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SUPERCONDUCTING MACHINES FOR WIND ENERGY

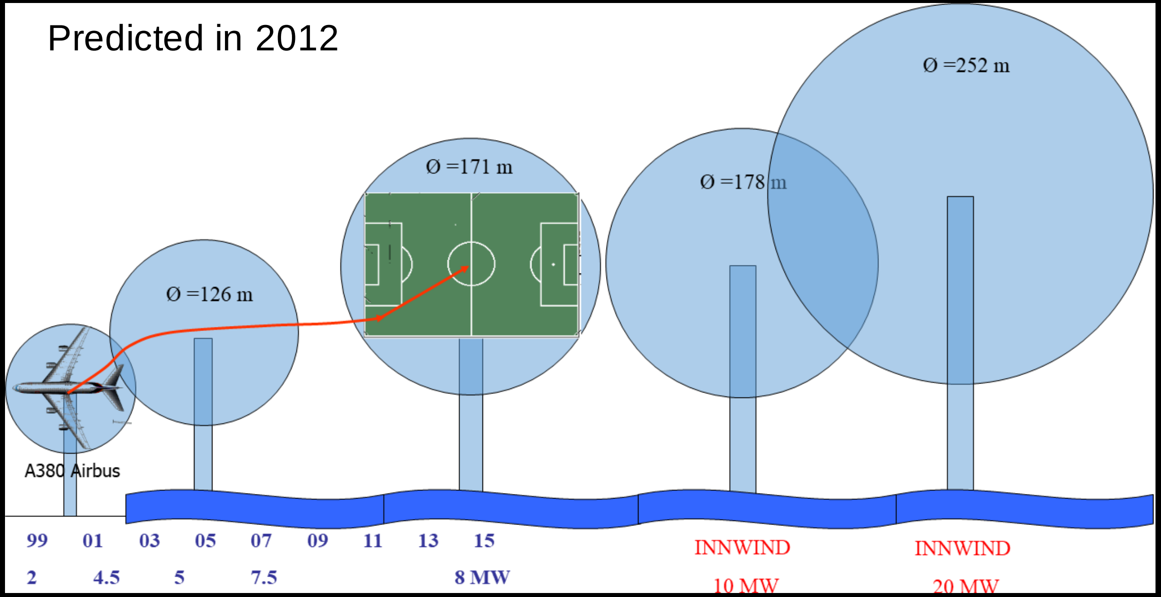
Dr. Dong Liu

Post-doctoral researcher

Lahti campus, LUT University

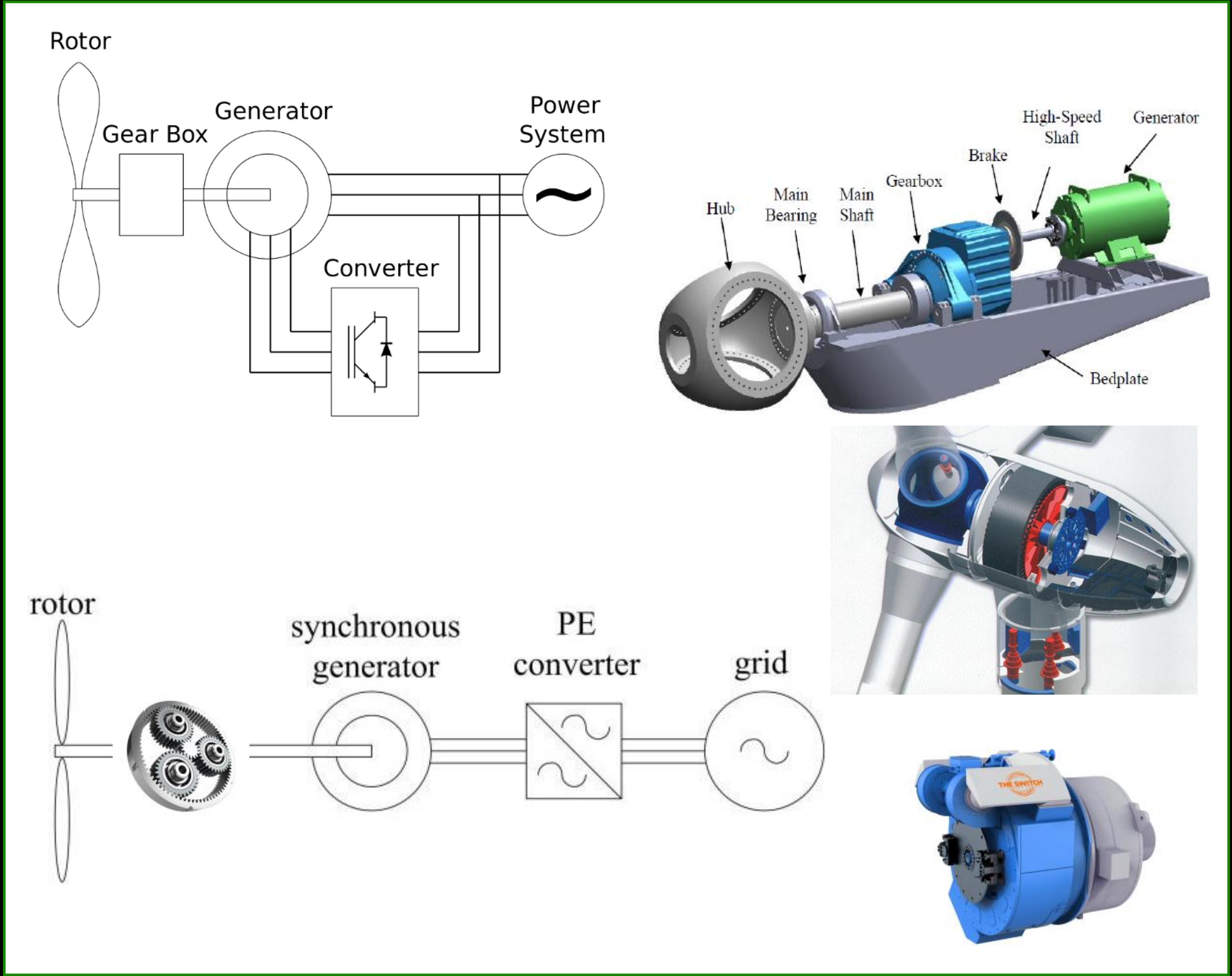
WIND ENERGY DEVELOPMENT

- Renewable and sustainble energy source
- Onshore and offshore
- Increasingly larger in turbine rotor diameter to capture more energy from wind
- High wind speed and low wind speed locations
- Direct and geared drive trains
  - MingYang MySE 16.0-242
  - Vestas V236-15.0 MW
  - SIEMENS Gamesa SG 14-236 DD
  - GE Haliabde-X 14 MW 220



DRIVE TRAIN EVOLUTION

- A three-stage gearbox with a doubly-fed induction generator, directly connected to the grid.
- A synchronous generator directly driven by the wind turbine shaft, connected to the grid via a full power back-to-back converter.
