

**Notes on Key Questions addressed at  
NIST/DOE Workshop on Enabling Technologies for Next Generation Electric Machines  
(September 8, 2015)**

Two previous electric machine technology workshops were recently convened at NIST: one on April 16-17 2014 to identify applications and approaches where advanced machine technologies, front end power electronics, and their integration might provide substantial benefit; and another on September 4th 2014 focused on machine designs/concepts, power conditioning system (PCS) architectures, and advanced technologies needed to implement advanced high-speed direct-drive machines.

A significant reduction of energy consumed world-wide can be achieved using advanced electric machine technologies including high performance conductors, high-temperature superconductors, soft magnetics, and other enabling technologies. The September 8<sup>th</sup> 2015 Workshop will focus on defining research and development needed to enable the use of these advanced technologies in future generations of electric machines.

**Panel – 1: Low Loss Soft Magnetic Materials (Pawel Gradzki)**

Key Questions:

- 1) What is state of the art in advanced soft magnetics that are suitable for motor applications? What is the present performance when compared to today's commercially available 3.2%wtSi electrical steel (i.e., electrical & thermal resistivity, magnetic permeability & saturation, mechanical strength etc.)?  
*What is the TRL level of 6.5% silicon steel? 6.5% Si can be made for small motors 2-3 inch diameter. TRL4-7 depending on the size of the motor lamination and maximum size of ingot. State of the art is 25 kg ingot in China. .1 mm available to 9 inch size. What is acceptable cost target? M19 0.35 mm has been most cost effective. Cost#1 efficiency #2. Automotive market switch to thinner laminations changes in the market. HF-10 is applicable to 400 kHz*
- 2) What is/are the key performance metrics (in the order of importance) if this technology is to be considered in industrial motors?  
*Saturatiion flux density at same cost. Increased resistivity. How much reduction can be tolerated to get loss reduction in the system?*
- 3) What are the key challenges in achieving 25% - 50% improvement over the identified key performance metrics (from question 2) of commercially available 3.2%wtSi electrical steel?  
*4.5% steel might be improved over existing Si steel. Mechanical properties yield strength, novel core plate coatings, thickness of insulation is important. Rotational losses in traditional steels.*
- 4) Are there any key barriers (show stoppers) in the workability and durability of this technology (i.e., too thin to handle, not scalable in thickness, too brittle etc.)?
- 5) What are the key challenges in scaling up the manufacturing process for size and volumes suitable for electric machine manufacturing?  
*POSCO steel opened transphormer group to advance amorphous and crystalline material. Lamination producers have interest in developing low cost production materials. Many are dismissive about Ni alloys, but these alloys are easier to work with. Post processing needs vertical integration from material, including processing and motor demonstration.  
Q: Amorphous material has lower saturation level. Is this resulting in larger motors?  
Induction comparison is tricky. If you can spin machine faster, the machine can have higher performance. Even at 60 Hz you can get better efficiency and smaller size.*

- How can you make Hyperco less lossy. How to adapt material to operate at low temperatures for superconducting motors? Specification needed for lower temperatures. Some nanocomposites have natural oxide for insulations, other will require coating. Partial crystallization can almost eliminate magnetostriction.*
- 6) Are there any other pre-requisites that need to be addressed prior to demonstrating the technology readiness for industrial motor applications?  
*There is a disconnect from lower loss and benefits for user. Users are very interested in cost saving. Efficiency is not the main card. New motor energy saving over lifetime needs to be more emphasized. Government can impose standards, but market is looking for lowest cost. Efficiency is a difficult barrier. Total cost of ownership is important for system designer. Motor drives mechanical load, so mechanical considerations are important, because motor speed impacts bearings, gear boxes, etc. If you could use technology to reduce losses for 5-10 MW motors, what energy saving can you expect? 3% is a lot, 1% is easily achievable? Partial load could be 10%. How is frequency increase impacting savings? Example is aviation industry. With purely linear flux you could have much better efficiency, but it is not practical for motors.*
- 7) What would be a good power level for prototype demonstration (i.e., fractional hp, integral hp or larger)?  
*How about amorphous? 20 kW in demo, could be pushed to 50 to 100 kW. Problems: making wide 14 inch wide now, making them into stator. Need plastic deformation for stamping. Significant efficiency gain 2x by proper magnetization. Even using grain oriented steel can reduce losses. Large high speed motors will have different requirements than mainstream machines. Baseline specification was described in previous FOA. Benchmarks were created from previous workshops.*
- 8) Which technologies fit in TRL 4-7? Amorphous, Si steel, 14 inch wide cast is at TRL-4. 6.5% Si steel in Japan is in production and researched in China.

