Karlsruhe Institute of Technology

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Advantages and Challenges in high-field Rotating Machinery

MT26 Special session “Magnet Technology and Conductor for future High-Field Applications”

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KIT-CENTRE ENERGY

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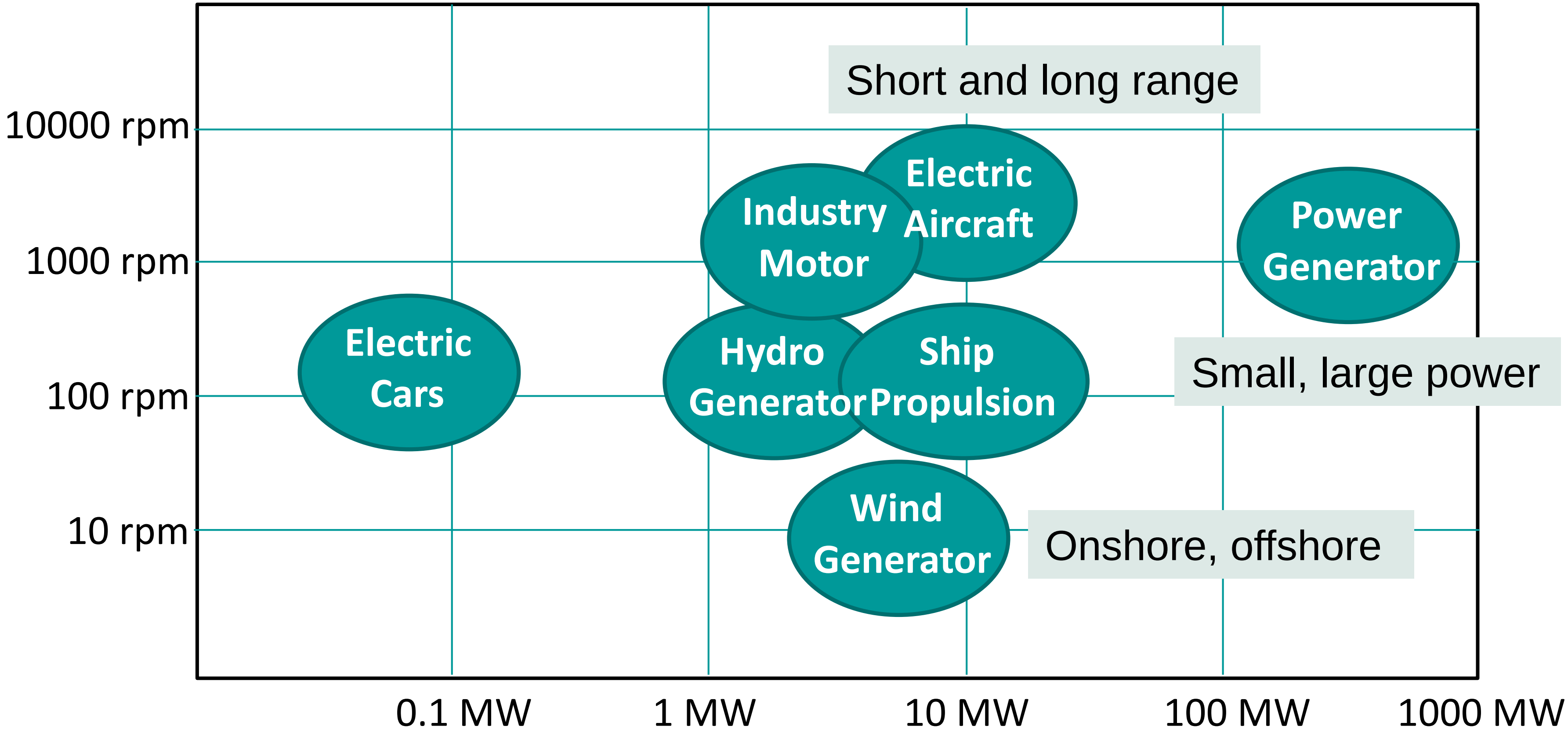
- Markus Bauer, Theva
- Thomas Hildinger, Voith Hydro

