Superconducting Generators for Large Wind Turbine: Design Trade-Off and Challenges

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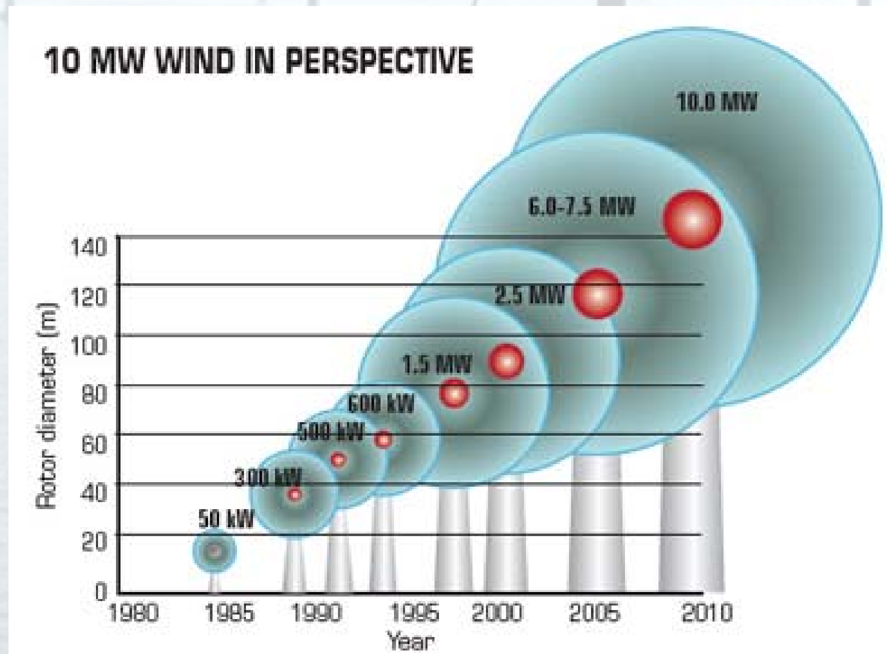

http://eetweb.com/wind/wind-turbines-go-supersized-20091001/

Outline

- Introduction
- Off-Shore wind power generation
- Current technology
- Superconducting generators
- Technology trade-offs
- Application to off-shore wind
- Ongoing projects
- Conclusion

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Superconducting Machines Features

Substantially reduce
- Losses
- Weight
- Volume

Increase
- Efficiency
- Power density
- Reactive power capability
- Stator cooling capacity

Eliminate
- Limitations in reactive power capability diagram
- Thermal cycling of field winding
- Coupling of stator and rotor cooling

✓ Savings in fuel costs
✓ Reduced emissions of greenhouse gases

✓ Smaller, lighter: easier to transport, requires less building space, allows for new drive concepts

✓ Superior steady-state stability
✓ Insensitive to load changes
✓ Reduced harmonics
✓ Superior short-time overload capability
✓ More reactive power

✓ No deterioration of rotor winding and its insulation

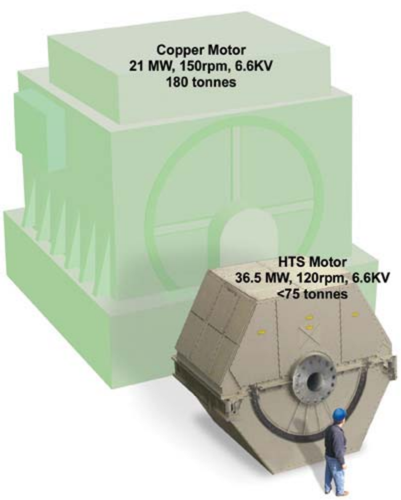
Courtesy of Siemens

In 2011…

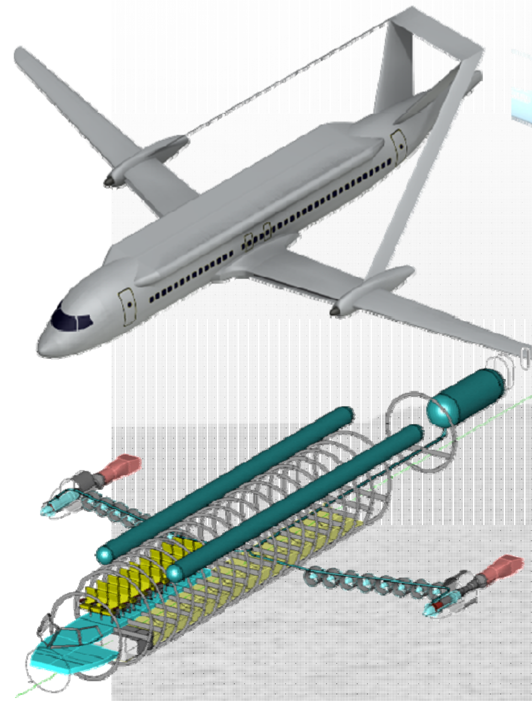
- First Sc. Machine built in 1966
- 45 years later, still no commercial applications…
  - Conventional machines are good for 99% of the industrial applications
    - Decent efficiency, very robust and reliable, inexpensive
  - HTS machines have drawbacks
    - Cooling required at all time
    - High capital cost
    - Reliability not proven
    - More complex with more parts
    - Cryogenic system perceived as high risk component

Markets for HTS Machines

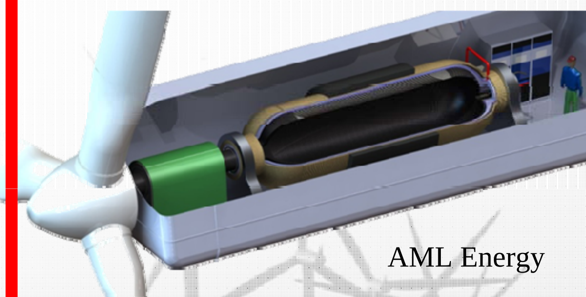
- Applications with requirements in terms of specific power/torque and efficiency that cannot be matched by conventional machines



