Additive Manufacturing Technology for Power Electronics Applications

Madhu Chinthavali

Power Electronics Team Lead,

Oak Ridge National Laboratory

Email: chinthavalim@ornl.gov

APEC Industrial Session

March 22, 2016

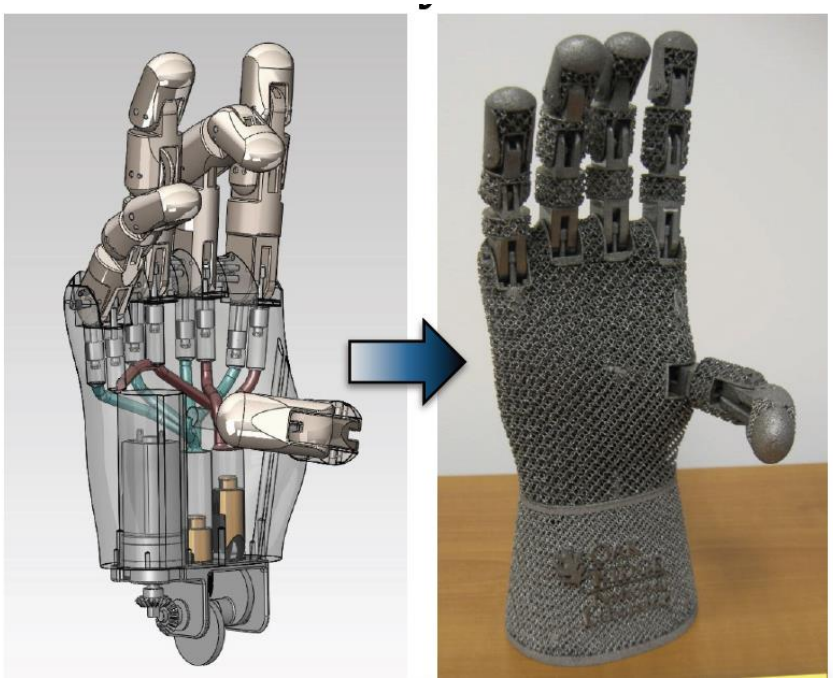
OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Why 3D Printing (Additive Manufacturing- AM)?

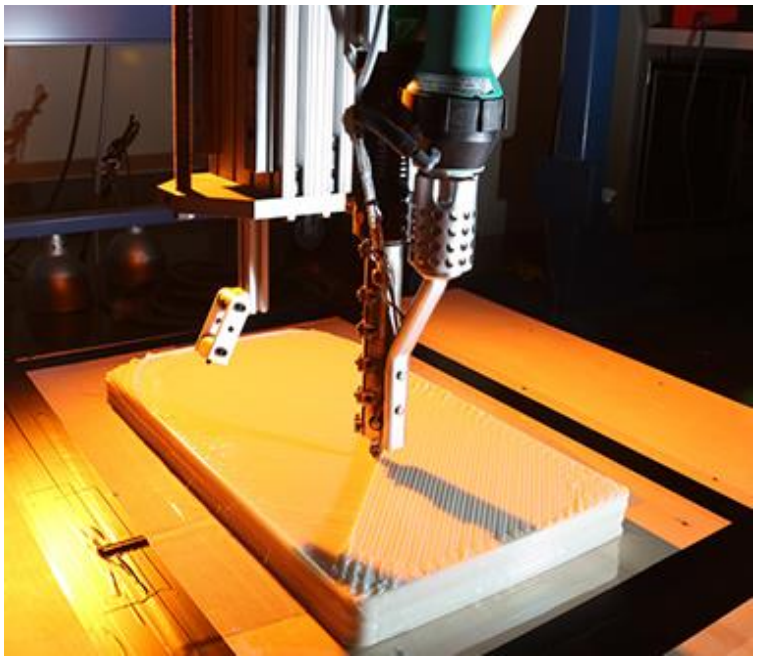
Faster. Less Expensive. Better designed.

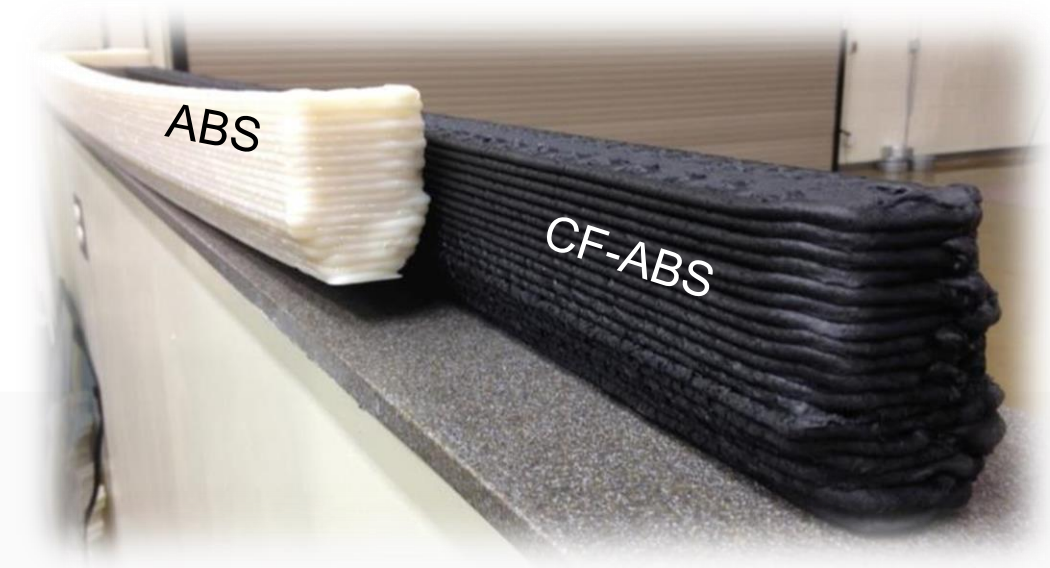
- **Increased complexity: Complexity is free?**
- **Less wasted material.**
- **Quick prototyping.**
- **Integrated functionality/components.**
- **Reduced part count**

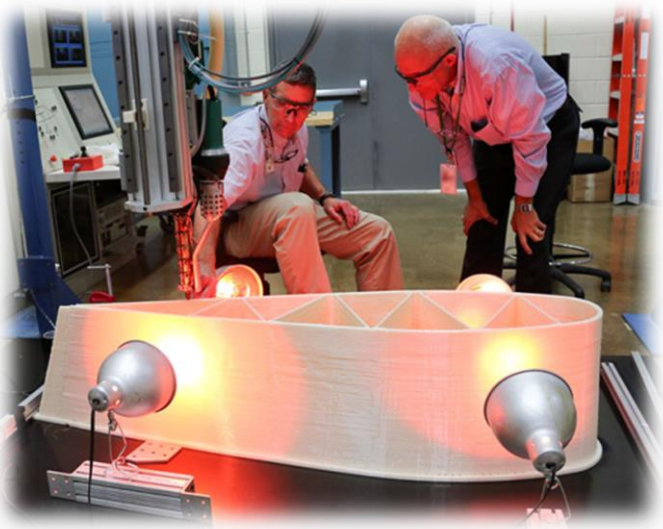


Available technologies and machines at ORNL's Manufacturing Demonstration Facility

- FDM
- BAAM
- Laser powder bed
- E-Beam powder bed
- Inkjet Binder powder bed







Materials for 3D Printing

- Polymers
- Metals
  - Titanium
  - Aluminum
  - Stainless Steel
  - Copper
  - Brass
  - others
- Ceramics

Multi-material printing is still challenging !

How large of a prototype can be printed?

A car? A house?

