Technical University of Denmark

Active materials for future wind turbine generators: From Copper to R2Fe14B and RBa2Cu3O6+x?

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Publication date:
2011

Active materials for future wind turbine generators: From Copper to $R_2Fe_{14}B$ and $RBa_2Cu_3O_{6+x}$?

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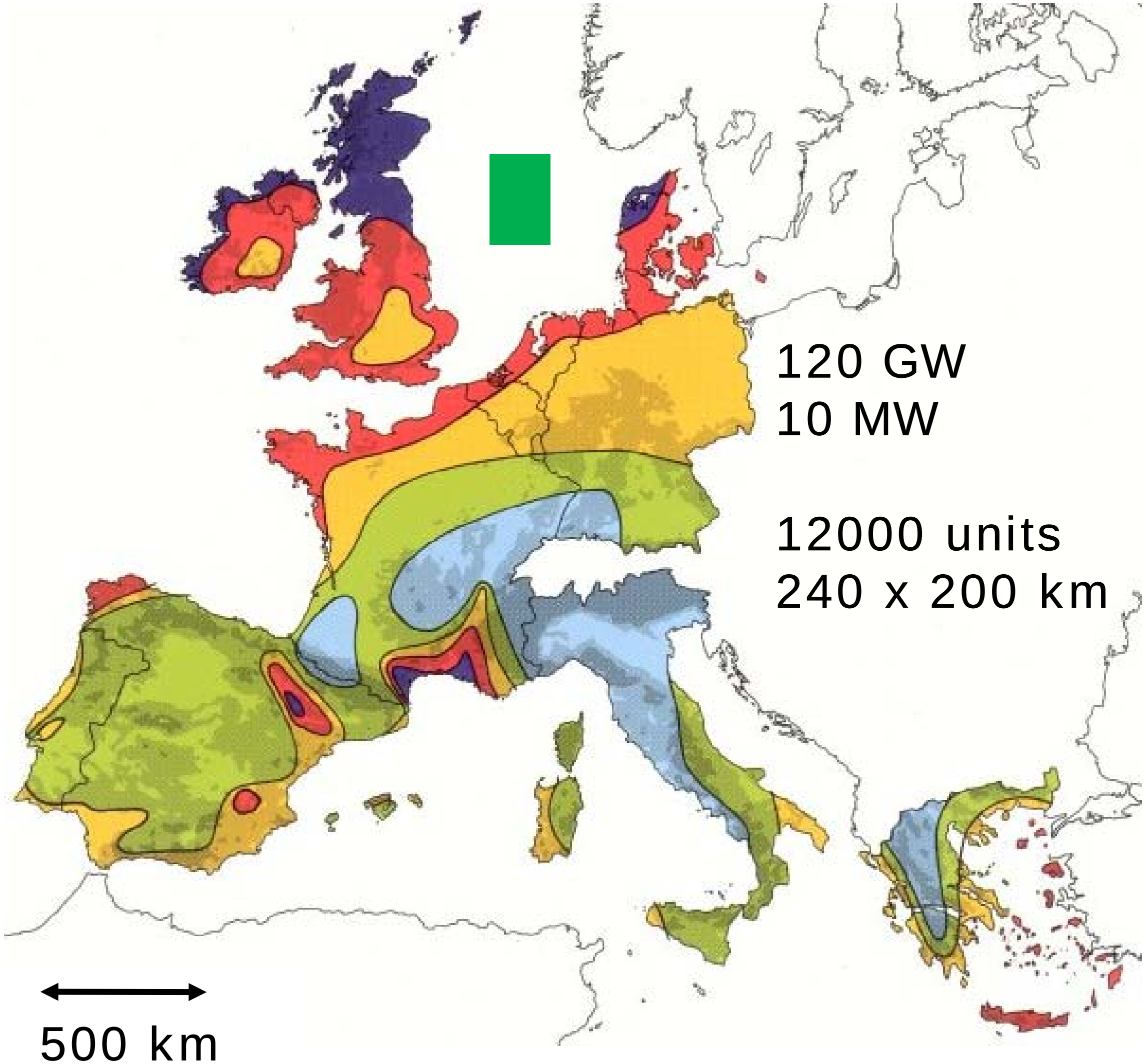
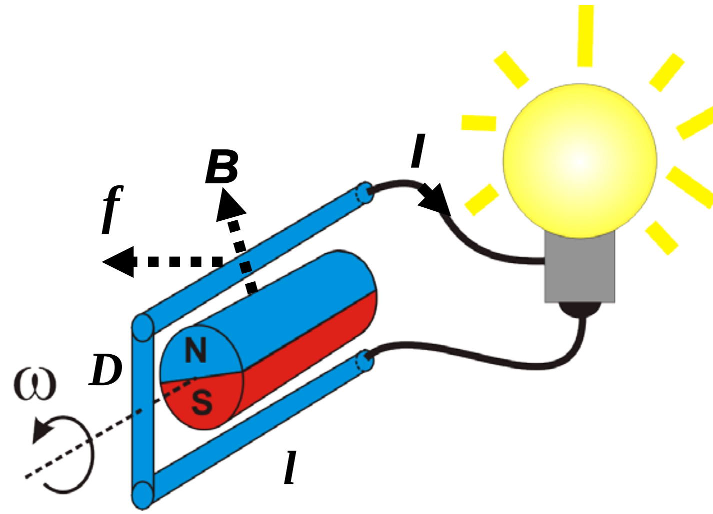
Outline



120 GW
10 MW

12000 units
240 x 200 km



$$Power \propto BI\ D^2 l\ \omega$$

1G : Copper + Iron

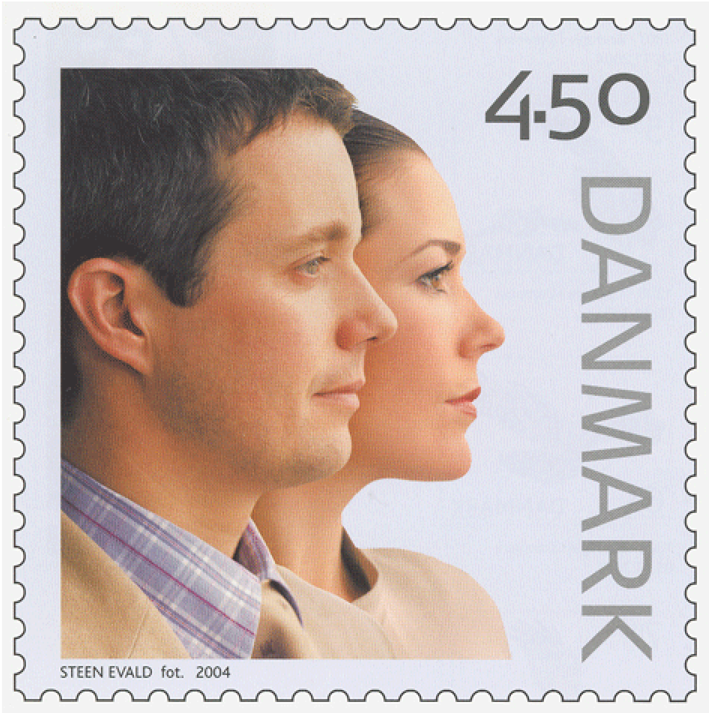
2G : $R_2Fe_{14}B$ magnets+Fe
10 MW ~ 6 tons PM

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

Program

9:00-9:45	Motivation
	Energy & wind power development
	Drive trains
	Generator concepts
	Direct drives and active materials
	Permanent magnets for wind turbines
	How much do we need?
10:00-10:30	Is it going to be hard to get the Rare Earths?
	High temperature superconductors as an alternative?
11:00-12:00	Superconducting direct drive train
	Tapes and Race track coils
	Topology and cooling
	Feasibility discussion
	State of the art
	Conclusion

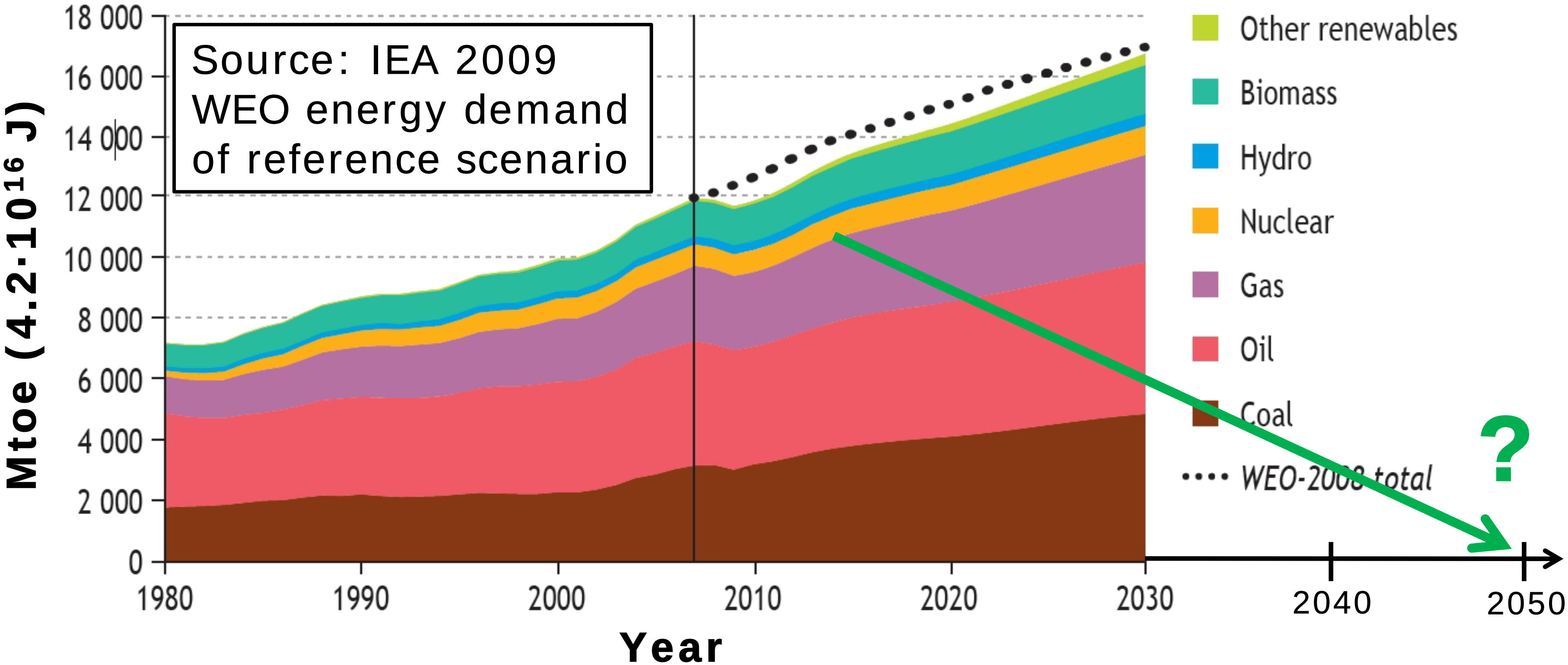
Motivation : Sex



$$\frac{dN}{dt} = \alpha \; N - \beta \; N \qquad N(t) = N_0 \exp([\alpha - \beta]t)$$

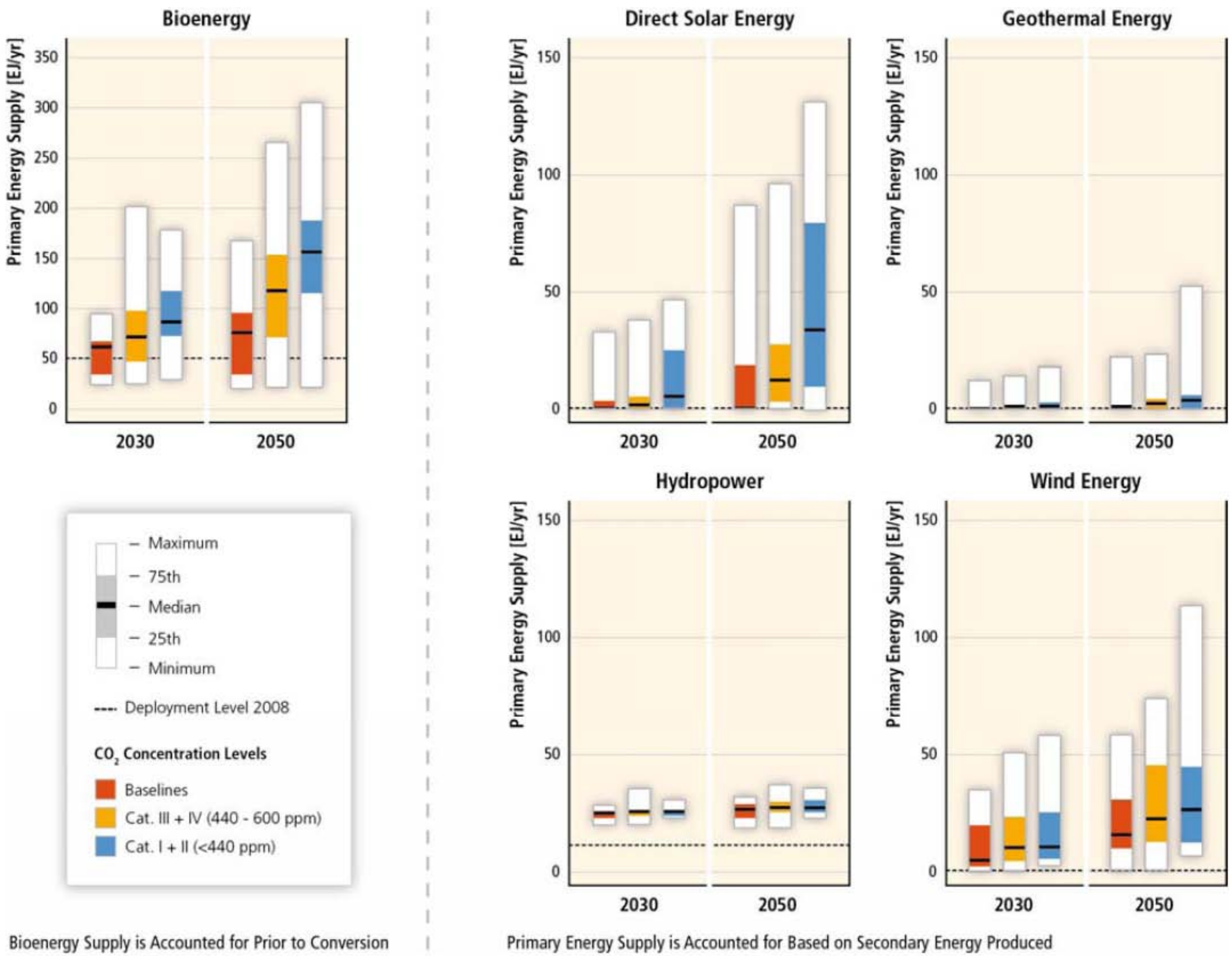
Birth rate : α(N, food, pollution, techno, energy,.) Death rate : β

The energy challenge



Global warming:	60-80 % reduction
Security of supply:	Fossil fuel free in 2050

Special Report on RENewable energy sources



1 EJ = 10^{18} J

= 24 Mtoe

= 33 GWyr

Demand (2009)

12000 Mtoe ~

500 EJ

Wind:

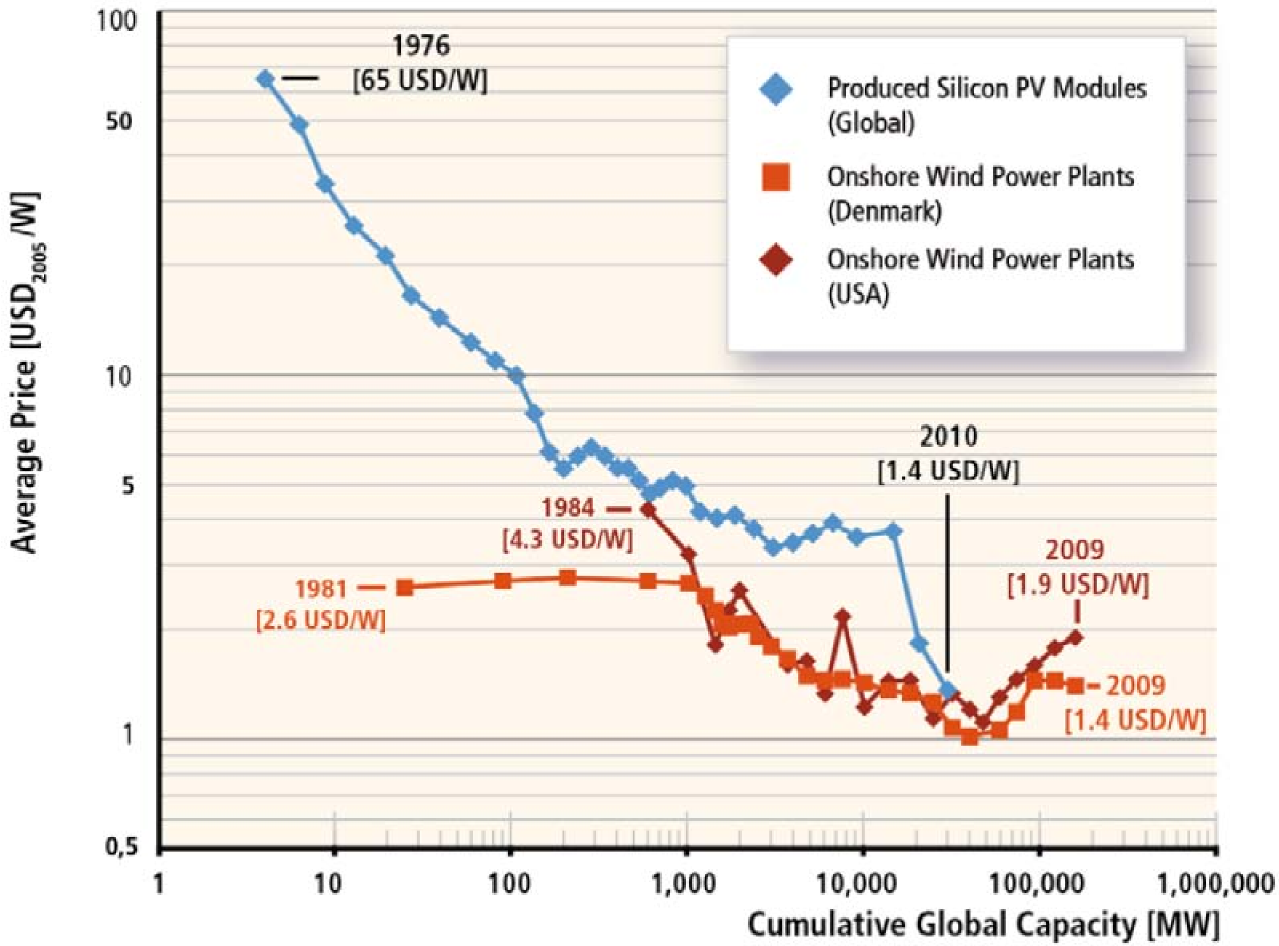
5-25 EJ (2030)
~ 330-1650 GW

10-45 EJ (2050)
~ 660-2970 GW

(Capacity factor = 0.5)

