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

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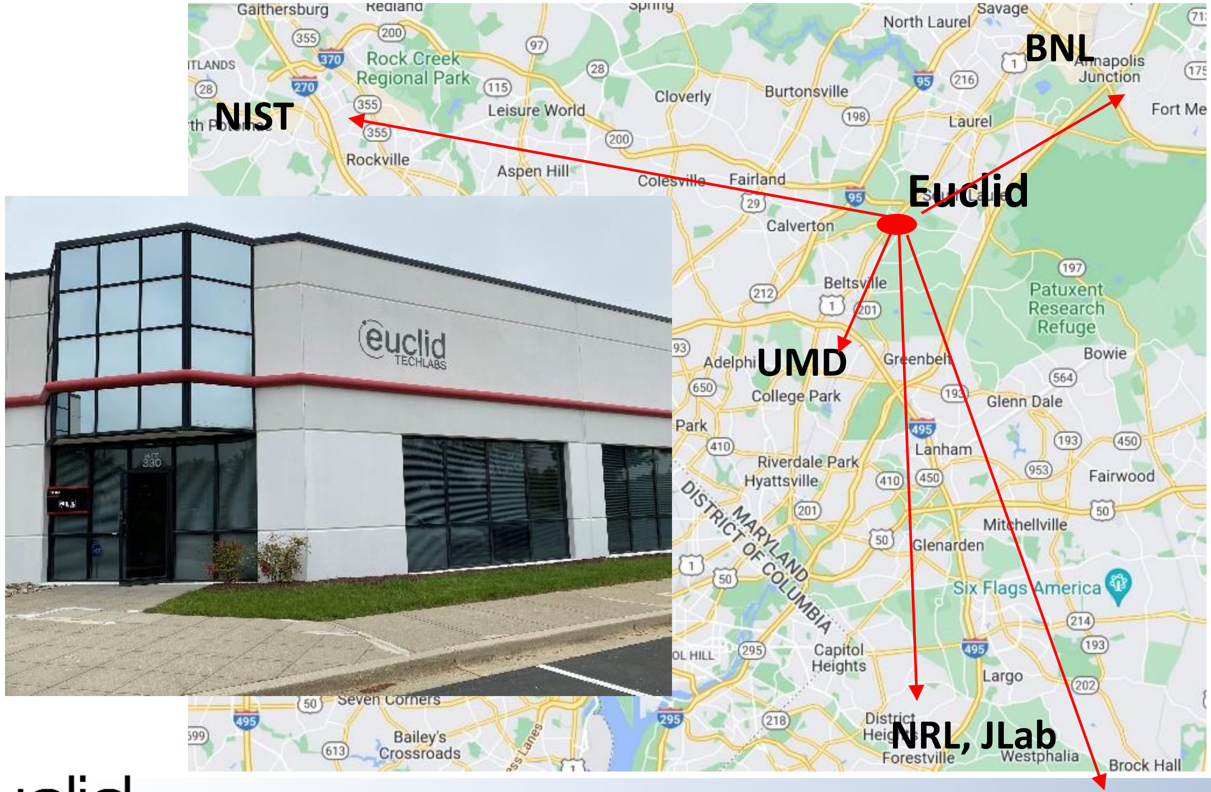
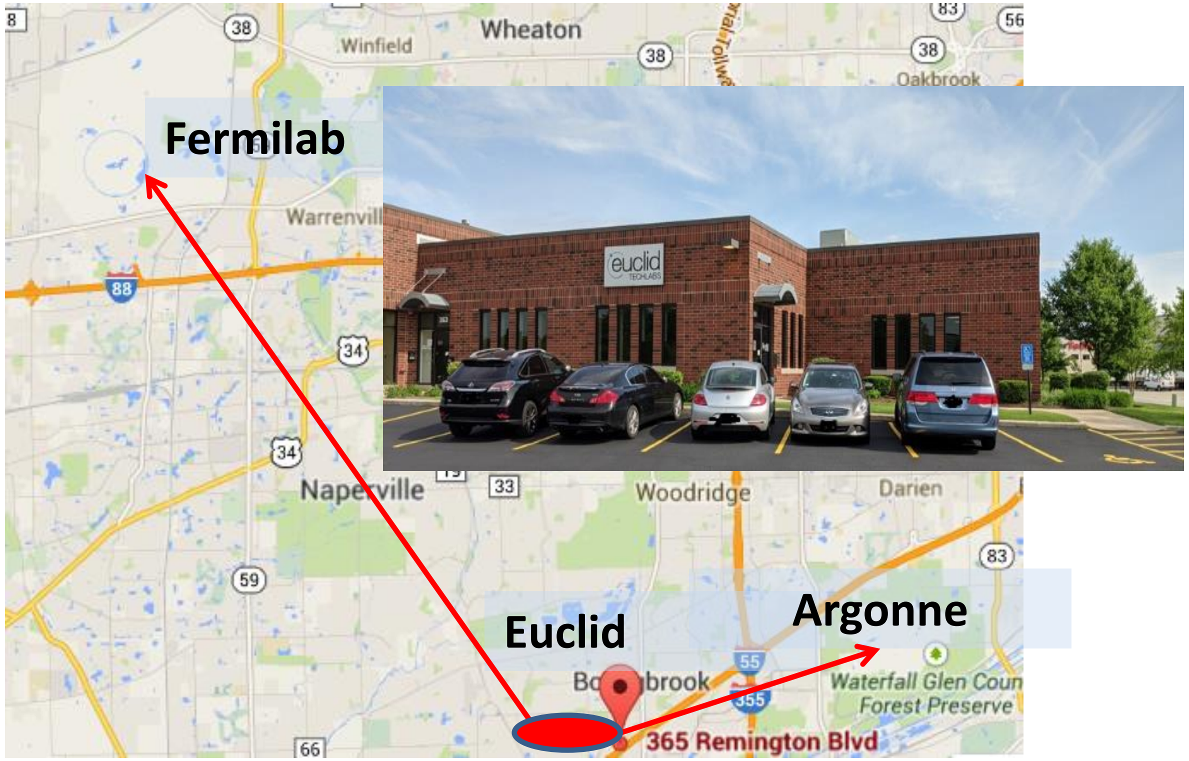
Outline

1. Euclid Techlabs background and capabilities
2. Motivation for low loss conductive ceramic windows
3. Review of work completed in Phase I & II
4. Phase IIA high-power test results
5. Summary

Euclid Techlabs

Euclid Techlabs, LLC is a research and development company specializing in linear particle accelerators, ultrafast electron microscopy, and advanced material technologies. 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; Present: 27 research staff (researchers, engineers, technicians) and 5 administrative. 16 PhDs in accelerator physics and material science. 2 labs: Bolingbrook, IL (accelerator R&D lab) and Beltsville, MD (material science lab). Long term collaborations with National Labs and Institutes: ANL, Fermilab, BNL, JLab, LBL, SLAC, LANL, NIST, NIU, IIT, etc.





