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

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DOE Peer Review Presentation

Ayman EL-Refaie, Project Manager & Principal Investigator

Frank Johnson, Materials Design Leader

GE Global Research

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This presentation does not contain any proprietary, confidential or otherwise restricted information

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

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Overview

Timeline

Phase I:

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

Phase II:

- Start: July 2009
- Finish: December 2011
- 75% 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 FY10 $1.6M
•Planned Funding (DoE+GE) for FY11 $1.1M

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

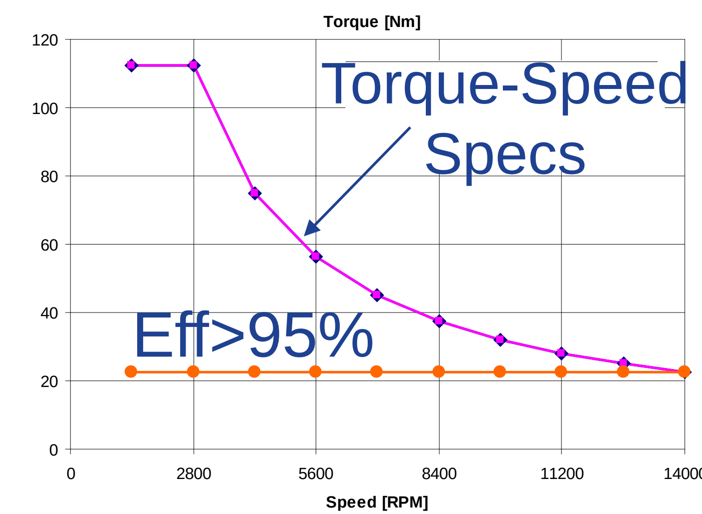
Purpose of work FY'10/FY'11

Design 55kWpk IPM motor to meet DOE specification and show scalability

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

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
•Show scalability by building a 65kW/120kWpk machine
•Novel sintered permanent magnet with 3X lower eddy current loss using co-sintered insulating phase

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

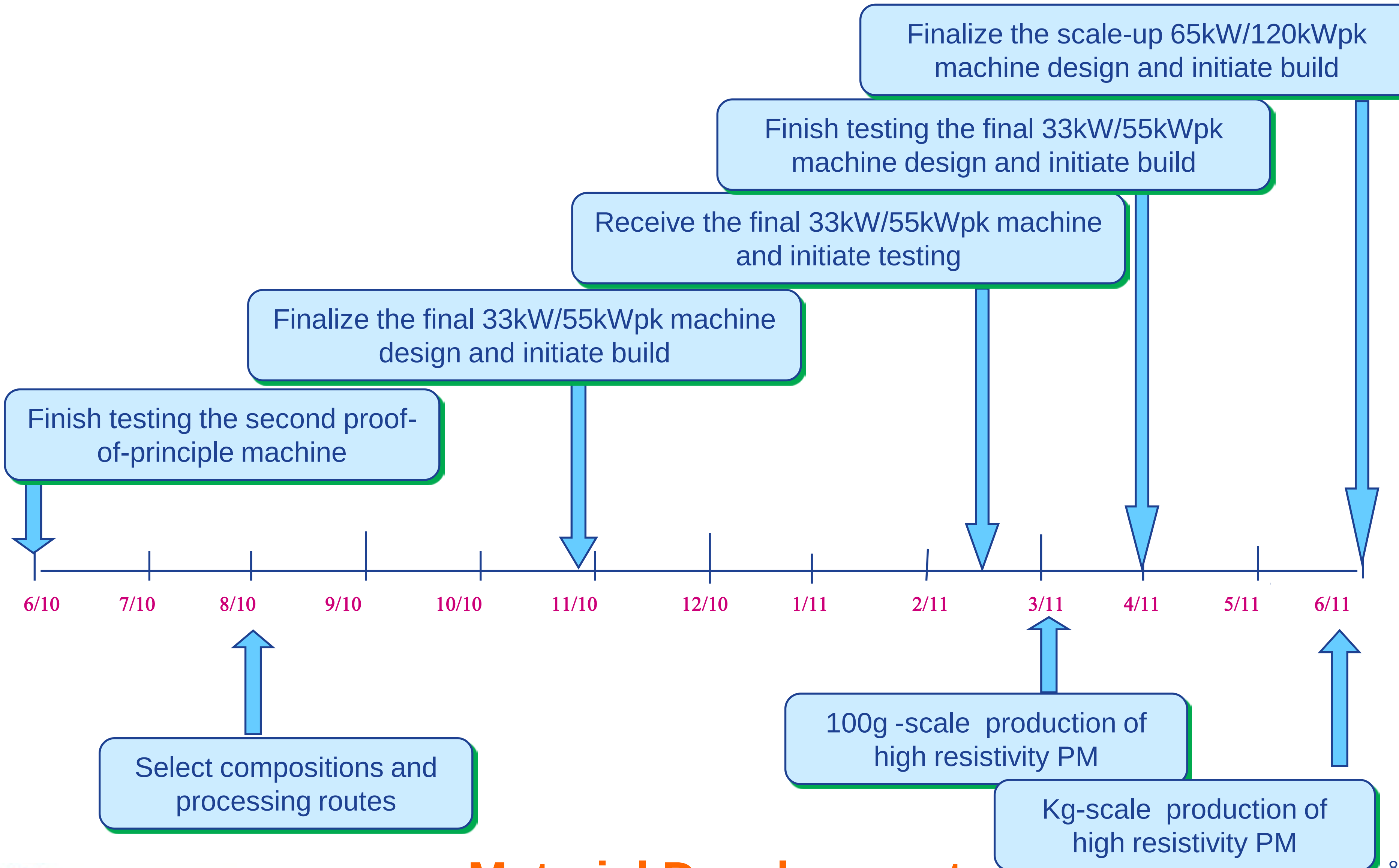
•Design rotor for mechanical integrity at high speed