CINCINNATI®
CINCINNATI INCORPORATED

LOCAL MOTORS

World's First 3D Printed Car Makes Debut

Layer by layer, inch my inch, the world's first 3-D printed vehicle seemingly emerged from thin air during the 2014 International Manufacturing Technology Show. In a matter of two days, history was made at Chicago's McCormick Place, as the world's first 3-D printed electric car -- named Strati, Italian for "layers"-- took its first test drive.

September 2014

ORNL 3D Prints Iconic Shelby Cobra as an All-Electric "Lab on Wheels"

concept to drivable car in 6 weeks

parts printed in 24 hours

8 hours to print tooling components, 4 hours to machine, and cost ~$250

1700 Btu per pound of printed material

0.2 in. diameter nozzle results in a 0.020 in. surface variation

Class A final surface finish through machining, sanding, and polishing.

estimated 1400 lb total vehicle weight

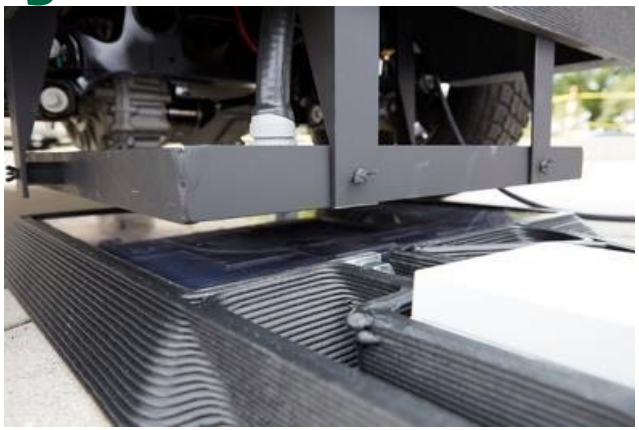
500 lb of printed parts containing 20% carbon fiber material

AMIE 1.0 and Printed Utility Vehicle

- **AMIE- Advance Manufacturing + Integrated Energy**

http://www.ornl.gov/amie

AMIE 1.0 and Printed Utility Vehicle



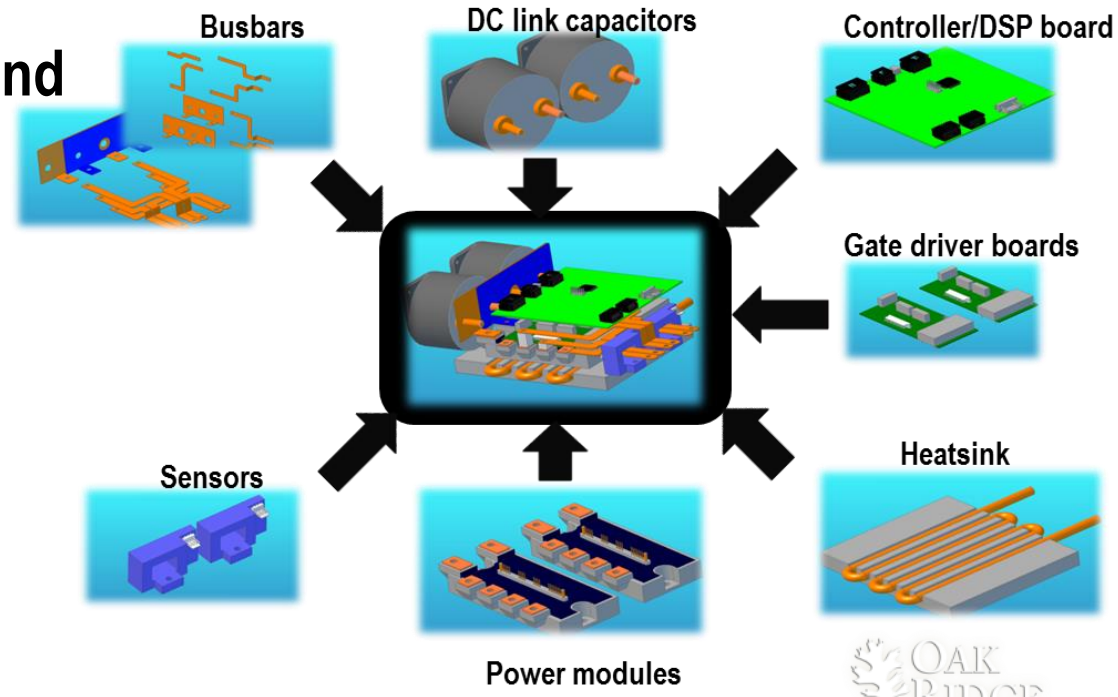
3D Printing for Power Electronics

Advantages

- Rapid prototyping
- Complex structures allowing better-designed, more-complex cooling systems
- Elimination of interfaces
- More integrated functions and components
- Reduction in component count
- More degrees of freedom: Better optimization

Possible 3D printed components

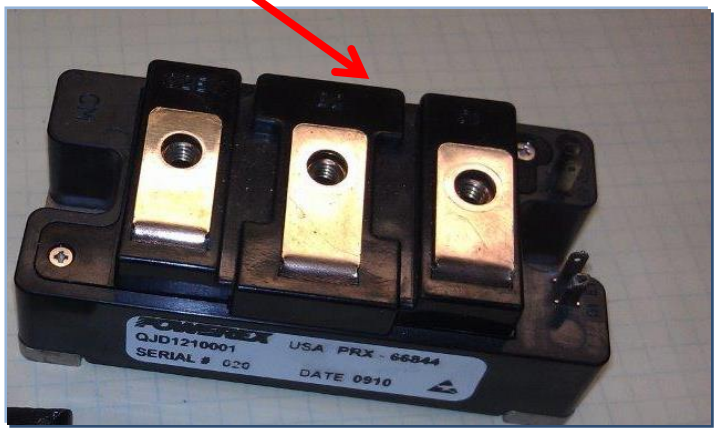
- Heat sinks
- Bus bars
- PCBs
- Packages/Modules
- Inductor cores
- Housing