Source: IPPC SRREN summary for policy makers, 5-8 May 2011. Fig. SPM 11

Installation price: Wind vs. Solar

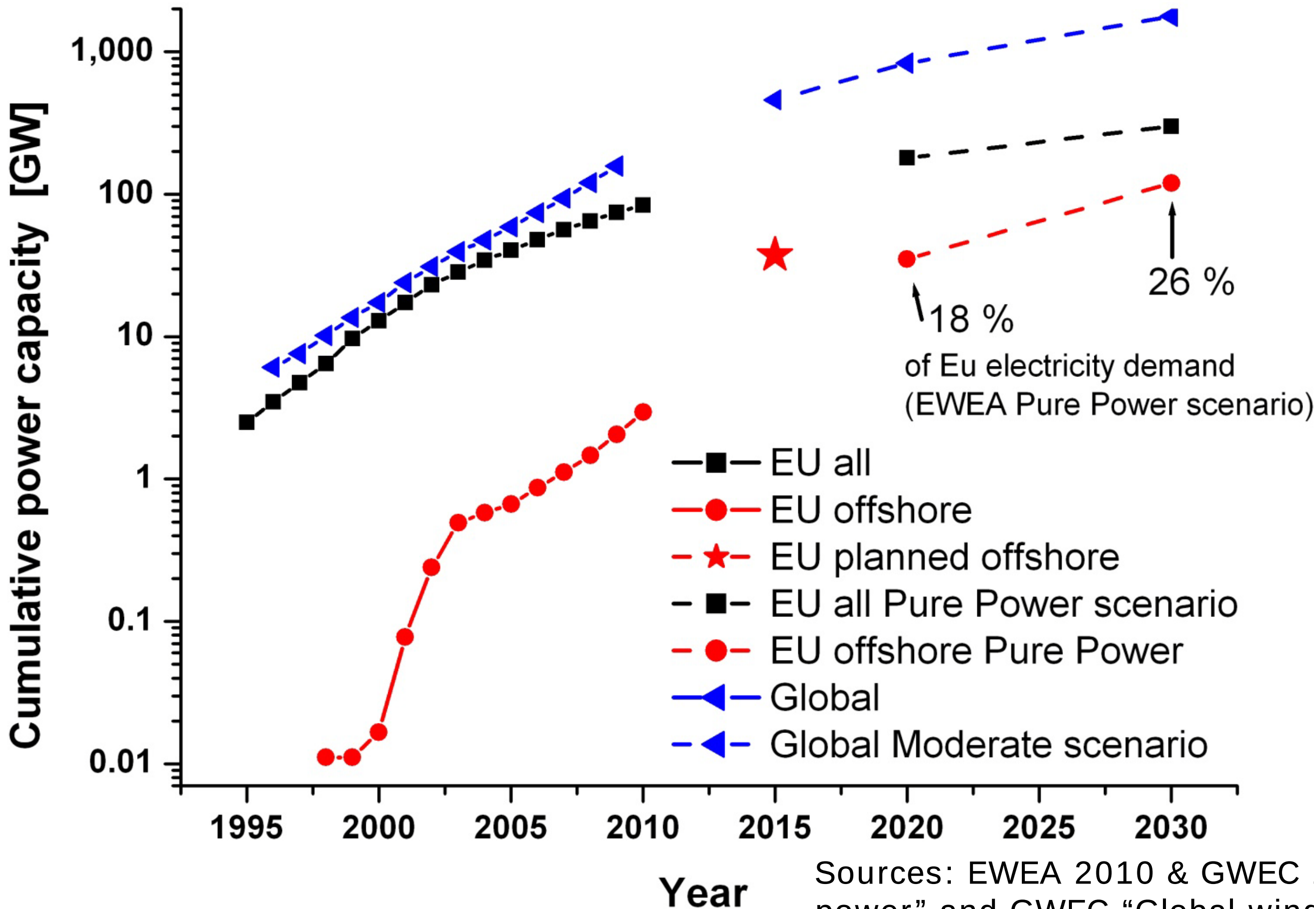


a) Reliable

b) Cheap
1 M€ / MW

Source: IPPC SRREN summary for policy makers, 5-8 May 2011. Fig. SPM 6a

Wind power capacity



Trends

On/offshore →
50 / 50% market

On/offshore →
3 MW / 10 MW

Onshore:
Neighbor Noise!
Offshore:
Engineering free!

COE over 20 year

Integration:
Supergrid needed

Sources: EWEA 2010 & GWEC 2009 statistics, EWEA "Pure power" and GWEC "Global wind energy outlook 2010" reports.
Abrahamsen et. at., "Wind Energy Conversion System: Technology and Trend", book chapter, Springer 2011.

Drive trains

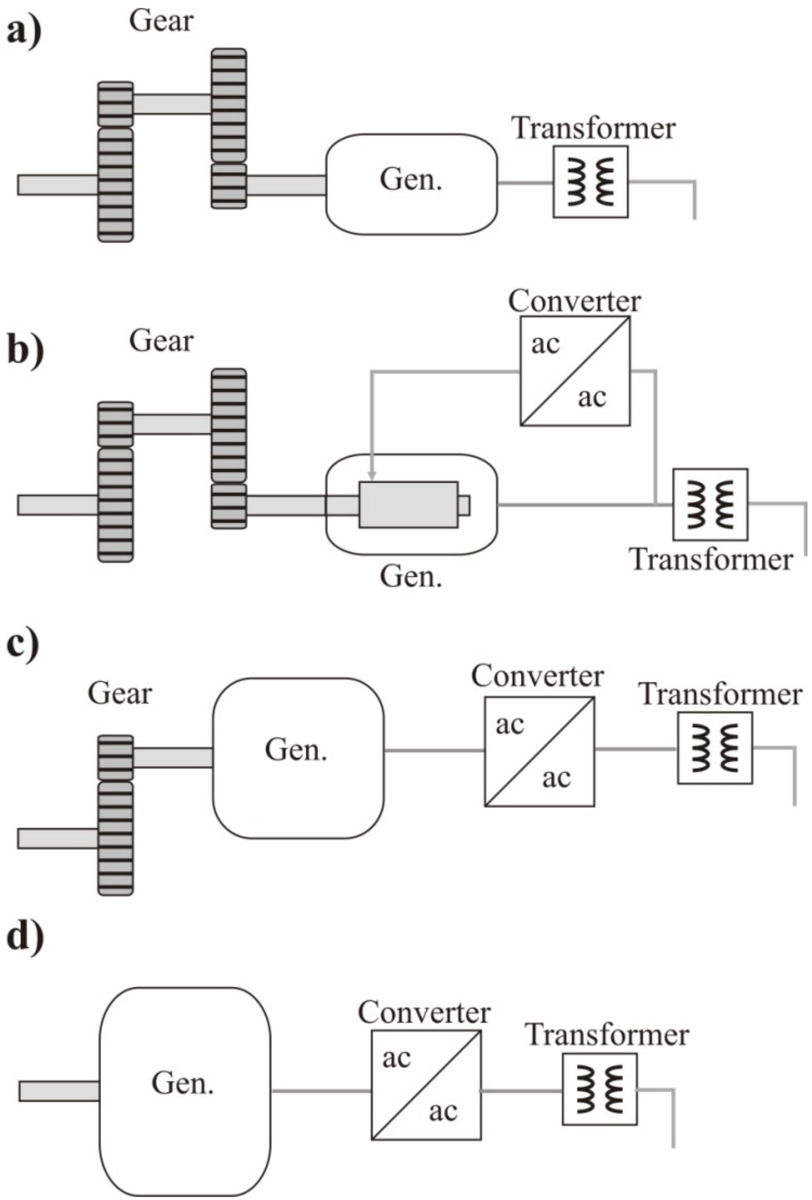
Geared

↓

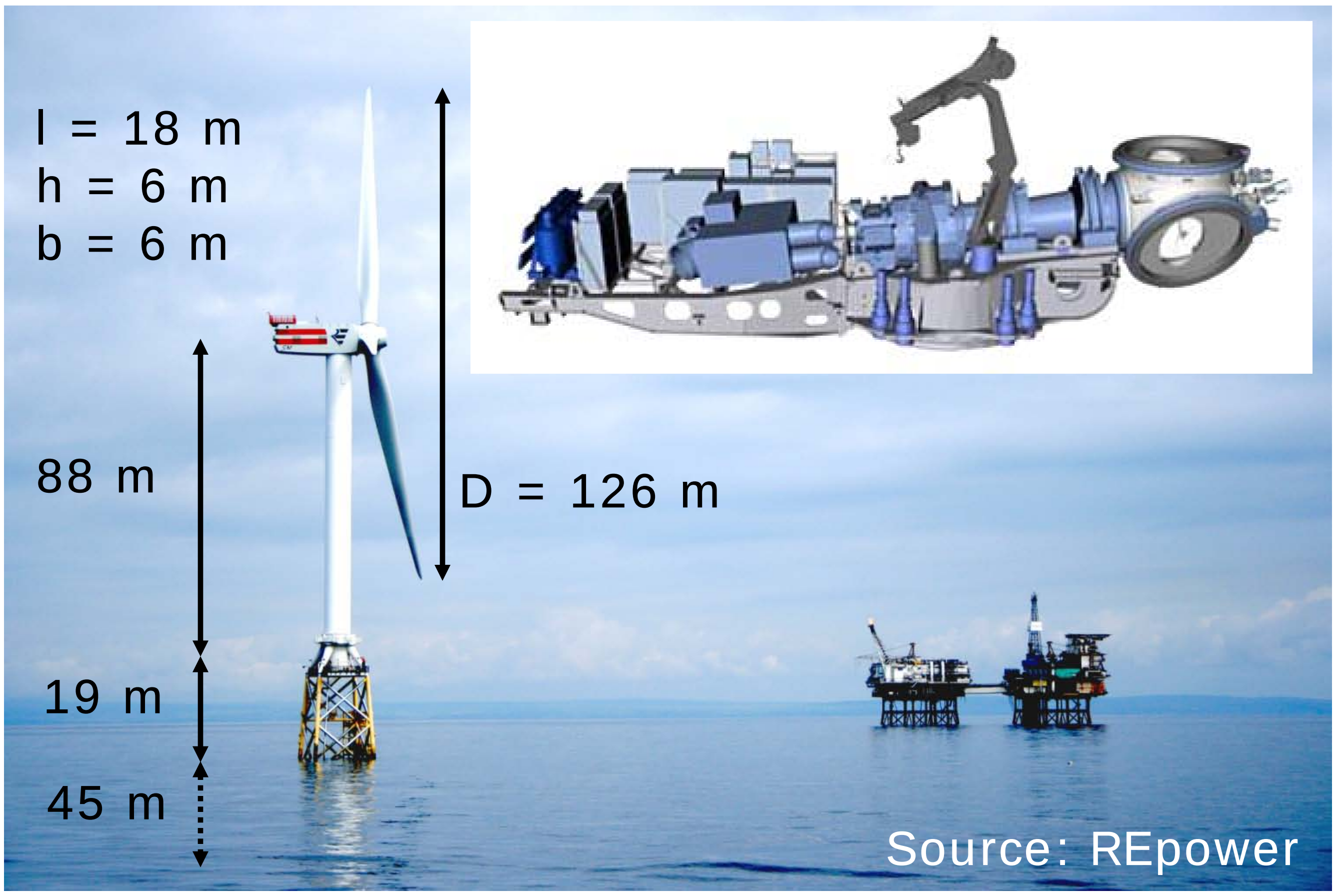
Hybrid

↓

Direct



Geared: REpower 5M @ Beatrice (5 MW)



- Pitch controll
- Geared ~ 1:97
- DFIG

Rotor:

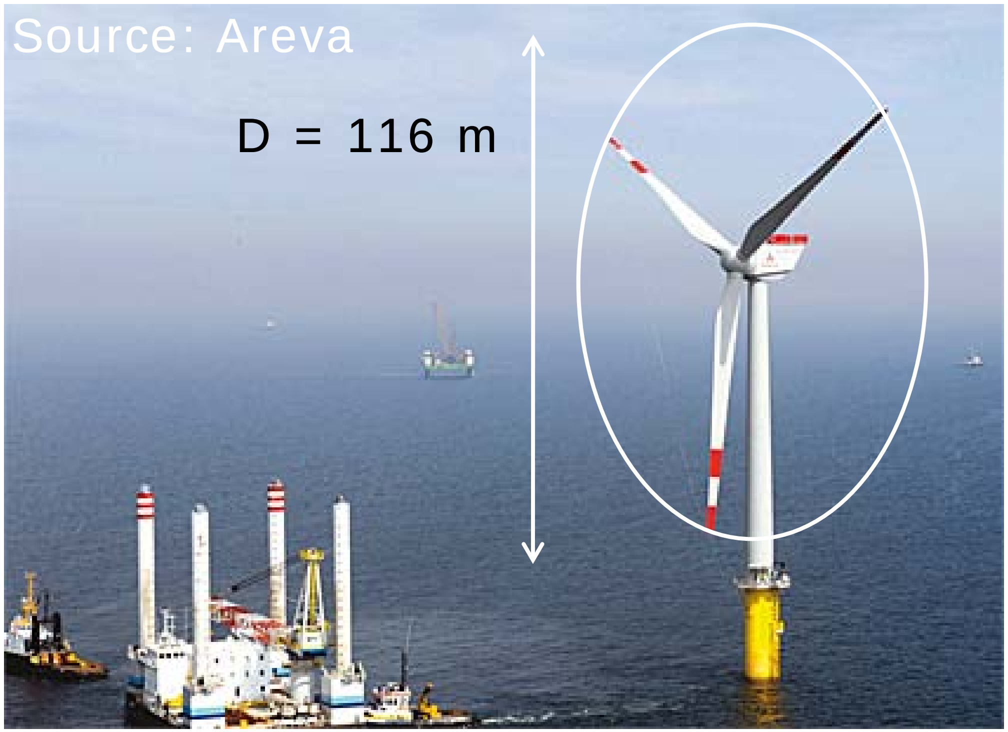
Blades	54 tons
Hub	66 tons
Total	120 tons

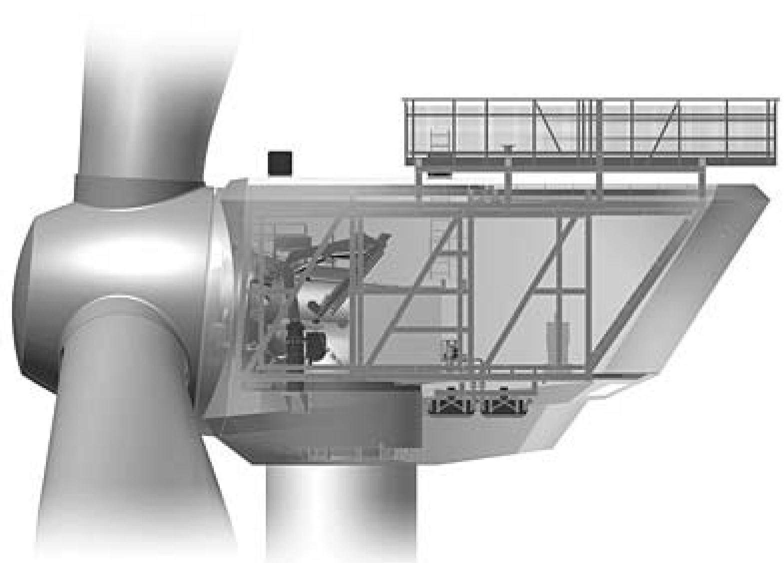
Nacelle:

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

Sum : 410 tons

Hybrid: Multibrid M5000 (5 MW)

