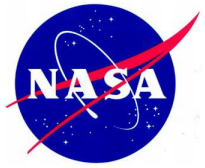

Scaling Electric Machines to a Megawatt and Material Options

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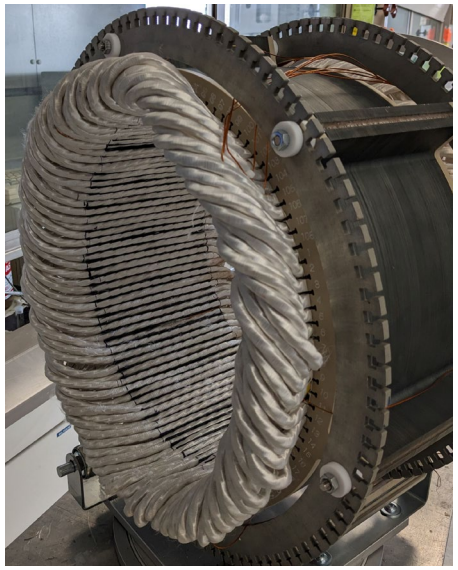
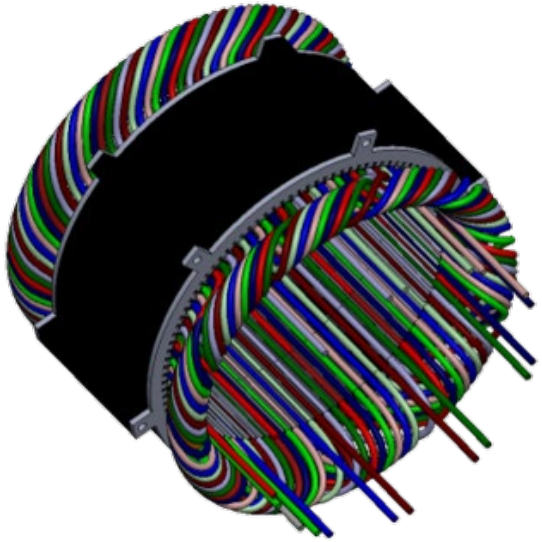
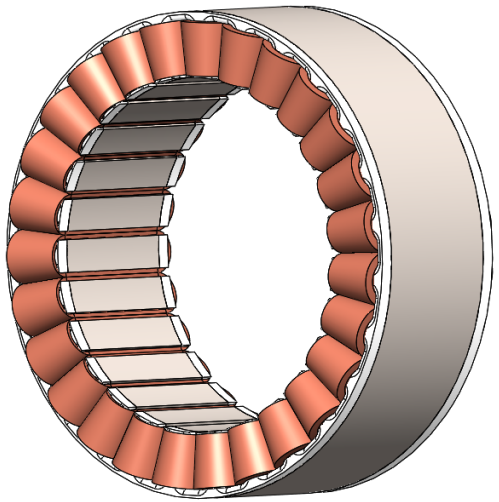
2023 AIAA/IEEE – Electric Aircraft Technologies Symposium,
June 14-16, 2023
San Diego, CA