- A planetary geabox with a synchronous generator, connected to the grid via a full power back-to-back converter.



DRIVE TRAIN SIZING

- Limitation between power, speed and torque:

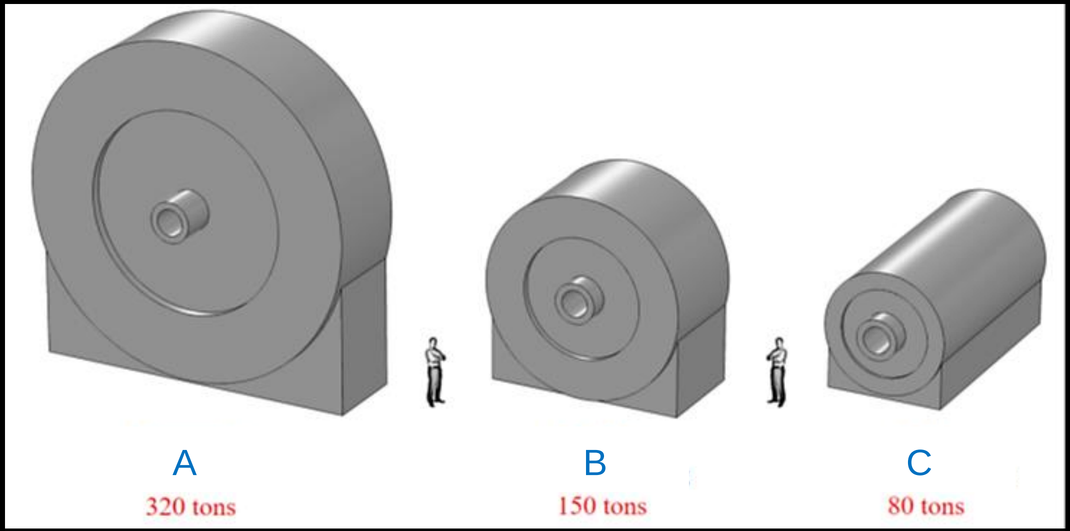
$$P = \omega_m T_e$$

- Torque T_e determines the size of a generator:

$$D^2 L \propto \frac{T_e}{BA}$$

D –diameter, L –axial stack length, B –magnetic loading, A – electrical loading

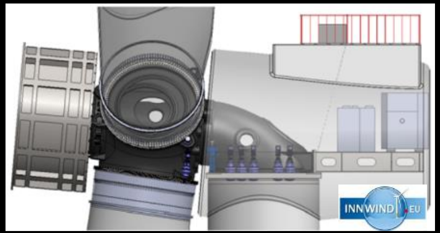
- Challenges for the direct drive train are especially huge. What to do with them?

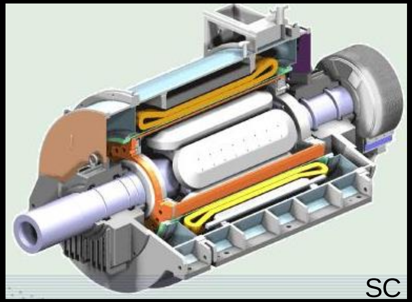


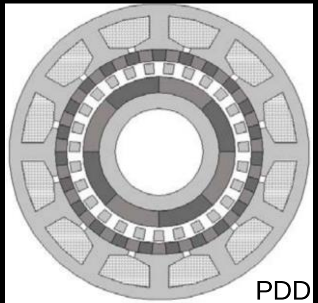
ROADS TO LARGER WIND TURBINES

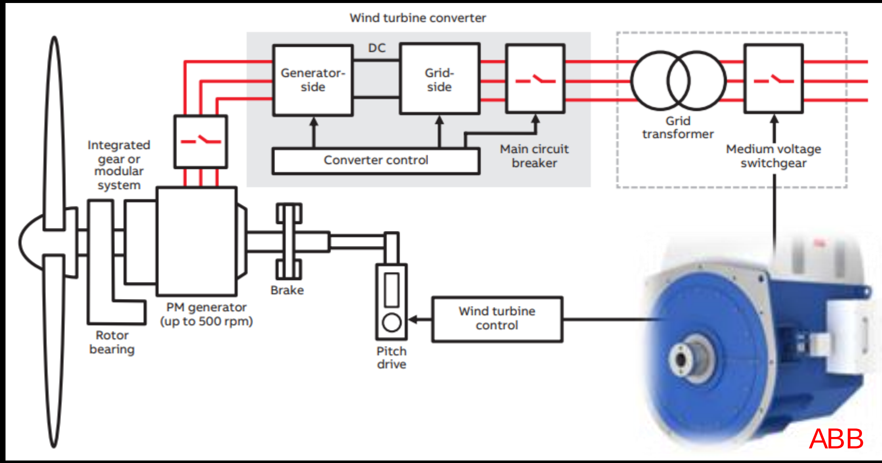
$$P = \omega_m T_e \qquad D^2 L \propto \frac{T_e}{BA}$$

