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

SBIR Phase I-II Grant DE-SC0021487

for DOE Office of Science, Office of Nuclear Physics

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2025 SBIR/STTR Exchange PI Meeting
July 30, 2025
Virtual

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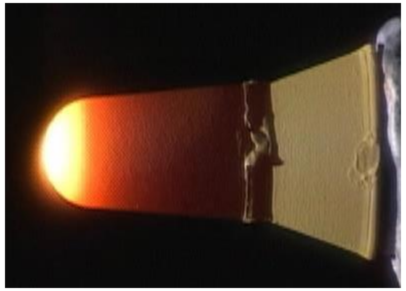
Agenda

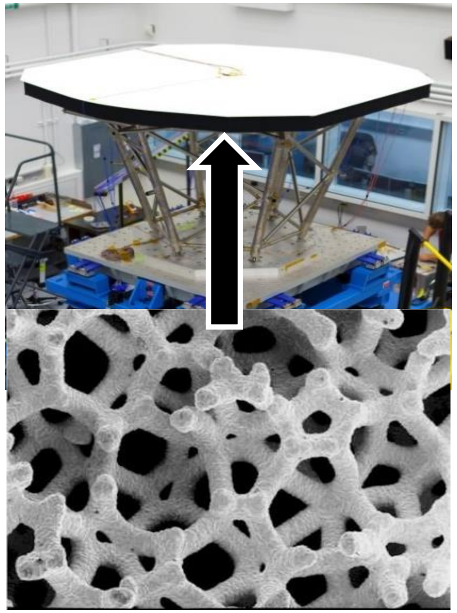
- **Company Overview**
- **Ultramet SRF-Related Work**
  - ❖ Thick-film (>50 µm) chemical vapor deposited (CVD) bulk niobium and on copper cavities
  - ❖ Thin-film CVD (<25 µm) triniobium tin (Nb_3Sn) on copper cavities
  - ❖ Advanced HOM absorber design
- **Phase I Summary**
- **Phase II Background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

Company Overview

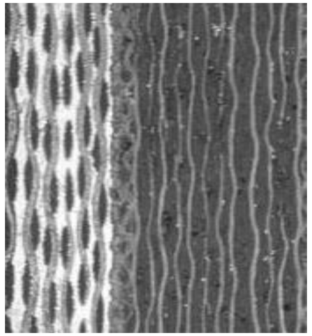
CVD Coatings



Open-Cell Foams



Ceramic Matrix Composites (CMC)

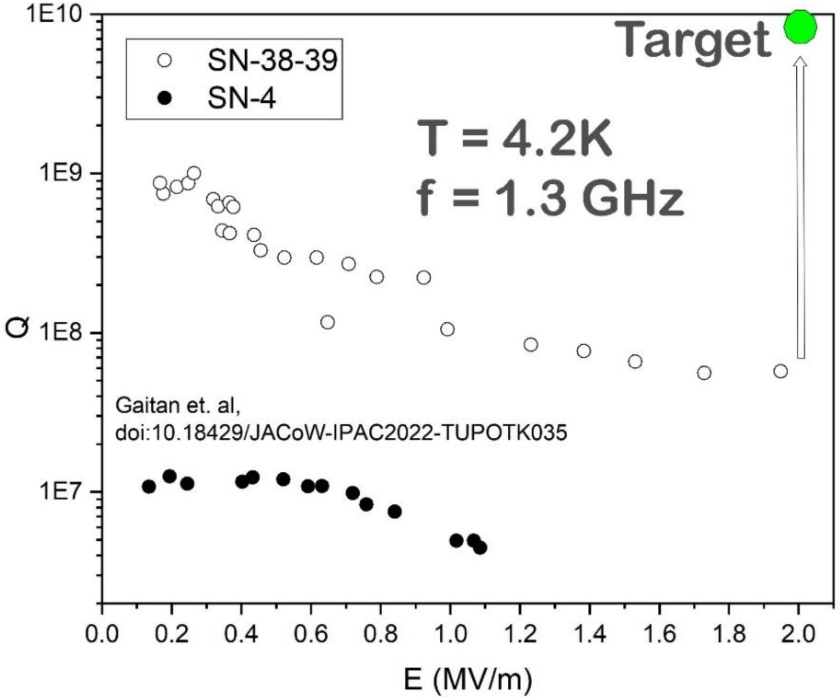


Ultramet SRF-Related Work

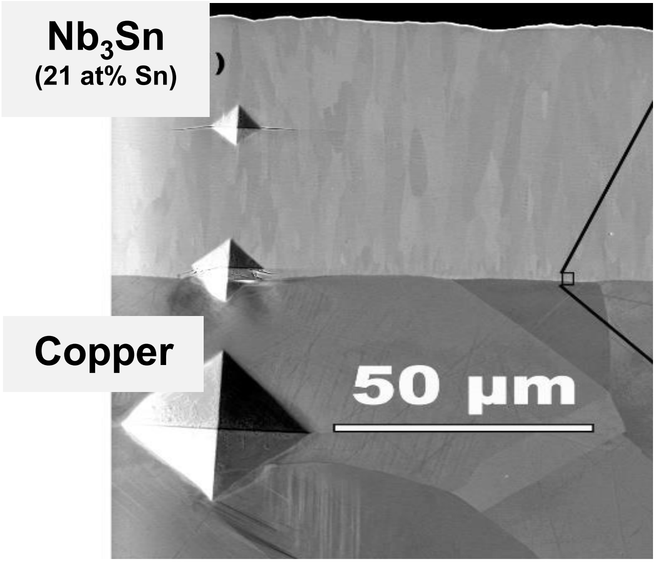
CVD high-RRR bulk Nb cavity

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

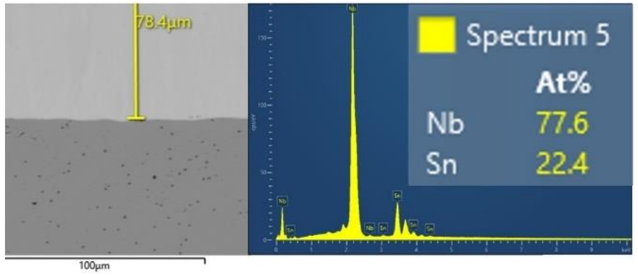
Progression: 2005-2025 Bulk CVD Nb to CVD Nb_3Sn on Cu



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 coating on copper substrate: excellent adhesion

