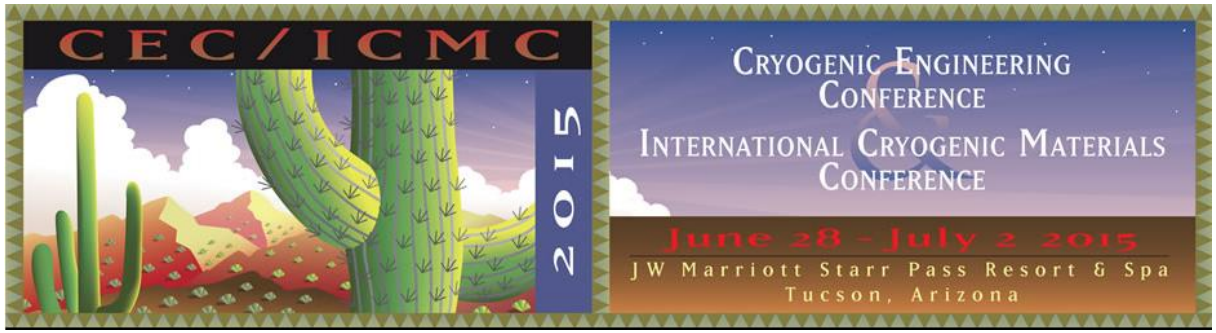

Superconducting Wind Generators: Development and Challenges

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TEXAS CENTER FOR SUPERCONDUCTIVITY

July 1st, 2015

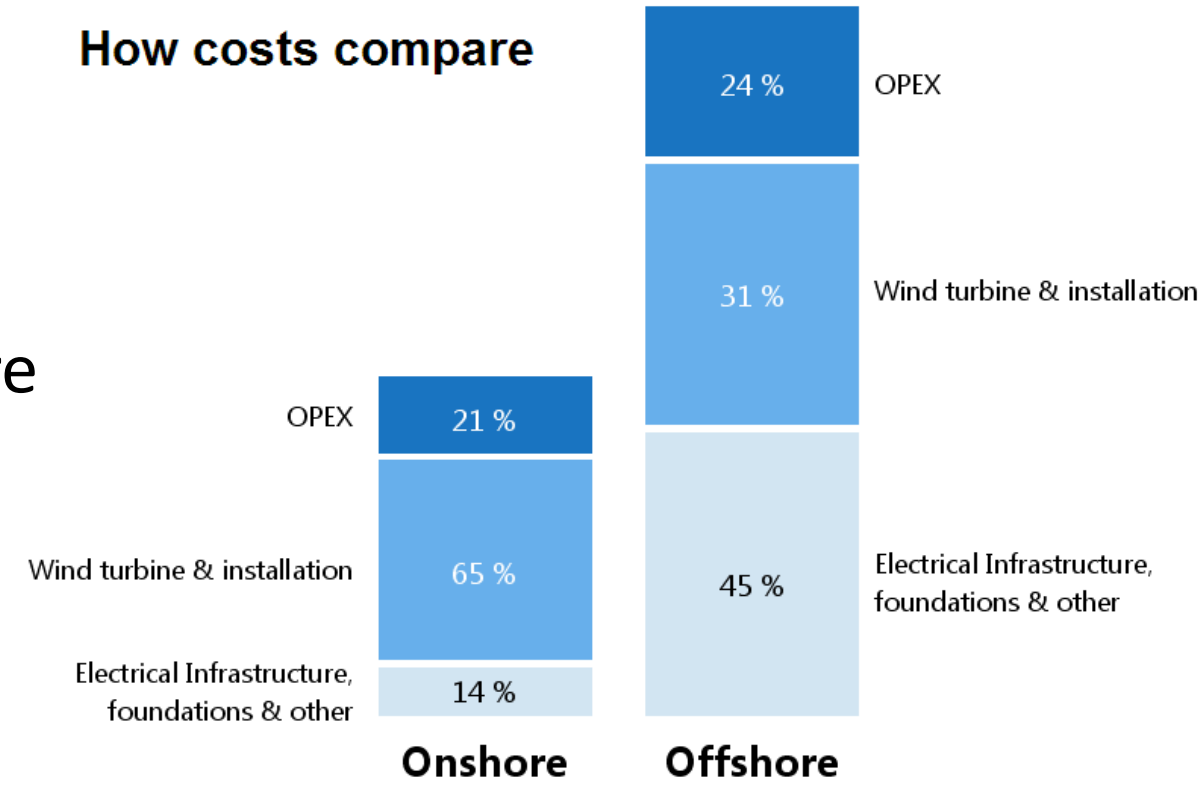
Outline

- Introduction
- Superconducting Generators
- Technical Challenges
  - Design methodology / value propositior
  - Superconducting wire
  - AC losses
    - Accurate estimation
    - Impact on design
  - Protection
    - Quench protection rotor
    - Quench protection stator
    - Short circuit fault
- Barriers to market entry
- R&D Topics Needed
- Summary

http://www.digitaljournal.com/article/319723

Wind Generators – Requirements

- High reliability; high availability
- Low capital cost (CAPEX)
- Ease of manufacture and assembly
- Ease of maintenance
- High efficiency



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

Why Off-Shore Wind?

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- Developed close to the consumer/load
  - Most of the big cities are located near the coast
- High power availability
  - Very steady wind is available off-shore
- Installation and connection cost is very high
  - Need to reduce the number of turbines
    - Increase single turbine power output
  - Need to keep nacelle mass as low as possible
    - Foundation cost
    - Installation cost
- Cost of maintenance is very high
  - Need very reliable turbines
  - Need to reduce required maintenance needs/servicing
- **Need lighter, reliable drivetrain / generators**

http://www.ngpowereu.com/news/europes-push-on-offshore-renewables/

Why Superconducting Generators?

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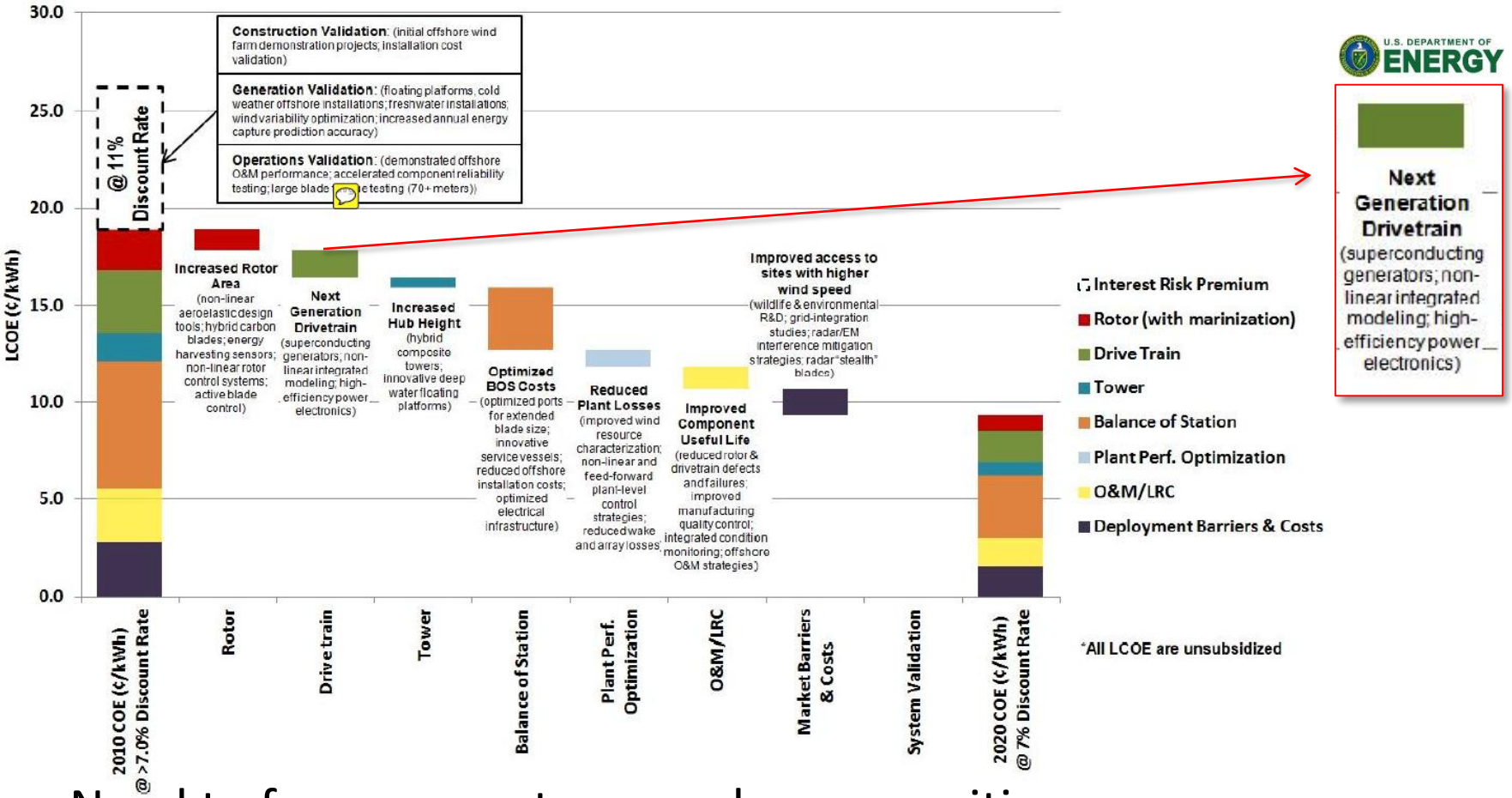
- 10 GW @ **10c/kWh** by 2020, 54 GW @ **7c/kWh** by 2030…today at **27c/kWh**



- Need to focus on customer value proposition
  - Technical advantages ≠ value proposition
- **Cost of energy needs to drive the generator design**

Introduction

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- First Sc. Machine built in 1966
- 49 years later, still no commercial applications…
  - Conventional machines are good for 99% of the industrial applications
    - Decent efficiency, very robust and reliable, inexpensive
  - HTS machines have drawbacks
    - Cooling required at all time
    - High capital cost
    - Reliability not yet proven
    - More complex with more parts
    - Cryogenic system perceived as high risk component
- **<u>Outstanding technical advantages</u>** but no customer value proposition

HTS Machine Possible Configurations

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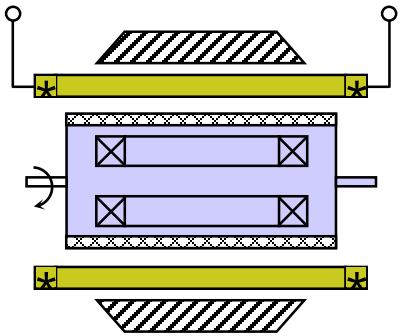
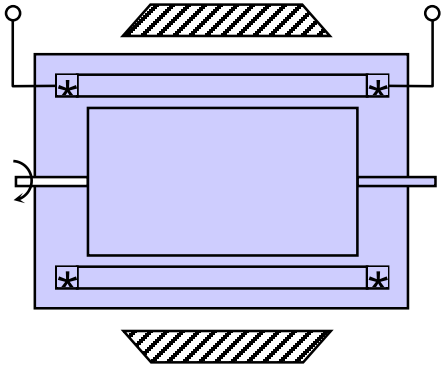
Back Iron



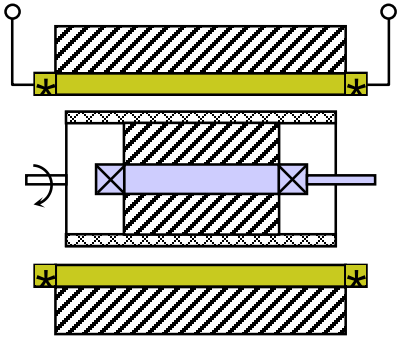
- Low mass
- Large number of poles
- Low x_d
- High short circuit current and torque
- High peak field
- Large quantity of HTS conductor
- Low cooling requirements

Ironless All-Cryo



- Low mass
- Low number of poles
- Low x_d
- **Fault current limitation**
- High peak field
- Very large quantity of HTS conductor
- AC losses
- High cooling requirements

Salient Iron

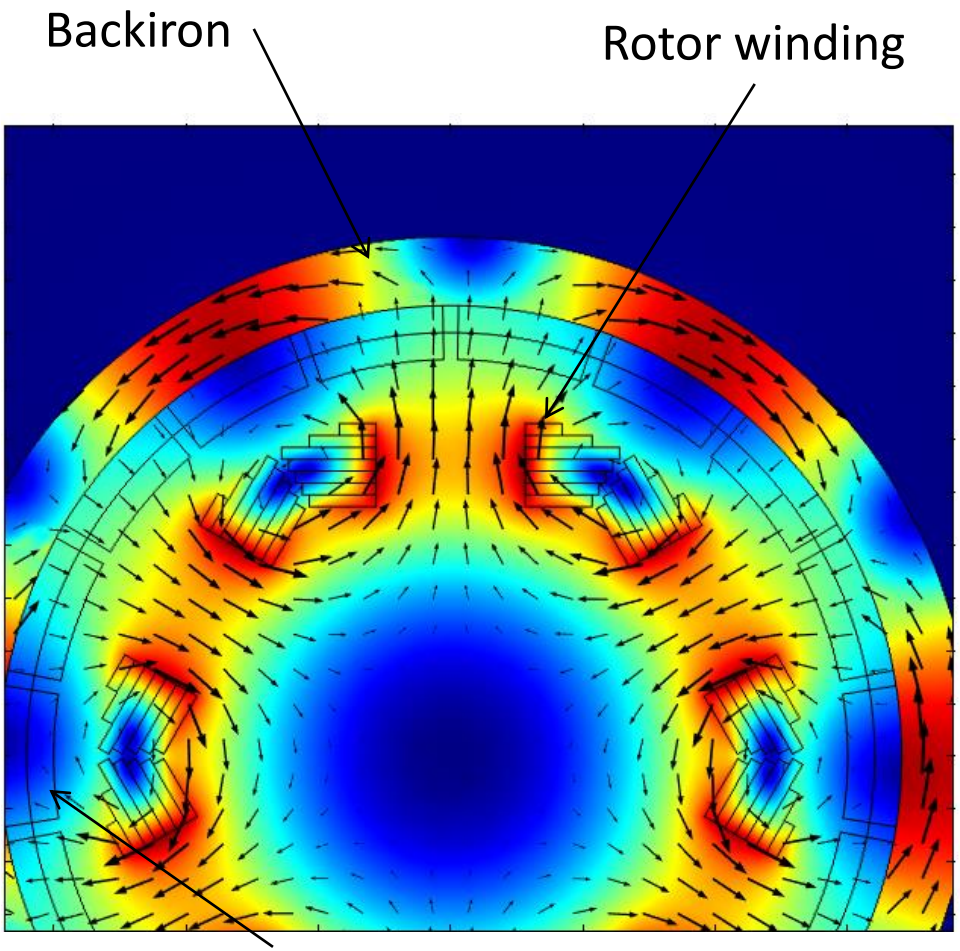


- Heavy
- Reg. x_d
- Low peak field (if not saturated)
- Low quantity of HTS conductor
- Low cooling requirements
- Modular cryostat possible

