Development and Testing of an Advanced HOM Absorber Design for SRF Accelerators Using Dielectric-Coated Cores

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for DOE Office of Science, Office of Nuclear Physics

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Agenda

- **Company Overview**
- **Ultramet SRF-Related Work**
  - Thick-film (>50 µm) chemical vapor deposited (CVD) bulk niobium and on copper cavities
  - Thin-film CVD (<25 µm) triniobium tin (Nb_3Sn) on copper cavities
  - Advanced HOM absorber design
- **Phase I Summary**
- **Phase II Status, Results to Date, Path Forward, and Schedule**
  - HOM absorber core material
  - CVD dielectric and attachment coatings
  - HOM absorber ring prototype fabrication and testing
- **Summary**

Company Overview

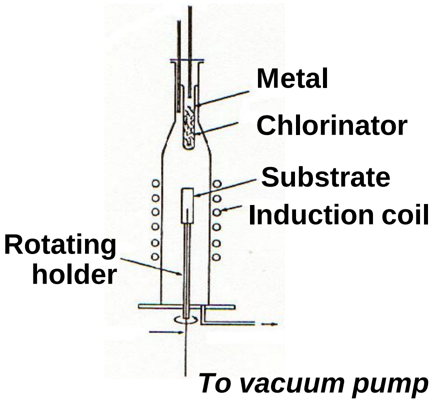
- Privately owned, founded in 1970
  - Manufacturing (aerospace/defense/medical)
  - R&D (government and commercial)
- Research, development, and manufacturing of advanced high temperature materials, primarily by chemical vapor deposition (CVD) technologies
- Quality management system based on ISO 9001:2015

Melting Points of Some Materials Deposited by Ultramet, °C

TaC	3987	TiN	2930	B	2027
HfC	3947	HfO_2	2897	Si_3N_4	1900
C	3827	TiB_2	2871	Ta_2O_5	1872
ZrC	3540	SiC	2797	Zr	1852
NbC	3500	WC	2777	TiO_2	1840
W	3410	ZrO_2	2715	Pt	1772
HfN	3305	W_2B	2671	SiO_2	1723
Re	3180	Mo	2610	Fe	1535
TiC	3140	Nb	2468	Ni	1455
TaN	3100	Ir	2443	Si	1410
ZrB_2	3038	B_4C	2350	Cu	1083
Ta	3014	NbN	2327		
BN	3000				
ZrN	2980				

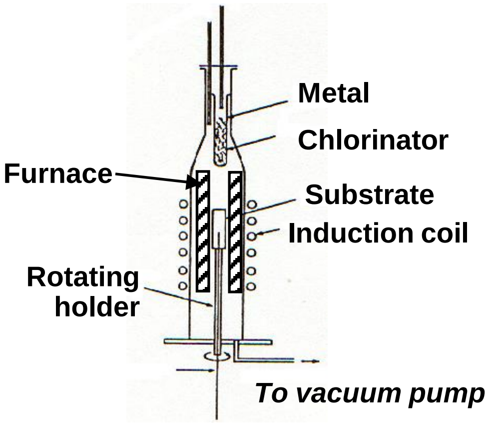
Cold Wall Process

Selective heating and preferential deposition



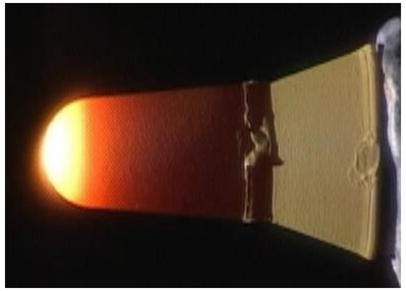
Hot Wall Process

Isothermal heating and uniform temperature control

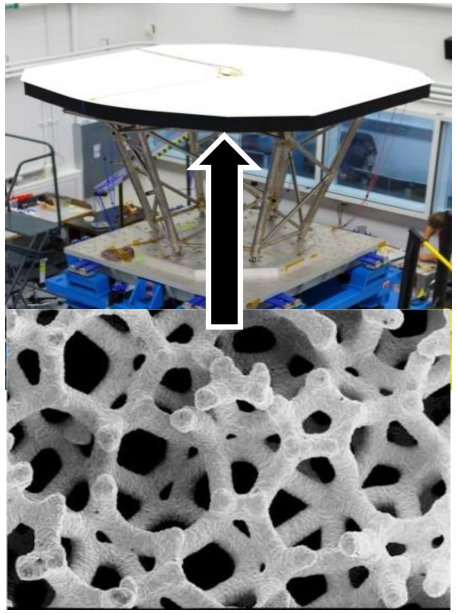


Company Overview (cont'd)

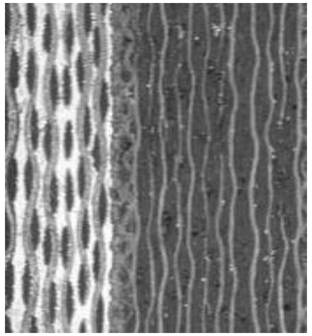
CVD Coatings



Open-Cell Foams



Ceramic Matrix Composites (CMC)



Ultramet SRF-Related Work

Ultramet SRF R&D Project Path (2005 to Present)

- CVD fabrication of seamless bulk niobium cavity
- High-RRR CVD niobium process evaluation and development
- Thick-film CVD niobium on copper process development
- CVD Nb_3Sn process development
- Thin-film CVD Nb_3Sn on copper via prealloyed precursors
- Advanced HOM absorber design development

Support

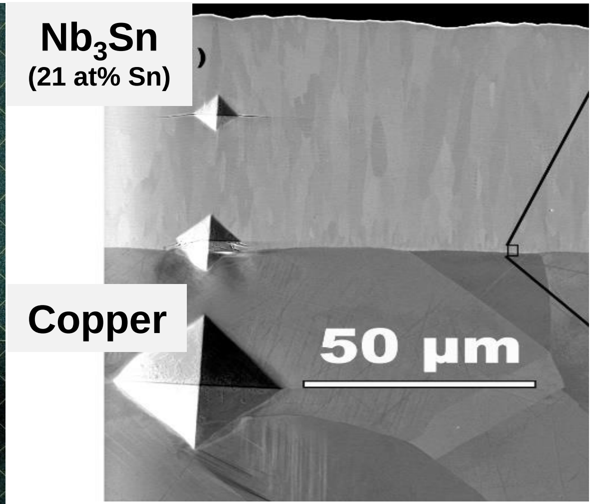
- DOE NP & HEP offices
- SRF Group at Cornell
- Jefferson Lab (JLab)
- Niowave
- UCLA
- Oak Ridge National Laboratory
- Florida State University - MagLab
- Bailey Tool & Manufacturing

Ultramet SRF-Related Projects (cont'd)

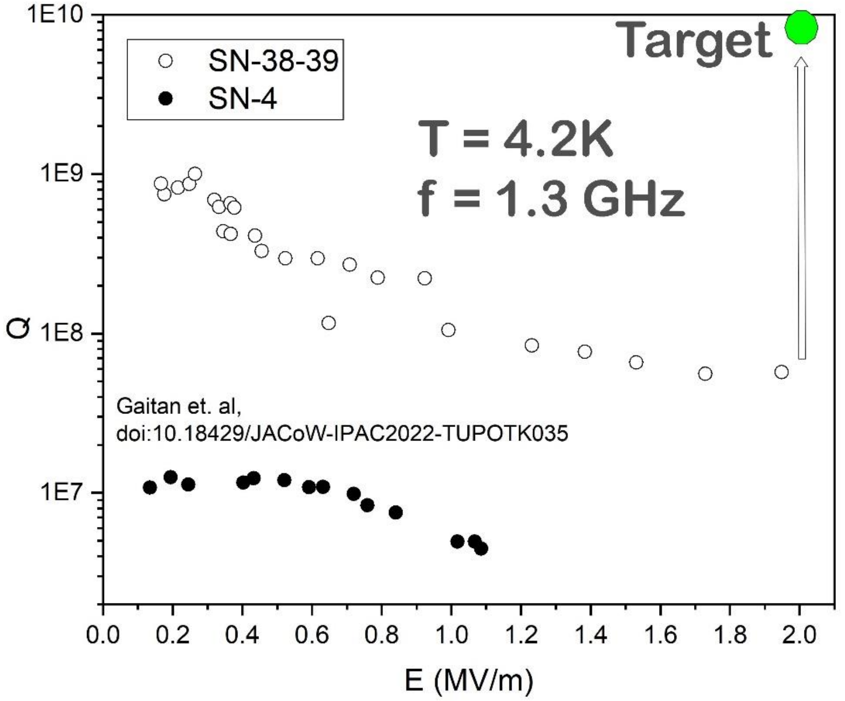
PROGRESS

CVD high-RRR bulk Nb cavity

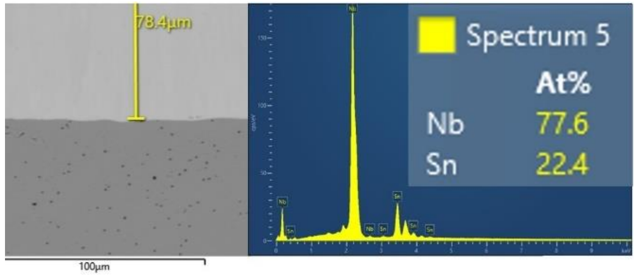
CVD Nb_3Sn coating on CVD niobium interlayer on welded copper cavity substrate (Niowave)



CVD Nb_3Sn coating on copper substrate: excellent adhesion



Q vs. E at 4.2 K for CVD Nb_3Sn on welded copper cavity (SN-38-39) and on seamless copper cavity (SN-4) (both on CVD niobium interlayer)