The Challenge of Scaling to a MW

Distributed



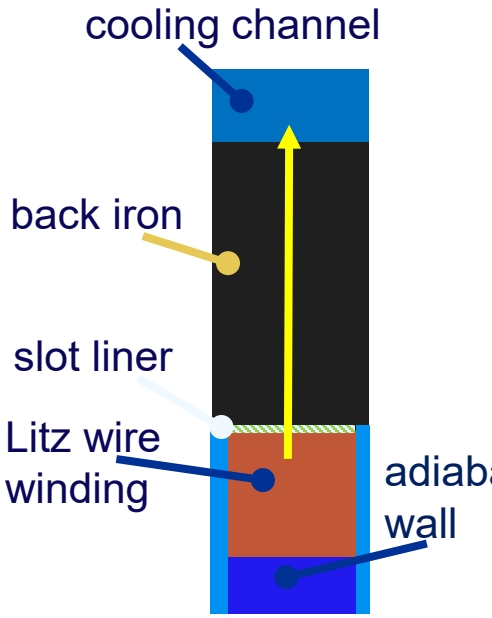




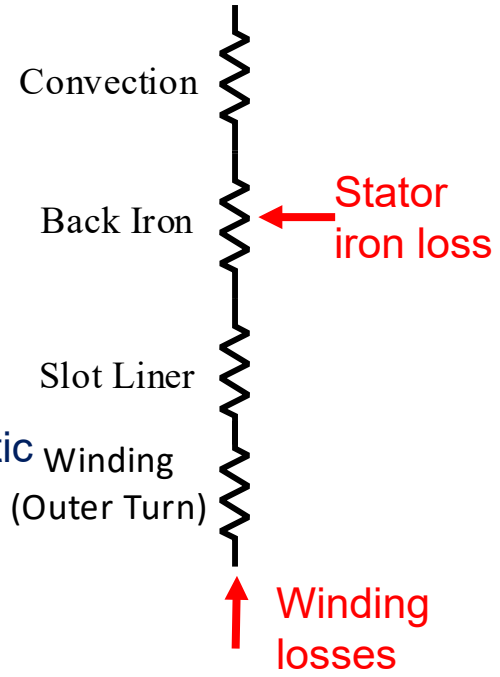
Concentrated

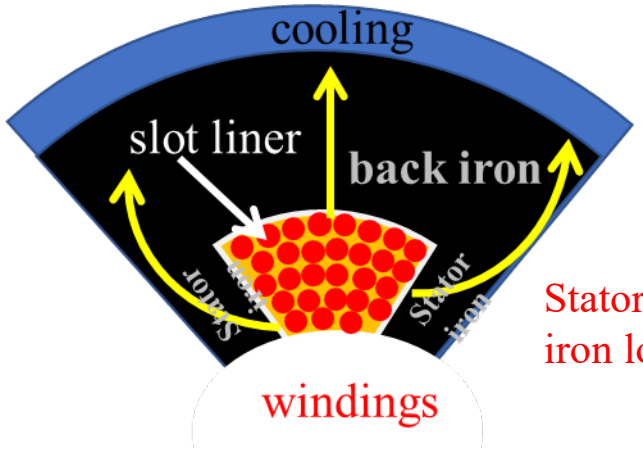
- Electric aircraft propulsion requires MW scale electric machines
- Must scale power dense machines from ~250kW
  - Increase speed ✗
  - Increase electric loading ✗
  - Increase rotor diameter ✓

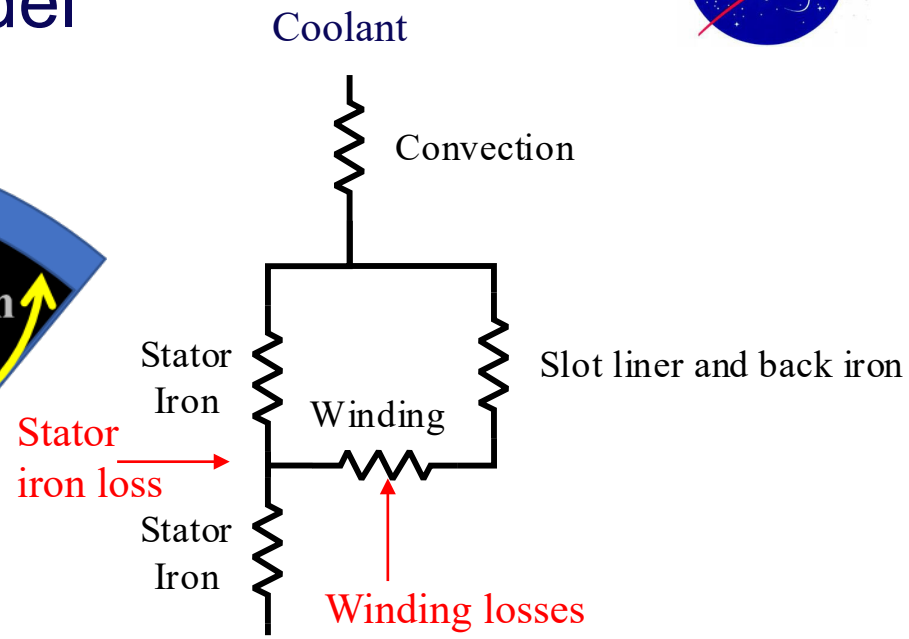
Resistance Network Model



Distributed







Concentrated

	Motor	Rotor Diameter (mm)	Power (MW)	Power Density (kW/kg)	Speed (krpm)
Distributed	High Efficiency Mega Watt Motor (HEMM)-NASA [1]	300	1.42	16	6.8
	Univ. of Illinois Urbana Champaign (UIUC) Motor [2]	263	1	13.8	18
Concentrated	Univ. of Wisconsin (UW) Motor[3]	191	1	23.7	20

