Technical University of Denmark

Advantages and Challenges of Superconducting Wind Turbine Generators

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Advantages and Challenges of Superconducting Wind Turbine Generators

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21st – 23rd May 2012, Bremen, Germany

Overview

- Background of superconductivity and its relevance for wind turbine generators
- Advantages of superconducting generators for wind turbines
- Challenges of superconducting generators for wind turbines
- Commercial activities

BACKGROUND

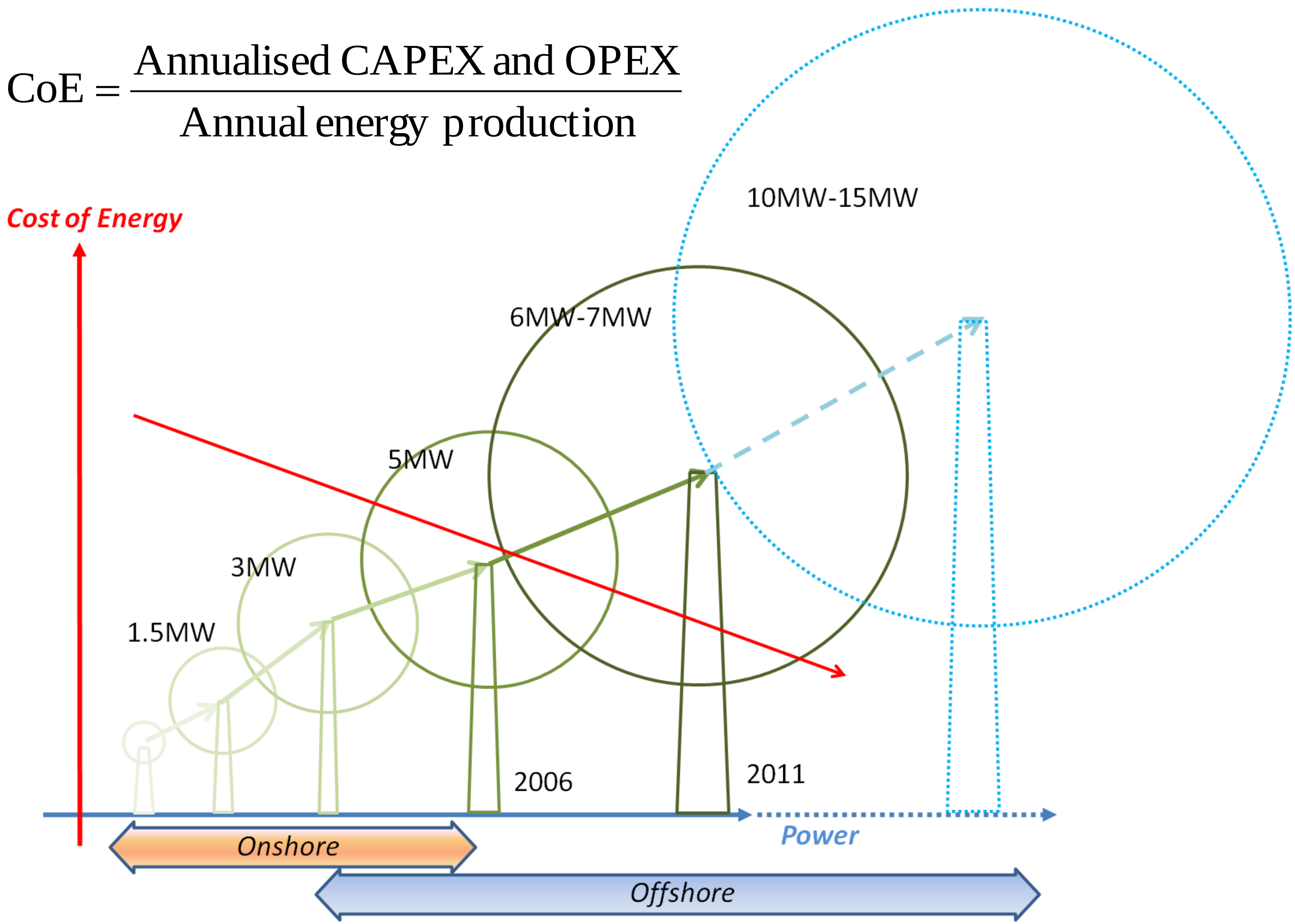
Technical University of Denmark (DTU)

- Based in Copenhagen, the Capital of Denmark
- 8200 students – 530 faculty – 1040 researchers
- Ranked 4th in Europe in the field of engineering by THE based on citations per journal paper from 2000-2010
  (http://www.timeshighereducation.co.uk/story.asp?storyCode=414302&sectioncode=26)



Development of wind turbines

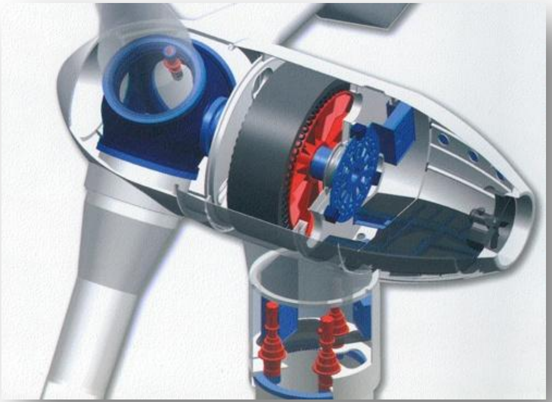
$$\text{CoE} = \frac{\text{Annualised CAPEX and OPEX}}{\text{Annual energy production}}$$



