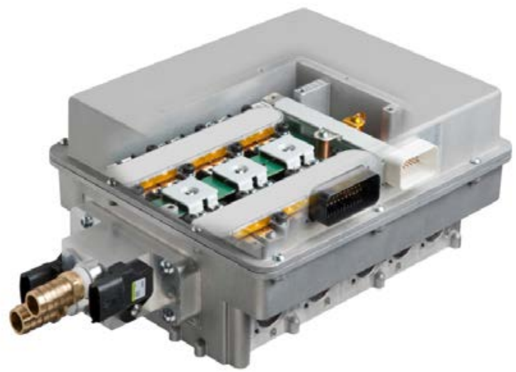
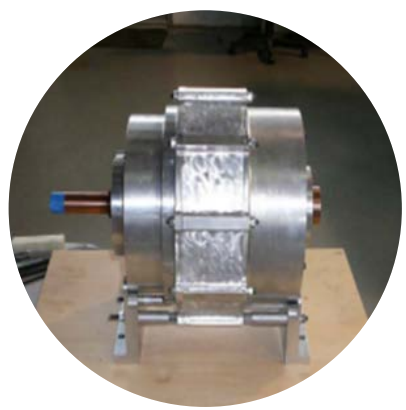
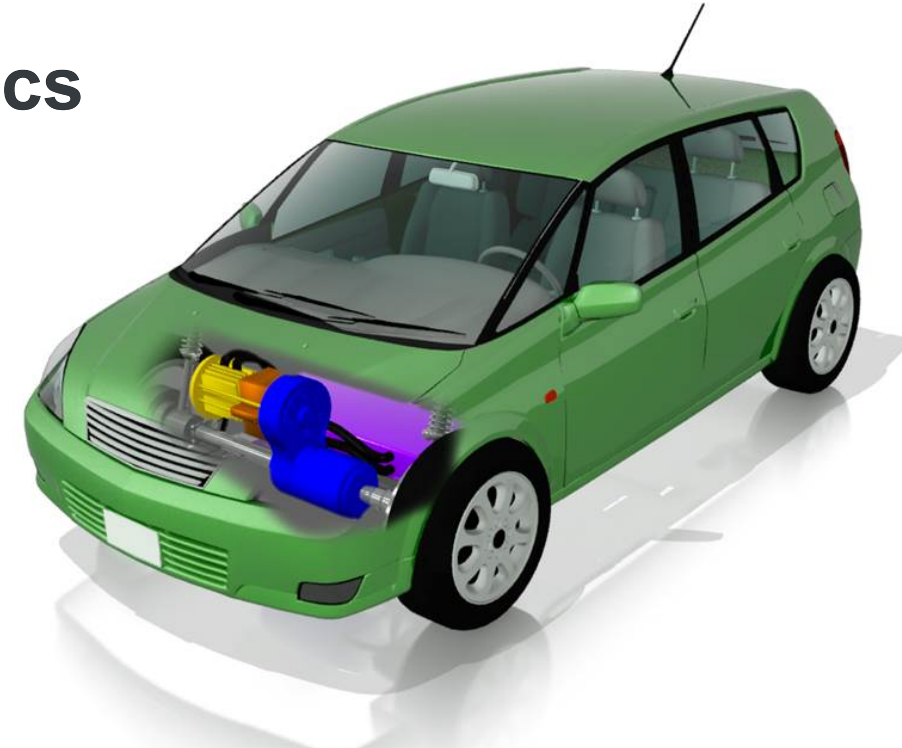
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Advanced Power Electronics and Electric Motors R&D







May 14, 2013

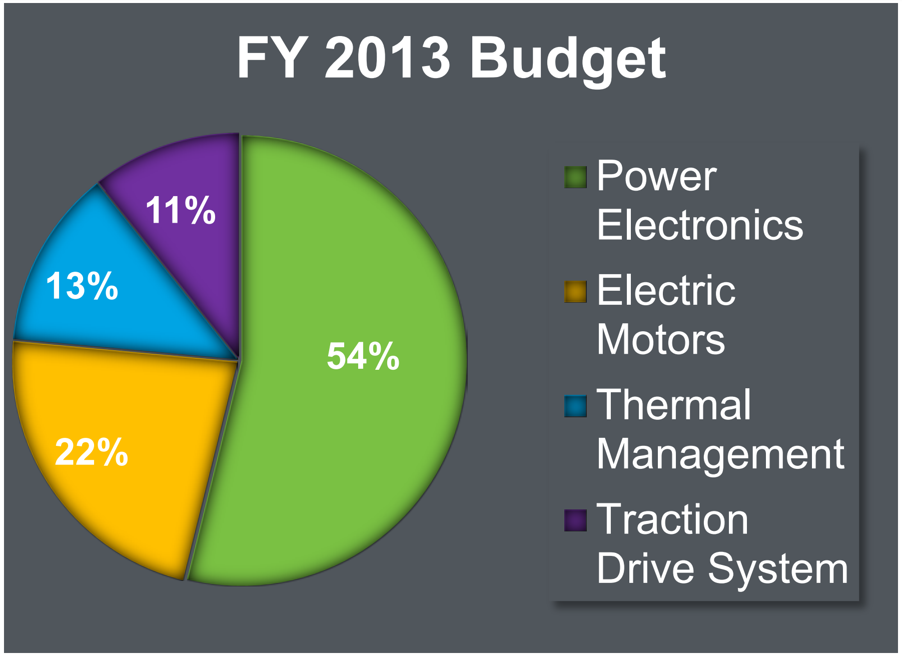
APE00A

Susan Rogers
Hybrid & Electric Vehicles R&D
Vehicle Technologies Office
U.S. Department of Energy
1000 Independence Avenue
Washington DC 20585