1."High Efficiency Megawatt Motor Preliminary Design," R. Jansen *et al. AIAA Propulsion and Energy 2019 Forum*. 2019.,
2."A high-speed, high-frequency, air-core PM machine for aircraft application," A. Yoon, *et al. 2016 IEEE Power and Energy Conference at Illinois (PECI)*. IEEE, Champaign, IL, 2016.
3."Design and testing of a modular high-speed permanent-magnet machine for aerospace propulsion," J. Swanke, *et al. 2021 IEEE International Electric Machines & Drives Conference (IEMDC)*. IEEE, 2021.

Network Model-Scaling Challenges (SOA material system)

	Rotor Diameter (mm)	Winding Resistance (%)	Slot Liner Resistance (%)	Iron Conduction Resistance (%)	Convection and Contact Resistance (%)
Concentrated	50	14	62	8	15
	100	23	51	13	13
UW →	200	34	37	19	9
	300	40	30	23	7
	500	47	21	27	5
	700	51	16	29	4
	1000	54	12	31	3
Distributed	50	8	57	5	30
	100	15	51	8	26
	200	24	41	13	21
UIUC →	300	31	35	17	18
HEMM →	500	39	26	21	14
	700	44	21	24	11
	1000	49	16	26	8

Note: resistance = thermal resistance

SOA materials values used in calculations:

- Winding conductivity: 3 W/m · K
- Slot liner conductivity: 0.1 W/m · K

SOA material thermal conductivities published in:

A. Woodworth, *et. al.* "Potential of Materials to Impact Megawatt-Scale Electric Machines," *AIAA Propulsion and Energy 2021 Forum*, 2021, p. 3275.

Advanced Materials in a Distributed Wound Motor

	Rotor Diameter (mm)	Winding Resistance (%)	Slot Liner Resistance (%)	Iron Conduction Resistance (%)	Convection and Contact Resistance (%)
	50	5	24	10	61
	100	9	21	17	53
UIUC HEMM	200	15	17	26	42
UIUC HEMM	300	18	14	33	35
	500	23	10	41	26
	700	25	8	46	21
	1000	28	6	50	16