Courtesy of C. Oberly, AFRL

Field Windings
Armature Windings
Iron
Eddy Current Shield
Cyrogenic region
Output Terminals

Superconducting Machines



- Superconductors operate at cryogenic temperature
  - Require thermal insulation
  - Require active cooling
- Superconductors exhibit a non measureable electrical resistivity
  - free “amp. turns”
  - Iron core can be removed, no saturation, less weight
  - High current density
  - Higher flux density possible
- Superconductors exhibit AC losses in variable field and current
  - Requires large enough cooling power
- Torque transfer and support structure
  - Composite material

Partially and Fully Superconducting Machines

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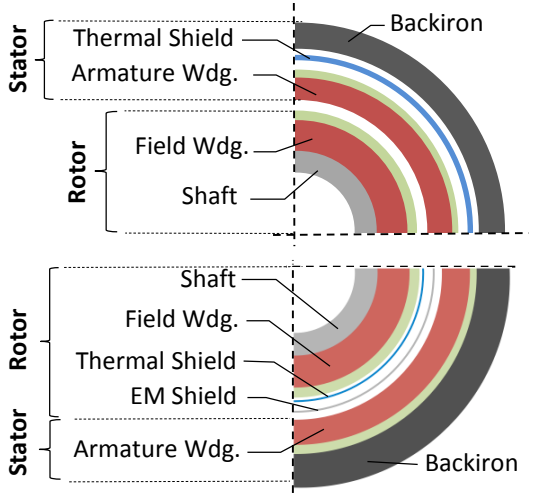
Fully Superconducting (FSG)



Partially Superconducting (PSG)

Apparent Power output of an electrical generator:

$$S = B_r^0 K_s \pi r_0^2 L_a \frac{\omega}{p}$$

Rotor contribution
Limited by conductor performance.
More conductor needed in PSG because of the large air gap

Active volume
Larger radius needed for PSG because of the limited electrical loading

Stator contribution
Much higher values obtained in FSG because of high current density in superconductor

Rotation speed
Frequency needs to be kept low in FSG to limit AC losses

S = *apparent power (VA)*
B_r^0 = *no-load excitation field (T)*
K_s = *electrical loading (A/m)*
R_0 = *average radius of armature winding (m)*
L_a = *active length (m)*
ω = *angular frequency (rd/s)*
p = *number of pole pairs*

Different Configurations

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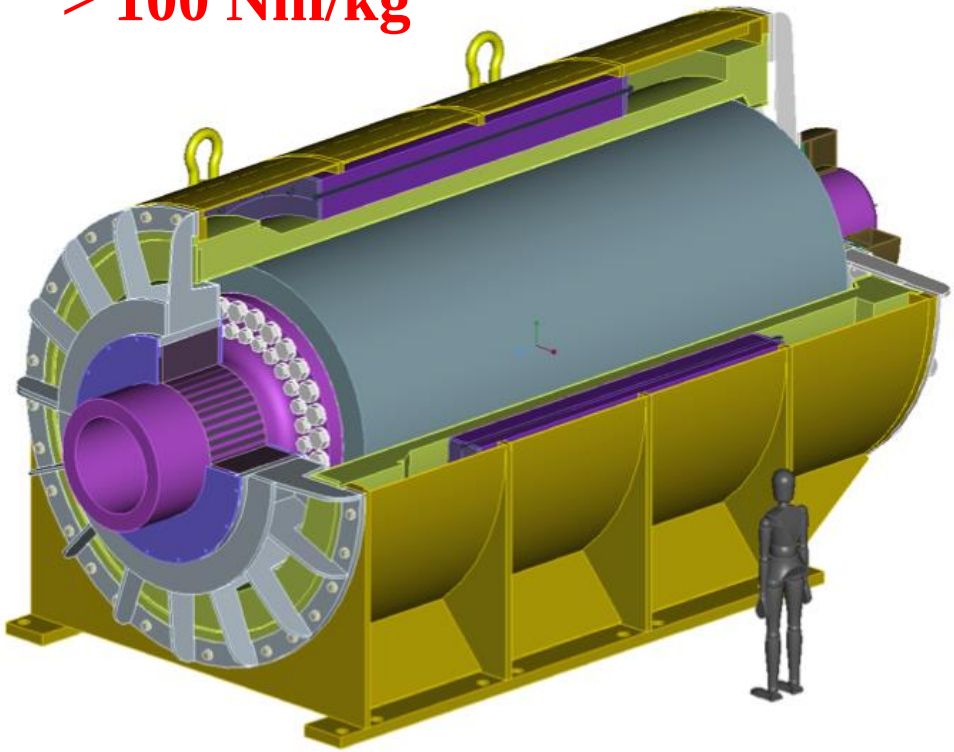
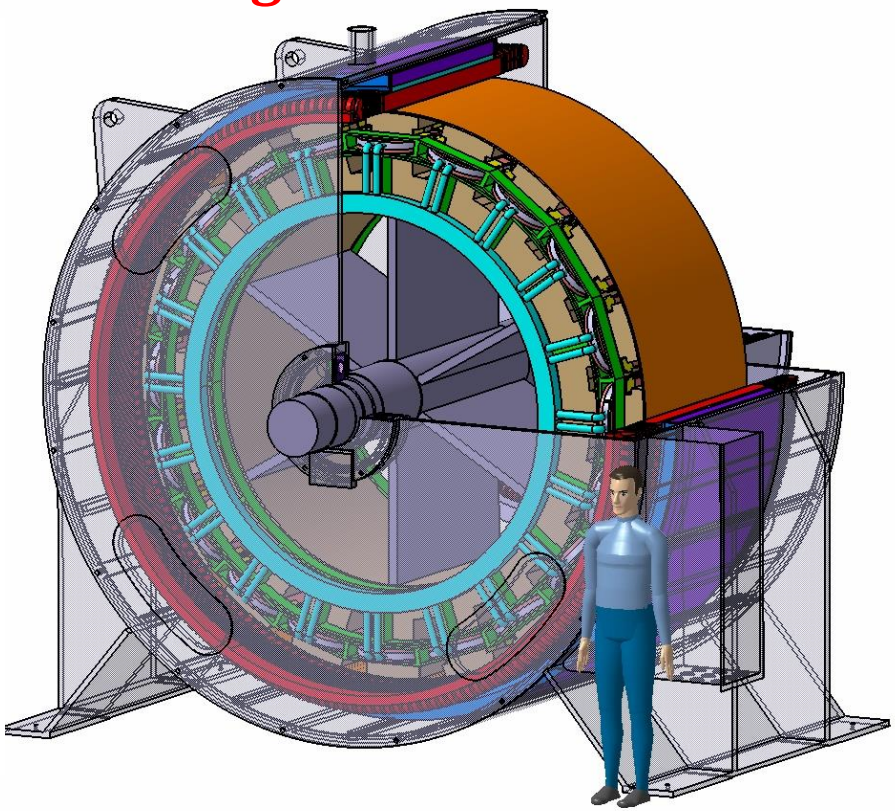
> 100 Nm/kg



> 50 Nm/kg



Fully superconducting generator

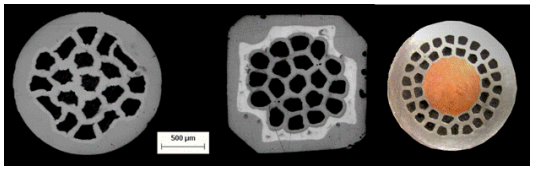
- Low number of poles
- Elongated machine

Partially superconducting generator

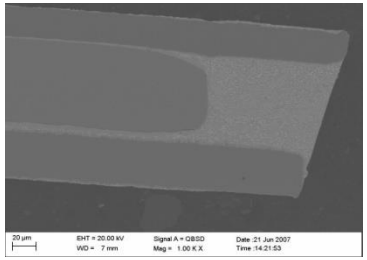
- High number of poles
- “Ring” machine

Design Requirements

- Economic
  - Low cost conductors
  - Low cost cryocoolers
  - Superconductor availability
  - Cost effective manufacturing
- Mechanical
  - Torque transmission/torque tube
    - Composite - steel
  - “Large” Lorentz forces (peak field >4 T)
  - Torque and forces applied on conductors

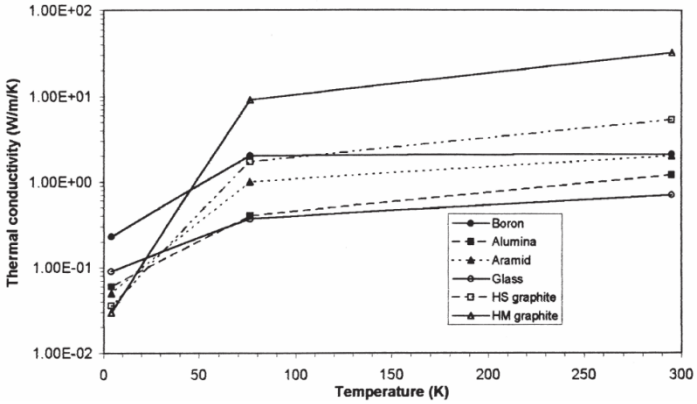


MgB2 conductor



2G conductor

- Thermal
  - Heat leaks need to be minimized
    - Conduction through shaft
    - Current leads
    - Splices
  - AC losses
    - Multifilament conductors
- Stability
  - Quench detection/protection
  - Fault current/torque



Carbon fiber composite thermal conductivity

HTS Generators – Value Proposition

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- Generator mass reduction ☑
  - Limited impact on LCOE
- High reliability; high availability ☑
  - No gear box
  - No thermal cycling
  - Sealed system
    - Long maintenance time if problem in cryostat
    - No failure allowed at cryogenic temperature
- Potential low capital cost (CAPEX) ☑
  - Driven by cost of conductor and cooling system
  - Expected to be competitive for large systems
- Ease of manufacture and assembly
- Ease of maintenance ☑
  - Less reliable components should be located outside of the cryostat
  - Modular approach can be used (individual cryostats…)
- High efficiency ☑
  - Low losses, high efficiency at fractional power output

http://www.ngpowereu.com/news/europes-push-on-offshore-renewables/

Design Methodology

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- Usually superconducting generators for wind turbines are designed for **mass and volume reduction**
  - Easier transportation, installation
  - Leads to high cost and requirements for less expensive conductors

- Mass may not be the key parameter
  - Need to **design** the generator w.r.t. the **LCOE** at the level of the wind turbine or even better of the wind farm
  - The generator mass/cost needs to be constrained but only represents a component of the system to optimize

LCOE Lead Generator Design

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- Developed to perform **Trade-Off Analysis** for 10 MW 4X HTS generator
  - 10 MW, 8 RPM
  - design space exploration to determine the configuration leading to minimum

arpa·e Advanced Research Projects Agency • ENERGY

OBJECTIVES

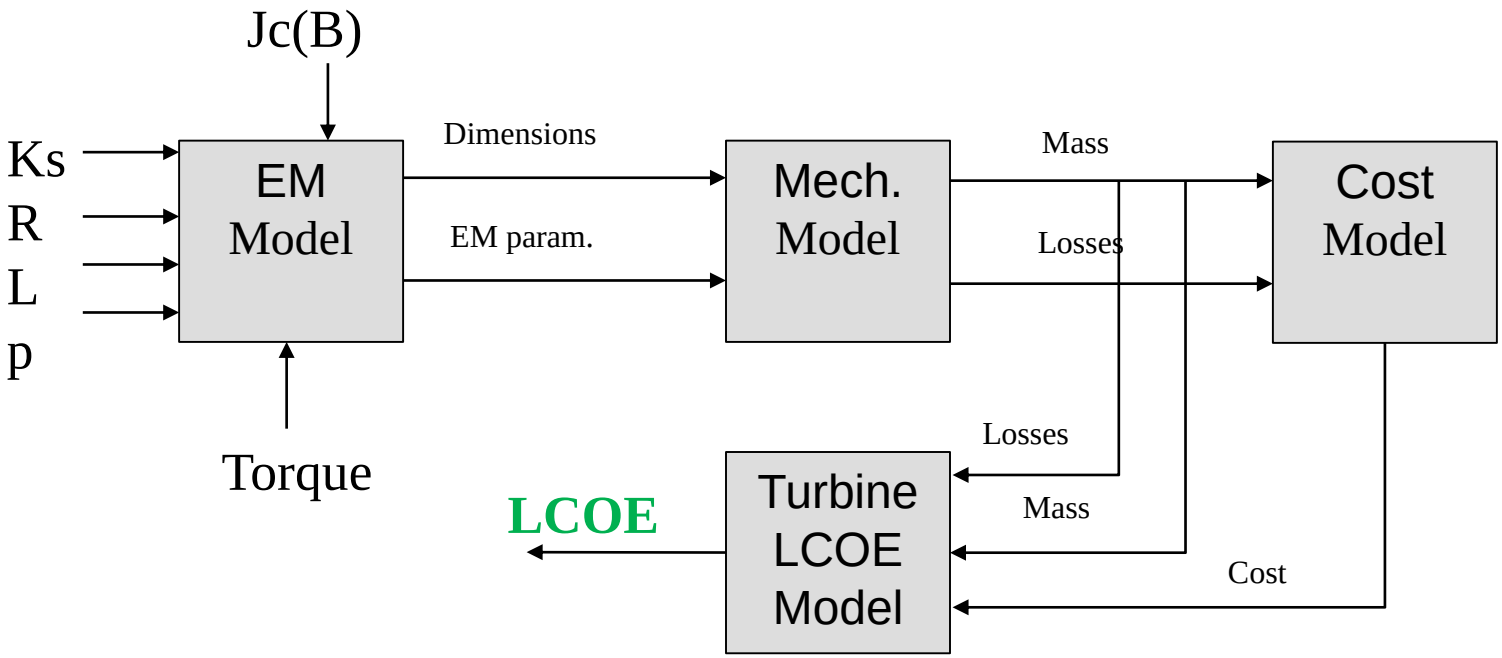
Investigate the impact of

- Number of pole pairs
- Radius and aspect ratio
- Electrical loading

On

- LCOE

LCOE Driven HTS Generator Design



- **Need better models for LCOE (<u>scaling laws are not enough</u>)**
- Current LCOE models are not able to capture some of the important aspects of the impact of superconducting generators on the turbine design

