Scalable, Low-Cost, High Performance IPM Motor for Hybrid Vehicles

DE-FC26-07NT43122
DOE Peer Review Presentation

Ayman EL-Refaie, Project Manager & Principal Investigator
Frank Johnson, Materials Design Leader

GE Global Research
June 10, 2010

Project ID: APE013

imagination at work

Team and stakeholders

Kelly Fletcher
Business Programs Manager
GE Energy

Margaret Blohm
Advanced Technology Leader
Nanotechnology

GE Global Research
Nanostructured Magnetic Materials and Advanced Motor Development

Ayman M. EL-Refaie
Program Manager
Principal Investigator

Francis Johnson
Materials Development Leader

GE Energy
(Motors)
Motor Manufacturing

Doug Hofmann
Motors and Controls

THE UNIVERSITY WISCONSIN MADISON
New IPM Motor Concept Designs and Testing

Prof. Thomas M. Jahns
Grainger Professor of Power Electronics and Electrical Machines

McCleer Power
Prototype Manufacturing

Patrick McCleer
President

imagination at work

Overview

Timeline

Phase I:
- Start: October 2007
- Finish: June 2009
- 100% complete

Phase II:
- Start: July 2009
- Finish: June 2011
- 30% complete

Budget

Phase I:
- $ 2.43M total budget
- $ 1.944M DOE share
- $ 486K GE cost share

Phase II:
- $ 3.37M total budget
- $ 1.618M DOE share
- $ 1.752M GE cost share

•Funding received (DoE+GE) in FY09 $1.1M
•Planned Funding (DoE+GE) for FY10 $2M

Barriers

Very challenging set of specs
- High efficiency over a wide speed and load ranges
- High power density and high coolant inlet temperature
- Low cost targets based on 100,000 units/year
- High speed poses mechanical challenges

Partners

- GE Global Research (lead)
- GE Motors
- University of Wisconsin-Madison
- McCleer Power

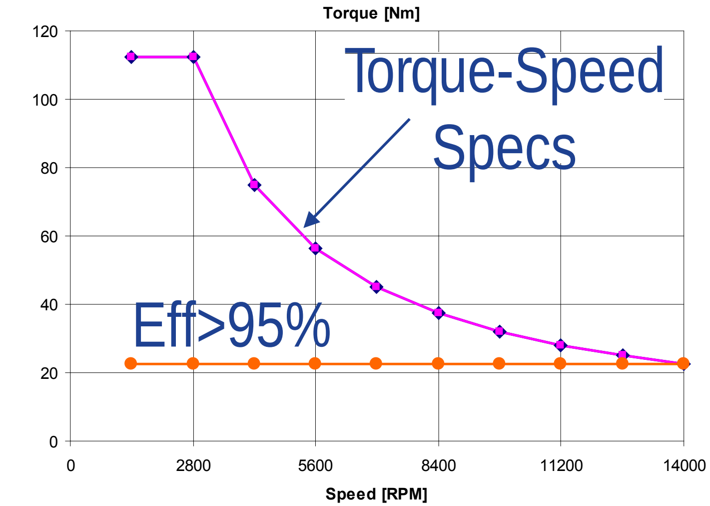
Purpose of work FY'09/FY'10

Design 55kWpk IPM motor to meet DOE specification

Table 2. Motor Specifications

Requirement	Target
Minimum top speed (rpm)	14,000
Peak power output at 20% of maximum speed for 18 seconds and nominal voltage (kW)	55
Continuous power output at 20 to 100% of maximum speed and nominal voltage (kW)	30
Weight (kg)	≤35
Volume (l)	≤9.7
Unit cost in quantities of 100,000 ($)	≤275
Operating voltage (Vdc)	200 to 450; nominal 325
Maximum per phase current at motor (Arms)	400
Characteristic current (ψmag/Ld)	< Maximum current
Efficiency at 10 to 100% of maximum speed for 20% of rated torque (%)	> 95
Back EMF at 100% of maximum speed, peak line-to-line voltage (V)	< 600
Torque pulsations-not to exceed at any speed, percent of peak torque (%)	< 5
Ambient (outside housing) operating temperature (°C)	-40 to +140
Coolant inlet temperature (°C)	105
Maximum coolant flow rate (liters/min)	10
Maximum coolant pressure drop (psi)	2
Maximum coolant inlet pressure (psi)	20
Minimum isolation impedance-phase terminals to ground (Mohm)	1

Very challenging set of specs



Relevance

Developing a low-cost, high-performance advanced traction motor is a key enabler to meeting the 2020 technical targets for the electric traction system

Table 1. Technical Targets for Electric Traction System

	2010[a]	2015[b]	2020[b]
Cost, $/kW	<19	<12	<8
Specific power, kW/kg	>1.06	>1.2	>1.4
Power density, kW/L	>2.6	>3.5	>4.0
Efficiency (10%-100% speed at 20% rated torque)	>90%	>93%	>94%

[a] Based on a coolant with a maximum temperature of 90 C.
[b] Based on air or a coolant with a maximum temperature of 105 C.
[c] A cost target for an on-board charger will be developed and is expected to be available in 2010.

