Compact, low-cost higher order mode absorbers formed by cold spray of metal matrix composites

DOE-NP SBIR/STTR Exchange Meeting

August 14, 2024

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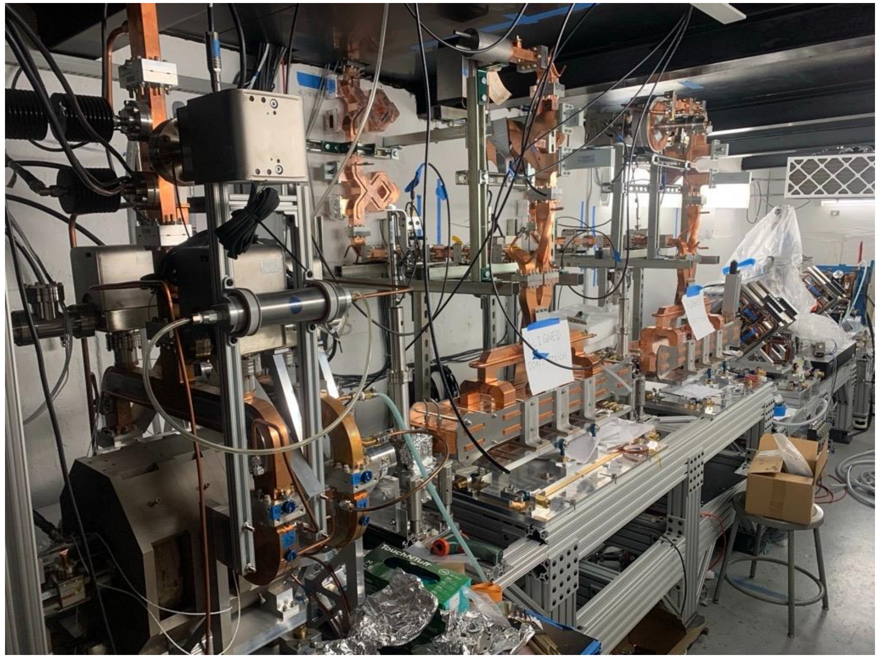
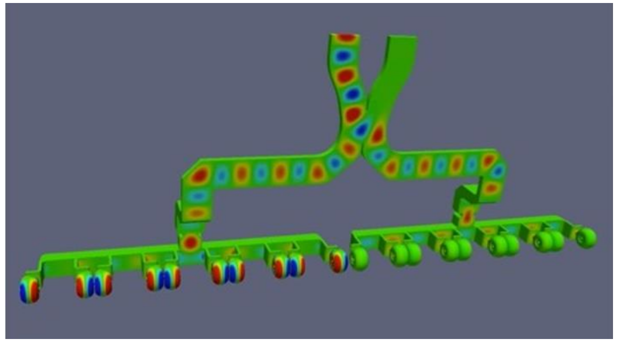
SBIR/STTR Award DE-SC0020562

RadiaBeam: Brightness, *Applied*

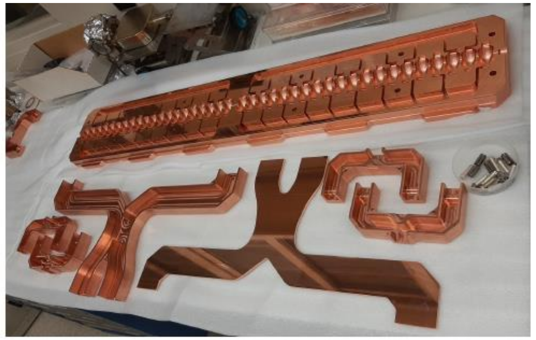
- Spin-out of UCLA Physics Department: 2004
  - Located in Santa Monica, California
  - Currently: 54 employees, 30,000 ft^2
- Charge particle optics, custom magnets & >MeV X-ray systems
  - Sim, design, fab and testing of high power RF structures
  - Custom instrumentation with vac-compatible manufacturing
  - Cryogenic engineering
  - 9MeV Radiography/CT services
  - Teams: R&D, Engineering, Manufacturing, Integration & Testing
  - In-house 'clean' machining, aqueous cleaning & RGA outgassing



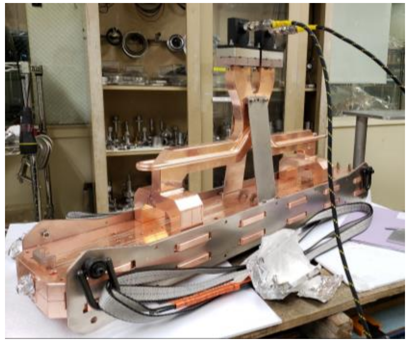
Inverse Compton scattering gamma-ray source



CST RF model



Machined components

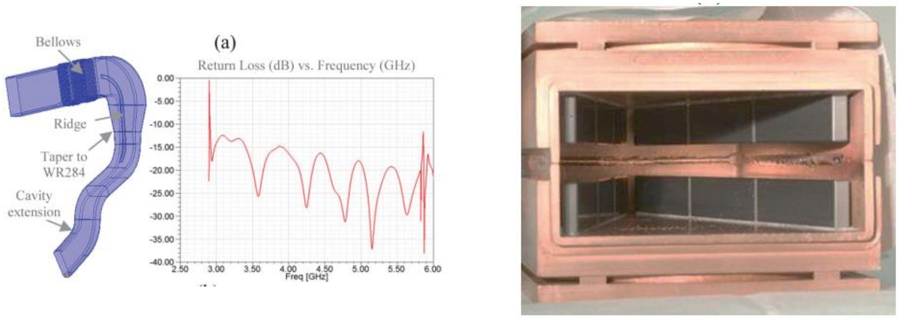


Low power RF

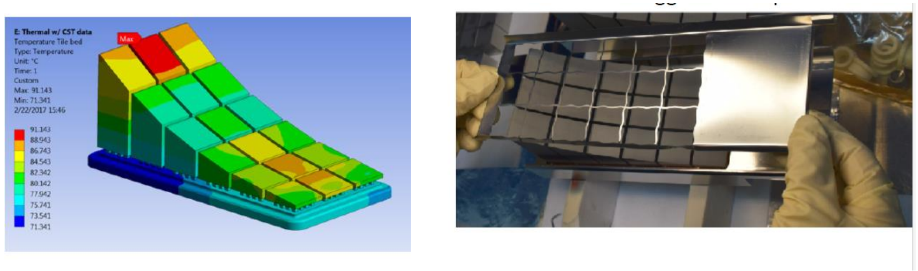
White room manufacturing of copper

Introduction- SRF beam line absorbers

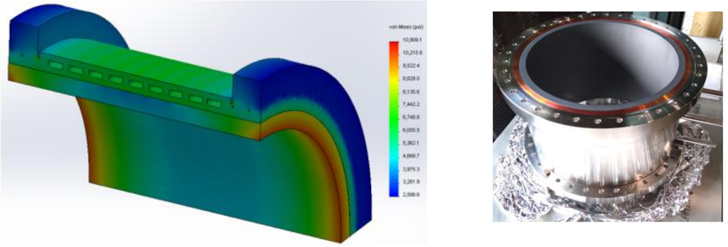
- **Motivation**: Long range wakefields at high currents can strongly affect the beam dynamics via higher order modes(HOM). As machines move to higher currents, higher bunch charges and shorter bunches, problem becomes more pronounced.
- **Solution:** HOM dampeners which preserve fundamental
  - Waveguide, loop/antenna-couplers, **beam line absorber (BLA)**



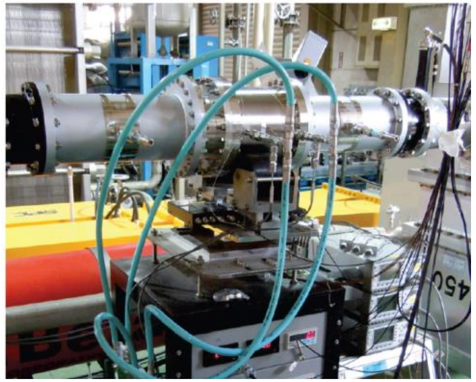
Argonne - APS WR284 Waveguide loads for SPX CM
Technology: Soldering + EBW (St Gobain Hexoloy)



JLab prototype waveguide-load developed for Helmholtz-Zentrum Berlin Technology: Brazed (Sienna STL-100HTZ)



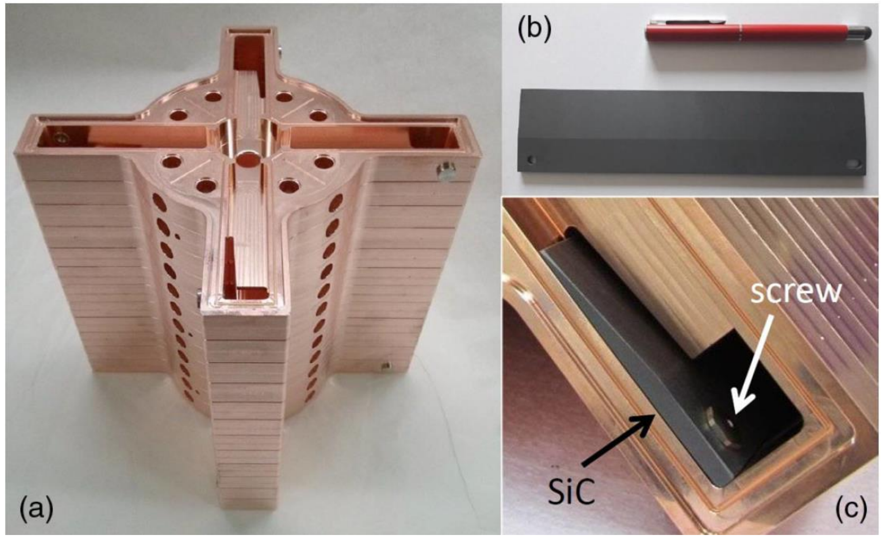
BNL LDRD three high power 308mm ID BLAs
Technology: Shrink fit SiC (Coorstek SC-35)

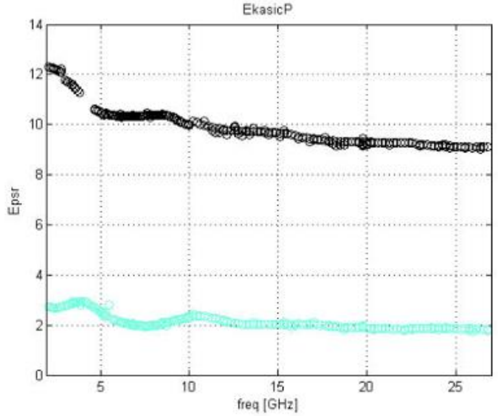


18kW high power tests of SiC at KEK in collaboration with Toshiba Energy Systems
Technology: SiC

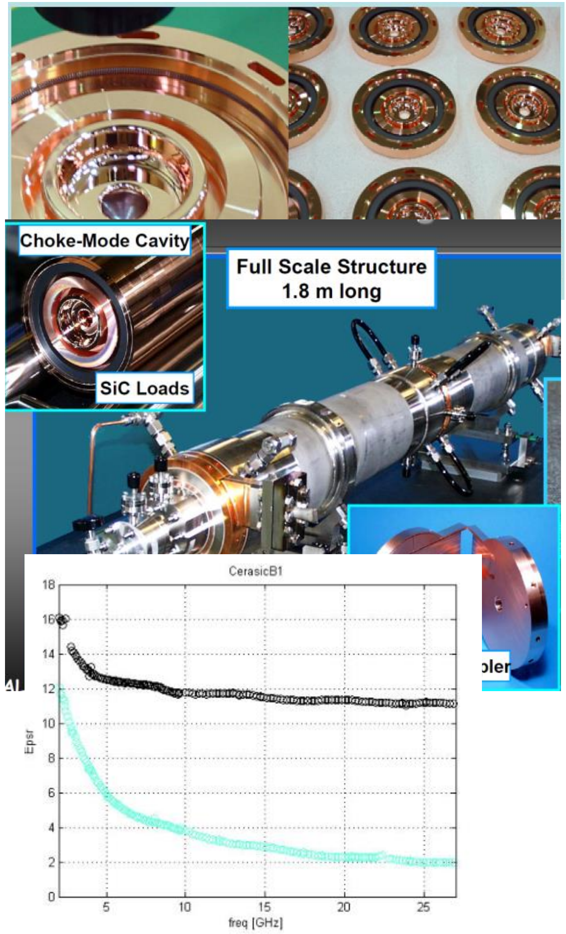
BLA developed by DESY/Kubrina Lumina (Poland)
Kubrina Lumina supplied x35 BLA assemblies to LCLS-II
Technology: Brazed 80K AlN (Sienna STL-150D)