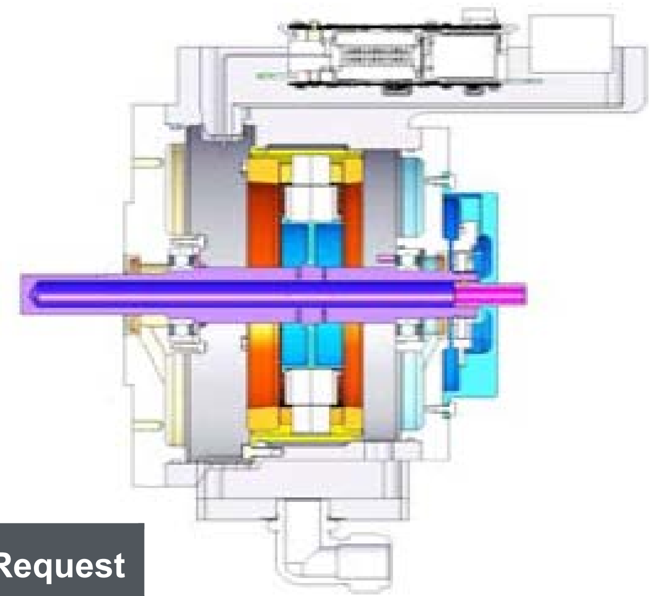
APEEM Mission and Budget

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

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



Integrated Traction Drive System Concept



Funding ($M)	FY 2012* Enacted	FY 2013** Full Year CR	FY 2014*** Request
APEEM R&D	$27.8	$27.2	$69.7

* FY 2012 SBIR/STTR removed
** FY 2013 full year CR inclusive of SBIR/STTR
*** FY 2014 budget request inclusive of SBIR/STTR

APEEM Program

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

EV Everywhere

- **Vehicle Technologies Office**
  - **Hybrid Electric Systems R&D**
    - **Energy Storage**
    - **Advanced Power Electronics & Electric Motors R&D**
      - **Academia**
      - **Federal Agencies**
      - **Industry**
      - **National Labs**
    - **Vehicle Systems**

APEEM – Who We Work With

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

Industry

NBE Tech, LLC — Enabling nanomaterials
Wolverine Tube, Inc. — Engineering Thermal Innovation
Ford
Chrysler
Johnson Controls
Fuji Electric
AVX
Microsemi
MER Corporation
Remy
USCAR
curamik
3M
Electronic Concepts
John Deere
Tesla Motors
CREE
sapa:
Nippon Electric Glass Co., Ltd.
International Rectifier
General Atomics and Affiliated Companies
GM
transphorm
HRL Laboratories, LLC
GE Global Research
UQM Technologies
DuPont
Corning
SCHOTT glass made of ideas
Magna
Baldor — A member of the ABB Group
Allison Transmission
SBE Inc.
Visteon
btechcorp
Delphi
Kyocera
Heraeus
QM Power
EEC Electron Energy Corporation
KEMET — The Capacitance Company — Charged
Powerex
Semikron — innovation + service
Magna Powertrain
SPS Strategic Polymer Sciences, Inc.
Orthodyne Wedge Bonders
Materion
APEI International
Momentive performance materials

Academia

University of Delaware
University of Nebraska
University of Minnesota — Driven to Discover
Virginia Tech
Iowa State University
calce
UIC The University of Illinois at Chicago
The University of Tennessee
Northeastern University
Dartmouth
University of Colorado
Purdue University
Case Western Reserve University est. 1826
VCU Virginia Commonwealth University
The University of Wisconsin Madison
Penn State
Brown
The University of Alabama

Federal Agencies

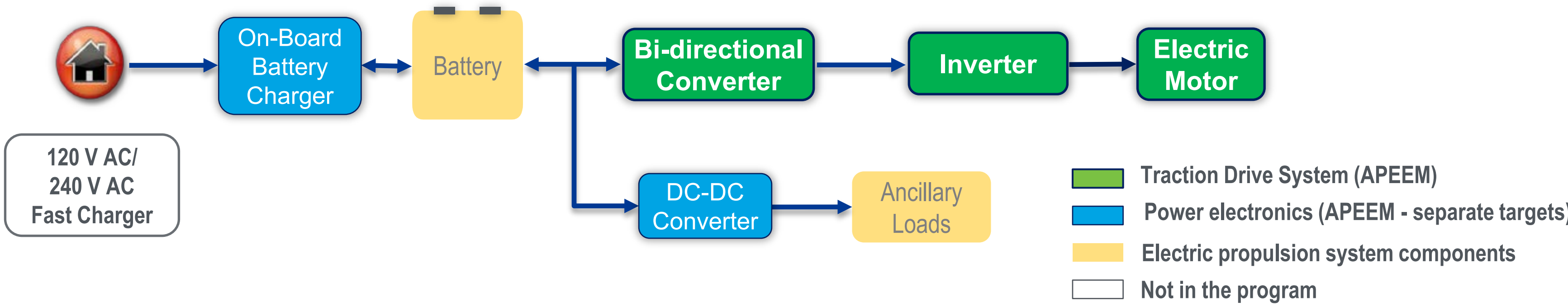
NASA
arpa·e Advanced Research Projects Agency • Energy
Interagency Advanced Power Group
NIST
TARDEC

National Labs

NREL National Renewable Energy Laboratory
Oak Ridge National Laboratory
Argonne National Laboratory
Sandia National Laboratories
The Ames Laboratory — Creating Materials & Energy Solutions
Pacific Northwest National Laboratory

APEEM Technical Targets

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



Traction Drive Systems (TDS)				
Impact	Reduce Cost	Reduce Weight	Reduce Volume	Reduce Energy Storage Requirements
Year	Cost ($/kW)	Specific Power (kW/kg)	Power Density (kW/l)	Efficiency (%)
2010*	19	1.06	2.6	>90
2013	**16**	**1.15**	**3.1**	**>91**
2015	12	1.2	3.5	>93
2020	8	1.4	4.0	>94

Power Electronics (PE)		
($/kW)	(kW/kg)	(kW/l)
7.9	10.8	8.7
6.5	**11.5**	**10.2**
5	12	12
3.3	14.1	13.4

