2. Application of superconductors for electrical energy converters

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2.2.1 Fault current limiter

2.2.2 Superconducting power cables

2.2.3 Superconducting magnetic energy storage (SMES)

2.2.4 Superconducting power transformers

2.2.5 Rotating electrical machines with superconductor winding

2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

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- Superconducting synchronous machines with electrical excitation

- Low-temperature superconductor excitation winding for synchronous machines

- High-temperature superconductor excitation winding for synchronous machines

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2.2.5 Superconducting rotating electrical machines

Energy conversion

● **Driving peripheral tangential force**:

Lorentz **force** *F***:** Current-carrying conductor (current I, conductor length l) in magnetic field B_δ in air gap between stator/rotor: Force F acts normal to the direction of current flow and the field direction.

z conductors at periphery, lever arm d/2 $\Rightarrow$ electromagnetic torque M_e:

$$\vec{F} = I \cdot (\vec{l} \times \vec{B}_\delta) \qquad \rightarrow F = I \cdot l \cdot B_\delta \qquad \rightarrow M_e = z \cdot I \cdot l \cdot B_\delta \cdot (d/2)$$

Reluctance force *F*: Slot-tooth structure ("**reluctance**") modulates air-gap field. Modulated field generates *Lorentz* forces with current coils.

● **Dimensioning rule:** $\qquad M_e \sim d^2 l \cdot A \cdot B_\delta \qquad$ "**Electric loading**": $A = \dfrac{z \cdot I}{d\pi}$

   Mechanical power: $\qquad P = 2\pi n \cdot M_e \qquad$ Rotor speed n

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Electrical machines: Increase of power *P*

$$P = 2\pi n \cdot M_e \qquad\qquad M_e \sim d^2 l \cdot A \cdot B_\delta$$

- **Speed *n* increased,** while machine's dimensions are unchanged: in case of large machines: rising centrifugal forces, hence not always possible

- **Dimensions *d*, *l* increased:** Diameter enhancement: Centrifugal force limit, length enhancement: Length limit due to the "natural bending frequency"

- **Electric loading *A* increased:**
  increased ohmic losses (I^2R): more intensive cooling necessary

- **Air-gap flux density B_δ increased:**
  Limited by the saturation of the iron teeth to maximum ca. 1.1 T, because in the teeth the magnetic flux fringes: Flux density increases to about the doubled value 2.2 T, yielding high iron saturation.

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Options for increasing power by SC

⇒ **Superconductive three-phase winding:** Electric loading increased, AC operation: AC losses in SC must be taken into account.

⇒ **Superconductive DC excitation winding:** Magnetic field increased in air gap, stator teeth removed, additional stator coils, electric loading doubled ("air gap winding"). Resulting large magnetically effective air gap needs high exciter Ampere-turns, which is possible without losses.

⇒ **Supra magnets:** Tubes of flux in solid superconductors (*Shubnikov* phase) with high *B* as "frozen flux". Supra currents prevent change of flux:

$$u_i = -d\Phi / dt = 0 \qquad \rightarrow \Phi = const.$$

⇒ **Increasing of the reluctance effect: Only small flux penetration into SC.** So SC in the inter-pole gaps amplifies the reluctance effect.

⇒ **Hysteresis torque:** Hysteresis loss in HTSC-Y(123) solid rotor: Phase shift between stator and rotor fields leads to slip-independent torque. In synchronous operation this is like a "permanent magnet" torque.

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Chances due to superconductors

- Increase of the air-gap flux density B_δ and the electric loading A

- Smaller dimensions of the E-machine: At equal torque M_e:
  Doubled electric current loading: Halved active masses

- Reduction of losses

  - Elimination of the ohmic DC losses in SC windings,

  - Lower total iron losses due to smaller machine dimensions

  - Lower gas friction losses due to smaller rotor surface

- In spite of increased cooling power (e .g LHeI liquefaction) the total efficiency increases:

  LTSC: economical solution above $P = 300$ MVA

  HTSC: economical solution above $P = 10$ MVA, because less cooling power

  BUT: HTSC wire BSCCO have still too low critical flux density at 77 K

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Machine types for the use of superconductors

$\Rightarrow$ *Homo-polar machine:* "Pure" DC machine, ideal for SC, but due to its design only low voltages/high currents and a big slip-ring system $\Rightarrow$ only partly interesting.

$\Rightarrow$ *DC machine:* Rotor AC current, commutator and carbon brushes, sparking due to "reactance voltage"; only DC excitation winding adequate for SC $\Rightarrow$ hence for SC application less adequate.

$\Rightarrow$ *Poly-phase AC machines:* Stator: AC winding: AC loss detrimental for SC operation, hence mostly conventional Cu winding.

  - **Asynchronous machines:** SC rotor cage cannot be operated asynchronously, because at ideal SC with $R_r = 0$ we get with zero rotor voltage $u_r = 0$:

$$u_r + u_i = R_r i_r = 0 \cdot i_r = 0 \qquad u_i = -d\Phi / dt = 0 \qquad \rightarrow \Phi = const.$$

Rotor frequency $f_r = s \cdot f_s$ is zero: **Slip *s* is always zero = no asynchronous mode.**

  - **Synchronous machines**: Rotor current: **DC** supplied to the rotor winding via slip rings. Rotor winding can be designed as SC winding

$\Rightarrow$ *Synchronous machine appropriate for SC operation.*

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**Institute of Electrical
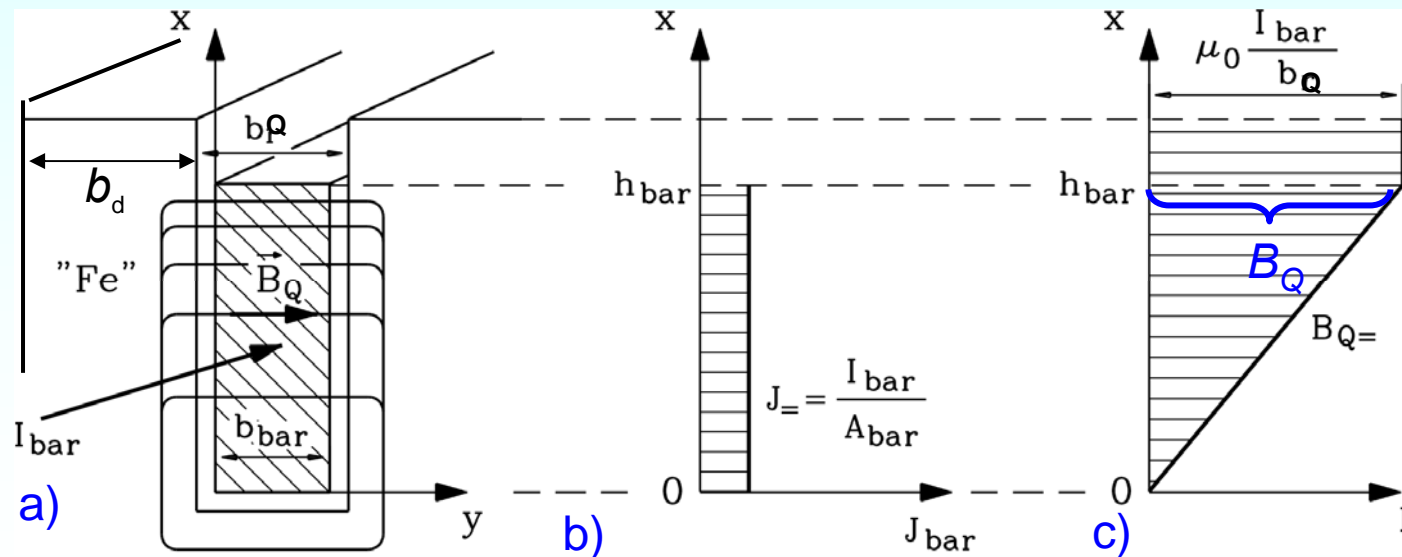Energy Conversion**

Three-phase AC winding superconductive?