Introduction: NCRF HOM absorbers

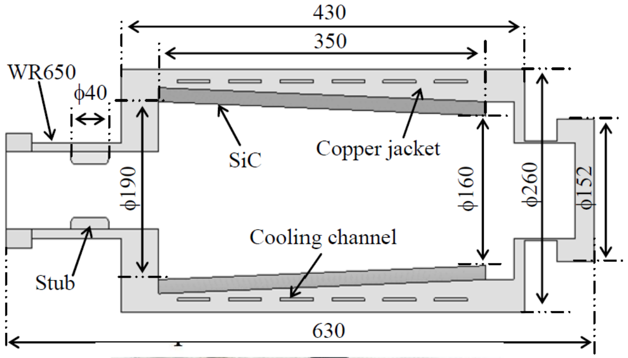




On-Cell waveguide loads for C-band NCRF structure
INFN & Andalo Gianni
Technology: Fastened SiC (Ekasic-P)



Choke-mode C-band NCRF structure for Spring-8
10,000+ cells
KEK & Mistubishi Heavy Industries
Technology: SiC (CERASIC) + Spring clips



10kW, 1.428GHz
Toshiba + KEK
CERASIC from
Covalent Materials Corporation

Requirements

Beam line absorber assembly requirements:

1. Amenable to bonding to a water-cooling circuit 2. Good thermal conductivity 3. Toughness/no cracking: integrity during fabrication and under load 4. Broadband RF absorption characteristics	Conventional-specification
5. Minimize beam-induced electrostatic charging/finite DC surface conductivity 6. UHV compatible/low outgassing 7. No dust/particulate generation 8. Stable against high energy radiation	Accelerator-specifications

Additional considerations

- Niche application with limited demand: supply and quality issues
- Ceramic variability: small RF coupons can be different than large, full-scale parts
- Establishing specifications and qualification methods requires lab support
- High power testing to failure is valuable for risk mitigation but expensive

EIC eSR Beam line absorber

- HOM damping is crucial for high beam current operation of EIC eSR SRF systems
  - x34 BLA assemblies: Large and small diameter
  - Self heating:15kW/26.5kW total – reduce ε
- Power handling capability assembly's thermal transport circuit
  - CESR-B: limit roughly 0.2W/mm^2
- Virtual leak due to shrink fit: 2.2E-10 Torr-Liters/sec-cm²,
- High power tests carried out in the air
  - 704 MHz 1 MW CW klystron is delivered to the BLA with WR 1500 waveguides: Asymmetric TE01 heating in SiC
  - SC-35 SiC: Radius 154mm, WT: 14mm
  - No damage at 0.44 W/mm^2, cracks at 0.65 W/mm^2
- Only 30% margin for SBLA #2
  - *All HOM absorbers for EIC SRF cavities will go through high power test, prior to the installation to the EIC SRF cryomodules.*

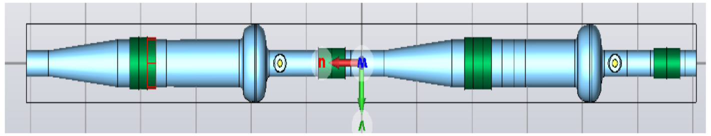
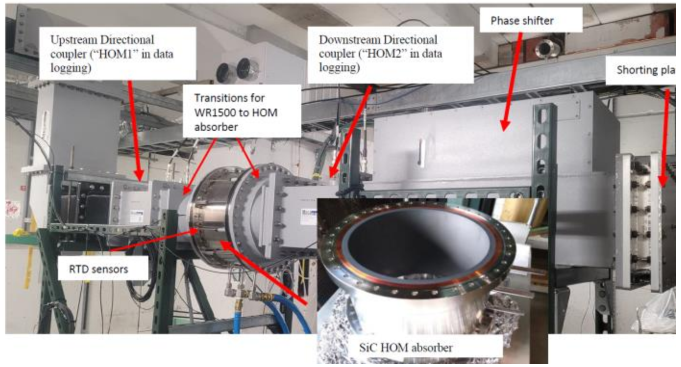


Figure 3. EIC ESR SRF cavities layout.

Table 2. HOM power absorbing in BLAs (compare lengths of SBLA)

	LBLA	SBLA #1	SBLA #2
Radius (mm)	137	75	75
Length (mm)	240	120	240
HOM power (kW)	34.4	26.5	38.3
Power flux (W/mm^2)	0.19	0.47	0.34



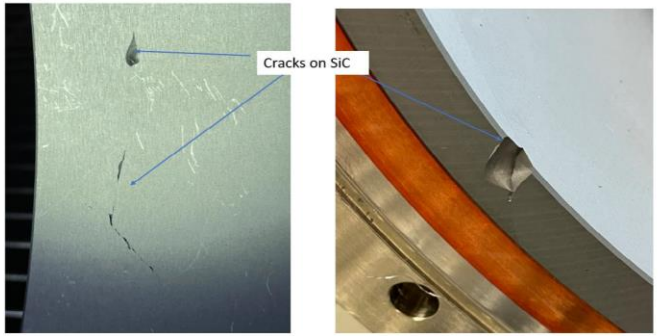
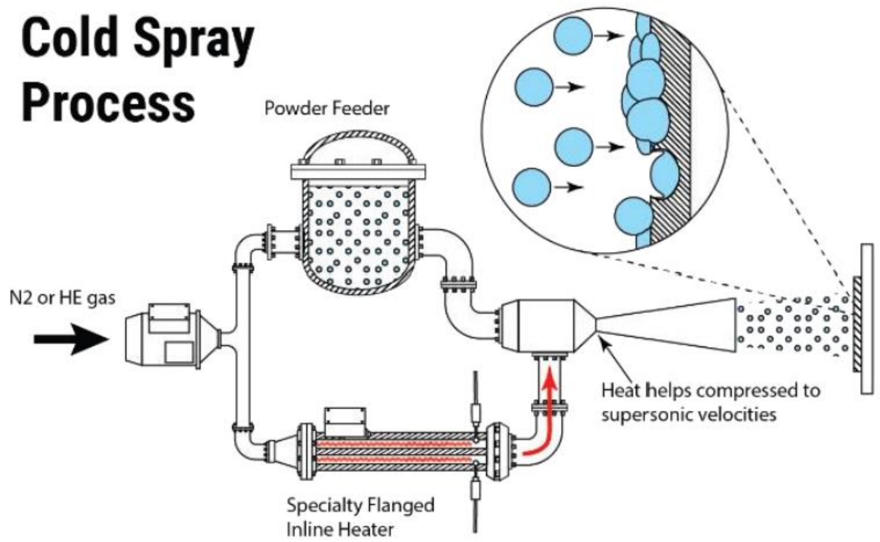


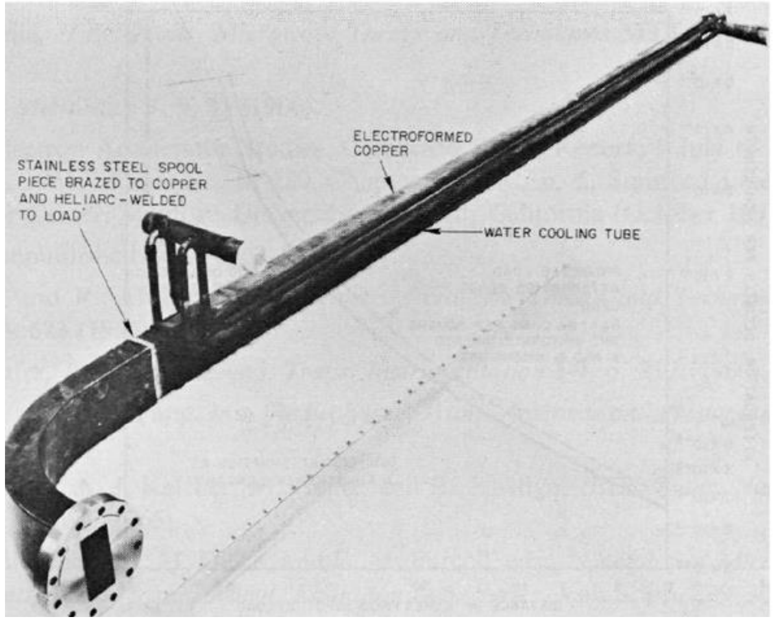
Figure 12. Crack found inside the SiC (left) and on the edge (right).

Xu, Wencan, et al. "High-power test results for a cylindrical-shell silicon carbide higher-order-mode damper." *Physical Review Accelerators and Beams* 27.3 (2024): 031601.

Approach

- Cold Spray: corrosion or wear resistance for repair and mitigation, dimensional restoration of mating surfaces like flanges
- Development challenges:
  - Nozzle clogging
  - High ceramic loading: feedstock ≠ coating composition
  - Low porosity w/o expensive He usage

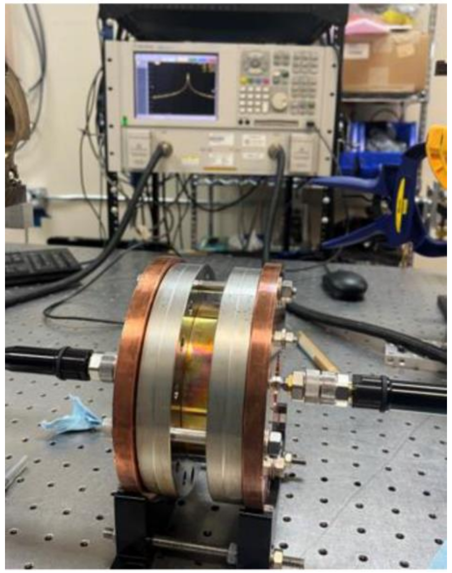




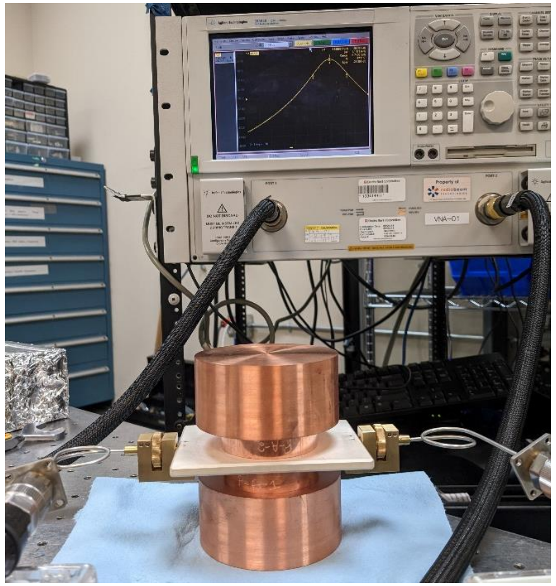
2MW S-band dry load at SLAC flame spray with Kanthal
Metallic/resistive loss = large surface area

