Trends in E-Machines Using Superconductors

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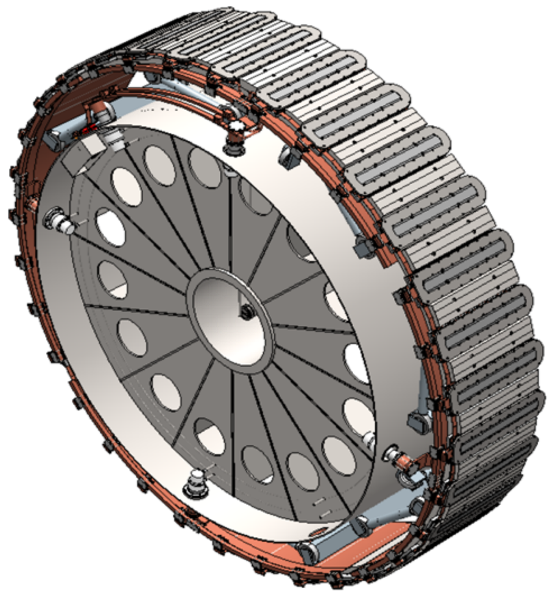


Superconducting rotor of wind generator

Source: ECO5 GmbH, WINDSPEED Report, 2016

Trends in E-Machines Using Superconductors
Contents

3D phase diagram of a super-conductor

T_c-B_c-J_c-"<u>S</u>afe <u>o</u>peration <u>ar</u>ea" (SOAR)

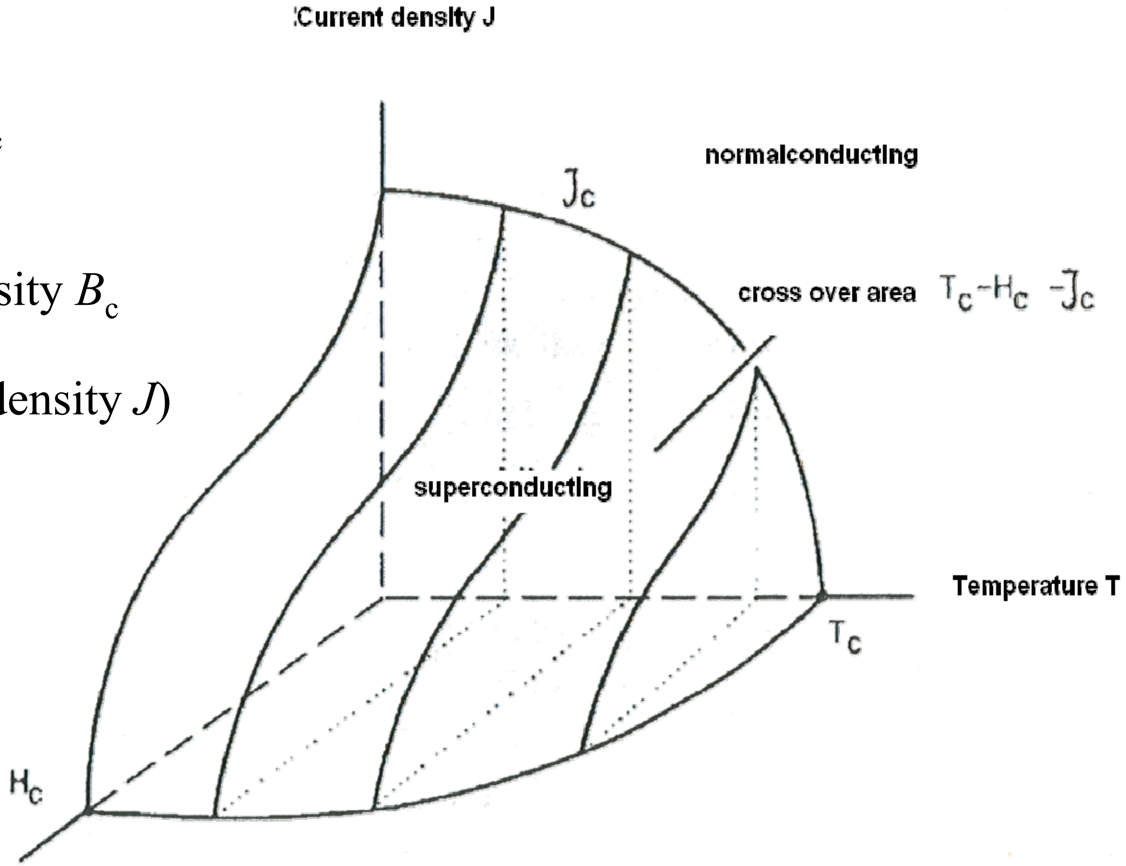
- Superconducting state is possible only within the T_c-B_c-J_c-region

1) Critical current density J_c

2) Critical temperature T_c

3) Critical <u>external</u> flux density B_c
   or field strength H_c
   (<u>not</u> self-field of current density J)

$$B_c = \mu_0 H_c$$



Source: Rödel, J.: Funktionswerkstoffe, Vorlesungs-Skript, TU Darmstadt

Progress and milestones
110 years of superconductivity

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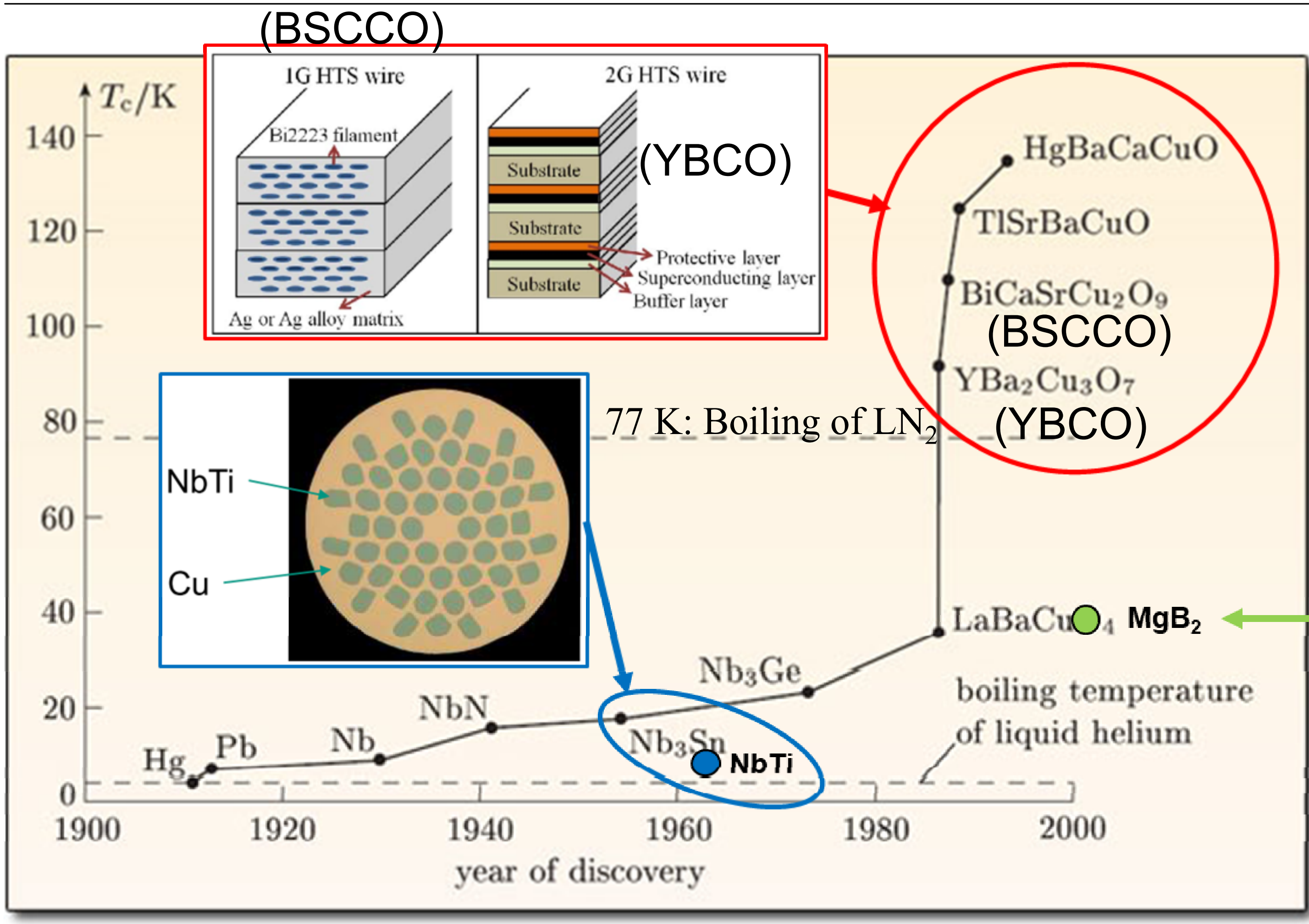
(at $J = 0$, $B = 0$)

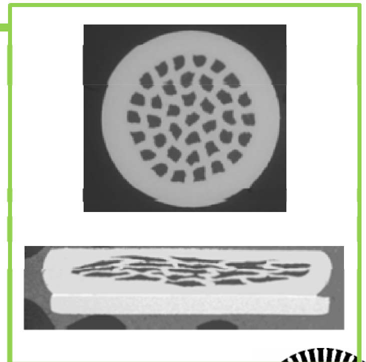
Year	Event	Material	T_c
1911	*H. Kammerlingh Onnes* discovers low temperature superconductor metals LTSC	Hg	4 K
1952	Niob-3-Tin intermetallic compound “hard” LTSC	Nb_3Sn	18 K
1986	*Müller* and *Bednorz* discover "high-temperature superconductor" HTSC	$(La,Ba)_2Cu_2O_4$	30 K
1987	HTSC ceramic material Gadolinium-Ba-Cu-O (GdBCO) & Yttrium-Ba-Cu-O (YBCO)	$GdBa_2Cu_3O_{7-x}$ $YBa_2Cu_3O_{7-\delta}$	94.5 K 93 K
1988	HTSC ceramic material BSCCO	Bi-Ca-Sr-Cu-O	120 K
2001	LTSC magnesium-diboride intermetallic compound	MgB_2	39 K

Timeline of Superconductors
Application in Rotating Electrical Machines



HTSC:
- Costly
- Moderate cooling effort

LTSC:
- Cheap
- High cooling requirements



Source: DoITPoMs - University of Cambridge & ASG Superconductors SPA; Genova, Italy

1st Generation (1G): BSCCO tapes

Flat-rolled twisted SC filament in Ag matrix

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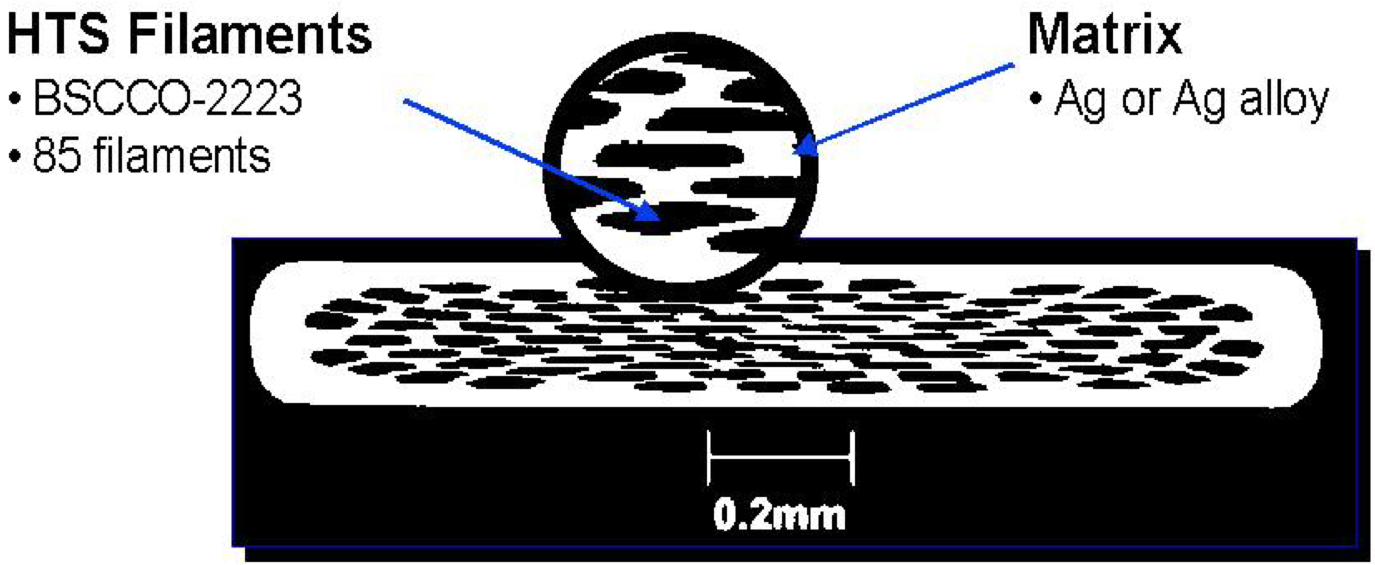
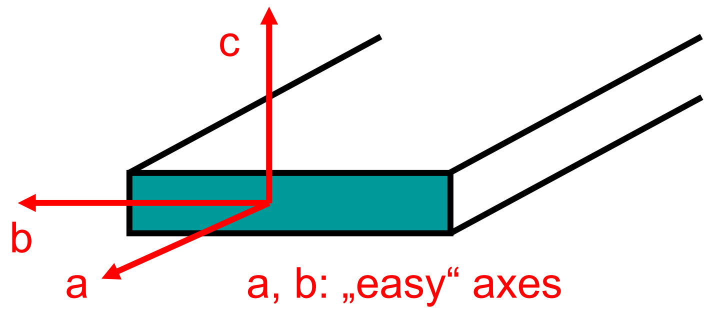