*Closing remarks Zia: thin laminations reduce losses, but stacking is harder and more expensive. Is bottleneck for Si steel rolling? Is brittleness of ribbon a roadblock for motor applications? Bulk amorphous can be made. Steinmetz eqn implies frequency limit. Thin laminations have poor stacking factor and are difficult to handle, so thickness cannot be reduced without increasing cost. Brittleness is the main problem for manufacturing.*

## **Panel – 2: Superconducting Machines (Zia Rahman).**

### Key Questions:

- 1) What is state of the art in superconductors that are suitable for motor applications? What is the present performance when compared to today's cost optimized Nb<sub>3</sub>Sn (i.e., price in \$/kA-m, critical current density, critical temperature T<sub>c</sub>, critical flux density, present production volume in km/year etc.)?
- 2) What is/are the key performance metrics (in the order of importance) if this technology is to be considered in industrial motors?  
 1000 A/cm weight @ LN<sub>2</sub> @ 1.5T – 2.5T is an important target.
- 3) What is an acceptable return on investment (ROI) for superconducting machine at MW range (cost and time)?

*Notes: Cryogenics, 65K and 55W heat rejection. MRIs DC magnet work at 4K. Two stage cryocoolers are used. Going down to 20K and 30K is viable. So don't just rule out lower temperature design because of cryogenics complexity. But MRI vs motors, stationary vs rotary. So simple cryogenic is a big decision factor.*

*What does increasing width of wire do to bandradius of the machine? Need study on that. AC losses in motors for 15000 rpm machines. Getting up to 18000 to 10000 rpm is a challenge. Is that only if you want SC in stator?*

*Operating cost of cryo in Goran's presentation, what was considered? The maintenance cost was not considered.*

*Collaboration in demonstrating a SC motor. 300kW demonstration done by Siemens. Look at the whole systems in stead of wires only.*

*What's the cost of copper today? Copper \$25kA/m. Is sources of Yittriuma problem? Joining issue in HTS. Is this a big problem in motors? Probably not. Has anybody operated YBCO rotors at 10000 rpm? Will delamination ordegradation be aproblem? No testing done on HTS at high speed? NASA did that on MgB2.*

*Coolant type/amount needed per megawatt*

- 4) What are the key challenges in improving wire performance and/or the manufacturing process to reduce price close to Nb<sub>3</sub>Sn (i.e., improve in critical current, increase in yield, waste reduction etc.)?  
*Yield limits continuous conductor pieced to about 500 meters. This would require 15 to 30 pieces spliced for a wind turbine application. However, the connection resistance is not a major factor in conduction losses.*
- 5) Are there any other pre-requisites that need to be addressed prior to demonstrating the technology readiness for industrial motor applications?  
*Superconducting wire cost is significantly higher than copper, but it could be manageable compared to the cost of the system. However, cryogenic cooler cost favors large machines, where cooling cost is relatively low compared to the cost of the system. Commercial cryogenic coolers have rating of 5 W, so 11 coolers are needed for 55 W heat rejection.*
- 6) What would be a good power level for prototype demonstration (i.e., 1 MW or larger)?  
What would be a good component level demonstration for the technology?

### **Panel – 3: High Performance Thermal and Electrical Conductors (Scott Coombe).**

Key Questions:

- 1) What is state of the art of advanced conductors that are suitable for motor applications? What is the present performance when compared to today's commercially available winding materials, such as copper and aluminum (i.e., electrical & thermal conductivity, weight & volume density, ductility etc.)? *CNT-only conductors are about 1/6<sup>th</sup> the electrical conductivity of Cu (10 MS/m vs. 59 MS/m) @ RT. CNT-Cu hybrids have achieved 2X elec conductivity of Cu but results are not stable. Current carrying capacity (CCC) of CNT conductors already on par with Cu on a volumetric basis. CCC of CNT conductors already higher (40%) than Cu on a mass basis. Thermal conductivity for CNT is 600 W/mK vs 400 W/mK for Cu. Strength of CNT-based conductors are 300% better than Cu. Be careful with today's experimental results. This is a large research space containing CNT-only conductors, and hybrids including CNT, Al, Cu, and other materials. Much fundamental work is still required and much investment (~\$100M). Sample sizes are currently in the range of 10-100g. MRL at 3-4 now. Should try to achieve MRL of 7 in the next few years. Roadmap for elec conductivity needed w/metrics. UCC – large samples achieved.*

