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

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DOE Peer Review Presentation

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New IPM Motor Concept Designs and Testing

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Grainger Professor of Power Electronics and Electrical Machines

McCleer Power

Prototype Manufacturing

Patrick McCleer
President

Overview

Timeline

Phase I:

- Start: October 2007
- Finish: June 2009
- 84% complete

Phase II:

- Start: July 2009
- Finish: June 2011

Budget

Phase I:

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

Phase II:

- $ 3.37M total budget
- $ 1.685M DOE share
- $ 1.685M GE cost share

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 Motors
- McCleer Power
- University of Wisconsin-Madison

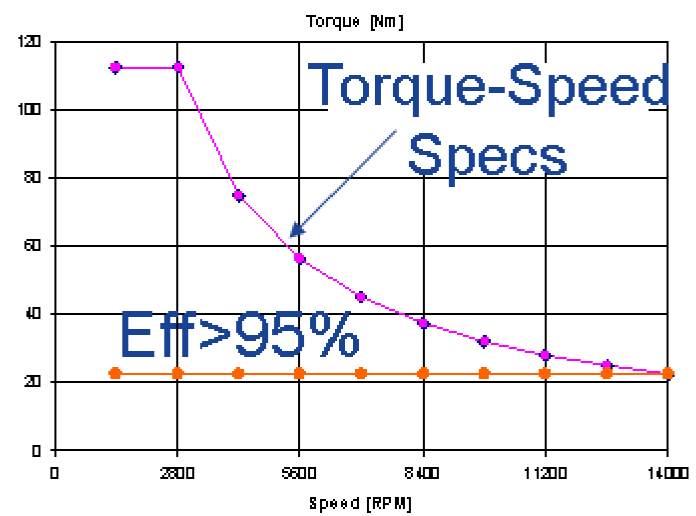
Purpose of work FY'08/FY'09