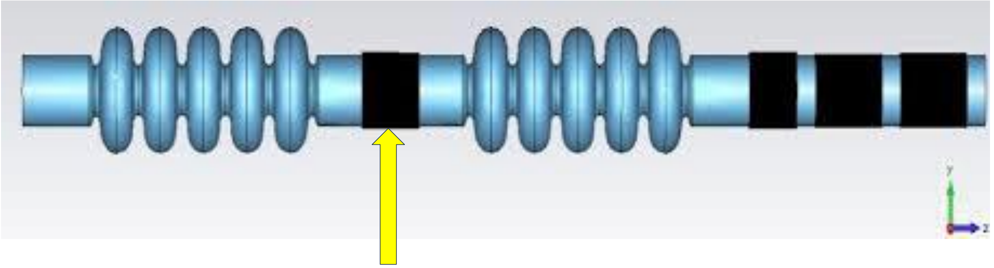


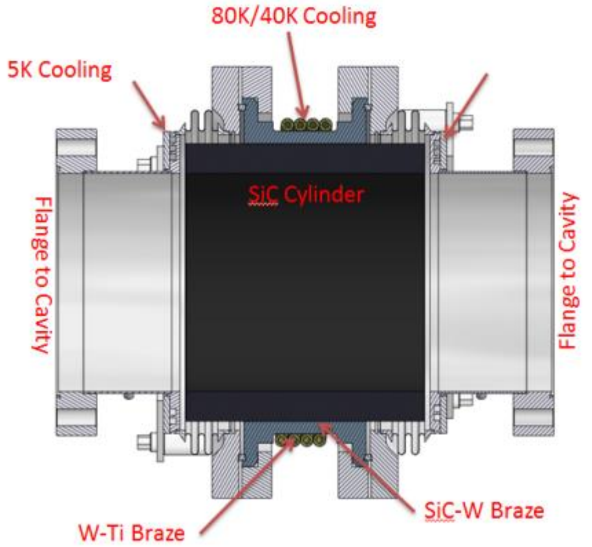
CVD Nb_3Sn on welded copper cavity

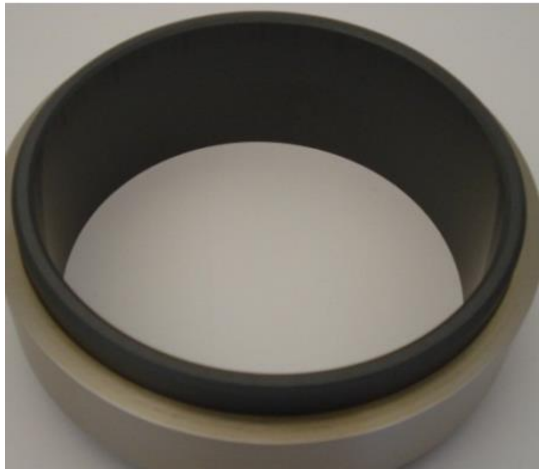
Overall HOM Absorber Design Goals

The Phase I-Phase II project focused on development of advanced beamline HOM absorbers of the type positioned in line between interconnecting superconducting cavity beam tubes and 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 surface charge accumulation effects





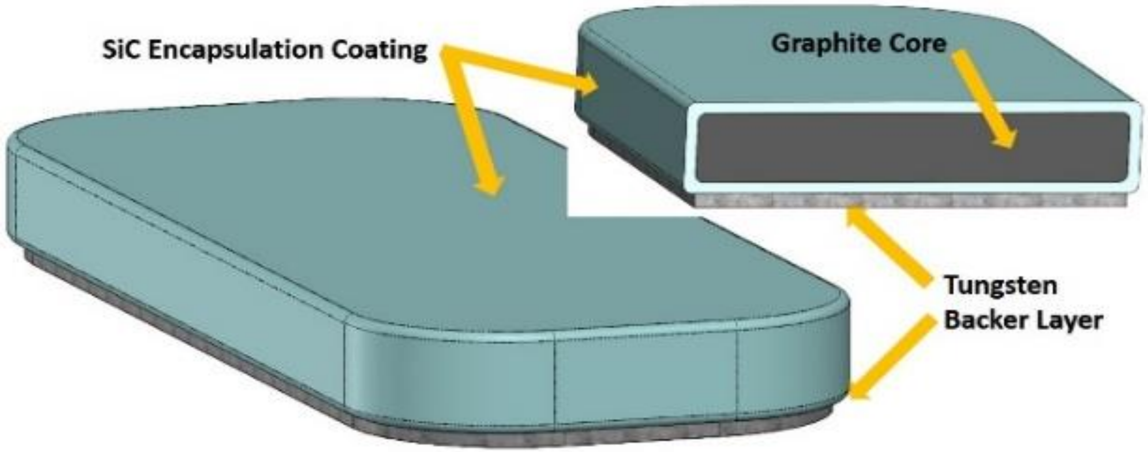


Beamline HOM absorbers (*left*) and Cornell University HOM design for energy recovery LINAC (ERL) (*center*)

Phase I Goals

The main goal of the Phase I project was to develop CVD processing techniques to enable fabrication of 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

CVD Coating Development

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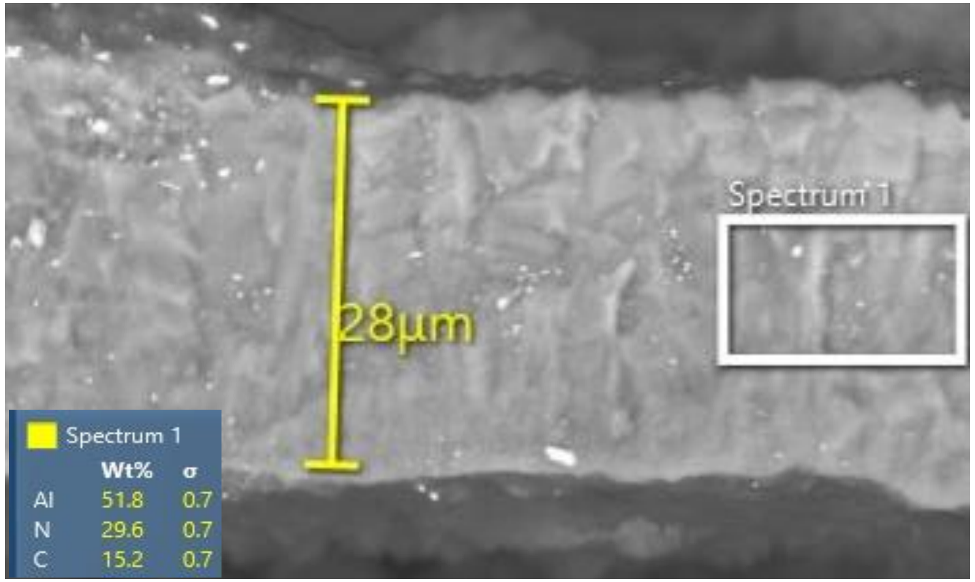
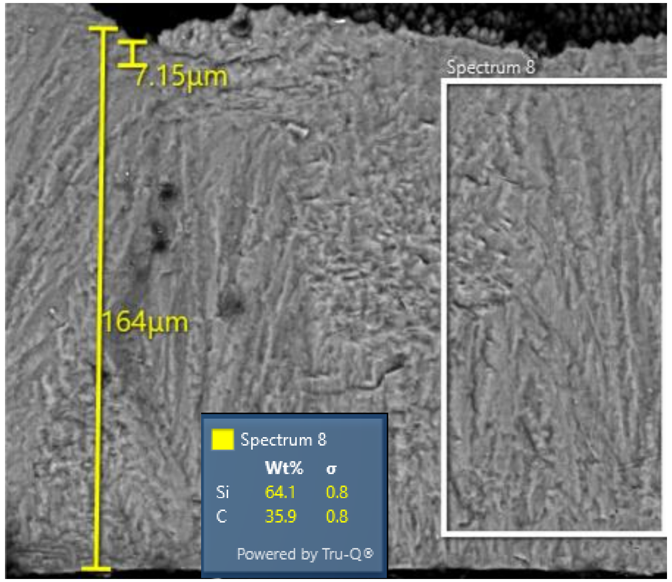
AlN- and SiC-encapsulated UHP graphite cores with CVD tungsten backing layer