Objectives

- Investigate the design space in order to meet the DOE specifications
- Develop scalable thermal management schemes
- Develop advanced rotor concepts to meet the high-speed requirement
- Build proof-of-principle machines to verify the various developed concepts
- Build a 30kW/55kWpk machine that meets the specs
- Develop a cost model based on 100,000 units/year
- Novel sintered permanent magnet with 3X lower eddy current loss using co-sintered insulating phase
- Rotor material selection study to improve thermal performance

Barriers

• Heroic motor efficiency requirements over a wide speed and load range – must address every significant loss component

•Minimization of high-cost materials in the motor design - get maximum performance value from rare-earth PM materials

•High power-density thermal management – how to control temperature and extract heat in very compact motor and with high coolant inlet temperature

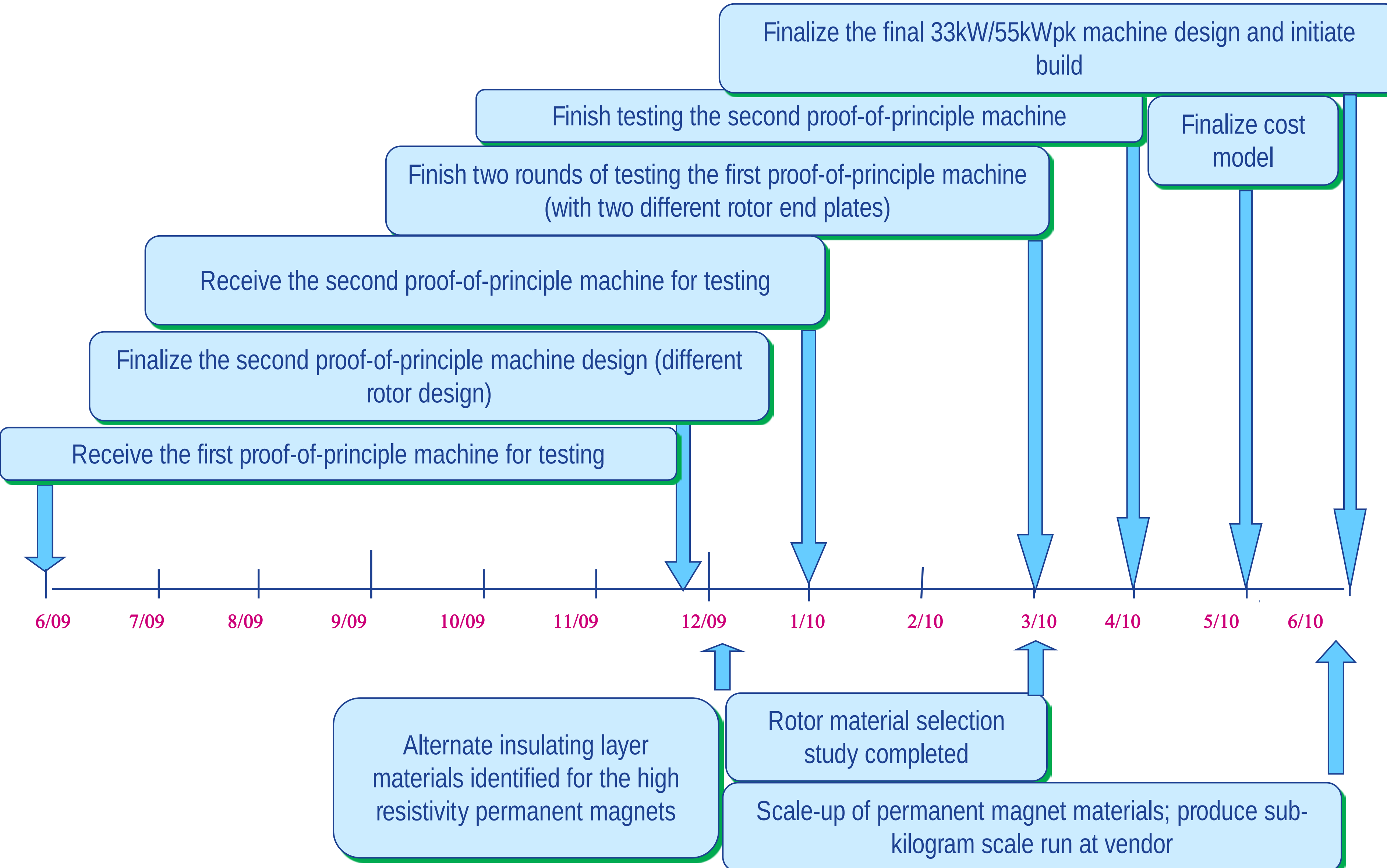
•Design rotor for mechanical integrity at high speed

•Scaling up high resistivity permanent to kg-scale needed for motors requires understanding sintering process parameters of permanent magnet and insulating phases.

• Eddy current reduction in permanent and permanent magnet stability must be maintained during scale up.