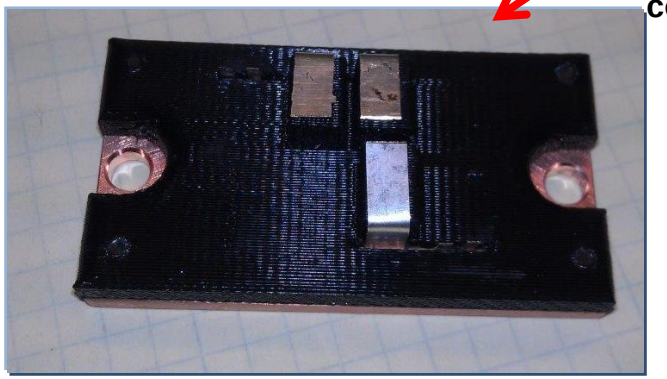
Rapid Prototyping of Power Modules

- *1200 V, 100 A SiC module*

Traditional Package

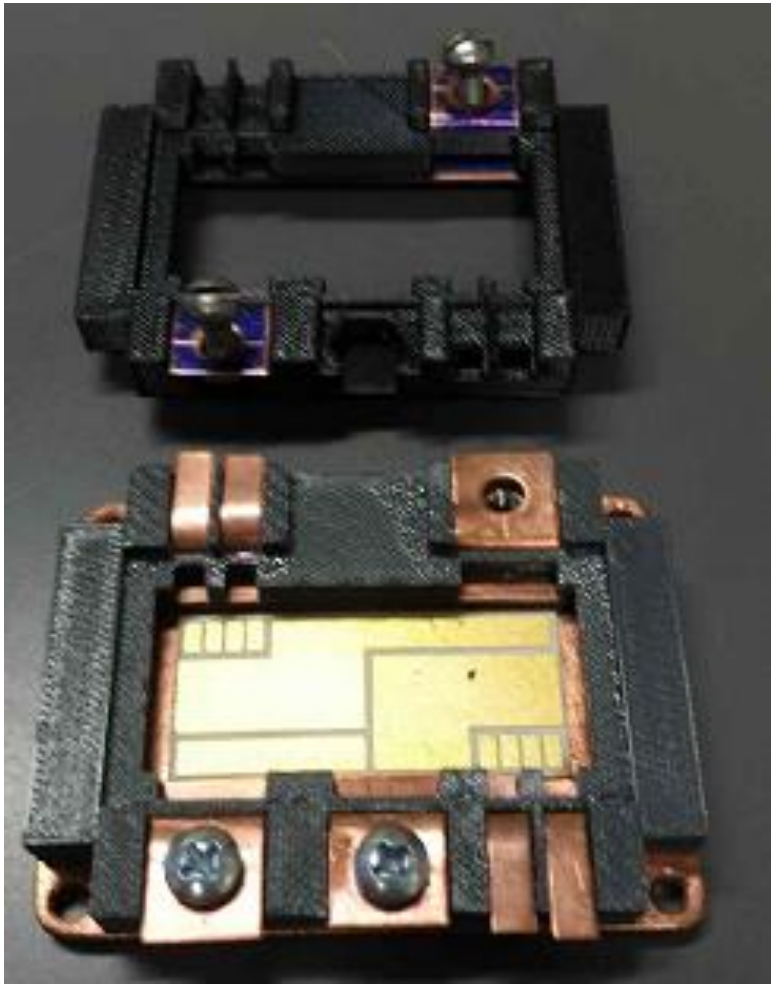


Single phase example module with AM lead frame – from quick-prototype request to complete, <1 day

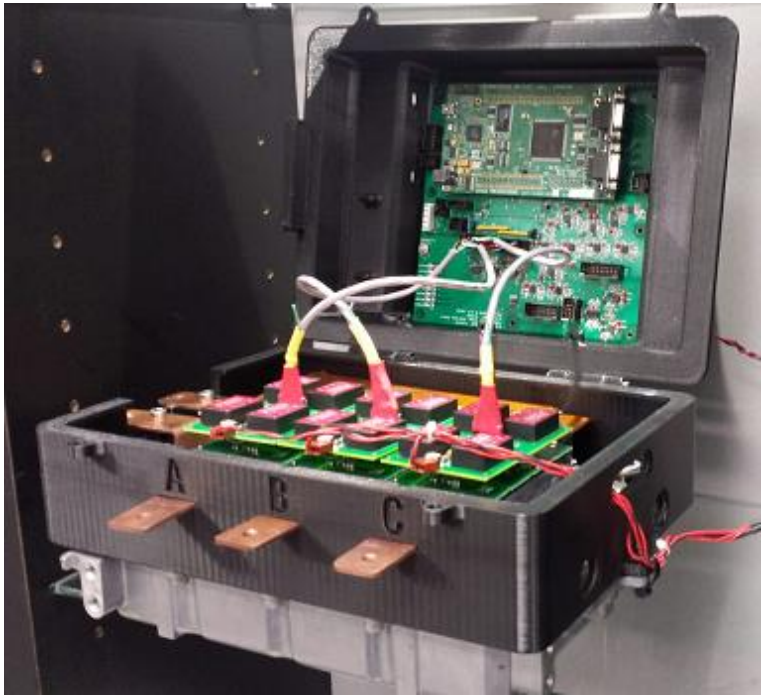


Comparison of the packages

Rapid Prototyping for Converters and Inverters

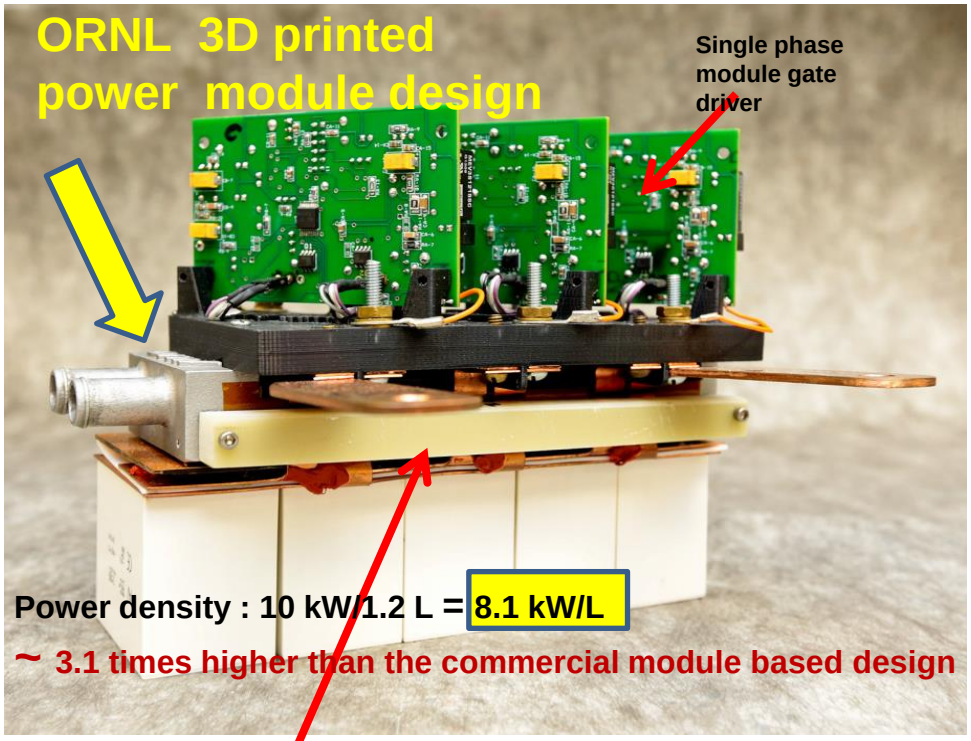


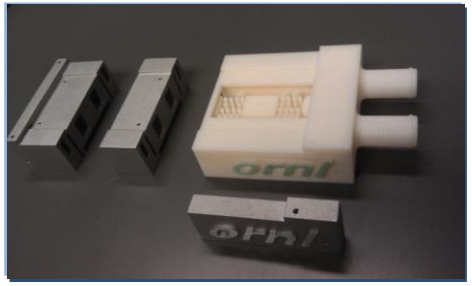
Designed and built a power module based on a small DBC phase leg, designed a copper base, and designed a 3D printed ABS lead frame & package.



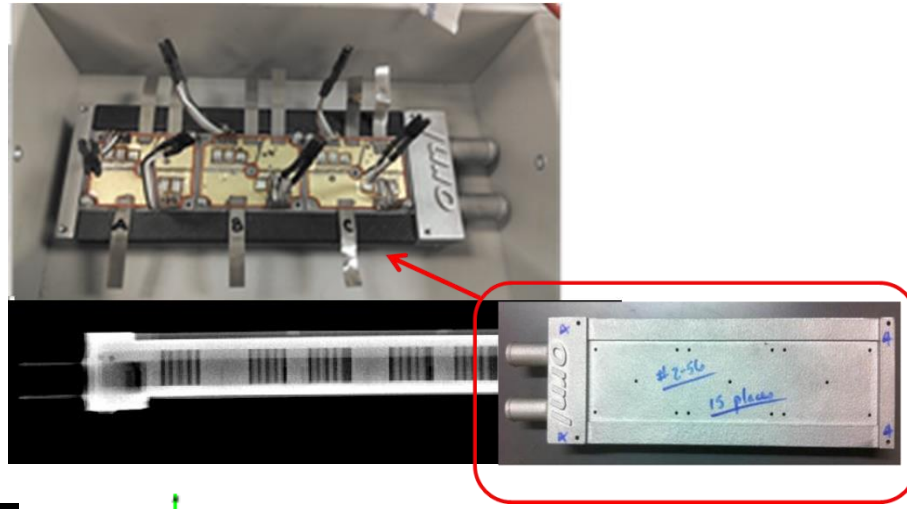
Packaging and housing was designed and 3D printed in-house for this all SiC Inverter