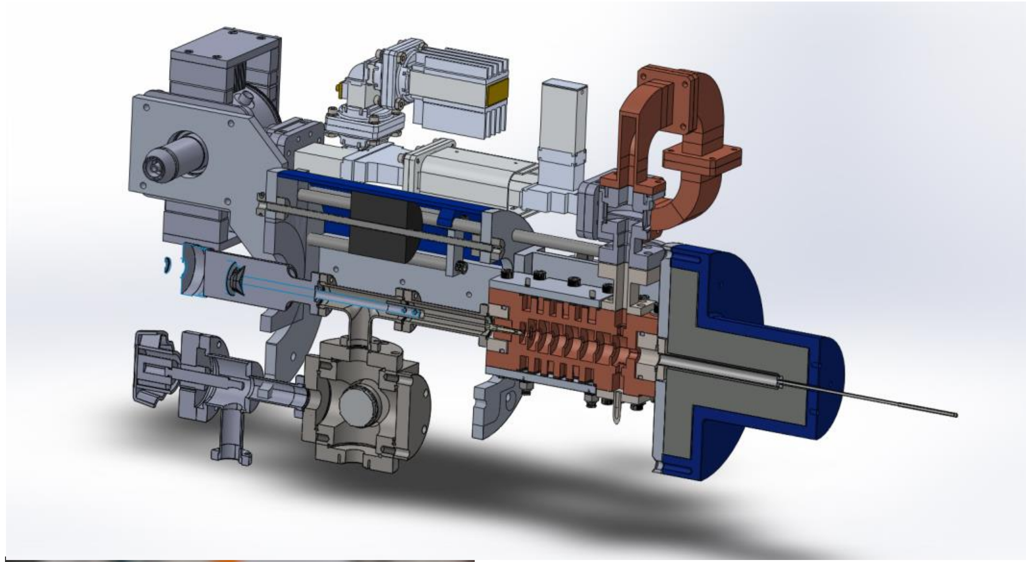
Products & Capabilities Snapshot

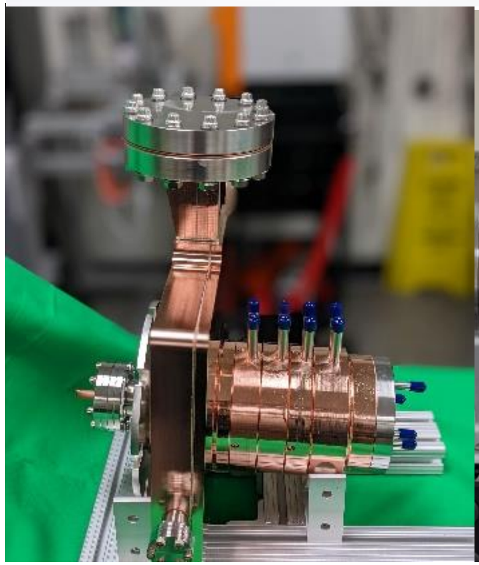
Products

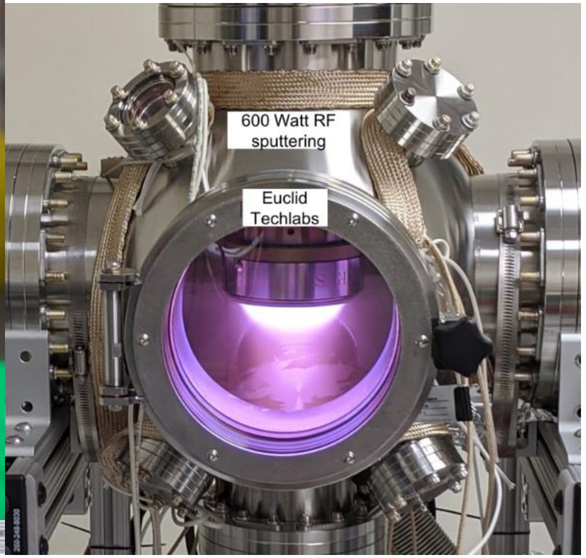
- UltraFast Pulser (UFP™) for TEM
- Compact Electronic Brachytherapy Device
- Low loss ceramics (linear and non-linear)
- Ultra-Nano Crystalline Diamond FE cathode
- L-band High Peak Current LINAC
- UHV L-band RF window
- BPM compact readout

Capabilities

- Femtosecond Laser Ablation System
- Thin Film Deposition Lab
- EM Testing Lab
- Radiation Shielding/Testing Lab
- Experimental electron beamlines

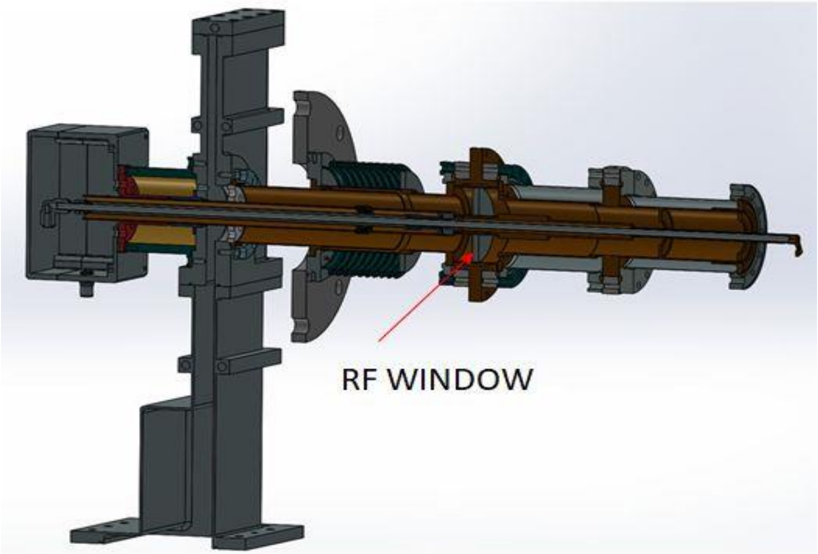


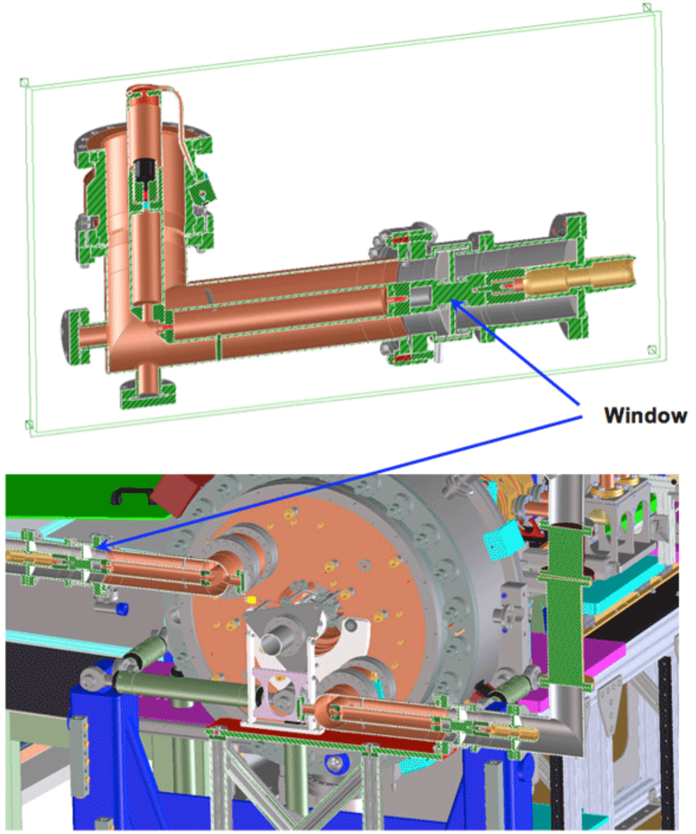




Motivation

- 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.

