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

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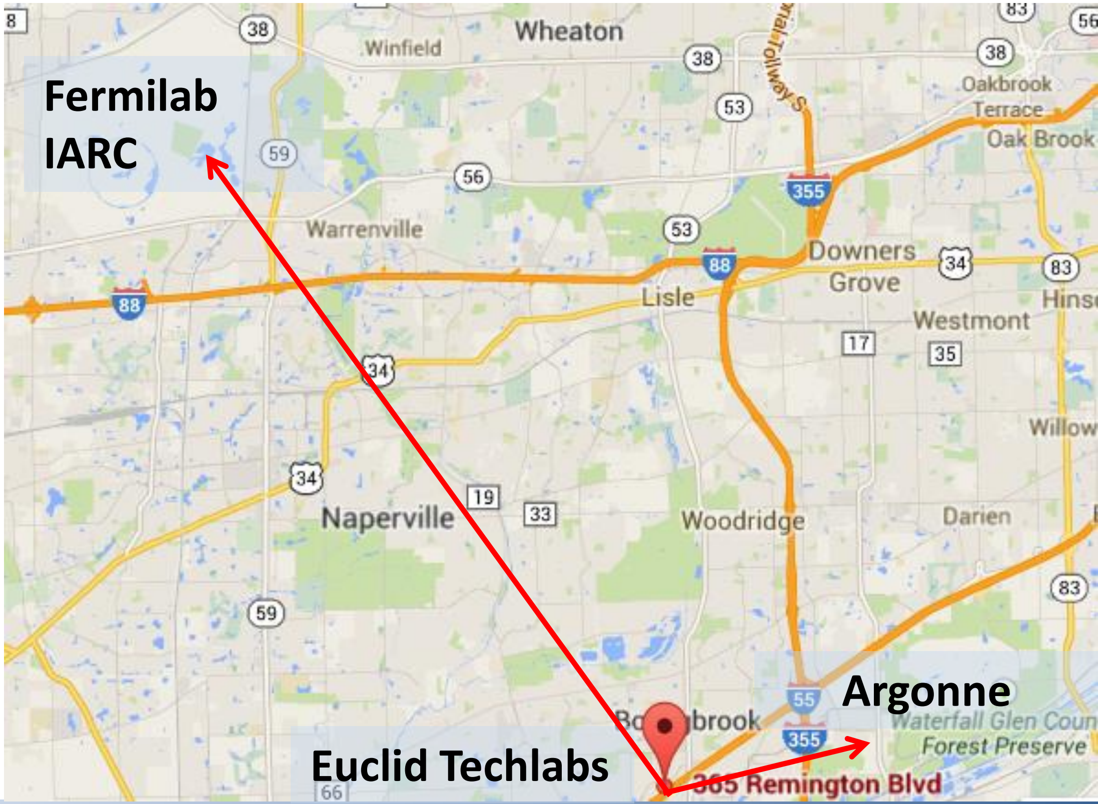
On behalf of Euclid Techlabs/JLab/FNAL/PSU collaboration

Department of Energy 2021 SBIR/STTR Exchange Meeting

Euclid Techlabs

Euclid TechLabs LLC, founded in 2003, specializes 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 Beltsville, MD (lab and HQ)
- Tight collaborations with National Labs: ANL, BNL, FNAL, LANL, LBNL.
- Actively participate in Universities research programs: Caltech, Columbia, Duke, Penn State, UMD, IIT.



Lab Facility in Bolingbrook, IL

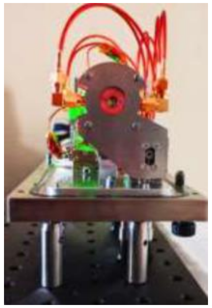
- Compact electron accelerator test facility (bunker)
- Time resolved TEM beamline
- Clean room/magnetron sputtering (TiN, copper, dielectrics)
- Field Emission cathode DC test stand
- Femtosecond laser
- RF/microwave/THz lab
- 3,00 sq.ft. – office, 5,000 sq.ft.-lab

Lab Facility in Beltsville, MD

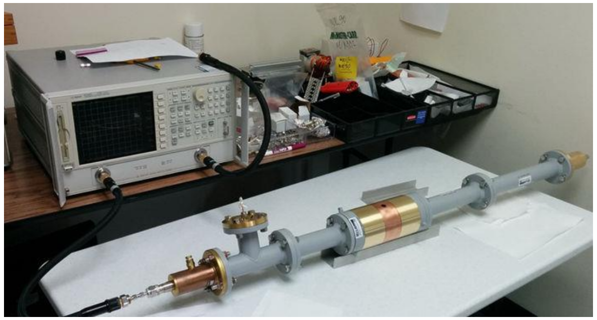
- Diamond growth lab
- HPHT and CVD reactors
- Photocathode lab
- 1,800 sq.ft. – office
- 5,000 sq.ft. - lab

Key Euclid Technologies

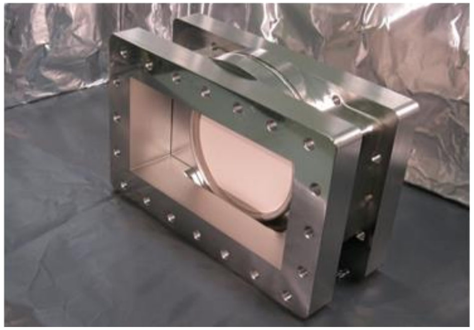
- Ultra-compact low energy accelerator (dielectric based)
- Stroboscopic pulser for Transmission Electron Microscope
- Electron guns for accelerators: Photo-, thermo-, field emission (FE)- and SRF guns
- Ferroelectric based fast tuner
- UNC Diamond based FE and photo cathodes
- Accelerator components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



