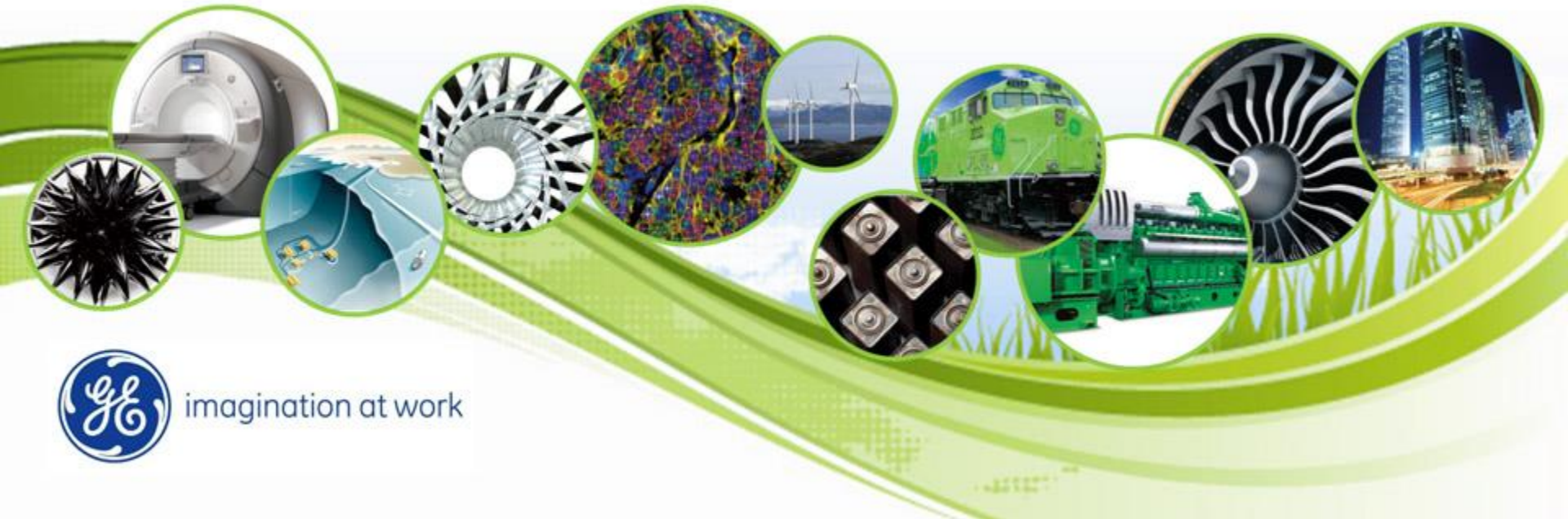
GE Electrical Machines-Enabling Technologies

NIST/DOE Workshop on Enabling Technologies for Next Generation Electric Machines

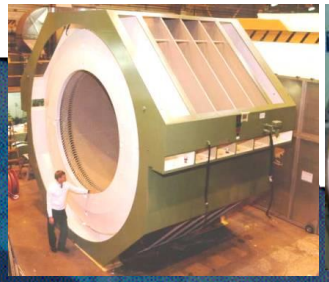
Frank Johnson
Ayman EL-Refaie
GE Global research
9/8/2015



imagination at work

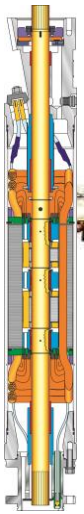
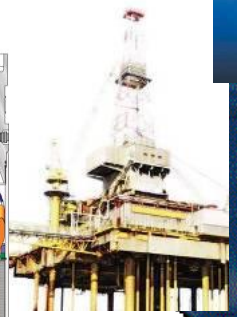
GE Electrical Machines Portfolio

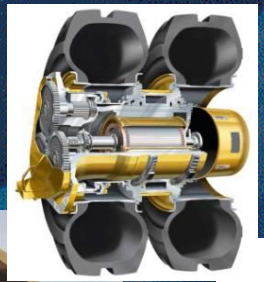


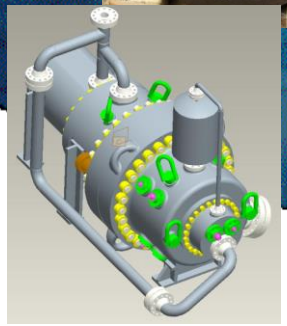
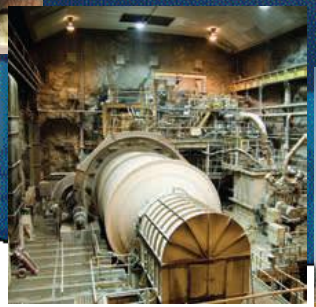








