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Jensen, Bogi Bech; Abrahamsen, Asger Bech

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High Temperature Superconducting (HTS) Technology for Generators

Dr Bogi Bech Jensen[1], Associate Professor (bbjj@elektro.dtu.dk)
Dr Asger B. Abrahamsen[2], Senior Scientist

[1]Depertment of Electrical Engineering, Technical University of Denmark (DTU)
[2]Materials Research Division, Risø DTU

17th – 19th October 2011
2nd International Conference on Drivetrain Concepts for Wind Turbines, Bremen, Germany.

Overview

- Working principle and requirements for superconducting generators in wind turbines
- Considerations for wind turbine solutions for large scale offshore wind power development
- Benefits of the HTS technology in terms of efficiency and power density
- Assessing the current cost situation
- How can HTS technology become commercially viable

Level of experience with HTS machines

- How many have constructed/tested a superconducting machine?
- How many have read about it and done some calculations?
- How many have had limited exposure?

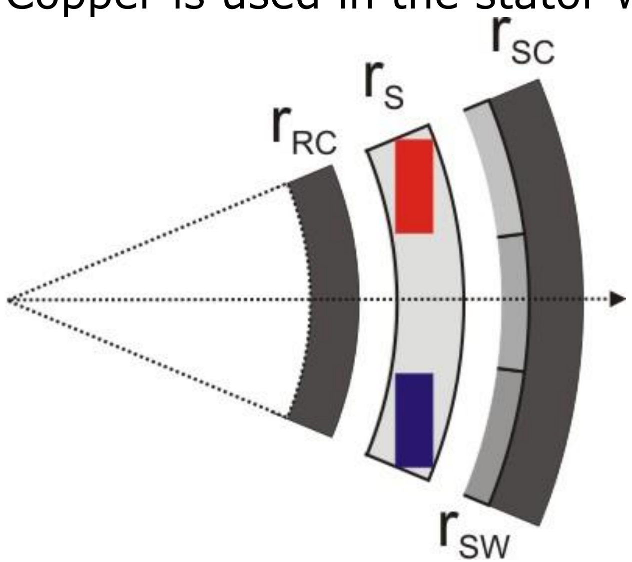
WORKING PRINCIPLE AND REQUIREMENTS

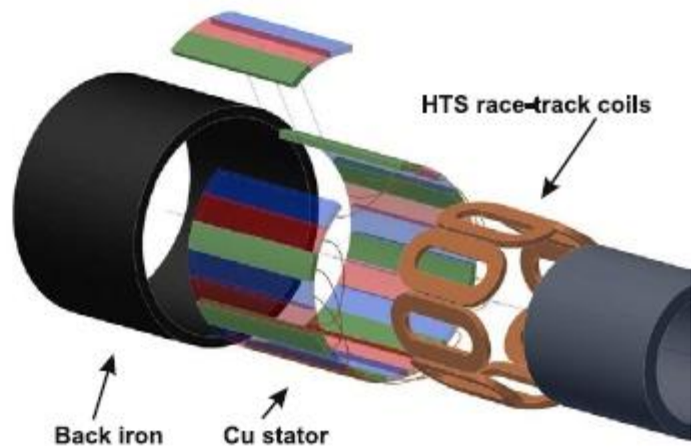
HTS machine principle

- Zero DC resistance is particularly attractive in the field winding of a synchronous machine
- Very high currents in the field winding result in a very high airgap flux density
- Hence very high torque densities can be achieved
- HTS tape is used in the field winding (the cold region)
- Copper is used in the stator winding (the warm region)

$$T \propto A\hat{B}_g V$$

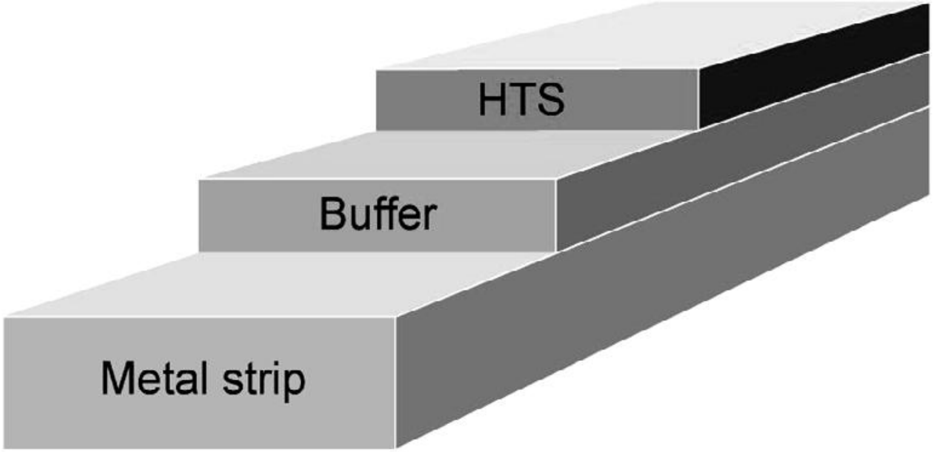
$$P = \omega_m T$$





2G HTS tape

- The tape thickness is around 100-200μm for 2G
- The HTS layer is just a few μm
- The remaining material is for mechanical and thermal stability



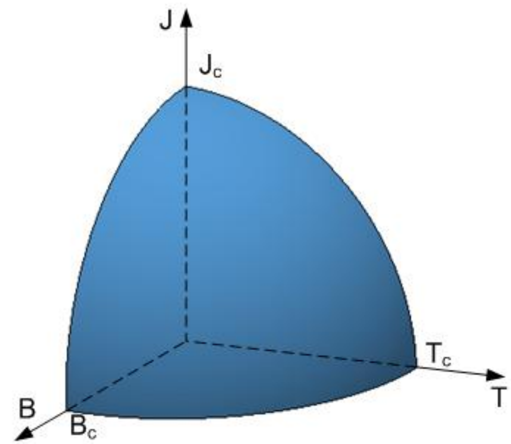
High Temperature Superconductors

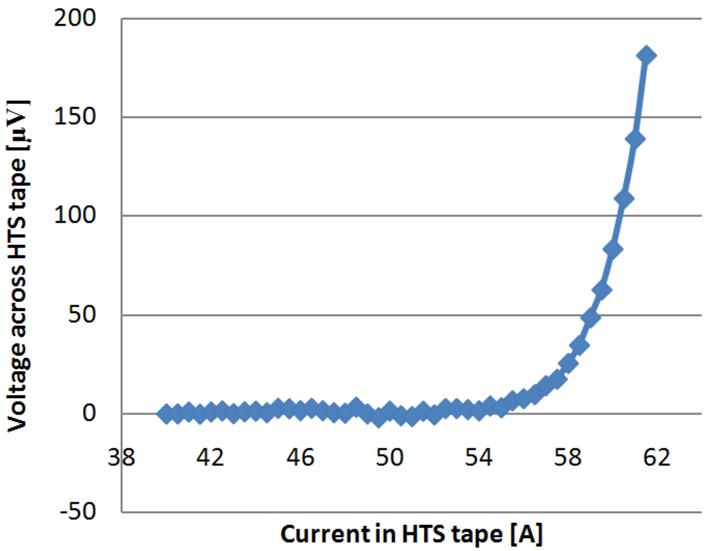
- The superconducting state is limited by
  - Critical flux density B_c
  - Critical current density J_c
  - Critical temperature T_c

- HTS 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)





The Superwind project

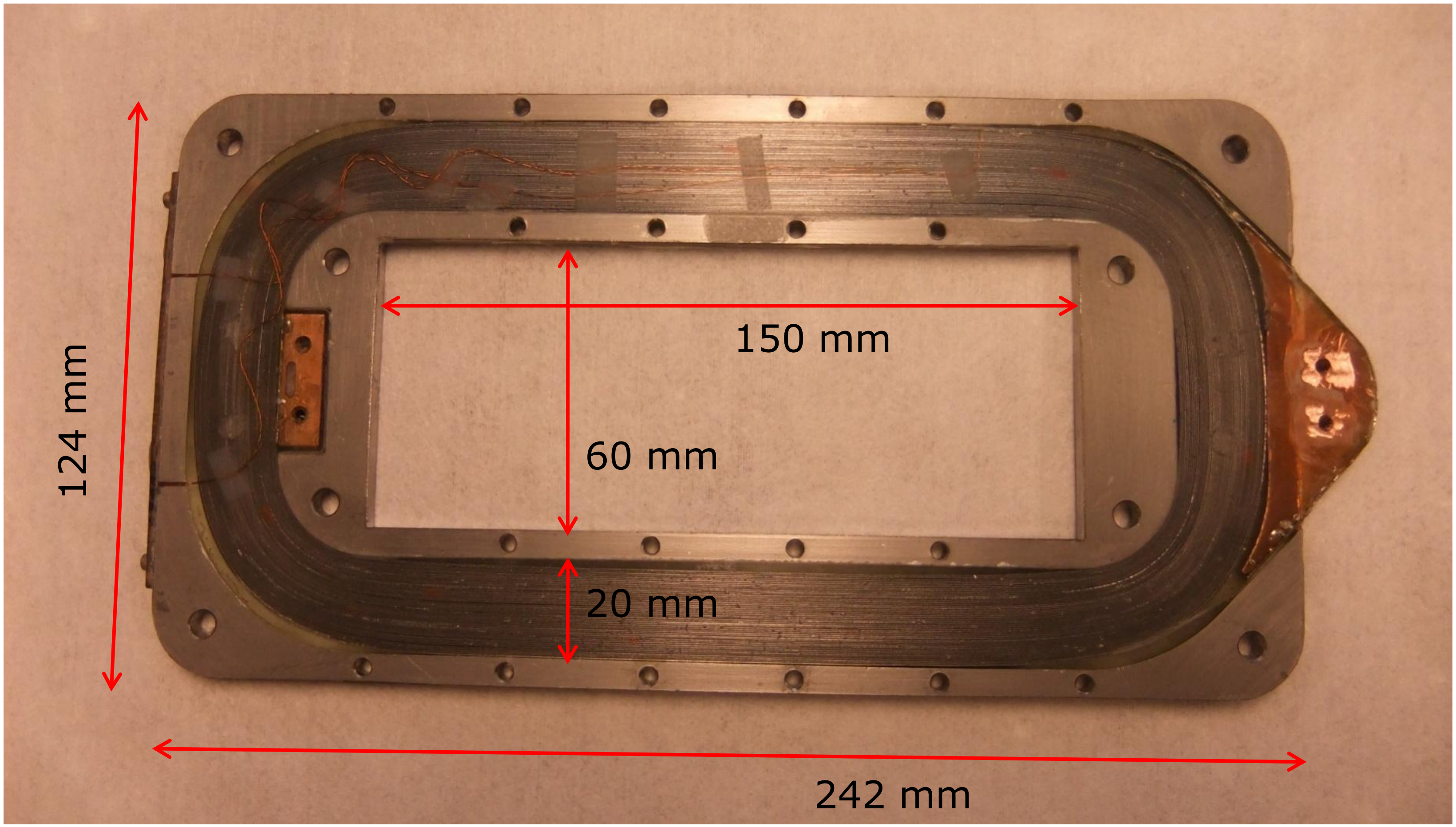
- Aims at assessing HTS machines for wind turbines

- Particularly for large scale direct drive wind turbines

- Constructed a prototype demonstrator
  - Assessing HTS coils
  - 1G – BSCCO (T_c ~ 110K)
  - 2G – YBCO (T_c ~93K)
  - Not investigated MgB2 (T_c ~39K)

