U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI Advanced Sensors and Instrumentation

Fiber-Embedded Wireless Sensors

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
October 30 – November 2, 2023

Principal Investigator: Joseph Pegna, Ph.D.
Free Form Fibers

DOE SBIR Phase I Award DE-SC0023772, PM: Daniel Nichols

Overview

BACKGROUND:

- Material-Agnostic Additive Manufacturing of filaments (1½ - D Printing)
- Phase 0 prior works

PROJECT VISION:

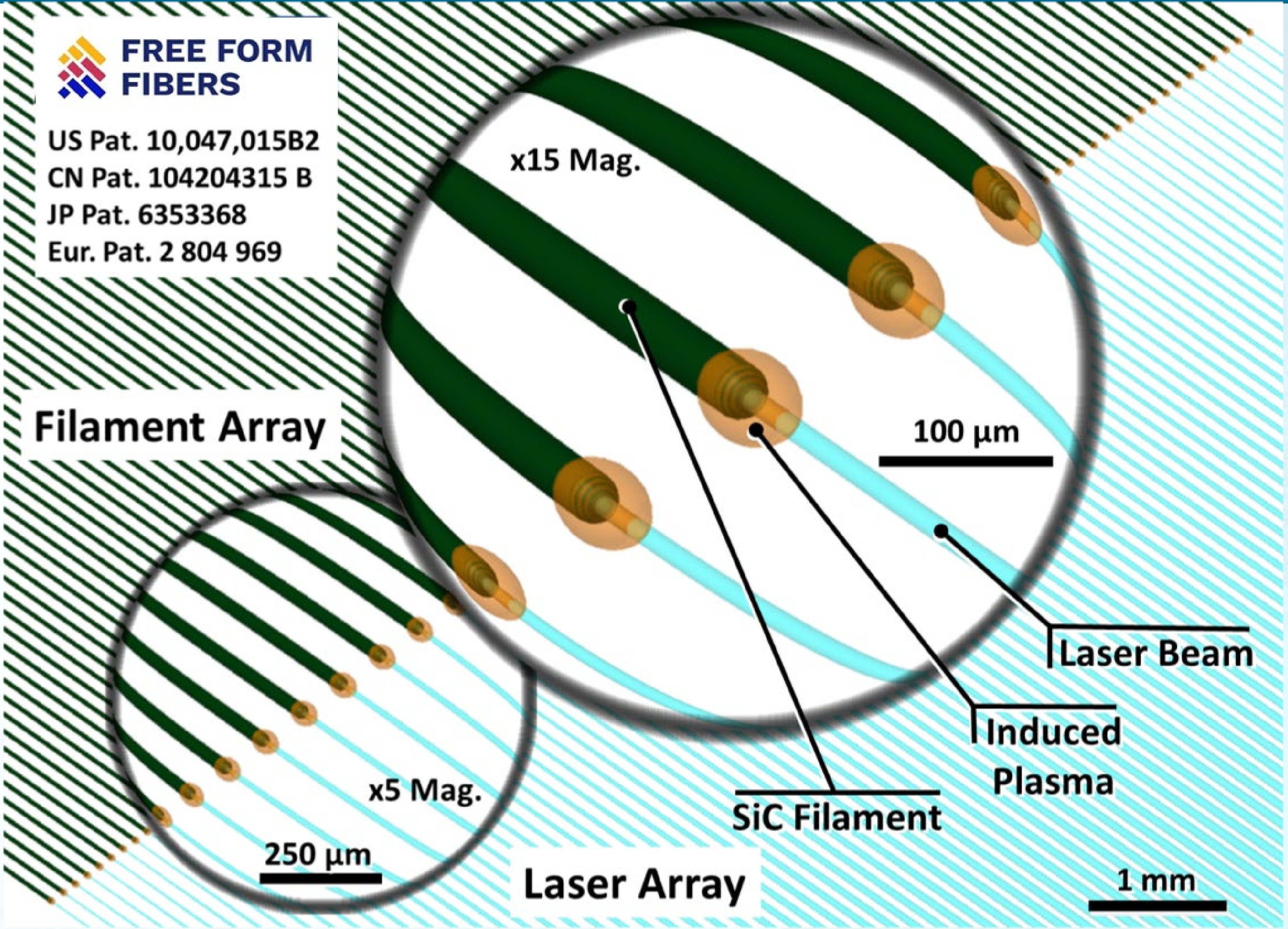
- Fiber-embedded wireless sensors

PHASE I SCOPE AND STATUS

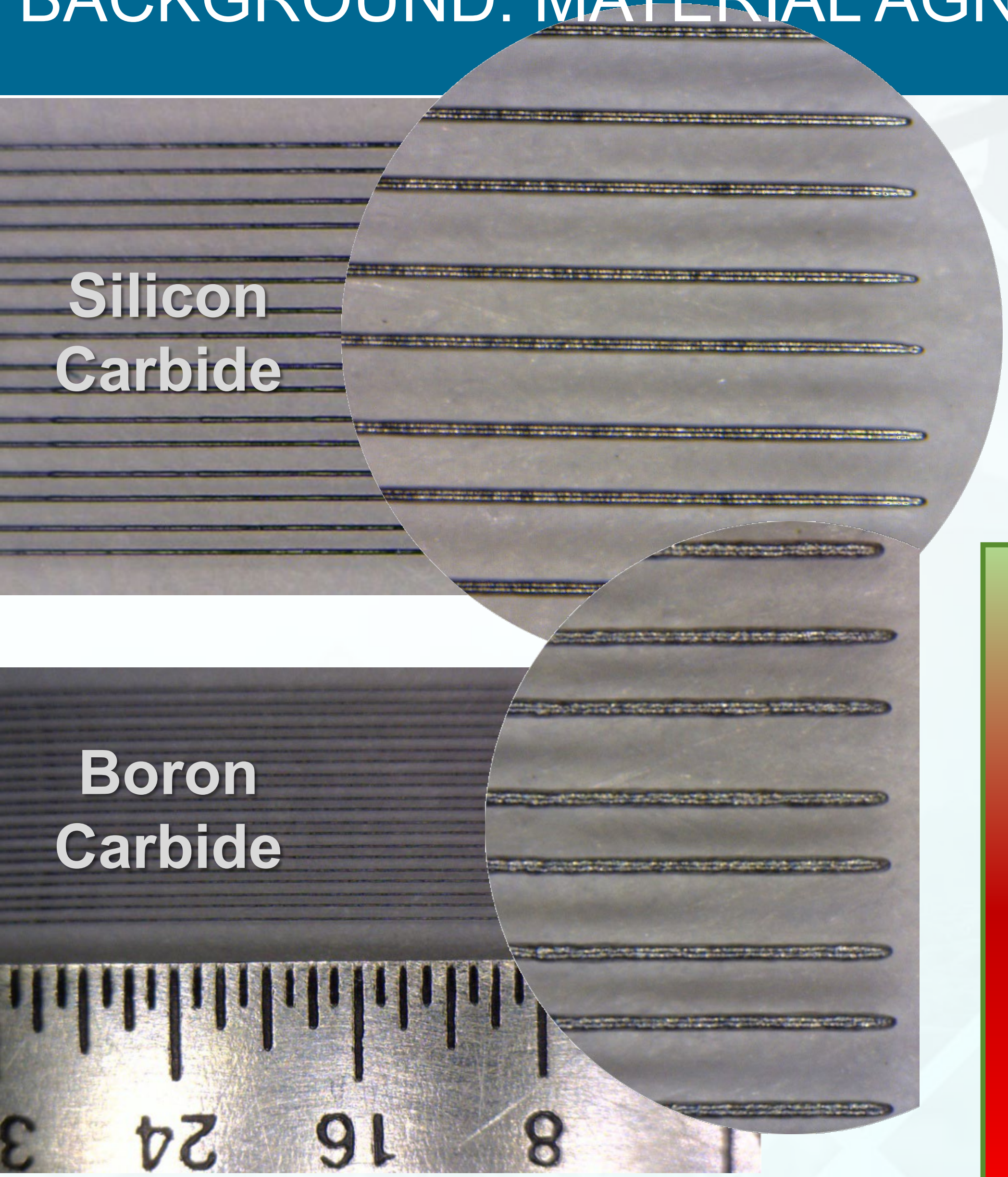
TECHNOLOGY IMPACT

CONCLUSIONS

BACKGROUND: Laser-Printed Fibers



BACKGROUND: MATERIAL AGNOSTIC AM OF FIBERS



Material Dimension

Compositional axial gradient

Maxwell, J.L., Pegna, J., DeAngelis, D., Messia, D.; Three-Dimensional Laser Chemical Vapor Deposition of Nickel-Iron Alloys, Materials Research Society. Vol. 397, Advanced Laser Processing of Materials, pp. 601-606 (1996)