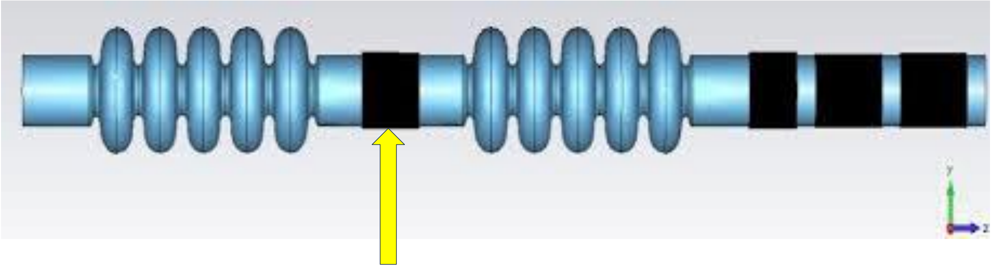


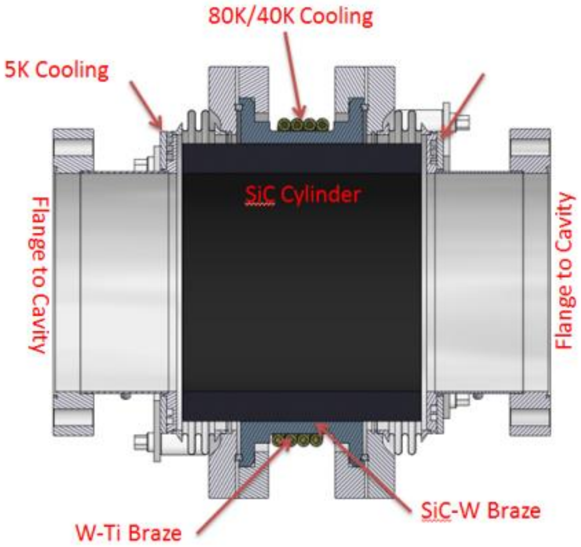
CVD Nb_3Sn on welded copper cavity

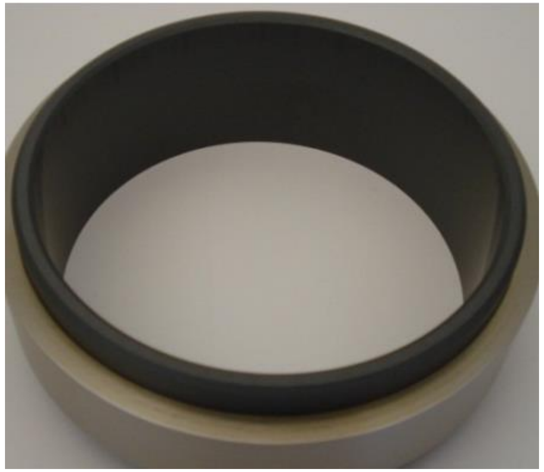
Overall HOM Absorber Design Goals

The overall focus of the Phase I-Phase II project is on development of beamline HOM absorbers of the type positioned inside superconducting cavity-interconnecting beam tubes meeting the following specifications:

- Strong broadband RF absorption over range from a few hundred MHz to GHz
- Very low material outgassing in ultrahigh vacuum (UHV) operating environment
- High heat transfer capability
- Cryogenic operating capability (typically ~80 K)
- Sufficient DC electrical conductivity to address any charge accumulation effects





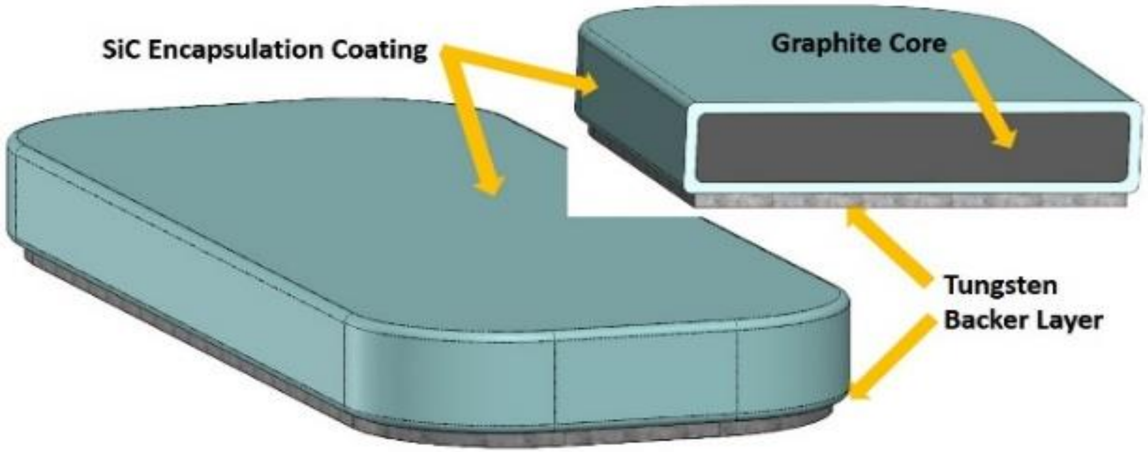


Beamline HOM absorbers (*left*) and Cornell University HOM design for energy recovery LINAC (ERL) (*center*)

Phase I Goals

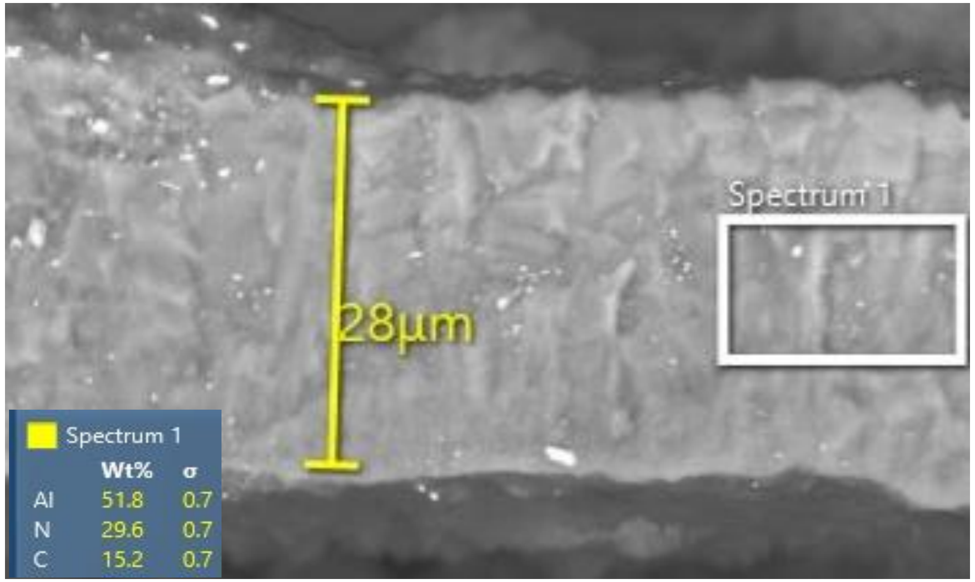
The main goal of the Phase I project was to develop CVD-based processing techniques to fabricate robust broadband HOM absorber structures for use in SRF accelerators. Specifically, an advanced HOM absorber design composed of a dielectric-coated high-purity graphite core with a high thermal conductivity tungsten backing surface for bonding purposes was fabricated. In this design:

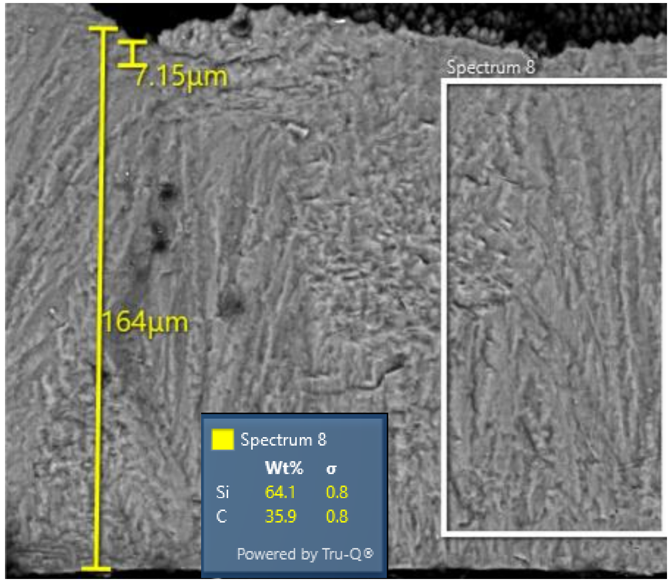
- ❖ The graphite core will dominate the absorption characteristics.
- ❖ The dielectric coating will contribute to broadening the frequency range attenuation capabilities while preventing outgassing of latent core materials.
- ❖ The tungsten backing surface will facilitate subsequent attachment to a parent component, and during operation will serve to provide an efficient path for removal of heat energy resulting from surface charge accumulation effects.