•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

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 insulating and magnet phase sintering parameters
  - Measure and verify resistivity and magnet stability

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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 and fully tested
- Third and final 30kW/55kWpk machine built and testing initiated
- Development of cost model is almost finalized (fine tuning is still needed)

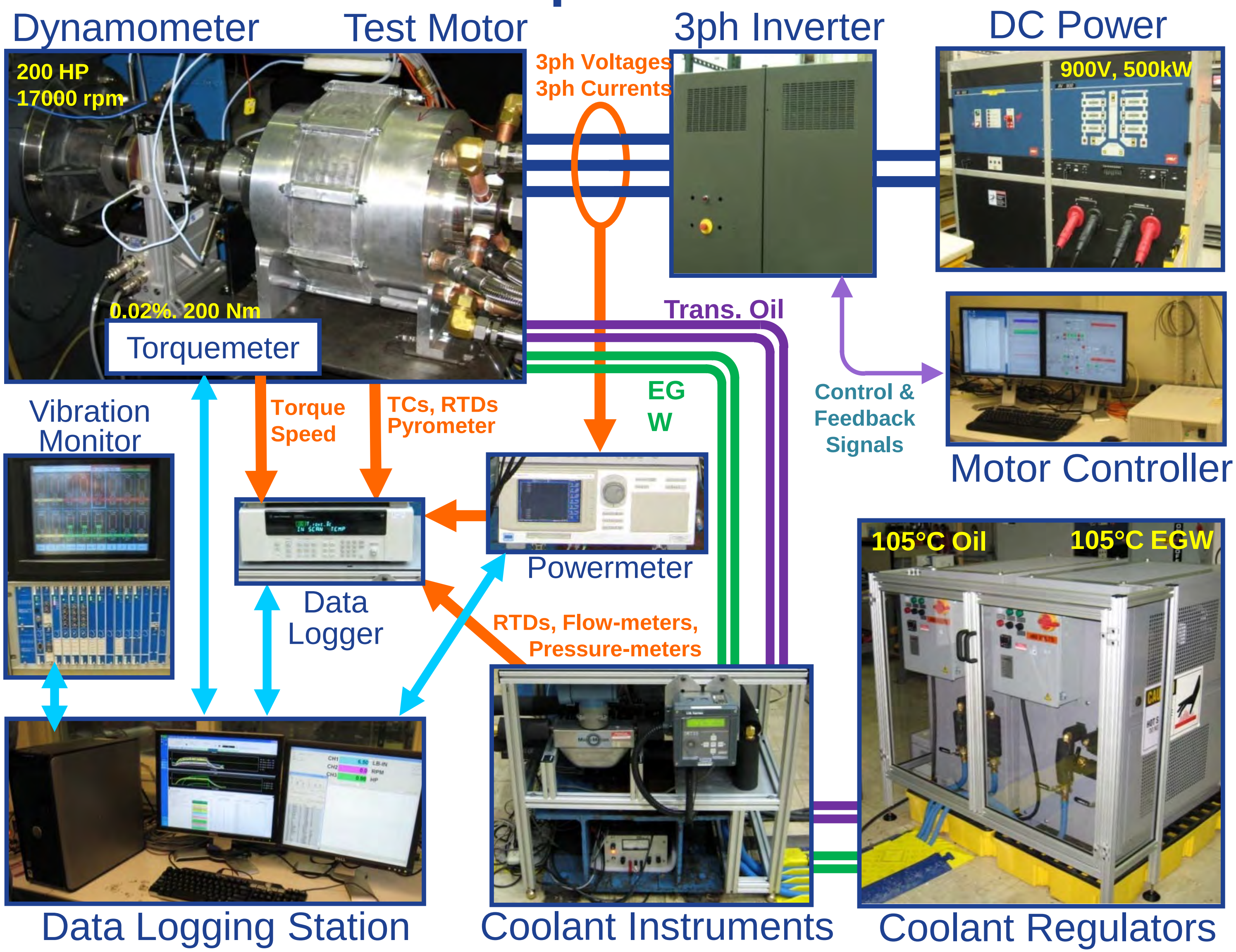
High resistivity permanent magnets

- Permanent magnet microstructure with 3-4X effective resistivity enhancement demonstrated
- Alternate set of insulating materials identified
- Subscale (≈50 gram) magnets produced at GE and vendor
- Continuing trials of kg scale-production at vendor High resistivity permanent magnets