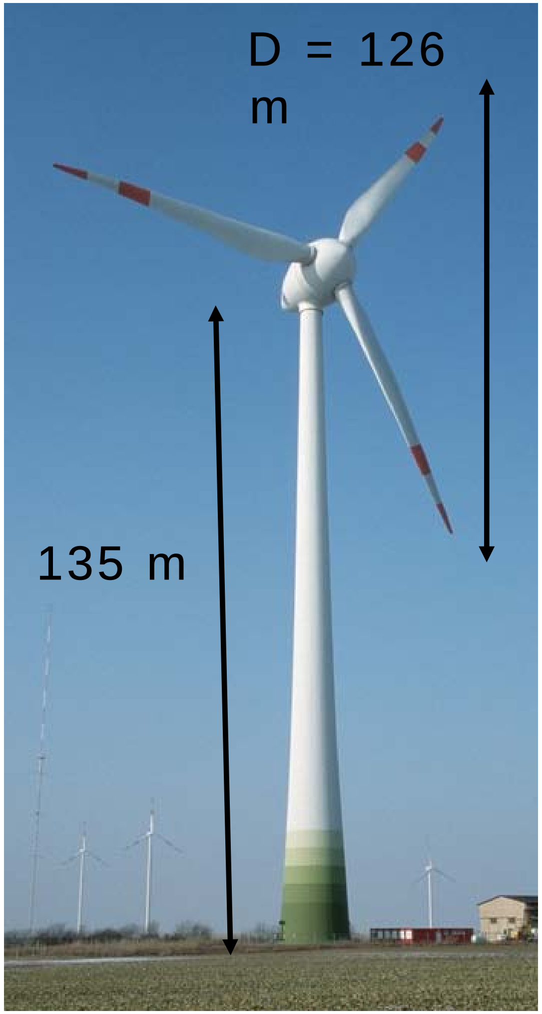


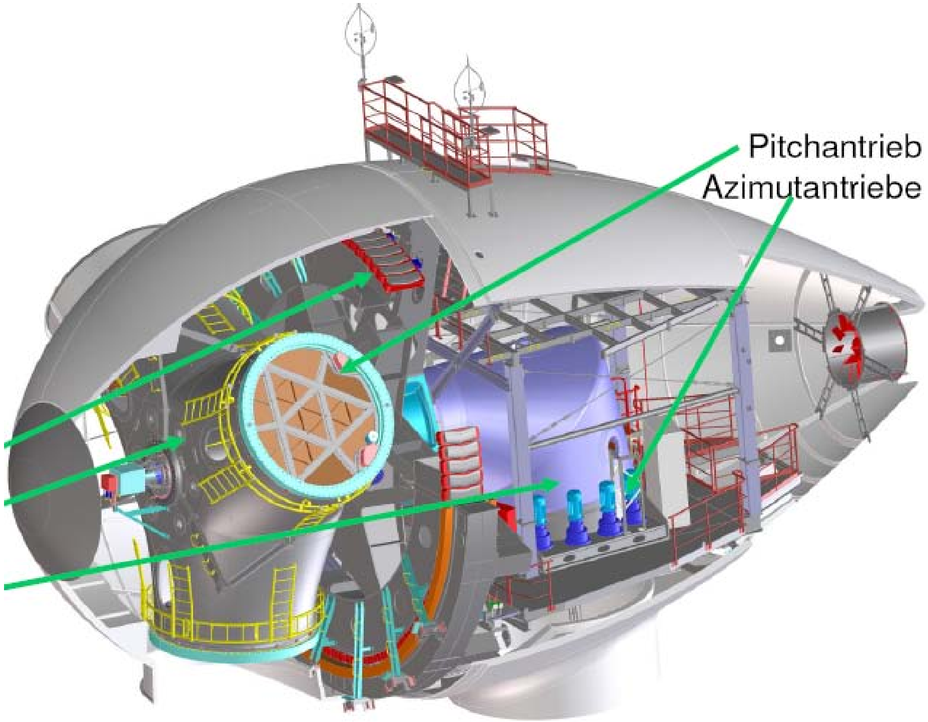


- Blade = 16.5 t
- Hub = 62.0 t
- Nacelle = 233.0 t
- Total = 349.0 t

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

Direct: Enercon E-126, 6 MW

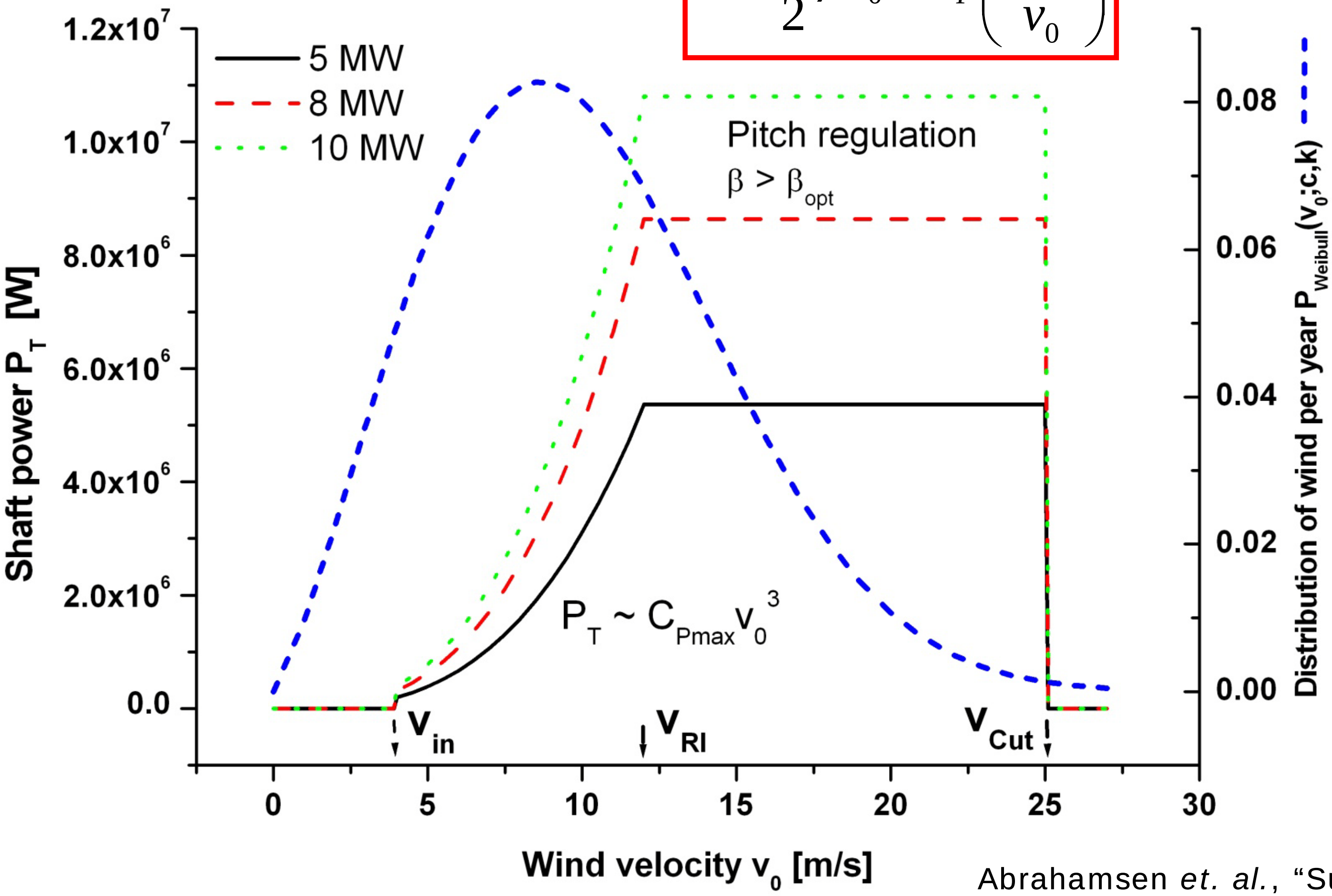




Rotor:	100 tons	Tower:	850 tons
Gen.:	212 tons		
Support :	188 tons		
Total:	500 tons		

Upscaling Multibrid M5000 to 10 MW

$$P = \frac{1}{2}\rho v_0^3 A C_P\left(\frac{R\omega}{v_0}\right)$$



Assume:

$C_{p,max}$ ~ 0.48
v_{tip} < 90 ms^{-1}

R = 58m – 82m
ω = 15-10 rpm

P = 10.8 MW
8 % loss

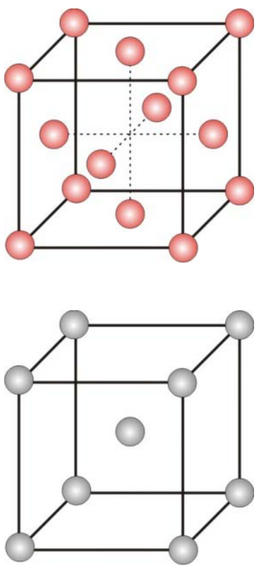
T =3.5-10 MNm

49 GWh / y

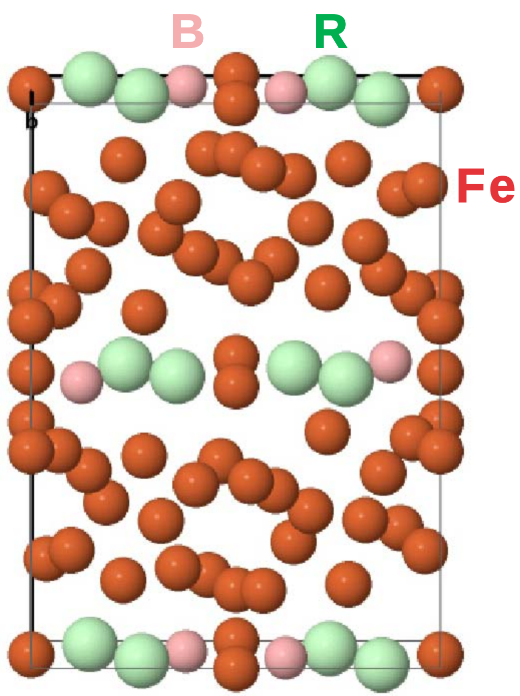
Abrahamsen *et. al.*, “Superconducting wind turbines”, SUST23, 034019 (2010).

Active materials in generators

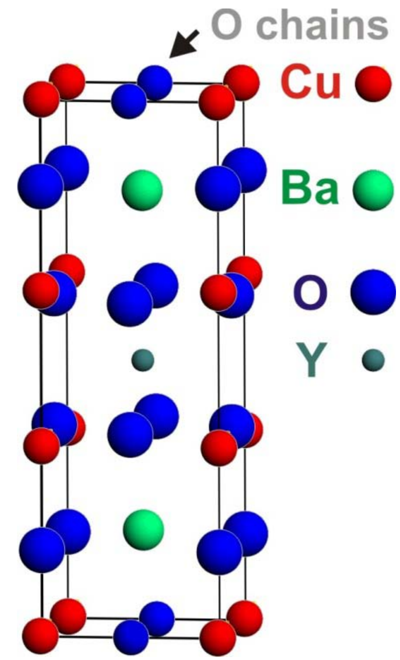
Cu & Fe (1G)



Permanent magnet(2G)



HTc superconductor(3G)



T_C ~ 1043 K

B_{sat} ~ 1.6 Tesla

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

T_C ~ 585 K (Nd)

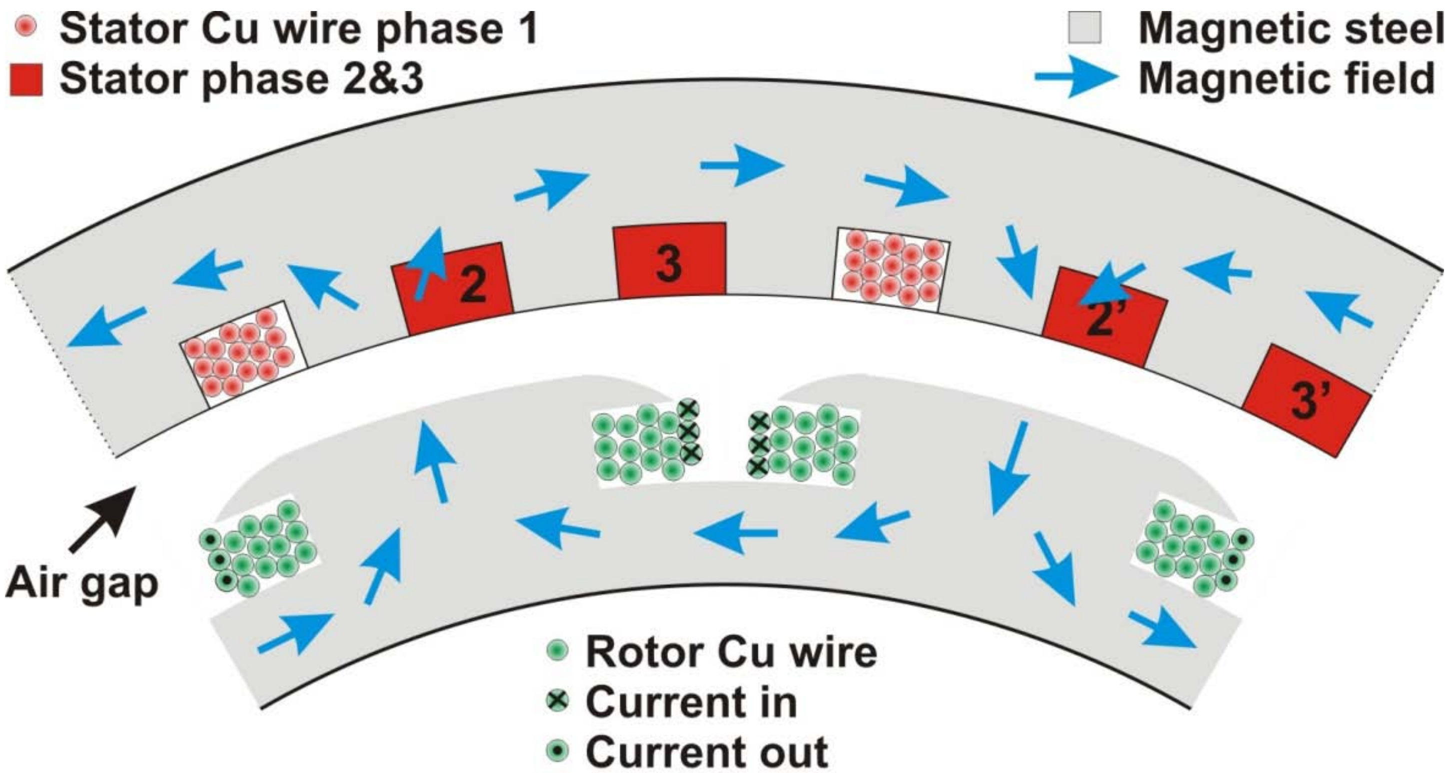
B_r ~ 1.2-1.4 Tesla

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

T_C ~ 93 K

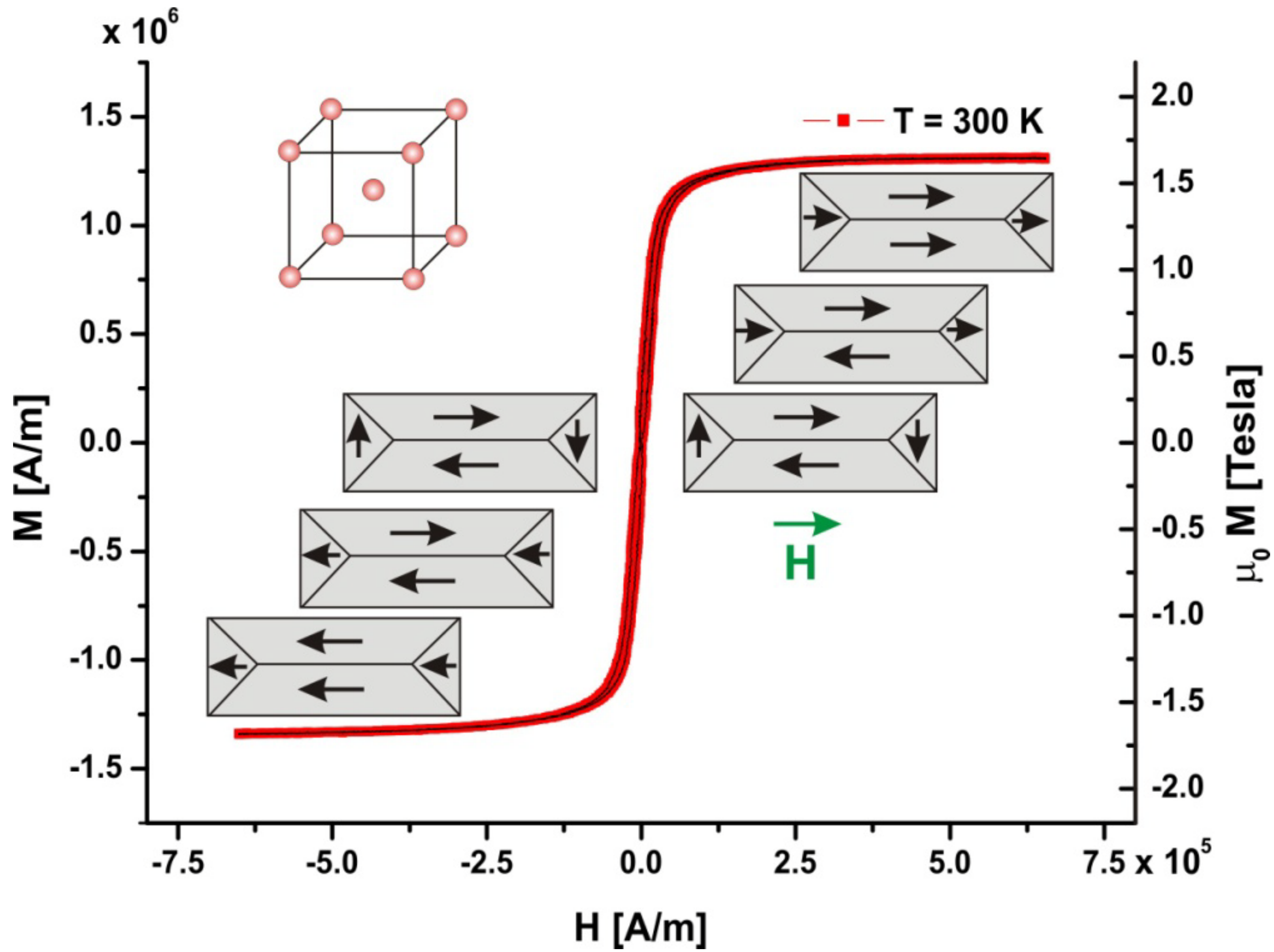
B_{C2} ~ 100 Tesla

Cu + Iron

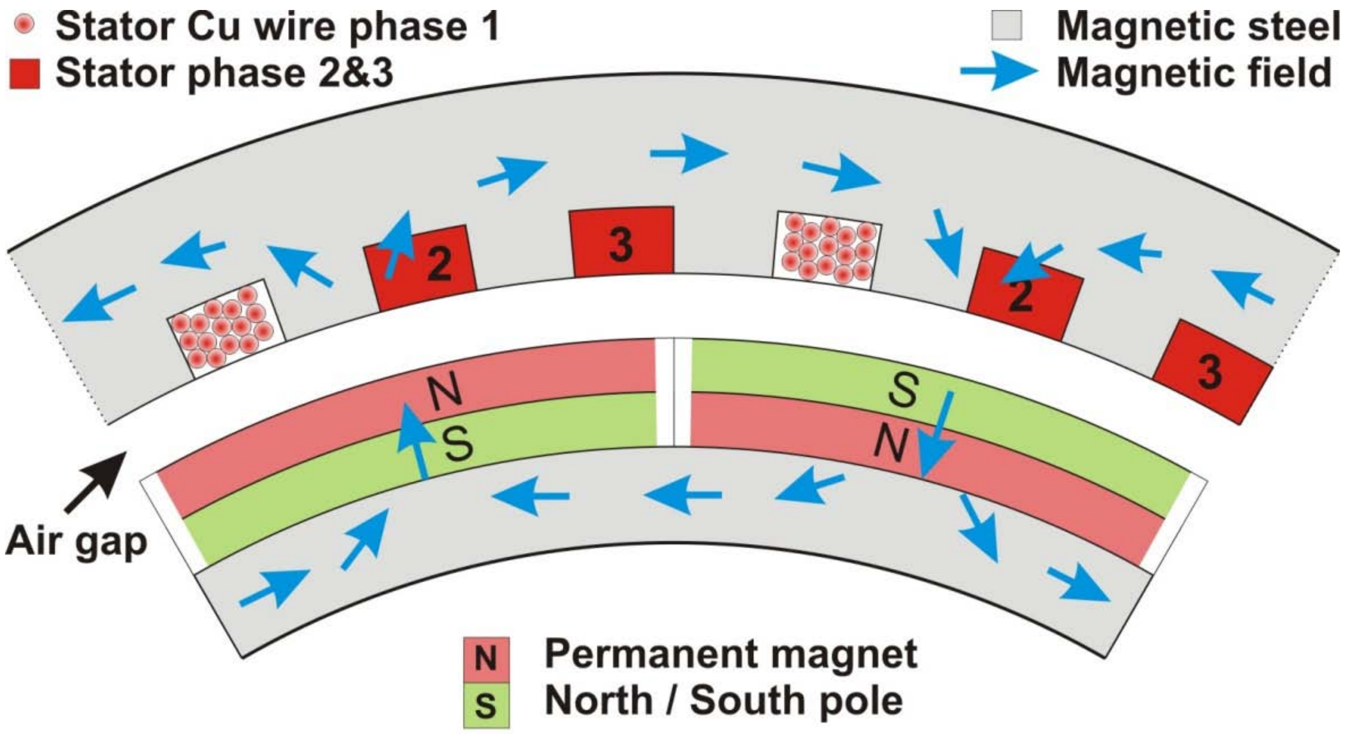


- Flux ~ NI/Rel
- Dissipation ~ R I^2
- Saturation of iron sets limit on air gap flux density !
- Thus at B ~ 1 Tesla then the machine can only become bigger !
- Enercon E-112: P = 6 MW, D = 12 m, $m_{generator}$ = 212 tons

Ferromagnetic domains aligned in Fe



$Nd_2Fe_{14}B$ + Iron + Cu



- 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

$R_2Fe_{14}B$ permanent magnets (R = Rare earth)

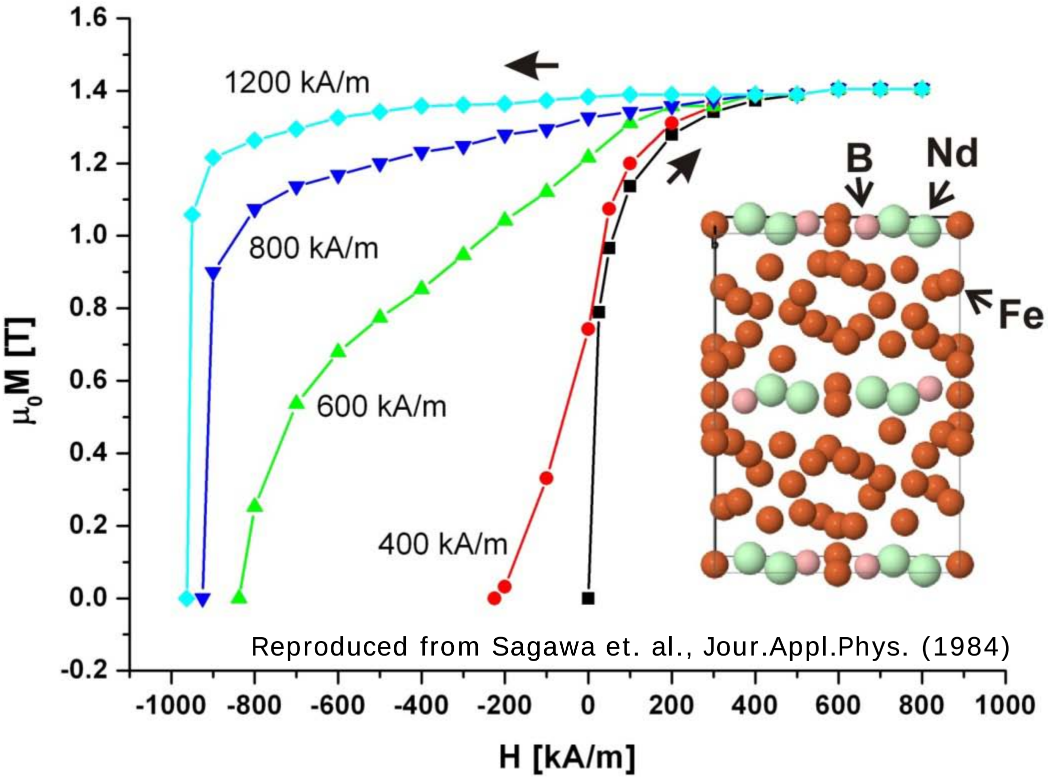
- Discovered 1982 by Sagawa et. al.

