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

Supported by the DOE SBIR DE-SC0017150, Phase IIA

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

Department of Energy SBIR/STTR Exchange Meeting
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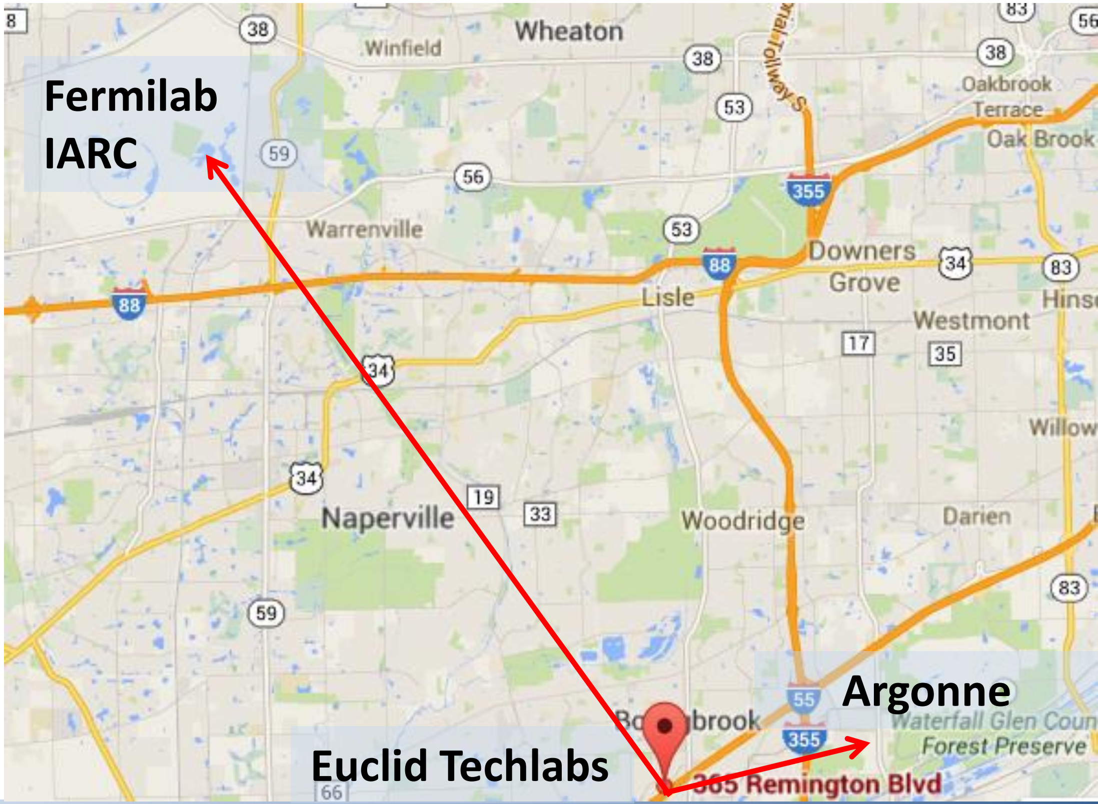
Euclid Techlabs

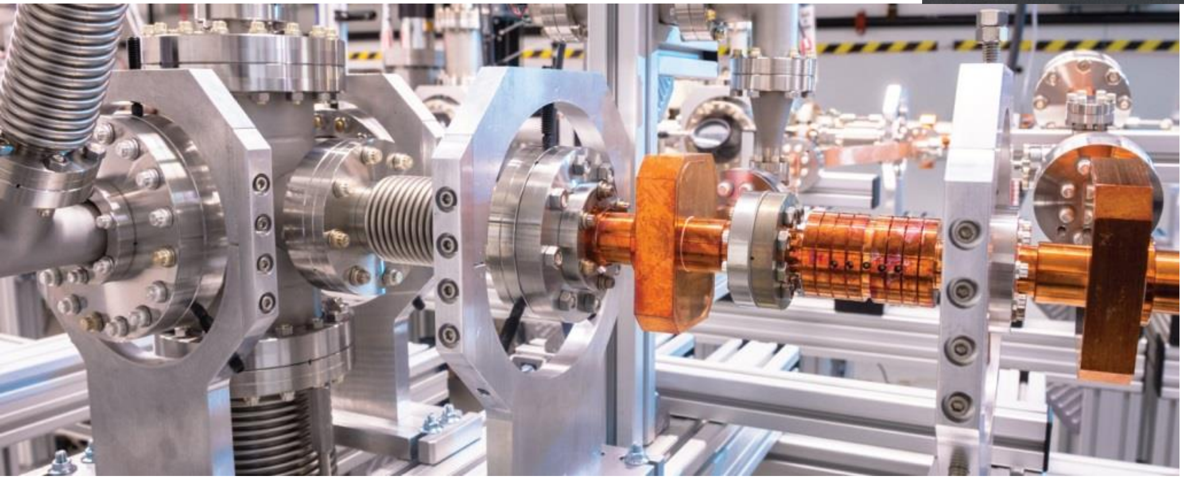
Euclid TechLabs LLC, founded in 2001 is a company specializing in the development of advanced materials and new designs for beam physics and high power/high frequency applications. Additional areas of expertise include dielectric structure based accelerators and "smart" materials technology and applications.

- 2 offices: Bolingbrook, IL (lab) and Gaithersburg, MD (administrative)
- Close collaboration with National Labs: ANL, BNL, FNAL, LANL, LBNL.



Lab Facility in Bolingbrook, IL

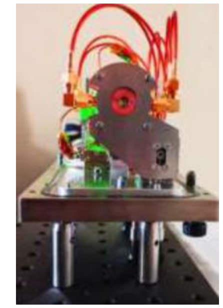
- Compact electron accelerator test facility
- Time resolved TEM beamline
- Clean room/magnetron sputtering (TiN, copper, dielectrics)
- Field Emission cathode DC test stand
- Femtosecond laser
- RF lab
- …other beam physics related equipment - www.euclidtechlabs.com



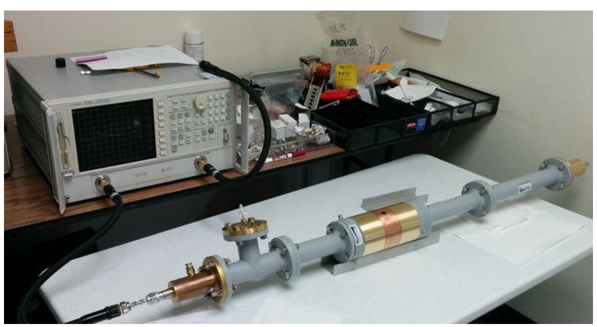
- 15 PhDs
- 25 staff total
- 11,000 sq ft - total
- 2,000 sq ft – office
- 9,000 sq ft - lab