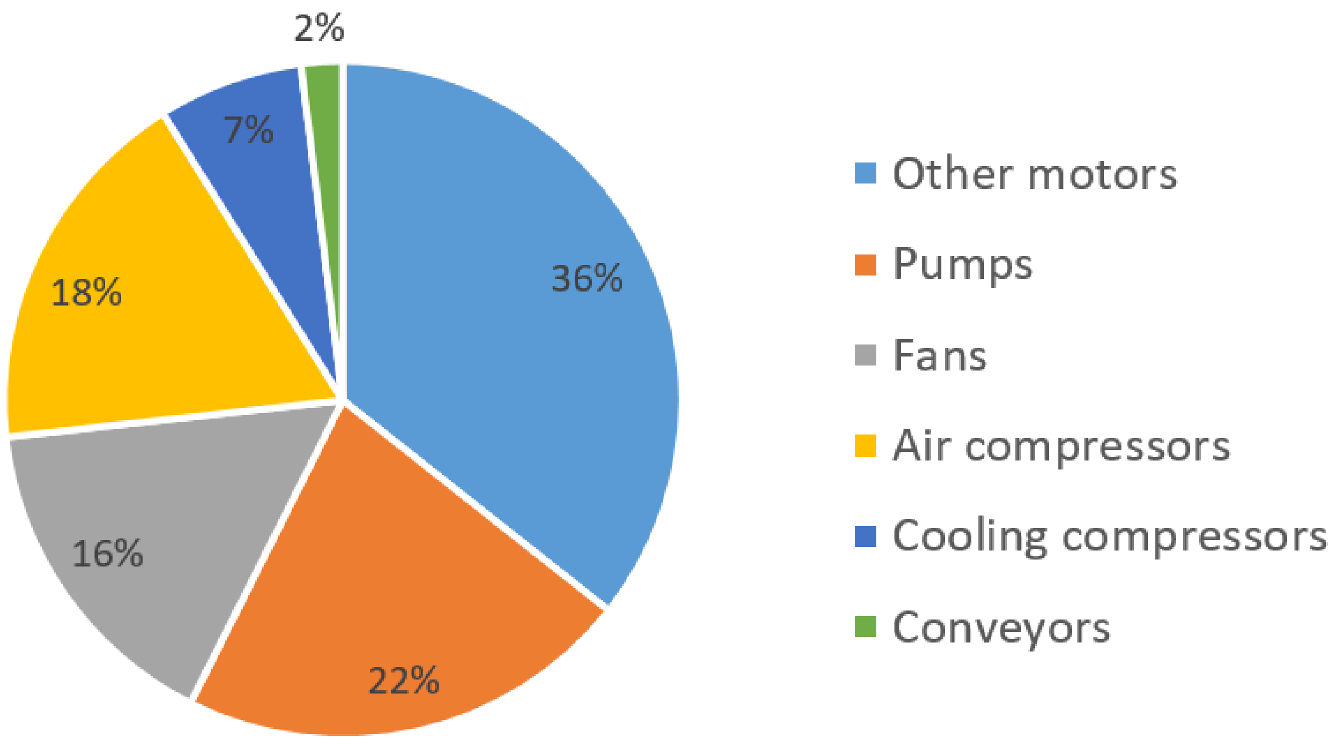
Which Application?

- There are many rotating machines that differ very much in torque, power and speed.



Which Application?

