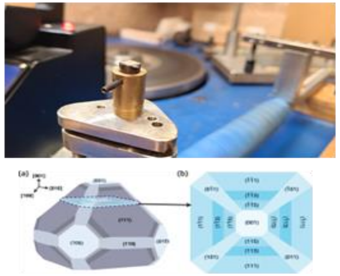
Optical Profilometer

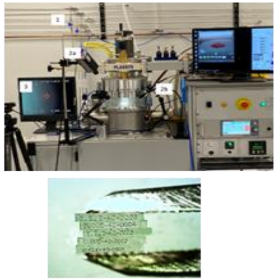
405nm Photoluminescence

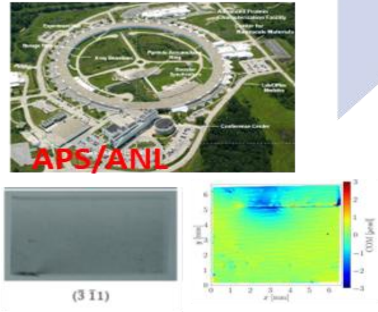
Diamond in Euclid – Material Research

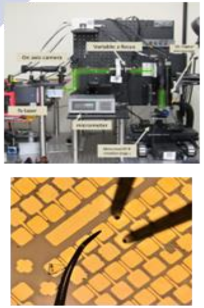
- Large sc dislocation-free HPHT substrates
- Diamond plates cutting and surface preparation
- High-purity MPECVD growth
- Material characterization
- Device fabrication



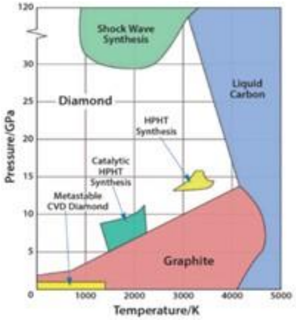


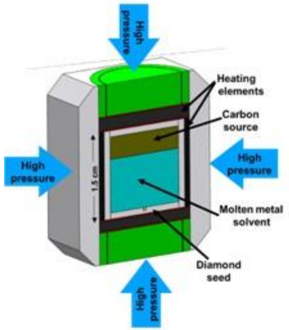


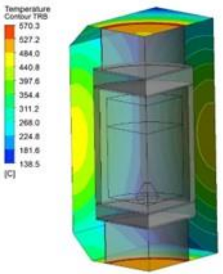




HPHT Diamond for X-ray optics

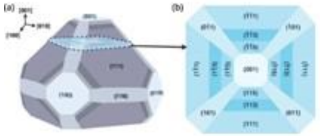


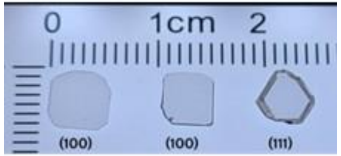




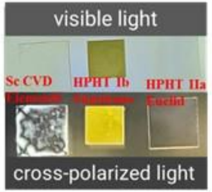
Growth optimization

Comparison with other vendors



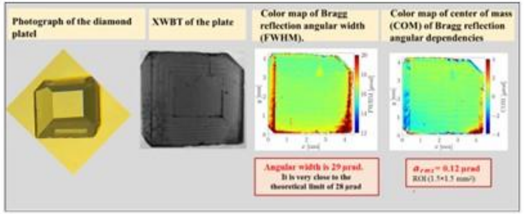


Cross-polarized Light



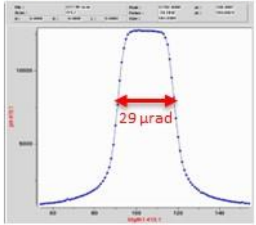
X-ray Analysis

Best sc CVD	HPHT Ib	HPHT IIa
Element Six	Sumitomo	Euclid Beamlabs



Photograph of the diamond platel	XWBT of the plate	Color map of Bragg reflection angular width (FWHM).	Color map of center of mass (COM) of Bragg reflection angular dependencies
		Angular width is 29 µrad. It is very close to the theoretical limit of 28 µrad	θ_{rms} = 0.12 µrad ROI (1.5×1.5 mm²)