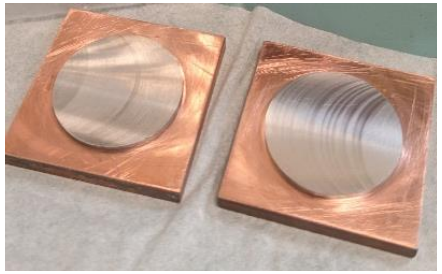
SiC-Al cold spray coatings

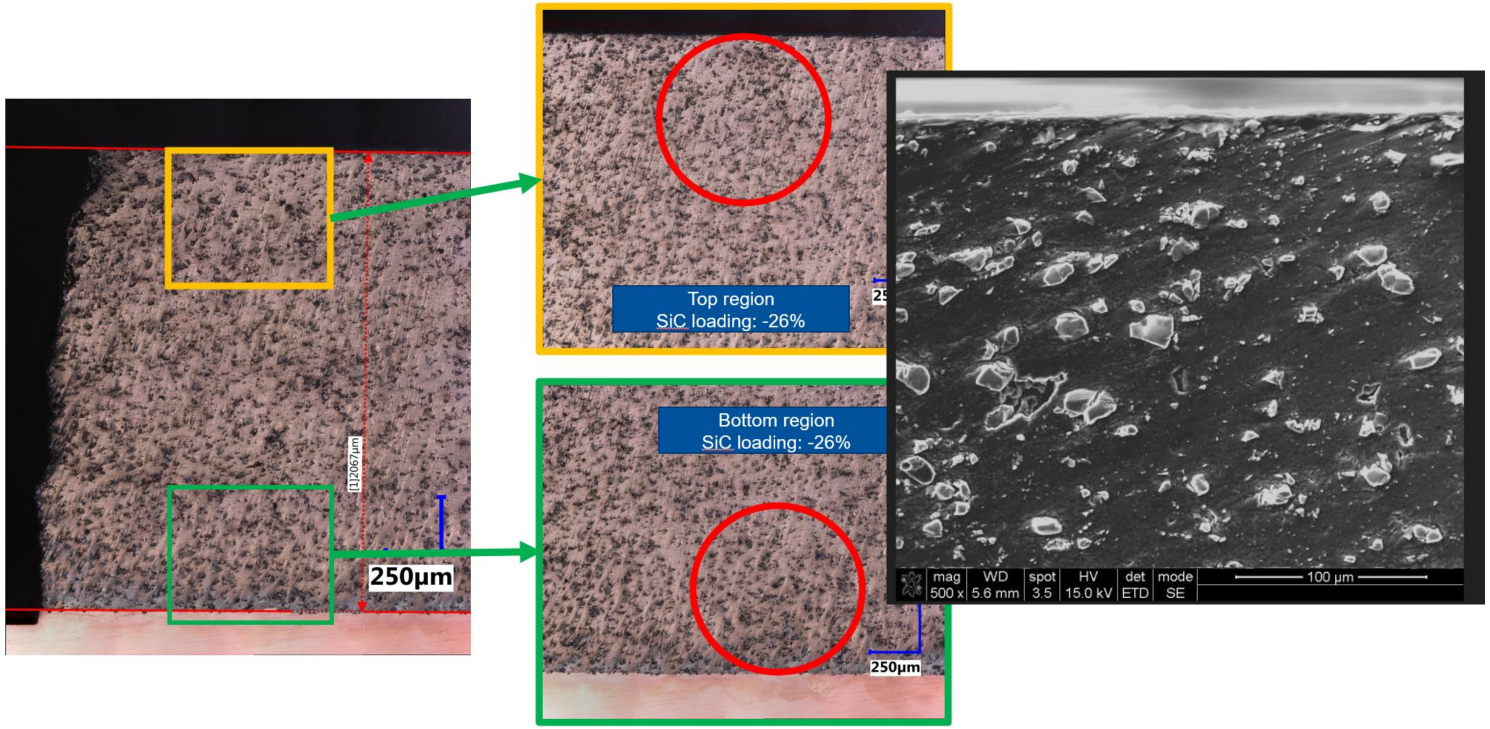
- Issues regarding loading SiC into cold spray coating: Multiple vendors and discussions
  - Ductile matrix with brittle particles needed for adhesion: Max loading was 26% SiC
- 6 GHz dielectric cavity measurements show ‘metal’ behavior with σ= 20-25% IACS



f_0= 3.0GHz
σ= 29% IACS

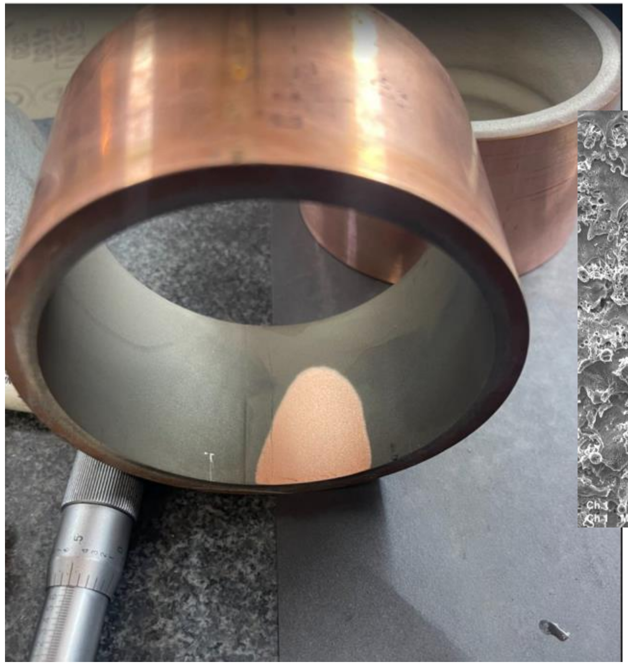


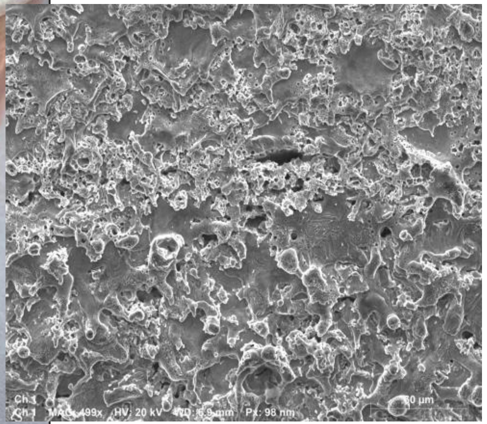




Ni-20Cr cold spray coating

- Nichrome Ni-20Cr cold spray coating:
  - Praxair– PWA 1319: good corrosion resistance, ceramic bond coat, general repair
  - σ = 1.5 %IACS
- Coating thickness hard to control & porosity of top layer is high
- Thin (50 μm) final coating: turn ID & OD

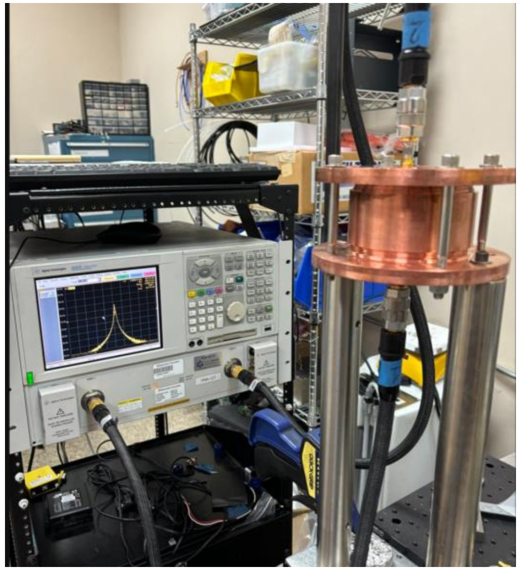




Ni-20Cr cold spray coating: conductivity

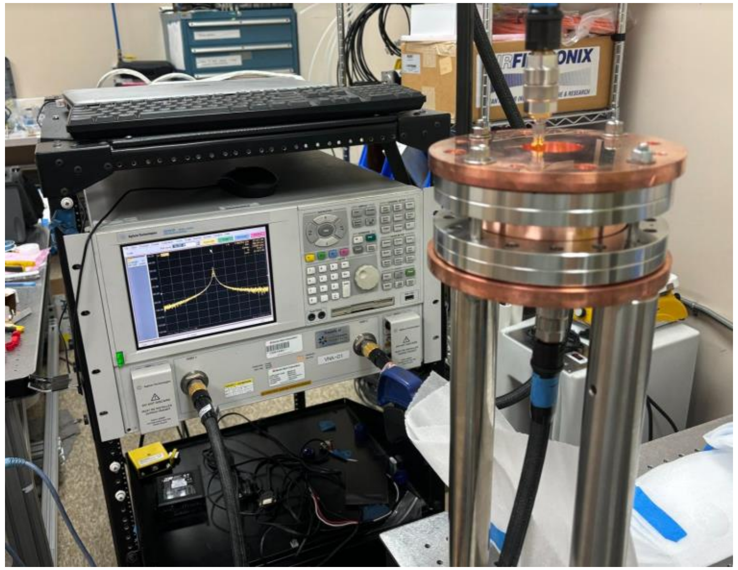
- Turned ID: 100 + 25 µm thickness

480kHZ Eddy current
σ = 2.1 ± 0.9 %IACS
δ = 12µm



2.8GHz pillbox
σ = 3.1 %IACS
δ = 0.12µm

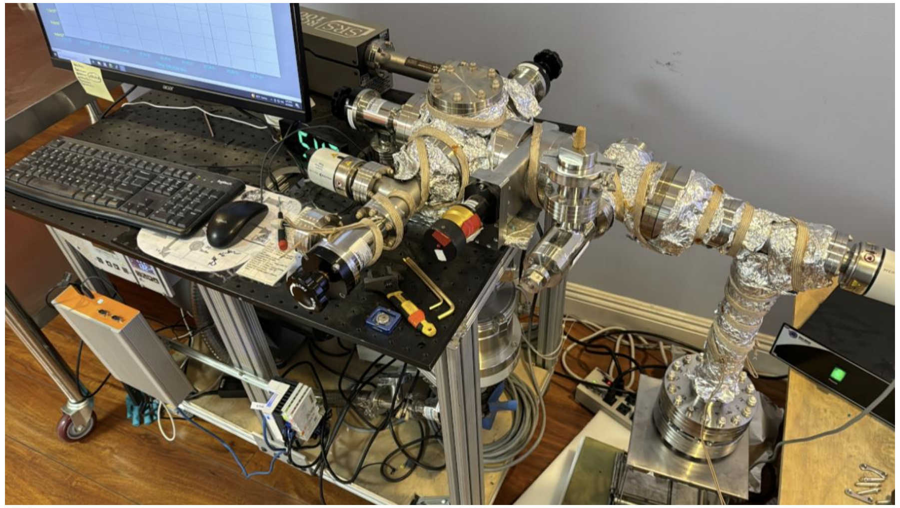
Cu-25Au vacuum brazing

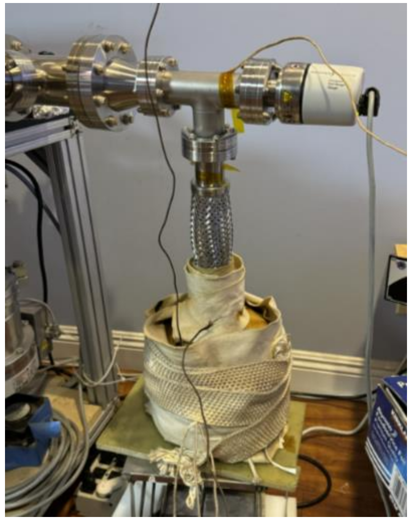


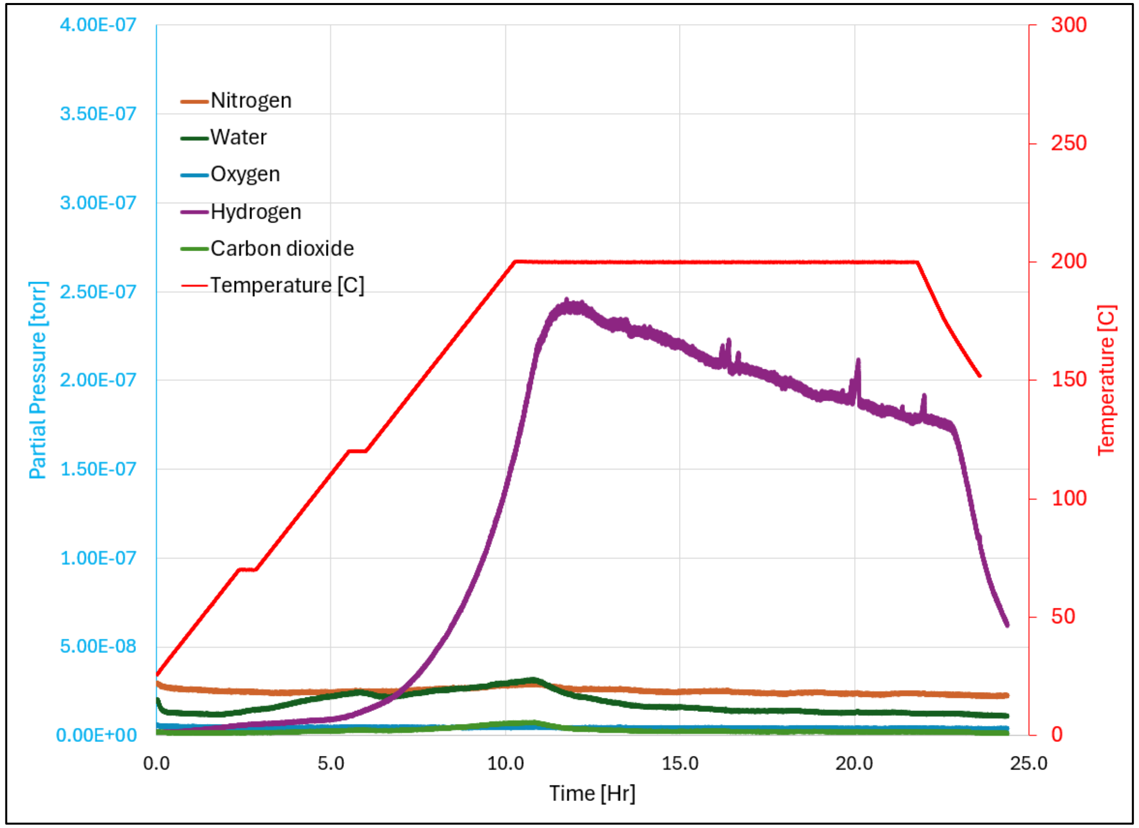
2.8GHz pillbox
σ = 4.1 %IACS
δ = 0.12µm

Ni-20Cr: Vacuum Outgassing

- Braze body passed He leak check
- Base pressure: 7.9 x 10^{-8} Torr
- Bake-out: 200C for 12hrs
- Significant H outgassing from RGA signal







