High Field Superconducting Machines

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Comment from a reviewer:

"This is, by now, a very old technology that has not yet found a place in society. Why are you beating this 30 year's old dead horse?"

Overview

SC rotating machine landscape, barriers to adoption

Opportunities

– high field motors for aircraft based on MRI technology

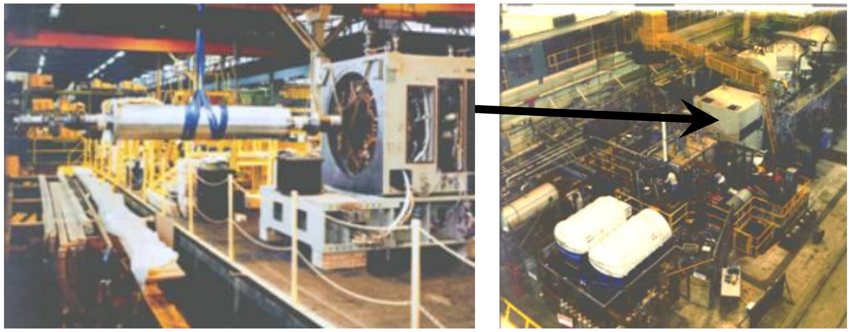
Extension to wind

Discussion

Technically Feasible

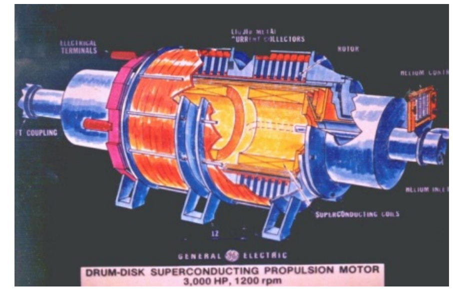
Superconducting Machines at GE

1970's – 1980's (LTS)



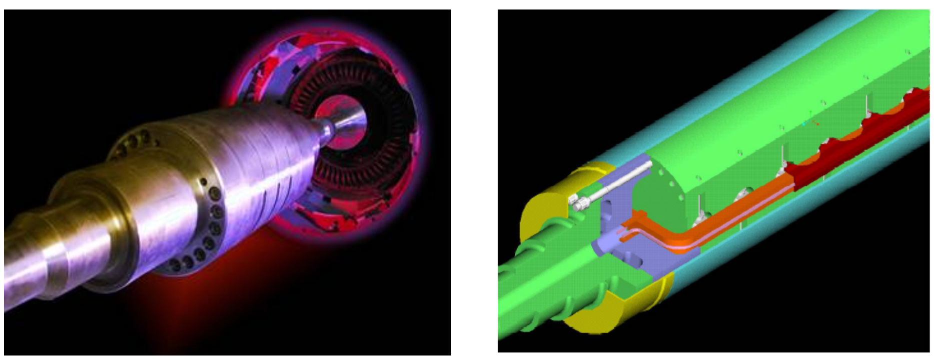
Commercial 20 MVA superconducting generator, 4K, liq. He, NbTi

Military 20 MW generator, 4.5/8 Kelvin - NbTi/Nb3Sn



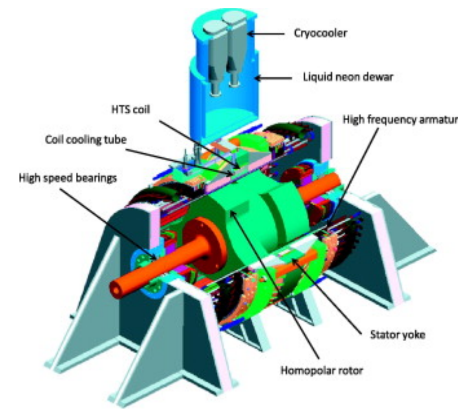
DC homopolar propulsion motor. 3000 hp, 1200rpm

1990's – 2000's (HTS)



1.5 MVA HTS generator demonstrator built and tested
Design of 100 MVA HTS generator for utility applications

1.7MW, HTS, 40K Hydrogenerator



5MW HTS-HIA generator, 30K – YBCO, 35000 rpm. 4MW demo tested at 10,500 rpm

Challenge: Need to improve perceived value vs risks/costs

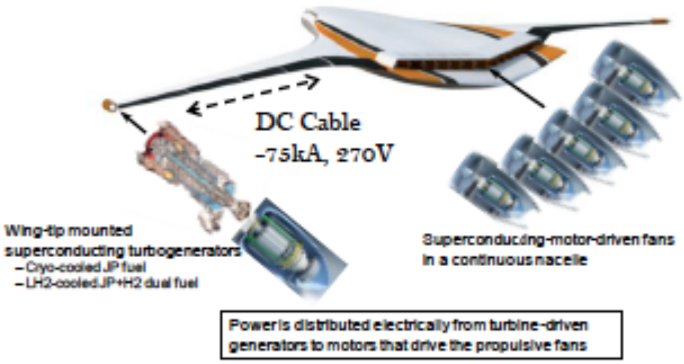
Is there a "Killer App" for SC Machines?

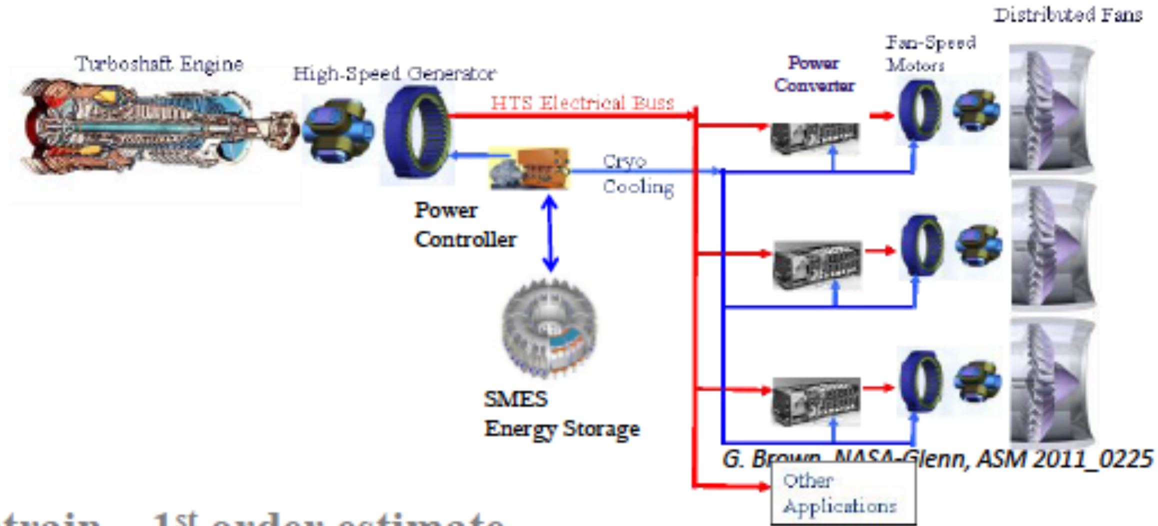
- "only superconducting solution makes the system viable"

Would the following come close to meeting this criteria?