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

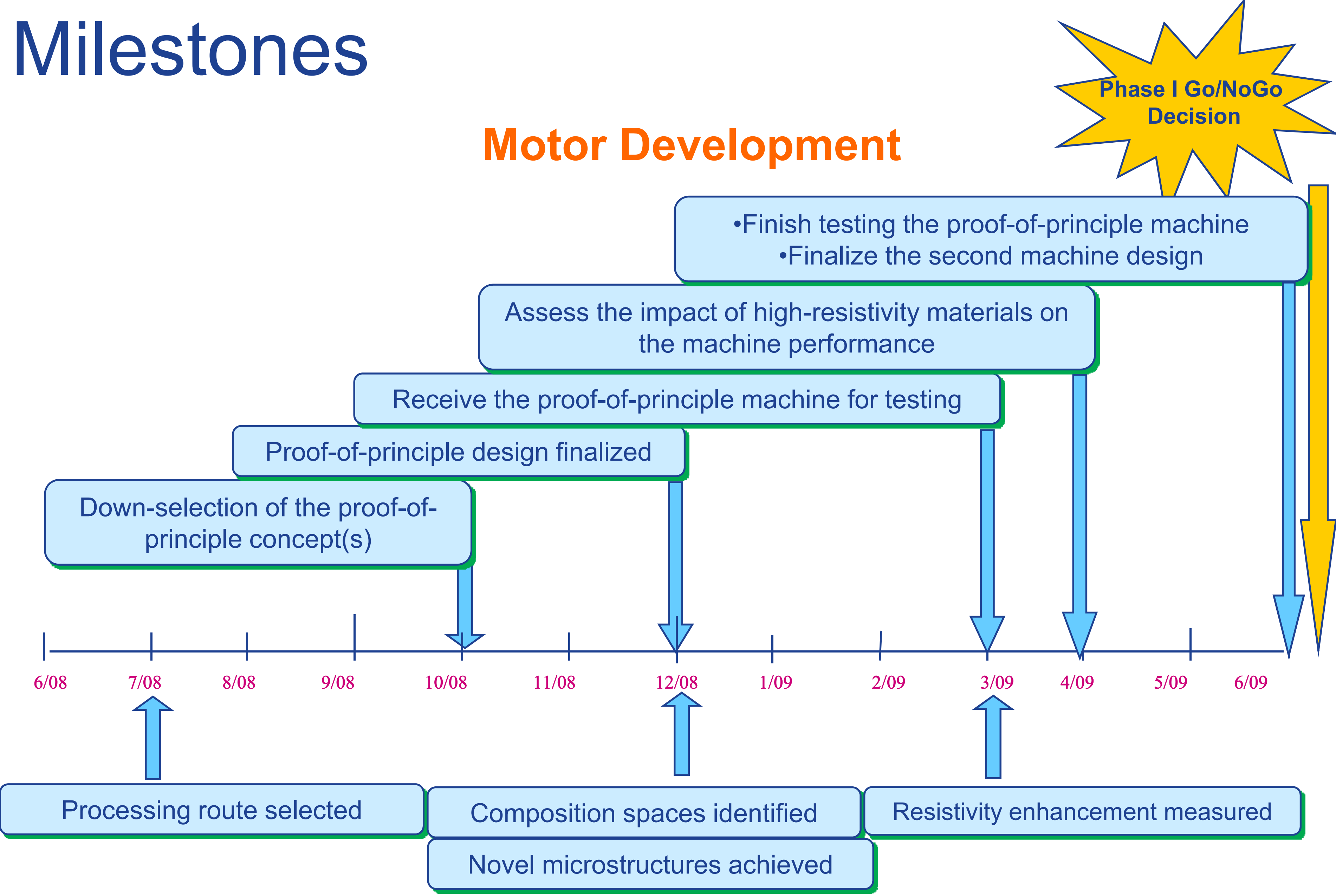
Very challenging set of specs



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 a proof-of-principle machine to verify the various developed concepts
- Build a 30kW/55kWpk machine that meets the specs
- Novel soft magnetic material with 3X resistivity enhancement
- Novel permanent magnet with 3X resistivity enhancement

Milestones



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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

•Enhancing magnetic material resistivity while maintaining balance of properties is key challenge – requires novel microstructures and processing

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.

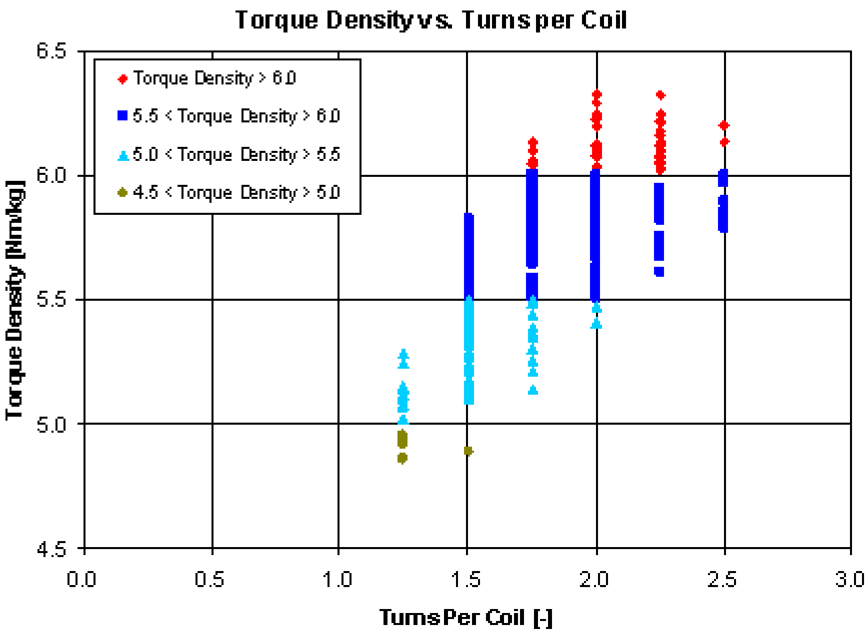
•Advanced scalable thermal management schemes for both the stator and the rotor to meet the required set of specifications.