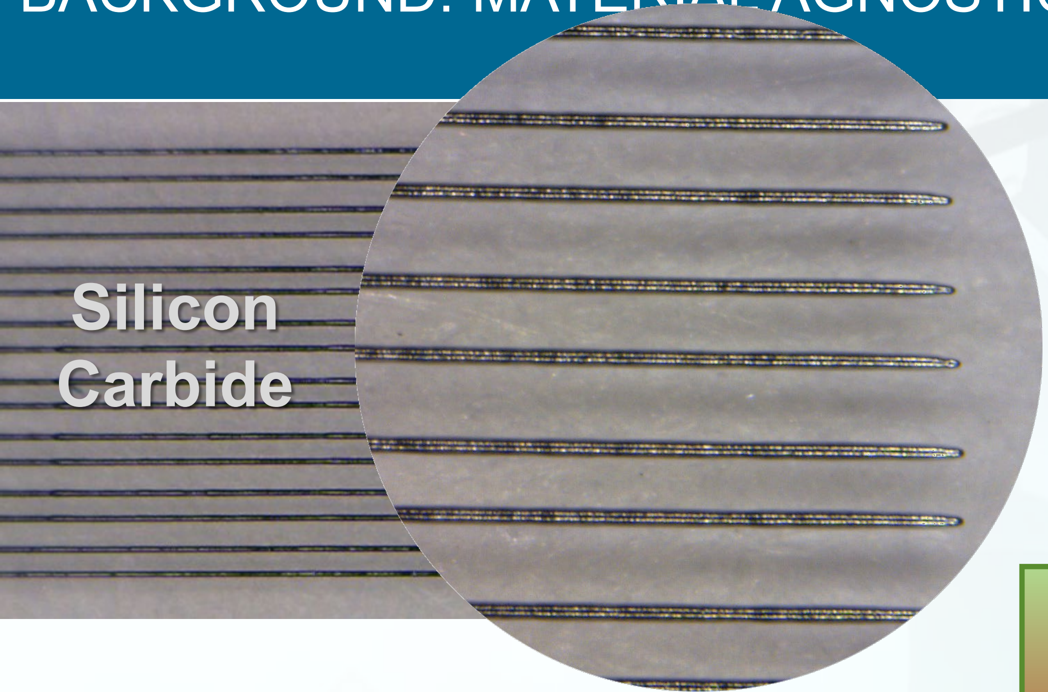
Axial growth rate

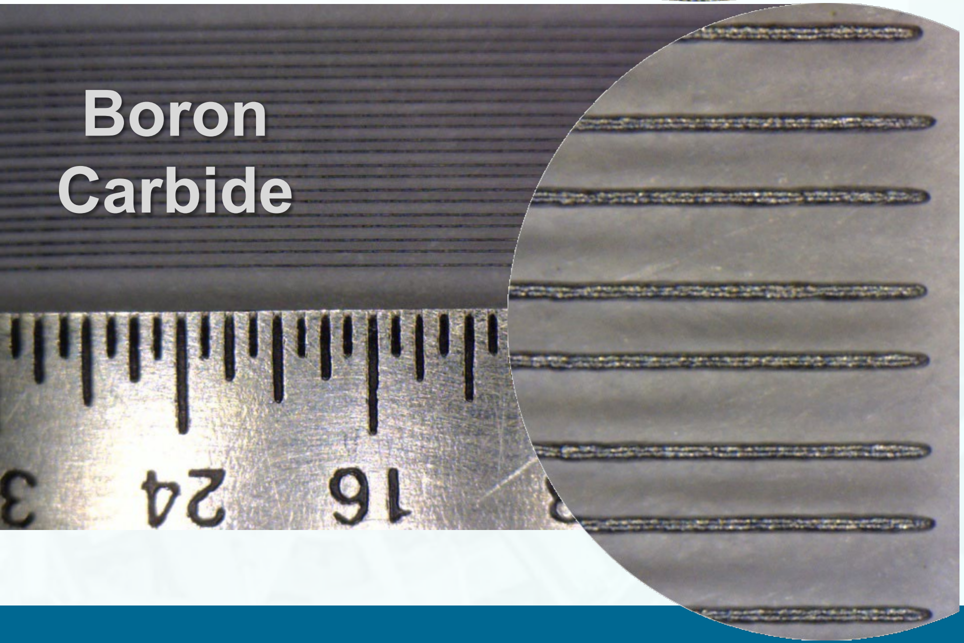
Maxwell, J.L.; Boman, M.; Springer, R.W.; Nobile, A.; DeFriend, K.; Espada, L.; Sandstrom, M.; Kommireddy, D.; Pegna, J.; Goodin, D.; Advanced Functional Materials, v 15, n 7, p 1077-87, July 2005

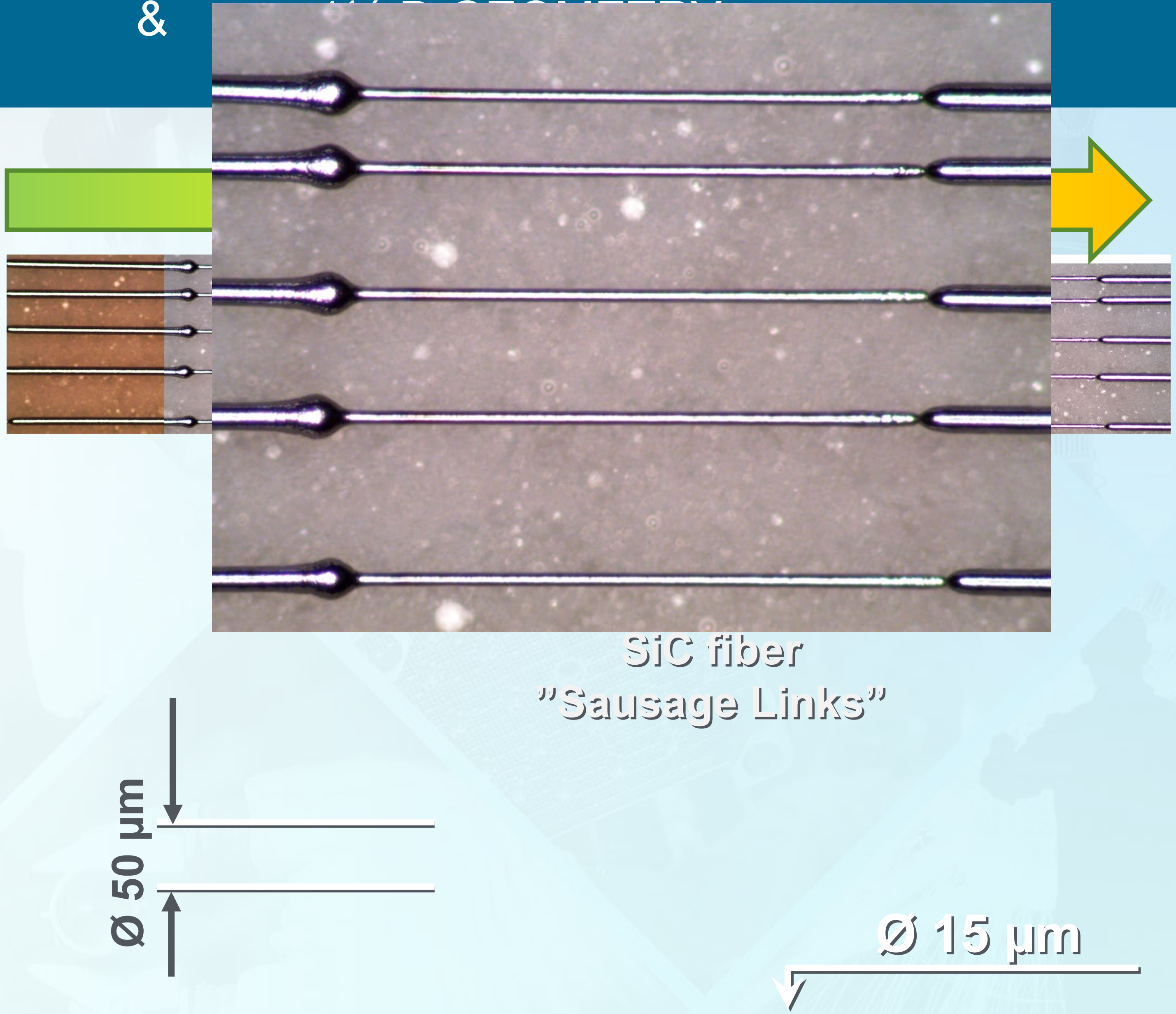
Multi-materials:

Si_3N_4, $B_{13}C_2$, B, BN, W, WC, HfC, ZrC, UC, U_xSi_y, UN

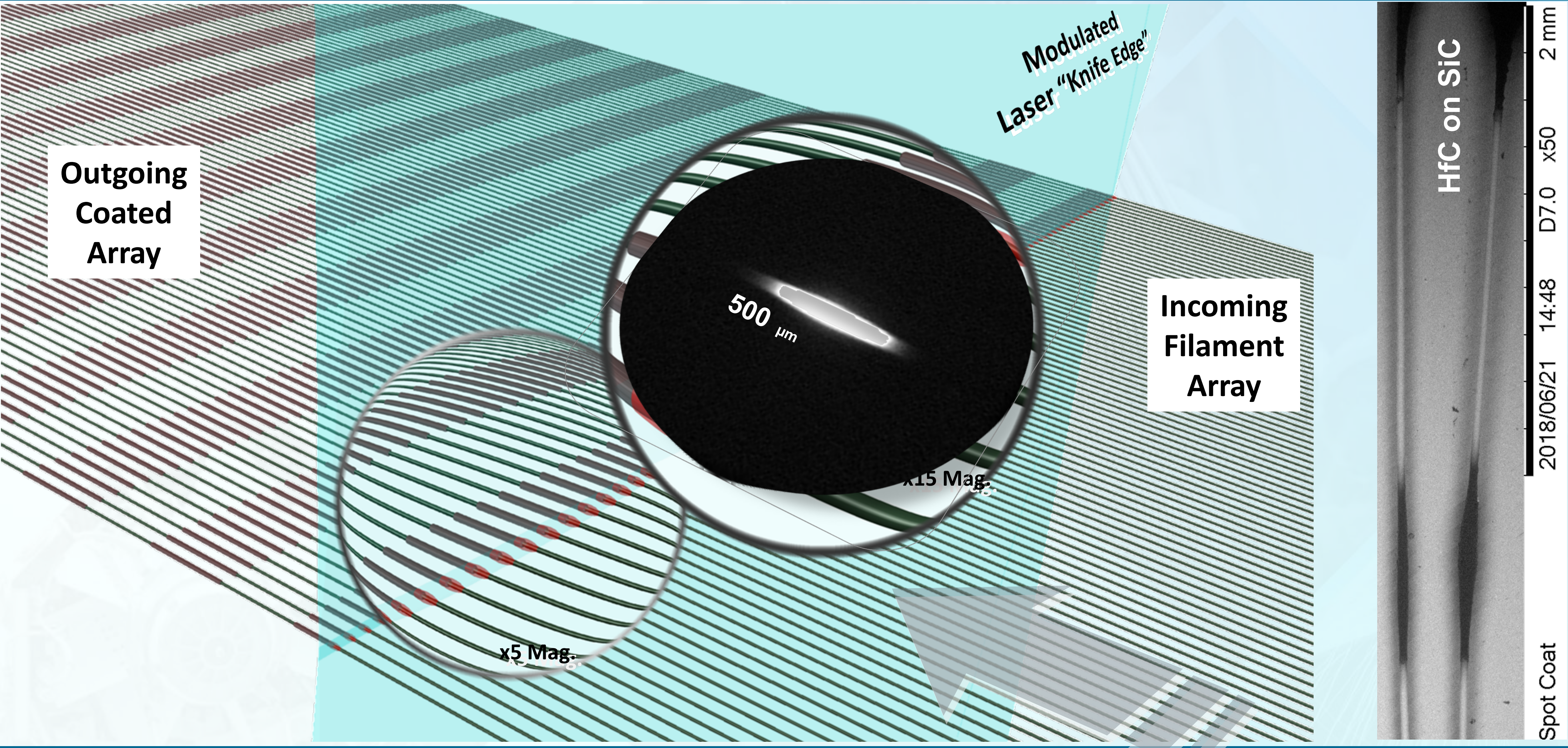
BACKGROUND: MATERIAL AGNOSTIC &





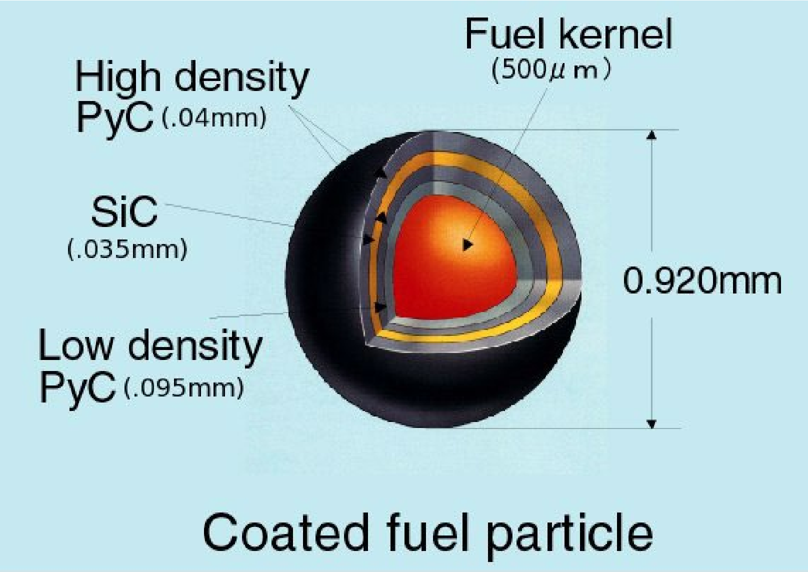


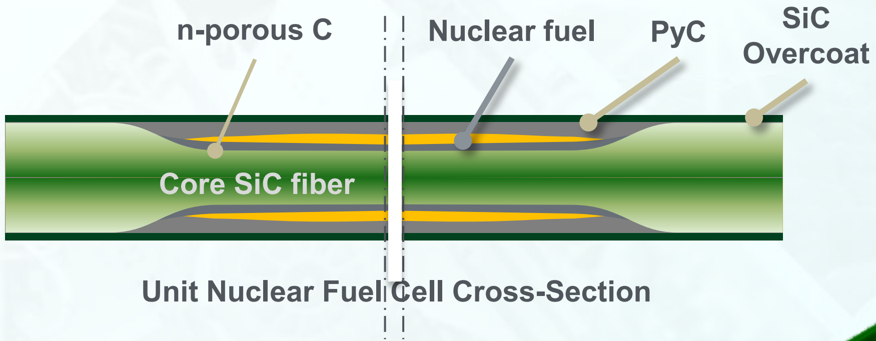
BACKGROUND: Laser CVD Spot Coating

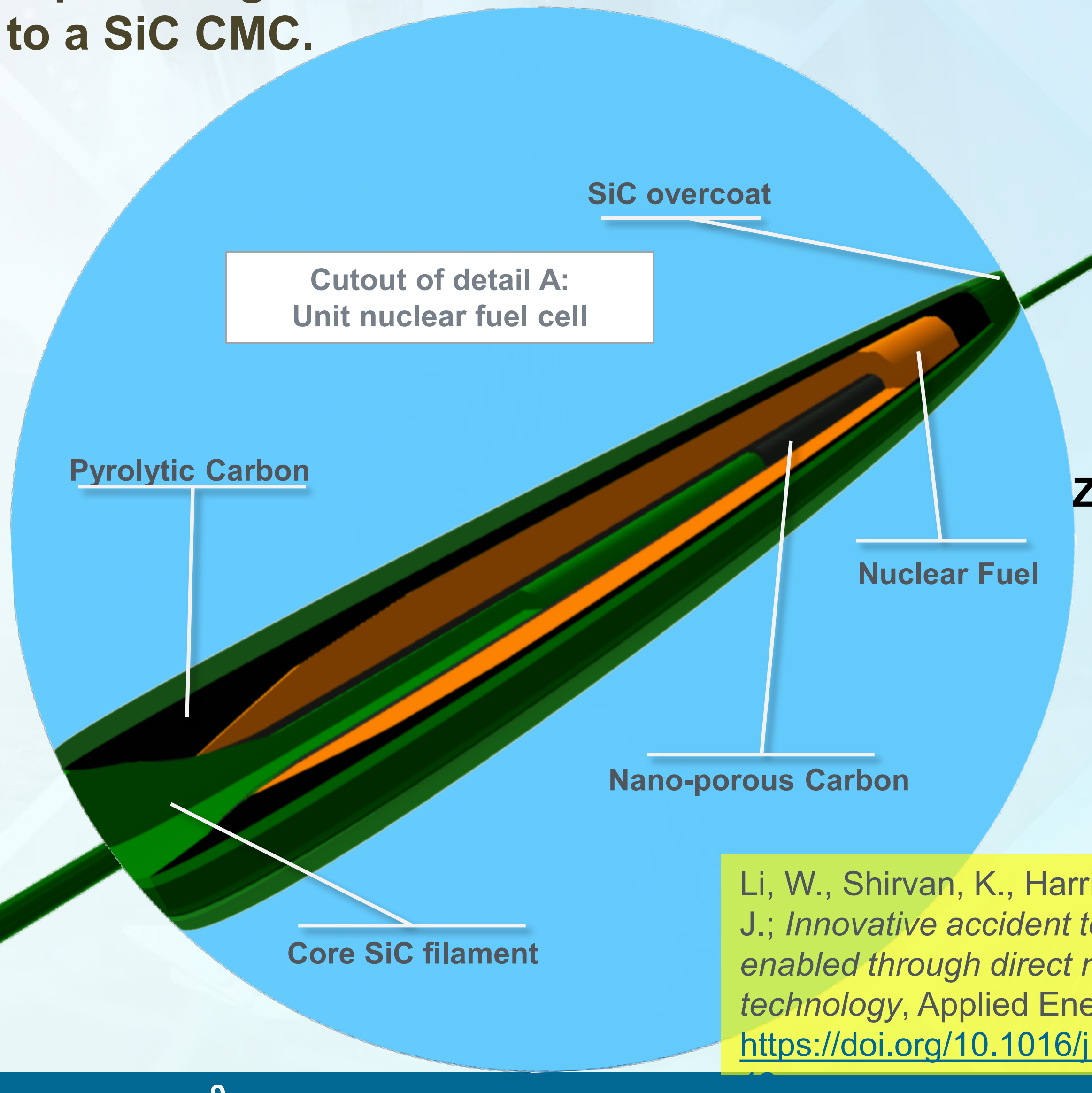


PRIOR PHASE-0 WORK: Fuel-in-Fiber -- 1½-D Printed TRISO-like fuel

TRISO-inspired multifunctional SiC fiber providing fuel containment and structural reinforcement to a SiC CMC.