- **Self-field in the slot** is at high electric loading A high. Often slot and tooth width are nearly equal ($b_Q \cong b_d$): Slot Ampere-turns: $\Theta_Q = A \cdot (b_Q + b_d) \cong 2A \cdot b_Q$

Slot stray field (self-field) across the slot:

$$B_Q = \mu_0 H_Q = \mu_0 \frac{\Theta_Q}{b_Q} \cong \mu_0 \cdot 2A$$

Example:

Electric loading A = 2000 A/cm: slot field B_Q = 0.5 T is high, hence *high AC losses in the slot conductors, so usually no SC stator winding!*

Slot stray field:

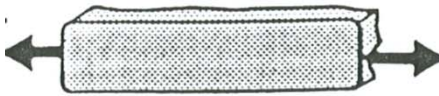a)   Flux lines

b)   Current density distribution in the slot conductor,

c)   Field distribution

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DC excitation winding superconductive?

- Current densities in DC excitation windings of large synchronous machines

Cooling:	Air indirect	Hydrogen direct	Water direct	LHeI Helium
Heat transfer				
Conductor cross section for the same current				
Current density A/mm^2	3	13	16	220
I^2R Joule losses kW/m^3	200	3500	5200	0

Source:

Siemens AG

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Loss density in the DC excitation winding

- Air cooling indirectly: $P_d / V = J^2 / \kappa_{Cu,90°C} = (3 \cdot 10^6)^2 / (45 \cdot 10^6) = 200 \text{kW/m}^3$

Source:

Siemens AG

Cooling:	Air indirect	Hydrogen direct	Water direct	LHeI Helium
Heat transfer				
Conductor cross section for the same current				
Current density A/mm^2	3	13	16	220
I^2R **Joule losses** kW/m^3	200	3500	5200	0

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Superconducting homo-polar machines

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Faraday´s disc

- It is a special case of a homo-polar machine, because *B* permeates the disc only in one direction ("one pole" = "homo"polar)!

Permanent magnet   **Copper disc**

Ω_S

$\vec{B}$

S — N

Conductive shaft

V U

Sliding contact

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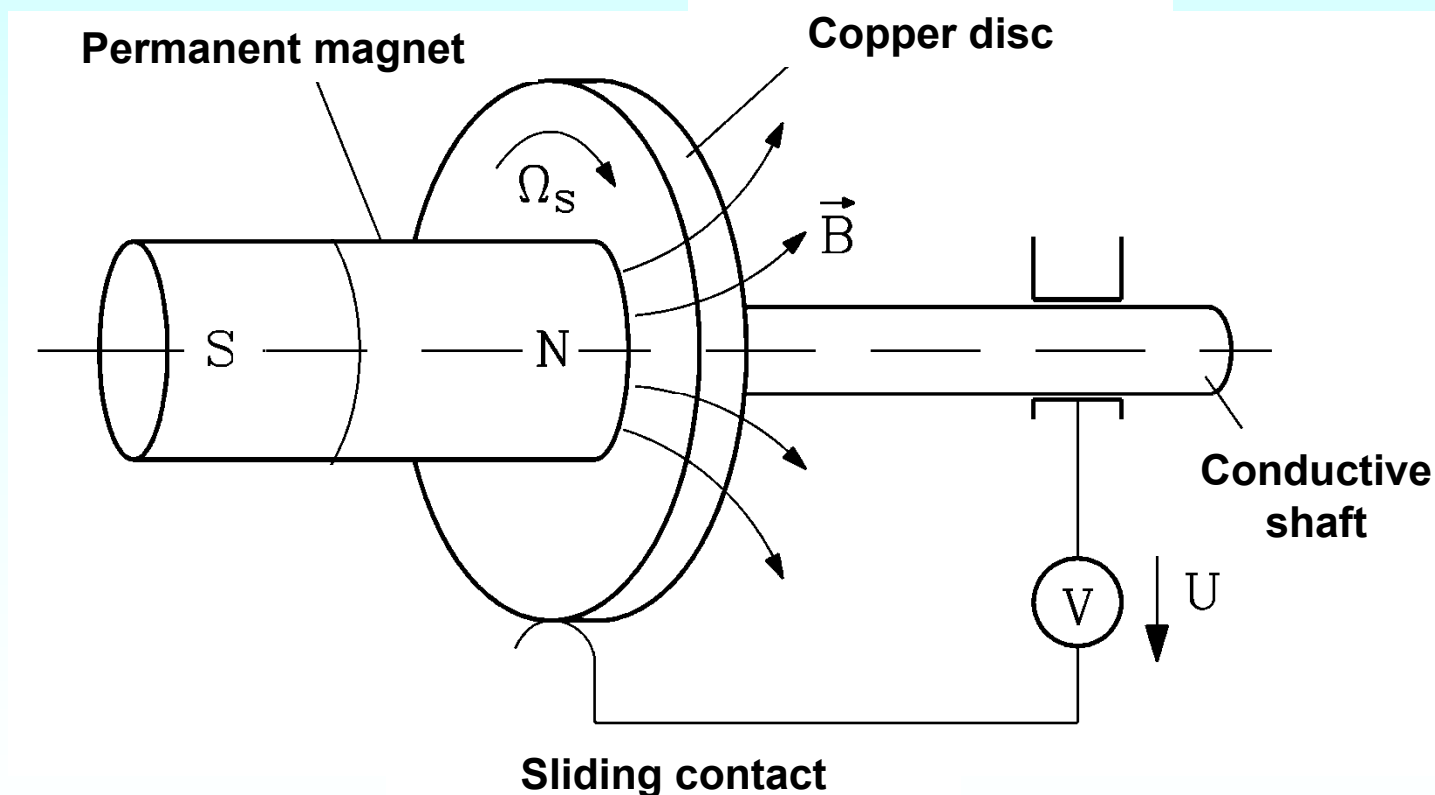
Faraday's disc – voltage induction

- *Faraday*'s conductive disc: Angular velocity $\Omega_m = 2\pi n$,

    rotationally symmetric magnetic field $B(r)$:

    - **Induction of motion:**

    $$\vec{E}_b = \vec{v} \times \vec{B} \quad \rightarrow E_b(r) = v(r) \cdot B(r) = \Omega_m r \cdot B(r)$$

    - **Induced DC voltage:**

    $$U_i = \int_0^R \vec{E}_b \bullet d\vec{s} = \int_0^R E_b(r)dr = \int_0^R \Omega_m B(r)rdr$$

- **Power conversion:**

    $B(r)$ with a mean value B estimated:

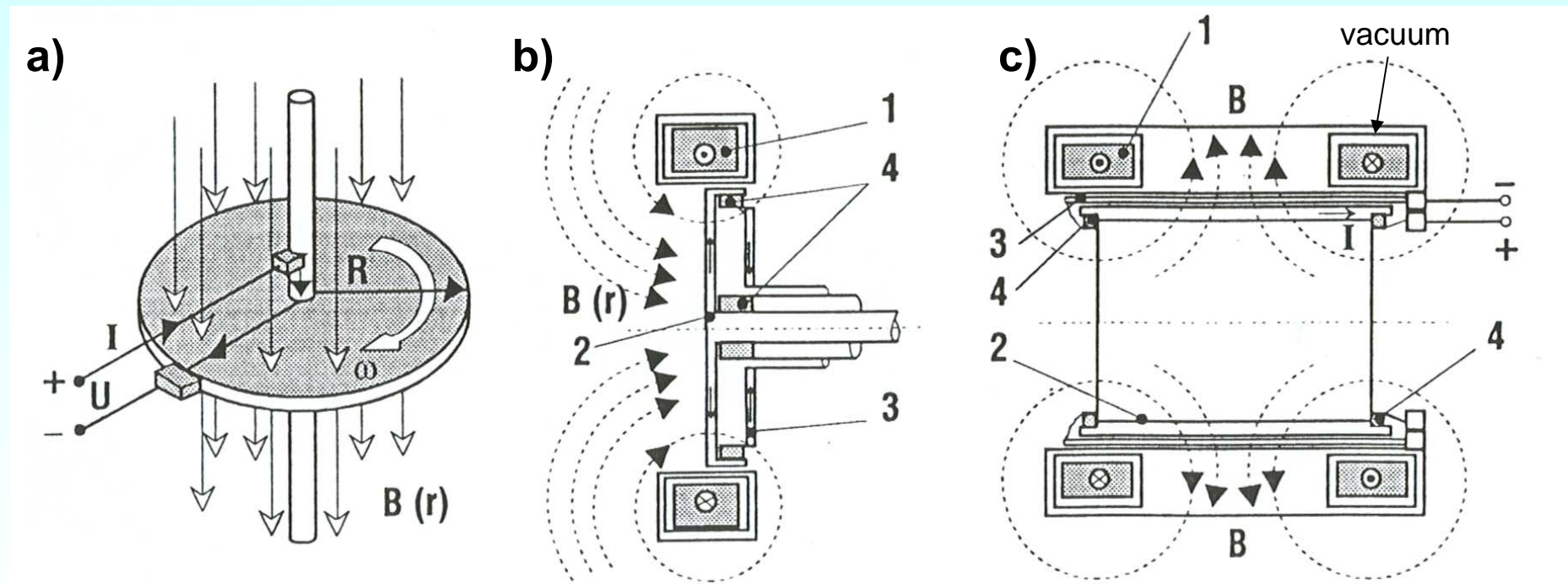 $$U_i = \Omega_m \cdot B \cdot R^2 / 2 \qquad \rightarrow P_i = U_i I$$