- The prototype and some results are presented in what follows

Race Track Coils

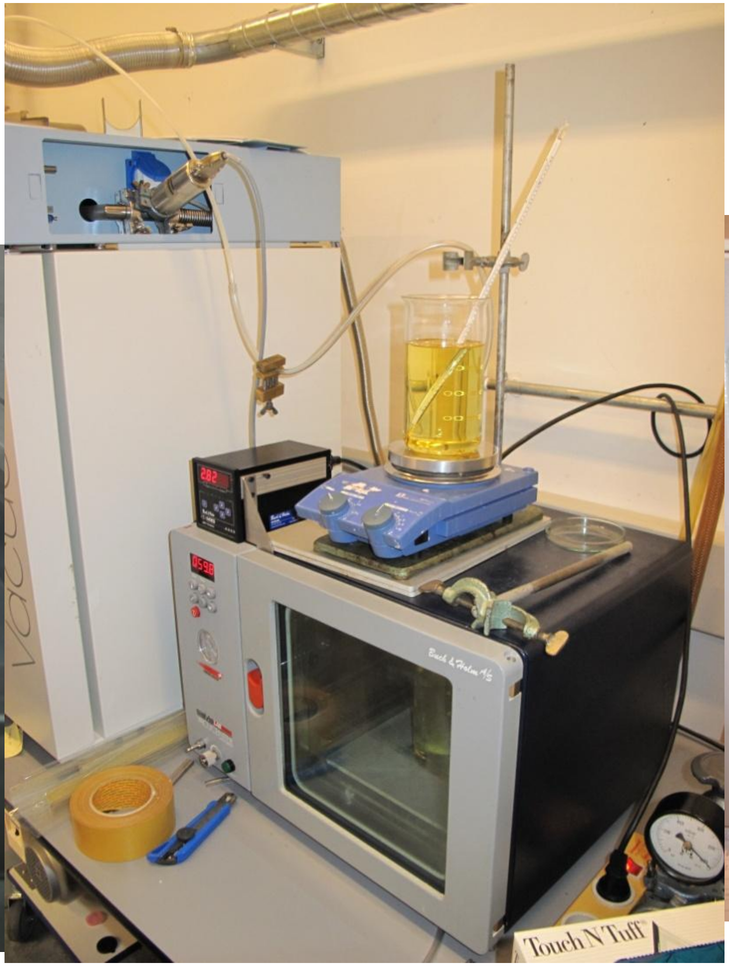


Winding

Glass fiber insulation

Vacuum impregnation

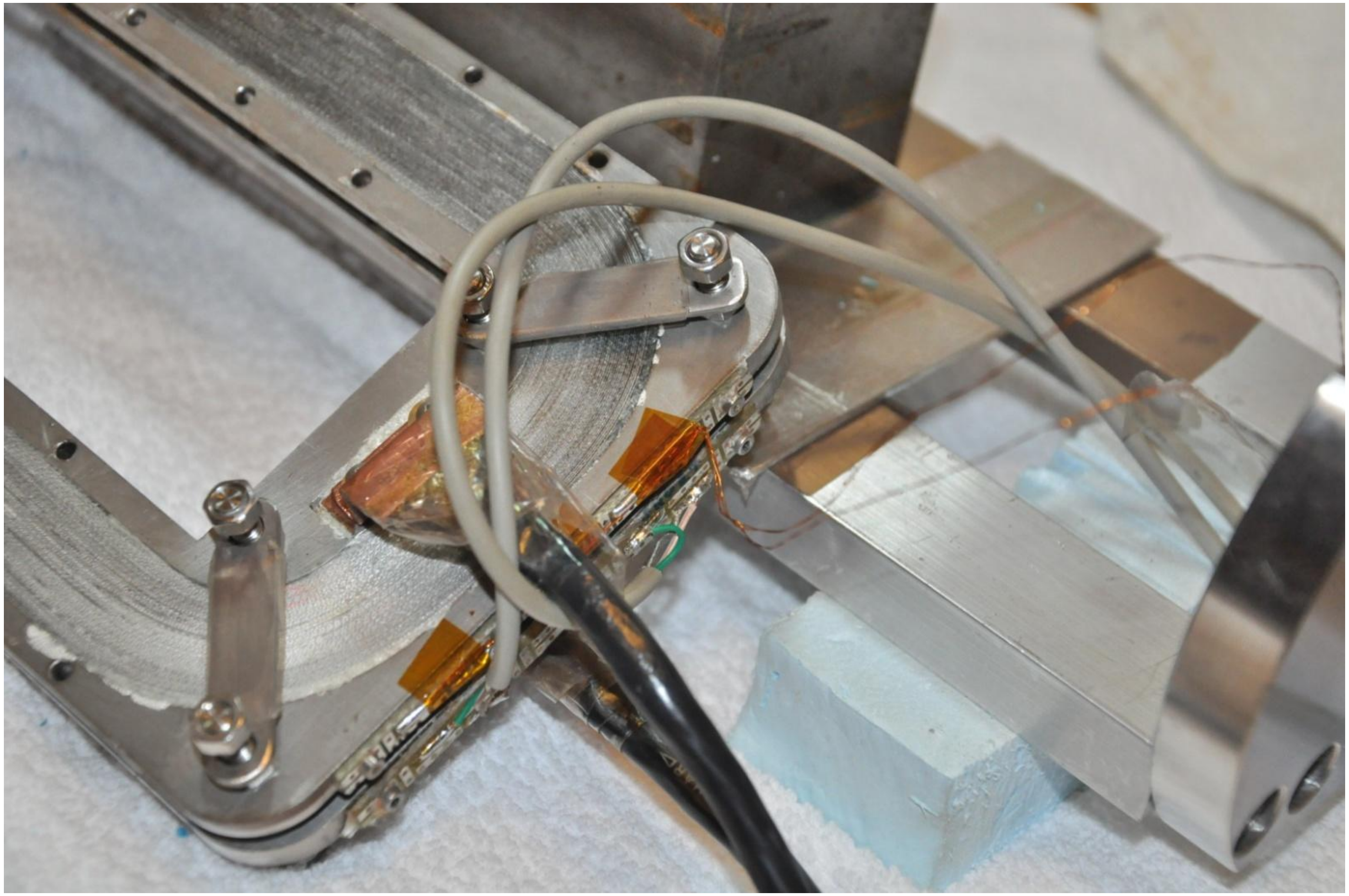
Vacuum Chamber



Epoxy degassing

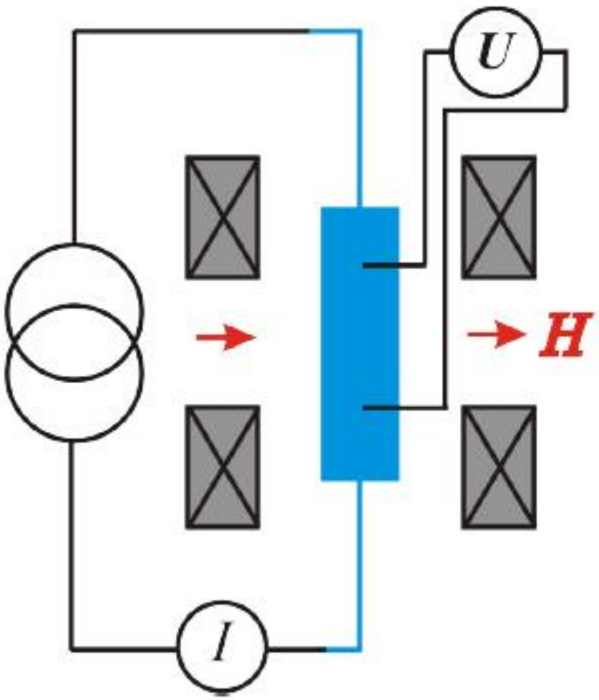
HTS coil connections

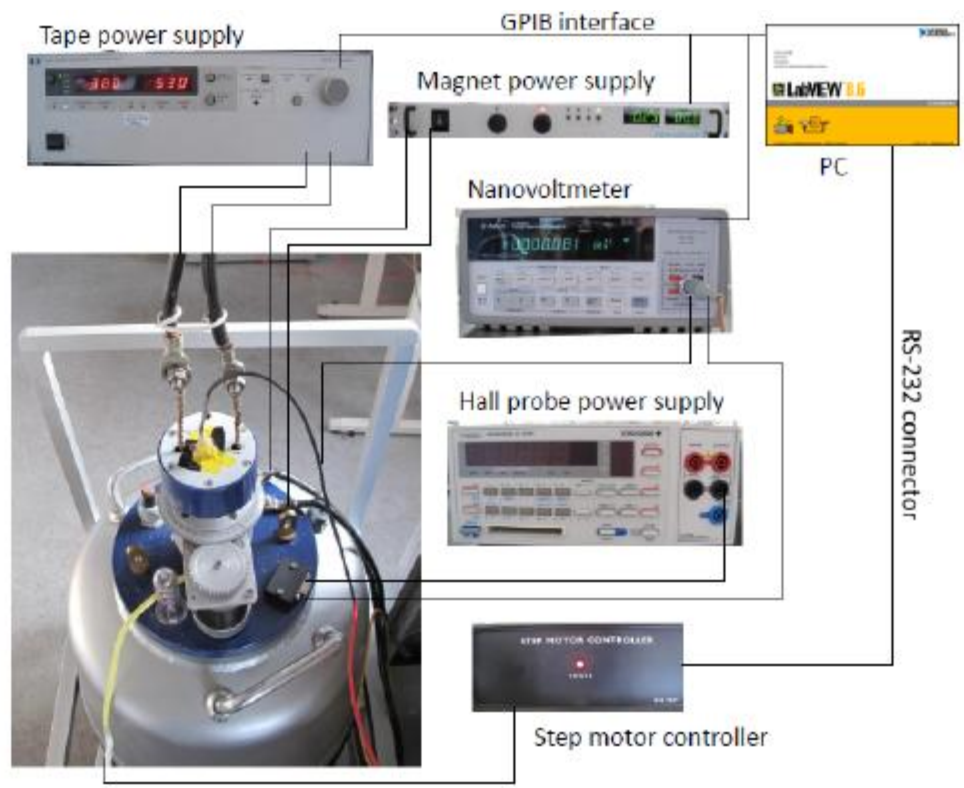
- Power connections and voltage monitoring connections



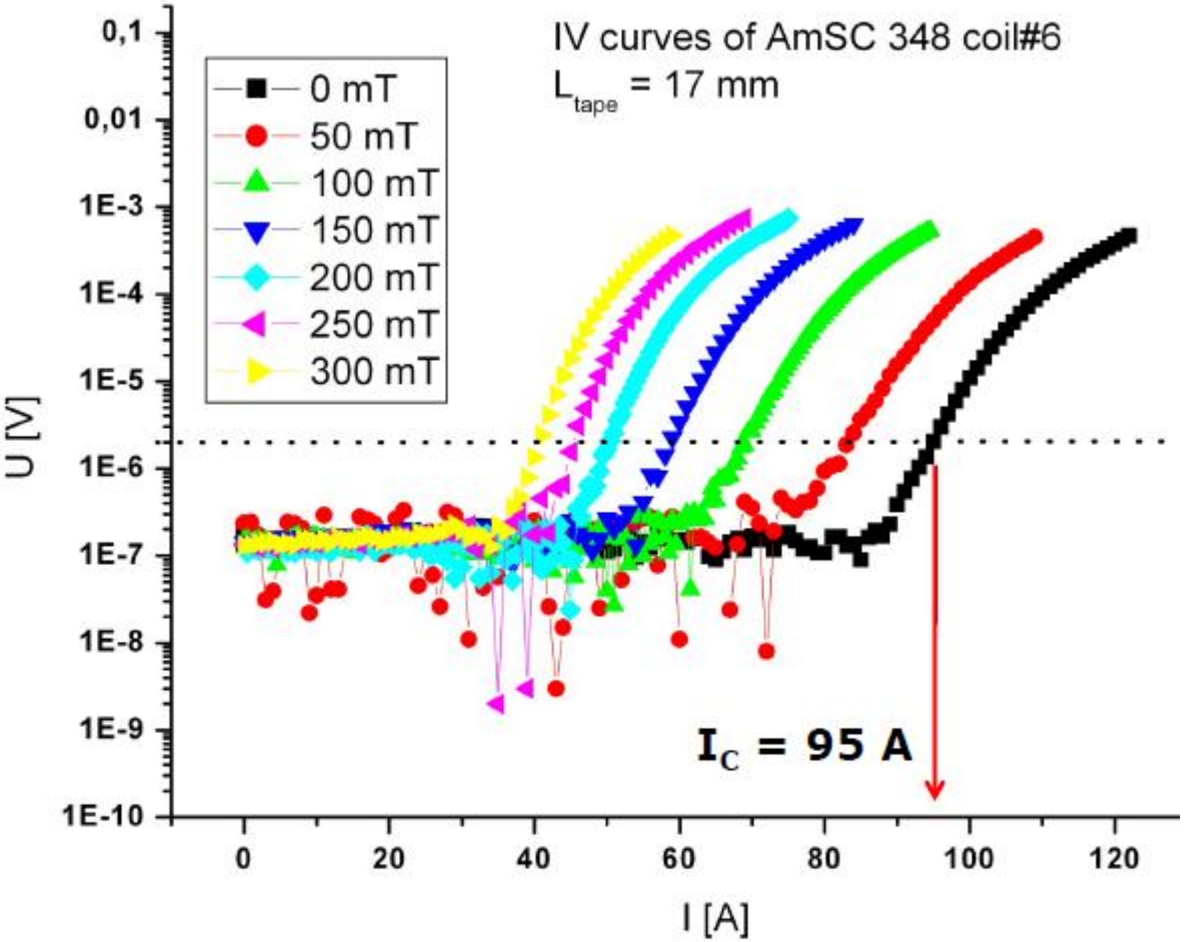
Characterising the tape: I-V curves

- $I_C(B,\theta)$ @ 77K

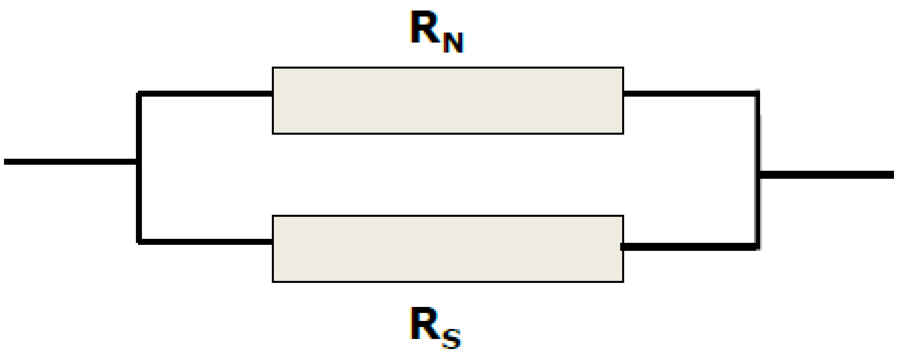




Testing AmSC CC348 tape (2G)



DC loss in the two sections of the HTS



$$U_S = U_0 \left(\frac{I}{I_C(T,B)} \right)^{n(T,B)}$$

I_C industrial definition:

V/L = 1μV/cm

Loss per length at I 85A:

P/L = 8.5μ W/cm

<u>(425W for 500km)</u>

Loss per length at I_C = 95A:

P/L = I_C V/L = 95 μ W/cm

<u>(4.8kW for 500km)</u>

Loss per length if non-superconducting:

P/L = I_C^2 R/L = 10^{-4}Ω/cm$(95A)^2$

=0.9W/cm

<u>(45MW for 500km)</u>

Requirements for HTS machines in general

- Reliability of the cooling system, including
  - Cryocoolers
  - Possible rotating gaskets
  - Redundancy

- Designed to withstand possible faults
  - Mechanically rigid
  - Thermally stabile
  - Quenching must be avoided

- The same requirements for the stator as found in other machines
  - Reliable cooling system
  - Short circuit protection

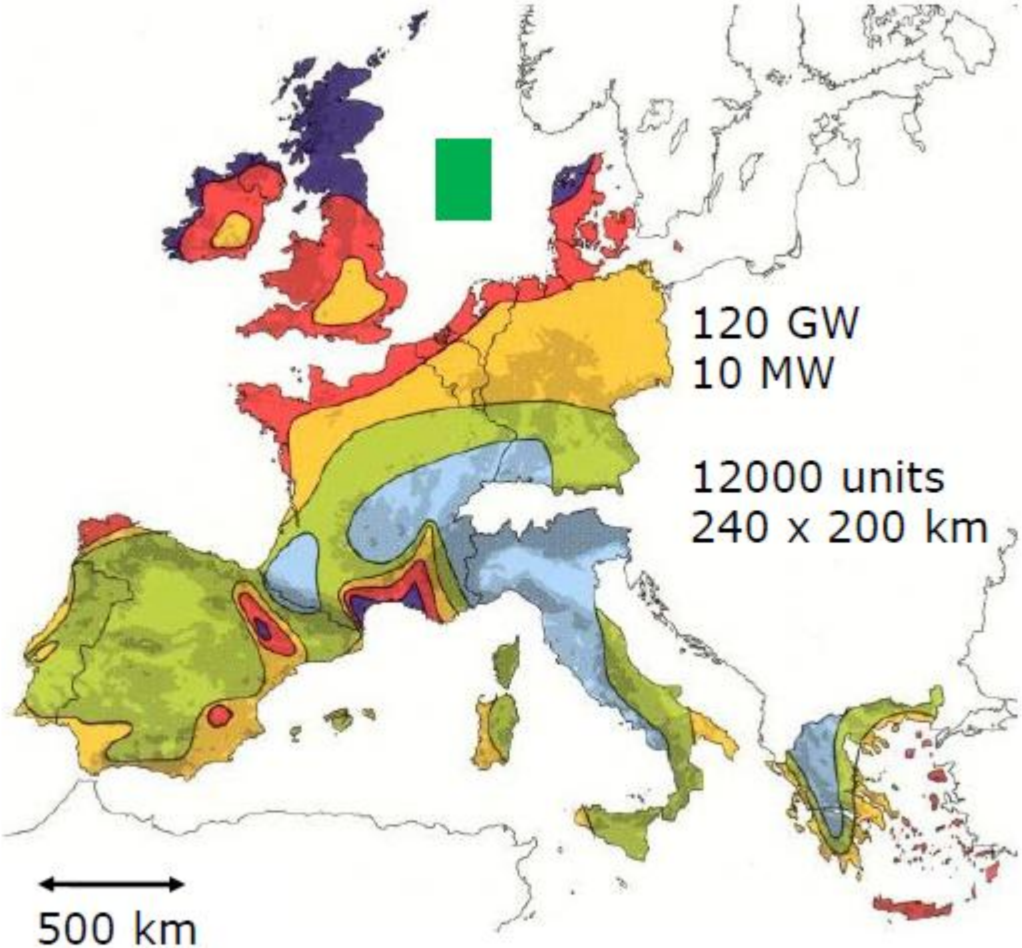
Point of discussion

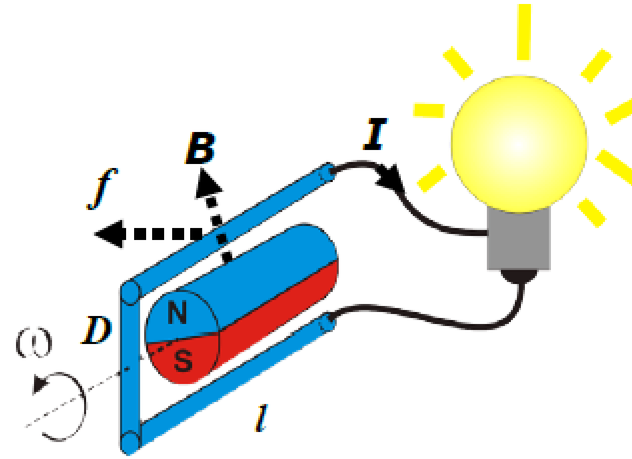
- Discuss with your neighbour (two and two):
  - The presentation on HTS generators for wind turbines from yesterday
  - What has been presented so far this afternoon

- Comments, questions, suggestions?