GE Businesses

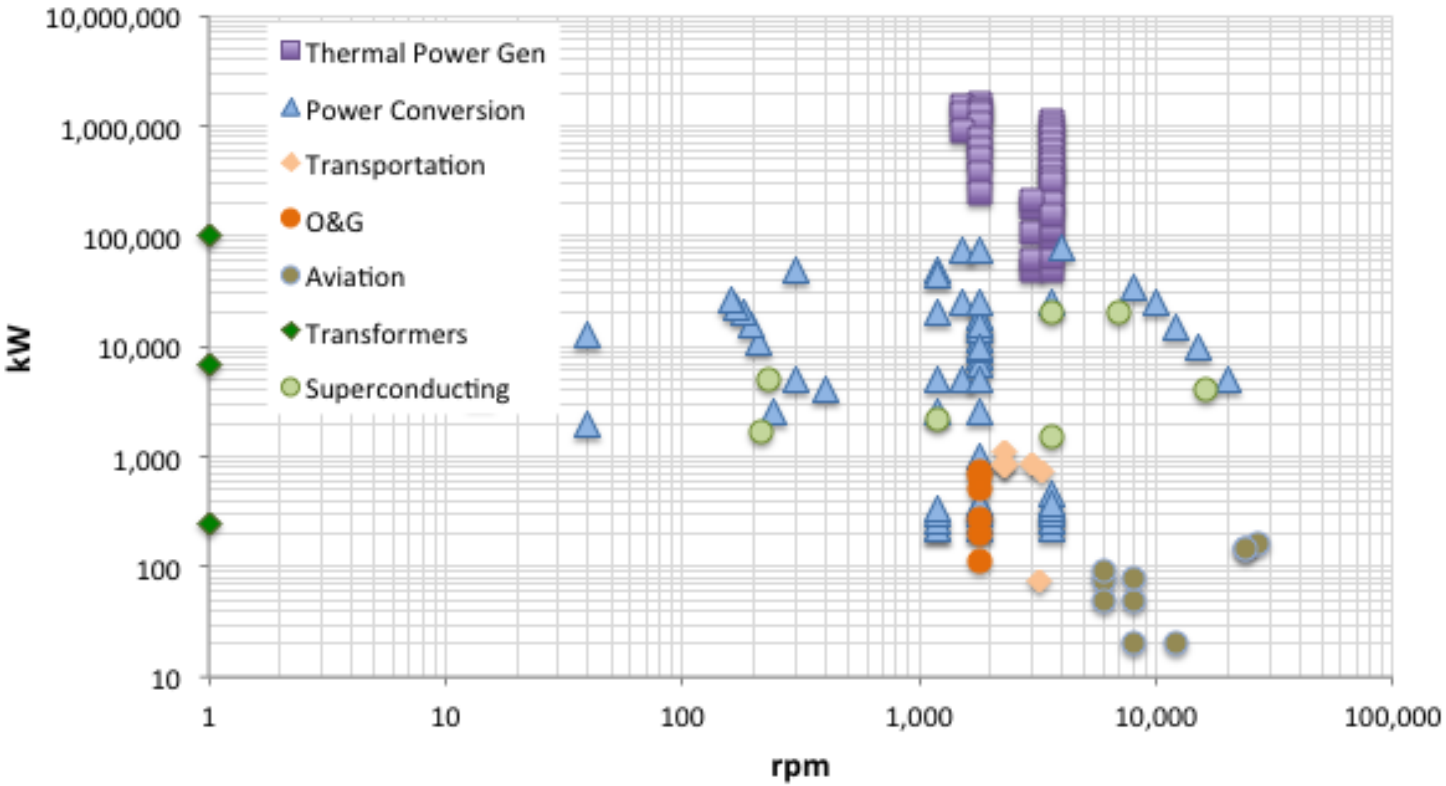
Joint Technology Development

Global Research

Technology incubation & prototyping

GE Electrical Machines Portfolio

develop ➤ design ➤ manufacture ➤ monitor ➤ service



Broad capability across infrastructure domain

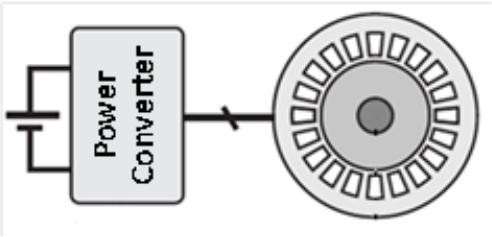
Electrical Machines Performance Entitlement Reached with Multi-Discipline Integration

Advanced Motor Controls
High speed/bandwidth, Optimal efficiency, sensorless, fault tolerant

Advanced Motor Topologies
Permanent magnet, reduced rare-earth topologies, self-sensing

Advanced Insulation Systems
High frequency/voltage, high temperature, high thermal conductivity

Advanced Power Converters
Wide-band gap devices (SiC) Integrated Motor & Drive



Advanced Magnetic Materials
Lower cost PM, high strength & dual phase soft magnetic materials

