Superconducting Generators for Offshore Wind Turbines

David Torrey
GE Research

August 30, 2022

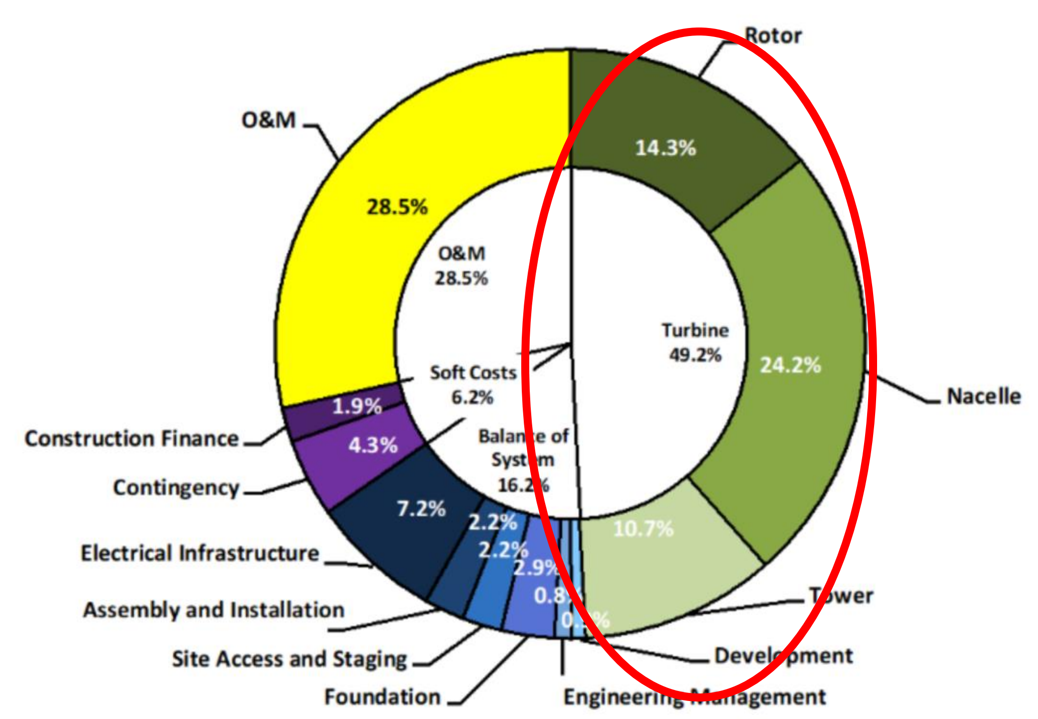
The Fine Print

Acknowledgement: This material is based on work supported by the United States Department of Energy under award number DE-EE0008787 through the Wind Energy Technology Office of the Office of Energy Efficiency and Renewable Energy. The productive interactions with the National Renewable Energy Laboratory, Golden, CO are gratefully acknowledged.