- Doubly-fed induction generators
  - A three-stage gearbox is too big and expensive for 10+ MW wind turbines
- Direct drive with a synchronous generator
  - Speed is already low, especially with long wind turbine blades
  - Increasing B: partially superconducting generators
  - Increasing A: using a water-cooled armature (e.g. 46 A/mm^2)
  - Increasing both B and A: fully superconducting generators
- Pseudo direct-drive (PDD) generators
  - Magnetic gearbox by field modulation
  - Gear ratio ~ 1 : 6
- Medium-speed drive train with a synchronous generator
  - A planetary gearbox increases the speed (up to about 500-600 rpm)
  - A permanent magnet is used due to its maturaty and affordable cost.



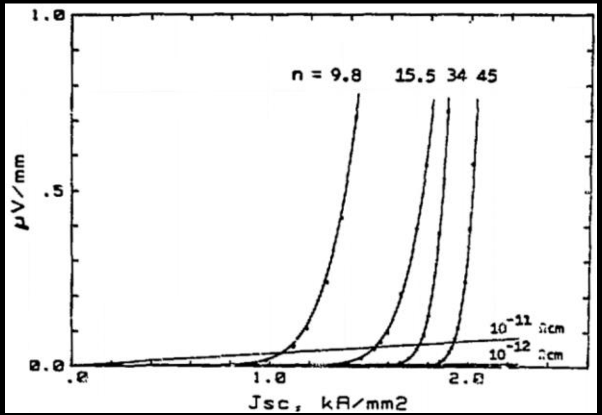




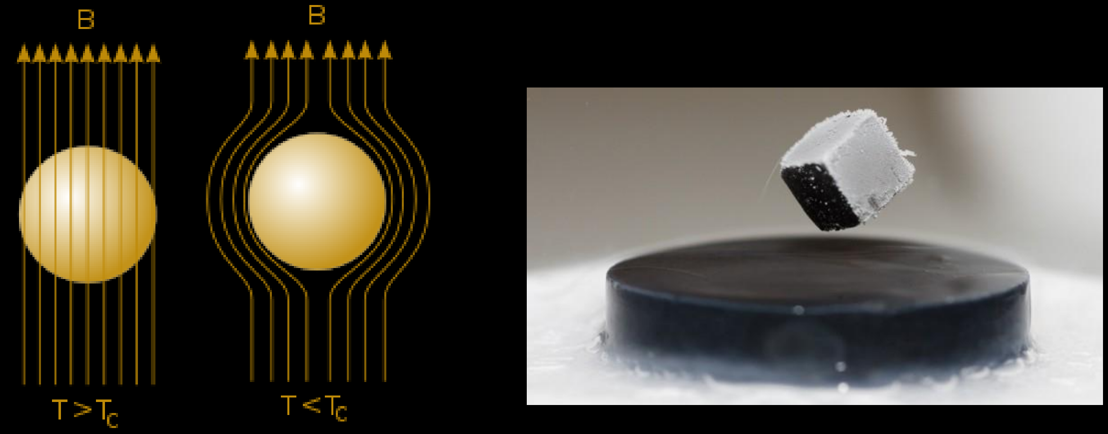


SUPERCONDUCTING MACHINES

- Superconductivity
  - Discovered in 1911 by Heike Kamerlingh Onnes, at Leiden University
  - Two distinct characteristics:
    - Zero resistance at a certain cryogenic temperature
    - Meissner effect