Note: resistance = thermal resistance

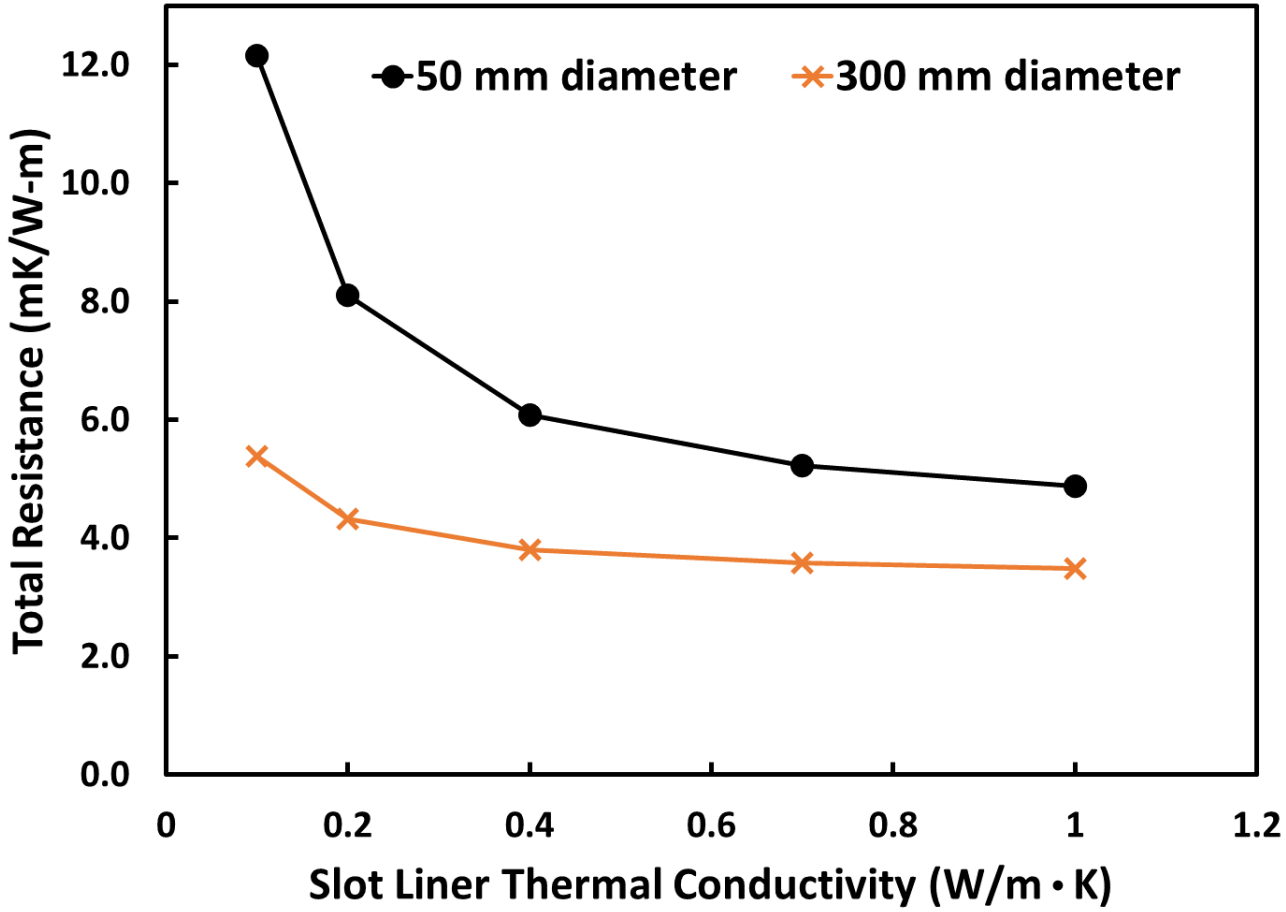
Advanced Material Properties

- Winding conductivity: 10 W/m•K
- Slot liner conductivity: 0.6 W/m•K

Advanced material prosperities published in:
Woodworth, A., Williams, T. S., Kelly, M., Sixel, W., Shin, E. E., Nguyen, B. N., and Naghipour, P., "Potential of Materials to Impact Megawatt-Scale Electric Machines," *AIAA Propulsion and Energy 2021 Forum*, 2021, p. 3275.

Advanced Materials in a Distributed Wound Motor

- Sensitivity of the system to the slot liner

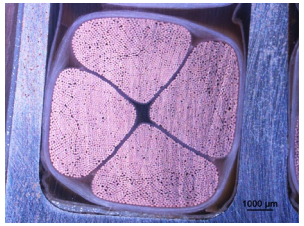


Multiscale Model

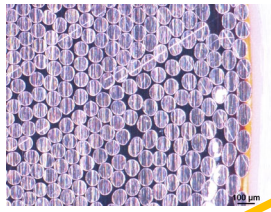
Distributed winding

stator slot

Litz wire



micro structure



top cooling flow

adiabatic sides

bottom cooling flow

electrical current

2
1
3

Repetitive Unit Cell (RUC)