Key Euclid Technologies

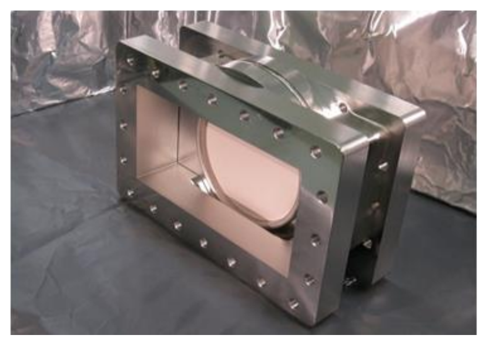
- Ultra-compact low energy accelerator (dielectric based)
- Stroboscopic pulser for Transmission Electron Microscope
- Electron guns for accelerators: Photo-, thermo-, field emission (FE)- and SRF guns
- Ferroelectric based fast tuner
- UNC Diamond based FE and photo cathodes
- Accelerator components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



5 GHz kicker for TEM, BES/NIST

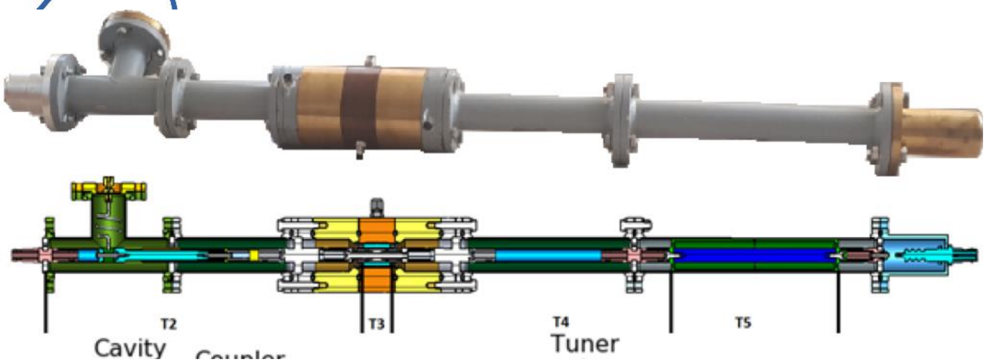


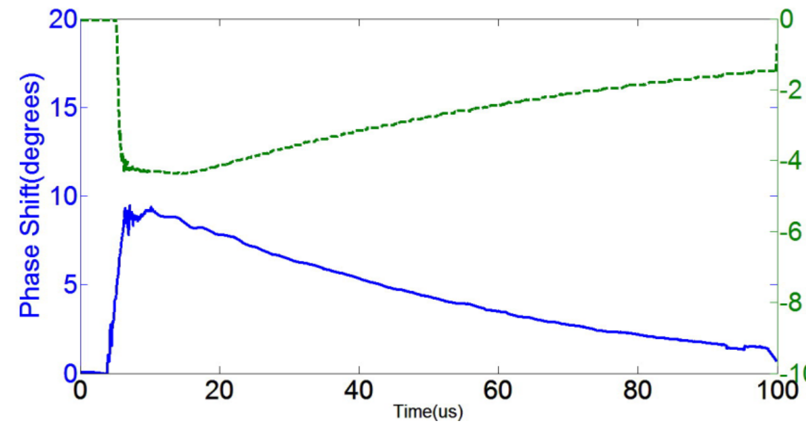
Fast ferroelectric 400 MHz tuner successfully tested at CERN



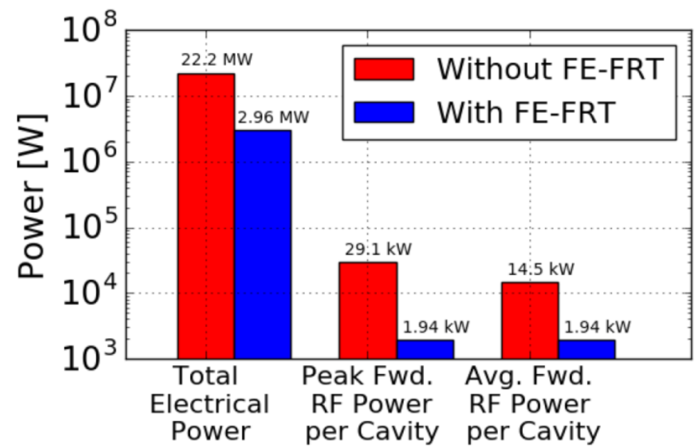
L-band RF window for AWA ANL

Ferroelectric Based High Power Tuner for SRF Cavities





- Ferroelectric Fast Reactive Tuner (FE-FRT) for SRF accelerator operations
  - Ultrafast tuner: 100 ns range
- Supported by DOE SBIR NP, DE-SC0007630
- In collaboration with CERN
  - Case study: LHeC application
- Offers potential for significant reduction in RF power consumption



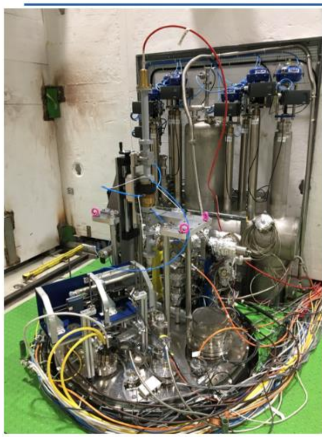
N. Shipman, et al., ERL'19, TUCOZBS02

Fast Tuner Testing, CERN 2020

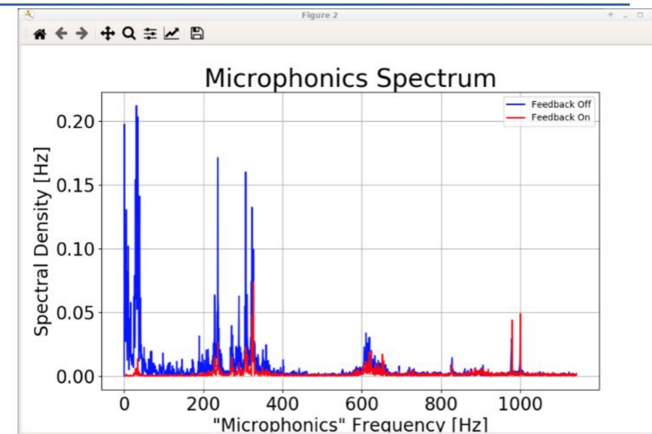
- First ever Ferroelectric Fast Reactive Tuner (FE-FRT) test with a superconducting cavity