J_c: Current density in HTSC filaments

J_e: Engineering current density of entire tape



Source: American Superconductor

2nd Generation (2G): YBCO & GdBCO
Flat conductor tapes

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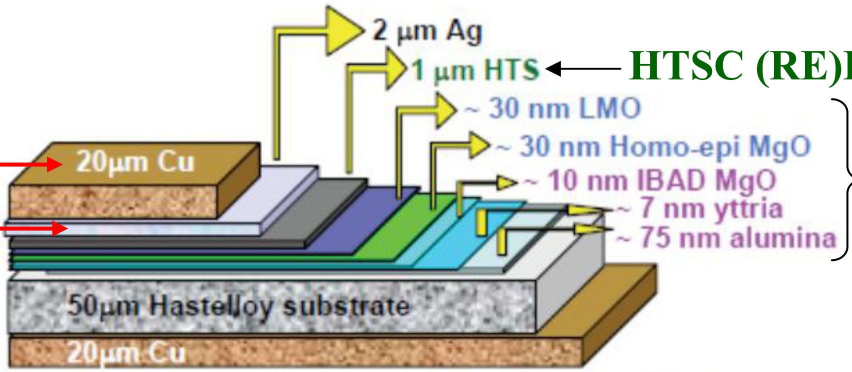
Cu/Ag sheet:
Cu stabilizer
Ag over-layer

Hastelloy substrate



HTSC (RE)BCO epitaxial

Buffer stack, MgO-based

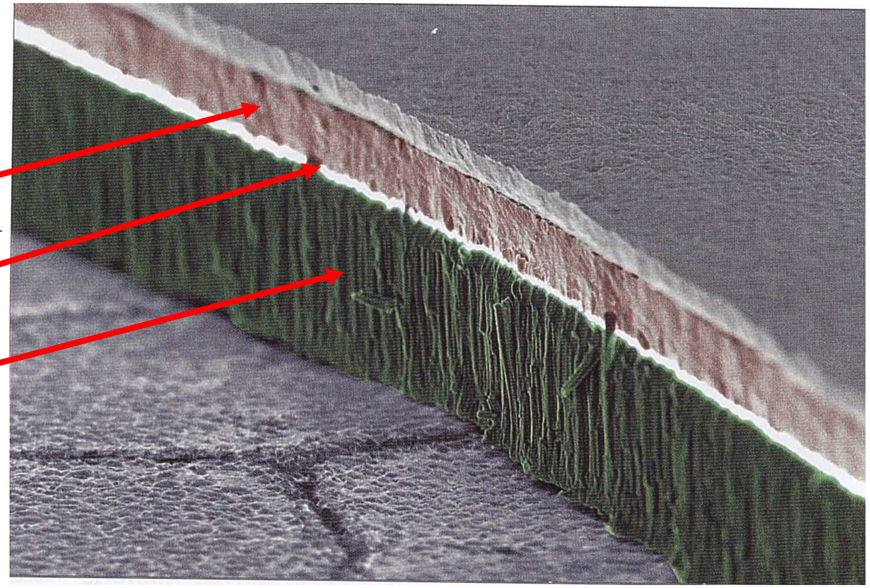
Source: SuperPower Inc., Glenville, USA

RE: Rare earth:
Yttrium Y
Europium Eu
Gadolinium Gd

Cu layer ca. 20 µm

YBCO layer ca. 1 … 3 µm

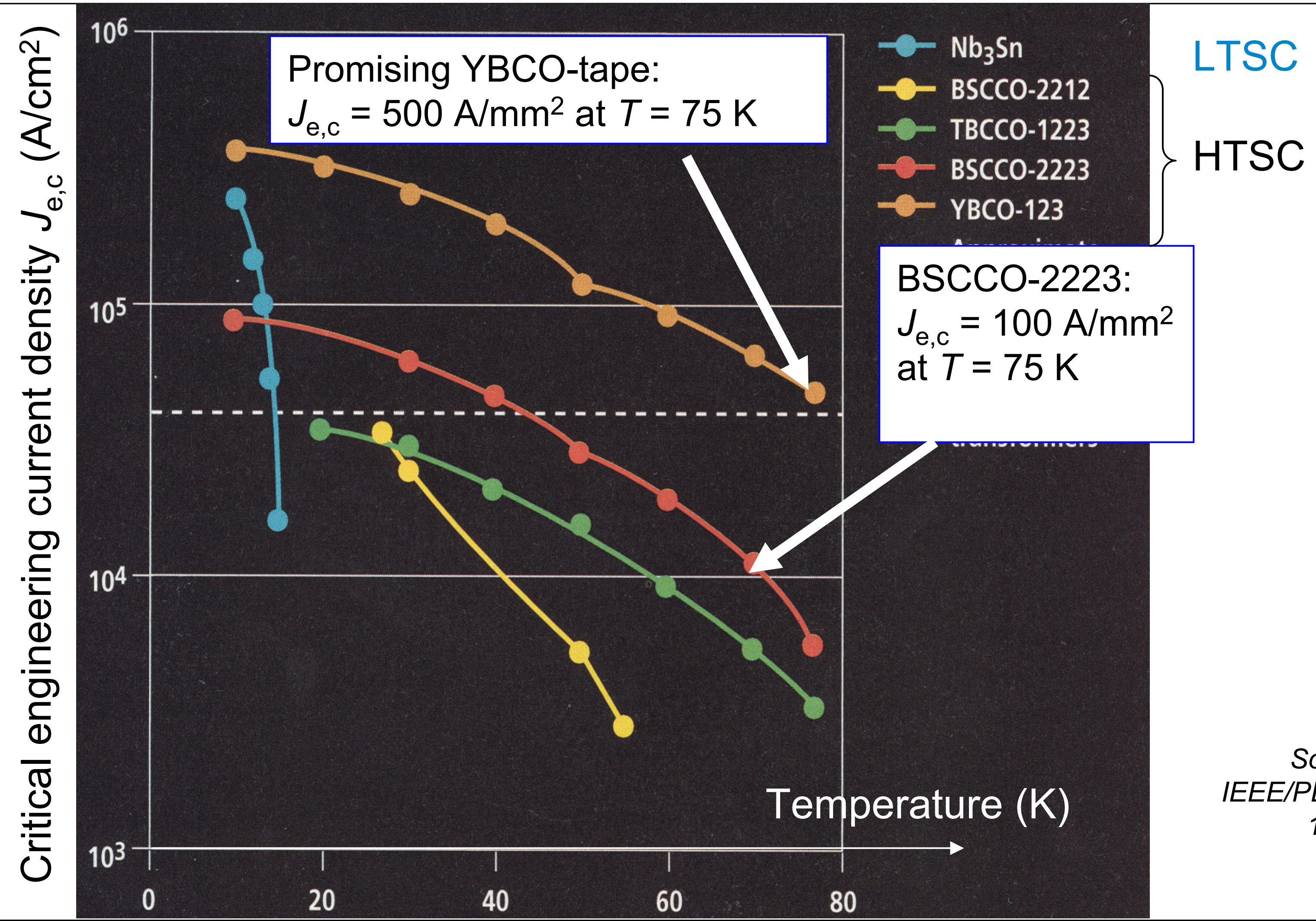
Stainless steel carrier tape ca. 0.1 mm



Source: Theva Dünnschichttechnik GmbH, Ismaning, Germany; Published in: energiewirtschaft 112, 2013, no. 6

LTSC vs. HTSC for technical use

At zero external magnetic field $B = 0$



Source:
IEEE/PES Journal,
1998

SC are operated “cold” in cryostats
Different types of cooling

- Cryostat:
  Thermally insulated (metallic or glass fibre) Dewar to keep SC cold.

- Refrigeration unit:
  Transport of heat inflow from cold to hot side (e. g. *Gifford-MacMahon*-cycle).

- Cooling power demand:
  Removing 1 W of heat inflow from cold side to ambient needs

  a) LTSC: At 4.2 K (liquid Helium I) ca. 700 … 1000 W electrical driving power

  b) HTSC: At 77 K (liquid nitrogen) ca. 30 … 50 W $\Rightarrow$ HTSC advantageous

- Types of cooling: a) Conductive cooling via e. g. “high purity” copper elements
  b) Convective cold gas flow cooling
  c) Convective cold liquid cooling
  d) Vaporization of liquid coolant

Trends in E-Machines Using Superconductors

Contents

Synchronous electrical machines
Electrical vs. PM excitation

- Electrically excited synchronous machines:
  1) Hetero-polar:
  a) Stator AC winding normally conducting (copper!)
  b) Rotor DC current in SC field winding: Lossless current flow!
  BUT: Rotating cryostat, rotating sealing, current slip rings!
  2) Homo-polar:
  a) Stator AC winding normally conducting (copper!)
  b) Stator DC current in SC field winding: Lossless current flow!
  NO rotating cryostat, rotating sealing, current slip rings!
  BUT: Only 50% of fundamental wave air-gap flux density!

- PM excited synchronous machines:
  Hetero-polar: SC AC winding (increased cooling power)
  1) Rare earth PM rotor
  2) SC YCBO stacks with trapped field rotor

Stator slot magnetic fields in E-machines
Exposition of conductors to self-field

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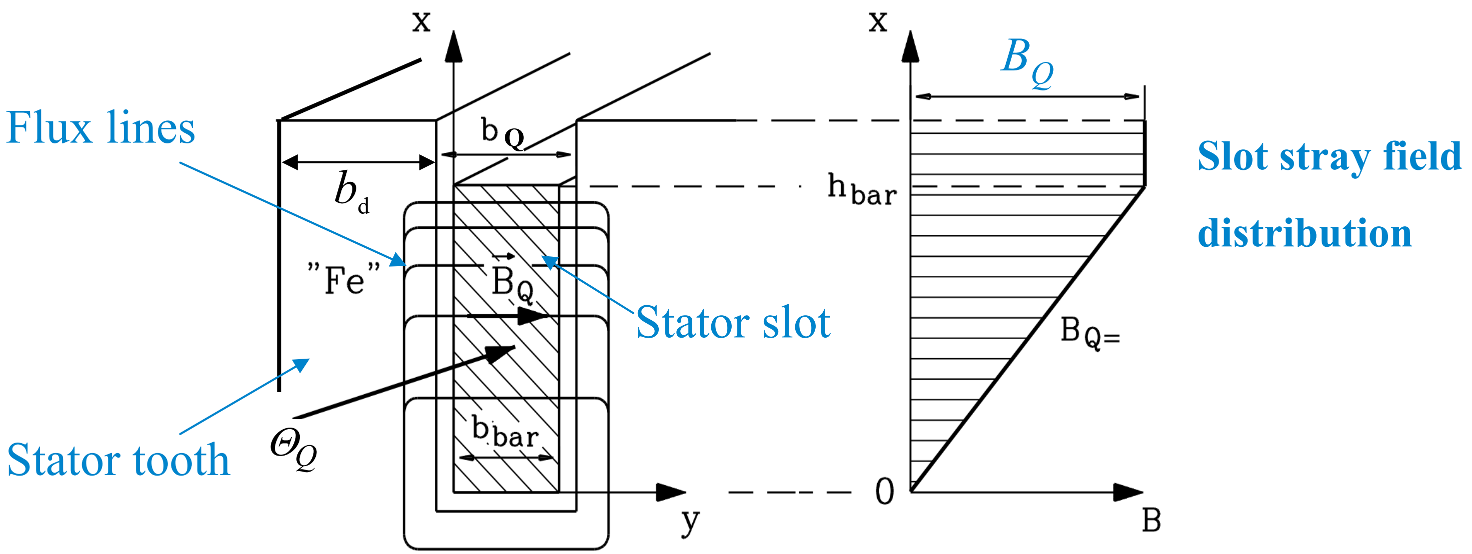
- **Magnetic self-field in the slot** at aimed high electric loading A_s = 2 kA/cm:
  At equal slot & tooth width $b_Q \cong b_d$:
  Slot Ampere-turns: $\Theta_Q = A_s \cdot (b_Q + b_d) \cong 2A_s \cdot b_Q$
  Slot field across the slot: $B_Q = \mu_0 H_Q \big|_{\mu_{Fe} >> \mu_0} = \mu_0 \cdot \Theta_Q / b_Q \cong \mu_0 \cdot 2A_s = 0.5\,\mathrm{T}$
- Rather big self field:
  Needs even for HTSC cooling temperatures at ca. 30 K << 77 K !



