LOW RF LOSS DC CONDUCTIVE CERAMIC FOR HIGH POWER INPUT COUPLER WINDOWS FOR SRF CAVITIES

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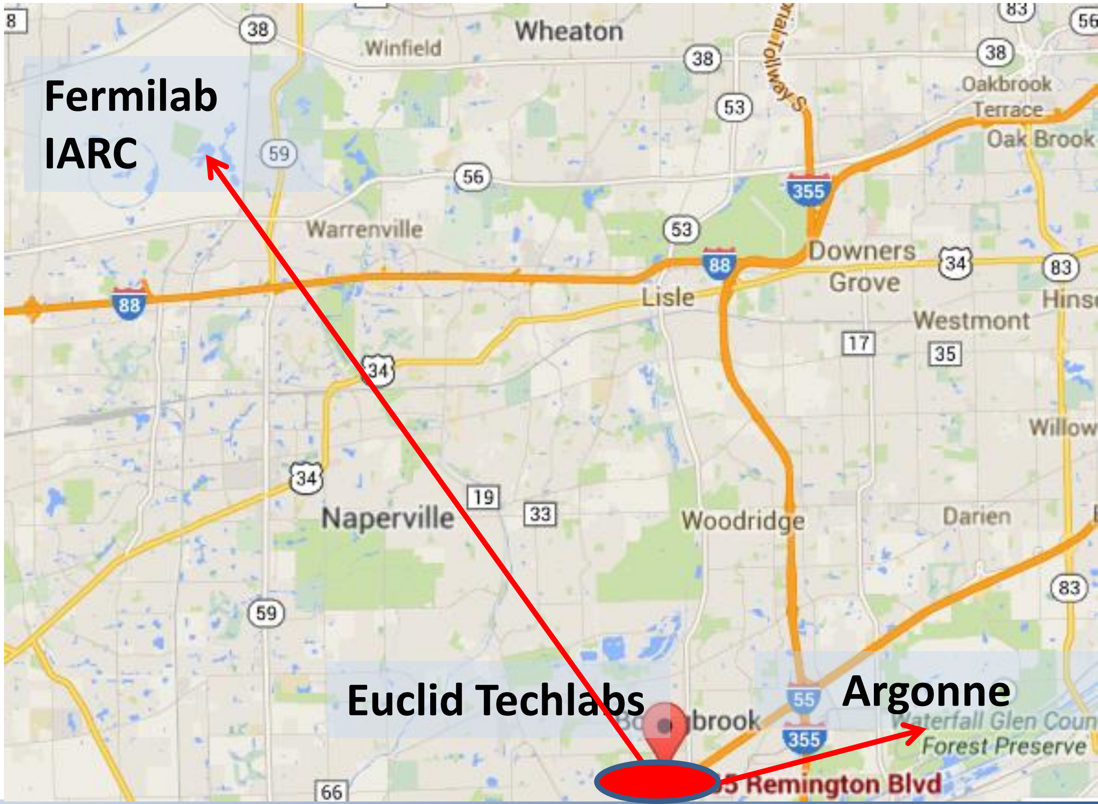
On behalf of Euclid Techlabs/JLAB/FNAL/PSU collaboration

Department of Energy SBIR/STTR Exchange Meeting
August 13-14, 2019

Euclid Techlabs LLC

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

- 2 offices: Bolingbrook, IL (lab) and Gaithersburg MD (administrative).
- Tight collaborations with National Labs: Argonne, Fermi, BNL, LBNL, LANL.
- Actively participate in Accelerator Stewardship DOE Program

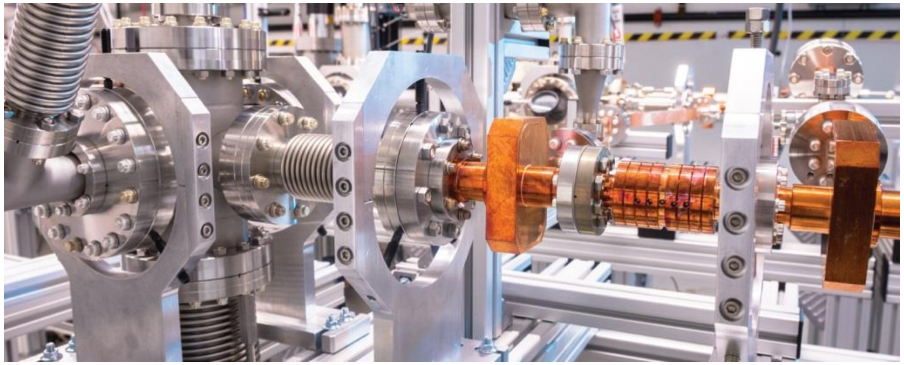


LAB FACILITY IN BOLINGBROOK IL

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

15 PhDs,
22 staff total

11,000 sq ft - total
2,000 sq ft – office
9,000 sq ft - lab

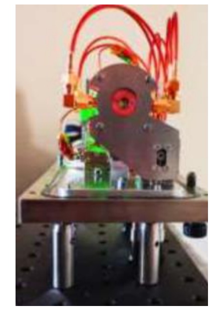


2 locations: Chicago IL and Maryland/DC

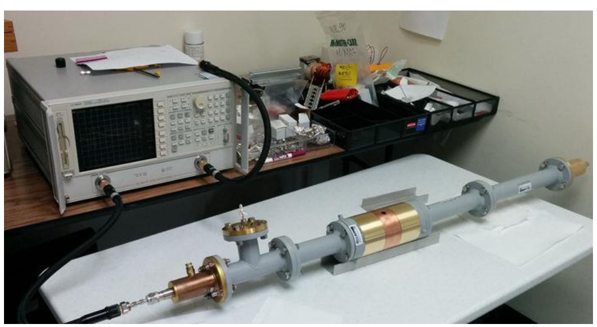
ANL/AWA accelerator, ANL/CNM - FE UNCD,
ANL/APS- diamond based X-ray optics
Jlab and Fermi: SRF tests