Ni-20Cr cold spray coating: microstructure

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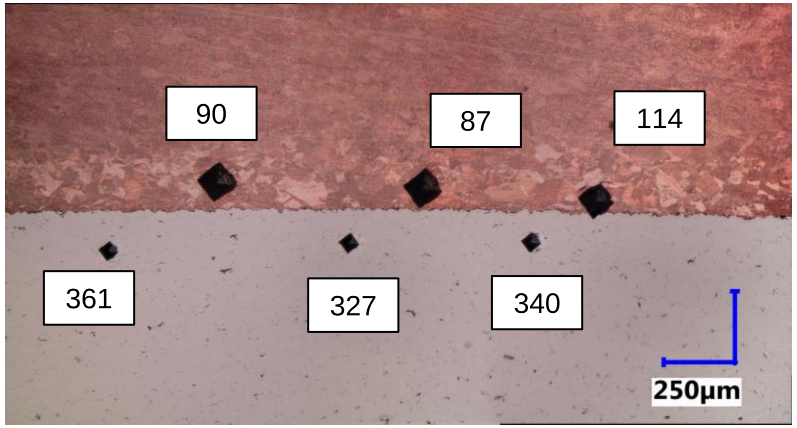
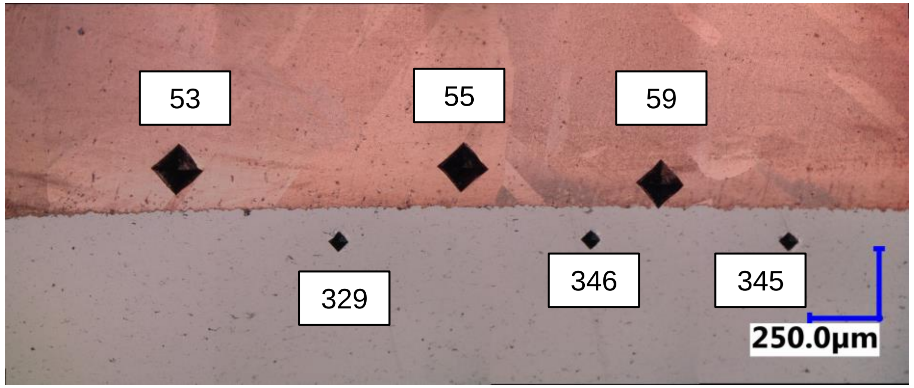
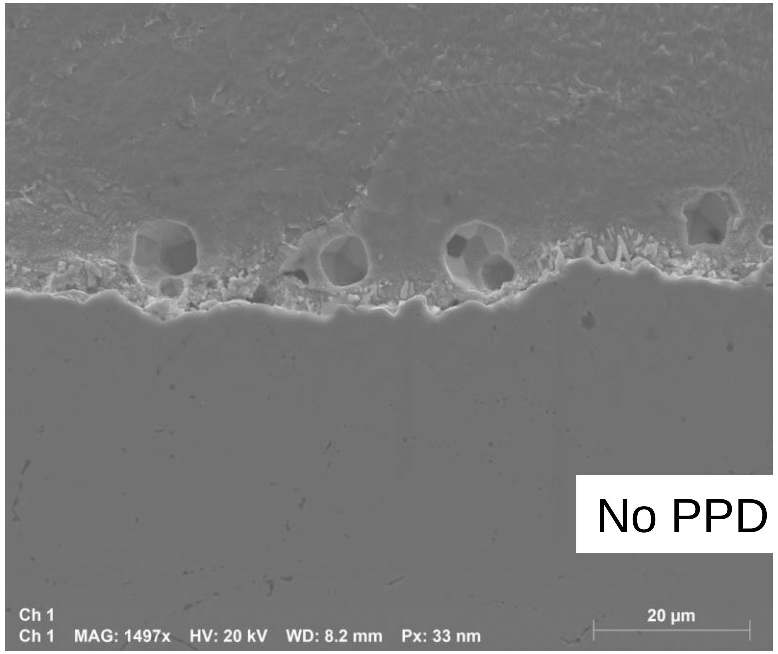


As-sprayed

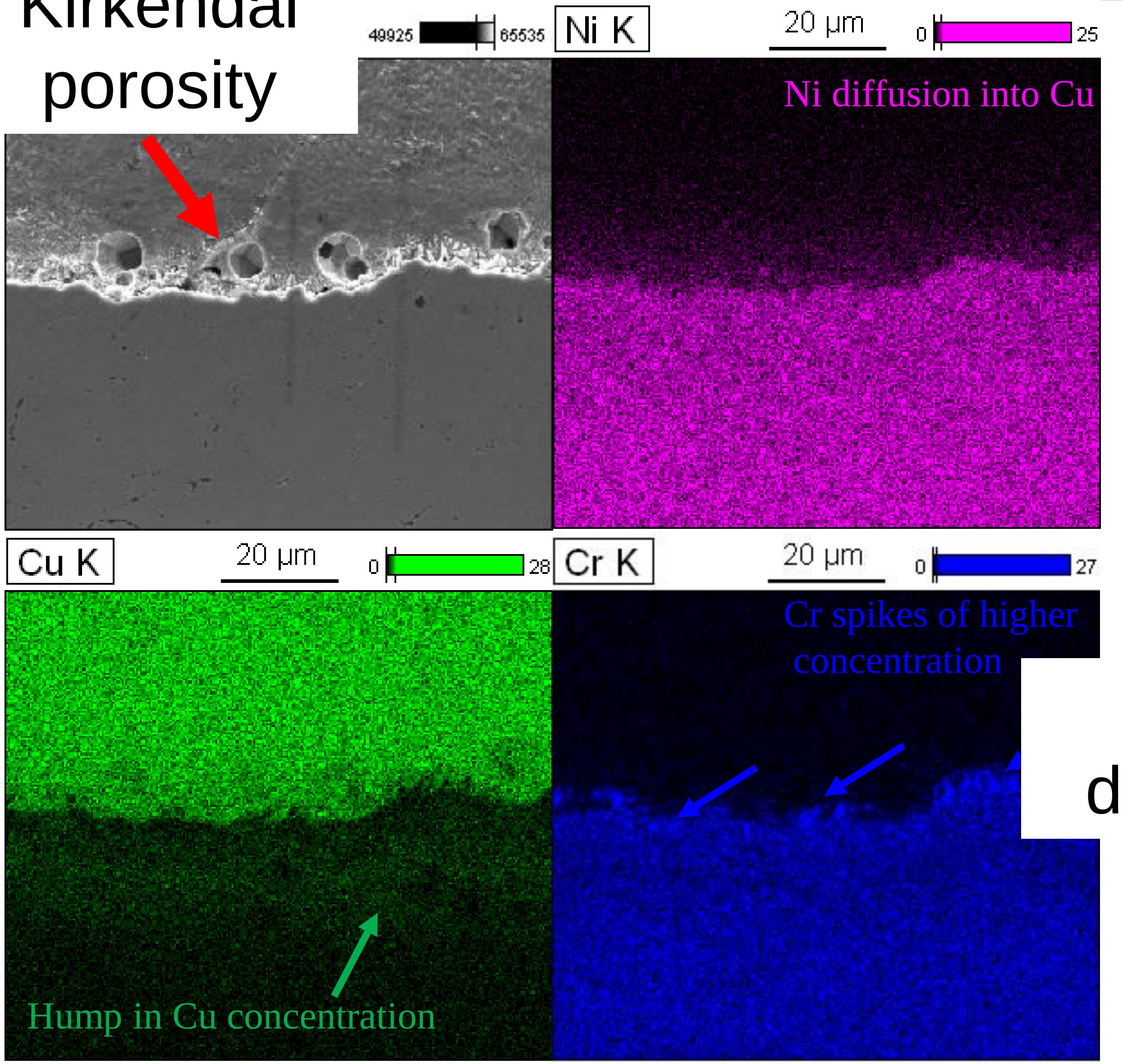


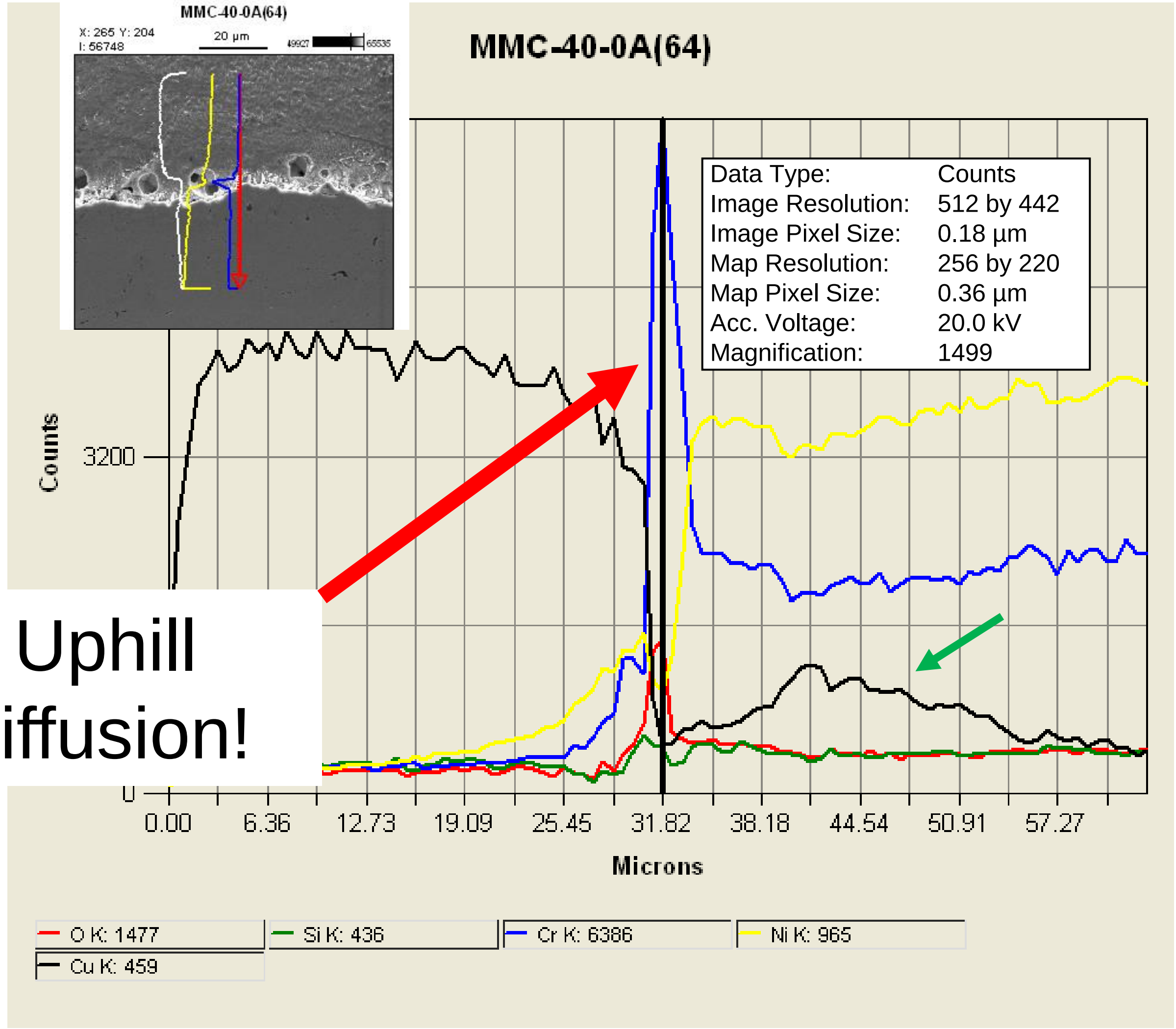
Brazed



All Hardness measurements are in HV1

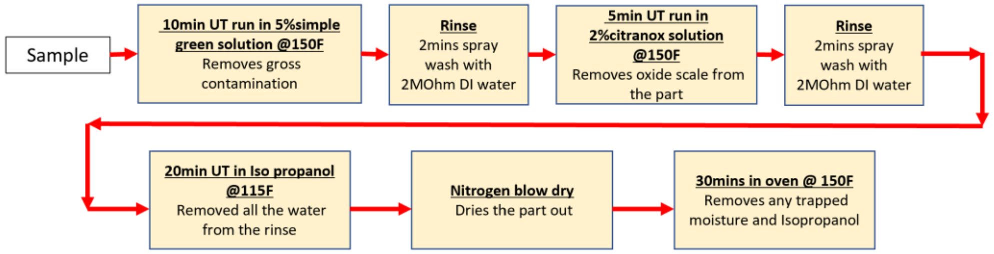
Ni-20Cr cold spray coating: Microstructure