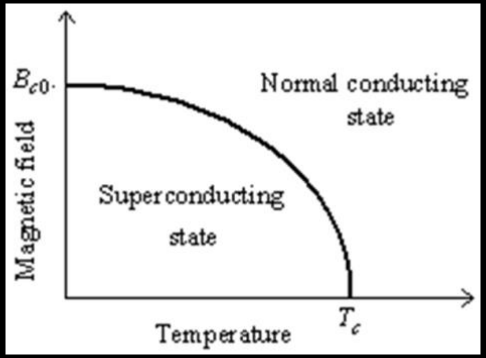
E-I characteristics



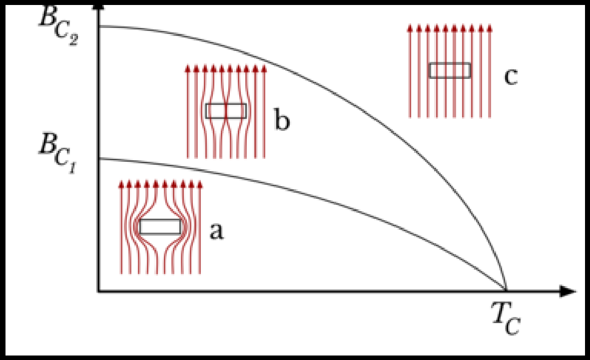
Meissner effect

SUPERCONDUCTING MACHINES

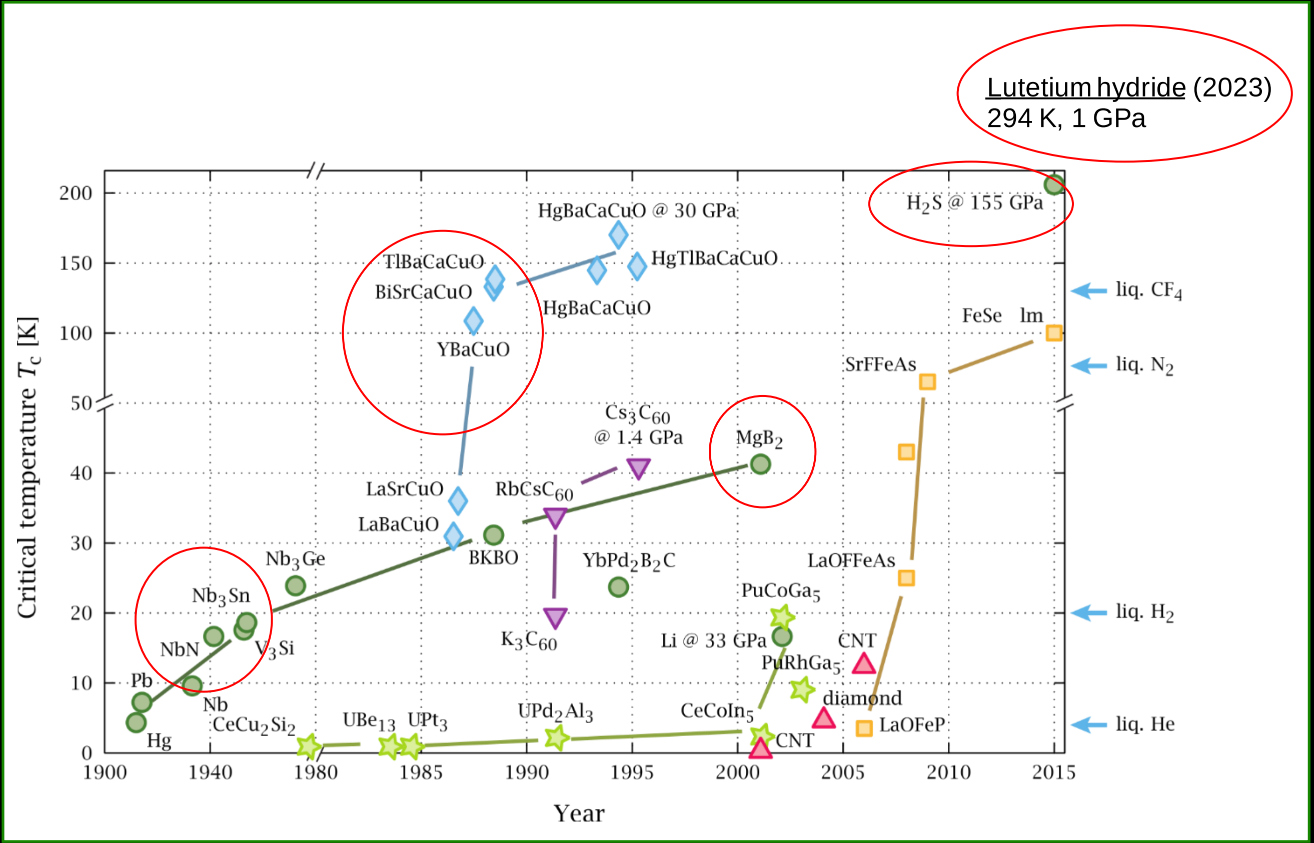
- Category of superconducting materials
  - Type-I, Type-II superconductors
  - Low-temperature, high-temperature superconductors
    - LTS
    - HTS



Type-I

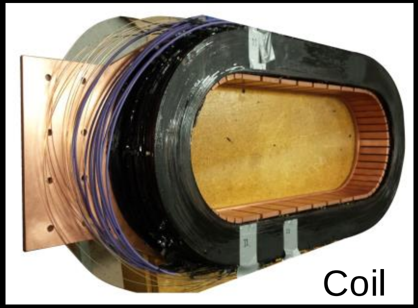


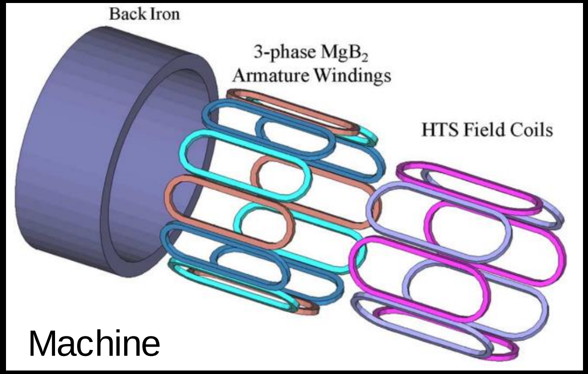
Type-II

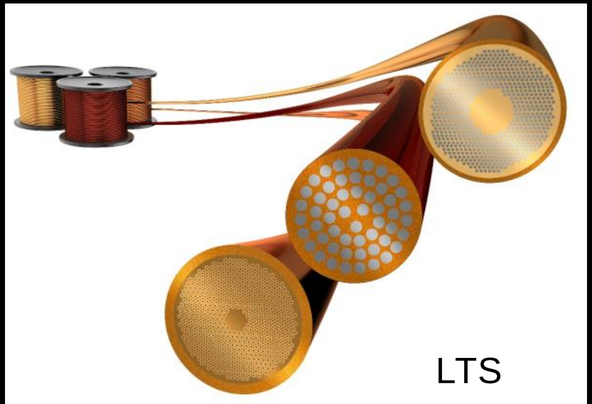


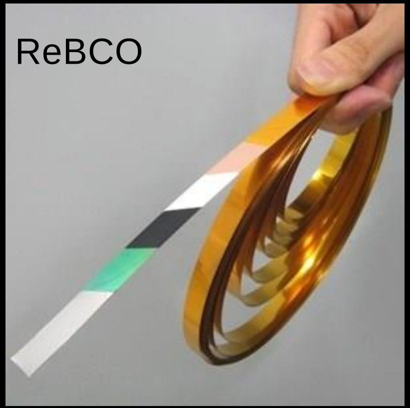
SUPERCONDUCTING MACHINES

- Type of superconducting wires for power applications
  - LTS: NbTi, Nb_3Sn
  - HTS: BSCCO, ReBCO
  - MgB_2