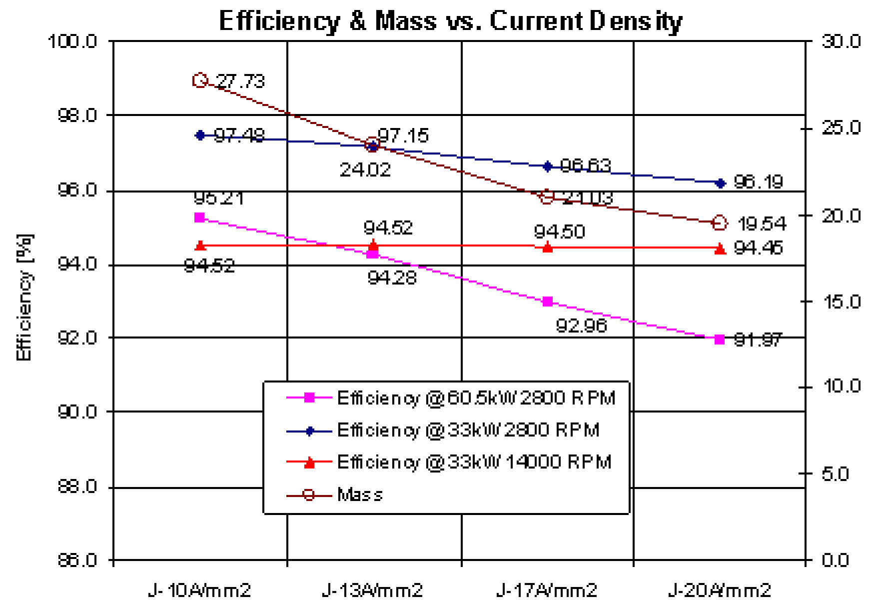
•To address high efficiency requirements, GE will engineer high-resistivity nanostructured magnetic materials.

•Novel high resistivity amorphous alloy compositions in composite microstructures will achieve resistivity enhancements while maintaining acceptable balance of properties

•Novel permanent magnet microstructure will enhance effective resistivity

Thorough Investigation of Design Space





- Design space thoroughly investigated using Design of Experiments
- Sensitivity analysis of the key parameters has been performed
- Good understanding of the tradeoffs and limitations of the various concepts is well developed

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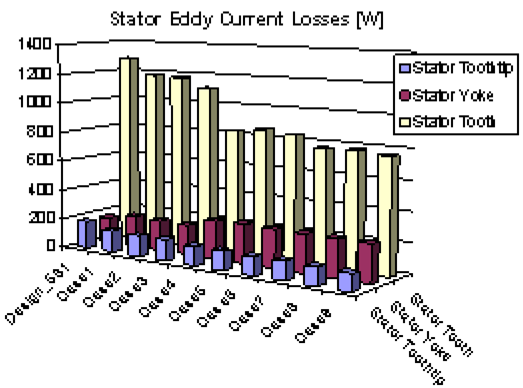
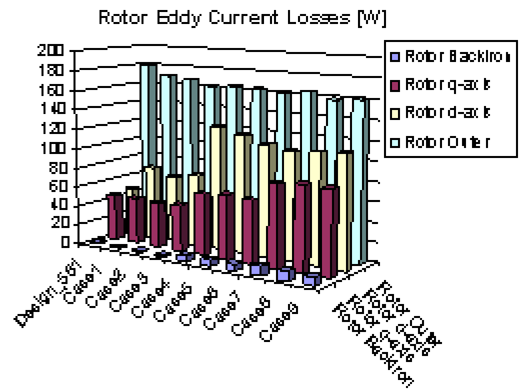
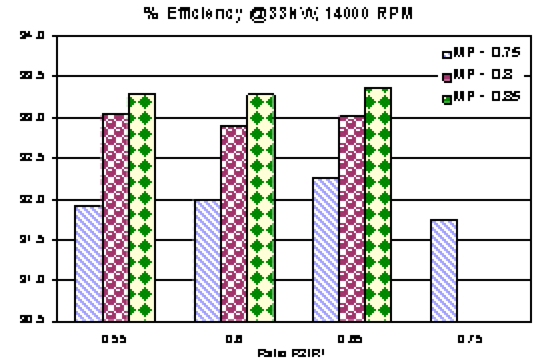
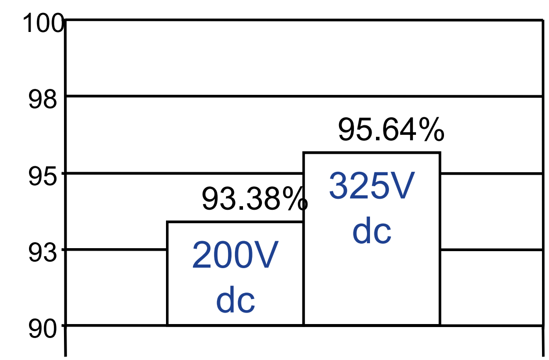
Loss Minimization