Key Euclid's technologies:

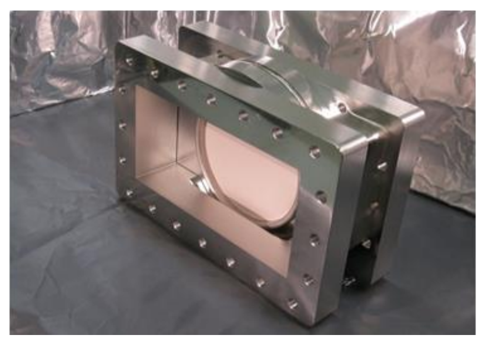
- Ultra-compact low energy accelerator (dielectric based)
- Stroboscopic pulser for Transmission Electron Microscope
- Electron guns for accelerators: Photo-, thermo-, field emission (FE)- and SRF guns.
- Ferroelectric based fast tuner.
- UNC_Diamond based FE and photo cathodes.
- Accelerator components (RF windows, couplers…)
- Other beam physics instrumentation.



5 GHz kicker for TEM, BES/NIST

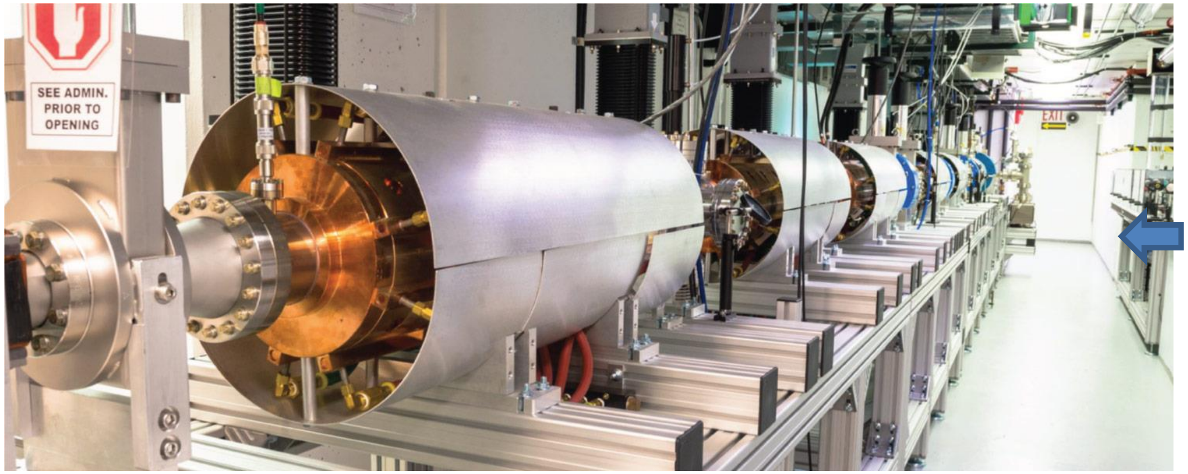


Fast ferroelectric 400 MHz tuner successfully tested at CERN



L-band RF window for AWA ANL

History: Research on **Dielectric** Wake Field Accelerating structures with ANL



Experiments with DWFA were done by Euclid Techlabs at Argonne,

- Externally powered dielectric structure: Naval Research Lab

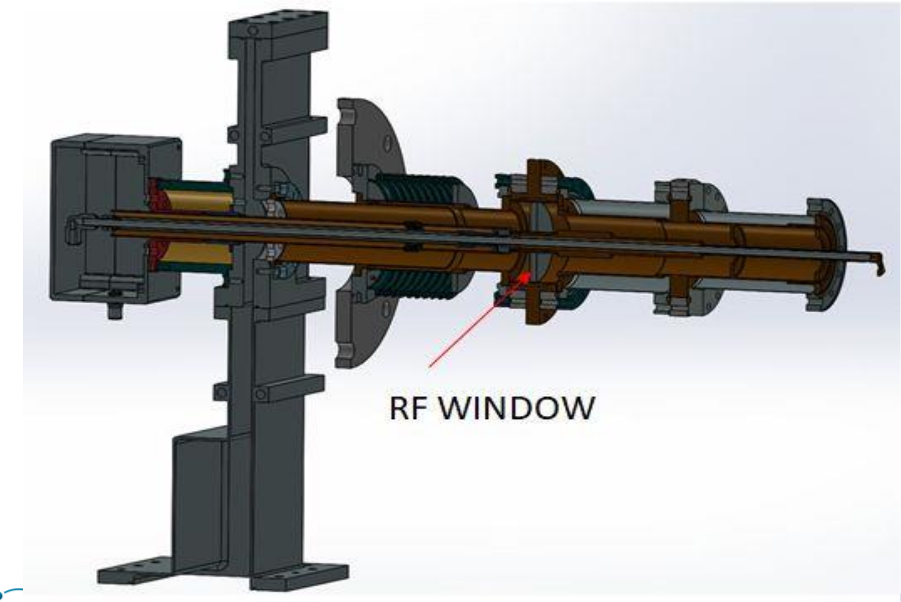
- designs: 7-26 GHz
- scalable to THz

Brookhaven, SLAC

Motivation (1)

- The high-power RF coupler connects the RF transmission line to the SRF cavity, and provides the RF power to the cavity that is used to accelerate the particle beam. The coupler also provides the vacuum barrier for the beam vacuum using RF windows.