Milestones

Motor Development



Material Development

imagination at work

Approach

- Simplified stator windings will reduce end-turn length and losses, together with motor mass and volume and manufacturing cost.
- Advanced rotor concepts to achieve higher power density as well as meeting the high-speed requirement.
- Advanced scalable thermal management schemes for both the stator and the rotor to meet the required set of specifications.
- High resistivity permanent magnets
    - Screen alternate insulating phase materials
    - Measure and insulating and magnet phase sintering parameters
    - Measure and verify resistivity and magnet stability
- Rotor material selection study
    - Employing “Material selection in mechanical design” formalism

Accomplishments to Date

Motor design

- 2 rotor & 2 stator EM concepts developed & analyzed in detail
- Scalable rotor and stator cooling concepts selected to meet performance, simplicity and scalability requirements
- Highest-performance EM concepts selected for proof-of-principle motors build.
- First proof-of-principle motor built and fully tested
- Second proof-of-principle machine (different rotor structure) is built and currently being tested (test will be concluded by end of April)
- Development of cost model is almost finalized (fine tuning is still needed)

High resistivity permanent magnets

- Permanent magnet microstructure with 3-4X effective resistivity enhancement demonstrated
- Alternate set of insulating materials identified
- Begun trials of kg scale-production at vendor

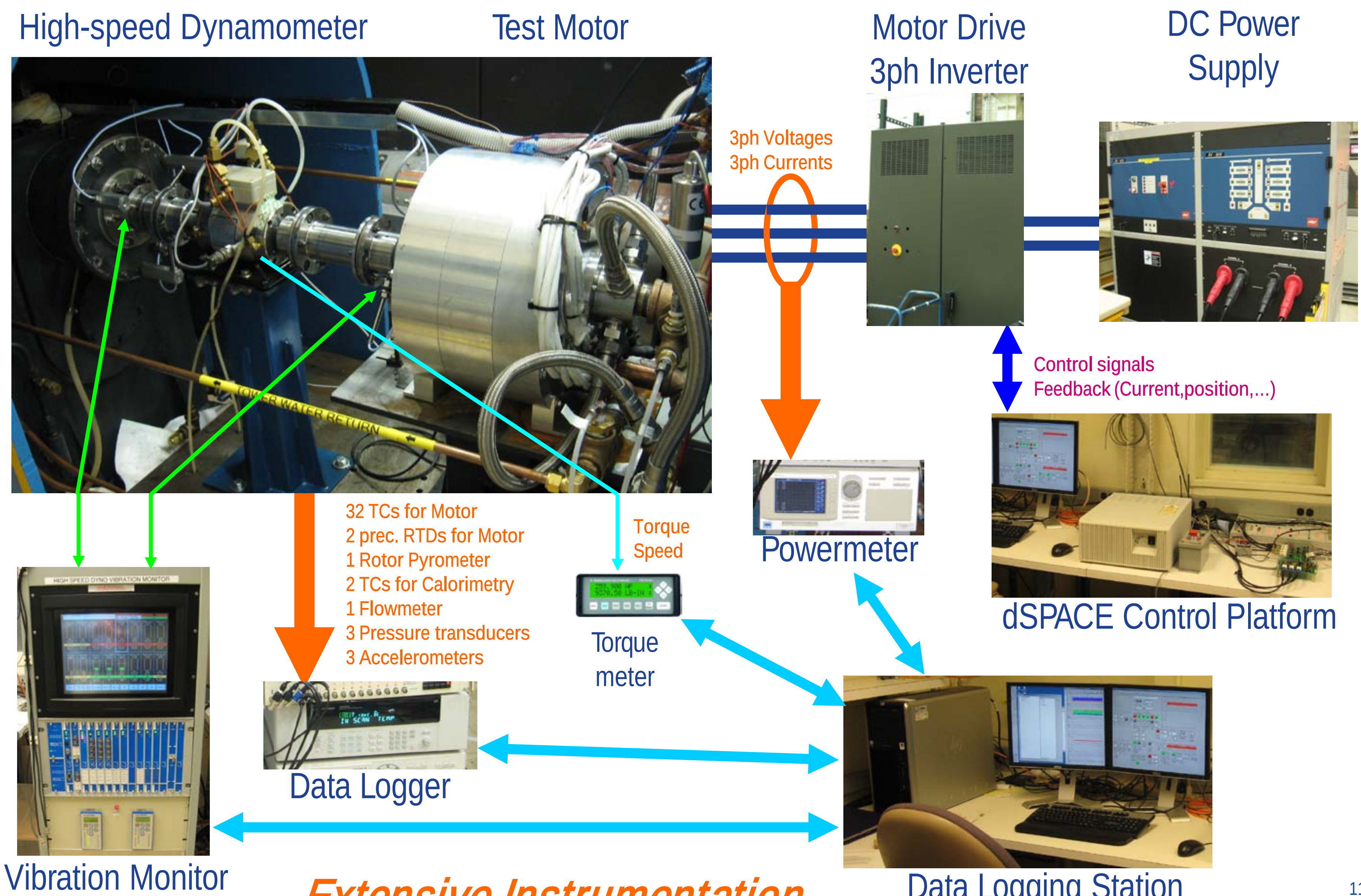
Rotor Materials Selection

- Rotor material selection study identified alternative material choices for rotor shaft, magnet retaining structural elements, and steel laminates for next prototypes.