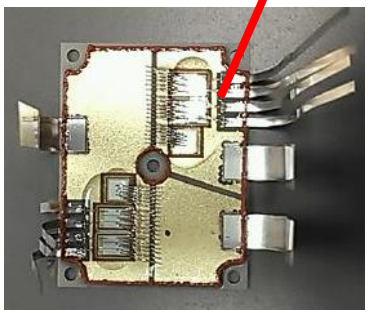
3D Printed Liquid-Cooled 10 kW Inverter

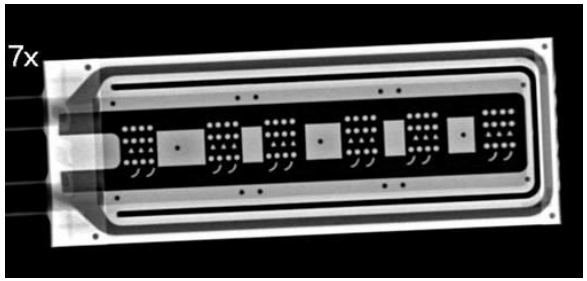




Initial proof of concept – subset pieces made in plastic first, then aluminum

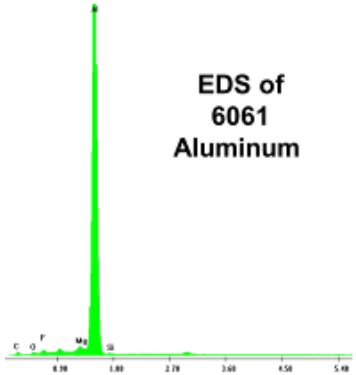


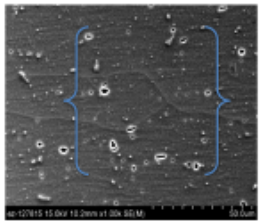




1200 V, 100 A SiC MOSFET single phase module layout designed at ORNL

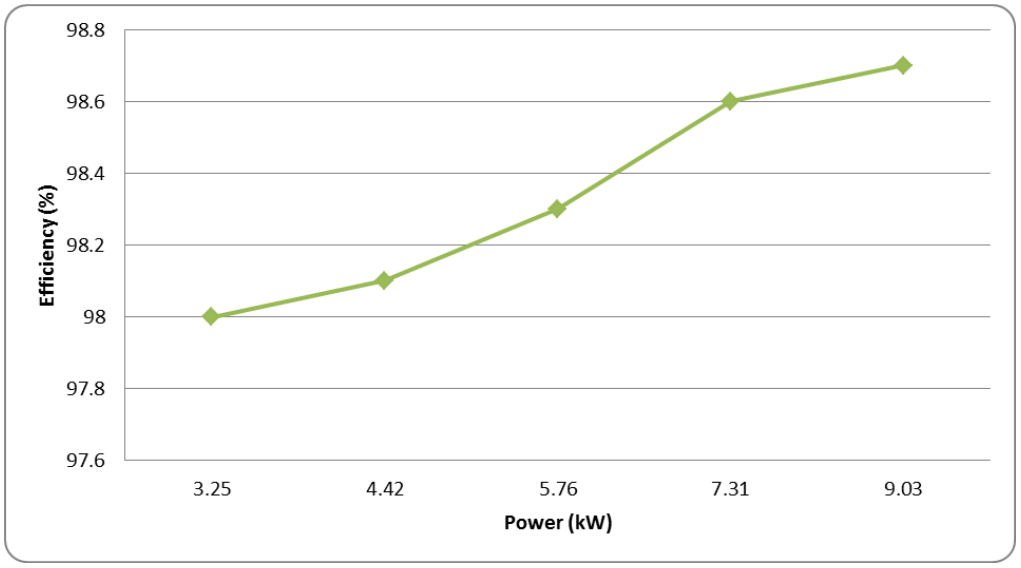
Multi zone integrated heat sink built with AM techniques for increased power density of traction drive inverter.

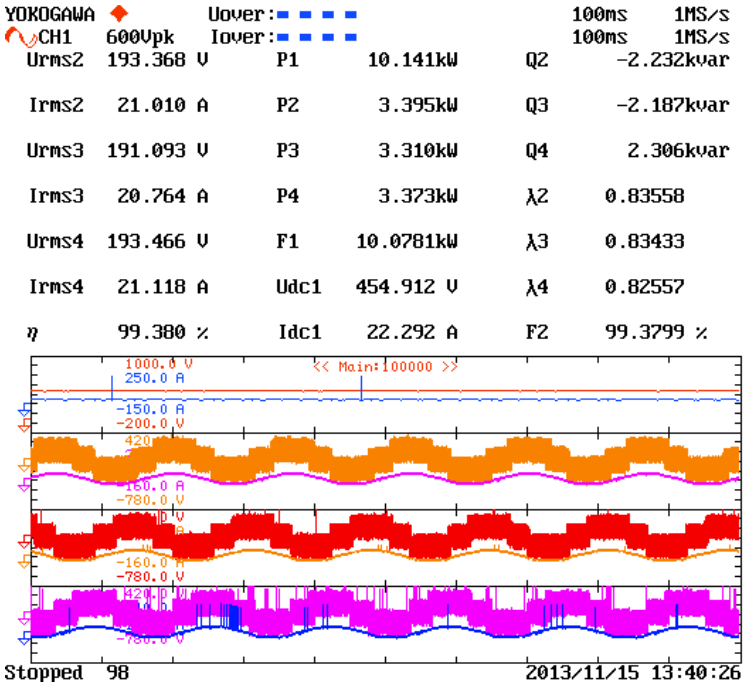




3D Printed Liquid-Cooled 10 kW Inverter

Experimental setup for evaluating inverter's performance

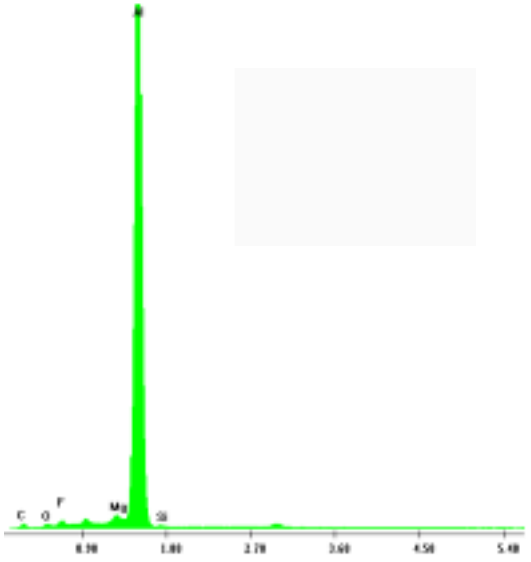




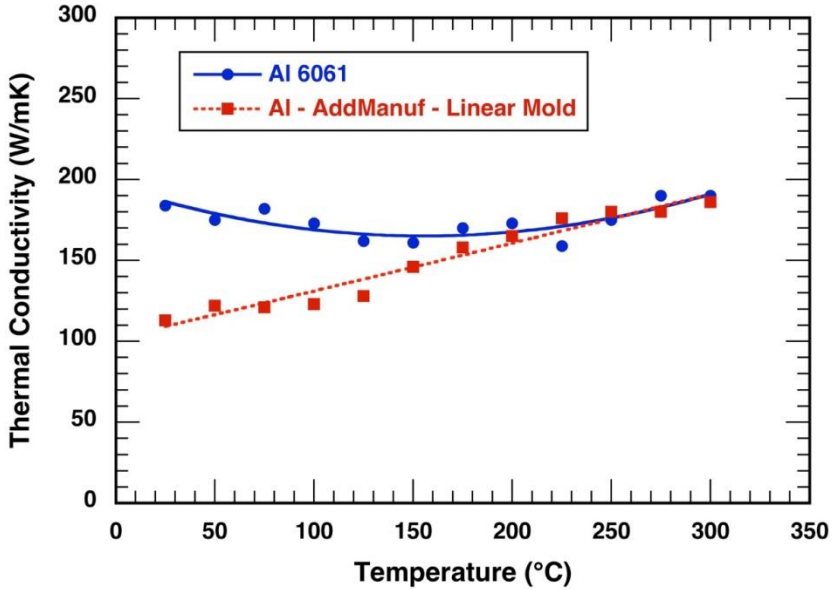
Experimental waveforms of 10 kW SiC inverter screen shot at 450 V dc-link operation