5 GHz kicker for TEM, BES/NIST



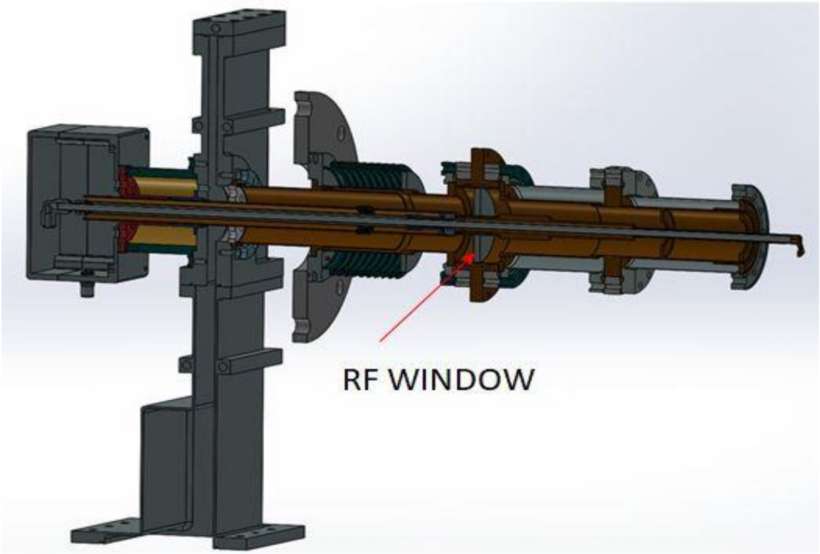
Fast ferroelectric 400 MHz tuner successfully tested at CERN

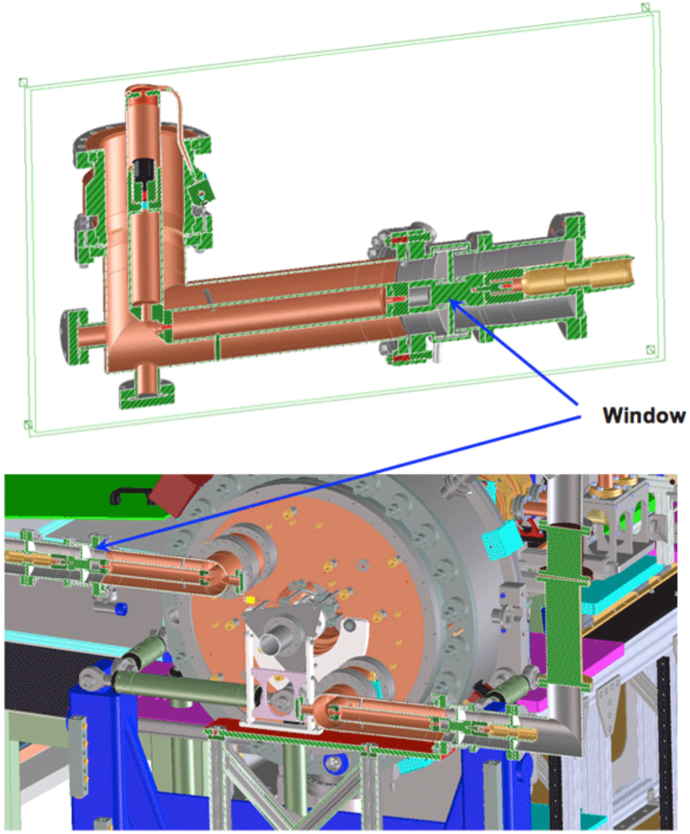


L-band RF window for AWA ANL

Motivation

- High power RF couplers connect RF transmission lines to SRF cavities, providing RF power and vacuum barrier for the beam vacuum using ceramic windows.
- Coupler RF windows experience breakdown (arcing and surface flashover) at much lower voltages than comparable insulators in DC fields. Major reasons for window failure include charging from the "triple junction“, multipacting and electron halo.



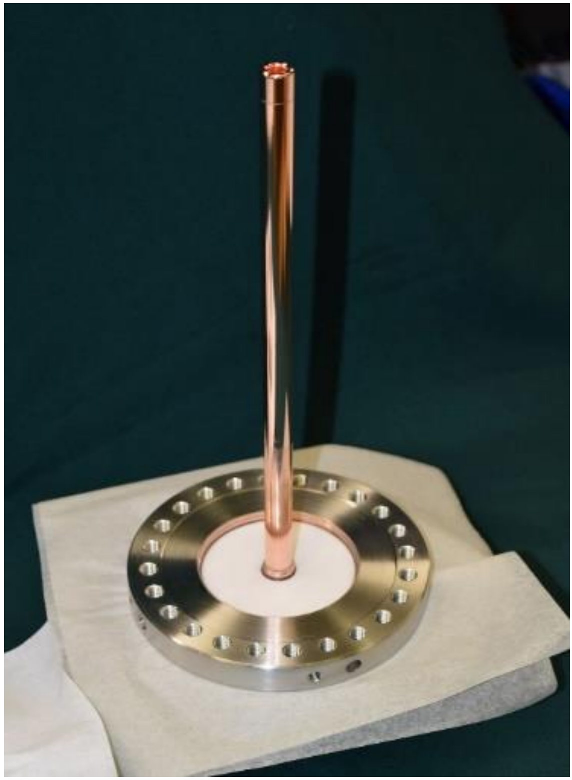


Example: the Advanced Photoinjector Experiment’s VHF gun in the LCLS-II injector. Window broke: charging because of the direct line of sight for the beam.
A new 90-degree coupler will keep ceramic vacuum window out of harm’s way

A Solution

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

- 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 accumulated charge. The low loss tangent will allow for high efficiency RF power transmission.*

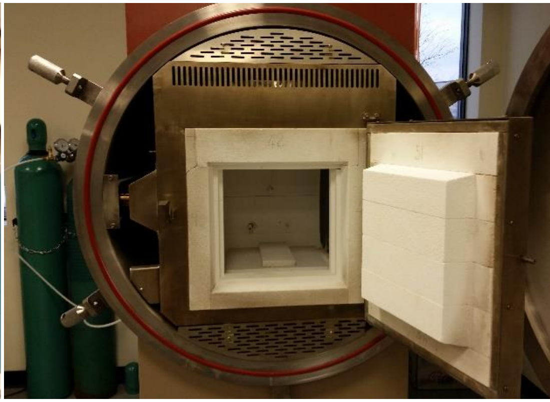


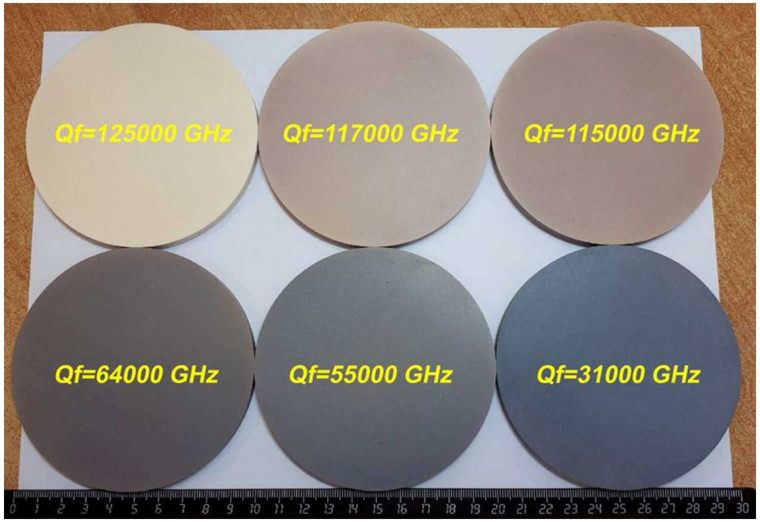
In Phase II of the project:

- Fabricated ceramic samples with controlled resistivity 2-3 orders lower in the range 10^8 -10^9 Ω·m,
- Conducted a beam test of the discharging properties of the ceramic components using Euclid's TEM DC gun
- Collaborated with JLab and Fermilab on the design and fabrication method for their high-power windows
- Fabricated 12 ceramic components for 650 MHz & 1.5 GHz high power RF windows; Tested the electrical properties

Fabrication and Sintering of Conductive Ceramic

- Euclid fabricated the 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

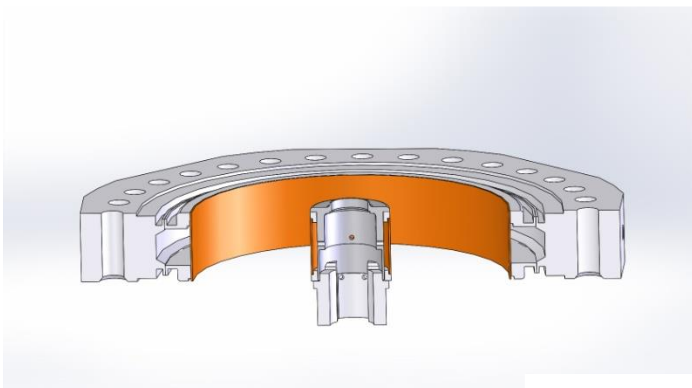
tan δ at 650 MHz

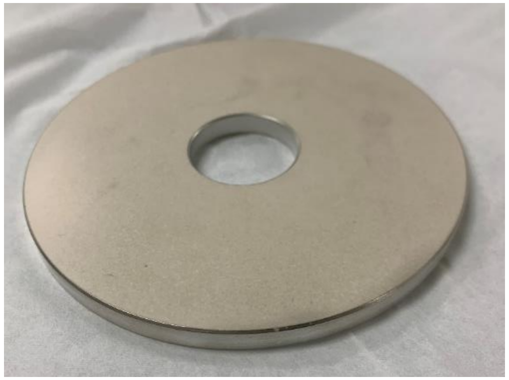
Key Accomplishments

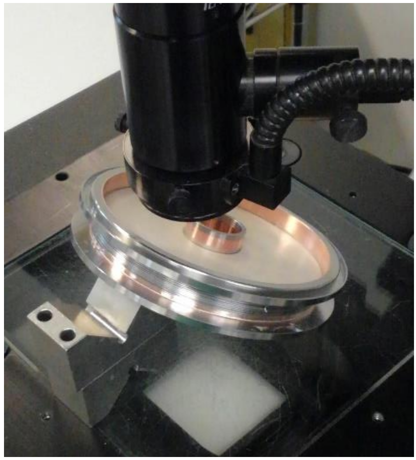
- Significant progress on finalizing the long term brazing process
  - Dependent on vendors and national labs
  - Started process of acquiring equipment for in-house brazing
  - Our ceramic requires modification of brazing process established for alumina
- Several windows brazed
- Post-braze sintering can be done in house
- First high power test complete

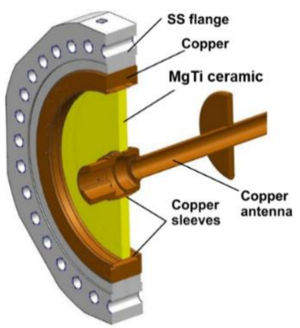
Coaxial Window Brazing Technology Development – I

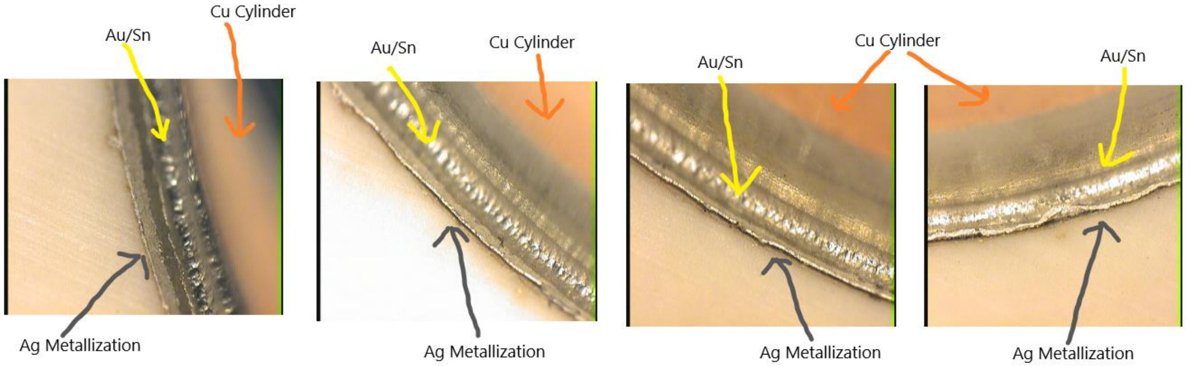
- Two Ag metallized windows brazed with non-active Au-Sn alloy at 350°C
- Inner braze joint leaked; Ag pulled back from ceramic during cooldown