Patents and publications

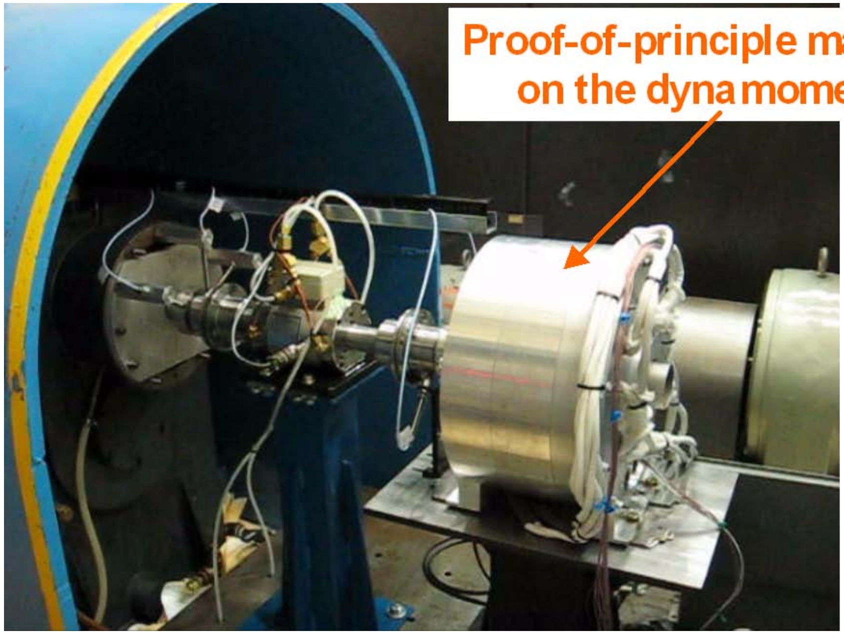
- 9 US patent applications out of more than 12 patent disclosures have been filed up-to-date with few others pending