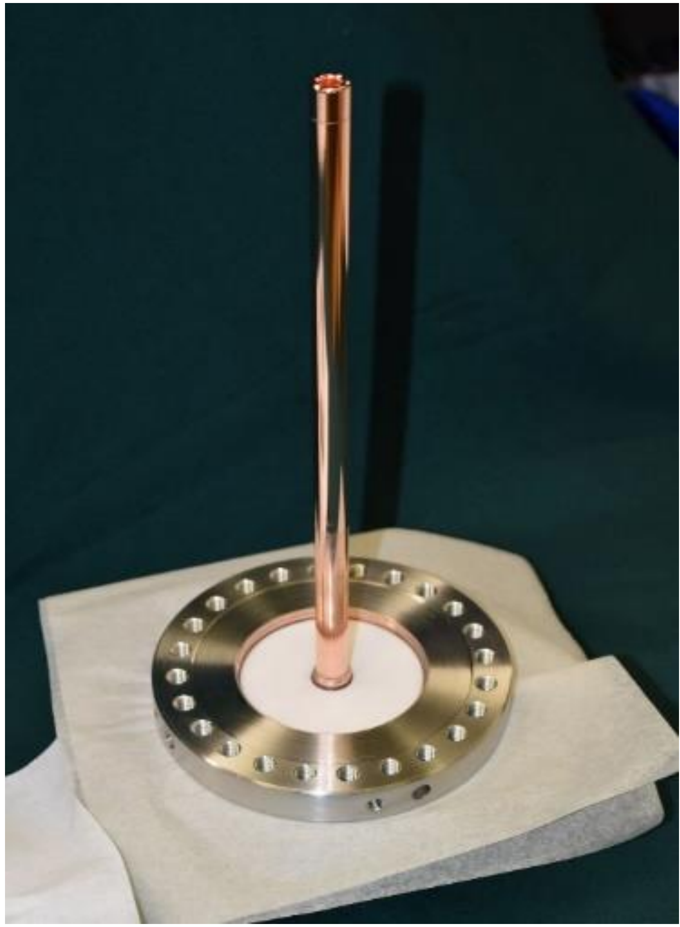




Example: the Advanced Photoinjector Experiment’s VHF gun in the LCLS-II injector. Window broke: charging because of the direct line of sight for the beam. A new 90-degree coupler will keep ceramic vacuum window out of harm’s way

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.*

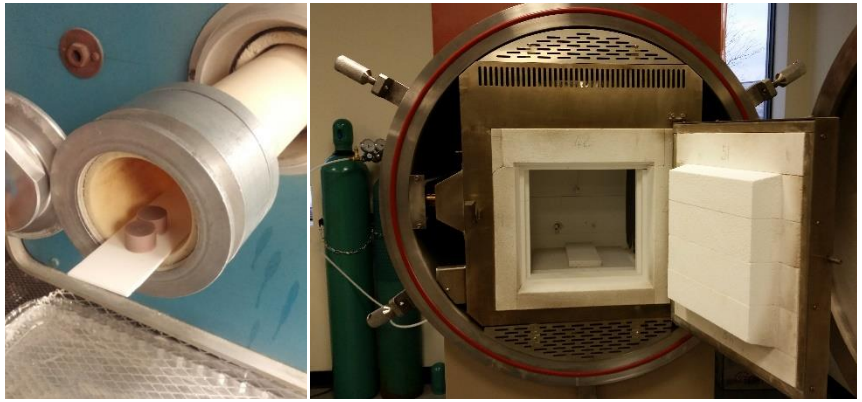


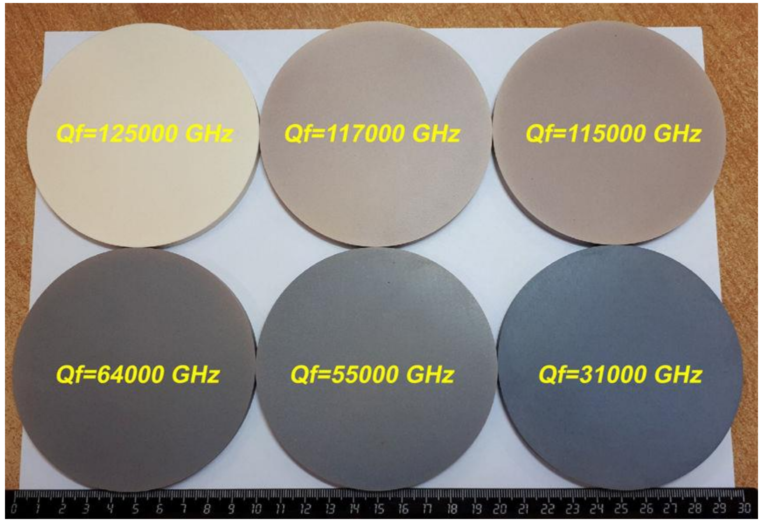
In Phase II of the project:

- Fabricated ceramic samples with controlled resistivity in the range 10^8 - 10^9 Ω·m (3-4 orders of magnitude less than traditional ceramics)
- 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 MgTi ceramic components for 650 MHz & 1.5 GHz high power RF windows; Tested the electrical properties

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

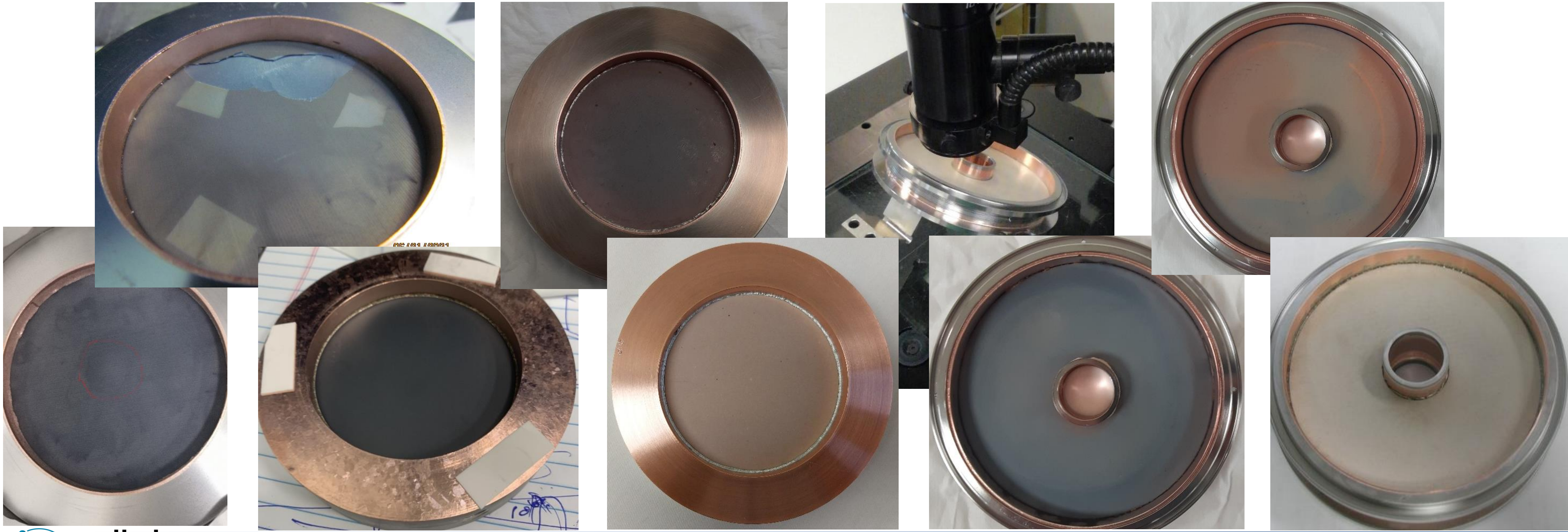
tan δ at 650 MHz

Key Accomplishments

- *During Phase IIA:*
  - Investigated brazing & soldering procedures
  - Fabricated several window assemblies
  - <u>Completed three high power tests of coaxial and waveguide windows</u>

Window Assembly Fabrication/Production

- Several window assemblies have been fabricated
- Many fabrication techniques and window conductivity values tested

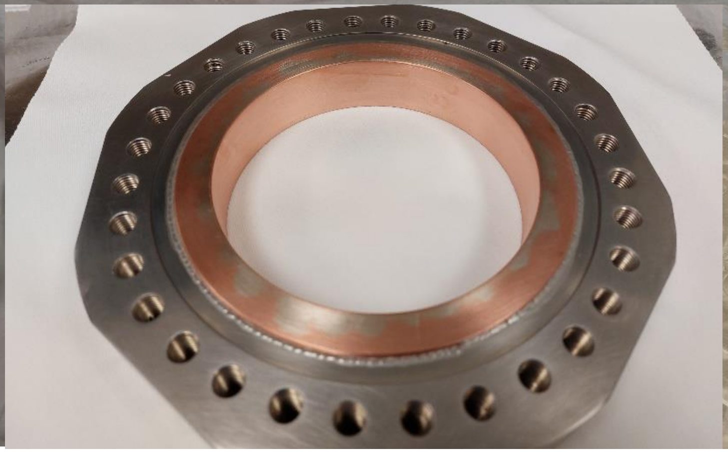


Window Brazing History

- Successfully sealed both waveguide and coaxial windows with Sn-Ag-Ti-Mg active solder @ 250°C
- Moderate success for both waveguide and coaxial windows with In-Cu-Ag-Ti active braze @ 740°C