Current trend

- Elimination of Gearbox
- Permanent Magnet Generators

10 MW

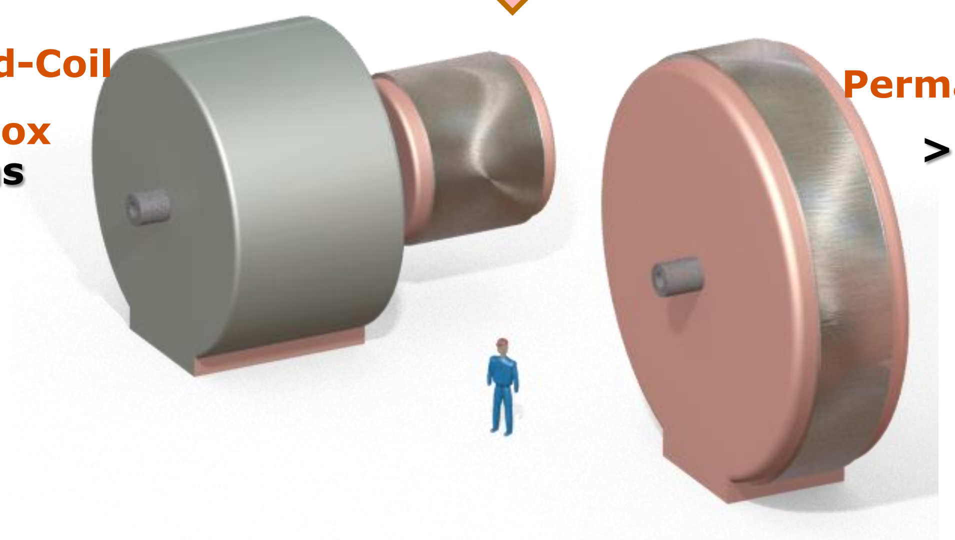


Conventional Turbine Generator

Next Generation - No Gearbox

Copper Wound-Coil with Gearbox

> 500 Tons



Permanent Magnet

> 320 Tons

5MW and beyond

Manufacturer	Transmission	Generator
Siemens Wind Power	Direct drive	PMSG 6.0MW
Vestas	Medium speed	PMSG 7.0MW
Enercon	Direct drive	EESG 7.5MW
Alstom	Direct drive	PMSG 6.0MW
REPower	High speed	DFIG 6.2MW
Areva	Low speed	PMSG 5.0MW

10MW and beyond – proposals/investigations

Manufacturer	Transmission	Generator
American Superconductor	Direct drive	HTS 10MW
General Electric	Direct drive	LTS 10-15MW
Advanced Magnet Lab	Direct drive	MgB_2 10MW