Small tile HOM absorber concept

AlN- and SiC-encapsulated graphite (UHP SIC-6) cores and tungsten backing layer





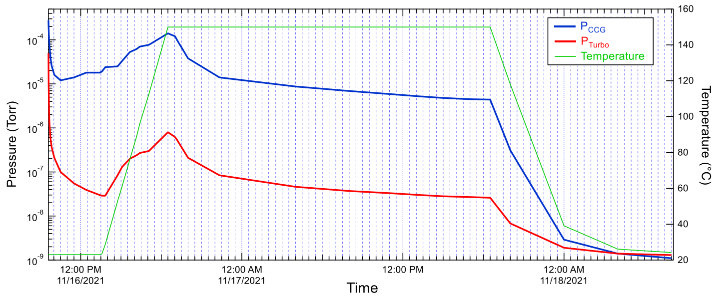
SEM/EDS analysis of ultrahigh-purity graphite core encapsulated with AlN (*left*) and SiC (*center*), with excellent coating/substrate interface boundary layer; SiC-encapsulated graphite tile with tungsten backing layer (*right*)

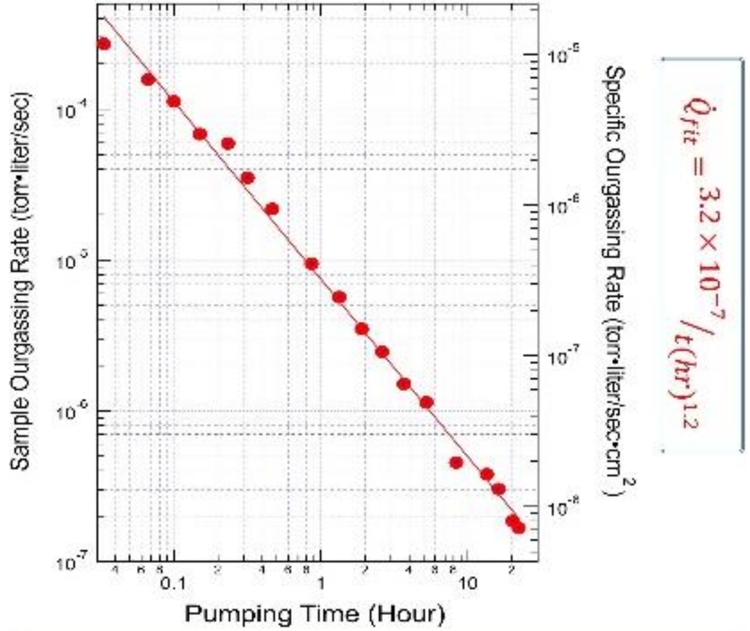
Outgassing and Thermal Cycle Testing

Thermal cycle testing of graphite core with AlN dielectric coating and tungsten backing layer

Ambient-to-cryogenic thermal cycling tests in an ultrahigh vacuum environment confirmed:

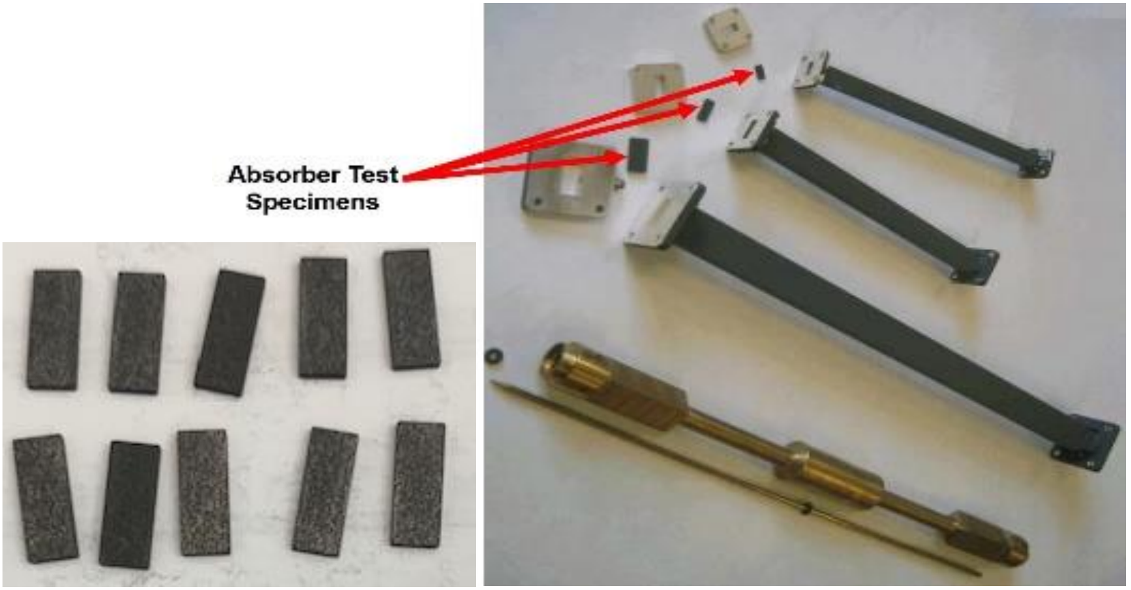
- Survivability and robustness of the dielectric CVD SiC encapsulation coating
- Survivability of CVD dielectric coating-to-CVD tungsten backing interface bond under cryocycling





Outgassing test results for an AlN-encapsulated graphite tile with tungsten backing plate following bakeout under vacuum at 150°C with nitrogen venting for 24 hours. Specimen outgassing rate significantly improved to ~3.2×10^{-7} (torr·liter/sec·cm^2)/(t/hr) following bakeout.

Cryogenic RF Testing



T1: RF Waveguides

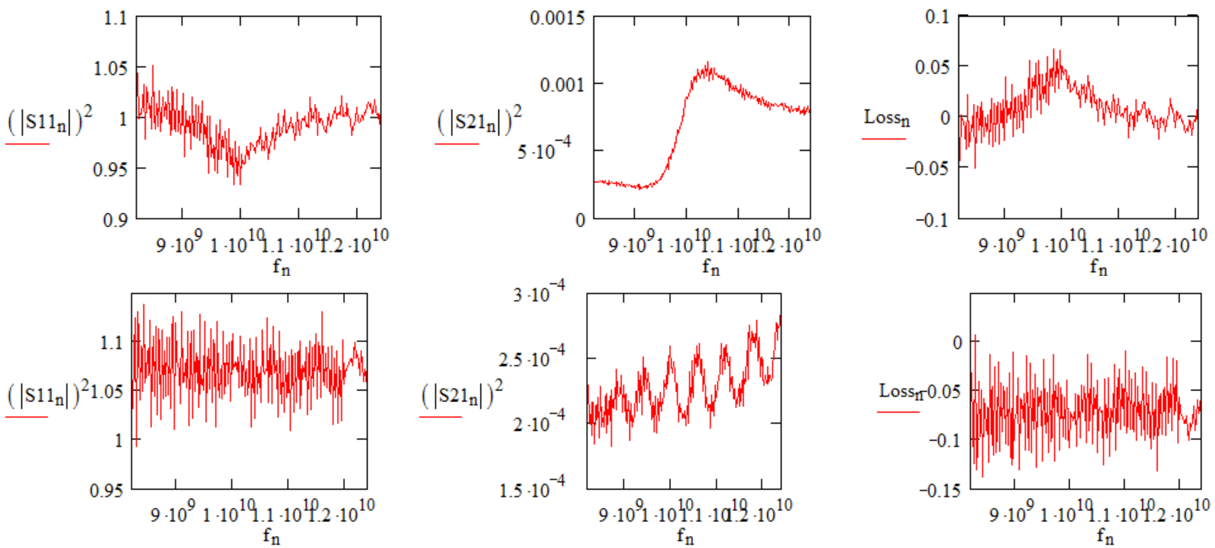
Table I: Nominal Specimen Dimensions Suitable for Three Waveguide Frequency Ranges

	Frequency range	Length (mm)	Width (mm)	Thickness (mm)
Waveguide 1	WR90 (8.2-12.4 GHz)	22.86	10.16	3
Waveguide 2	WR62 (12.4-18 GHz)	15.79	7.8994	2
Waveguide 3	WR42 (18-26.5 GHz)	10.668	4.318	1

Cornell test setup used for cryogenic RF measurements, including Agilent network analyzer. The waveguide line portion containing the test specimen was immersed in a bath isolated by foam material. This assembly was contained in a transparent plastic bag to prevent condensation of water and cooled using liquid nitrogen (boiling point –320°F). The temperature of the waveguide shim with the specimen was measured by a thermocouple.

RF Testing Results

Room and cryotemperature RF test results for CVD SiC-encapsulated graphite core material



RF absorption characterization of bare and dielectric-coated graphite core materials was performed to quantify and compare the performance capabilities of each.

S-parameters and losses for SiC-coated graphite specimen at 76°F (*top row*) and at –192°F (*bottom row*)

The test results show low-loss capability for specimen SiC-1-1 (beta-SiC), typical of the highly reflective Ultramet graphite core test specimens due to the highly conductive graphite.

Cornell concluded that within the framework of existing theory, the high electrical conductivity of the graphite core material made it impossible to use the S-parameter measurements for calculation of dielectric permittivity and magnetic permeability as intended due to nearly all RF power being reflected from the specimens, giving an excessively high and unusable value of dielectric permittivity.

Phase I Summary

- RF testing at Cornell determined standalone ultrahigh-purity graphite core materials are too electrically conductive and incompatible with the HOM absorber application.
- RF testing also determined the dielectric coatings were highly reflective.
- Core materials with low conductivity such as Al_2O_3, ZrO_2, SiO_2, SiC, carbide composites, and matrix doping agents such as carbon were identified as potential HOM absorbers.
- Validation of the CVD process for the AlN and SiC dielectric coatings was performed.
- Validation of the CVD process for the tungsten backing layer was performed.

Phase II Goals

The objective of the Phase II project is to test the core materials and CVD dielectric coatings identified in Phase I and fabricate and test a prototype HOM ring assembly. Specifically:

- Fabricate test specimens of core materials with low electrical conductivity such as Al_2O_3, ZrO_2, SiO_2, SiC, carbide composites, and matrix doping agents such as carbon.
- Perform RF absorption characterization and downselect core material.
- Optimize CVD process for BN dielectric encapsulation coating.
- Scale and optimize CVD process to form well-adhered tungsten on dielectric core and encapsulation coating(s) sufficiently thick to enable bonding to a parent component.
- Bond tungsten-clad dielectric-encapsulated core materials to surrogate component.
- Fabricate prototype HOM absorber ring assembly and perform RF absorption characterization to quantify performance.