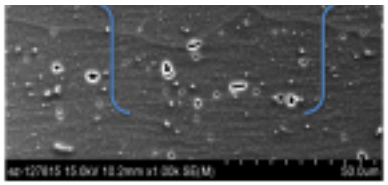
Overall inverter efficiency: 325 V dc, 10 kHz, 1.6 gpm, fixed R-L load

Comparison of Machined and 3D Printed Aluminum Material



< 1% Si
~ 1.5 % Mg





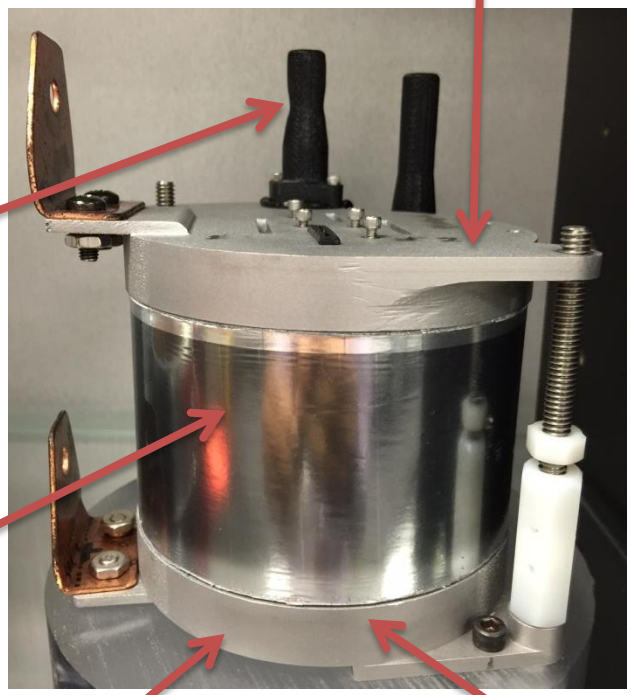
Elem	Wt%	At%	K-Ratio	Z	A	F
C K	3.47	7.38	0.0035	1.0549	0.0523	1.0001
O K	0.77	1.22	0.0022	1.0740	0.2703	1.0014
F K	1.73	2.33	0.0077	1.0693	0.4371	1.0035
MgK	1.48	1.55	0.0143	1.0261	0.9050	1.0417
AlK	92.19	87.19	0.8768	0.9948	0.9560	1.0001
SiK	0.36	0.33	0.0014	1.0205	0.3826	1.0000
Total	100.00	100.00				

Multifunctional Integrated Power Module

Multifunctional:

- **Universal power module that can be used for Ac-dc, dc-ac, dc-dc, ac-ac conversion.**
- **Integrated cooling**
- **Integrated lead frame:**
  - ➢**Bus bar structure for power routing**
  - ➢**Interconnects for low power electronics**
  - ➢**Cylindrical capacitor between the busses**

Initial proof of concept

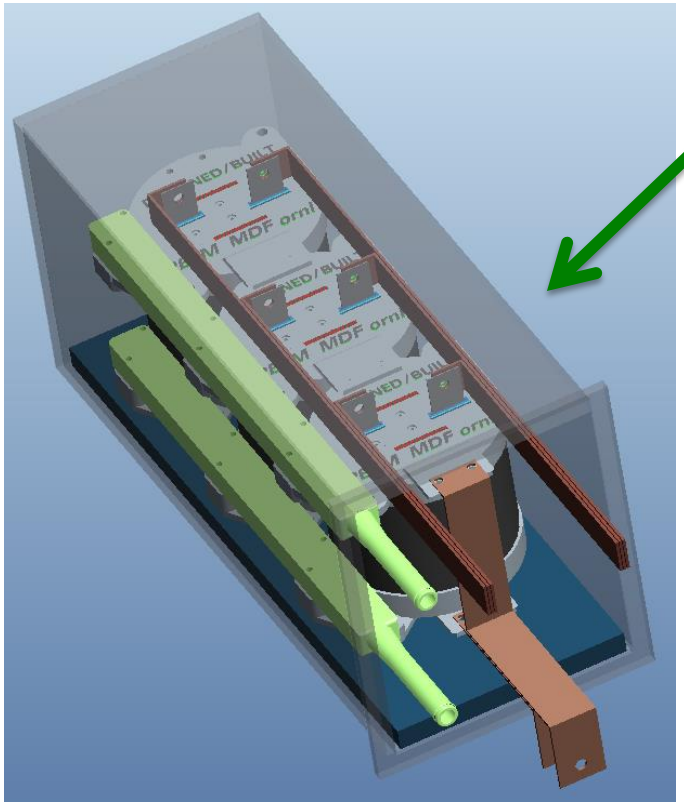


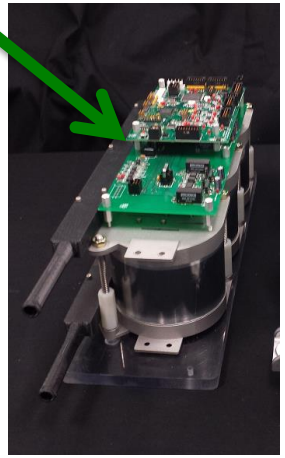
Aluminum endcaps

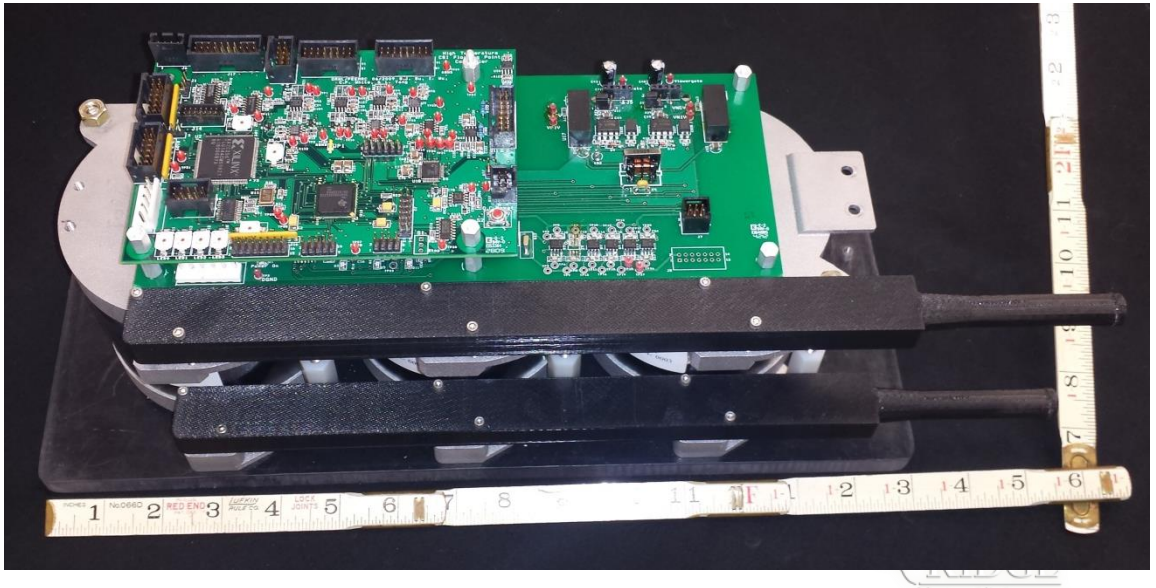
- **serve as main structure**
- **serve as electrical busses**
- **contain flow paths and injectors for coolant**