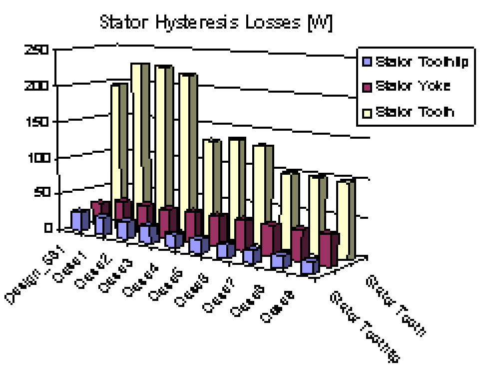


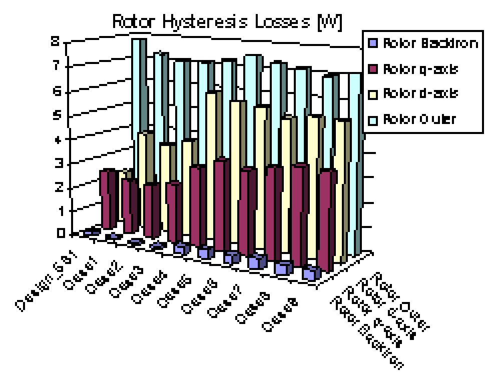




Efficiency Comparison @ 33kW, 14000 RPM



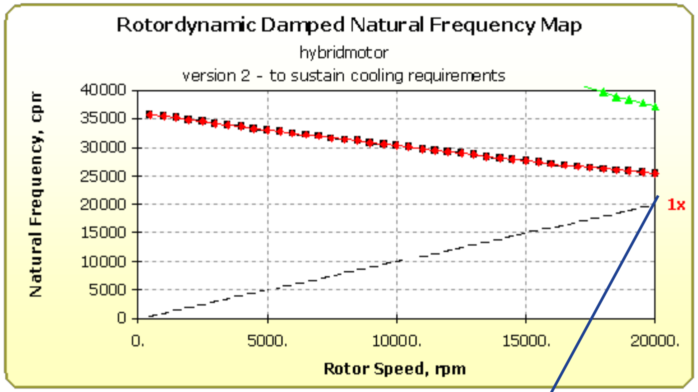


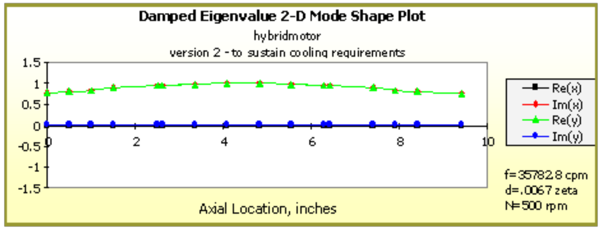


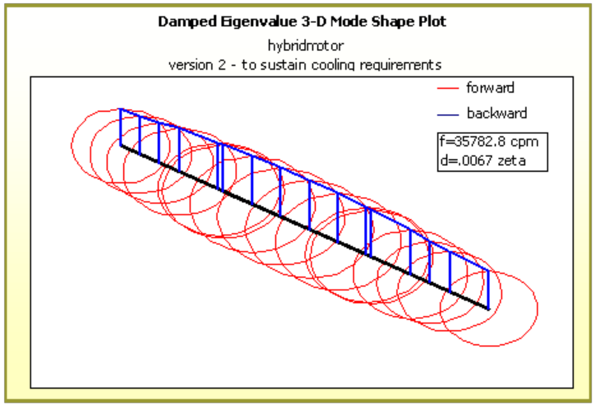
At nominal 325Vdc, meet 95% efficiency

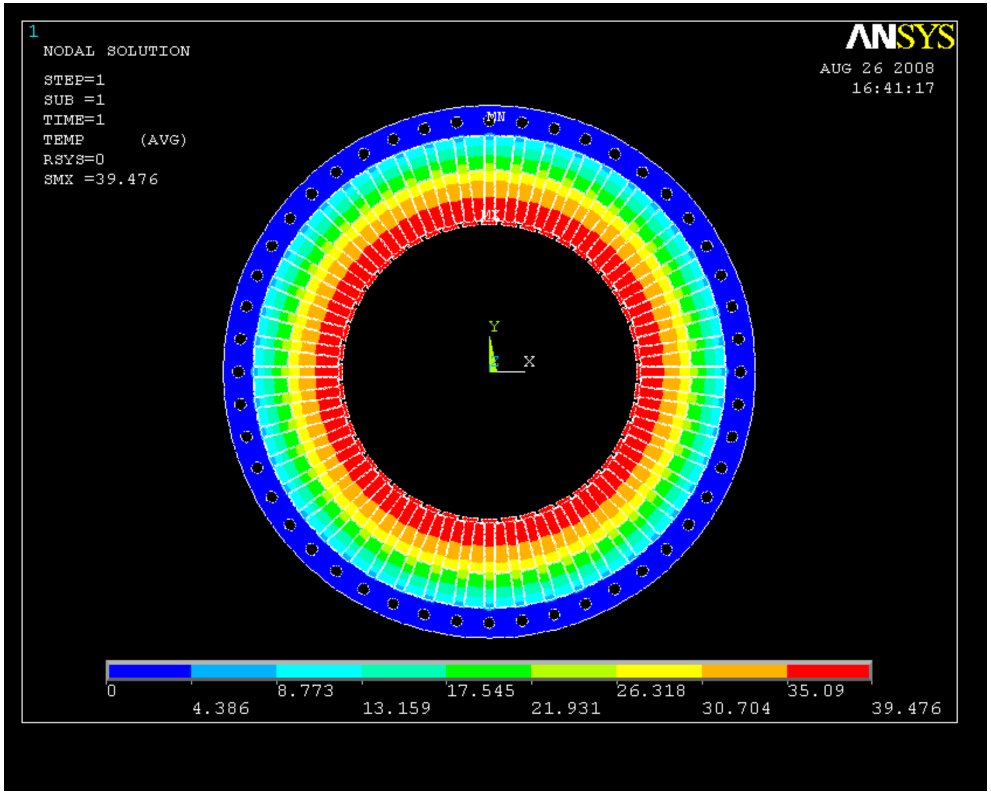
- A lot of effort went into loss minimization to meet efficiency targets

Mechanical and Thermal Analysis









- Complete thermal analysis for the various concepts performed (both transient and steady state)
- Complete mechanical analysis of the various concepts performed (including stress, life, and rotor dynamic analysis)

Accomplishments

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 concept selected for proof-of-principle motor build. Machine will be ready for testing by end of March 09.