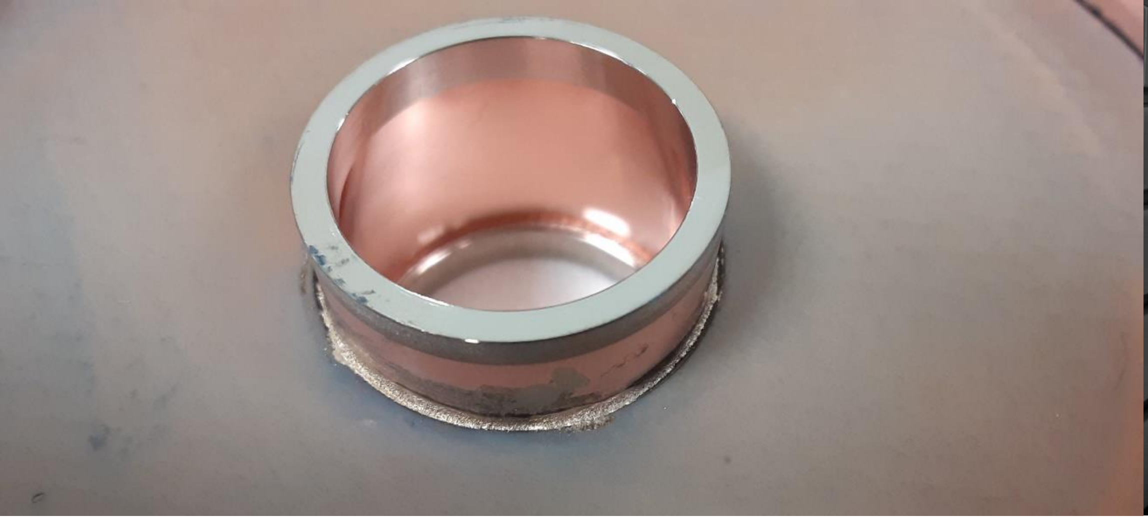






Coaxial Window Brazing Technology Development – II

- Second set of windows brazed using an Incusil ABA at 750°C
  - Both windows leaked on ID joint
- 1st repair attempt improved leak rate
- 2nd repair attempt did not improve leak rate
  - Signs of cracking near joint

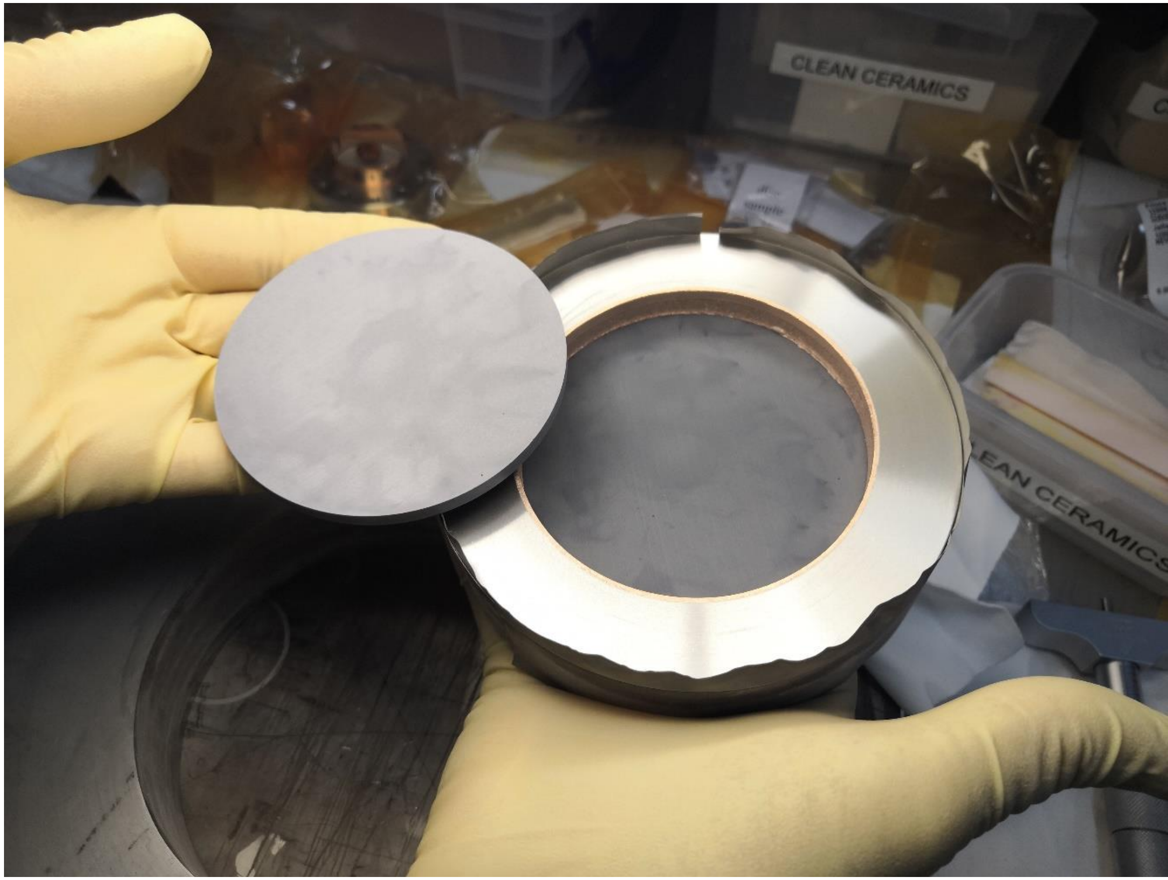


Coaxial Window Brazing Technology Development – III

- Outer braze joint seals reasonably well; problem on interior joint
- CTE mismatch between copper (16.8×10^{-6} 1/°C) and ceramic (~10×10^{-6} 1/°C) results in faster copper contraction during cooldown
- Two new sets of window assemblies in progress in parallel
- Route 1: Solder windows to pre-brazed metal assemblies using Sn-Ag-Ti-Mg alloy
  - Hermetic seal and no vacuum contamination already demonstrated on coupon
  - SS flange in fabrication; all other components in hand
- Route 2: Braze windows to copper-tungsten sleeves (CTE 8-10×10^{-6} 1/°C)
  - CuW sleeves to be ordered; all other components in hand