Electromagnetic and Mechanical Model

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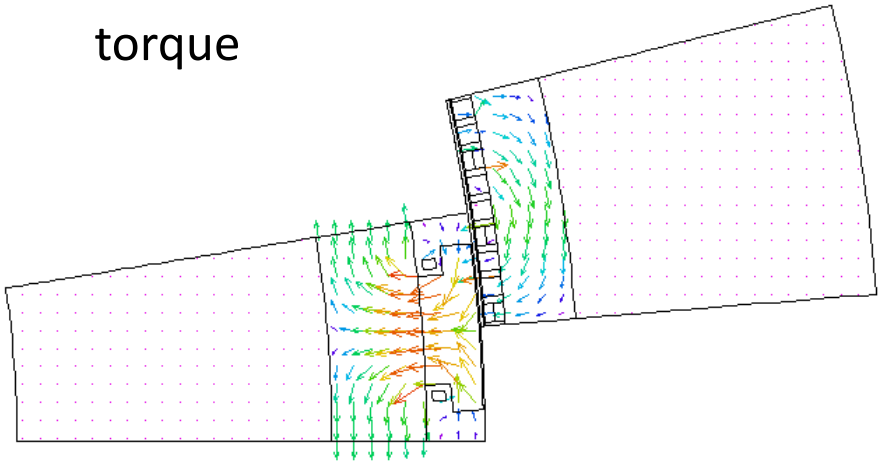
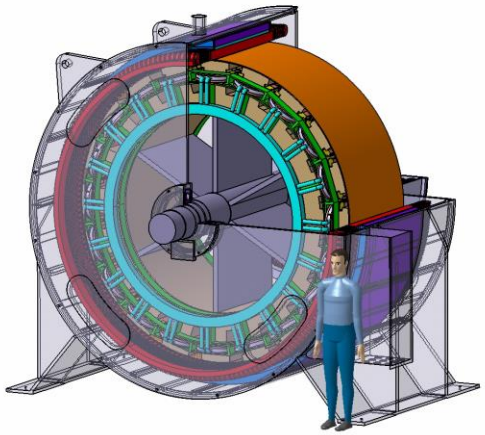
- Based on FlexPDE
- Inputs:
  - KS, R, La, p, Torque, Jc(B)
- Outputs:
  - dimensions of the active components
  - Excitation coils operating current

- A solver finds the volume of HTS tapes and the machine radius to reach the desired torque

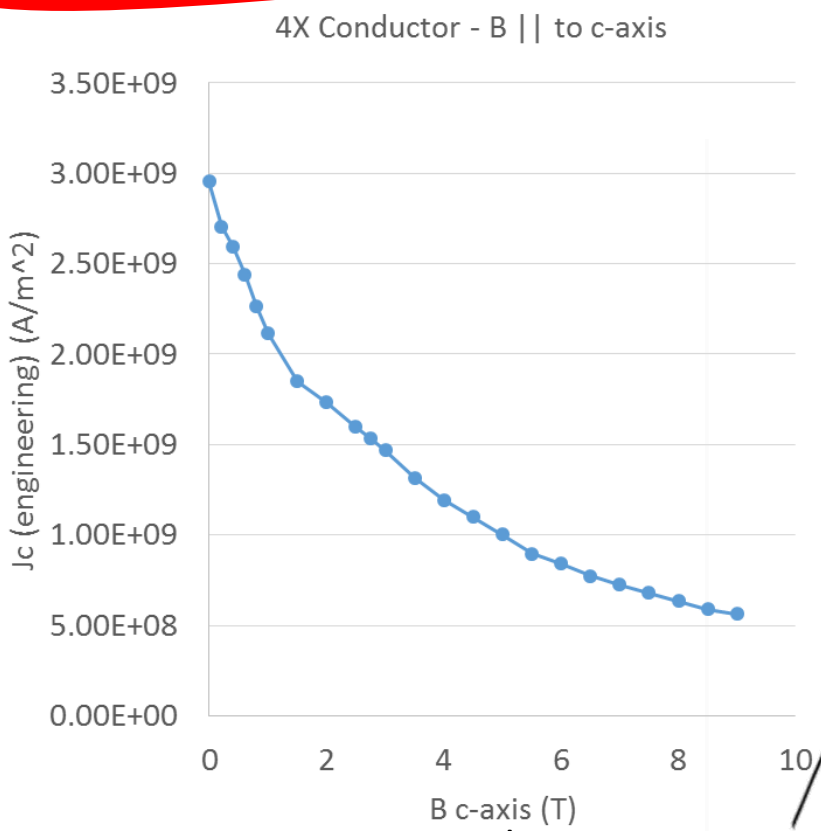


- Mechanical model was developed in collaboration with motor manufacturer
  - Includes all inactive components (structure, cooling…)

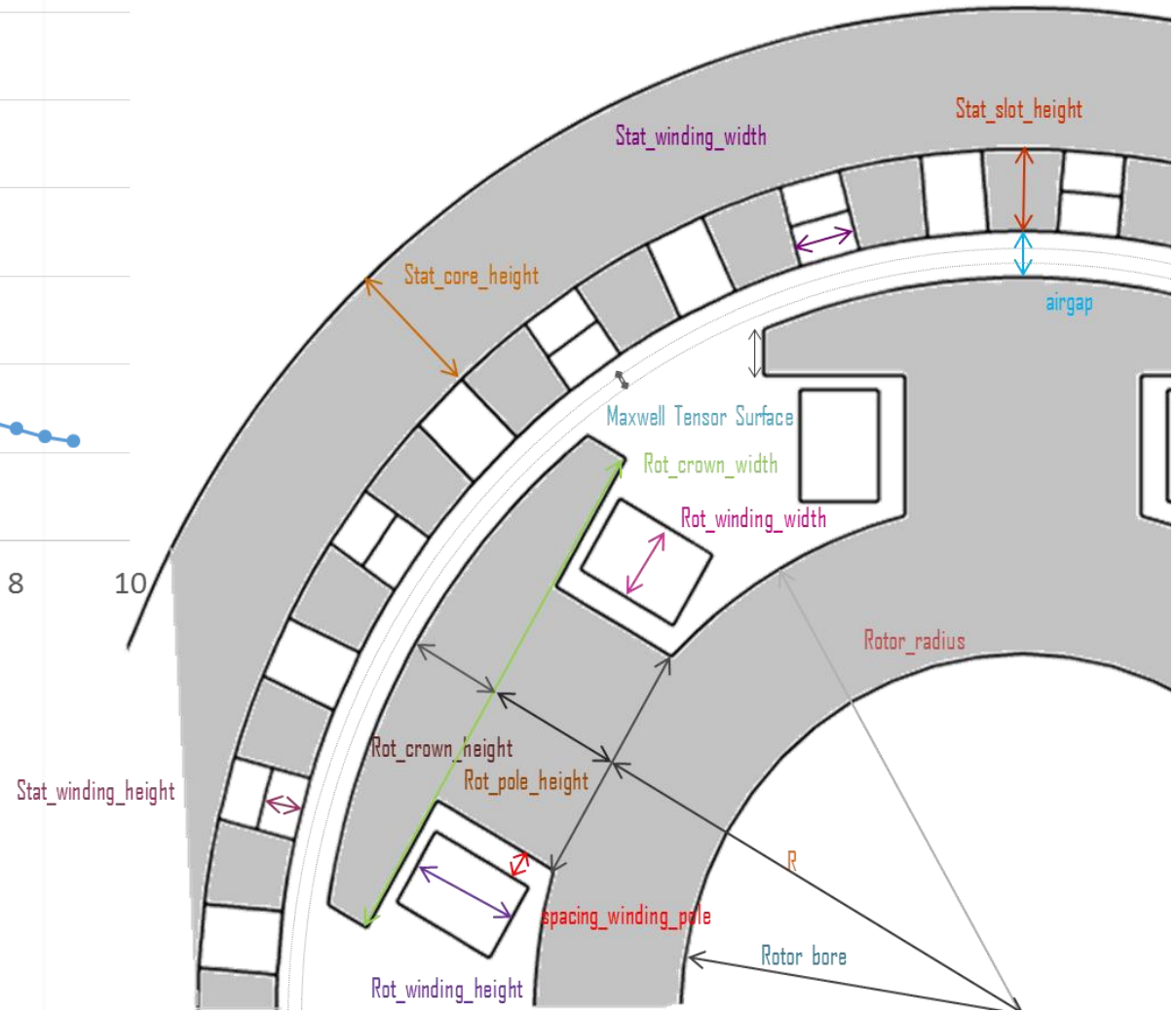


- Cost was model was built based on machine manufacturer estimate for
  - Active materials
  - Inactive components
  - Labor
  - The cost estimate is aggressive and includes uncertainties to be considered in the analysis

Fully Parameterized Generator Model



- In-house code in Python
- FEA solver – **FlexPDE**



- Engineering current density Jc(B) was estimated for tapes based on:
  - 12mm width
  - 0.15 mm thickness
  - Ic=2760 A @ 2.75 T @ 35 K

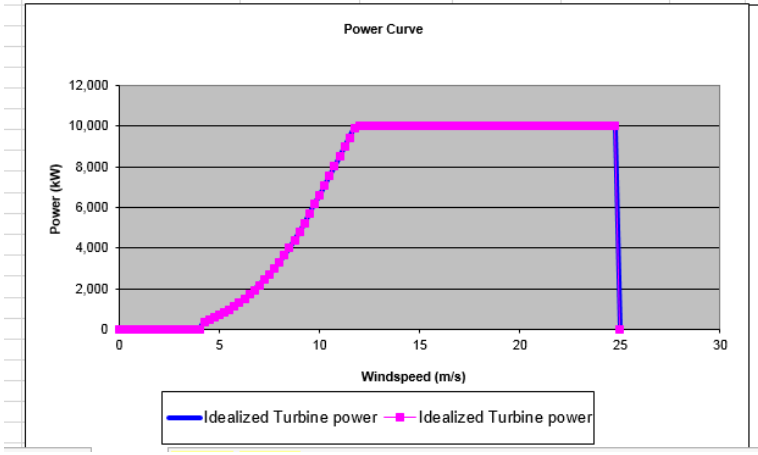
LCOE Model

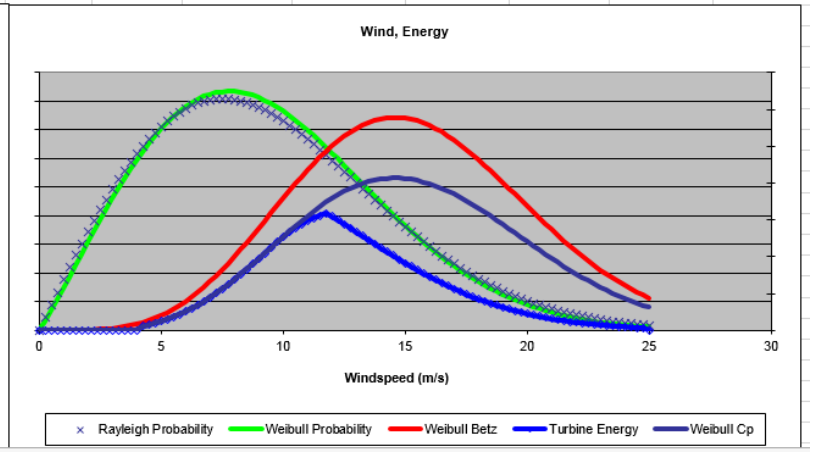
- LCOE model was developed by NREL
  - 10 MW – 8 RPM turbine

50 m windspeed	8.4	m/s		
Weibull K parameter	2.10			
Rated power	10000	kW		
Rotor Dia.	181	meters		
Hub height	110	meters		
Altitude	0	meters		
Rotor Cp	0.47			
Tip speed ratio for max Cp	8			
Maximum tip speed	76	m/s		
Region 2 1/2 slope	5%			
Cut-in windspeed	4	m/s		
Cut-out windspeed	25	m/s		
Power law shear exponent	0.143			
Rated RPM	8.0	OK	508.9423338	
Air Density	1.225	kg/m^3		
Hub height windspeed	9.40			
Rated hub power	11086.475	kW		
Rated windspeed	11.80	m/s	11.44	11.97
Soiling Losses	0.0%			
Array Losses	15.0%			
Availability	95.0%			
Torque	13,201,657	Nm		
Energy capture (MWh/year)	36362.91	Weibull Cp	Weibull betz	
Capacity Factor	41.51%	85318.19	120241.23	
Energy capture ratio	42.62%	63988.6451		

