VEHICLE TECHNOLOGIES OFFICE

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Overview of the DOE Advanced Power Electronics and Electric Motor R&D Program

June 17, 2014

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Advanced Power Electronics and Electric Motors
Vehicle Technologies Office

APEEM R&D Program

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Vehicle Technologies Office

Hybrid Electric Systems R&D

Energy Storage

Advanced Power Electronics & Electric Motors (APEEM) R&D

Vehicle Systems

Industry

Federal Agencies

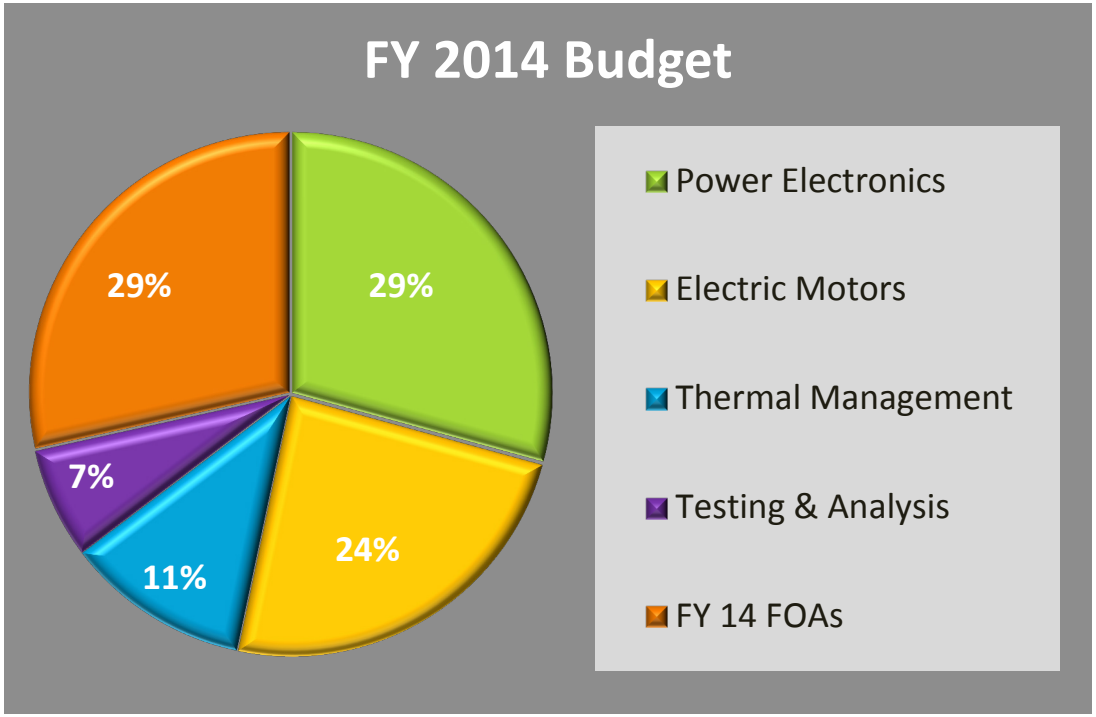
Academia

National Labs

APEEM R&D Mission and Budget

Develop advanced power electronics, electric motors and electric drive systems to enable large market penetration of hybrid and electric vehicles

Meeting program targets will enable market success: increase performance, efficiency and reliability, while lowering cost, weight, and volume



FY 2013	FY 2014	FY 2015 Request
$27.2 M	$24 M	$35.5 M

R&D emphasis accelerates:

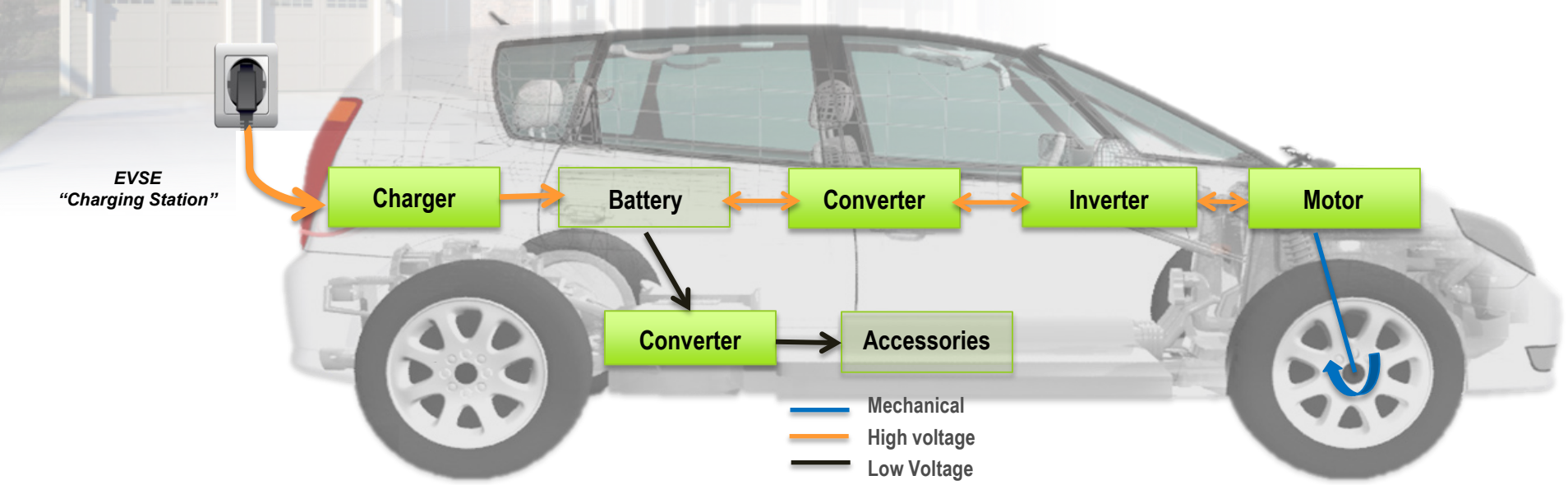
- Adoption of wide bandgap semiconductors
- Reduction or elimination of rare earth magnets

FY 2014 FOAs:

- Power Electronics - $6M
  - Wide bandgap commercialization
- Incubator - $1.6M
  - "Off-Roadmap" technology R&D

Electric Drive System Components

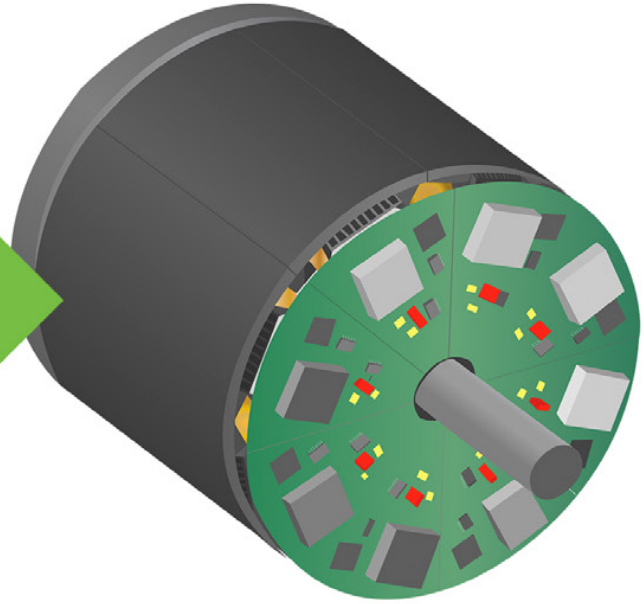
- **Electric motor** – converts electrical energy to mechanical power for motive power
- **Inverter** – converts high voltage direct current to varying pulses that control and power the electric motor
- **Charger** – modifies and controls electrical energy to re-energize the battery
- **Converter(s)** – increases the battery voltage for the traction drive system and decreases the voltage for the accessories