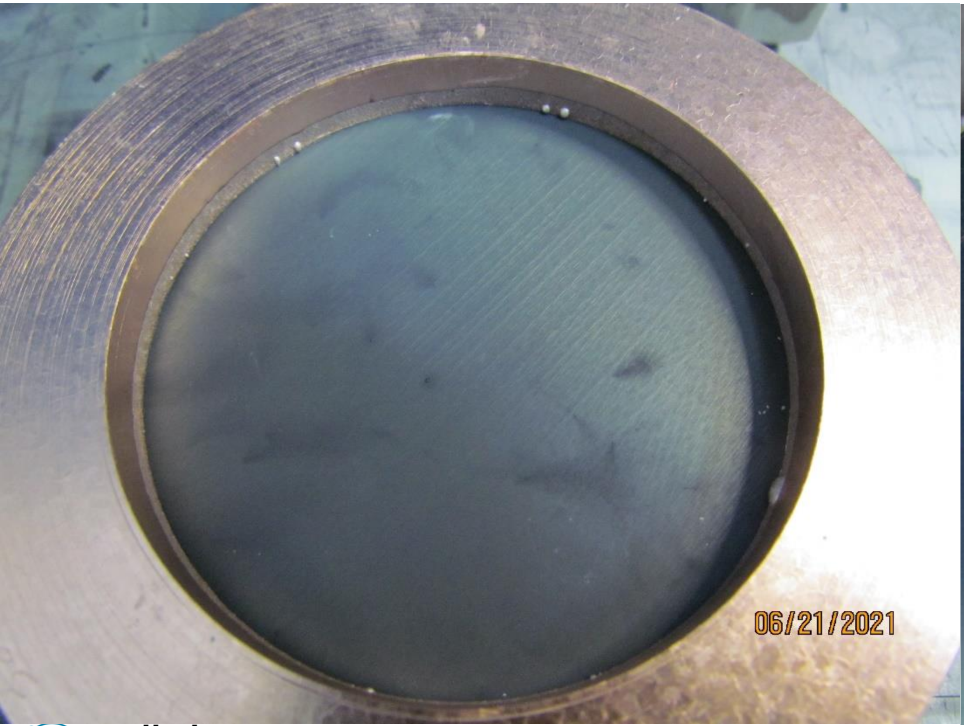
Waveguide Window Brazing Technology Development – I

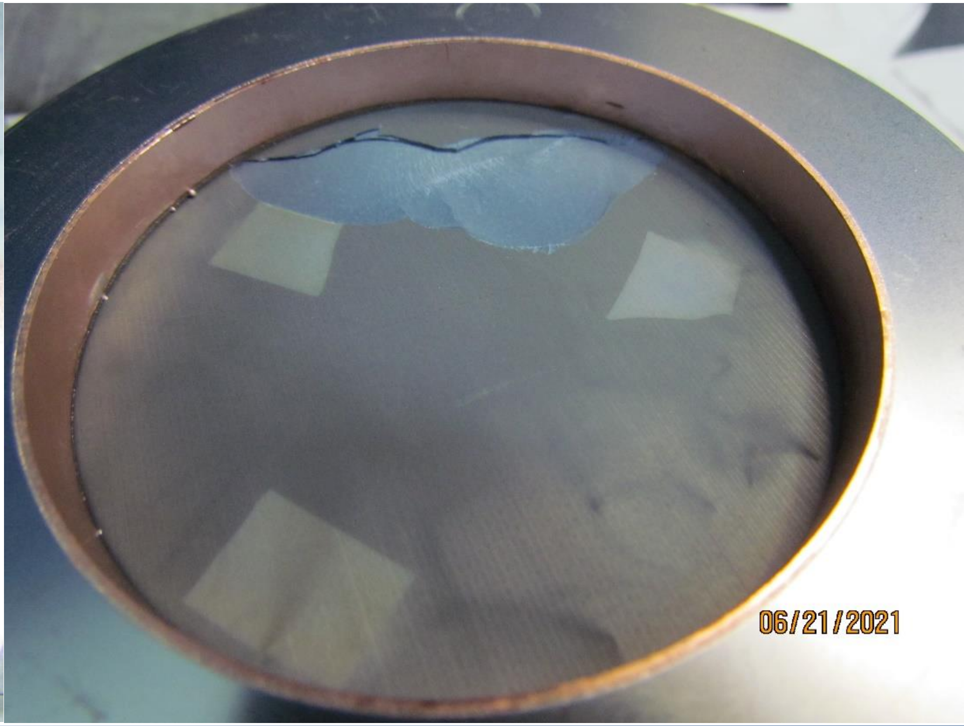
- One window brazed with Ticusil active alloy at 950°C
- Imperfect wetting resulted in leak
- Repair attempt delayed in favor of high power testing



Waveguide Window Brazing Technology Development – II

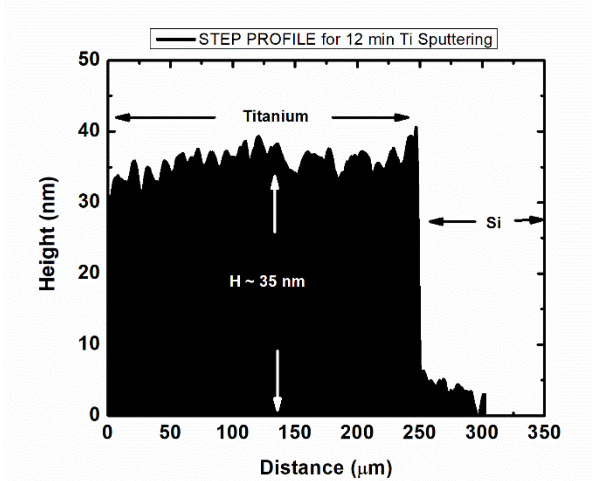
- Second window brazed with Ticusil active alloy at 1010°C
- Window cracked during brazing
  - 0.003" (0.076 mm) smaller gap between frame and ceramic than first window
  - Subsequent waveguide windows will have chamfer on edge to alleviate stress