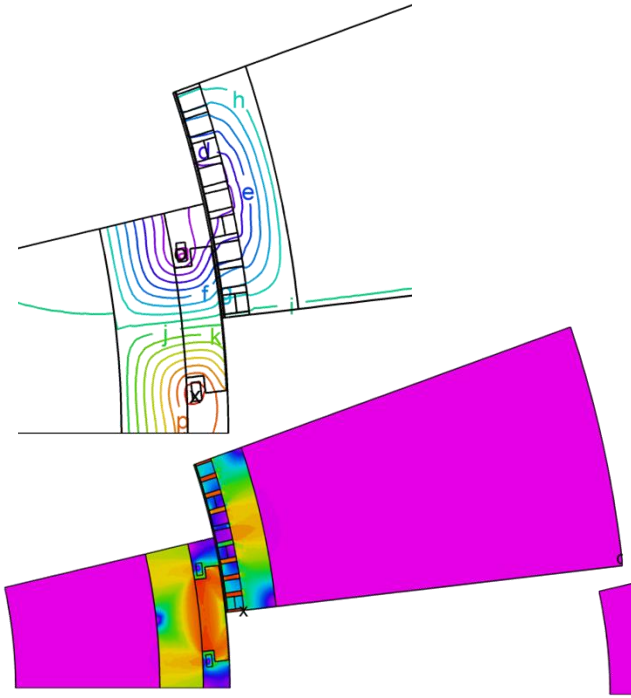
		Notes
Other Capital Costs ($)	42,000,000	Represents items not influenced by generator design.
Tower Capital Cost ($)	696,375	Simplified assumption
Foundation Capital Cost ($)	6,551,300	Simplified assumption
Fixed Charge Rate	8%	Value used by DOE
Annual Energy Capture (MWh/yr)	36,363	From cell C24
HTS Generator Cost ($)	-	From UH/TECO models
HTS Generator Mass (Tonnes)	0.0	From UH/TECO models
Remaining Drivetrain Cost ($)	2,500,000	
LCOE ($/kWh)	**0.114**	
Drivetrain LCOE ($/kWh)	0.006	Change the FCR to 14% to compare to <$0.022/kWh goal

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



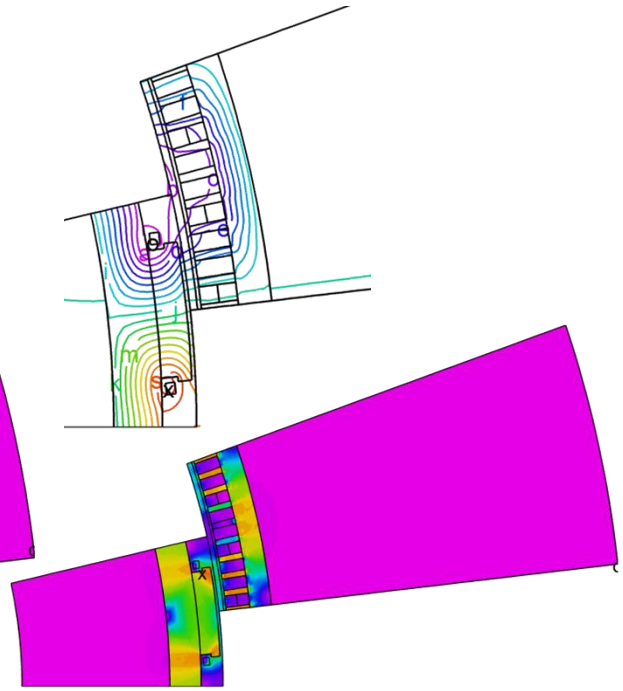


Examples of Designs Generated



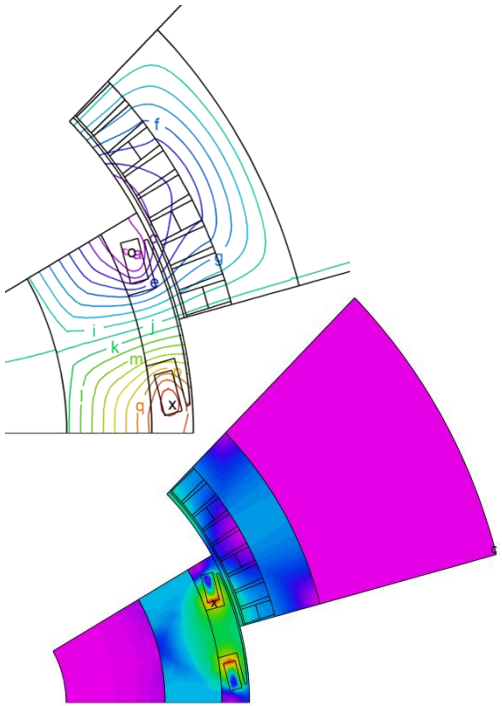
model A

Iron poles
15 km of
HTS



model B

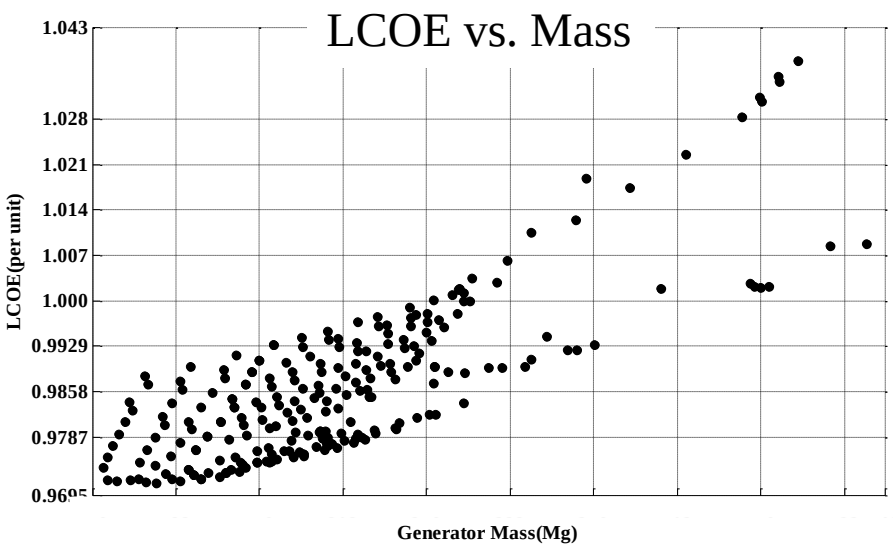
Iron poles
Lower rotor field
Thicker stator
7 km of HTS

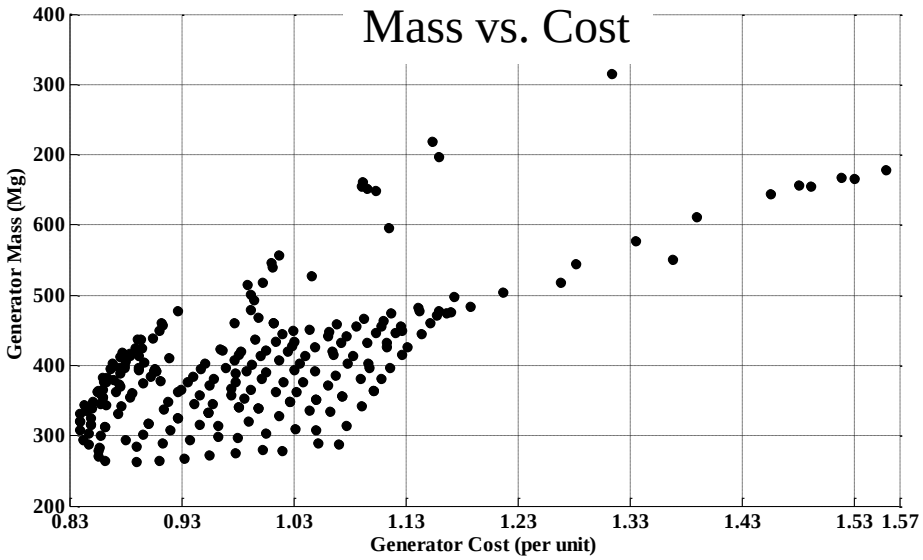


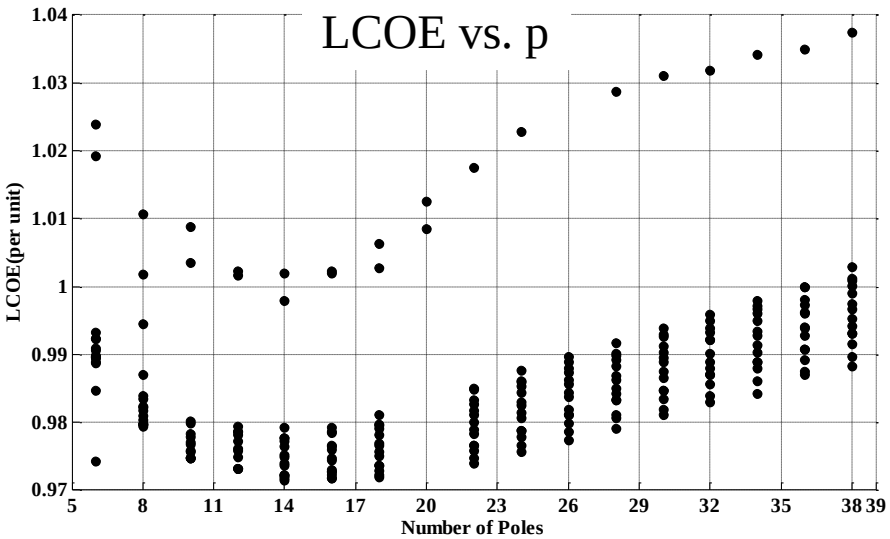
model C

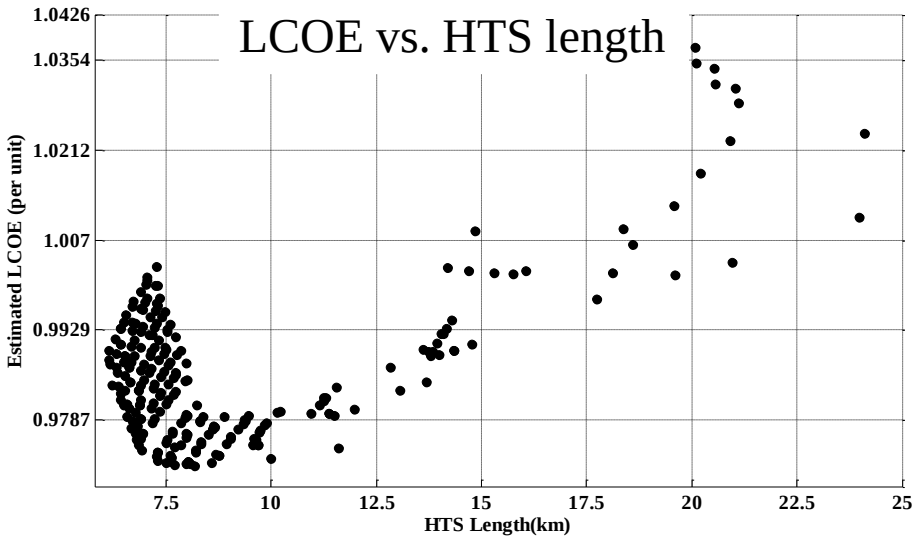
No iron poles
High excitation
field
92 km of HTS