- Rare earth locks magnetization direction to the crystal lattice.

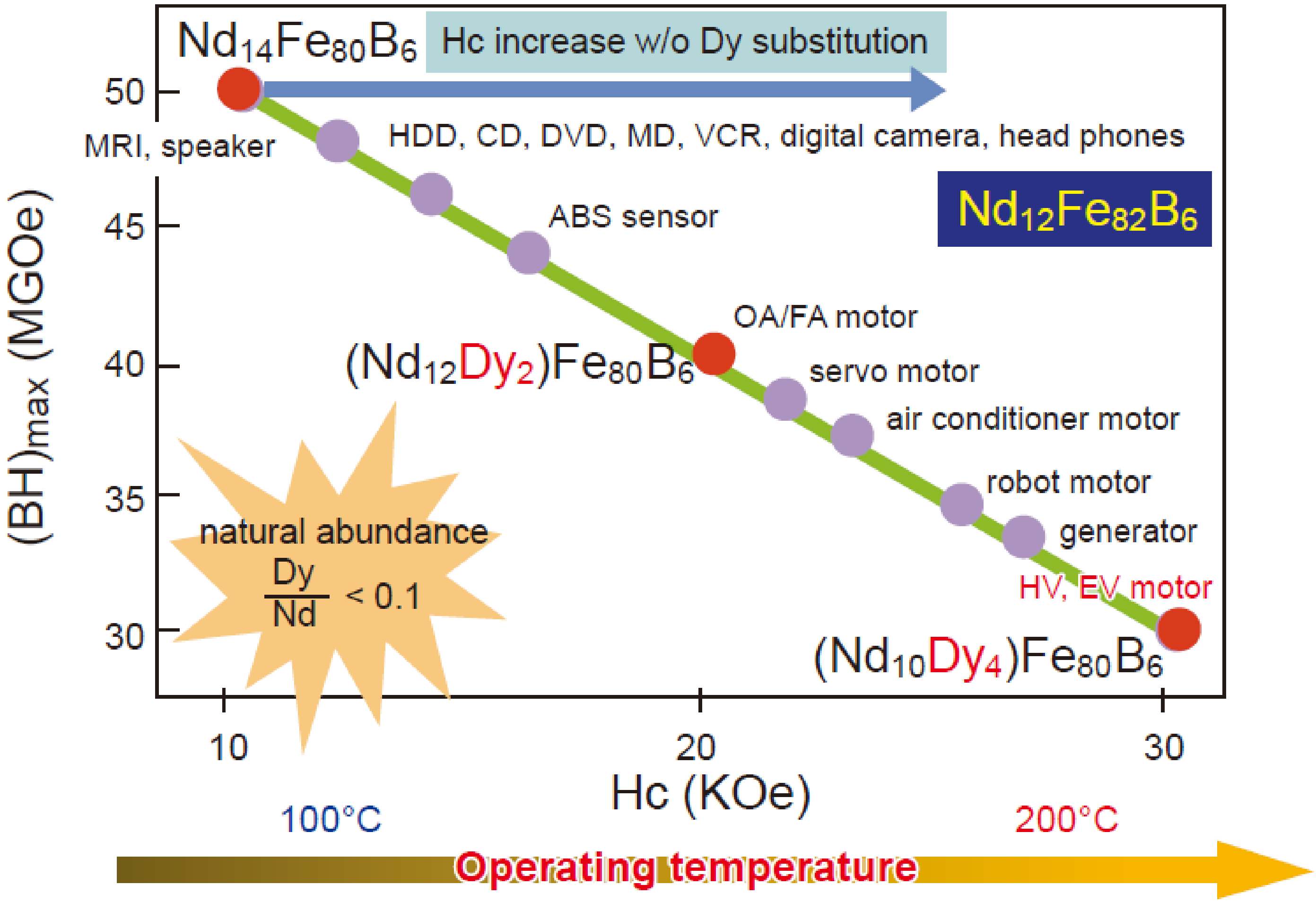
- Alignment of $R_2Fe_{14}B$ powder
- Press under magnetic field
- Sintering into blocks
- Surface treatment
- Magnetization by pulsed field

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

- Curie temperature T_C

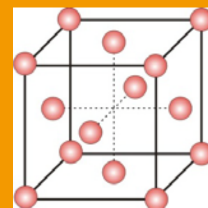
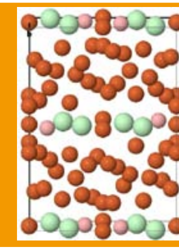
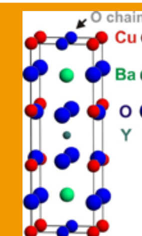
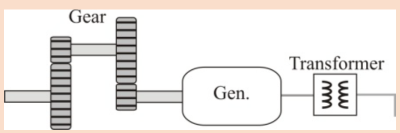
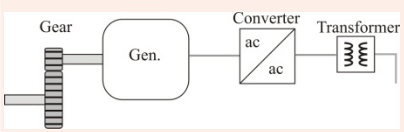
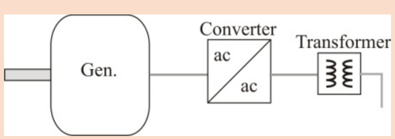


Scaling of Curie temperature by adding Dy



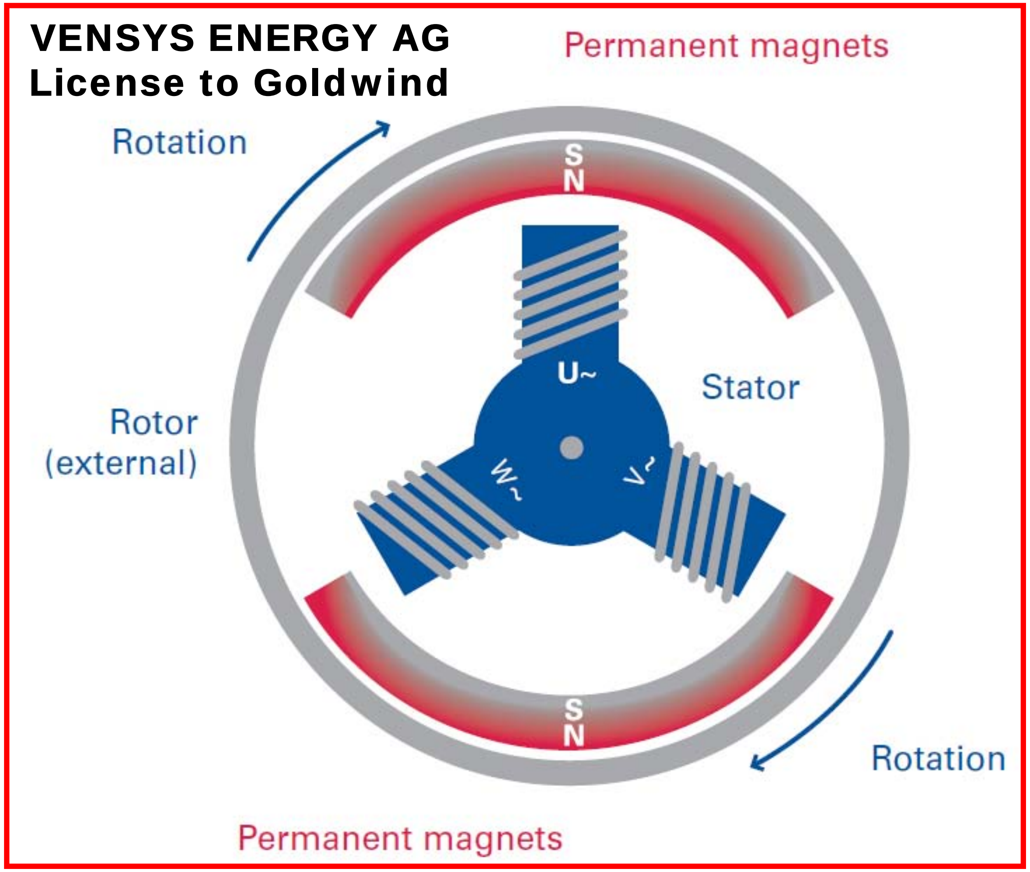
Source: K. Hono, NIMS now international, vol.8, no. 10, p.4 (2010). Oono et. al., Journal of magnetism and magnetic materials 323, 297 (2010).

Drive train comparisons – Rare earth usage

	Cu & Fe 	PM 	HTC 
Geared 	0		
Hybrid 	0		
Direct 	0		

Direct drive capacity

- 15 % of the world market in 2010*
  - Goldwind 3.5 GW PMDD
  - XEMC 0.5 GW PMDD
  - Enercon 3.0 GW Wound



*Source: World Market update 2010- BTM consult APS – A part of Navigant consulting

Magnet material usage

	Switch[1] PMRF	Lloyd[2] PMTF	Jensen[3]
Geared	80 kg R/ 3 MW		20 kg R / 1 MW
Hybrid	130 kg R/ 3 MW		
Direct	800 kg R/ 3 MW	1500 kg PM / 3 MW	200 kg R / 1 MW

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

[1] Dr. Kurronen, “PMG topology features and future trends”, IQPC 12 May 14:00
[2] Dr. Götschmann, “Transverse flux technology on the way to becoming a reliable light weight direct drive generator”, IQPC 12 May 12:00
[3] Jensen, Abrahamsen & Henriksen, “Influence of Rare Earth Element Supply on Future Offshore Wind Turbine Generators”, Risø International Energy conference 2011

Program

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Energy & wind power development
Drive trains
Generator concepts
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Permanent magnets for wind turbines
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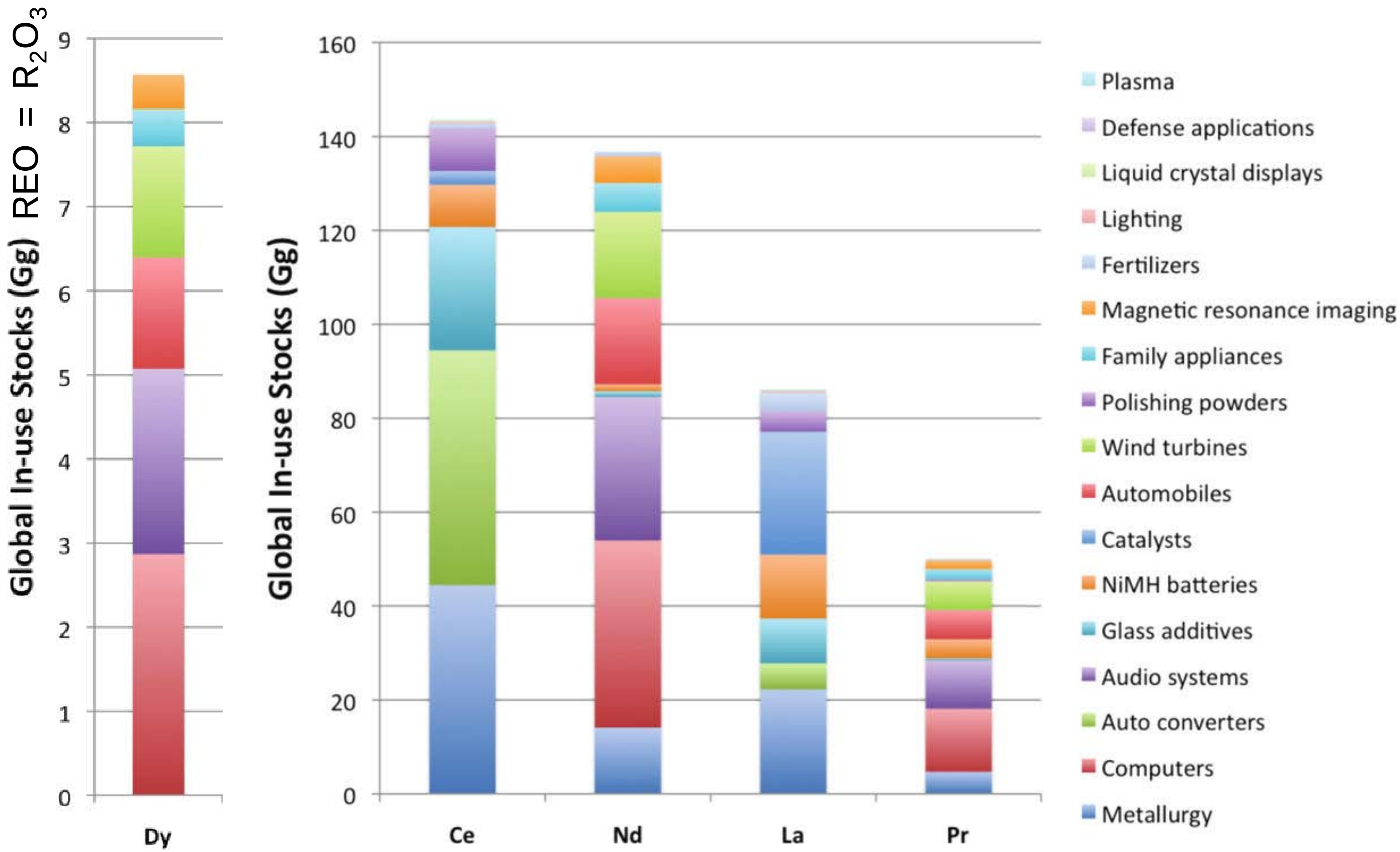
In-use stock of Rare Earth material (2007)



Source: X. Du et. al., "Global In-Use Stocks of the Rare Earth Elements: A First Estimate", Environmental Science & Technology 2011

Flows into use

Table 1. Flows into Use and in-Use Stocks Calculated for the Rare Earth Elements in 2007

element	flows into use (Gg/yr)	in-use stock (Gg)
La	21.9	86
Ce	27.9	144
Pr	4.1	50
Nd	14.8	137
Sm	2.1	3.3
Eu	0.3	0.4
Gd	2.2	3.6
Tb	0.3	0.7
Dy	1.7	8.6
Ho	0.3	2.1
Er	0.9	3.9
Tm	0.2	0.2
Yb	0.7	0.7
Lu	0.1	0.6
Y	12.3	6.9

$m_R = 0.86 \cdot m_{R2O3}$

1 Gg $= 10^9$ g
$= 10^6$ kg
$= 1000$ tons

Source: X. Du et. al., “Global In-Use Stocks of the Rare Earth Elements: A First Estimate”, Environmental Science & Technology 2011

Wind power induced increase of Nd demand

USAGE OF THE RARE EARTH ELEMENTS NEODYMIUM AND YTTRIUM, FOR THE DIFFERENT DRIVE TRAINS. COLUMNS THREE TO FIVE SHOW THE ESTIMATED NEED TO FULFIL THE EU OFFSHORE, THE TOTAL EU AND THE GLOBAL WIND POWER CAPACITY IN THE PERIOD 2015-2030.

TYPE	Nd/Y metal usage [kg/MW]	EU offshore 110GW [ton of metal]	EU total 170GW [ton of metal]	Global 1280GW [ton of metal]
DDPM	200	22,000	34,000	260,000
2GPM	20	2,200	3,400	26,000
DDHTS				
DDIG	0	0	0	0

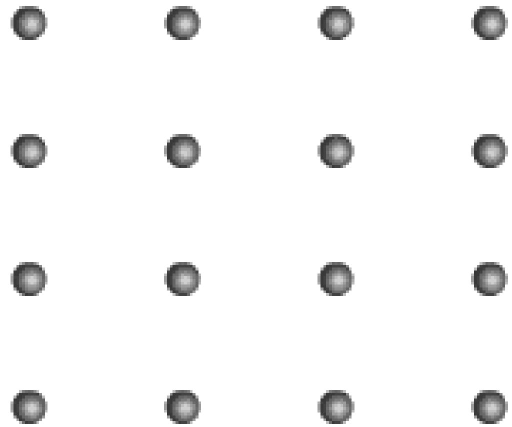
DDPM: Direct Drive Permanent Magnet Generator; 2GPM: Two Stage Gearbox Permanent Magnet Generator; DDHTS: Direct Drive High Temperature Superconducting Generator; DDIG: Direct Drive Induction Generator. Note: The weight fraction of Nd in $Nd_2Fe_{14}B$ and of Y in $YBa_2Cu_3O_{6+x}$ is 0.27 and 0.13 respectively.