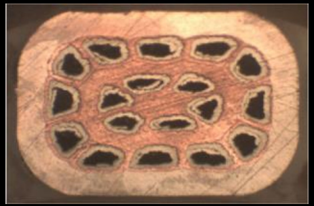


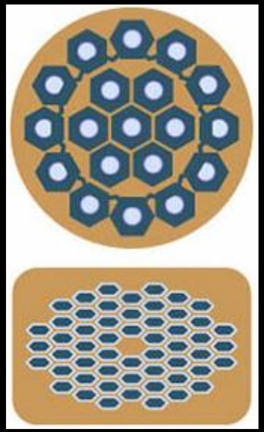




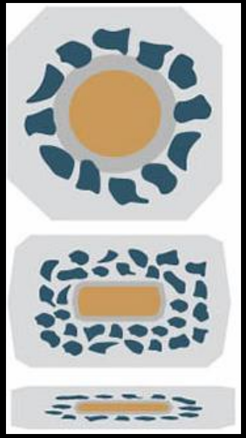


MgB_2





LTS @4 K
NbTi, Nb_3Sn



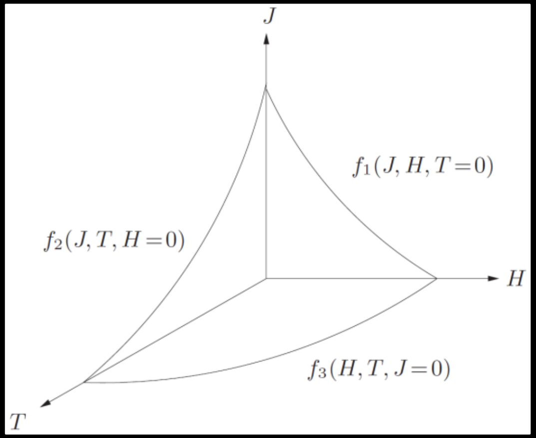
MgB_2
@ 10-20 K

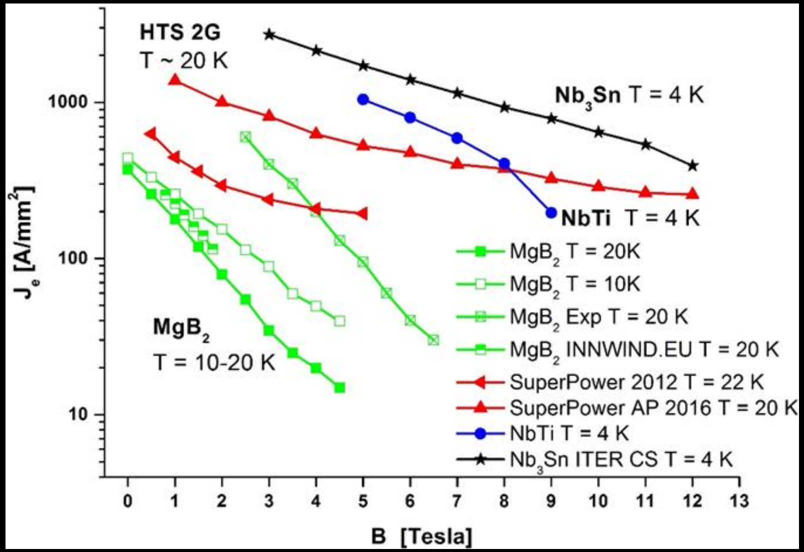
BSCCO (1G HTS)
@20-50 K

ReBCO (2G HTS)
@20-50 K

SUPERCONDUCTING MACHINES

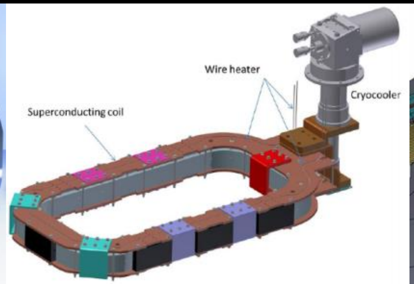
- Critical surface of a superconducting material
  - J, H, T or I, B, T limit each other
  - Determines electromagnetic performance of superconducting machines
- AC losses despite zero resistance
  - Hysteresis loss
  - Coupling loss
  - Eddy current loss
- Suitable electrical machine types
  - DC machines?
  - AC machines? Induction or synchronous machines?