Integration of components will reduce electric drive system cost and improve efficiency

APEEM Electric Drive System Targets

4X Cost Reduction
35% Size Reduction
40% Weight Reduction
40% Loss Reduction



2012 Electric Drive System

$30/kW, 1.1 kW/kg, 2.6 kW/L
90% system efficiency
(on-road status)

- Discrete Components
- Silicon Semiconductors
- Rare Earth Motor Magnets

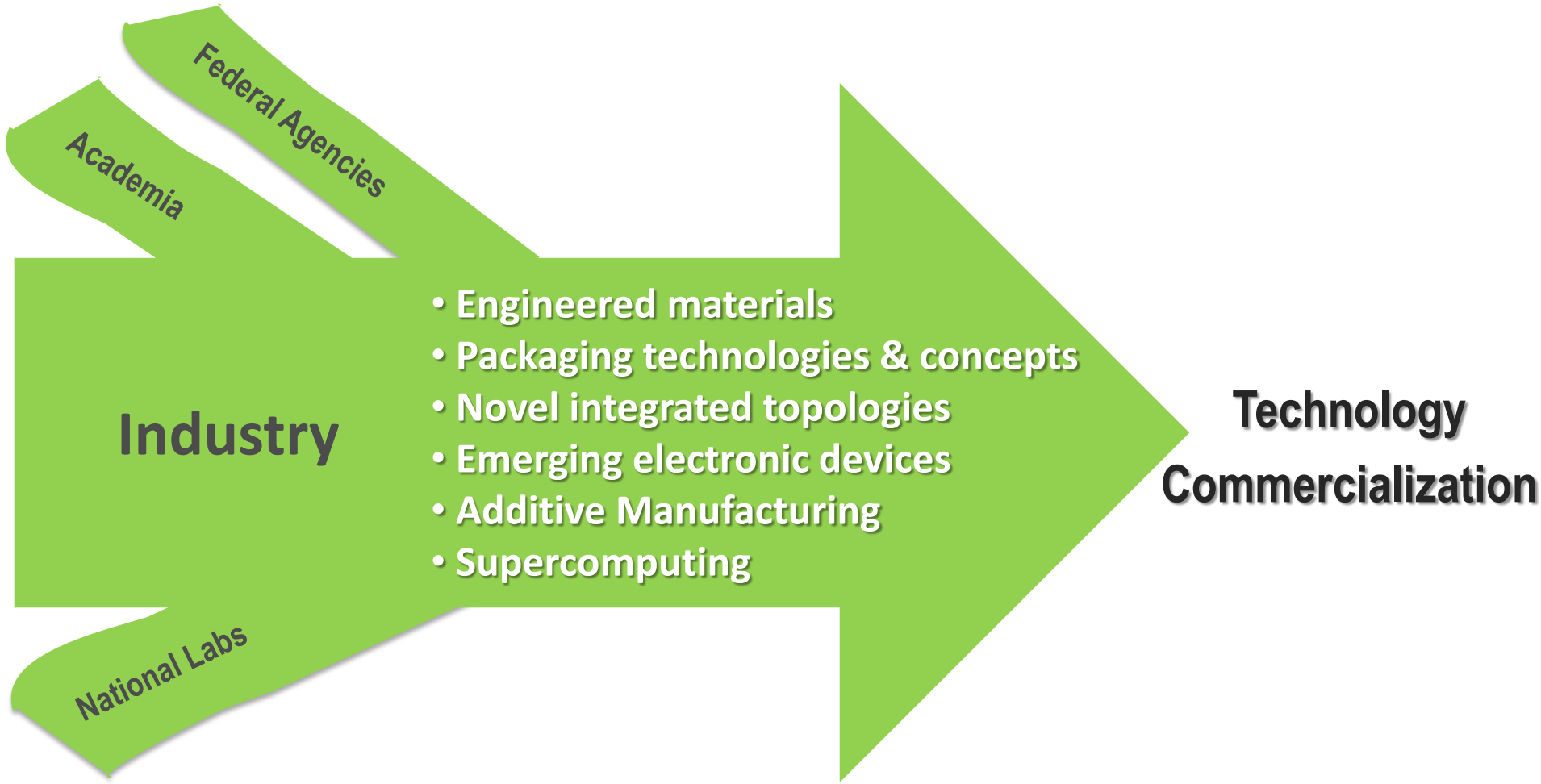
2014 Electric Drive System
(R&D target)
$15/kW

2022 Electric Drive System

$8/kW, 1.4 kW/kg, 4.0 kW/L
94% system efficiency
(R&D target)

- Fully Integrated Components
- Wide Bandgap Semiconductors
- Non-rare Earth Motors

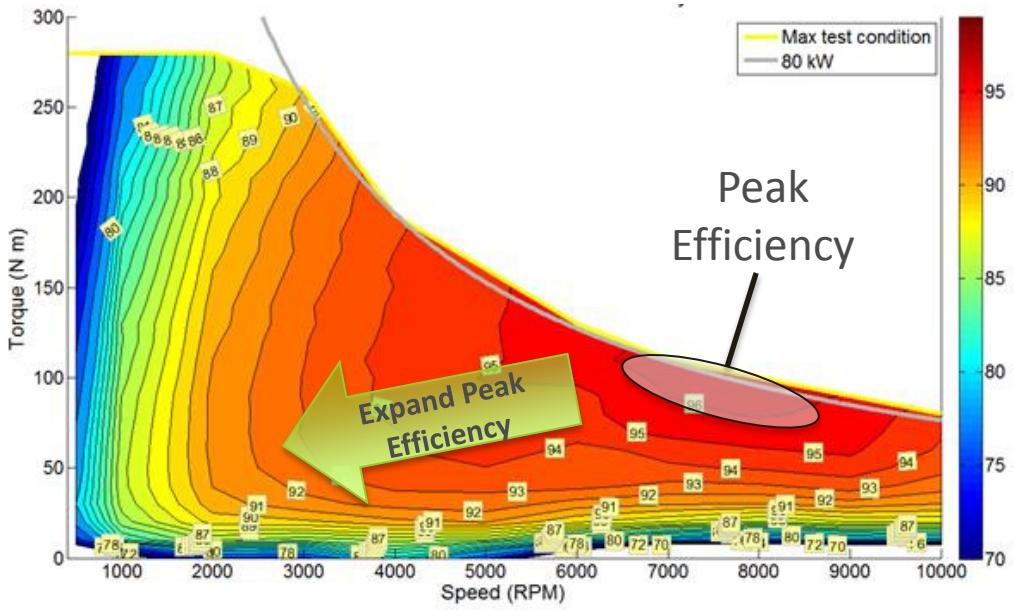
Innovations are Required to Achieve Targets