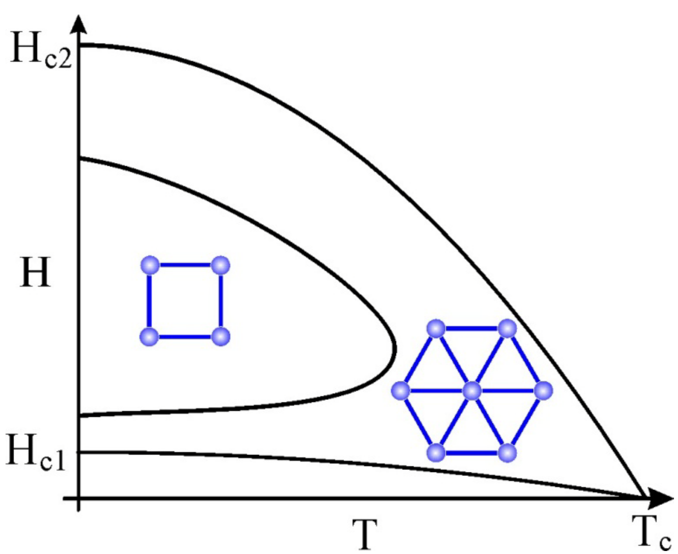
Source: Jensen, Abrahamsen & Henriksen, “Influence of Rare Earth Element Supply on Future Offshore Wind Turbine Generators”, Risø International Energy conference 2011

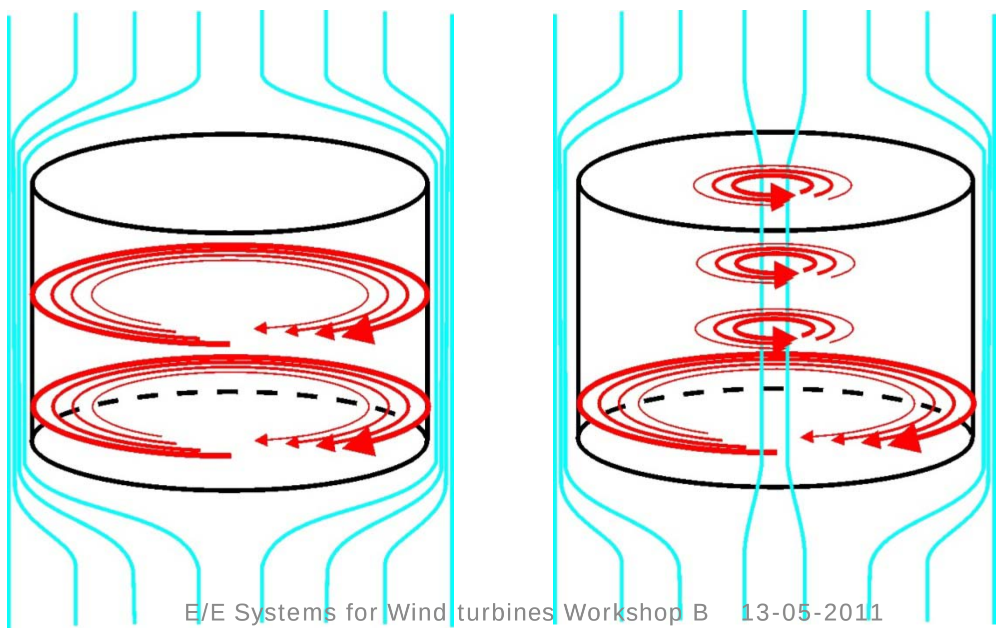
Superconductors and high magnetic field

- Electrons pair due to lattice distortion
- Quantum fluid of Cooper pairs ($+k\uparrow$, $-k\downarrow$)
- $R = 0$!

- Magnetic field causes rotational flow
- $B = 0$ Meissner state $H < H_{c1}$
- Vortex state $H_{c1} < H < H_{c2}$
- Quantization of flux $\Phi_0 = h/2e$

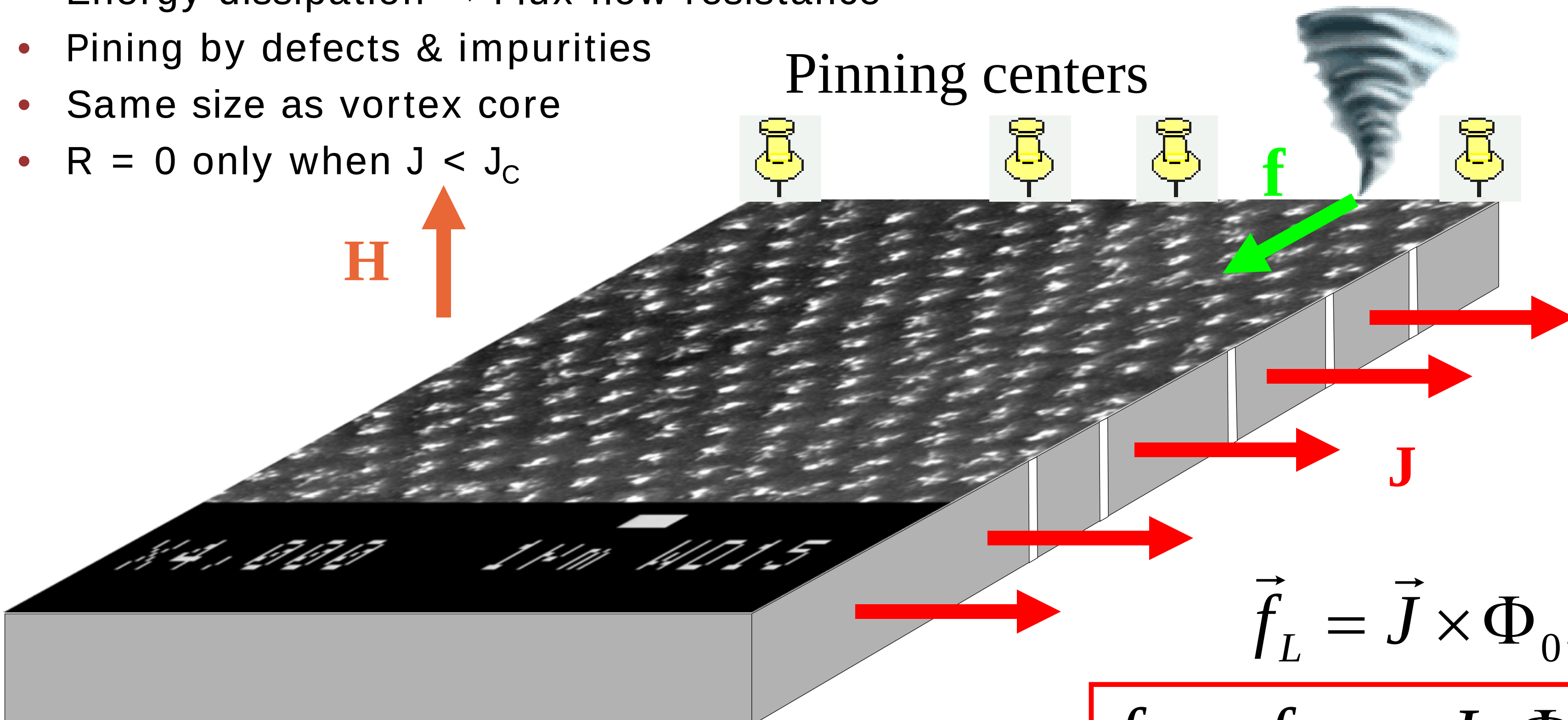






Vortex movement and pinning

- Lorentz like force is acting on vortex lines when a supercurrent is flowing
- Energy dissipation → Flux flow resistance
- Pining by defects & impurities
- Same size as vortex core
- R = 0 only when $J < J_C$

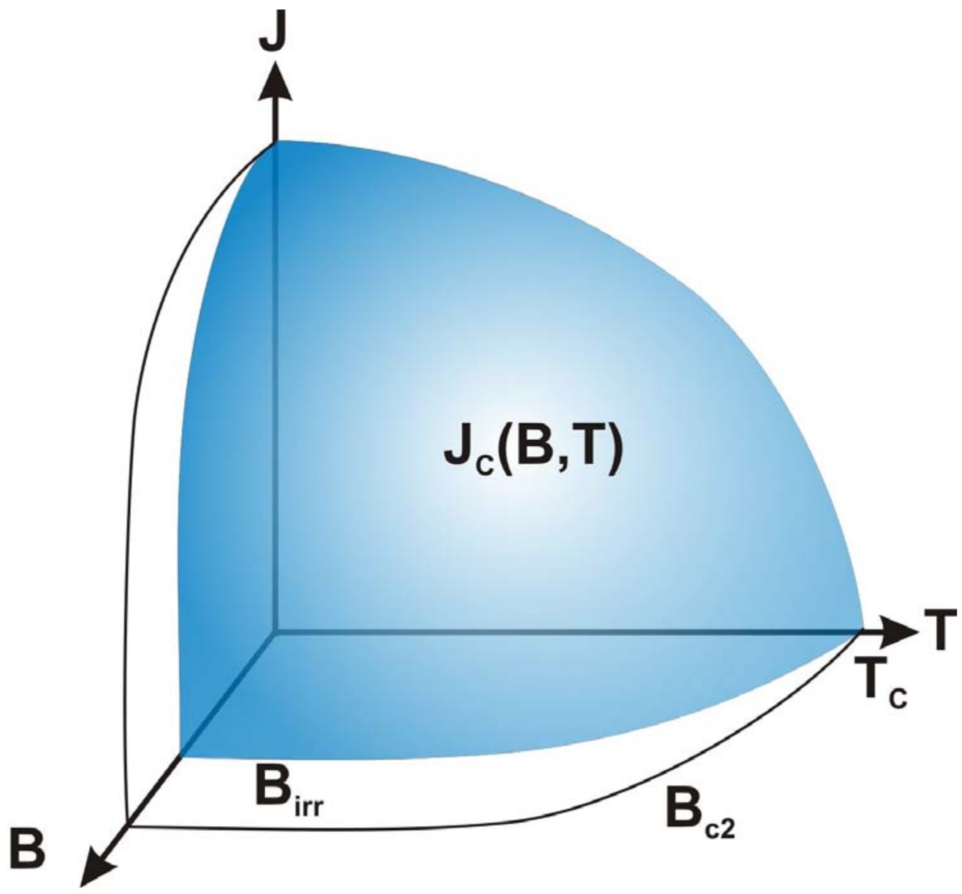


$$\vec{f}_L = \vec{J} \times \Phi_0 \vec{z}$$

$$f_L < f_{pin} = J_C \Phi_0$$

H = 0.002 Tesla

Critical surface of practical superconductors



- Temperature
- Magnetic field (angular)

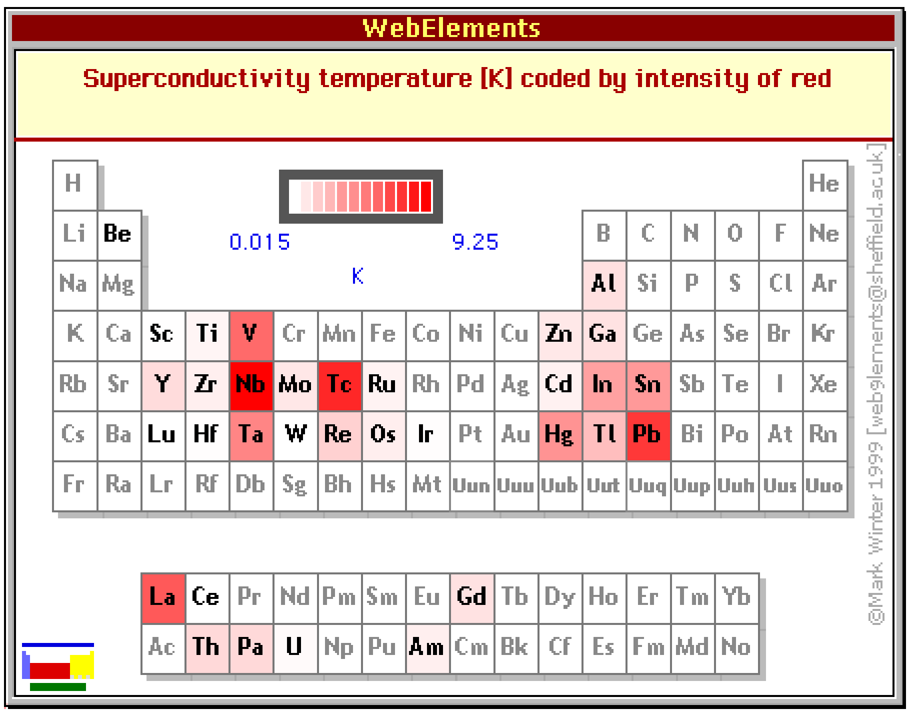
Engineering current density

$$J_e = \frac{I_C}{A_{conductor}} \quad \left[\frac{A}{mm^2}\right]$$

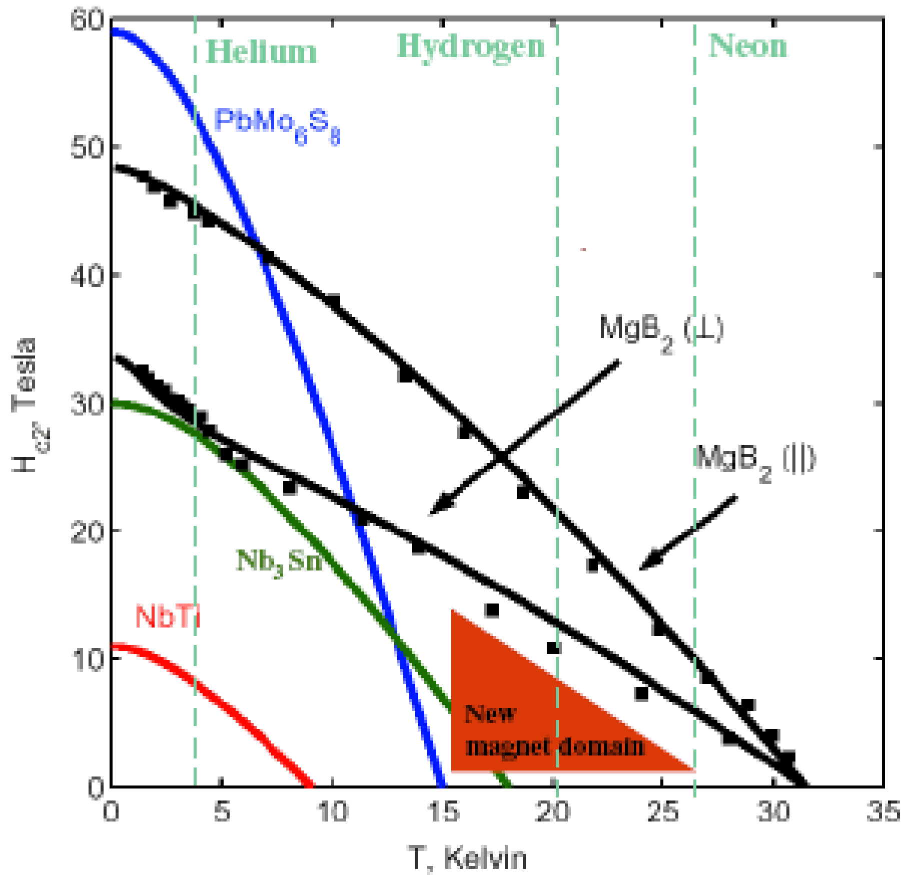
$J_{e,Cu}$ ~ 2-7 A/mm^2

Superconducting materials

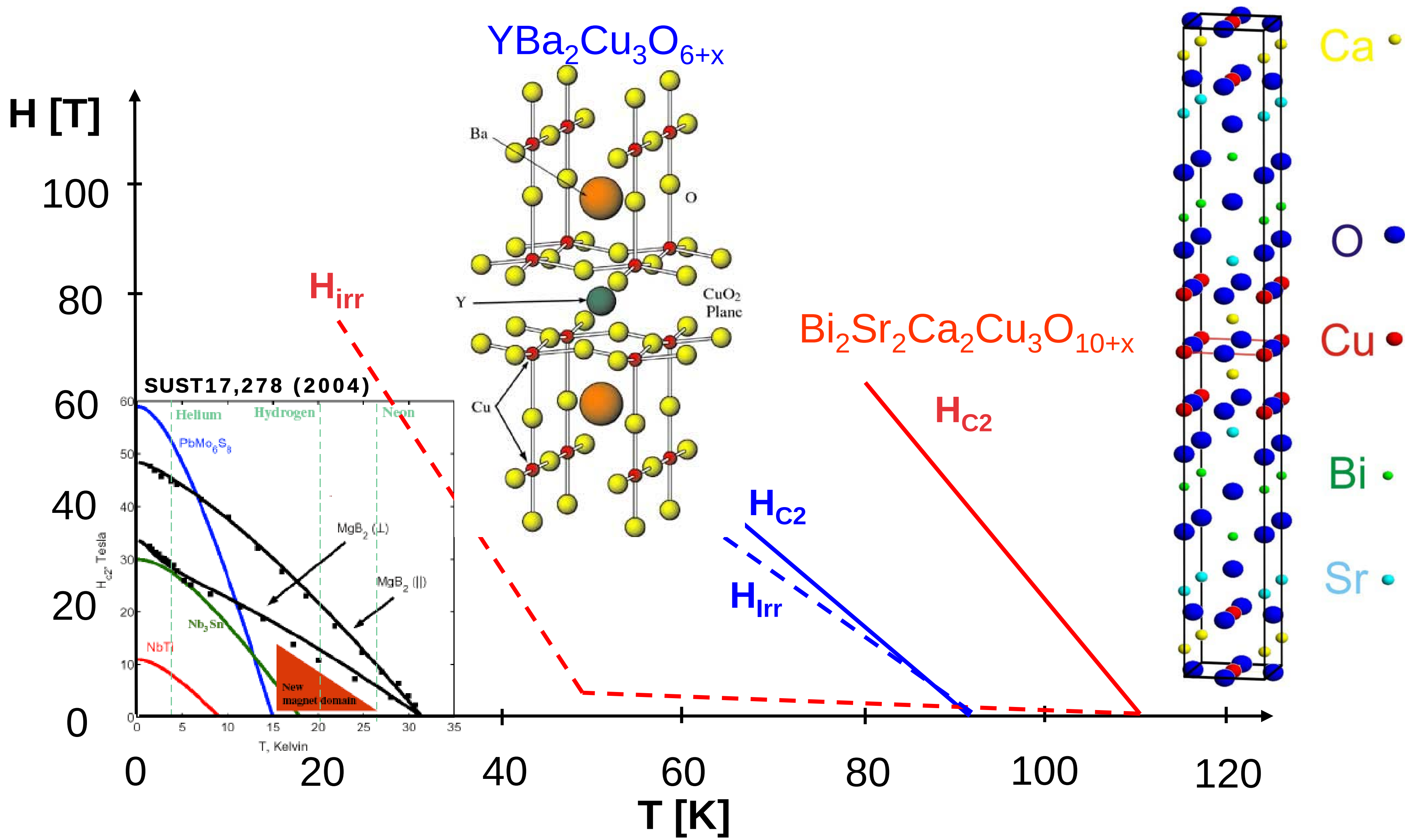
- Most simple metals
- Metallic alloys
- Semiconducting ceramics !