- Industrial Motors
- Utility Generators
- Ship propulsion motors
- Wind turbine generators
- Electric drives for aircraft

45 MW Turbo-Electric Distributed Propulsion (TEDP): NASA N3-X





G. Brown, NASA-Glenn, ASM 2011_0225

H. Kim, NASA-Glenn, ASM 2011_0222

45 MW Electrical Drivetrain – 1st order estimate

Specifications	Cu Wire or PM @ 293K	All-Superconductor or Cryogenic
Motor/Generator Power Density (kW/kg)	3 - 7	40 - 65
Efficiency (%)	85 %	99 %
Heat Loss	6.8 MW	0.45 MW
Mass	146 klb	11 klb
TRL Level - Airborne	9	1 - 3

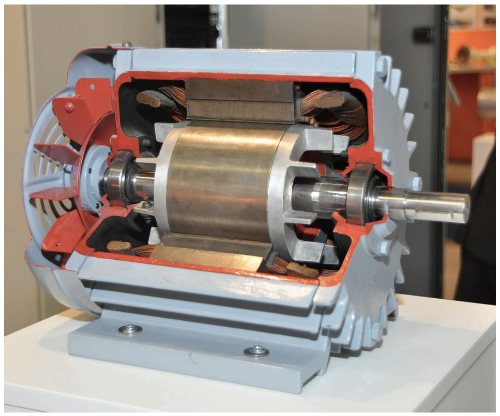
Erases gains from HEDP drag reduction

Higher than payload = 118 klb !

Cryogenics enabling technology for HEDP

J. Felder et al, NASA-Glenn, ISABE_ 2011_1340

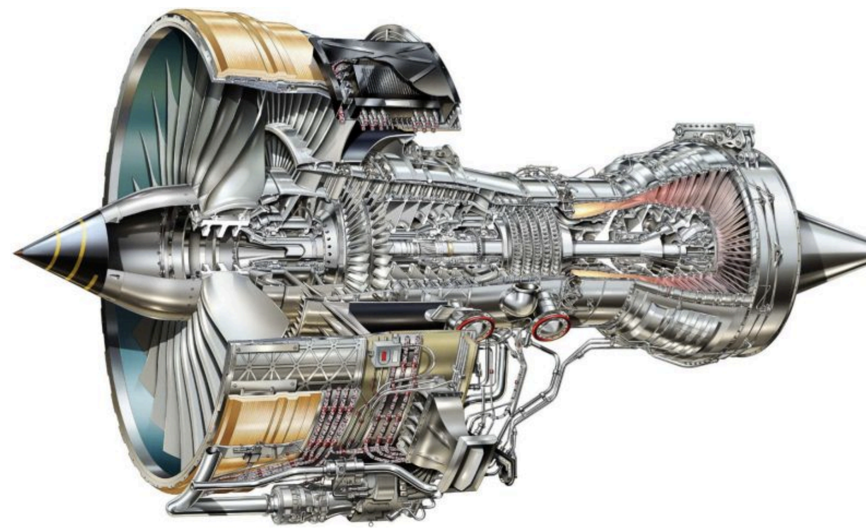
Benefits versus cost + risk



http://en.wikipedia.org/wiki/Electric_motor

Induction machine

Hydrogenie from GE



Jet Engine

Rolls Royce Trent 700 engine
http://aviationnewsportal.com/

National Aeronautics
and Space Administration

THE FUNDAMENTAL AERONAUTICS PROGRAM

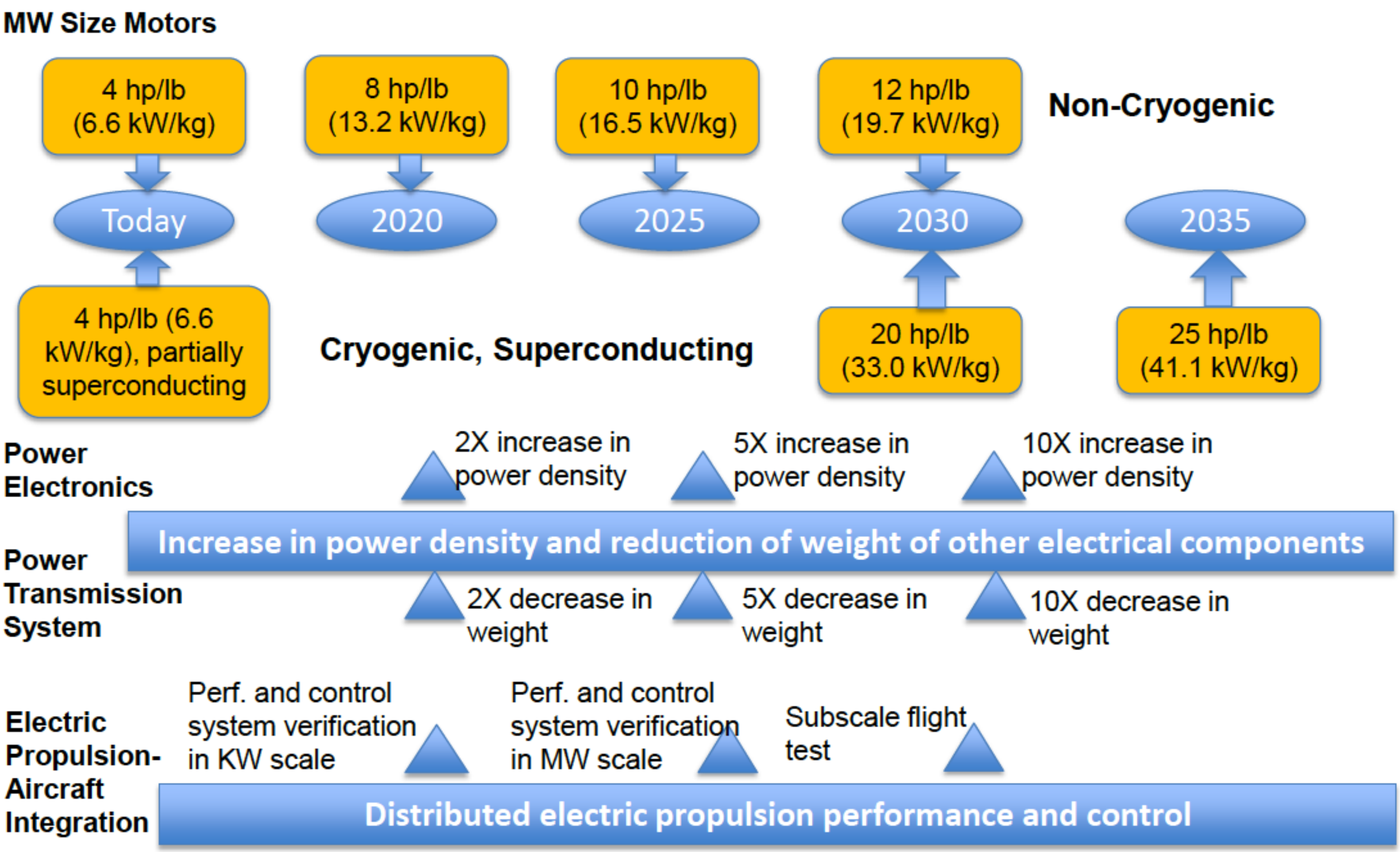
NASA's Fundamental Aeronautics Program addresses national challenges in air transportation by enabling advanced technologies that will improve the performance and environmental impact of future air vehicles. Projects: Fixed Wing, Rotary Wing, High Speed, Aeronautical Sciences,.

THE FIXED WING PROJECT

Fixed wing research includes exploring and developing tools, technologies and concepts for vastly improved energy efficiency and environmental compatibility necessary for the sustained growth of commercial aviation vital to the U.S. economy and quality of life.