http://www.amsc.com/products/motorsgenerators/shipPropulsion.html



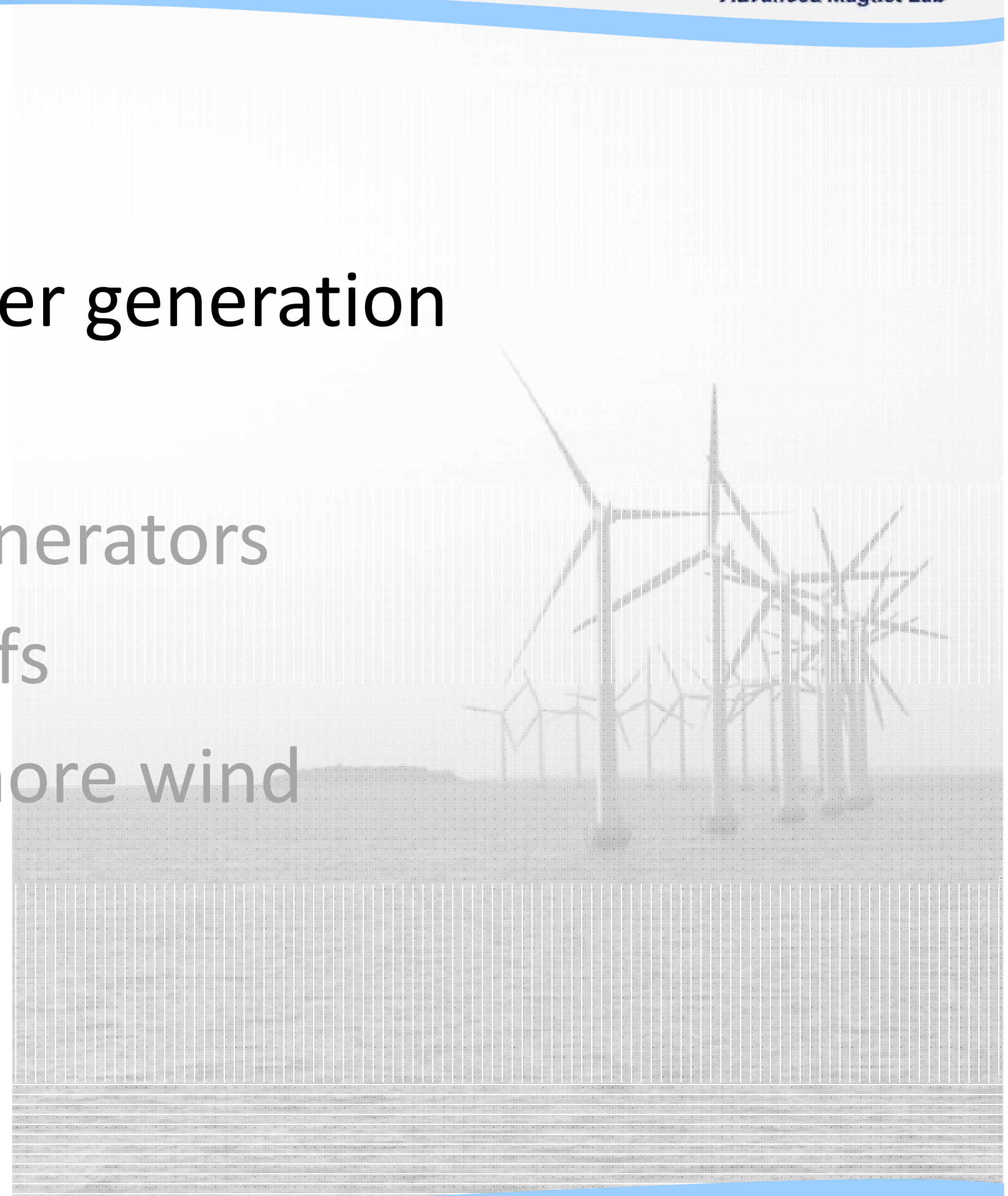
AML – ESAero – NASA GRC



AML Energy

American Superconductor

Outline



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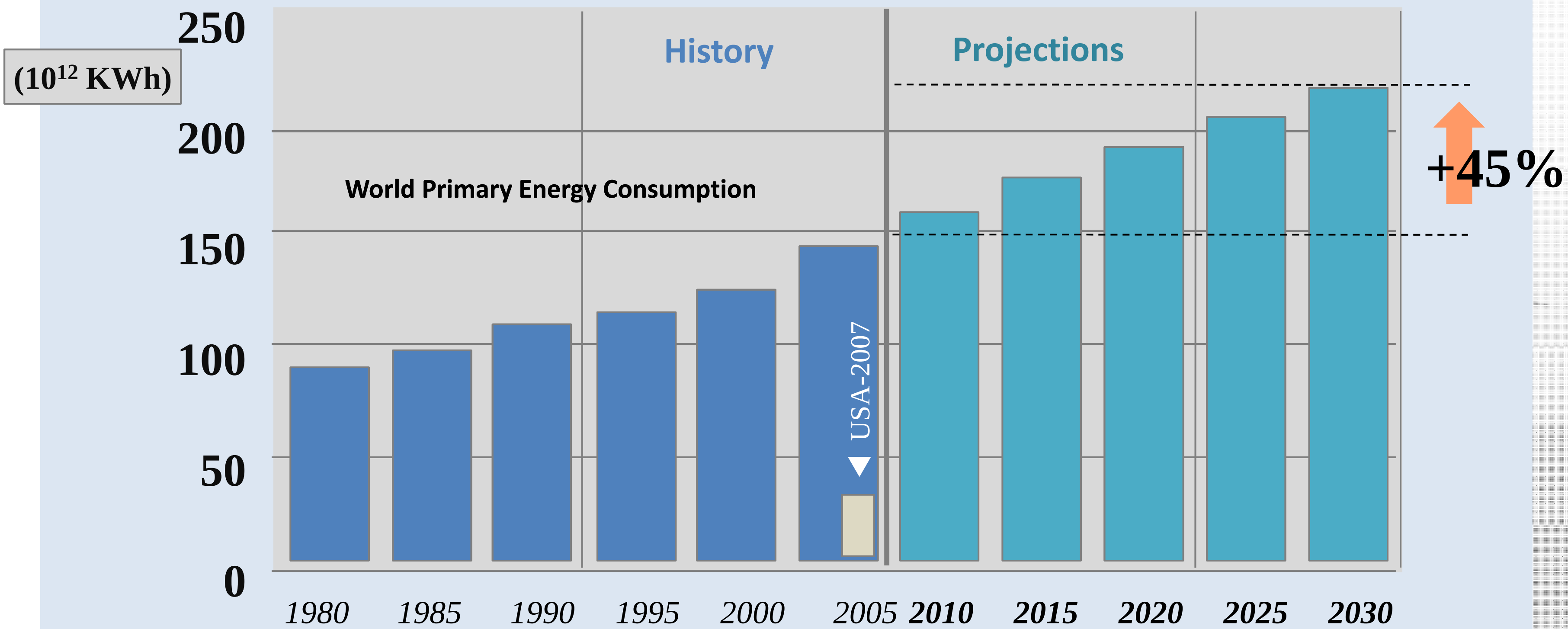
Global Energy – A "Hungry" Market

- Existing and expanding global economies have a large appetite for Energy…

…with no signs of letting up!



Sources: **History**: EIA, International Energy Annual 2005 (June-October 2007). **Projections**: International Energy Agency World Energy Projections Plus (2008)

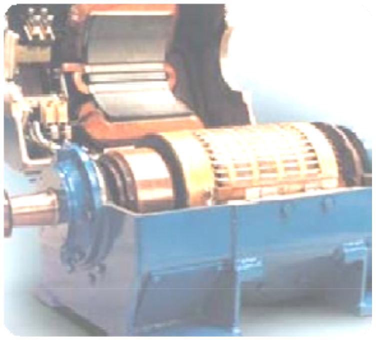
*"In order to meet the **45%** increase in projected demand, an investment of over **$26 trillion** will be required …"*

Energy "Landscape" and Superconductivity

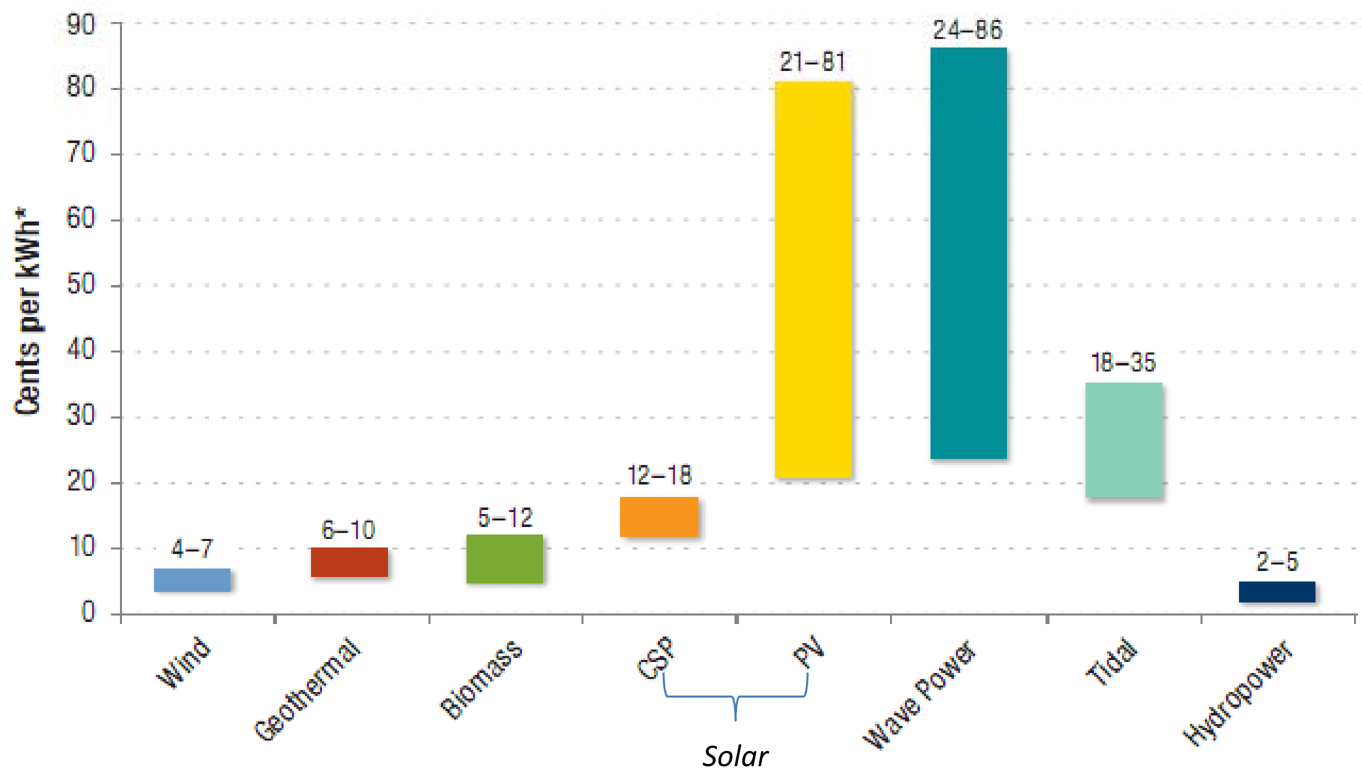
- *Power* Generation
  - Cost per Kilowatt Hour!!!!!
  - Minimal carbon footprint
- *Power* Distribution
  - Power Transmission
  - Grid Management
  - Energy Storage
- *Power* Use
  - Energy Efficiency

For all, cost, efficiency and environment are the driving factors!

Superconductivity is a very attractive technology



Price Range of Renewable Electricity (2008)



* Average cost will vary according to financing used and the quality of the renewable energy resource available.

Sources: Idaho National Laboratory, Carbon Trust, Simmons Energy Monthly, U.S. DOE-EERE, IEA, Solarbuzz LLC, REN21, LBNL

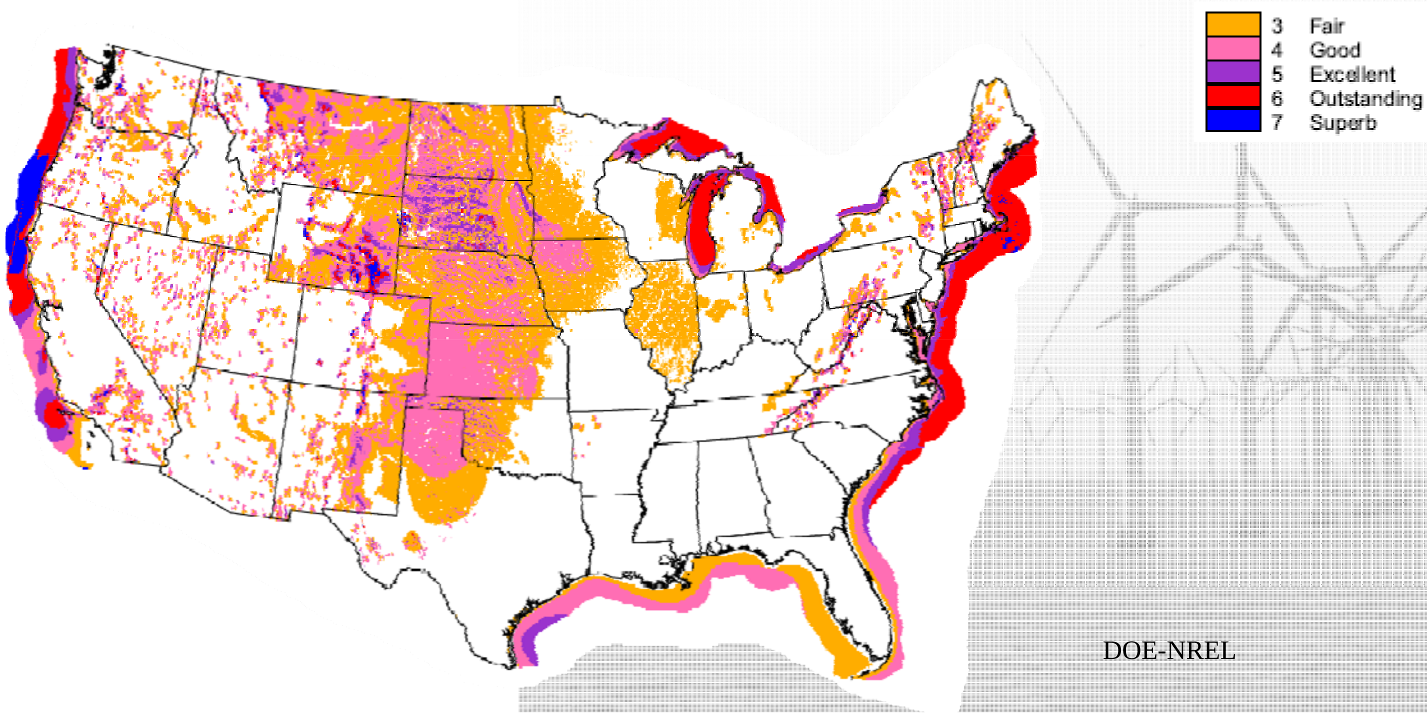
Why Off-Shore Wind?

- 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/

Offshore Wind – poised for growth

- European offshore windfarms are generating **1,100 MWatts** with **70-90% availability.** Deep water offshore is progressing.
- Off-shore wind is on its way in the US with a very large potential market.