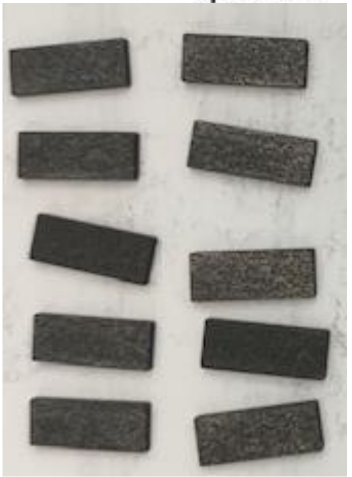


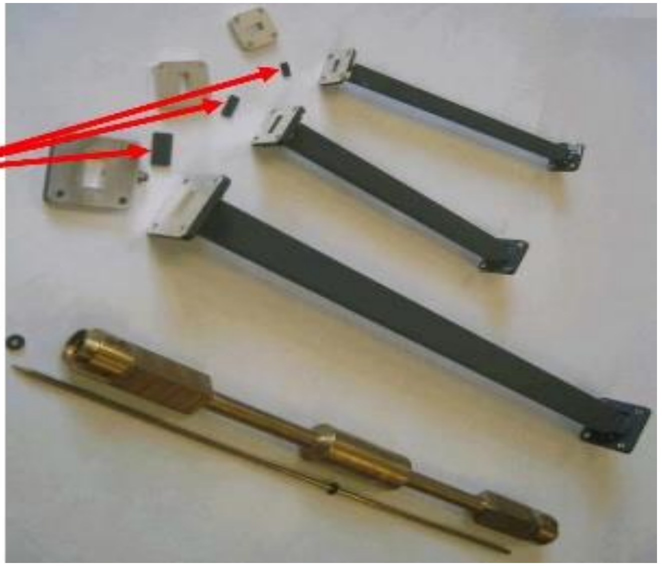
SEM/EDS analysis of ultrahigh-purity (UHP) graphite core encapsulated with AlN (*left*) and SiC (*center*), with excellent coating/substrate interface boundary layer; SiC-encapsulated graphite tile with tungsten backing layer (*right*)

RF Testing

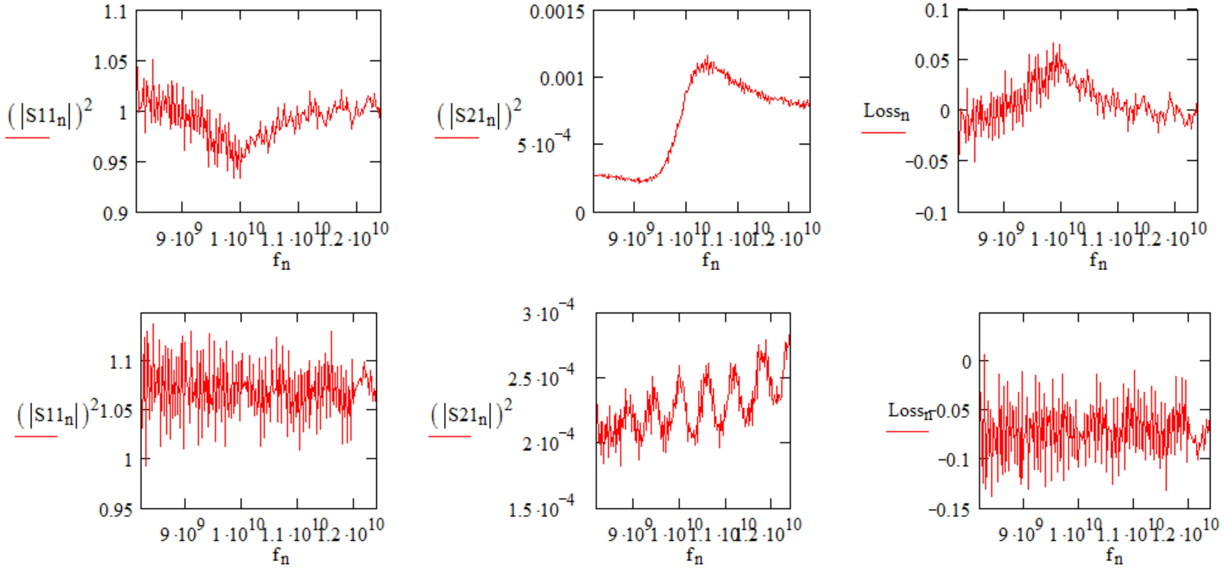
RF waveguide test results for UHP graphite from Agilent network analyzer

Absorber Test Specimens





Cornell rectangular waveguide test apparatus



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

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

The results indicated low-loss capability for the beta-SiC specimen (P/N SiC-1-1), typical of the highly conductive UHP graphite core specimens tested.

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 was to identify effective HOM absorber core materials and CVD dielectric coatings, and to fabricate and test a prototype ring-style HOM absorber(s) for design validation. Specifically:

- Fabricate test specimens of candidate core materials with low electrical conductivity such as Al_2O_3, ZrO_2, SiO_2, SiC, carbide composites, and with matrix doping agents such as carbon.
- Perform RF absorption characterization to enable core material downselection.
- 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

Core Material Downselection

- Commercially available: AlN, Al_2O_3, ZrO_2, SiO_2, SiC
- Ultramet materials: C_f/ZrC and C_f/SiC ceramic matrix composites; open-cell SiC foam
- Pennsylvania State University, via field assisted sintering technology (FAST):
  - Pure α-SiC
  - Doped SiC (graphene @ 1%, 7%, 25%)
  - Chaotic carbides/cermets: (HfNbTiVZr)C, (HfNbTaTiZr)C, (MoNbTaVW)C, (CrMoNbTaW)C

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

Core Material Downselection

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Candidate HOM core test tiles: Types and Sources

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

(2-4 of each fabricated)