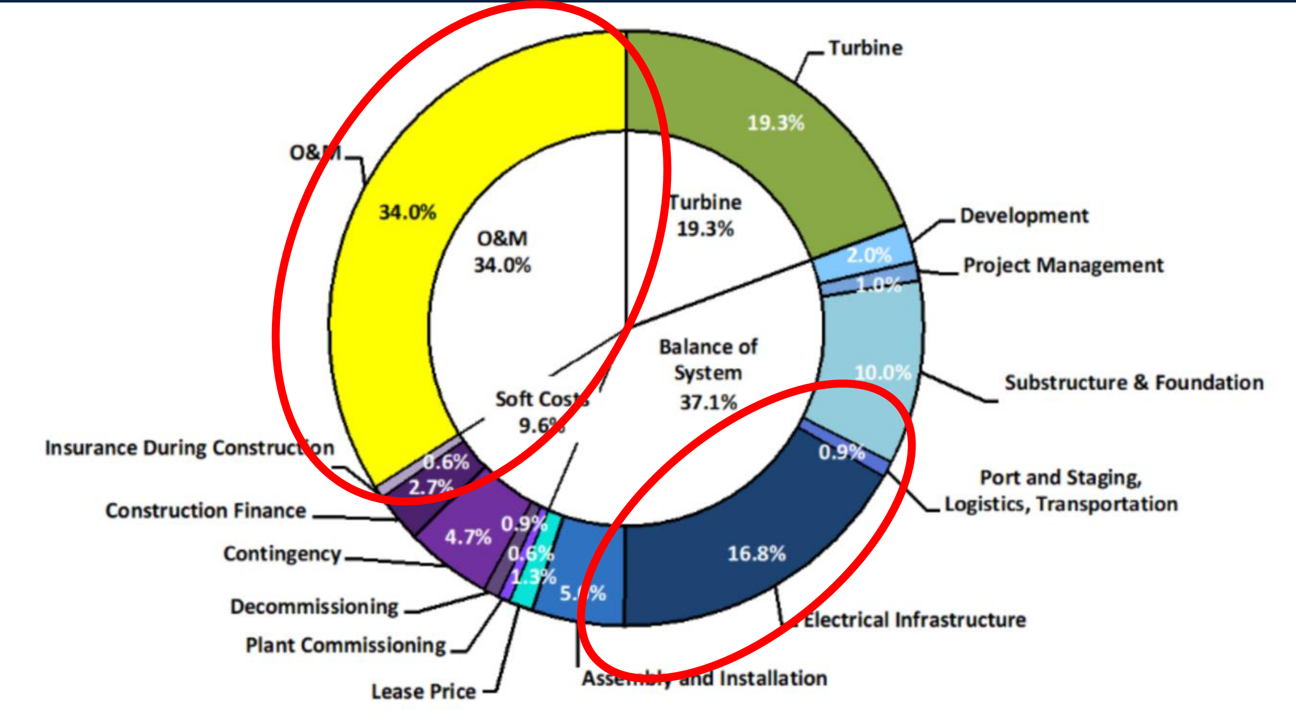
Wind Energy

Onshore v. Offshore Wind

Onshore Wind



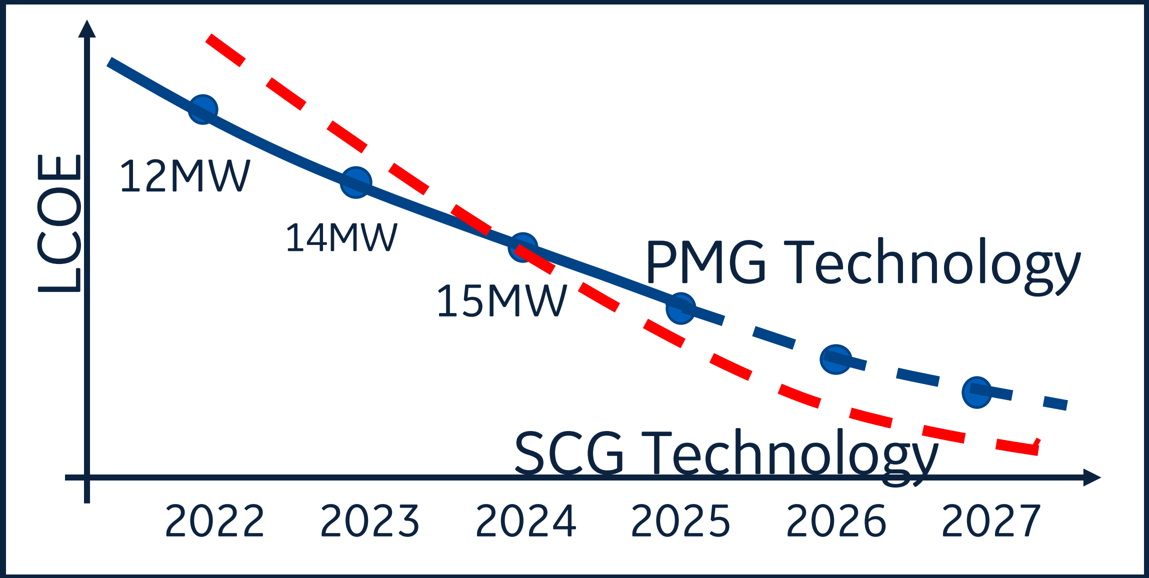
Offshore Wind

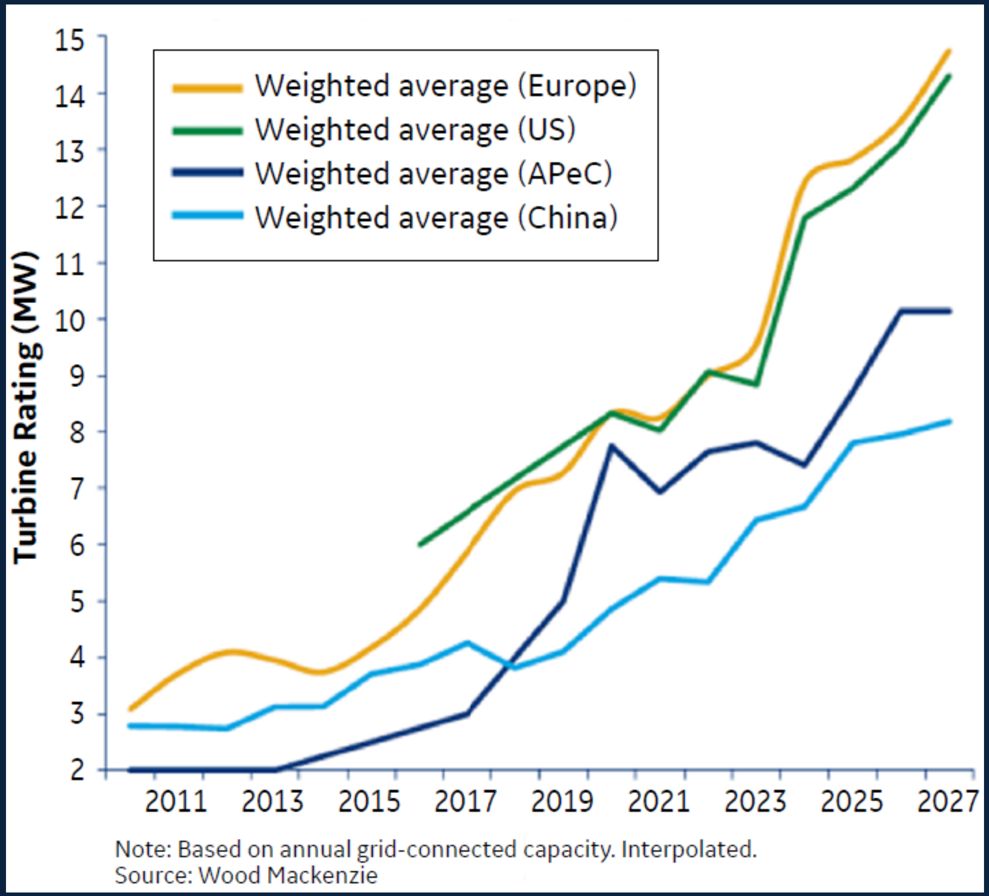


Source: Stehly, Tyler, and Philipp Beiter. 2020. 2018 Cost of Wind Energy Review. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-74598. https://www.nrel.gov/docs/fy20osti/74598.pdf.

- Onshore wind economics are driven by turbine cost.
- Offshore wind economics are driven by O&M and infrastructure costs.