DOE-NREL

Over the next 5 years Offshore Wind will be a significant component of the US Renewable Energy spectrum

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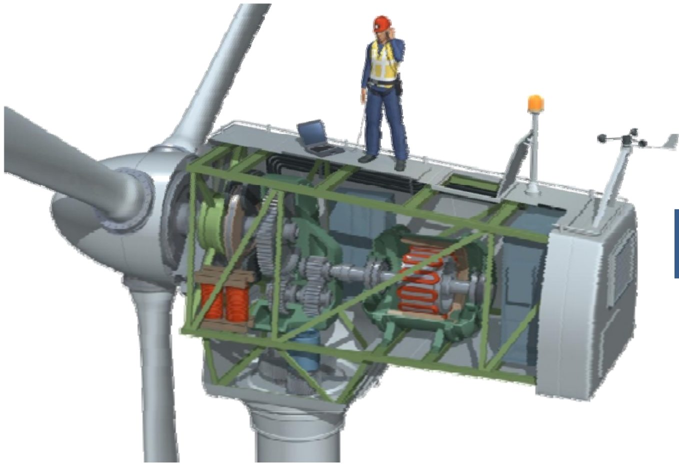
Current Issues of Conventional Drivetrains

- Reliability
  - Gear boxes
    - major cause of failure, high maintenance needs
  - Thermal cycling
    - Insulation fatigue
- Power output
  - Low efficiency at fractional power
  - Power factor
  - Controls
- Scalability
  - Limited specific power
  - Availability of rare-earth magnets

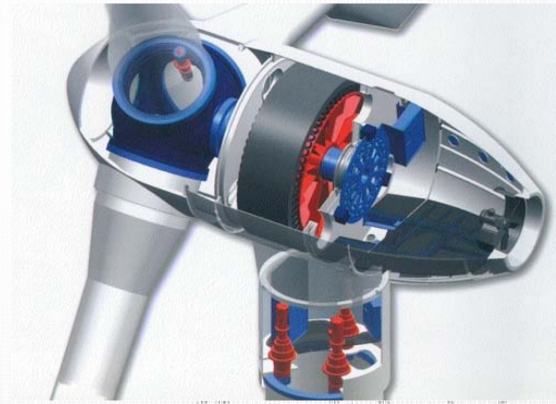
Next Generation



Conventional Turbine Generator

- Elimination of Gearbox
- Permanent Magnet Generators

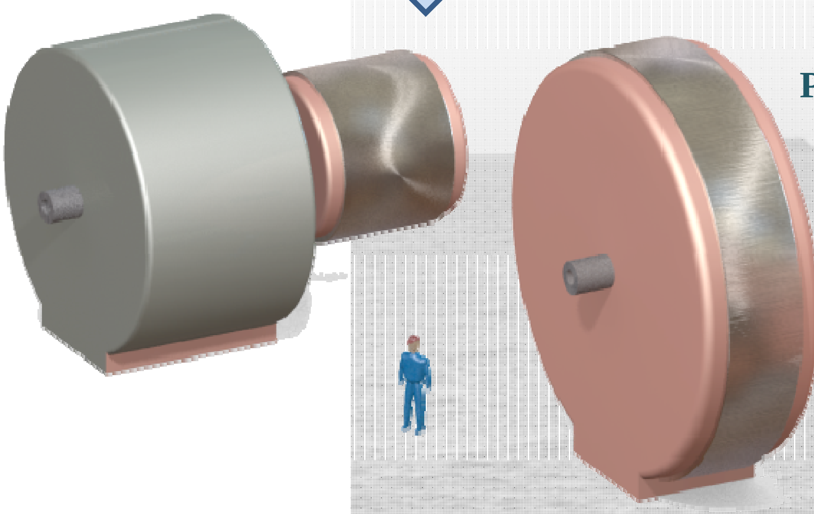
10 MW



Next Generation - No Gearbox

Copper Wound-Coil with Gearbox

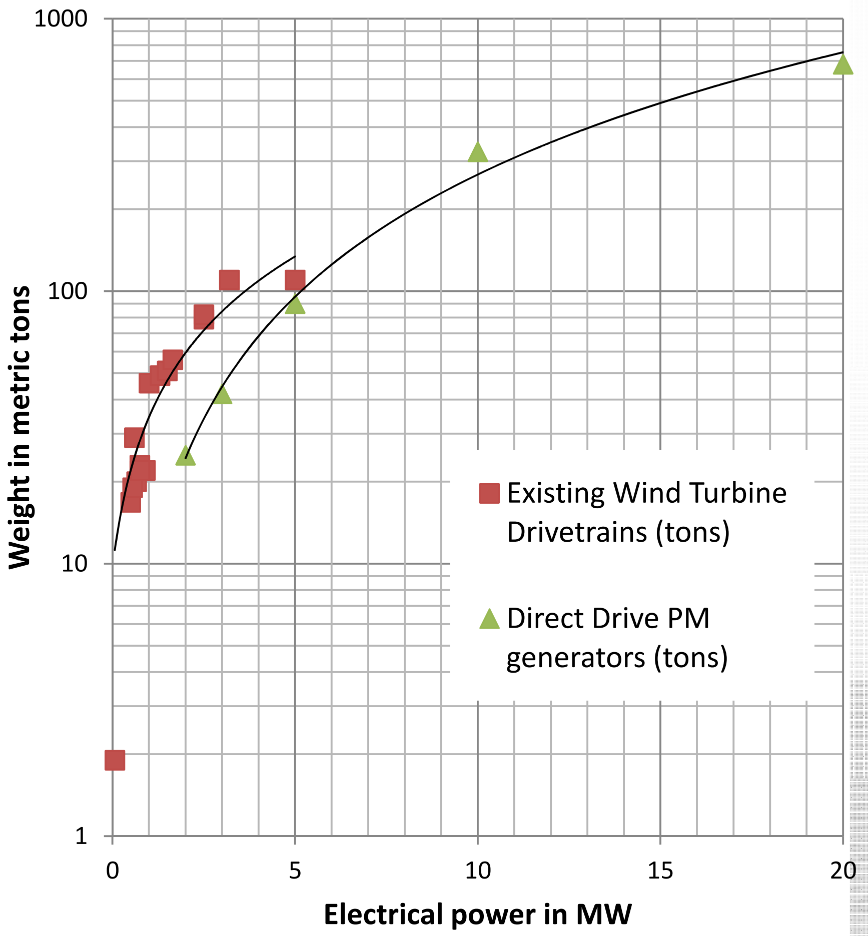
> 500 Tons



Permanent Magnet

> 320 Tons

Large Wind Generators



Large wind turbines are desired for offshore deployment. **Lightweight, reliable generators** are paramount to the economic feasibility of such systems.

- Sizes > 10+ MW @ 10 RPM
- No gearbox > higher reliability

Permanent Magnet Generators are currently in favor for large power systems. However:

- Weight is very high
  - Iron based machines
  - Large radius (~10 m)
  - 10 MW -> mass over 300 tons
- Require large starting torque

A different technology platform is required …

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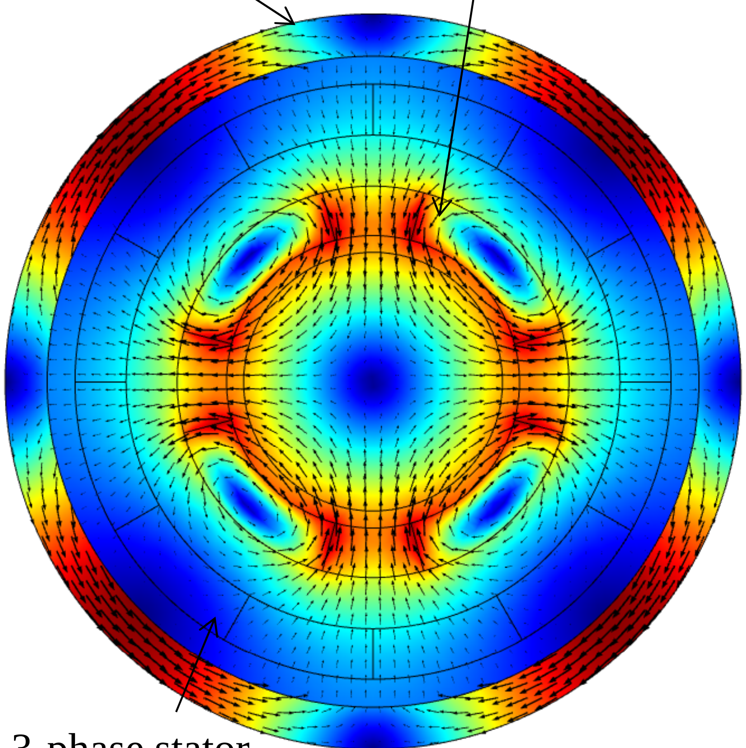
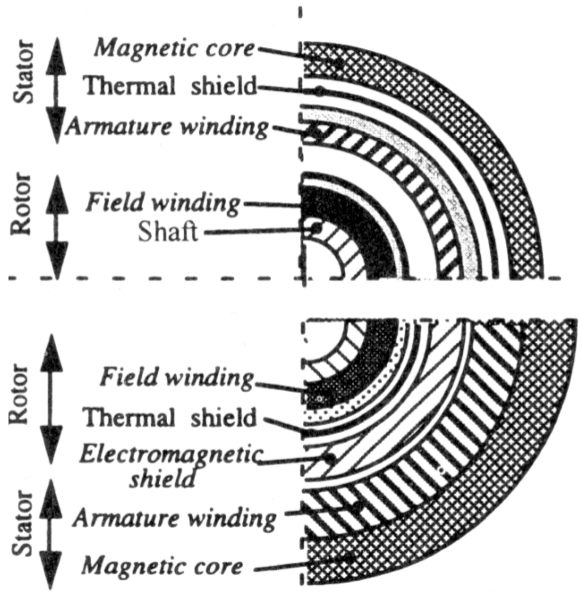
Facts about Superconducting Machines



- Superconductors operate at cryogenic temperature (below -200C)
  - 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 cooling power
  - Usually not used in AC components

Partially and Fully Superconducting Machines

Fully Superconducting (***FSc***)



Partially Superconducting (***PSc***)

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

Apparent Power output of an electrical generator:

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

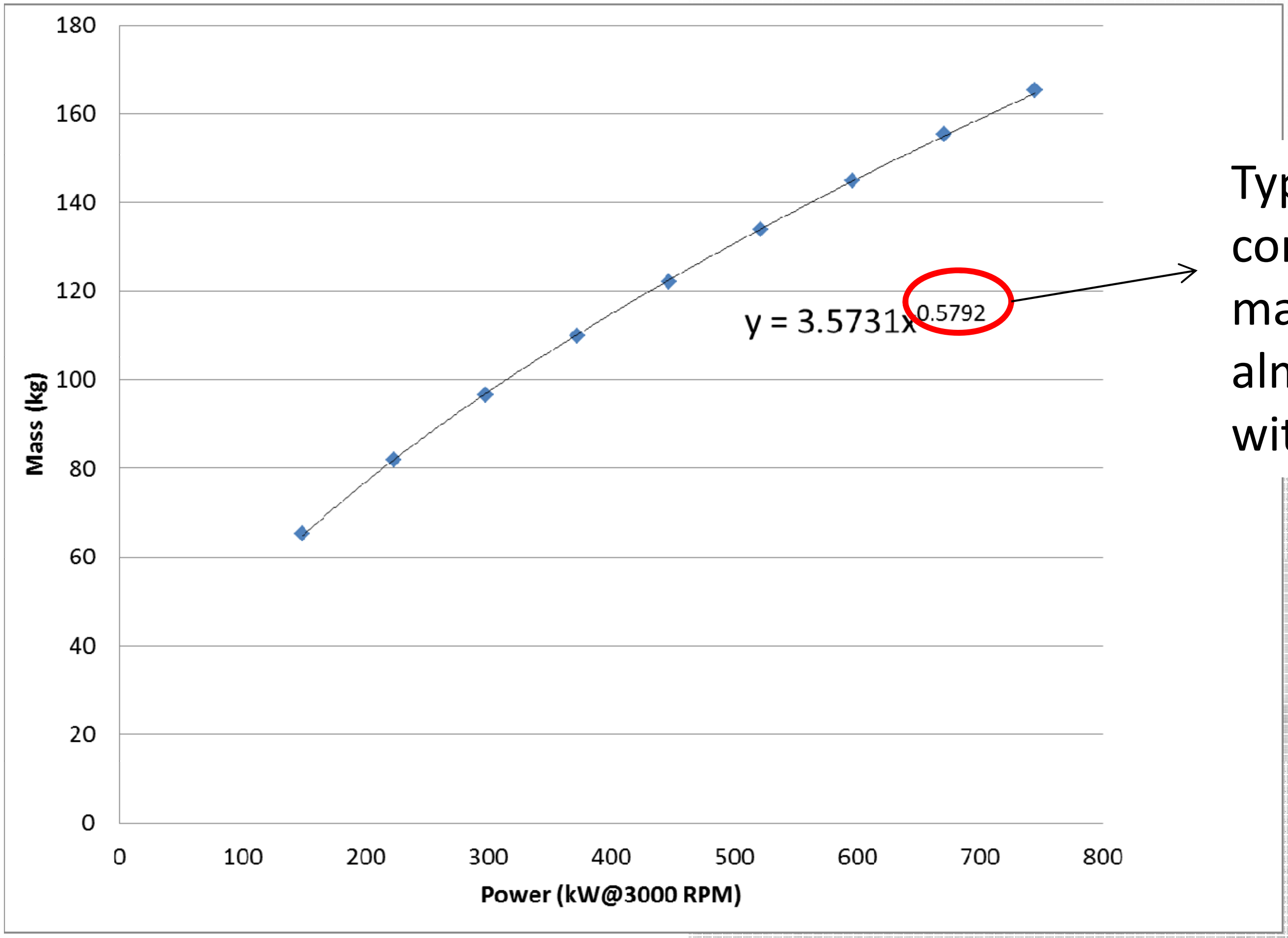
Rotor contribution
Limited by conductor performance.
More conductor needed in PSc because of the large air gap

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

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

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

Scaling of Sc. Machines

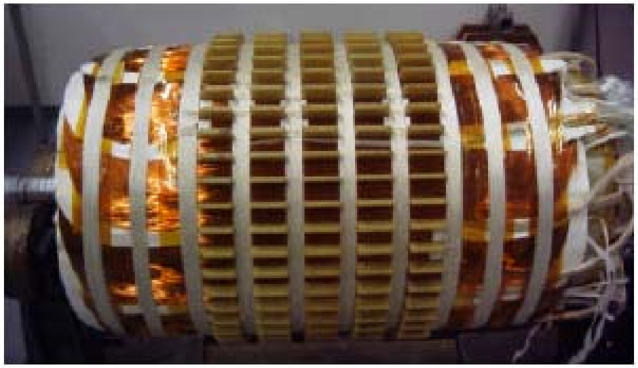


Typically, conventional machines scale almost linearly with the power

Sc. Machines very interesting for high torque applications

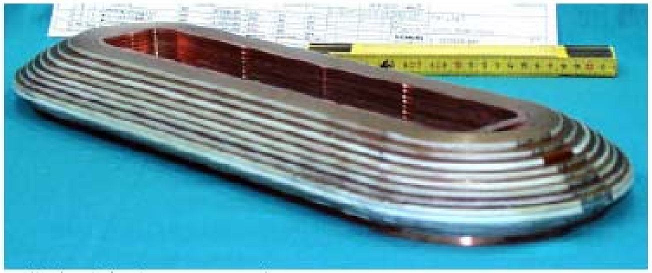
Possible Configurations – Partially Superconducting

- Partially Superconducting Generator (PSG)
  - High number of poles
  - Superconducting rotor
    - Low cooling requirements
  - Air-core stator winding
    - Resistive losses limit electrical loading
  - Large "air gap"
    - cryostat between stator and rotor
    - High peak field
  - Large Lorentz forces on HTS coils



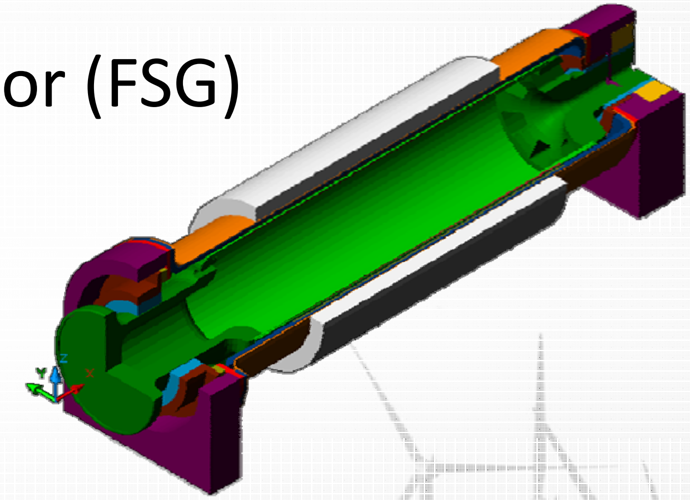
Photos from Siemens and AMSC

HTS pancake coils



coil stack to form one pole

- Fully superconducting Generator (FSG)
  - High cooling requirements
    - AC losses in stator
  - Very high specific torque
    - High electrical loading
  - Low number of poles
    - Need low frequency for low losses
  - Large Lorentz forces
    - Need reliable conductor stabilization
  - Torque transfer at "small" radius
    - Large conduction heat leak



CNC manufacturing of 1200mm diameter, six pole Double-Helix™ rotor coil

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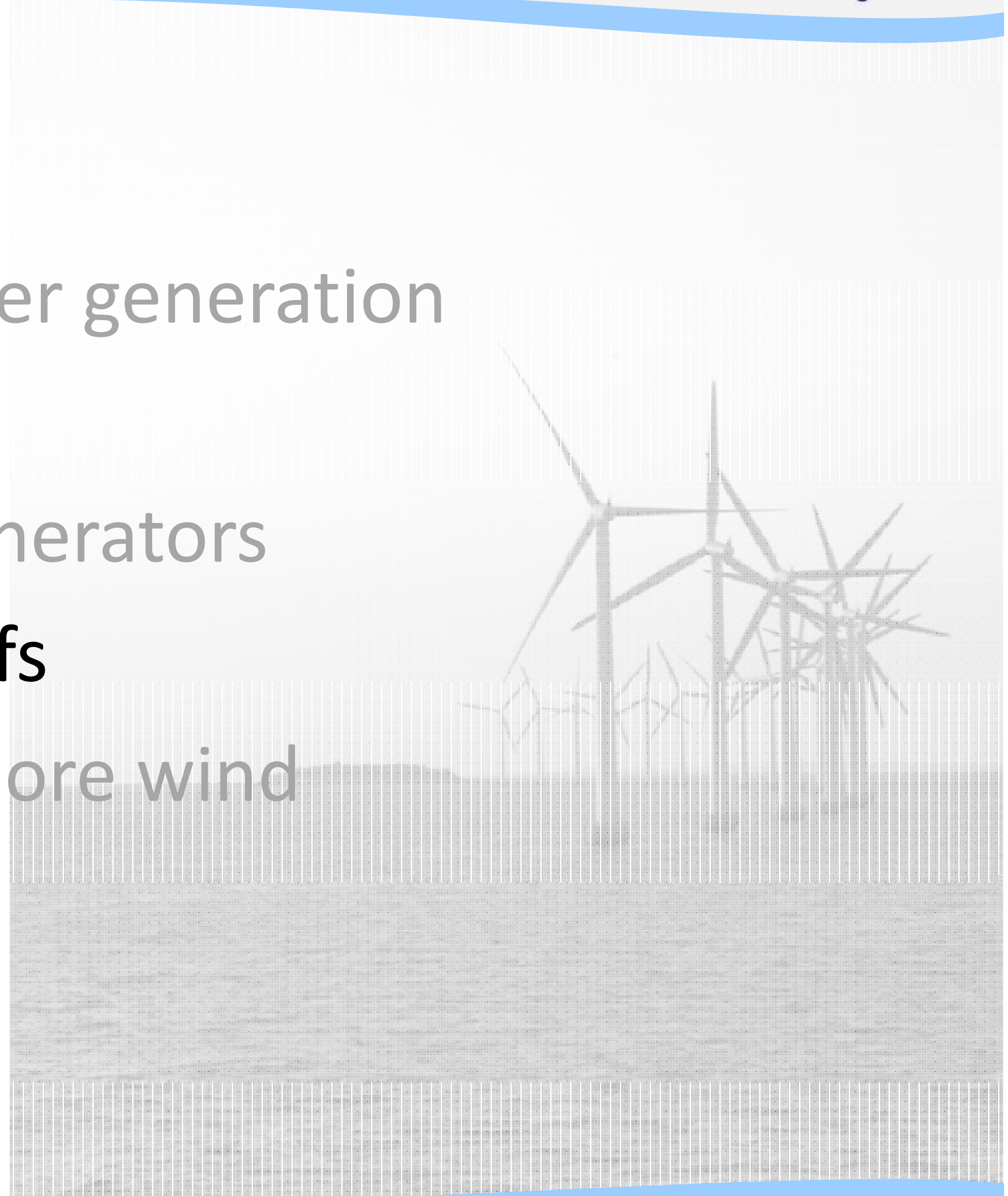
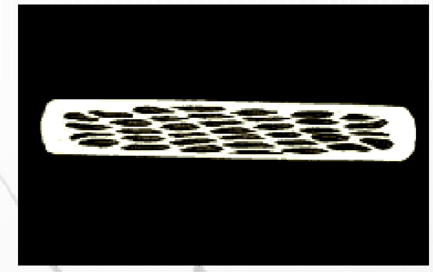