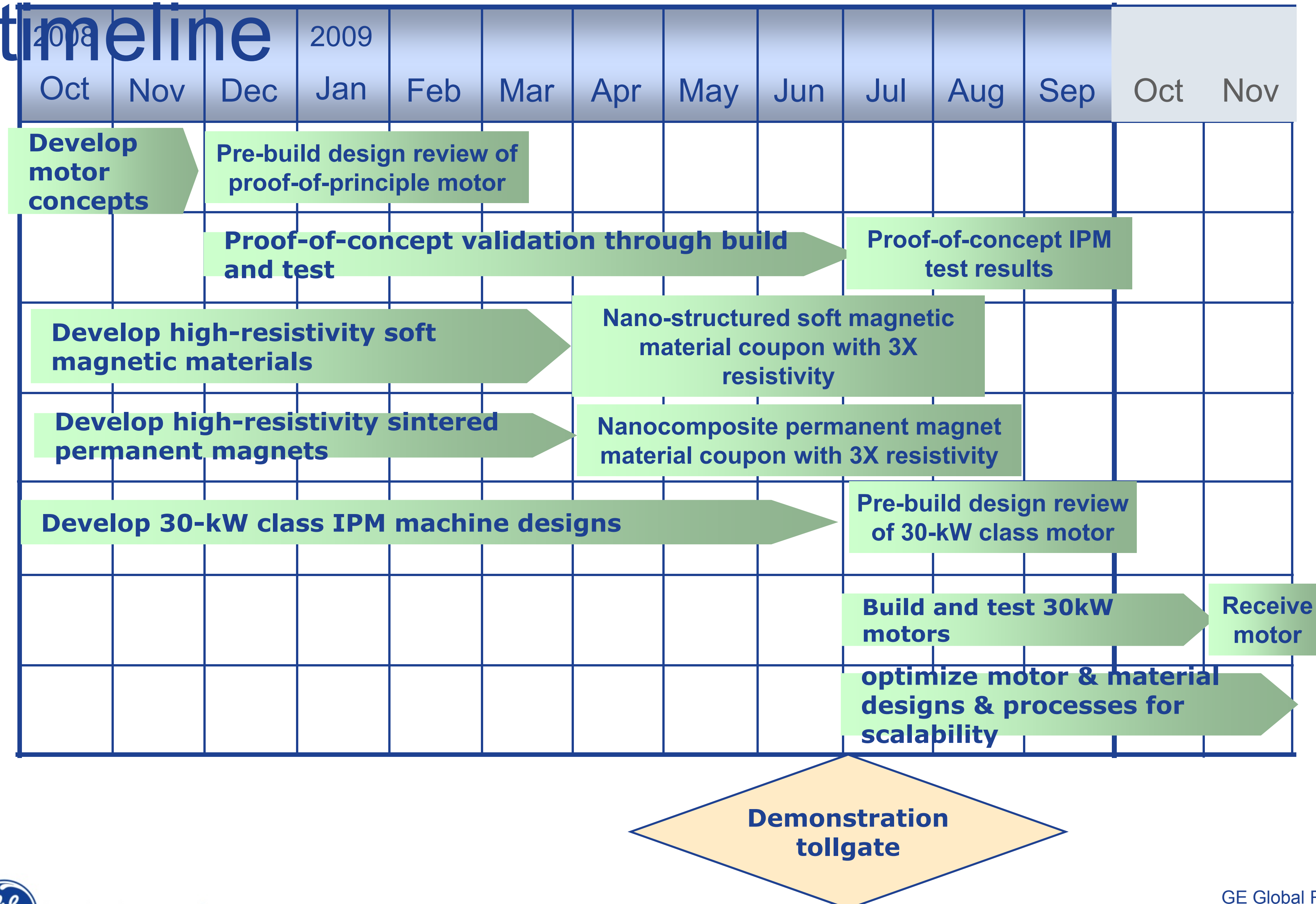
Low-loss soft magnetic materials

- Bulk amorphous alloy composition identified & kg-scale production by gas atomization
- Novel microstructure developed to enhance resistivity and magnetic properties
- Composite soft magnetic material with 2X resistivity enhancement demonstrated

Low-loss permanent magnet materials

- Hydrogen-based route for processing NdFeB PM materials
- Demonstrated novel composite microstructure to minimize eddy current losses
- Permanent magnet microstructure with 3-4X resistivity enhancement demonstrated

High-performance, low-cost IPM timeline



High-Performance, Low-Cost IPM Technical Approach for FY09 – Feasibility Phase

Build and test proof-of-principle IPM motor

- ✓ incorporate key rotor and stator concepts
- ✓ partly optimized design, to meet power and weight requirement
- ✓ receive motor end of 3/09
- ✓ feed results back to design cycle: performance, manufacturing experience

Develop optimized 30kW$_{avg}$/55kW$_{pk}$ IPM designs to meet specs

- ✓ utilize learning from proof-of-principle motor (1)
- ✓ evaluate material properties related to test results from (3) & (4)

Design, synthesize and test high-resistivity soft magnetic material

- ✓ Produce and characterize sample of soft magnetic material with enhanced resistivity by bulk amorphous alloy powder consolidation
- ✓ Understand sensitivity of magnetic properties to resistivity enhancement

Design, synthesize and test high-resistivity permanent-magnet material

- ✓ Produce sample of sintered permanent magnet with microstructure to yield high effective resistivity (more iterations)

High-Performance, Low-Cost IPM Technical Approach for FY09 – Development Phase