Why Turbine Size Matters in Offshore Wind





CAPEX, machine-head mass, BOP

O&M

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Energy produced (drivetrain efficiency)

Generators for Offshore Wind Turbines

First Principles: Power, Torque and Radial Forces

Energy Conversion Principles

Power

Electrical Network ⟷ Electric Machine ⟷ Mechanical Network

Voltage, Current

Speed, Torque

$$P \propto n\, L\, D^2\, \sigma\, \beta$$

Utilization Factors

***Magnetic*: Flux density**

- Magnetic Materials

***Thermal*: Heating from current**

- Insulation Materials
- Cooling systems

***Kinetic*: Material Strength**

- Machine architecture
- Magnetic / Structural Materials

Torque Density, Efficiency

$$\frac{T}{D^2 L} \propto \sigma\, \beta, \quad \frac{T}{\sigma} \propto LD^2\beta$$

- Here D is the diameter of the armature winding, L is the effective length of field interaction
- Volumetric torque density requires high shear stress; High efficiency requires high magnetic loading

Radial Force

$$F_r \propto \frac{\pi}{2\mu_0} LD\beta^2$$

- Here D is the diameter of the armature yoke, L is the yoke length
- Higher magnetic loading increases requirement on handling radial forces

Increasing magnetic utilization drives increased efficiency and reduced volume, but has large impact on radial forces

Some Representative Numbers

For a 15MW wind turbine:

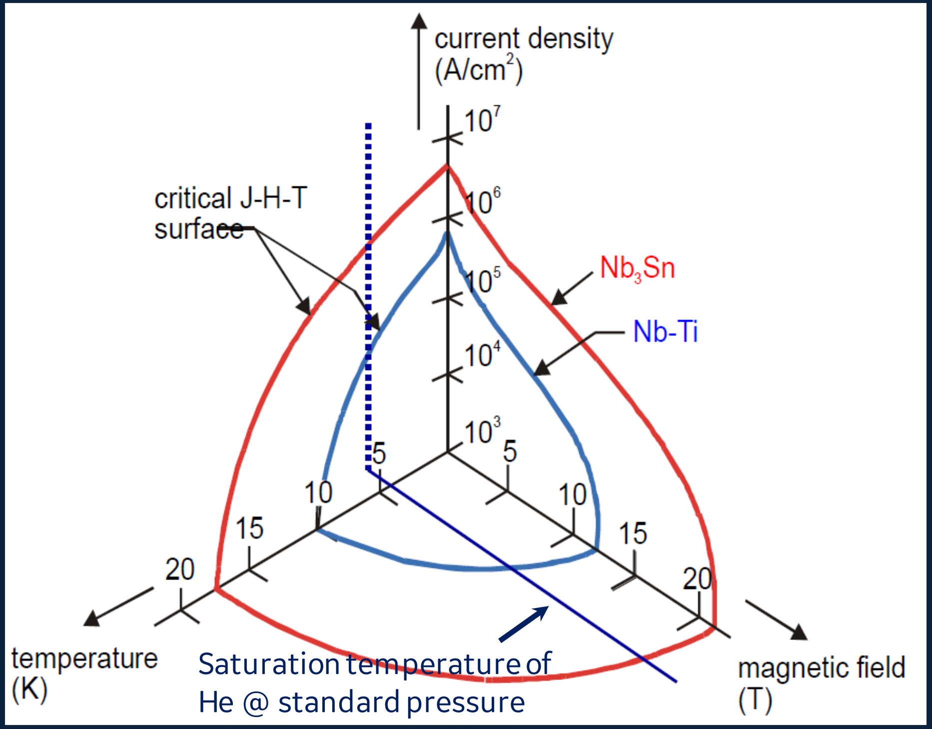
- Rotational speed is ~8 r/min
- Shaft torque is ~18 MNm
- Number of pole pairs to produce 60 Hz: 900!
- If $N_p = 120$, the fundamental frequency is 8 Hz

A power converter is necessary for frequency conversion

The high pole count favors synchronous generators over asynchronous generators, using the power converter to support variable speed operation