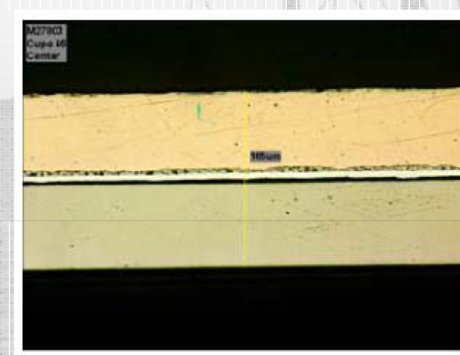
Choice of Conductor

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

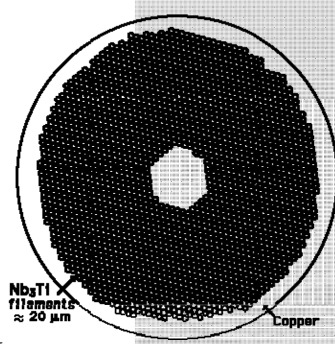
- **Key conductor parameters :**
  - Engineering critical current density @ operating field
  - Filament size
  - Ratio superconductor/ non superconductor
  - Minimum quench energy
  - Normal zone propagation velocity
  - Minimum bending radius
  - Cost



BiSrCaCuO conductors
• Silver matrix
• Operation at 25-35 K

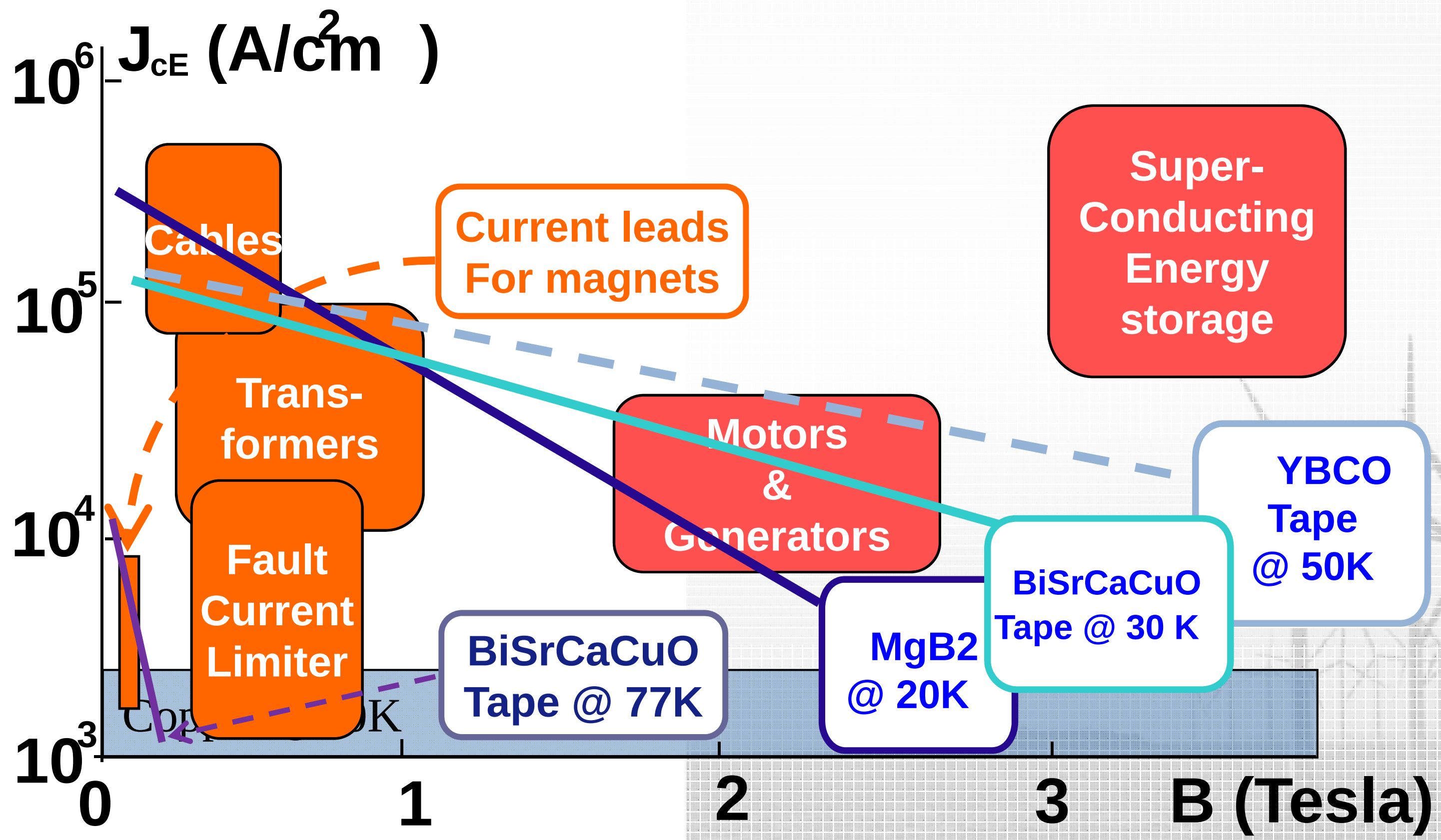


YBCO conductors
• Layer configuration
• Resistive inter-layer interfaces
• Operation at 55-77 K



NbTi conductors
• Cu matrix
• Excellent current sharing
• Operation at or below 4.2 K

Available Conductors



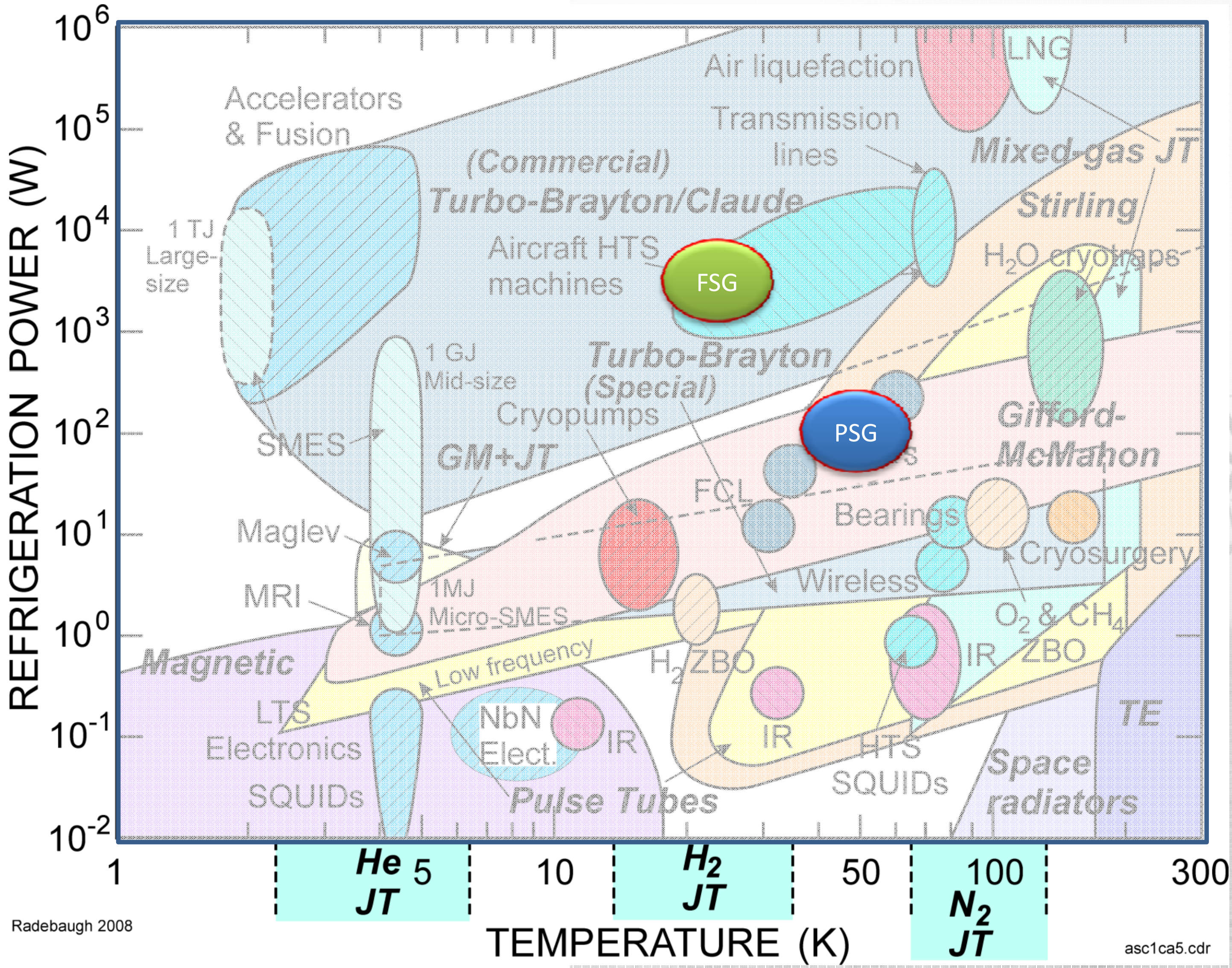
- 3 possible conductors
  - YBCO, Bi2223 – tape (limited to racetrack winding)
  - MgB_2 – tape and round wire

High Level Conductors Comparison

Superconductors	Price	Bending radius	"SC" Splice	Small Filaments	Quench Detection	Isotropic Field Dependence	Critical Temp (T_c)	Operating Temp
1G (BSCCO)	✗	✗	✗	✗	✓	✗	110K	~30K
2G (YBCO)	✗ (circled)	✓	✗	✗ (circled)	✗ (circled)	✗	92K	50-77K
MgB_2	✓	✗ (circled)	✓	✓	✓	✓	39K	15-20K