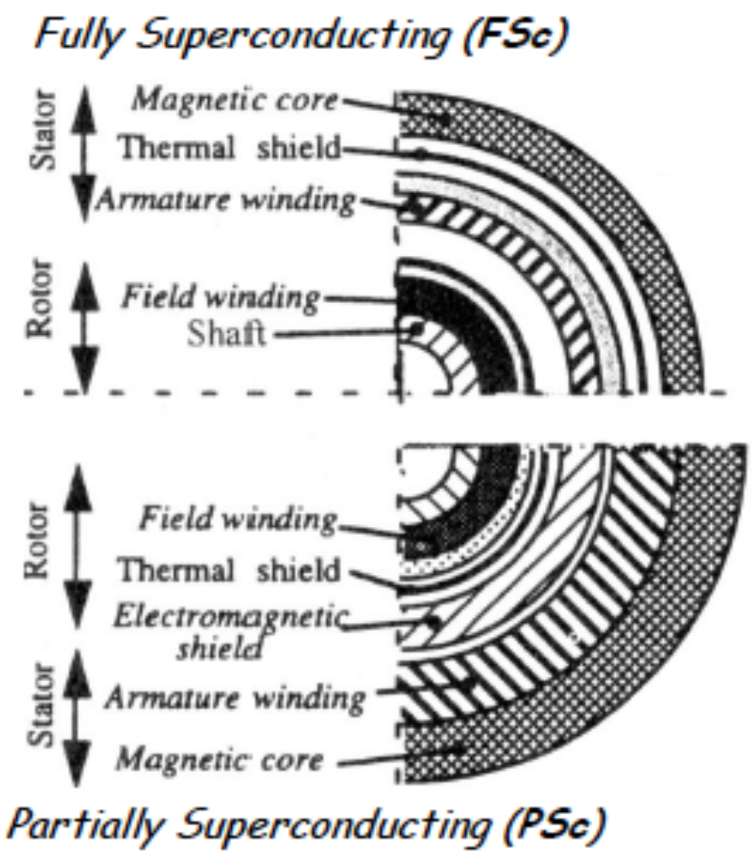
Research Themes and Technical Challenges (TCs)		
Theme	**TC Title**	**TC Description**
Lighter-Weight, Lower-Drag Fuselage	Fuselage Structural Weight	Reduce fuselage structural weight by 15% with neutral or positive drag impacts while not affecting certification and passenger comfort (TRL4)
Higher Aspect Ratio Optimal Wing	Optimal Aspect Ratio	Enable a 1.5-2X increase in the optimal wing aspect ratio with certifiable structures and flight control (TRL 3)
Quieter Low-Speed Performance	Community Noise	Reduce perceived community noise by 12 dB cum with minimal impact on weight and performance (TRL5)
Cleaner, Compact, Higher Bypass Ratio Propulsion	Low NOx, Fuel-Flex Combustor	Reduce NOx emissions from fuel-flexible combustors to 80% below the CAEP6 standard with minimal impacts on weight, noise, or component life (TRL3)
Cleaner, Compact, Higher Bypass Ratio Propulsion	Compact, High OPR Gas Generator	Enable reduced size/flow gas generators with 50+ OPR and disk/seal temperatures of 1500F with minimal impact on noise and component life (TRL4)
Hybrid Gas-Electric Propulsion	**Electric Motor Power Density**	**Achieve a 2X increase in the power density of an electric motor (TRL 3)**
Unconventional Propulsion-Airframe Integration	Integrated Boundary-Layer Ingestion System	Achieve a vehicle-level net system benefit with a distortion-tolerant inlet/fan, boundary-layer ingesting propulsion system on a representative vehicle (TRL3)
Alternative Fuel Emissions	Alternative Fuel Emissions at Cruise	Fundamental characterization of a representative range of alternative fuel emissions at cruise altitude

NASA FW/AATT HEP Technology Roadmap



Fixed Wing Project
Fundamental Aeronautics Program

Wound Field Synchronous Machines



Bogi, Jensen, Masson, ICEM 2012 Tutorial

Electrical machine power density:

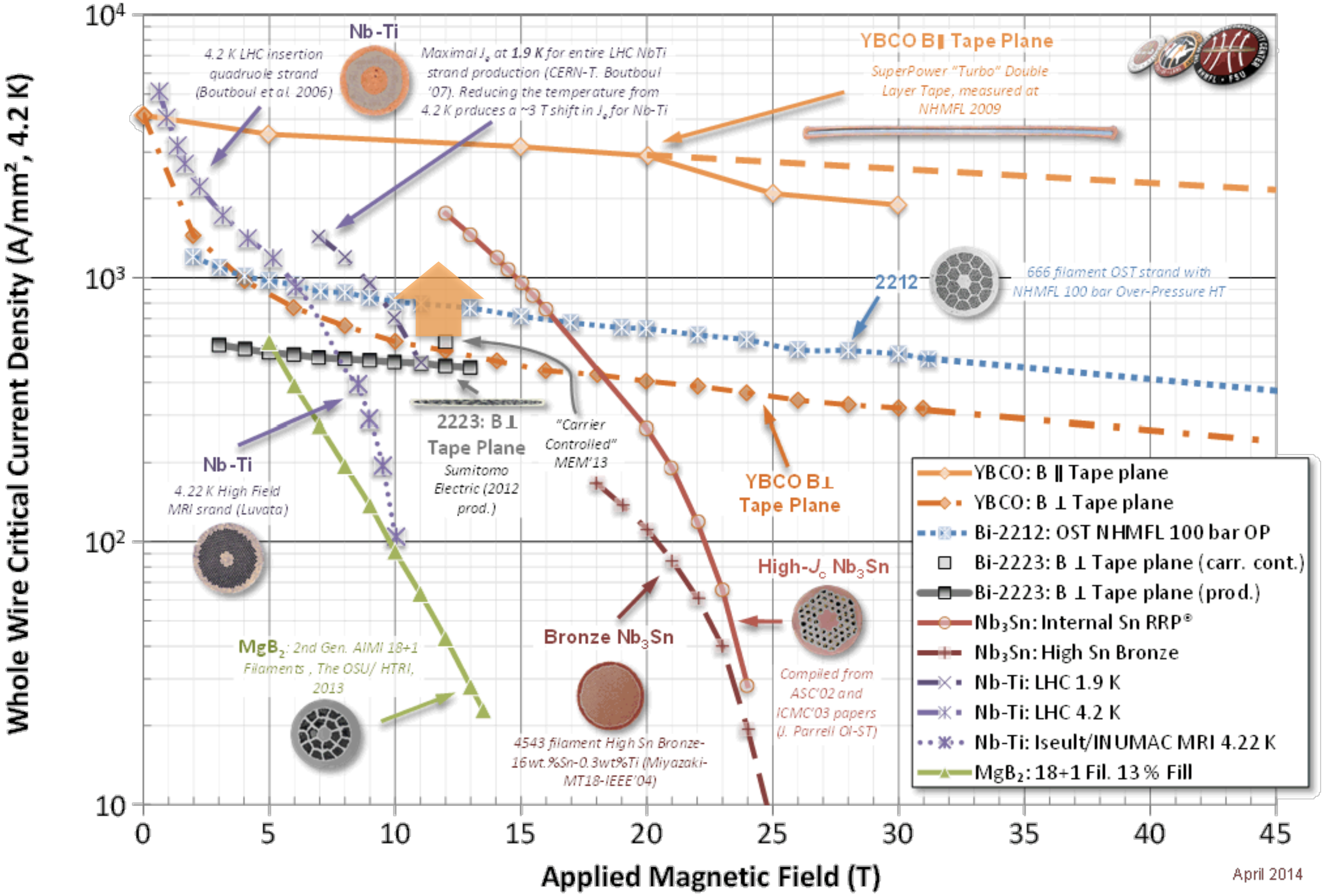
$$P_R = \frac{1}{1+K_\phi}\frac{m}{m_i}\frac{\pi}{2}K_e K_i K_p \eta B_g A \frac{f}{p}\lambda_o^2 D_o^2 L_e.$$

Maximize electrical loading, magnetic loading, and rotor tip speed - simultaneously!