CONSIDERATIONS FOR LARGE SCALE OFFSHORE

Generations of wind turbine generators





$$P \propto IBD^2 l\omega$$

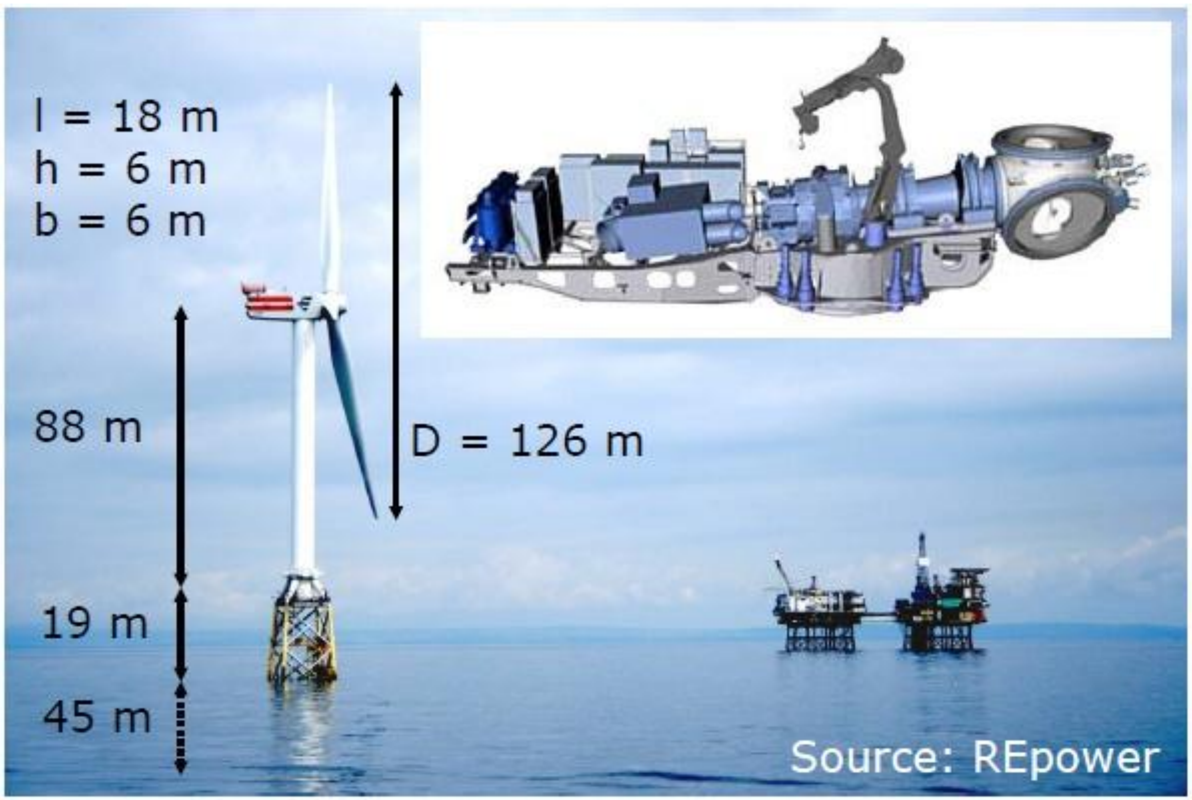
1G : Copper + Iron

2G : $R_2Fe_{14}B$ magnets+Fe
10 MW ~ 10 tons PM

3G : $RBa_2Cu_3O_{6+x}$ HTS + Fe
10 MW ~ 10 kg RBCO

1G wind turbine generator REpower 5MW

- Generator: Geared doubly fed induction generator



- Pitch controll
- Geared ~ 1:97
- DFIG

Rotor:

Blades	54 tons
Hub	66 tons
Total	120 tons

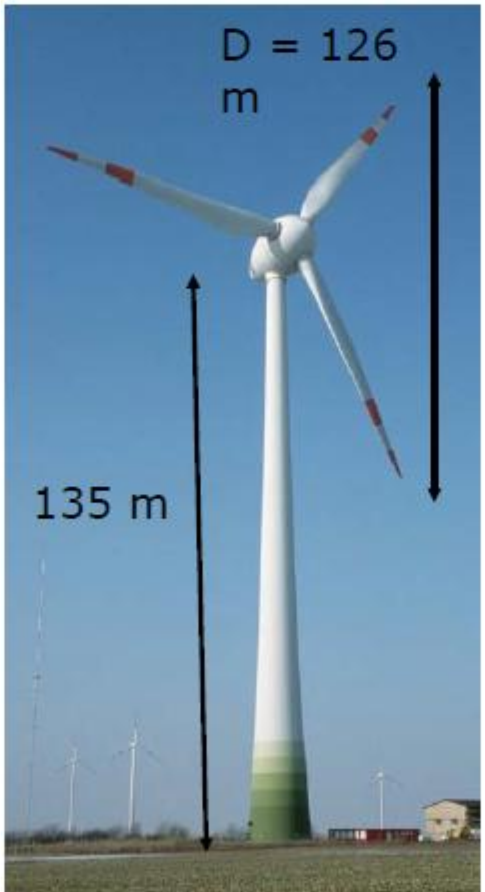
Nacelle:

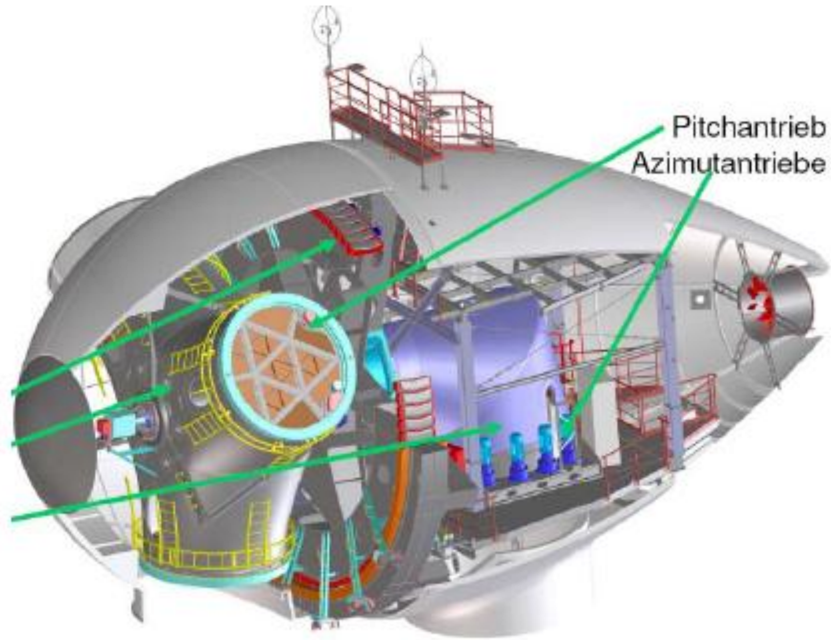
Shaft	27 tons
Bearing	63 tons
Gear	63 tons
Gen.	17 tons
Sup.	120 tons
Total	290 tons

Sum : 410 tons

1G wind turbine generator
Enercon E-126 6MW

- Generator: Direct drive wound field synchronous generator

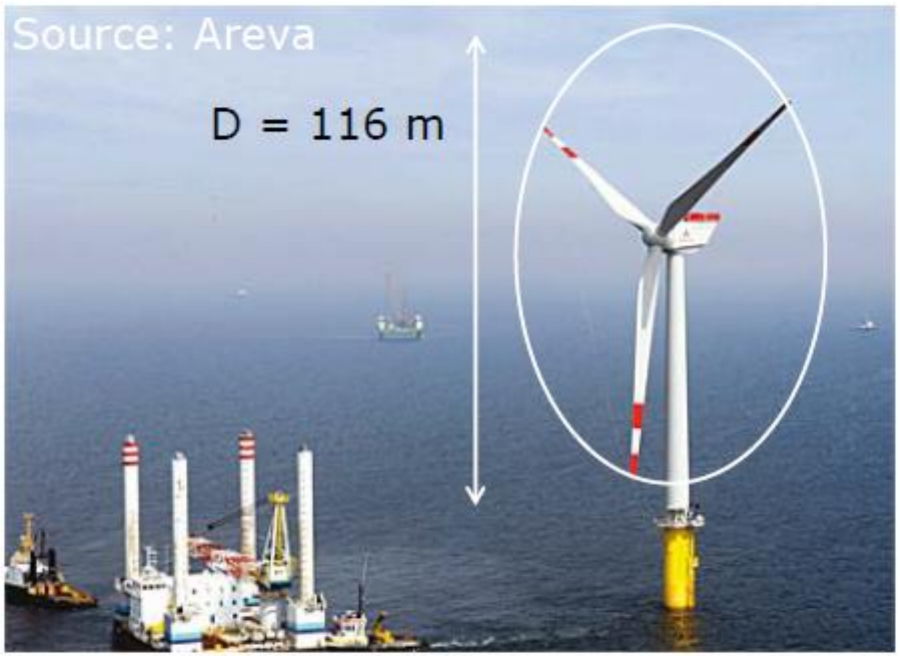


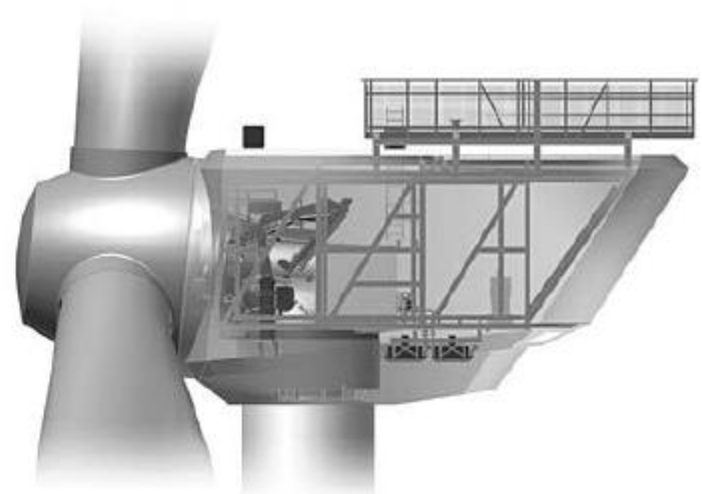


Rotor:	100 tons	Tower:	850 tons
Gen.:	212 tons		
Support :	188 tons		
Total:	500 tons		

2G wind turbine generator Multibrid M5000 5MW

- Generator: Hybrid geared permanent magnet generator



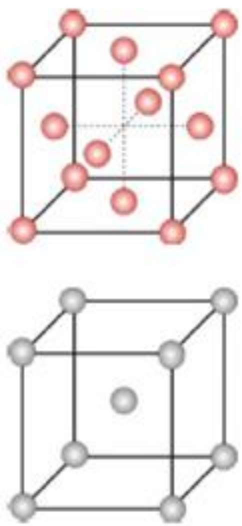


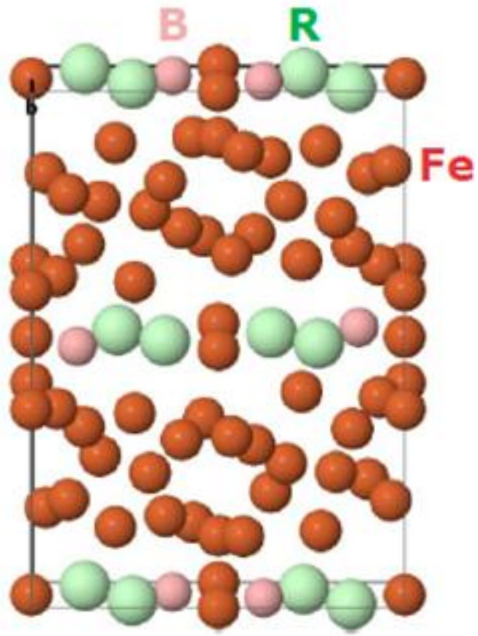
- Blade = 16.5 t
- Hub = 62.0 t
- Nacelle = 233.0 t
- Total = 349.0 t

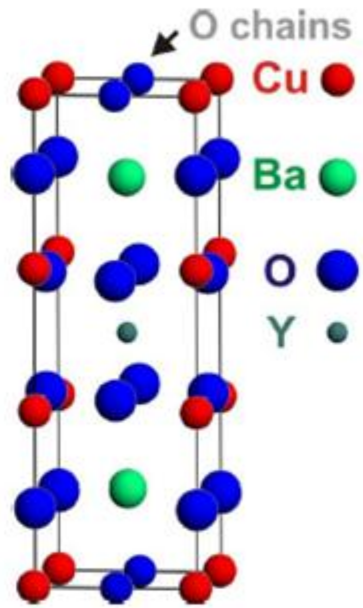
- Pitch control
- Hybrid drive train
- Gear ~ 1:10
- PM generator

Active materials in the generators

Cu & Fe (1G) | Permanent magnet(2G) | HTc superconductor(3G)







$R_2Fe_{14}B$ (R = Rare Earth, Y)