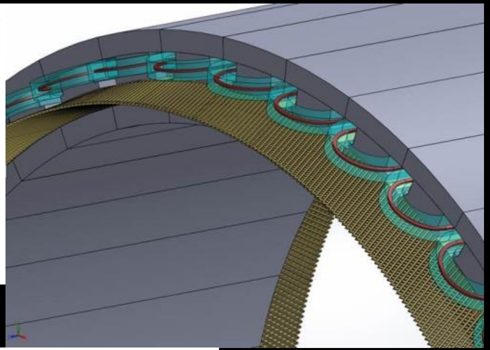


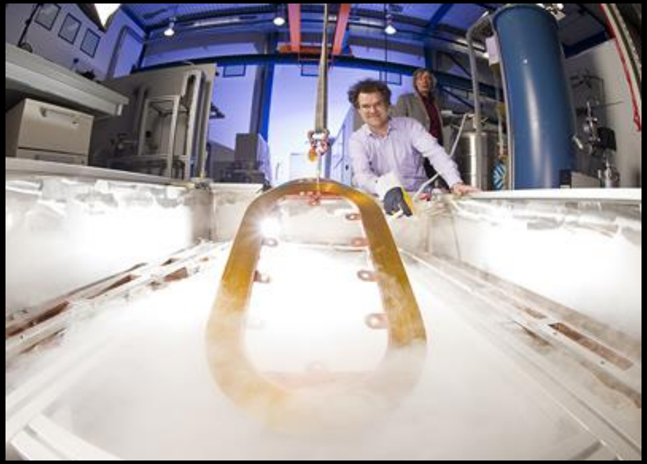


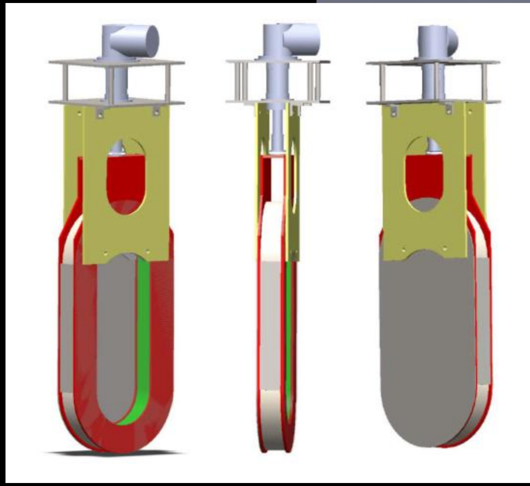
COOLING FOR SUPERCONDUCTING COILS

- Cryostats are needed to thermally isolate the coils from the ambient temperature
  - Cylindrical cryostat
  - Modular cryostat
- Cooling methods
  - Immersion cooling
  - Conduction cooling



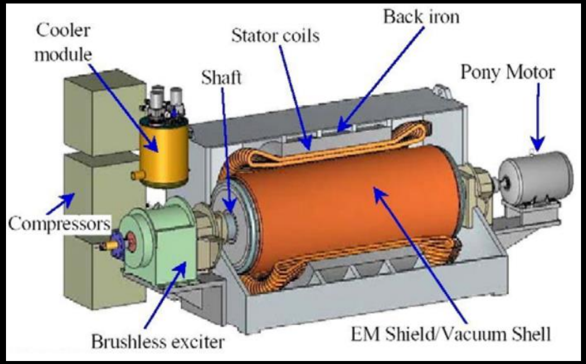


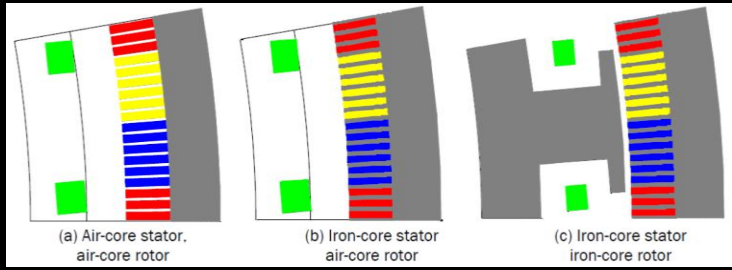


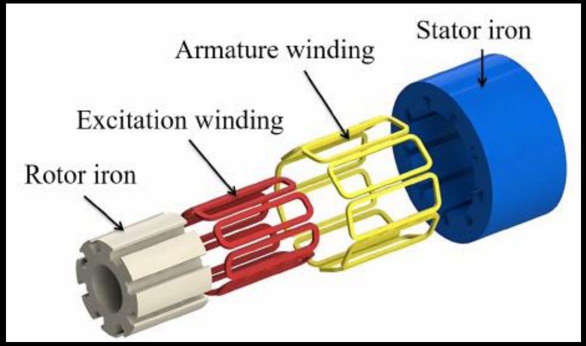


MACHINE STRUCTURES

- Partially superconducting machines
  - Stator/armature winding: copper wires, room temperature
  - Rotor/field winding: superconducting wires, cryogenic temperature
  - Cryostat: only encloses the field winding or the rotor
  - To avoid AC environments
- Fully superconducting machines
  - Stator/armature wining: superconducting wires, cryogenic temperature
  - Rotor/field winding: superconducting wires, cryogenic temperature
  - Cryostat: encloses the whole machine, or rotor and stator separately; or modular