If rpm and diameter limited (e.g. wind generators) => maximize torque density.

Huang, S., Luo, J., Leonardi, F., & Lipo, T. A. (1998). A general approach to sizing and power density equations for comparison of electrical machines. Industry Applications, IEEE Transactions on, 34(1), 92-97.

Available Conductors

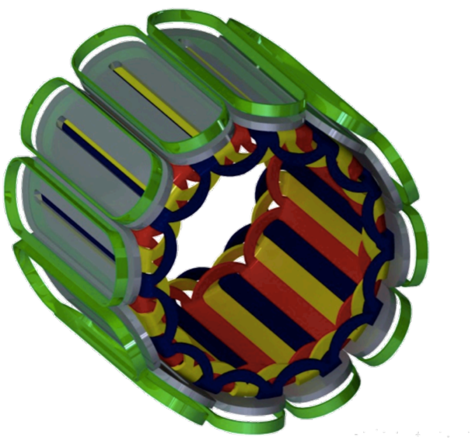


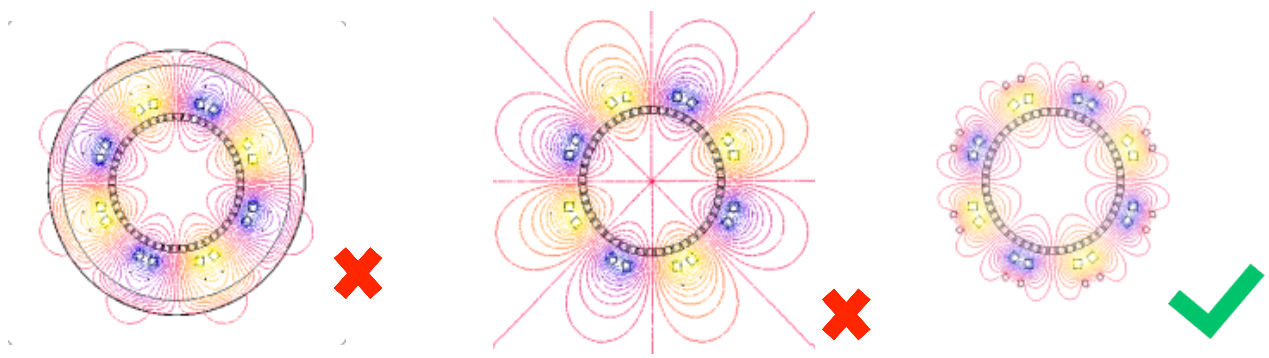
The National High Magnetic Field Laboratory

High Field Superconducting Motor

NASA LEARN Phase 1: Establish feasibility of superconducting motor with:

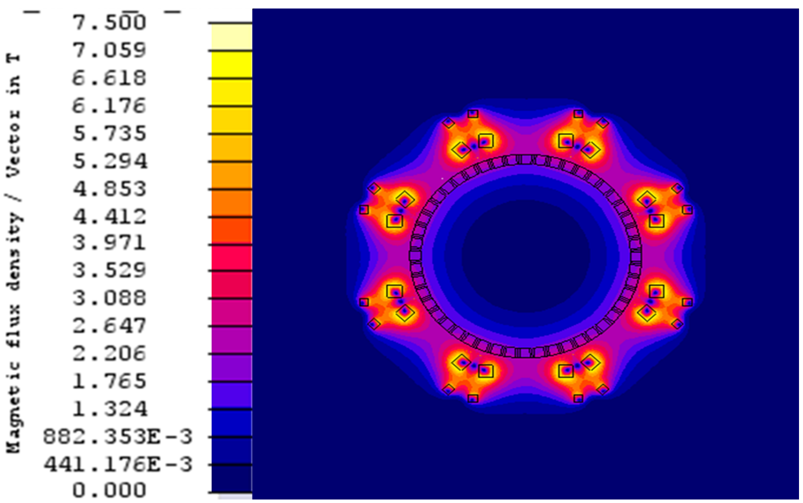
- Stationary field winding assembly to utilize MRI technology
- Explore peak fields up to 10T
- Active magnetic shield to eliminate field outside while maximizing ”air gap” flux density
- High field superconductor (e.g. Nb_3Sn)



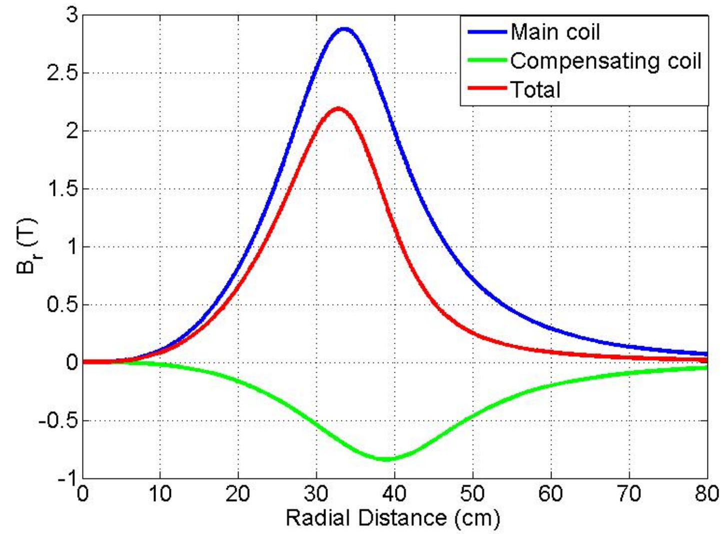


ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN AFRL THE OHIO STATE UNIVERSITY MAGSOFT CORPORATION

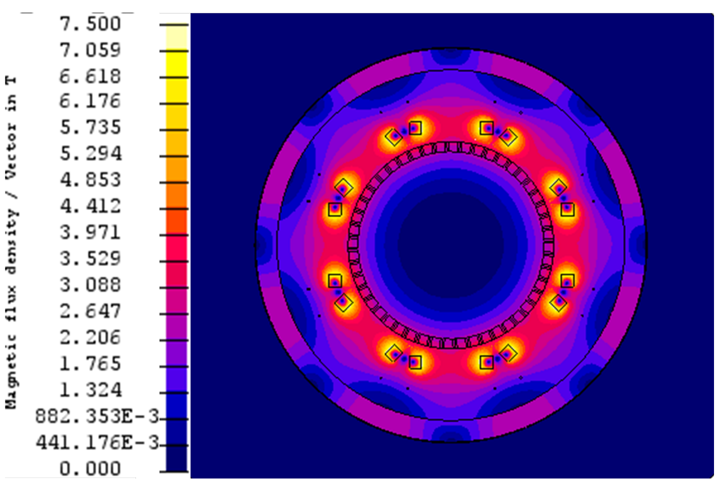
Electromagnetics



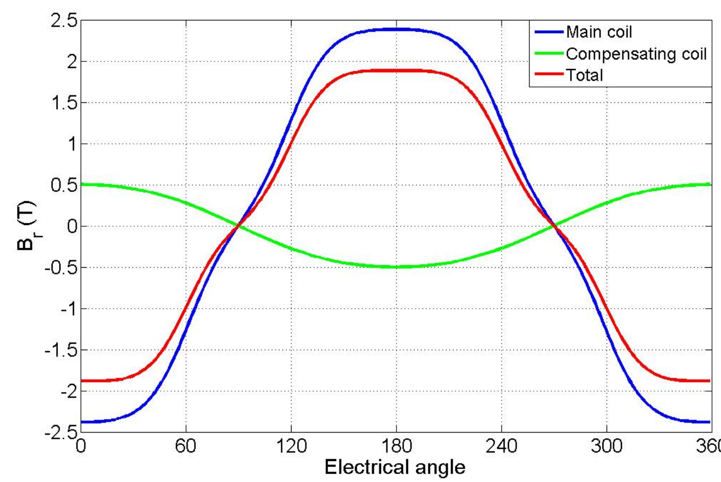
Flux density distribution in a cross section of the machine with an active EM shield