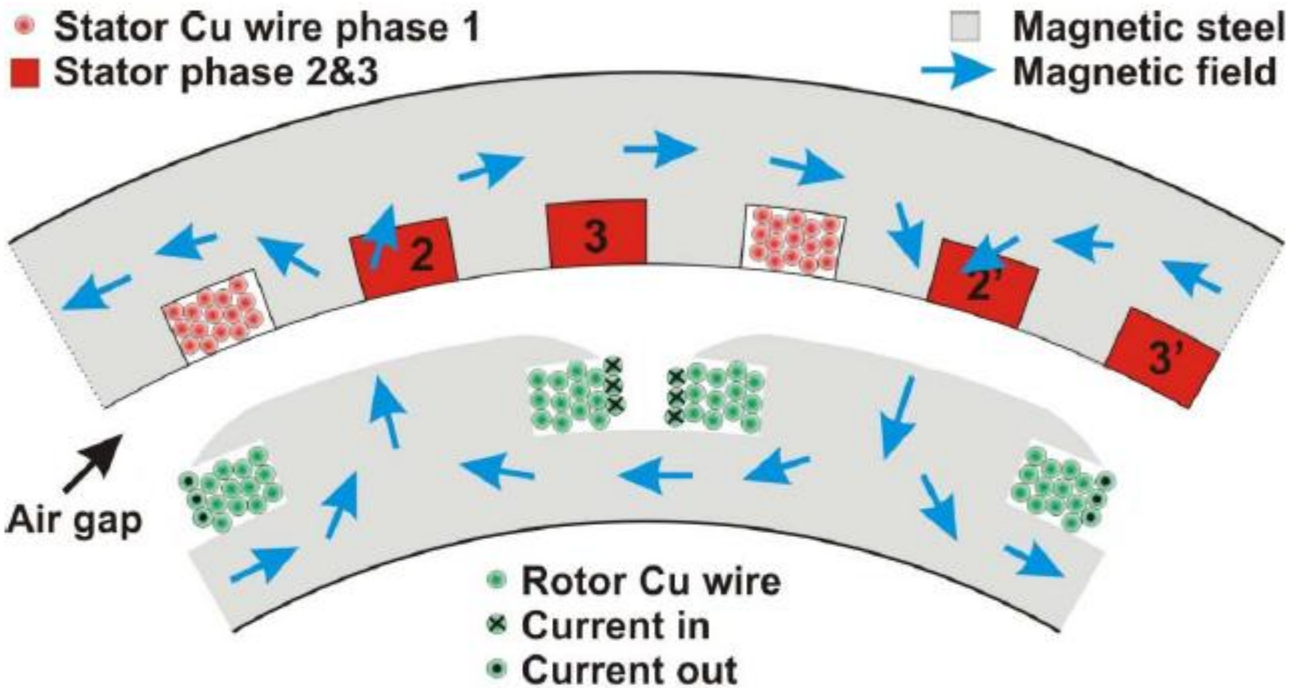
$RBa_2Cu_3O_{6+x}$ (R = Rare Earth, Y)

B_{sat} ~ 1.6 Tesla

B_r ~ 1.2-1.4 Tesla

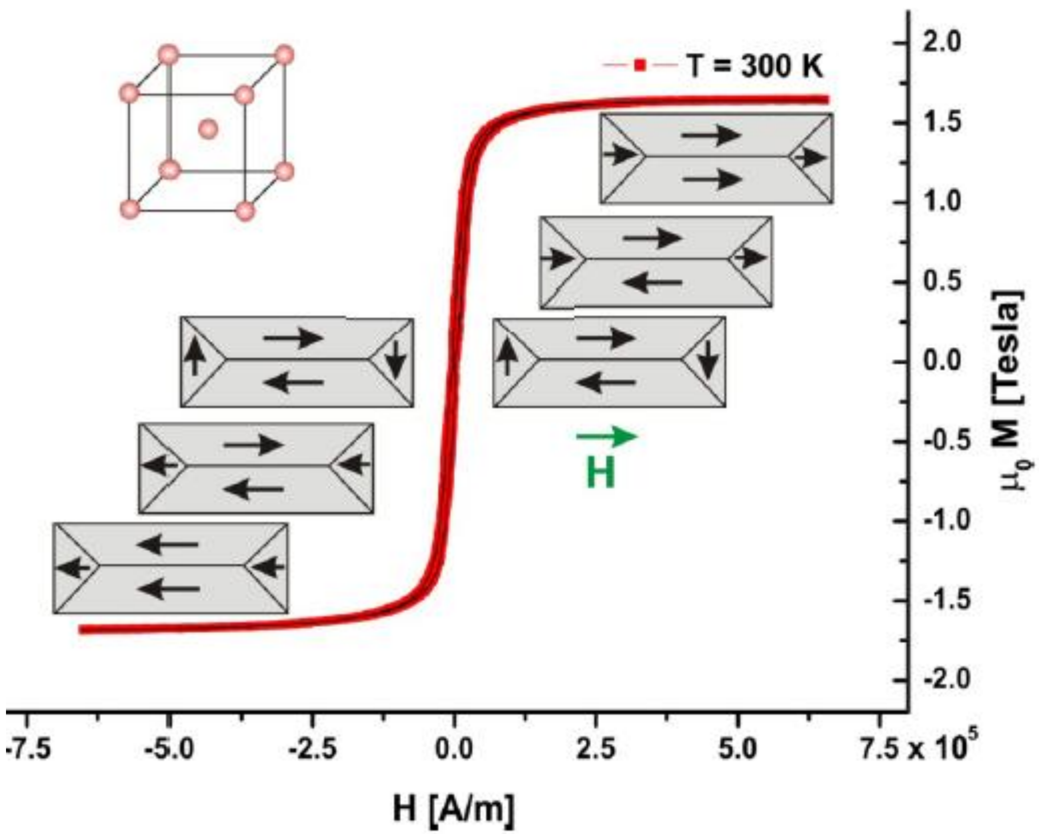
B_{C2} ~ 100 Tesla

1G – Iron and Copper

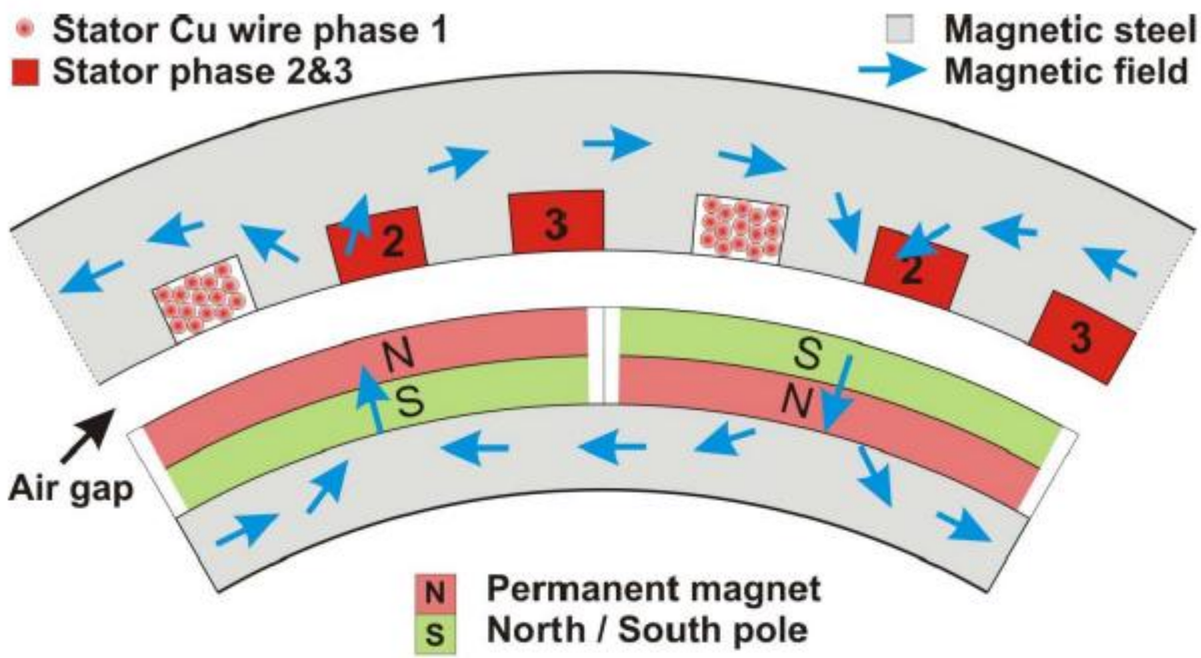


- Flux ~ NI/Rel
- Dissipation ~ R I^2
- Saturation of iron sets limit on air gap flux density !
- Thus at B ~ 1 Tesla then the machine can only become bigger !
- Enercon E-112: P = 6 MW, D = 12 m, $m_{generator}$ = 212 tons

Ferromagnetic domains aligned in Fe



2G – NdFeB, Iron and Copper



- Strong sintered $Nd_2Fe_{14}B$ magnets needed.
- No wires going to rotor + no resistive losses
- Simplified mechanical design -> Improved reliability
- Siemens SWT 3.0-101: P = 3 MW, D ~ 4.2 m, $m_{Nacelle}$ ~ 73 tons

RFeB permanent magnets (R = Rare earth)

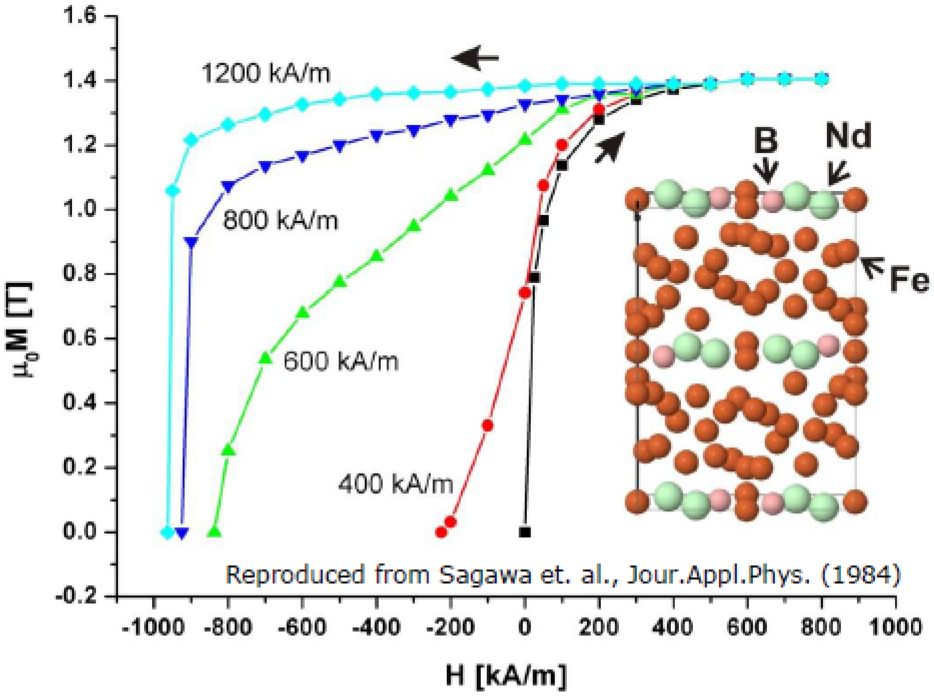
- Discovered 1982 by Sagawa et. al.

- Rare earth locks magnetization direction to the crystal lattice.

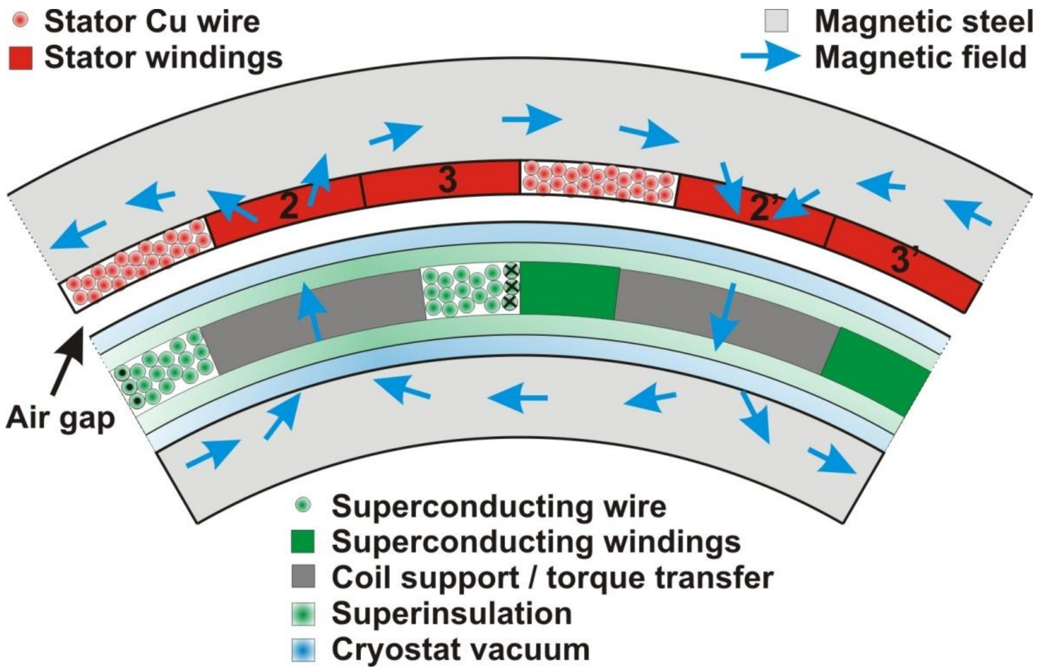
- Alignment of $R_2Fe_{14}B$ powder
- Press under magnetic field
- Sintering into blocks
- Surface treatment
- Magnetization by pulsed field

- Residual flux density B_r
- Coercivity force H_C
- Energy product (BH_{max})