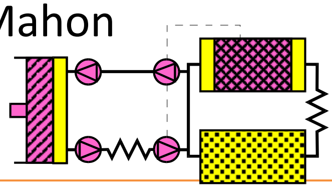
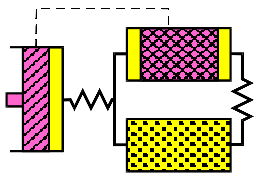
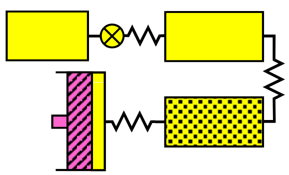
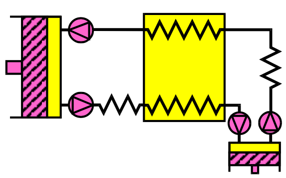
- The choice of conductor is done at the system level considering the total cost of system **conductor-cooling system**
- MgB2 is very promising:
  - Price point of **MgB_2** moving towards $20/kAm @ 2T, 20 K
  - Development of high filament count conductors (~10 μm)
- 2G (YBCO) is improving fast:
  - Current price point of **YBCO** at $500/kAm @ 2T, 60 K
  - Active development towards cost reduction and multi-filaments

Cryocooler Applications and Operating Regions



From Ray Radebaugh, NIST

Comparison of Different Types of Cryocoolers

Type of Cooler	Advantages	Disadvantages
Gifford-McMahon 	High reliability (1-3 yrs) Moderate cost Good service Over 20,000/yr made	Large and heavy Intrinsic vibration from displacer Low efficiency
Stirling 	High efficiency Moderate cost Small size and weight Over 140,000 made to date	Dry or no lubrication Intrinsic vibration from displacer Long lifetime expensive (3-10 yrs)
Pulse Tube 	Highest cryocooler efficiency for 40 K<T<200 K No cold moving parts •Higher reliability •Lower vibration and EMI •Lower cost	Short history (OPTR since 1984) Gravity-induced convective instability Lower limit to size for efficient pulse tube
Brayton 	Steady flow (low vibration, turbo-expander Long lifetime (gas bearings, turbo system) Transport cold long distance Good efficiency except in small sizes	Difficult to miniaturize Requires large heat exchanger Expensive to fabricate

From Ray Radebaugh, NIST

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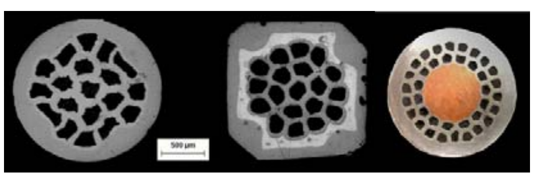
Next Generation Generator Requirements

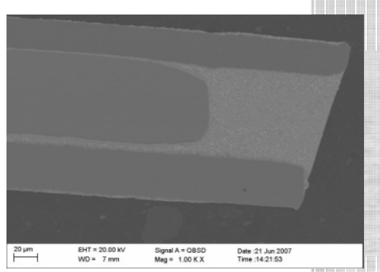
Requirement		Superconducting Machines
Direct drive – large torque	☑	Scale very well
Lightweight	☑	High specific torque
Reliable/Robust	☑	No thermal cycling, stable – need more data/experience
Efficient	☑	Low losses, high efficiency at fractional power output
Low maintenance	☑	No gearbox, sealed system, no brushes
Low cost	☑	Competitive at high power

Challenges

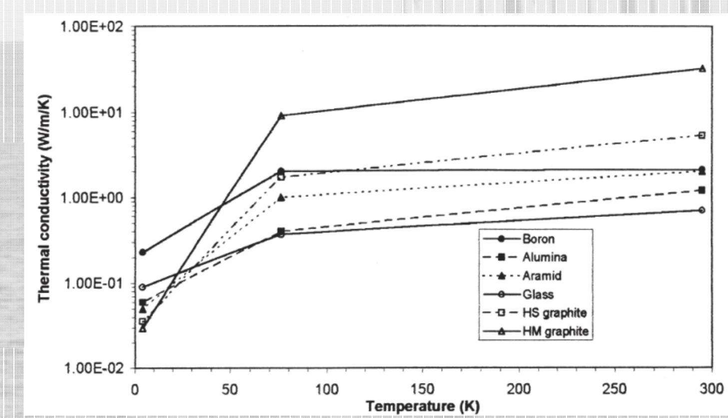
- Economic
  - Low cost conductors
  - Low cost cryocoolers
  - Superconductor availability
  - Cost effective manufacturing
- Mechanical
  - Torque transmission/torque tube
    - 10s MNm to be transferred (fault)
  - Large Lorentz forces (peak field >4 T)
  - Torque and forces applied on conductors
- Thermal
  - Heat leaks need to be minimized
    - Conduction through shaft
    - Current leads
    - Splices
  - Multifilament conductors
- Stability
  - Quench detection/protection
  - Fault current/torque



MgB2 conductor



2G conductor

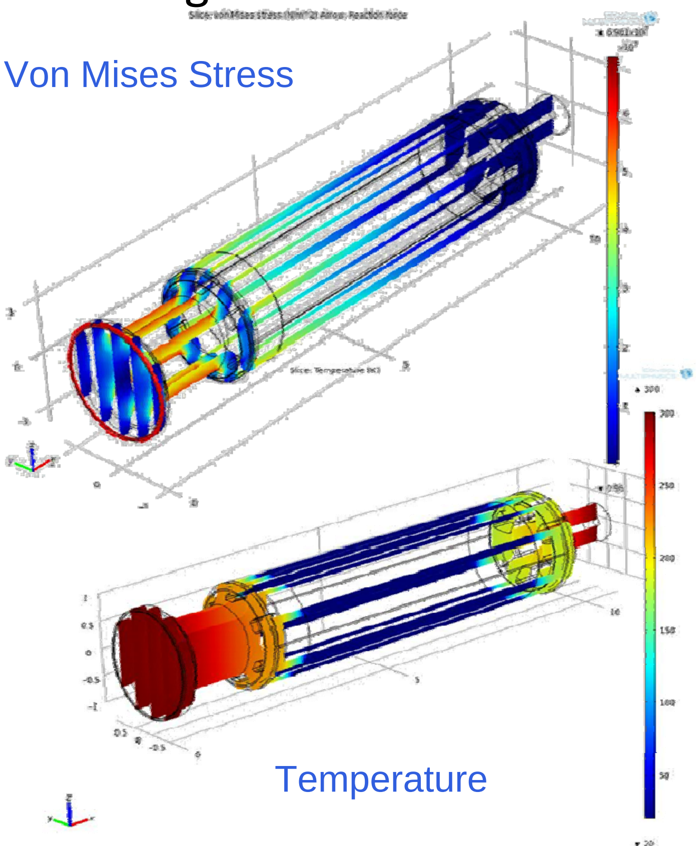


Carbon fiber composite thermal conductivity

Thermal Insulation and Torque Transmission

- Shaft sees a very large thermal gradient
- Torque tube needed to transfer torque to room temperature
  - Because of turbine rotor inertia, the full fault torque needs to be transferred
  - Design trade-off between structural and thermal

Von Mises Stress



Temperature

Layers of ceramics or Fiber glass composite to thermally insulate the shaft end

Photo courtesy of AMSC

Losses in Superconducting Machines

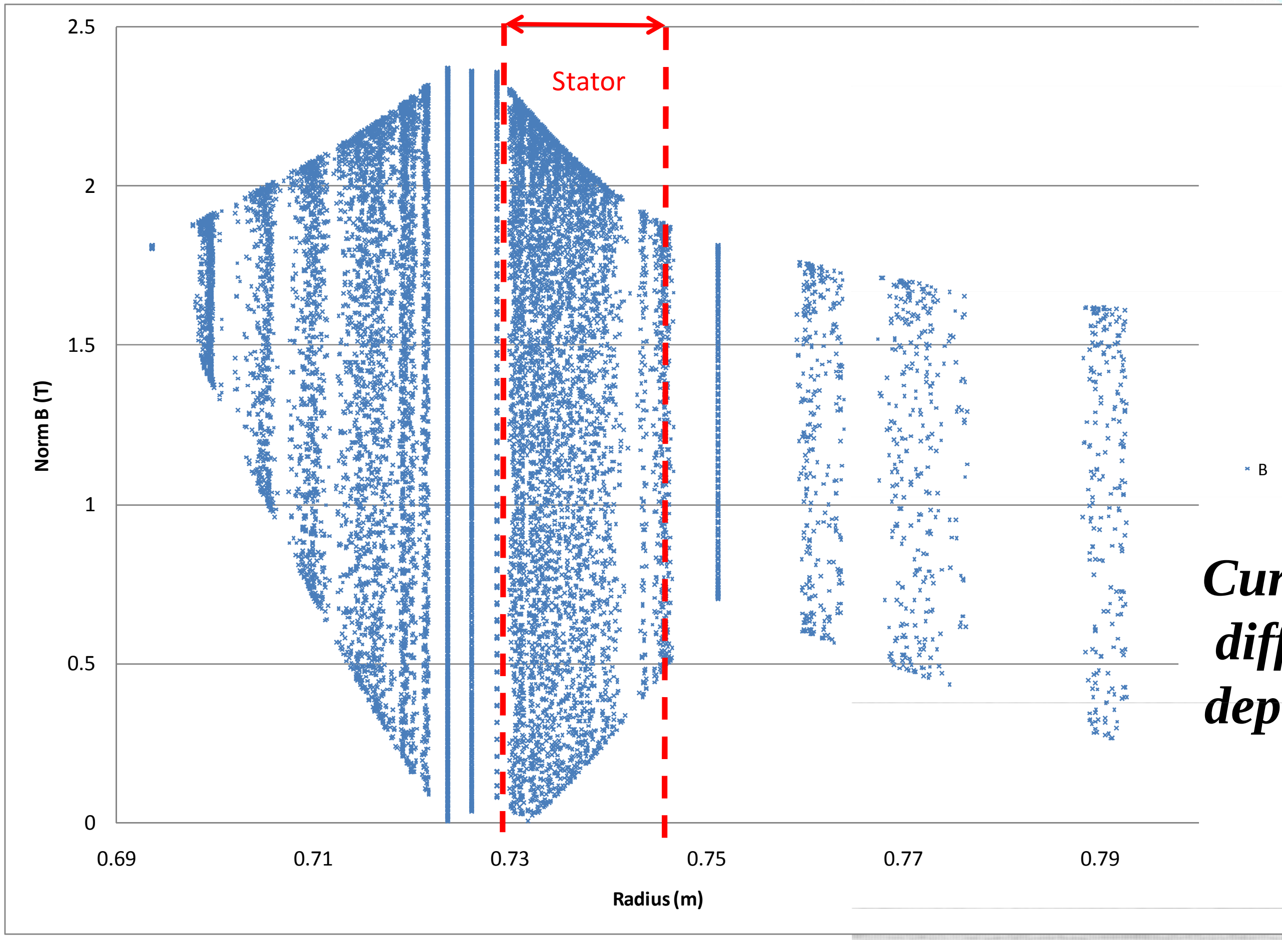
In Superconducting Machines, losses are almost independent from the load