Volume manufacturing of incremental improvements will not achieve APEEM targets

Electric Drive System Challenges

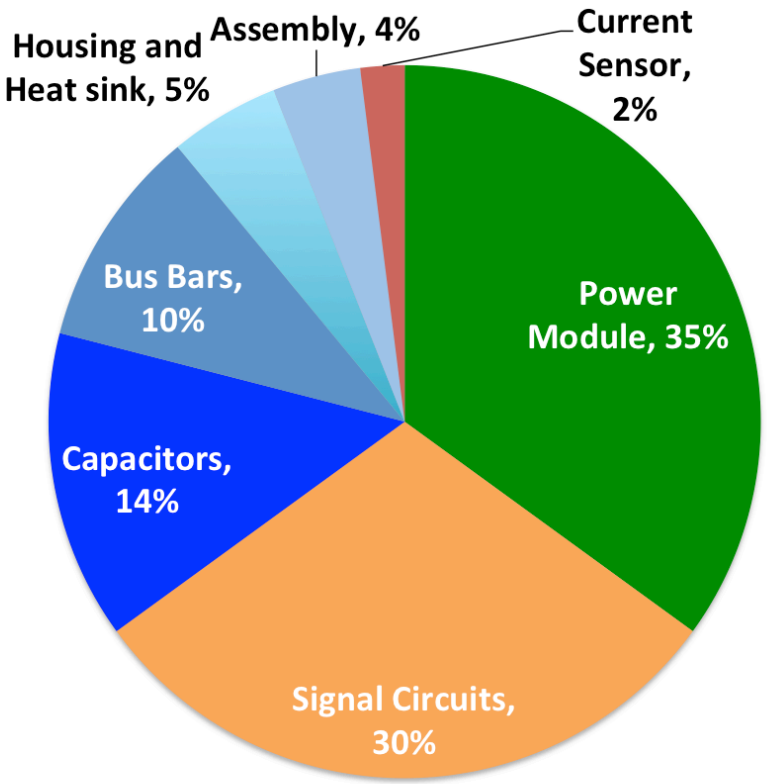
- Cost reduction is the most significant challenge
  - 4X cost reduction required
- Weight and volume reductions
- Reliability improvements
- Efficiency improvements to increase vehicle range
- Expand regions of high efficiency operation
  - Current peak efficiency regions do not match the most frequent operating points



Typical On-road Traction Motor Efficiency Map

Cost Breakdown for an Inverter

Current specific cost: $13.7/kW
2020 R&D target: $3.3/kW

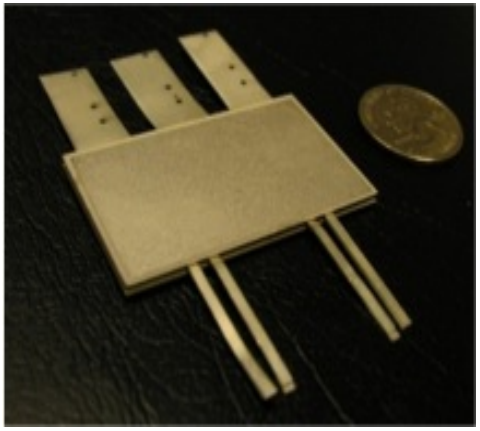


On-road Inverter Cost $1092

Power Electronics R&D

Challenges

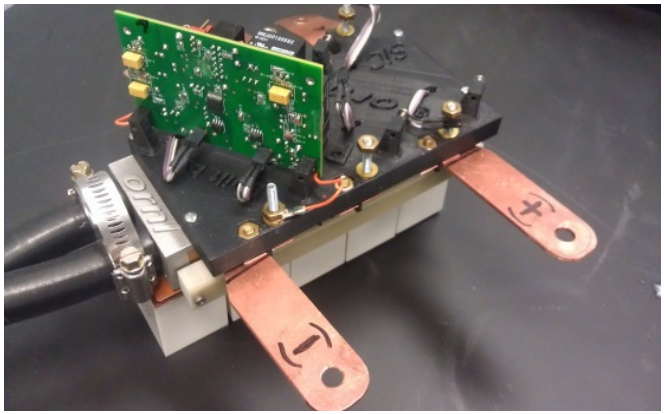
- **Cost is the biggest challenge**
  - Power module and passive components
  - Integrated, modular, scalable designs
- **Volume and weight reductions**
  - Driven by passive device size
  - Packaging issues exist at all levels
- **Packaging and advanced materials**
  - High-temperature operation
  - Increase thermal conductivity
- **Reliability**
  - Electrical interconnects, interface materials, substrates and epoxies
- **Thermal management**
  - Improve heat transfer
  - Liquid cooling to air cooling
  - Single-sided to double-sided
- **Efficiency**
  - Utilize WBG devices
  - Reduce parasitic losses
  - Optimize efficiency at the most frequent operating points



SiC Phase Leg Power Module Prototype 100A/1,200V

Strategies

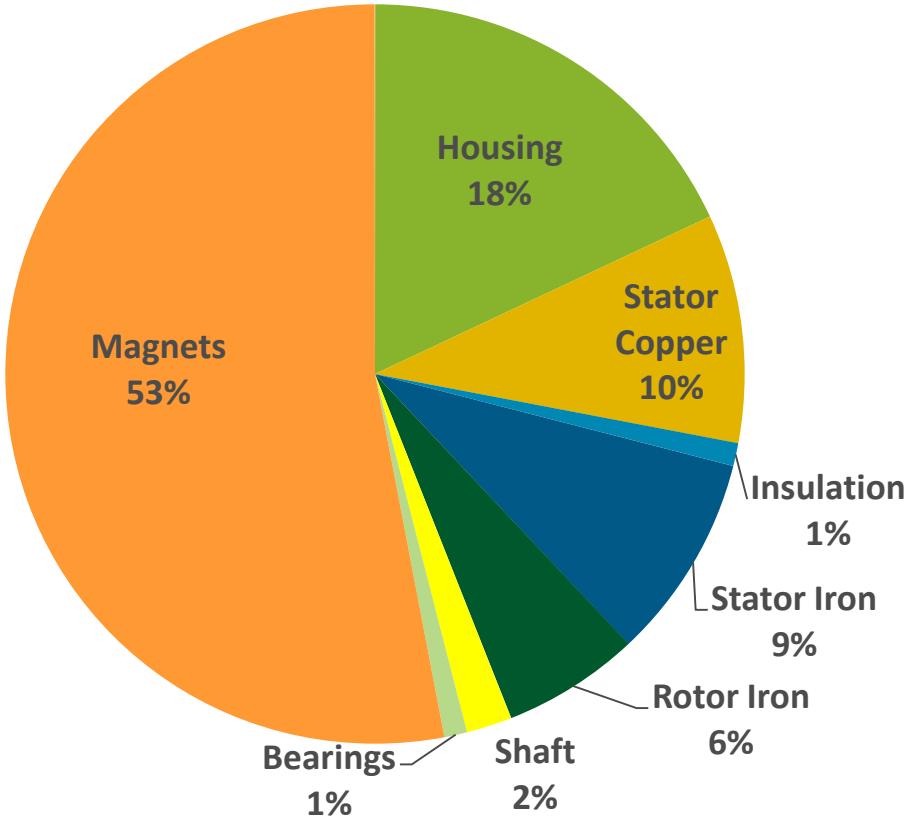
- **New Topologies and Designs**
  - Decrease cost and size
  - Improve reliability
- **WBG Semiconductors**
  - Improve performance
- **Packaging**
  - Reduce cost, size, and weight
- **Capacitors**
  - Reduce volume and weight
- **Vehicle Charging**
  - Provide function at minimum cost
- **Manufacturability**