Patents and publications

- **12 US patent applications have been filed up-to-date with few others pending.**

Motor Test Set Up



Setup upgraded to meet the 105°C coolant inlet temp. requirement

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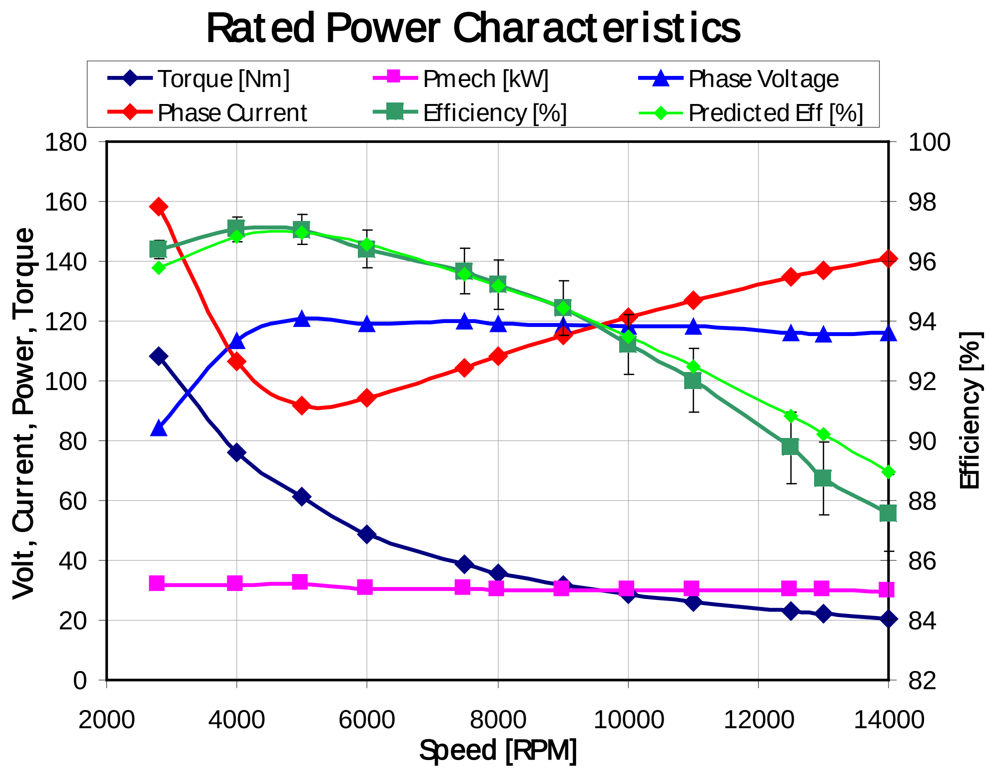
First Proof-of-Principle Machine



- 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 ~88% at 14000 rpm (significantly better than the state of the art)
- Machine meets 105ºC coolant inlet temperature up to 7500 rpm on stator side and 9000 rpm on rotor side. More work needed at higher speeds