Superconductors

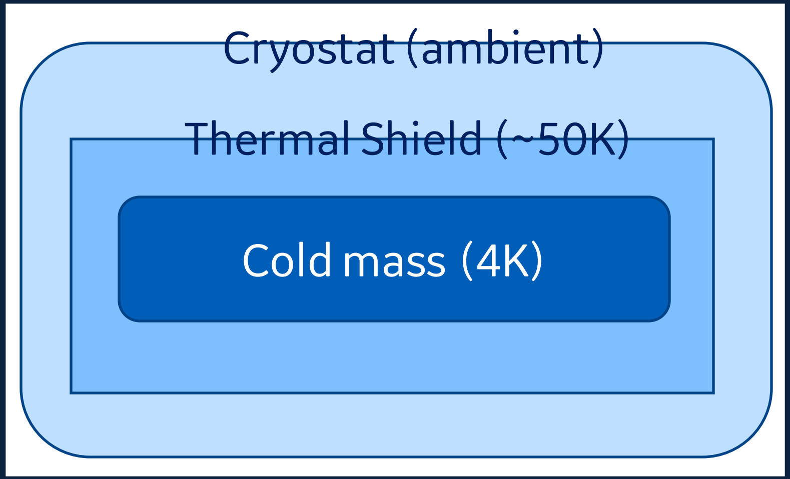
- Temperature, current density, and temperature determine conductivity:
  - Under the critical surface conductor is superconducting with no dc loss
  - Outside the critical surface conductor is normally conducting with resistive loss
- NbTi is the superconducting wire used for MRI machines; it is commercially available in adequate quantities and at acceptable cost
- NbTi is a low temperature superconductor
- High temperature superconductors exist, but are not appropriate for a commercial generator

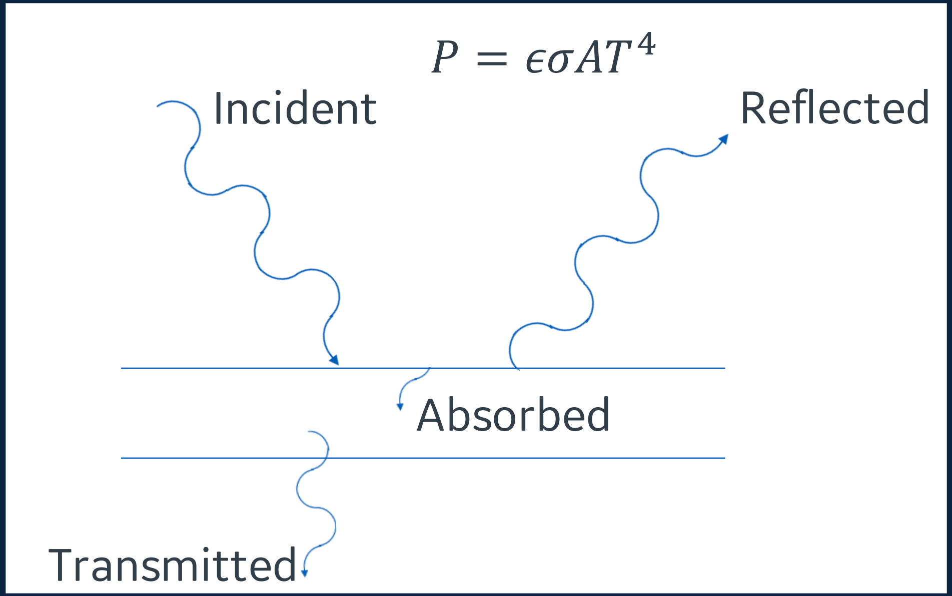


1 A/cm^2 = 10^4 A/m^2

Keeping the Superconductors Cold

- Use vacuum as thermal insulation to prevent thermal conduction
- Limit radiation heat transfer using emissivity control
- Limit thermal conduction through the torque-reacting structure