Initiate build of optimized 30kW$_{avg}$/55kW$_{pk}$ IPM designs to meet specs

- ✓ Address design review issues and release to motor builder
- ✓ Receive motor 11/09
- ✓ Vendor for scale-up of permanent magnets identified – must determine yield and address variability
- ✓ Enhance balance of magnetic properties of soft magnetic materials while retaining resistivity enhancements

Optimize IPM motor designs and advanced magnetic material processes for scalability (complete FY'10)

- ✓ Utilize learning from 30/55kW motor design
- ✓ Identify motor components for scaled-up advanced material production
- ✓ Begin initial scaled-up material production to support motor build
- ✓ Provide production cost data for motor price model

High-performance, low-cost IPM - beyond FY09

FY10

- Test 30/55kW motor(s)
- Deliver 30/55kW motor to DOE for evaluation
- Design scaled-up IPM > 65/120kW and initiate build
- Produce high-resistivity magnetic material components

FY11

- Receive and test scaled-up IPM
- Price estimate for large-scale IPM motor production

Summary

• All key deliverables of phase I are either met or are on their way to be met.

•Several advanced concepts on the machine side have been developed. These concepts provide a very promising path to ultimately meeting the very challenging set of specs

•Testing of the proof-of-principle machine will help fine-tune the design process and improve the second design to be built.

•Novel high resistivity materials identified and developed. Pathway to scale-up identified.

•More than 12 invention disclosures have been filed up-to-date.

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