Hetero-polar synchronous machine
Example: Rotor 2-pole magnetic field at load

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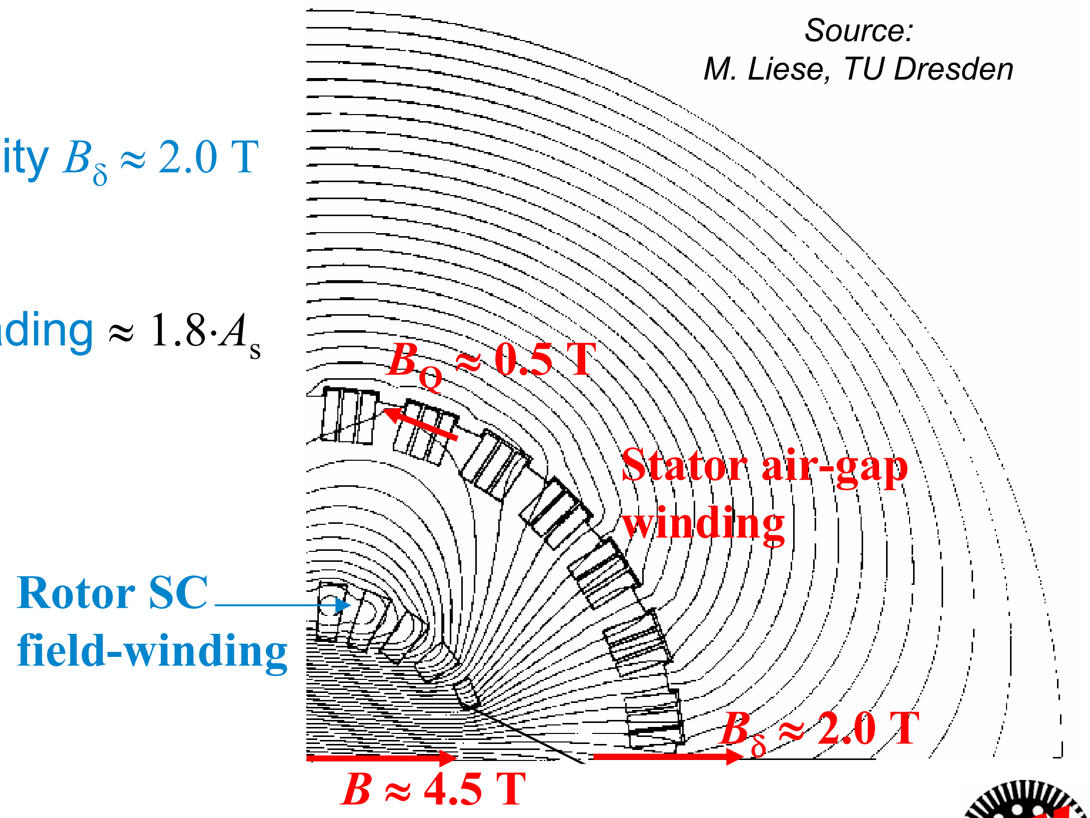
A) Increase of efficiency: Zero excitation losses $P_f = 0$.
Cryo cooling power P_{cryo} removes external heat inflow via thermal insulation.
$P_{cryo} << P_f$: Total losses REDUCED: $+P_{cryo} - P_f$!

B) Decreasing machine size:
a) Increase of air-gap flux density $B_\delta \approx 2.0\ \mathrm{T}$ at stator AC winding!
b) Air-gap winding =
Increase of stator current loading $\approx 1.8 \cdot A_s$
Self field stays constant:

$$B_Q = \frac{\mu_0 \cdot 1.8 \Theta_Q}{2 b_Q} \approx \frac{\mu_0 \cdot \Theta_Q}{b_Q}$$

e.g. $B_Q = 0.5\,\mathrm{T}$



Smaller machine size by SC
Aimed reduction -70%

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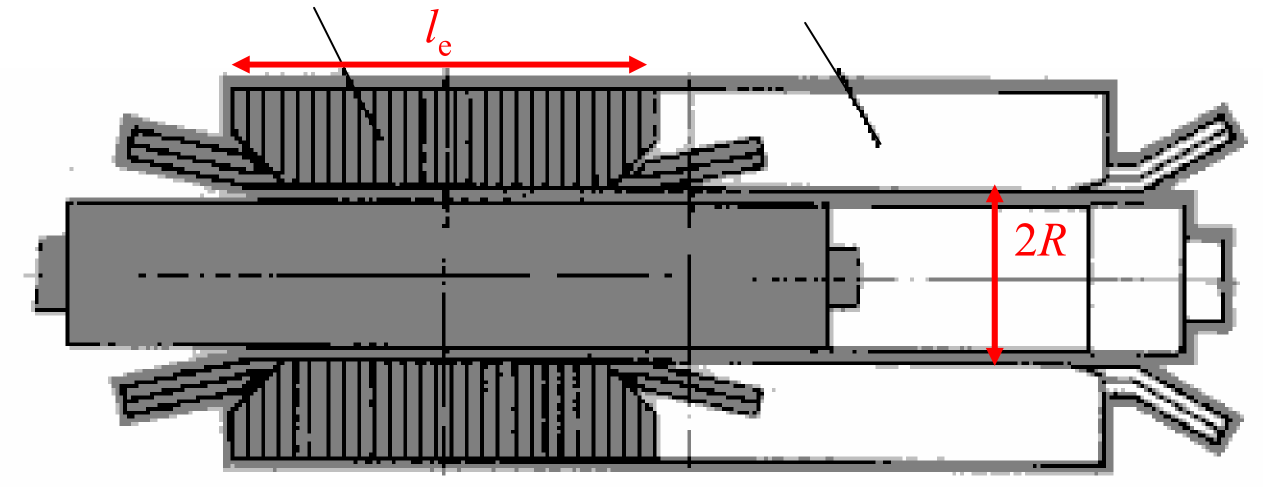
$$\frac{\text{Torque}}{\text{Volume}} \sim \frac{M_e}{l_e \cdot (2R)^2} \sim \underbrace{A_s}_{180\,\%} \cdot \underbrace{B_\delta}_{170\,\%}$$

$$\boxed{A_s \cdot B_\delta \sim 1.8 \cdot 1.7 \approx 3.0}$$

- Increase of torque/volume up to ca. 300%!

SC machine

normally conducing machine



Source:
M. Liese, TU Dresden

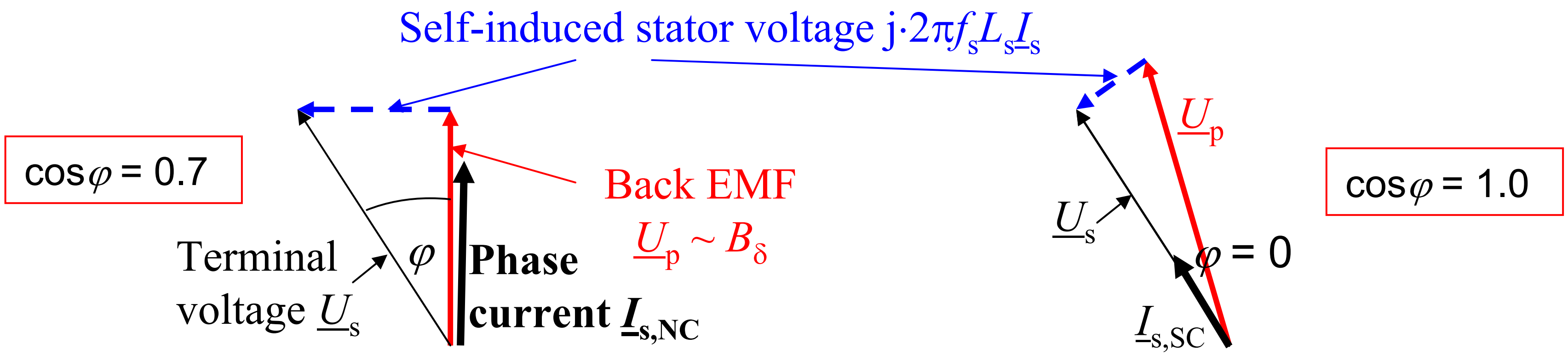
SC machine operated at $\cos\varphi = 1$
Inverter down-sizing

- In comparison to PM rotor excitation a SC field winding
  a) allows much higher air-gap field $B_\delta \Rightarrow$ higher back EMF U_p!
  b) Due to non-magnetic rotor cryostat the stator inductance L_s small!

- Inverter sizing reduced by -30% by increased $\cos\varphi$ from ca. 0.7 to 1!

- Motor operation at $R_s \approx 0$:

PM rotor, $\underline{U}_p$ in phase with $\underline{I}_s$ — SC rotor winding, $\underline{U}_s$ in phase with $\underline{I}_s$



$$P_e \sim U_s I_s \cos\varphi : \text{ At } P_e \,\&\, U_s = \text{const.}: \ \frac{I_{s,SC}}{I_{s,NC}} = \cos\varphi \approx 0.7$$

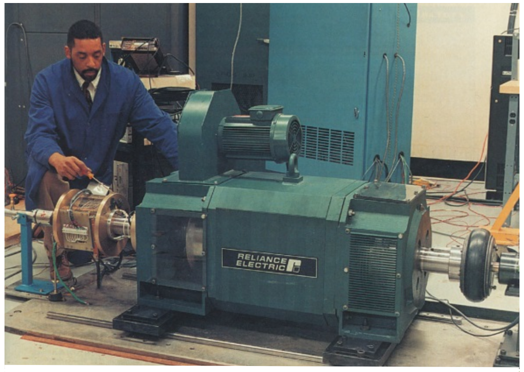
SC stator AC winding?
SC AC losses must be cooled as well

- Inverter-fed SC motors with
  a) variable stator fundamental frequency f_s and
  b) harmonic currents at switching frequency f_T and related harmonics!
- SC stator poly-phase winding, made of HTSC, cooled by cryo-cooler.
- AC SC losses: - Hysteresis losses in the HTSC,
  - Thermally activated flux-creeping losses,
  - Eddy-current losses in conductive “matrix” or Cu/Ag sheet
- Increased cooling power must comprise:
  Heat inflow AND AC SC losses!
- Therefore very often normally conducting stator poly-phase AC windings with conventional cooling circuit (air, oil, water …) are used.

Selected HTSC el. sync. machines (1)

Hetero-polar projects, 1G HTSC BSCCO wires

- Mid-1990: Inverter-fed motor 149 kW,
  He gas cooling, *Reliance, USA,*
  BSCCO rotor field winding,
  Demonstrator

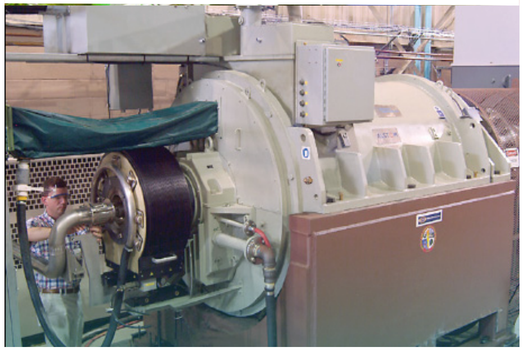


Source:
Reliance Electric, USA

- 2000: Inverter-fed 4-pole motor 350 kW,
  Neon gas cooling, *Siemens AG,*
  BSCCO rotor field winding,
  Demonstrator

Source:
Siemens AG,
Nuremberg, Germany

- 2003: Inverter-fed 6-pole motor 5 MW,
  He gas cooling, *Alstom, UK,*
  BSCCO rotor field winding,
  U.S. Navy Ship propulsion



Source:
Alstom, Rugby, UK

Selected HTSC el. sync. machines (1)

Hetero-polar projects, 1G HTSC BSCCO wires

- 2008: Inverter-fed 16-pole motor 36.5 MW,
  He gas cooling,
  BSCCO rotor field winding,
  Northrop Grumman, USA
  U.S. Navy Ship propulsion

Source:
Northrop Grumman, USA

- 2008: 2-pole generator 60 Hz, 4 MW,
  Neon gas cooling, *Siemens AG,*
  BSCCO rotor field winding,
  Ship generator

Source:
Siemens AG,
Nuremberg, Germany

- 2011: Inverter-fed 8-pole motor 4 MW,
  Neon gas cooling, *Siemens AG,*
  BSCCO rotor field winding,
  Ship propulsion

Source:
Siemens AG,
Nuremberg, Germany

Trends in E-Machines Using Superconductors
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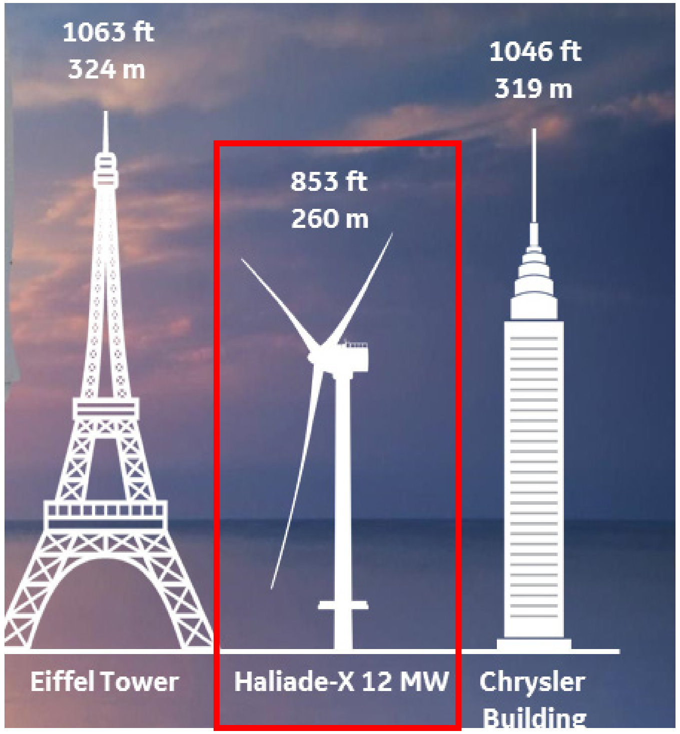
HTSC synchronous wind generators

- Off-shore wind power:
  Gearless generator: Absence of gear box to reduce maintenance!
- Most direct drive wind gen-sets operate with rotor permanent magnets (PM).
- Several tons of PM and rather low $\cos\varphi \approx 0.8$, which increases inverter size!
- With HTSC excitation $\cos\varphi \approx 1$ possible.
- Amount of HTSC material very small
  due to high current densities.