Additive Manufacturing Prototype Inverter

Cost Breakdown for an IPM Motor

Current specific cost: $11.7/kW
2020 R&D target: $4.7/kW



On-road Motor Cost $938

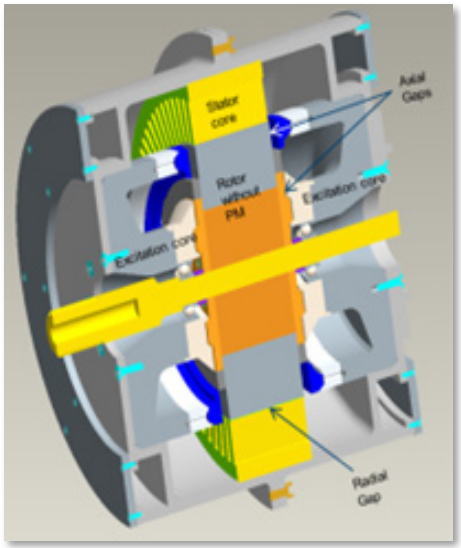
Electric Motors R&D

Challenges

- **Cost is the biggest challenge**
  - Rare earth cost and uncertainty
  - Uncertainty of copper prices
- **Packaging and advanced materials**
  - High-temperature capability
  - Increase thermal conductivity
- **Volume and mass reductions**
  - Higher operating speeds
  - Low loss laminations
  - Higher slot fill (round vs. rectangular wire)
- **Thermal management**
  - Temperature limitations of existing materials
  - Improve heat transfer
- **Reliability**
  - Welds, solders, connectors, insulation
  - Epoxies
- **Efficiency**
  - Optimize efficiency at the most frequent operating points

Strategies

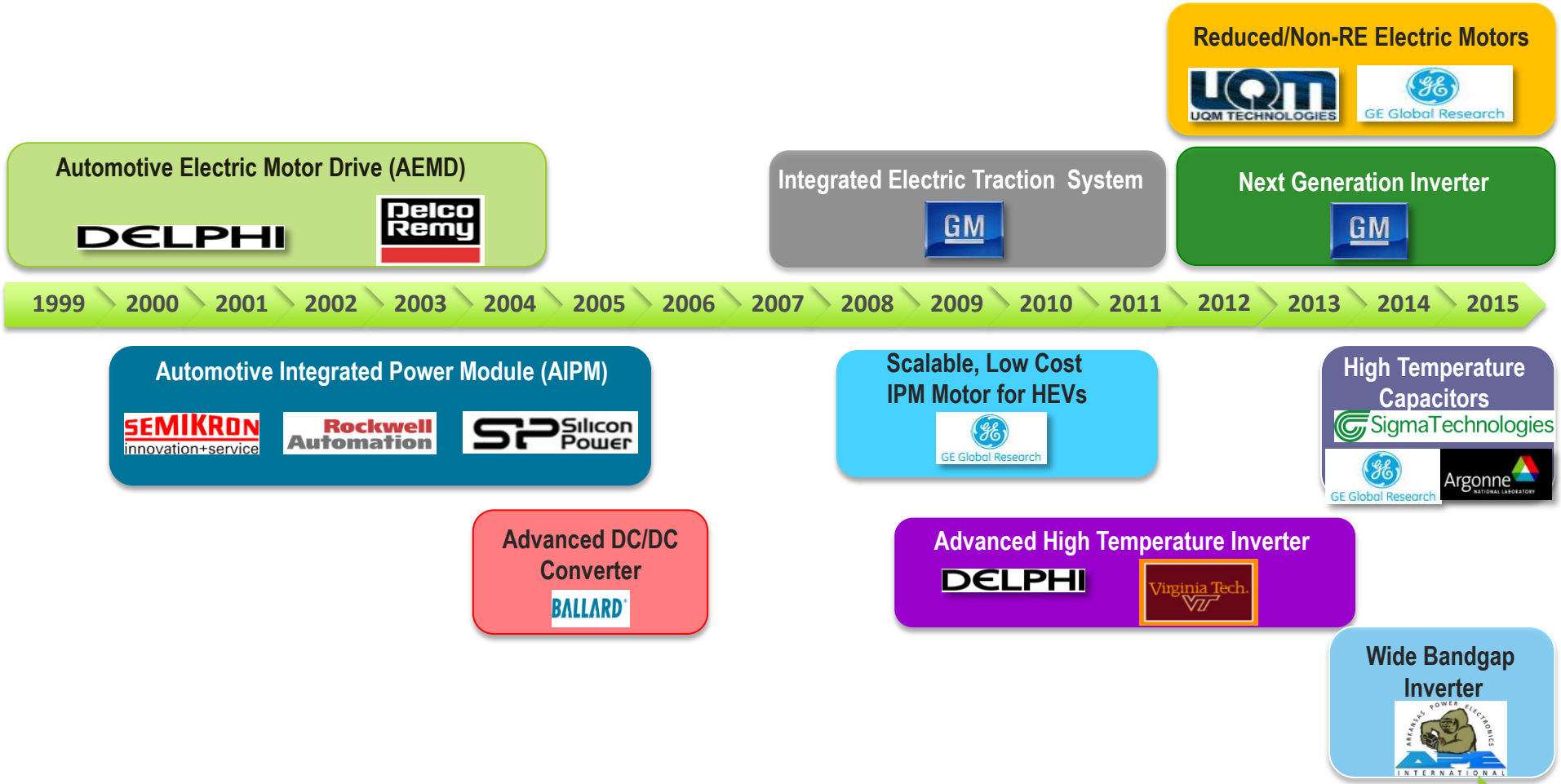
- **Non-Rare Earth Permanent Magnet (PM) Motors**
  - Reduce cost and maintain performance
- **Non-PM Motors**
  - Reduce cost and improve performance
- **Magnetic Materials**
  - Reduce cost
  - Improve high-temperature performance
- **Innovative Materials**
  - Improve performance and reliability
- **Manufacturability**



ORNL Non-Rare Earth Motor Prototypes

Who We Work With

Timeline of Successful Industry R&D



PNGV

FreedomCAR

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Commercialization of Innovations

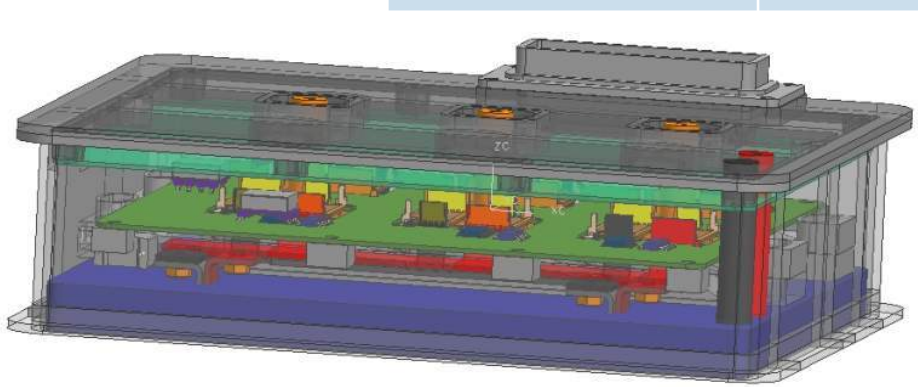
- Automotive Electric Motor Drive (AEMD) – DELPHI
  - Developed and demonstrated motor manufacturing Innovations
  - Surpassed cost target by 39%
- Automotive Integrated Power Module (AIPM) – SEMIKRON innovation+service
  - Established 1st Semikron power electronics manufacturing plant in the US
  - Packaging innovations utilized by US OEM fuel cell vehicle
- Advanced DC/DC Converter – BALLARD
  - Developed innovative packaging topologies which reduced volume and weight
  - Technologies used in US OEM hybrid-electric vehicles
- Integrated Electric Drive System – GM
  - Motor winding and control algorithm innovations to optimize power and torque
  - Met 2010 electric drive system cost target
- Advanced High Temperature Inverter – DELPHI
  - Packaging, switch, & capacitor advances
  - Technology innovations led to inverter production
- Scalable, Low Cost IPM Motor for HEVs – GE Global Research
  - Rare earth magnet manufacturing advances
  - High temperature magnet operation with significant loss reduction