Monitoring and Diagnostics
On-line turn fault diag.
Fault tolerant operation

Advanced Manufacturing
Smart, integrated, automated manufacturing

- *Smaller system footprint*
- *Lower system cost*
- *Higher efficiency*
- *Reliability / harsh environment*

Thermal Management
Air cooling, liquid cooling, phase-change cooling

Magnetic Materials for Electrical Machines

Soft magnetic materials:

1. **Mechanical Properties**
   - Yield strength,
   - Ductility,
   - Creep and fatigue strength
2. **Magnetic and Electrical Properties**
   - Saturation magnetization
   - Coercivity
   - Electrical resistivity
3. **Thermal conductivity**

Permanent magnet materials:

1. **Magnetic and Electrical Properties**
   - Energy product
   - Temperature Stability
   - Electrical resistivity
2. **Thermal conductivity**
3. **Sustainability**
   - Rare earth content
   - Recyclability

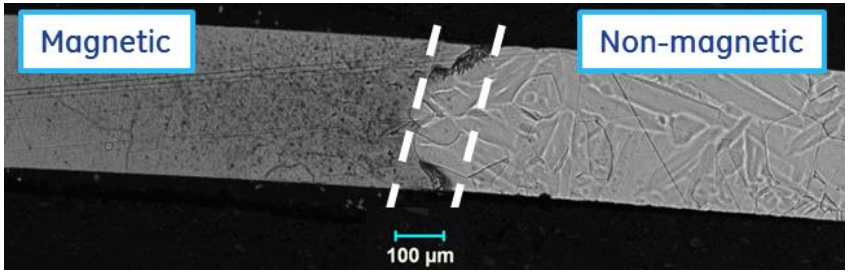
Machine Power = Speed x Thermal Utilization x Magnetic Utilization x Volume

High strength rotor

Low core loss, high thermal conductivity material

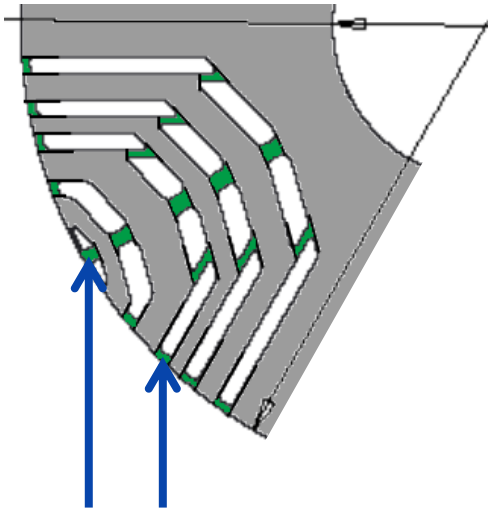
High magnetic saturation/energy product material

Dual Phase Magnetic Material

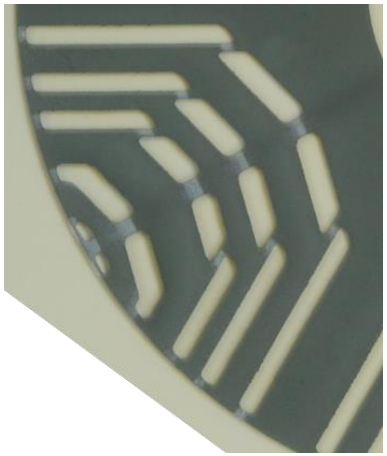


Cross section of interface between magnetic and non-magnetic regions

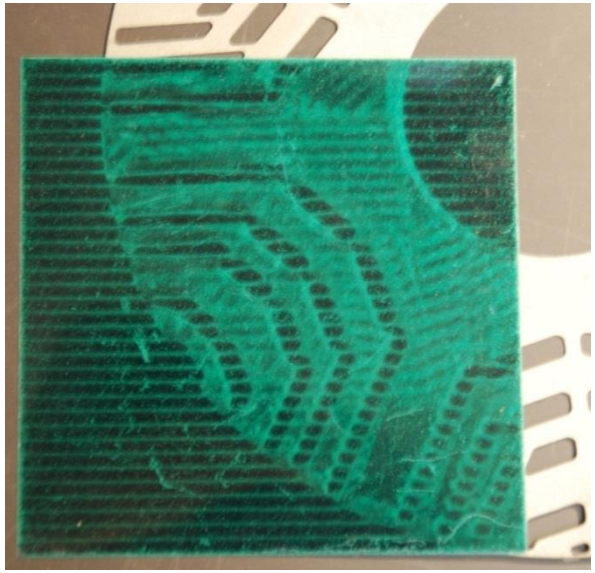
- A new alloy and process for producing motor laminations with locally patterned non-magnetic regions
- This enables improved control of magnetic flux distribution in motor laminations
- Enables Synchronous Reluctance machines to have performance on par with IPM's using NdFeB permanent magnets