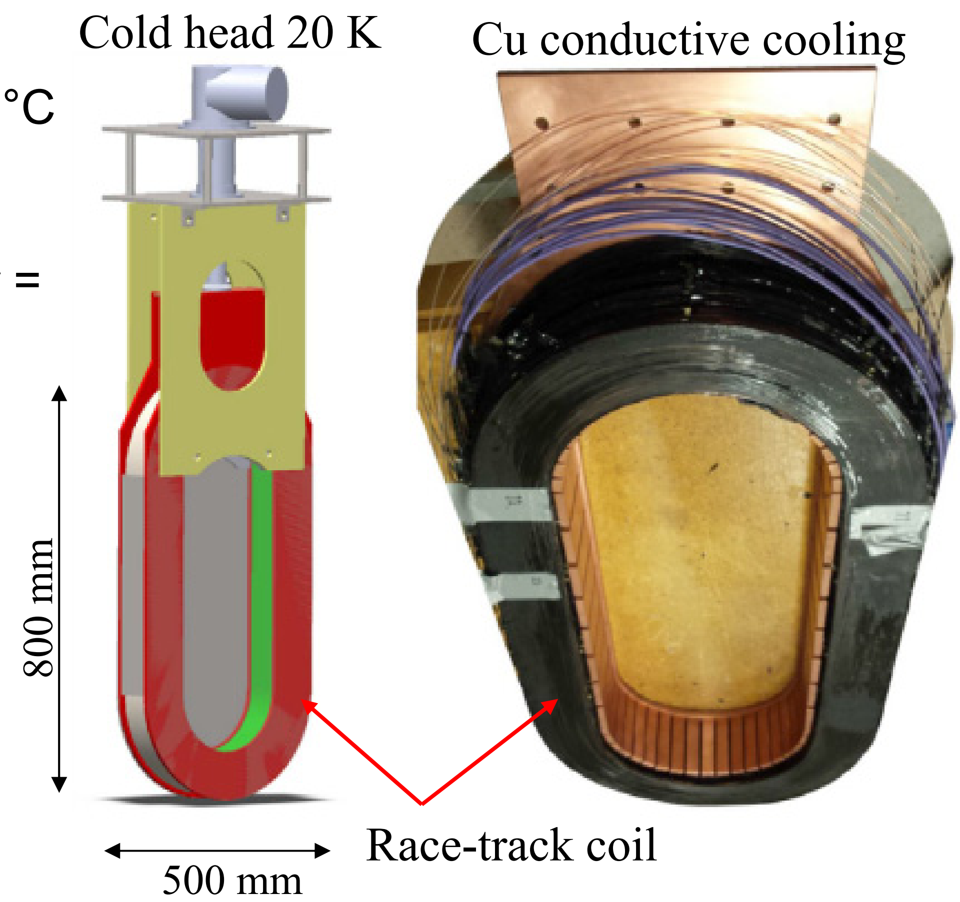


12 MW wind turbine with gearless
PM synchronous ring generator *Haliade-X*

Source: *General Electric*

SC 10 MW Wind turbine generator
INNWIND: MgB_2 rotor field demo coil

- "Cheap" MgB_2 "race track" coils at -253°C
- DC field current 145 A
- Thermal support of „high purity" copper = Conductive cooling
- Mechanical side support: Stainless steel due to high forces.
- 10 pancake coils: Stacked in final coil assembly,
- NASA technology readiness level: TRL = 4 (Laboratory proven level)

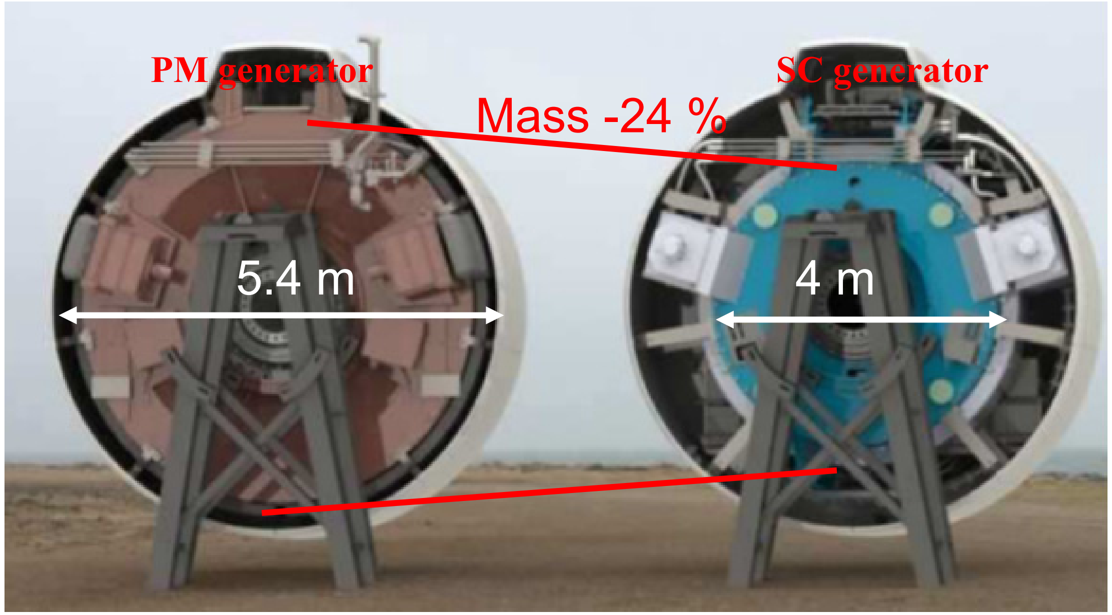


Source: INNWIND.EU project consortium, TU Delft, NL 2017

HTSC gearless wind generator *EcoSwing*

600 h successful off-shore inverter-fed operation

- 3.6 MW, 15 rpm, 40-pole synchronous generator, HTSC $GdBa_2Cu_3O_{7-x}$ excitation
- 3-phase stator copper winding, q = 2 slots/pole & phase, inverter-operated
- 2-blade existing wind turbine used, 7 months under cryogenic condition in 2018/19
- Generator mass 65 t: -24 % compared to PM generator, using the same housing!



Source: EcoSwing Consortium, ZIEHL Conf. 2020, Berlin

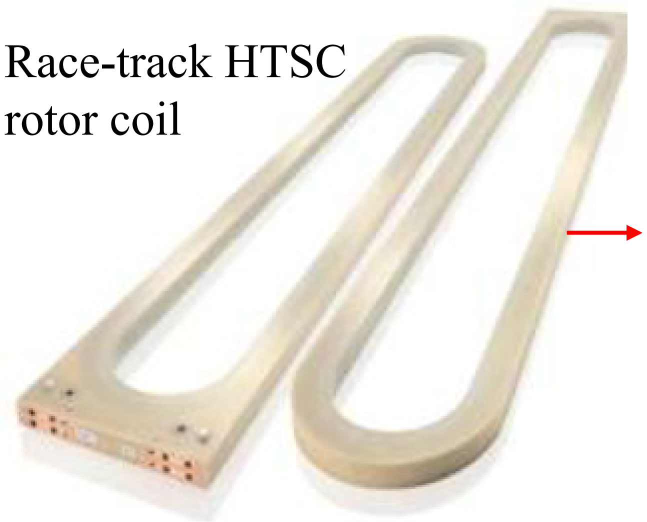
Two-blade wind turbine 3.6 MW,
IWES Fraunhofer, Bremen, Germany

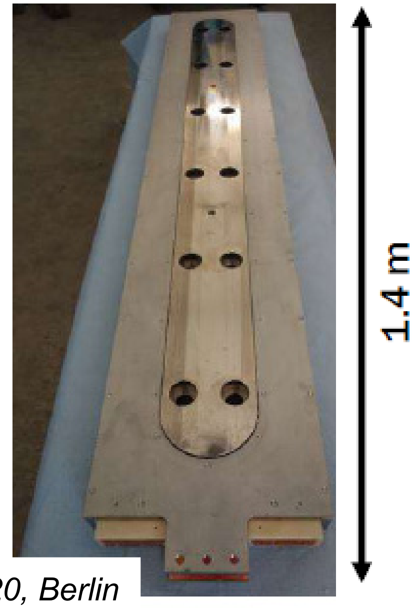
HTSC poles of wind generator *EcoSwing*

Successful off-shore inverter-fed operation

- Wound “race-track” HTSC rotor pole winding of 500 m/pole, tape 20 km in total!
- Coils potted, using commercial resin, glass fiber reinforced.
- Magnetic steel package for pole mounting on rotor Fe-Ni-body.
- Conduction cooled with cold heads at 30 K He-gas.
- Helium gas rotating seal at ambient temperature & rotating coolers.

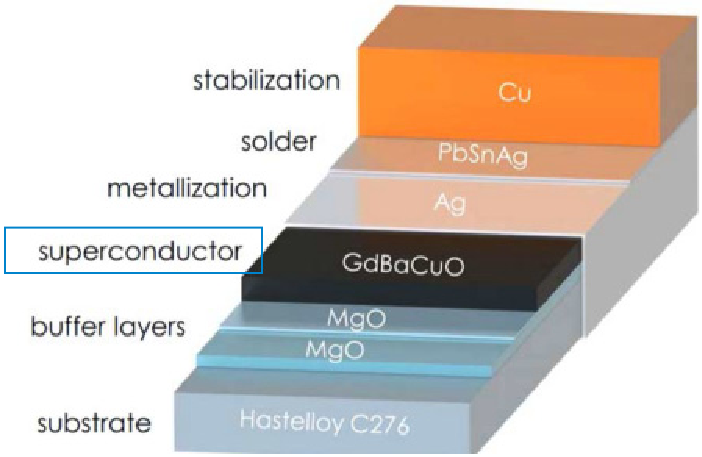
Race-track HTSC rotor coil





Source: EcoSwing Consortium, ZIEHL Conf. 2020, Berlin

$GdBa_2Cu_3O_{7-x}$



Source: THEVA, Germany

HTSC gearless wind generator *EcoSwing*

Assembled rotor & generator cut-view

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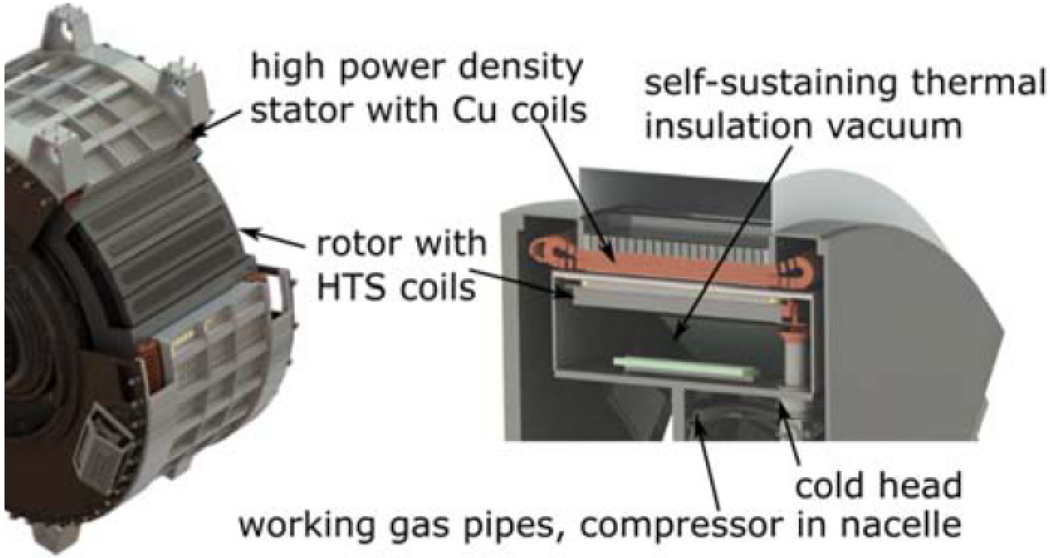
EcoSwing rotor enveloped in three MLI blankets



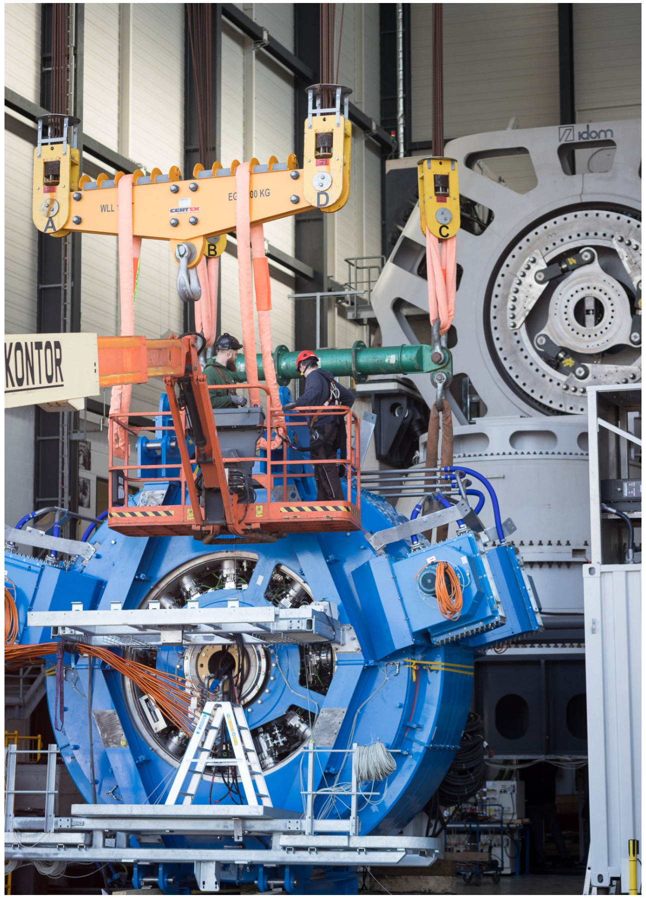
EcoSwing generator cut-view

Thermal Multi-Layer Insulation (MLI, super-insulation): Multiple layers of thin e. g. *Kapton* sheets deposited over silver aluminized *Mylar* in vacuum.

Source: Supercond. Sci. Technol. 32 (2019), 12 pp.