- Share of **motor** energy use by type of end-use in the **industrial sector**



Source: Almeida AT, Ferreira FJTE, Busch JF, Angers P (2002) Comparative analysis of IEEE 112-B and IEC 34–2 efficiency testing standards using stray load losses in low-voltage threephase,cage induction motors. IEEE Trans Ind Appl 38(2):608–614

Each application and each market has specific requirements and different users

Market Perspective for Rotating Machines

- Airbus global market https://www.airbus.com/aircraft/market/global-market-forecast.html

New deliveries 2018-2037

Source: Ascend, Airbus
Note: 100+ seaters (passenger aircraft)
Categories: Demand forecast is based on generic neutral seating categories grouped into the following segments for simplification purpose

Pax Units

Category	Africa	Asia-Pacific	CIS	Europe	Latin America	Middle East	North America	Total
Small	843	12494	998	5512	2425	1214	5066	**28552**
Medium	204	2204	140	1042	210	533	679	**5012**
Large	50	565	39	315	55	466	150	**1640**
X-Large	34	380	44	203	17	612	69	**1359**
Total	**1131**	**15643**	**1221**	**7072**	**2707**	**2825**	**5964**	**36563**

Pax Values ($US billion)

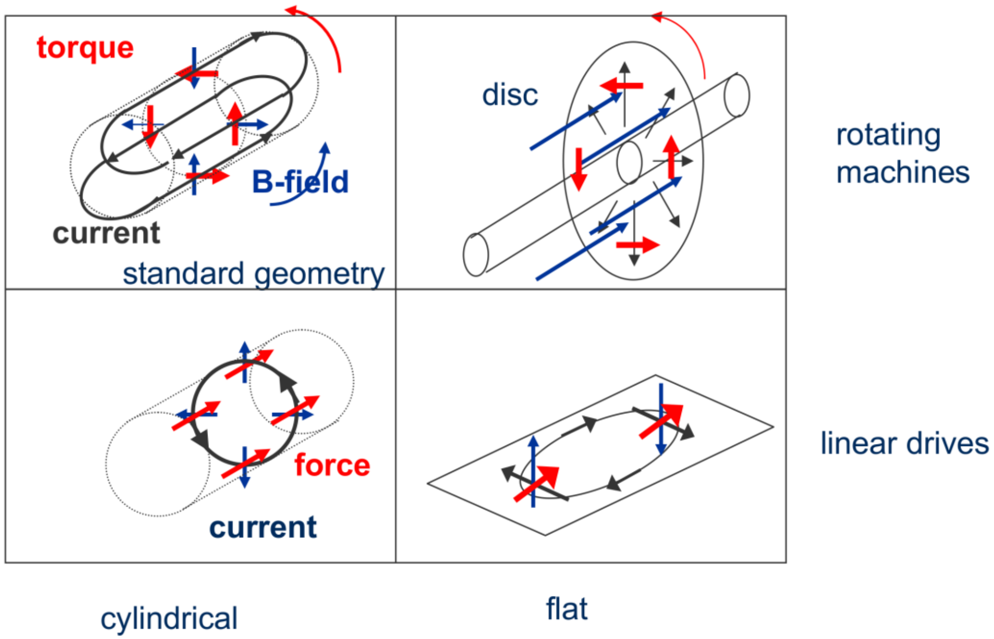
Category	Africa	Asia-Pacific	CIS	Europe	Latin America	Middle East	North America	Total
Small	88	1424	107	618	265	133	539	**3174**
Medium	55	585	37	276	56	144	181	**1334**
Large	17	192	13	107	19	159	51	**558**
X-Large	13	147	18	80	6	246	27	**537**
Total	**173**	**2348**	**175**	**1081**	**346**	**682**	**798**	**5603**

There is a huge market perspective (e.g. 70 billion USD in 2030 for offshore wind)

Which Type?

- Synchronous machine
  - Fully superconducting
    - Electrical excitation
    - Permanent magnets
  - Rotor superconducting
    - Electrical excitation
    - Permanent magnets
- Asynchronous machine
- DC machine
- Reluctance machine
- Homopolar motor
- Transversal flux machine
- Linear drives
- and some more