Non-magnetic bridges and posts patterned into magnetic laminate

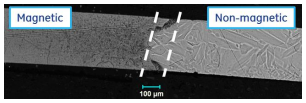


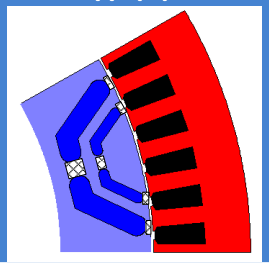
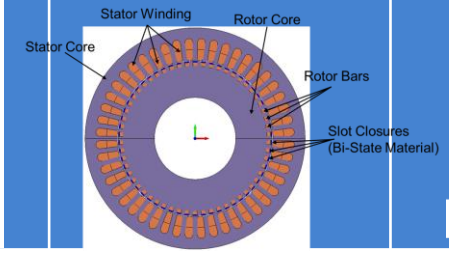
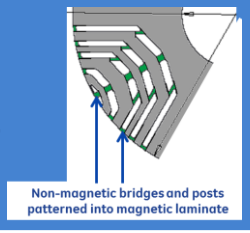
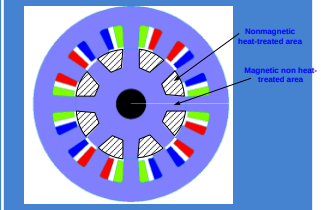
Masked laminate with un-masked bridges and posts ready for nitriding



Nitrided and cleaned laminate. Stripe domain pattern shows through non-magnetic bridges and posts

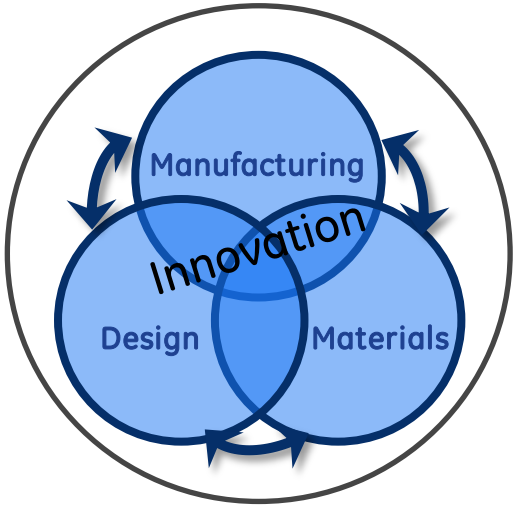
Cross-Cutting Impact of Dual-Phase Material



Machine Topology	IPM	Induction	Synch. Rel.	Switched Rel.
				
Performance Benefits	• Higher power density Improved power factor • Pole shaping-> torque ripple reduction • Sensorless control	• Improved power density (ability to go to higher tip speeds) • Improved power factor->(a) Reduction in converter VA rating (b) Reduction in cable sizing/cost • Sensorless control	• Higher power density • Improved power factor • Wider constant power speed range (CPSR) • Pole shaping-> torque ripple reduction • Sensorless control	• Lower windage losses at high speeds • Torque ripple reduction

Composite Structures and Additive Manufacturing

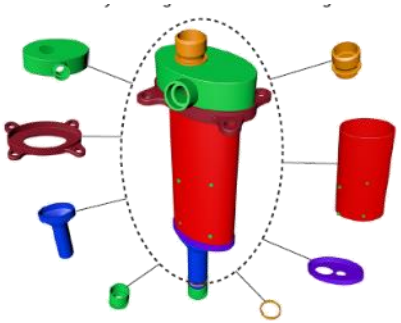
GE is considered a leader in industrializing additive manufacturing



Integration of additive design, materials, and manufacturing for novel capabilities

+

Over 350k sq ft of development & manufacturing at 6 locations in the US (NY, PA, OH, SC, WI, AL)