Schematic of a Superconducting Machine

- The superconductor must be kept at cryogenic temperatures

- The armature winding is usually proposed to be copper at ambient temperature

$$P = \omega \times T$$

$$T \propto A \times B \times V$$

P : *power*

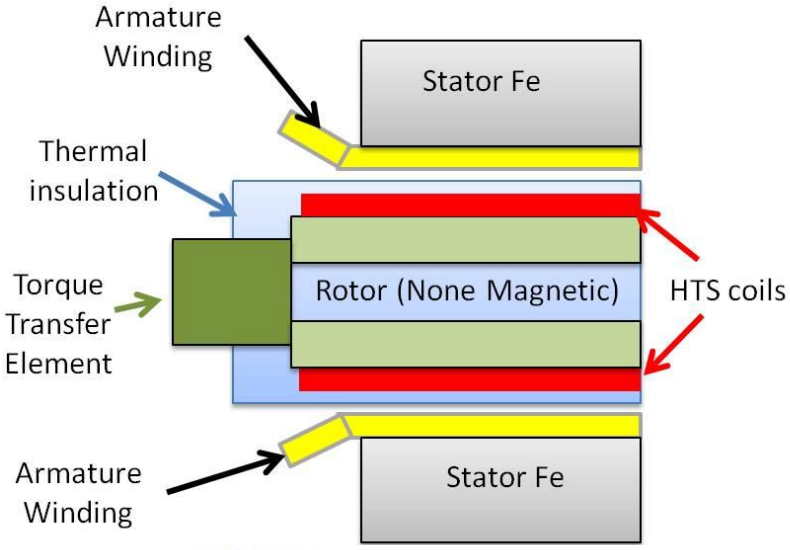
T : *torque*

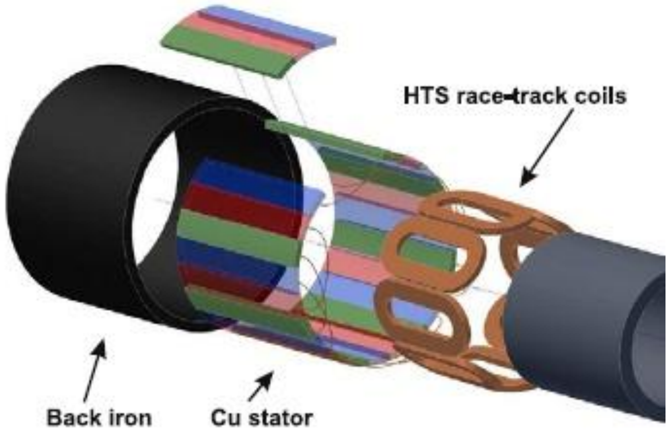
ω : *rotational speed*

A : *electric loading*

B : *magnetic loading*

V : *volume*





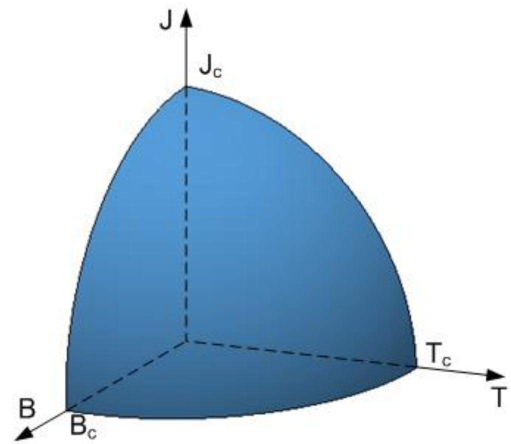
High Temperature Superconductors

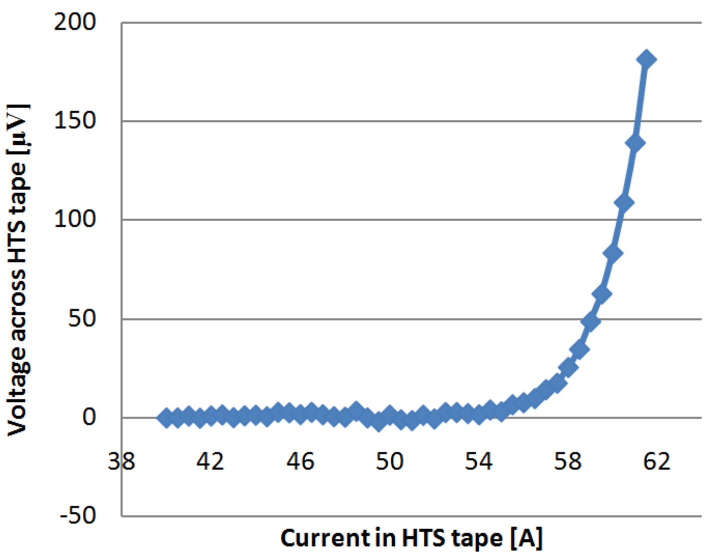
- The superconducting state is limited by
  - Critical flux density B_c
  - Critical current density J_c
  - Critical temperature T_c

- Superconducting materials can be characterised by IV curves

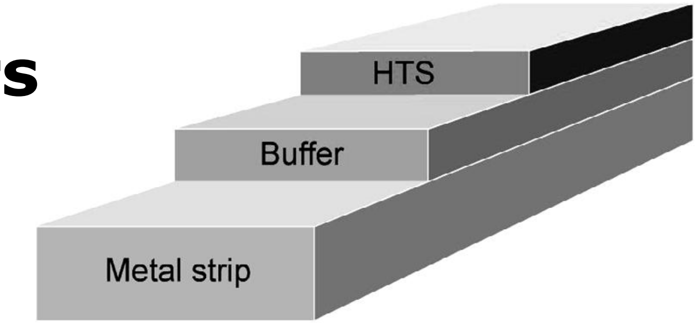
$$E[V/m] = E_0 \left(\frac{J}{J_c(B,T)} \right)^{n(B,T)}$$

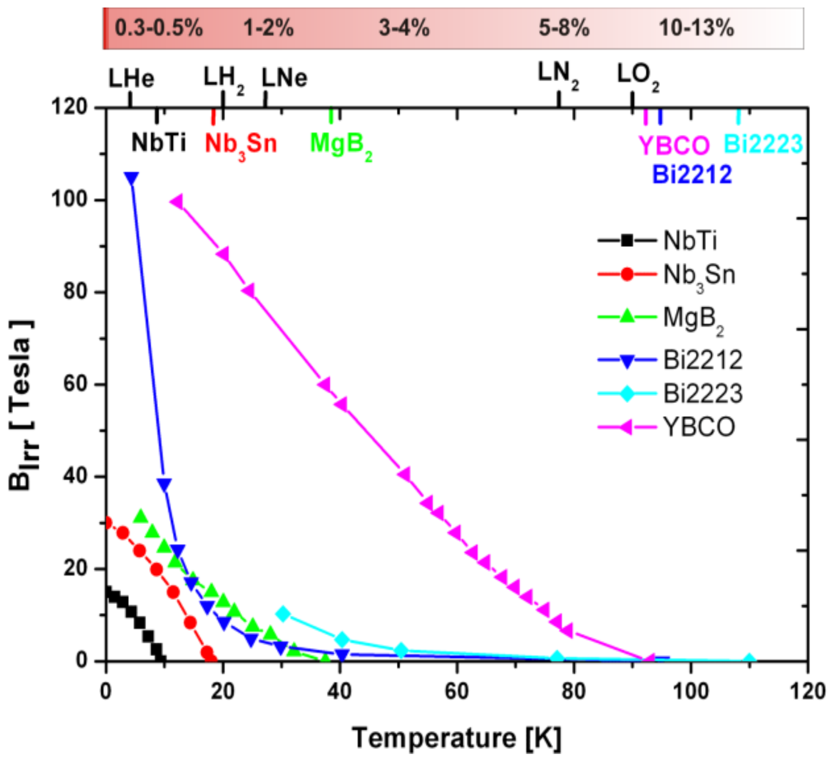
- E_0 is the electric field at the critical current (1μV/cm)





Overview of superconductors





Type	Price €/m	J_e A/mm^2	Flux density [T]	Temp. [K]
NbTi	0.4	10^3	5	4.2
Nb_3Sn	3	1-4x10^3	5	4.2
MgB_2	4	10^2	3	20
Bi-2223	20	390 10	3 ⊥tape 3 ⊥tape	20 50
YBCO	30	98 (480) 49 (190)	3 ⊥tape 3 ⊥tape	20 50

ADVANTAGES

Generator Power

$$P = \omega_m T = \omega_m \sqrt{2} A \hat{B}_g V \cos(p\psi)$$

$A \approx 70{,}000\,\mathrm{A/m}$ limited by stator cooling

$\omega \approx 1.05\,\mathrm{rad/s}$ limited by the power rating of the WT (around 10rpm at 10MW)

PM Generator B_g = 0.9T   HTS Generator B_g = 2.5T

$P = 10\,\mathrm{MW} \Rightarrow V_{PM} = 115\,\mathrm{m}^3$ $P = 10\,\mathrm{MW} \Rightarrow V_{HTS} = 42\,\mathrm{m}^3$

With an axial stack length of 2.0m, this would result in a airgap diameter of:

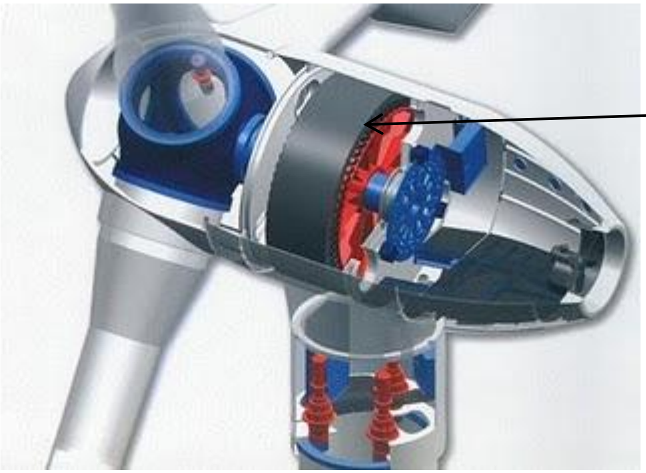
D_g = 8.6m D_g = 5.2m

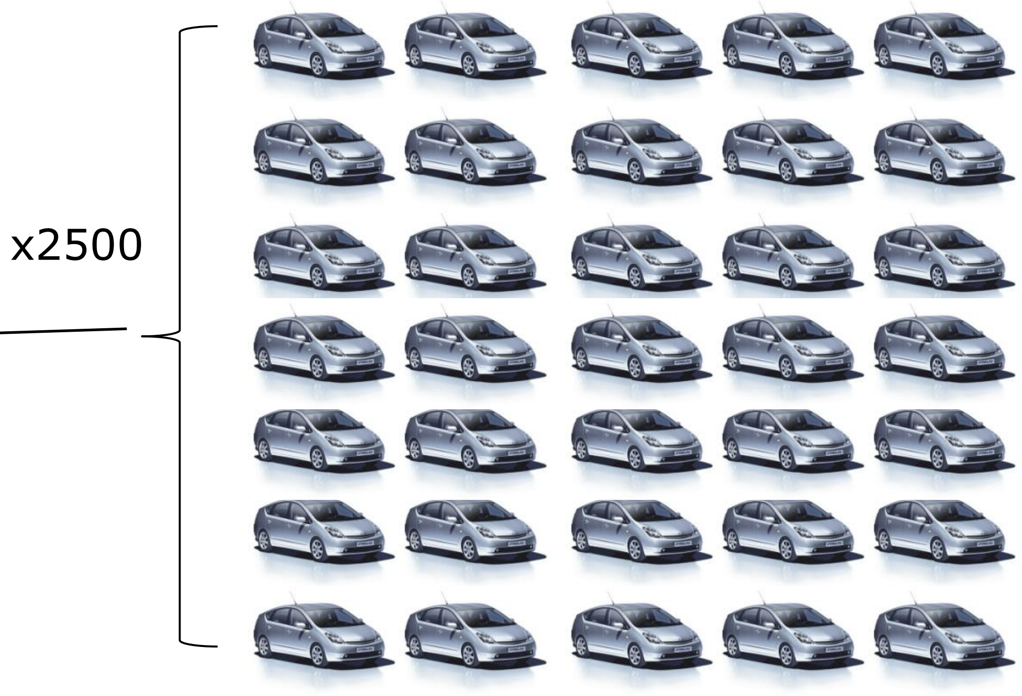
PM in wind turbines

- A 6MW direct drive wind turbine is estimated to use 5 tons of permanent magnets

- This is the same as 2500 Toyota Prius

- Should we be worried?



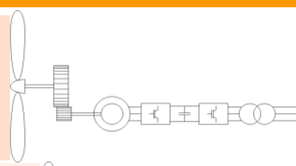
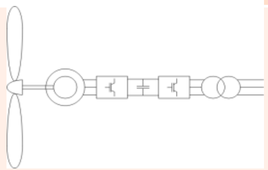


Summary

- Very high torque density

$$P = \omega \times T \qquad , \qquad T \propto A \times B \times V$$

- Very limited dependence on rare earth materials

	PM	HTS
Hybrid 	50kgR/MW	20gR/MW
Direct drive 	250kgR/MW	100gR/MW

$m_R = 0.27 m_{R\text{-}B\text{-}Fe}$

- Higher efficiency than an equivalent direct drive PM generator

$$P_{Cu} = I_{Cu}{}^2 R_{Cu} \quad = J_{Cu}{}^2 A_{Cu}{}^2 \frac{l_{Cu}}{A_{Cu}\sigma_{Cu}} \quad = \frac{J_{Cu}{}^2 V_{Cu}}{\sigma_{Cu}}$$

CHALLENGES

Cooling system

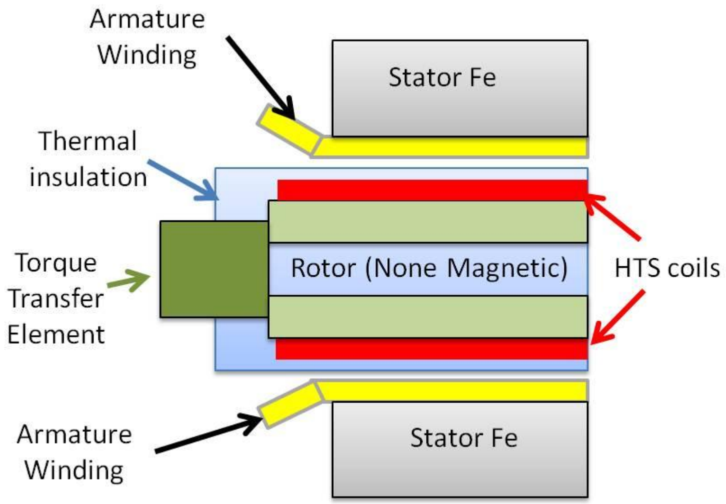
- The superconductors need to be cold:
  <5K for LTS
  <20K for MgB_2
  30-50K for HTS

- Insulation requires large effective airgap
  – Large fault currents and torques

- Torque transfer

- Reliability has yet to be proven and requires years of operating experience

- Production capacity of HTS and MgB_2 are currently not adequate for large-scale commercialisation – this should change if the need is present