Example of Monte-Carlo Design Space Exploration



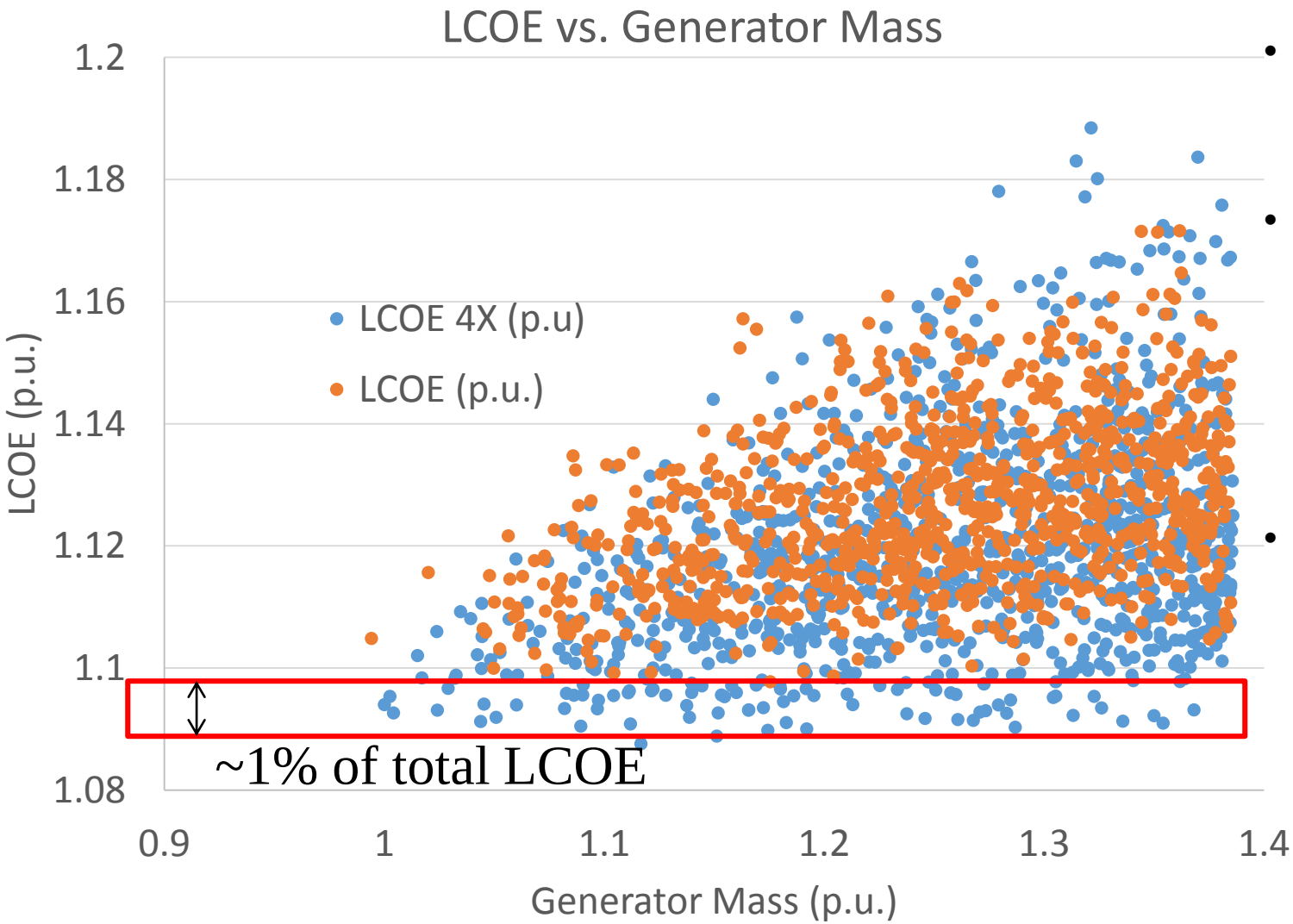






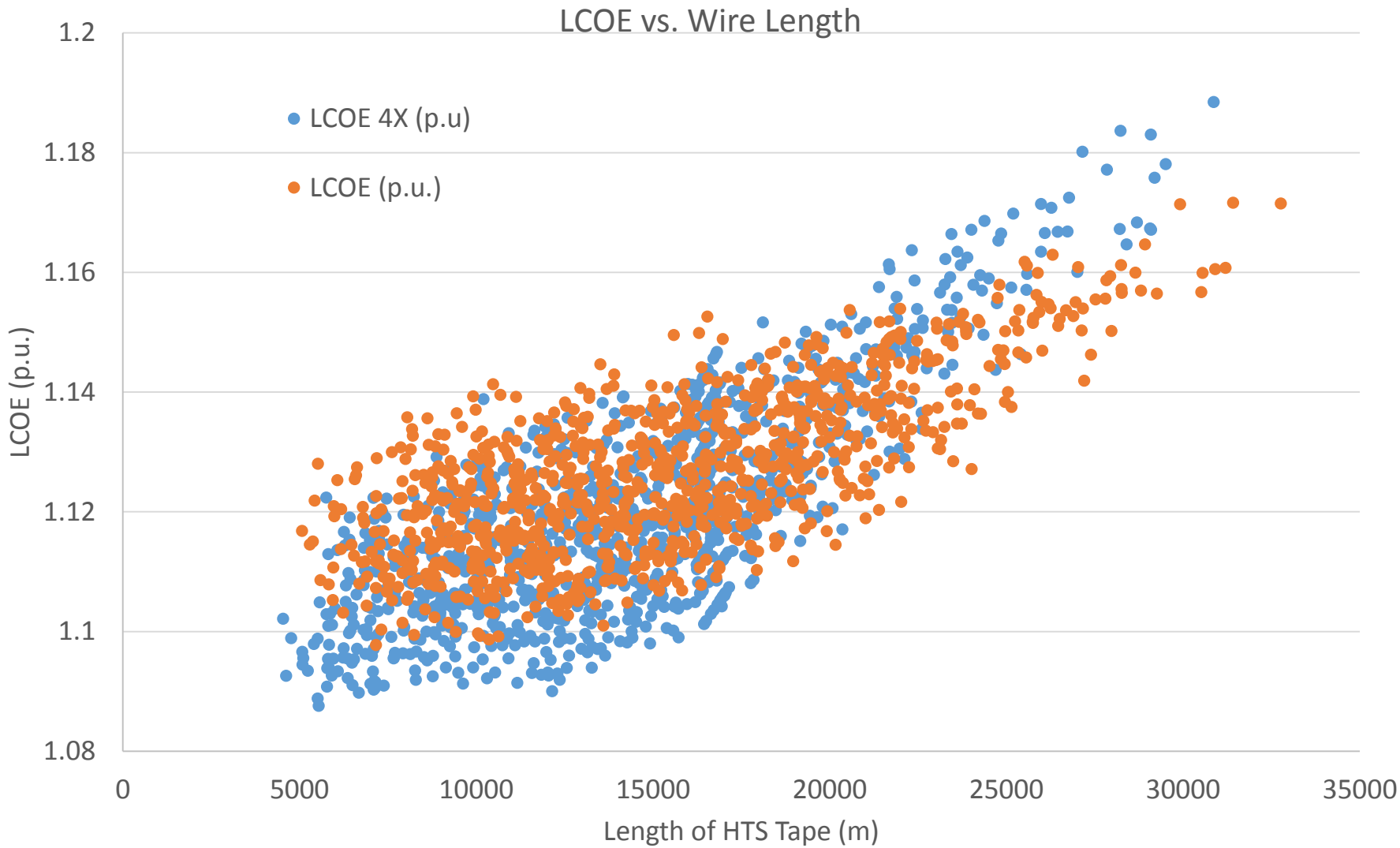
10MW, 8RPM Iron-core generator with YBCO excitation coils

Impact of Conductor Performance on LCOE – Iron-core Generator



- Design is very flexible
- A different optimum is found w.r.t. conductor performance
- Estimating impact of high performance conductors is not straightforward

LCOE vs. HTS Length - Iron-core Generator



LCOE Lead Generator Design

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- Higher fidelity LCOE models are needed at the wind farm level
  - Considering the unique properties of superconducting generators
    - Short circuit conditions (current limitation)
    - Low frequency
    - Potential low mass and volume
- Higher fidelity large scale production generator cost model needed
  - Manufacturing
  - Projected cost of material
- High fidelity wind farm components cost and sizing models needed
  - Cooling plants
  - Power converters
  - …

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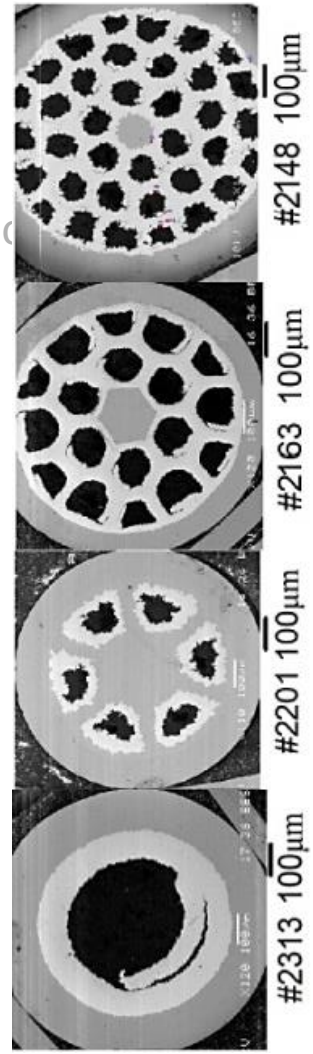


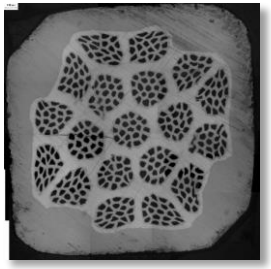
Supercond. Sci. Technol. 26 (2013) 025002

http://www.uh.edu/news-events/stories/2010articles/March2010/033010UHResearchModernizesUSPowerGrid.php

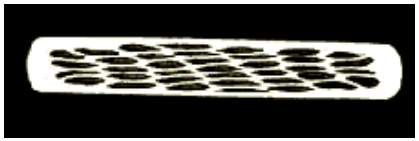
Choice of Conductor

- **The conductor defines the operating temperature of the system**

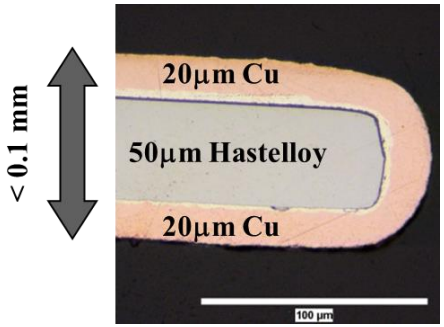
- **Key conductor parameters :**
  - Engineering critical current density @ operating field
  - Filament size (AC applications)
  - Twist pitch
  - Ratio superconductor/ non superconductor
  - Minimum quench energy
  - **Normal zone propagation velocity**
  - Minimum bending radius
  - **Cost**



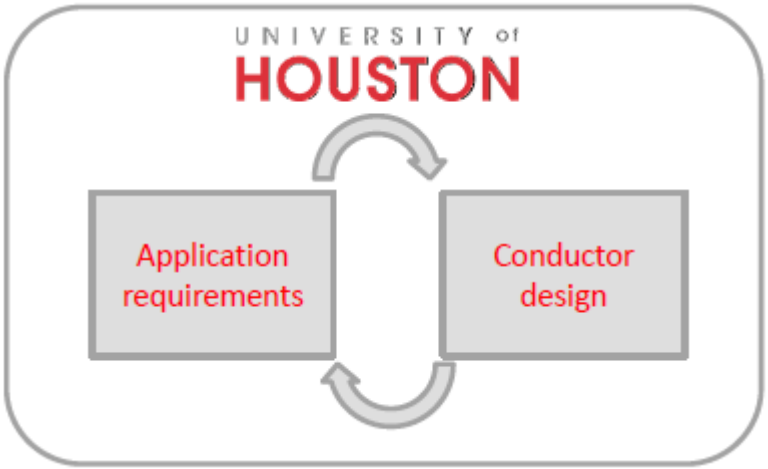
MgB2 conductors



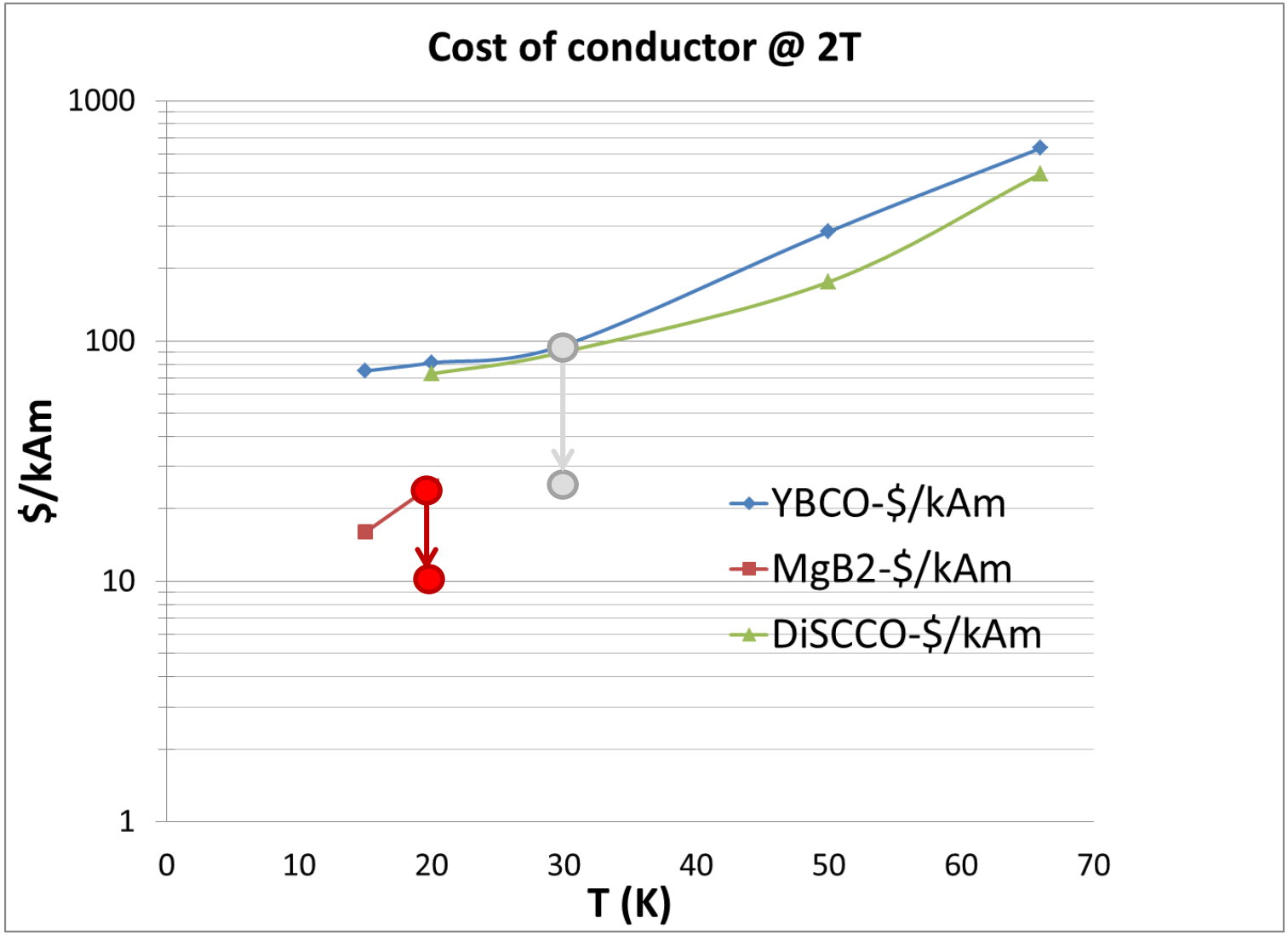
BiSrCaCuO conductors



YBCO conductors



Current and Predicted Cost of HTS Wires



ARPA-E funded program for High Performance Superconducting Wires and Coils

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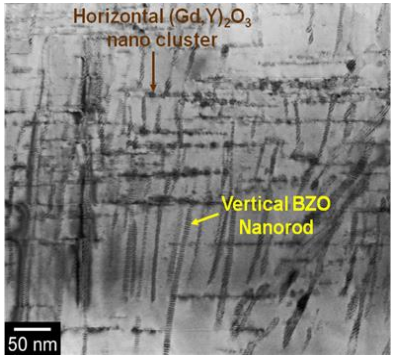
5X performance achieved at 30K, 3T

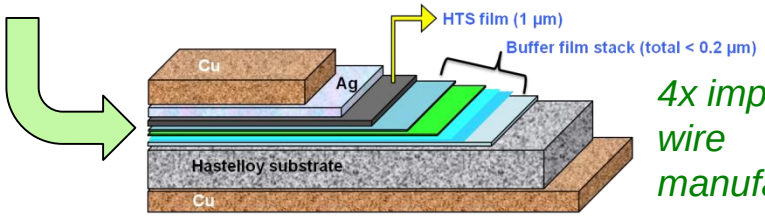
- ARPA-E funded program
- UH-led program with SuperPower, TECO-Westinghouse, Tai-Yang Research and NREL.