different choices, but always: B-field ⊥ current I ⊥ motion



Picture: Courtesy T. Arndt

State of the Art of HTS rotating machines

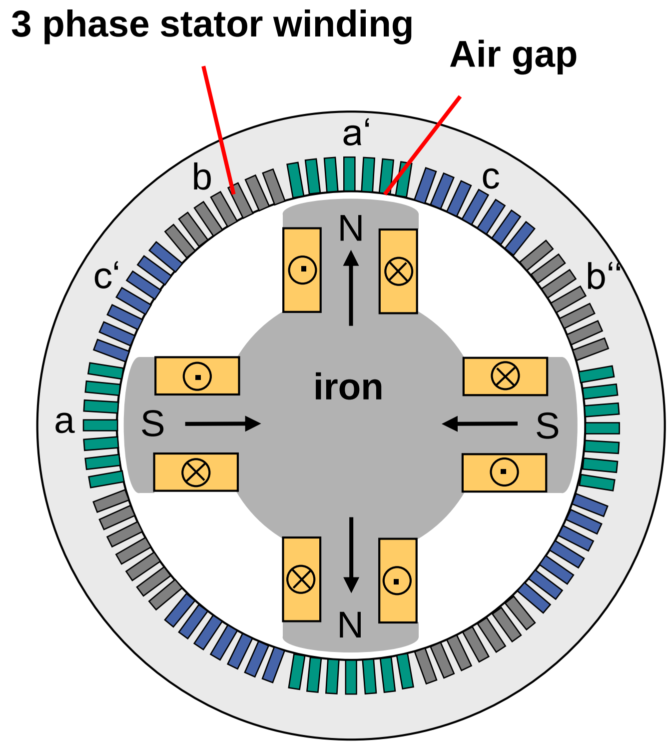
- Machines with a rating of up to 36 MVA were built and tested

Manufacturer / Country	Machine	Timeline
AMSC (US)	5 MW demo-motor	2004
	8 MVA, 12 MVA synchronous condenser	2005/2006 (**Field test**)
	36 MW ship propulsion motor	2008
GE (US)	5 MVA homopolar induction motor	2008
LEI (US)	5 MVA high speed generator	2006
Kawasaki (JP)	1 MW ship propulsion	200?
IHI Marine, SEI (JP)	2.5MW ship propulsion motor	2010
Doosan, KERI (Korea)	1 MVA demo-generator	2007
	5 MW motor ship propulsion	2011
Siemens (Germany)	4 MVA industrial generator	2008 (**Field test**)
	4 MW ship propulsion motor	2010
Converteam (UK)	1.25 MVA hydro-generator	2010
Ecoswing (EU)	3 MW wind generator	2018 (Field test)

So far three field test of more than a MW superconducting machines were reported

What is important for rotating machinery

- Example: Conventional synchronous machine with electrical excitation

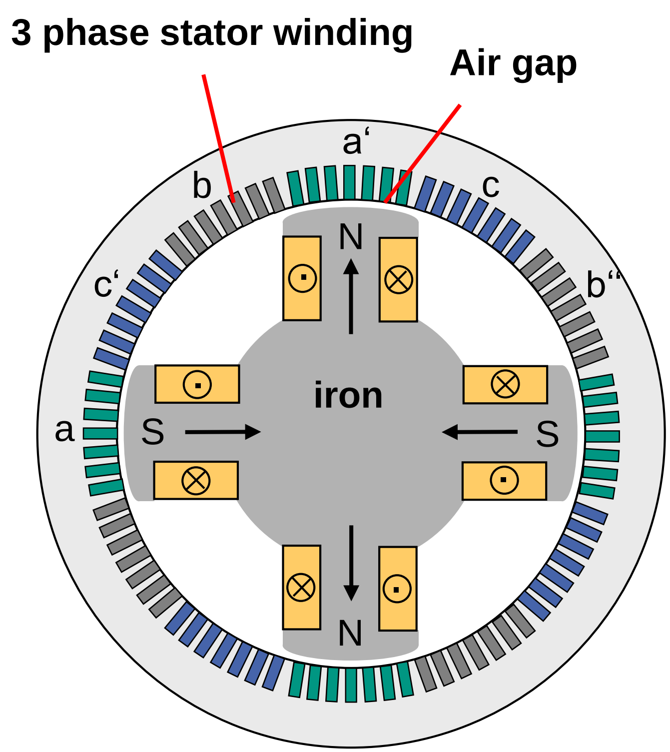


Characeristic

- Stator winding in iron grooves
- Backiron to confine flux to machine and close magnetic circuit
- Copper windings
- Iron in rotor and stator
- Small air gap