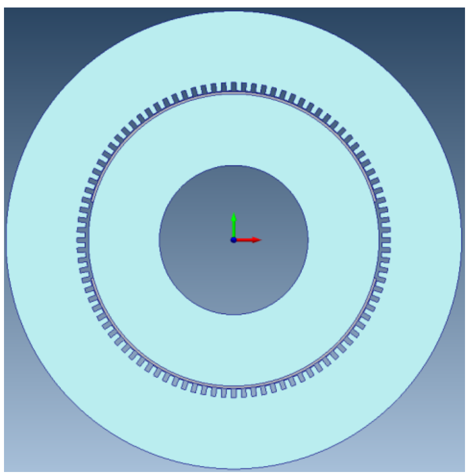
Size and weight

- Size and weight do not necessarily scale linearly

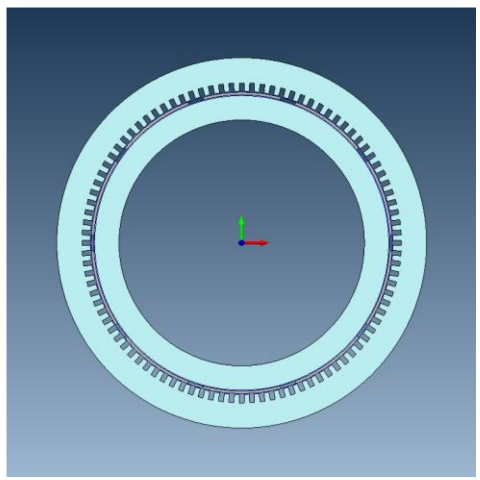
$$P = \omega \times T \qquad , \qquad T \propto A \times B \times V$$

- Iron coreback is required to shield the magnetic field from ambient

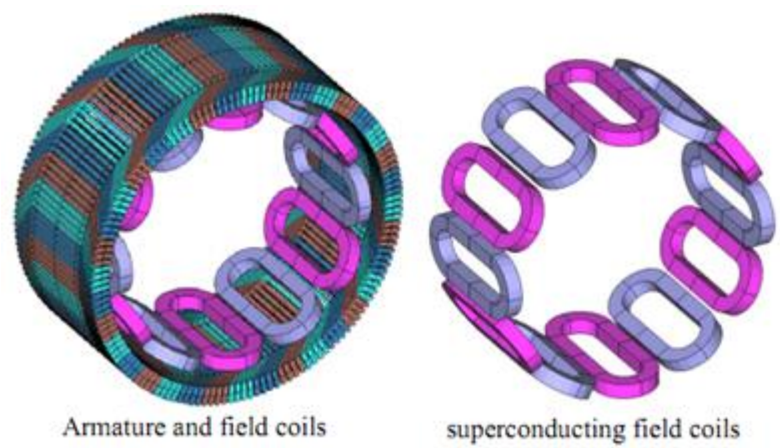
- Not as cheap to increase the number of poles



2 Poles

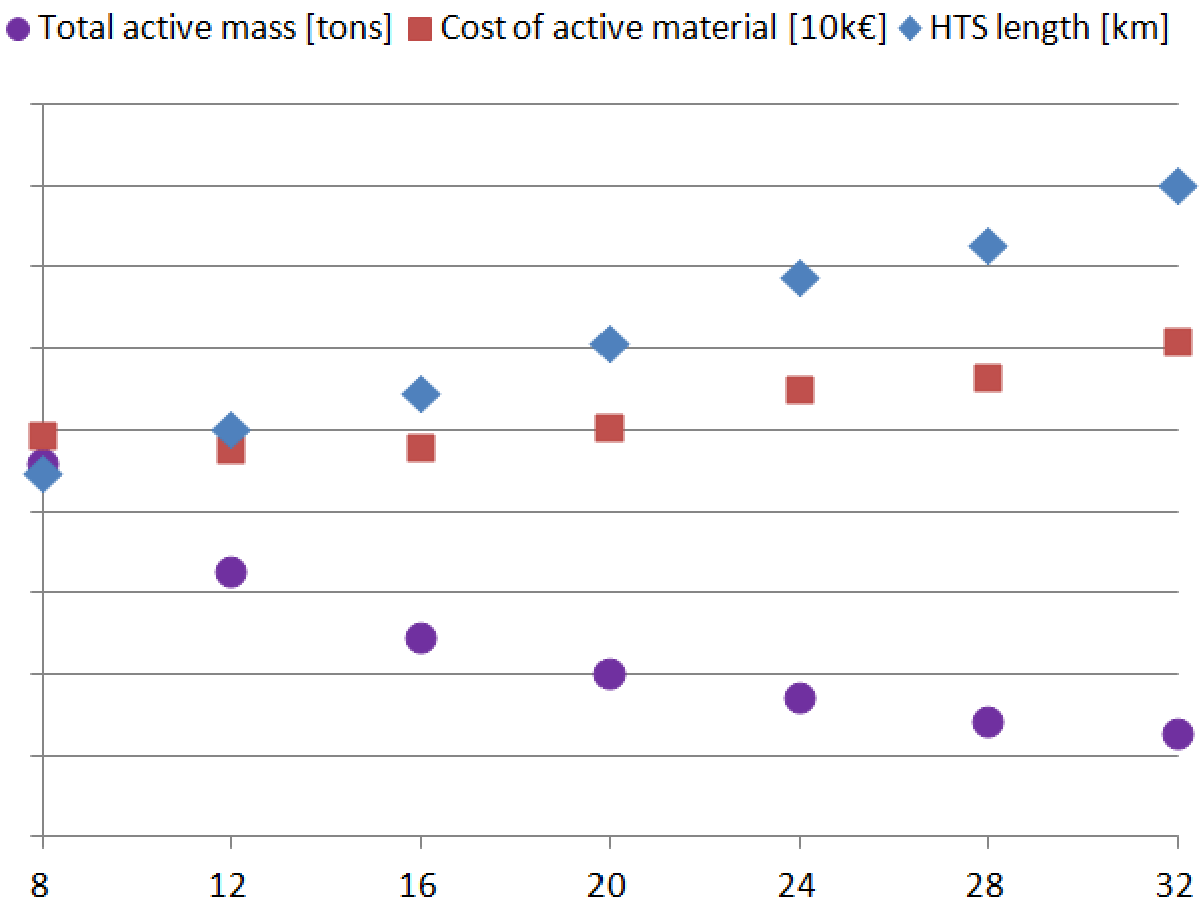


10 Poles



Source: H. Ohsaki *et al*. "Electromagnetic Characteristics of 10 MW Class Superconducting Wind Turbine Generators", ICEMS, 2010.