- RF windows exhibit breakdown as arcing and surface flashover at much lower voltages than comparable insulators in DC fields. At higher RF fields, there can be electron emission from the "triple junction“ and multipacting leading to window failure due to arching and/or thermal runaway.

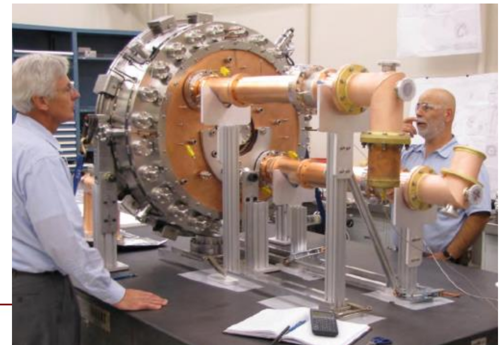


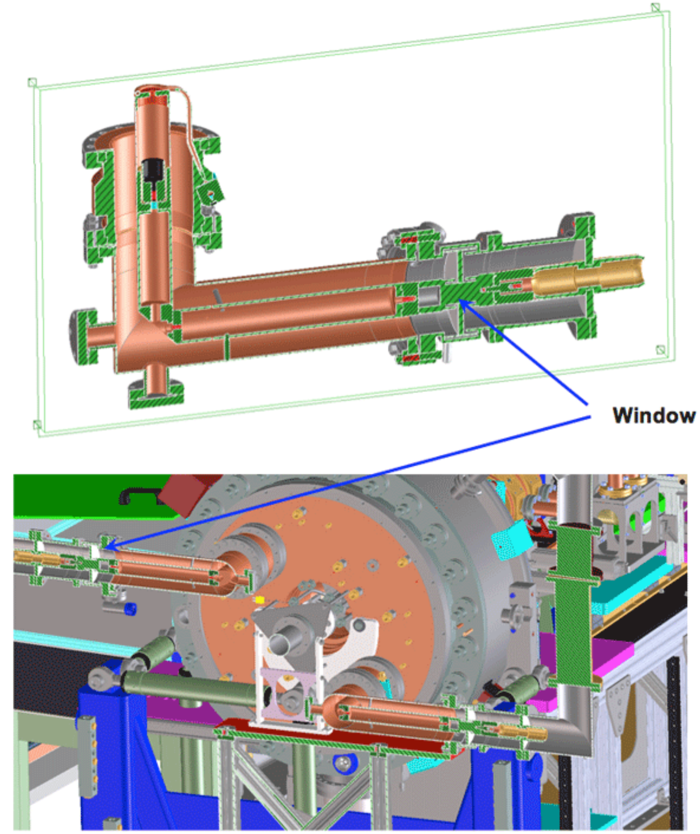
- These processes are a major problem for RF windows and couplers, and are responsible for damages and lost beam-time in SRF cavity and cryomodule operation.

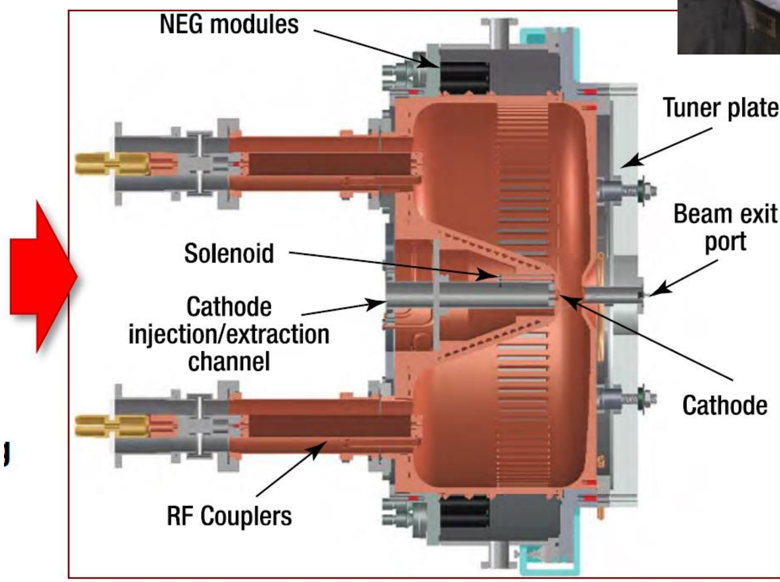
Motivation (2)

Example: in the Advanced Photoinjector Experiment's VHF gun and in the LCLS-II injector

Window was broken: charging because of the direct line of site for the beam.