What is important for rotating machinery

- Example: Conventional synchronous machine with electrical excitation



Torque/Length

$$\sim n\, A_1\, B_r\, r$$

$$\sim A_1\, r\, B_r\, r$$

Power

$$\sim A_1\, B_r\, r^2\, L\, n$$

Power density per volume

$$\sim A_1\, B_r\, n$$

A_1 Current density in stator
B_r Magnetic field from rotor at stator winding
r Radius
l active machine length
n speed of rotation

A high magnetic field enables a considerable increase in all important machine parameters

Limitations

- Length
  - Oscillations, mechanical stability, bending→varying airgap, stress cycles
- Diameter
  - Transport, circumferential speed, maximum available forgings
- Current Density
  - Losses, heating
- Magnetic Field
  - Saturation of iron, ferromagnetic behaviour
- Speed
  - Depends on application, maximum forces
- Plus many other constraints
  - User benefit
  - Cost pressure
  - Robust and reliable

Limitations Onshore Wind Generators

Manufacturer	Platform	Capacity	Rotor diameter	Max hub height	Drivetrain	Specific power rating	Current status
Enercon	EP5	Up to 5MW	147m, 160m	166m	Direct drive	294W/m2 (E147)	Prototype imminent
GE	Cypress	5.3MW	158m	161m	HSG	270W/m2	Prototype installed late 2018
Nordex	Delta4000	Up to 5MW	149m, 155m	164m	HSG	239W/m2 (N155/4.5)	In series production
Siemens Gamesa	5.X	5.8MW	155m, 170m	165m	HSG	256W/m2 (SG-155)	Prototype expected mid-2020
Vestas	EnVentus	5.6MW	150m, 162m	166m	MSG	272W/m2 (V162)	Prototype imminent

Source: Windpower Monthly

Hot Topics

- Two piece blades to overcome transport and logistical challenge
- New installation technology and techniques to speed up process of hoisting

Limitations Large Hydro Generators

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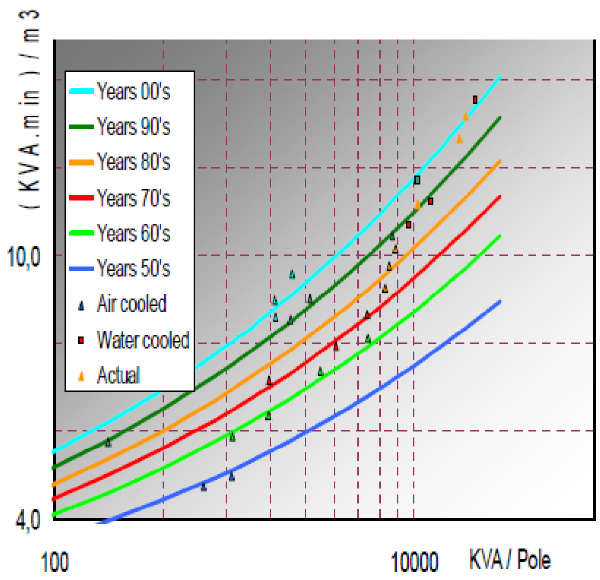
Hydro Generators - **Generator Technology Index**