HTSC gearless wind generator *EcoSwing*

Mounting of the generator on the test bed



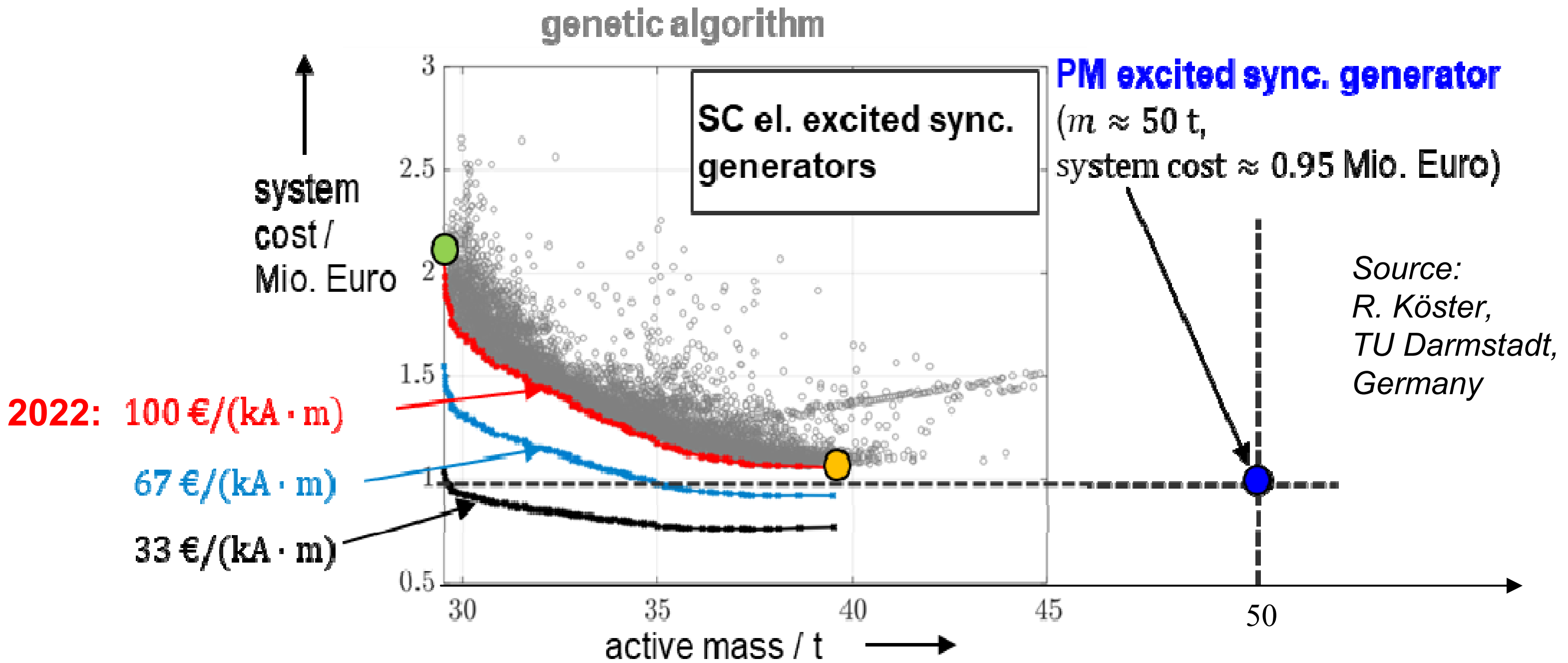
Source: EcoSwing Consortium & IWES, Fraunhofer, Bremerhaven, Germany

Lessons learned from *EcoSwing*

Half-year operation off-shore

- Robust design well-fitted also for rough “off-shore” weather conditions.
- Redundant cooling system.
- Cold rotor iron as „long thermal time constant“!
- Generator mass reduction would be higher,
  if freely chosen machine nacelle dimensions are allowed.
- Unfavorably high pole count machines need too much SC tape.
- As HTSC material is still too expensive, a further cost reduction is needed!

8 MW wind generator, <u>high</u> pole count
PM (cosφ = 0.8) vs. HTSC excitation (cosφ = 1)



- "System cost": - Active generator mass cost (iron, copper, SC or PM),
  - Cooling system 30 K for HTSC GdBCO-tape,
  - Voltage-source IGBT inverter.
- HTSC generator 20 t mass reduction, but SC still too expensive!

15 MW LTSC wind generator
Project 2020-2026: *General Electric / USA*

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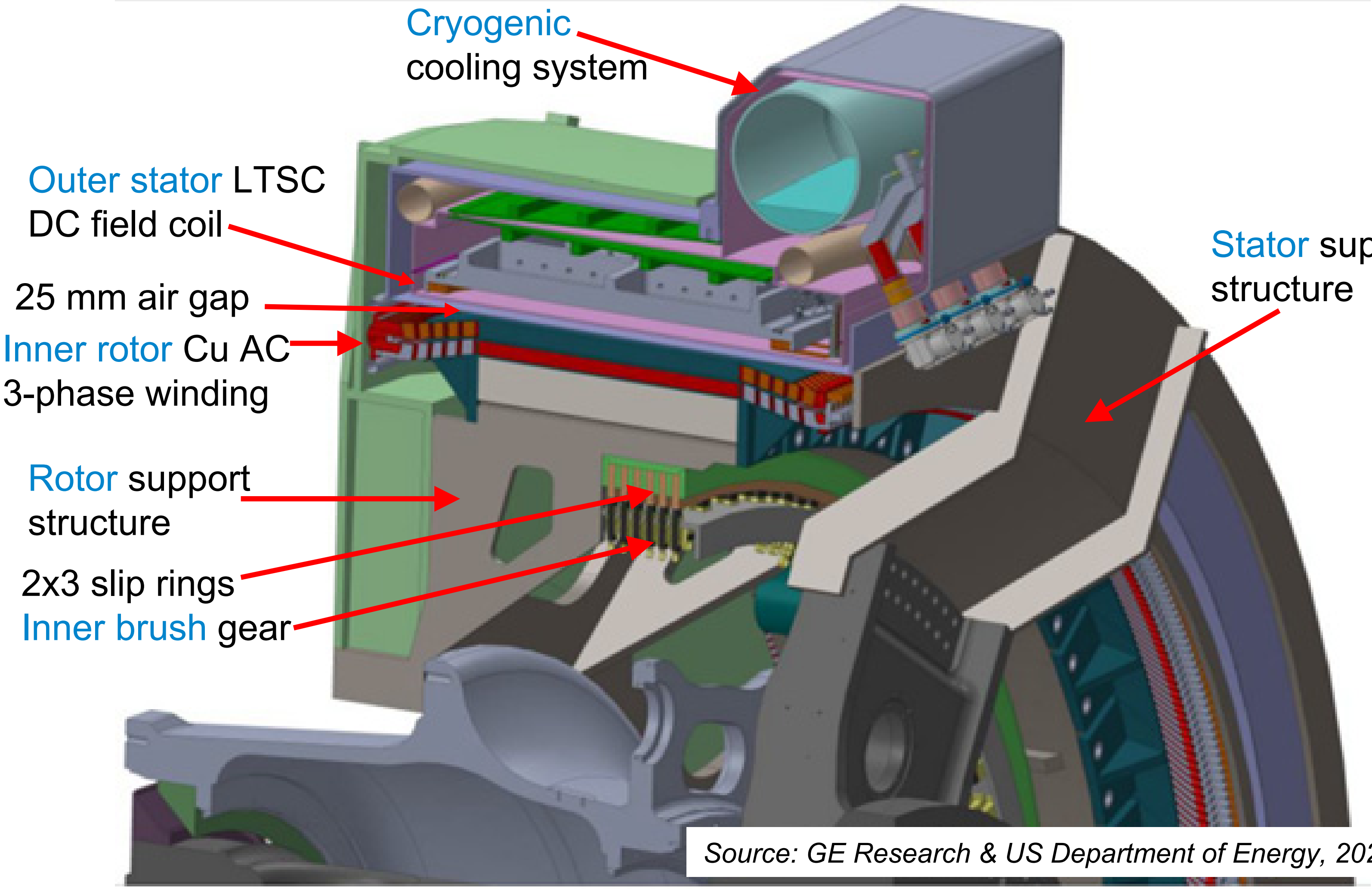
- Total project budget: 53.8 Mio. USD; US DOE share is 20.8 Mio. USD.
- 15 MW low-weight high-power prototype test on a wind turbine 2025-2026.
- Gearless generator: Mass reduction ca. -50%, compared to PM excitation.
- Cheap LTSC NbTi DC field coils in stationary cryostat:
  - No rotating seals for liquid He cooling 4.2 K,
  - No rotating DC current contacts,
  - NO rotating cryostat,
  - NO expensive tons of PM!
- Rotating 3-phase Cu stator AC winding with 3-phase carbon brush system.
- Iron stack as iron back with teeth & slots for 3-phase winding.
- Low rotational speed < 10/min.

Source: GE Research & US Department of Energy, 2021

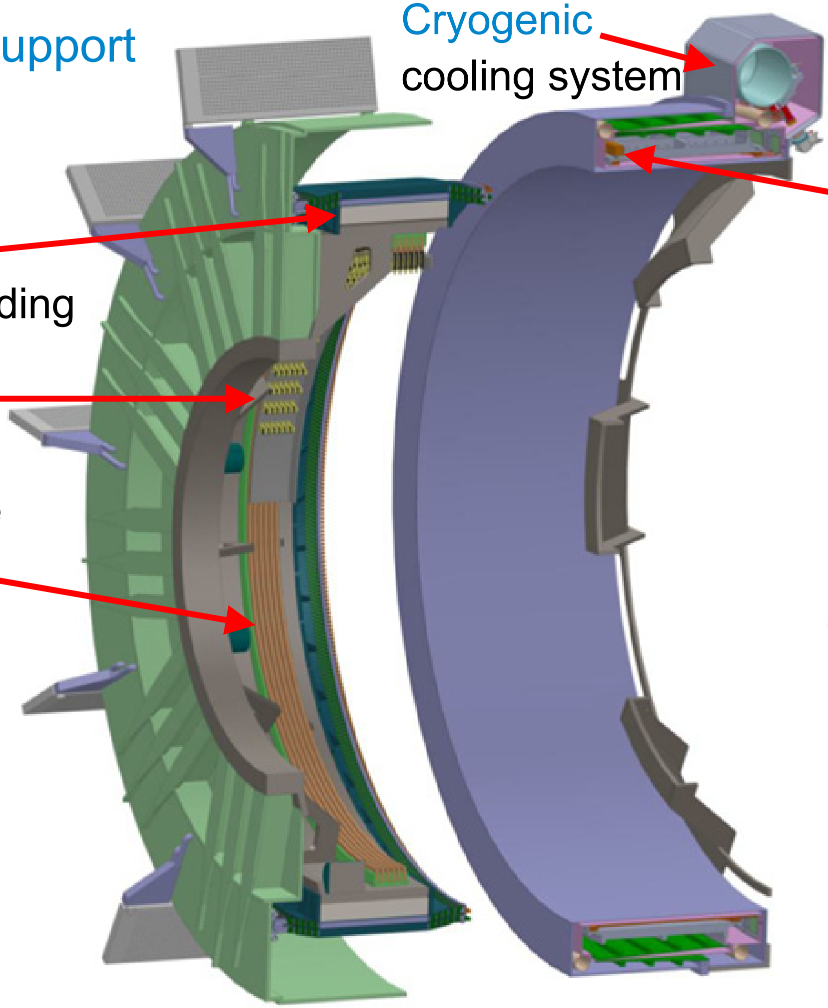
15 MW LTSC wind generator
Stationary LTSC field coil excitation



Source: GE Research & US Department of Energy, 2021

15 MW LTSC wind generator

High-pole count synchronous ring generator



Source:
GE Research &
US Department of Energy,
2021

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- Superconductors of interest for E-machines
- Preferred machine types for SC E-machines
- Wind generator projects on SC E-machines
- Aircraft propulsion projects on SC E-machines
- E-Mobility for fuel-cell operated trucks
- Conclusions

"Hybrid electric" aircraft propulsion

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- Series-hybrid electric propulsion for civil aircraft
- Regional planes:
  - Take-off: 8 MW electrical propulsion power (4 x 2 MW) 10 … 30 min.
  - Propeller rotational speed 1000/min, cruising power: 60 % … 75 %
- Short range planes:
  - Take-off: 20 MW electrical propulsion power (4 x 5 MW) 10 … 30 min.
  - Propeller rotational speed 800/min, fan drive: 2000/min