WG-1 type tiles tested by Cornell

Commercially available materials

Al_2O_3

SiO_2

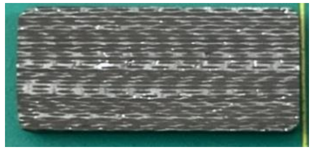
ZrO_2

SiC

Ultramet materials

C_f/ZrC CMC

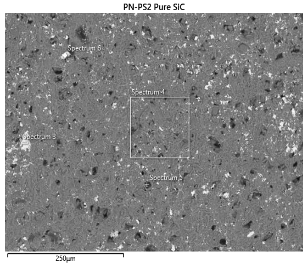
C_f/SiC CMC



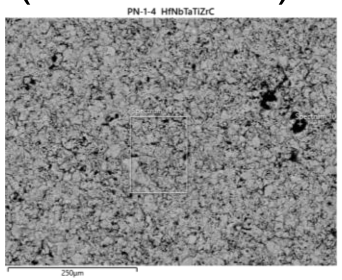
SiC foam

Penn State FAST materials

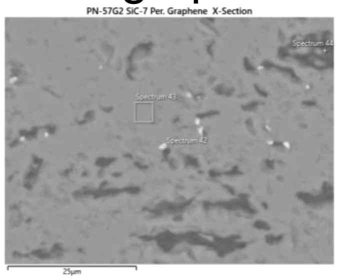
Pure α-SiC



(HfNbTaTiZr)C



SiC/graphene



Core Material Downselection (cont'd)

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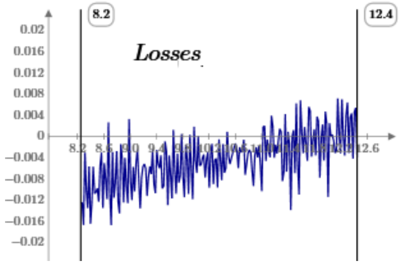
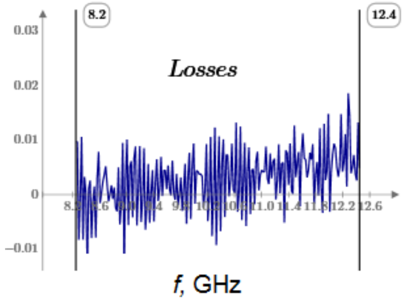
Commercially available Al_2O_3, SiO_2, and ZrO_2

Al_2O_3

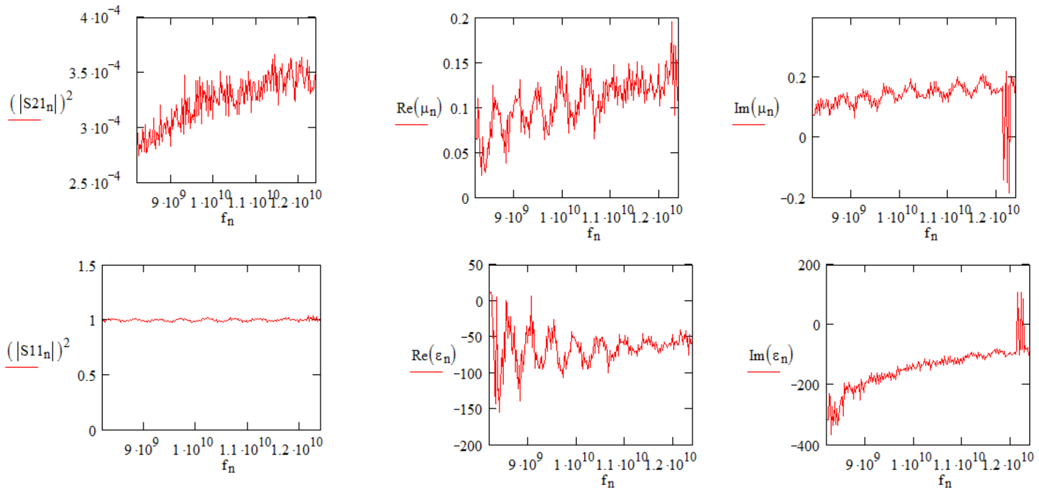


SiO_2



Low losses were determined for 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.

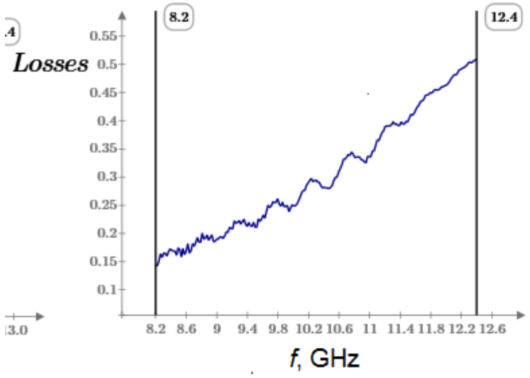
ZrO_2



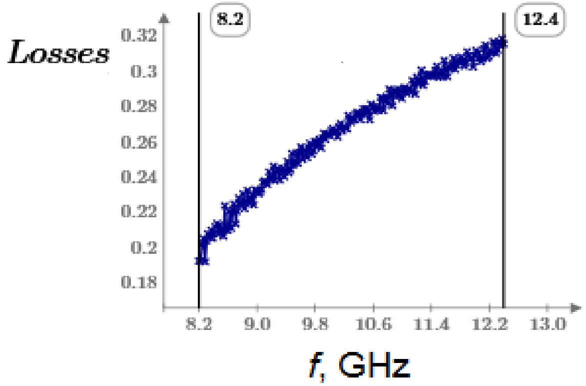
S-parameter measurements for a ZrO_2 sample

Core Material Downselection (cont'd)

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



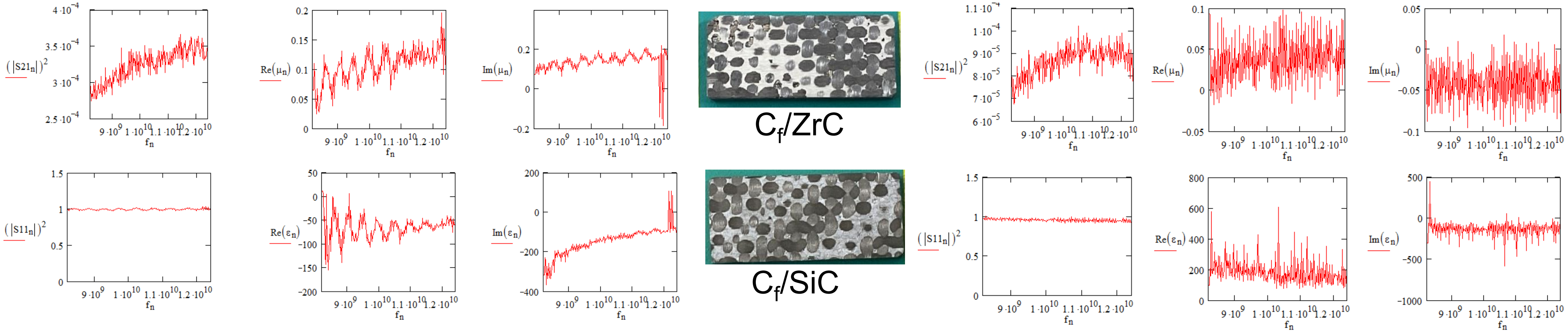
Ambient temperature test data for SiC sample showing high losses, up to 32% of incoming power at 12.4 GHz