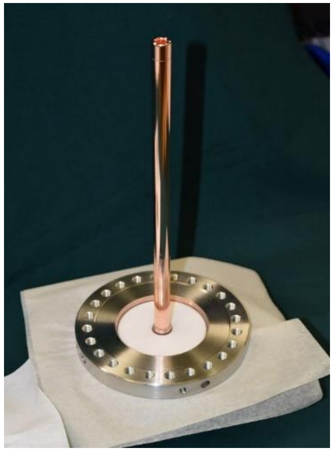
The LBNL approach uses a CW photogun designed to meet all requirements

The new 90-degree coupler will keep the ceramic vacuum window out of harm's way with regard to field emission

The solution would be to have new ceramic material with low losses in the MHz-GHz frequency ranges **with increased DC conductivity** to discharge the RF window.

The challenging goal of this proposal is to develop a ceramic material with a finite DC electrical conductivity and low loss tangent for use in high power coupler windows.

The main innovation of the proposed approach is the following: a new low-loss microwave ceramic material with a increased DC electrical conductivity and low loss tangent for use in high power coupler windows. The electrical conductivity will drain the field-emission induced charge away. The low loss tangent will allow realizations of high efficiency RF power transmission.



Previous experience and collaboration: Since 2001 Euclid Techlabs LLC has worked on microwave ceramic development and its application to accelerator physics. Collaboration with Jlab, BNL, ANL, FNAL, CERN, other

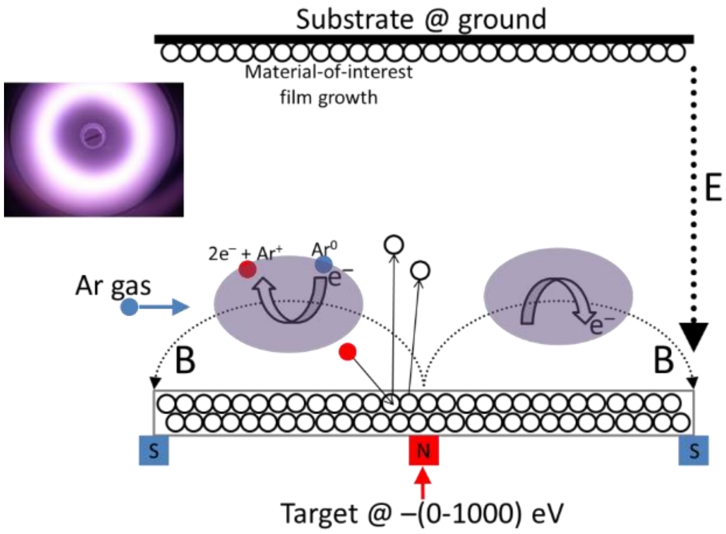
Tasks

- **Task 1.** Fabrication of the ceramic samples consisting of MgO-TiO2 system (MgTi) compounds with the decreased resistivity in the range 10^8 -10^9 , dielectric constant in the range 14-16, and the loss factors with figure of merit in the range of Qxf=30,000-60,000 GHz at microwaves.
- **Task 2.** Development of a method for controlling the bulk and surface conductivity of the new MgTi ceramic components for the RF windows.
- **Task 3.** Beam test of the discharging properties of the new developed MgTi ceramic components to be carried out at Euclid linear accelerator DC gun.
- **Task 4.** Fabrication of 12 MgTi ceramic components of 650 MHz high power RF windows. Testing of electrical and mechanical properties of the fabricated ceramic components.
- **Task 5.** Fabrication of four high power 650 MHz RF windows. Brazing technology development.
- **Task 6, Task 7.** High power testing of the fabricated 650 MHz RF windows.
- **Task 8**. Final Phase II report preparation.

Surface conductivity

TASK from Phase I results. Surface conductivity of new ceramic development with a physical vapor deposition process. Surface conductivity measurements.

Since the RF window has a simple planar disk geometry, we plan to use a physical vapor deposition method called magnetron sputtering (PVD) to find a solution to the surface charge problem. We enhance surface conductivity of ceramic oxide disks with a dielectric constant of 10-20. In this method, the evacuated vacuum chamber (to a base pressure $\leq 10^{-6}$ Torr) is filled with a working gas, which is typically argon. In the vicinity of a magnetron argon atoms collide with an electron cloud confined along magnetic field lines (a permanent magnet is installed in the magnetron head).



In progress, TiN standard deposition

We will work with the bulk conductivity with this project !

Wrong ways review …

Composition	#	ε at microwave	Q×f, GHz	ρ_v, Ω·m
M,T	1	15.42	82,500	2.30×10^{11}
	2	15.59	36,649	$1.98*10^{9}$
Zn	1	23.85	104,237	5.00×10^{11}
Zn-M03	2	24.15	48,135	4.10×10^{11}
Zn-M05	3	24.32	36,530	3.90×10^{11}
T0	1	27.6	22,672	2.00×10^{11}
T3	2	39.7	24,000	1.50×10^{11}

Zn based composition showed decrease of resistivity 2-3 times only by adding of Ag while figure of merit is Q*f=24,000 only.

Mg,Ti based composition after synthesis showed 2 orders of magnitude loss in resistivity, from 10^{11} to 10^{9}, while figure of merit was still high Q*f=36,649

Fabrication and Sintering of the Mg,Ti conductive ceramic

In Year I of Phase II of this project,

- Euclid fabricated the MgTi ceramic elements with a increased **conductivity from 10^{-12} to 10^{-8}-10^{-9} Sm/M**, relative **dielectric constants ε=15**, and loss factors with figures of merit Q×f in the range of 30,000–60,000 GHz, providing ***tanδ*~(6–8)×10^{-5}, 650 MHz**.
- Electrical and microwave properties of the ceramic window components **have been optimized** using the technology of increased conductivity ceramic sintering developed in Phase I of the project.