Mass, HTS length and price as a function of pole number



Cost of HTS and PM in a 10MW wind turbine

- If 400km of 4mm HTS tape is assumed for a 10MW wind turbine generator
- With a current carrying capacity of 80A and a price of €50/kAm, this gives €4/m
- The cost of the HTS tape for a 10MW would therefore be **€1.6 million**
- In addition the cryostat, cryocooler etc. will have to be added
- PM price today? €50/kg
- If 10 tons of PM is required for a 10MW wind turbine
- The cost of the PM for a 10MW would be **k€500**

Future cost of HTS must/will come down

- It is not unlikely that the price of HTS tape will come down to €15/kAm
- This would result in **€480,000** for a 10MW wind turbine
- This would be competitive with PM technology
- But it is clear that the usage of HTS tape must be minimised!

COMMERCIAL ACTIVITIES

American Superconductor (AMSC) SeaTitan 10MW

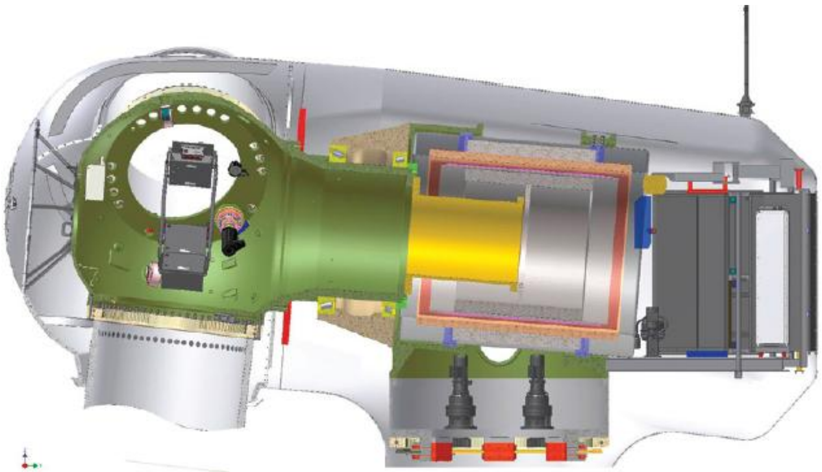
- HTS – Superconducting field winding
- Copper armature winding
- Generator diameter: 4.5–5 meters
- Weight: 150-180 tonnes (55-66Nm/kg)
- Efficiency at rated load: 96%

- Challenge
  - HTS price and availability

- Advantage
  - Relatively simple cooling system with off-the-shelf solutions
  - Cooling power

Highest torque HTS machine intended for ship propulsion:

- 36.5MW @ 120rpm
- 2.9MNm @ 75 tons
- 39Nm/kg



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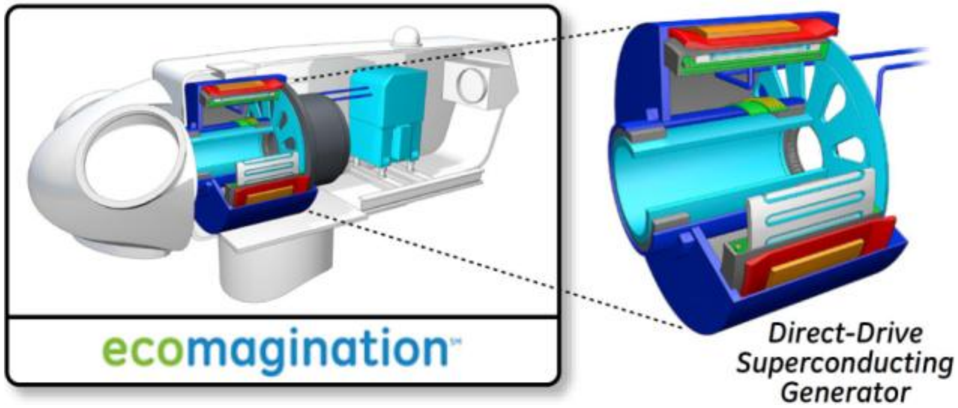
General Electric (GE) 10-15MW

- LTS – Superconducting field winding
- Extensive experience from the MRI sector
- Rotating armature