$$c = \frac{S}{n \cdot D^2 \cdot L} = \frac{power}{speed \cdot volume}$$

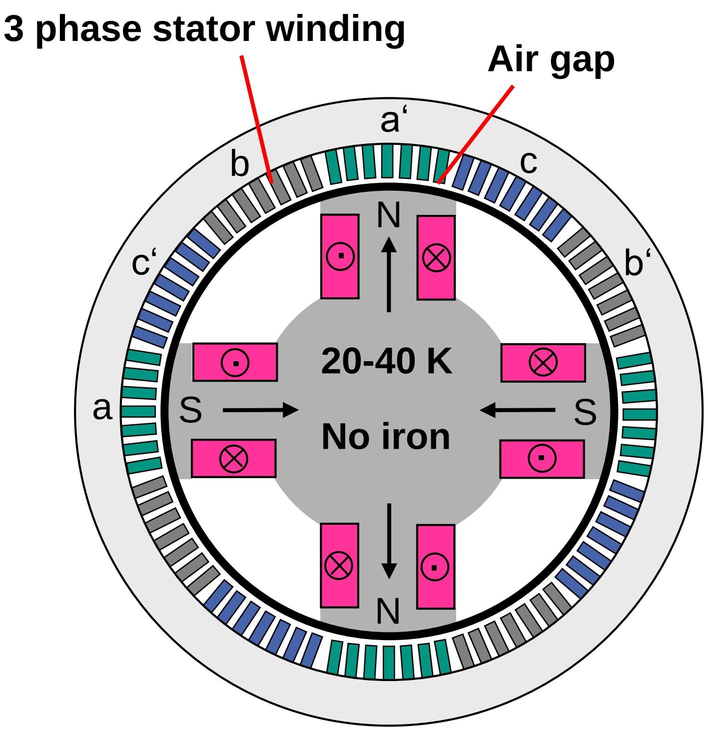
Data from Thomas Hildinger, Voith Hydro

- Energy Density of generators increased by 50% since the fifties!
  → development over 5 decades
- New Silicon Steel Grades
  → low grades GNO (M270, M250, M230, ...)
- Vacuum Pressure Impregnation Insulation
  → from Polyester to Epoxy
  → from Mica-Split to Mica-Paper
  → process control improvements
  → automatic taping machines
  → reduced thickness of ground wall
- New Calculation Methods and Design Tools
  → FEM, CFD, CAD, ...

Present limitations: B ≤ 1.3 T, A_1 < 100 A/mm, diameter < 20 m, length < 4 m

What are the Implications of HTS?

- Example: Synchronous Machine with electrical excitation



Characteristic of HTS winding in rotor for higher magnetic fields

- Air gap normal conducting stator winding
- Rotorwinding with HTS
- No iron in motor
- Cryostat acts as damper winding

As a result

- Larger air gap
- Smaller synchronous reactance
- Different excitation system

What are the Implications of HTS?

Example Wind Generator

3.6 MW I 14 rpm

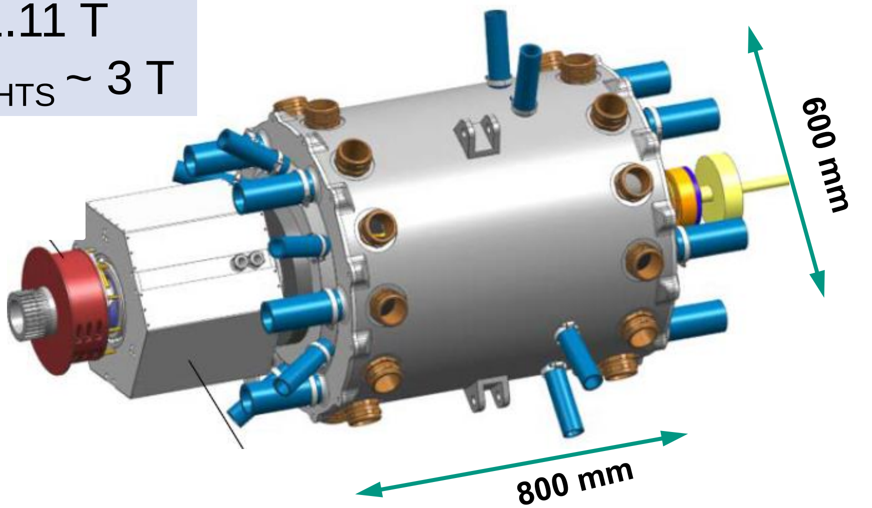
Data and picture: M. Bauer Results and lessons learned from the 3 MW EcoSwing wind power generator, EUCAS 2019, Glasgow