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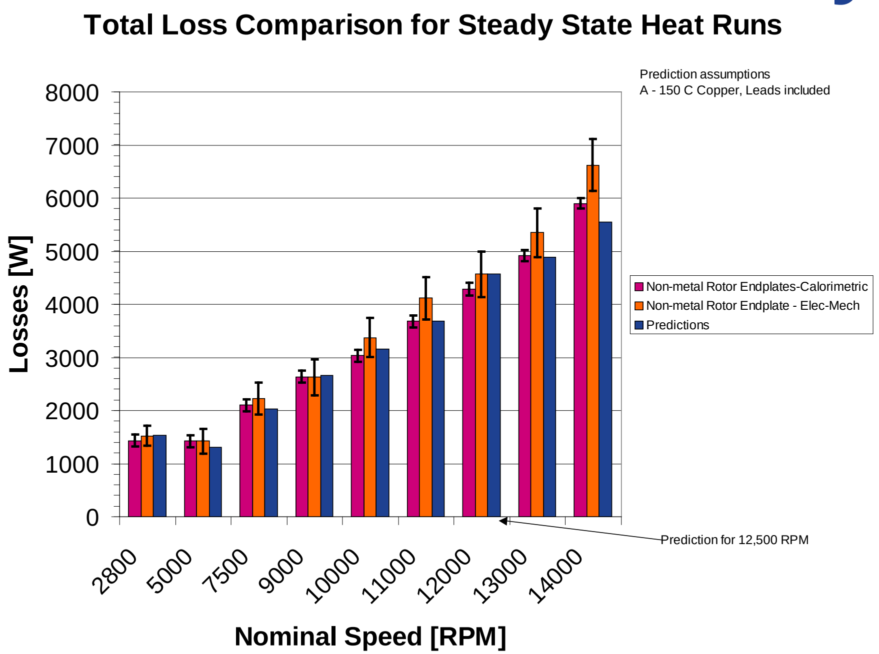
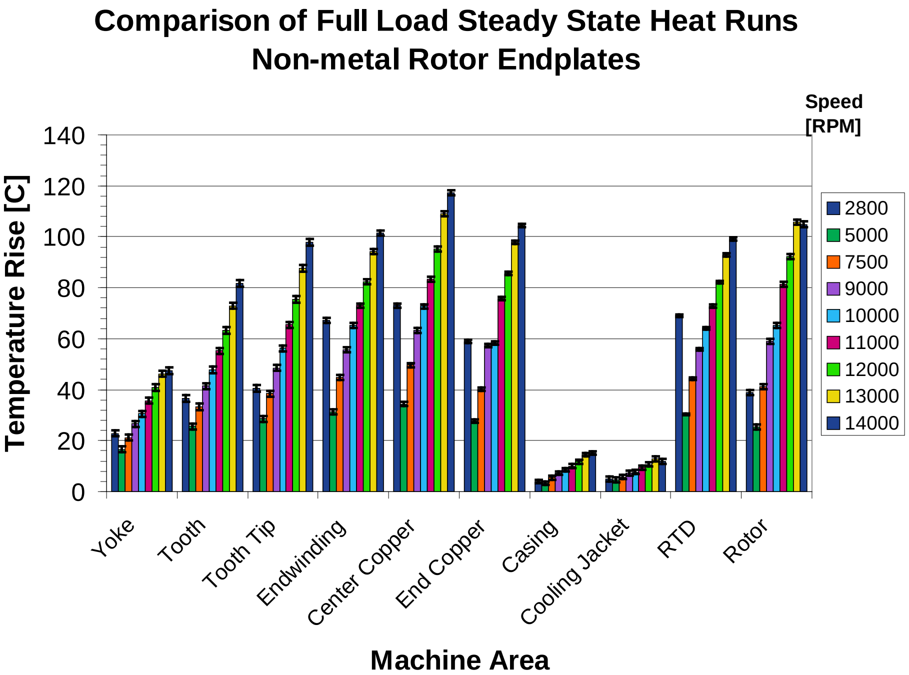
Thermal Summary





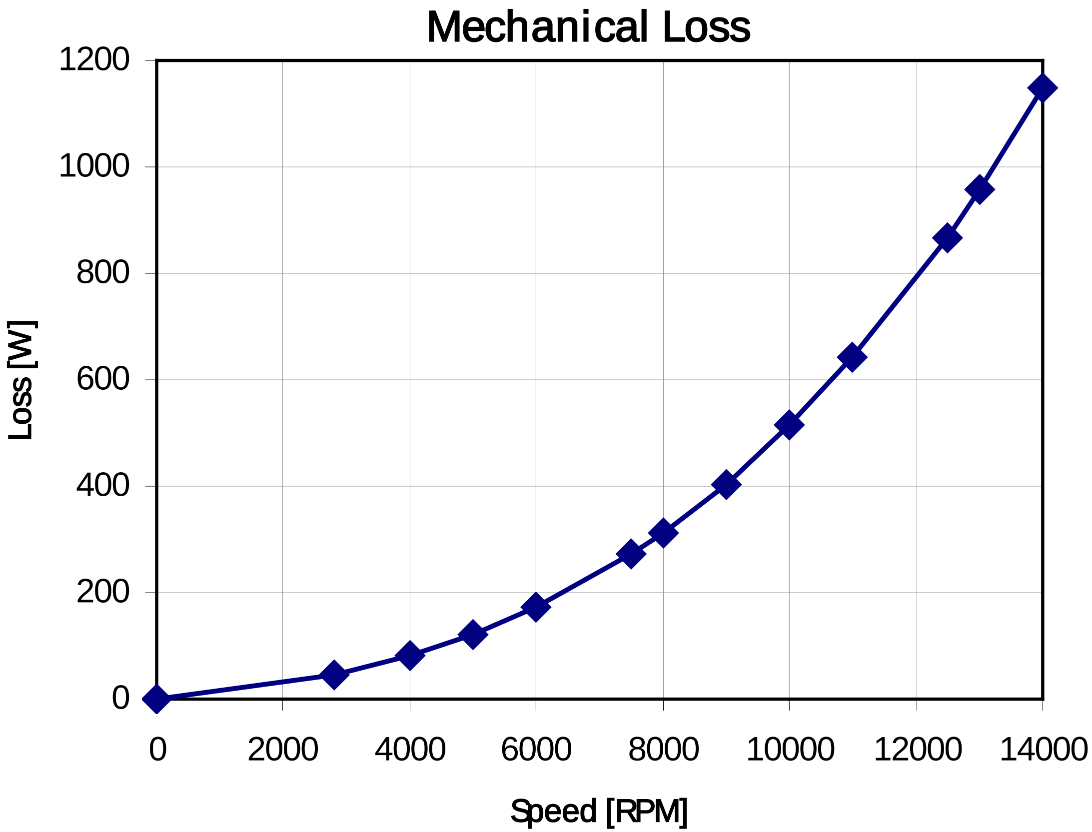
•Calorimetric based loss measurements (temp. and flow rate measurement) and electrical input/mechanical output based loss measurements have reasonable agreement.