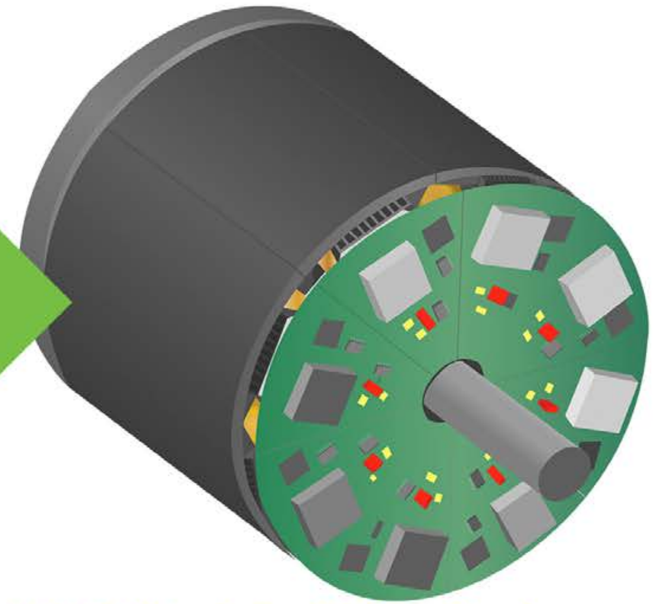
Electric Motors (EM)		
($/kW)	(kW/kg)	(kW/l)
11.1	1.2	3.7
9.5	**1.3**	**4.8**
7	1.3	5
4.7	1.6	5.7

Traction Drive System Requirements: 55 kW peak power for 18 sec; 30 kW continuous power; 15-year life

* **2010 traction drive system cost target met** with GM integrated traction drive system; 2015 weight and size targets were also met

EV Everywhere Electric Drive 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

- Discrete Components
- Silicon Semiconductors
- Rare Earth Motor Magnets

EV Everywhere

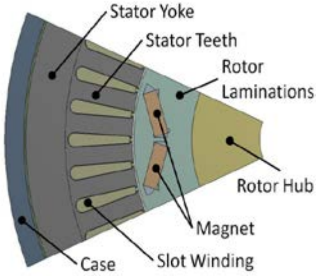
2022 Electric Drive System

$8/kW, 1.4 kW/kg, 4.0 kW/L
94% system efficiency

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

APEEM R&D – Advances Technologies & Reduces Cost

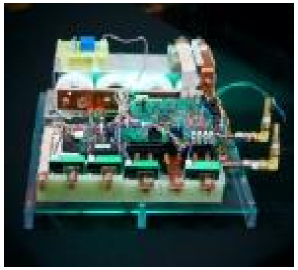
Advanced Materials Research



Materials required for:

- High temperature operation
- Thermal conductivity
- Performance & reliability
- Manufacturing processes
- Cost reduction

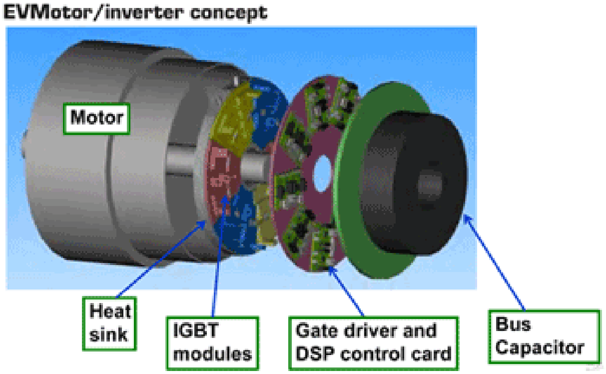
Architecture Optimization



Innovative designs optimize:

- Voltage
- Current
- Frequency
- Temperature
- Speed
- Cost reduction

Traction Drive Systems



Affordable, reliable systems:

- Integrate power electronics, motor, & cooling
- Modular & scalable designs
- Manufacturable technologies
- Improve performance

APEEM Traction Drive System Status

Benchmarking and analysis of on-road technologies:

- identifies gaps and research opportunities
- confirms innovations are required to achieve 2020 targets

APEEM 2020 Targets	Traction Drive System	HEV	BEV
Specific Cost ($/kW)	8.0		
Specific Power (kW/kg)	1.4		
Power Density (kW/l)	4.0		
Efficiency (%)	>94		

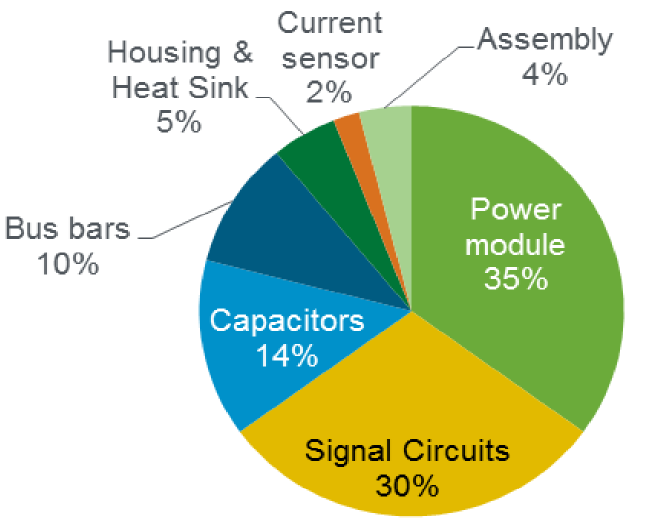
Cost must be reduced for consumer acceptance

Strategies to Achieve PE Targets

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

Cost analysis

On-road 80 kW Inverter Manufactured Cost: $1,092



Specific cost: $13.65/kW
2020 target: $3.3/kW

R&D emphasis

35% Power Module
- Utilize WBG devices for high temperature operation & increase efficiency to reduce cooling system requirements
- Reduce heat loss & improve heat transfer with improved packaging materials and heat exchangers
- Integrate designs to minimize components

30% Signal Circuits
- Integrate gate driver, isolation circuit, and fault logic to match WBG performance

14% Capacitors
- Implement advanced circuit designs to reduce capacitor requirements
- Improve capacitor performance characteristics