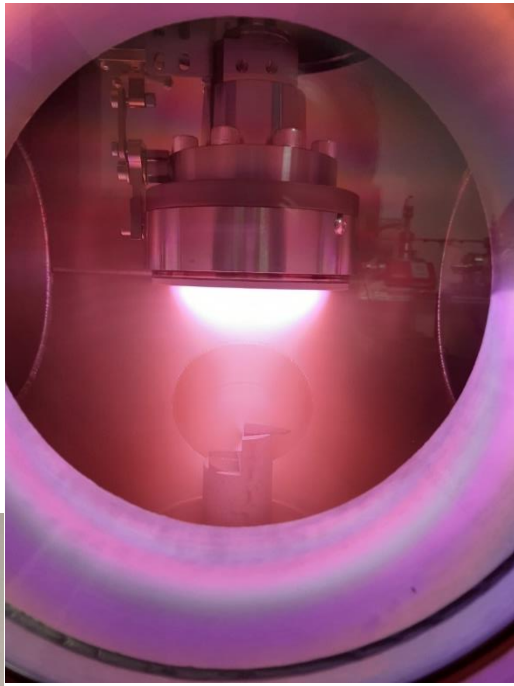
- Have been unsuccessful with:
  - Au-Sn w/ Ag metallization @ 350°C
  - Cu-Ag w/ Ag metallization @ 750°C
  - In-Cu-Ag active braze @ 750°C
  - Ti-Cu-Ag active braze @ 950, 980 & 1000°C

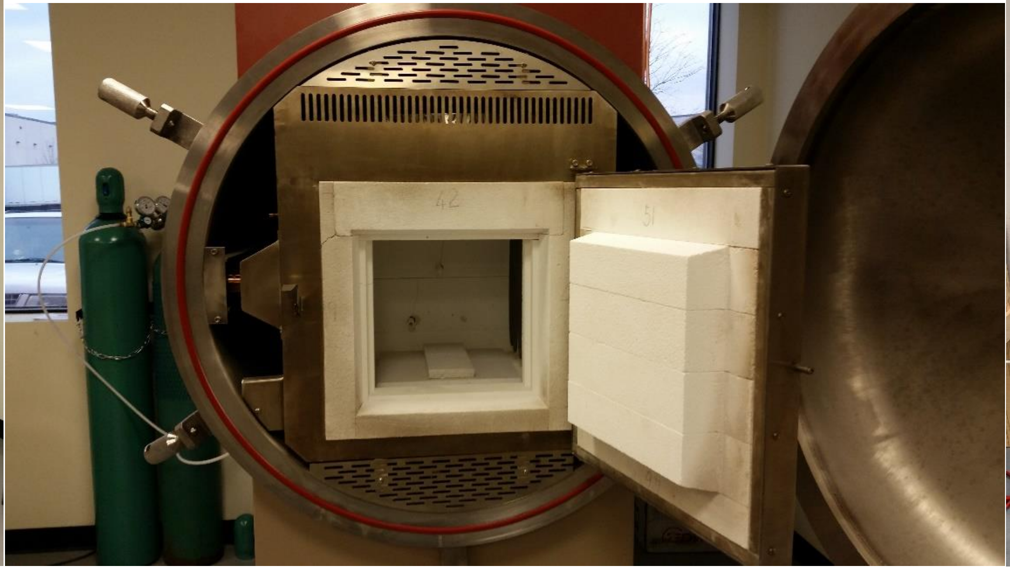


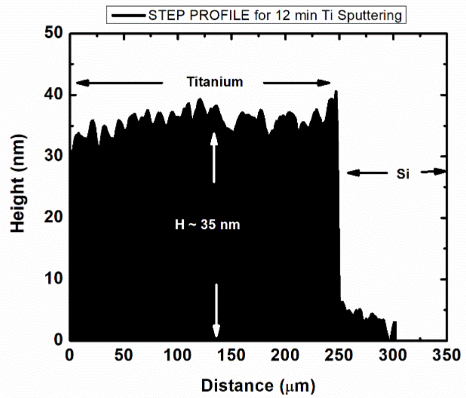




In-House Brazing Development

- Euclid owns/operates 3 furnaces for ceramic development and brazing
  - 1500°C, 12x12x16” controlled atmosphere box furnace
  - 1200°C, 5.6” diameter vacuum tube furnace
  - 1200°C, 1” diameter vacuum tube furnace
- Euclid owns/operates 3 sputtering chambers for metallization
- Brazing operations being relocated to Euclid to improve turnaround time & cost