•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

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%

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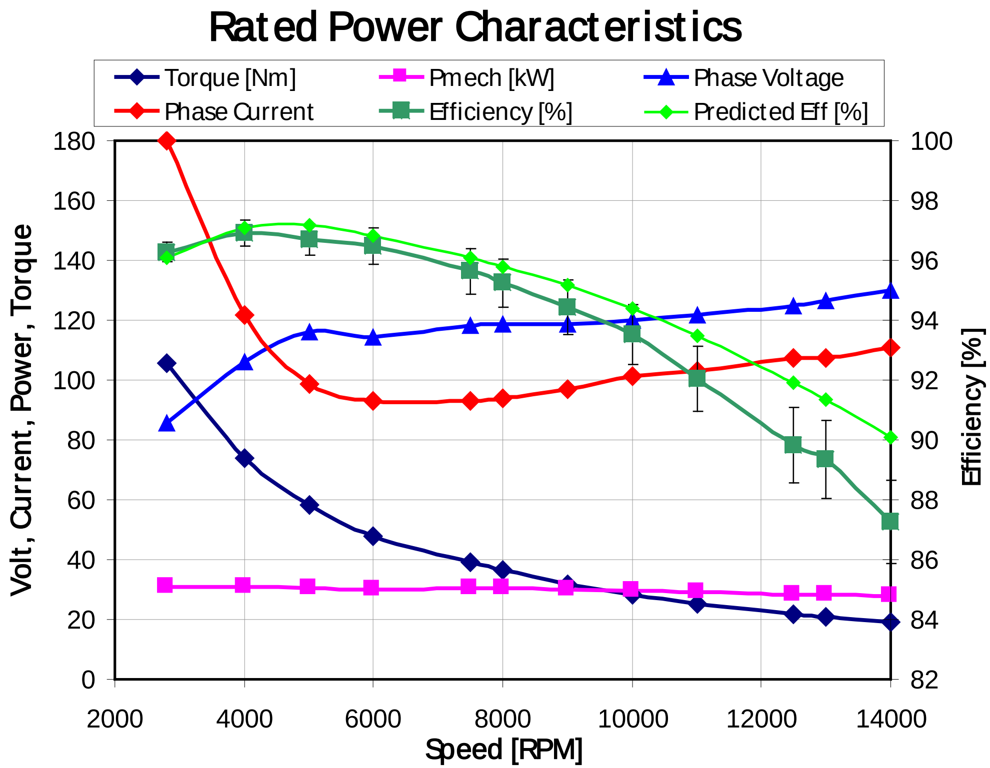
Second Proof-of-Principle Machine