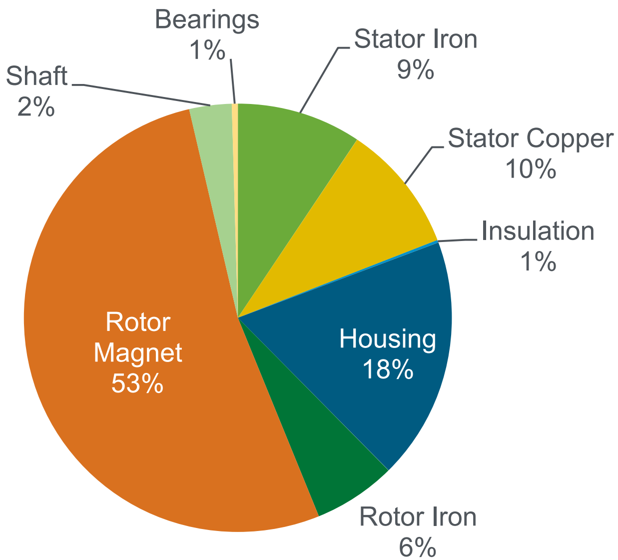
10% Bus Bars
- Reduce the size and bulk of the dc bus with a novel heat blocking strategy

Strategies to Achieve EM Targets

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

Cost analysis

On-road 80 kW Motor Manufacture Price: $938



Specific cost: $11.73/kW
2020 target: $4.7/kW

R&D emphasis

53% Rotor magnet
- Research motor design concepts that *eliminate* rare-earth magnets – IM, SRM, etc.
- Research motor design concepts that *reduce* rare earth content
- Develop and refine less expensive magnets – ALNICO or ferrite

18% Housing
10% Stator Copper
9% Stator Iron
6% Rotor Iron
Total 43%
- Develop advanced scalable packaging designs & materials to reduce losses, improve heat removal, and increase efficiency
- Evaluate higher speed strategies to reduce volume and mass
- Integrate less costly, low loss materials

Why Use Wide Bandgap Devices?

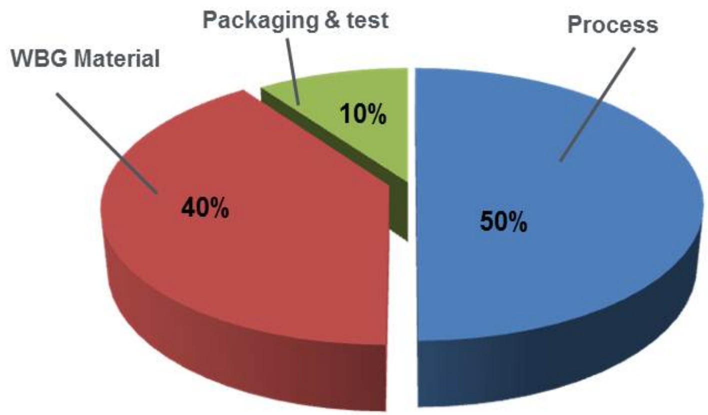
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Attributes + Requirements → Benefits

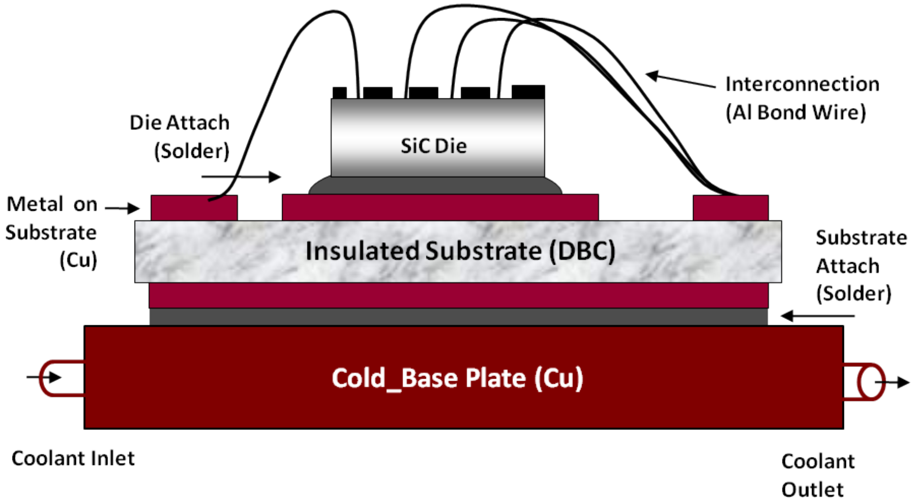
Attributes
- Tolerates higher voltages
- Tolerates higher temperatures
- Enables improved efficiency

Requirements
- High temperature packaging
- High temperature capacitors
- Smaller capacitors

Benefits
- Reduce cost
- Reduce size
- Increase efficiency



Cost Breakdown



SiC Module Packaging Design with Integrated Cooling

WBG devices are key to achieving 2020 targets

Motor Technologies vs. 2020 Targets

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

Analysis of motor designs confirms gaps & R&D opportunities

Motor Technology Comparison	Permanent Magnet Motor*	Induction Motor	Reluctance Motor
Cost ($/kW)	$$$	$$	$
Power density (kW/L)	Highest	Moderate	Moderate
Specific power (kW/kg)	Highest	Moderate	Moderate
Efficiency (%)	Good	Good	Moderate
Noise and vibration	Good	Good	Challenging
Manufacturability	Difficult	Mature	Easy
Potential for improvement	Significant	Minimal	Significant

Rare earth costs drive need for motor innovation

* Majority of on-road technology

APEEM Program Highlights - Pathways to Commercialization

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

UQM TECHNOLOGIES
- SBIR Awards with DOE 2002 - 2005
- Traction Motor Development R&D Award 2005
- ARRA Drive Electronics & Electric Motor/Generator 2009
- Non Rare Earth Traction Motor Development R&D Award 2011