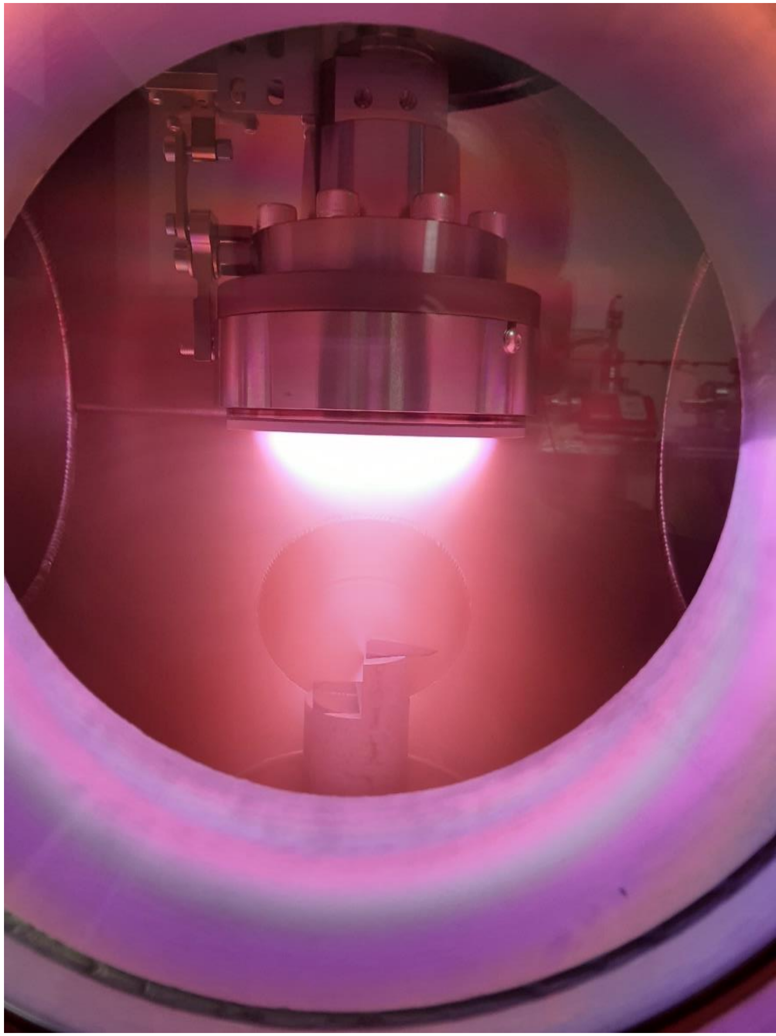




Brazing Technology Development

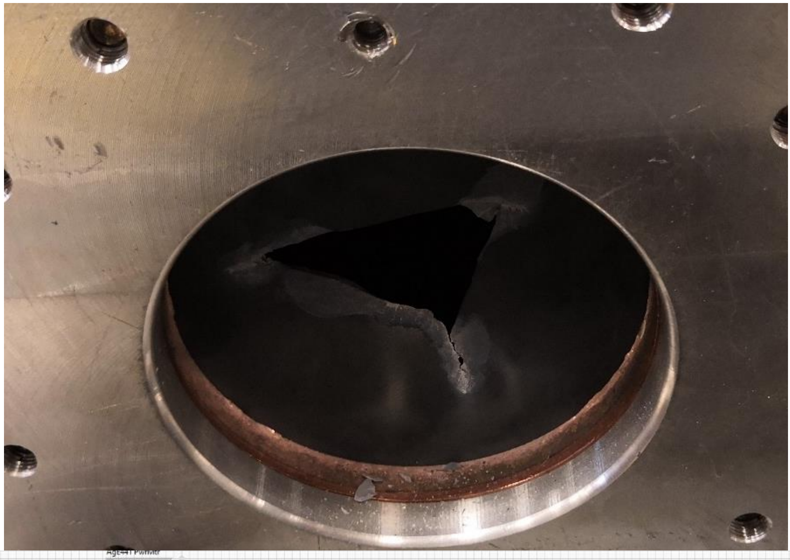
- Most metallization techniques require incompatible temperature or gas environment for this ceramic
- Sputtering is an alternative
  - Typically 50-250 nm titanium deposited first
  - 0.25-1.0 µm second layer deposited on top; silver and copper will be tried
- Coupon sputtering underway