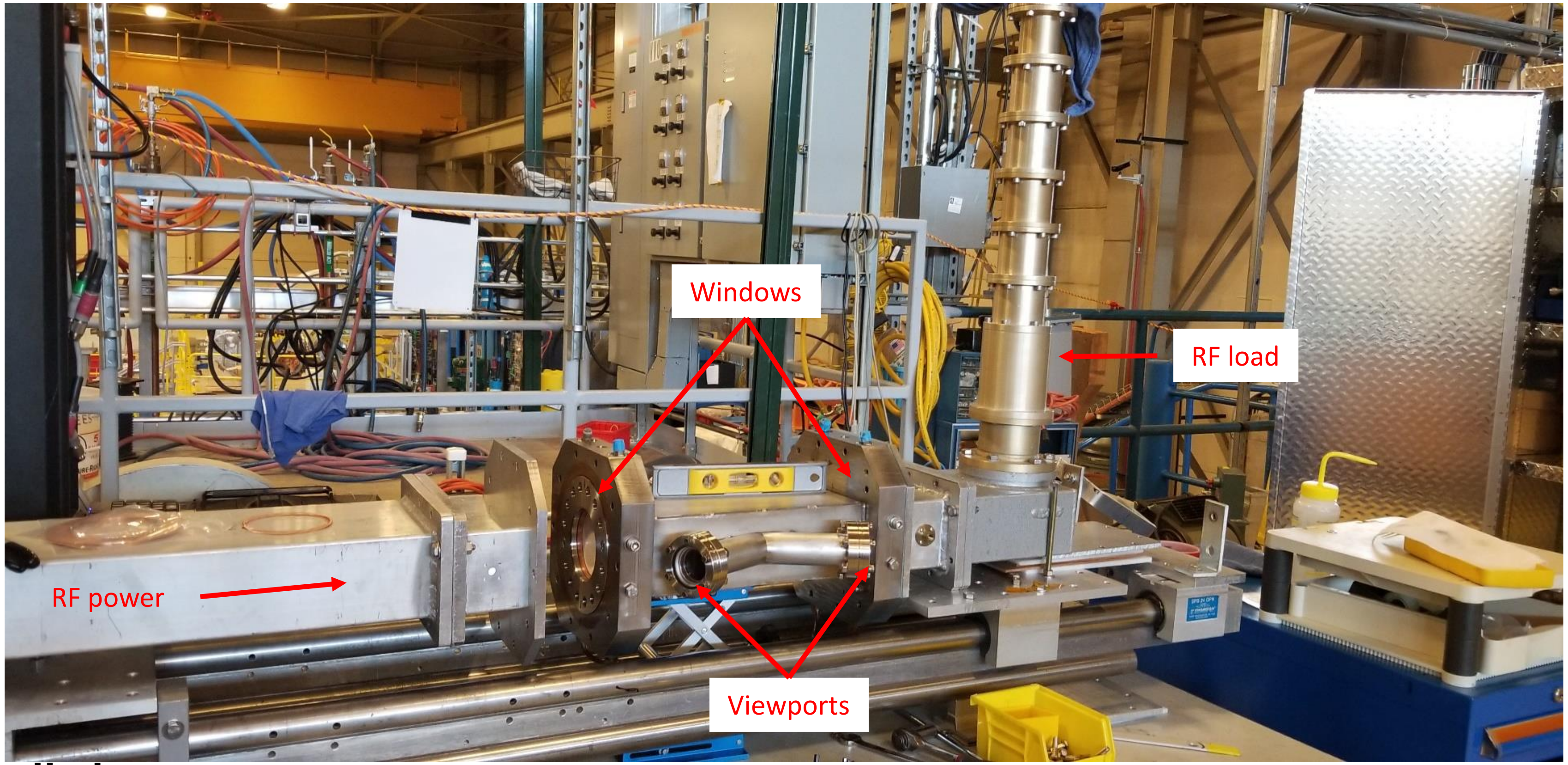


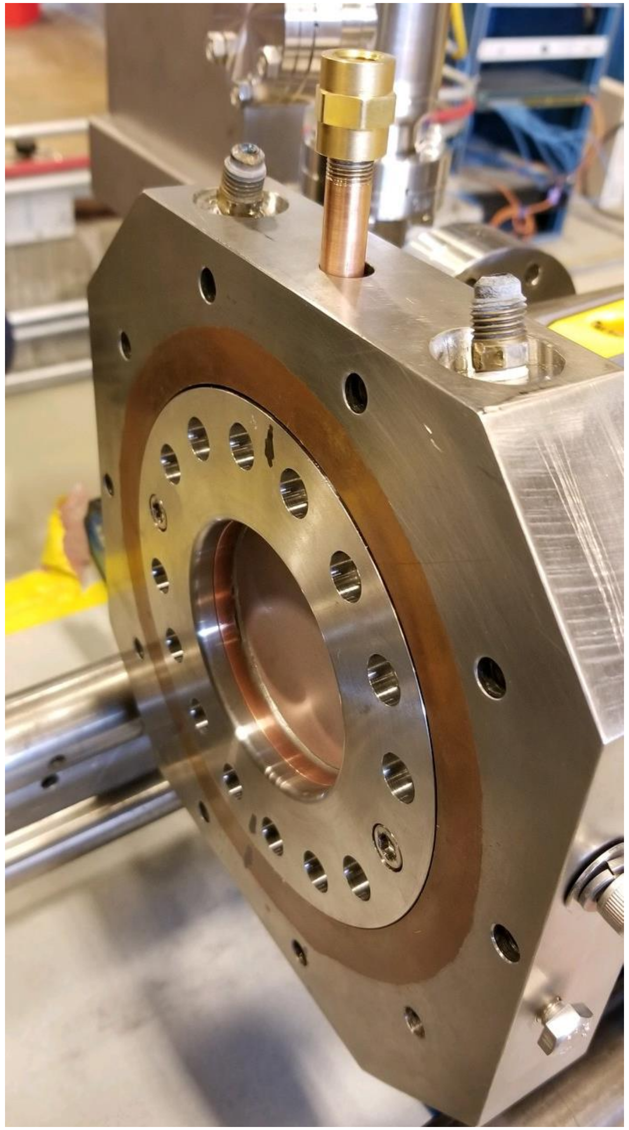




High-Power Test Stand at JLab

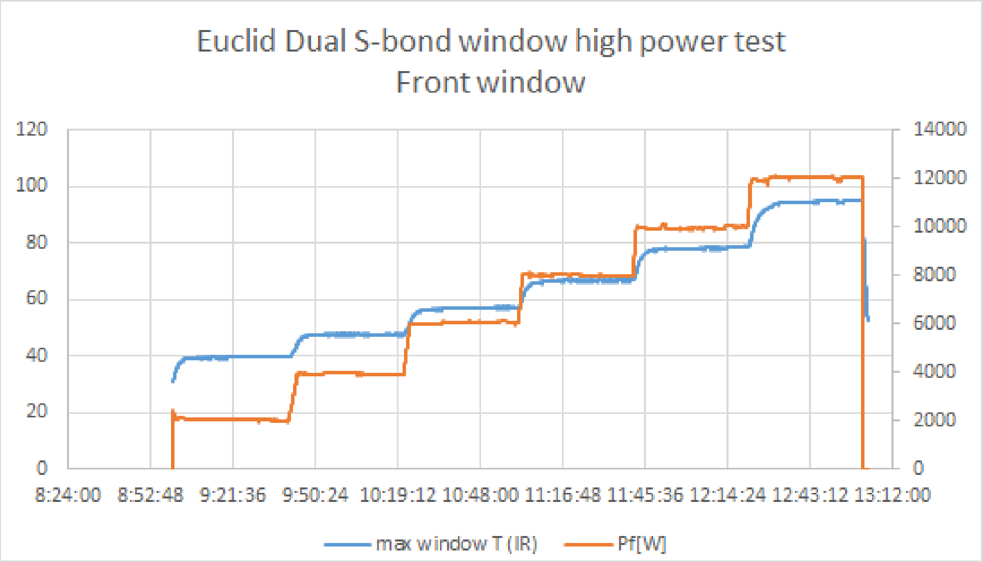
- Two high-power tests: Two windows in vacuum & single window in air
  - Water cooled
- 1.3 GHz CW RF power up to 12 kW, TW
- IR cameras pointed at both windows