Type of losses	*Depending variables*	*Comments*
AC losses	*Frequency (RPM) (f and f^2)* *Excitation field*	***AC Losses** are manageable using current MgB2 conductors at very low frequency (low RPM low number of poles)*
Rotor current leads	*Excitation current*	*MgB2 allows for the use of a flux pump for lower losses*
Stator current leads	*Output current*	*In the case of a FSG, the stator could be connected to a superconducting transformer directly*
Radiations	*External temperature*	*Might require an active thermal shield (2-stage cryocooler)*
Windage	*RPM*	*Negligible at low RPM*
Conduction (torque tube)	*External temperature*	*Largest heat load, present even when machine not in operation*
Iron losses	*Frequency (RPM)* *Excitation field*	*Negligible at low frequency*

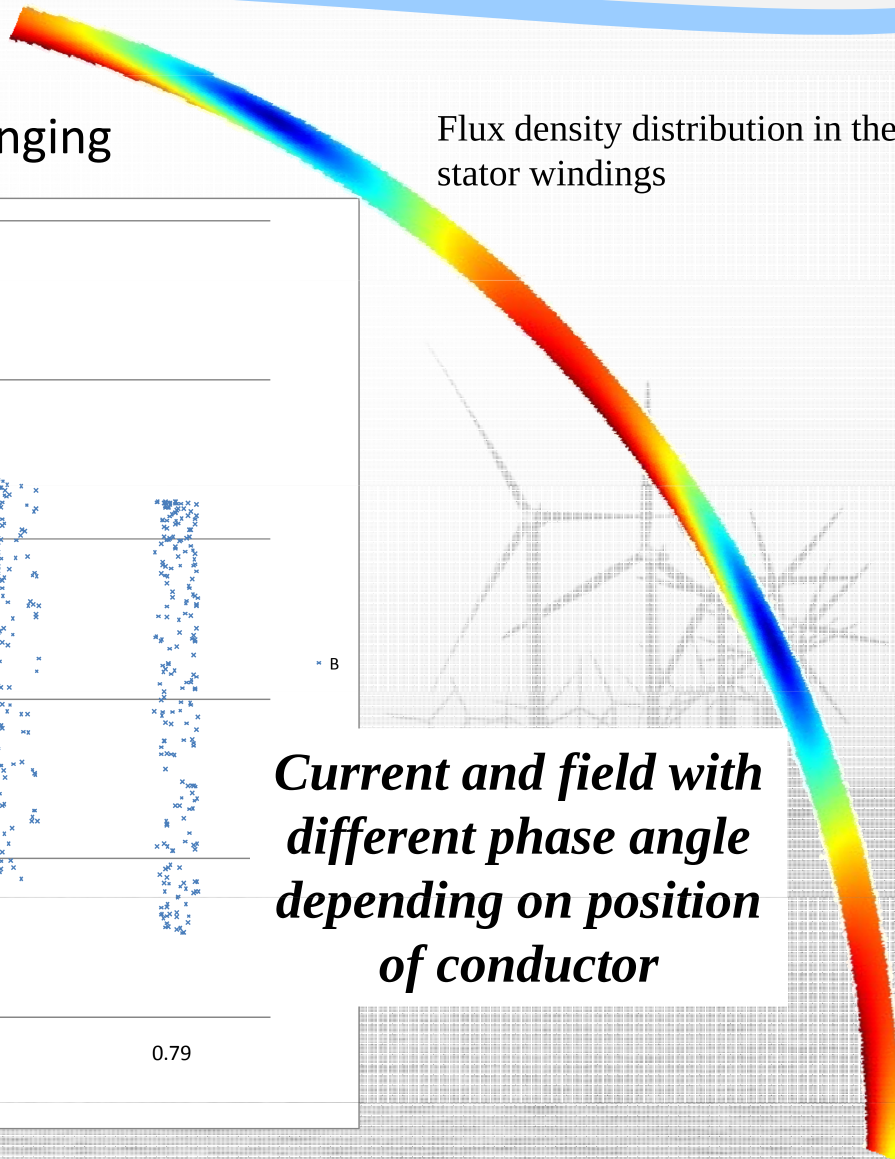
- Electrical power is needed to keep the superconducting generator cold even if no power is generated from wind.
- Parasitic losses are present even if the turbine is not rotating.

Electromagnetic Analysis – Stator AC losses

AC losses estimation in stator is challenging



Flux density in superconducting stator for AC losses calculation

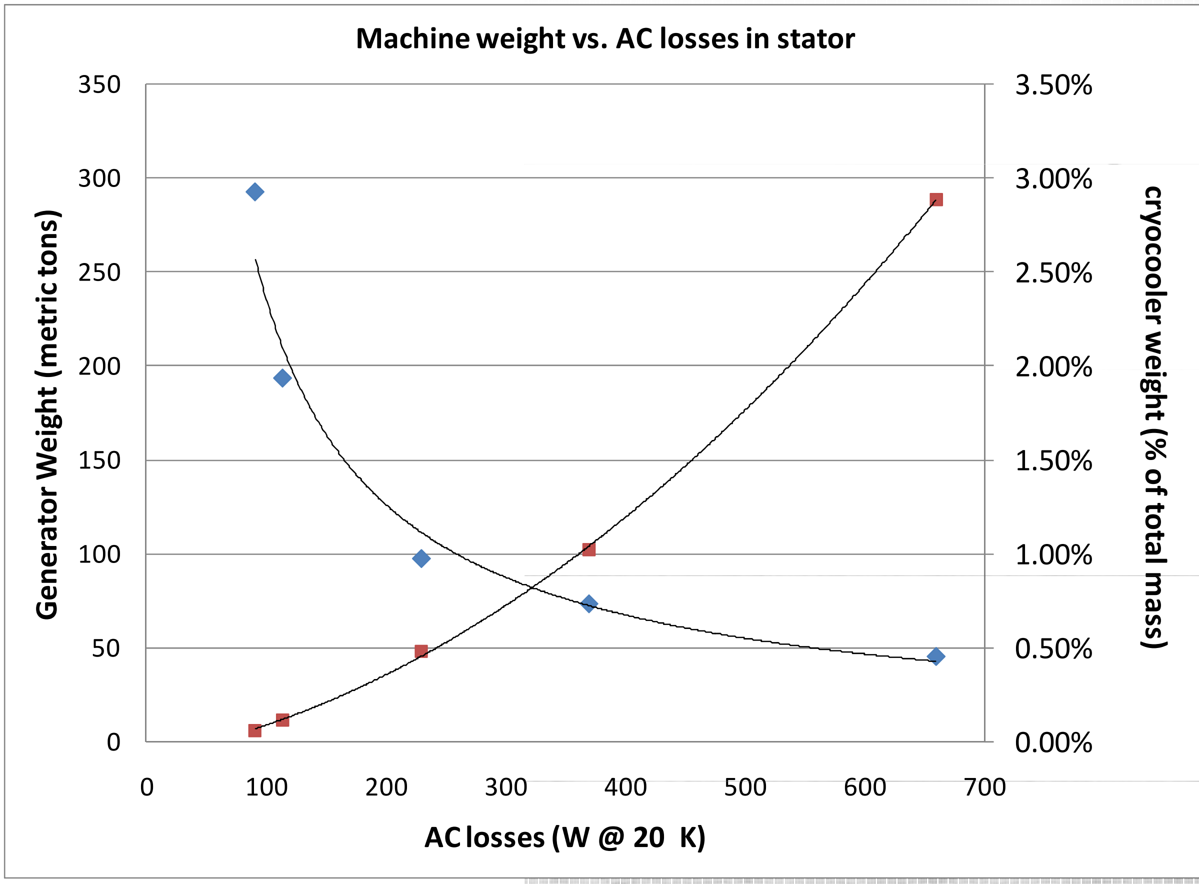


Flux density distribution in the stator windings

Current and field with different phase angle depending on position of conductor

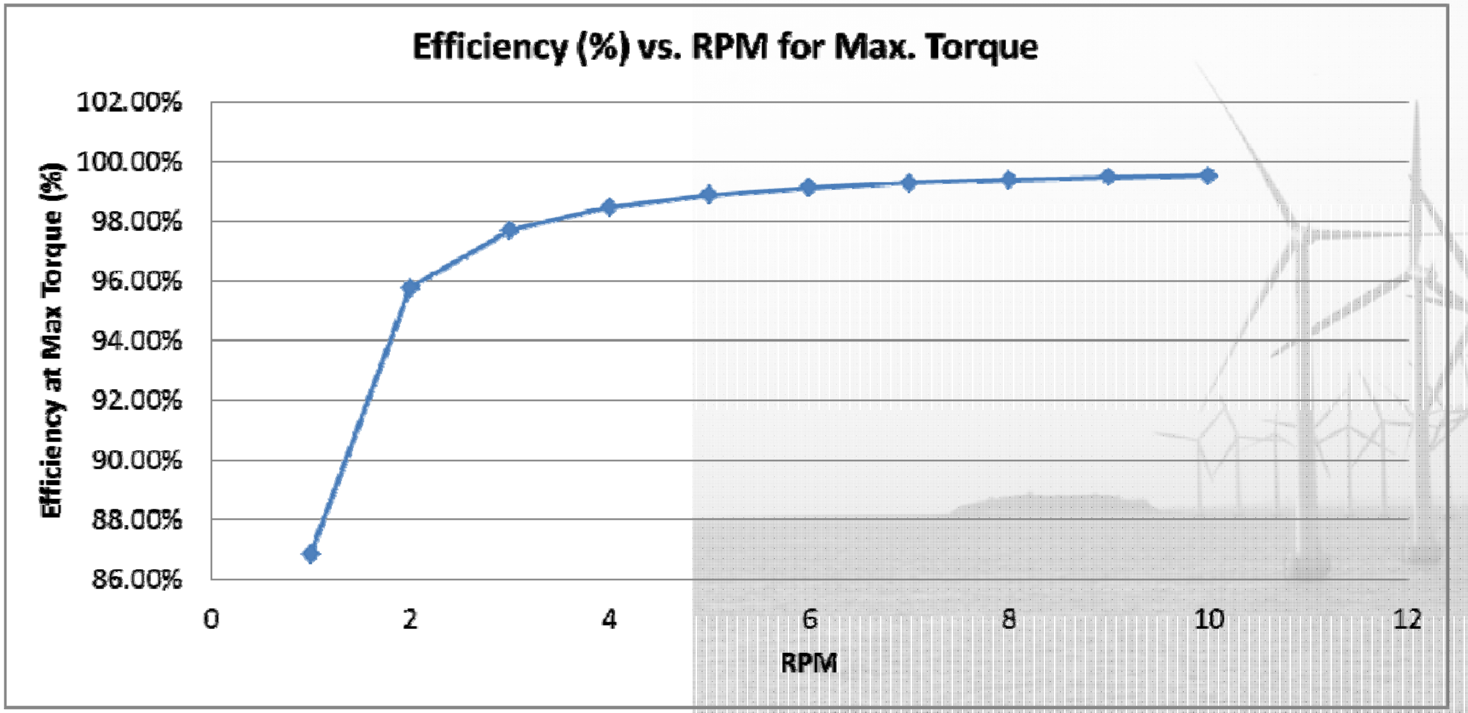
AC Losses and Machine Mass

- AC losses can be reduced at the expense of additional weight
- Cryocooler represents a small fraction of the total weight