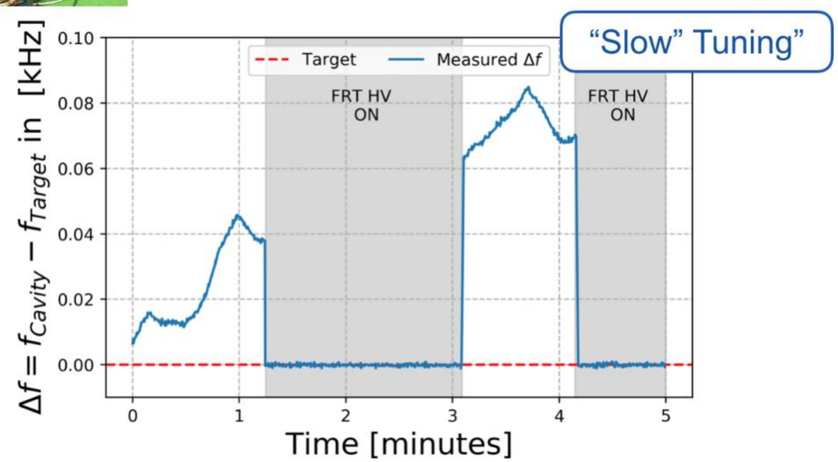
Snapshot of preliminary FE-FRT tuning loop results

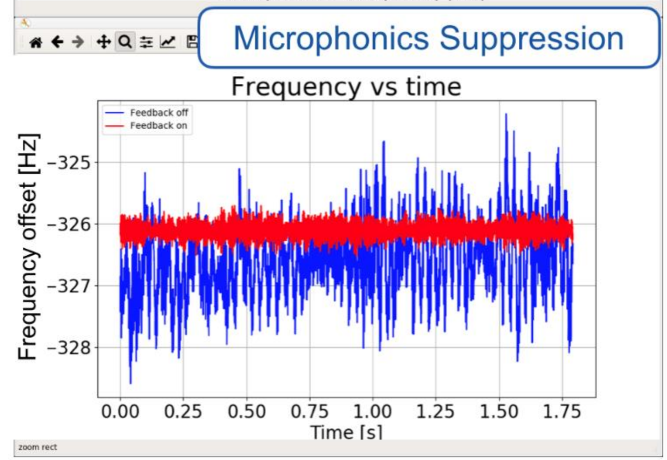
FE-FRT Tuning Loop validation: Initial Results - 30-07-2020



FE-FRT:
- A non-mechanical tuner for RF cavities
- Validated tuning loop
- Microphonics suppression
- Wide operational parameter space
  - Achievable Δf > 50 kHz (depends on Q_L)
  - Configurable tuning ranges from Hz to kHz
  - Configuration depends on FRT application







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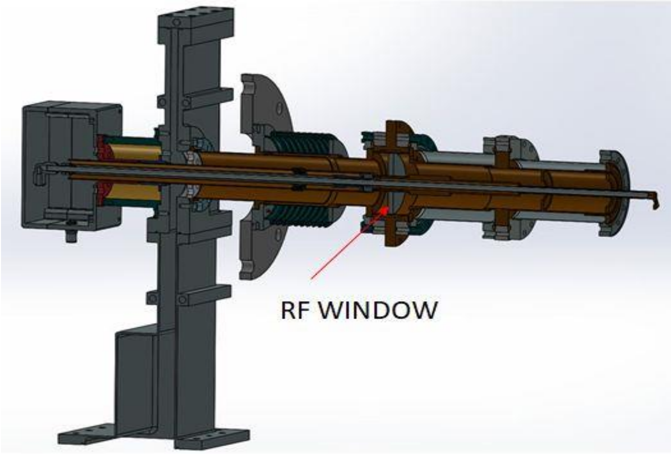
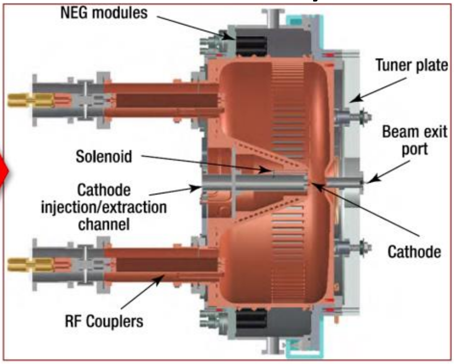
Courtesy of Alick Macpherson

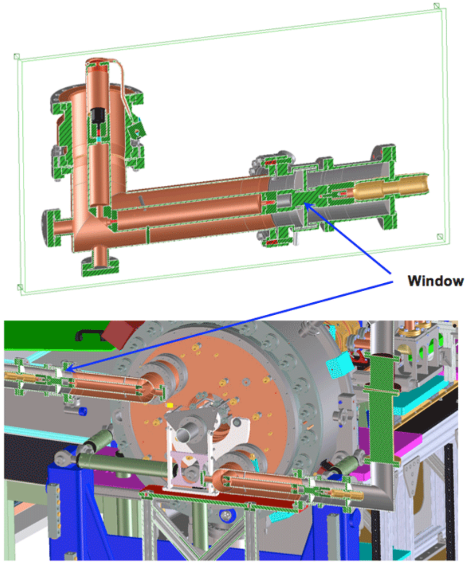
Motivation

- 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





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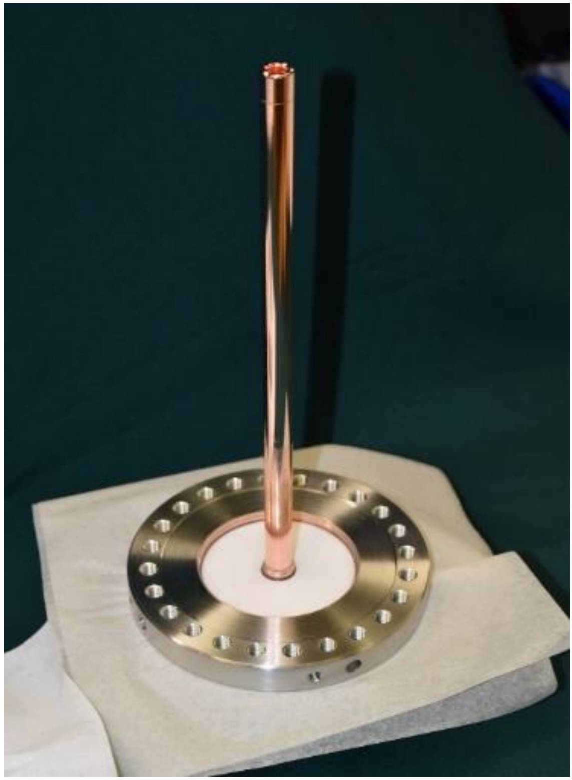
A Solution

- *Mitigate charge accumulation on RF windows by using a conductive ceramic that avoids the need for complicated geometry*

- The challenging goal of this project is to develop a ceramic material with a finite DC electrical conductivity and low loss tangent that can be incorporated into high power couplers

- The main innovation of the proposed approach is the following: a new low-loss microwave ceramic material with 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 for high efficiency RF power transmission.