Phase II Results to Date

Core Material Downselection

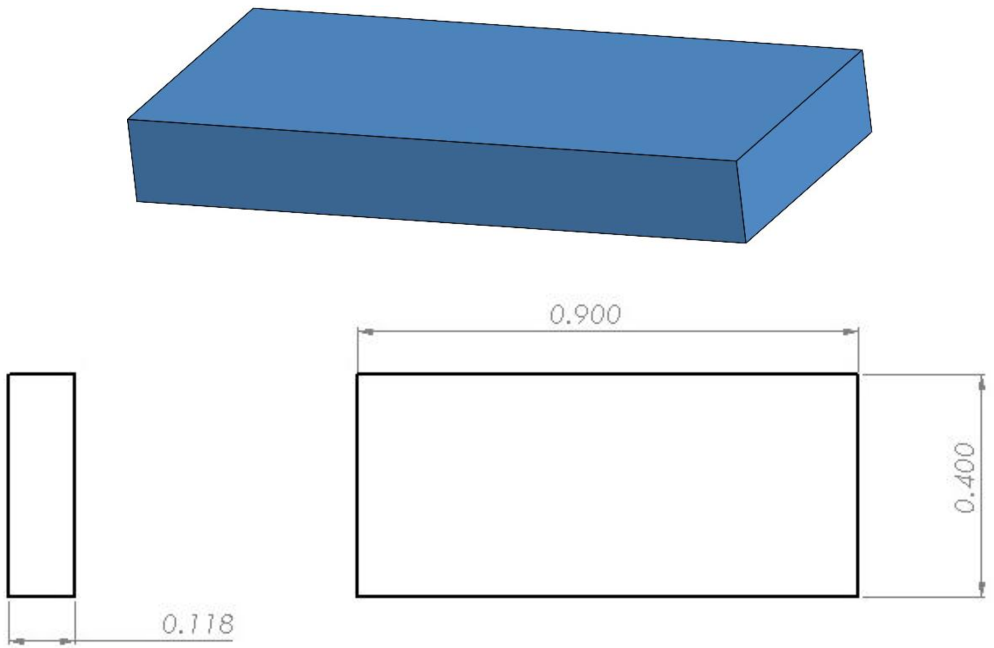
- Commercially available: Al_2O_3, ZrO_2, SiO_2, SiC
- Ultramet composites: C_f/ZrC and C_f/SiC; SiC foam
- Pennsylvania State University, via field assisted sintering technology (FAST):
    - Pure α-SiC
    - Doped SiC (graphene @ 1%, 7%, 25%)
    - Chaotic carbides/cermets: HfNbTiVZrC, HfNbTaTiZrC, MoNbTaVWC, CrMoNbTaWC

(Selected chaotic carbide recipes resulted from modeling performed by Dr. S. Curtarolo of Auro Scientific Consulting/Duke University.)

Core Material Downselection

HOM Core Test Part Types and Sources (2-4 each fabricated)

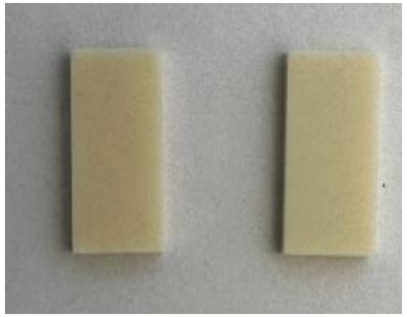
Cornell RF Report #	PN	Material	Source
240715	1%G-SiC-1	1% graphene-doped SiC	PSU - FAST
240715	1%G-SIC-2	1% graphene-doped SiC	PSU - FAST
240312	S7G1	7% graphene-doped SiC	PSU - FAST
240312	S7G2	7% graphene-doped SiC	PSU - FAST
240312	S25G1	25% graphene-doped SiC	PSU - FAST
240312	S25G2	25% graphene-doped SiC	PSU - FAST
240312	PS1	Pure SiC	PSU - FAST
240312	PS2	Pure SiC	PSU - FAST
240312	PN1-0	MoNbTaVWC	PSU - FAST
240312	PN1-1	MoNbTaVWC	PSU - FAST
240312	PN1-2	CrMoNbTaWC	PSU - FAST
240312	PN1-3	HfNbTiVZrC	PSU - FAST
240312	PN1-4	HfNbTaTiZrC	PSU - FAST
230614	SiC-7	CVI SiC Foam	Ultramet
220914	ZC-1	ZrC-f CMC	Ultramet
220914	ZC-2	ZrC-f CMC	Ultramet
220914	SiC-1	SiC-f CMC	Ultramet
220914	SiC-2	SiC-f CMC	Ultramet
221007	ZO-1	ZrO2	Commercial OTS
221007	SiC-5	SiC	Commercial OTS
221007	SiC-6	SiC	Commercial OTS
221007	AlO-vd-1	Al2O3	Commercial OTS
221007	AlO-vd-2	Al2O3	Commercial OTS
221007	SIO-vd-1	SiO2	Commercial OTS
221007	SIO-vd-2	SiO2	Commercial OTS
221219	AlN-1	AlN	Commercial OTS
221219	AlN-2	AlN	Commercial OTS
220914	ZO-1	ZrO2	Commercial OTS
220914	ZO-2	ZrO2	Commercial OTS

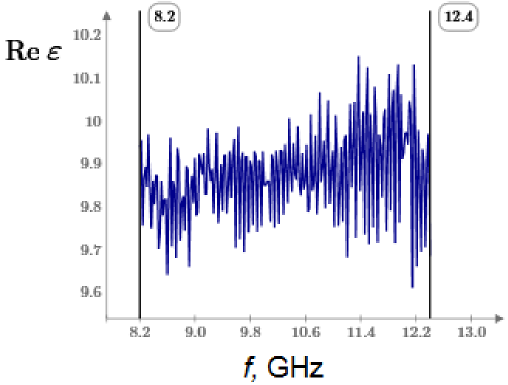


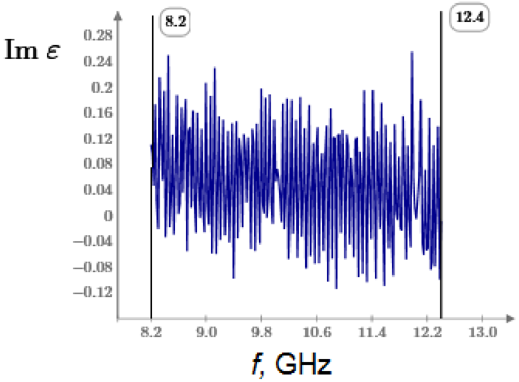
WG-1 style tiles produced and tested by Cornell

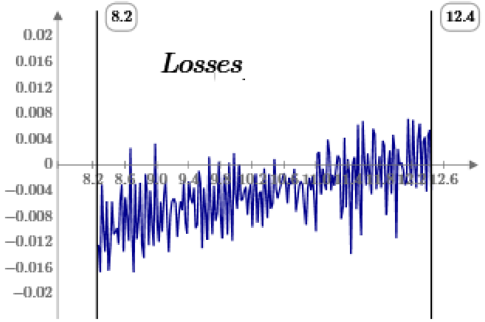
Core Material Downselection (cont'd)

Commercially available Al_2O_3

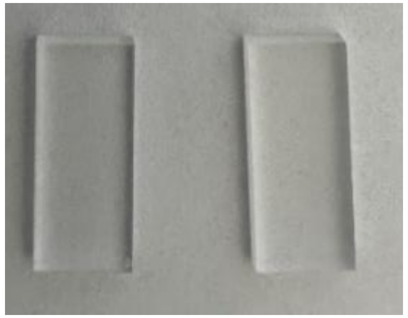


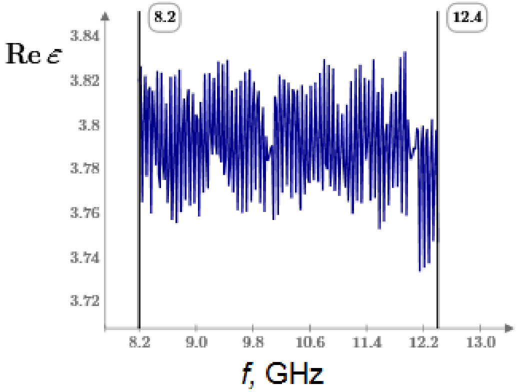


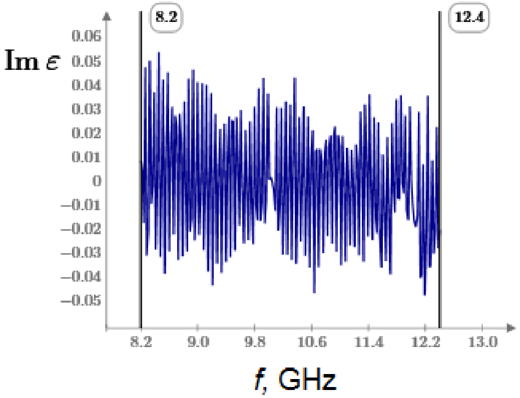


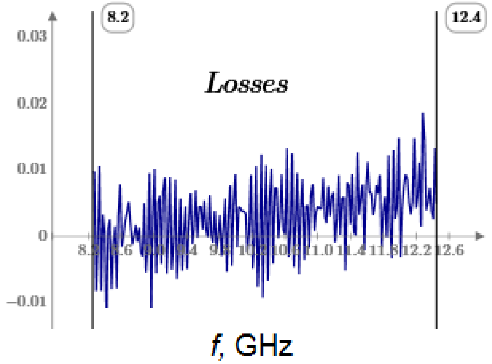


Commercially available SiO_2





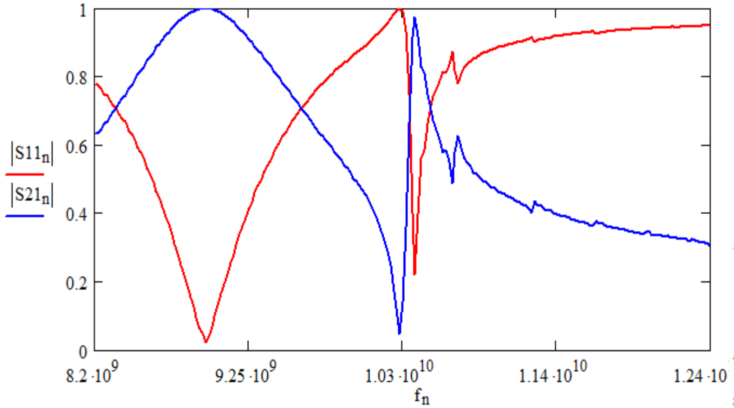


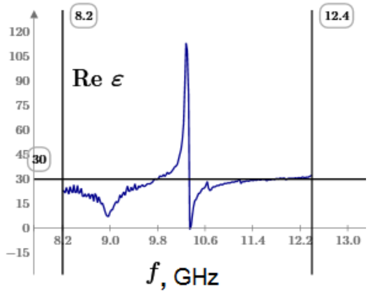


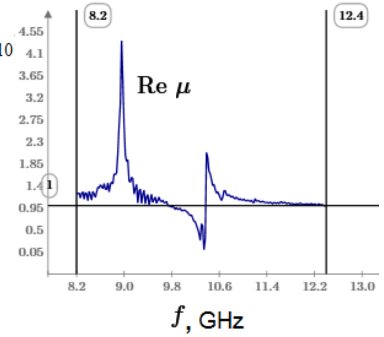
Low losses were determined for the Al_2O_3 and SiO_2 samples. The RF measurement data were used to generate the real (Re) and imaginary (Im) parts of the dielectric permittivity (ε), used in turn to determine the losses.