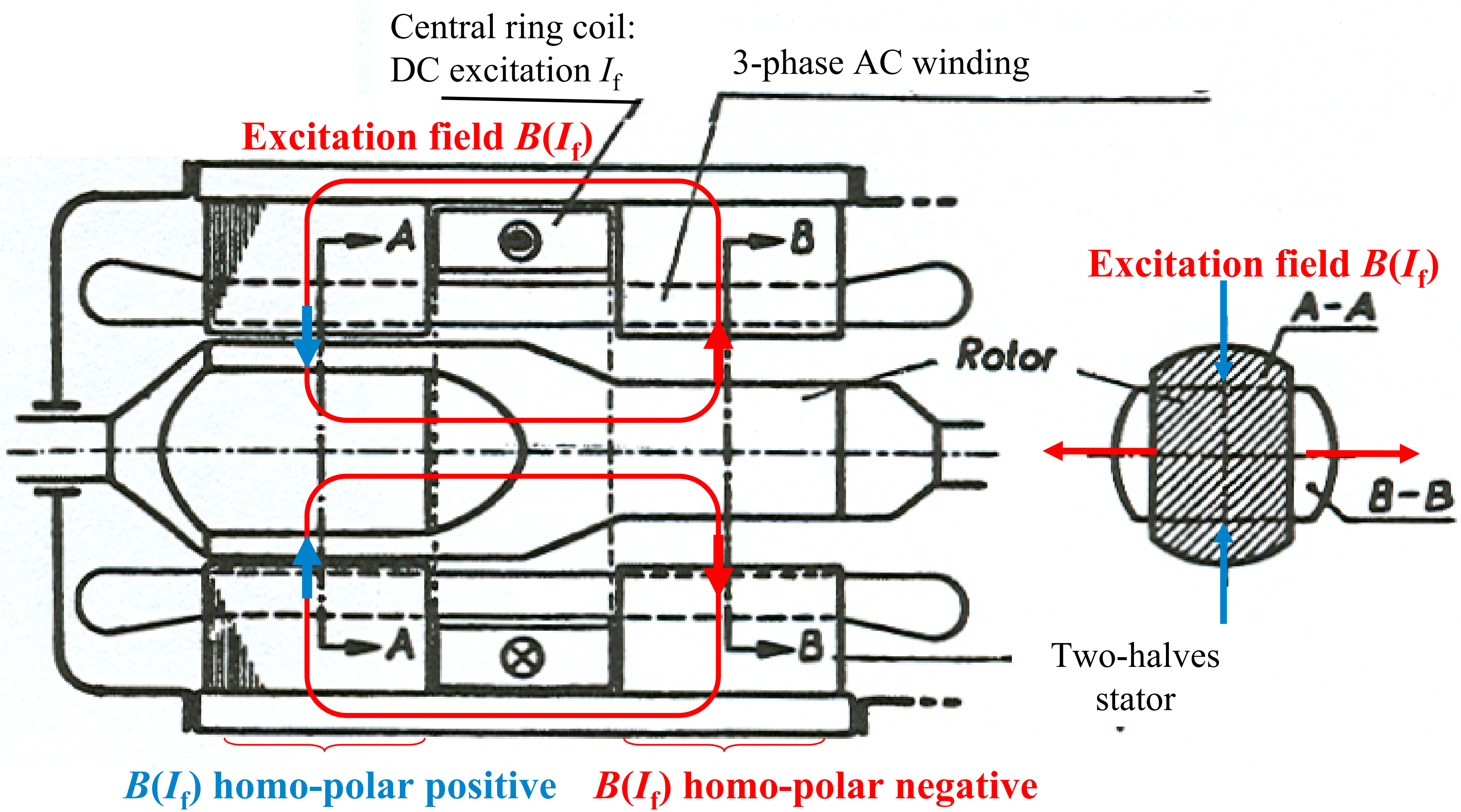
Source: Airbus/Rolls-Royce/ Siemens 2020

Hybrid electric aircraft demonstrator **E-Fan X**:
One 2 MW PM el. synchr. motor should replace one Lycoming ALF502 turbofan

Trends in E-Machines Using Superconductors
Aircraft propulsion projects on SC E-machines

- Homo-polar synchronous machines
- Hetero-polar synchronous machines

Homo-polar high-speed sync. machine
Stationary D.C. and A.C. winding

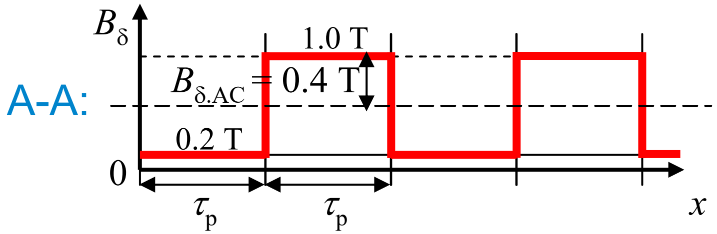


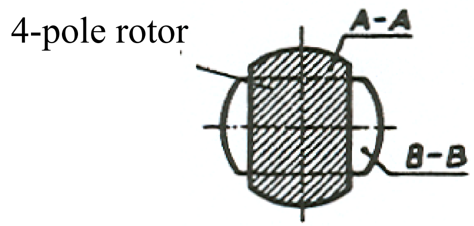
Source: H. Kleinrath, Stromrichtergespeiste Drehfeldmaschinen, Springer, Wien, 1980

Homo-polar high-speed sync. machine

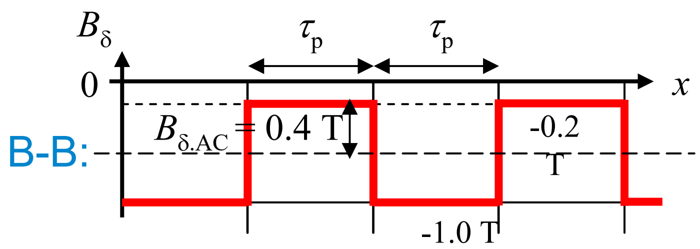
NC: Radial air gap flux density $B_\delta(I_f)$ at no-load ($I_s = 0$)

a) Rotor half A-A: Homo-polar positive 4-pole field

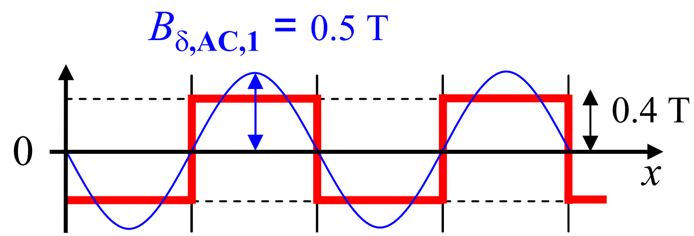




b) Rotor half B-B: Homo-polar negative 4-pole field

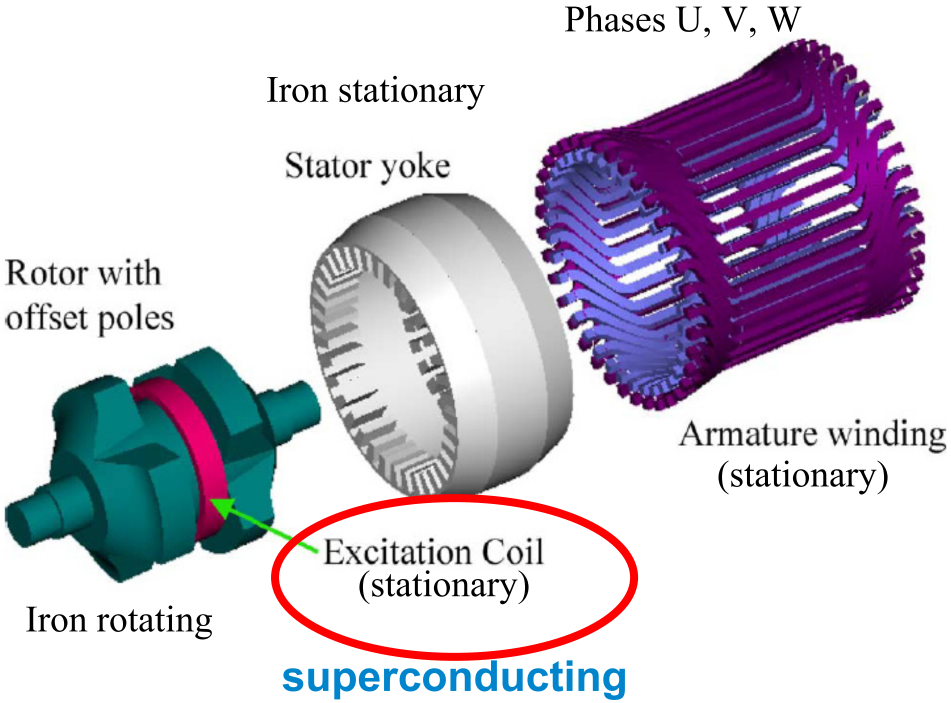


a) + b) Rotor field:



- 4-pole AC air gap field component $B_{\delta,AC}$ **is IN PHASE** for both motor halves A-A, B-B
- The **fundamental wave** 4-pole AC air gap field component $B_{\delta,AC,1}$ induces the stator 3-phase winding with back EMF $U_p(I_f)$ as in rotor-excited synch. machines!

Homo-polar high-speed sync. machine
Machine elements with slotted stator iron



Source: K. Sivasubramaniam et al., IEEE, 2009

Homo-polar SC high-speed sync. machine
Pros and Cons for SC operation

+ No rotor winding or magnet = robust rotor for high speed

+ Variable SC excitation via I_{f}

+ No slip rings, no rotating seals for coolant in cryostat

+ Standard field oriented d-q-stator current control for inverter-feeding

+ Stationary SC field coil in cryostat not exposed to centrifugal forces

+ Simple SC solenoid coil of BSCCO or REBCO tapes (RE: Y or Gd or Eu)

- Massive rotor: Slot ripple eddy current losses in rotor surface

- Saturation limit of *B* in stator teeth 2 T $\Rightarrow$ Air-gap flux density max. 1 T:
  Low air-gap flux density $B_{\delta,\mathrm{AC},1} \approx 0.5\ \mathrm{T} \Rightarrow$ low torque/volume $M_{\mathrm{e}}/V \sim A_{\mathrm{s}} \cdot B_{\delta,\mathrm{AC},1}$

Homo-polar high-speed sync. machine
Benefits of SC excitation

- Stator and rotor iron, stator 3-phase copper winding

a) either in iron slots $\Rightarrow B_\delta$-limit = 1 T due to tooth saturation
$\Rightarrow B_{\delta;AC,1} = 0.5$ T

or

b) air-gap winding with increased current loading $A_s' = 1.8 \cdot A_s$, $\boxed{\times 1.8}$
then no teeth
$\Rightarrow B_\delta$-limit = 2 T due to yoke saturation
$\Rightarrow B_{\delta;AC,1} = 1$ T $\boxed{\times 2.0}$

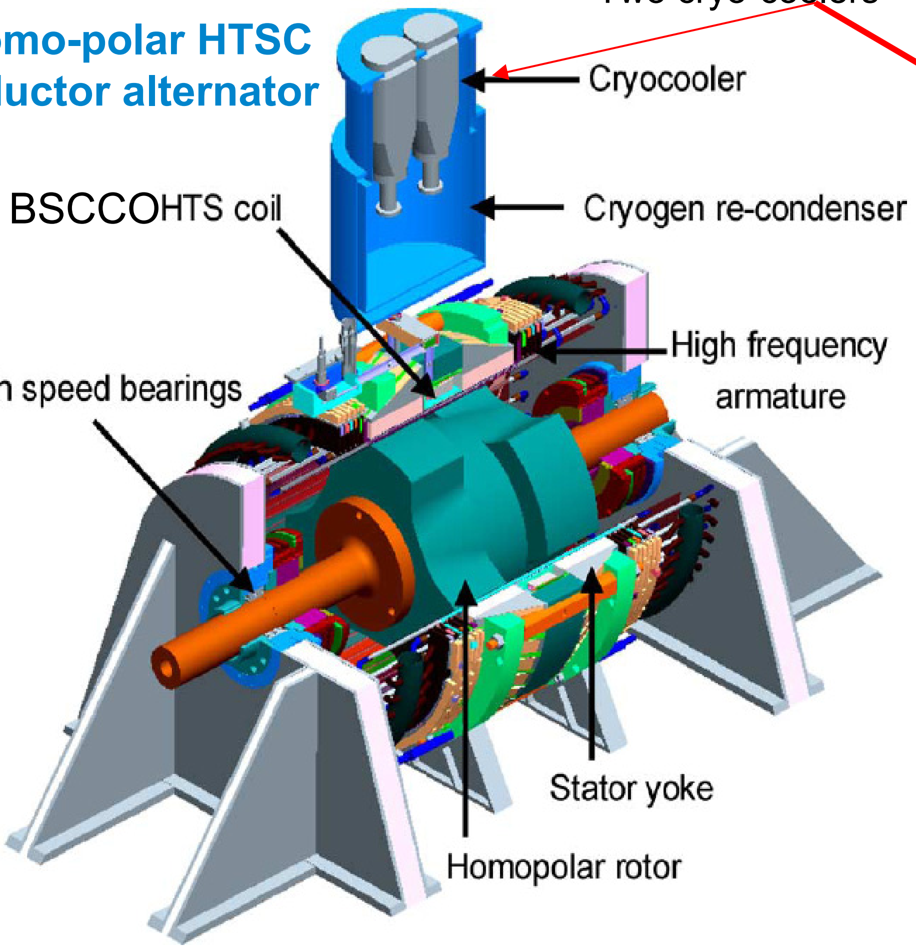
$\boxed{\text{Torque/volume} \sim A_s' \cdot B_{\delta;AC,1} \text{ increased by 360\%!}}$ $\boxed{3.6 = 1.8 \times 2.0}$