Phase II Accomplishments

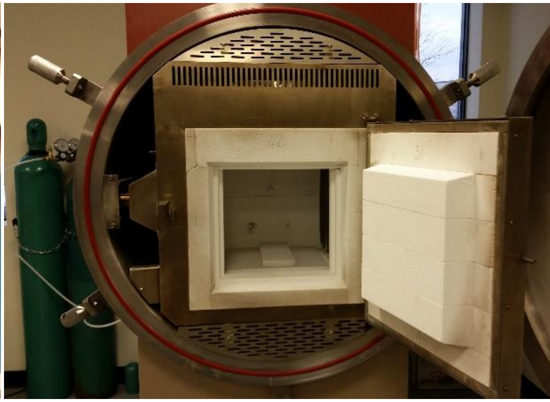
- Fabricated ceramic samples consisting of MgO-TiO_2 system (MgTi) compounds with the decreased resistivity 2-3 orders in the range 10^8 -10^9 Ω·m,
- Developed a method for controlling the bulk and surface conductivity of the new MgTi ceramic
- Conducted a beam test of the discharging properties of the MgTi ceramic components using Euclid's linear accelerator DC gun
- Collaborated with JLab and Fermilab on design and fabrication method for their high-power windows
- Fabricated 12 MgTi ceramic components for 650 MHz & 1.3 GHz high power RF windows; Tested the electrical properties

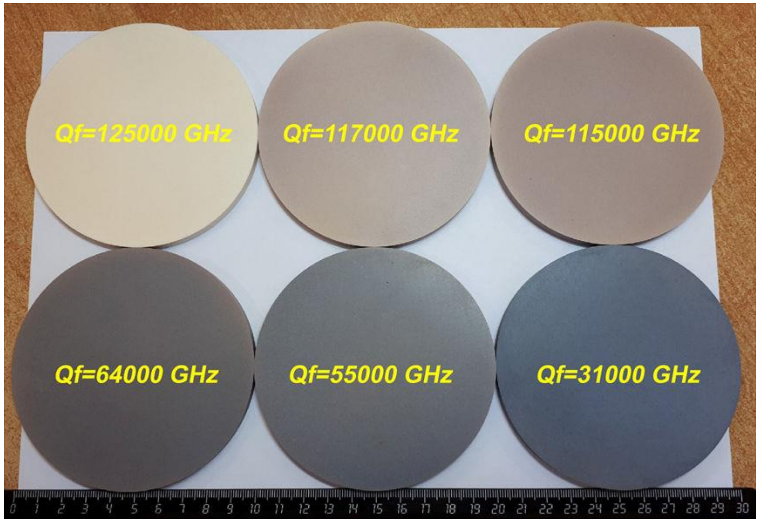
Phase IIA Tasks

- **Task 1.** Formalize window production and coupler brazing process
- **Task 2.** Produce additional RF couplers of varying conductivity for high power testing
- **Task 3.** Perform high power tests at JLab and Fermilab
- **Task 4.** Design, fabricate, and test a coupler utilizing a conductive ceramic window for the EIC
- **Task 5.** Design, fabricate, and test a coupler utilizing a conductive ceramic window for CERN
- **Task 6.** Transfer this technology to the production of normal conducting RF windows
- **Task 7.** Preparation of final report

Fabrication and Sintering of MgTi 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 in Phase I





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

tan δ at 650 MHz

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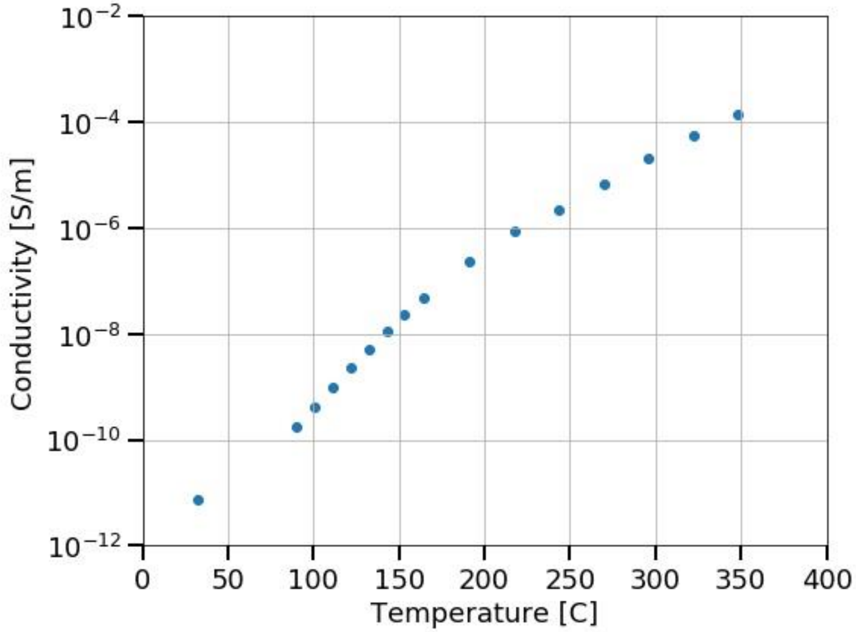
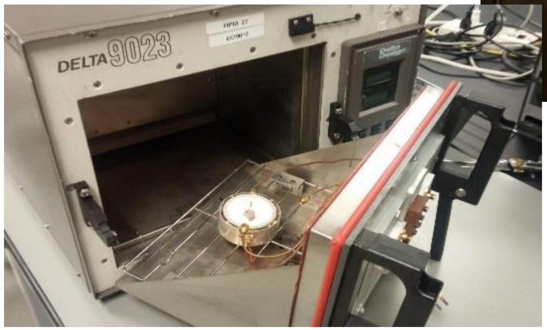
Temperature Dependence