US Pat.
10,546,661B2
11,518,719B2

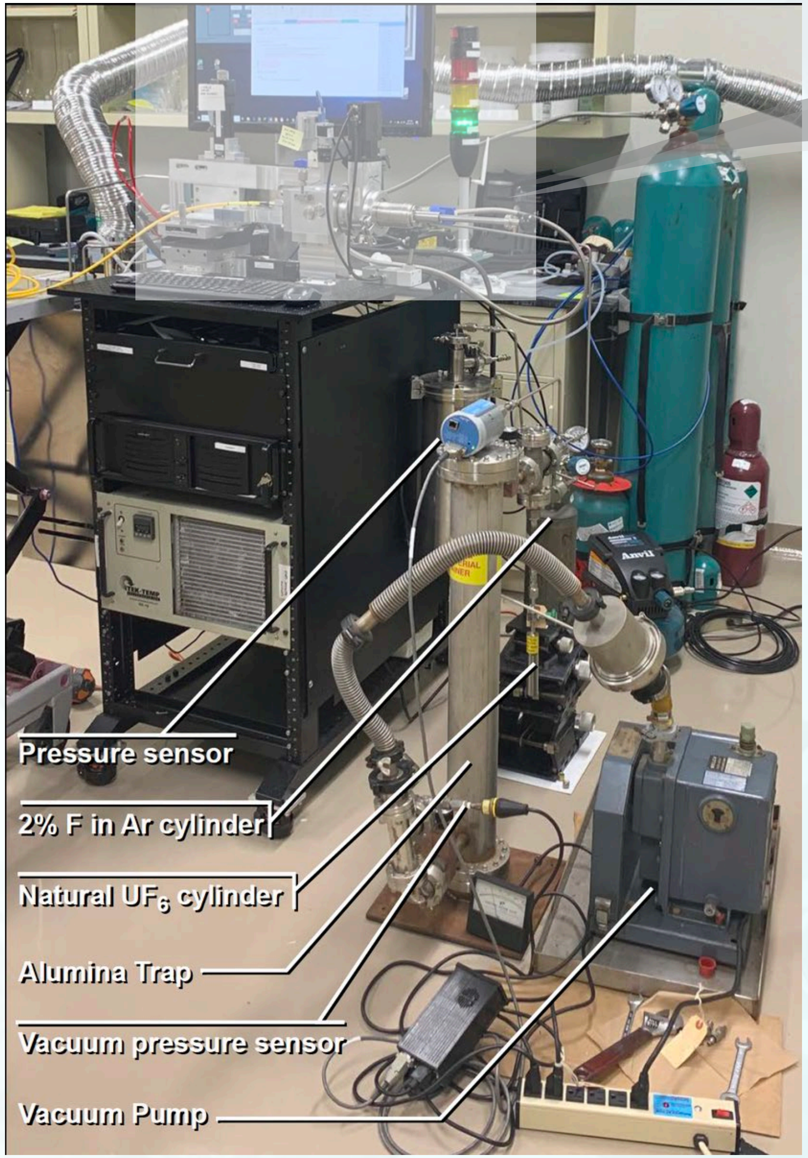
CN Pat.
ZL201580045509.0

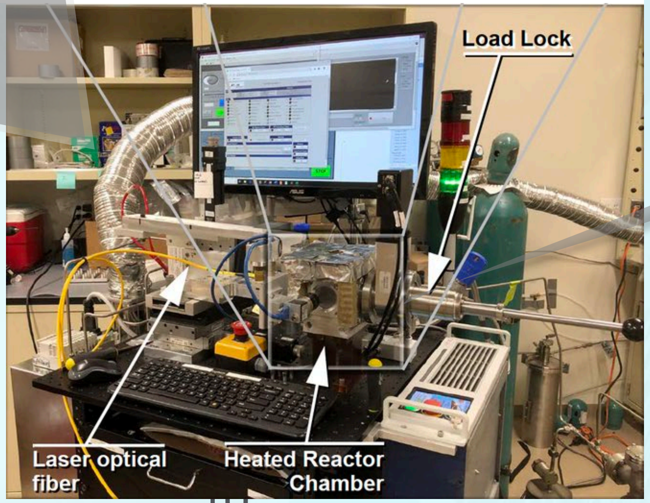
JP Pat.
JP6693891
JP7065145

Euro. Pat.
EP3158563

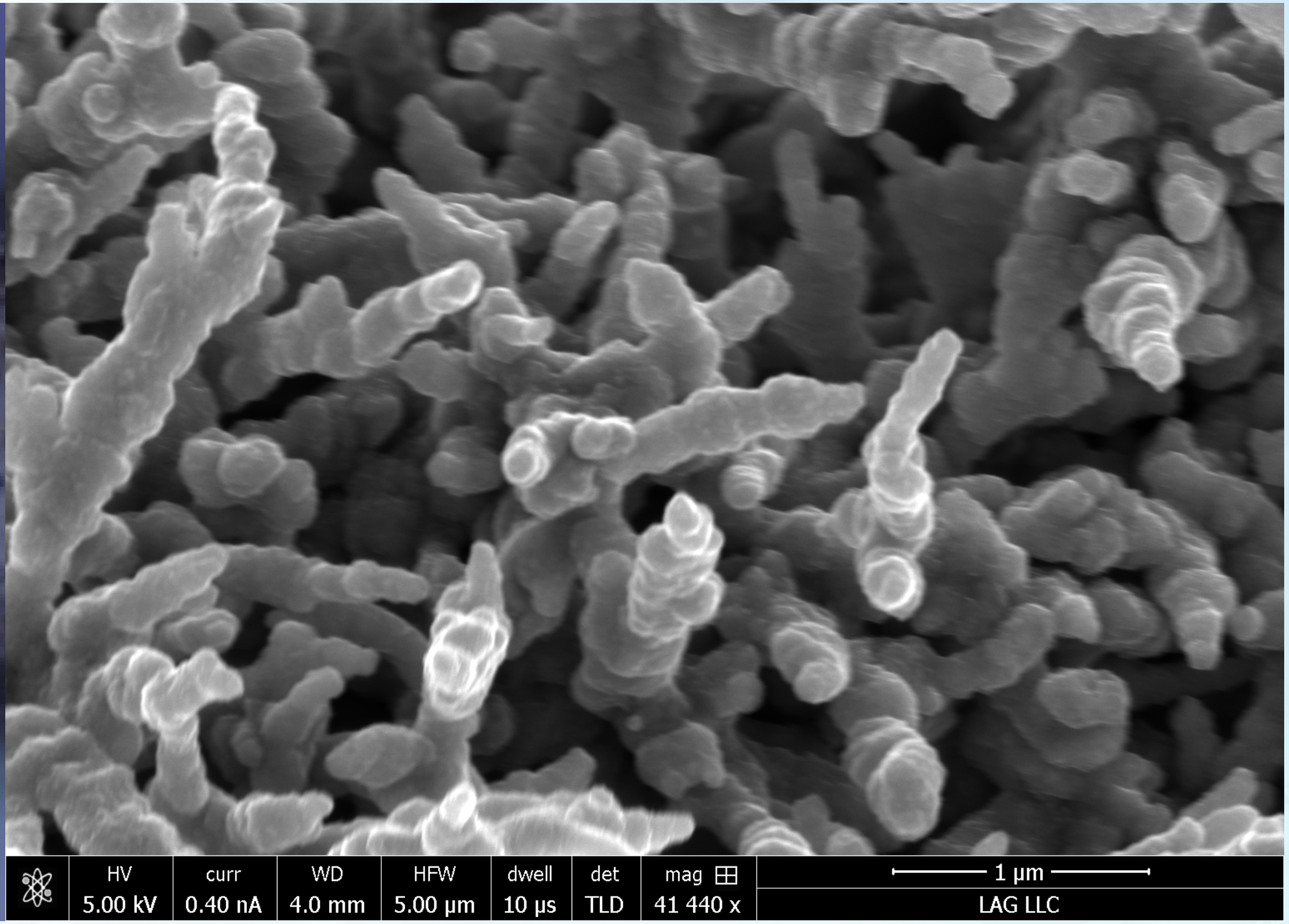
Li, W., Shirvan, K., Harrison, S. and Pegna, J.; *Innovative accident tolerant fuel concept enabled through direct manufacturing technology*, Applied Energy, Vol. 264 (2020) https://doi.org/10.1016/j.apenergy.2020.1147