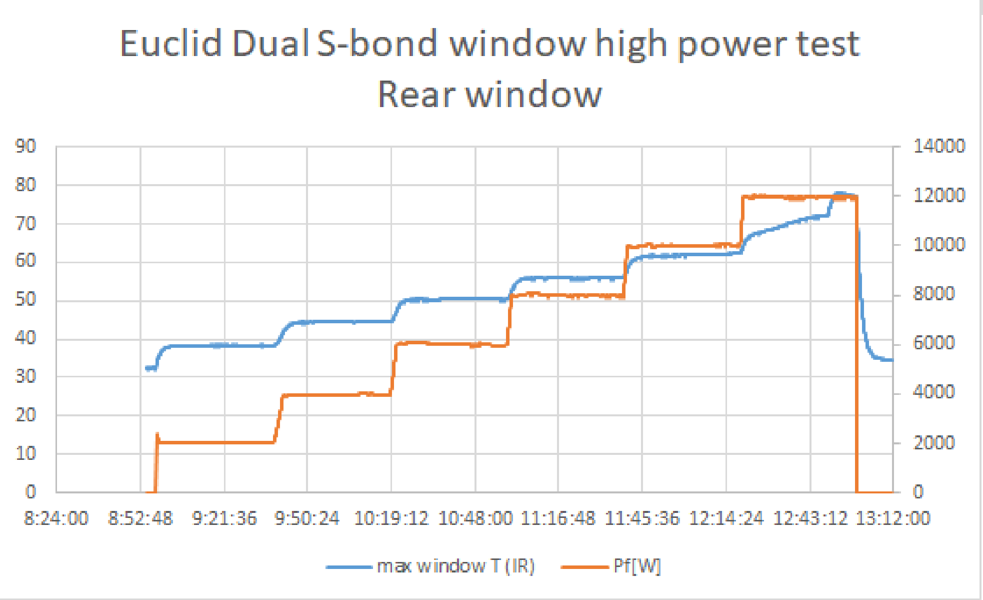




High Power Test at JLab

- 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





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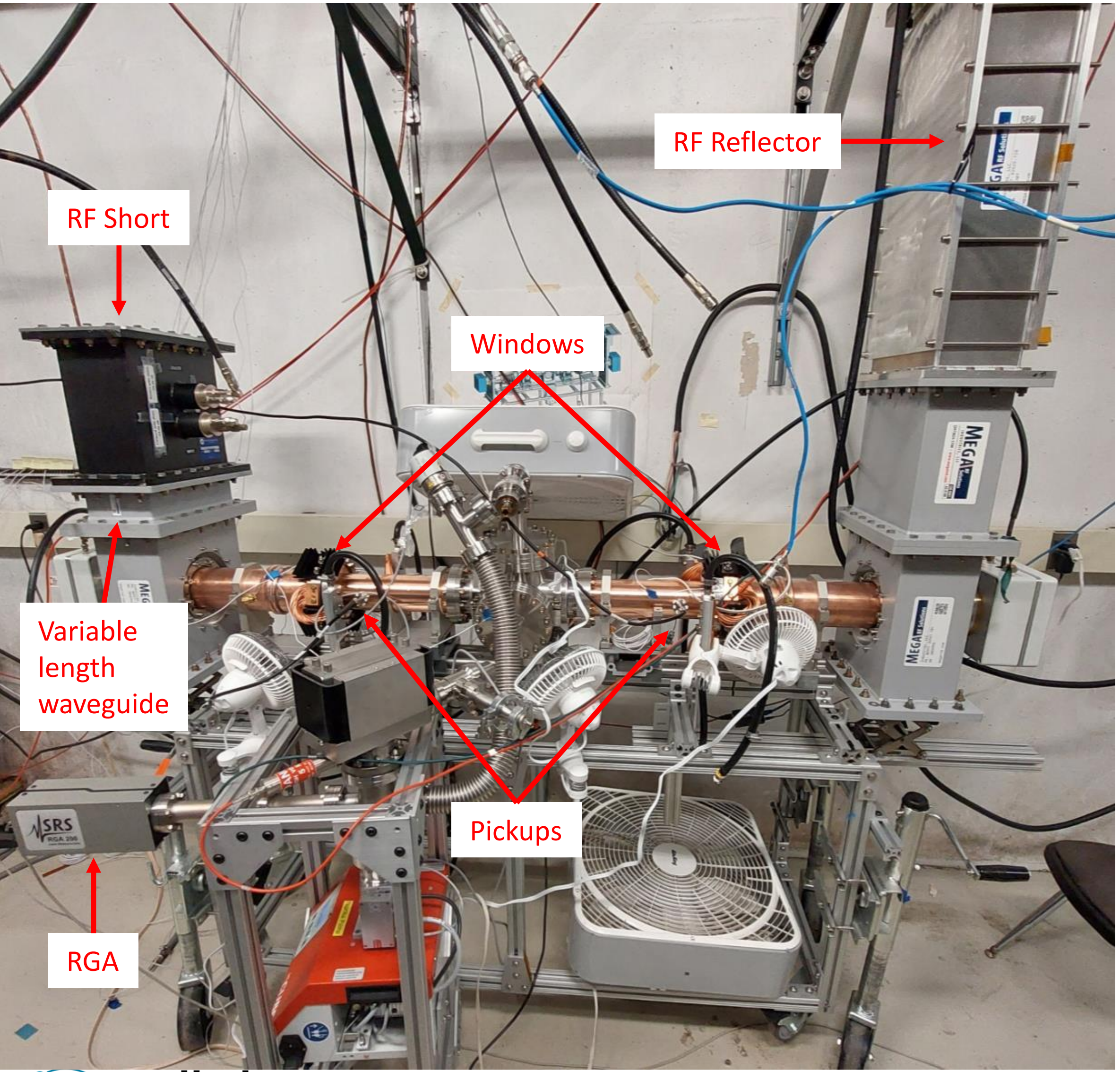
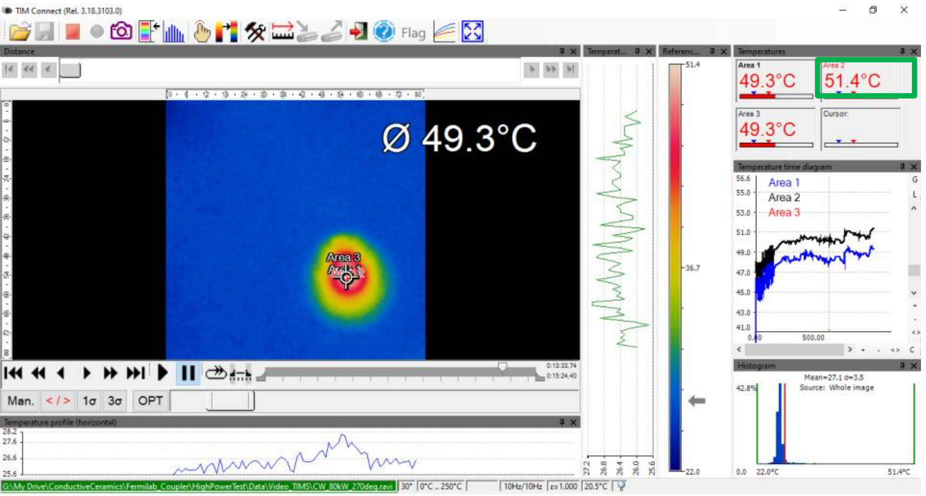
High-Power Test Stand at Fermilab

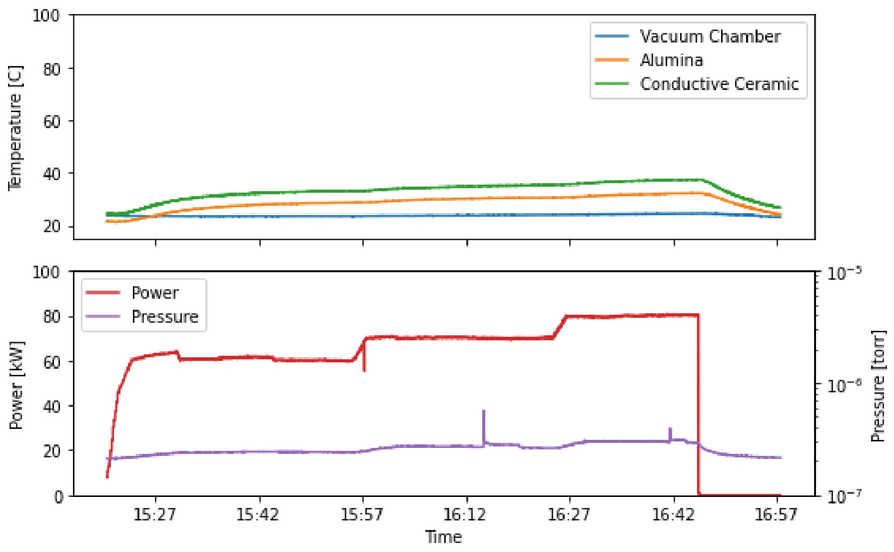


- One conductive ceramic and one alumina window tested together
- 650 MHz CW RF power up to 100 kW, SW
- Test stand allows change position of E field maxima & increase power over what klystron could normally provide
  - Four phases tested (designated 0, 90, 180 & 270°)
- Temperatures measured:
  - Thermocouples 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°