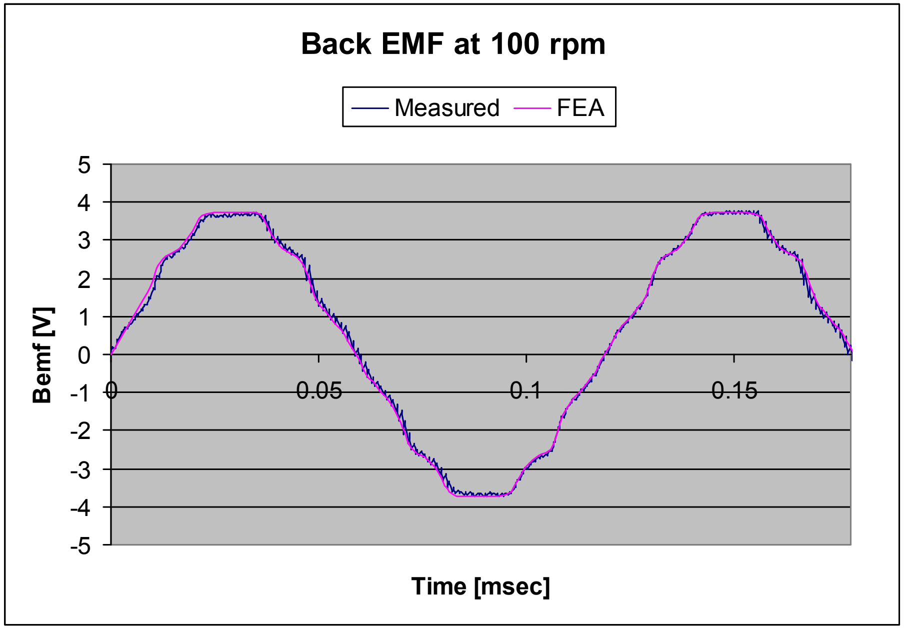
Motor Test Set Up



Extensive Instrumentation

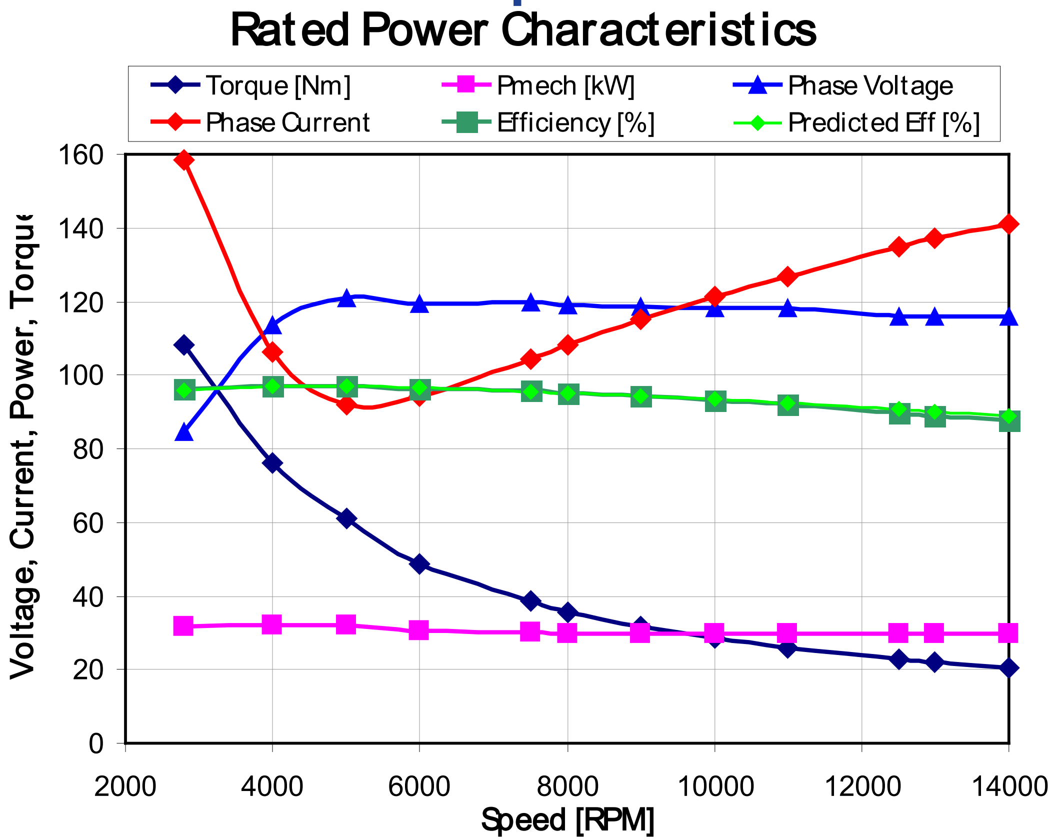
First Proof-of-Principle Machine





- Machine parameters closely match predictions
- Machine tested electrically up to 14000 rpm
- Machine with its fundamentally novel rotor structure has been tested mechanically up to 14000 rpm (machine designed with 20% overspeed on top of the 14000 rpm)

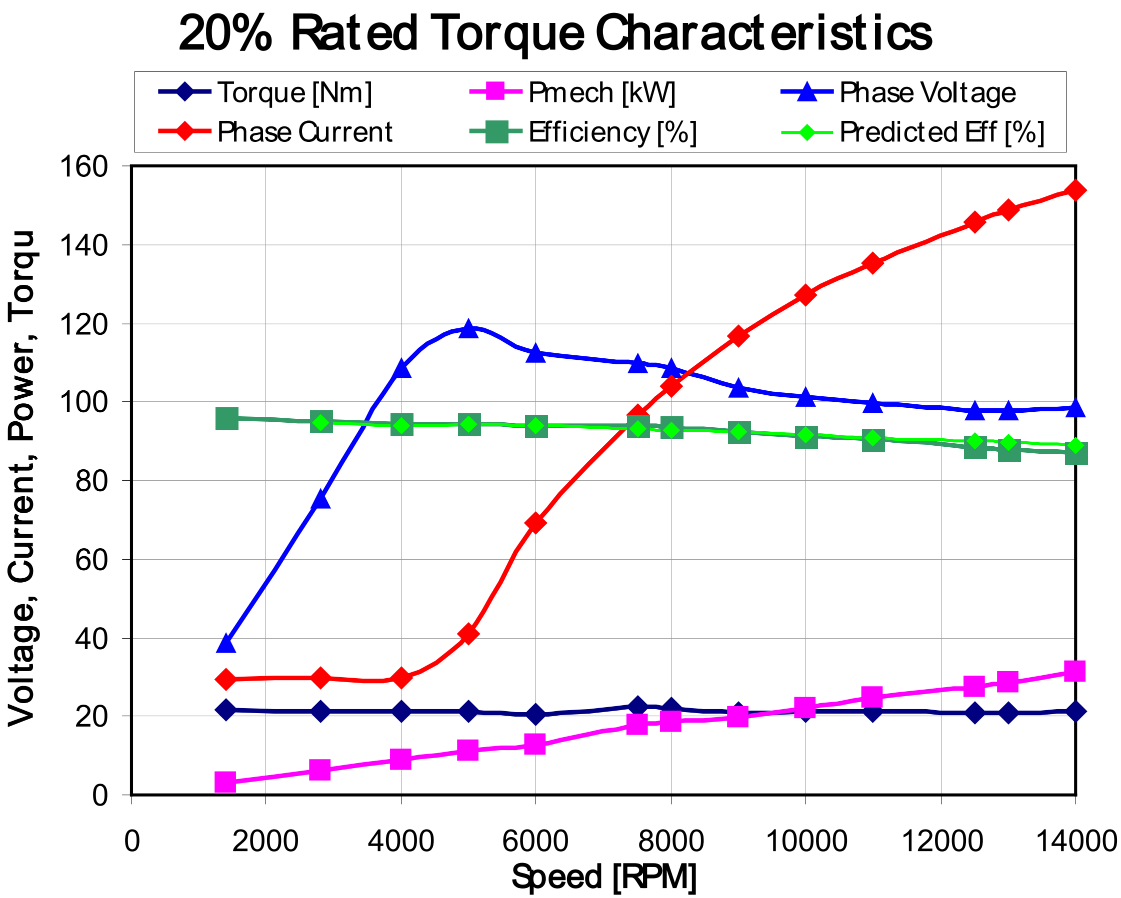
First Proof-of-Principle Machine



- Measurements match predictions very closely
- Machine meets and exceeds both peak and steady state power requirements
- Machine meets 95% efficiency target up to 9000 rpm. Efficiency progressively drops to ~89% at 14000 rpm (significantly better than the state of the art)
- Machine meets 105ºC coolant inlet temperature up to 7500 rpm. More work needed at higher speeds