Increased conductivity MgTi development results

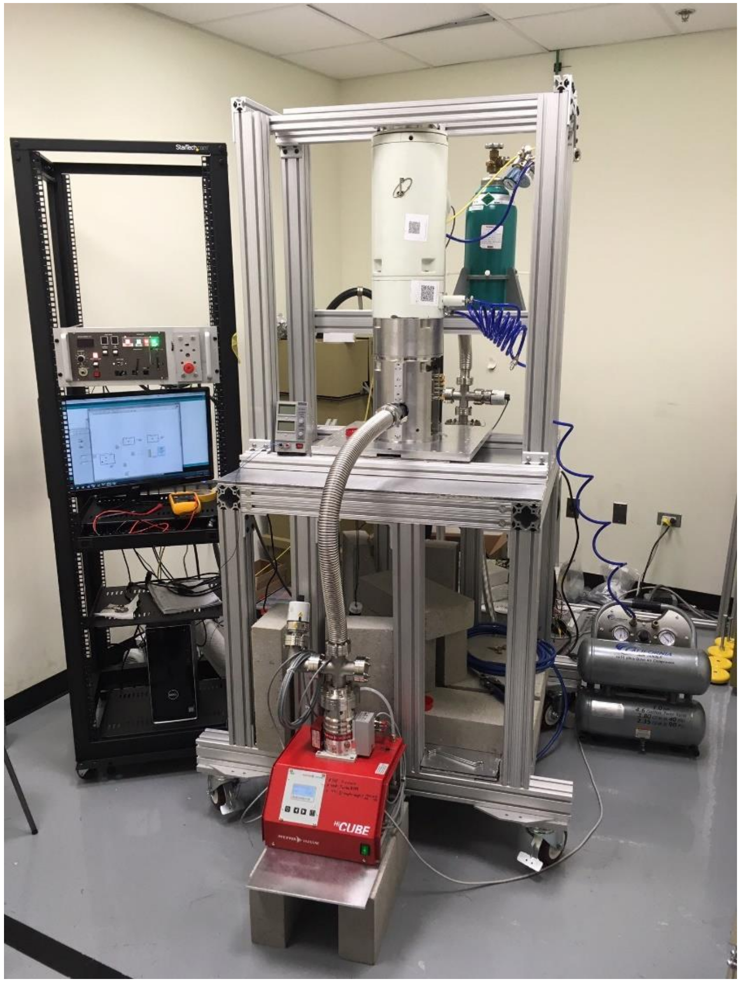
We developed a ***reproducible technology*** for sintering these materials providing still lower loss tangent ceramics in the GHz frequency range, and exhibiting 2–3 orders of magnitude **increased conductivity** (**10^2 –10^3 times).**

We observed and studied the interesting new phenomenon of abnormal **~10^4 conductivity increase** of the developed MgTi ceramic in the 25^0C–100^0C temperature range, while the loss tangent variation at 100^0C did not exceed **a 20%** change compared to the room temperature value.

This ability to tune the conductivity will allow one to effectively discharge high power RF windows by controlling their operating temperature.

DC 200 kV BEAM CHARGING TEST OF CERAMIC

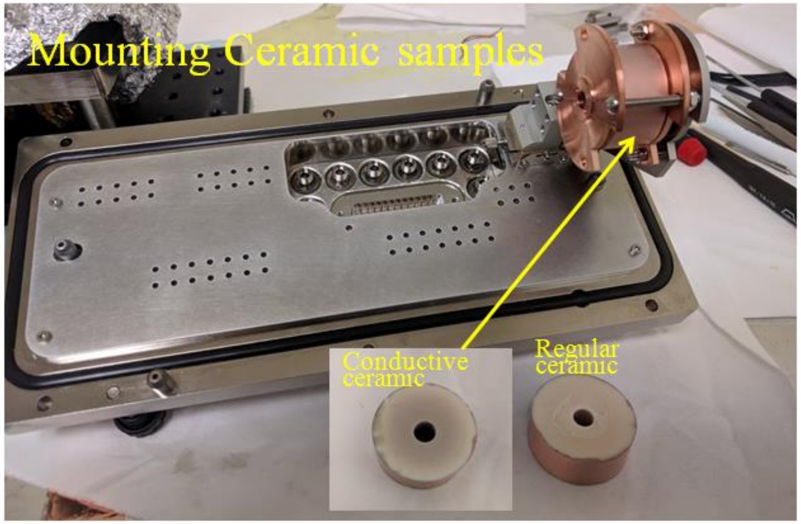
DC beam test using TEM DC gun:

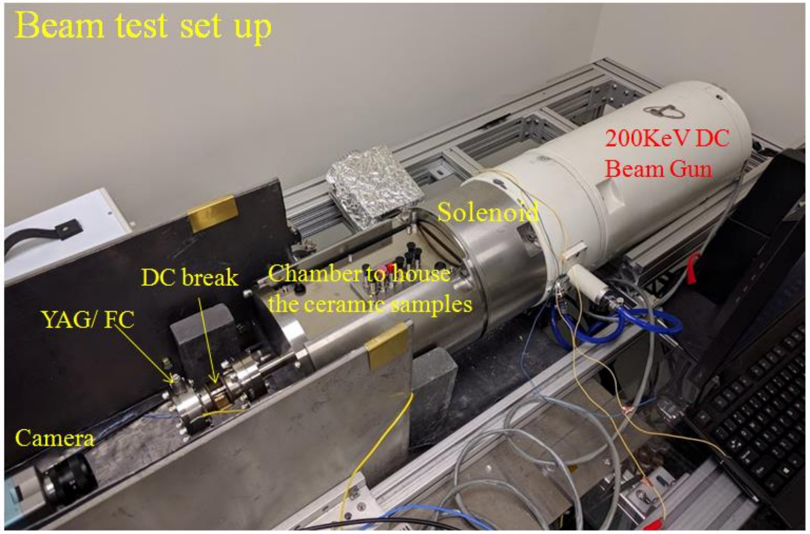


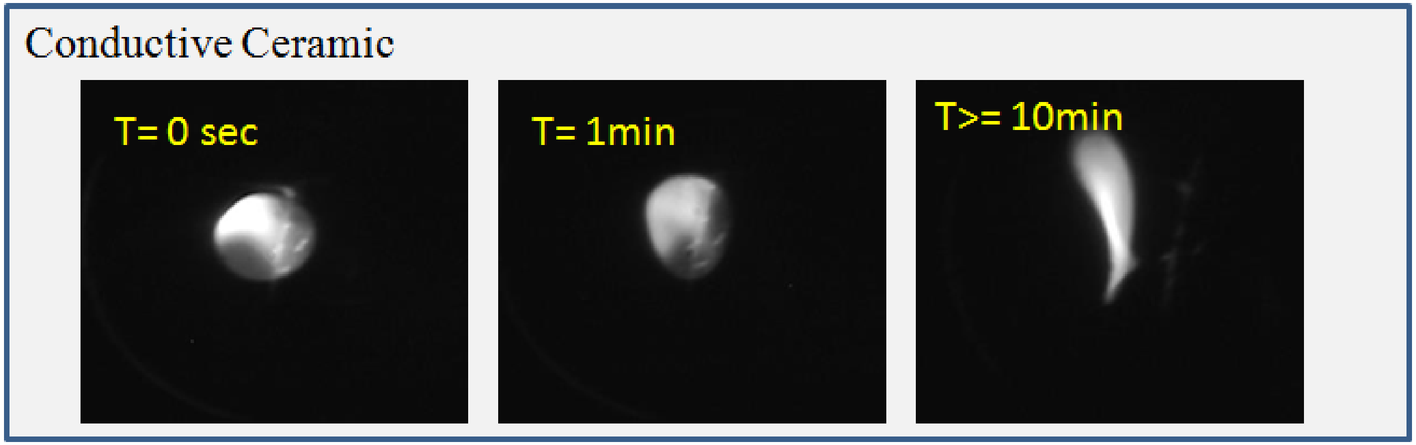
We are currently carrying out beam tests on the developed ceramic. Using the 200-keV DC gun available at the Euclid lab facility, we are exposing two types of ceramics to the DC beam: the standard MgTi ceramic and our new (Mg,Ti) ceramic with increased conductivity. The goal of the ongoing experiments is to **quantitatively study the charging** – discharging mechanism of the MgTi.

DC 200 kV electron beam for charging testing

Beam Charging Test Results



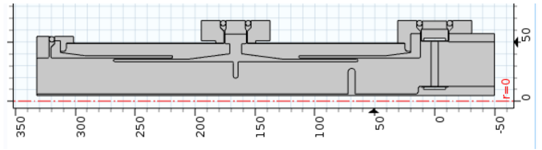


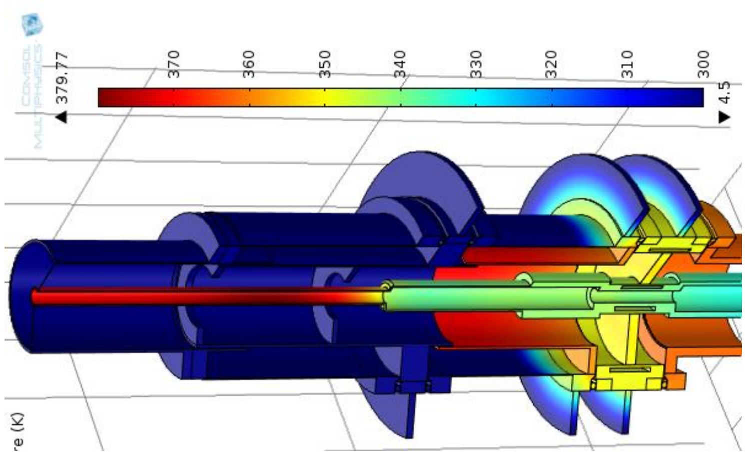


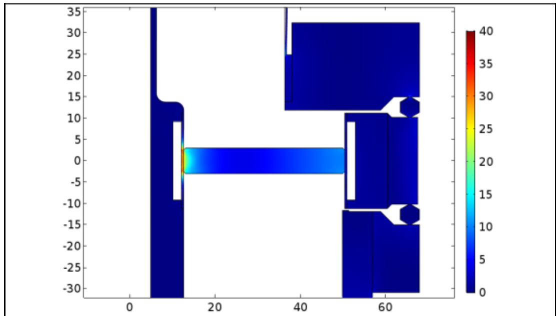
The beam images at the downstream YAG, which were captured at different times. T=0 second represents the turn-on time of the DC beam: with the regular ceramic sample beam disappeared in 15 sec, with the new MgTi ceramic it is stable in hours…