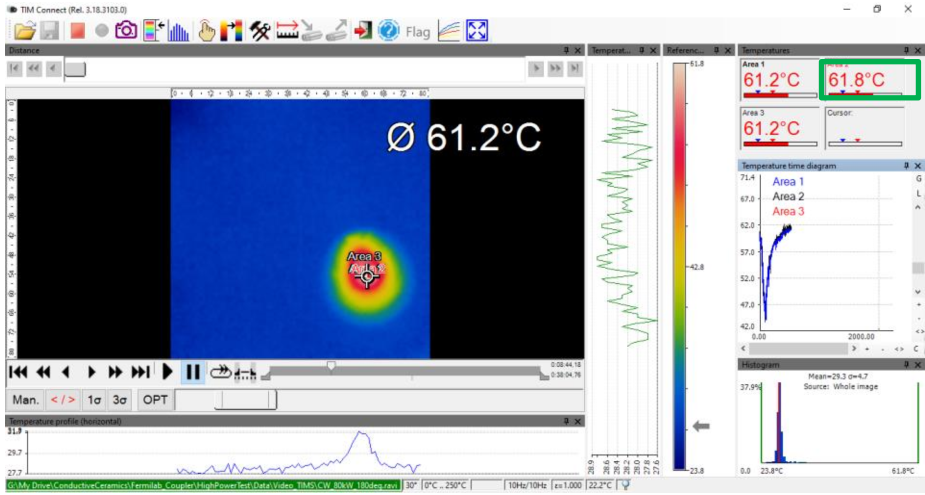


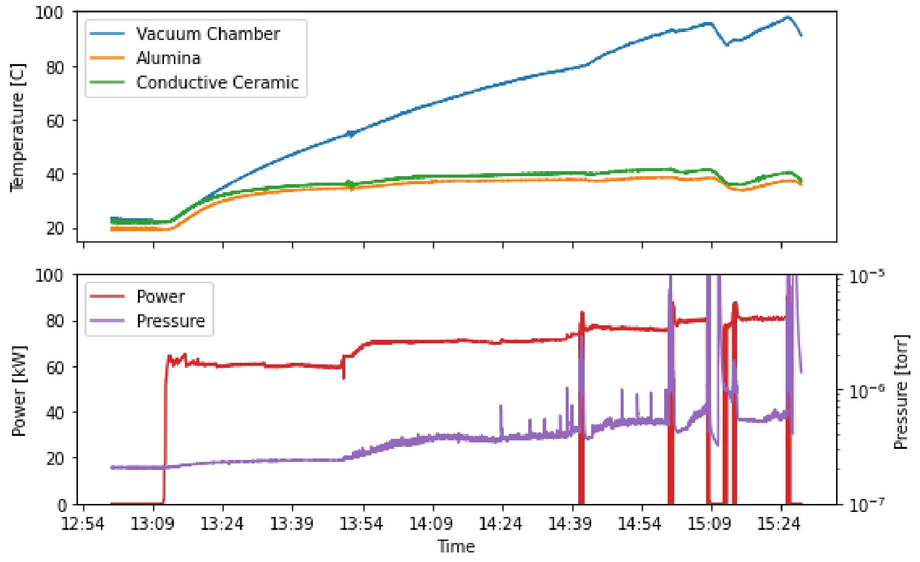


- *80 kW CW reached for two phases*
  - Not fundamental limit, only hesitant to damage window
- Max. temp. on flanges:
  - Left:
    - Conductive Ceramic = 41.8 C
    - Alumina = 38.7 C
  - Right:
    - Conductive Ceramic = 37.5 C
    - Alumina = 32.3 C