Core Material Downselection (cont'd)

Commercially available ZrO_2

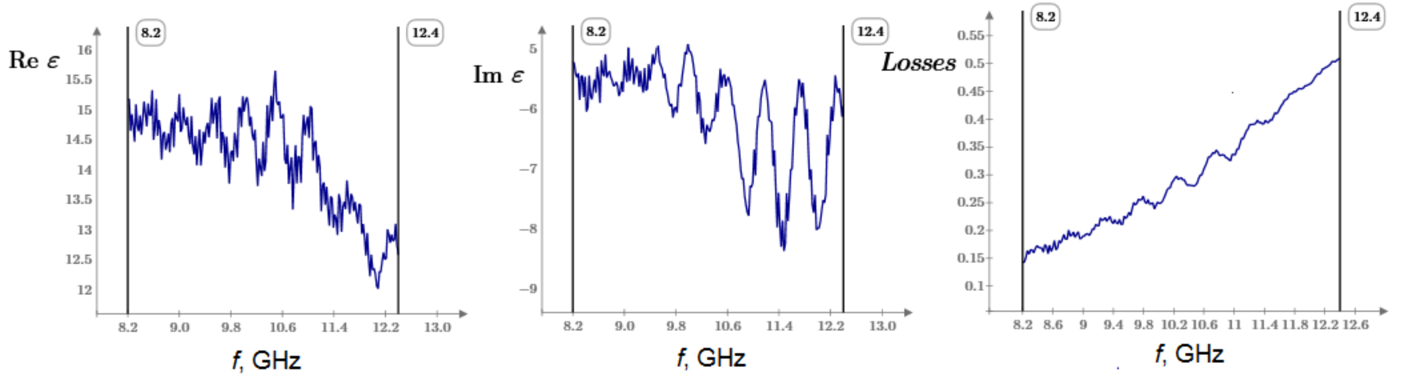




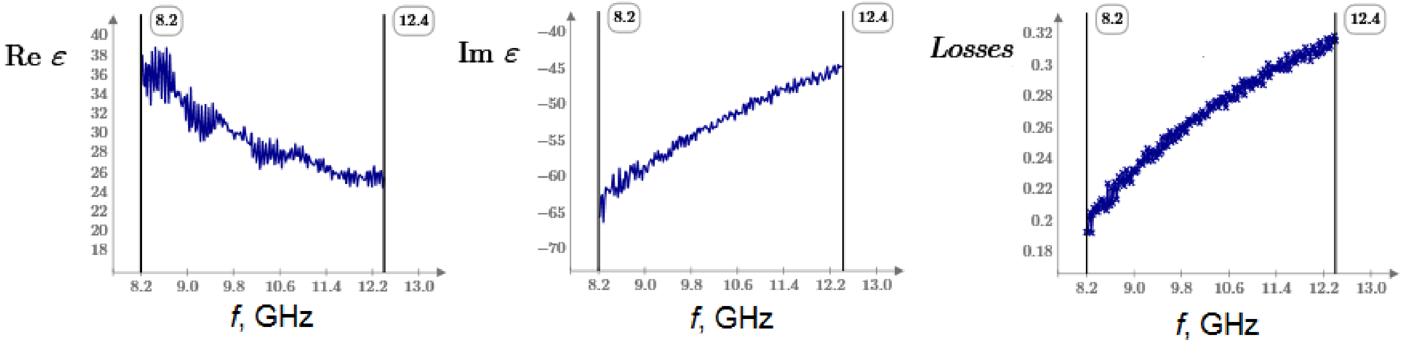


RF measurements and deduced data for a ZrO_2 sample in the frequency range of 8.2–12.4 GHz

Commercially available α-SiC



Cryogenic temperature (LN_2, –320°F) test data for SiC sample showing high losses, up to 50% of incoming power at 12.4 GHz



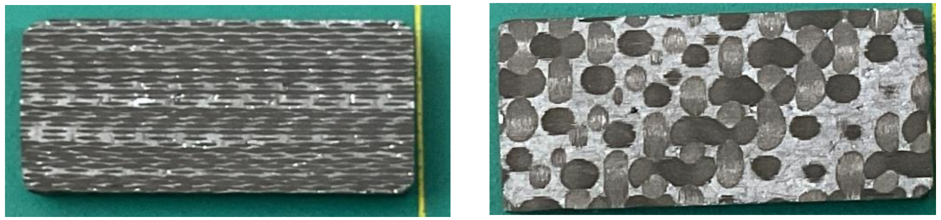
Ambient temperature test data for SiC sample showing high losses, up to 32% of incoming power at 12.4 GHz

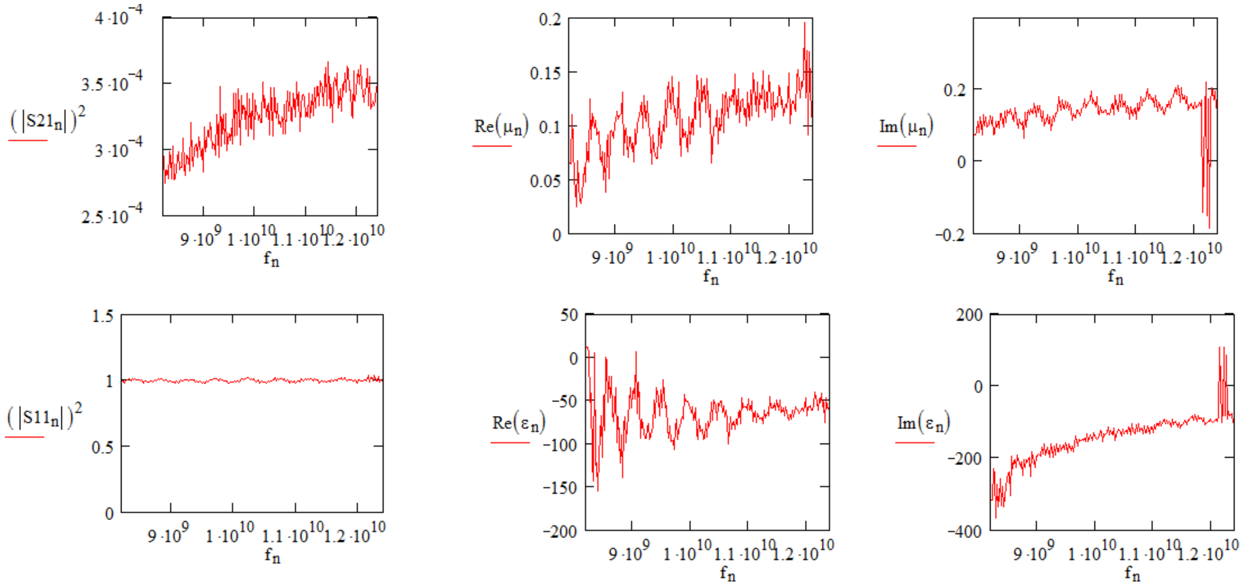
Core Material Downselection (cont'd)