- 2) What is/are the key performance metrics (in the order of importance) if this technology is to be considered in industrial motors? *No major barriers to affordability for CNT conductors, but progress in the science, processing, and scale-up is necessary. Some of the properties are already attractive (yield strength, fatigue strength, current carrying capacity, etc) but better (non powder based) processing is needed for scaleup to the sizes necessary for electrical machines.*
- 3) What are the key challenges in achieving 25% - 50% improvement over the identified key performance metrics (from question 2) of commercial metal conductors? *Need more investment to enable better, more repeatable experimental characterization of conductors. Need to understand the science behind the enhanced performance in conductivity in CNT/Cu hybrid structures. Supply chain issues – joining, bonding, terminations...*
- 4) Are there any key barriers (show stoppers) in the workability and durability of this technology (i.e., not friendly towards insulation, varnishing and soldering mechanisms, etc.)? *Yield strength and fatigue strength of CNT-based wire are high in comparison to Cu. Again, scale-up is required to bulk levels. There are substantial challenges in the area of contacts, splicing CNT materials. Need to understand AC loss mechanisms. Property uniformity is an issue.*
- 5) What are the key challenges in scaling up the manufacturing process for lengths and volumes suitable for electric machine manufacturing? *Need to move beyond powder processing of CNTs. This approach may not have a viable path for affordability. Other, more scalable methods currently being pursued. Are there any other pre-requisites that need to be addressed prior to demonstrating the technology readiness for industrial motor applications? CNT-only materials – need scaleup but no inherent affordability barriers.*
- 6) What would be a good power level for prototype demonstration (i.e., fractional hp, integral hp or larger)? *Electrical cable may be a good demo. Railgun? Wearable conductive fabrics.*

#### **Panel – 4: Other Enabling Technologies (Steve Boyd).**

##### Key Questions:

- 1) What is are other technologies that can improve efficiency of electric motors (i.e., new motor topologies, low loss high speed bearings, high resolution sensors and advanced controls, improved insulation and varnishing materials, novel cooling mechanisms & cryogenics etc.)? *From the presentations, consider HTS cable cooling, cryo-refrigerators, quench sensors, rotating couplings, soft/hard magnetic materials, additive manufacturing approaches, thermal management improvements, and advanced insulation.*
  - a. What is considered high voltage for insulation? *Above 4160V – 13.8kV. What is high temp? Is several hundred degrees possible? Maybe just above 150... possibly above 200 for organic. Polymers might allow a jump further. Aerospace and do 270-280 deg C. High temps affect efficiency and other associated motor materials.*
  - b. Is cryo-cooler a research or engineering problem? *Technology is almost there... TRL 4-5, but need system demonstration / first system proof of principle.*
  - c. Possible to add CNTs to epoxy or insulation systems to remove heat axially? *CNTs typically are electrical conductors, so presents a challenge. Lots of other materials being considered for insulation AND heat removal.*
  - d. Possible to improve saturation – especially for induction machines? *Higher saturation magnetization material would definitely be a benefit – open to new ideas and materials considered at a machine design level.*
  - e. *Cooling is important for power density and efficiency, so many approaches are considered, especially liquid cooling.*
  - f. Impact of cryogenics on insulators? *Generally easier but can include brittleness at low temperatures. Analysis for thermal cycling and lifetime may be incomplete here.*

- 2) What is/are the key performance metrics (in the order of importance) if these technologies are to be considered in industrial motors?
  - a. *Reducing machine size and improved thermal conductivity – typically 0.3 W/m\*K. Anything better than this would be great!*
  - b. *For cryo-cooling, could reference EERE targets from 2007 Navigant report. These are still aggressive goals.*
- 3) What are the key challenges in achieving 25% - 50% improvement over the identified key performance metrics (from question 2) of present base line technologies?
  - a. *Most are limited by material properties and intrinsic tradeoffs.*
  - b. *Possible other applications for cryogenic cooling systems to advance knowledge, volume, reduce cost outside of SC machines? Natural gas liquefaction through magneto caloric (short term field use at source 1-5 tons/day, can also produce helium), cell phone towers.*
- 4) Are there any key barriers (show stoppers) in the workability and durability of this technology?
  - a. *Dual phase laminations – what about manufacturing? We have proved the concept, can selectively orient steel. Just concluded spin test and verified OK properties. For industrial motors, we are going to retrofit a motor and test. Would like vendors to work with and scale up process.*
  - b. *Significant differences between SC machines and typical machines. Failure modes for cryogenic cooling – backup power or redundant systems, recovery time? Or just consider as system down time, system complexity and cost.*
- 5) What are the key challenges in scaling up the manufacturing process suitable for electric machine manufacturing?
- 6) Are there any other pre-requisites that need to be addressed prior to demonstrating the technology readiness for industrial motor applications?
- 7) What would be a good power level for prototype demonstration for these enabling technologies (i.e., fractional hp, integral hp or larger)?