PRIOR PHASE-0 WORK: Experimental Setup

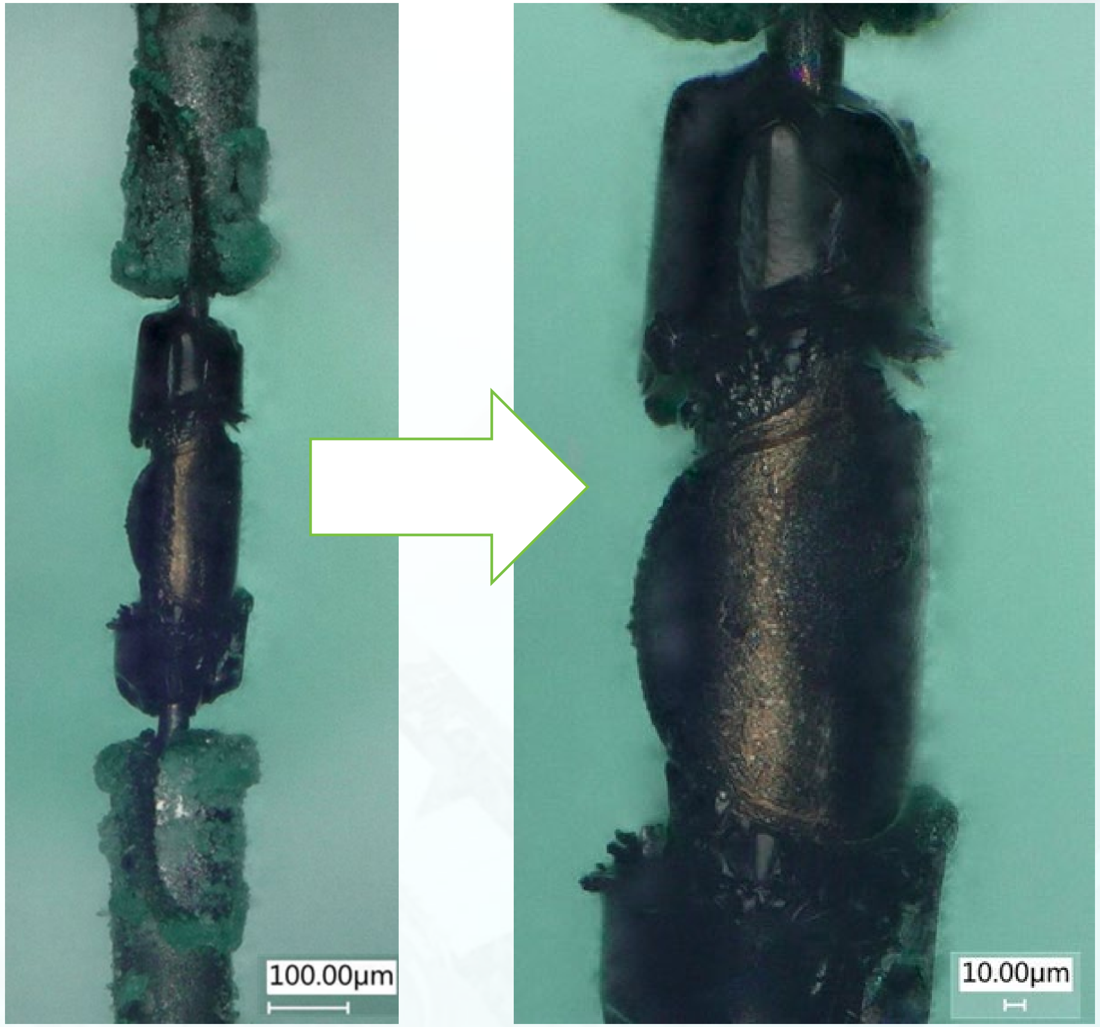


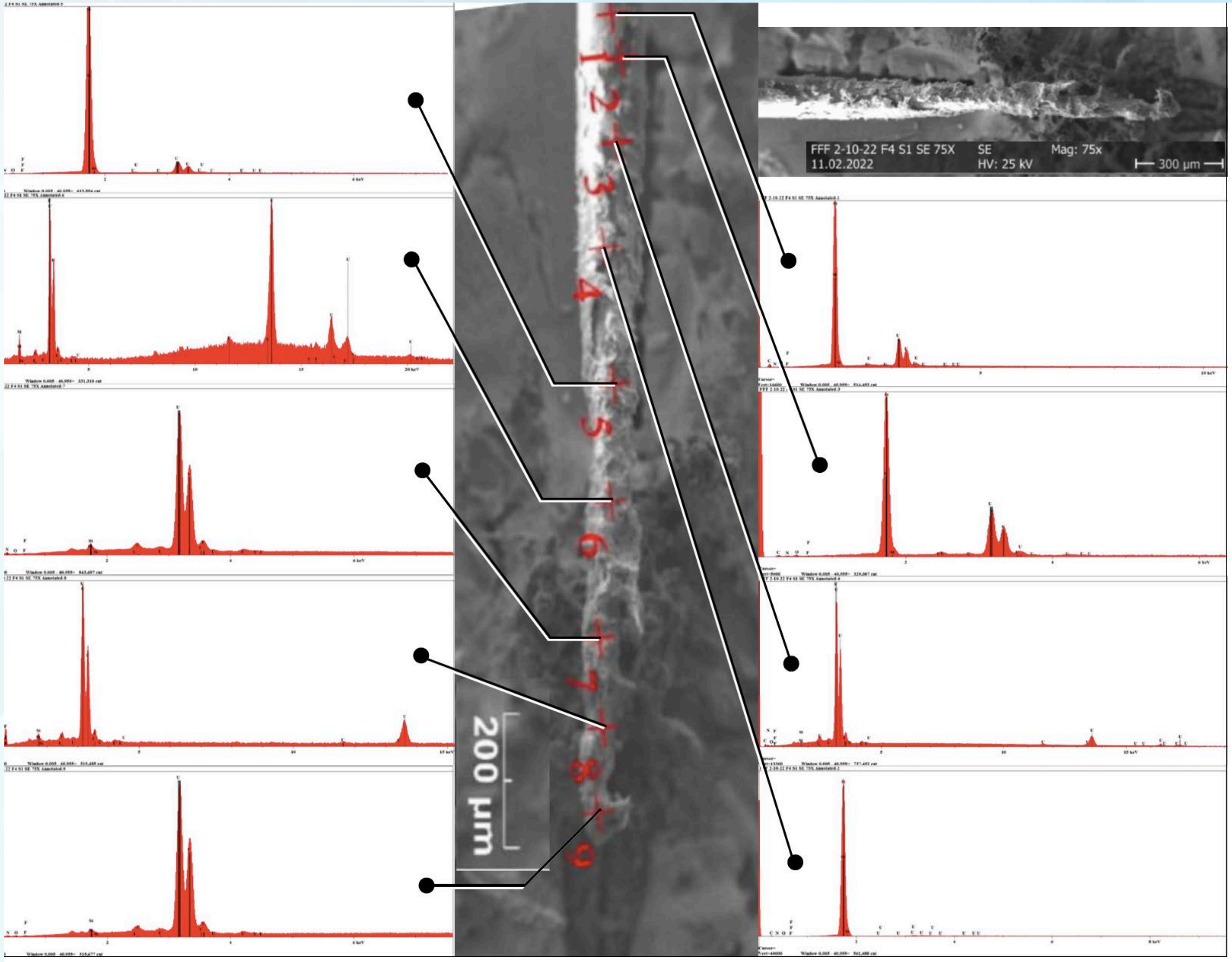


PRIOR PHASE-0 WORK: NanoPorous Carbon Spot Coat



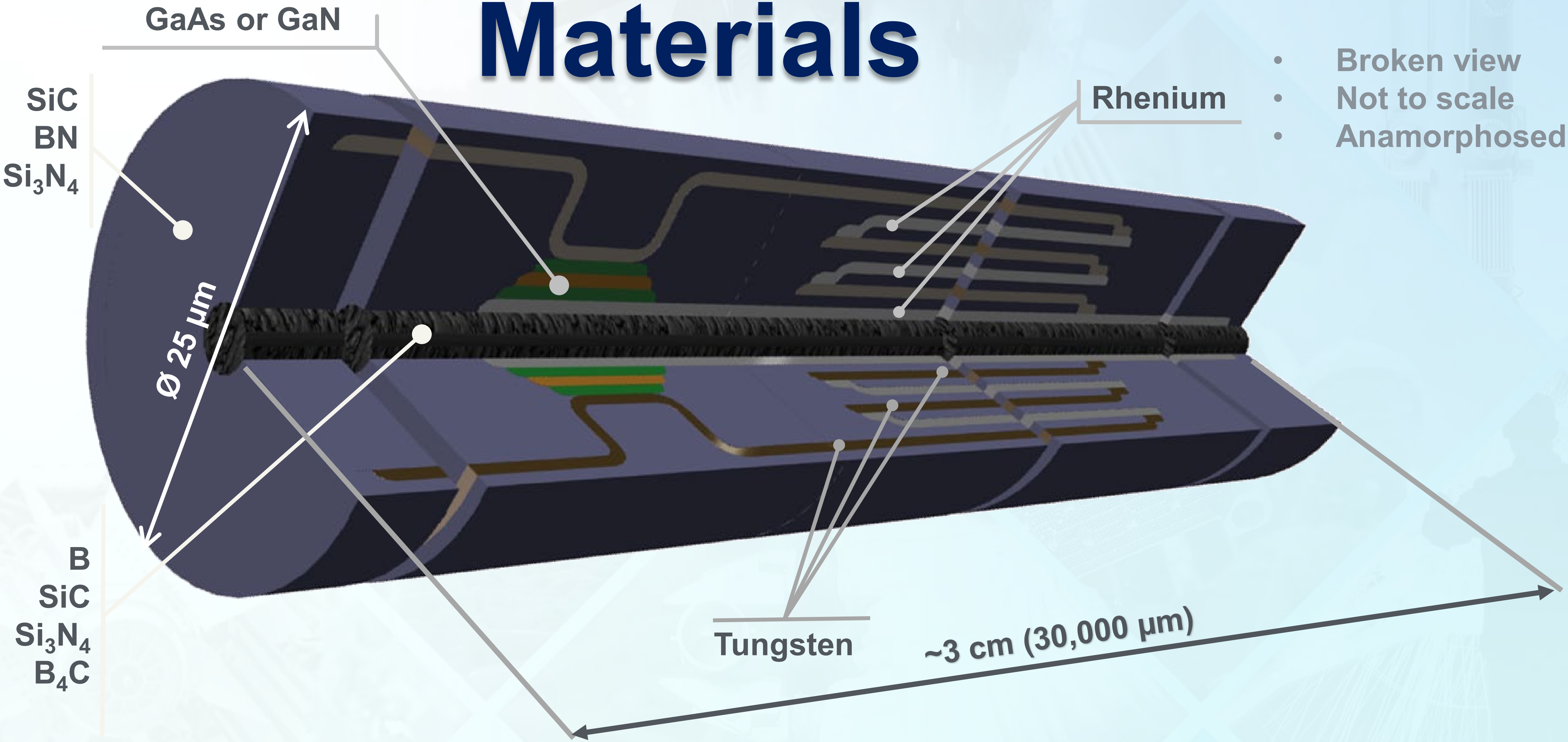
Optical microscope view of C coating direct-write