Measured DC Conductivity:
$\sigma(\text{warm}) = 0.8\cdot10^{-3}\ \Omega^{-1}m^{-1}$; $\sigma(\text{cryo}) = 0.9\cdot10^{-5}\ \Omega^{-1}m^{-1}$

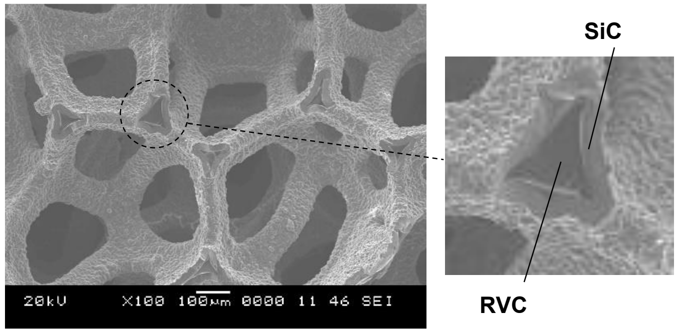
Cornell noted that this material satisfied the discharging requirement at 80 K: $\sigma \gg 10^{-9}\ \Omega^{-1}m^{-1}$ for time constant <1 sec

Core Material Downselection (cont’d)

Ultramet materials: Carbide CMCs and SiC foam

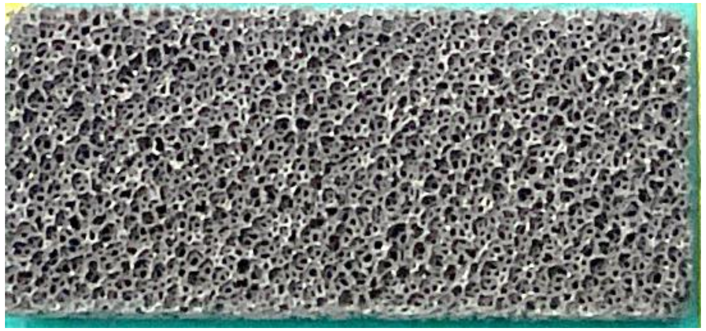


RF measurement results for C_f/ZrC CMC (*left*) and C_f/SiC CMC (*right*)



SEM images of SiC foam structure

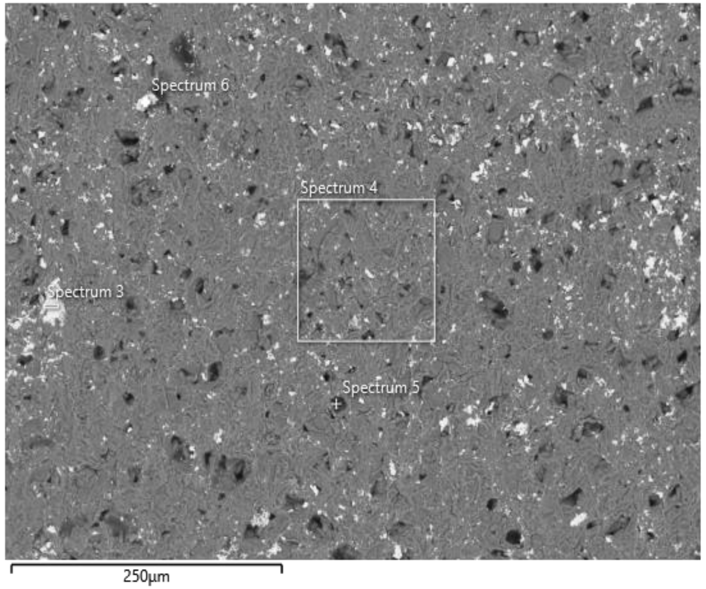
RF testing at Cornell determined the CMCs to be highly reflective, while the SiC foam behaved like a lossy conductor rather than a dielectric conductor.

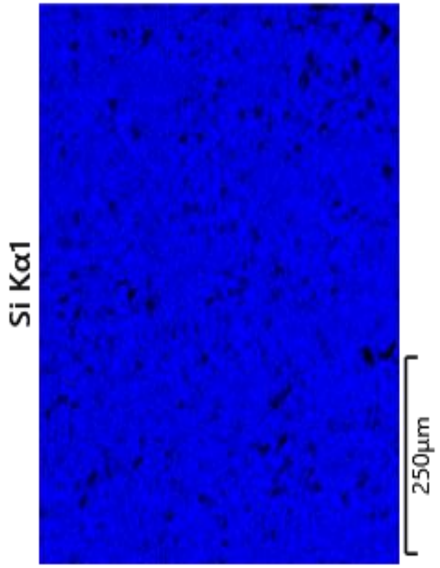


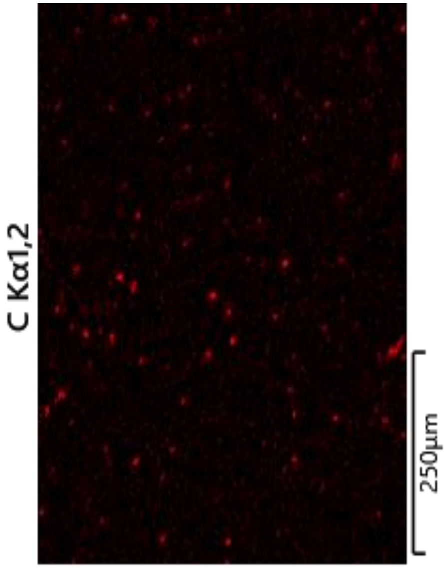
Photograph of typical SiC foam

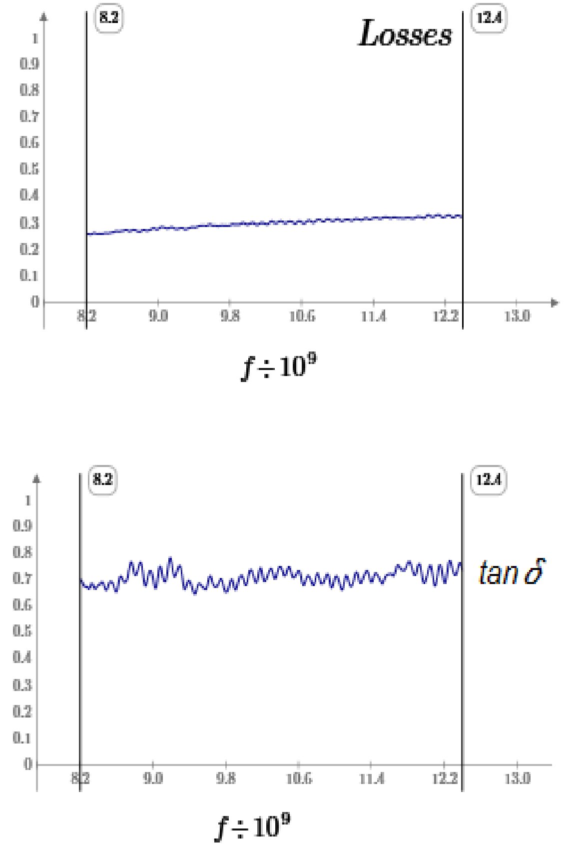
α-SiC via Field Assisted Sintering Technology (FAST) at Penn State

The pure α-SiC produced by Penn State via the FAST process was downselected 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."