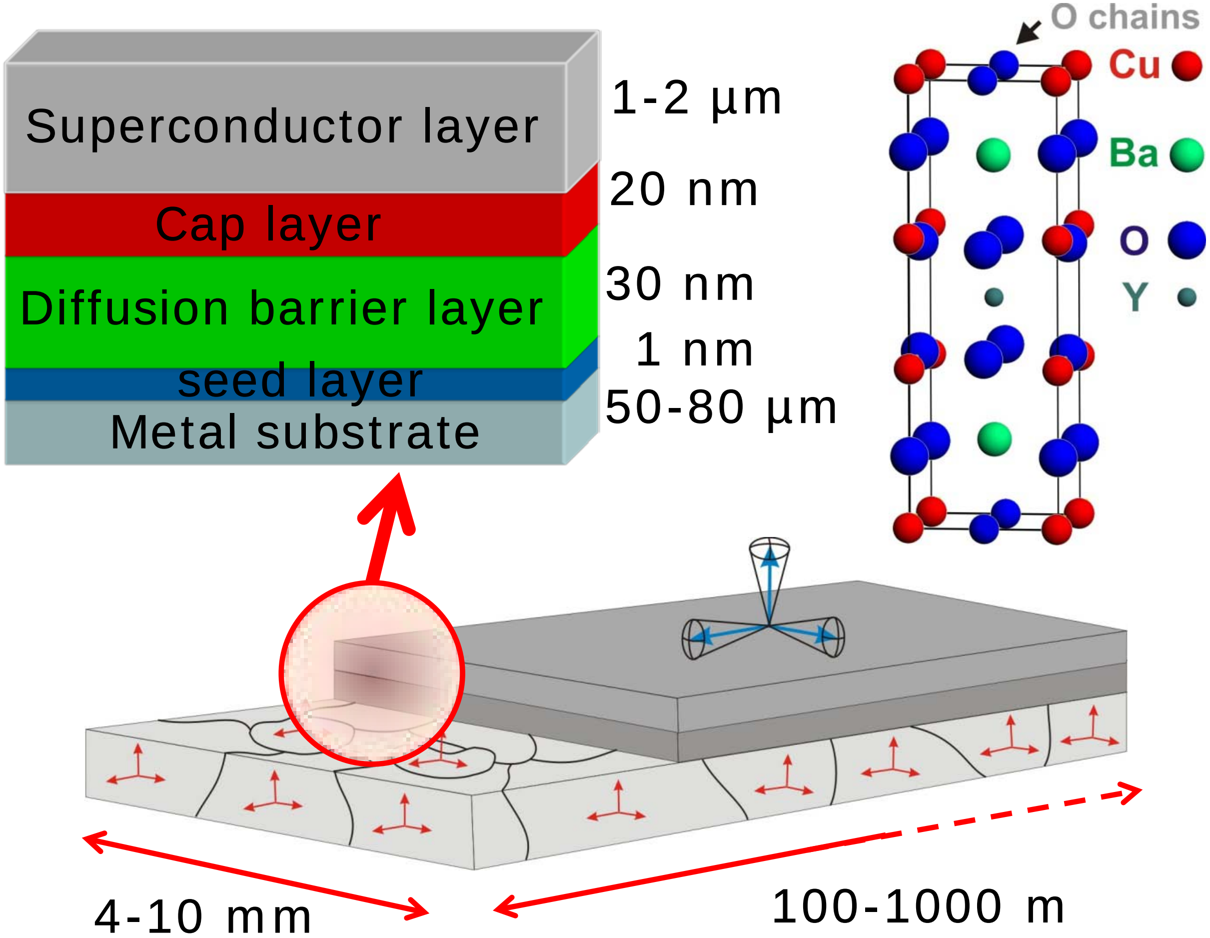
Gurevich *at. al.*, SuST17,278 (2004)



Critical fields of practical superconductors



Coated conductors



Superconductor in 1 km tape:

V_{RBCO} = 4 cm^3 !!

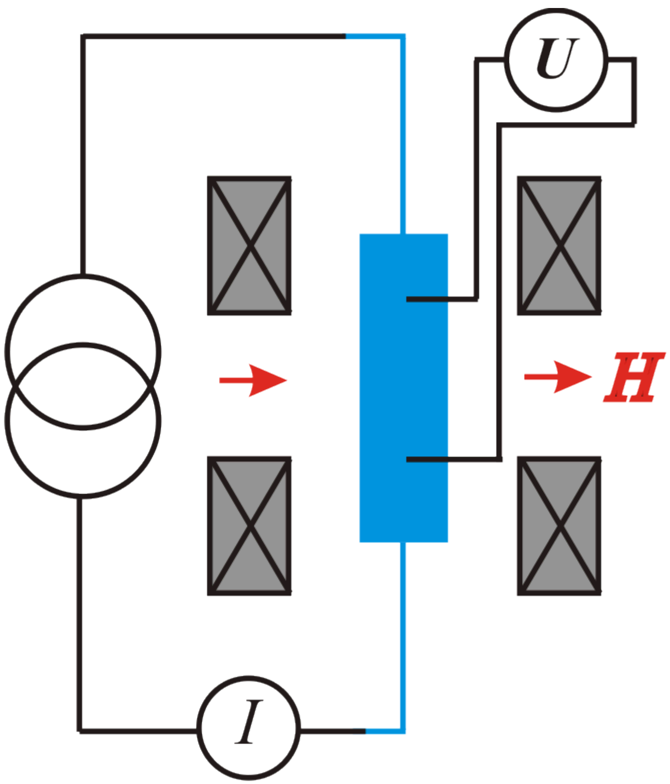
ρ_{RBCO} = 6.4-7.2 g/cm^3

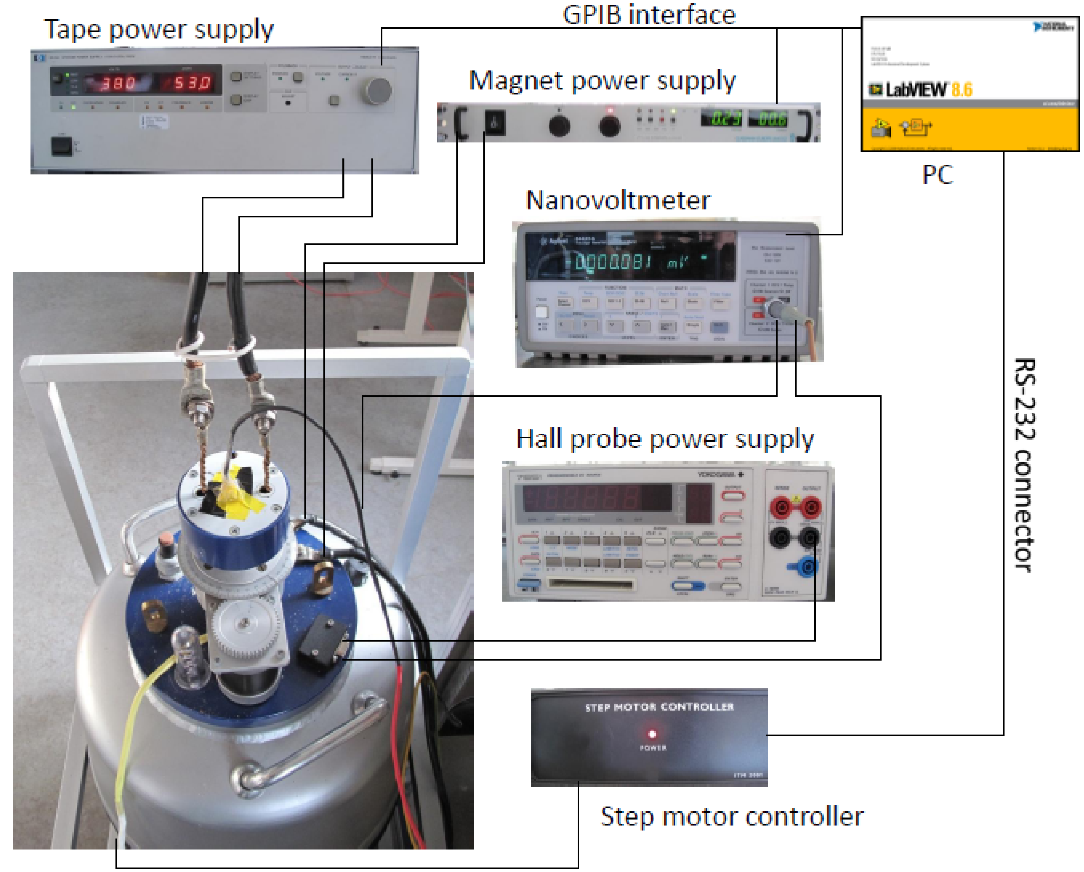
m_{RBCO} = 29 g

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

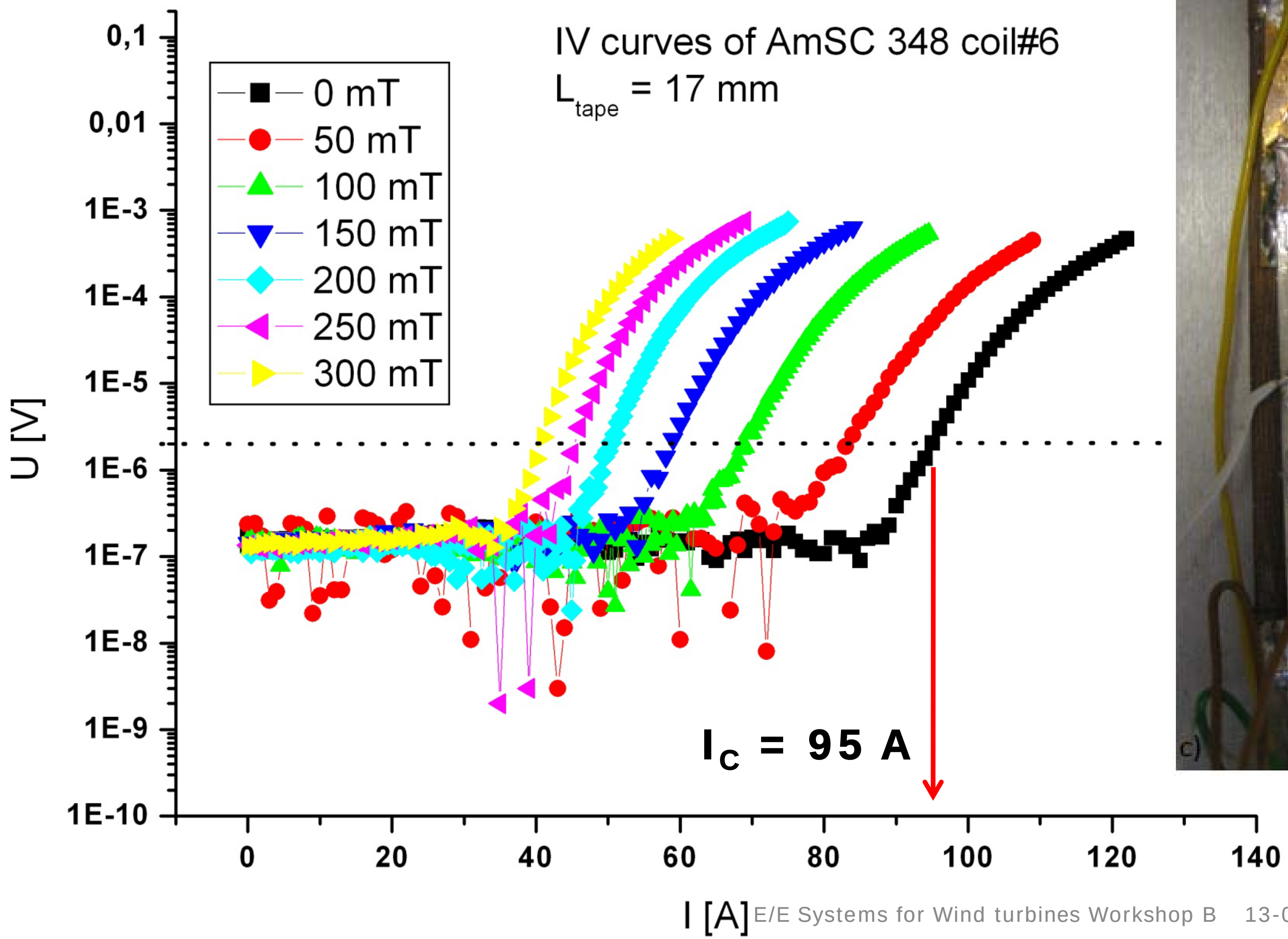
Characterization of wires: I-V curves

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

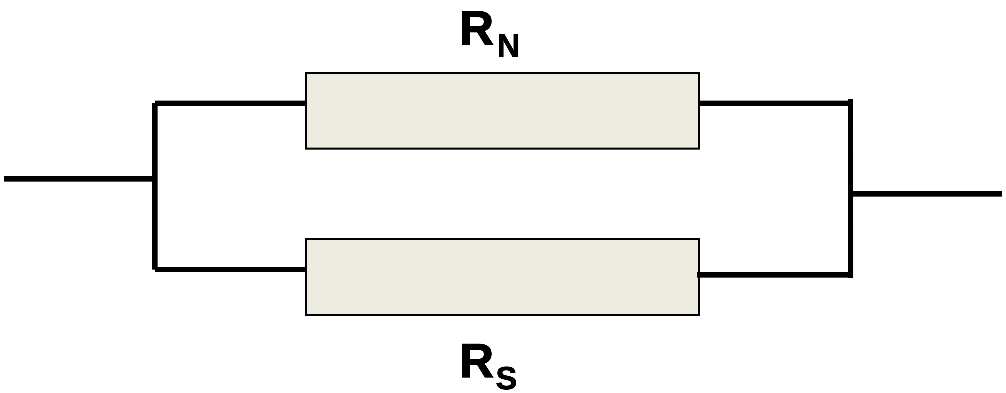




Coated conductor AmSC CC348 tape



DC loss in wire



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

I_C industrial definition:

U_S/L = 1 μV/cm

Loss per length:

P/L = $U_S \cdot I_C / L$
= 1 μV/cm·95 A
= 95 μW/cm

Normal loss per length:

P/L = R/L · I_C^2
= 10^{-4} Ω/cm·(95 A)^2
= 0.9 W/cm

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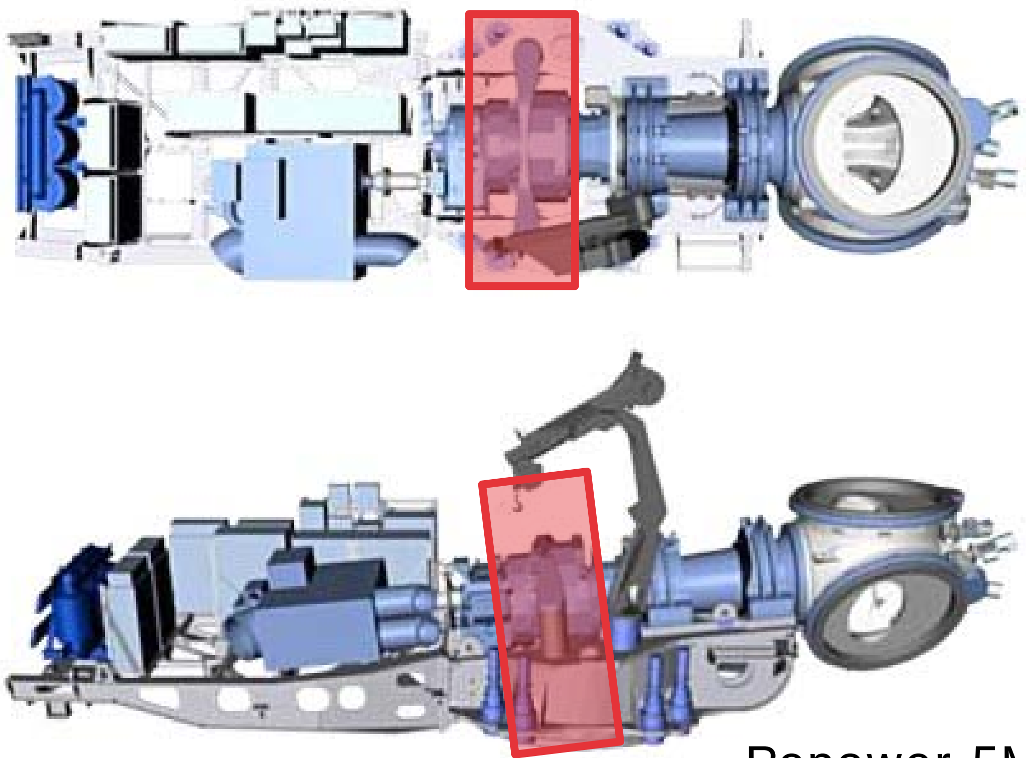
	Tapes and Race track coils
	Topology and cooling
	Feasibility discussion
	State of the art
	Conclusion

Superconducting direct drive?



Repower 5M

$m_{gear+gen.}$ = 17 tons + 63 tons = 80 tons

SC Drive train:

m_{active} < 40 tons

D ~ 4.2 m
L_{active} ~ 1.5 m

Price: 2 M€/MW
10 M€

Turbine: 1/3
Drive train: 1/2
Max: 1.65 M€

Coated conductors?