Electrodynamic and Thermo-Mechanical Modeling

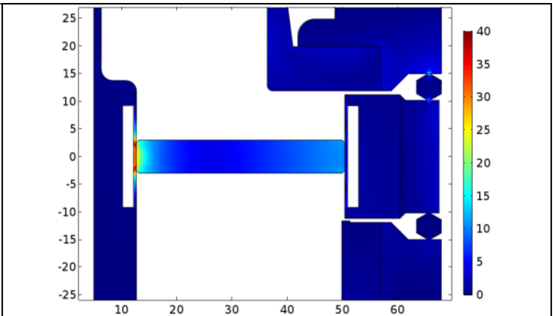
We carried out electrodynamic-thermomechanical modeling of the vacuum portion of the 650-MHz high power coupler. The modeling results showed **the same range of maximum temperatures of the RF window, maximum stress values, and temperature and stress distributions for both the commonly used alumina and for the disc made from the MgTi** ceramic developed by Euclid.



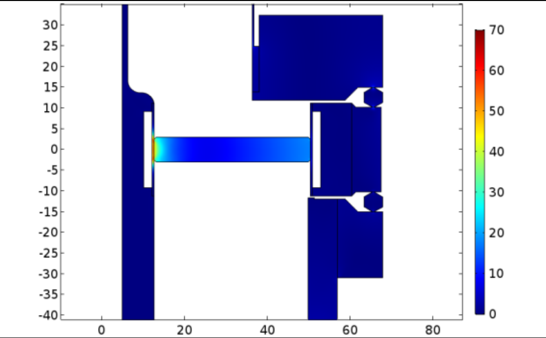




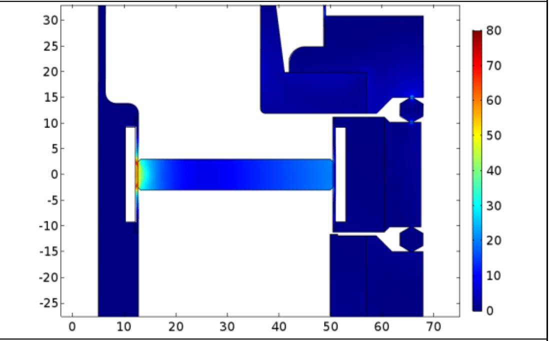
Al_2O_3 ver 1



Al_2O_3 ver 2



MCT ver 1



MCT ver 2

Tasks

- done   - In progress   - to be done

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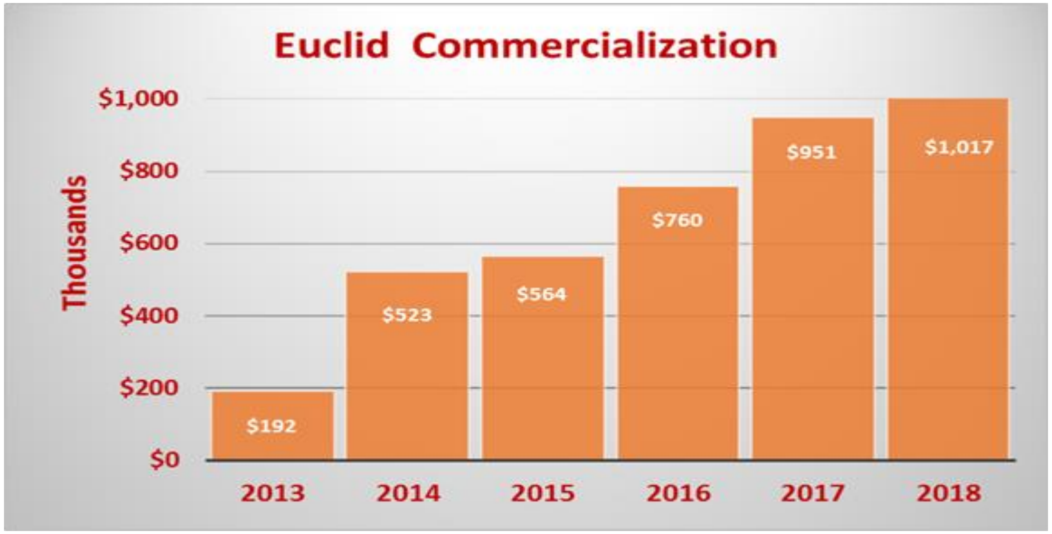
Commercialization

- Two periods:
  2003-2014 - spinoff from Argonne Wakefield Accelerator group (DOE SBIR)
  2014- now - commercialization of advanced material technologies and TEM.



11 patents +5 currently in progress

Fast Ferroelectric Based Tuner - Phase II 2016 Nuclear Physics

Tuner is purchased, installed and tested in 2019 by CERN, SRF'2019 invited talk by CERN. 80MHz – new project !