3D Printed Liquid-Cooled 80 kW Inverter

80-kW ORNL COMPACT Inverter

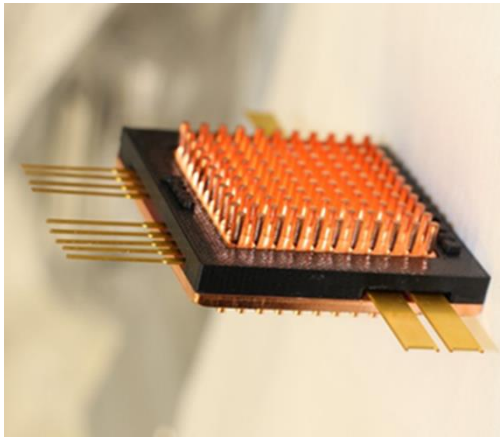




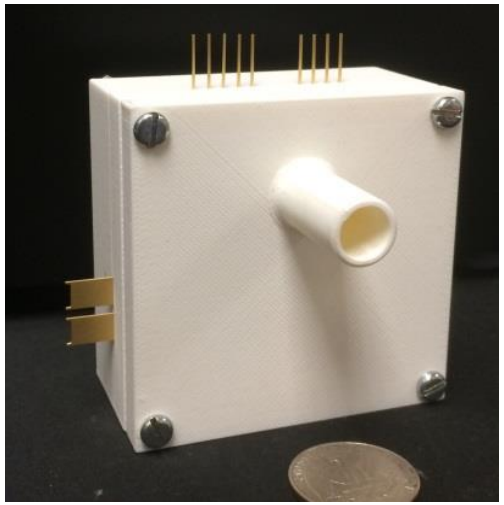


Integrated high power density traction drive Inverter

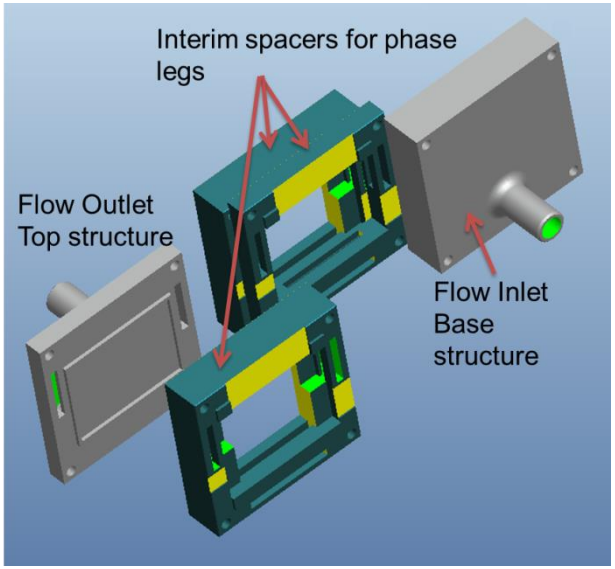
- Multi-layer housings serve as leadframe, cooling ports, and mounting structure
- Can be made with aluminum or high-temperature plastic via additive manufacturing
- Pieces shown have already been built with ABS plastic
- Pieces stack up with phase leg units spaced in between