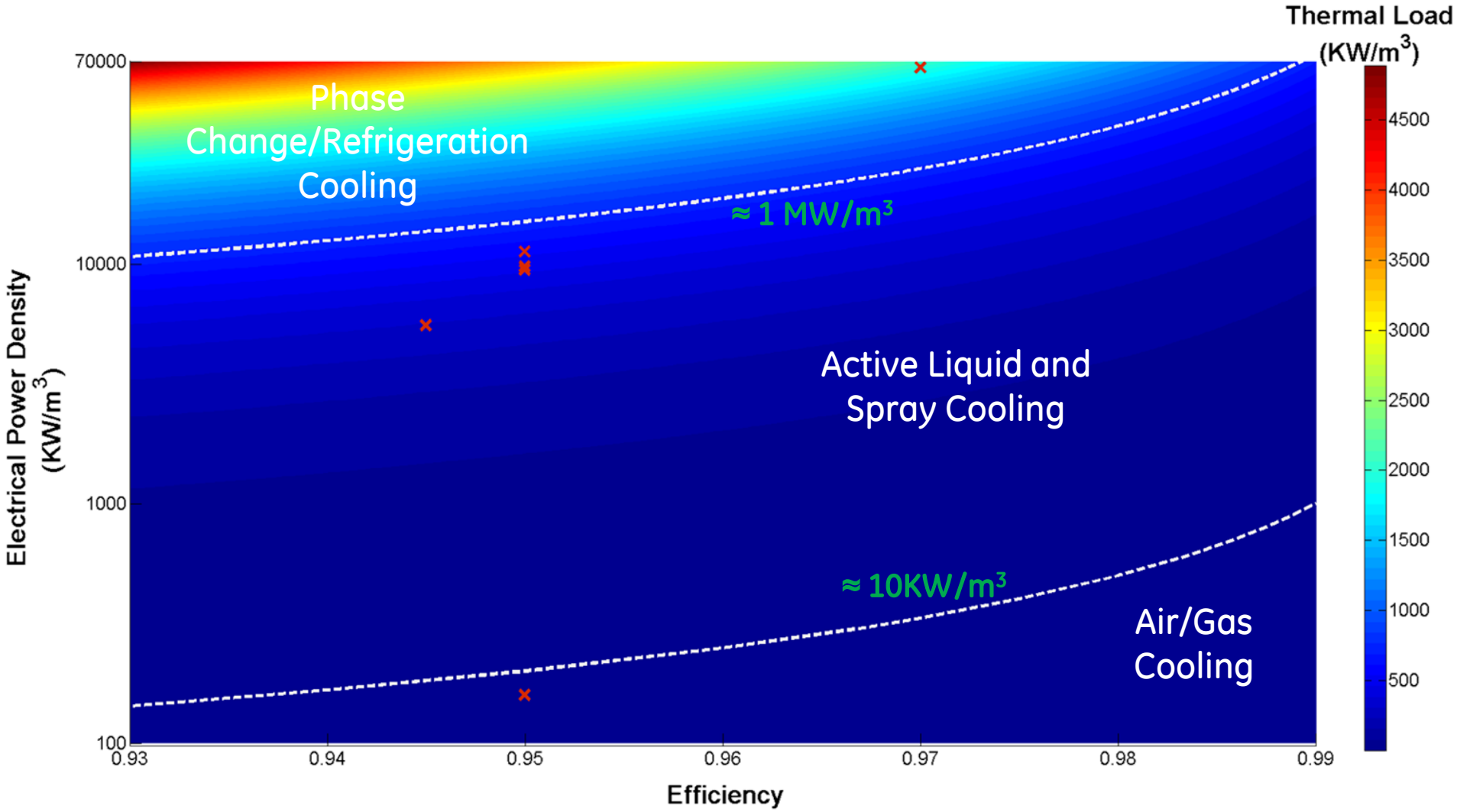


Original

Re-designed (conceptual)

Novel weight-saving components for aircraft engines

Thermal Management



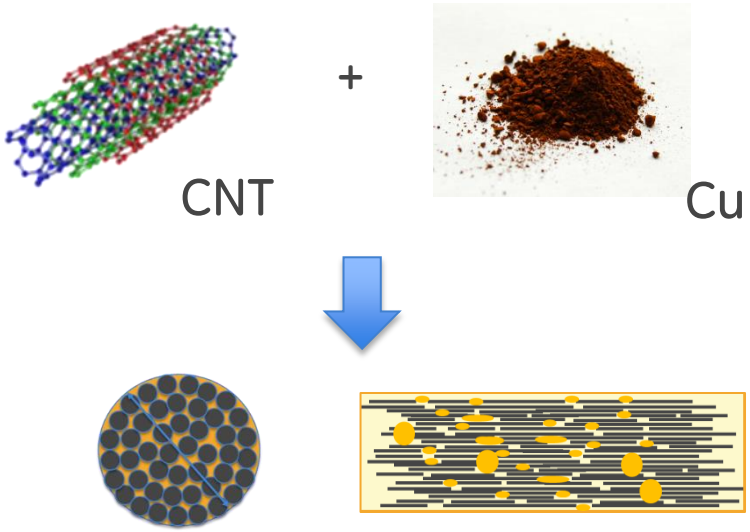
$$P_{th} = (1 - \eta) \times P_{el}$$

P_{el} : Electrical Power Density (KW/m³)

P_{th}: Thermal Load (KW/m³)