SBE Inc.
- SBIR Awards with DOE 2008-2009
- ARRA DC Bus Capacitors 2009

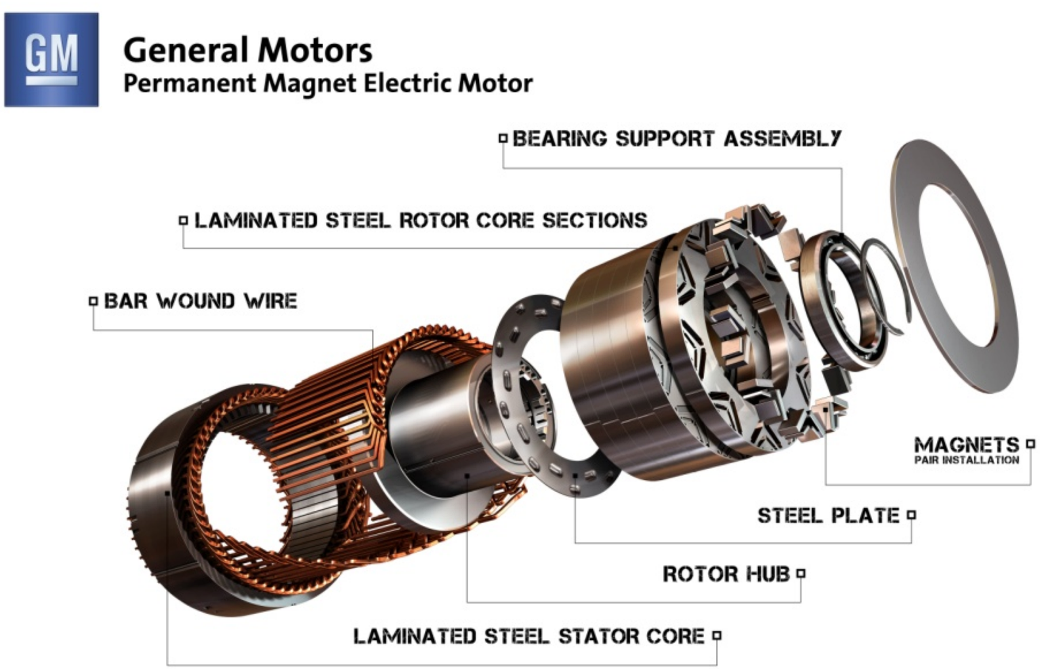
POWEREX
- Inverter R&D Award 2006
- ARRA Semiconductor Devices 2009

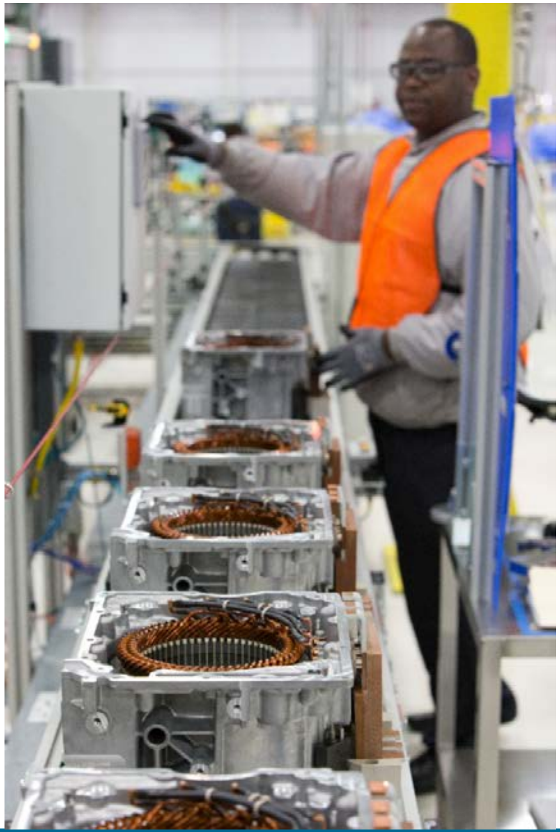
DELPHI
- Inverter R&D Award 2006
- ARRA Electric Drive Power Electronics 2009

GM / Allison Transmission
- GM/Allison AHHPS Award 2003
- Traction Drive System R&D Award 2006
- ARRA Electric Drive 2009
- Next Generation Inverter R&D Award 2011
- ARRA Commercial-duty Hybrid Systems 2009

APEEM - GM Electric Motor Commercialization

- GM is the first U.S.-based automaker to manufacture electric motors in America at their plant in White Marsh, MD
- Facility was built as part of the cost shared DOE Recovery Act project
- Motors will be used for the new Chevrolet Spark EV
- Spark EV electric motor will produce 130 hp (100 kW) and 400 lb-ft of torque

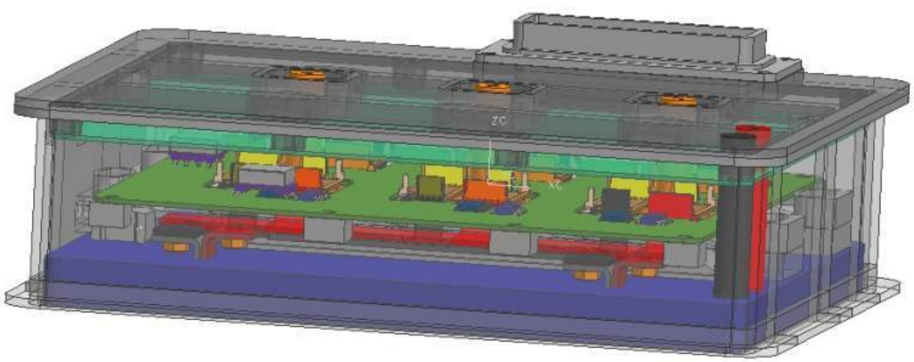




APEEM - Delphi Power Electronics Commercialization

- Delphi R&D of advanced inverter with integrated controller met APEEM 2015 R&D targets
- Delphi is going to production with an inverter based on technology innovations developed with DOE
- National lab expertise and facilities supported this project, 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



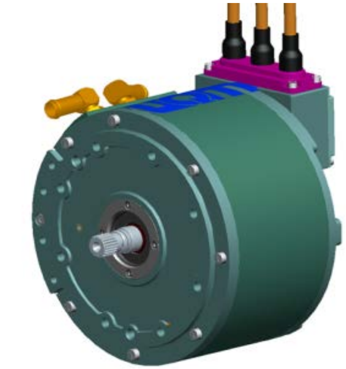
* Based on production intent design using PEEM technologies – assuming volume of 100,000 units/year, cost/kW would be lower for upper end of 55-120 kW power range and higher for lower end of power range; kW/kg and kW/L would be higher for upper end of power range and lower for the lower power.