Homo-polar el. aircraft sync. generator

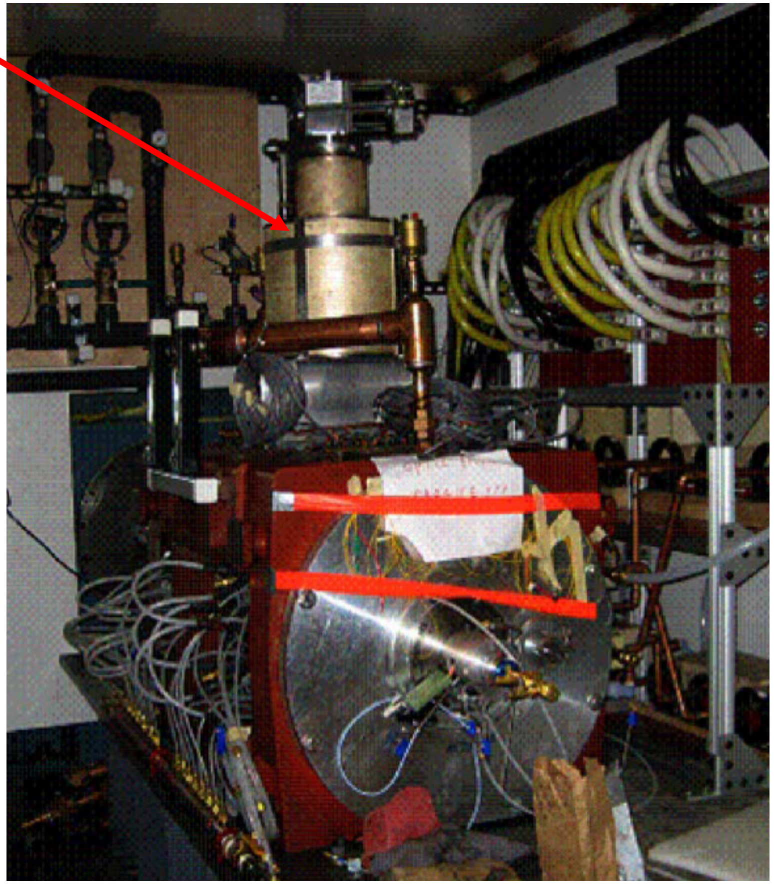
8.8 kW/kg, 10 000/min, 1 MW, *General Electric/USA*

Two cryo-coolers = redundancy: Liquid Neon boiling **27 K**

Homo-polar HTSC inductor alternator



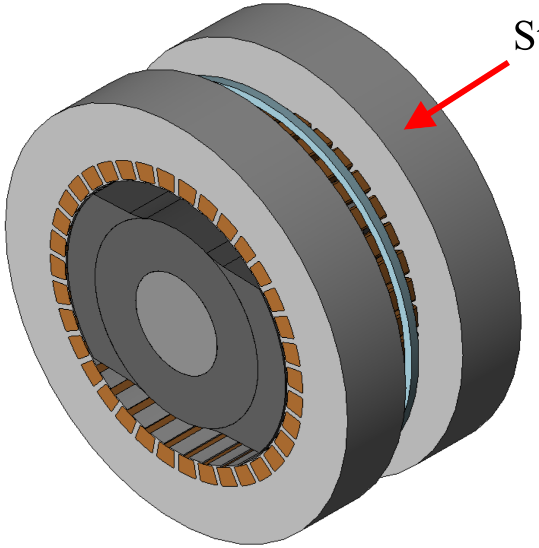
Source: K. Sivasubramaniam et al., IEEE, 2009



1 MW HTSC-generator test-rig

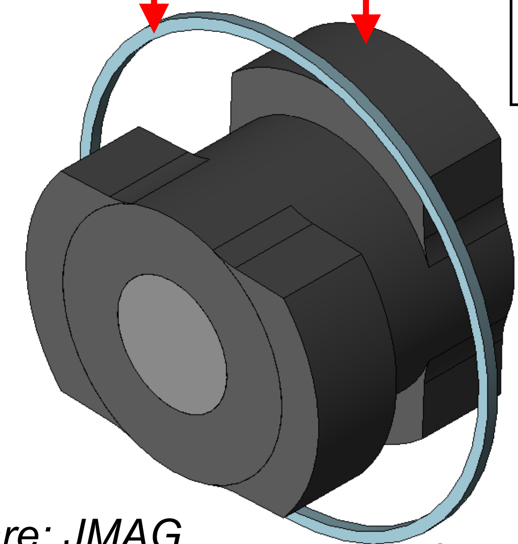
Small-sized homo-polar HTSC motor

Four-pole high-speed motor 120 kW, 30 000 rpm

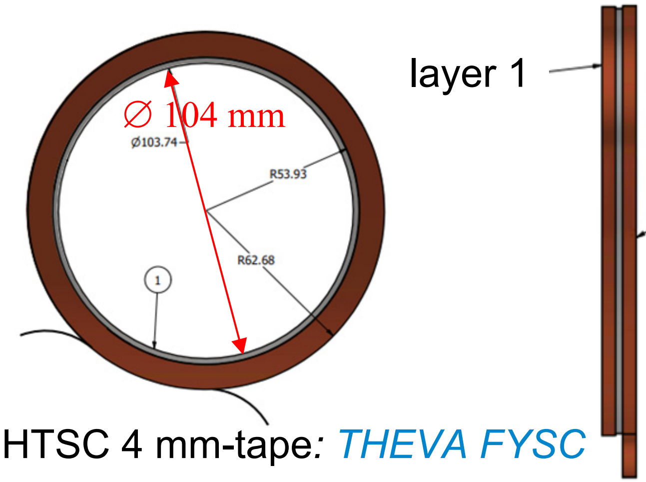


HTSC excitation winding 70 turns

Massive rotor iron



Pancake coil, HTSC GdBCO



HTSC 4 mm-tape: *THEVA FYSC*

$$2p = 4$$
$$n_N = 30000 \text{ rpm}$$
$$P_N = 120 \text{ kW}$$
$$M_N = 38.2 \text{ Nm}$$
$$f_N = 1000 \text{ Hz}$$

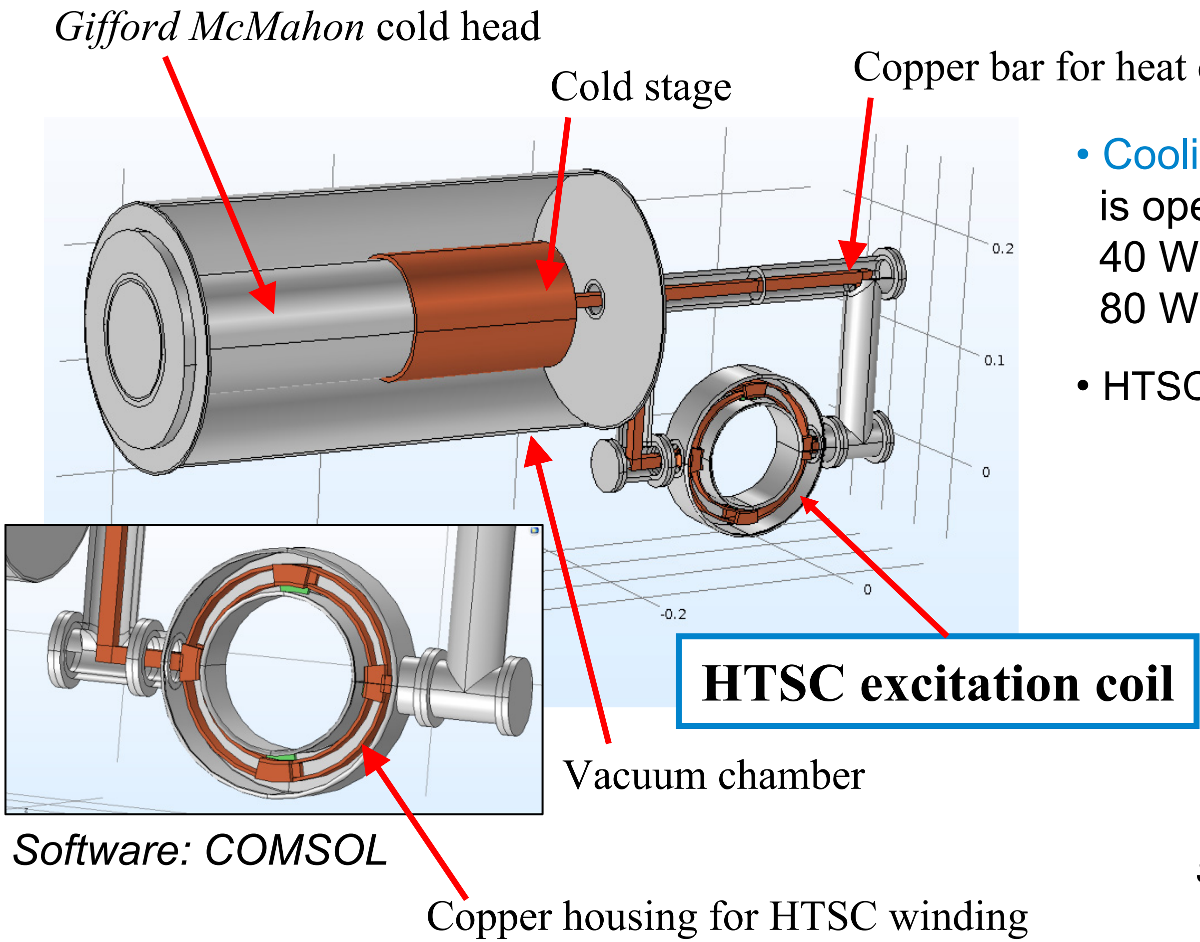
$$l_{Fe} \approx 80 \text{ mm}$$
$$d_{si} \approx 150 \text{ mm}$$

$$v_{u,max} \approx 288 \text{ m/s}$$

Software: JMAG

Source: TU Darmstadt, Germany

Small-sized homo-polar HTSC motor
Conductive cryogenic cooling system



Software: COMSOL

- Cooling capacity, when compressor is operated at 50 Hz:
  40 W at 20 K,
  80 W at 30 K.
- HTSC tape GdBCO at 30 K, 0.5 T

$$\frac{I_f}{I_c} = \frac{1}{1.3}$$

$$N_f = 70, I_{f,max} = 430\ \text{A}$$

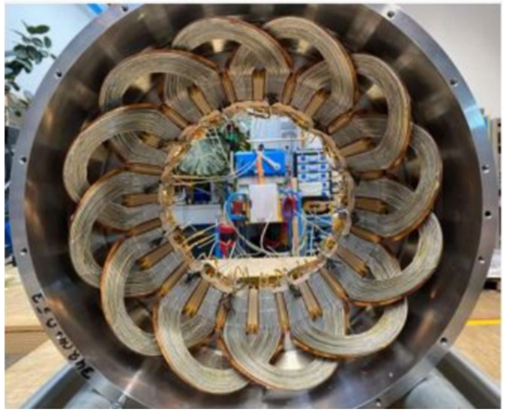
Source: TU Darmstadt & Sumitomo Heavy Industries, Germany

Trends in E-Machines Using Superconductors
Aircraft propulsion projects on SC E-machines

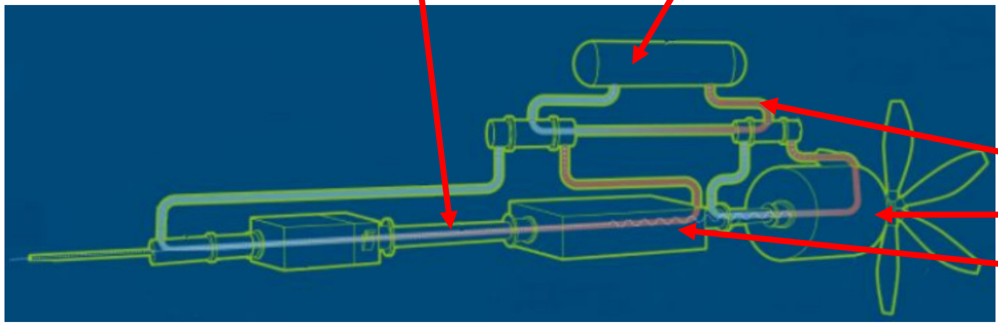
- Homo-polar synchronous machines
- Hetero-polar synchronous machines

HTSC propulsion motor for electric aircraft
ASCNED project, *AIRBUS company*

- Project phase 1: 2020 … 2023, phases 2 & 3: 2023 … 2028.
- 500 kW power-train ground demonstrator ("laboratory level"):
  - Superconducting distribution system: AC-/DC-cables, fault current limiter,
  - Superconducting motor, cryogenic inverter power electronics,
  - LH_2-cooling.
- Aims:
  - Total weight reduction by factor 2…3.
  - Power-train efficiency > 97%.