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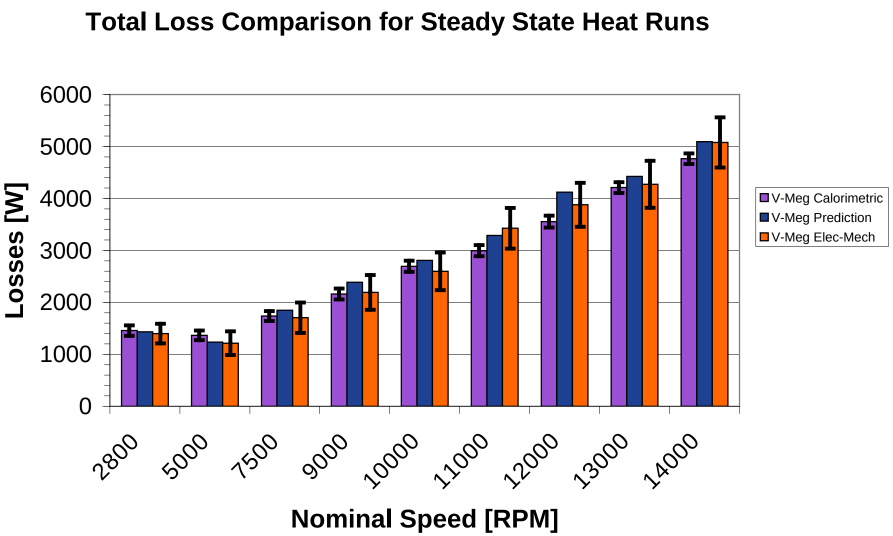
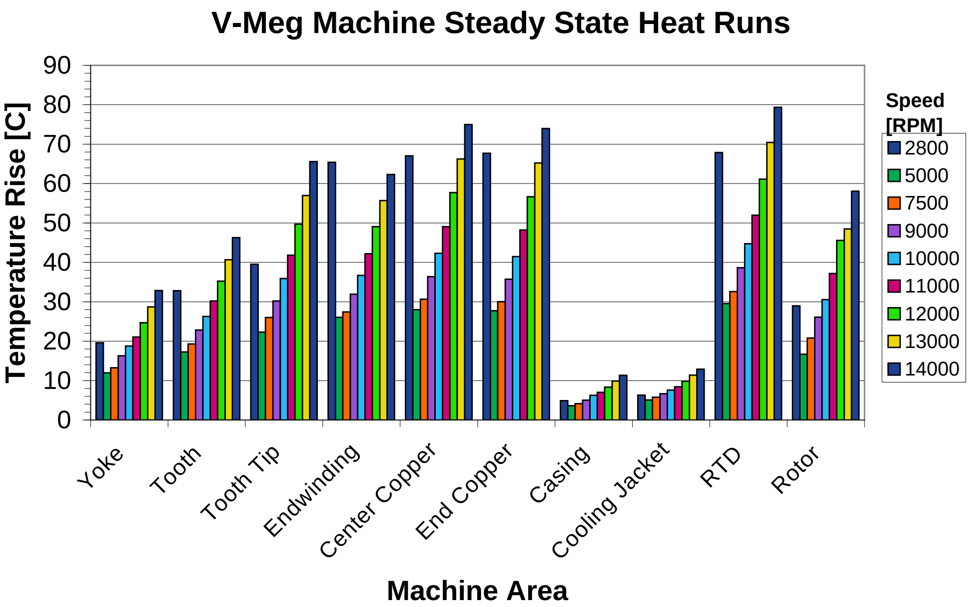




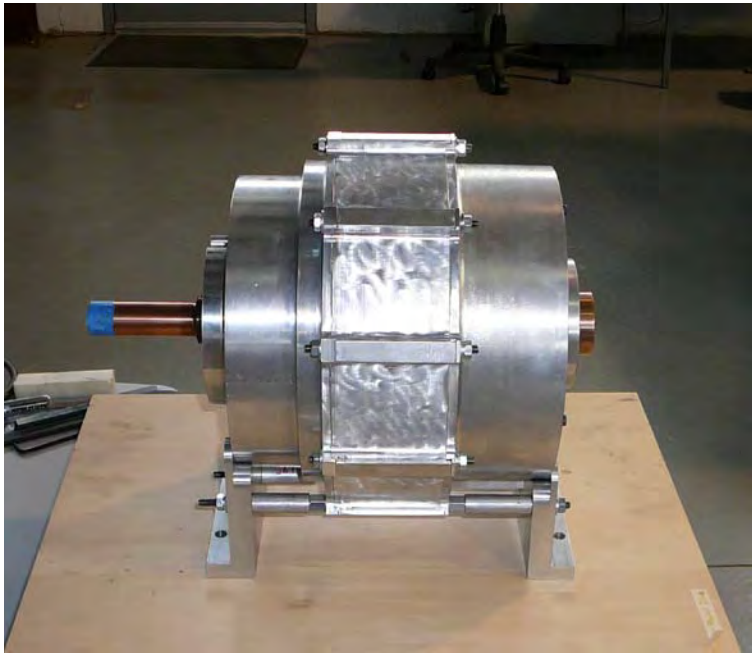
•Calorimetric based loss measurements (temp. and flow rate measurement) and electrical input/mechanical output based loss measurements have reasonable agreement.

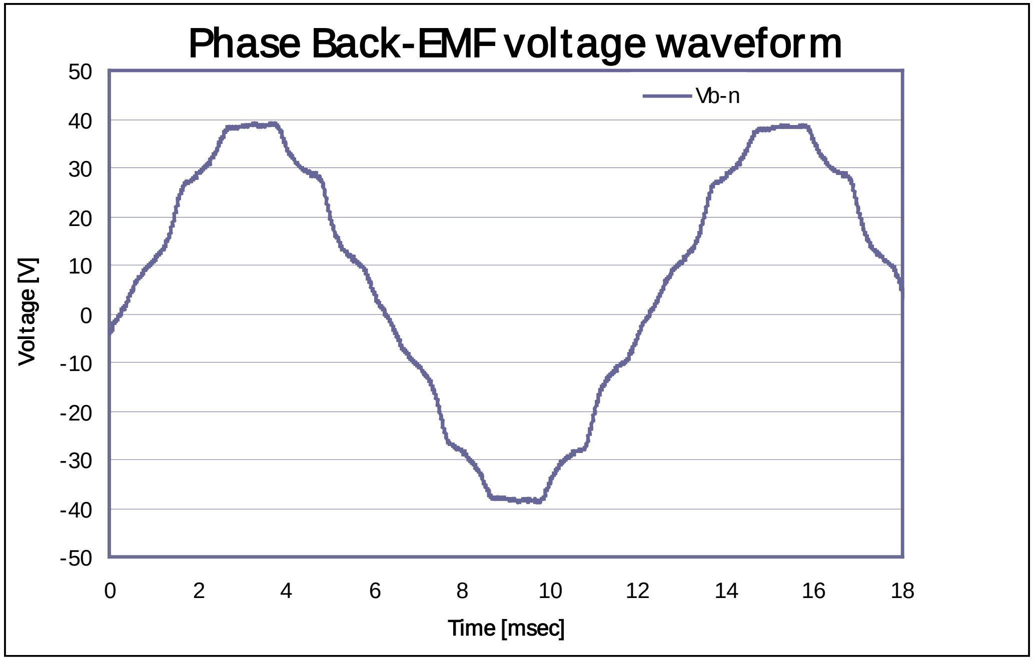
•Measurements match predictions. Within measurement uncertainty.