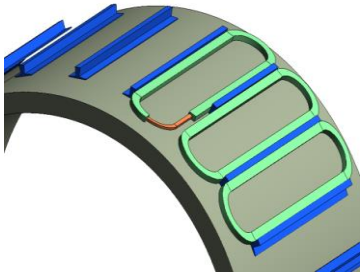
Technology Impact

Present-day superconducting wire constitutes more than 60% of the cost of a 10 MW superconducting wind generator. By quadrupling the superconducting wire performance at the generator operation temperature, the amount of wire needed would be reduced by four which will greatly enhance commercial viability and spur a tremendous growth in wind energy production in the U.S.

Engineered nanoscale defects



4x improved wire manufacturing



Lower cost Generator coils

High-power, Efficient Wind Turbines

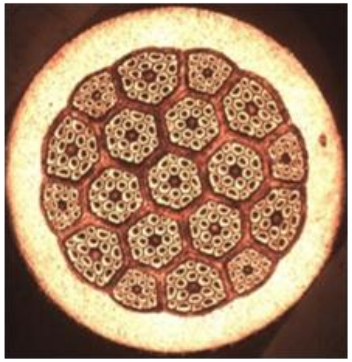
Quadrupling Superconductor Wire Performance for Commercialization of 10 MW Wind Generators

Low AC loss MgB_2 conductor development

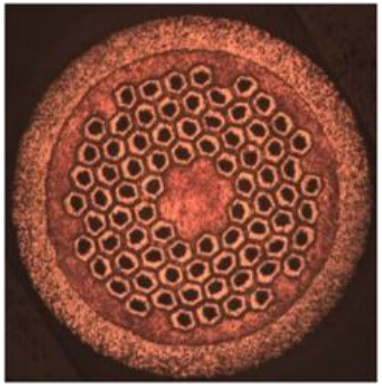
Successful strand design recipe:

- small d_{eff}
- small twist pitch
- resistive matrix
- non-magnetic sheaths
- higher T_{op} (e.g. 20K); lower B_{op} (e.g. 0.6T)

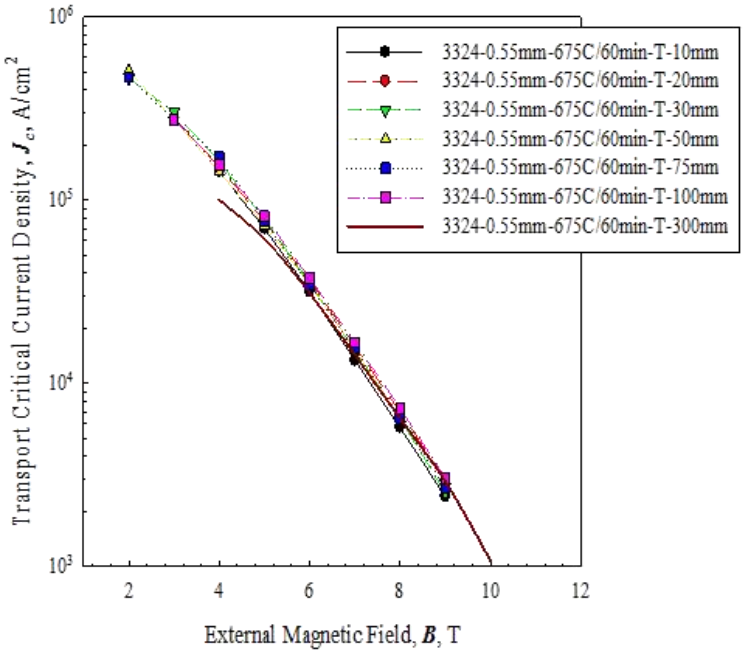
Good J_c measured at 10 μm filaments at 0.29 mm diameter. Work progressing to t obtain 10 μm filaments with larger wire diameters.



342 filaments



78 filaments



J_c maintained with twist pitches as low as 10 mm.

Hyper Tech

2

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    - Quench protection rotor
    - Quench protection stator
    - Short circuit fault
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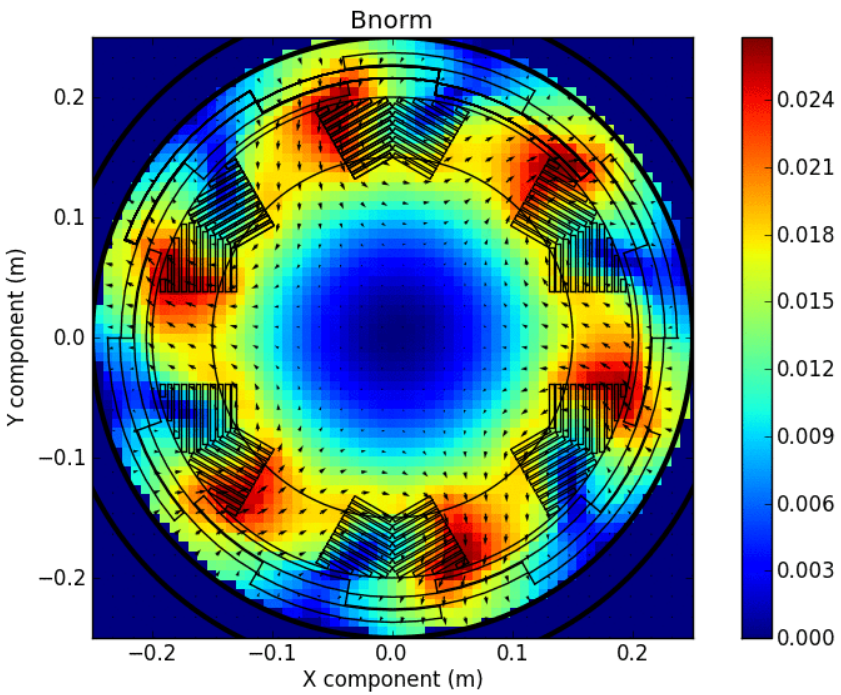
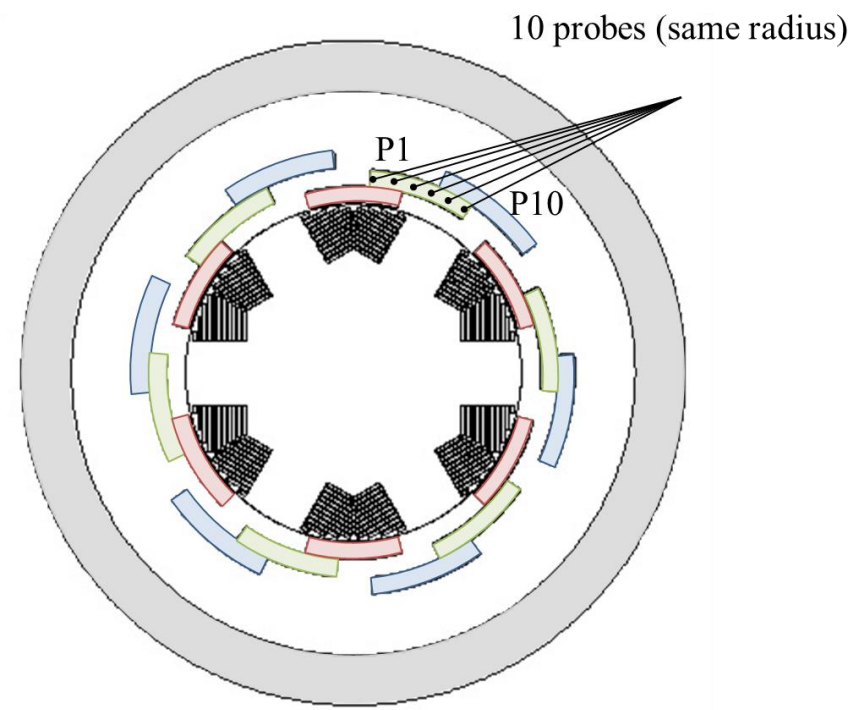
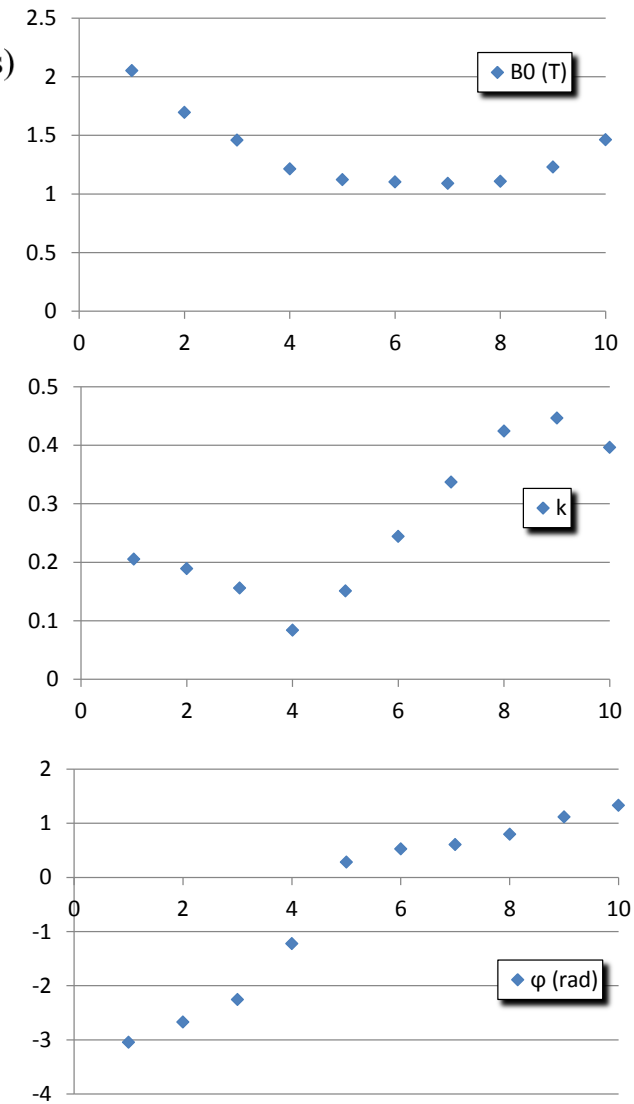


Stator Conductors Magnetic Environment





Peak field

Rotating/pulsating

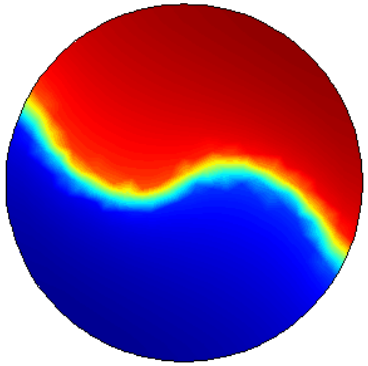
Phase angle rotating-pulsating

In 1 pole, each stator conductor is in a unique magnetic configuration

+ out-of-phase transport current

AC Losses Estimation

- AC losses in in stator
  - Largest heat load in the system
  - key design parameter
- Conductors are exposed to magnetic flux densities in the range 0-2 T
- Elliptical field + out-of-phase transport current
  - Conventional scaling laws are not usable
  - Need validated new scaling laws



Current density in superconducting filament subjected to elliptical field

AC Losses Model for Multi-Filamentary Conductors in Elliptical Field with Out-Of-Phase Transport Current

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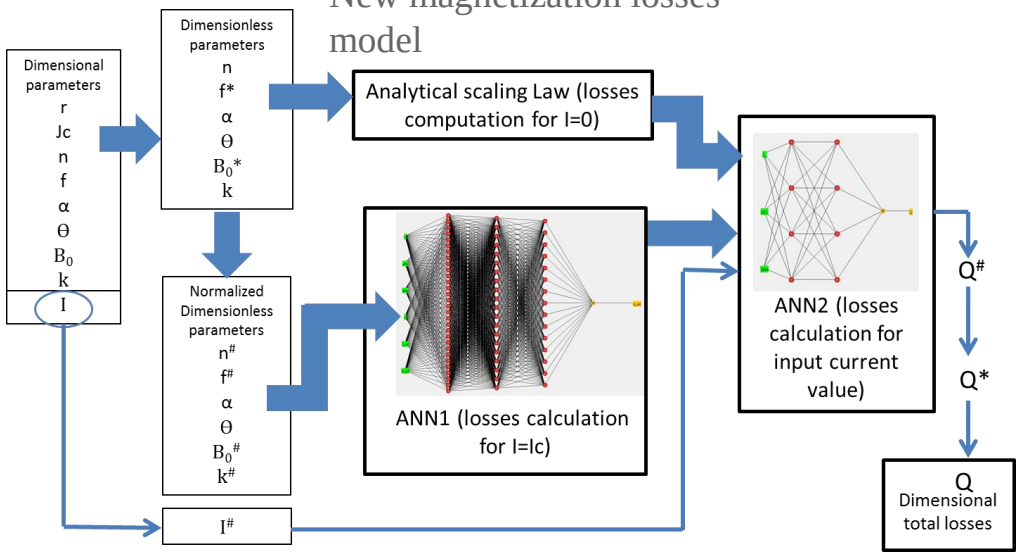
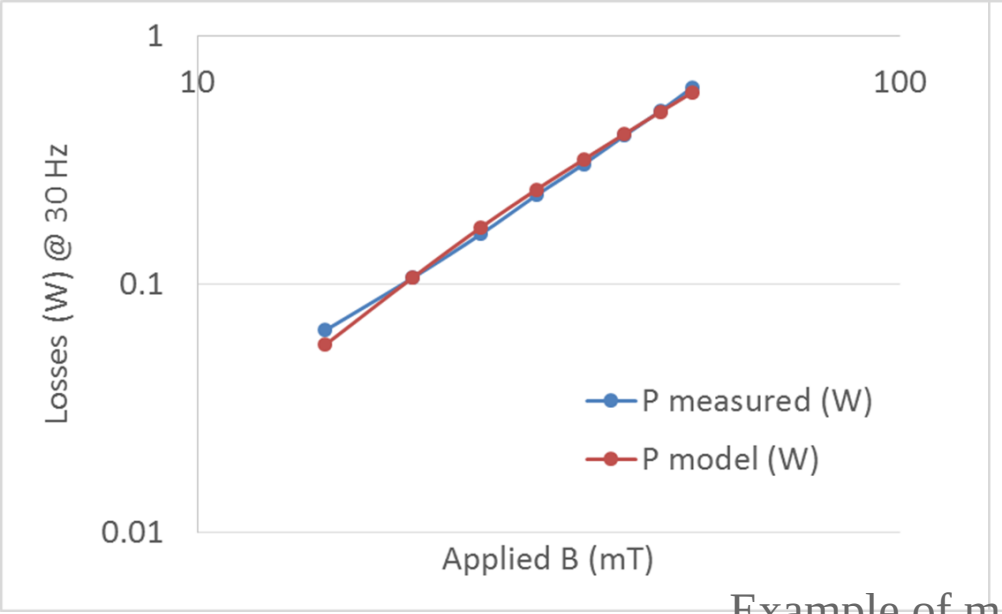
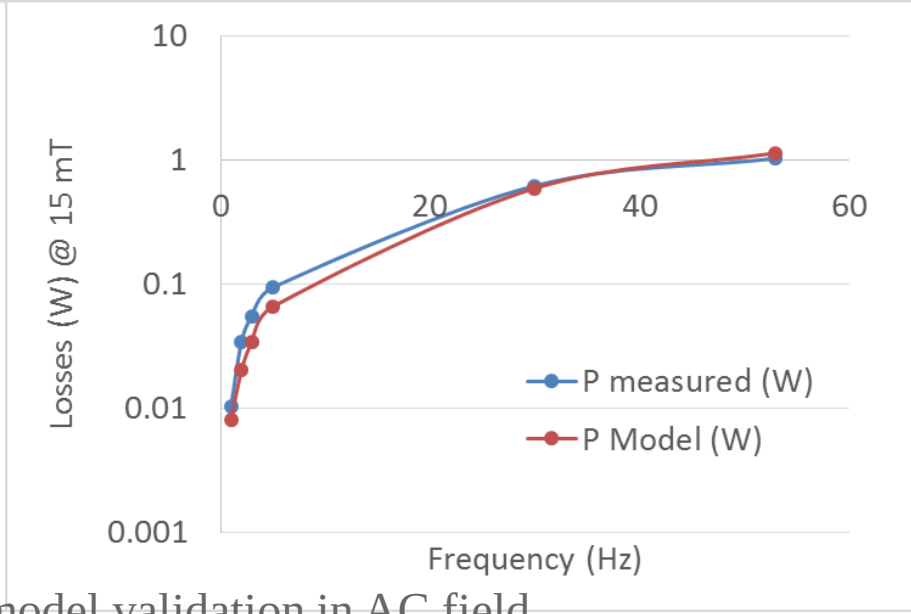
New magnetization losses model