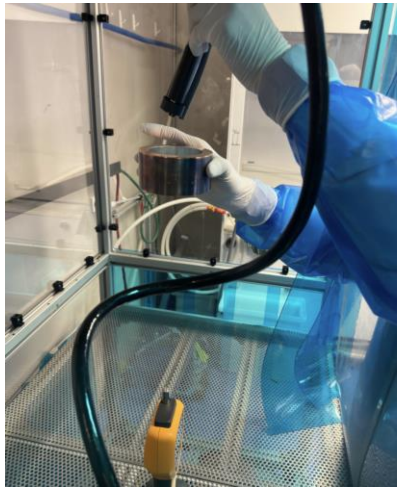


Cleaning & particulate shedding

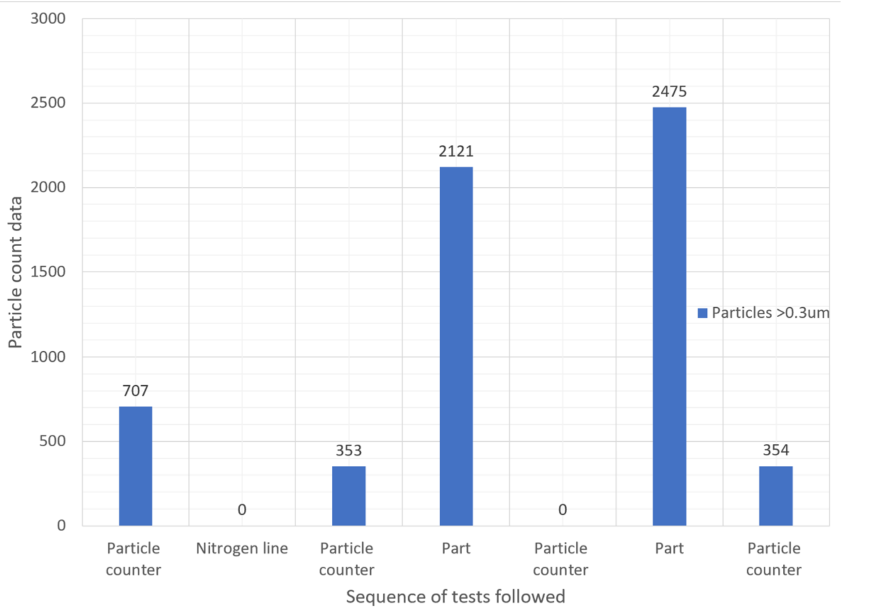
- Contaminate and particulate free BLAs critical to UHV beamline operation near SRF cavities
- Cleaning performed at Radiabeam:
  - 2MOhm-cm Type 2 DI water;
  - Custom 40kHz, 45 W/L large ultrasonic tank for cleaning large assemblies (27”x 20” x 14”)
- Particulate count testing performed in ISO5 hood according standards
  - ASTM E2042/2042M *Standard Practice for Cleaning and Maintaining Controlled Areas and Clean Rooms*
  - ISO-14644-2 *Monitoring to provide evidence of cleanroom performance related to air cleanliness by particle concentration*
- 0.3um and 5um particle channels monitored sampled at 2.8L/min for 1 min w/ Top gun ionizer blow off gun
- Particle count high: improvements to cleaning and blow-off procedure needs



RadiaBeam BLA cleaning procedure



Particle counting in soft-wall clean hood @ RBT



Shrink-fit SiC

- Quality control of lossy ceramic is decades-long problem
- Coorstek SC-35: Graphite Loaded Direct Sintered Silicon Carbide
  - Oil & Gas: Dry-running bearing for extreme environments
    - Graphite: built-in lubrication
    - Side-benefit: charge dissipation
  - Similar ‘dry-running’ graphite-loaded SiC products:
    - Saint Gobain-Hexoloy SG
    - 3M EkaSiC-P


X18 SC-35 cylinders: [3,5,10]mm WT at Radiabeam


Set-up with deadweight


Die set in inert gas oven


SiC fully inserted in the copper tube


Shrink-fit SC-35 in copper

Calculation and Simulation

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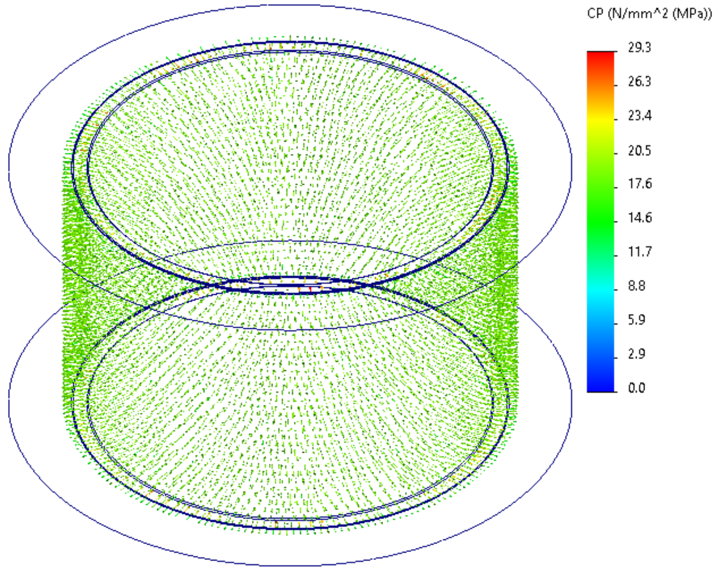
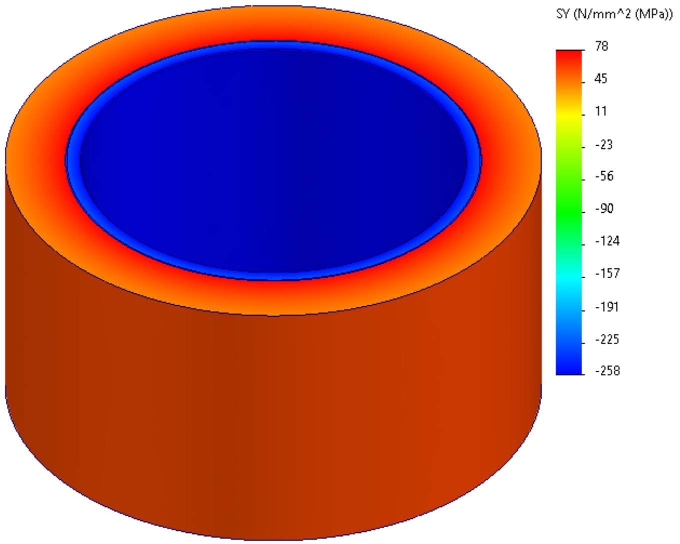
Interfering Surface Radial Pressure (MPa)

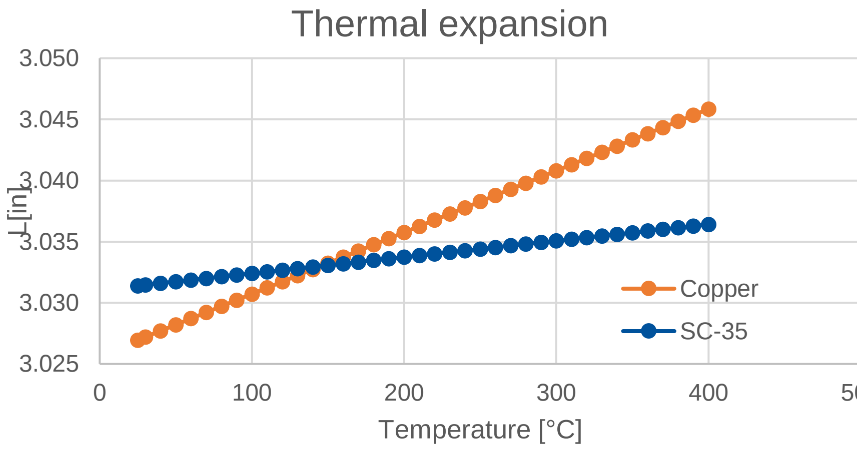


Calculation Summary

Inputs	
SiC inner radius, ri	1.398
SiC outer radius, Nominal radius R	1.516
Cu tube inner radius, Rcu	1.513
Cu tube outer radius, ro	1.951
Outputs	
Radial interference, δ [in]	0.0022
Heating temperature for zero clearance ΔT[°C]	141.5
Radial pressure on interfering surface, P [Mpa]	18.7
Maximum compressive stress on SiC, σSiC [Mpa]	**-231.7**
Maximum tensile stress on Cu tube, σCu [Mpa]	**75.8**

Hoop Stresses (MPa)





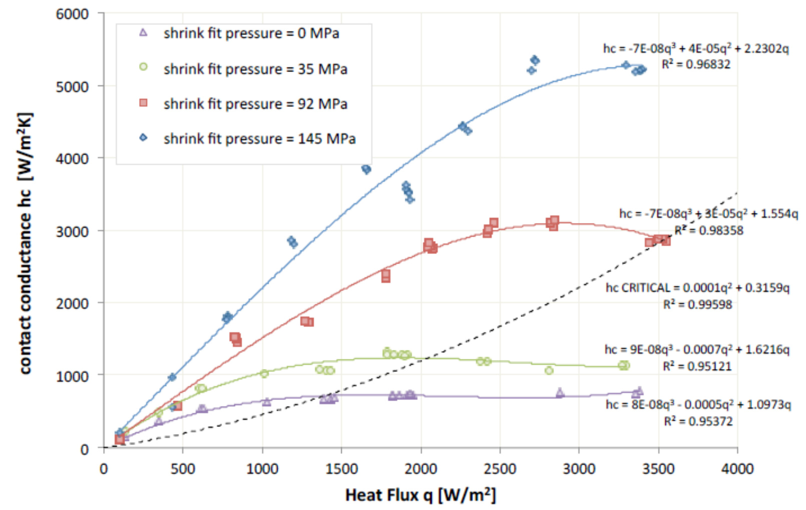
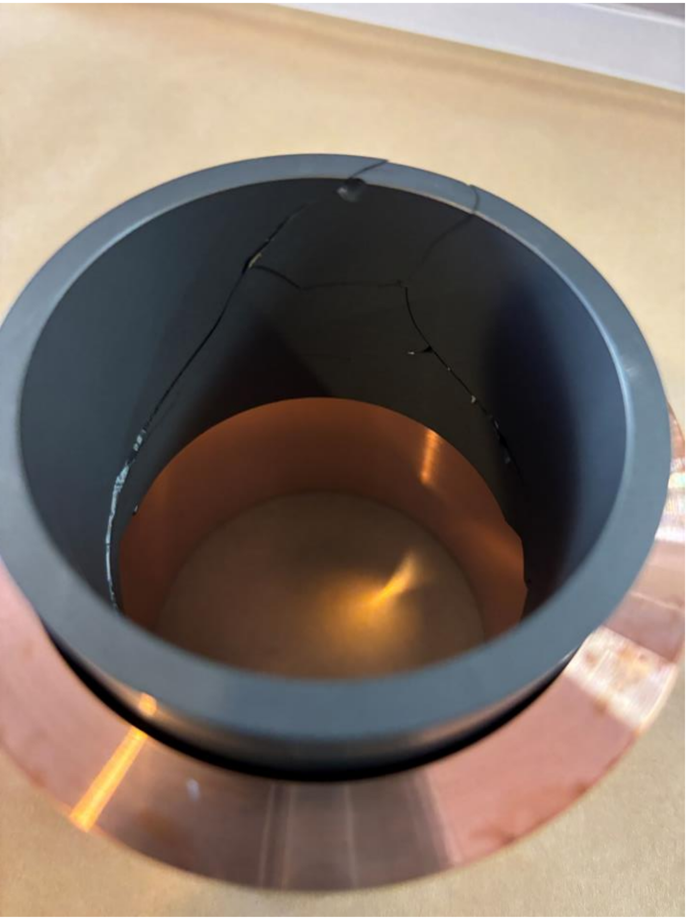
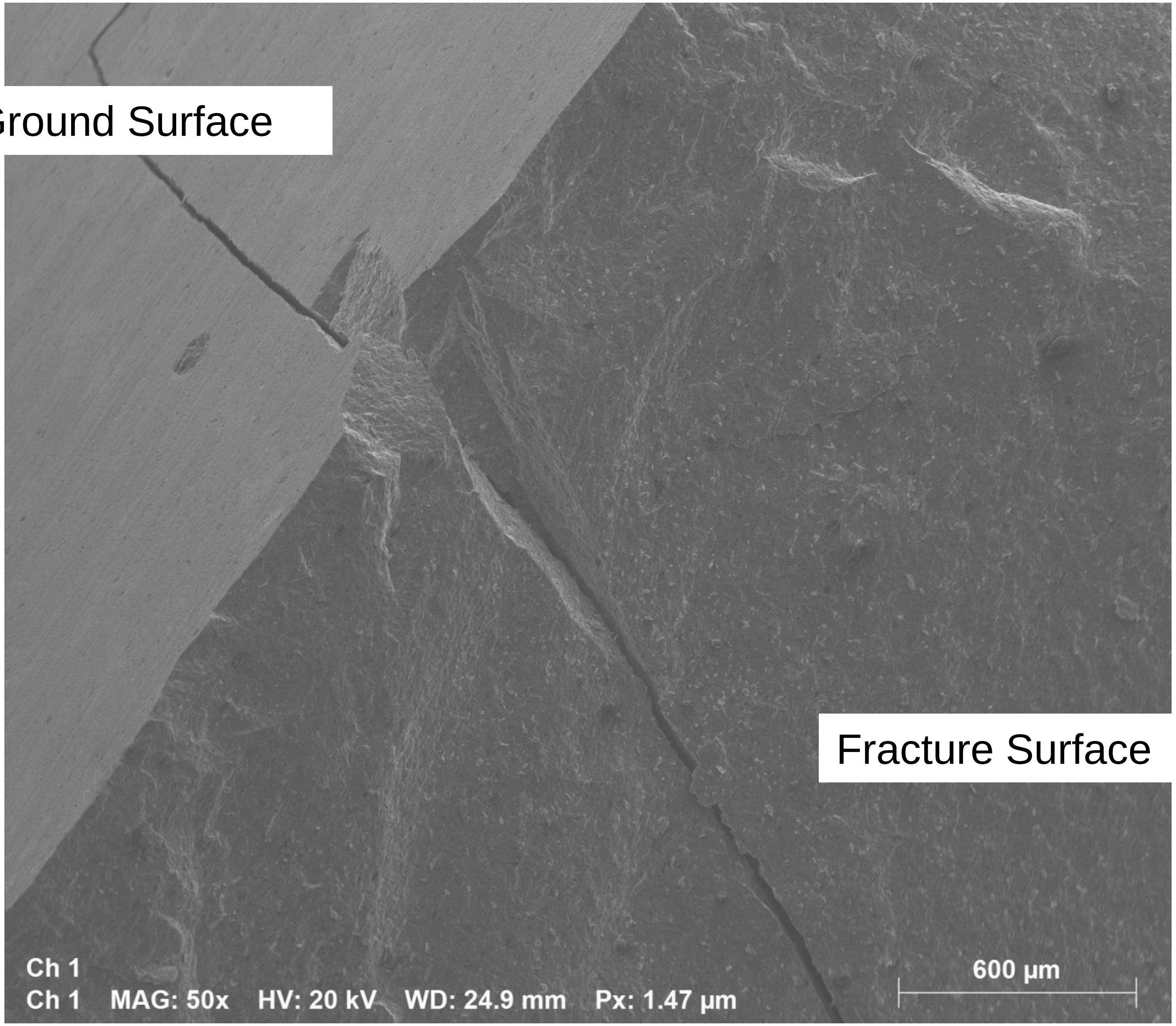