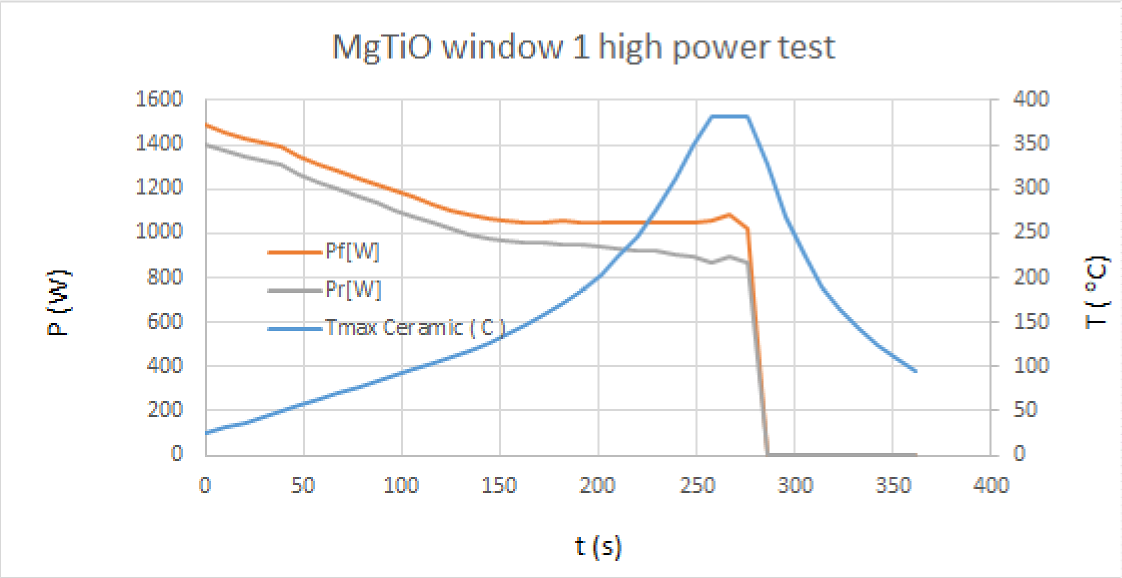


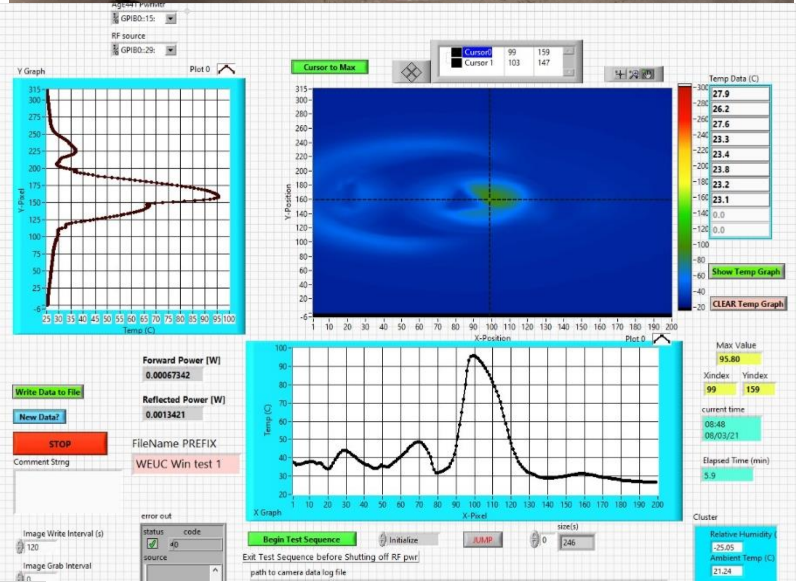


High Power Test at JLab – I

- Initial 1.5 kW CW power, down to 1.0 kW
- Drastic increase in window temperature led to failure
  - 25°C water cooled frame
- No signs of arcing



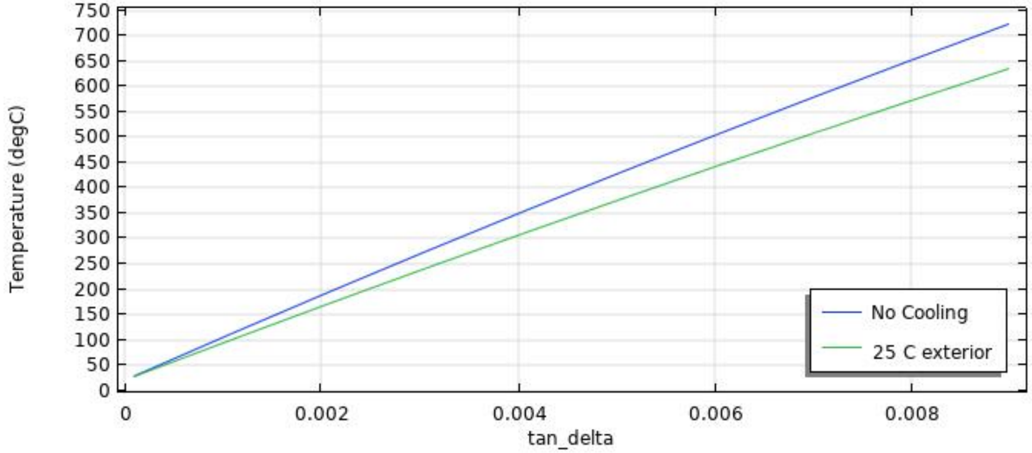


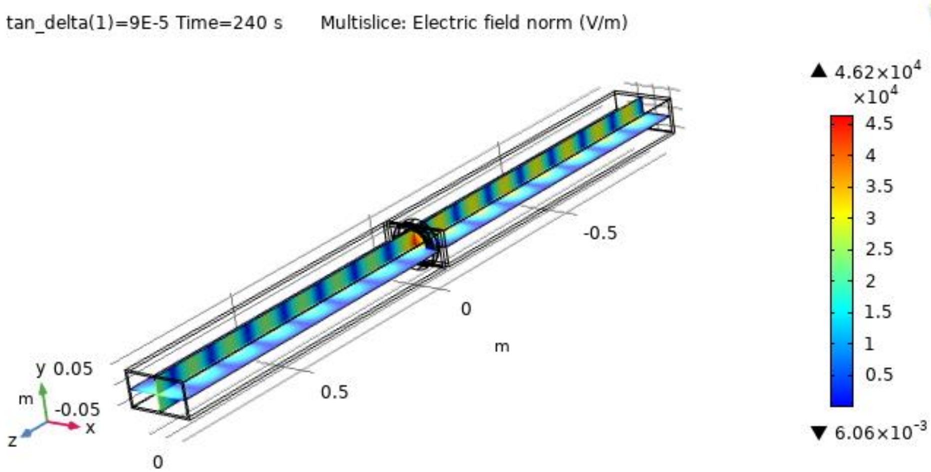


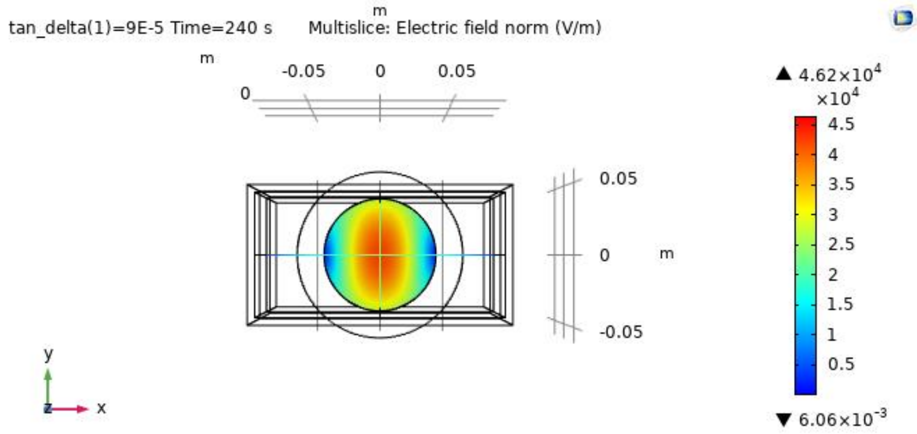
High Power Test at JLab – II

- Thermal simulation indicates ceramic loss tangent closer to 4×10^{-4}
  - Closer to predicted value based on color and coupon measurement
- Puts constraint on upper bound of conductivity & loss
- Next windows to be tested with lower loss & conductivity