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

•Thermal contact between the cooling jacket and the stator improved significantly, although thermal resistance still higher than expected.

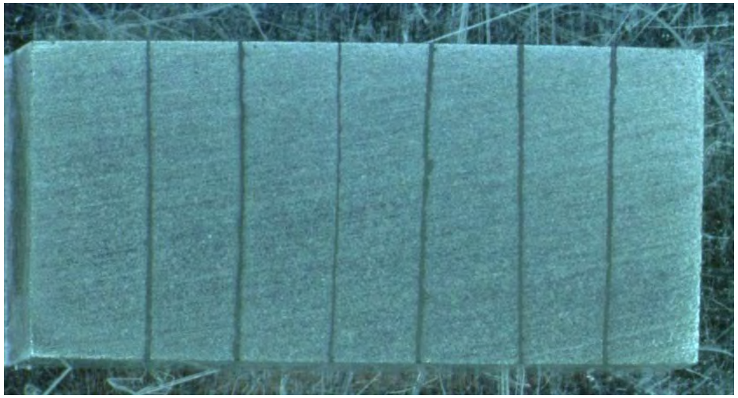
Third and Final 30kW/55kWpk Machine

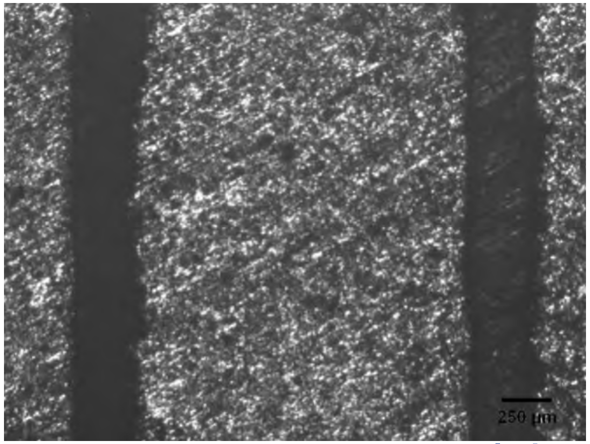




- Machine back emf at 100^{o}C and 1000 rpm closely matches predictions
- Third machine optimized to meet the 35kg mass requirement as well as the 105^{o}C coolant inlet temperatures
- Machine is currently mounted on the test setup and testing initiated

High Resistivity Permanent magnets





Insulating layer | NdFeB | Insulating layer

Phase I Conclusions

• Demonstrated sintered NdFeB multilayer 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)