η : Efficiency

CNT-Cu Wire

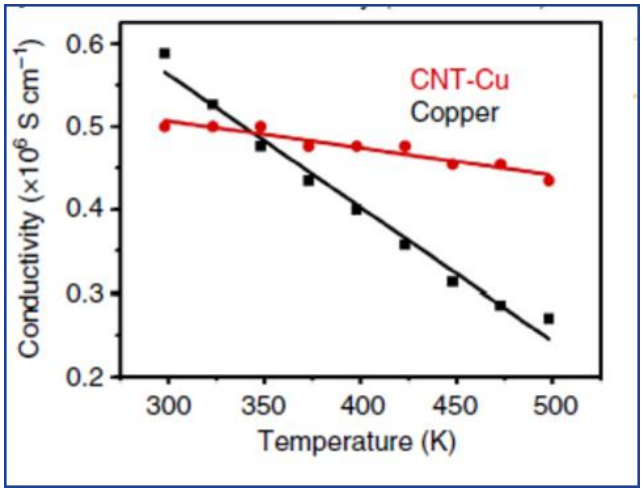


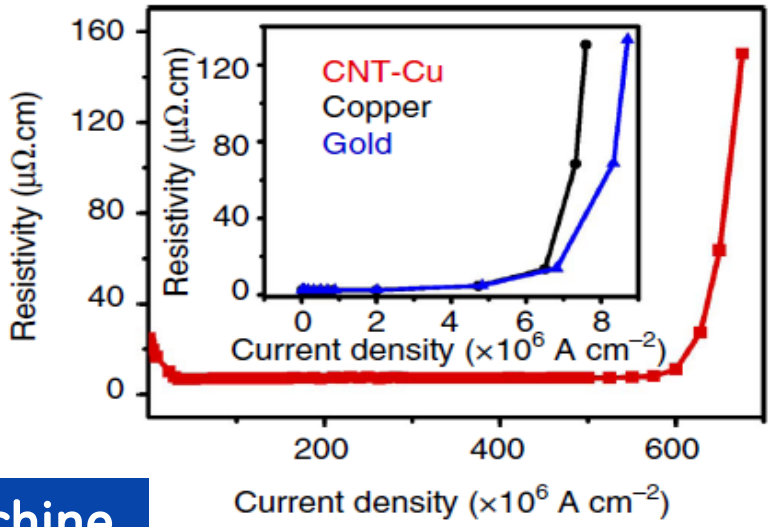
CNT-Cu composite wire

~ 65% of CNT
~ 35% Cu

→

50% Cu weight
100x Cu current density



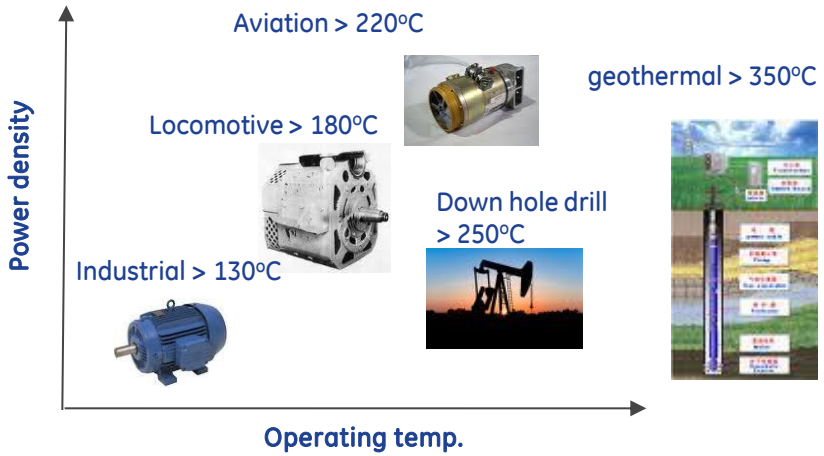


Enabler for high power density electric machine

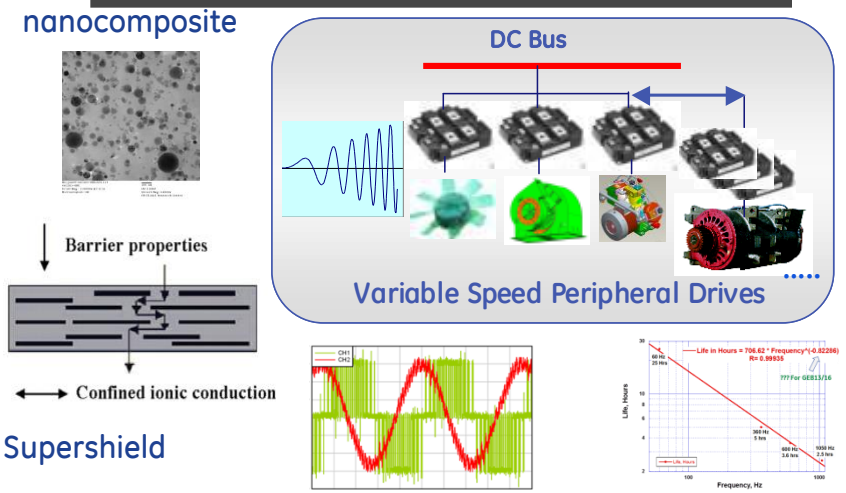
C. Subramamian, et. al., Nature Comm., DOI:10.1038/ncomms3202