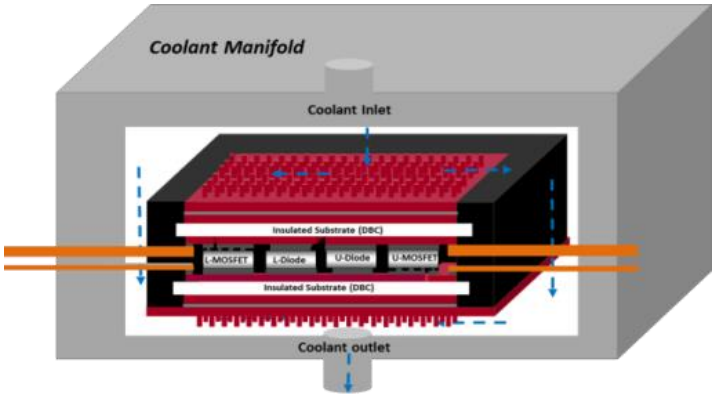


SiC PBA Module with Dual Pin-fin Baseplates

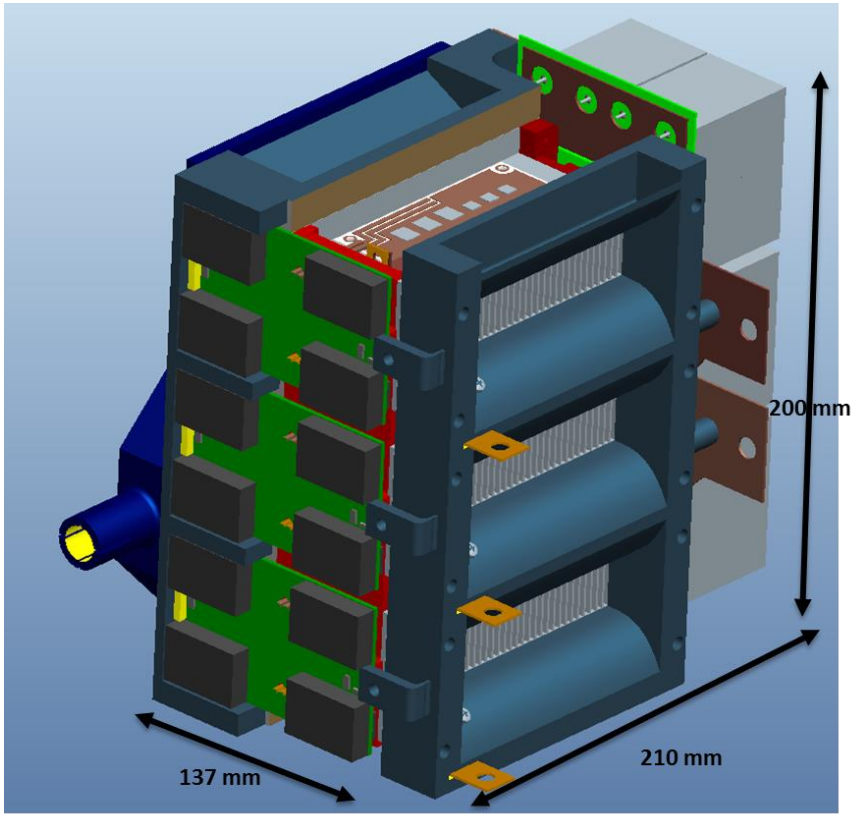


Integrated Double Sided Liquid Cooling Assembly

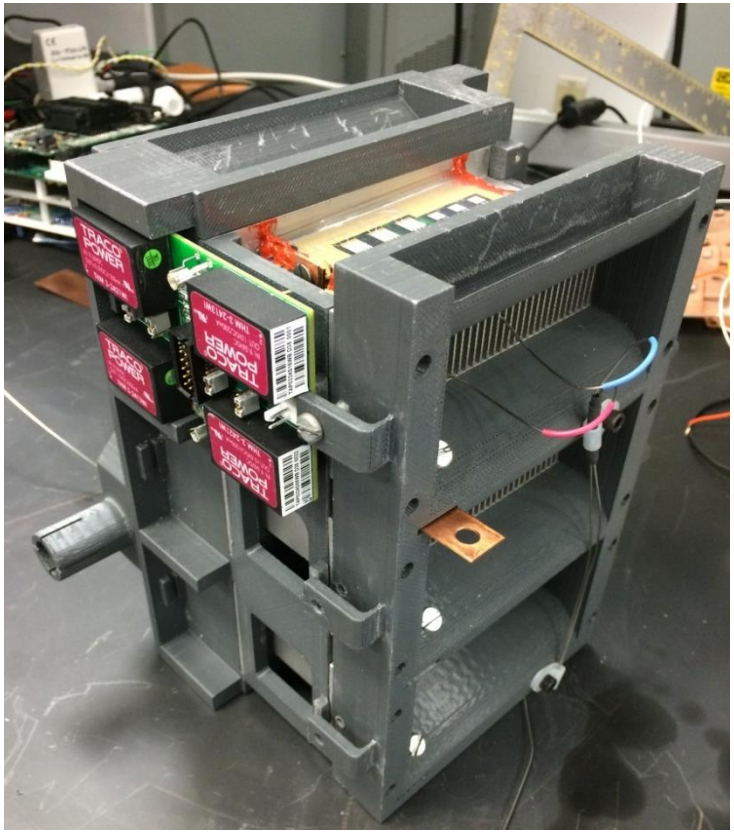




3D Printed Air-Cooled 10 kW Inverter



Three Phase Air-Cooled Converter - 3D drawing



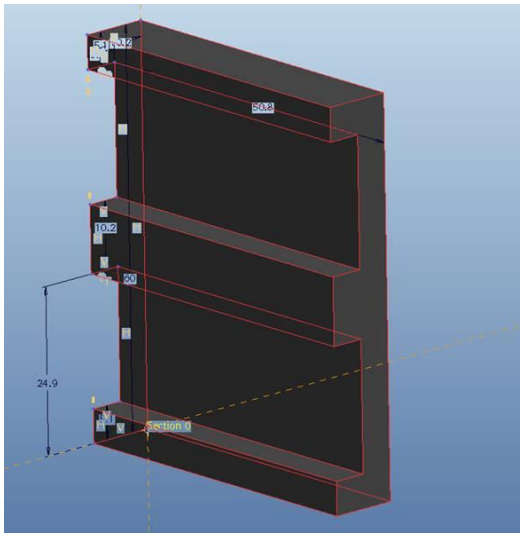
Three Phase Air-Cooled Converter - Prototype

Power density: 10 kW/ 5.8 L = 1.72 kW/L

3D Printed Ferrite inductor E-core

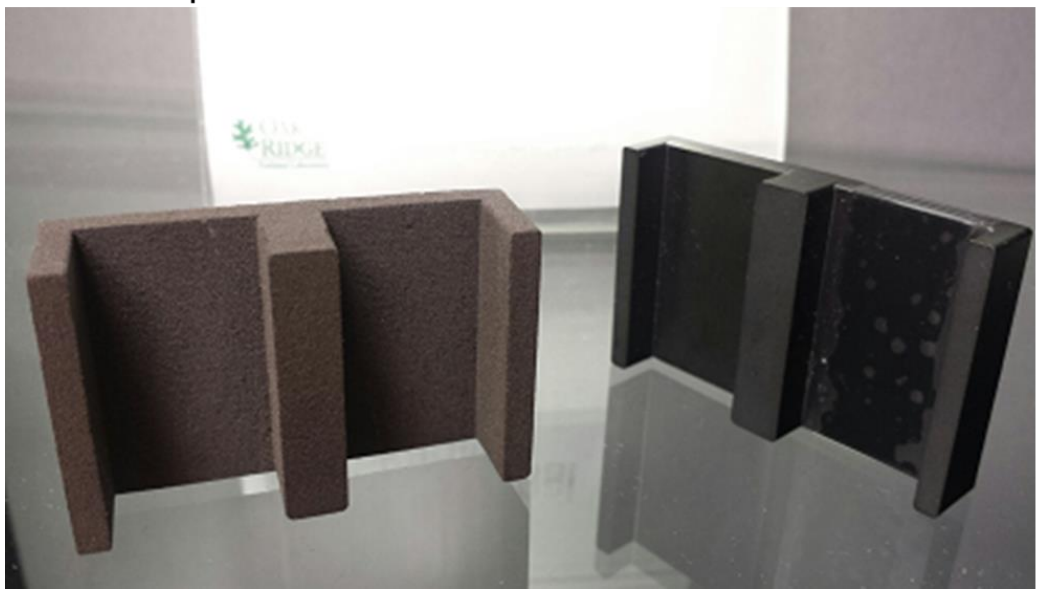
- Working with industry partners, generated a transformer core design using their light-weight, low loss nano-magnetic powder material and 3D printed an E-core at ORNL's manufacturing demonstration facility.
- Inductance increased less than 2 times compared to the air core; about 100 times increase was measured with a similar size commercial ferrite core
- Insignificant change in resistance with or without the printed core; 4 to 47 times increase were observed with the commercial core

Core design

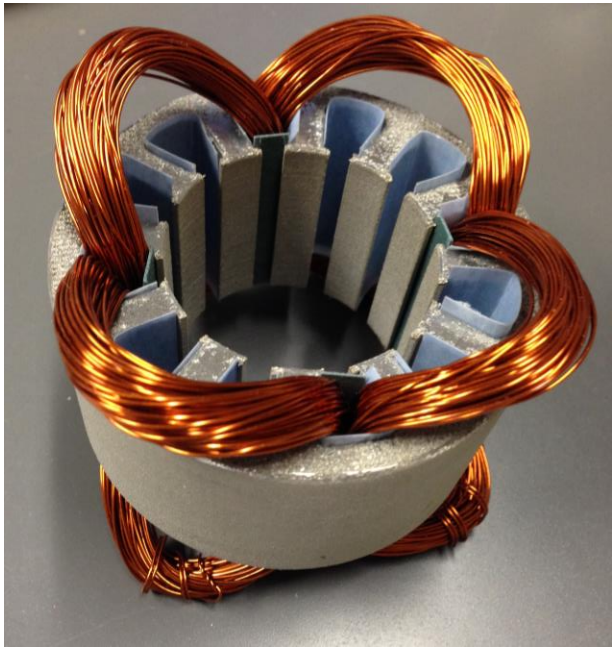


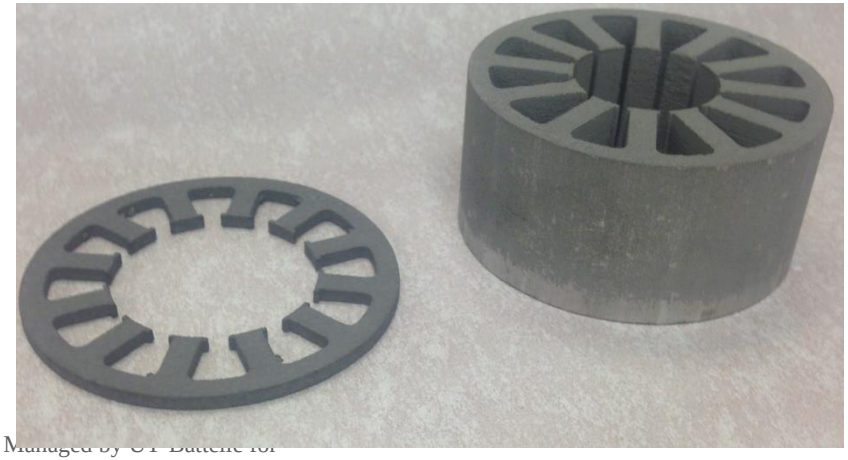
ORNL printed E-core

Commercial ferrite core



3D Printed Electric Motors





Redesigning the modern motor.