- Challenge
  - Complicated cooling system and higher cooling power

- Advantage
  - Proven technology from MRI
  - Cheaper superconductor



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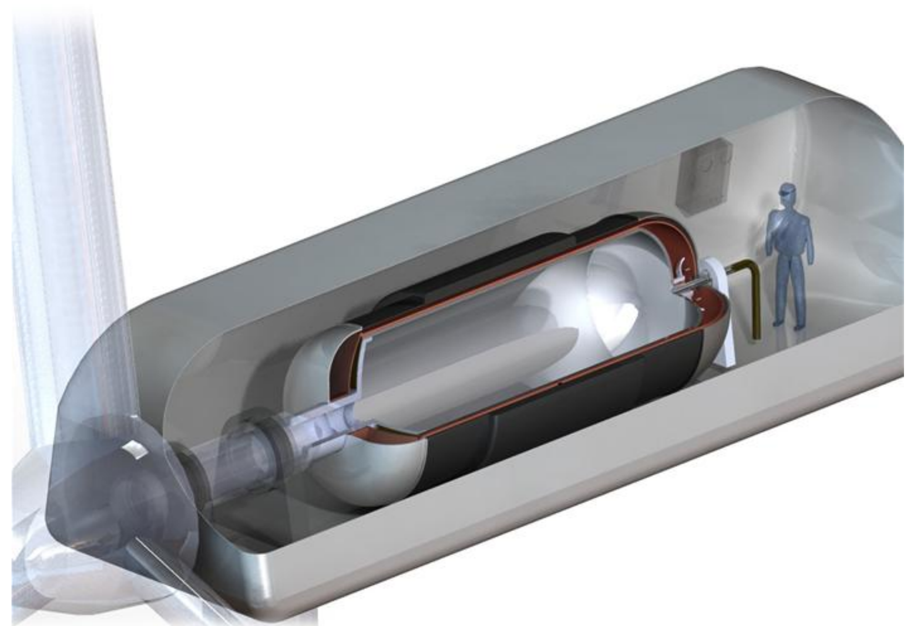
Advanced Magnet Lab (AML) 10MW fully superconducting

- MgB_2 – Fully superconducting generator
- Superconducting field winding
- Superconducting armature winding

- Challenge
  - Complicated cooling system and higher cooling power
  - Improvement in MgB_2 wire is needed
  - AC losses

- Advantage
  - Cheap superconductor
  - Fully superconducting
  - More torque dense

$$P = \omega \times T \qquad , \qquad T \propto A \times B \times V$$



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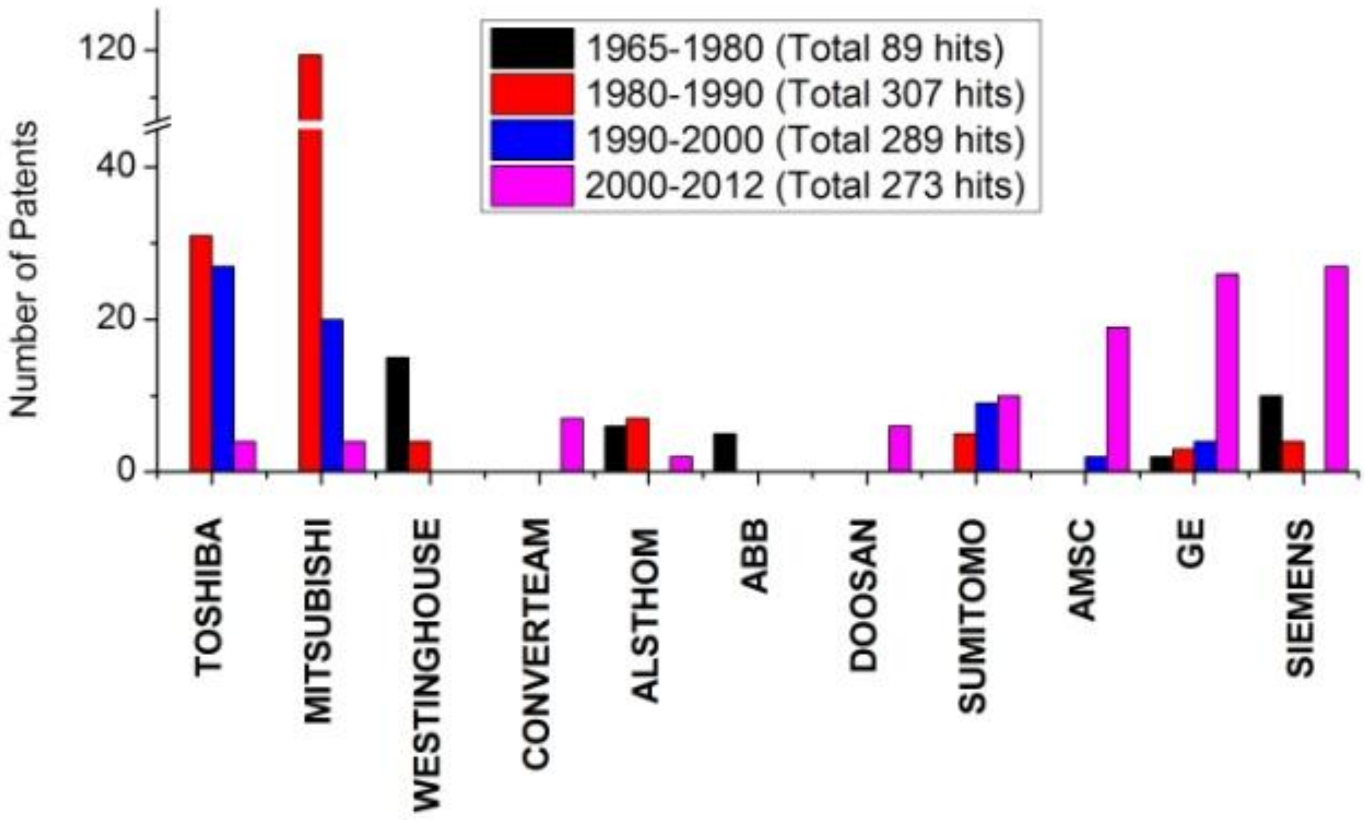
Patent Development

- Web of Knowledge search with keywords: “Supercond*” and “machin*”