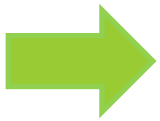
R&D Projects Lead to Commercialization

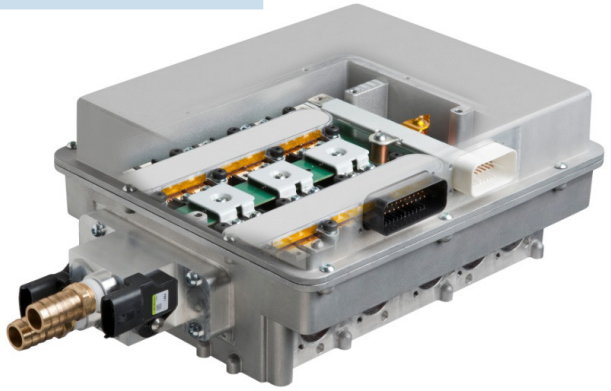
Delphi R&D of Advanced Inverter with Integrated Controller met APEEM 2015 R&D targets

- Delphi going to production with an inverter based on technology innovations developed with DOE
- National lab expertise and facilities provided project support, including: capacitor development and testing, power device characterization and system modeling, thermal/heat exchanger experiments and interface material characterization, and inverter system testing

Metrics	DOE Specified	Delphi Achievement*
Cost	$5/kW	$5/kW
Specific Power	12 kW/kg	17 kW/kg
Power Density	12 kW/L	15 kW/L





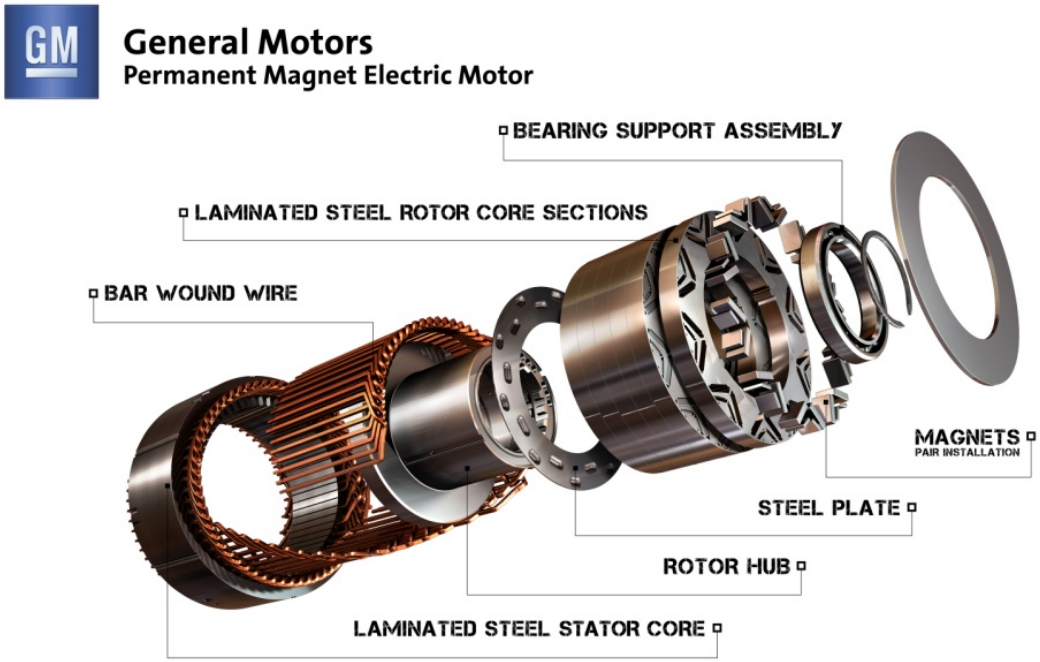


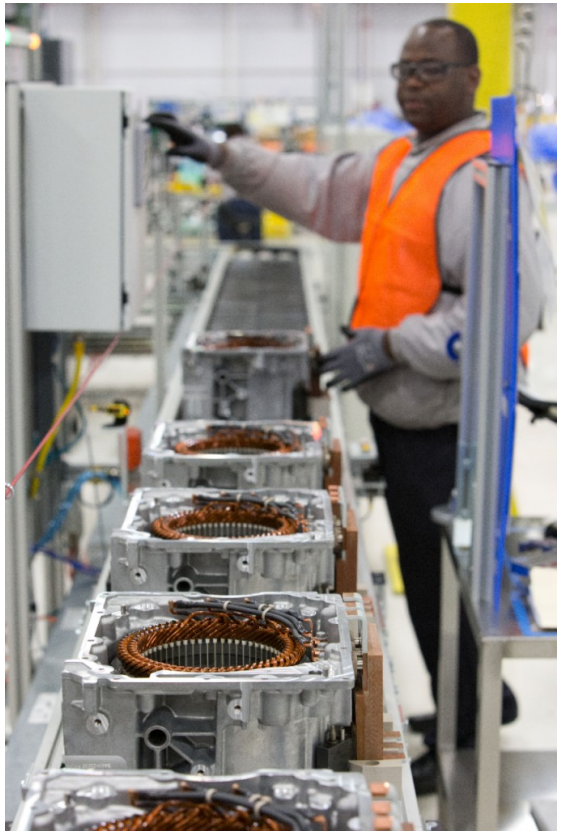
* Based on production intent design using PEEM technologies – assuming volume of 100,000 units/year, cost/kW would be lower for upper end of 55-120 kW power range and higher for lower end of power range; kW/kg and kW/L would be higher for upper end of power range and lower for the lower power.

R&D Projects Lead to Commercialization

GM is the first U.S.-based automaker to manufacture electric motors in America

- White Marsh, Maryland facility built as part of cost shared DOE Recovery Act project
- Motors used in Chevrolet Spark EV
- Spark EV electric motor produces 140 hp and 400 lb-ft of torque





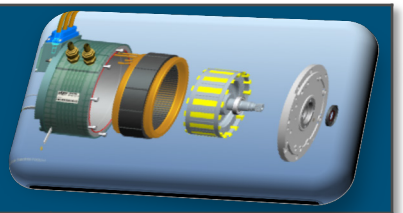
Current Industry-led R&D Efforts

Power Electronics

WBG Inverters for EV Traction Drives*	APEI
High Performance dc Link Film Capacitors*	GE
High Temperature Capacitors for PE*	Sigma Technologies
Small, Lightweight Low Loss Magnetic Materials for Passive Inductors (SBIR)	Aegis Technology
Next Generation Inverter	GM