AC losses model based on analytical functions and Neural Networks depends on 9 parameters

- Superconducting wire
  - Jc(B), n, filament size, twist pitch, matrix resistivity
- Applied field
  - AC component, rotating component, phase shift AC/rotating, frequency
- Transport current
  - Magnitude, phase shift, frequency



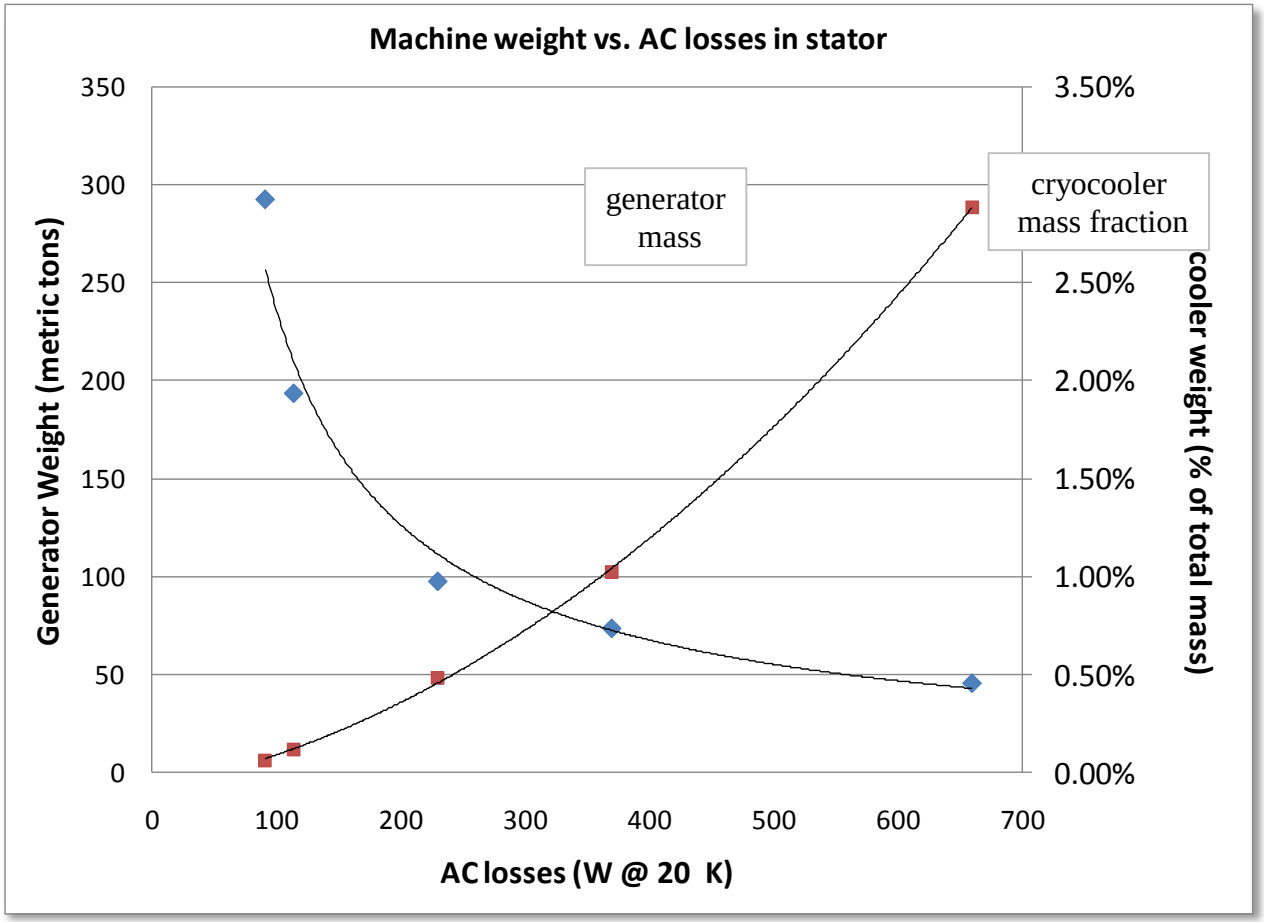


Example of model validation in AC field

AC Losses Impact on Generator Design

Philippe Masson, AML

- AC losses can be reduced at the expense of
  - additional mass (lower number of poles)
  - lower frequency (**derated power converter**)
- Cryocooler represents a small fraction of the total weight



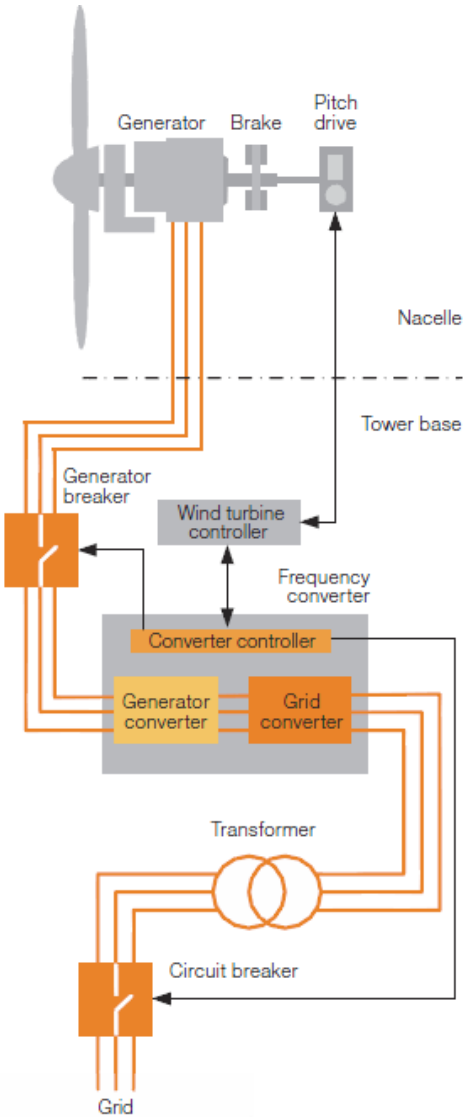
6-pole 10 MW, 10 RPM generator

- ~ 100 Nm/kg
- **< 300 W @ 20 K** total AC losses
- Total cooling power required < 700 W @ 20 K achievable with RTBC cryocoolers
- Nominal frequency 0.5 Hz

Converter Data

ABB - PCS6000 – Up to 9 MVA

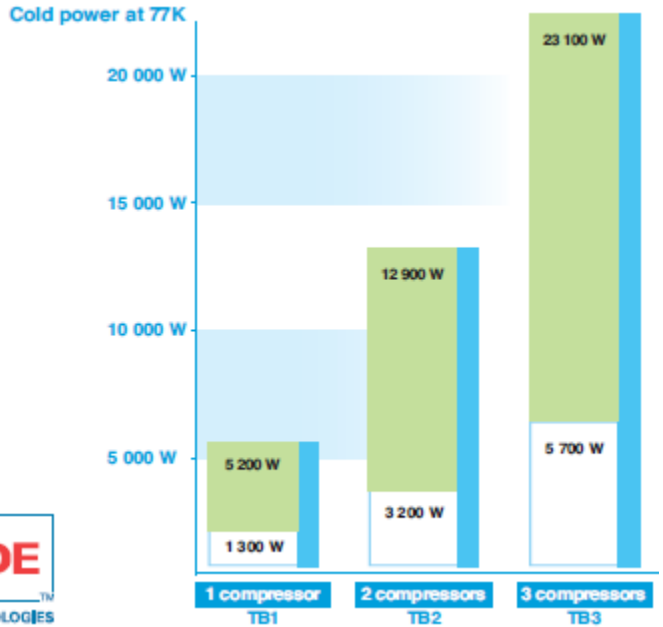
Converter data			
Converter voltage nom.	3.3 kV	4.16 kV	3.3 kV
Generator-side voltage	0 to 3.4 kV	0 to 4.3 kV	0 to 3.4 kV
Grid-side voltage	0 to 3.4 kV	0 to 4.3 kV	0 to 3.4 kV
Semiconductor type	RC–IGCT	RC–IGCT	Sym.–IGCT
Number of IGCTs	12 + 12		
Generator-side frequency nom.	8 – 100 [1)]		
Grid-side frequency	50/60 Hz		
Power rating	4 MVA	4.5 MVA	9 MVA
Efficiency at converters rated point	~0.980		
Generator side du/dt	< 1.5 kV / µs		



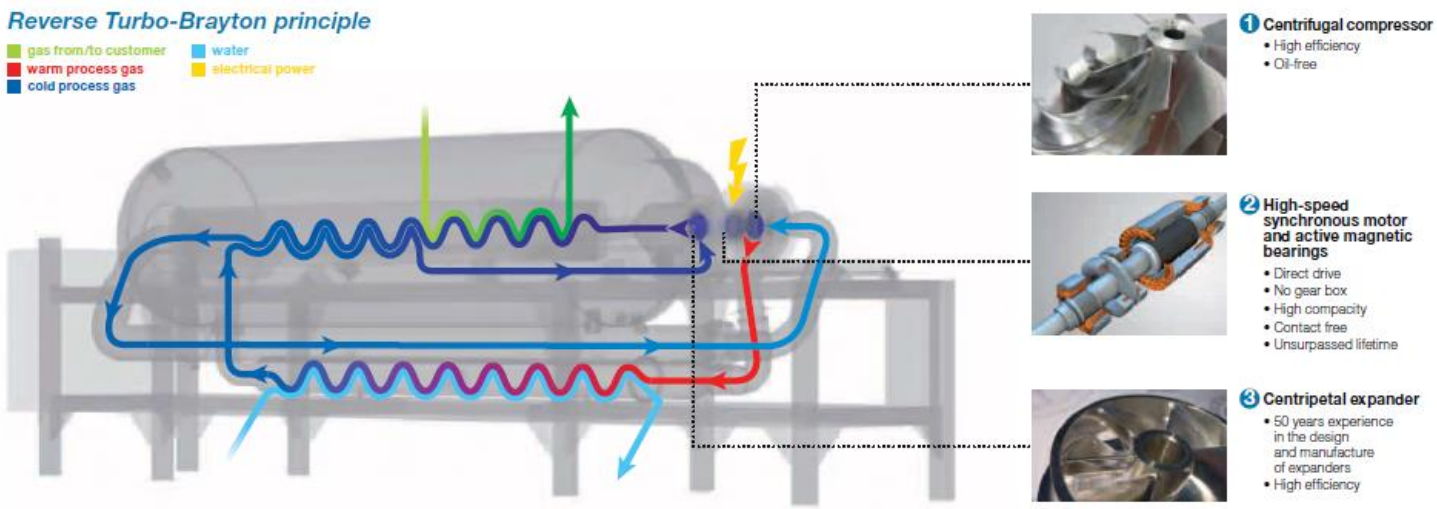
- ABB Converters rated for operation above 8
  - Phase frequency < 2 Hz => **Power derated**
- Several converters can be used in parallel
- Need new low frequency power converter?