- **The excitation winding can be produced of SC material.**

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Faraday´s disc and homo-polar machine

a) Principle: *Faraday*'s disc, Homo-polar machine: b) Disc type, c) Drum type

1: Superconductor coil with cryostat, 2: rotating disc or drum, resp.,
3: fixed reaction disc or drum, resp., 4: Sliding brush contact

B: homo-polar flux density
U: terminal DC voltage

*Komarek, P.:
Teubner,
Stuttgart, 1995*

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Superconductive homo-polar machines

- **DC coils of the stator made of SC material: *B* excited lossless, so it may be considerably increased** from e.g. 1 T to 3 T. At the field coils B_{max} occurs with ca. 8 ... 10 T, so for NbTi-SC the critical field strength reached.

- **Historically first large SC machine:**

  Thermal power plant *Fawley*, England, water feed pump drive for the steam generation: Homo-polar motor (drum type) 2.4 MW, 200/min, gearing to pump, superconductive field winding as solenoid excitation winding within a ring cryostat with LHeI cooling and NbTi conductors

  2 year test operation 1970/71

- **2000:** US research project: 300 kW homo-polar ship drive of the U.S. Navy, retrofit from LTSC field coils (4.2 K cooling) to HTSC BSCCO strip conductor coils.

The potential of homo-polar technology is limited, because of "U small, I large". A huge amount of carbon brushes as sliding contact with friction and electric losses limits the speed, reduces the efficiency and requires maintenance. Therefore the superconductive homo-polar machine is currently not developed further.

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Superconducting synchronous machines with electrical excitation

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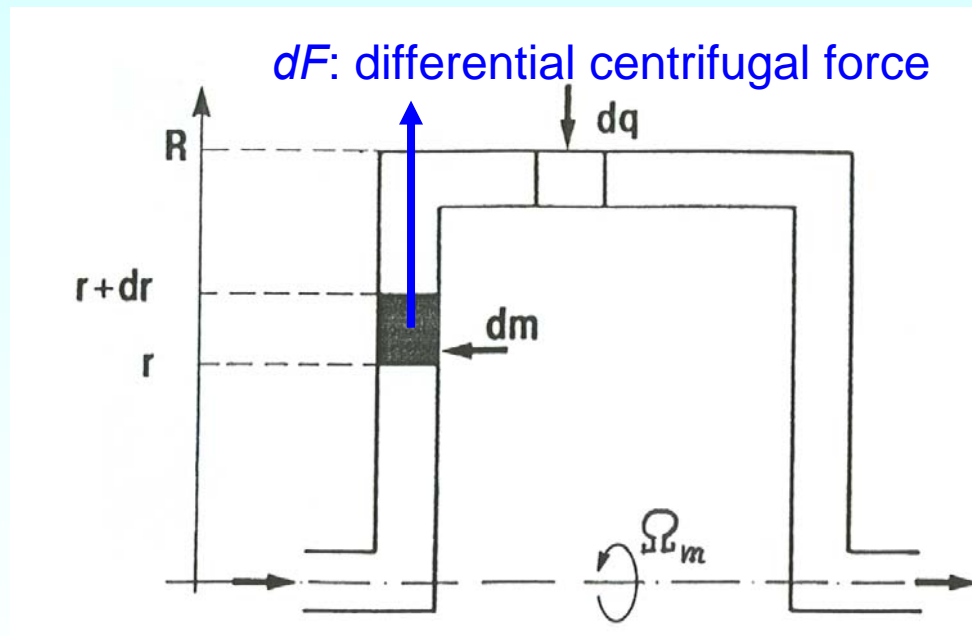**2_2/18**

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Cooling of rotating SC windings

Pressure increase in a rotating radial flow channel: Mass element *dm* of the cooling medium, *r*: radius, *dq*: differential heat in-flow,

R: outer radius, A_k: channel cross section, ρ: mass density

$$dF(r) = dm \cdot r \cdot \Omega_m^2$$

$$dm = dr \cdot A_k \cdot \rho$$
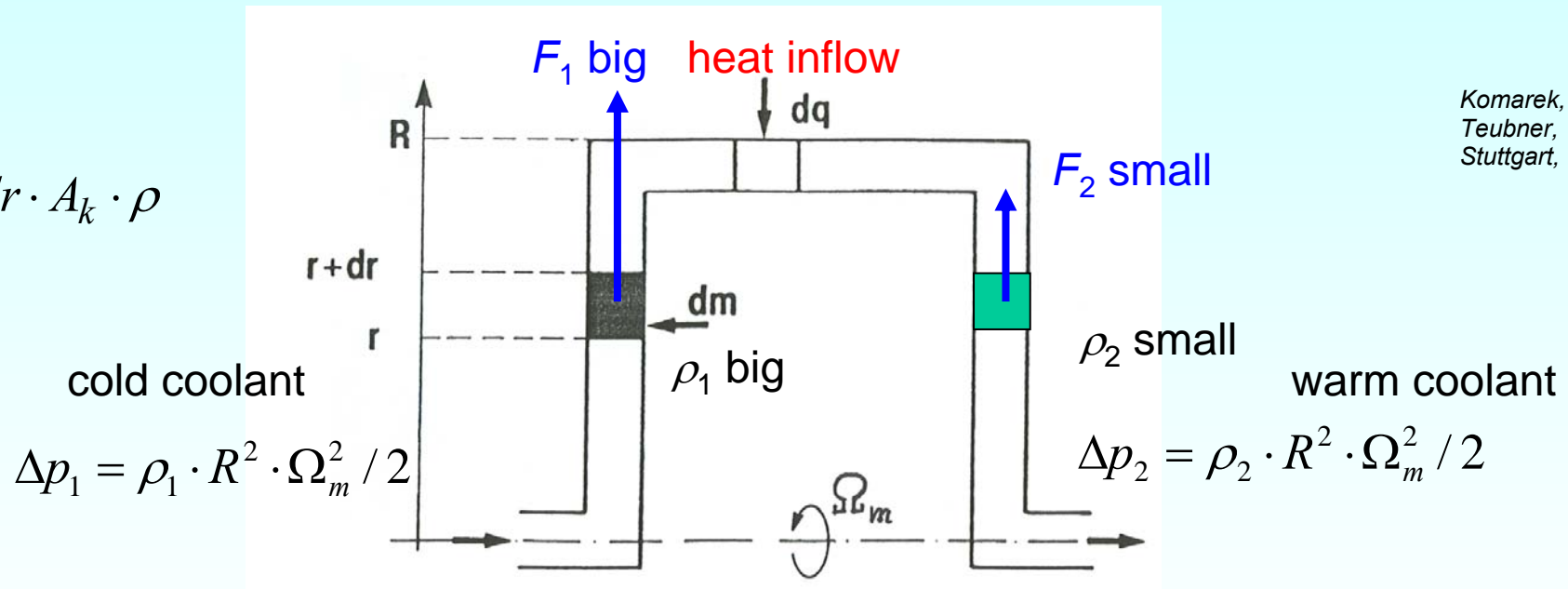
Komarek, P.:
Teubner,
Stuttgart, 1995