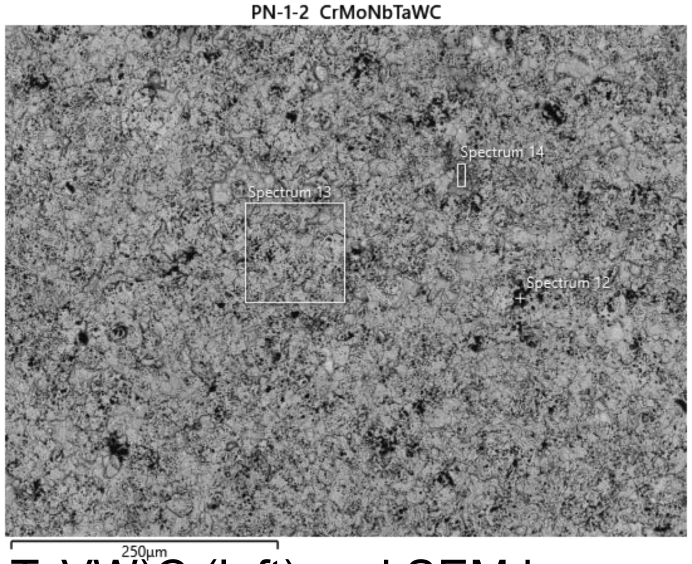


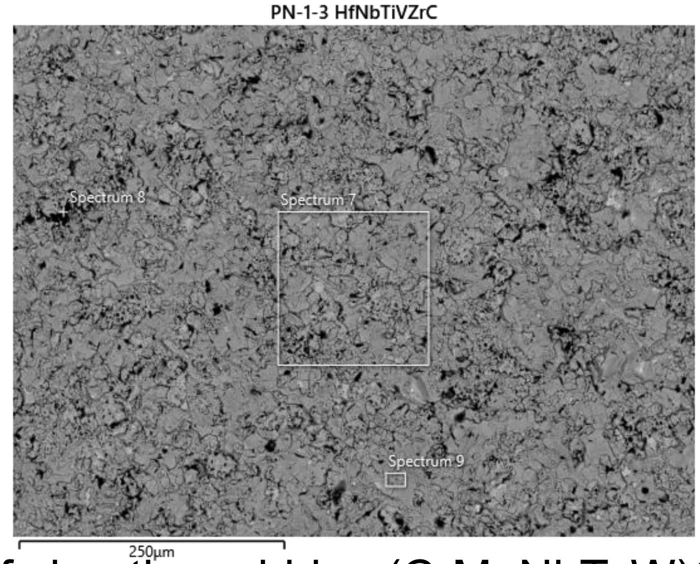
SEM image (*left*) and EDS elemental mapping (*center*) of pure (undoped) α-SiC produced via FAST at Penn State using α-SiC starting material, and photograph of α-SiC test tile produced by Penn State

Core Material Downselection (cont'd)

Graphene-doped SiC and Chaotic Carbides via FAST

RF testing at Cornell concluded that the Penn State FAST graphene-doped SiC materials were highly reflective, and all of the FAST chaotic carbides had an electrical conductivity comparable to that of metals, making them unsuitable for the HOM absorber application.





Photograph of chaotic carbide (MoNbTaVW)C (left) and SEM images of chaotic carbides (CrMoNbTaW)C (center) and (HfNbTiVZr)C (right), all produced via FAST at Penn State

FAST α-SiC Test Specimens

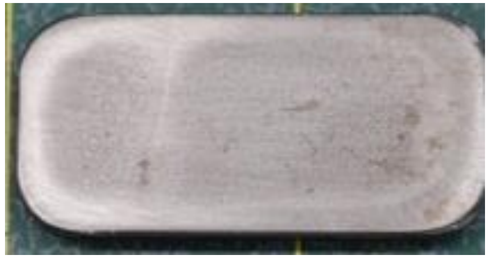
Test specimens fabricated from downselected FAST α-SiC

Penn State FAST α-SiC test tiles with and without downselected CVD coatings

	Substrate size	PN	FAST SiC condition	CVD Coating	Test
WG-2	Full	11969-SiC-WG-2	Porous	None	N/A
	Full	11970-SiC-WG-2	Dense	None	RF
	Full	11971-SiC-WG-2	Dense	None	RF
WG-3	Full	11969-SiC-WG-3	Porous	None	RF
	Full	11970-SiC-WG-3	Dense	None	RF
	Full	11971-SiC-WG-3	Dense	None	RF
WG-1′	Reduced	11969-SiC-WG-1′	Dense	Defect	N/A
	Reduced	11970-SiC-WG-1'	Dense	BN	RF
	Reduced	11971-SiC-WG-1′	Porous	BN	RF
WG-2′	Reduced	11969-SiC-WG-2′	Porous	Defect	N/A
	Reduced	11970-SiC-WG-2′	Dense	BN	RF
	Reduced	11971-SiC-WG-2′	Dense	BN	RF
WG-3′	Reduced	11969-SiC-WG-3′	Porous	Defect	N/A
	Reduced	11970-SiC-WG-3′	Dense	BN	RF
	Reduced	11971-SiC-WG-3′	Porous	BN	RF
Small Tiles		11983-SIC-ST1	Porous	BN + W	Cryo-cycle
		11983-SIC-ST2	Porous	BN	N/A
		11984-SIC-ST1	Porous	BN-OxyN + tungsten	Cryo-cycle

FAST SiC small tile, as-fabricated

FAST SiC small tile + CVD BN encapsulation coating



FAST SiC small tile + CVD BN encapsulation coating + CVD W backing plate (shown)