Advanced Insulation Technology

High temperature insulation

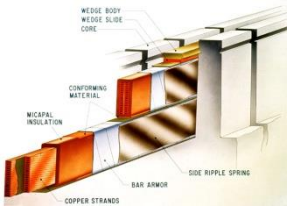


Converter-duty HVHF insulation



High thermal conductivity (TC) insulation

- Nano dielectric fluid
- High TC ground wall insulation
- High TC varnish



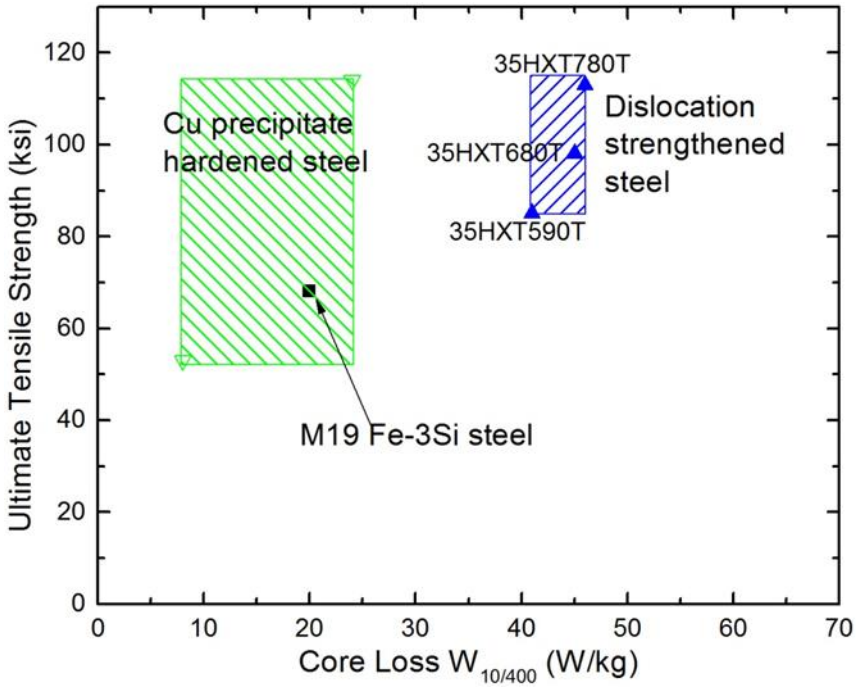
- High thermal stability
- High voltage, thin film insulation
- High dV/dt pulse resistant
- High thermal conductivity
- Chemical resistant

Enable

Reliable, high power density power generation & conversion

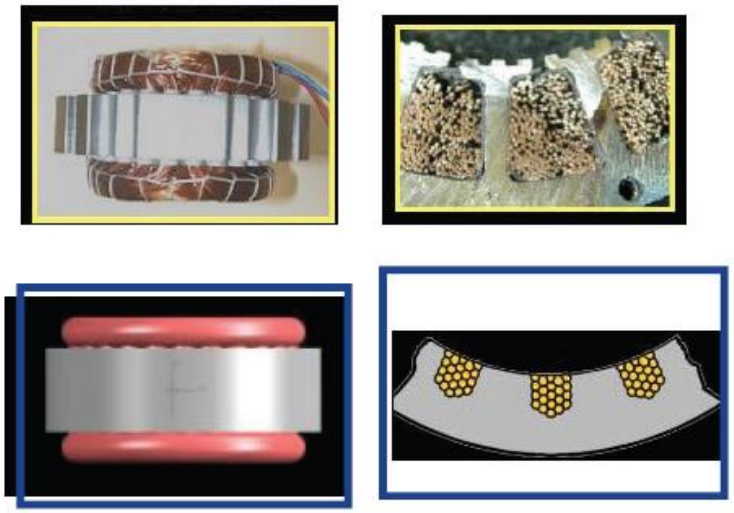
Higher Strength Silicon Steel Alternatives

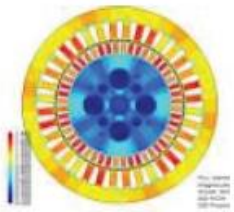
	Composition (mass%)	$W_{10/400}$ (W/kg)	RT YS (ksi)	RT UTS (ksi)	Strengthening Mechanism	Reference
Cu precipitate hardened steel **(Nippon Steel)**	0.93~8.53 Cu <2.5Al (1~8 Cr)	8~24		53~114	High density of ultrafine Cu precipitates (<15nm)	US patent 2007/0062611 A1, Max-Planck 2010 MRS talk, JP 2004 339603
Dislocation strengthened steel **(Nippon Steel)**	35HXT590T 35HXT680T 35HXT780T (2Si, <0.15Nb)	41 45 46		≥85 ≥98 ≥113	Nb moderately suppress dislocation annihilation and recrystallization	Nippon Steel Property sheets, I. Tanaka, H. Yashiki, IEEE Trans. On Magnetics, 2010; 46; p290
Conventional Fe-3Si M19 steel	3Si	20	60	68	Si solid solution	Protolam data 0.35mm sheet