Figure 3: Chart showing measurements of how the thermal contact conductance varies with contact pressure and heat flux.

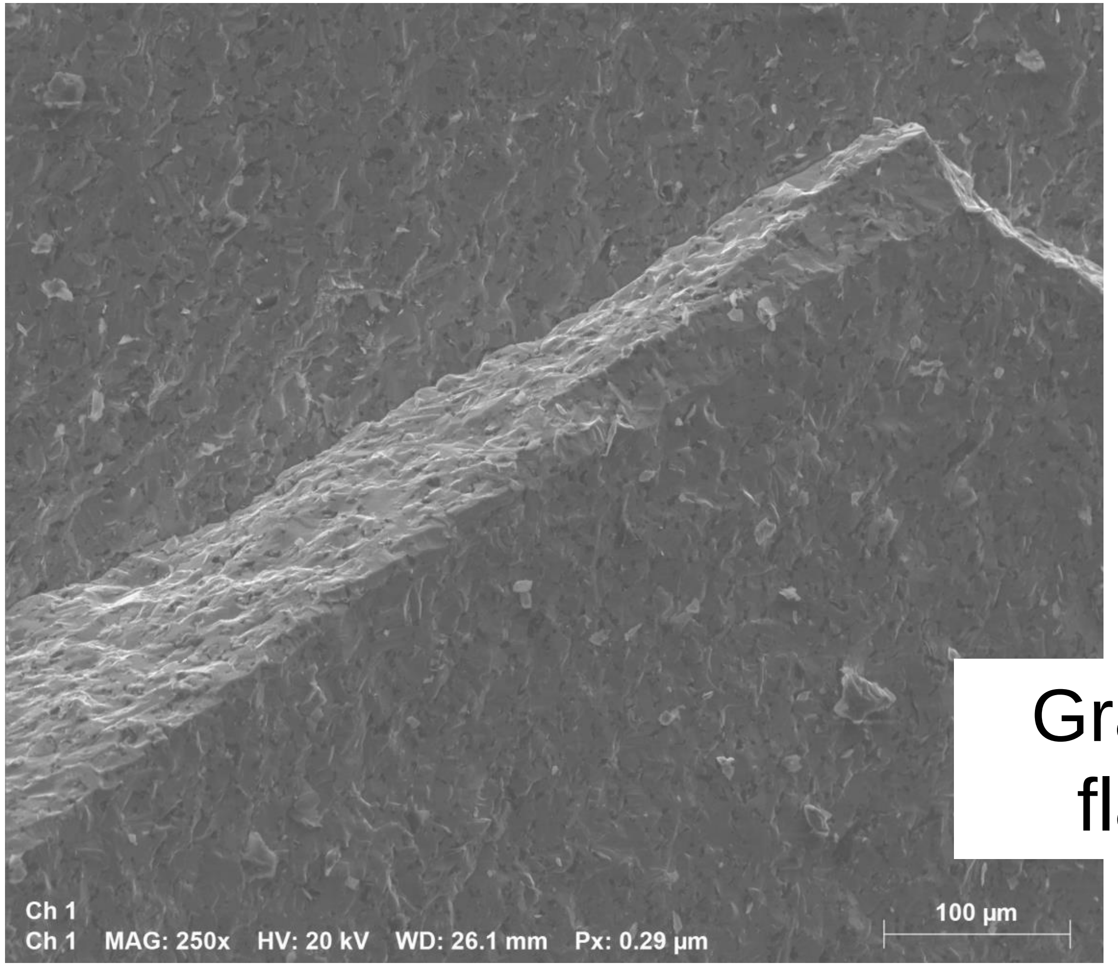
Camilleri, "Experimental investigation of the thermal contact resistance in shrink fit assemblies with relevance to electrical machines." (2014): 0444-0444.