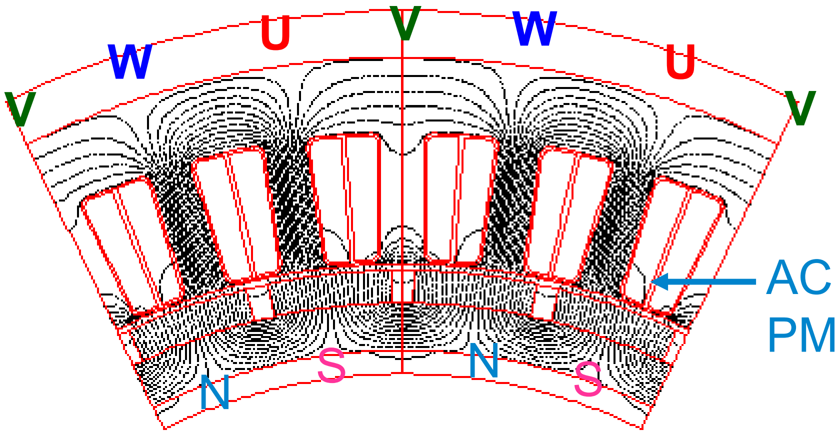
Motor 8-pole air-gap
3-phase distributed winding



Source: Ybanez, L. (Airbus 2021): IEEE CSC & ESAS Superconductivity News Forum

Tooth-coil HTSC YBCO tape stator winding
q = ½ slots per pole & phase, rotor PM

- Stator poly-phase tooth-coil winding with HTSC YBCO tapes
- Short winding overhangs = reduced expensive HTSC tape length
- Compact stator (non-rotating) cryostat
- Stator slotting shields the HTSC tape from rotor PM field



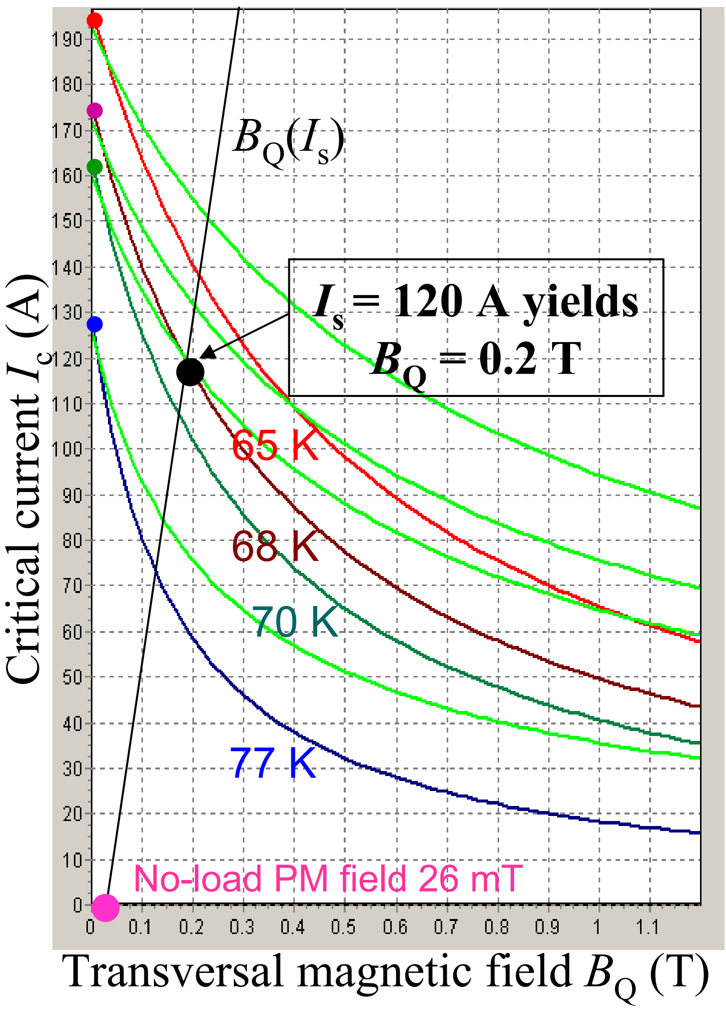
4 poles of PM rotor no-load field, $I_s = 0$

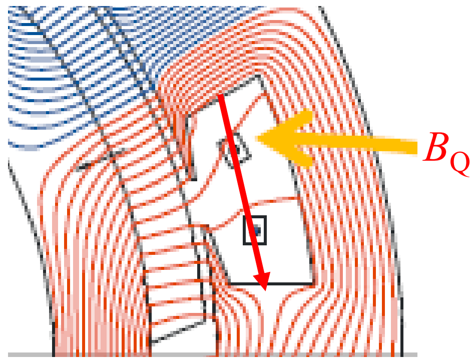
HTSC YBCO tape test coil

Source: Company Oswald, Miltenberg, Germany

Tooth-coil HTSC YBCO tape stator winding

SC stator 3-phase winding, self-field exposition





Slot transversal field B_Q at $I_s > 0$

Source: Company Oswald, Miltenberg, Germany

HTSC propulsion motor for electric aircraft
ASuMED: Tooth coils q = ½, 3 phases, 8 poles

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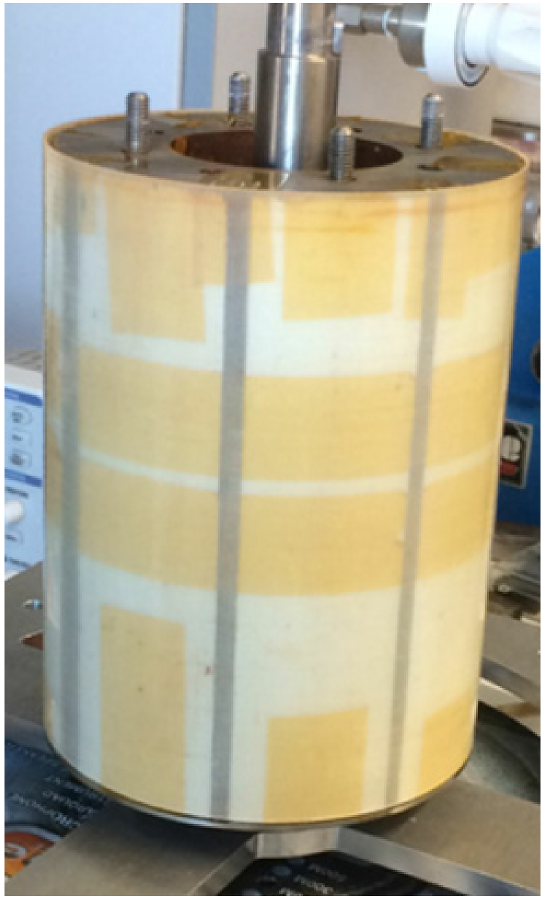
- Fully SC inverter-fed 8-pole motor:
  Power density up to ~ 20 kW/kg

- Instead of PM: YBCO-HTSC-stacks
  at rotor side (“trapped field” magnets)

- 4 mm x 1 µm-YBCO-layer as AC tooth coil
  stator winding, q = ½, total 2 km!

- Magnetization of HTSC-stacks
  with coils on stator side

- Cooling via pressurized liquid H_2
  27 K … < 33 K
  (H_2 “critical point“ 33 K, 13 bar, 30 g/dm^3)

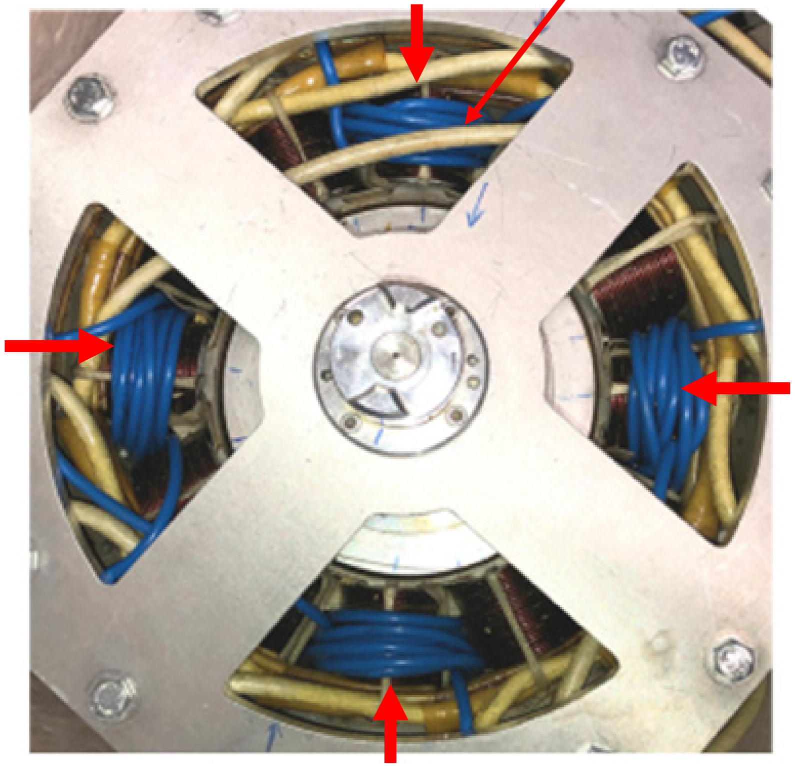


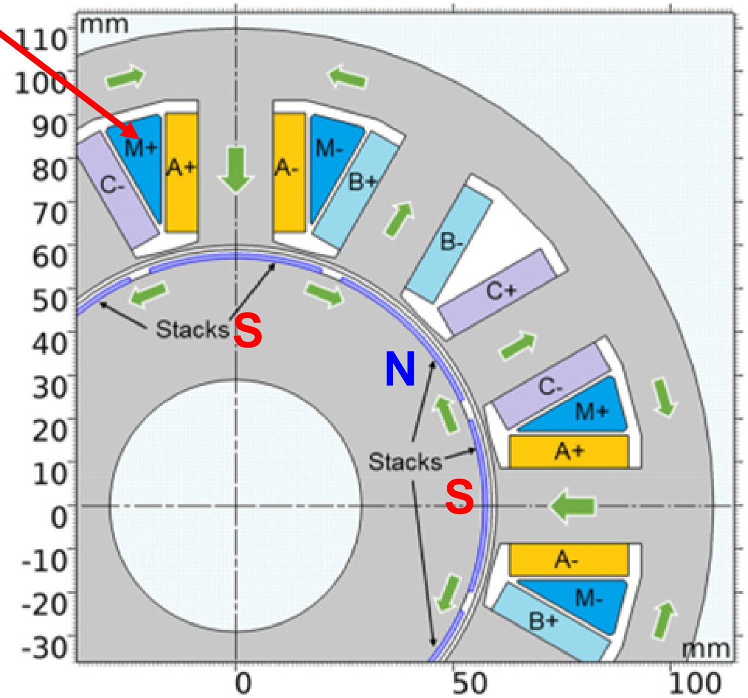
Rotor assembly with 8 HTSC stacks

Source: Climente-Alarcon et al., ASuMED Consortium, 2020

HTSC propulsion motor for electric aircraft
ASuMED: Magnetizing 8 rotor HTSC stacks

4 magnetisation coils for 8 rotor HTSC stack poles





- $2p = 8$, $m = 3$ phases, $Q_s = 12$ stator slots

Source: Climente-Alarcon et al., ASuMED Consortium, 2020

Trends in E-Machines Using Superconductors
Contents

Mobility for fuel-cell operated trucks
Liquid hydrogen for fuel cell operation

- Liquid hydrogen LH_2
- Energy density 2.4 kWh/dm^3 at 1 bar, -253°C (20 K)

Average power long-range truck	94 kW
Efficiency fuel cell	60 %
Hydrogen fuel requirement per hour	4,7 kg/h
Tank capacity LH_2 for 10 h mission	660 l
Power for evap. & warming up LH_2	5,8 kW
Efficiency electric motor	95 %
Motor loss power	4,7 kW

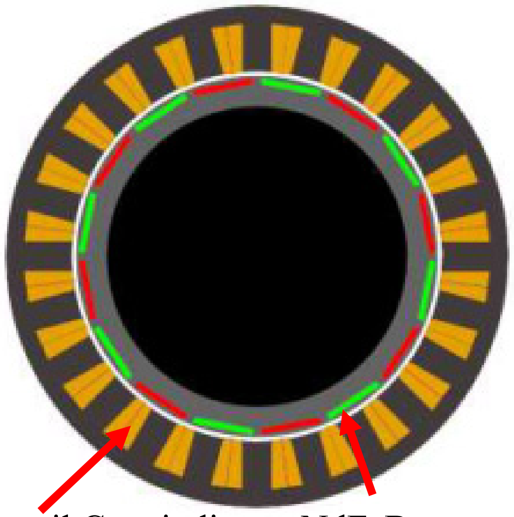
→ Use of a HTSC synchronous motor at 20 K

Source: Wolf, M. J.: AppLHy! – Wasserstoff u. Supraleitung, ZIEHL VIII, Berlin, 5.4.2022

Mobility for fuel-cell operated trucks

16-pole motor, $q = ½$ slots /pole & phase, at 20 K

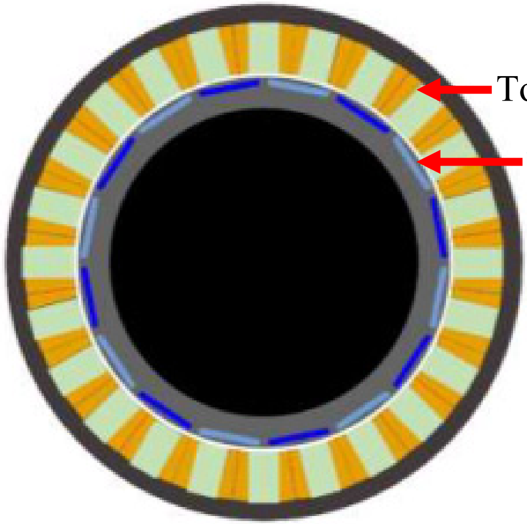
- Stator water-jacket or oil cooling



1) *Honda Accord*

conventional e-motor of a passenger car[1]	
Outer diameter:	0.3155 m
Rotational speed:	1500 rpm
Power:	22 kW
Power density:	1.5 kW/kg

- Superconducting stator and rotor
- LH_2 : Liquid or vaporization cooling < 20 K



LH_2 & HTS e-Motor	
Outer diameter:	0.3155 m
Rotational speed :	1500 rpm
Power:	202 kW
Power density:	15 kW/kg

Rough estimate:

- Flux density increase 250%
- Stator current loading 400%
- Torque density: $M_e \sim A_s \times B_\delta$
  Increase by $2.5 \times 4.0 = 10$!

Source: Wolf, M. J. (KIT), ZIEHL VIII, Berlin, 5.4.2022

Trends in E-Machines Using Superconductors
Contents

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- Superconductors of interest for E-machines
- Preferred machine types for SC E-machines
- Wind generator projects on SC E-machines
- Aircraft propulsion projects on SC E-machines
- E-Mobility for fuel-cell operated trucks
- Conclusions

Trends in E-Machines Using Superconductors
Conclusions

- Mainly SC electrically excited synchronous machines with SC DC rotor winding

- No commercial use until now, only prototypes for (field) tests

- High temperature superconductors need ca. 30 K cooling due to high *B*-field

- SC machines allow for
  reduced mass, increased efficiency, unity power factor, huge overload torque,
  but are still expensive especially at high pole count.

- Reliability issue of total cryostat system is crucial for robust operation.

- Current interest:
  Ship propulsion motors & generators due to reduced size,
  Wind generators: No expensive magnets, reduced size at increased power,
  High speed generators & motors for „hybrid-electric“ aircraft.

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Thank you for your attention !