- Curie temperature T_C



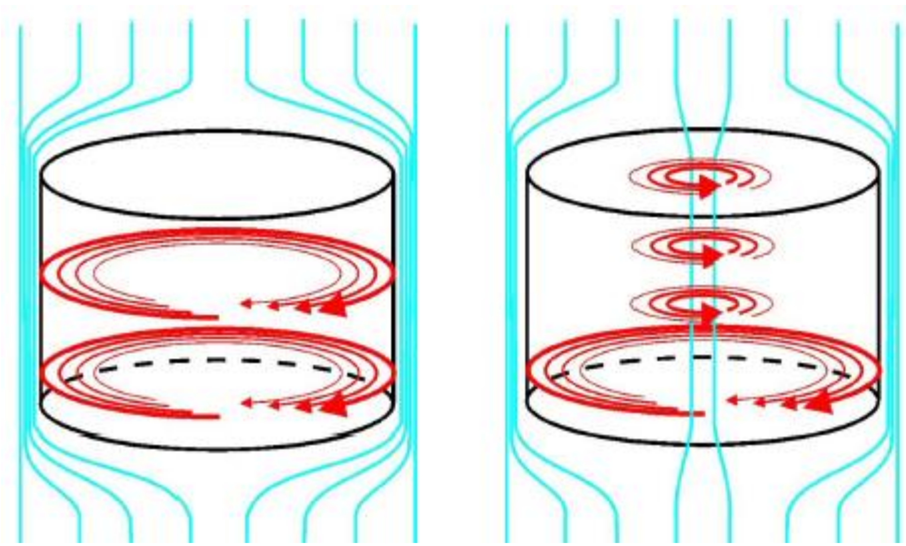
3G – YBCO, Iron and Copper

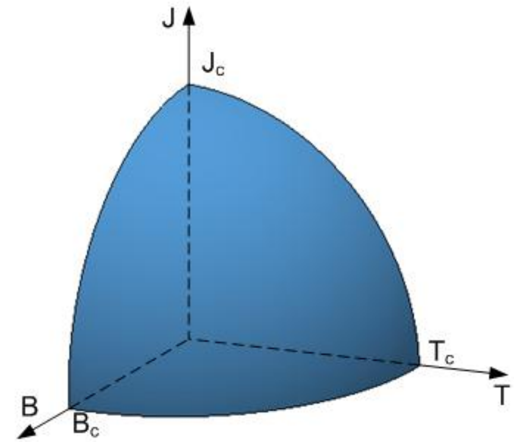


- Rotor requires leads for the very stable DC supply (brushless?)
- Rotating cooling system or rotating gaskets
- Extremely high current densities leading to very high airgap flux densities
- Slotless designs are commonly proposed, such that B ~2.5T can be achieved
- SeaTitan (design by AmSC): P = 10MW, D~5m, L~5m, m = 150-180 tons

Behaviour of the superconductor

- Meissner effect





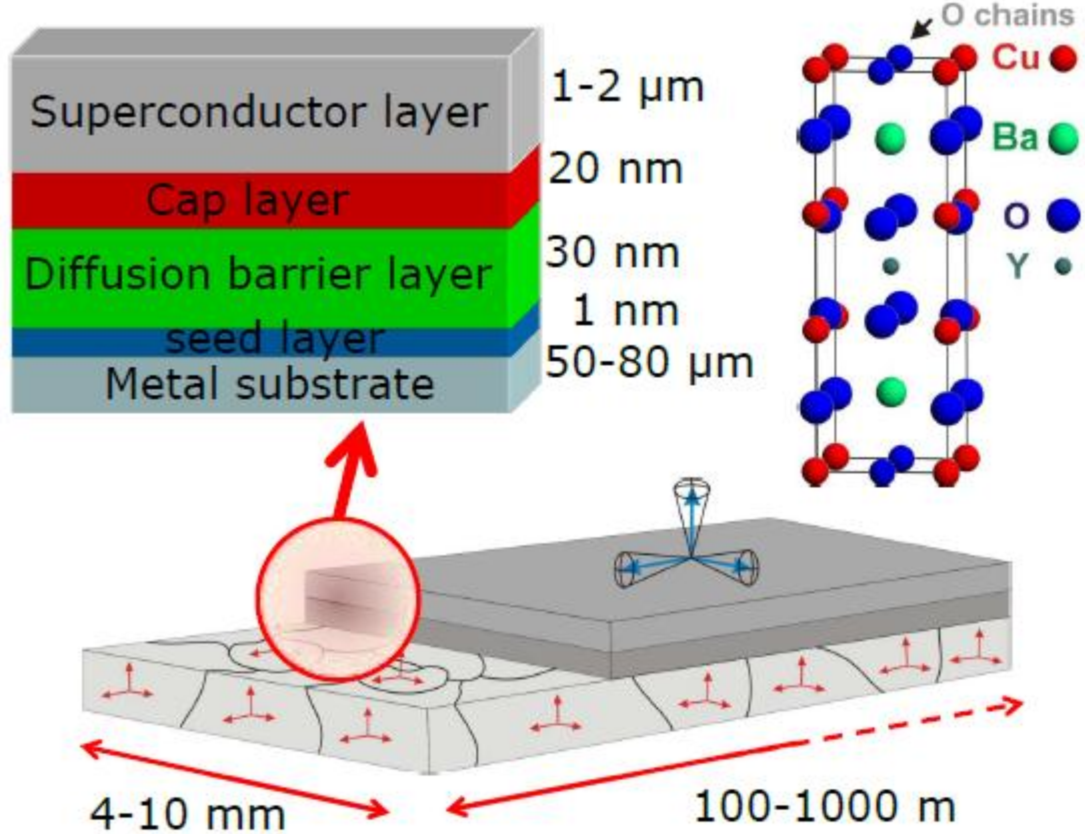
- Critical engineering current densities:

$$J_{e,C} = \frac{I_C}{A_{conductor+insulation}}$$

- The superconductor must be operated within the critical surface

- 2-3A/mm^2 is common in conventional large machines
- 2-300A/mm^2 can be achieved in HTS machines

Materials for coated conductors (2G HTS tape)



Superconductor in 1 km tape:

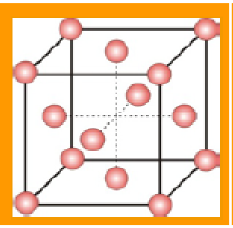
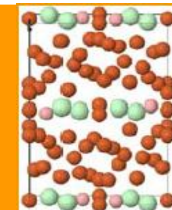
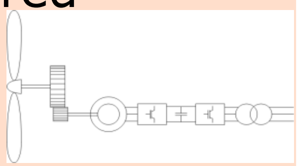
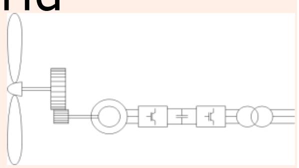
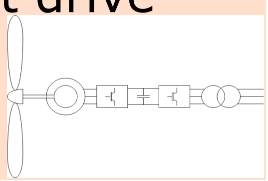
V_{RBCO} = 4 cm^3 !!

ρ_{RBCO} = 6.4-7.2 g/cm^3

m_{RBCO} = 29 g

$m_R = 0.13 m_{RBCO}$
= 4 g

Drivetrain comparison – Rare earth usage

	Cu & Fe 	PM 	HTS 
Geared 	0	25kgR/MW	Have not been proposed
Hybrid 	0	45kgR/MW	20gR/MW
Direct drive 	0	250kgR/MW	100gR/MW

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

Point of discussion

- Discuss with your neighbour (two and two):
  - The difference between the drivetrains
  - Your opinion on the HTS alternative, based on your experience and background
  - What do you see as the biggest advantage?
  - What do you see as the biggest challenge?
  - How is this relevant for your company?

- Comments, questions, suggestions?

Advantages

- High torque density
- Less rare earth usage
- Less top mass => lighter structure
- Ease of transportation
- Efficiency
- Less lubricant

Challenges/Disadvantages

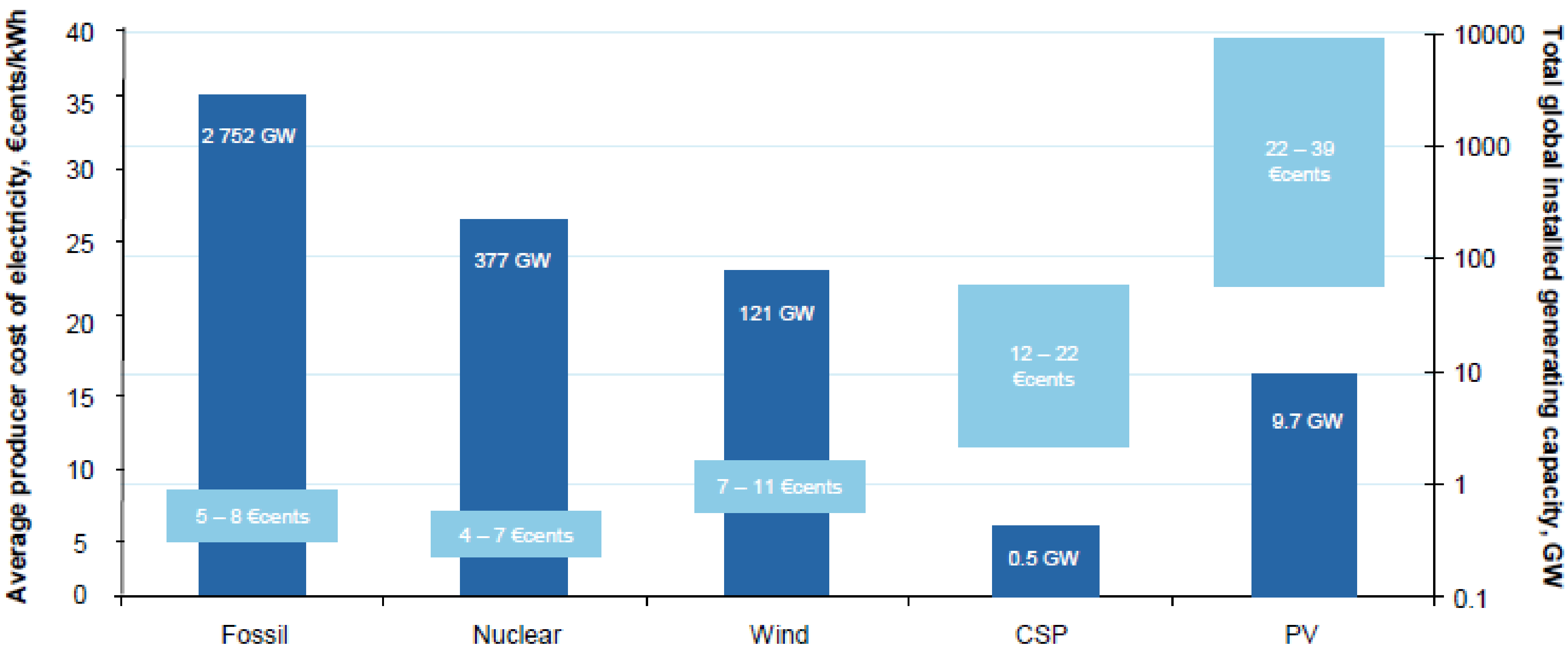
- Cooling
- Insulation
- Reliability of the cooling system
- Supply of components
- Immaturity of the technology/supply chain
- Cost!
- Cool down time
- Maintenance
- Short circuit
- Materials
- Failure modes
- Torque transmission
- Slip rings

Relevance for your company

- Size, logistics, material usage
- Makes for interesting research

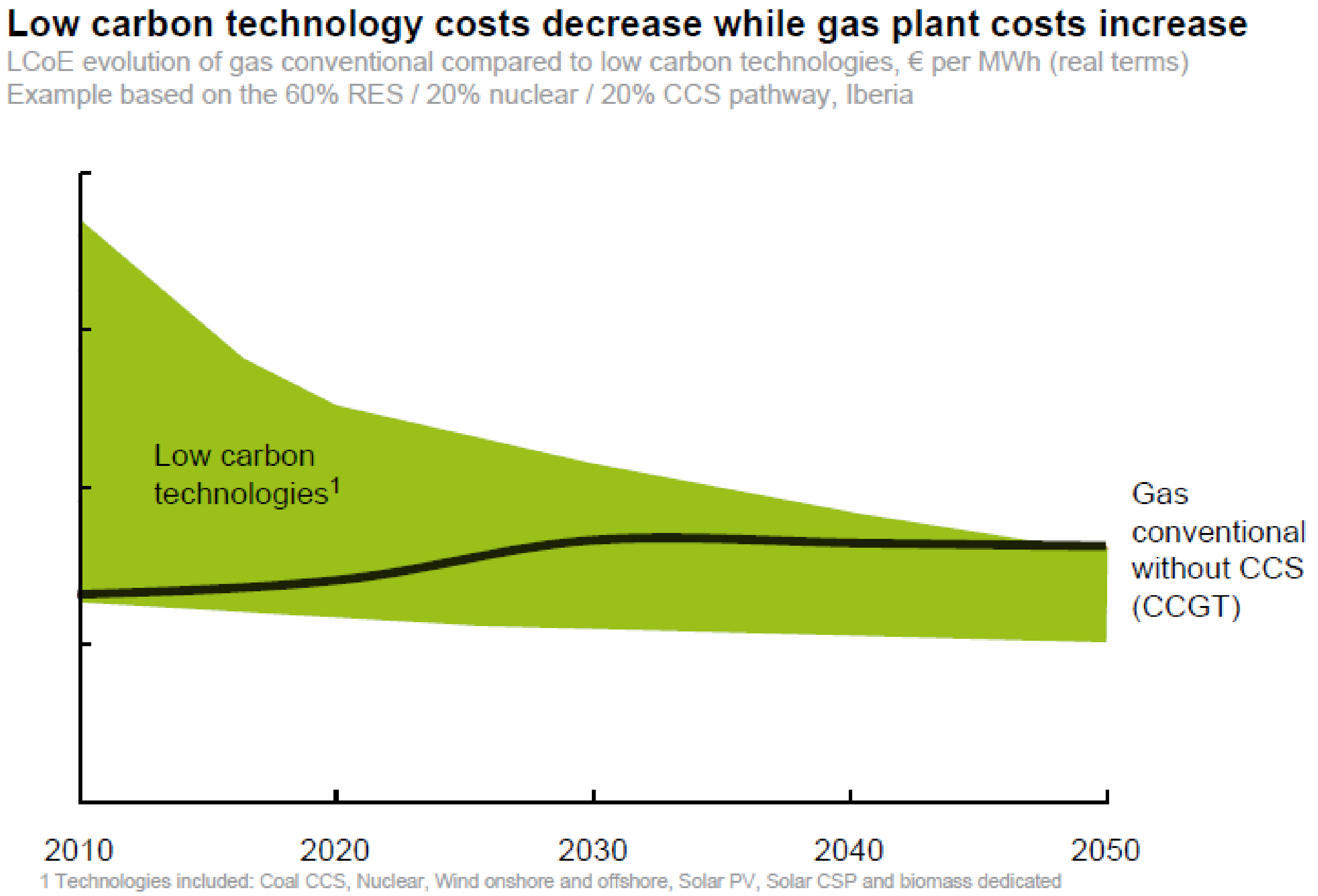
Importance of cost of energy (CoE)

- CoE is reduced as the total installed capacity is increased
- 121GW (2008) – 215GW (June 2011)



Source: www.pwc.com/sustainability

CoE from renewable energy sources will become lower than from fossil fuel sources