Radial Flux Density along D-axis

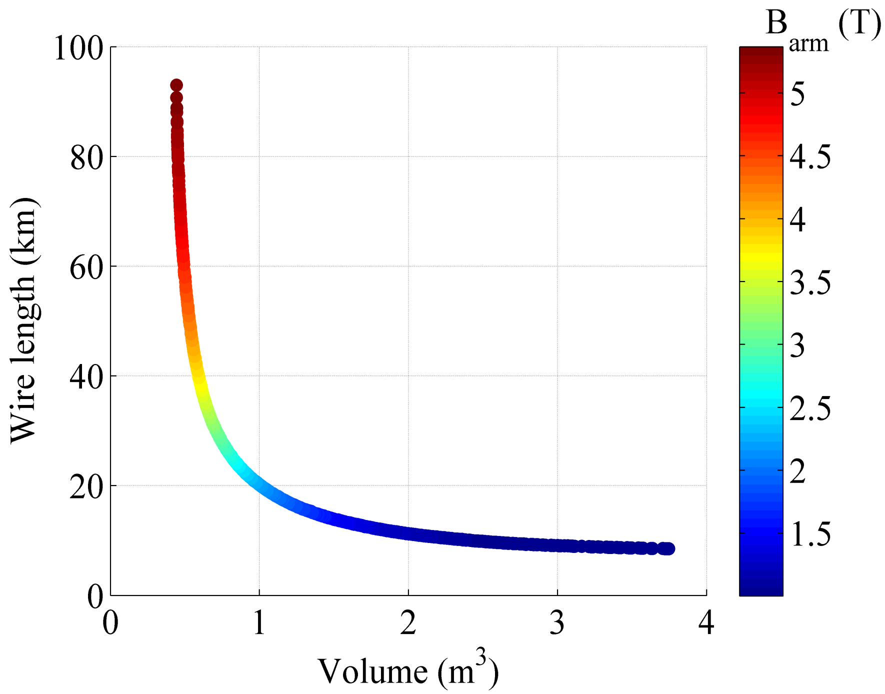


Flux density distribution in a cross section of the machine with a passive ferromagnetic shield.

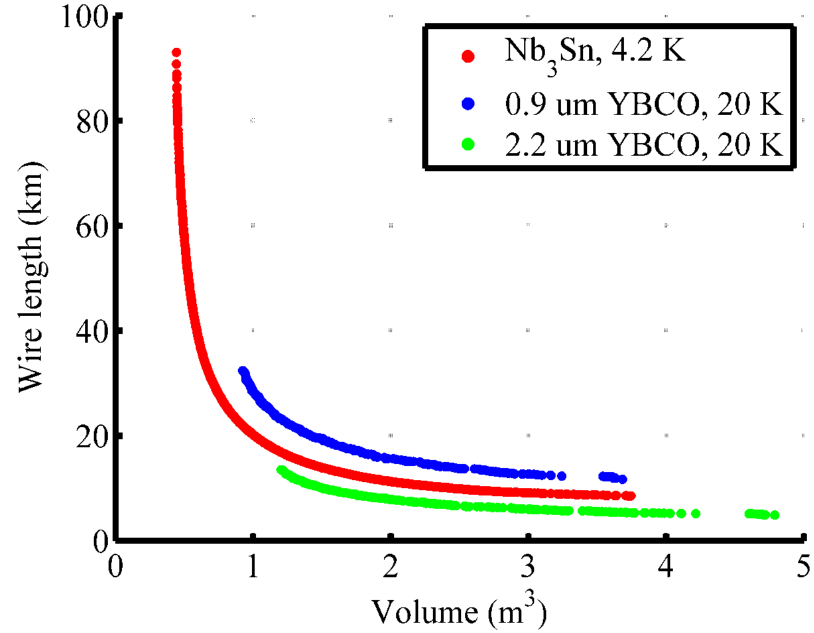


Radial Flux Density at Armature

Optimization – First pass



Pareto-Optimal Front for Nb_3Sn Tube-Type



Comparison with YBCO

Key Design Parameters	
Output Power	10 MW
Speed	3000 rpm
Maximum External Field	0.5 mT
LTS Critical Surface Safety Margin	50%
HTS Critical Surface Safety Margin	80%
Rotor Tip Speed	95m/s
Electrical Loading	1700A/in

Critical current density above 15MAcm−2 at 30K, 3T in 2.2μm thick heavily-doped (Gd,Y)Ba2Cu3Ox superconductor tapes

Initial analysis with conservative electrical loading and rotor tip speed

Key Technical Challenges

Cryogenic Thermal Management System
- reliability, cryogen free?

High field SC coils, stability
- Racetrack coils, cyclic torques, ac losses, ramps