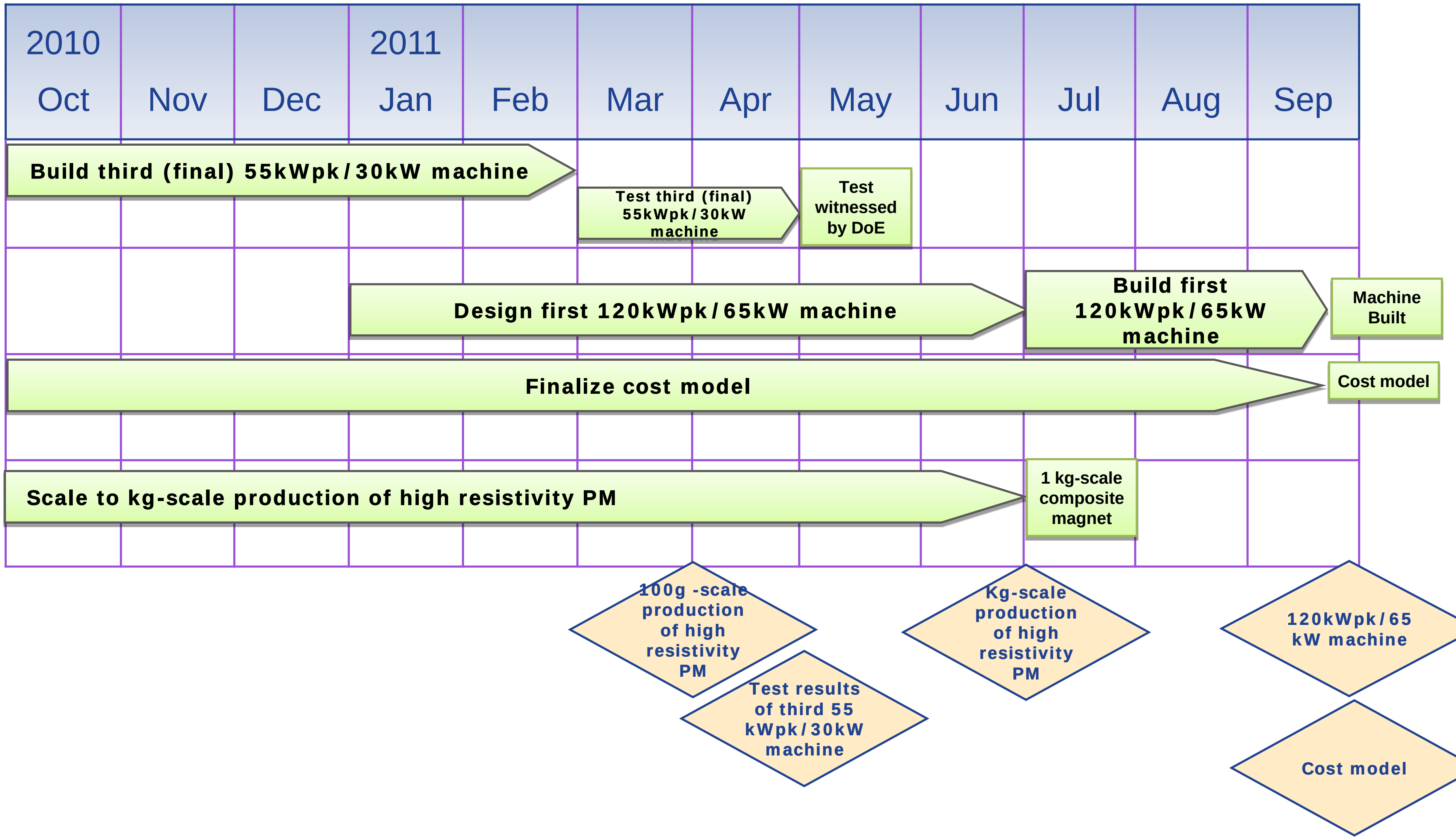
Phase II plans

• 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 FY11 timeline



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Future Work for FY11

- Finish testing of the final 55kWpk/30kW machine
- Design and build the scale-up 120kWpk/65kW machines
- High resistivity permanent magnet
  - Refine sintering process conditions
  - Scale to kg-scale production at vendor (EEC)

Beyond FY11

FY12

- Test 120 kWpk/ 65 kW machine
- Finalize cost model
- Write final report

Summary

- Significant progress made since last year
- Two advanced proof-of-principle machines were built. Both were fully tested
- 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
- Final 55kWpk/30kW machine designed and built and testing begun
- Novel high resistivity materials identified and scale-up begun
- 12 US patent applications filed to date

Comparison to Required Specifications

Requirement	Target	Units	PoP Machine1	PoP Machine2	Expected performance of Machine 3
Minimum top speed	14000	RPM	14000	14000	14000
Peak power output at 20% of maximum speed for 18 seconds and nominal voltage	55 @ 325 Vdc	kW	55	55	55
Continuous power output at 20 to 100% of maximum speed and nominal voltage	**30 @ 325 Vdc**	**kW**	30	30	30
Weight	<= 35	kg	<= 35 (22 Active)	>35 (27 Active)	<= 35 (22 Active)
Volume	<= 9.7	liters	<= 9.7	>9.7	<= 9.7
Operating voltage (Vdc)	200 to 450	Vdc	200 to 450	200 to 450	200 to 450
Nominal Operating voltage (Vdc-n)	325	Vdc	325	325	325
Maximum per phase current at motor	400	Arms	400	400	400
Characteristic current	< Max current	Arms	< Max current	< Max current	< Max current
Efficiency at 10 to 100% of maximum speed for 20% of rated torque	> 95	%	Refer to figs	Refer to figs	Similar to PoP Machines 1, and 2
Back EMF at 100% of maximum speed, peak line-line voltage	< 600	Vdc	845	673	880
Torque pulsations - not to exceed at any speed, Percent of peak torque	< 5	%	< 5	< 5	< 5
Ambient (outside housing) operating temperature	-40 to 140	Deg C	-40 to 140	-40 to 140	-40 to 140
Coolant inlet temperature	105	Deg C	Rotor up to 9000 rpm Satator up to 7500 rpm	Rotor and stator up to 9000 rpm	Meets that requirment over the entire speed range
Maximum coolant flow rate	10	liters/min	10	10	10
Maximum coolant pressure drop	2	psi	2	2	2
Maximum coolant inlet pressure	20	psi	20	20	20

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