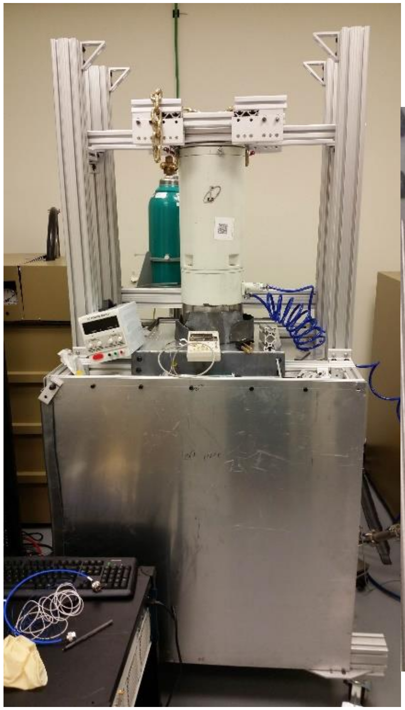
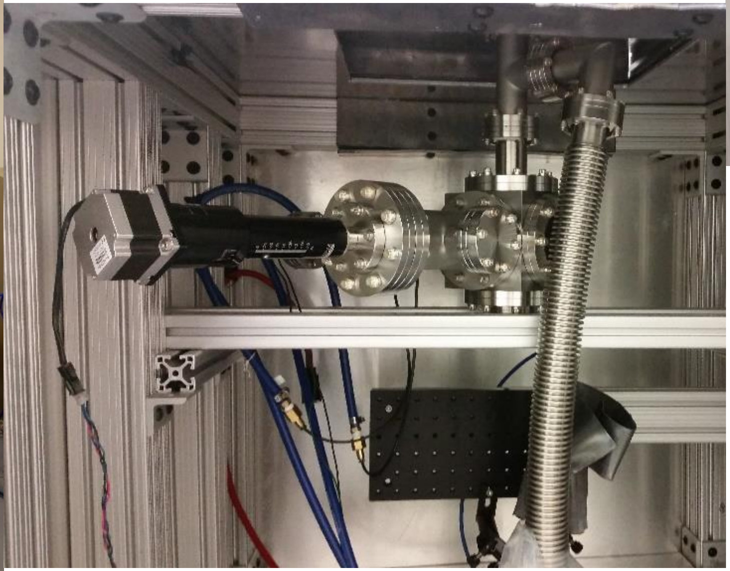
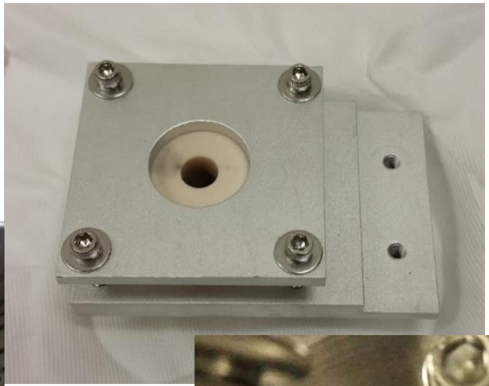
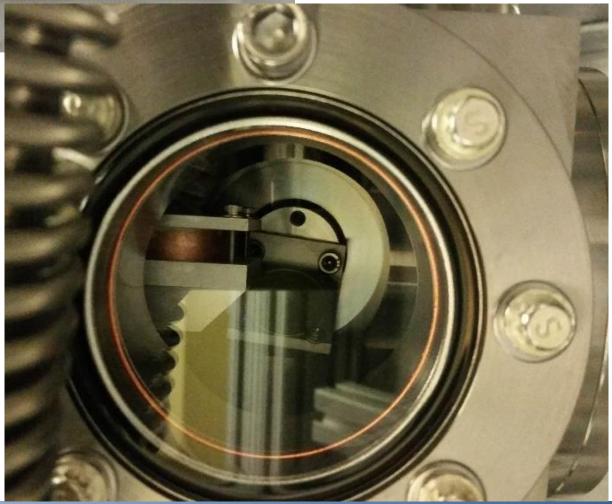
- Conductivity and loss tangent measured over wide temperature range
- Conductivity increased >100x between room temperature and 100°C
- Loss tangent decreased only 20%
- *Natural benefit of temperature rise during operation is increased conductivity*





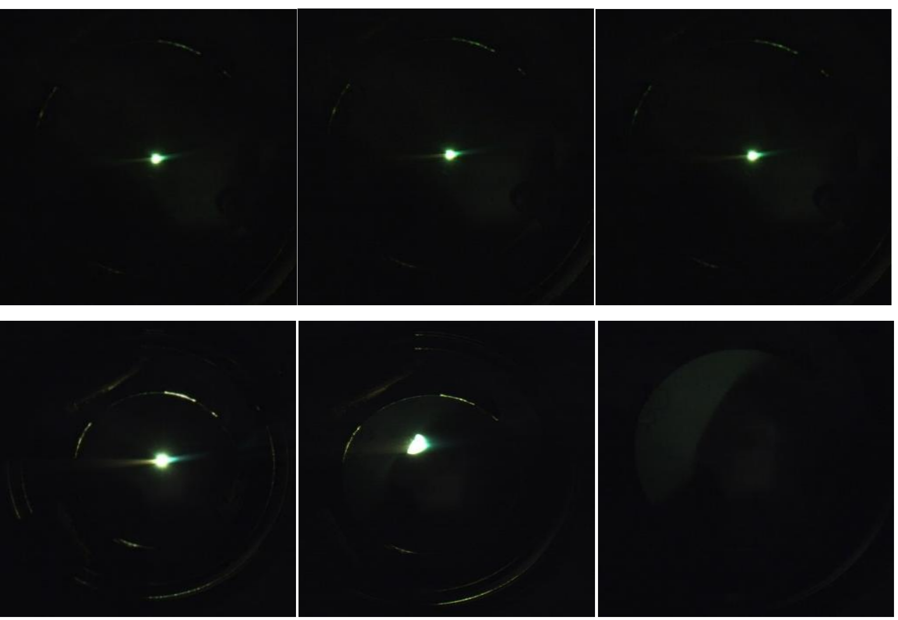
Beam Charging Test of Conductive Ceramic