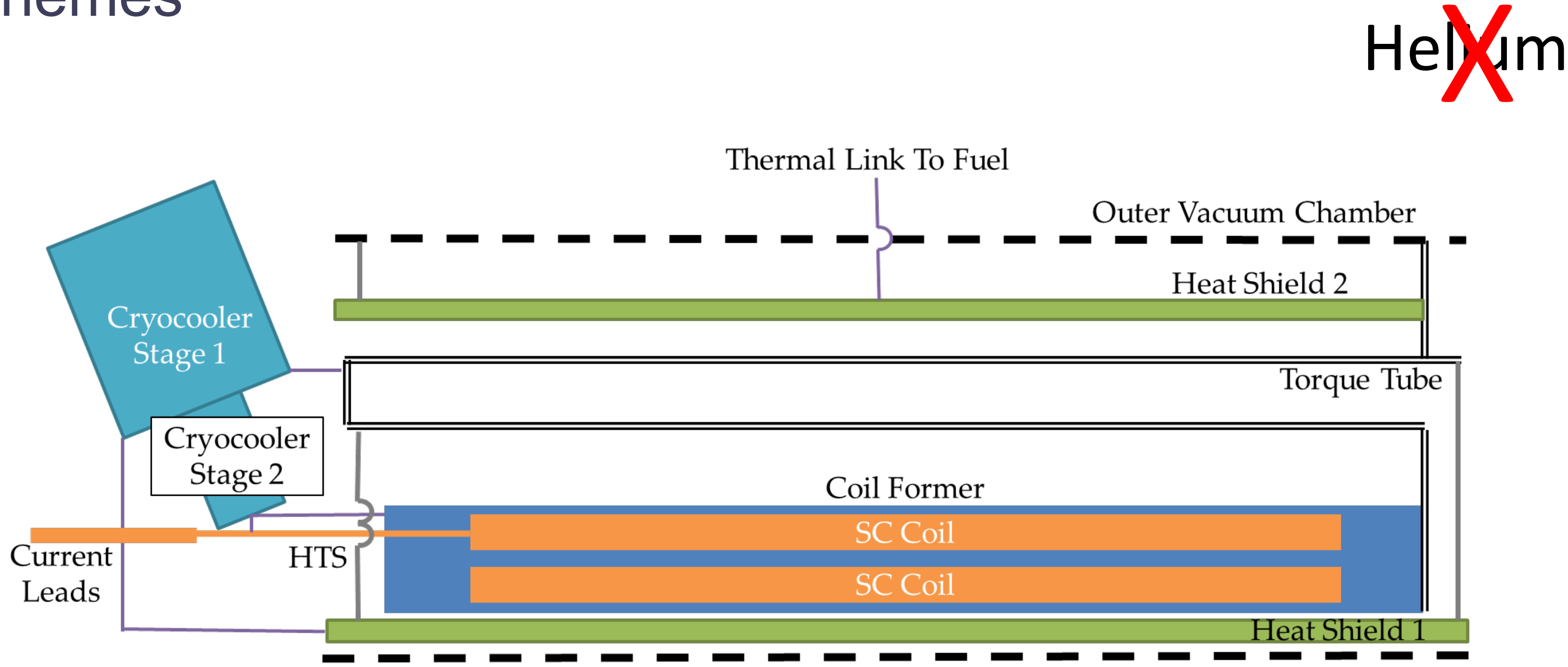
Structural integrity

Overall motor configuration

Cooling System

Key Design Considerations:

- Heat loads: torque tube, radiation, current leads
- Most efficient cooling at ~4-10K
- Borrow best practices from prior cryogen free cooling schemes



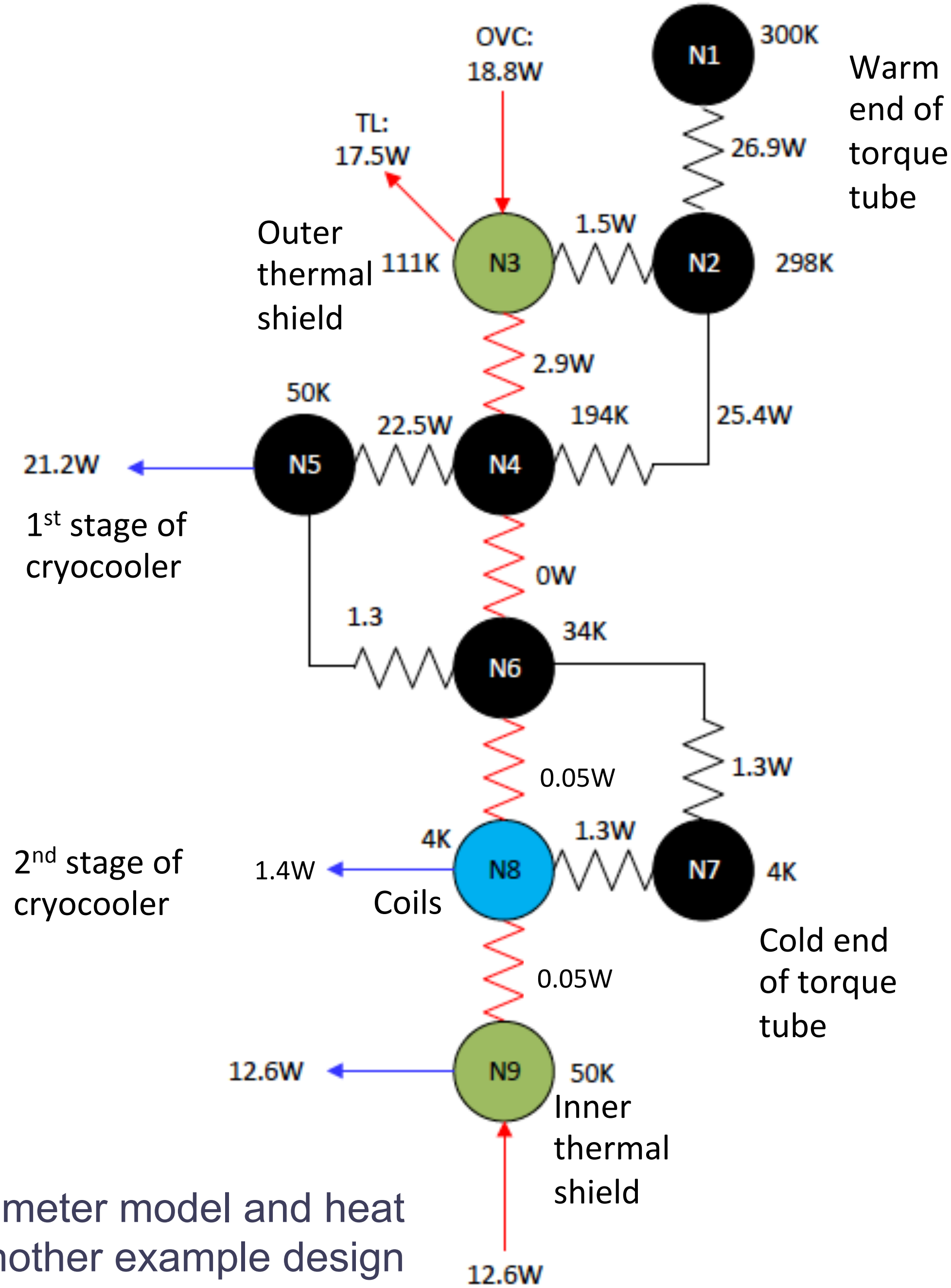
Schematic of Thermal Management System

Heat Loads

<u>Heat loads for current baseline design</u>

Cryocooler Stage 1
Radiation: 31.74W
Conduction w/ TT: 23.06W
Current Leads: 13.9W
Total: 68.7W

Cryocooler Stage 2
Radiation: 0.1W
Conduction w/ TT: 1.32W
Current Leads: 0.2W
Total: 1.62W

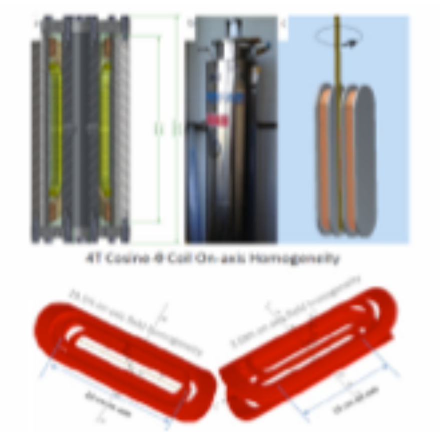


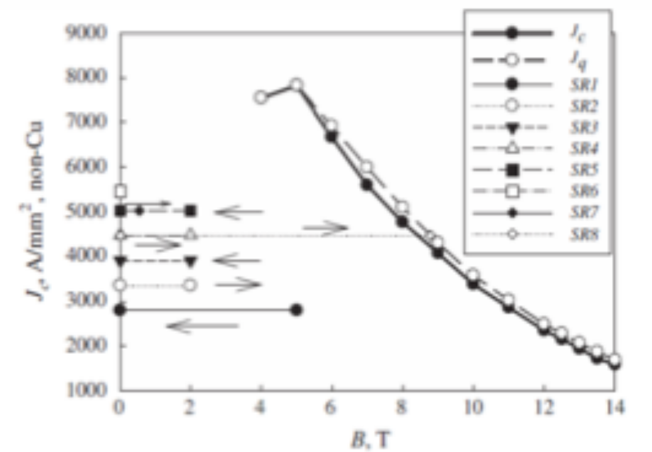
Lumped Parameter model and heat loads for another example design