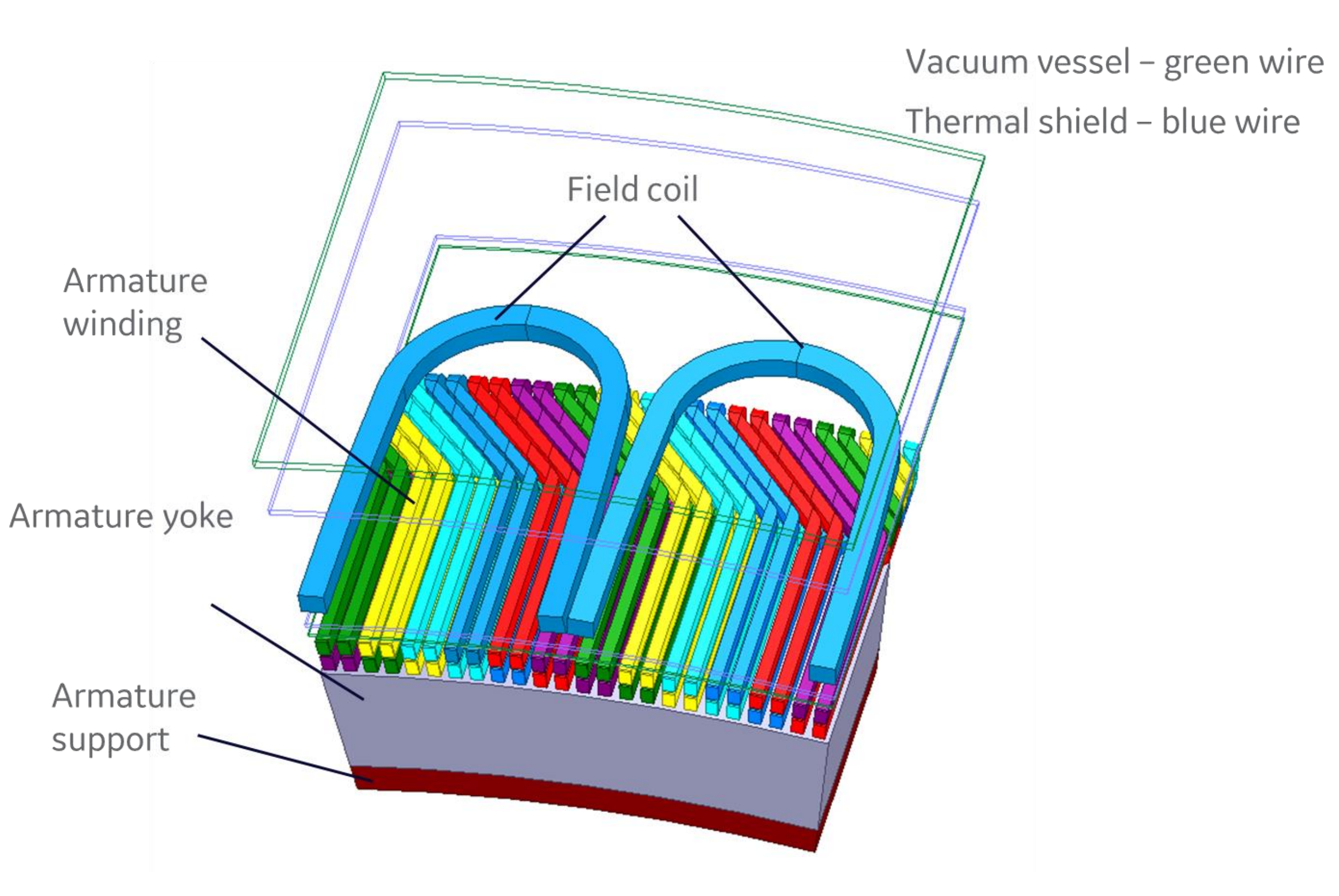




Superconducting Generators

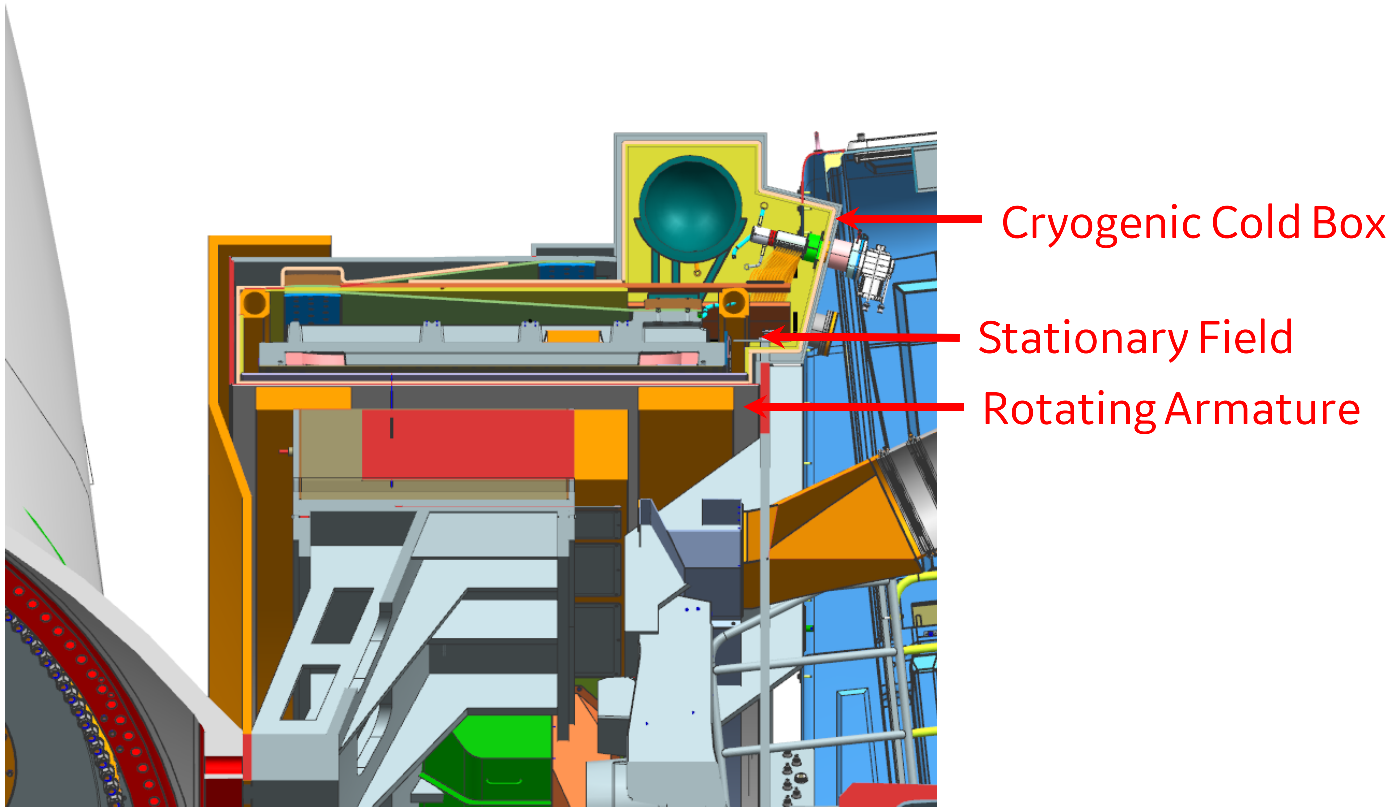
- The superconducting field winding produces the magnetic loading
- The armature winding produces the electric loading
- Armature windings may need to be integral slot to reduce losses in the cold regions where it is expensive to reject heat

- The thesis is that the higher magnetic loading buys increased efficiency with less mass



Superconducting Generators

- The field is stationary to eliminate a rotating cryogenic coupling
- The armature rotates, power is passed to the stationary frame through brushes, slip rings
- Armature windings are integral slot to reduce losses in the cold regions where it is expensive to reject heat
- The field leverages developments in superconducting magnets for MRI



Implementation Challenges

- Design
  - Structural support of field coils
  - Minimization of heat entering low temperature zones
- Manufacturing
  - Large, thin cylindrical shells
  - Precision winding of racetrack field coils
- Assembly
  - Nesting of temperature zones within field assembly
  - Integration of cold box

Summary

- Offshore wind economics are driven by OPEX
- Increasing turbine rating drives down LCOE

- Drivetrains rely on full power conversion to support variable speed operation

- Generator design is seeking high magnetic loading for high efficiency and high torque density
- Superconducting generators have the promise of providing high magnetic loading without rare earth elements