Efficiency vs. RPM

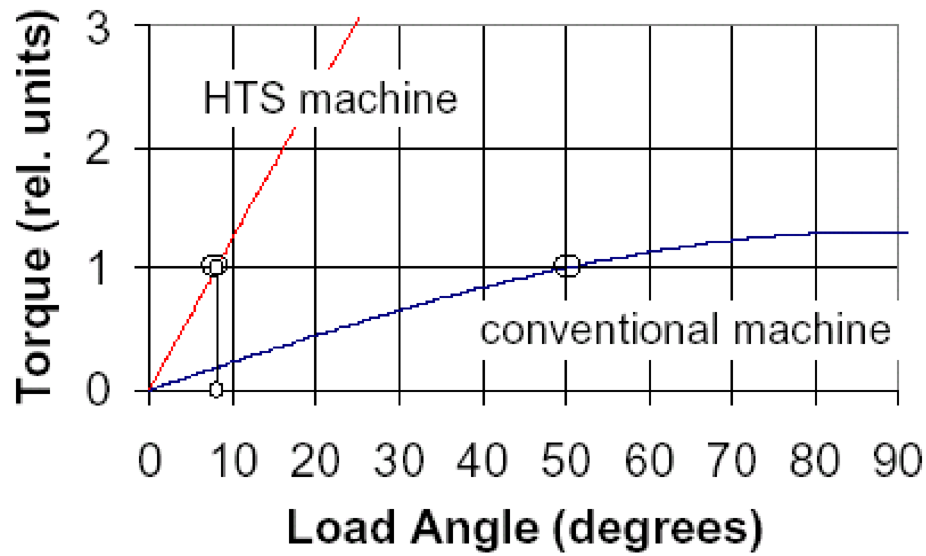
- Assumptions
  - Cooling system operating at 15 % of Carnot



- Efficiency remains very high at low power output

Machine Dynamics

- Small synchronous reactance
- Small load angle
- Very high dynamic response
- Very high stability
- Possibility of overloading
- Small variations of excitation current needed for power factor control



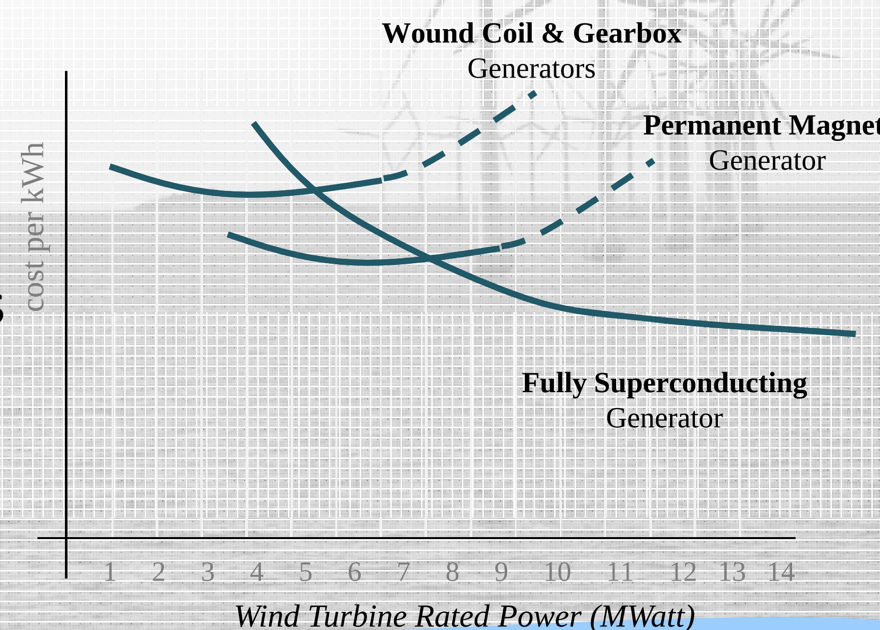
- Short-circuit power
  - Fully-superconducting, xd~0.2 p.u

    -> large short circuit power/torque
  - Partially superconducting, xd ~0.5 – 1 p.u.

    -> Superconducting stator acts as current limiter, thus limiting the short circuit torque (frequency ~1Hz)

Cost consideration

- A 10 MW, 10 RPM generator requires a very large amount of conductors (10s of km)
  - Cost of system conductor-cryocooler is dominated by conductor
    - Low cost conductor is the best option
- Drivetrain mass reduction -> lower capital and installation cost
  - Foundations, Tower, Crane…
- Higher efficiency and reliability
  - More energy produced
  - Less down time
- Cost of Energy estimation shows very promising results
  - Large Sc. Generator would lead to a lower $/kWh



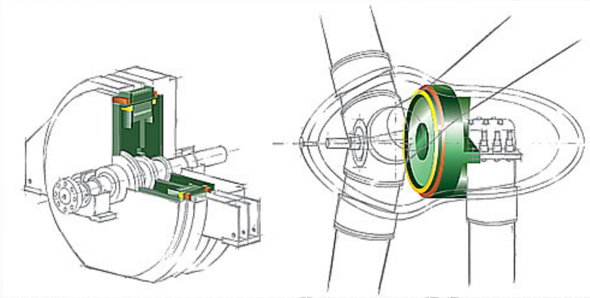
Outline

- Introduction
- Off-Shore wind power generation
- Current technology
- Superconducting generators
- Technology trade-offs
- Application to off-shore wind
- Ongoing projects
- Conclusion

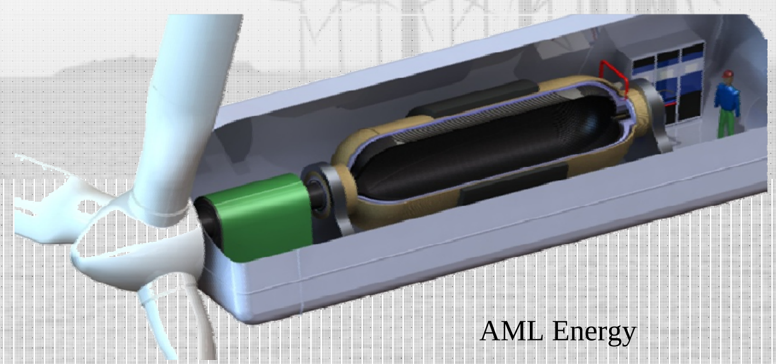
Ongoing Projects

- Some superconducting wind generators ongoing projects
  - Converteam/Zenergy
    - 8 MW
    - 12 RPM
    - Partially superconducting 2G
  - American Superconductor/TECO Westinghouse
    - 10 MW
    - 10 RPM
    - Partially superconducting 2G
  - AML Energy
    - 10 MW
    - 10 RPM
    - Fully superconducting MgB_2

- Others

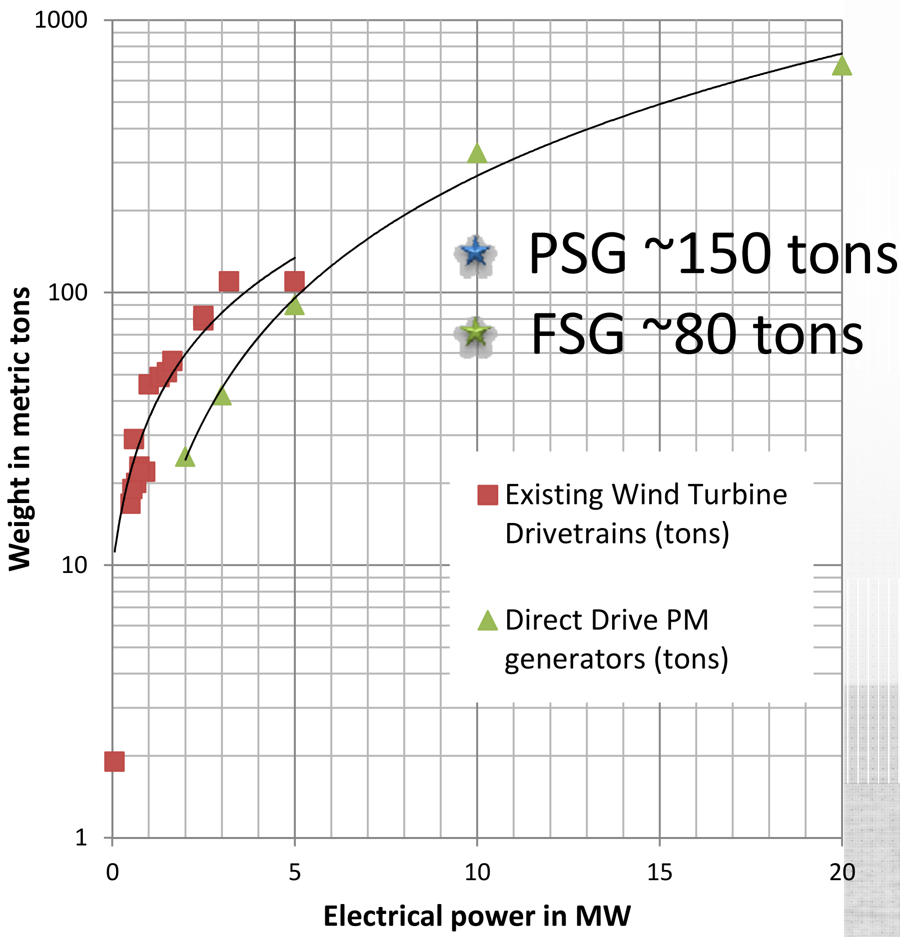


Converteam/Zenergy



AML Energy

Conclusion



- HTS machines present a strong value proposition for large direct drive wind turbine generators
  - Mass is a key design parameter and conventional machines cannot compete
- Large turbines with low drivetrain mass, high efficiency and low maintenance needs will lead to significant Cost of Energy reduction
- It is likely that wind power generation will become the first market for superconducting generators