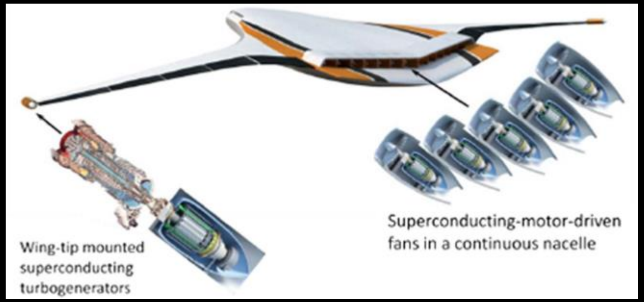






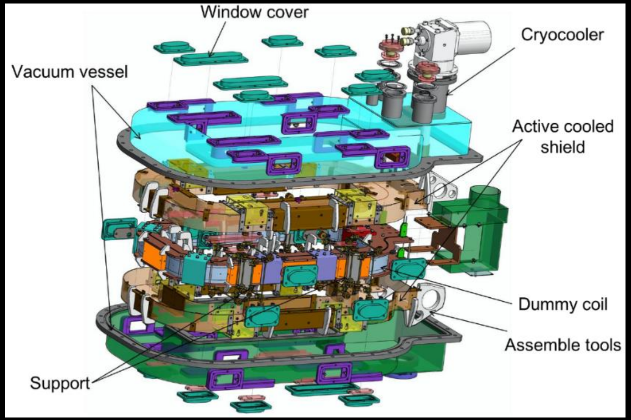
APPLICATION AREAS

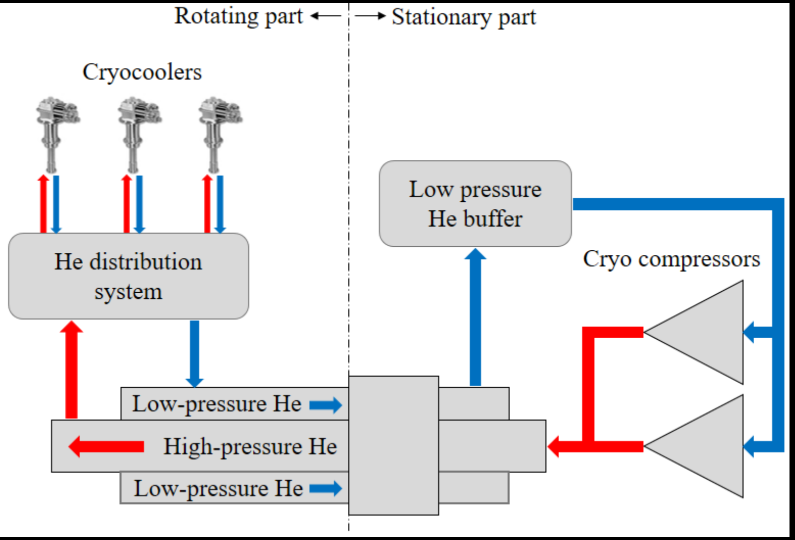
- Propulsion motor for ships
  - Used as motor
  - Compact, lightweight, less sensitive to costs
- Aircraft
  - Used as motor or generator
  - Compact, lightweight, less sensitive to costs
- Power generation
  - Hydropower, wind power
  - Compact, lightweight, critical in costs



CHALLENGES

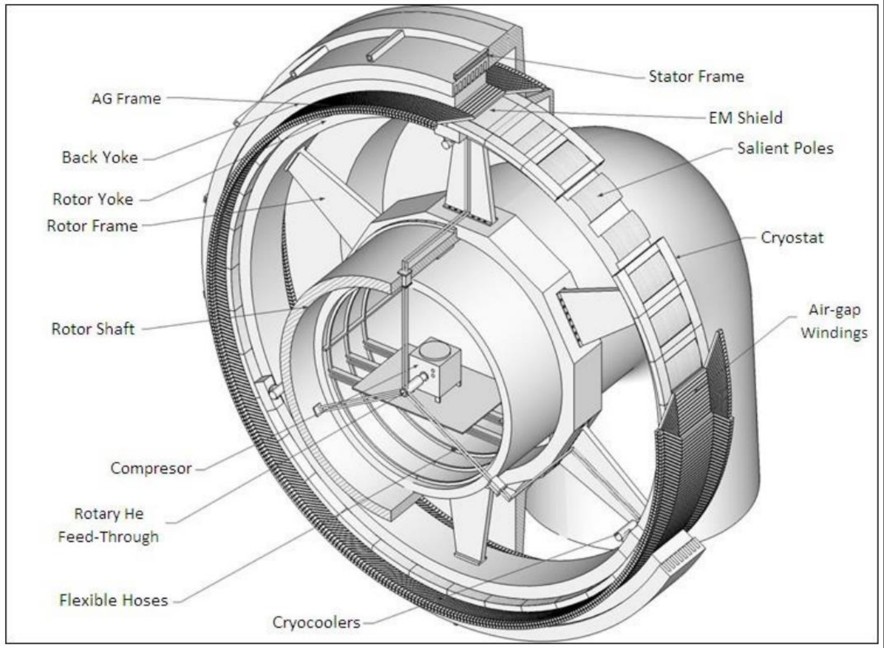
- Difficult cooling
  - Cryostat
  - Coupling of rotating and stationary parts
- High costs
  - Superconducting wires
  - Cryogenic cooling
- Reliability
  - Implementation of new technologies
  - No enough operation data for statistics
- Hard control of field excitation
  - Constant current operation only