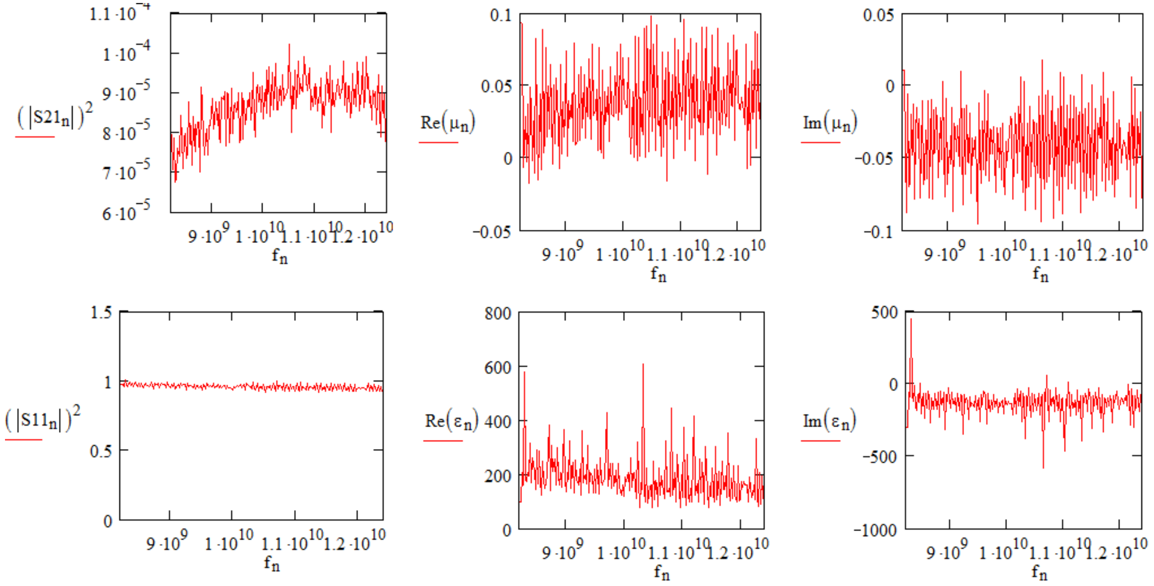
Ultramet materials: Carbide CMCs

C_f/ZrC CMC

C_f/SiC CMC





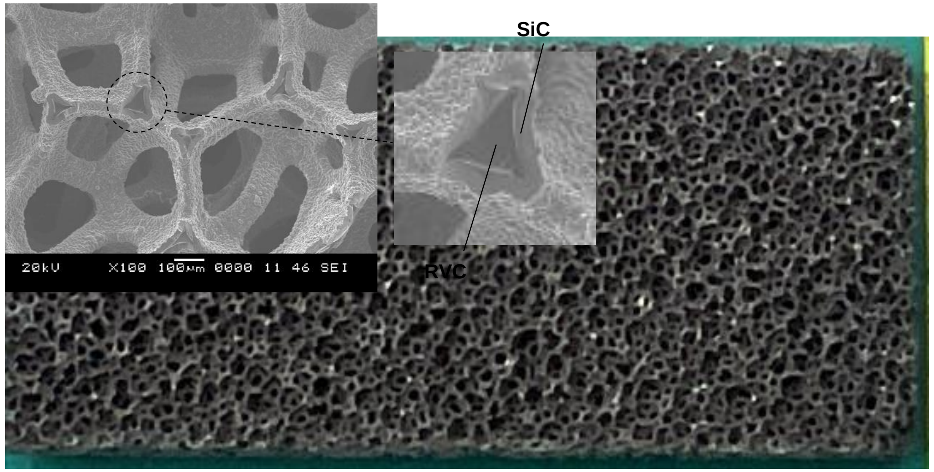


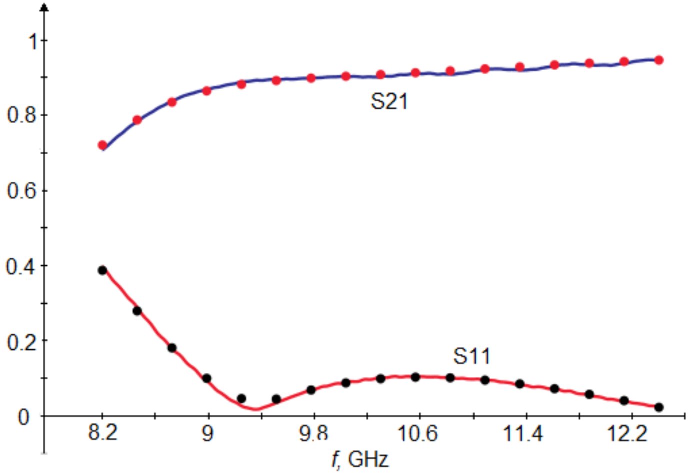
RF measurement results for C_f/ZrC CMC (*left*) and C_f/SiC CMC (*right*)

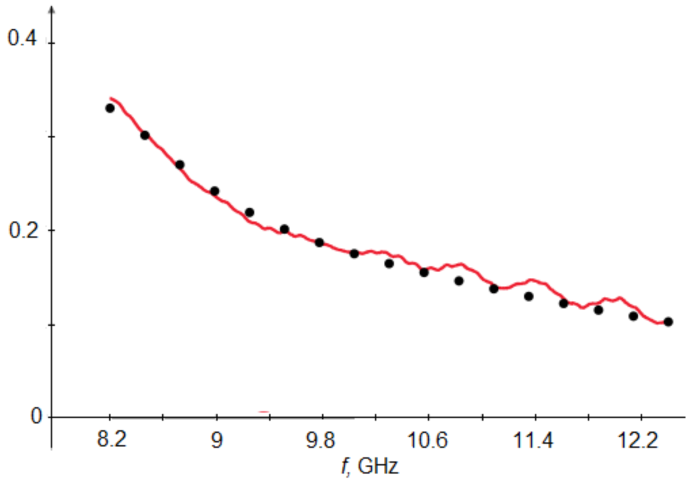
Ultramet materials: SiC Foam

Performing RF measurements on the open-cell SiC foam structure posed some challenges:

- When oriented perpendicular to the waveguide window, dielectric permittivity (ε) calculated from the S-parameters yielded non-physical results indicative of high ε (>10 typ.) and gaps at the walls of the waveguide.
- By orienting the sample adjacent to the narrow waveguide wall and using CST Microwave Studio, values for the real and imaginary parts of permittivity were selected that correlated with the measured values as shown below.
- The foam behaved like a lossy conductor rather than a dielectric conductor.





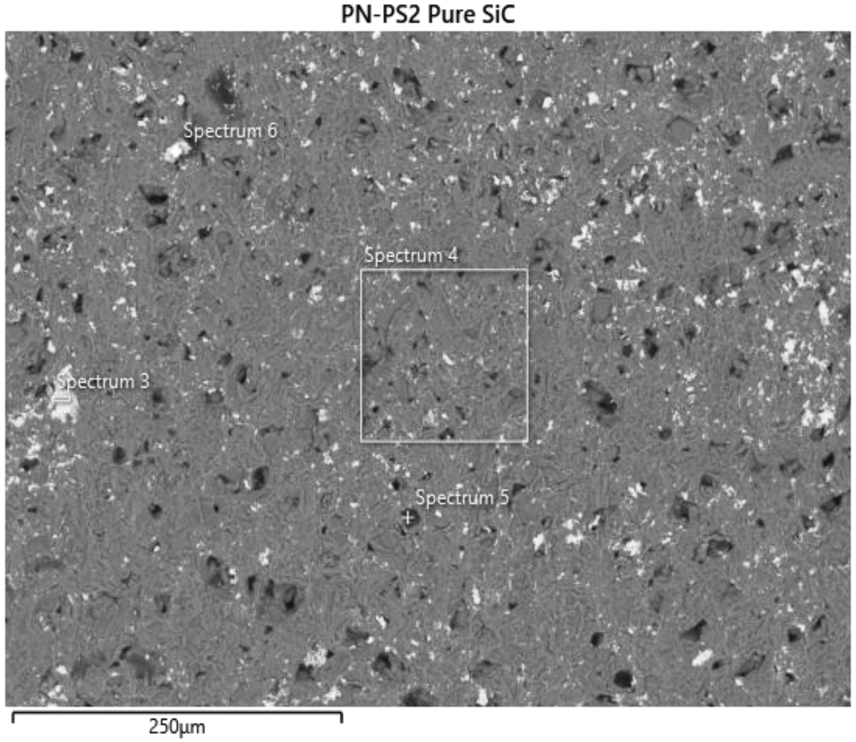


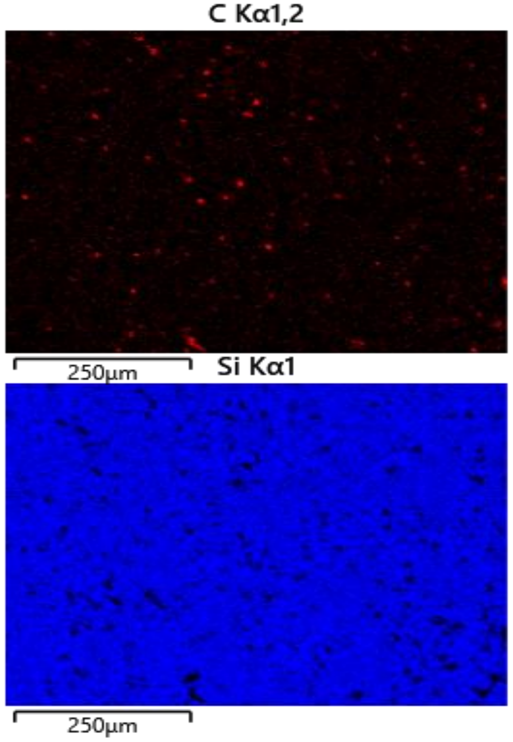
SEM image of typical SiC foam structure embedded in image of actual SiC foam sample (*left*) and CST Microwave Studio S-parameters generated from the measured values from waveguide wall-adjacent sample orientation (*right*)

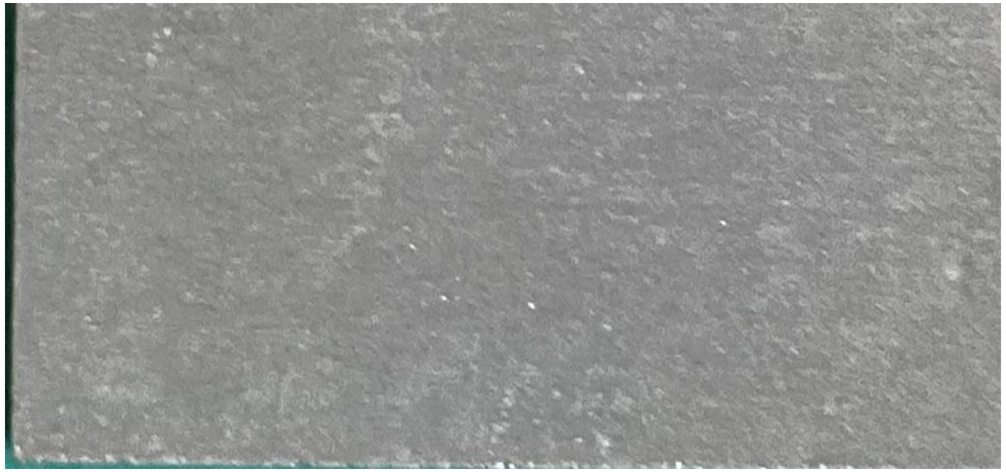
Core Material Downselection (cont'd)

α-SiC via Field Assisted Sintering Technology (FAST) at Penn State

The most encouraging results were obtained from the pure α-SiC produced by Penn State via the FAST process, which has since been selected as the preferred core material for use in the Ultramet HOM absorber design. Cornell reported that "this material has a very high ability to absorb RF power."