* New Awards Since 2013 AMR

Electric Motors



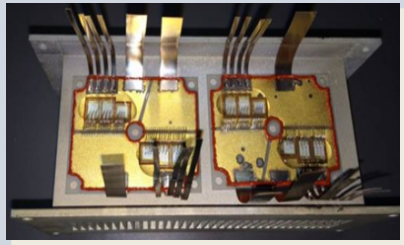
High Performance Permanent Magnets for Advanced Motors (SBIR)	Electron Energy Corporation
Alternative High-Performance Motors with Non-Rare Earth Materials	GE
Development of Advanced Soft Magnetic Nanocomposite Materials with Low Loss (SBIR)	Spectrum Magnetics
Unique Lanthanide-Free Motor Construction	UQM

National Lab Inventions Accelerate Innovations

Expertise and Unique Capabilities

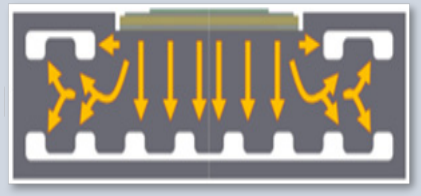
ORNL

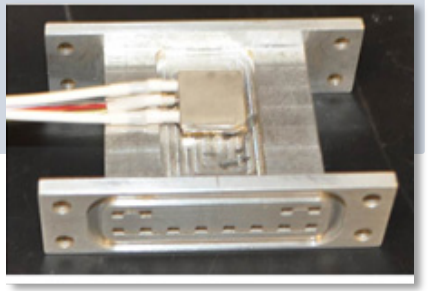
- Power electronics
- Packaging
- WBGs
- Electric motors



NREL

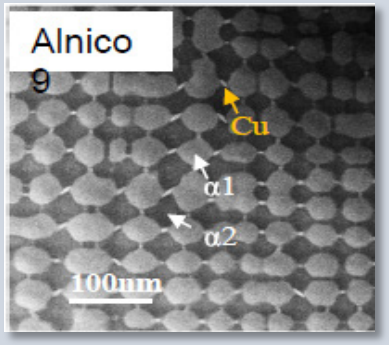
- Thermal management & reliability

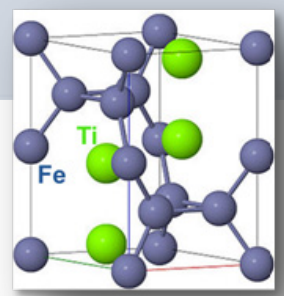




Ames

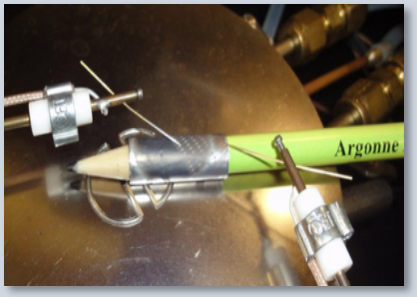
- Magnetic materials

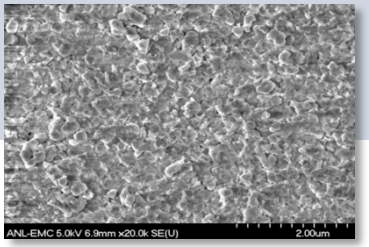




ANL

- High temperature capacitors*



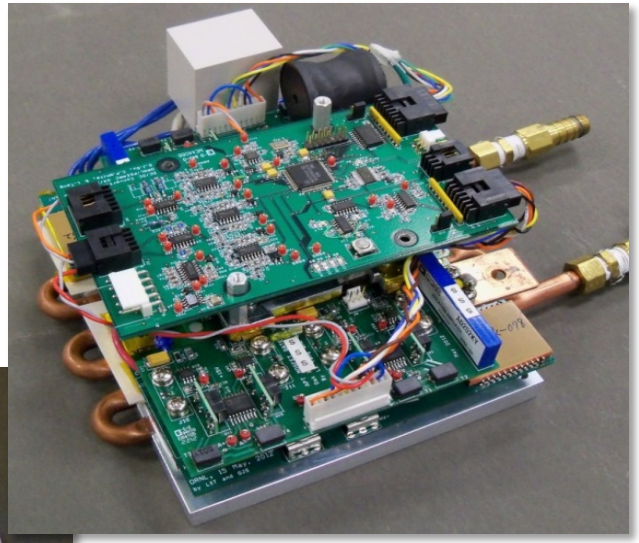


* New Award Since 2013 AMR

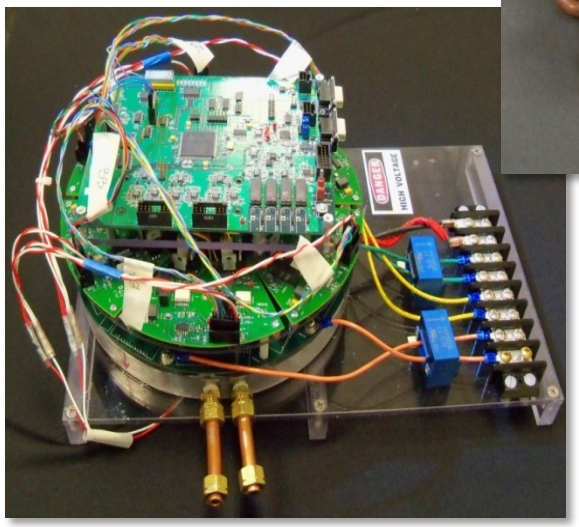
ORNL Integrated Charger/Converter Project Leads to Commercialization

Exclusive license granted to Arcimoto, Inc.

- Eliminates the need for a stand-alone external charger
- Capable of safe, high-temperature operation
- Integrates three innovations developed under APEEM R&D Program:
  - Innovative dc-ac inverter
  - Battery system charger
  - dc-dc converter
- Enhancements include:
  - Efficient bi-directional charging
  - Improved electric motor control
  - Reduced cost and weight



Integrated Charger & dc-dc Converter

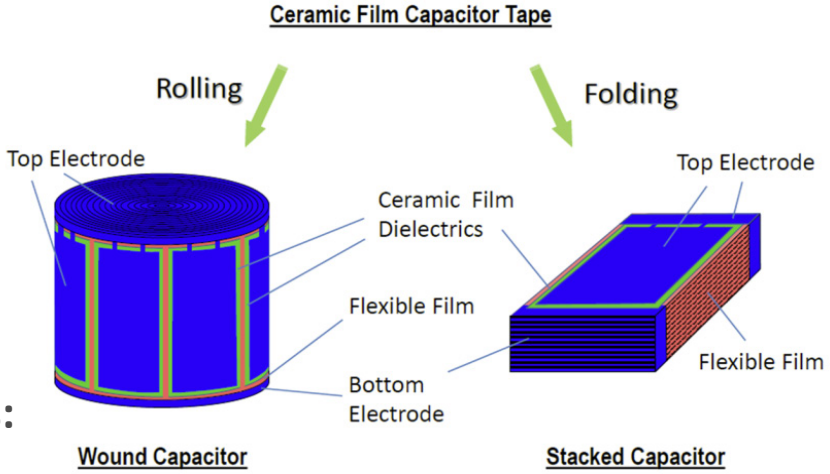


dc-ac Inverter

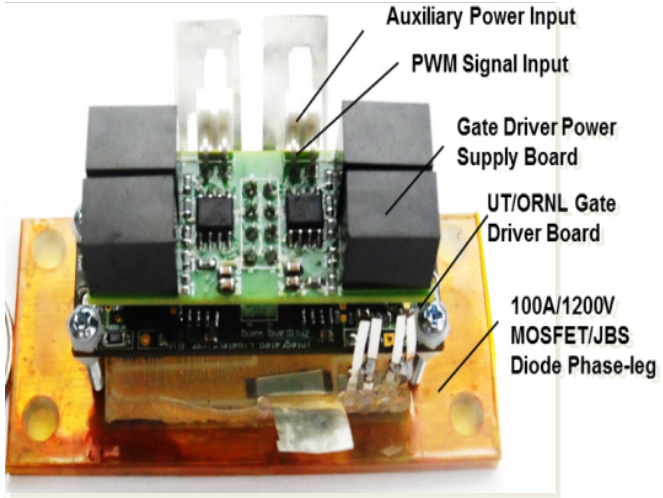
Patent	Inventor	Patent Number	Issue Date
Electrical Motor/Generator Drive Apparatus and Method	G-J Su	8,373,372	February 12, 2013
Electric Vehicle Recharging and/or Supplying Electrical Power	G-J Su	61/709,529	October 4, 2012
Electric Vehicle System for Charging and Supplying Electrical Power	G-J Su	7,733,039	June 8, 2010