dF: differential centrifugal force

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Self-acting pump

R: outer radius, A_k: channel cross section, ρ: mass density

$$dF(r) = dm \cdot r \cdot \Omega_m^2$$

Komarek, P.:
Teubner,
Stuttgart, 1995

F_1 big   heat inflow dq

F_2 small

R

$r+dr$

r

dm

ρ_2 small

$$dm = dr \cdot A_k \cdot \rho$$

cold coolant ρ_1 big   warm coolant

$$\Delta p_1 = \rho_1 \cdot R^2 \cdot \Omega_m^2 / 2$$

$$\Delta p_2 = \rho_2 \cdot R^2 \cdot \Omega_m^2 / 2$$

Ω_m

$\Delta p_1 - \Delta p_2$ drives automatically coolant flow from cold to warm side

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Pressure increase of the coolant by means of centrifugal force

- Rotating channel: Pressure increase $dp(r)$ in the channel by means of centrifugal force $dF(r)$:

$$dp(r) = dF(r)/A_k = dm \cdot r \cdot \Omega_m^2 / A_k = \rho \cdot (dr \cdot A_k) \cdot r \cdot \Omega_m^2 / A_k = \rho \cdot dr \cdot r \cdot \Omega_m^2$$

- Resulting increase in pressure between $r = 0$ and $r = R = 0.5m$:

$$\Delta p = \int_0^R dp(r) = \int_0^R \rho \cdot r \cdot \Omega_m^2 \cdot dr = \rho \cdot R^2 \cdot \Omega_m^2 / 2$$

Example:

50 Hz turbine generator, $2p = 2$, rotor diameter $d = 2R = 1$ m:

$$n = f / p = 50/1 = 50/s = 3000/\min$$

$$\Delta p / \rho = R^2 \cdot \Omega_m^2 / 2 = 0.5^2 \cdot (2\pi \cdot 50)^2 / 2 = 12.4 kWs / kg$$

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Temperature increase of an ideal gas at pressure increase

p: pressure (Pa)
V: volume (m³)
T: temperature (K)
M: mass (kg)

● Ideal gas equation: $p \cdot V = \nu_m \cdot R \cdot T$

      - Ideal gas constant: $R = 8.31$ J/(K·mol)

      - ν_m: Number of moles of the substance per kg mass

$$p \cdot V / M = p \cdot V /(\rho \cdot V) = p / \rho = \nu_m \cdot R \cdot T / M \quad \rightarrow \Delta p / \rho = \nu_m \cdot R \cdot \Delta T / M$$

Example: He approximated as ideal gas:

- 1 mol of a gas contains N_A molecules ($N_A = 6 \cdot 10^{23}$: *Avogadro* constant).

- Mass of a helium gas molecule: $m_{He} = 6.64 \cdot 10^{-27}$ kg

- Mass of a mole of He gas: $N_A \cdot m_{He} = 6 \cdot 10^{23} \cdot 6.64 \cdot 10^{-27} = 4 \cdot 10^{-3} kg$

- $M = 1$ kg He gas = amount of substance $\nu_m = 250$ mol:

. $\nu_m = M /(N_A m_{He}) = 1kg /(4 \cdot 10^{-3} kg) = 250$

With $\Delta p / \rho = 12.4 kWs / kg$ follows a temperature increase:

$$\Delta T = (M / \nu_m) \cdot (\Delta p / \rho) / R = 4 \cdot 10^{-3} \cdot 12400 / 8.31 = 6K$$

Real gas: Temperature increase is less: typically *only ca. 2 K.*

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Pressure increase in gaseous He / liquid LHeI

- He gas: He gas density at 1 bar, 273 K: $\rho = 0.178$ kg/m³
  Calculating the gas density with the ideal gas equation:

$$\frac{\rho_1}{\rho_2} = \frac{T_2 \, p_1}{T_1 \, p_2} \qquad M = \text{const.}$$

  a) $T = 300$ K, $p = 1$ bar: $\rho = 0.162$ kg/m³:

$\rho(T, p)$ calculated

$$\Delta p = 12.4 kWs / kg \cdot \rho = 2008 Pa = \underline{\underline{0.02 bar}}$$

  b) $T = 3$ K, $p = 0.3$ bar: $\rho = 4.86$ kg/m³:

$$\Delta p = 12.4 kWs / kg \cdot \rho = 60256 Pa = \underline{\underline{0.6 bar}}$$

- Liquid LHeI at 1 bar, 4.2 K: $\rho = 124.8$ kg/m³ (see He-Table of Chapter 1)

$$\Delta p = 12.4 kWs / kg \cdot \rho = 1547520 Pa = \underline{\underline{15.5 bar}}$$

- At room temperature, the gas compression by means of centrifugal
  force in a turbine generator rotor with 1 m diameter at 3000/min is with
  0.02 bar very small, but for liquid LHeI helium it already amounts to ca. 15.5 bar.
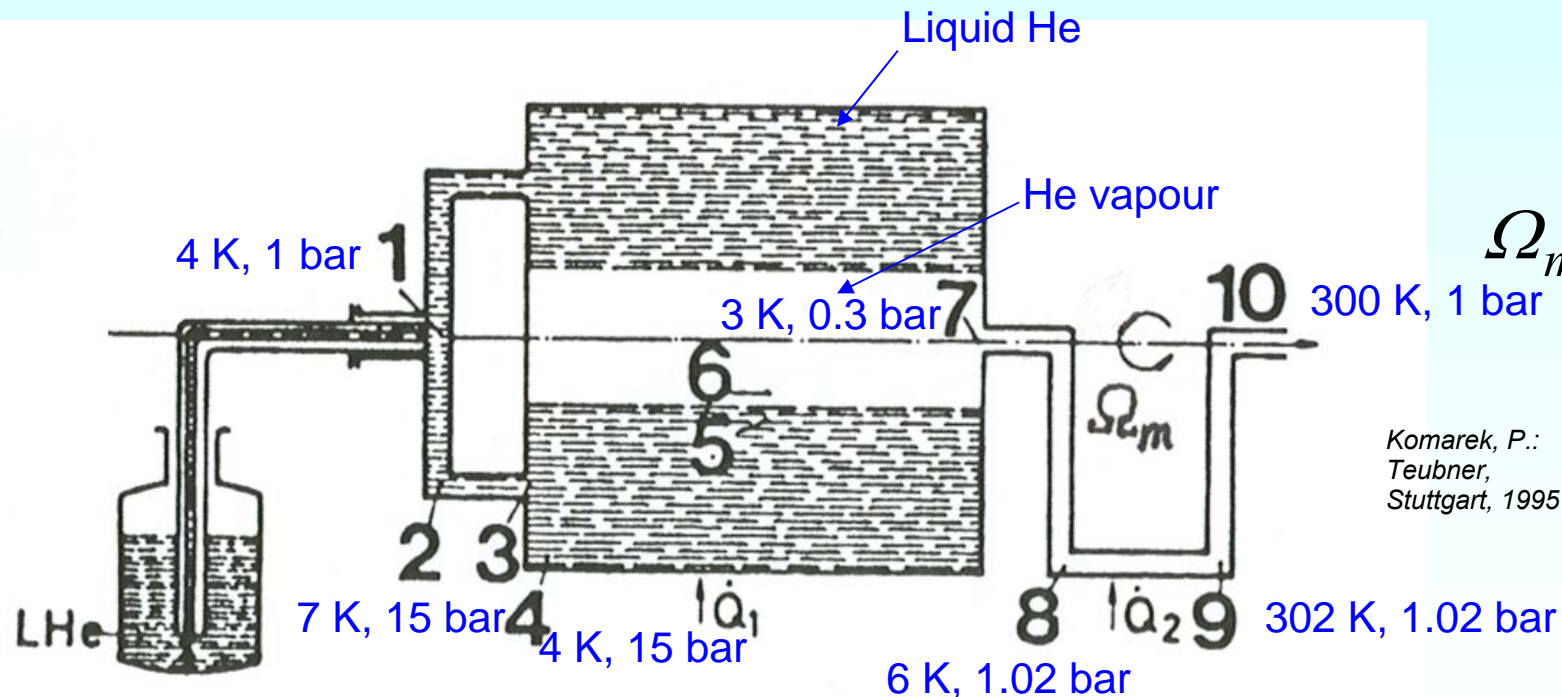
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Cooling principle with LHeI