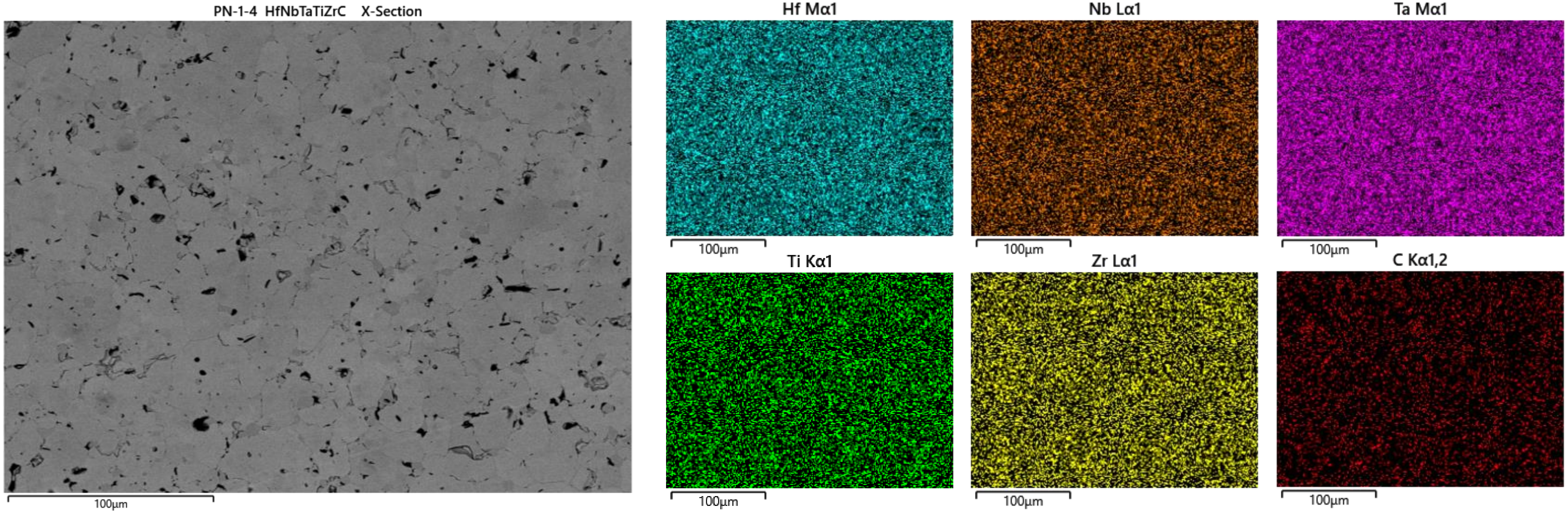




SEM image (*left*) and EDS elemental mapping (*center*) of pure (undoped) α-SiC produced via FAST at Penn State using α-SiC starting material, and photograph of α-SiC test tile produced by PSU

Chaotic Carbides via FAST

Structure/polytype uniformity is key to predictable electrical and RF absorption performance characteristics. The FAST system consistently demonstrated uniform distribution and composition in the substrate materials (especially chaotic carbides) produced.

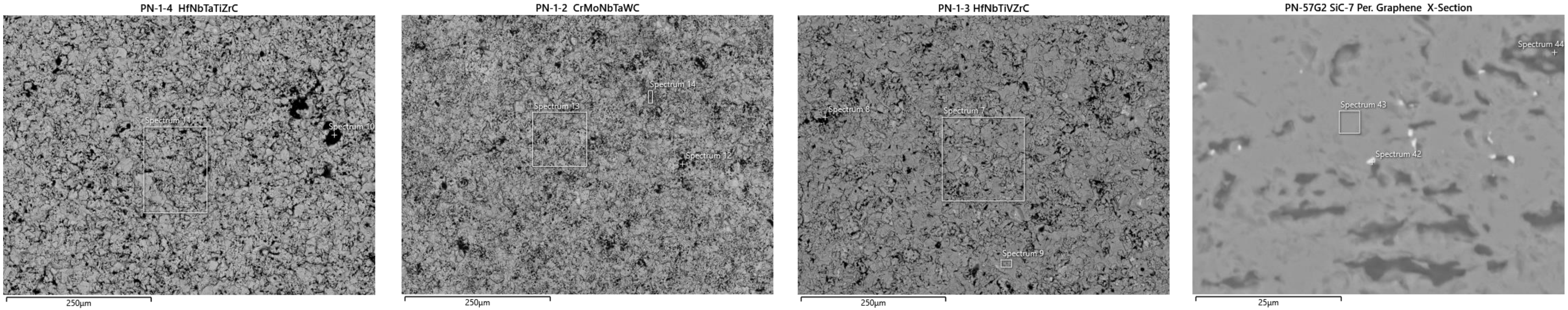


SEM image (*left*) and EDS elemental mapping of HfNbTaTiZrC chaotic carbide produced via FAST at Penn State

Core Material Downselection (cont'd)

RF Test Results

RF testing at Cornell concluded that the graphene-doped SiC materials and the chaotic carbides produced by Penn State are highly reflective and have an electrical conductivity comparable with that of metals, making them unsuitable for the HOM absorber application.



SEM images of, respectively, the three chaotic carbide materials (HfNbTaTiZrC, CrMoNbTaW, and HfNbTiVZrC) and the 7% graphene-doped SiC material produced via FAST at Penn State

Core Material Downselection (cont'd)

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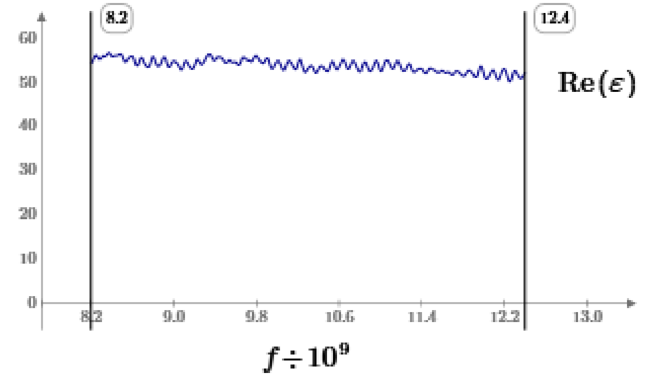
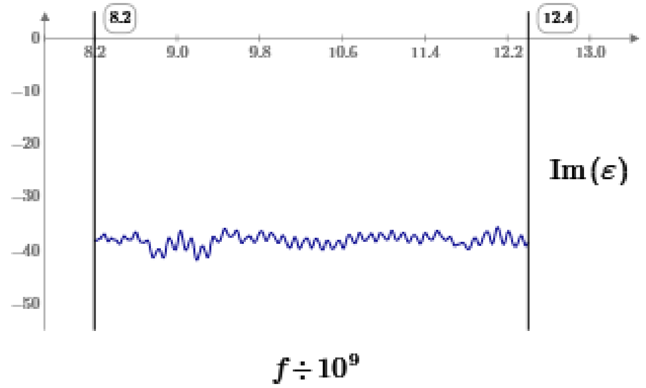
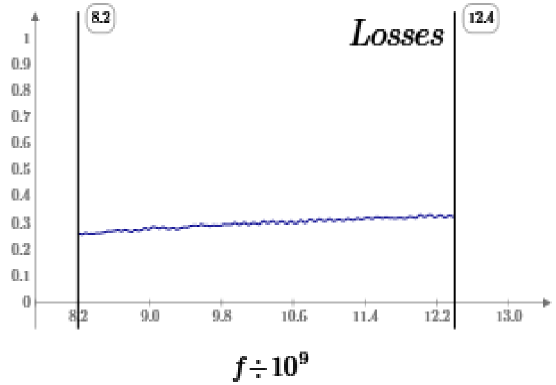
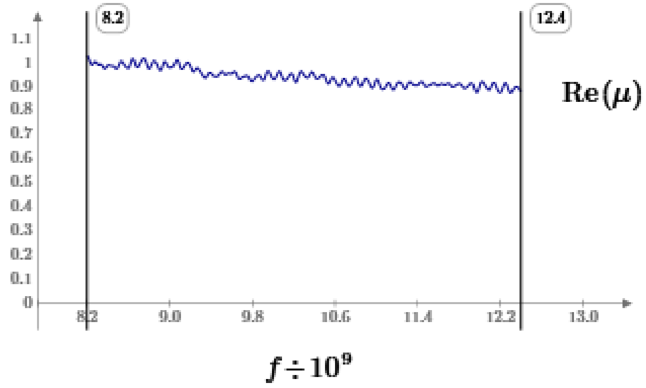
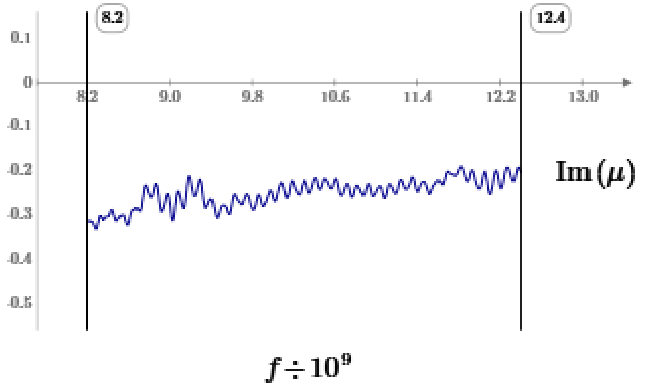
Final downselected core material: Pure α-SiC produced via FAST