Rocking Curve Imaging



Defect densities

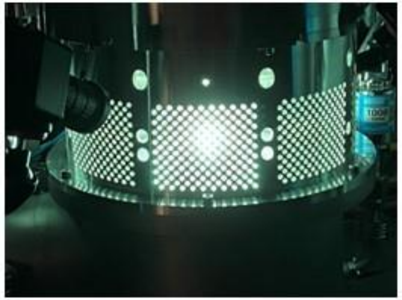
Euclid HPHT vs best sc CVD

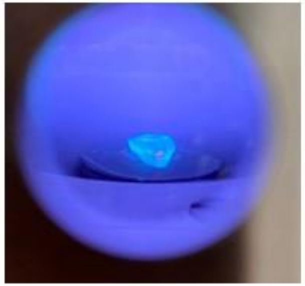
$10^{0-1}\ \mathrm{cm}^{-2}$ $10^{3-7}\ \mathrm{cm}^{-2}$

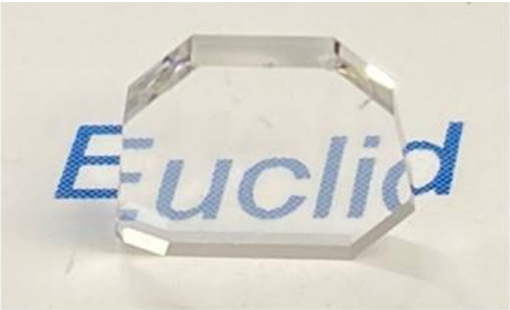
APS Comments (Y.S.):

This is very good. Theoretical curve for a plane incident wave is 28 rad. The rectangular shape is also right.

CVD Diamond for X-ray optics



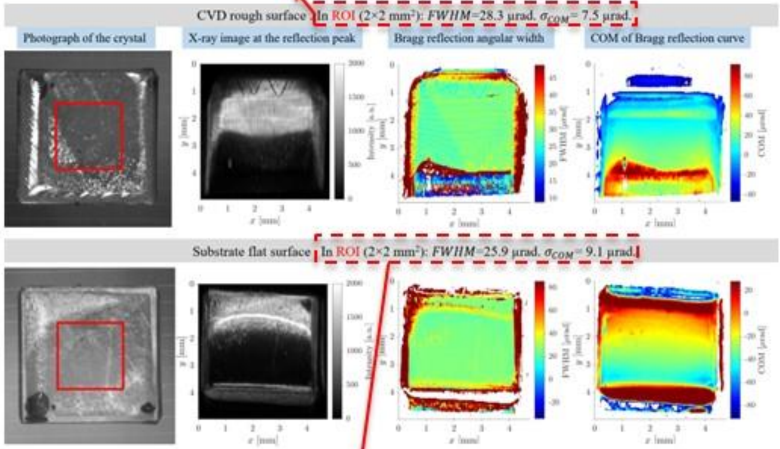




Scalable
high clarity
high purity

WBXT Analysis

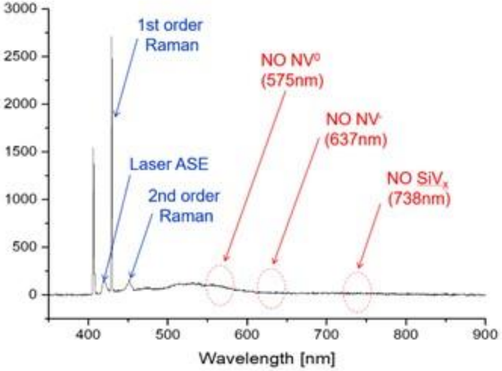
In ROI (2×2 mm^2): *FWHM*=28.3 µrad. σ_{COM}= 7.5 µrad.



In ROI (2×2 mm^2): *FWHM*=25.9 µrad. σ_{COM}= 9.1 µrad

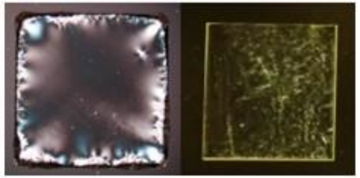
Ultrahigh Purity

PL spectra shows no vacancies



Stress-free

Removal of birefringence



350 µm stressed epitaxial film on HPHT substrate

200 µm stress-free epitaxial film

In conclusion,

- New ferroelectric ceramic material was developed with the set of parameters satisfying the Ferroelectric Fast Reactive Tuner (F-FRT) requirements for microphonic compensation, transient detuning, and fast switching. First F-FRT prototype was designed, fabricated and successfully demonstrated at CERN
- Euclid has developed a new conductive low loss ceramic for high power RF windows. 650 MHz windows made of this type of ceramic overperformed the standard alumina window at ~90kW CW tests at Fermilab.
- The HPHT and CVD diamond growth lab allows to produce ultrahigh purity, no-dislocation, stress-free single crystal diamonds for X-ray optics