imagination at work

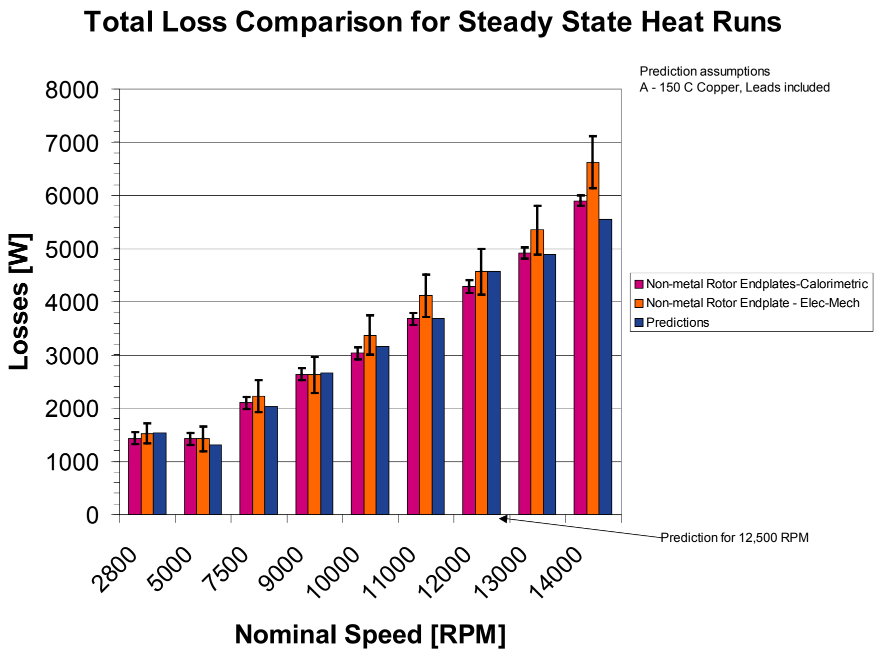
First Proof-of-Principle Machine

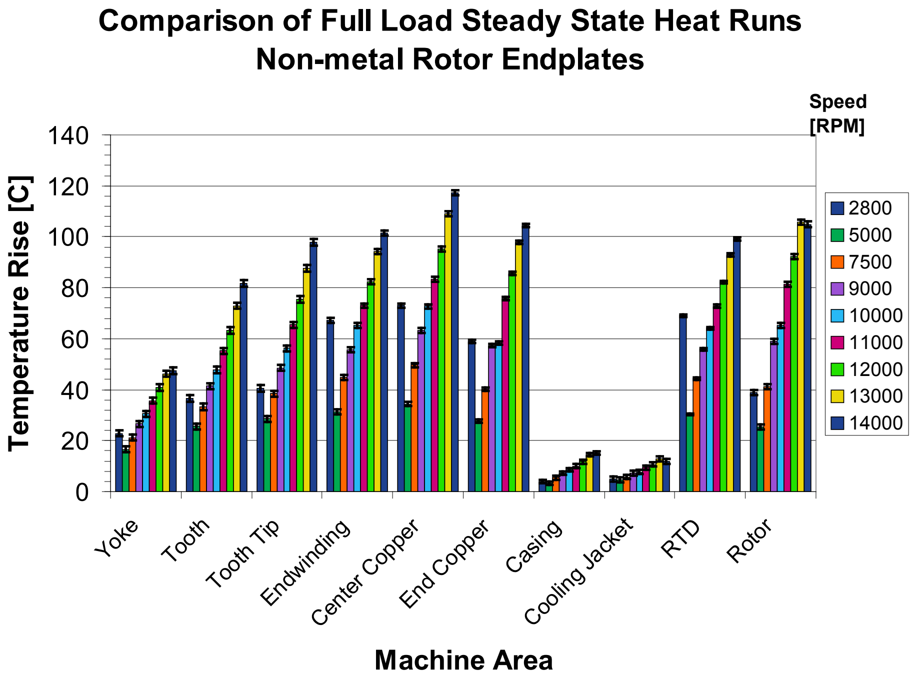


- Measurements match predictions very closely
- 20% rated torque efficiency ranges between 96% at 10% of the max speed to 89% at 100% of max speed

imagination at work

Thermal Summary





•Calorimetric based loss measurements (temp. and flow rate measurement) and electrical input/mechanical output based loss measurements have reasonable agreement.