100.00µm
10.00µm


1
2
3
4
5
6
7
8
9
200 µm
FFF 2-10-22 F4 S1 SE 75X
11.02.2022
SE
HV: 25 kV
Mag: 75x
300 µm

U / UN on SiC

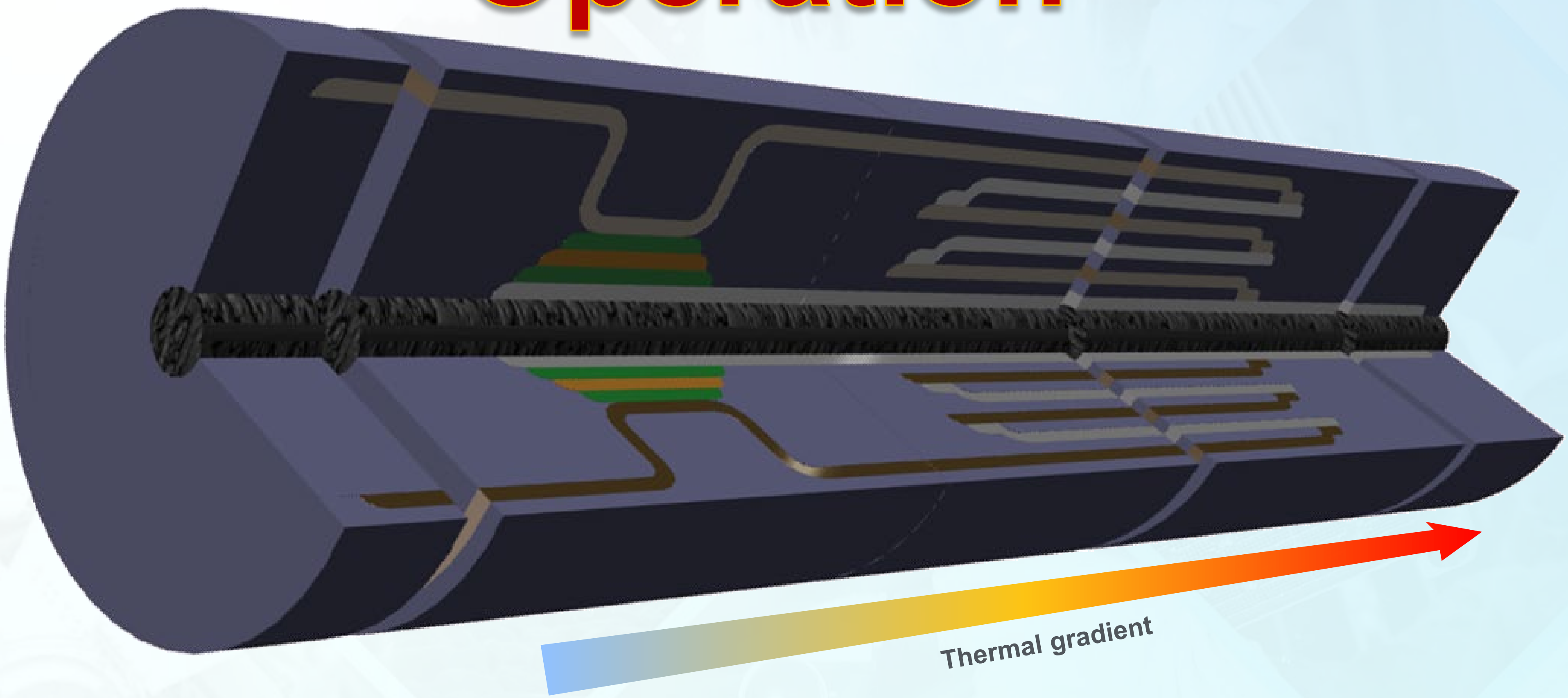
Materials



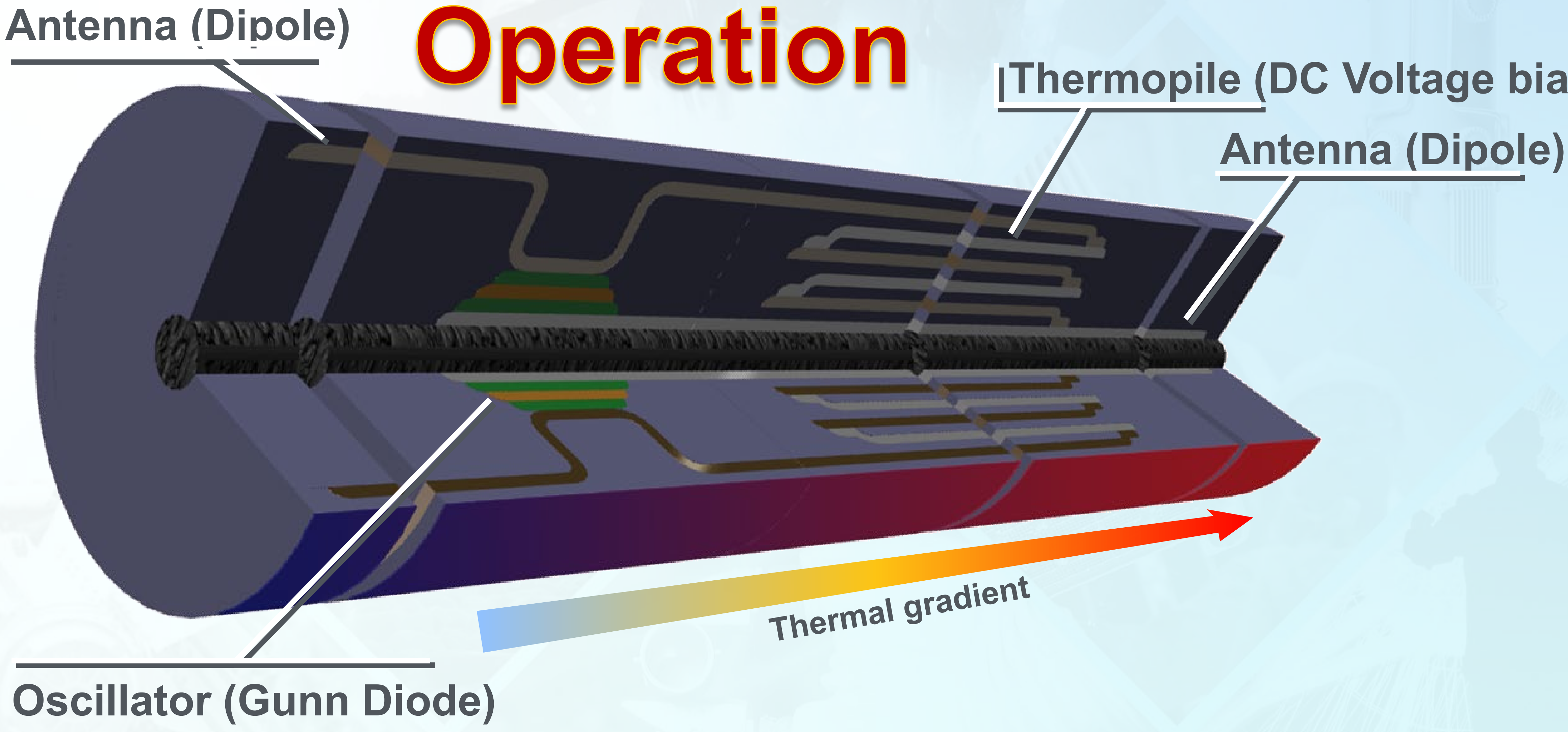
- Broken view
- Not to scale
- Anamorphosed