$\dot{Q}_1$: heat in-flow to the cryostat and the SC winding,

$\dot{Q}_2$: heat in-flow from the warm rotor iron

Liquid He

He vapour

4 K, 1 bar **1**

3 K, 0.3 bar **7**

10 300 K, 1 bar

$$\Omega_m = 2\pi \cdot n$$

6

5

Ω_m

Komarek, P.:
Teubner,
Stuttgart, 1995

2 3

$\dot{Q}_1$

8 $\dot{Q}_2$ **9** 302 K, 1.02 bar

7 K, 15 bar **4**

4 K, 15 bar

LHe

6 K, 1.02 bar

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Cooling principle of rotating windings with LHeI

1: LHeI high tank: LHeI flows via gravity towards shaft: 4 K, 1 bar (air pressure)

2: Centrifugal force conveys LHeI at rotor periphery; LHeI compressed/heated up: 7 K/15bar

3-4: Hollow rotor: Large rotating amount of LHeI (4 K, 15 bar). Amount of LHeI streaming towards it mixes up, cools down to 4 K.

5-6: Pump effect of the channel 7-8-9-10 (creation of low air pressure in rotor interior):

- Rotor interior (item 6): He gas cooled to 0.3 bar, 3 K.

- Centrifugal force difference between 4/5: p(LHeI) drops from 15 to 1 bar, T from 4 K to 3 K,

- Loss from $\dot{Q}_1$ SC winding evaporates LHeI at 3 K against vapor pressure 0.3 bar. He gas lighter than LHeI $\Rightarrow$ gas inside, liquid outside.

7-8: He gas sucked off from rotor interior by pumping effect from channel 7-8 and compressed from 3 K, 0.3 bar to 1.02 bar, 6 K.

8-9: Loss $\dot{Q}_2$ from rotor iron heats He gas at 1.02 bar to 302 K.

9-10: Rotating channel 9-10: pressure difference in He gas 0.03 bar, 2 K betw. 10 and 9
     (room temperature 300K, 1 bar air pressure).

$\Delta p_{9\text{-}10} < \Delta p_{7\text{-}8}$: Resulting pumping effect 7-8-9-10: Determines – assuming 300 K room temperature and 1 bar air pressure – T and p in 6. $\dot{Q}_1$ changes evaporation rate only.

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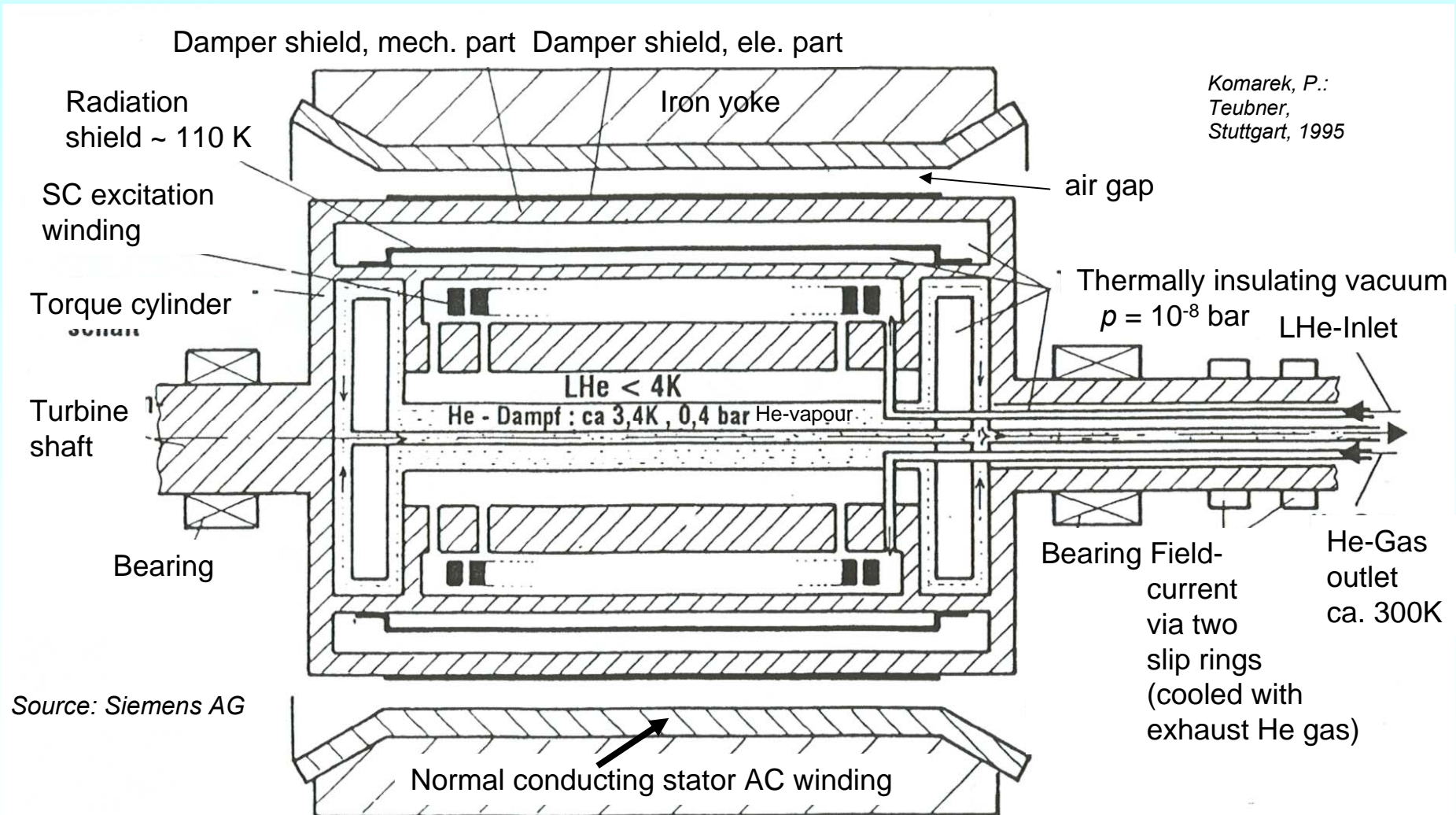
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Low-temperature superconductor excitation winding for synchronous machines

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Design of an LTSC synchronous machine

Damper shield, mech. part   Damper shield, ele. part

Radiation shield ~ 110 K

SC excitation winding

Torque cylinder

Turbine shaft

Bearing

Iron yoke

air gap

Thermally insulating vacuum $p = 10^{-8}$ bar

LHe-Inlet

LHe < 4K

He - Dampf : ca 3,4K , 0,4 bar   He-vapour

Bearing Field-current via two slip rings (cooled with exhaust He gas)

He-Gas outlet ca. 300K

Komarek, P.: Teubner, Stuttgart, 1995

Source: Siemens AG

Normal conducting stator AC winding

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Components of SC synchronous machines

- **Thermal rotor insulation:** vacuum-insulated hollow space V at $p = 10^{-5}$ mbar,

- **Thermal radiation shield:** at 110 K, reflection of incoming radiation

- **Electrical damper:** Shielding of stator field transients, <u>double shell:</u> bronze outside (mechanical strength), copper inside (good conductivity)