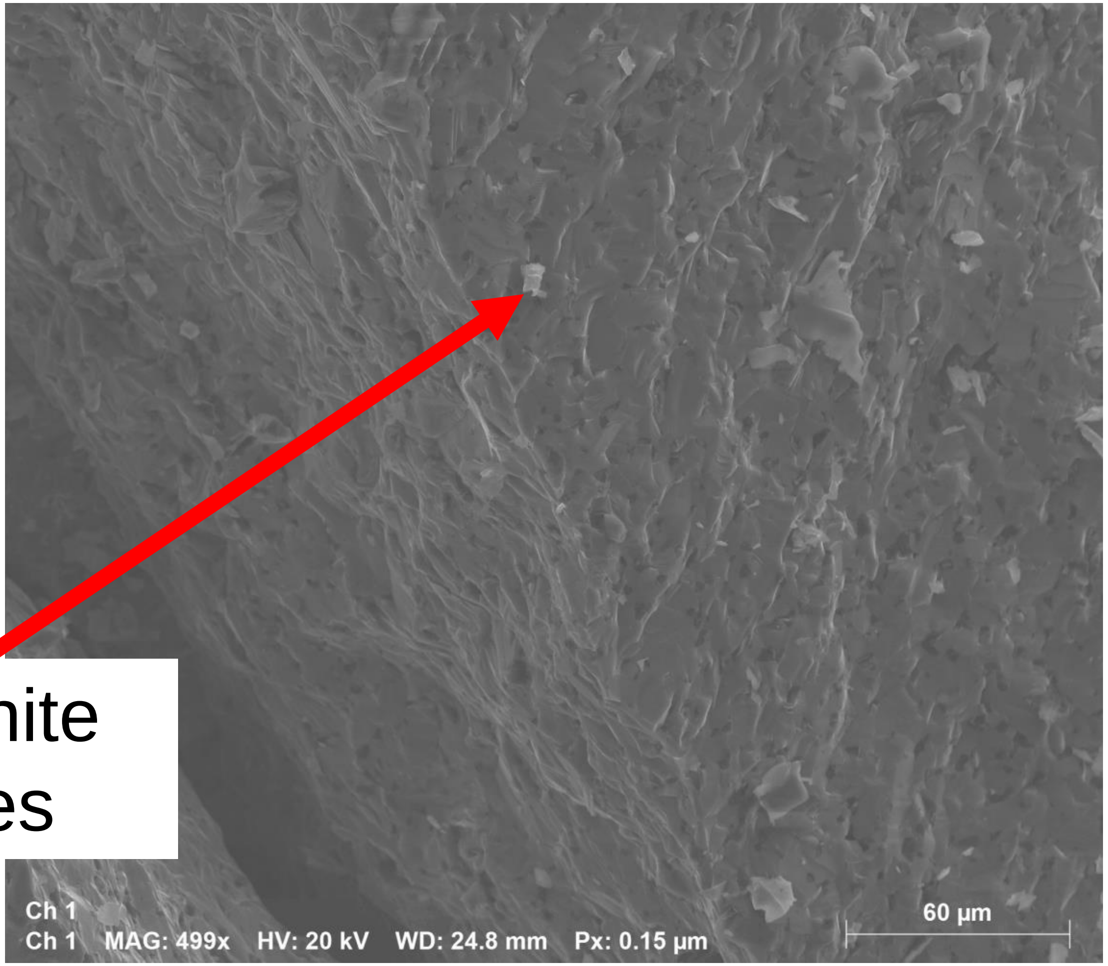
SC-35 fracture surface





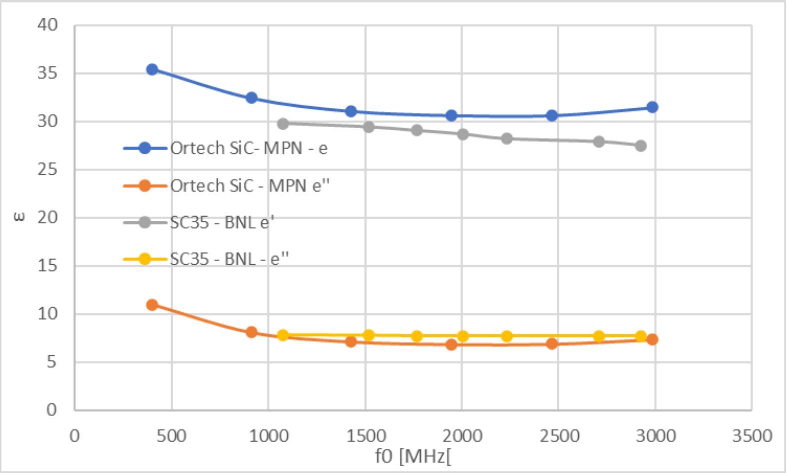
SC-35 fracture surface

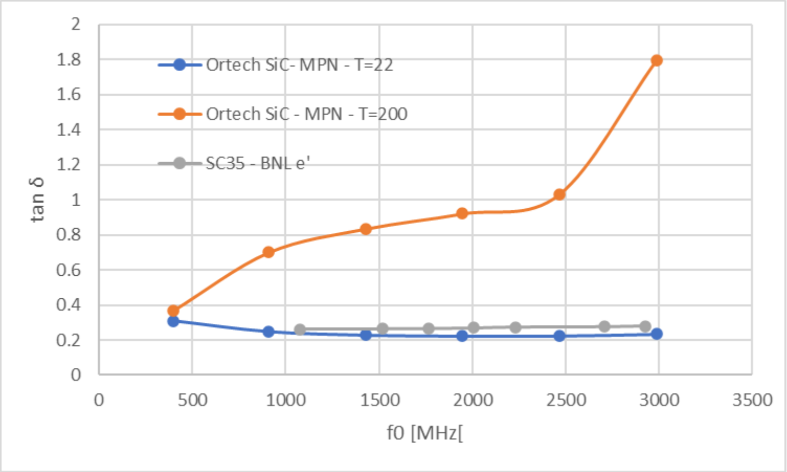


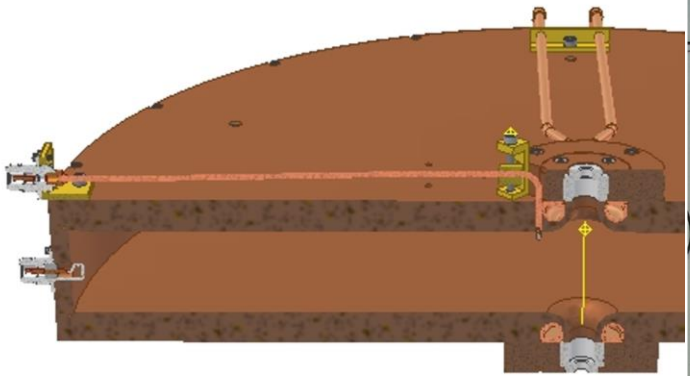


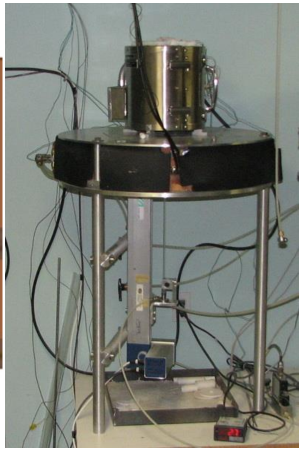
Resonant Cavity Characterization

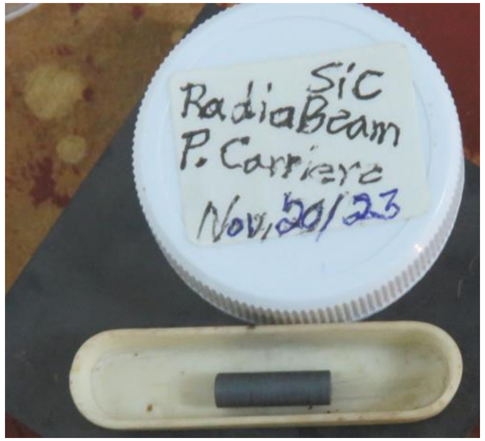
- Microwave Properties North: dielectric characterization of lossy dielectrics
  - Prior experience with CEBAF and CESR-B absorbers
  - Fixture is capable of measuring permittivity as function of temperature, compensate for CTE effects
  - Cylindrical sample: diameter 3.70mm, length= 12.05





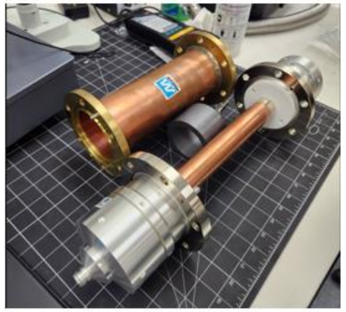


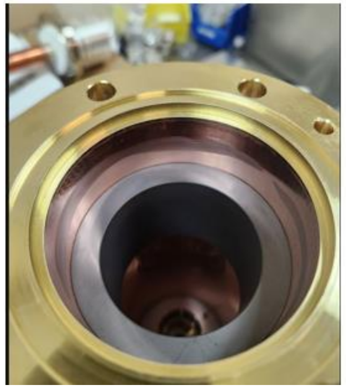


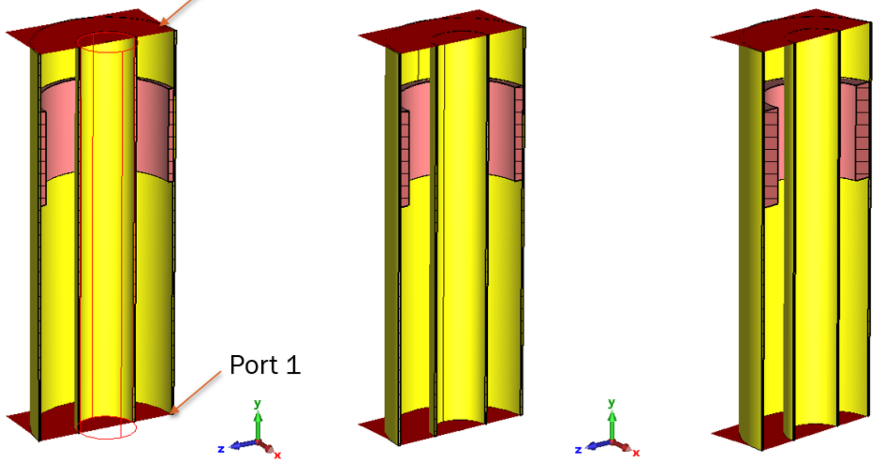


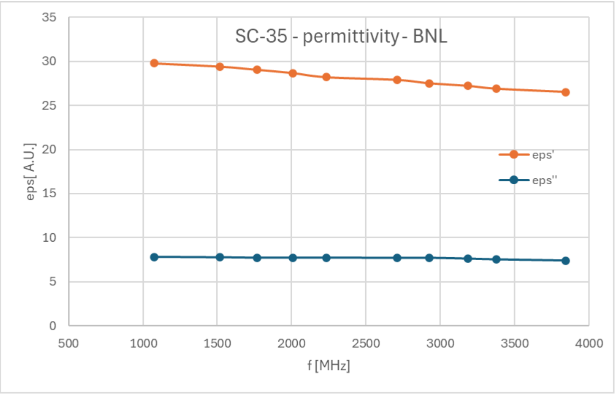
Low-power RF: Modelling & testing

- Calibrated, low power VNA measurements performed with EIA 3 1/8” coaxial cable
- RF modelling performed in CST Studio
  - Complex permittivity data provided by BNL





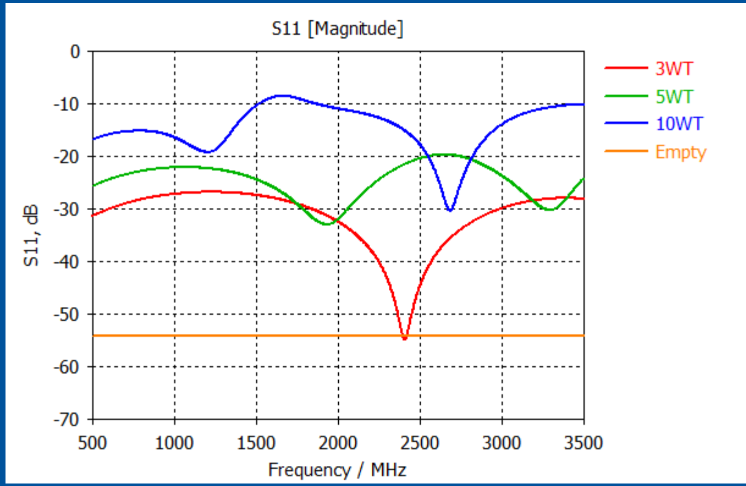


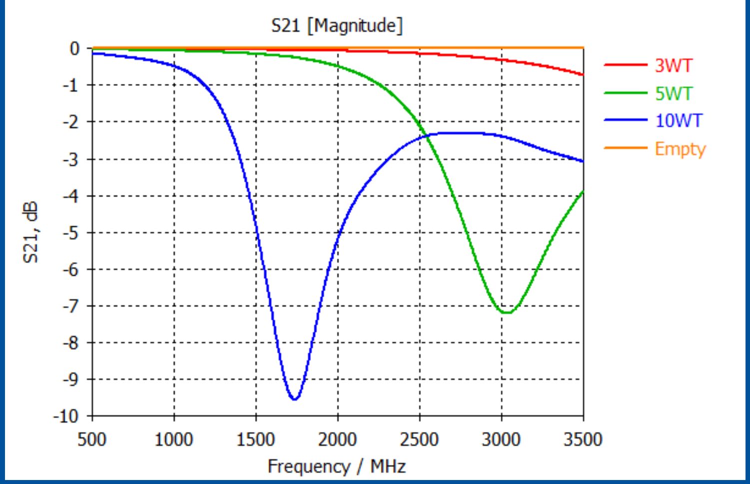


Low-power RF: Modelling & testing

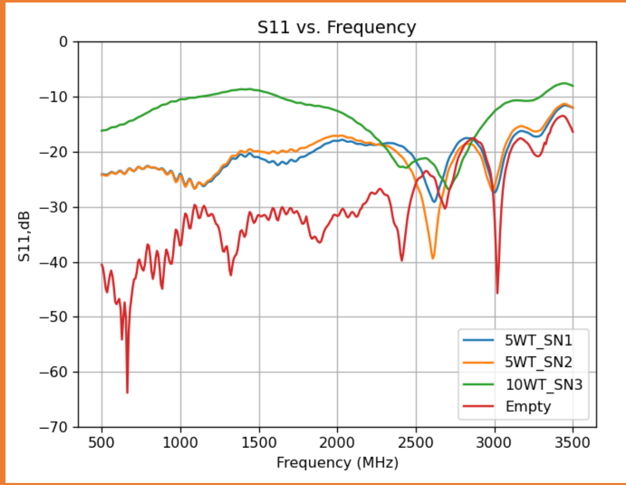
RadiaBeam

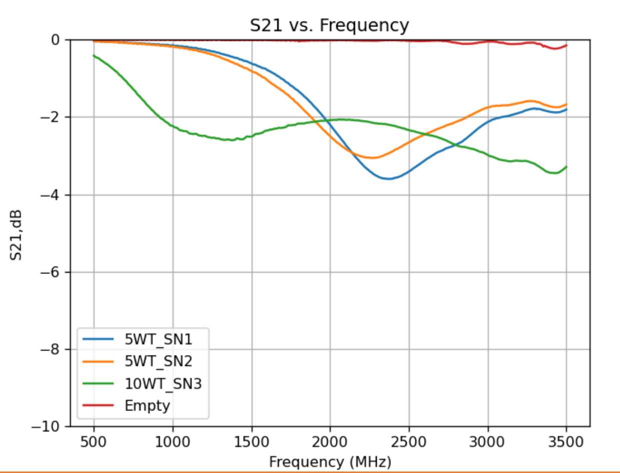
CST Results





Measurement Results



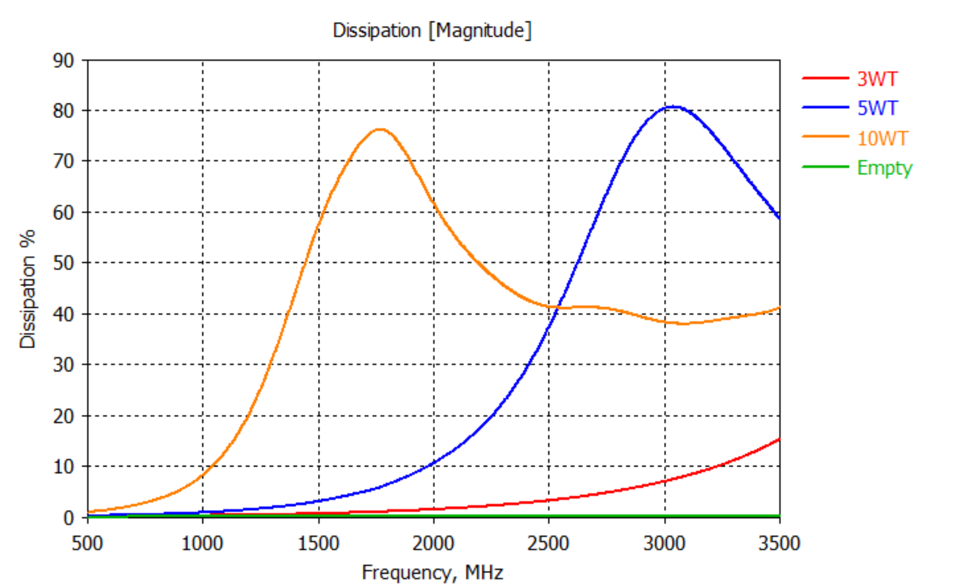


Low-power RF: Modelling & testing

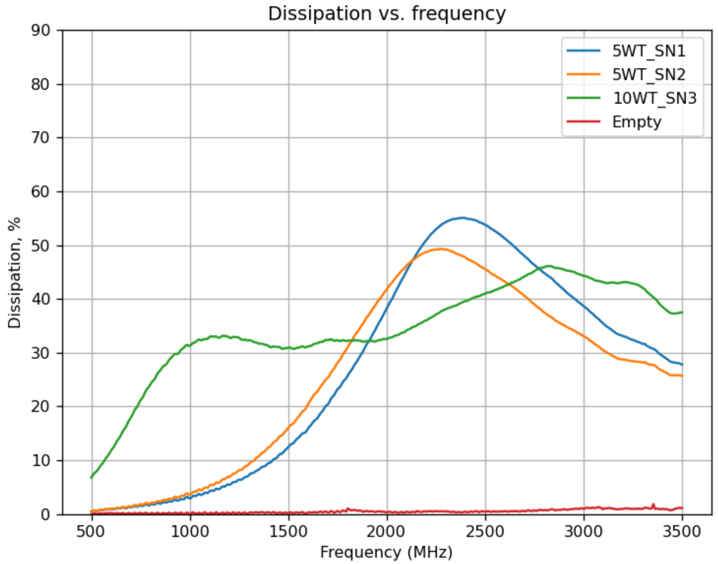
- Resonance absorption due to thickness effects of material
- Resonance frequency does not match CST
  - Differences in ε between material and model
- Variability in dissipation between nominally identical parts