- Latest Noticeable Contracts:

NIST (2016-2018) – "Time Resolved TEM" → JEOL, Inc. installation at the US facility, then BNL and NIST
GWU (2017) – "UNCD Emission Chamber"
UMD (2016-2018) – "Single Crystal Diamond FET"
SJTU (2016-2019) – "Photoinjector", "Thermionic Gun"

Phase II 2016 Ferroelectric Tuner results

12:15 N.C. Shipman *(European Organization for Nuclear Research Beams Department (BE))* WETEB7

A Ferroelectric Fast Reactive Tuner for Superconducting Cavities

A prototype FerroElectric Fast Reactive Tuner (FE-FRT) for superconducting cavities has been developed, which allows the frequency to be controlled by application of a potential difference across a ferroelectric residing within the tuner. This technique has now become practically feasible due to the recent development of a new extremely low loss ferroelectric material. In a world first, CERN has tested the prototype FE-FRT with a superconducting cavity, and frequency tuning has been successfully demonstrated. This is a significant first step in the development of an entirely new class of tuner. These will allow electronic control of cavity frequencies, by a device operating at room temperature, within timescales that will allow active compensation of microphonics. For many applications this could eliminate the need to use over-coupled fundamental power couplers, thus significantly reducing RF amplifier power.

Download

A FERROELECTRIC FAST REACTIVE TUNER FOR SUPERCONDUCTING CAVITIES

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E. Nenasheva, Ceramics Ltd, St.Petersburg, Russia

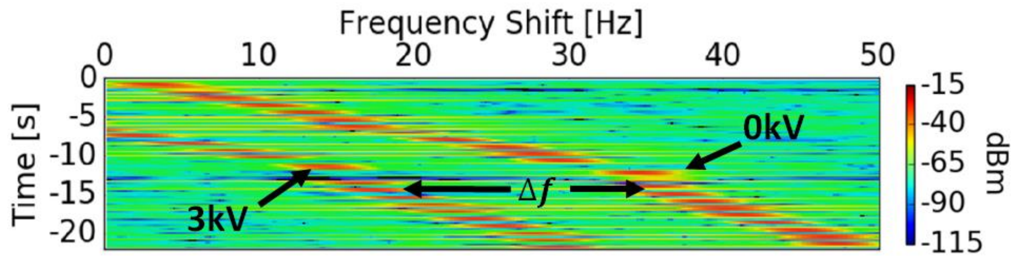
Abstract

A prototype FerroElectric Fast Reactive Tuner (FE-FRT) for superconducting cavities has been developed, which allows the frequency to be controlled by application of a potential difference across a ferroelectric residing within the tuner. This technique has now become practically feasible

HISTORY OF REACTIVE TUNERS

Reactive tuning is the controlled change of a cavity frequency by coupling to a tunable reactance. The control is electronic and no mechanical motion is needed so the change can be fast. Two types of reactive tuner already exist: pin diode based reactive tuners and ferrite based reactive tuners.

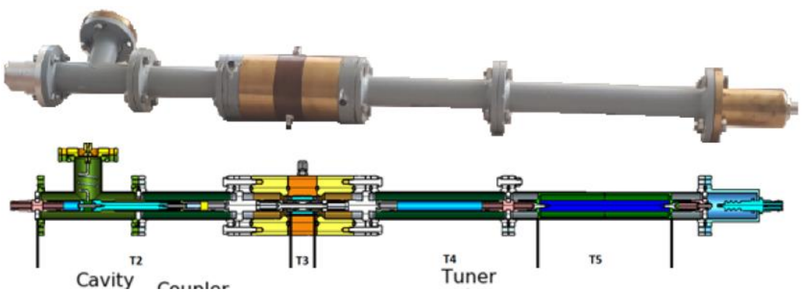
Fast Tuner Testing, CERN 2019



Direct observations of the frequency shift caused by the FE-FRT made with the signal analyser.

The first ever FE-FRT test with a superconducting cavity has been performed and successfully demonstrated frequency tuning. The timescale in which the FE-FRT is able toshift the cavity frequency across the entire tuning range wasmeasured to be < 50 μs, this is significantly faster than any other cavity tuning device. A **maximum frequency tuning of ≈ 12 Hz was observed** with an applied voltage of 3 kV, this could easily be increased by coupling more power to the tuner.

A case study of an FE-FRT applied to PERLE show RF power could be reduced by a factor of ≈ 15.



PERLE- Powerful Energy Recovery LINAC, Orsay

Summary

The ultimate goal of the Phase II project is (1) to develop a ceramic material with a increased DC electrical conductivity and low loss tangent for use in high power coupler windows; (2) to fabricate a set of high power 100 MHz – 900 MHz RF windows; (3) high power testing at Jlab, Fermilab and CERN of the fabricated RF high power windows.

- We developed MgTi ceramic elements with a increased conductivity 10^{-8}-10^{-9} Sm/M, relative dielectric constants ε=15, and loss tangent $tan\delta \sim (6–8)\times 10^{-5}$, 650 MHz.
- We observed and studied the interesting new phenomenon of abnormal ~10^4 conductivity increase of MgTi ceramic in the 25^0C–100^0C temperature range, while the loss tangent variation at 100^0C did not exceed a 20% change.
- We carried out the beam charging tests, and thermo-mechanical and electromagnetic modeling of the SRF fundamental couplers with the developed ceramic.

Current plans are: brazing of the RF windows and high power testing at Jlab, FNAL and CERN.

Acknowledgments

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Ceramic Ltd**.: E.Nenasheva**
Jlab: **Robert Rimmer, Frank Marhauser**
CERN**: Eric Montesinos**
Fermilab: **Sergey Kazakov**