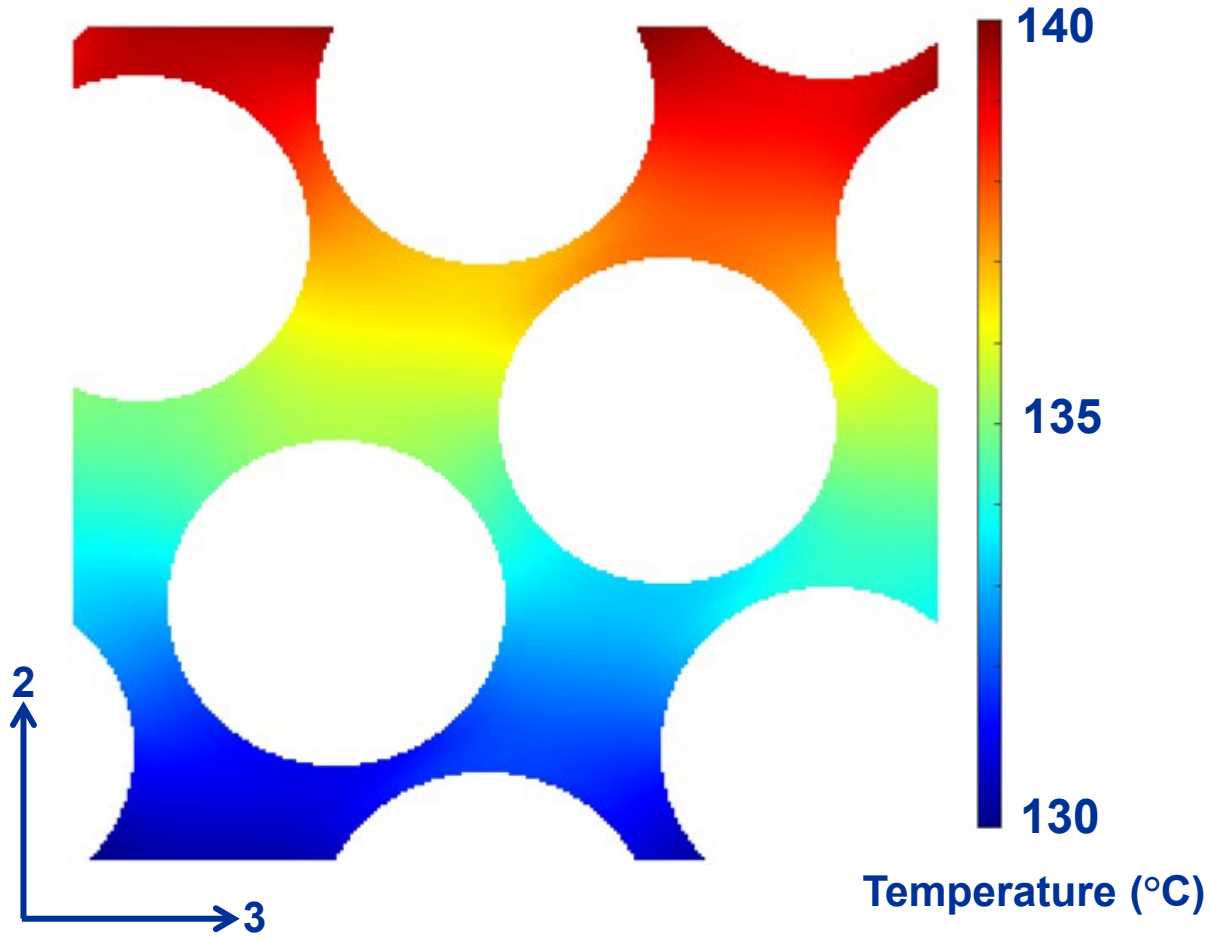
2
3

Temperature (°C)

+1.545e+02
+1.417e+02
+1.288e+02
+1.159e+02
+1.030e+02
+9.014e+01
+7.726e+01
+6.439e+01

Multiscale Model

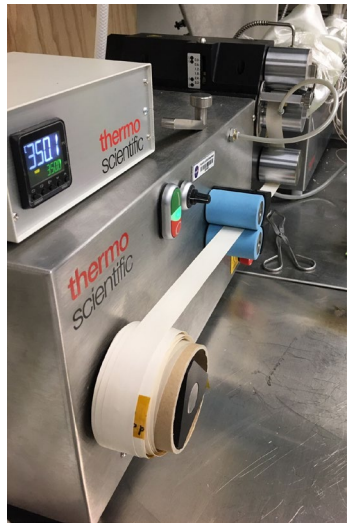
- **Outer hotspots can be 10 °C higher than the interiors hotspots**
- **Outer areas are not homogenous**