Superconductor stability

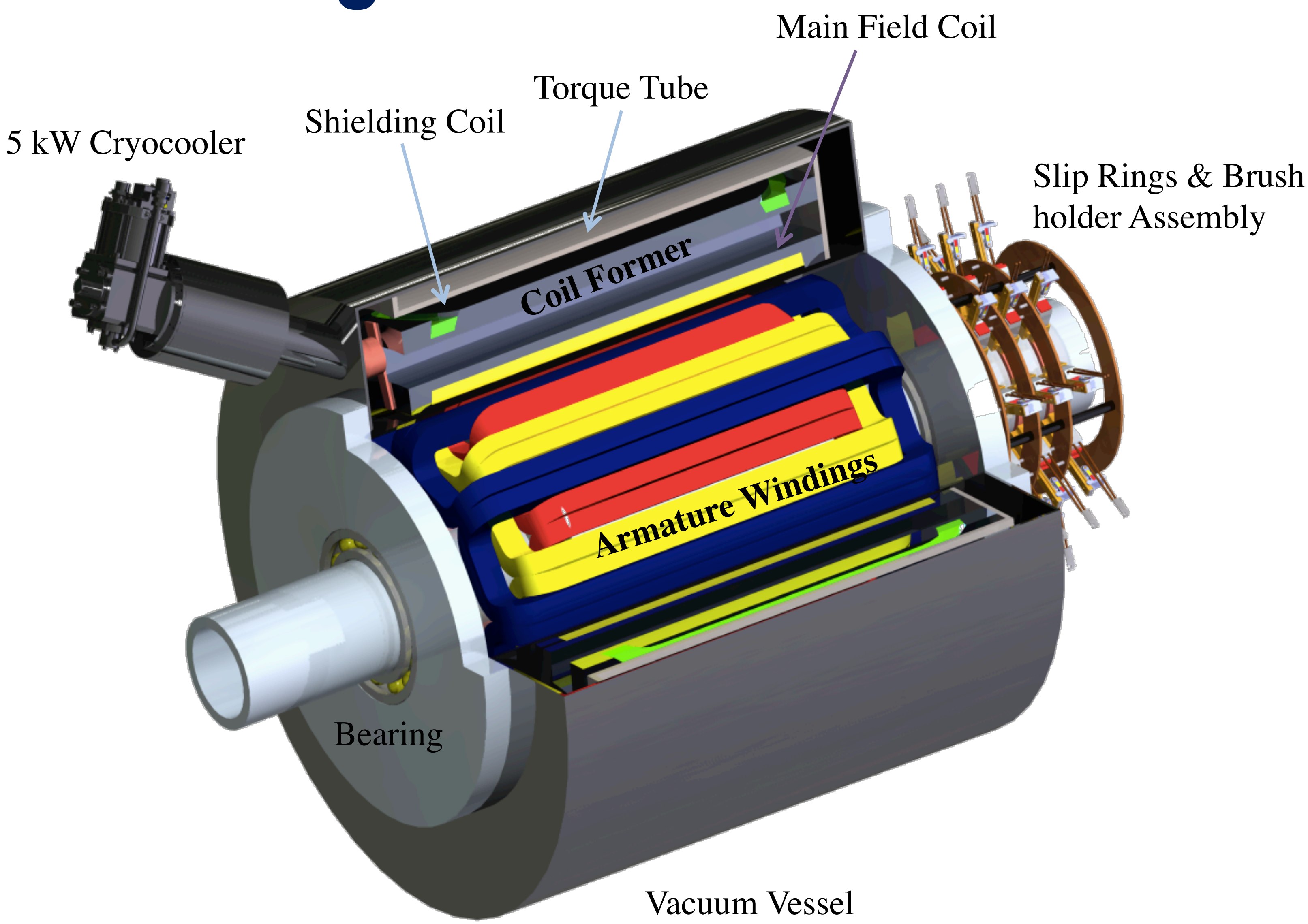
Conductor Characterization at OSU (Sumption) and AFRL (Haugan)

- Conductor J_c vs B for a given conductor type
- Field Ramping stability measurements
- RRR for selected strands
- SEM for a given strand type
- AC losses