8 €/m ~ 200 km *
16 €/m ~ 100 km
24 €/m ~ 66 km

Superwind.dk DTU

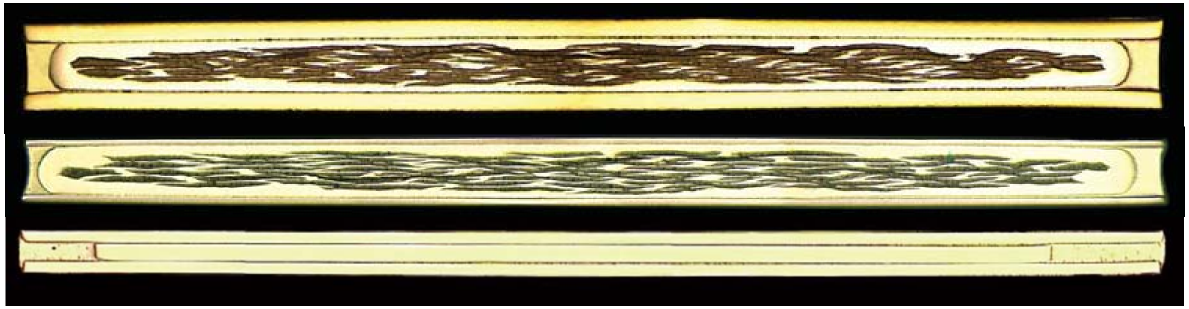
High temperature superconductor tapes

Coil#	Tape	I_c@77K A	Width mm	Thick-ness mm	Insula-tion mm	Je A/mm²
1	Bi2223/ Brass	149	4.3	0.39	0.1	68.8
2-5	Bi2223/ Steel	145	4.3	0.28	0.1	88.7
6	CC348	95	4.8	0.22	0.1	61.8
7&8	SP4050	125	4.2	0.1	0.06	186.0

Brass

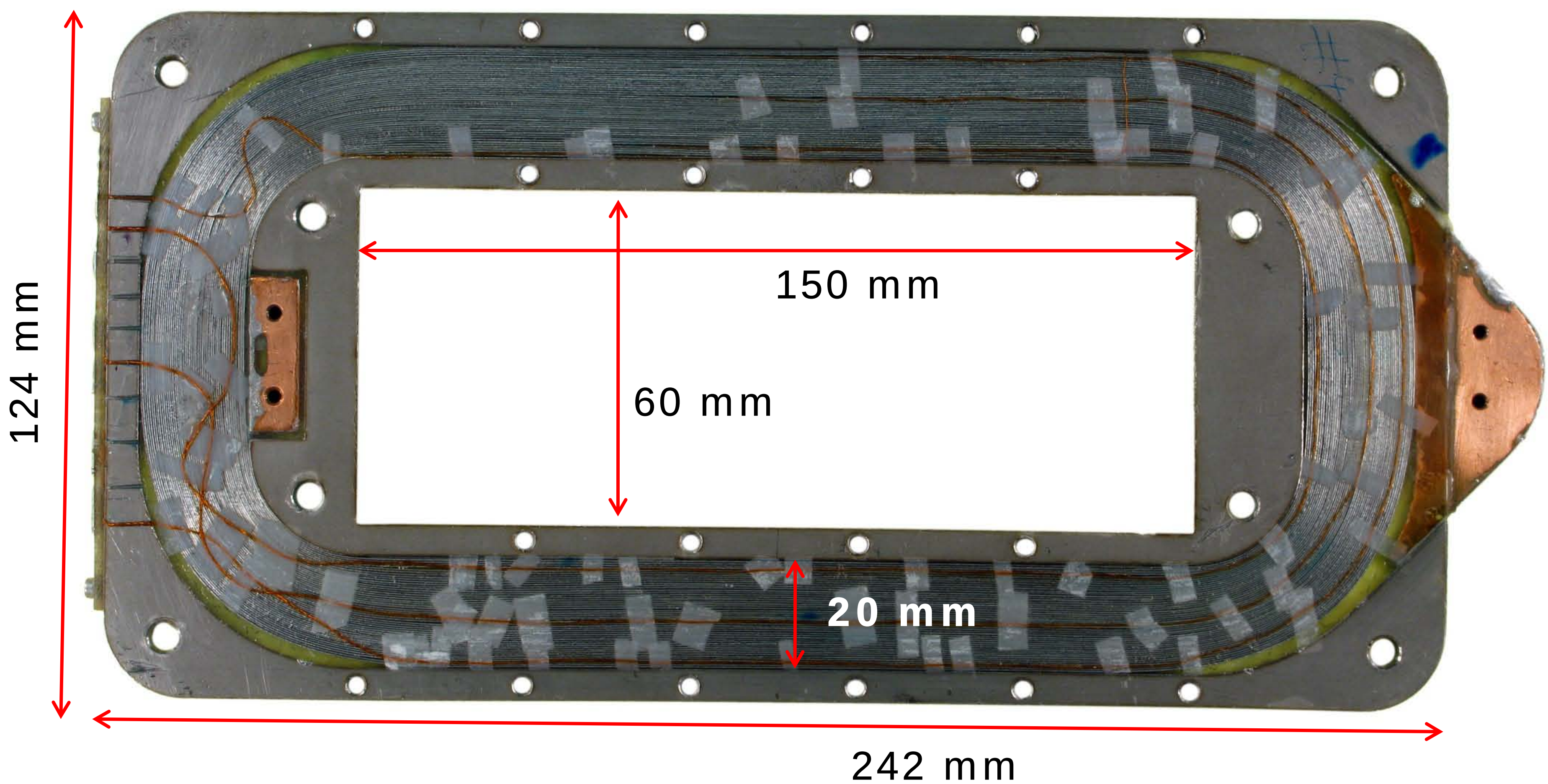
Steel

CC348



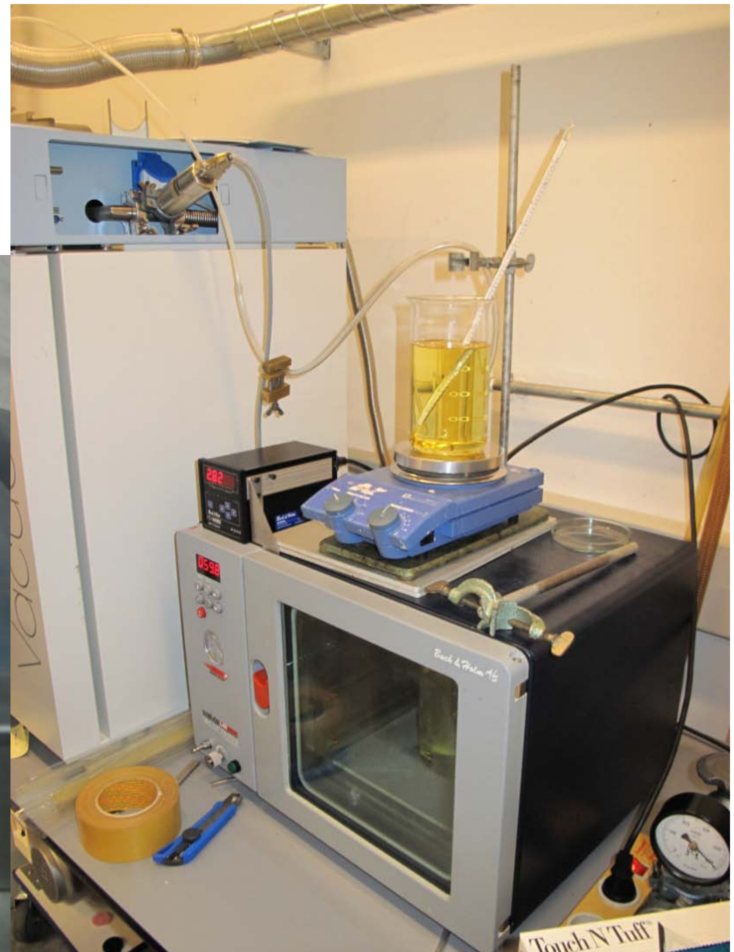
American Superconductor

Race track coils

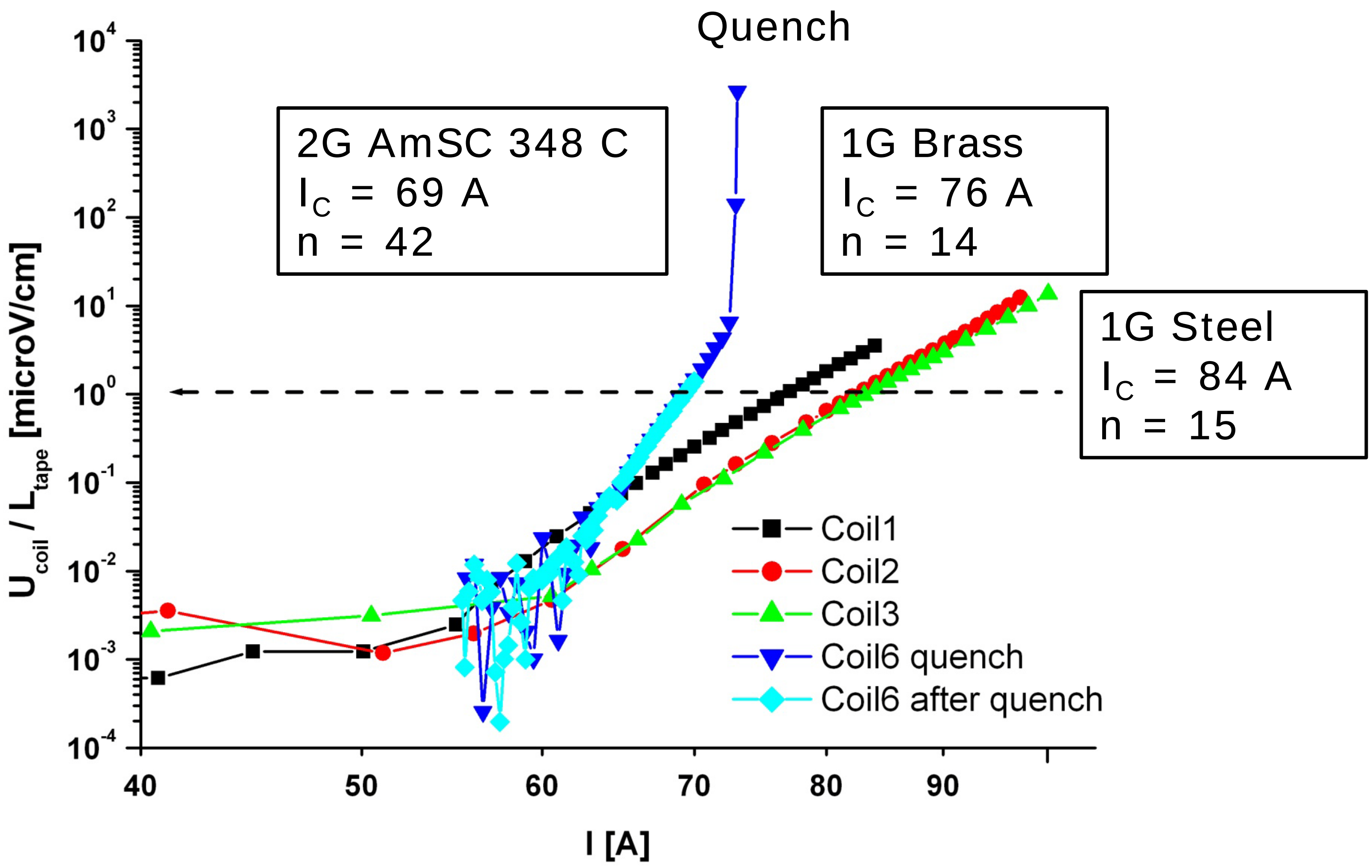


Winding

Vacuum impregnation with epoxy

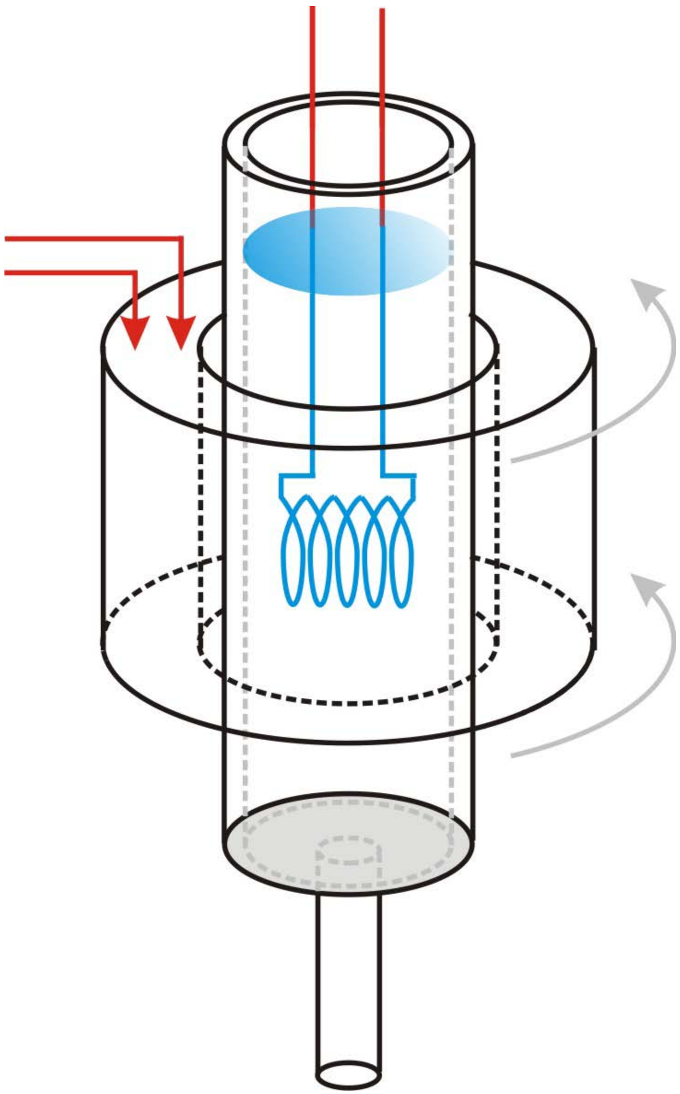


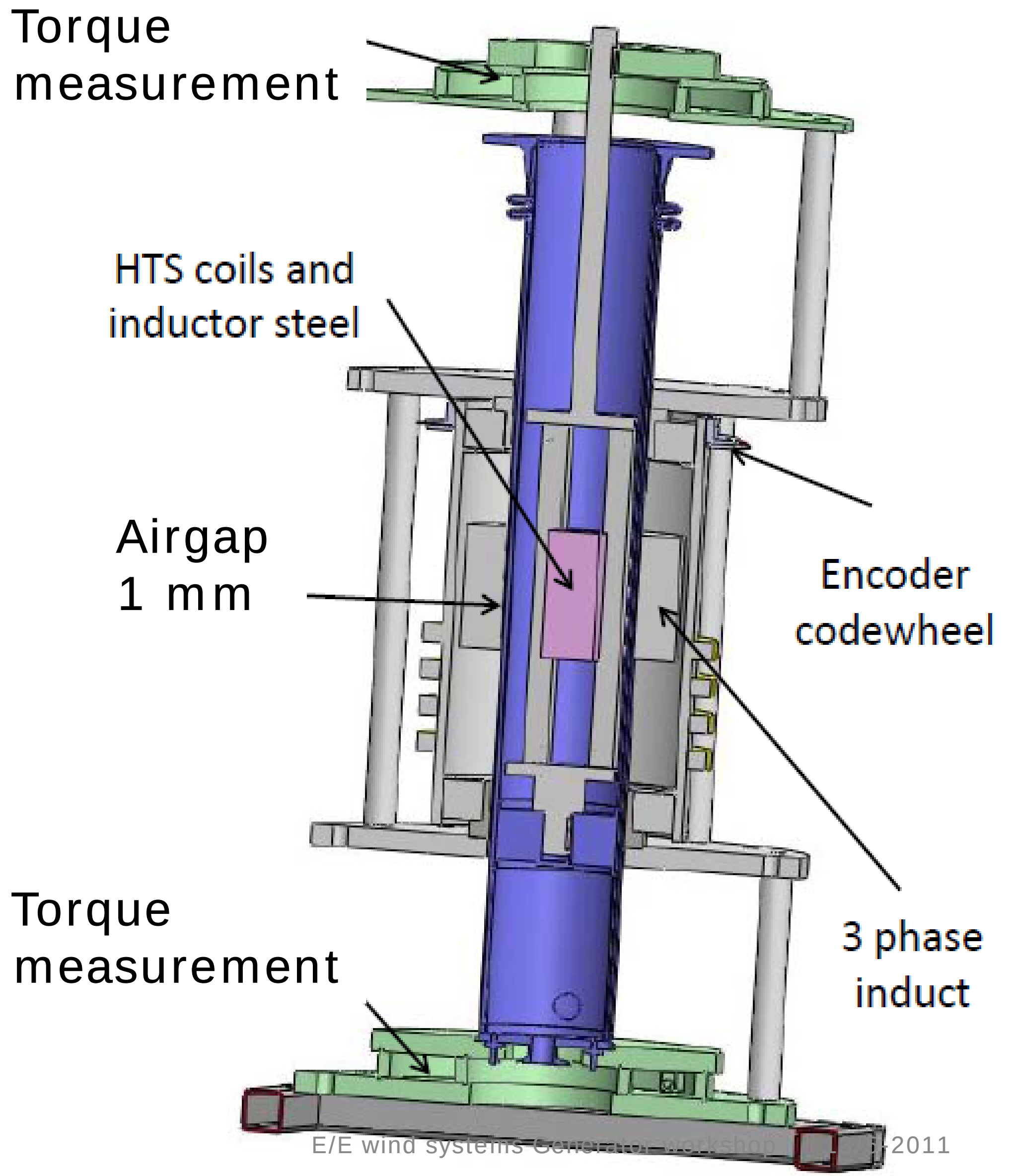
IV curves of coils @ 77 K in liquid nitrogen



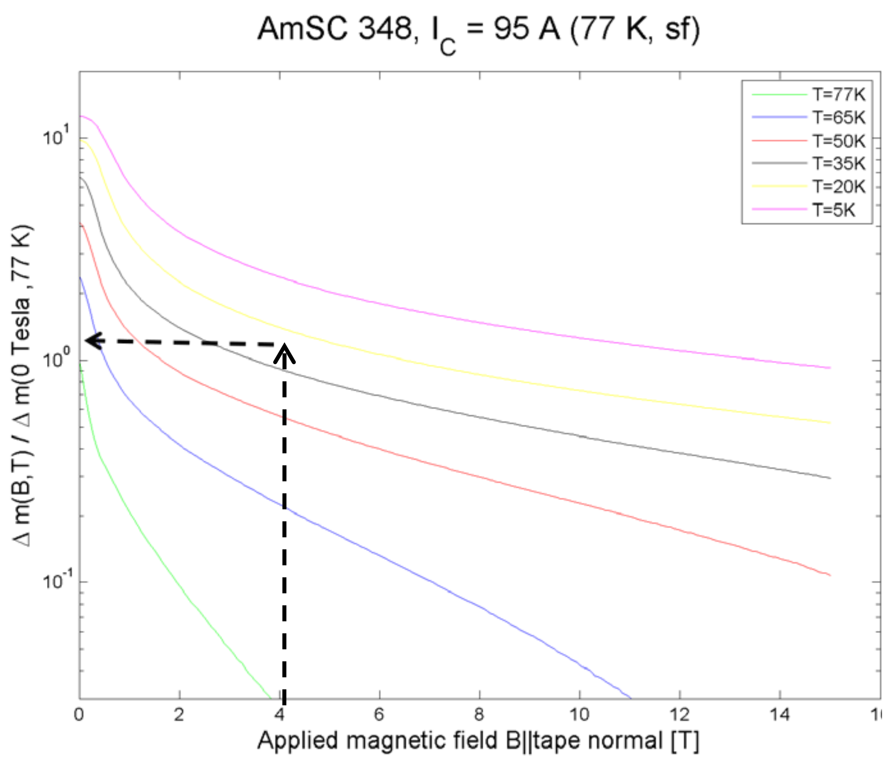
Abrahamsen *et. al.*,"Feasibility of 5 MW superconducting wind turbine generator", Acc. Physica C 2011