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

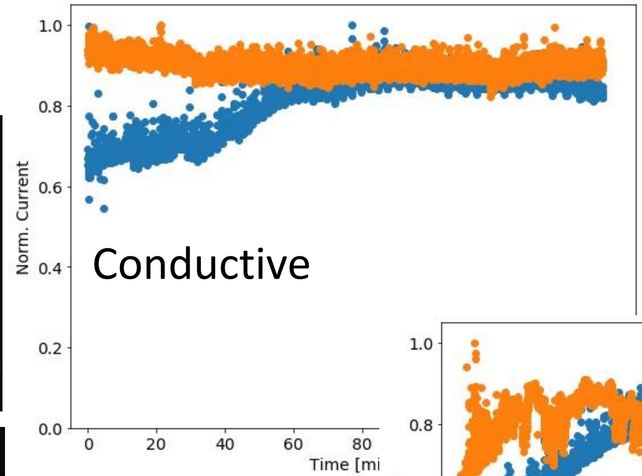





Beam Charging Results

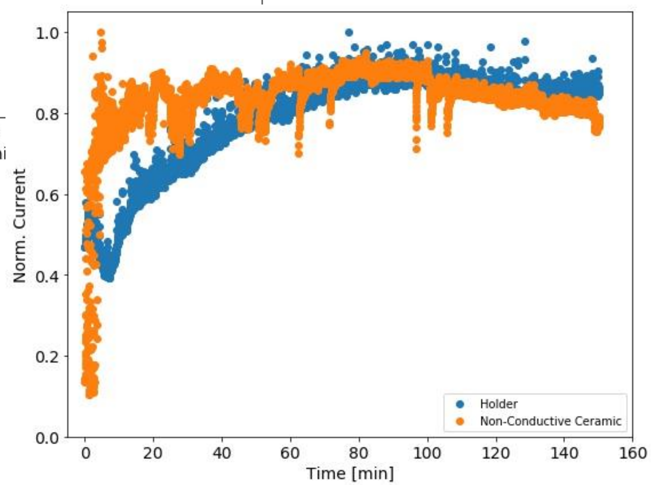
- Ceramics subject to DC electron beam for 2.5 hours
- *Conductive ceramic effectively discharges DC electron beam directly impinging on surface*



30 sec 60 sec 90 sec

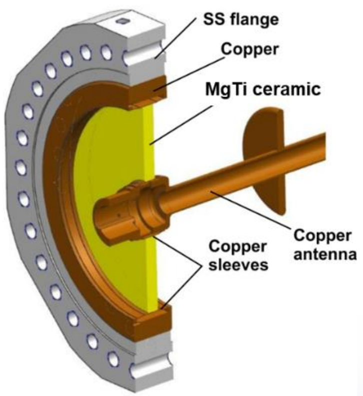


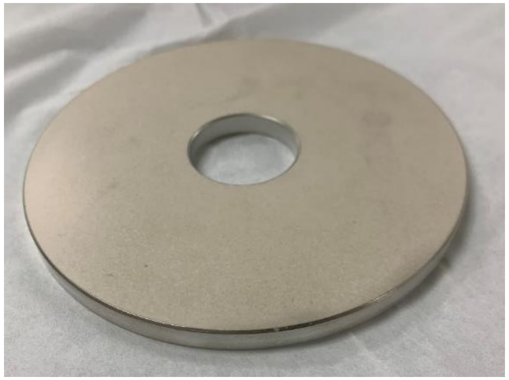
Non-conductive

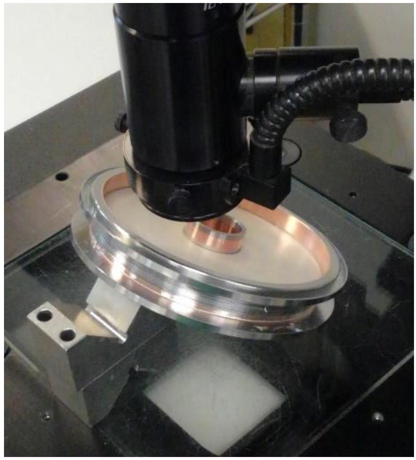


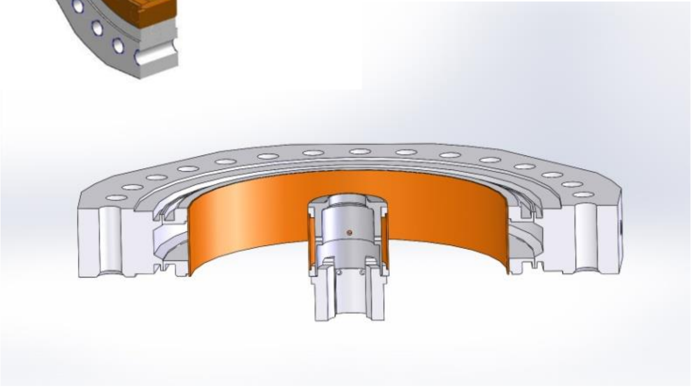
Brazing Technology Development – I

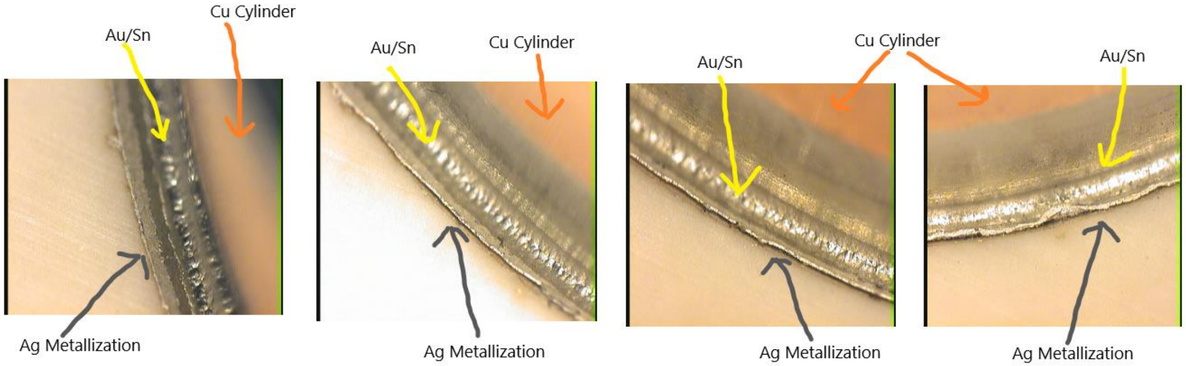
- High temperature (≥800°C) brazing results in poor window performance
- Low temperature (350°C) braze with Ag metallized ceramic and Au-Sn alloy attempted
  - Inner braze joint leaked; Ag pulled back from ceramic during cooldown