- **Torque cylinder:** Transmitting electric forces from SC winding to the shaft

- **Coolant supply** and **DC current supply** by hollow rotor shaft

- **Air-gap stator winding:** No teeth = doubles the electric loading, Cu strands, twisted to reduce the AC losses due to the AC self field ("cross field") and AC main field ("direct axis field"), water-cooled by hollow conductors
    <u>Stator copper strand:</u> twisted litz wire conductors
    <u>Stator supporting cylinder:</u> - Fixation of the stator coils via non-conductive cylinder,
                                        - Torque transmission via bolts from Cu-conductors to core stack

- **Core stack:** Magnetic yoke, magneto-static shielding of the main flux

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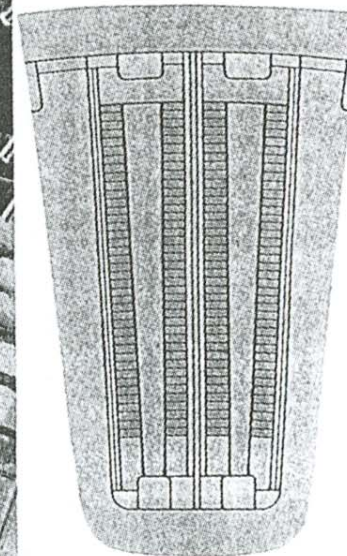
800 MW turbo rotor (prototype)

• Rotor iron core: austenitic steel, milled slots for DC excitation winding
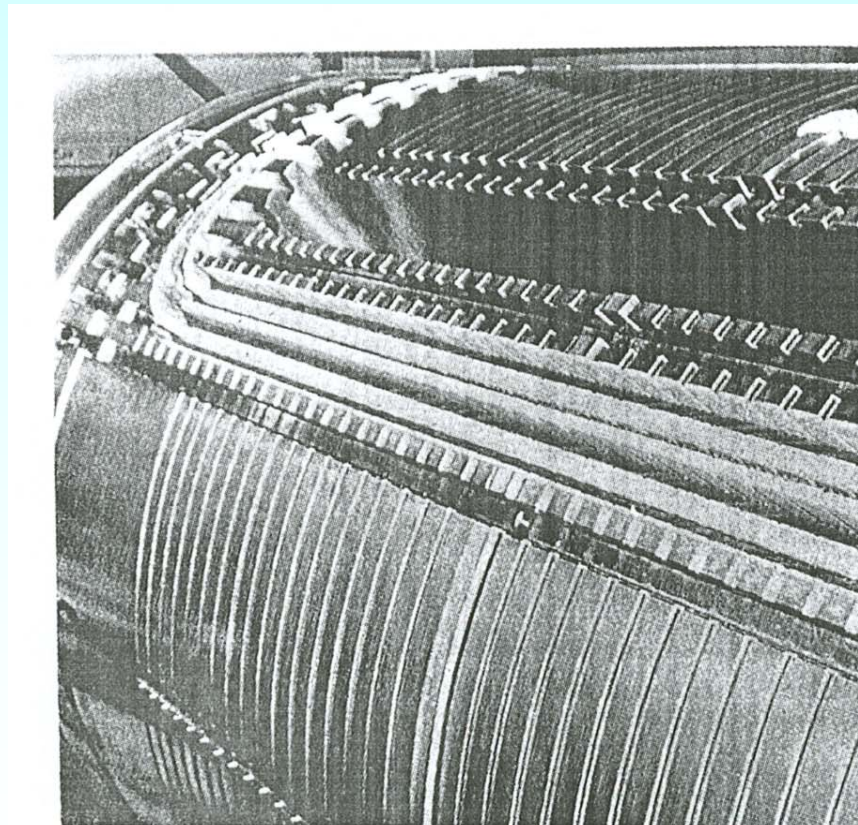
Rotor slot cross-section

Source: Siemens AG
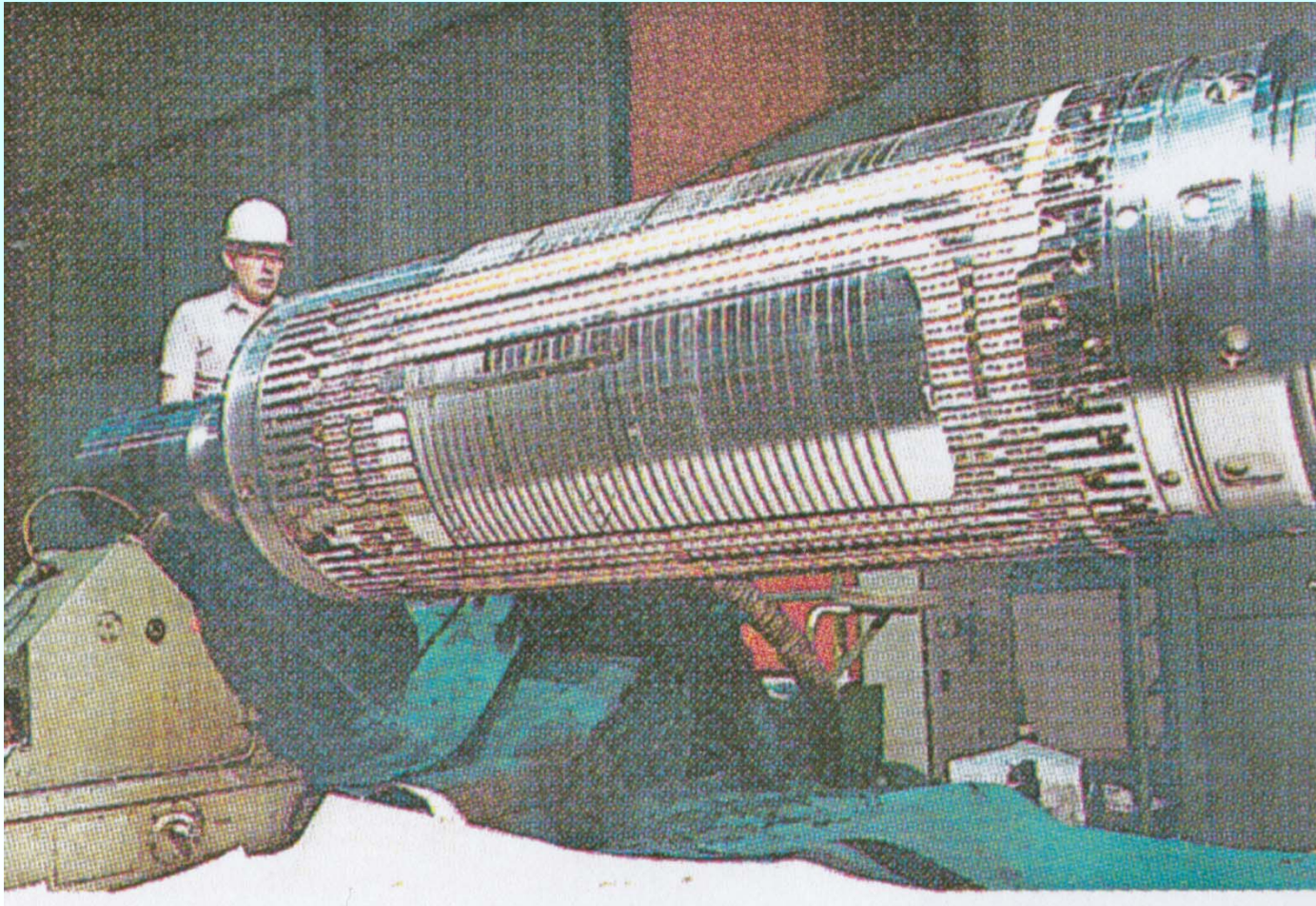
Komarek, P.:
Teubner,
Stuttgart, 1995

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800 MW turbo rotor (prototype)

Source: Siemens AG

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**Institute of Electrical
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Conductor arrangement in rotor slot

- 11 parallel strands twisted with each other (diameter ca. 1.8 mm, 2.55 mm²) made of NbTi-LTSC filaments (5 μm diameter) in Cu matrix