PROJECT VISION: Sample Fiber-Embedded Device

Operation



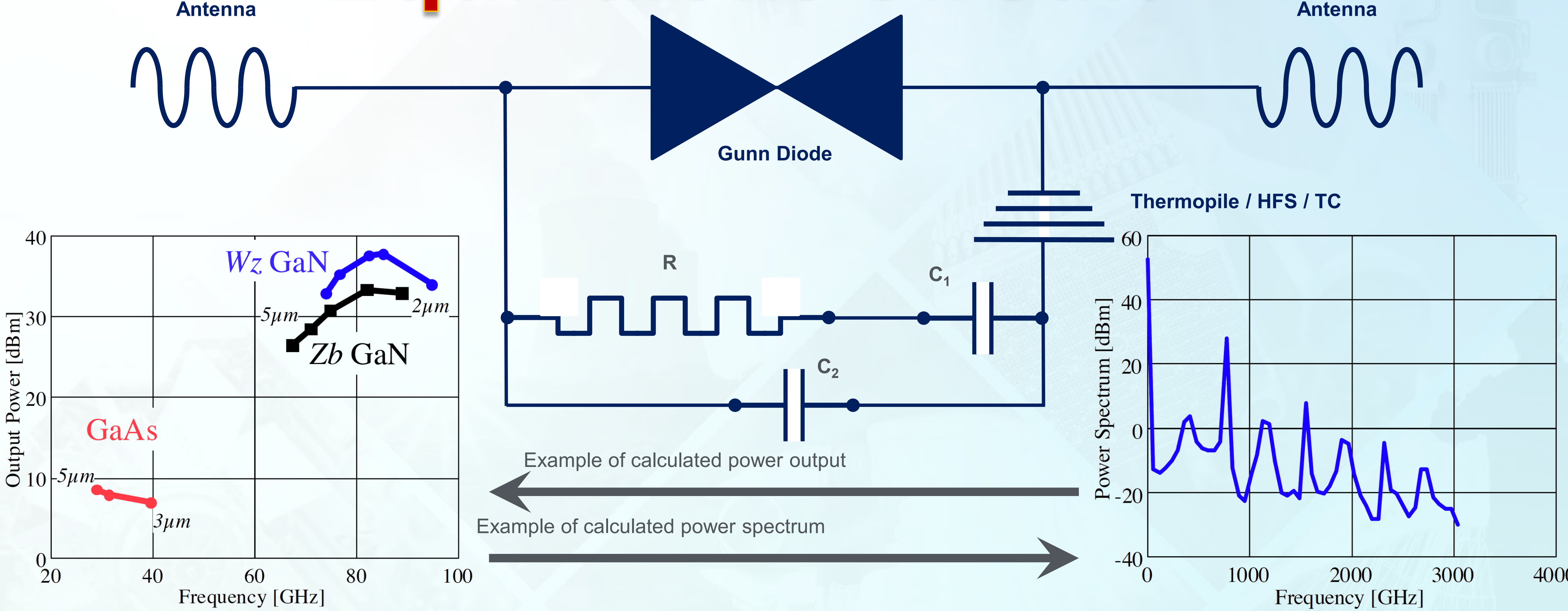
Operation



Antenna (Dipole)
Thermopile (DC Voltage bia
Antenna (Dipole)
Thermal gradient
Oscillator (Gunn Diode)

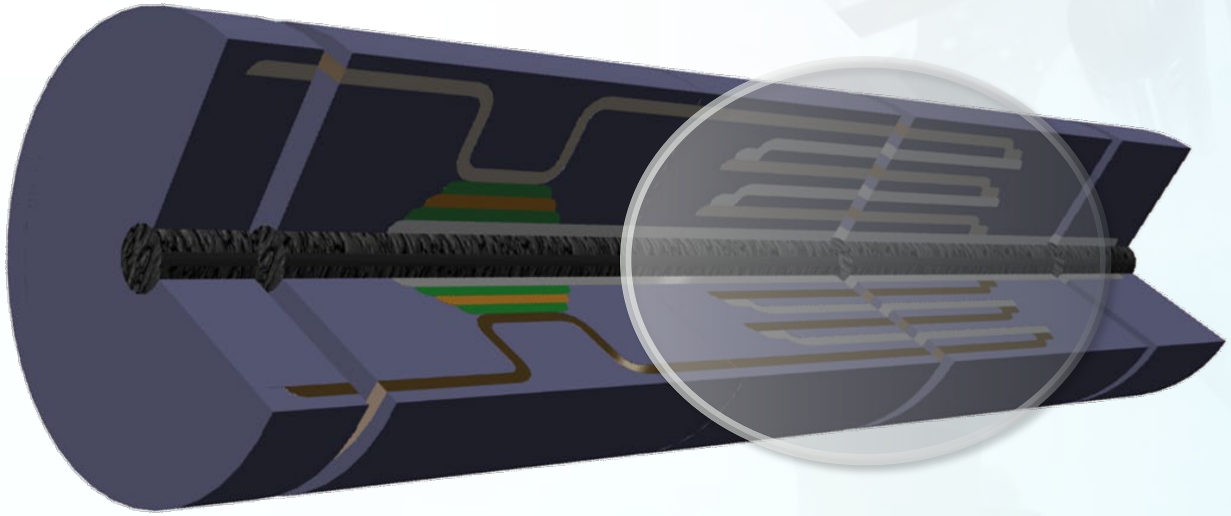
PROJECT VISION: Sample Fiber-Embedded Device

Equivalent Circuit

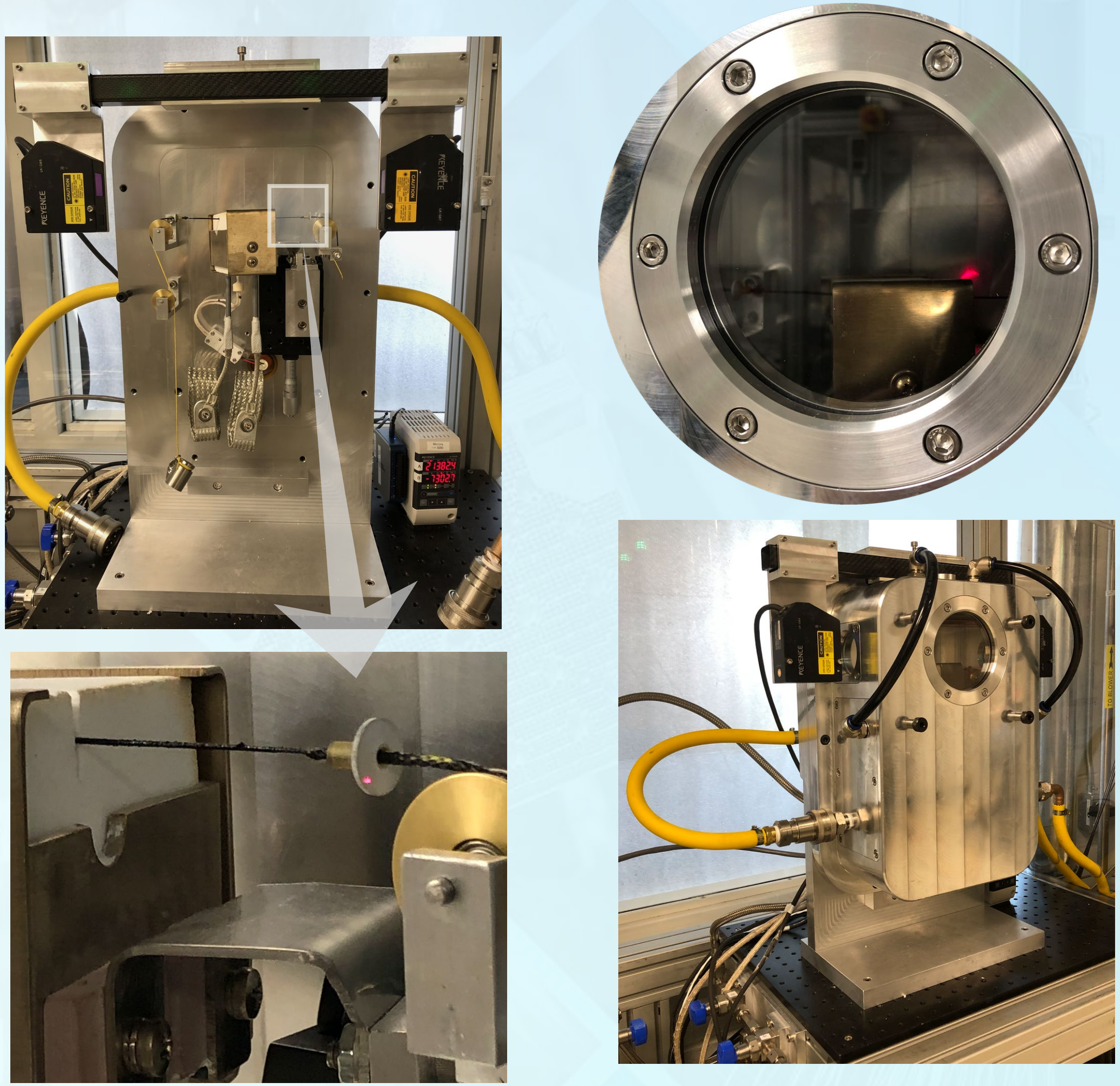


Source: Alekseev, E., Pavlidis, D., Sutton, W.E., Piner, E., Redwing, J.; IEICE Trans. on Electronics Vol. E84C No.10 pp.1462-1469 (2001)

PHASE I SCOPE: Demonstration and Testing of Fiber-Embedded Thermocouple / Thermopile



- Existing single fiber environmental testing.
  - Temp. Max 1750ºC
  - No combustion
  - Gases: H_2, CH_4, H_2O, CO_2, and other neutrals
- Needed:
  - Microprobe instrumentation (Tom Budka, Ph.D., Consultant)



S. Harrison, J. Schneiter, J. Pegna, E. Vaaler, R. Goduguchinta, and K. Williams, "High-Temperature Performance of Next-Generation Silicon Carbide Fibers for CMCs," Materials Performance and Characterization 10, no. 2 (2021): 207–223. https://doi.org/10.1520/MPC20200131