Power Electronics FY 2013 Progress

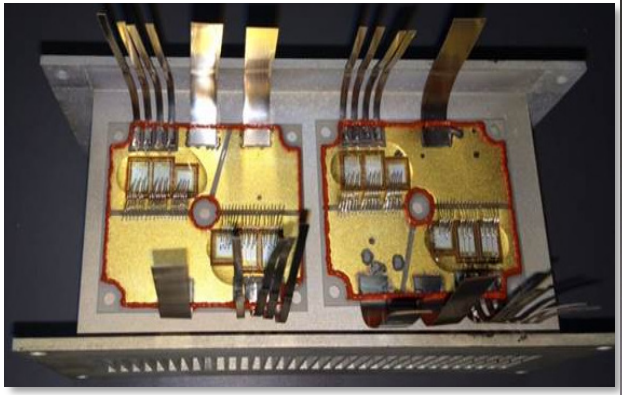
- **ANL demonstrated an aerosol deposition process for film-on-foil ceramic capacitor**



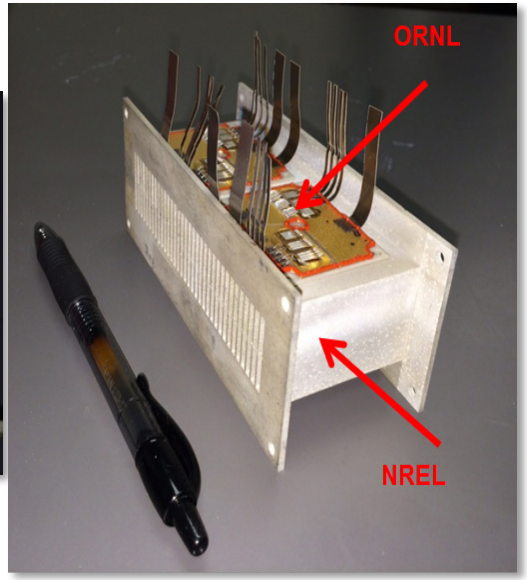
- **Prototypes of integrated ORNL & NREL inventions:**
  - Exploited superior attributes of WBG devices
  - Integrated double-sided cooling and optimized heat exchangers
  - Integrated functionality reduced cost, part count, and size
  - Reduced passive component requirements
  - Validated innovative topologies, materials, and packages



ORNL SiC Integrated Power Module



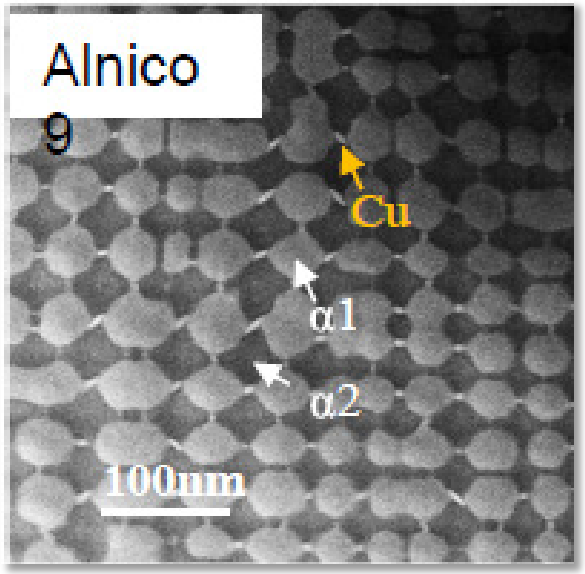
ORNL/NREL Single phase power module for air cooled inverter



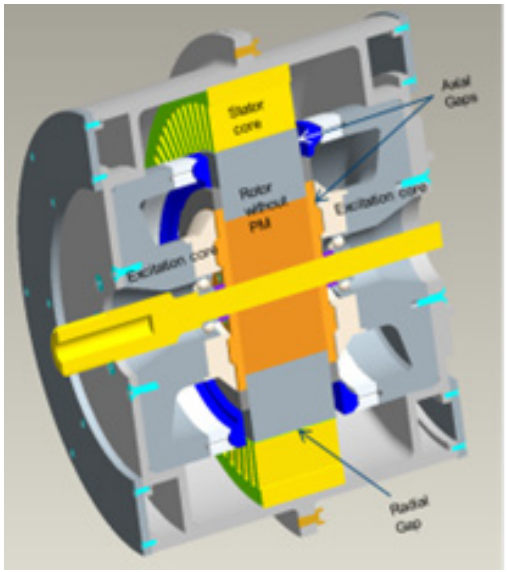
Electric Motors FY 2013 Progress

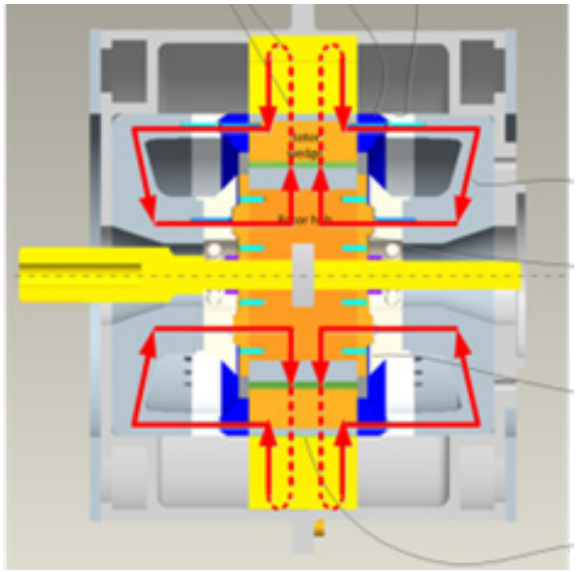
Optimized scalable, non-rare earth electric motor designs:

- Developed unique tools for advanced modeling and implementation on parallel computing systems to optimize new motor technologies
- Developed process for lamination steel with high Silicon content (~6.5%) to reduce iron losses and improve efficiency by up to 40%
  - Designed and implemented new materials characterization system
  - Impacted materials development and advanced modeling
- Validated improved properties of commercial and developmental high silicon steel
- Demonstrated improved alnico magnetic properties



Ames Magnet Alloy





ORNL Non- Rare Earth Motor Prototype

Recent Patents

Patents Filed:

- K. Bennion and M. Thornton, “Parallel Integrated Thermal Management,” Application No. 13/035,082, Notice of Allowance Received May 15, 2014.
- B. Ma, M. Narayanan, U. Balachandran, S. Chao, S. Liu, “Method for Fabrication of Crack-free Ceramic Dielectric Films”, US Patent Application 2014/0120736 A1, published on May 1, 2014.
- M. R. Fairchild, R. S. Taylor, C. W. Berlin, C. W. Wong, B. Ma, U. Balachandran, “PLZT Capacitor on Glass Substrate”, US Patent Application filed on October 22, 2013.
- M. Chinthavali, “Gas Cooled Traction Drive Inverter,” App. No: 14/016,327, DOE-S No. S-124,056, September 3, 2013.
- T. Burress and C. Ayers, “Reluctance Motor,” App. No.: 13/944,731, DOE-S No: S-124,185; July 17, 2013.
- M. Narayanan, B. Ma, U. Balachandran, S. E. Dorris, “Method for Producing Thin Film Electrodes”, US Patent Application 2013/0071670 A1, published March 31, 2013.