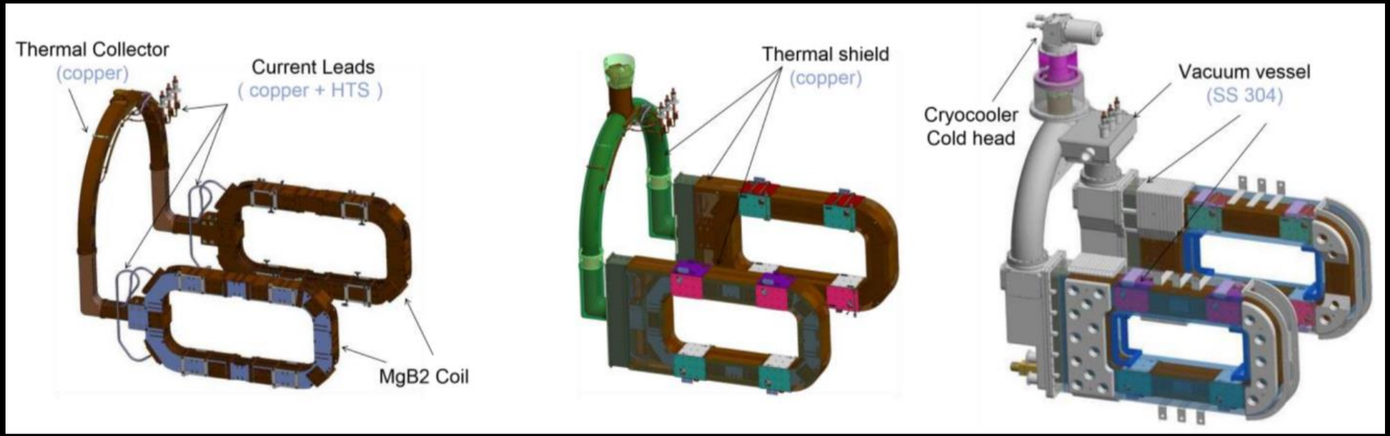




DEMONSTRATION RESEARCH PROJECTS

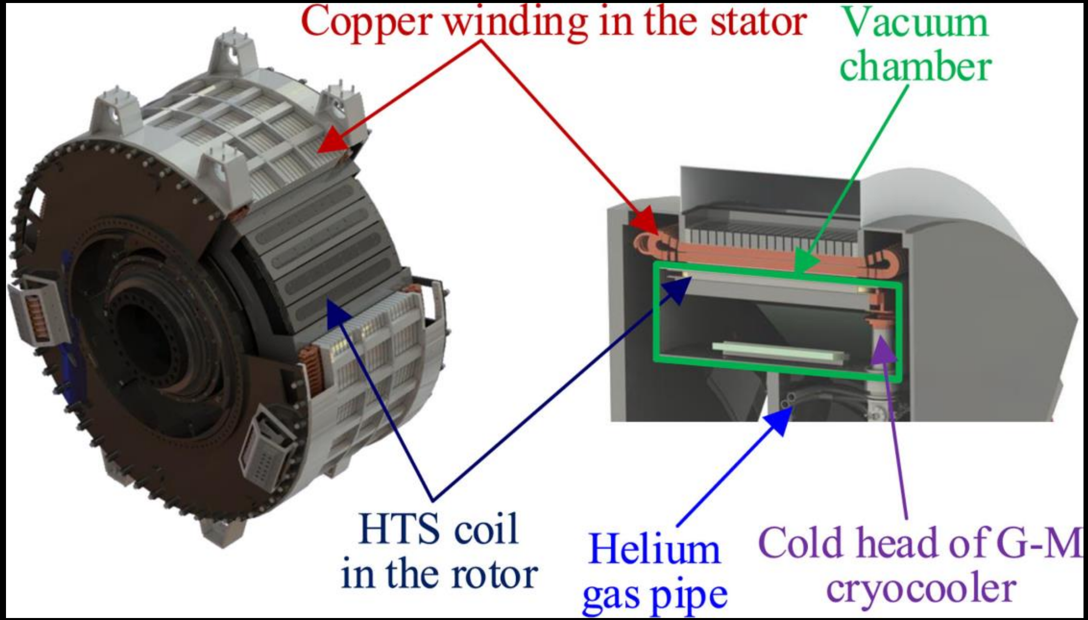
- Suprapower (EU FP7, 2012 - 2017)
  - 10 MW, 8.1 rpm, 48 poles, toothless design
  - MgB_2 superconducting field winding, partially superconducting
  - Conceptual design of generator and small-scale test
  - Design and test of MgB_2 field coils and modular cryostats





DEMONSTRATION RESEARCH PROJECTS

- EcoSwing (Horizon 2020, EU FP7, 2015 - 2019)
    - 3.6 MW, 15 rpm, iron pole, iron core
    - 2G HTS superconducting field winding (GdBCO)
    - Operating on a wind turbine for nearly one year, generating power to the grid



TRENDS OF SUPERCONDUCTING GENERATORS FOR WIND ENERGY

- Demonstration and theoretical research projects show that

a superconducting generator system is currently too expensive in terms of investment and levelized cost of energy.

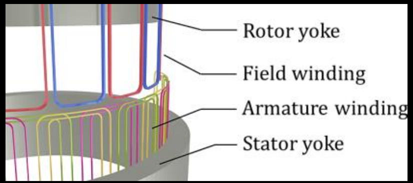
  - Superconducting wires are expensive.
  - Cryogenic cooling is quite complicated, especially with modular cryostats.
  - Not yet competitive compared to permanent magnet generators.

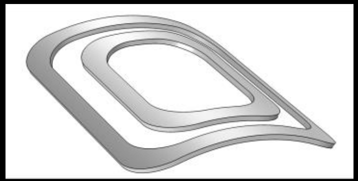
TRENDS OF SUPERCONDUCTING GENERATORS FOR WIND ENERGY

- Many technical issues need to be solved to increase TRL
  - The large magnetic air gap that limits torque production
  - The critical surface
  - AC losses
  - Degradation due to strain on superconducting wires
  - Quench protection
  - Transient performance

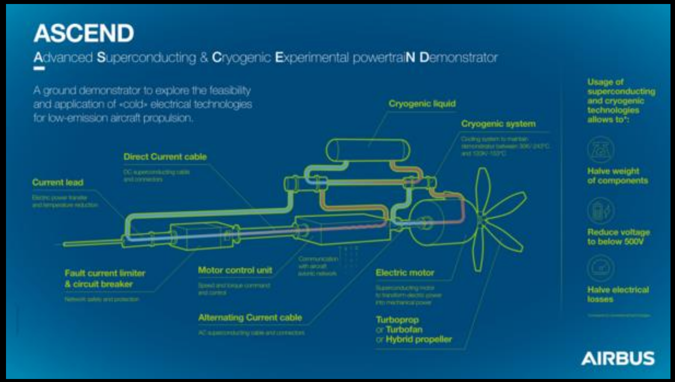
TRENDS OF SUPERCONDUCTING GENERATORS FOR WIND ENERGY

- Less interesting for wind energy industry, but research continues:
  - Modeling of different superconducting wires (coated, multi-filamentary, Rutherford cables, etc.)
    - In normal operation
    - In transients
  - Design of novel coils for superconducting wires
    - Distributed windings with racetrack coils





- To get inspired by aviation application research
  - High speed
  - Fully superconducting
  - Less cost-sensitive
  - Integration with hydrogen for cooling and powering

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