Source: European Climate Foundation – Roadmap 2050

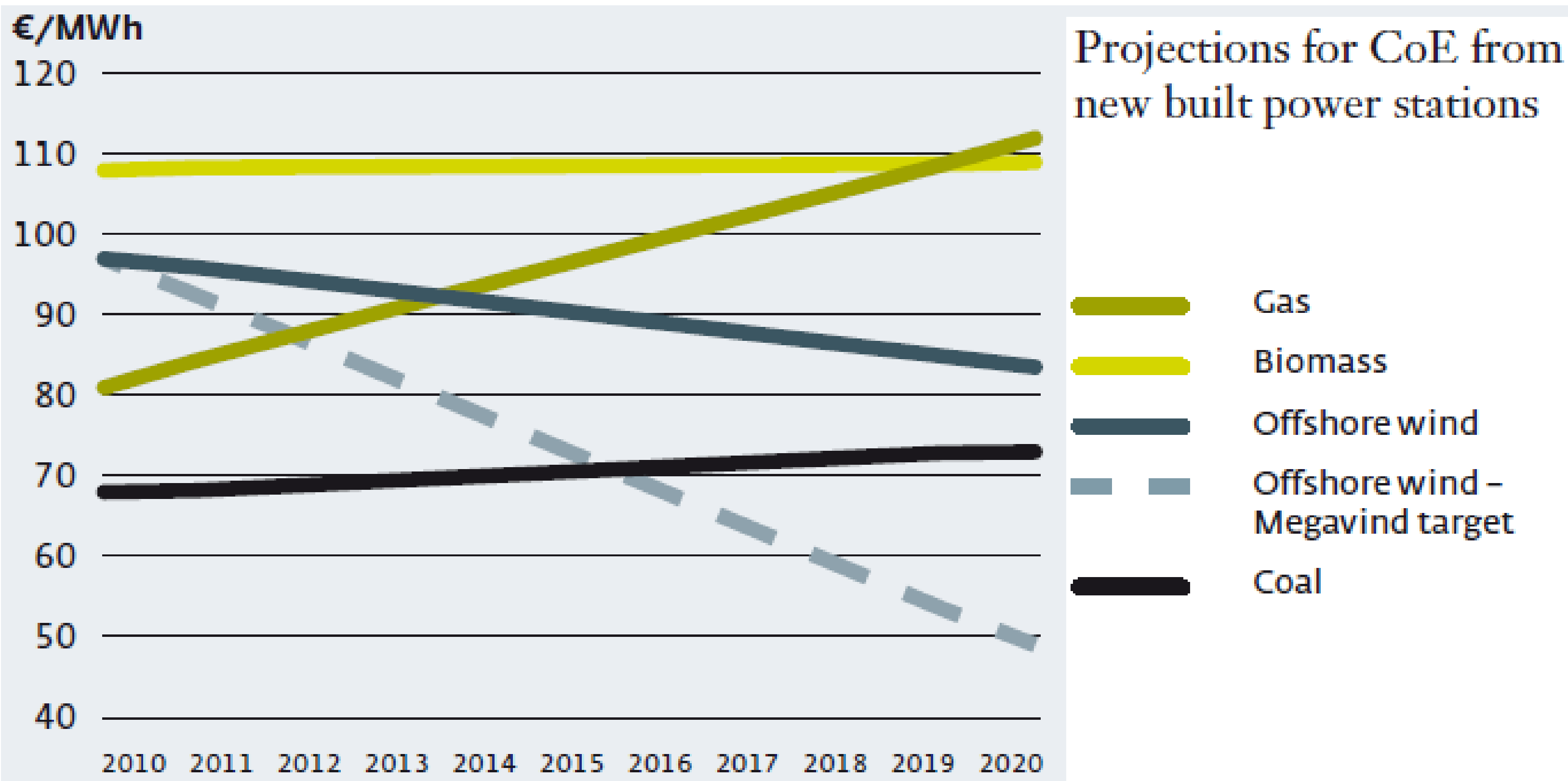
Danish Wind Industry Association MegaVind – 2020 Strategy

- Vestas Wind Systems
- Siemens Wind Power
- DONG Energy
- Grontmij
- Technical University of Denmark (DTU)
- Aalborg University

- Half CoE from offshore wind farms
- Achieved by:
  - 25% increase in capacity factor
  - 40% reduction in CAPEX
  - 50% reduction in OPEX

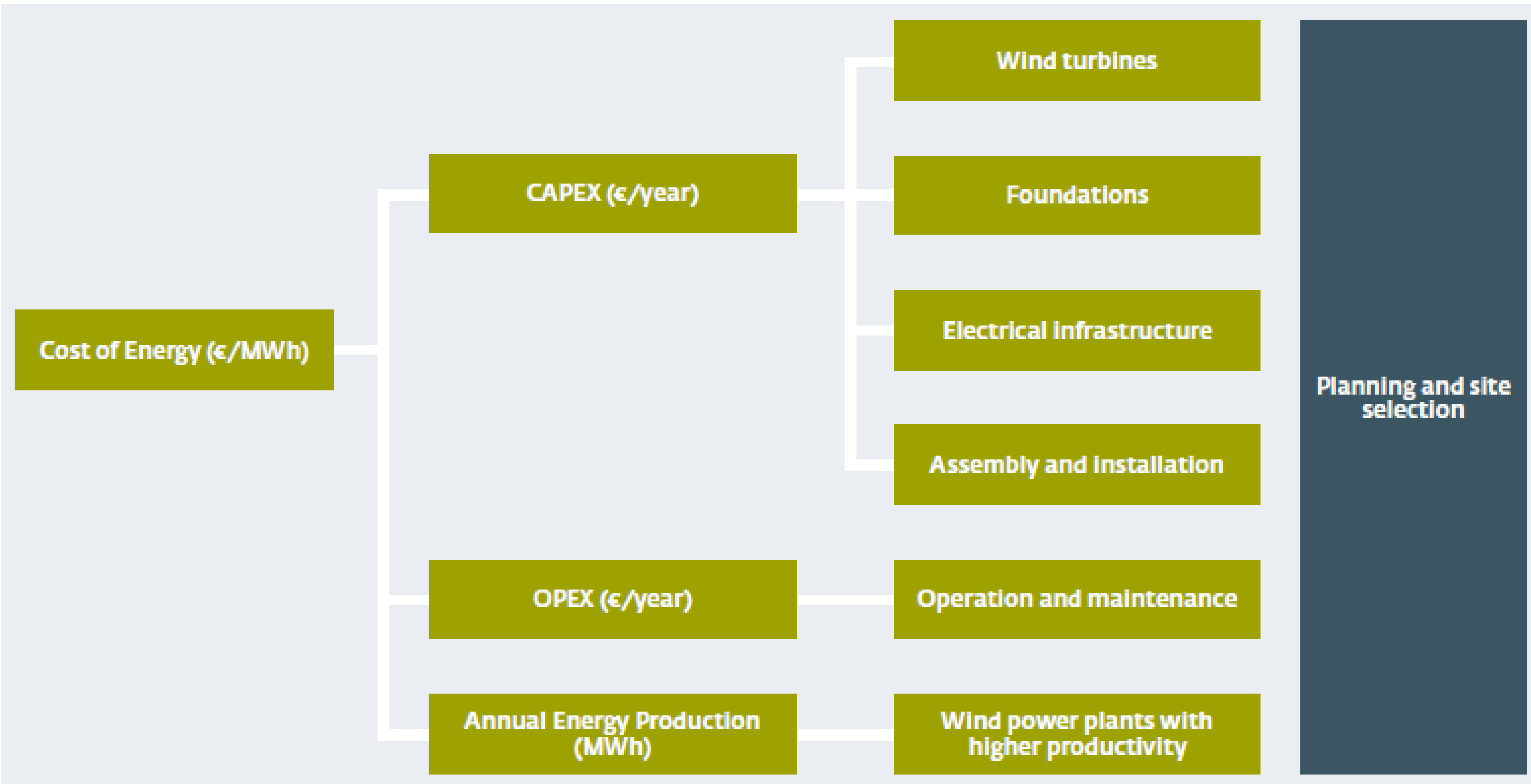
$$\text{CoE} = \frac{\text{Annualised CAPEX} + \text{Annualised OPEX}}{\text{Annual Energy Production}}$$

MegaVind – 2020 Strategy
50% reduction in CoE from offshore wind



Source: Danish Wind Industry Association – MegaVind Strategy

MegaVind – 2020 Strategy
Focus areas



Source: Danish Wind Industry Association – MegaVind Strategy

Point of discussion

- Discuss with your neighbour (two and two):
  - Most important requirements for future offshore wind turbines
  - or even wind farms
- List suggestions?
- Any that are not compatible with HTS machines?

EFFICIENCY AND POWER DENSITY

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:

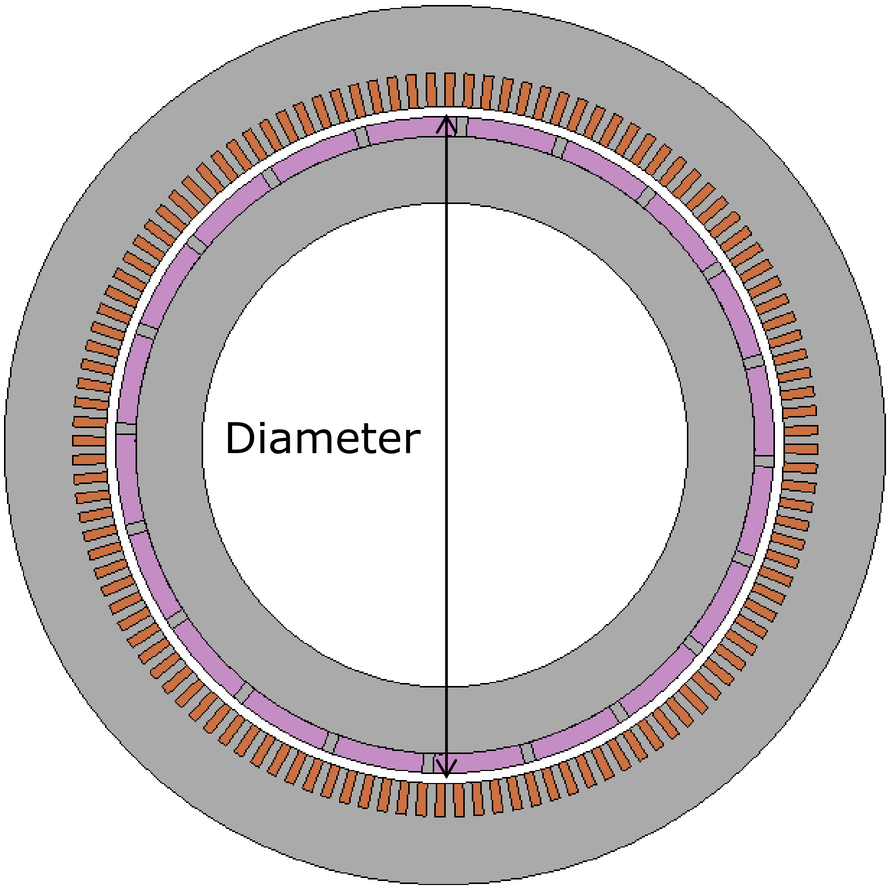
D_g = 8.6m D_g = 5.2m

Amount of copper in a PM and HTS

- If the electric loading (A/m circumference) and the armature current density is the same in both machines:
  - Amount of copper will be proportional to the diameter

- Hence if a 10MW PM machine has
  - 20 tons of copper and
  - 8.6m airgap diameter

- A 10MW HTS machine will have
  - 12 tons of copper at
  - 5.2m airgap diameter



Copper loss comparison

- The copper losses are the dominating losses in a large direct drive wind turbine generator
- The copper losses are:

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

- Using ρ_{Cu} = 8950kg/m^3, σ_{Cu} =45MS/m, J_{Cu} = 2.7A/mm^2 gives

- 360kW Cu losses in the PM (3.6% of rated output power)
- 220kW Cu losses in the HTS (2.2% of rated output power)

Cooling losses in an HTS machine

Previously we had:

425W for 500km

If additional 375W come from:

Conduction through connections

Radiation through the insulation

The total power to be removed needs to be 800W

In order to remove this at 30K, 50 times more power is needed:

40kW (0.40% of rated output power)

The total losses (excluding iron and mechanical) are therefore:

2.6% for HTS (efficiency excluding Fe and Mech: 97.4%)

3.6% for PM (efficiency excluding Fe and Mech: 96.4%)

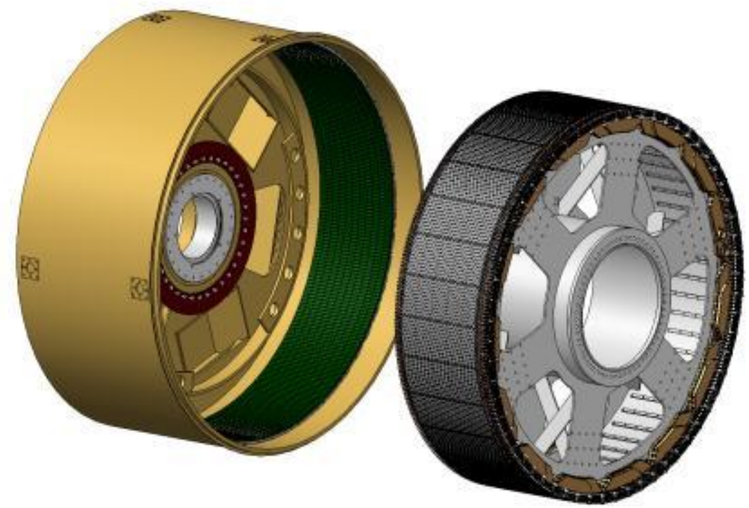
Point of discussion

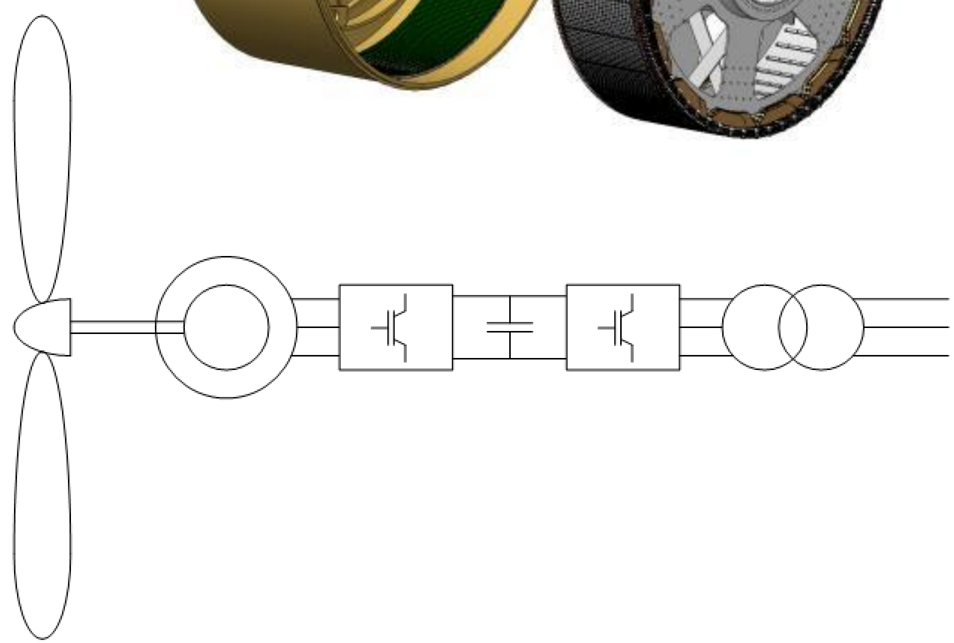
- Discuss with your neighbour (two and two):
  - The simplistic approach to efficiency estimation
- Comments, questions, suggestions?