APEEM Industry R&D Highlights

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

UQM

- Completed analysis of non-RE motor design
- Magnetic finite element analysis demonstrates a feasible architecture to enable the use of non-RE magnets
- Motor build this year to demonstrate feasibility of the approach



UQM motor package

GE imagination at work

- Evaluated multiple motor topologies and completed preliminary down-select; 3 designs to be built and tested
- First design is almost finalized and build will be initiated soon
- Test coupons of advanced motor materials manufactured and characterized
- Identified scalable manufacturing methods for advanced materials

GE soft magnetic laminates

GM

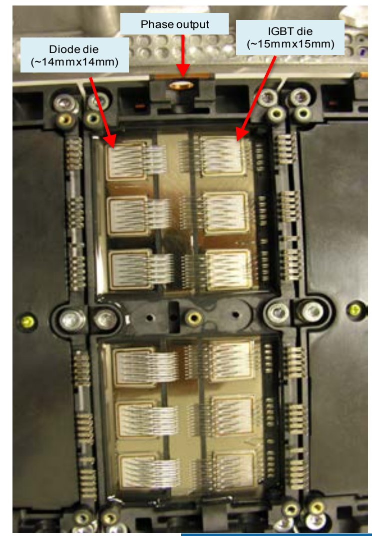
- Completed assessment of three inverter types with complete cost models
- Developed understanding of cost reduction attributed to technology improvements and commonality of design

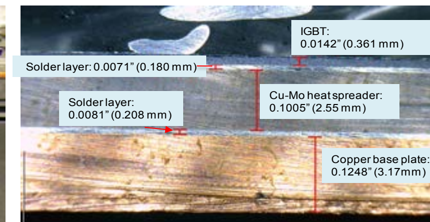
Module Testing at GM

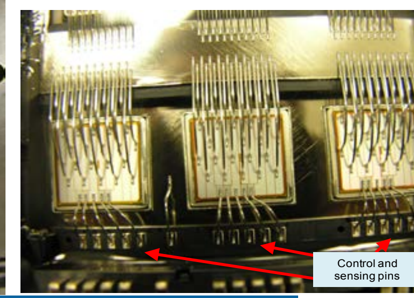
Traction Drive System Benchmarking

- Confirms on-road, state-of-the-art status to identify gaps and R&D priorities
- Identifies cost, performance, reliability, efficiency, manufacturability & assembly

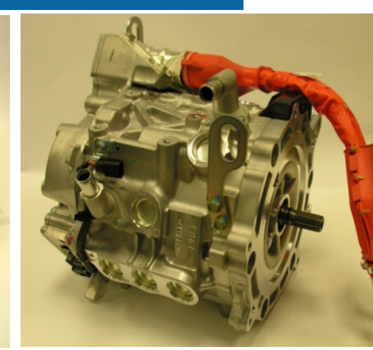
Metric	Units	2020 Target	2010 Prius (w/o boost)	2012 LEAF	2011 Sonata
Peak Power	(kW)	55	60	80	30
Inverter	SP (kW/kg)	14.1	16.7 (6.9)	4.94	6.9
	PD (kW/liter)	13.4	11.1 (5.9)	5.14	7.3
Motor	SP (kW/kg)	1.6	1.6	1.43	1.1
	PD (kW/liter)	5.7	4.8	4.21	3.0
System	SP (kW/kg)	1.44	1.46 (1.25)	1.1	0.95
	PD (kW/liter)	4.0	3.35 (2.8)	2.3	2.13
Sys Eff	(avg %)	>94	91.6	92.5	~91
Cost	$/kW	$	$$$	$$$	$$$$







2012 Nissan LEAF



National Lab Power Electronics FY13 Accomplishments

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

WBG device benchmarking - validates status & confirms potential

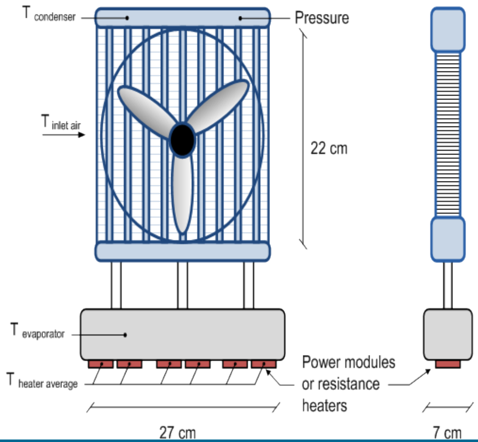
- Unique Wide Bandgap Characterization Test Facility
- Public data base accelerates commercialization of WBG devices:
  (www.ornl.gov/sci/ees/etsd/pes/device_testing.shtml)
- Enables design and development of WBG power modules with optimum electrical and thermal performance

Improved Fabrication of High Temperature Polymer Film Capacitor

- Demonstrated inexpensive, extruded, high temperature, polymer film
- Enables lighter, smaller, less expensive inverters with improved reliability

Increased Power Density & System Efficiency via 2-Phase-Cooling

- Fabricated 2-phase cooling system and characterized performance
- Confirmed potential for cooling automotive power electronics
- 2-phase cooling increases power density of power electronics by 75% and increases system efficiency