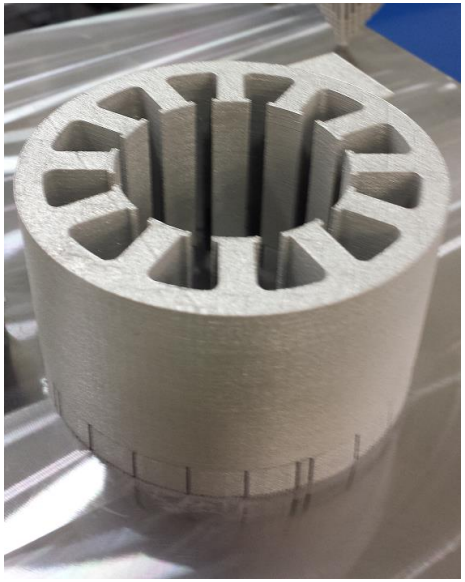
- **Complex rotor and stator structures that can only be manufactured using 3D printing.**
- **Steel grain orientation control**

Challenges:

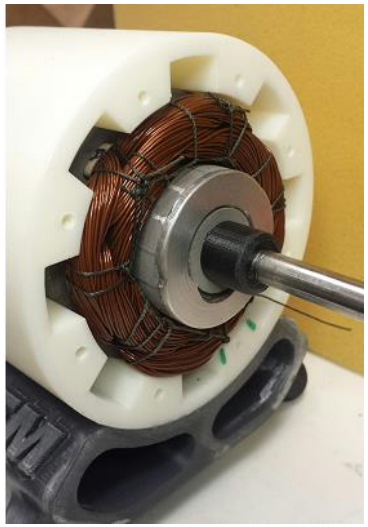
- **Printing multiple materials together**
- **Laminations or no laminations: opportunity to eliminate many manufacturing steps**

3D Printed Electric Motors

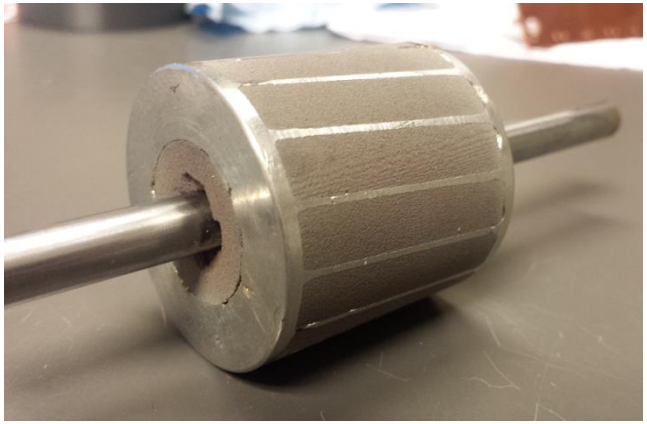
Stator 3D printed with steel, conventionally wound.



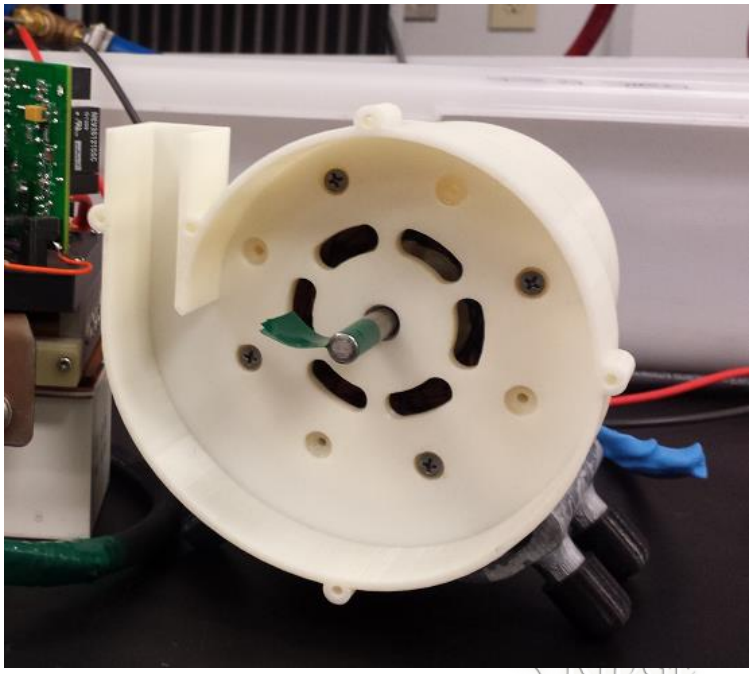
Completed pieces inserted in 3D printed housings



Rotor mag core printed with steel, cast rotor bars and end rings.



Complete functional unit

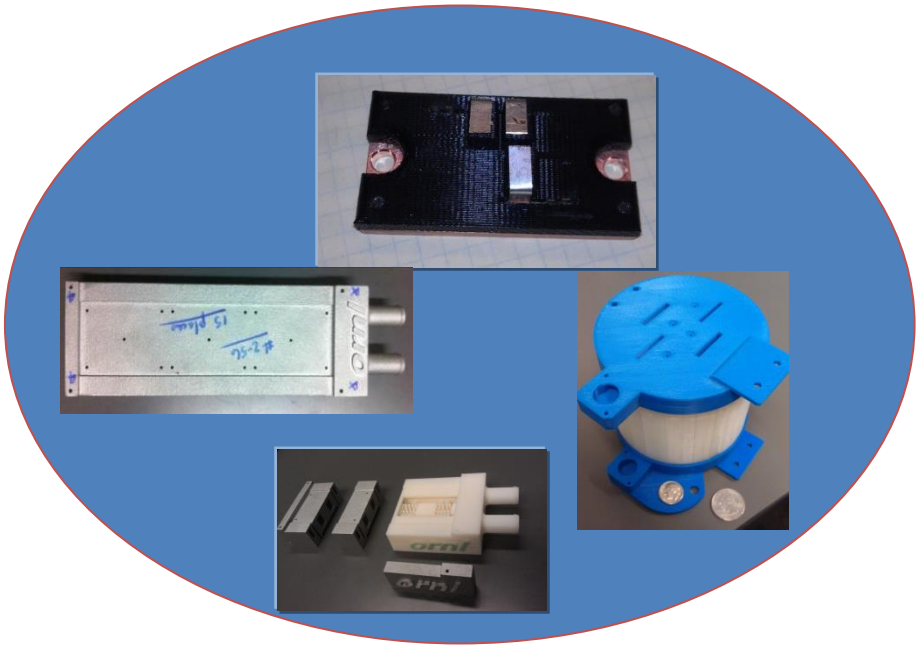


3D Printing Questions and Summary

- Is the technology ready?
  - For mass manufacturing?
  - For rapid prototyping?
  - For power electronics?
  - For electric motors?
  - Control electronics?
  - Sensors?
  - Semiconductors?
- How fast is it?
- How expensive is it?

3D Printing R&D Summary

- ORNL 3D printing R&D has proven initial technologies for different functionalities.
- Initial proof of concept : additively manufactured high power density inverter and a conceptual motor drive
- Multi material printing for inverters to achieve isolation functionality
- System level packaging with AM techniques to reduce assembly and manufacturing costs.



ORNL 3D printed drive inverter