- Partial load
- Stray losses
- Mechanical retention

Why use Multi-Pole Generators?

- The converter is indifferent (to a certain extent)
- Power is independent of pole numbers
- Voltage is independent of pole numbers
- Traditionally: weight (and cost) savings!

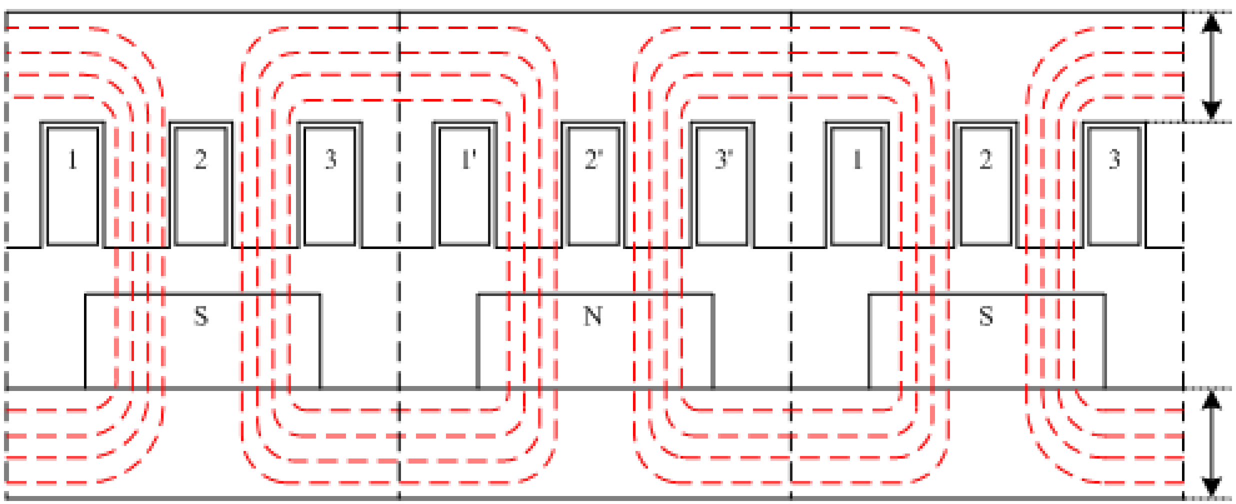




Core Back Thickness

- The flux path is from one pole to the next.

$$\hat{\phi} = 2\hat{B}_{cb} A_{cb} = 2\hat{B}_{cb} l_a d_{cb}$$

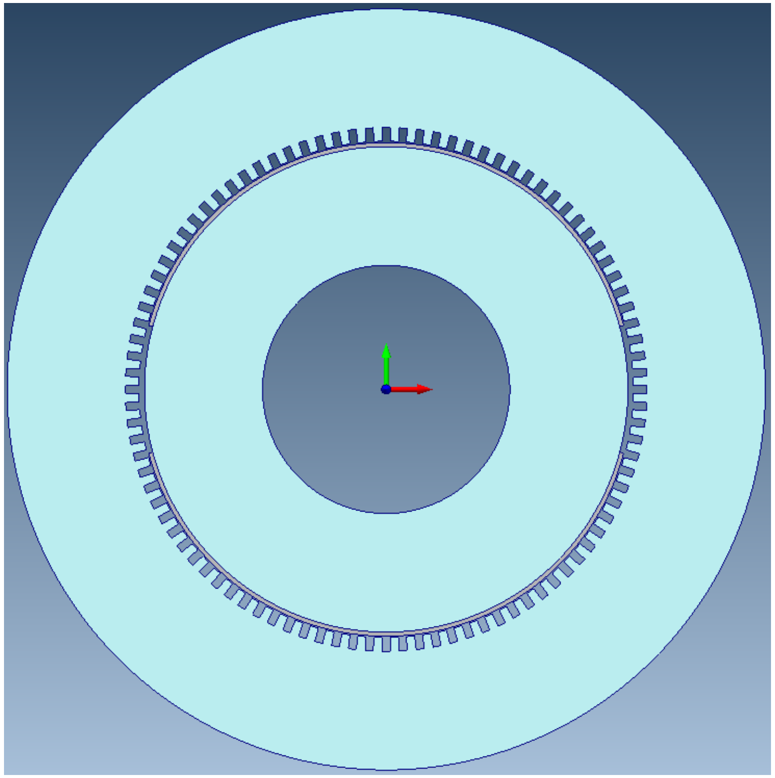


$$d_{cb,stator} \propto \frac{1}{p}$$

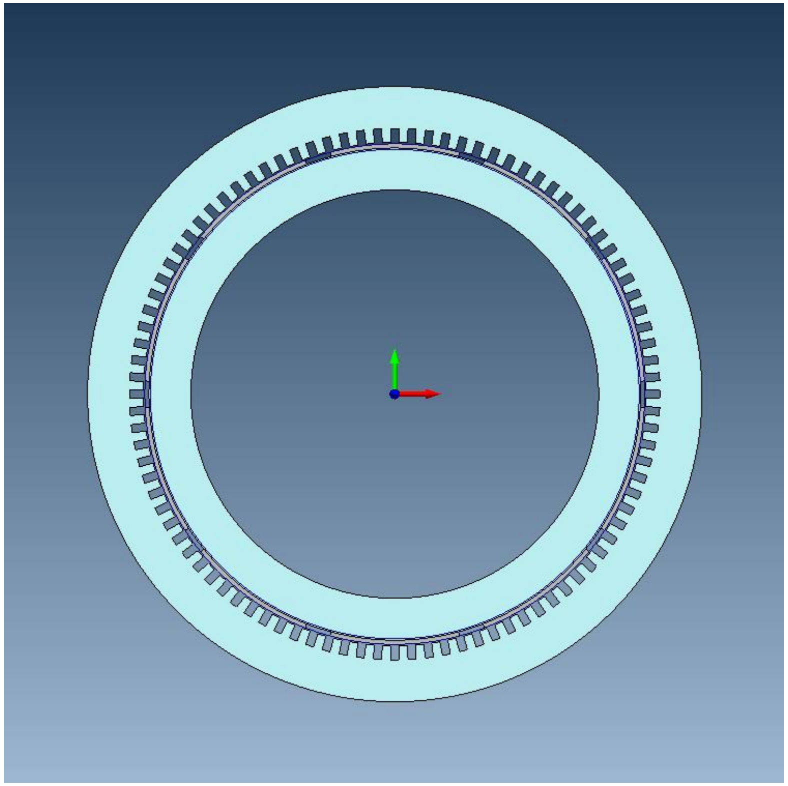
$$d_{cb,rotor} \propto \frac{1}{p}$$

PM Direct Drive Generator

2 Poles



10 Poles

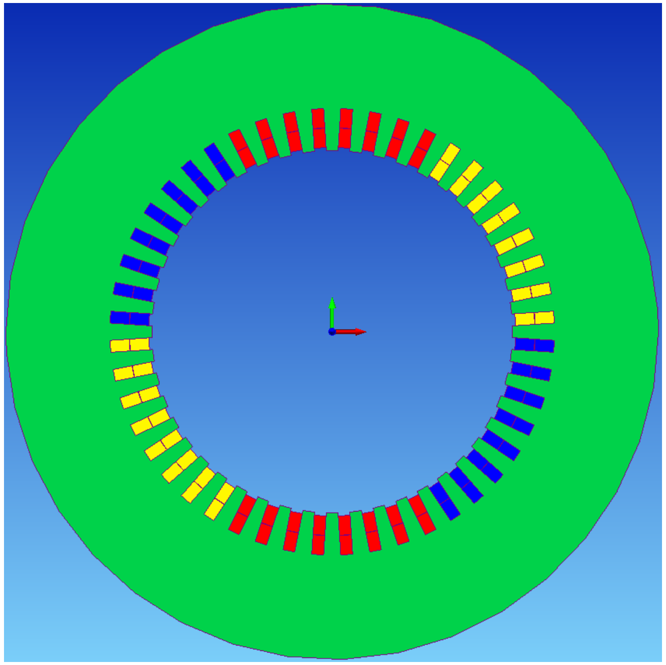


- The mass of the nacelle can be significantly reduced

End windings

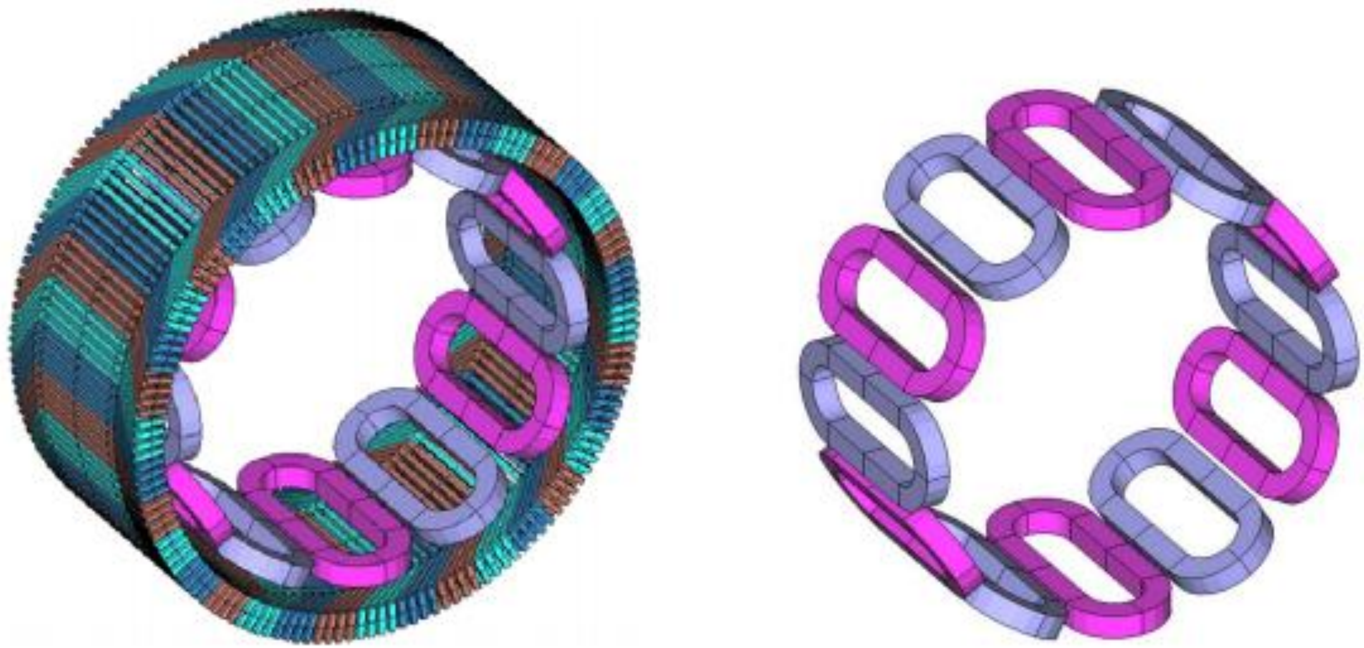
- Copper and HTS end winding length is reduced

2 Pole



Multi-Pole

Simplified calculations of HTS usage



(a) Armature and field coils (b) superconducting field coils

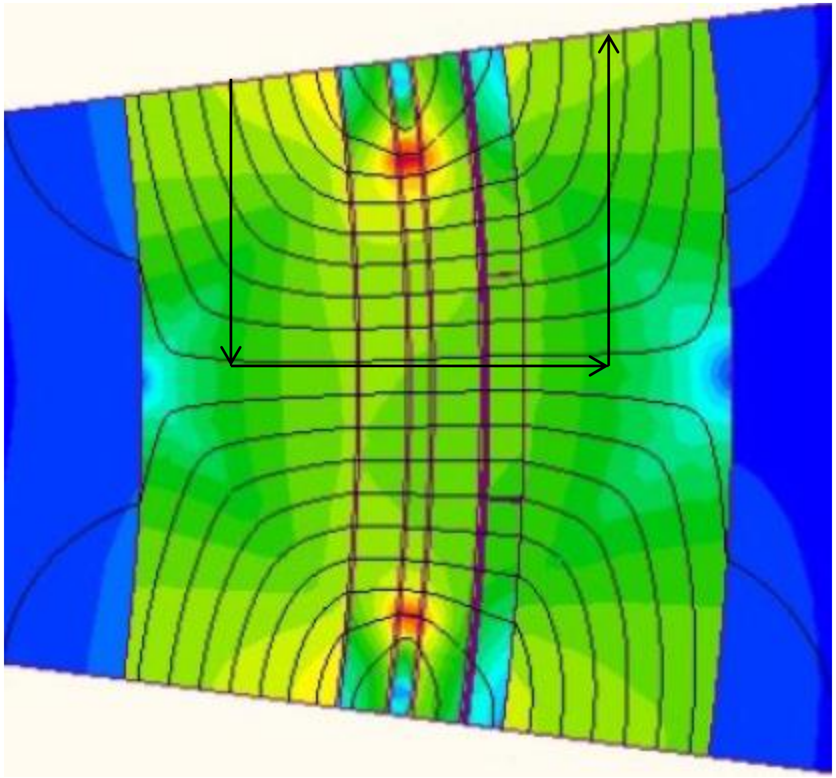
Fig. 1. Superconducting field coils and air-gap armature windings of a 12-pole wind turbine generator.