Patents Issued:

- B. Ma, U. Balachandran, S. Chao, S. Liu, and M. Narayanan, “Method for Fabrication of Crack-free Ceramic Dielectric Films”, US Patent No. 8,647,737 B2, issued on February 11, 2014.
- K. Bennion and J. Lustbader, “Integrated Three-Dimensional Module Heat Exchanger for Power Electronics Cooling,” Patent No. US 8,541,875 B2, September 24, 2013.
- G-J. Su, “Electrical Motor/Generator Drive Apparatus and Method,” US Patent No. 8,373, 372; DOE-S No. S-115,264, February 12, 2013.
- Z. Liang et al., “Power Module Packaging with Double Sided Planar Interconnection and Heat Exchangers” Patent No. US 2013/0020694 A1, published January 24, 2013.
- J. Hsu, “Substantially Parallel Flux Uncluttered Rotor Machines,” US Patent No. 8,330,319, DOE-S No. S-115,261, December 11, 2012.
- J. Hsu, “Flux Control and One-Hundred and Eighty Degree Core Systems,” US Patent No. 8,319,464, DOE-S No. S-115,303, November 27, 2012.

Recent Inventions and Disclosures

Records of Invention/Disclosures:

- G. Moreno, K. Bennion, and S. Narumanchi, “Two-Phase System for Cooling a Vehicle’s Electric Motor and Power Electronics ,” ROI submitted May, 2014.
- B. Ma, U. Balachandran, S. E. Dorris, T. H. Lee, “Method For Making Wound Or Stacked Ceramic Films Capacitors With Enhanced Breakdown Strength,” Record of Invention ANL-IN-14-038, reported on April 3, 2014.
- K. Bennion, J. Lustbader, and R. Farrington, “Multiple Mode Cooling System for Power Electronics,” ROI-14-42, February, 2014.
- D. DeVoto and C. King, “Liquid thermal interface material for electronic component cooling and attachment,” ROI-14-21, December, 2013.
- A. Wereszczak, D. DeVoto, and P. Paret, “Perimetric Structure for Improved Reliability in Electronic Device Interconnection,” Invention Disclosure DOE-S No. S-124,788, October 2013.
- C. Ayers and J. M. Miller, “Hybrid Transflux Motor utilizing Variable Flux Intensifying and Weakening Operation,” Invention Disclosure IP-1250, September 10, 2013.
- B. Radhakrishnan and J. M. Miller, “Additively Manufactured Fe-6.5 Si wt. % Si steel Cores for Motor Applications,” Invention Disclosure IP1247, September 9, 2013.
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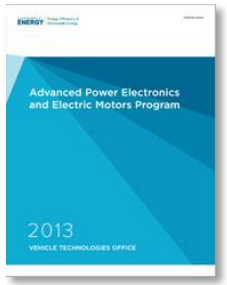

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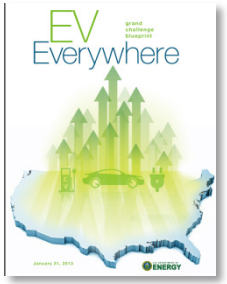

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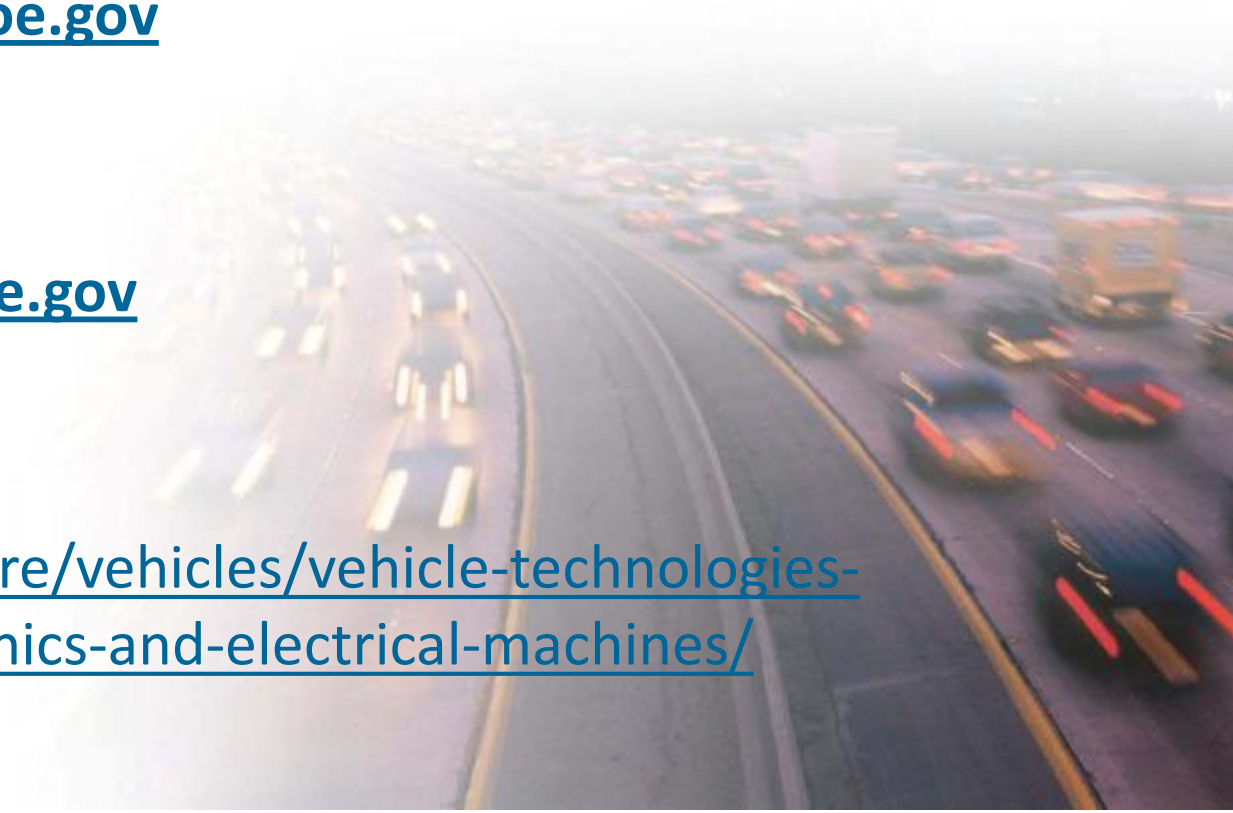

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