RF Testing of FAST α-SiC Core Material

Final RF test specimens of FAST pure α-SiC produced by Penn State

Cornell RF Measurements and Calculated Parameters for FAST α-SiC

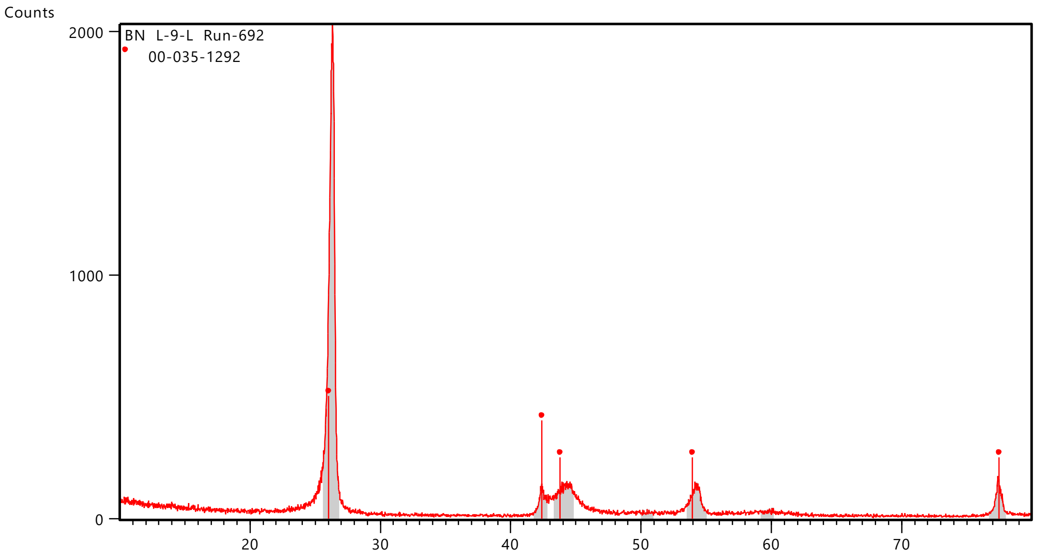
	Frequency, GHz	ALoss	LossAv	ΔS11 (dB)	S21_Avg (dB)	width, in
Uncoated 11970-WG2	12.4–18	−0.026	0.493	0.020	0.251	0.311
11971-WG2	12.4–18	0.070	0.260	−0.041	0.007	0.312
11971-WG2 (repeated test)	12.4–18	0.069	0.246	−0.040	0.009	0.312
11969-WG3 (porous SiC)	18–26	−0.018	0.150	0.010	0.073	0.170
11970-WG3	18–26	−0.025	0.291	0.015	0.140	0.170
11971-WG3	18–26	−0.030	0.194	0.017	0.354	0.170
Coated 11970-WG1′	8.2–12.4	−0.046	0.334	0.028	0.043	0.400
11971-WG1′	8.2–12.4	−0.057	0.473	0.041	0.041	0.400
11970-WG2′	12.4–18	−0.041	0.411	0.029	0.273	0.311
11971-WG2′	12.4–18	−0.102	0.402	0.067	0.123	0.310
11970-WG3′	18–26	−0.038	0.229	0.023	0.317	0.167
11971-WG3′	18–26	−0.022	0.203	0.012	0.371	0.168
Control Teflon	8.2–12.4	0.007	0.038	−0.001	0.893	0.399
Teflon	12.4–18	0.008	0.035	0.006	0.873	0.312
Ceramics Al_2O_3	18–26	−0.025	−0.013	0.013	0.556	0.170

Cornell noted, "For the uncoated specimens an accurate calculation of ε and μ from the measurements of reflection and transmission can be done only when there are no gaps between the sample and the wall of the waveguide. The gap between these two surfaces is inevitable, otherwise the sample cannot be inserted in the waveguide. The error of measurements grows very fast with the value of ε, and for $\varepsilon > 10$, a gap width >1% of the waveguide height becomes unacceptable (>50%)."

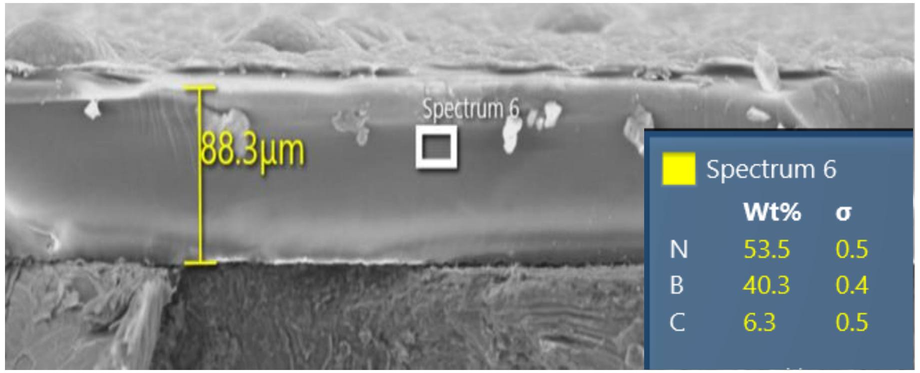
Cornell also noted the difference in the measured parameters between coated and uncoated samples was insignificant and that the difference between parameters for different samples was defined by the dimensions of the gaps between the test sample and the waveguide window.

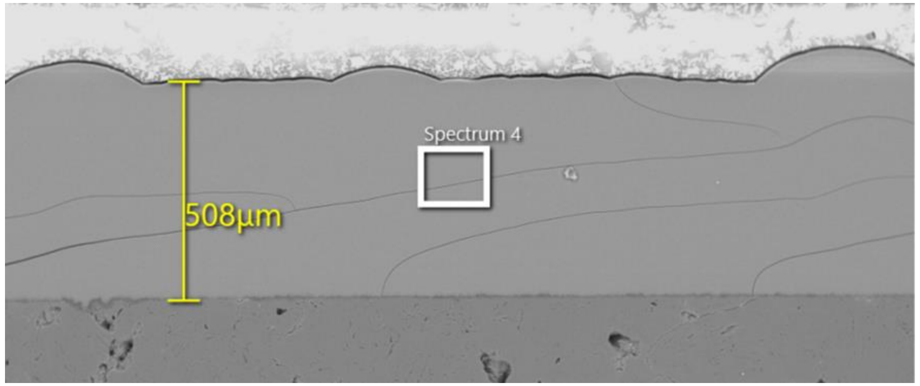
RF measurement data for FAST α-SiC used to generate the real and imaginary parts of the dielectric permittivity (ε) and permeability (μ), subsequently used to determine the losses and the loss tangent (tan δ)

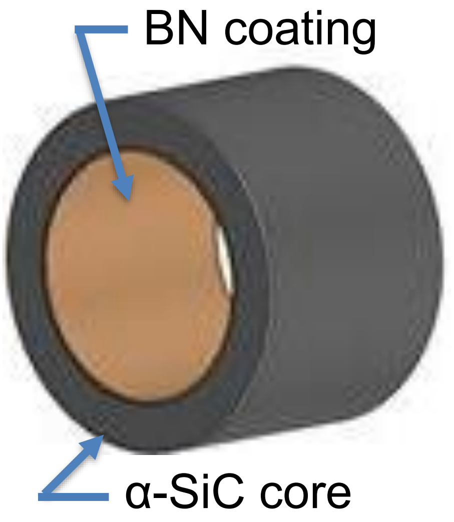
CVD boron nitride (BN) dielectric coating