$$Dissipation\ \% = \left(1 - S11^2 - S21^2\right) * 100$$

CST Results

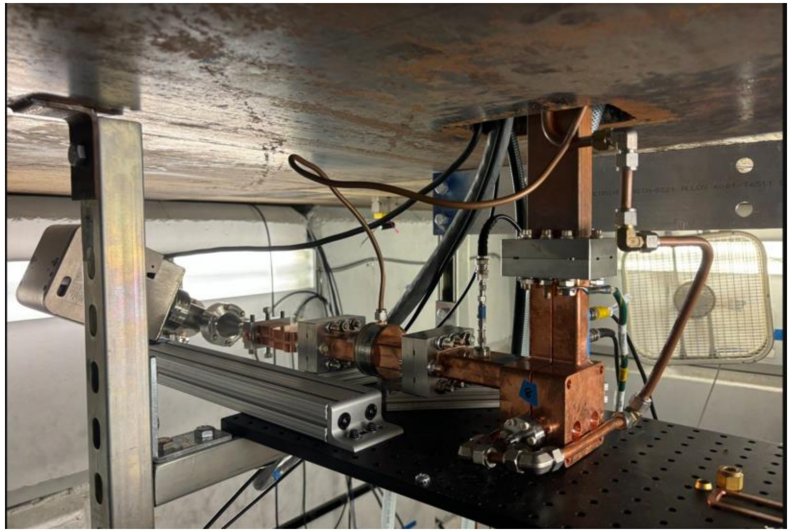


Measurement Results



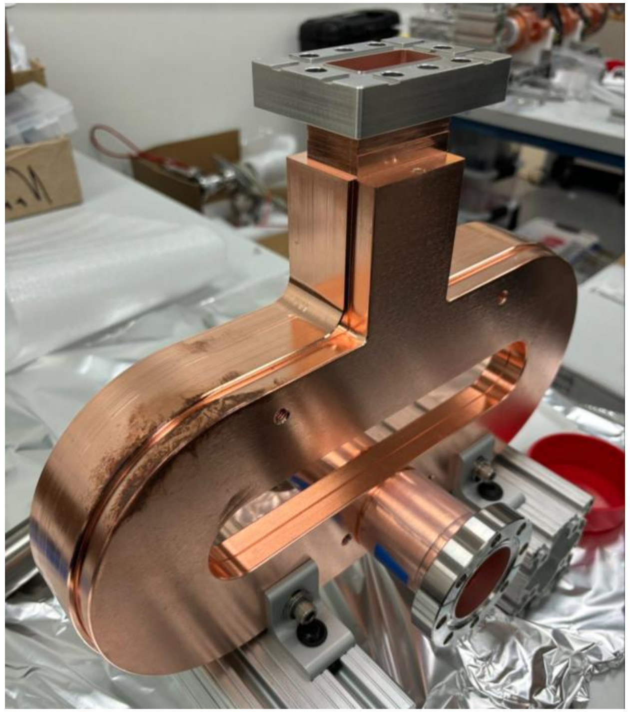
High power RF testing

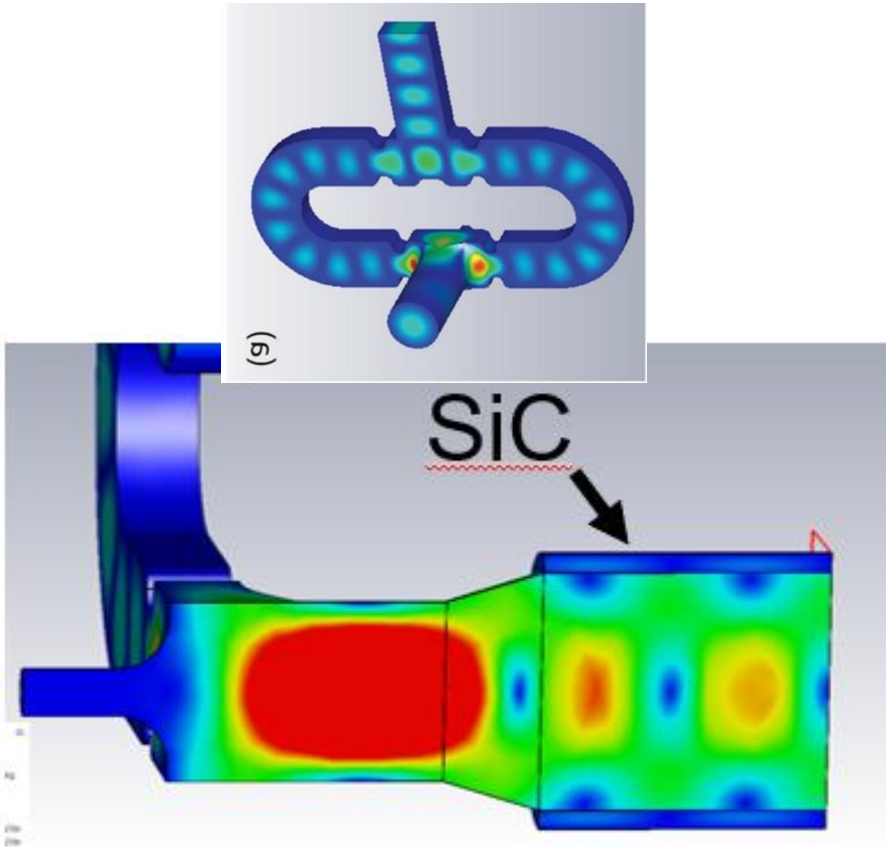
- In-house high power RF testing infrastructure
- 50MW Canon klystron with Scandinova modulator, 5kW max, 5712 MHz
- Vacuum waveguides, EPICS datalogging system (radiation, vacuum, RF)
- Concrete radiation bunker rated to 21MW

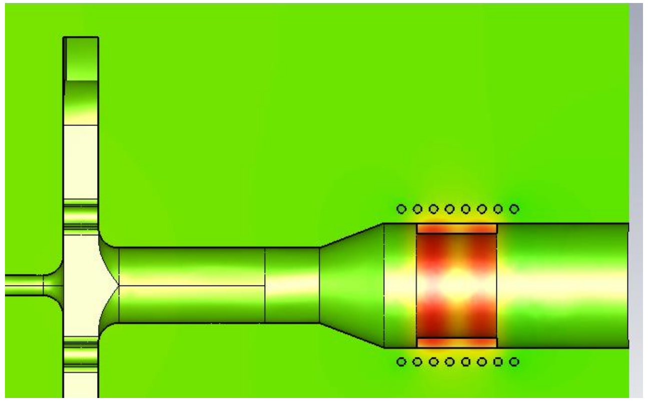


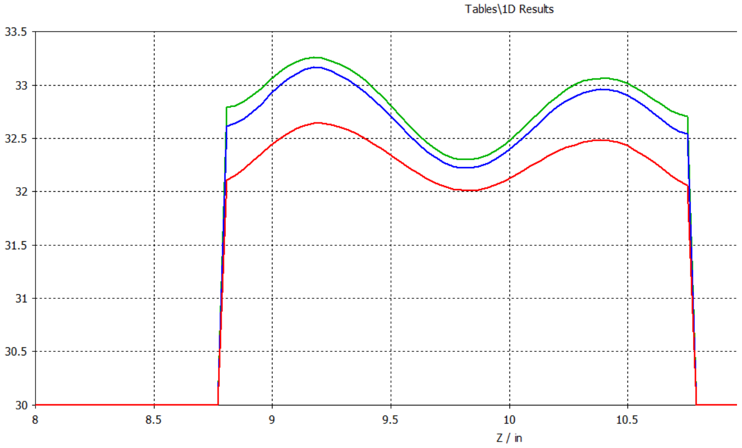
High power RF vacuum testing

- TE01 rectangular to TM01 circular mode convertedr
- Vacuum RF volume
- 5MW pk, (0.01% duty) 1uS pulse length 100Hz: 500W average
- Tune short but concerns about reflections to klystrons without circulator









Absorbed: (450W)
Equiv 6.1 mW/mm^3 (450W)
BNL: 5.7 mW/mm^3 (20kW)
-Reflected: 13dB (25W)
Wall cooling: 10kW/m^2 K

Nuclear Physics community - Discussion

- Testing standard: clear, unambiguous test results for dry UHV RF loads?
  - How to address variability of broadband RF data?
- Market demand signal from Lab??
  - Internal Lab development versus commercial BLAs
    - LCLS-II BLA: purchased from Europe with Sienna Tech(US) ceramic and DESY development
    - APS-U BLA: fabricated internally
    - EIC BLA: BNL LDRD for fabrication, design and testing
- Best value versus domestic production?
- SuperKEK-B upgrade, high power (37kW) BLA’s were jointly developed by KEK and Toshiba Energy Systems

Summary

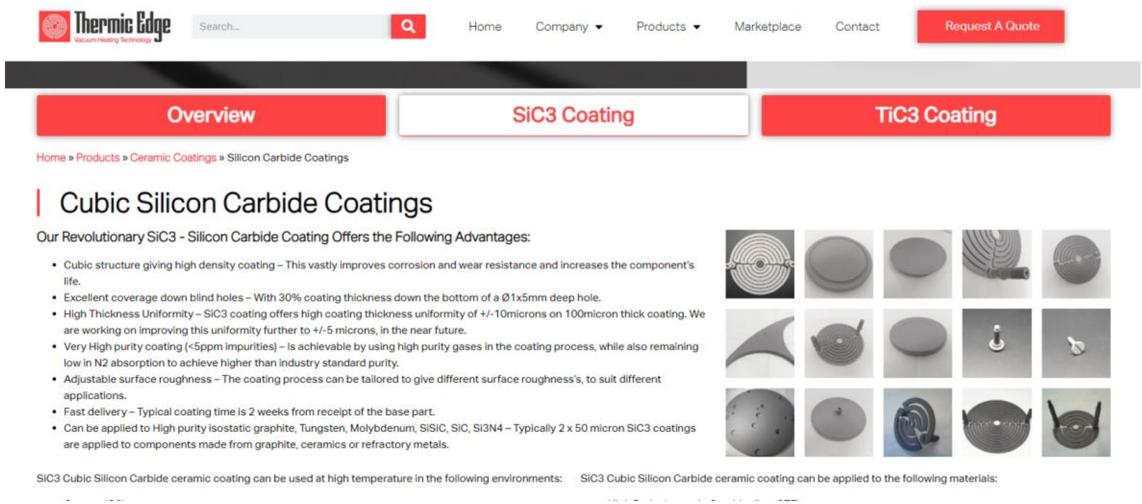
- Dry, UHV RF loads like BLAs have been a challenge for accelerator community
  - Demand is limited, usually ‘off-label’ application
  - Size matters: small samples ≠ full size assembly
  - Variability in test results, no ‘accelerator’ focused materials qualification exists
  - Coorstek SC-35 is standard in US: Japan and Europe have demonstrated other materials SiC
- Compact BLAs: volumetric heat dissipation, lossy dielectrics with high thermal conductivity
  - Heavy ceramic loading of cold spray coatings to make into dielectric is extremely difficult
  - Outgassing from coating porosity is a challenge
  - Shrink-fit SiC BLA solution is mechanically and thermally robust
- Comprehensive testing plan for reduced diameter BLA developed
  - Cost and performance comparison between conventional ceramics and cold spray parts
  - High power tests under vacuum critical to establishing commercial product for NP community

Thank you

- DOE Office of Science Nuclear Physics – Michelle Shinn
  - SBIR/STTR Award DE-SC0020562
- RadiaBeam: Kenichi Kanata, Nanda Matavalam, Camille Clement
- ANL: Michael Kelly
- JLab: Jiquan Gao & Haipeng Wang

Parts and Process

RadiaBeam



<u>100um CVD SiC coating on tungsten</u>

<u>CTE:</u> 4.2 x ppm / C

Fast delivery – Typical coating time is 2 weeks from receipt of the base part.

Can be applied to High purity isostatic graphite, Tungsten, Molybdenum, SiSiC, SiC, Si3N4

<u>Cost:</u> Total cost to plate x4 parts is **$408.**