Discussion and conclusion

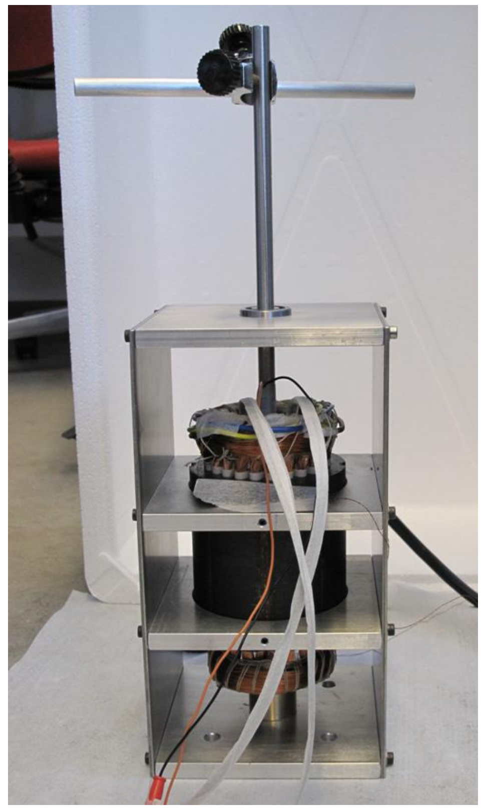
- Superconducting generators might be the answer to large wind turbines
  - Smaller generator
  - Less RE demand by a three orders of magnitude

- A collaborative effort is needed including:
  - Wire manufacturers
  - Wind turbine manufacturers
  - Wind turbine operators

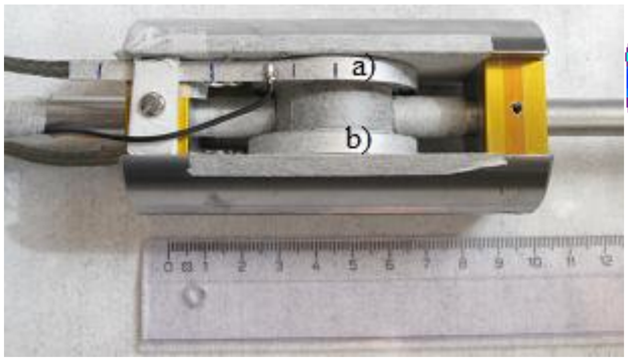
- Large-scale demonstrators are needed
  - To test the performance in a wind turbine
  - To test the reliability

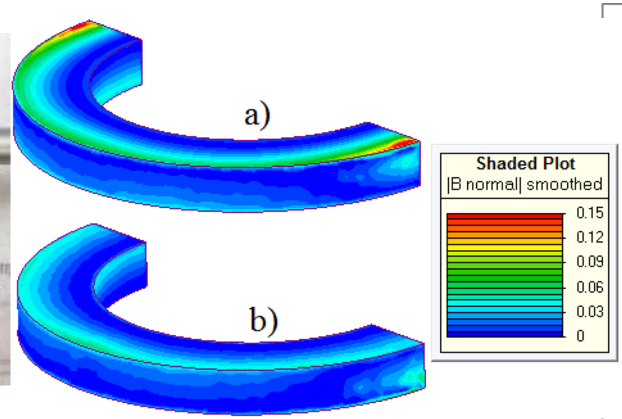
Continue research at universities

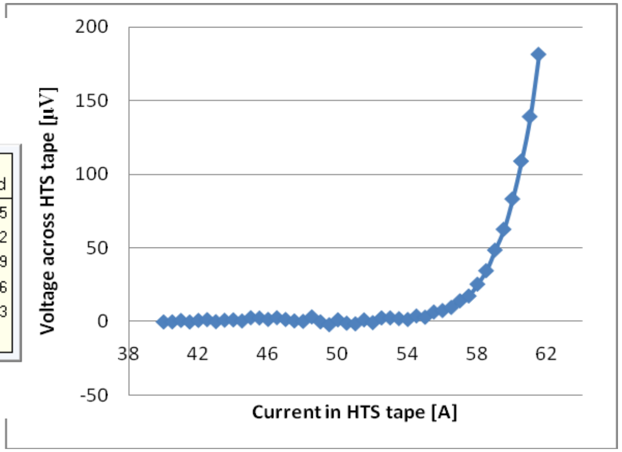
- Building small scale prototypes
- Learning from these and extrapolating to large scale

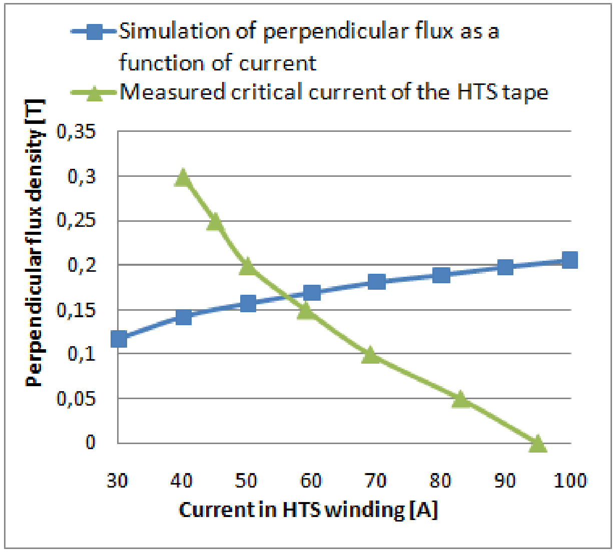


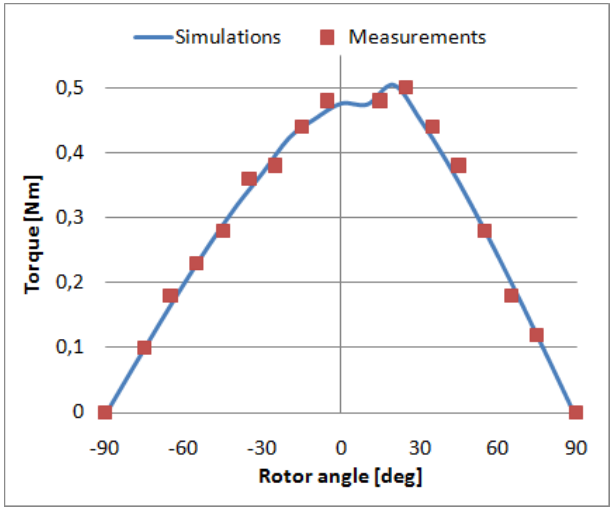
Results for a simple prototype











THANK YOU!
QUESTIONS?