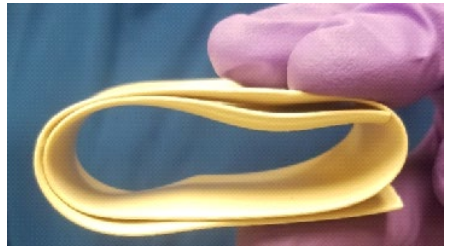


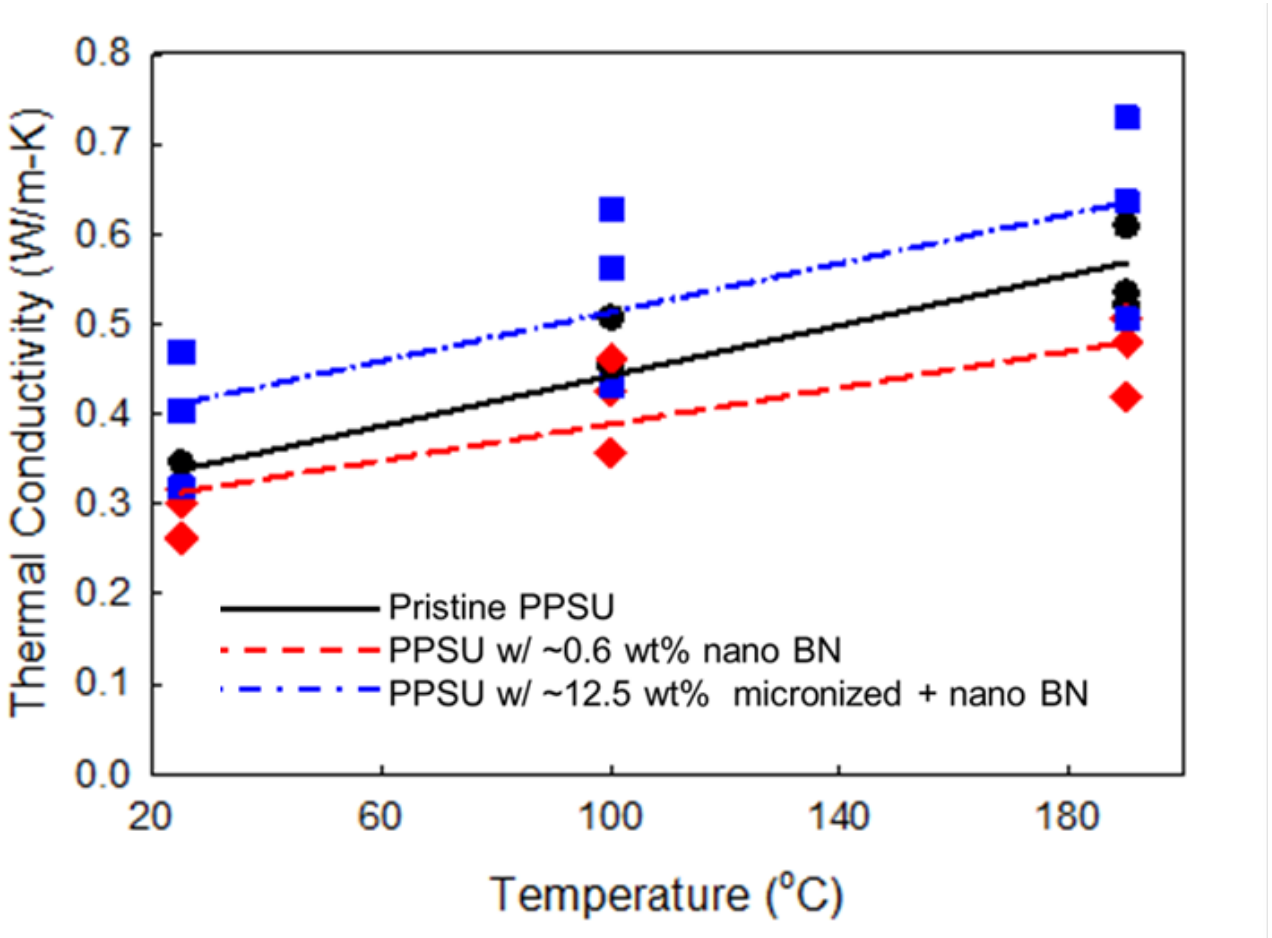
Material Solutions

Thermoplastic-BN Composites

Can be made into many different shapes and forms (extrusion, injection molded) [1]