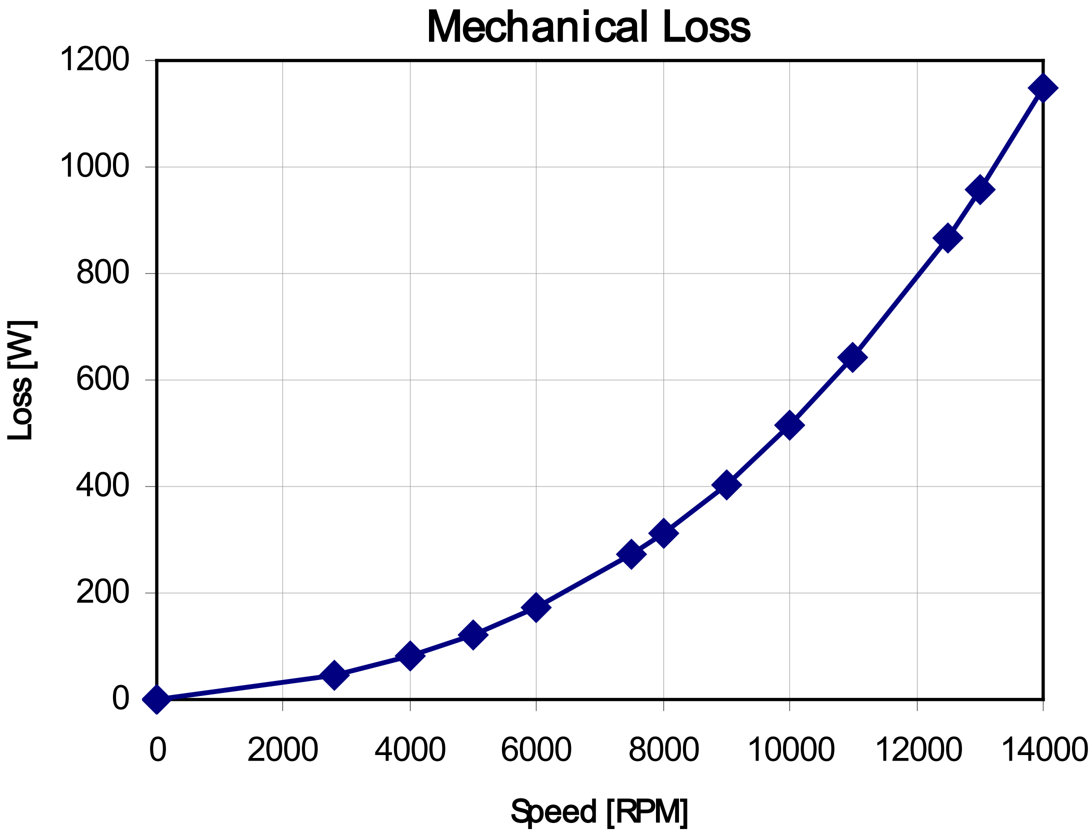
•Measurements match predictions. Within measurement uncertainty except for the highest speed

•Temperature rise behavior in the various machine locations are reasonably as expected.

•However, the thermal resistance between the cooling jacket and stator is higher than expected. 2nd machine attempts to improve thermal conductance in this area

imagination at work

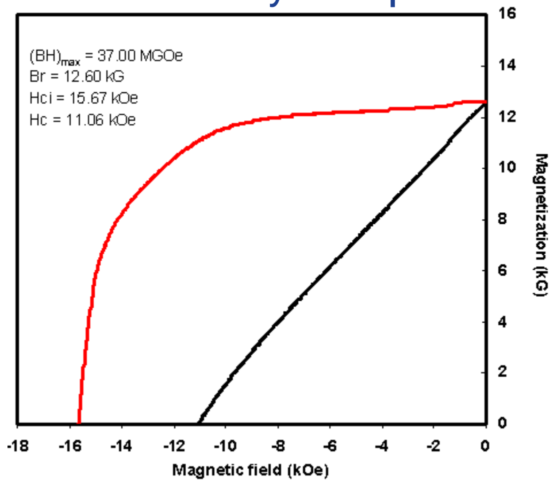
Second Proof-of-Principle Machine



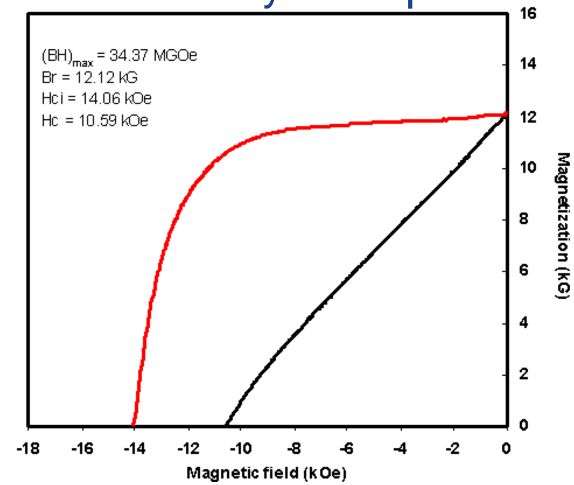
- Machine first tested with unmagnetized magnets to separate mechanical losses
- Based on the test results, more modifications are planned to reduce mechanical losses at 14000 rpm by ~35%
- Machine is currently being tested without magnets
- The third round of testing will be with magnetized magnets

High Resistivity Permanent magnets

Baseline NdFeB Magnet
•Energy product: 37 MGOe
•Effective Resistivity: 140 μΩ-cm



Composite NdFeB Magnet
•Energy product: 34 MGOe
•Effective Resistivity: >450 μΩ-cm



Phase I Conclusions

• Demonstrated sintered NdFeB composite permanent magnet with effective resistivity 3X baseline NdFeB and 5-10 % reduction in energy product (effectively the same reduction as in the case of axially-segmented magnets)