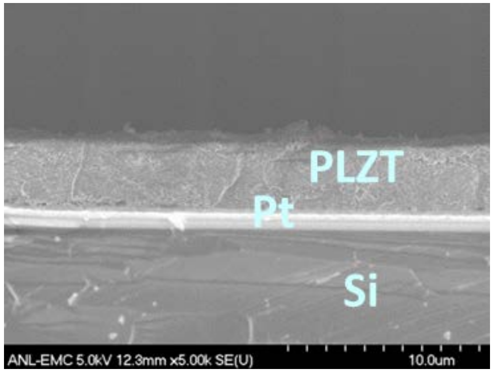


National Lab Power Electronics FY13 Accomplishments

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

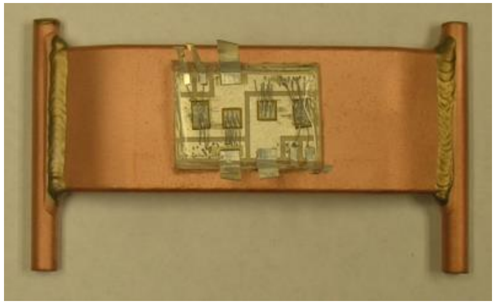
Improved Processes for Ceramic Capacitors

- Developed faster deposition of 3.2 µm thick ceramic dielectric film on substrates at room temperature
- Enable smaller, less expensive dc bus capacitors capable of tolerating significantly higher temperatures



Developed Innovative WBG Inverter Packaging

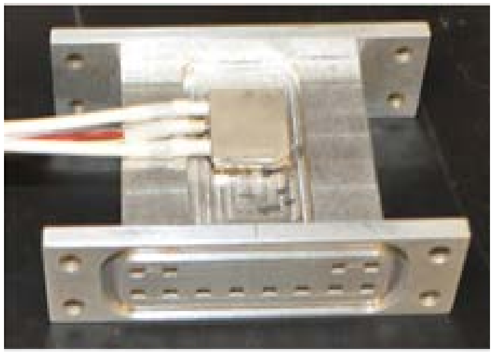
- Built and tested 50 A/1,200 V highly integrated silicon carbide (SiC) phase-leg power module
- Enables 40% cost reduction and 60% power density increase of power modules



Prototype of a 50A/1200V highly integrated SiC phase leg power module

Developed Integrated Power Module Heat Exchanger

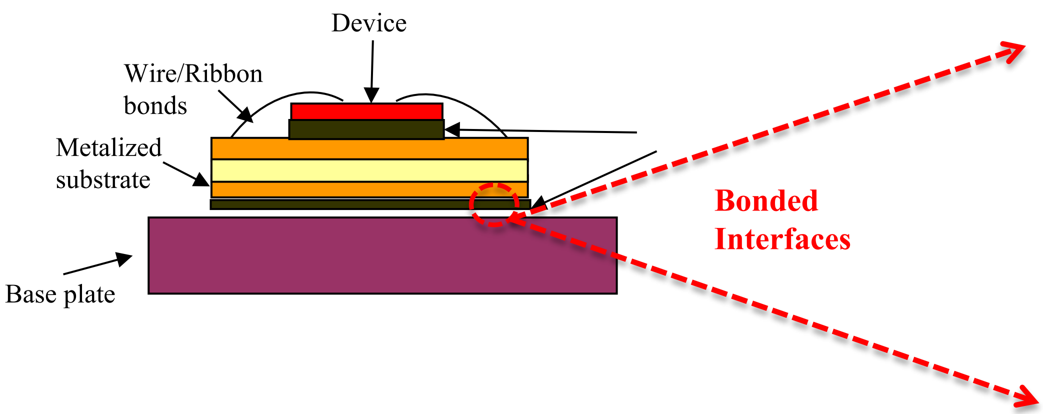
- Integrating heat spreader & heat exchanger doubles power per die area
- Confirmed power density improvements

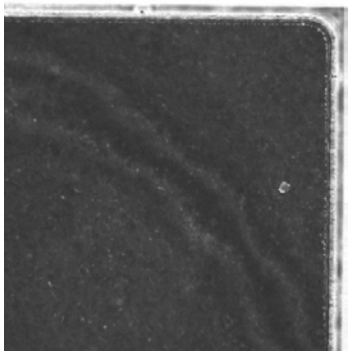


Prototype Hardware

Confirmed Reliability of New Bonded Interfaces

- Characterized reliability of large-area bonded interfaces based on sintered silver, thermoplastics, and lead-based solder
- Demonstrated reliability of thermoplastics after 2,000 thermal cycles (-40 to 150 C)





Acoustic microscope image of **thermoplastic** bonded interface with no defects

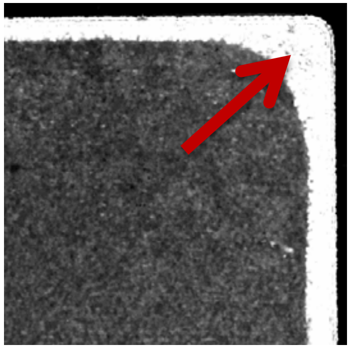


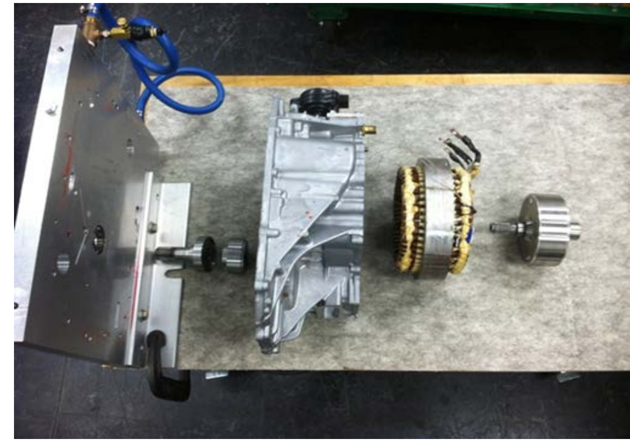
Image of **sintered silver** bonded interface with edge fracture defect