PHASE I KEY TECHNICAL CHALLENGE

FABRICATE SAMPLE EMBEDDED THERMOCOUPLE WITHIN A PHASE I BUDGET & TIMEFRAME

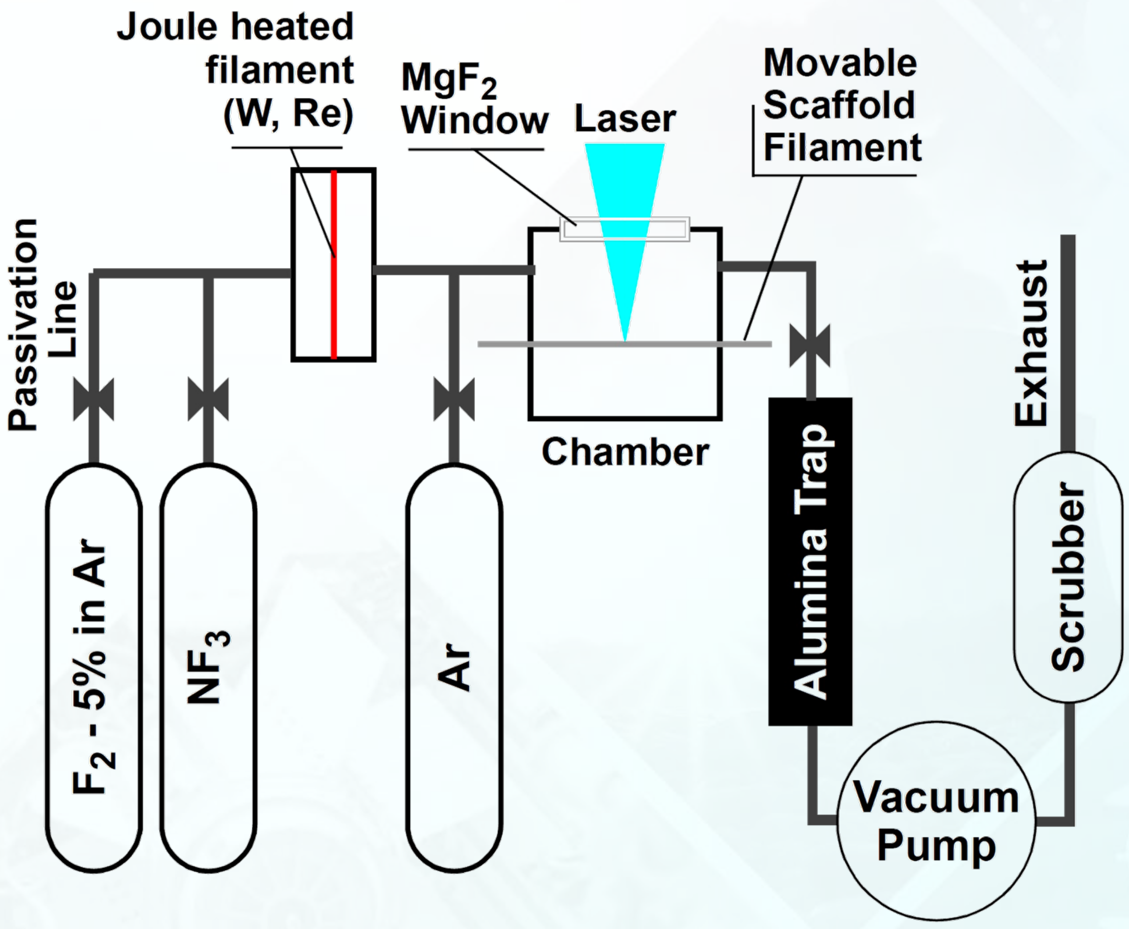


Fig. 14: Schematic of the Spot Coating reactor for this project. Everything upstream of the vacuum pump is new.

Gas box

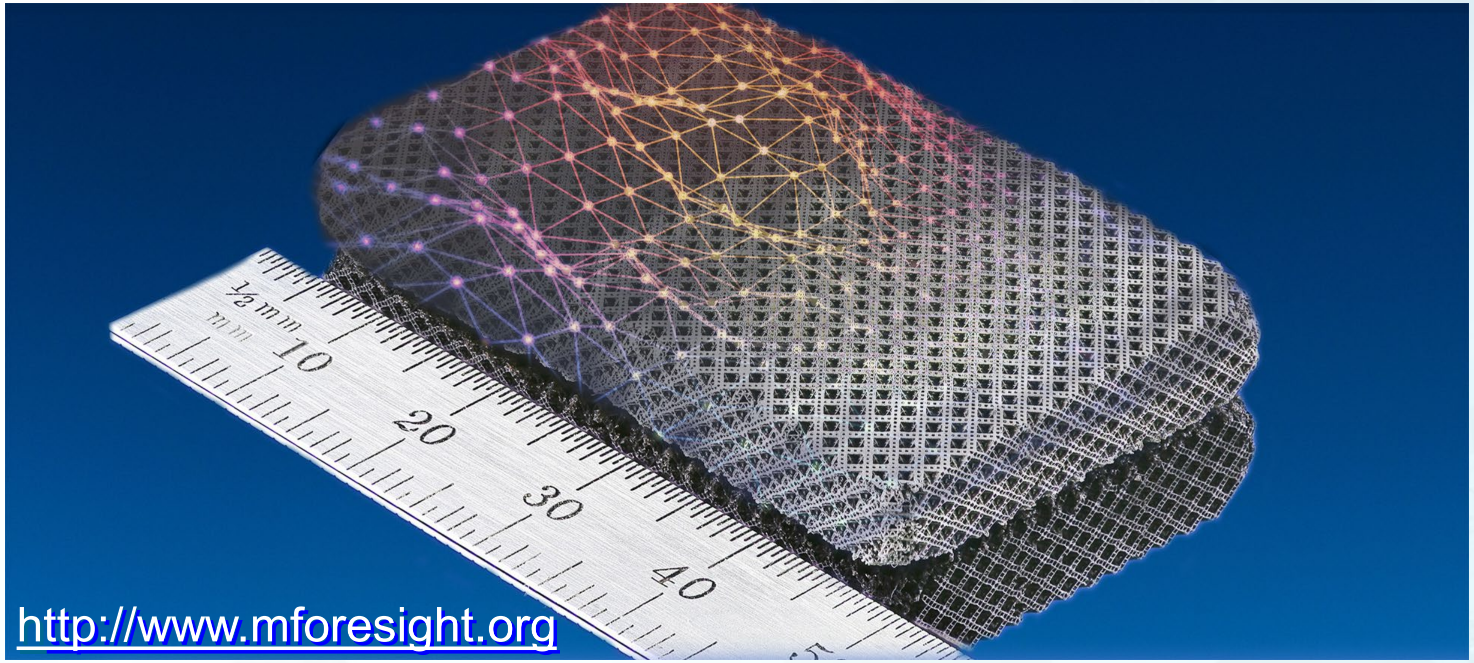
Scrubber-Burner

Alumina trap

Technology Impact: Nuclear Reactor S&I Challenges

#	Challenge	Description
1	Radiation Exposure	Damage or degrade sensors and instrumentation Reduced accuracy and reliability Transmutations / Amorphization • Fiber optics can opacify under irradiation
2	Extreme Temperatures	Design basis: 100's ºC. Beyond design basis: 1000+ºC Sensors and instrumentation failure • Thermocouple weakness • Discriminate signal from thermal rads with fiber optics
3	High Pressure	Damage to pressure sensors • Pressure sensitive readings, such as acoustic or optical
4	Corrosive Environment	Can cause corrosion failure with sensors and instrumentation • Molten salt reactors • Challenging for most metals, glasses, and some ceramics
5	Interference from Electromagnetic Fields	Reactor generated EM fields interfere with the sensors and instrumentation • False readings or total failure
6	Size and Accessibility	Crowded space Feedthroughs for sensors and instruments that require cables or optical fibers to send out signals

Technology Impact: Beyond Nuclear Reactor S&I



"In 1989, United Airlines Flight 232 crashed, killing 111 and injuring many more. In 2007, the I-35 Mississippi River Bridge collapsed, killing 13 and injuring 145. In 2010, the San Bruno pipeline exploded, killing 8, injuring 58, and causing immense residential property damage. In 2017, the Ohio State Fair ride failure killed one and injured seven. For each of these events, advanced rapid reliability assessment through nondestructive evaluation (NDE) could have potentially saved lives if employed in time to reveal the defects that led to catastrophic failures …"

J. Bishop-Moser et al., Rapid Reliability Assessment of Safety-Critical and Emerging Technologies, *Next-Generation Nondestructive Evaluation*, Manufacturing Foresight Institute (June 2019) http://mforesight.org/projects-events/nde/

Manufacturing Foresight:
- Non-Destructive Evaluation (NDE) introduced early in manufacturing
- Additive Manufacturing (AM) well adapted
- NDE external instrumentation to component

Free Form Fibers
- NDE built into component

Strategies:
- Built-in redundant sensors at nodes +
- Digital Twin
- Machine Learning / Artificial Intelligence (ML/AI)

Technology Impact: Built-in NDE S&I Challenges

#	Challenge	Description
7	Non-Intrusiveness	Sensors and actuators fully part of a multifunctional structure, as opposed to single purpose add-on instruments
8	Seamless Fabrication	Sensors fully integrated during the fabrication of the instrumented structure or system (as per Mforesight)
9	Ultra-low unit cost	Unit cost of mass-fabricated devices comparable to individual MEMS devices
10	Wireless signal & Decentralized power	Power / signal lines prohibitive Power generation must be localized Signal transmission must be wireless (E.g. Wifi, RFID)

Conclusions and Ongoing Work

1. ***Non-intrusive embedded sensors for IVHM, SHM and on-board NDE for intelligent composite structures & harsh environments***
2. ***Seamless product integration.***
3. ***Flexible devices***
4. ***Negligibly detrimental compared to SOTA.***
5. ***On-board wireless "Nervous systems"***
6. ***Low-cost devices (~10's m¢/device)***

Acknowledgment:

- **DOE Award DE-SC0023772**

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Thank You

FREE FORM FIBERS