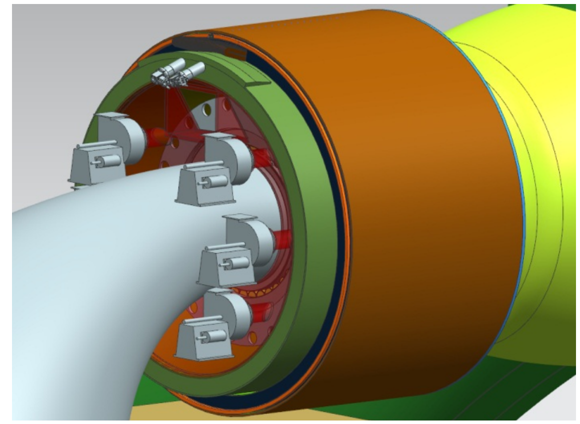
Motor Configuration

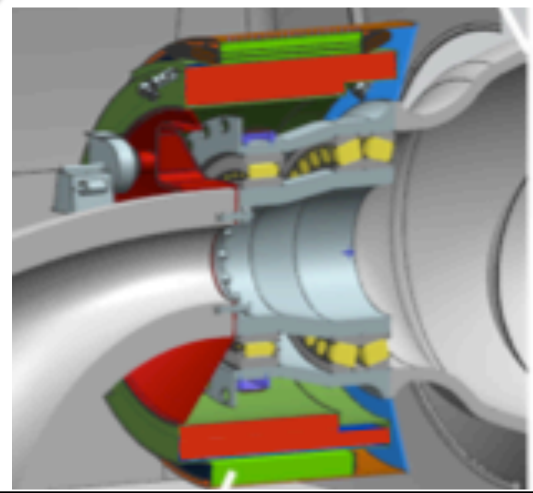


Other applications: Offshore Wind

K. Haran, "10MW+ Direct-Drive Offshore Wind Turbines", Advanced Energy Conference, New York, 2013

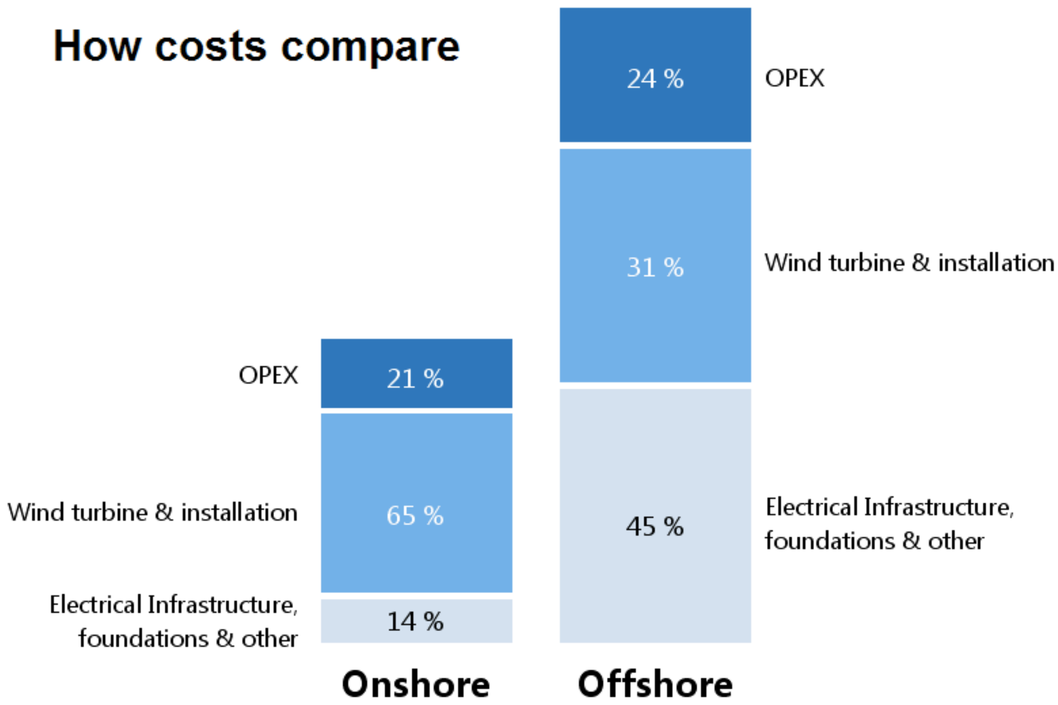
imagination at work



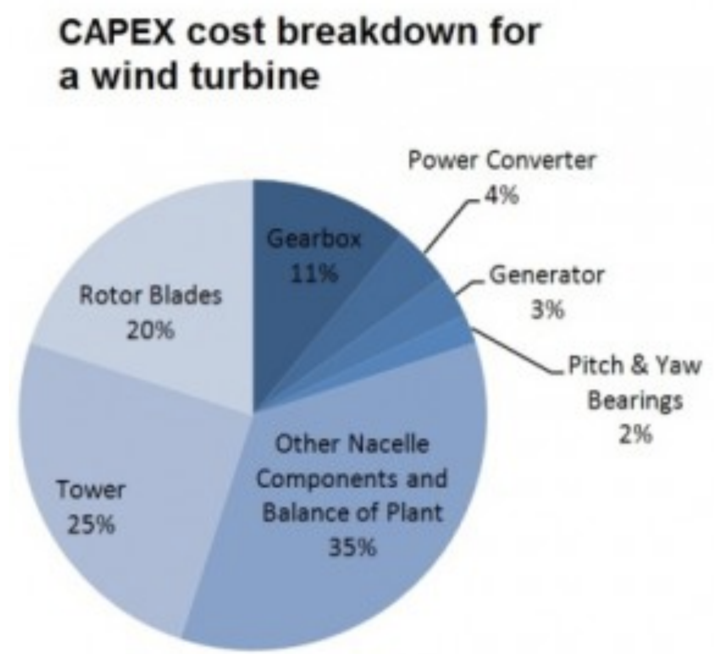


Weight of GE 10MW LTS generator = 93 mt
Further weight reduction possible with completely air core design with higher fields

Offshore wind costs



http://www.windpowerengineering.com/design/mechanical/understanding-costs-for-large-wind-turbine-drivetrains/



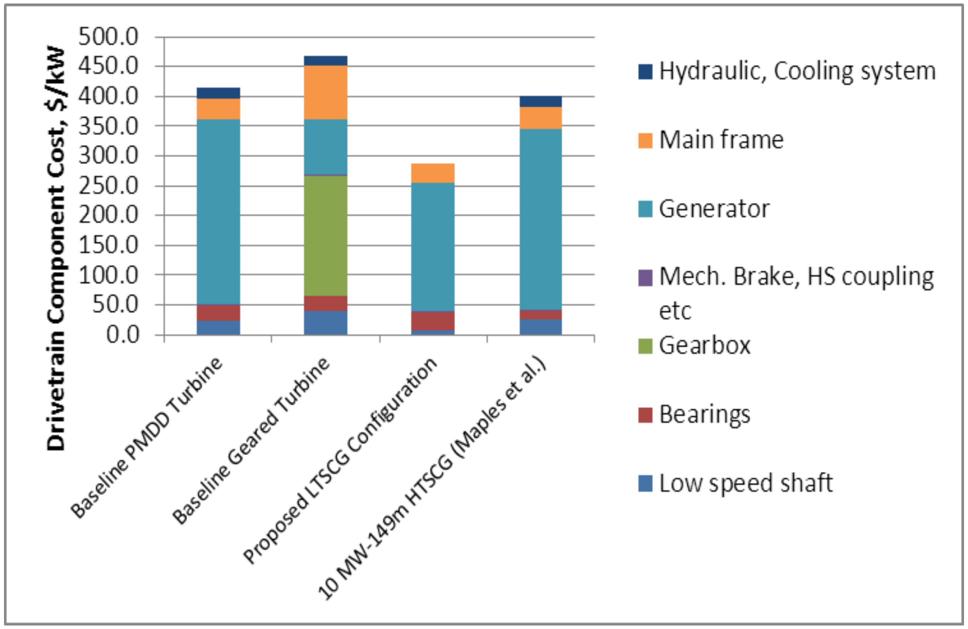
http://www.midwestenergynews.com/2012/03/27/breaking-down-the-costs-of-wind-turbine-components/

Large deviation across different wind sites, turbine architecture, OEM, etc.., but overall costs need to reduced significantly

LCOE Comparisons

Drivetrain Capex

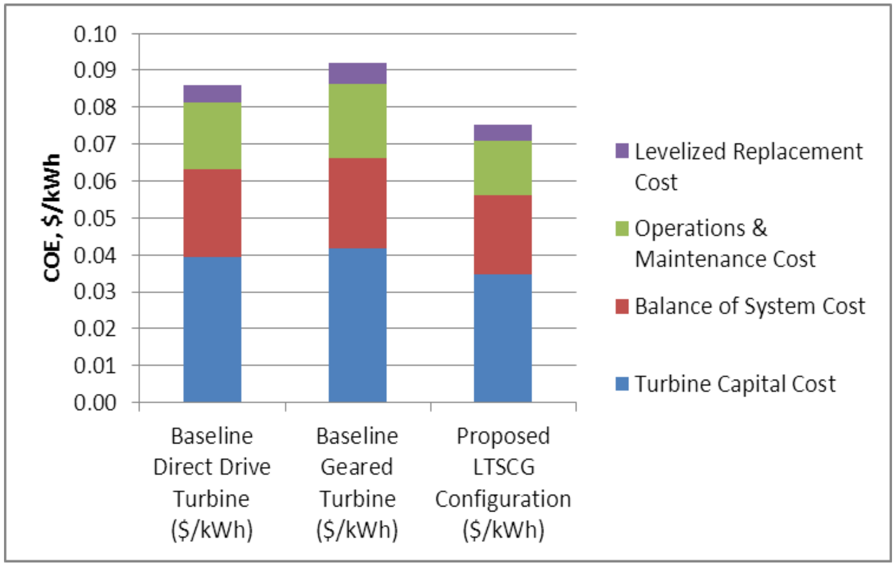
LTSC Generator allows Increasing rating to 10MW and drivetrain cost ($/kW) reduction by 30% over PMDD*, 38% over Geared, 28% over HTSCG



* Based on 2010 Maples et al. (NREL/TP-5000-49086), which assumes 2010 rare-earth material prices

Cost of Energy

- Baseline is 5MW-126m
- Proposed LTSC Gen is 10MW-160m
- COE Reduction
  - 13% reduction from PMDD, with potential to reduce SC wire cost further
  - 18% reduction over geared



imagination at work

Fair, R., et al. "Superconductivity for large scale wind turbines." DOE report (2012).

Discussion