Air Liquide

- Mature technology
- Now off-the-shelf product
- Temperature range 20K-77K
- Large cooling power
- Very high efficienc



AIR LIQUIDE
ADVANCED BUSINESS & TECHNOLOGIES



Turbo Cryogenics

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Turbo Cryogenics

Advantages

	Best Competitor	Turbo Cryogenics	TC Benefit
Cooling	1kW @ 50K	1kW @ 50K	**Same Cooling**
Units Needed	3	1	**1 Unit**
Input Power	47 kW	26 kW	**1/2 the Power**
Weight	800 kg	110 kg	**7 Times Lighter**
Volume	1 m^3	0.2 m^3	**5 Times Smaller**
Maintenance	Every 10,000 hrs	Never	**Maintenance Free**
Price	>$300k	<$250k	**20% Cheaper**

- Spin-off from Creare
- Reverse Turbo Brayton cryocoolers
  - Proven technology
  - Extremely reliable (Hubble Telescope)
  - Maintenance free
  - High efficiency
  - Distributed cooling

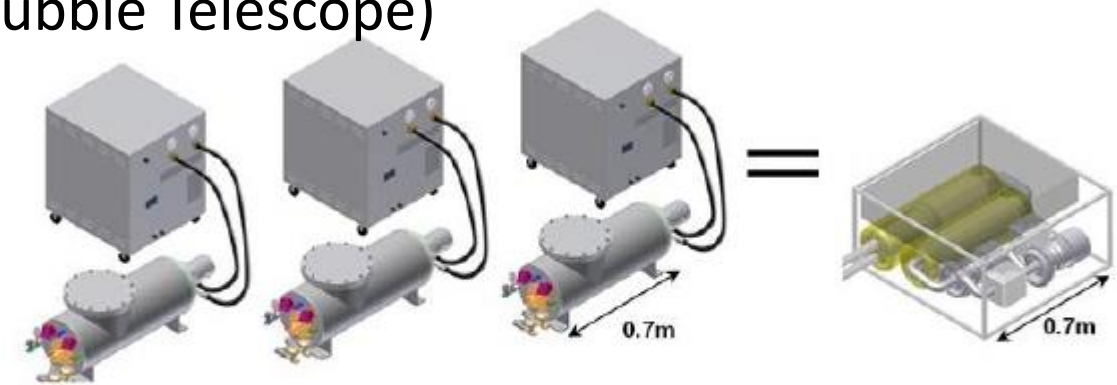

Figure 1: It takes **3** Current Commercial Systems (Cryomech GM AL600 + Cryozone Circulator) to equal **1** Turbo Cryogenics unit.

Example of Generator Output vs. RPM

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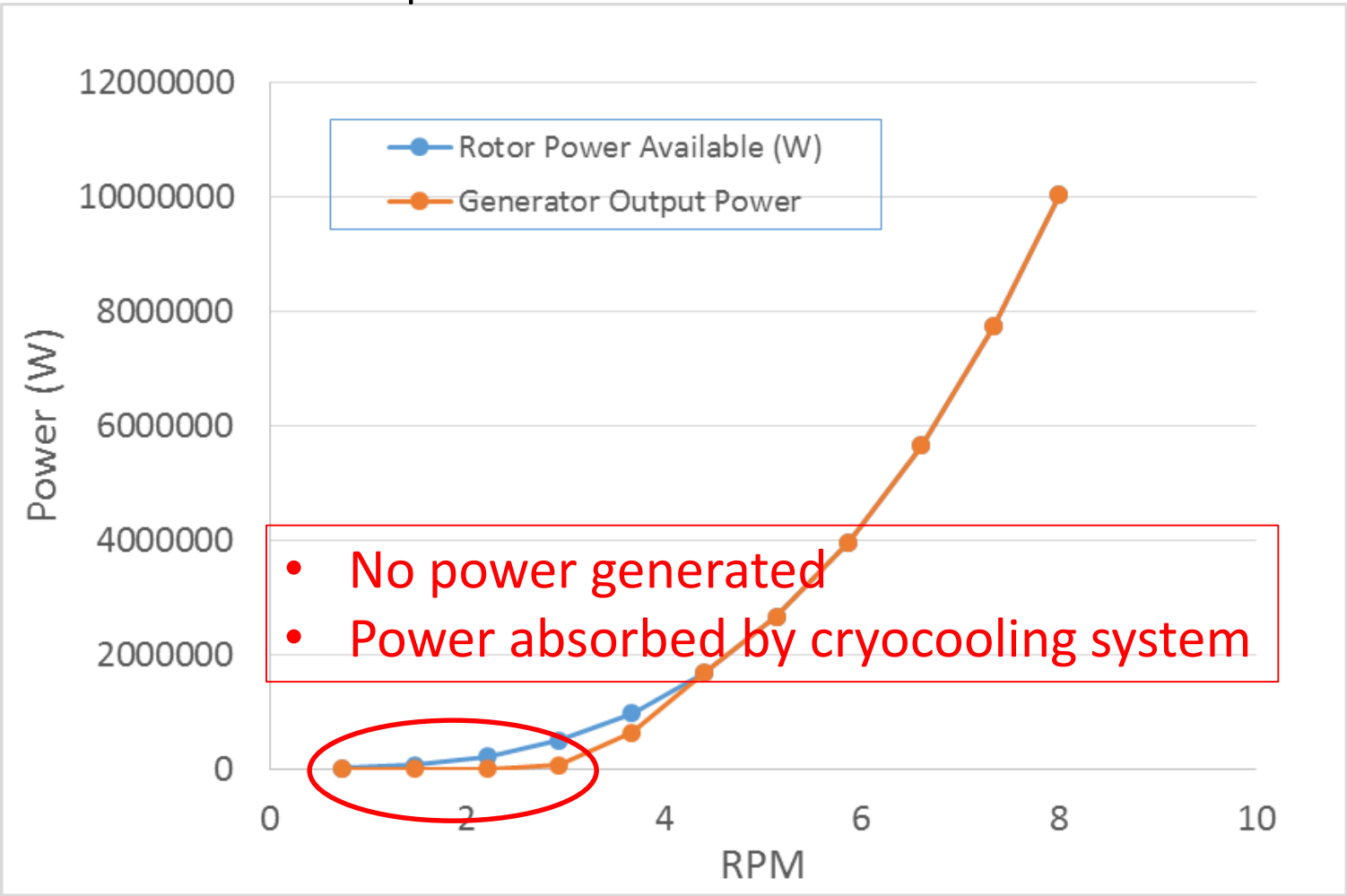
- No power generated below 3 RPM
- Current limited to the nominal phase current



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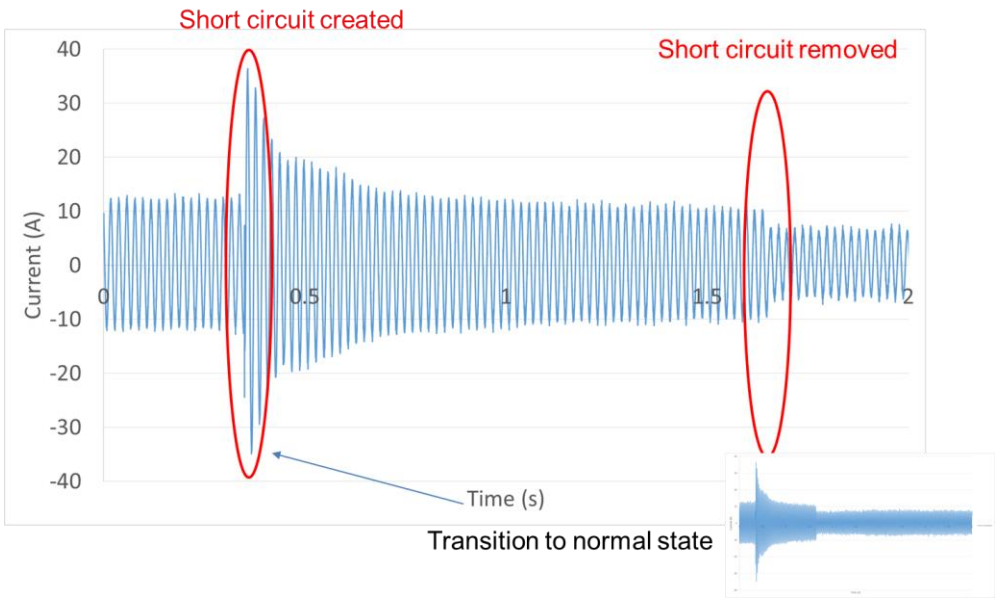

Rotor Quench Detection/Protection

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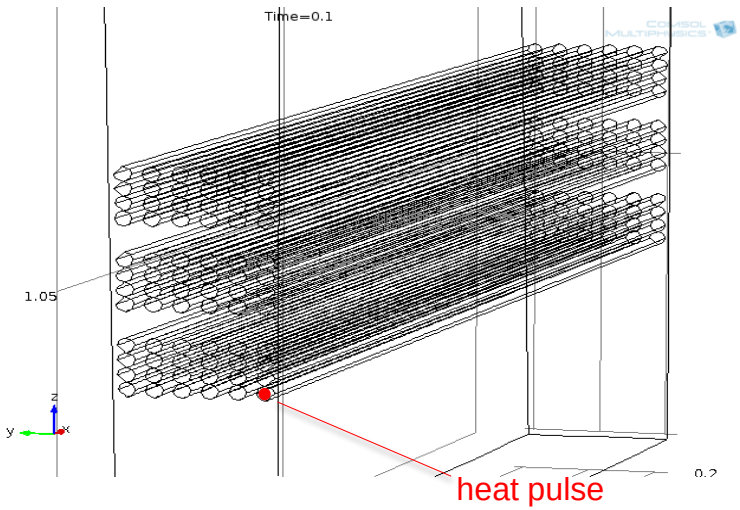
- Current is fed to rotating coils
  - Brushless exciter, sliding contact…
- Quench detection is challenging
  - Very noisy electromagnetic environment
  - Slow propagation velocities
  - Adiabatic conditions (cooling through insulation)



- If quench is detected
  - stored energy needs to be dumped (preferably) outside of the cryostat
  - Rotor inductance is usually very large to reduce the current leads heat load (slow discharge)
  - Margin is usually chosen very large (leading to very slow propagation)

Stator Quench Detection/Protection

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- AC current -> no energy stored, current can be interrupted within ½ cycle
- Stator voltage
  - includes harmonics making voltage detection complicated
  - Sees the rotor mechanical transients
- A heat load exists as soon as the rotor rotates, the heat loads depends (not strongly) on the loading conditions
- Stator conductors operate at high operating factor and use a high resistivity matrix (for short circuit current limitation)

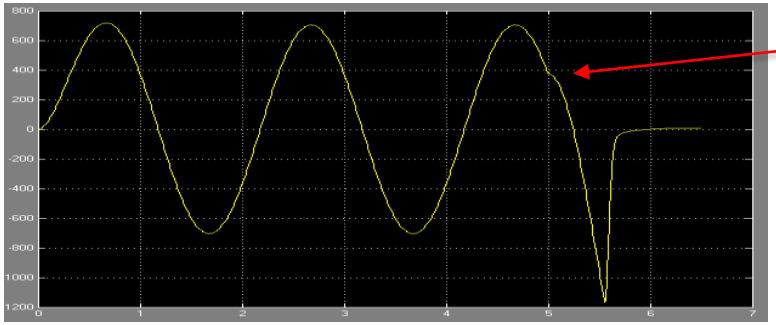
- Need reliable quench detection in noisy AC environment

Example of Stator Current Limitation

- **The superconducting stator acts as fault current limiter**
  - ✓ Provides lower short circuit torque
  - ✓ Provides lower short circuit power without impacting dynamics

- **Fault Sequence:**

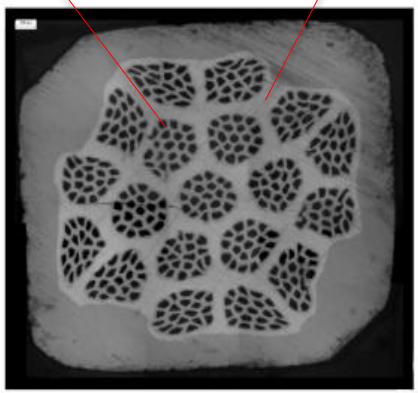
1. Short circuit occurs and phase current rises
2. Current level exceeds I_c (MgB_2 critical current)
3. Stator current diffuses from the superconductor to the matrix material throughout entire coil
4. Coil impedance changes from inductive to resistive
5. Single phase impedance rises from ~ 4 Ω to **>600 Ω**
6. Fault current drops from >1,000 A to **~ 6 A** (dissipating ~22 kW)
7. Phase imbalance is detected
8. Temperature rise in windings has to be limited to less then **60K**



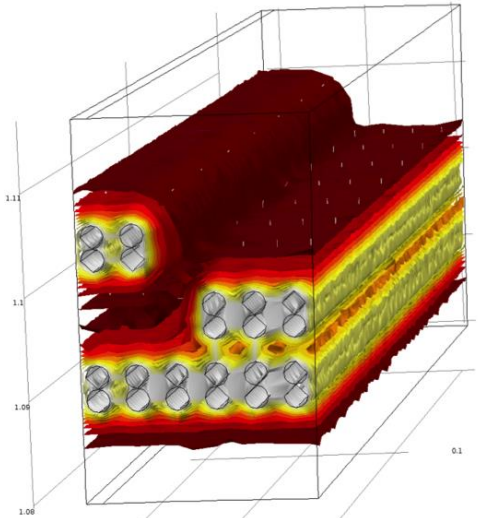
short circuit

Phase current vs. time

superconductor resistive matrix



Multi-filament MgB_2 conductor



Temperature distribution after 1 second of short circuit

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Barrier to Market Entry

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- New technology for wind farm developers
  - Perceived “high risk”
    - cryogenics
  - Lack of reliability data for the full system (data exists for individual components)
  - Lack of application standards (IEEE WG6?)
  - Concerns that technicians will not be able to work/service the new systems
  - Lengthy cool-down/warm up
  - If failures can happens inside the cryostat, then the superconducting generators cannot be considered for wind power generation
- Conventional drivetrain can still be used (at higher cost) and present less risks
- Direct Drive Systems at 6MW exists and are being deployed

Proposed Research/Development Topics

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- Demonstrate reliability of HTS coils and associated systems
  - Build coils and test them to failure
  - Implement reliable quench detection/protection
- Generate higher fidelity LCOE model able to capture the features of HTS generators and their impact on turbine design and wind farms
- Build a small scale unit (~1-1.5MW)
  - Demonstrate reliable operation in turbine
- Develop cooling plants in the power range of interest at 10-30 K
  - Centralized cooling
  - Individual cryocoolers
- Develop low frequency power converters able to operate at 10+ MW and sub-Hz frequency

Summary

- Superconducting generators would enable very large turbines >10 MW for off-shore wind farms
- Many technical challenges need to be addressed before commercial deployment
- Many of the technical points presented have been studied and addressed to a point (more work is needed to remove the risks)