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

Estimating the effective airgap

- 12 pole, D_g = 5.2m, J_{Cu} = 2.7A/mm^2, A = 70kA/m, FF_{Cu} = 50%
- Radial copper depth:

$$d_{Cu} = \frac{70\times10^3}{2.7\times10^3\times0.5} = 50\text{mm}$$



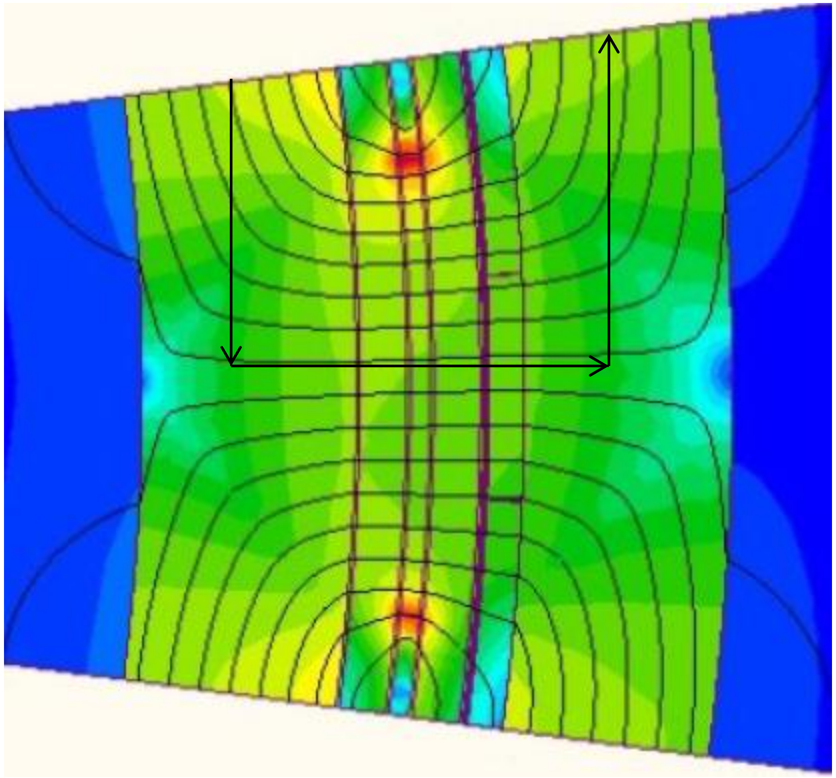
- Airgap: g = 10mm
- Cryostat thickness: 30mm each
- HTS radial thickness: 30mm
  - iterative
- Each pole has 2.7m of heavily saturated iron. This can be simply represented by 50mm of air (corresponding to μ_r~50
- Total effective airgap: 200mm

Estimating the required number of turns

- 12 pole, D_g = 5.2m, J_{Cu} = 2.7A/mm^2, A = 70kA/m, FF_{Cu} = 50%
- Effective airgap: 200mm
- If B_g = 2.5T → H_g = 2MA/m
- Required mmf per pole:

$$mmf = \oint \vec{H} \cdot d\vec{l}$$

$$mmf = 400\text{kA}$$



- If each HTS conductor can carry 100A then 4000 turns are needed

$$d_{Cu} = \frac{70 \times 10^3}{2.7 \times 10^3 \times 0.5} = 50\text{mm}$$

Estimating the required length of HTS tape

- 12 pole, D_g = 5.2m, J_{Cu} = 2.7A/mm^2, A = 70kA/m, FF_{Cu} = 50%
- HTS turns per pole: N_{HTS} = 4,000
- Pole arc length

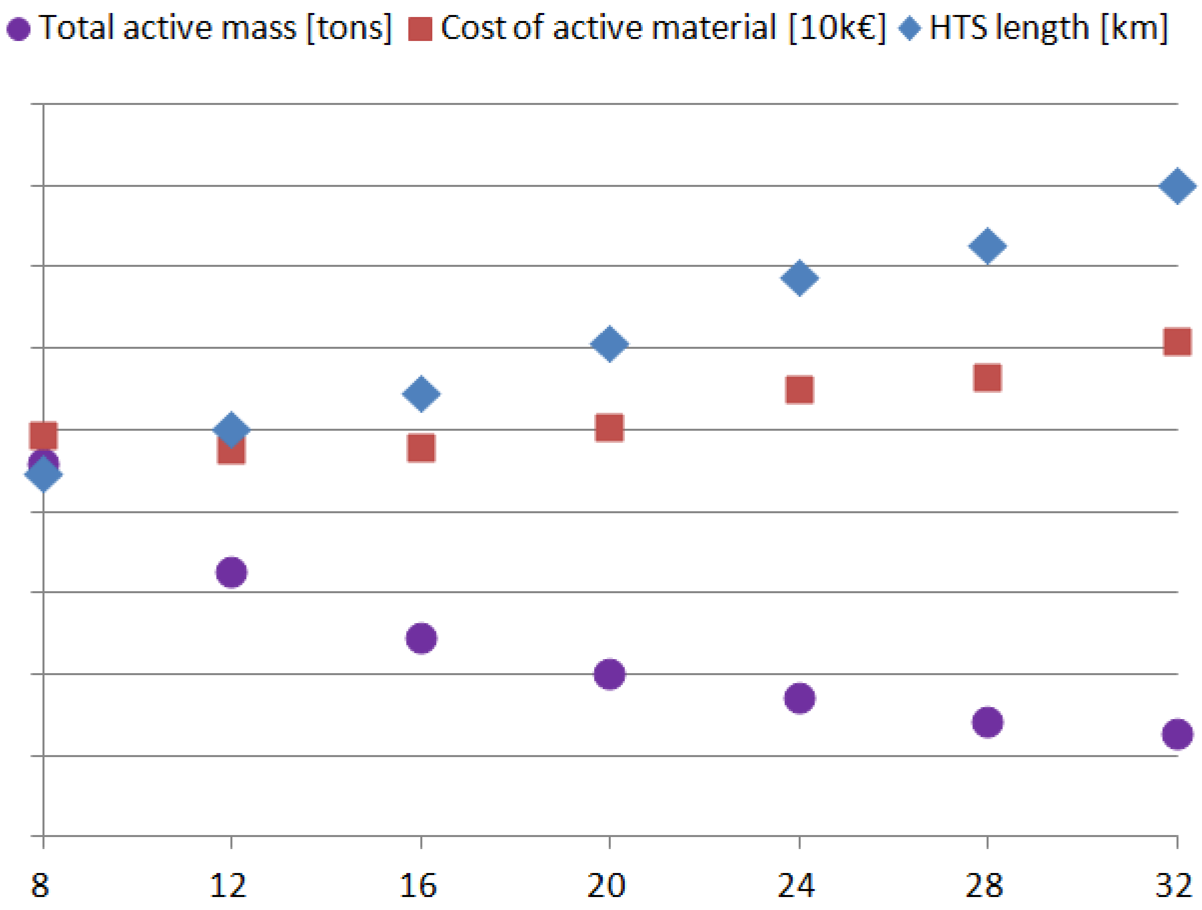
$$l_{pole} = \frac{D_g \pi}{2p} = 1.4\text{m}$$

- As the HTS has circular ends the average turn length is:

$$l_{turn} = l_{pole}\pi + 2l_{axial} = 8.4\text{m}$$

- The total length of HTS tape in a 12 pole machine would therefore be:
- $l_{HTS} = N_{HTS} l_{turn} 2p = 400\text{km}$

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



Power density

- The power density of an HTS generator can therefore be expected to be higher than for a PM generator
- The power density will depend on the specific design and varies in the literature
- Most scientific papers do not account for the entire mass of the generator
- AmSC promise 15-18kg/kW (10MW)
- A 10MW PM generator might have 30kg/kW (Bang 2008)

(D. Bang *et al*. "Review of generator systems for direct-drive wind turbines", EWEC 2008)

Point of discussion

- Discuss with your neighbour (two and two):
  - The simplistic assessment of the HTS tape usage

- Comments, questions, suggestions?

ASSESSING THE CURRENT COST SITUATION

Cost of HTS tape

- If 500km of HTS tape is assumed for a 10MW wind turbine generator
- The current carrying capacity is 100A and the cheapest price on the market is €100/kAm, which gives €10/m
- The cost of the HTS tape for a 10MW would therefore be €5 million
- In addition the cryostat, cryocooler etc. will have to be added
- PM price today? €100-200/kg
- If 10 tons of PM is required for a 10MW wind turbine
- The cost of the PM for a 10MW would be €1-2 million

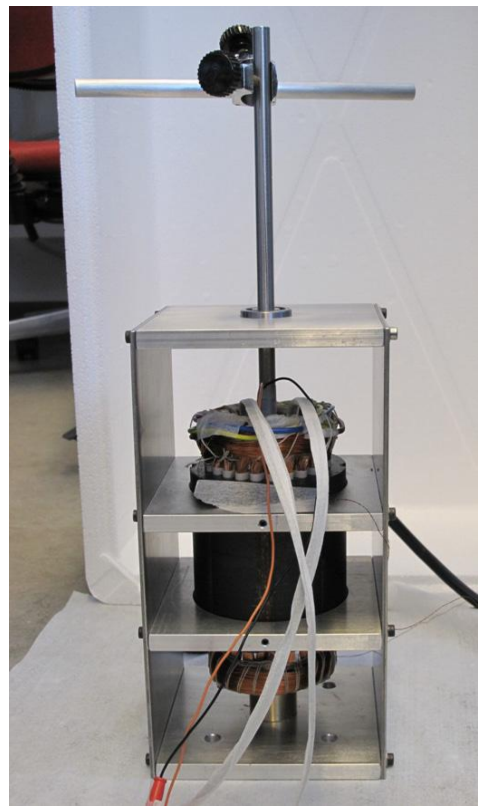
Future cost of HTS must/will come down

- It is not unlikely that the price of HTS tape will come down to €15/kAm
- This would result in €750,000, if 500km of HTS tape was required for a 10MW wind turbine
- This would be competitive with PM technology

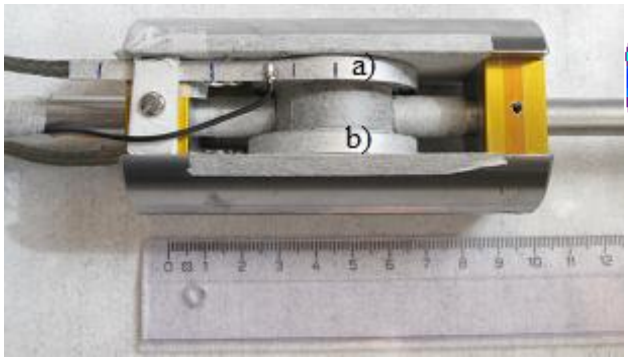
BECOMING COMMERCIALLY VIABLE

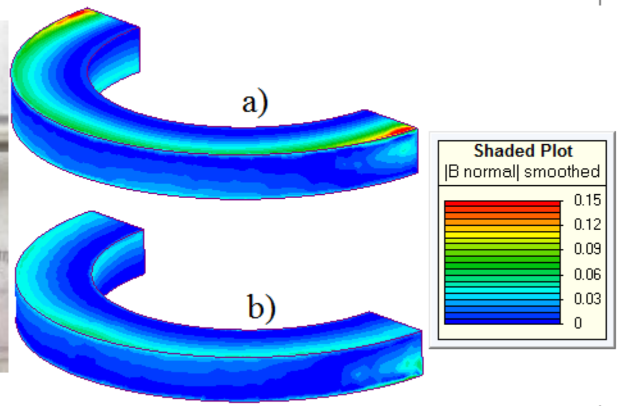
Continue research in universities

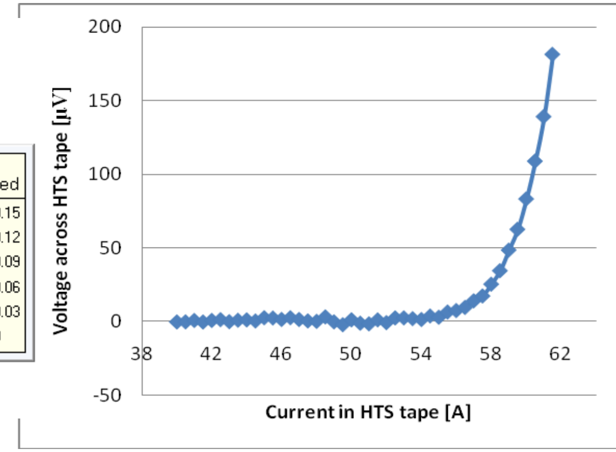
- Building small scale prototypes
- Learning from these and extrapolating to large scale

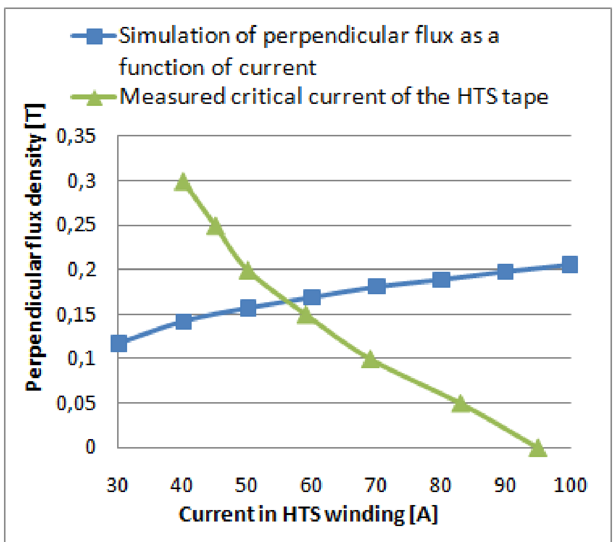


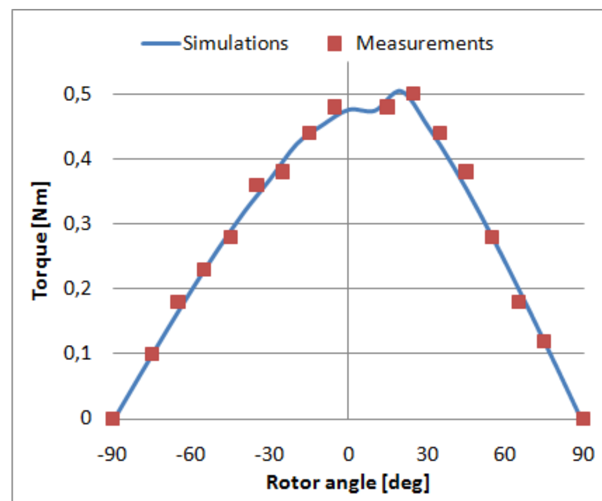
Results for a simple prototype











Design and construct large scale demonstrators

- AmSC and Northrop-Grumman (NGC) built a 36.5MW for the US Navy in 2007
- AmSC and Converteam built a 5MW for the US Office of Naval Research in 2005
- AmSC would like to build the SeaTitan – a 10MW direct drive wind turbine generator
- Converteam and Zenergy built a small HTS hydrogenerator
- Converteam are building an 8MW direct drive wind turbine generator
- Siemens has had much HTS machine activity
- GE just announced that they would construct a 10MW direct drive wind turbine generator based on LTS

Collaboration and commitment is needed

- Collaboration and commitment is needed from the
  - Wind turbine manufacturers
  - HTS tape manufacturers
  - Wind turbine operators

- Commitment is needed from the funding bodies
  - This seems to be in place – HTS generators for wind turbines have been mentioned specifically in an FP7 call

- Mass production of the HTS tape is required
  - Avoid the chicken and egg scenario

THANK YOU!
QUESTIONS?

VIND I ØRESUND

Interreg IVA
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LUNDS UNIVERSITET

This presentation is part of an EU Interreg project, which is informing about projects connected to Wind in the Øresund-region of Eastern Denmark and Southern Sweden.

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