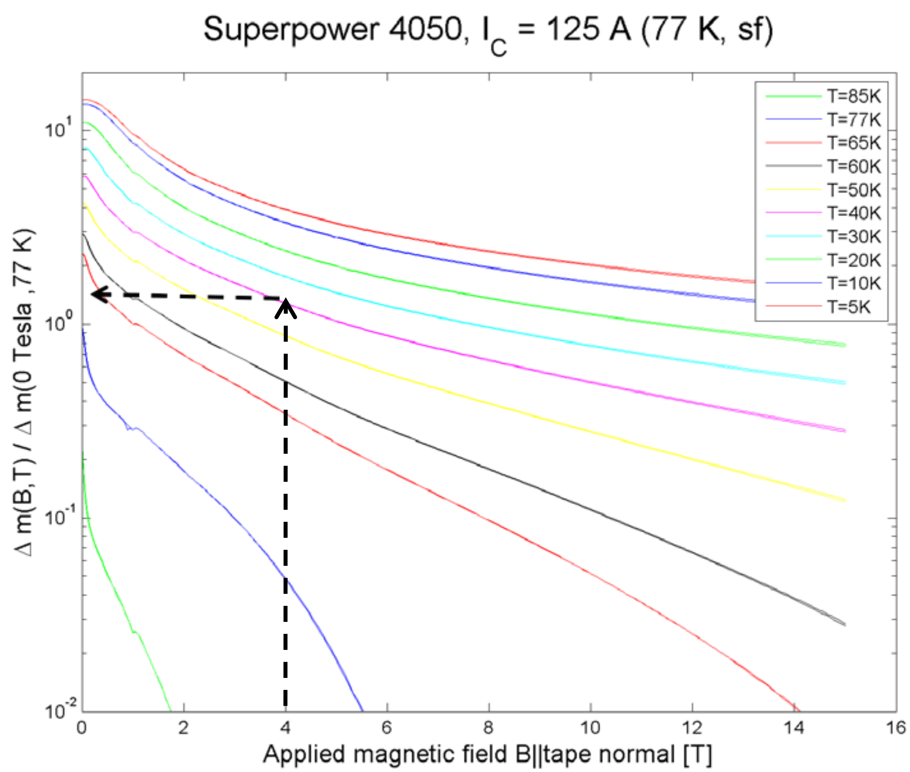
Test generator @ DTU





$J_e(B,T)$ scaling from magnetization curves

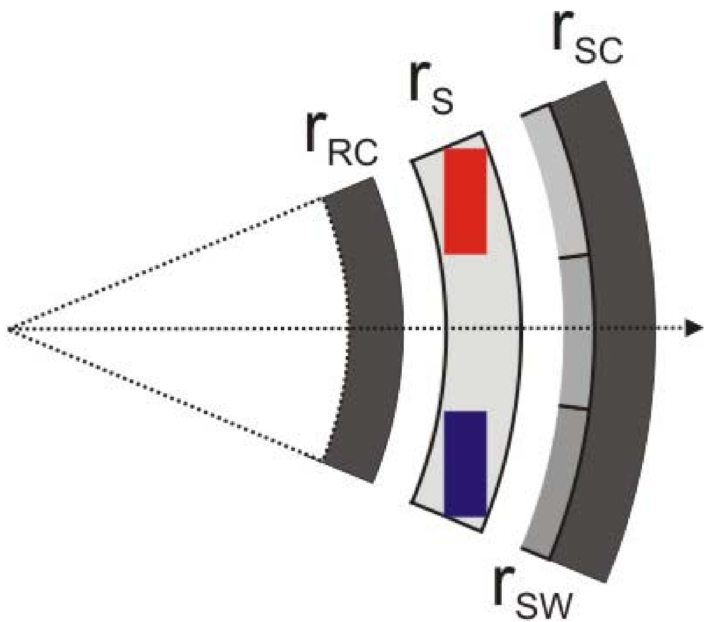


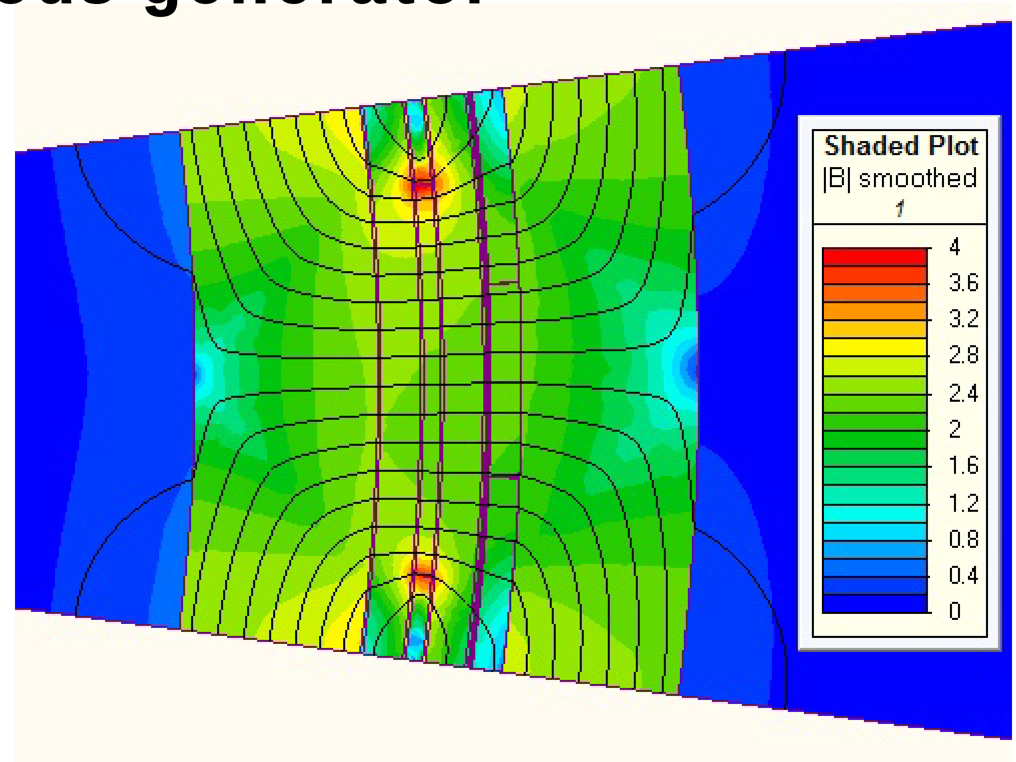


B = 4 Tesla, T = 30 K
$J_e \sim 70$ A/mm^2

B = 4 Tesla, T = 40 K
$J_e \sim 300$ A/mm^2

Multi-pole synchronous generator





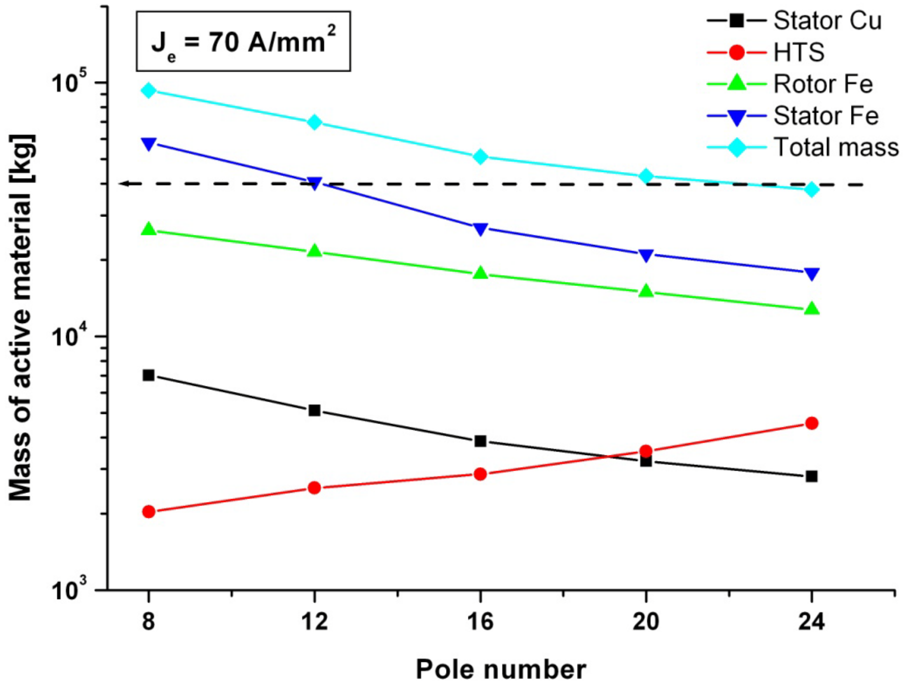
Warm rotor and stator Fe
$t_{cryostat}$ ~ 4 cm

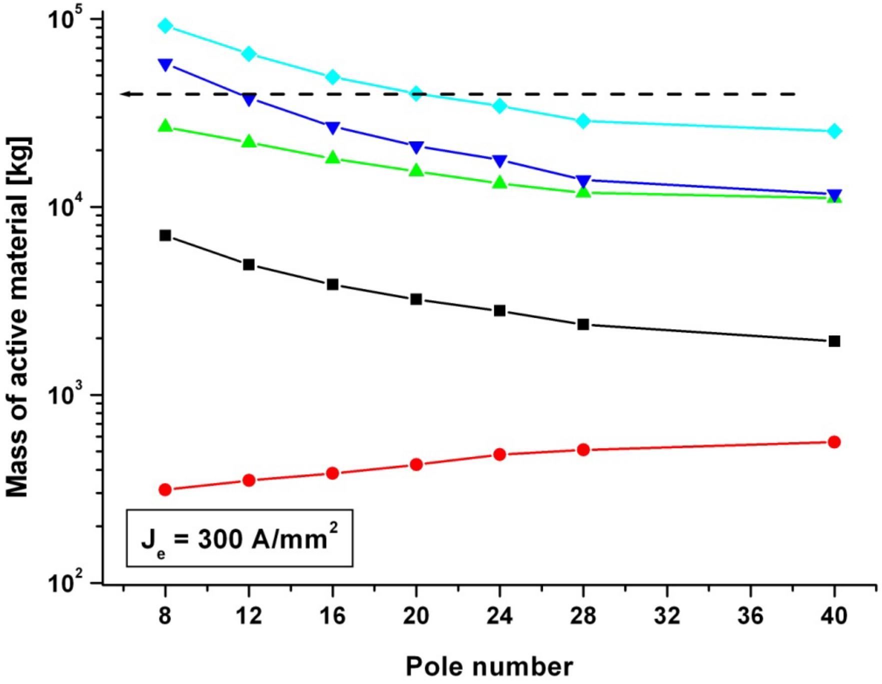
B_{airgap} ~ 2.3 Tesla
B_{Fe} < 2.5 Tesla
A_{stator} ~ 90 kA/m
Cu loss ~ 5 %

D = 4.2 m   L = 1.5 m

ρ_{FE} = 7600 kg m^{-3}
ρ_{Cu} = 8940 kg m^{-3}
$\rho_{AmSC\ 348\ +\ insu}$ = 6546 kg m^{-3}
$\rho_{SP4050+\ insu}$ = 4982 kg m^{-3}

Active mass of direct drive generators





Weight target ☺
HTS usage ☹

Weight target ☺
HTS usage ☺

Superconductor & heat losses

- 24 poles needs L = 130 km of Superpower tape
- Assume I = 70 A being 10% below I_C and n = 40
- DC loss:

$$P = UI = E_0 L \left(\frac{I}{I_C} \right)^n I$$

$$= 1\,\mu V cm^{-1} \cdot 130\,km \cdot 0.9^{40} \cdot 70\,A$$

$$= 13.5\,W$$

- Heat conduction gas: P = 10^{-6} mbar @ T = 40 K $\rightarrow$ Q ~0.02 W/m^2
- Heat radiation: T = 40 K $\rightarrow$ Q ~0.4 W/m^2
- Heat load at T = 40 K: 0.42 W/m2 x 40 m2 +13.5 W = 30 W
- Torque tube : Remove heat input at T = 77 K
- Total 500 W ?

Cooling

CH-210 10K CRYOCOOLER

Performance Specifications Sumitomo

Power Supply Hz	**50**	**60**
2nd Stage Capacity Watts @ 20 K	6.0	7.0
1st Stage Capacity Watts @ 77 K	110	120
Maximum 2nd Stage Capacity Watts @ 20 K (No 1st Stage Load)	6.0	7.0
Cooldown Time to 20 K Minutes	35	30
Weight Lbs. (kg)	30.4 (13.8)	

- Number of cryocoolers: 30 W / 6 W/cooler ~|5-6 coolers
- $P_{cooling}$ = 6*110 W = 660 W @ T = 77 K
- Input power: P_{in} = 6 x 7 kW = 42 kW
- Fraction of production: Pin / Pturbine = 42 kW / 5 MW ~ 1 %

State of the art

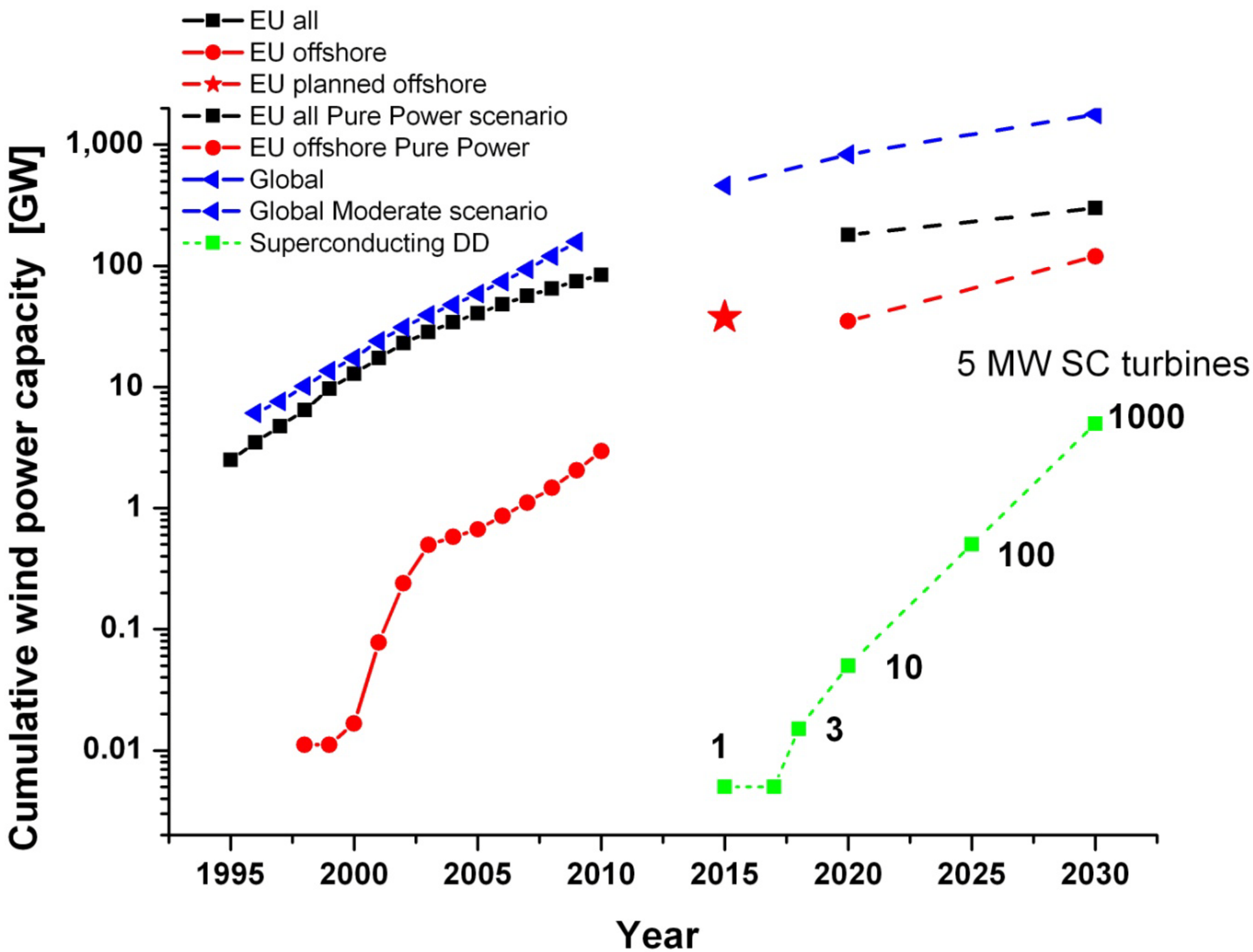
- Seatitan: American Superconductors

  - P = 10 MW
  - D ~ 5 m
  - L ~ 5 m
  - W ~150-180 tons
  - www.amsc.com
  - **G. Snitchler** , “Progress on high temperature superconductor propulsion motors and direct drive wind generators”, International Power Electronics Conference, 2010. - p. 5.

- Converteam / Zenergy

  - P = 8 MW
  - **C.Lewis C. and J.Muller** ,“A Direct Drive Wind Turbine HTS Generator”, IEEE Power Engineering Society General Meeting, 2007. - p. 1.

Superconducting Direct Drive Road map



Needed

150000 km tape
6000 cryocoolers
1000 cryostats

Tape production

2000 km/ year ↑

Wind power induced increase of Nd demand

USAGE OF THE RARE EARTH ELEMENTS NEODYMIUM AND YTTRIUM, FOR THE DIFFERENT DRIVE TRAINS. COLUMNS THREE TO FIVE SHOW THE ESTIMATED NEED TO FULFIL THE EU OFFSHORE, THE TOTAL EU AND THE GLOBAL WIND POWER CAPACITY IN THE PERIOD 2015-2030.

TYPE	Nd/Y metal usage [kg/MW]	EU offshore 110GW [ton of metal]	EU total 170GW [ton of metal]	Global 1280GW [ton of metal]
DDPM	200	22,000	34,000	260,000
2GPM	20	2,200	3,400	26,000
DDHTS	0.10	11	17	130
DDIG	0	0	0	0

DDPM: Direct Drive Permanent Magnet Generator; 2GPM: Two Stage Gearbox Permanent Magnet Generator; DDHTS: Direct Drive High Temperature Superconducting Generator; DDIG: Direct Drive Induction Generator. Note: The weight fraction of Nd in $Nd_2Fe_{14}B$ and of Y in $YBa_2Cu_3O_{6+x}$ is 0.27 and 0.13 respectively.

Source: Jensen, Abrahamsen & Henriksen, "Influence of Rare Earth Element Supply on Future Offshore Wind Turbine Generators", Risø International Energy conference 2011

Conclusion

- Can superconducting direct drive generators enter the EU offshore wind turbine market?
  - 10 turbines of 5-10 MW in 2020
  - 1000 turbines of 5-10 MW in 2030
- The 5 MW NREL reference turbine is proposed for system investigations
- Race track coils holding Bi-2223 and coated conductors have been used to estimate J_e for a synchronous multi-pole generator.
- A current density of J_e = 300 A/mm2 @ B = 4 Tesla & T = 40 K would enable a compact direct drive trains with
  - D = 4.2 m, L_{active} = 1.2 m, m_{active} = 34 tons
  - Compete with $Nd_2Fe_{14}B$ PM on performance and RE usage !

Collaborators

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Acknowledgement

- Technical University of Denmark for funding the Superwind project from the Globalization initiative.

- One of the authors (VMRZ) acknowledges financial support from: Technical University of Denmark, The Research School of the Danish Center for Applied Mathematics and Mechanics, Vestas Wind Systems and SEP-Mexico.

- Ultera A/S for supply of Bi-2223 brass tape and Danfysik A/S for support on insulation of Superpower 4050 tape.

- Financial support from EFDA to the Risø-DTU fusion research contribution on studies of coated conductors in high magnetic fields.

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