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 (*center*), and HOM absorber ring prototype sketch (*right*)

FAST α-SiC HOM Ring Process Development

FAST WG-style test tile development

FAST WG-style test tiles of doped and pure materials were successfully produced and tested.
Challenges: Fe-SiC -- process R&D needed; dopant size (i.e., nm), dopant fraction (<0.5-0.2%)
Fe-AlN -- molten Fe caused graphite die failure (Fe MP < AlN sinter temp)

Ring-style HOM absorber prototype development

Several attempts were made to produce a testable FAST-SiC HOM absorber without success.
Challenges: nonuniform heating, incomplete sintering/non-structural material, die failures

FAST α-SiC small tile specimen with CVD BN dielectric coating and CVD tungsten backing layer

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

- Survivability and robustness of CVD BN dielectric coating and CVD tungsten backing layer
- Survivability of CVD BN-to-CVD tungsten interface bond under cryocycling

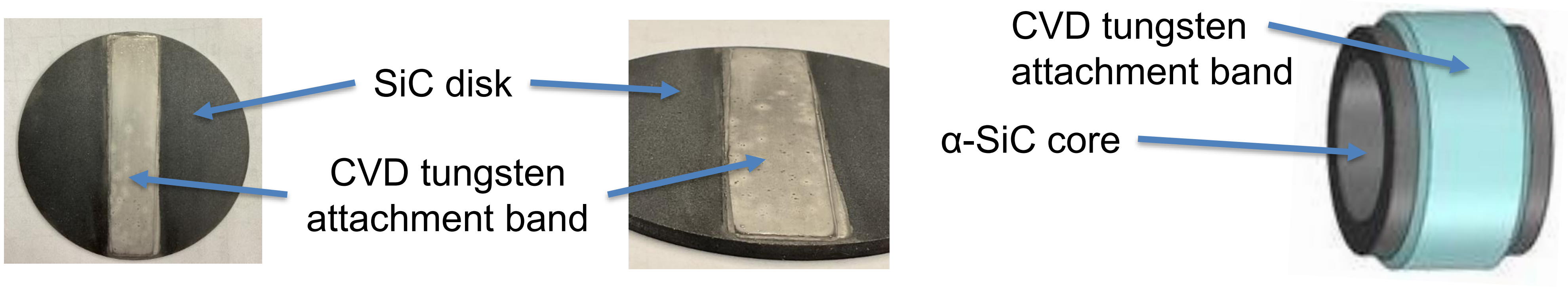
Before After

FAST α-SiC small tile-style substrate produced by Penn State with Ultramet CVD BN coating and CVD tungsten backing plate before (*left*) and after (*right*) cryocycle testing at Cornell, demonstrating excellent adhesion of both coatings

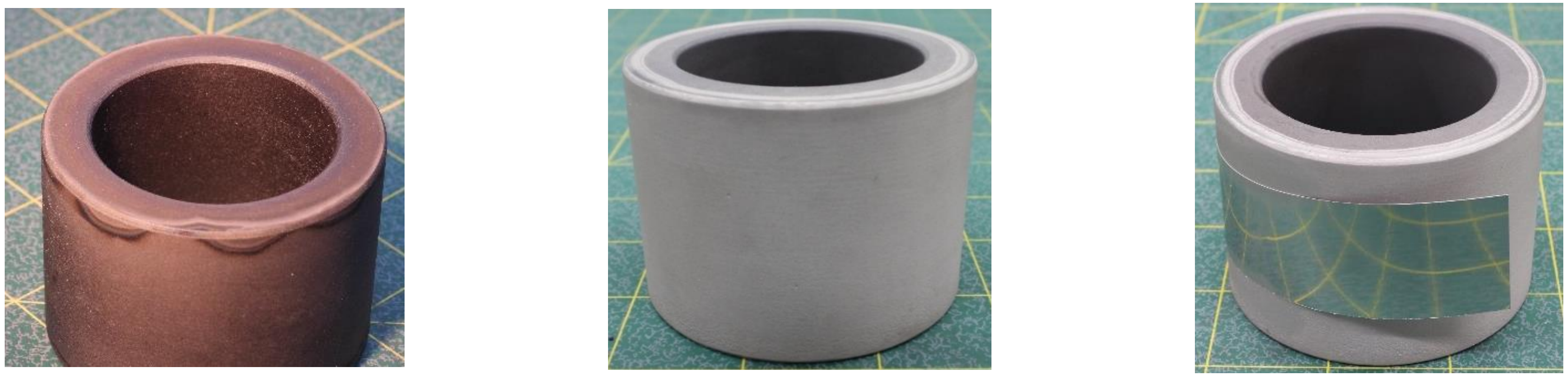
Post-test inspection revealed shear stress failure of FAST SiC substrate near interface between BN and tungsten coatings

Attachment Material CVD Processing

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



Graphite HOM core absorber prototypes



Prototype ring-style HOM absorbers fabricated by Ultramet: graphite core with CVD BN ID coating (*left*), graphite core with CVD tungsten OD coating (*center*), and tungsten sheet bonded (brazed) to CVD tungsten coating (*right*)

Phase II Summary

- Sintered (FAST) α-SiC was shown to have useful RF absorption properties.
- Impurities within the α-SiC matrix appear to have an effect on its absorption properties.
- CVD coatings increased the reflectivity and/or conductivity of candidate HOM absorber materials tested.
- Ultramet successfully scaled and optimized the CVD tungsten coating process and masking techniques needed to demonstrate the feasibility of a component-to-parent system attachment method.
- Penn State produced pure FAST α-SiC RF test tiles at full scale (bare) and at reduced size to accommodate a CVD BN dielectric coating wall thickness of 0.004”.
- During cryotesting, FAST α-SiC specimens with and without a BN coating experienced interlaminar failure.
- Penn State made several attempts to fabricate prototype HOM absorber rings, but it was not possible due to technical challenges and resource (schedule, budget) constraints. More process optimization is needed.
- The Cornell RF testing of FAST α-SiC tiles was inconclusive due to gap and specimen-to-flange fitment issues.
- Cornell and Ultramet discussed the need for a more appropriate RF test method for HOM absorber materials development to address varying gap sizes and/or pinch points during testing due to thermal expansion mismatch issues between dissimilar sample and waveguide flange materials.

Acknowledgments

- Dr. Michelle Shinn (DOE Office of Nuclear Physics)
- Dr. Matthias Liepe (Cornell University)
- Dr. Valery Shemelin (Cornell University)
- Dr. Stefano Curtarolo (Auro Scientific Consulting/Duke University)
- Dr. Douglas Wolfe (Pennsylvania State University)
- Dr. Caillin Ryan (Pennsylvania State University)

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