Example Generator for E-Aircraft Study

10 MW | 7000 rpm | **21 kW/kg** | > 98 %, 476 kg

B = 1.11 T

$B_{max\ HTS}$ ~ 3 T

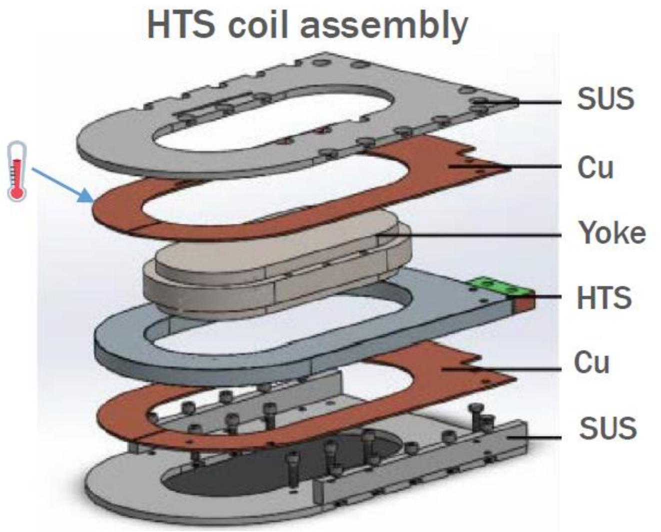


Data and picture: L. Kühn, et.al. High Power Density 10 MW HTS-Generator for eAircraft, EUCAS 2019, Glasgow

What is the reason for the choosen magnetic field?

Implications of High Magnetic Field for a Wind Generator

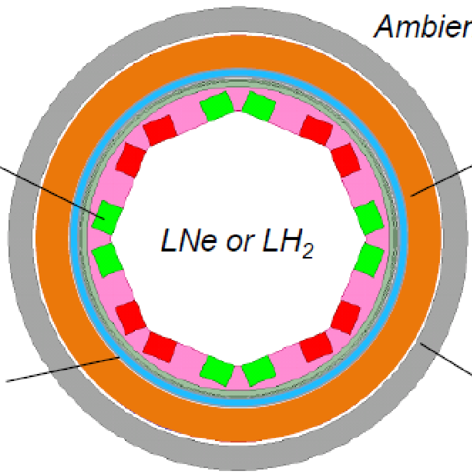
- Example: Synchronous machine with electrical excitation
- Design Option 1: Warm iron, limited magnetic field
  - Smallest air gap, smallest amount of HTS tape, a cryostat around each coil
- Design Option 2: Cold iron, limited magnetic field
  - Cryostat enlarges air gap, more HTS tapes to reach same magnetic field
  - Ecoswing used 20 km of 12 mm wide tapes
- Design Option 3: no iron, high magnetic field
  - Large air gap, considerable amount of HTS tapes to reach magnetic field



Picture: M. Bauer„„Results and lessons learned from the 3 MW EcoSwingwind power generator" EUCAS 2019, Glasgow

Implications of High Magnetic Field for an Aircraft Generator

10 MW | 7000 rpm | **21 kW/kg** | > 98 %, 476 kg



Data and picture: L. Kühn, et.al. High Power Density 10 MW HTS-Generator for eAircraft, EUCAS 2019, Glasgow

Mechanical loads

Strain from sleeve to stress carrier
Thermal contraction
High centrifugal load
Torque transmission from 20 K to RT

Rotation 7000 rpm
Max. circumferential speed 133 m/s
Results in force of 9000 g

The rotor design balances superconducting limits with mechanical stress limits

Open Questions for Discussion

- Can we imagine a rotating machine with much more than 5 T?
- Is a HTS bulk material with high magnetic fields the better option than 2G HTS?
- In which application can we exploit best the high magnetic field?
- What will be the first commercial HTS application for rotating machines?
- …?

- **Many thanks for your attention !**