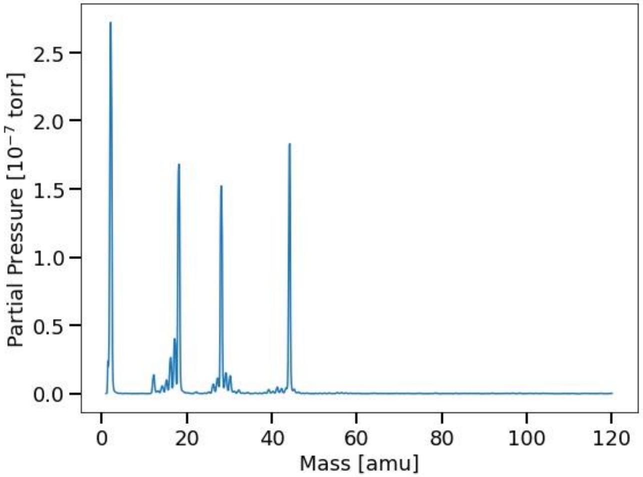




Brazing Technology Development – II

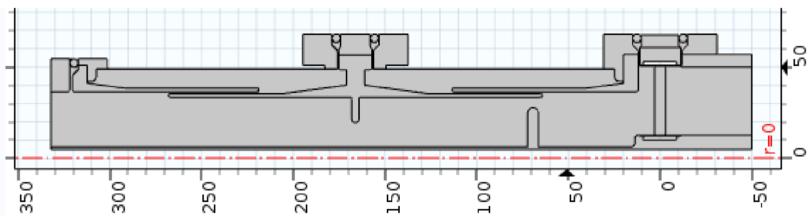
- Alternative brazing approaches underway:
  - Lower temperature ABA (≈740°C) using windows recovered from first braze iteration
  - Cu sputtering/electroplating
  - S-Bond solder, 250°C, Sn-Ag-Ti-Mg
    - First bonding attempt vacuum leak-tight
    - No detectable contaminants in RGA scan at 3×10^{-8} torr

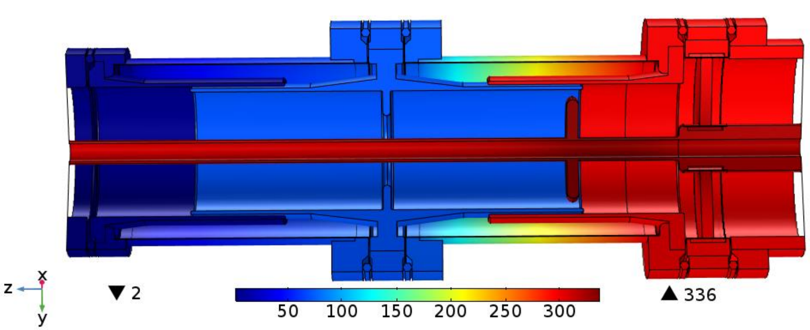


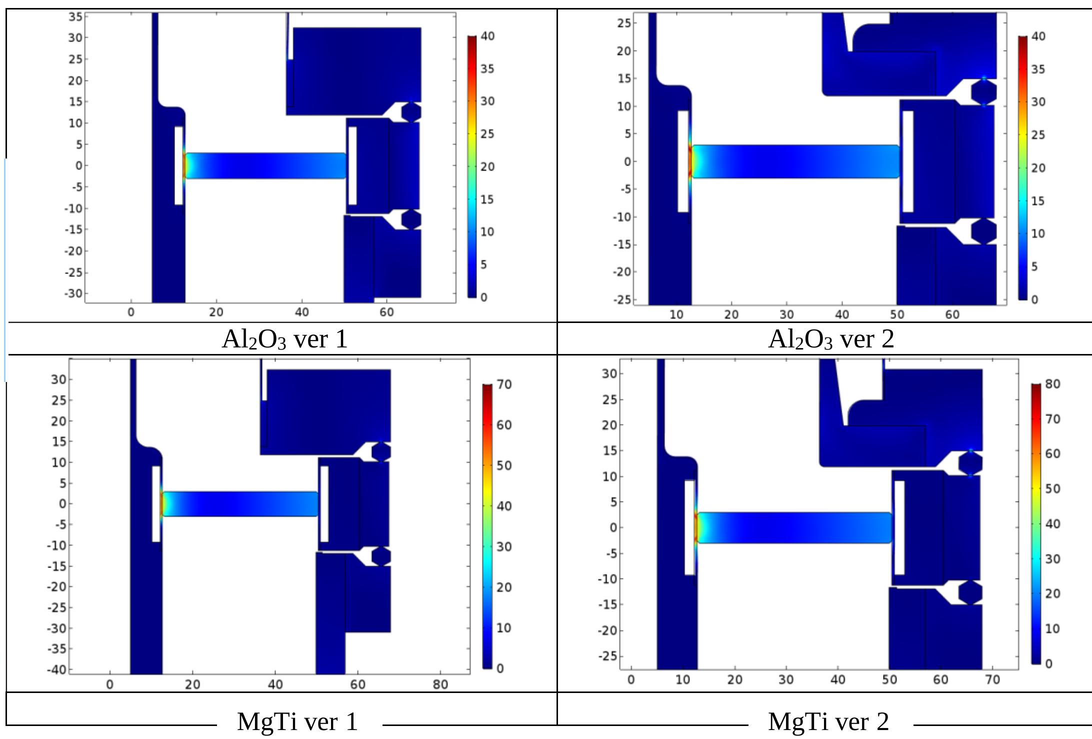


Electrodynamic and Thermomechanical Modelling

- Thermomechanical simulations (100 kW CW input power) show slightly worse performance than alumina, but still within acceptable range