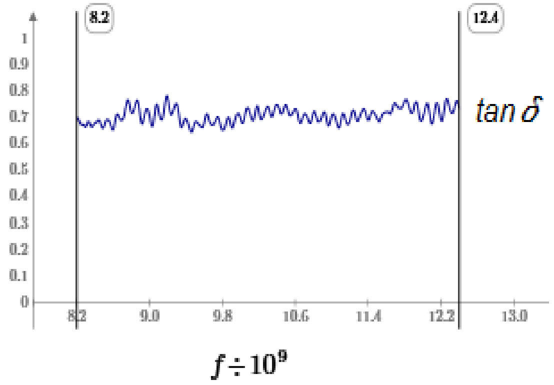








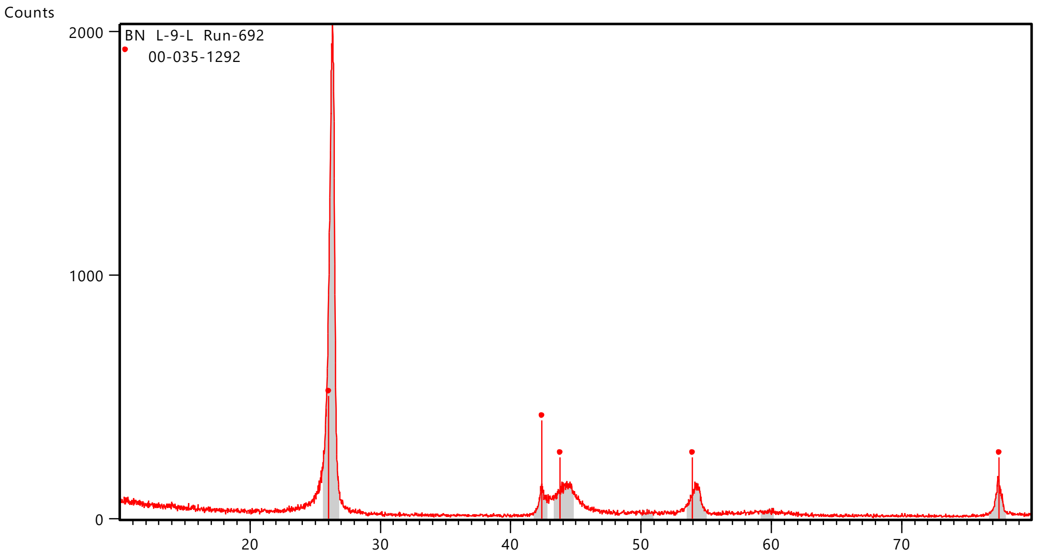




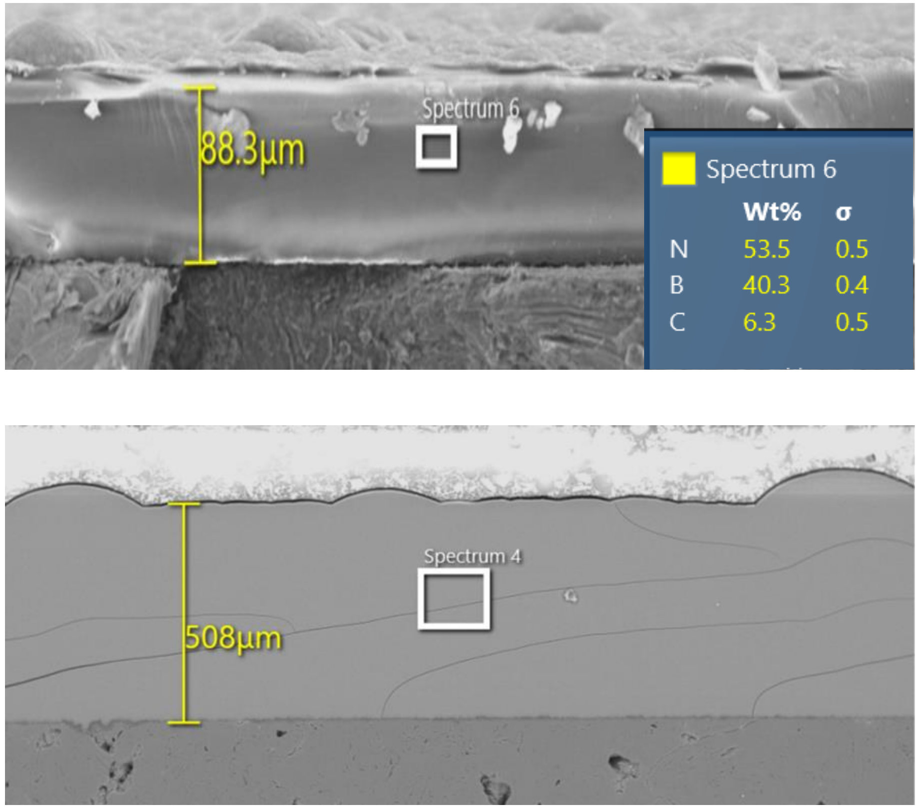
RF measurement data for α-SiC produced via FAST at Penn State, used to generate the real and imaginary parts of the dielectric permittivity (ε) and the permeability (μ), used in turn to determine the losses and the loss tangent (tan δ)

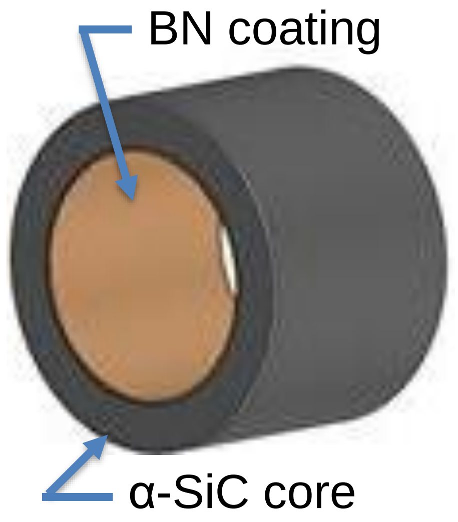
Dielectric Material CVD Processing

CVD boron nitride (BN) dielectric coating



Visible	Ref.Code	Score	Compound Name	Displ.[°2θ]	Scale Fac.	Chem. Formula
	00-041-1487	88	Carbon	0.000	0.887	C
*red	00-035-1292	58	Boron Nitride Carbide	0.000	0.248	(B N)0.26 C0.74





XRD analysis of Ultramet CVD BN coating (*left*), SEM images with EDS compositional analysis of Ultramet CVD BN coating on graphite substrate (*right*), and HOM absorber ring prototype sketch (*center*)

Attachment Material CVD Processing

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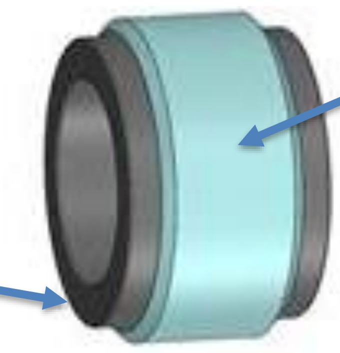
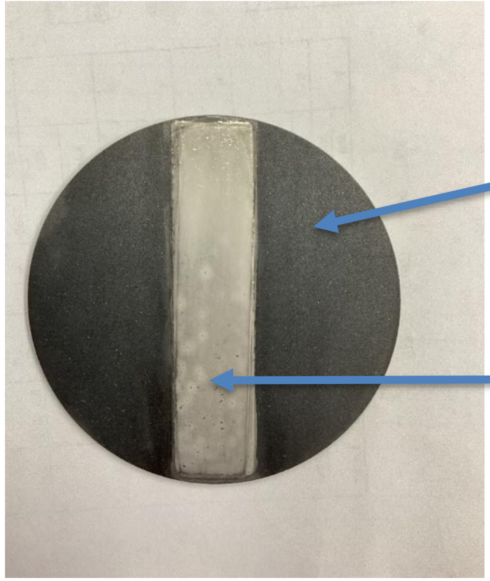
CVD tungsten band (~700 μm thick) formed on sintered SiC disk



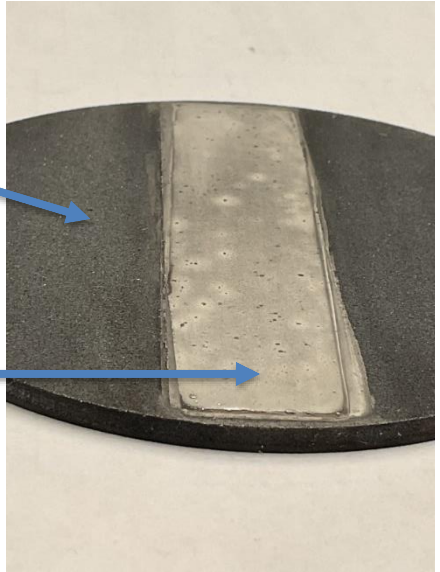
Tungsten attachment band

α-SiC core



SiC disk

Tungsten attachment band



Phase II Path Forward

- Ultramet will continue with CVD BN coating process optimization to achieve deposition on α-SiC and/or hexagonal β-SiC.
- Ultramet will continue with CVD tungsten process scaling and masking technique optimization needed for attachment demonstration.
- Penn State is now producing the remaining pure SiC RF test bricks at full scale (i.e., bare) and at slightly reduced size to accommodate a 0.004" thick CVD BN dielectric coating.
- Penn State will then produce the small tiles for the planned cryocycling, outgassing, and DC surface charge studies, followed by fabrication of the prototype HOM absorber rings.
- Cornell has requested the following ring prototype configurations to accommodate specific testing requirements that will provide the most relevant performance data for the intended HOM absorber application:
  - One pure SiC ring with no dielectric coating
  - One pure SiC ring with CVD BN coating on inner diameter
  - One pure SiC ring with CVD tungsten mounting band on outer diameter and no dielectric coating
  - Size: 50 mm long × 49 mm ID × 10 mm thick

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- Caillin Ryan (Ph.D. candidate, Pennsylvania State University)

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