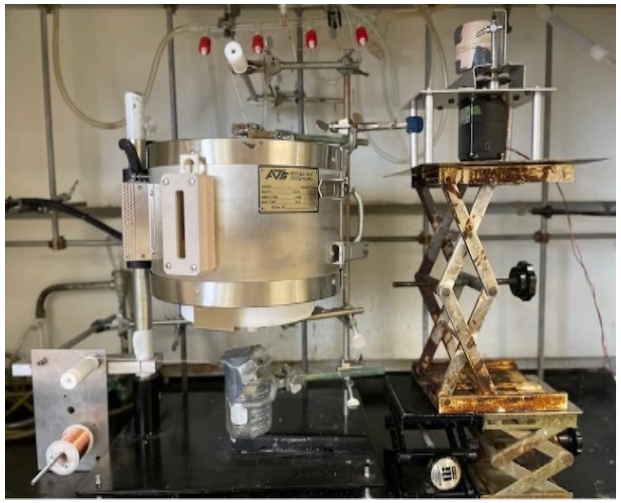


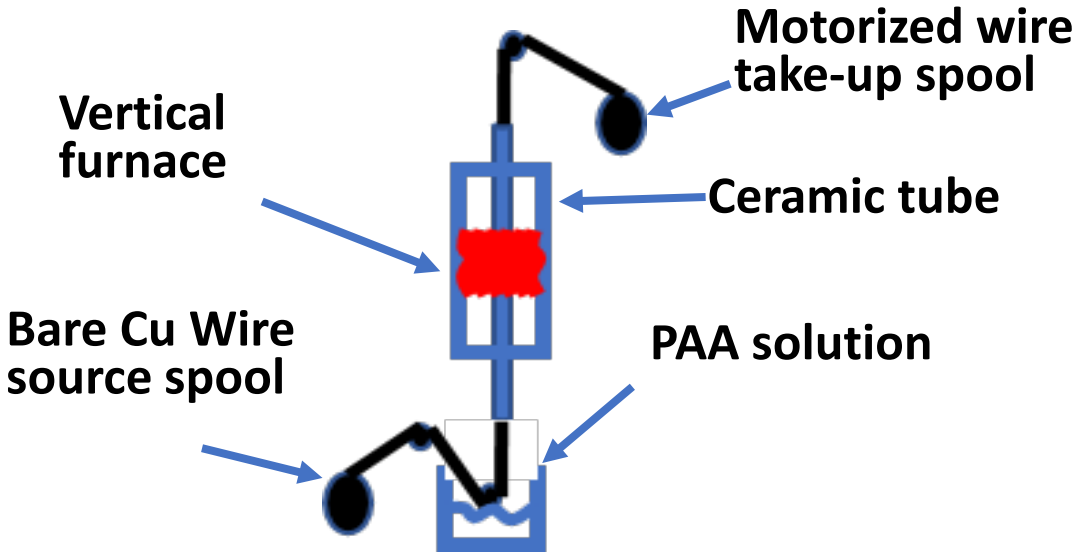
[1] A. Woodworth, *et al.*, "Potential of Materials to Impact Megawatt-Scale Electric Machines," *AIAA Propulsion and Energy 2021 Forum*, 2021, p. 3275.

Material Solutions

Polyimide-BN Composite Films (magnet wire coating)

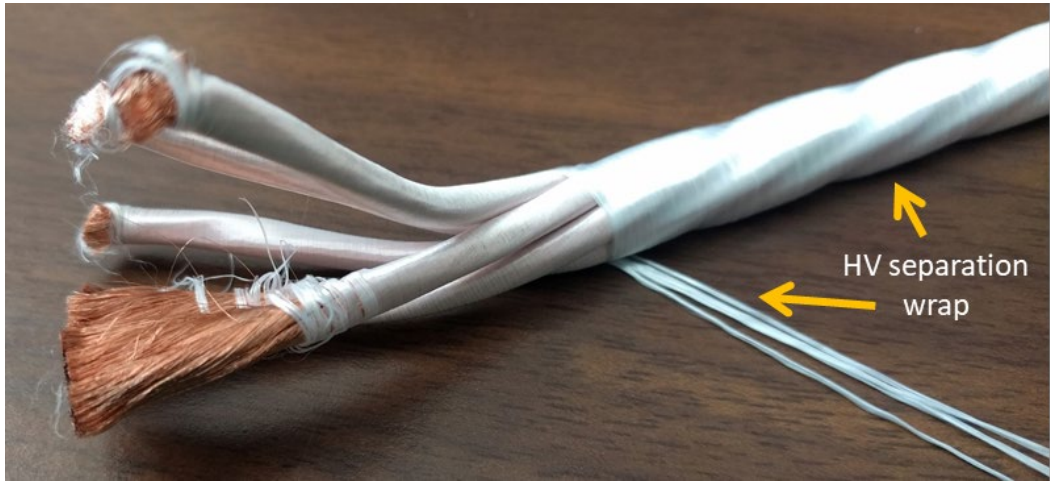
Previously shown to have a thermal conductivity up to 2.5 W/m·K [1]