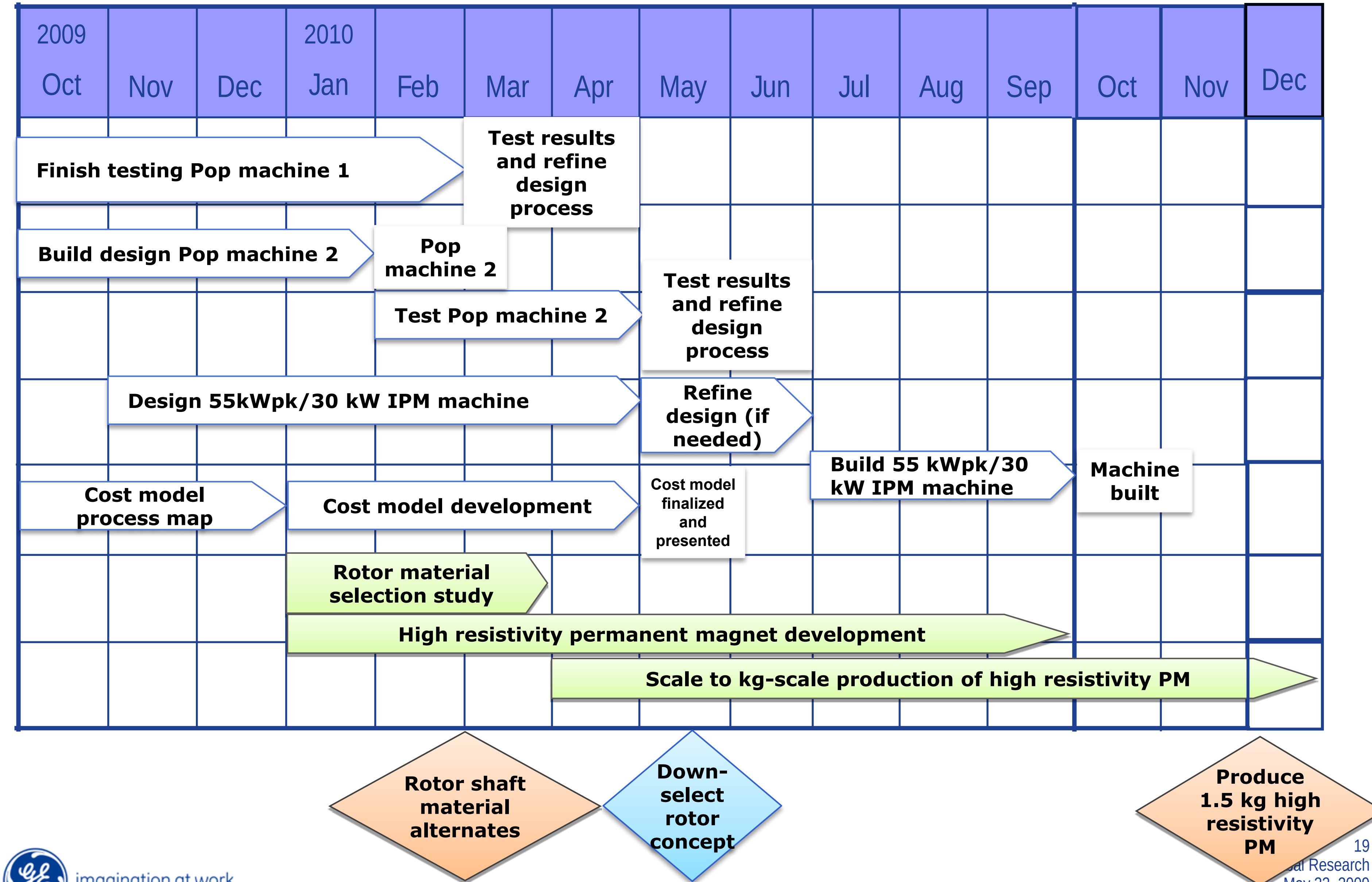
Phase II plans

• Improve reproducibility of composite microstructure and resistivity
• Scale production process to be capable of supporting prototype motor (>1 kg)
• Demonstrate cost advantage relative to conventional materials (bonded, segmented)

Collaboration with Other Institutions

- University of Wisconsin-Madison: Collaboration on developing design tools, exploring the design space, designing the second proof-of-principle machine
- McCleer Power (Industry): Collaboration on building prototypes and developing manufacturing processes
- University of Dayton: Collaboration on high-resistivity material development
- Electron Energy Corporation (Industry): Collaboration on high-resistivity magnet scale-up

High-performance, low-cost IPM timeline



imagination at work

Future Work for FY10

- Finish testing the second proof-of-principle machine
- Finalize the cost model
- Finalize the design and build the final 30kW/55kWpk machine
- Initiate the testing of the final 30kW/55kWpk machine
- High resistivity permanent magnet
  - -Produce and characterize insulating and magnet material powders
  - -Determine optimum sintering process conditions
  - -Scale to kg-scale production at vendor

High-performance, low-cost IPM - beyond FY10

FY11

- Design and build scaled-up IPM > 65/120kW
- Receive and test scaled-up IPM
- Price estimate for large-scale IPM motor production

Summary

- Significant progress made since last year

•Two advanced proof-of-principle machines were built. The first is fully tested and the second will be fully tested by end of April

•Major risks including spinning the novel rotor concept at 14000 rpm have been retired

•Test results closely match predictions. This provides confidence in design process

•Torque and power density requirements are met

•Efficiency requirements are met up to 9000 rpm. Achieved efficiency values at higher speeds exceed the state of the art.

•Alternate rotor materials identified to enhance thermal management and efficiency capabilities of the final 30kW/55kWpk machine

•Novel high resistivity materials identified and scale-up begun

•9 US patent applications filed to date

imagination at work