- Post braze sintering

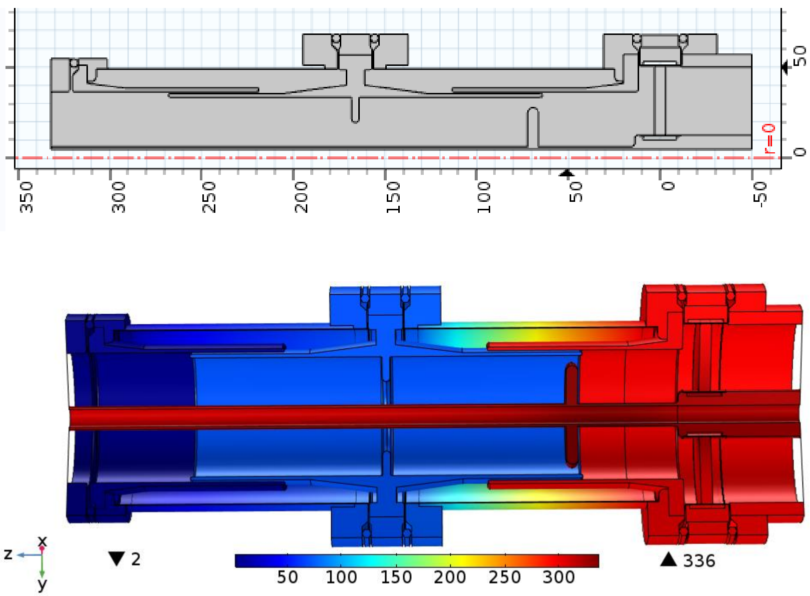


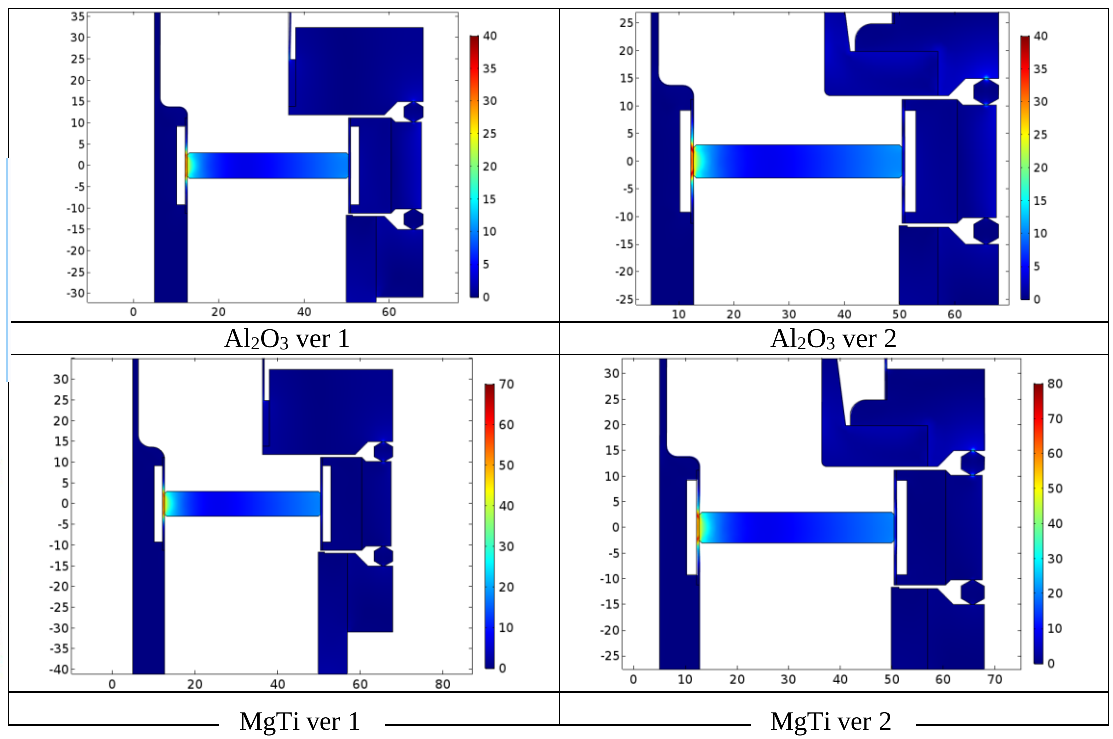




Coaxial Window Thermomechanical Modelling

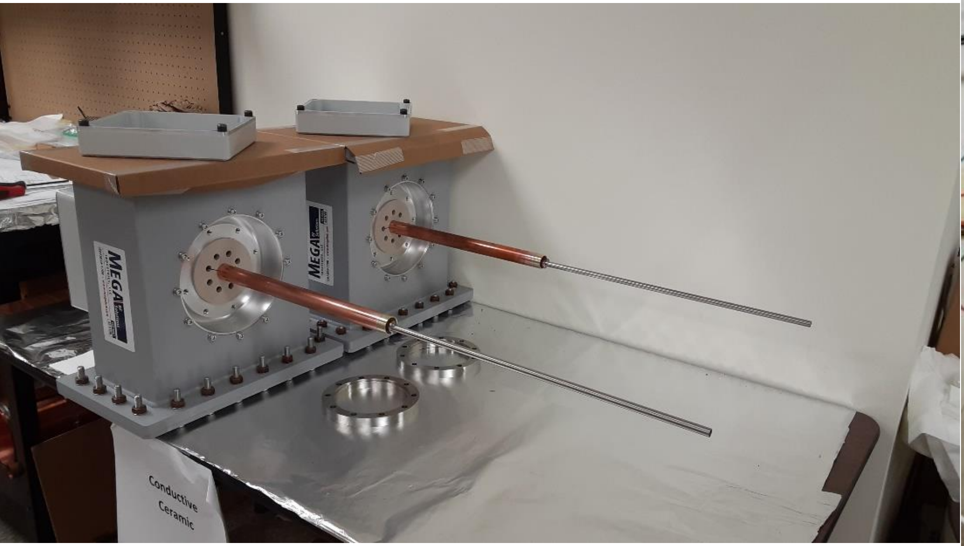
- Thermomechanical simulations (100 kW CW input power) show large conductivity ceramic performs similar to alumina
- Performance beats alumina for less conductive case





High Power Test Stand at FNAL

- All components of high power test stand at Fermilab in hand
- First high power test pending successful seal of coaxial window assemblies



Summary

- Accomplishments during Phase IIA:
  - Two sets of coaxial windows and two waveguide windows brazed
  - Strategies for ensuring hermetic seal for both coaxial and waveguide assemblies identified and in progress
  - High power test of waveguide window performed
    - Upper limit on conductivity/loss found
  - All components of coaxial window assembly test stand at Fermilab in hand; awaiting leak tight assemblies
- In progress / planned during Phase IIA:
  - Brazing and high-power testing of additional waveguide and coaxial window assemblies
  - Design & fabrication of RF window assemblies for EIC, CERN, and normal conducting applications

Acknowledgements

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  - Michelle Shinn, Manouchehr Farkhondeh

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