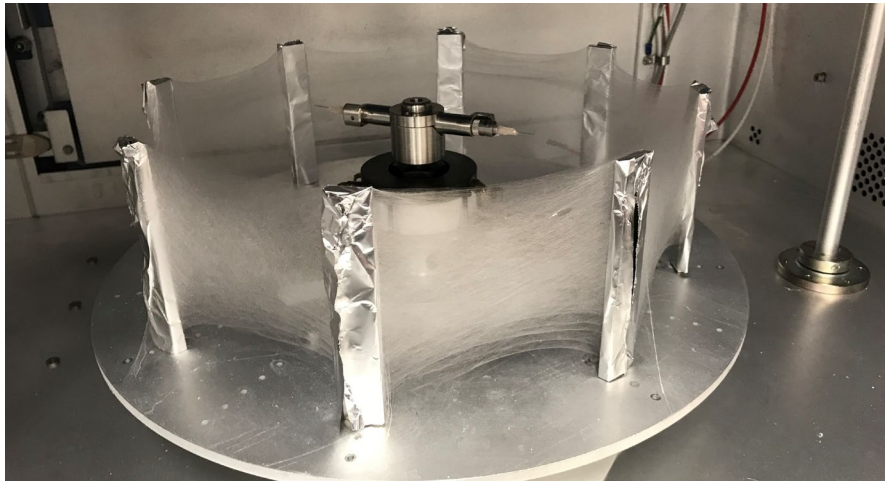




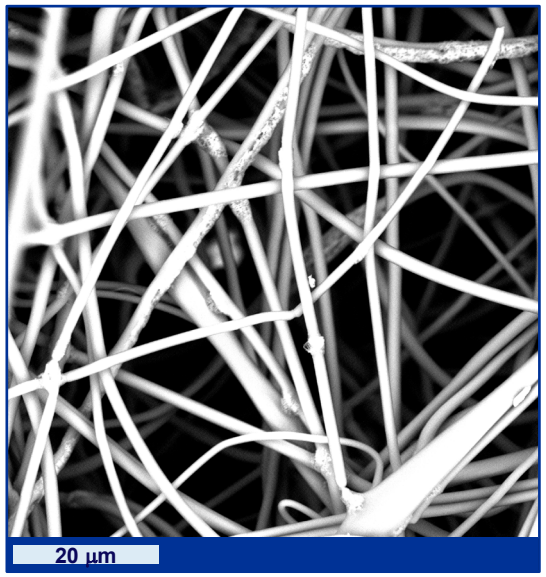
PI-BN coated and cured film on a Cu 0.81-mm (20 AWG) wire

[1] A. Woodworth, *et al.*, "Potential of Materials to Impact Megawatt-Scale Electric Machines," *AIAA Propulsion and Energy 2021 Forum*, 2021, p. 3275.

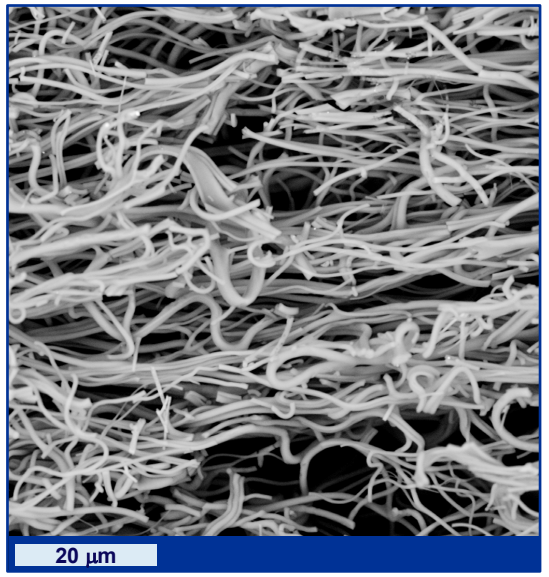




Polymer polyvinylpyrrolidone (PVP) $[C_6H_9NO]_n$ + boron oxide (B_2O_3) as spun fibers



heat treatment



Converted BN fibers (confirmed by FTIR and XRD

Conclusion

- Network thermal model gives an indication of the role of materials as a function of rotor diameter
- Network model demonstrates a diminishing return for increasing slot liner thermal conductivity beyond 0.7 W/m·K and highlights a need to bring different solutions
- Multiscale modeling revealed unexpected hotspots, higher predicted temperatures and significant thermal gradients on the microlevel
- Novel material solutions are enabling to scaling electric machines to MW power levels

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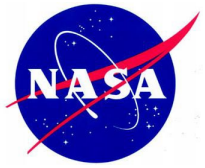

Thank you!

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