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

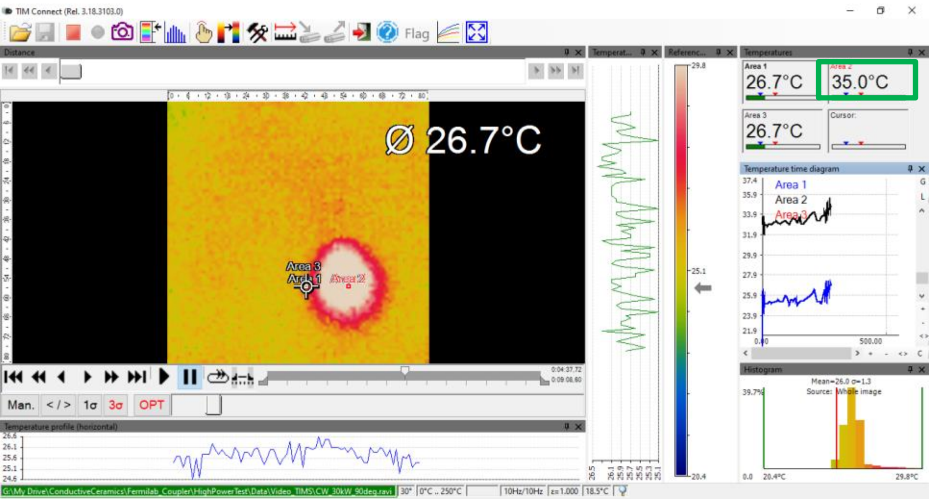
180°



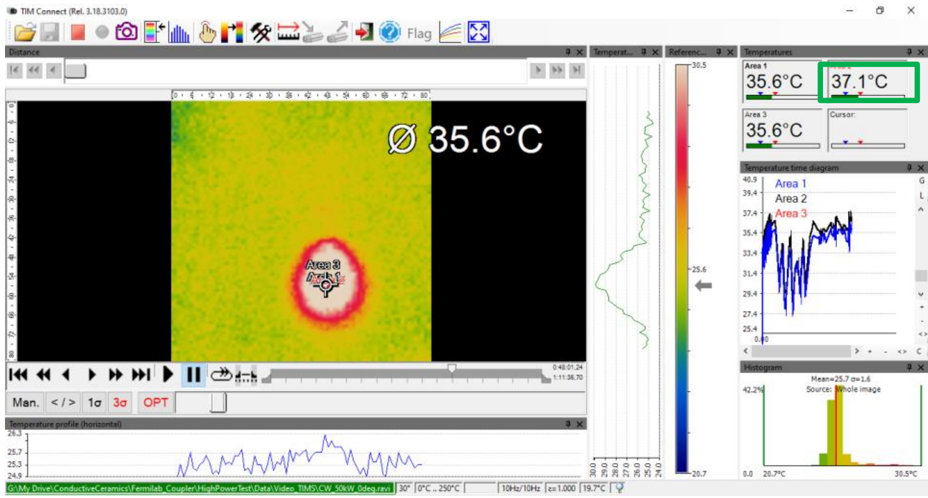


High-Power Test at Fermilab – II

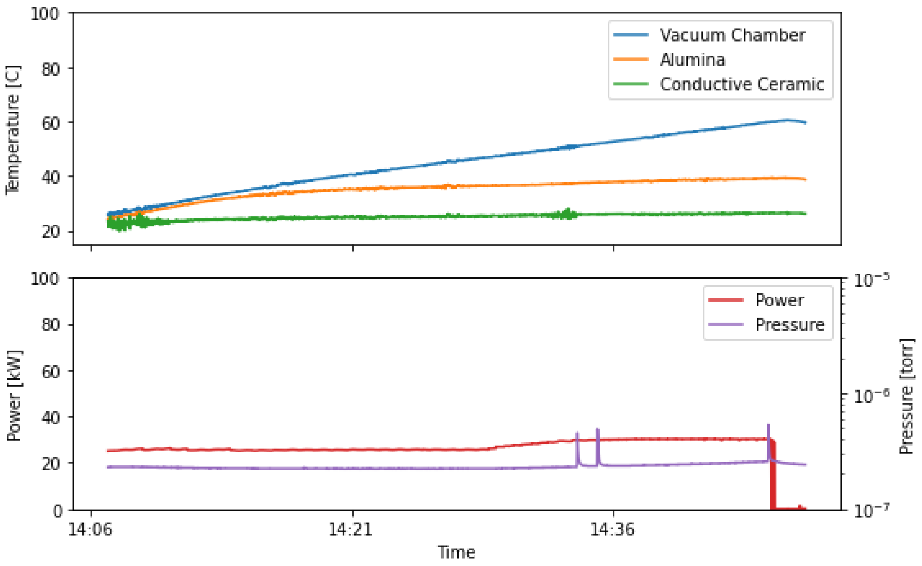
90°

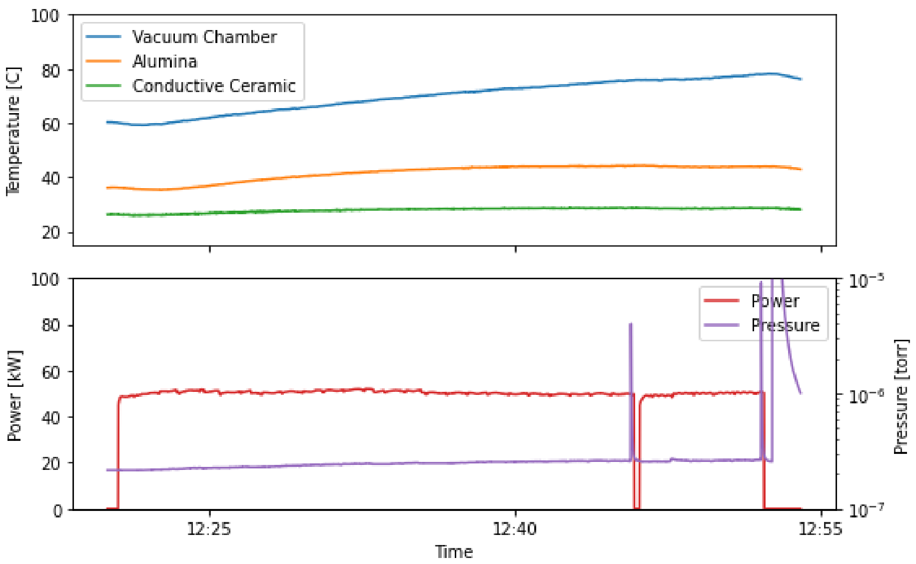


0°



- 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

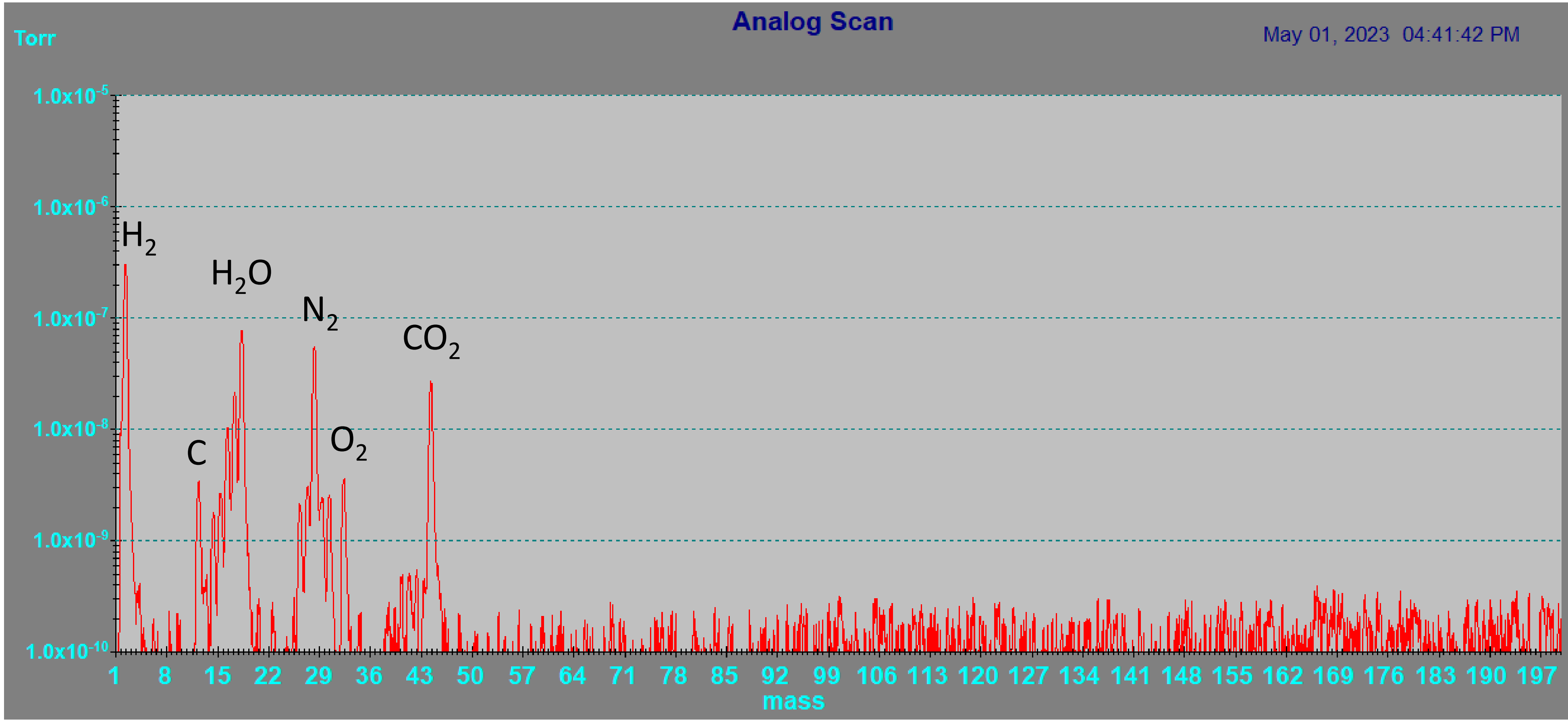




High-Power Test at Fermilab – RGA & Pickups

- 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



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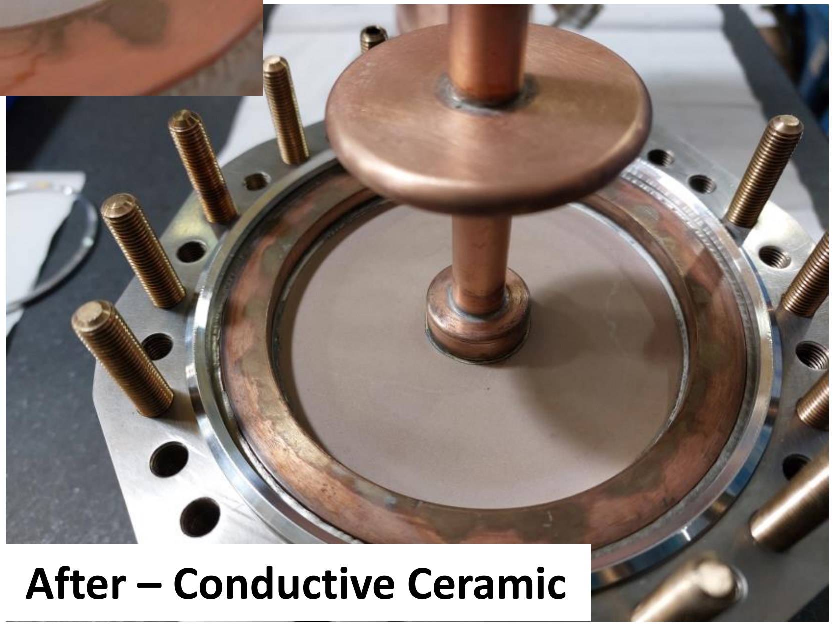
High-Power Test at Fermilab Inspection


Before – Conductive Ceramic


After – Conductive Ceramic

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

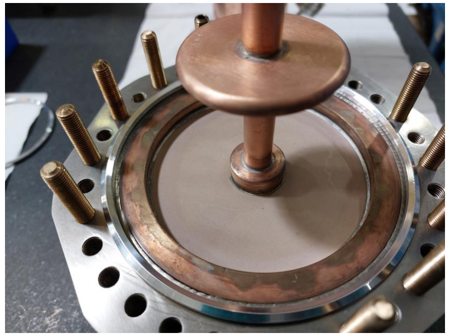

Before – Alumina


After – Alumina

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

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
  - Highest power ever achieved in Fermilab test stand



Conclusions

- We have developed a brand-new ceramic material, which possesses counter-intuitive properties: low RF losses and yet it is conductive (3 orders of magnitude variation).
- It has been successfully tested in the hardest environments – brazed into high-power RF windows.
- Window assemblies of 650 MHz and 1.5 GHz have been successfully tested in vacuum at high power (up to 80 kW CW). The conductive ceramic 650 MHz window overperformed its alumina counterpart.
- This material opens new possibilities for many microwave components, especially those where radiation hardness or controlled conductivity / RF loss is required.

Acknowledgements

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