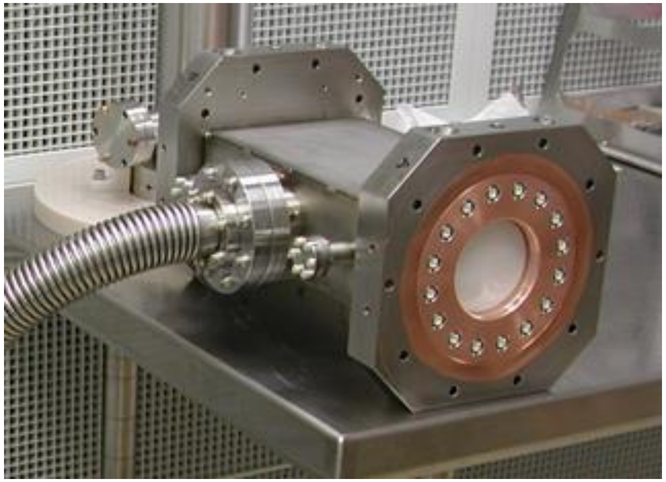


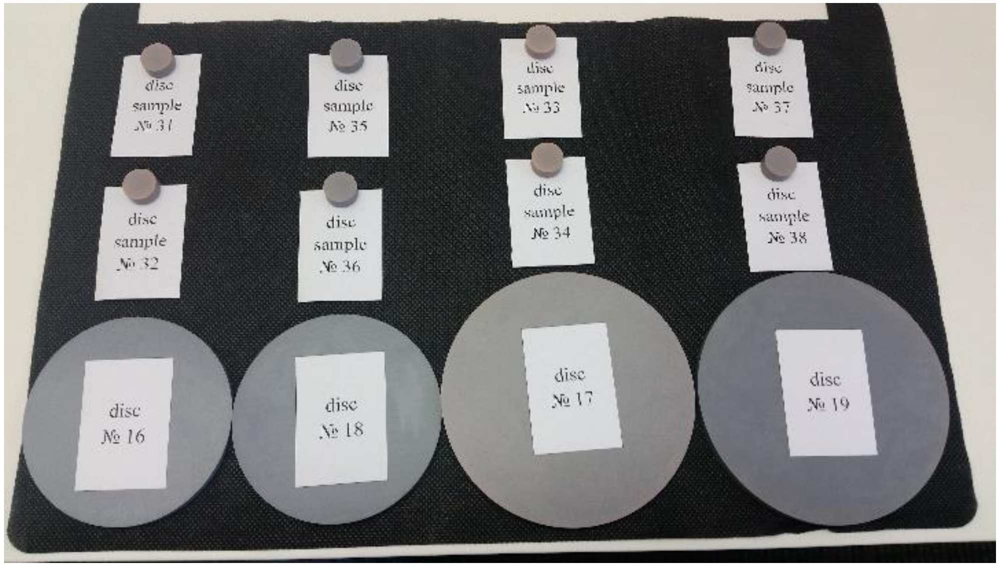


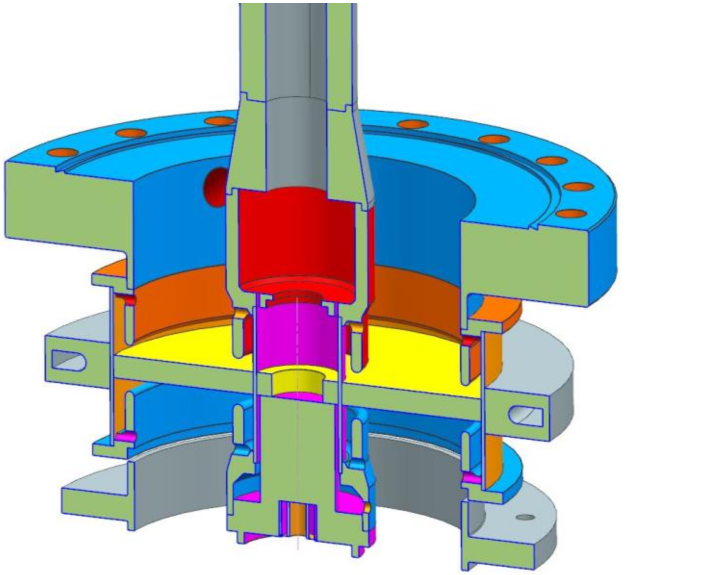


Windows for JLab

- Two conductive ceramic windows provided to JLab for brazing into waveguide assembly
  - Significant delay due to pandemic
- High power test stand fabrication and assembly begun
- Preliminary design for EIC coaxial coupler exists







High-Power Test Stand at FNAL

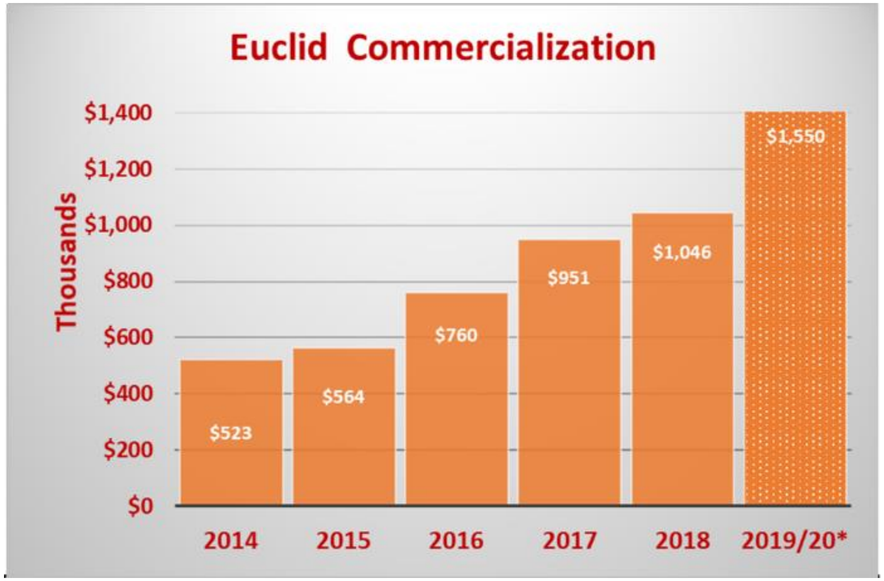
- High-power test stands at FNAL under construction
  - Significant delays due to pandemic and confiscation of components for PIP-II
  - Most components in hand
  - Limited personnel allowed on site impacting preparation and assembly

Summary

- Accomplishments during Phase II:
  - Procedure determined for producing MgTi ceramic with 10^{-9}-10^{-8} S/m conductivity and tan $\delta \sim 10^{-5}$ at 650 MHz
  - Windows to be tested at 650 MHz & 1.3 GHz fabricated
  - One brazing process identified and tested; several more in development
  - Electrodynamic and thermomechanical simulations show MgTi performance similar to Alumina
  - Direct beam charging experiment shows conductive ceramic capable of effectively discharging electrons
- In progress / planned during Phase IIA:
  - Assembly of high-power test stands at JLab and FNAL
  - Brazing and high-power testing of JLab and FNAL windows
  - Design, fabrication and testing of RF windows for EIC, CERN, and normal conducting applications

Commercialization

- Two periods
  - 2003-2014 – Spinoff from Argonne Wakefield Accelerator group (DOE SBIR)
  - 2014-Present – Commercialization of advanced accelerating technologies and TEM



- Euclid currently holds 15 patents, with two pending
- Fast Ferroelectric Based Tuner (Phase II 2016 Nuclear Physics)
- Tuner purchased, installed and tested in 2019 by CERN, SRF’2019 invited talk by CERN
- 80MHz – new project !

- Notable contracts
  - NIST (2016-2018) – “Time Resolved TEM”
  - GWU (2017) – “UNCD Emission Chamber”
  - UMD (2016-2018) – “Single Crystal Diamond FET”
  - SJTU (2016-2019) – “Photoinjector”, “Thermionic Gun”

- JEOL, Inc. installation at the US facility, then BNL and NIST

Acknowledgements

- DOE, Office of Science Nuclear Physics
  - Michelle Shinn, Manouchehr Farkhondeh

- Our collaborators
  - JLab: Robert Rimmer, Jiquan Guo, Frank Marhauser
  - Fermilab: Sergey Kazakov, Nikolay Solyak
  - CERN: Erk Jensen, Eric Montesinos
  - Penn State University: Michael Lanagan, Steve Perini
  - Ceramic Ltd.: Elizabeta Nenasheva