- Nippon Steel technologies not commercially available in U.S.
- Other strengthening mechanisms (i.e. nanoferritically strengthened steels) at early level of technology readiness

Soft Magnetic Composites





Soft magnetic composites are pressed Fe powder parts suitable for some motor designs

Enables 3-D flux paths

- Size and weight reduction
- Suitable for claw-pole and linear brushless DC motors
- High speed motors

Products include Somaloy from Höganäs:

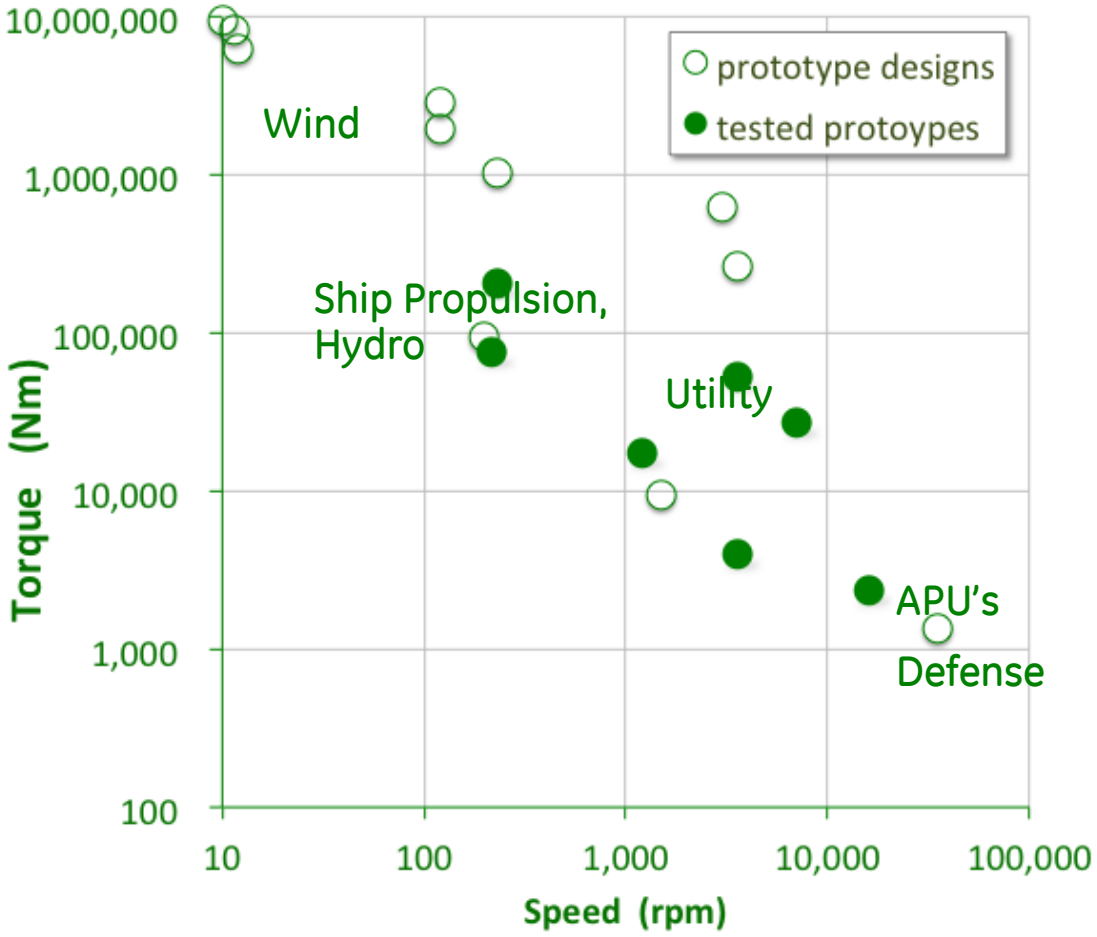
Somaloy Material	ρ (μΩ-cm)	B/10,000 A/m (T)	μ_{max}	$W_{1.0/100}$ (W/kg)
130i	8000	1.4	290	12
700	400	1.56	540	10
700 HR	1000	1.53	440	10

IMFINE sintered lamellar SMC:

- W 1.0/60 < 2 W/kg, μ > 2,000, B_{max} 1.7 T

P. Lemieux, JOM, Vol. 64, 2012, pp. 374-387

GE SC Machine Experience



Topologies

- Conductors: LTS, HTS, MgB_2
- Machine Type: Wound field synchronous, Homopolar Inductor Alternator
- Magnetics: Iron core, Airgap winding, Air core
- Mechanical Configuration: rotating field winding stationary field winding

GE has the broadest experience in Superconducting machines