National Lab Electric Motor FY13 Accomplishments

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

Non-Rare Earth Electric Motor Technologies and Advanced Materials

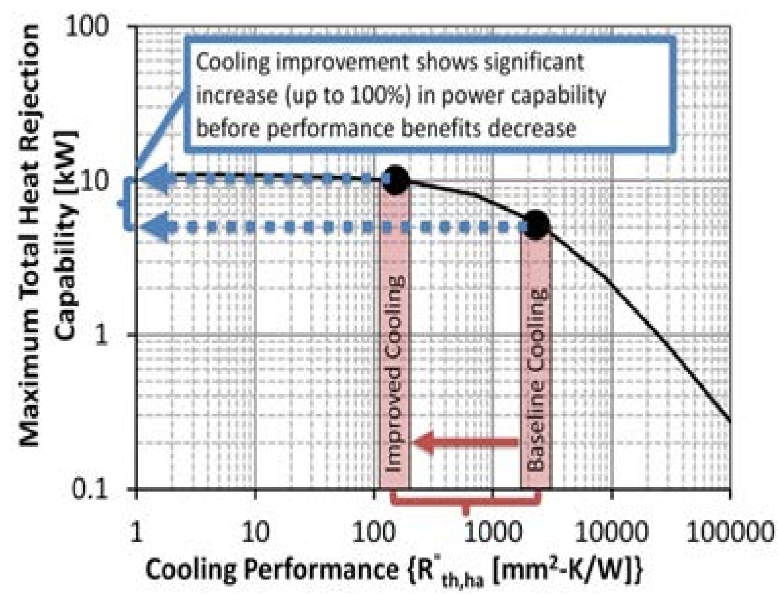
- Evaluated new, low loss, motor lamination materials and thermal conducting materials for slot liner and wire potting
- Completed static tests of magnetic and thermal materials.
- Characterized prototype stators in dynamic setting for spin loss and efficiency benefits.



Characterization of new stator materials

Confirmed Impact of Cooling on Motor Performance

- Measured thermal conductivity and contact resistances for motor steel laminations in the stator and rotor
- Completed parametric finite element thermal sensitivity analysis for multiple motor designs
- Identified areas for focused R&D improvements; potential to increases motor power capability by 100%



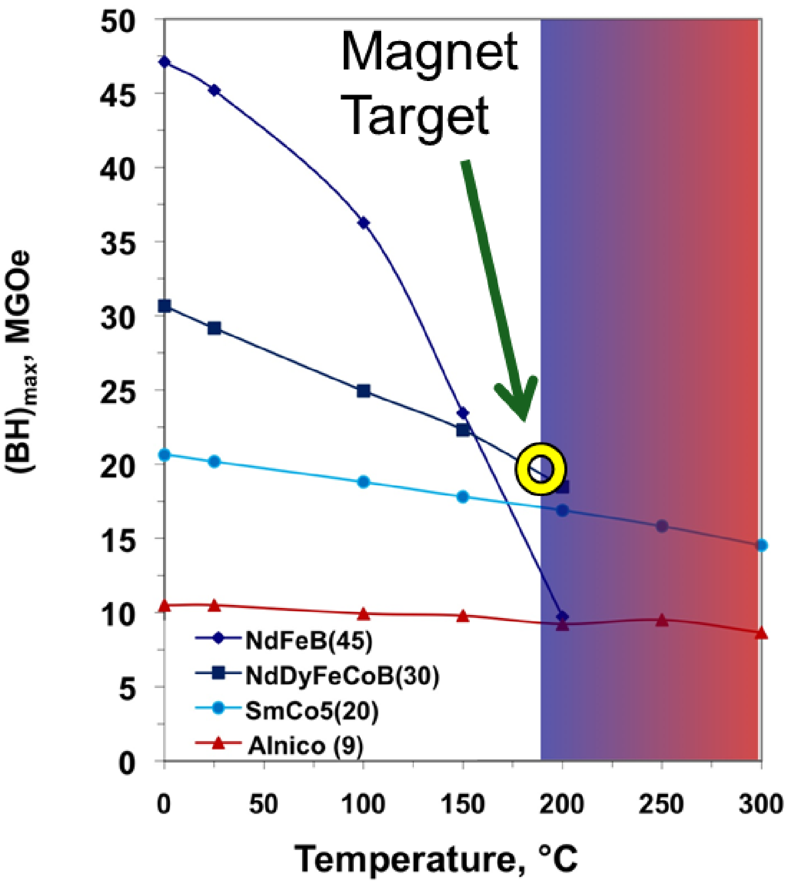
Improved convective cooling improves motor power capability

National Lab Electric Motor FY13 Accomplishments

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

New Understanding of Non-Rare Earth AlNiCo Magnet Capabilities

- AlNiCo is best near-term candidate to replace rare earth magnets in permanent magnet (PM) motors
- Performance matches RE magnets at high motor temperatures
- Efforts ongoing to increase magnet coercivity to further reduce magnet content required for electric motors



APEEM Long Term R&D Strategy

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- **Lower cost is the most critical element for consumer acceptance**
- **Technology breakthroughs are necessary to achieve R&D targets**
- **Traction Drive System R&D emphasis enables:**
  - Cost, weight, and volume reduction
  - Performance, efficiency and reliability improvements
  - Modular and scalable designs
  - Manufacturability for commercialization
- **Pathways to achieve Traction Drive System targets include:**
  - Utilize Wide Bandgap (WBG) devices
  - Develop advanced motor designs to reduce/eliminate rare earth materials
  - Integrate power electronics functions in advanced architectures
  - Develop novel packaging materials and designs
  - Improve heat transfer and thermal management

Information Sources

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

- **FY 2012 Advanced Power Electronics and Electric Motors Annual Progress Report**
  - https://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2012_apeem_report.pdf
- **Electrical and Electronics Technical Team Roadmap**
  - http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_12-7-10.pdf
- **Vehicle Technologies Multi-year Program Plan 2011-2015**; Section 2.2.1
  - http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

Contact Information

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www.vehicles.energy.gov