- Nominal current density per strand 150 A/mm²,
  nominal current $11 \cdot 2.55 \cdot 150 = 4200\,A$
  maximum self-field at conductor surface: 6 T during operation.
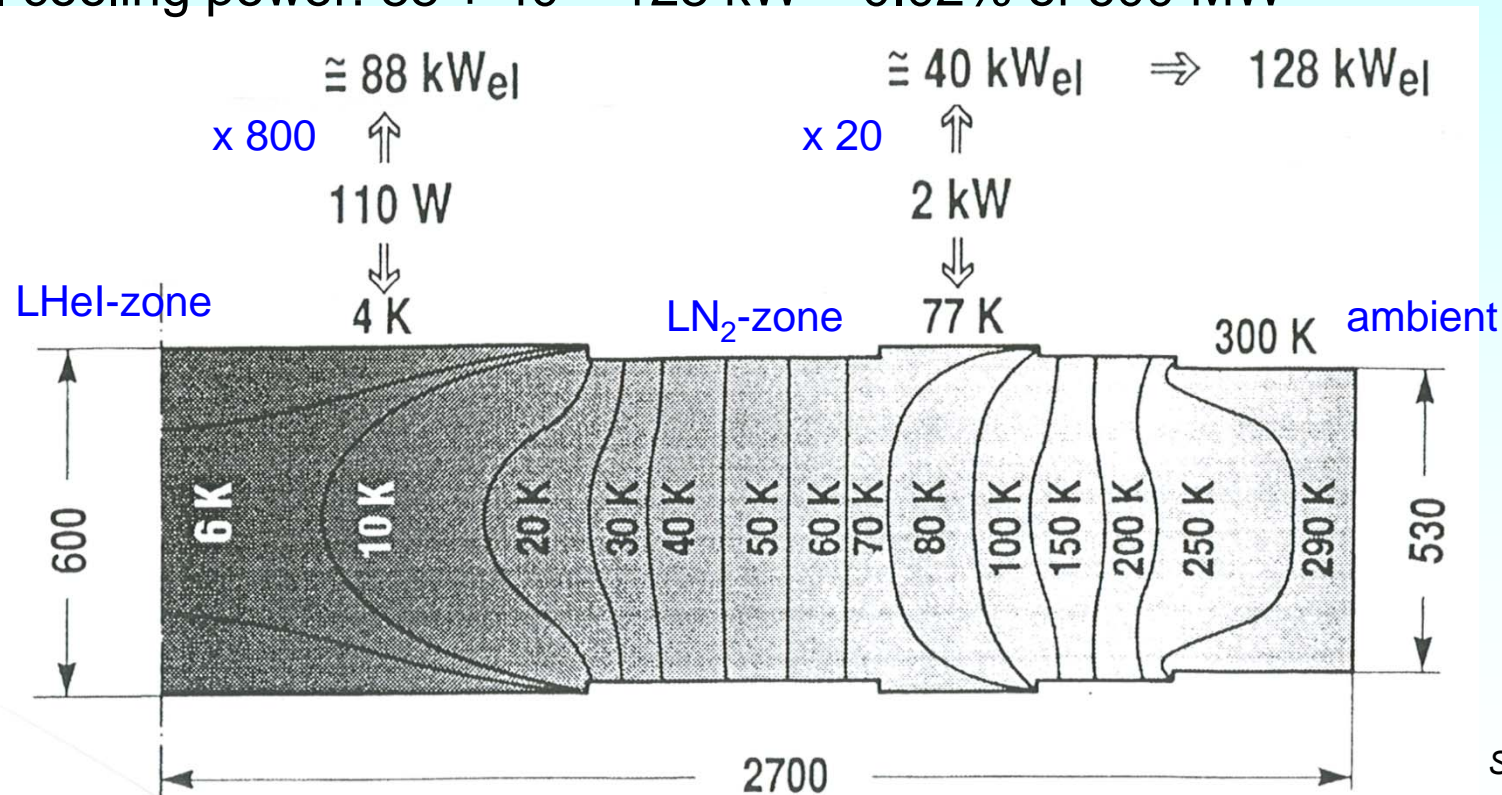 Critical limit of the winding: 6 kA, 8 T, 4.2 K

1 strand   copper   11 twisted strands = 1 conductor; 4.2 kA   Rotor slot

NbTi 5µm

1.8 mm

Source: Siemens AG

Komarek, P.: Teubner, Stuttgart, 1995

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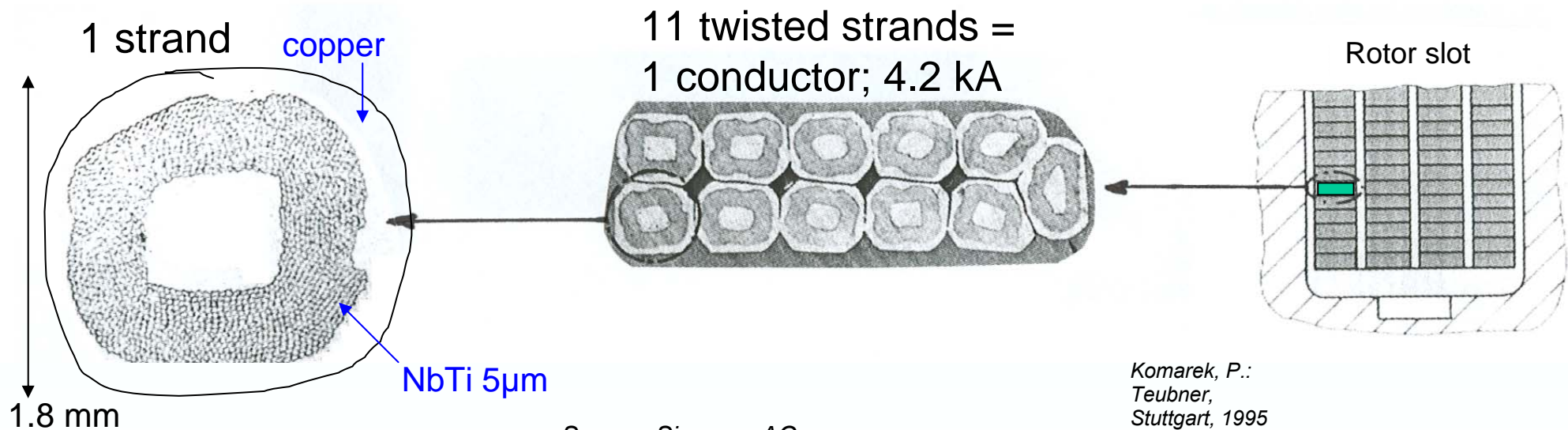
Simple rotor iron cooling: 600 MW generator

- Cold side: 4 K, warm side 300 K, intermediate cooling with LN_2 to 77 K

- 110 W from winding at 4 K, 2000 W heat influx from turbine at 77 K

- Total cooling power: 88 + 40 = 128 kW = 0.02% of 600 MW

Komarek, P.: Teubner, Stuttgart, 1995

Source: Siemens AG

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Thermal vacuum-insulation

- **"Vacuum" $p = 10^{-5}$ mbar:** Hollow space: 600 MVA turbo: $V = 1000$ dm^3

  Permitted leakage rate L for operation time $t = 1$ year:

$$L = \frac{p \cdot V}{t} = \frac{10^{-5} \cdot 1000}{3600 \cdot 8760} = 3 \cdot 10^{-10}\, mbar \cdot dm^3 / s$$
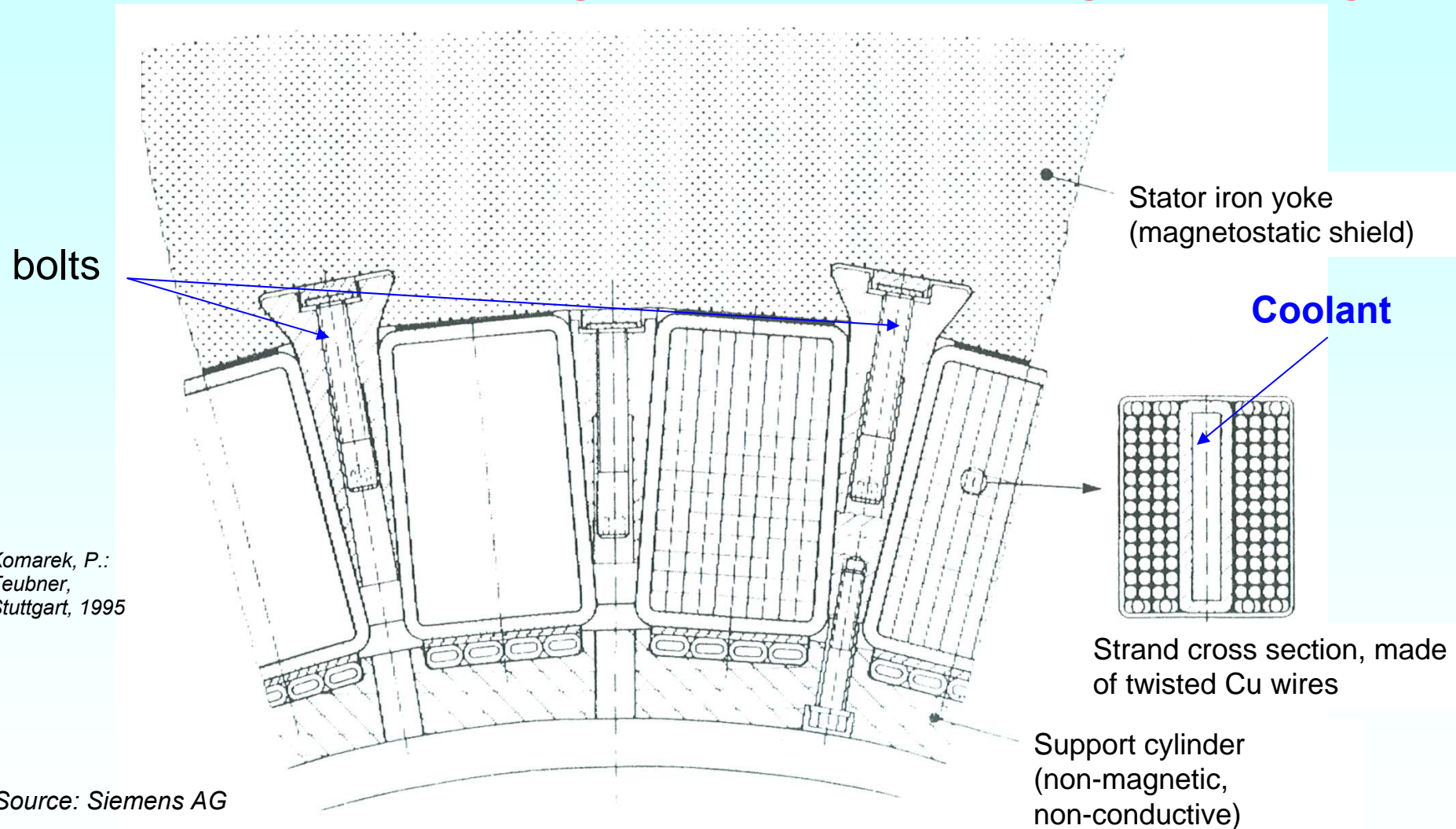
- **Leakage rate L as He steam (vapour)!**

  All other substances (air, ...) frozen as crystals at cold side (ca. 4 ... 6K).

- **Vacuum containers** do not in general fulfill necessary leakage rate L, so a sorption pump is integrated in the cold part of the vacuum chamber.

- **Sorption agent** (e.g. 100 g Zeolith) absorbs He molecules at 4 ... 6 K, so that at common leakage rates $L = 10^{-7}$ mbar.dm^3/s the vacuum is maintained over at least one year.

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Normal-conducting three-phase AC air-gap winding

bolts

Stator iron yoke
(magnetostatic shield)

Coolant

*Komarek, P.:
Teubner,
Stuttgart, 1995*

Strand cross section, made
of twisted Cu wires

Support cylinder
(non-magnetic,
non-conductive)

Source: Siemens AG

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Radial main field B_n and tangential stray field B_t permeate the air-gap winding

1. development step:

AC stator 3-phase winding:

Top layer winding

Bottom layer winding

Source: ABB, Switzerland

Conventional rotor with copper winding and magnetic steel rotor

generator operation

field axis

B_t

rotation

B_n

rotor field axis

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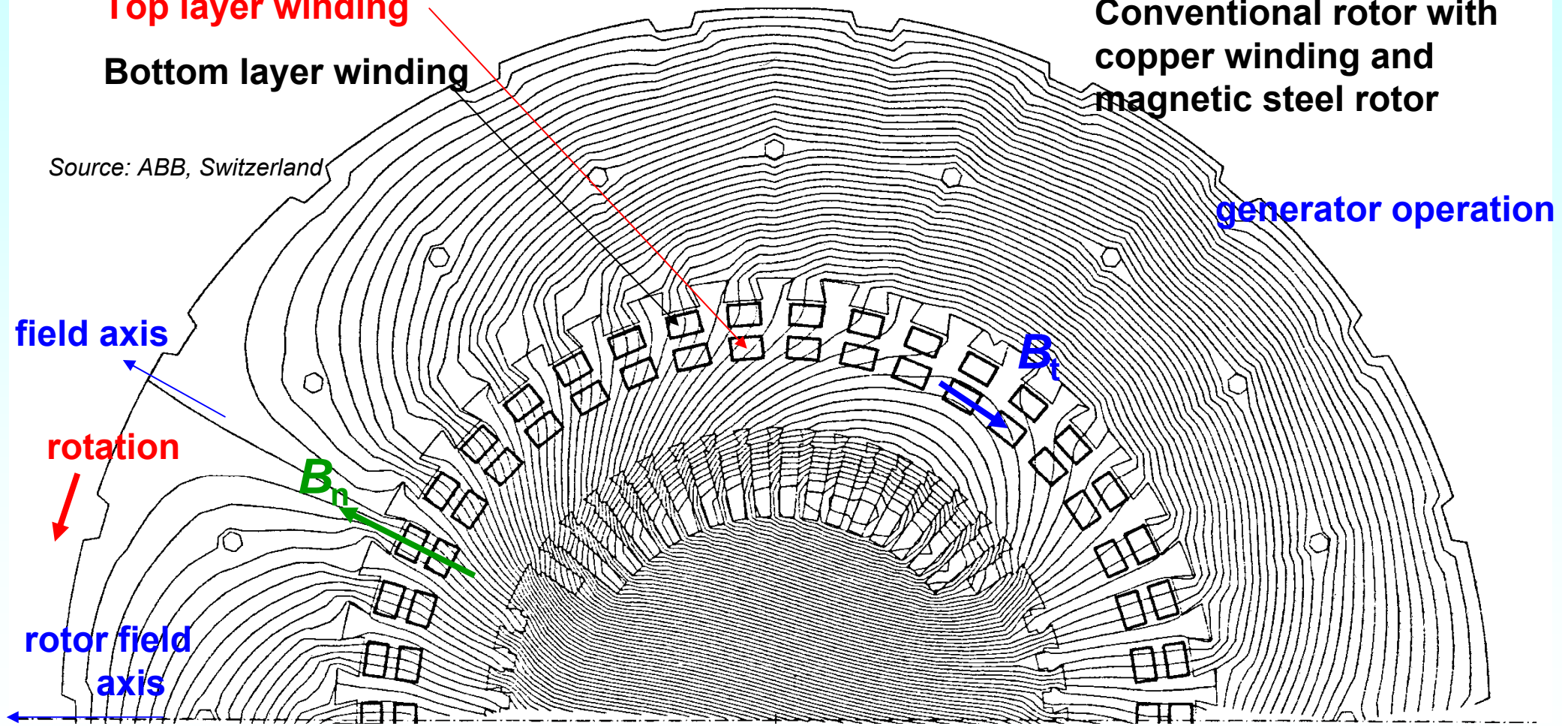
Multiple-twisted strands of the three-phase AC air-gap winding

Radial field B_n
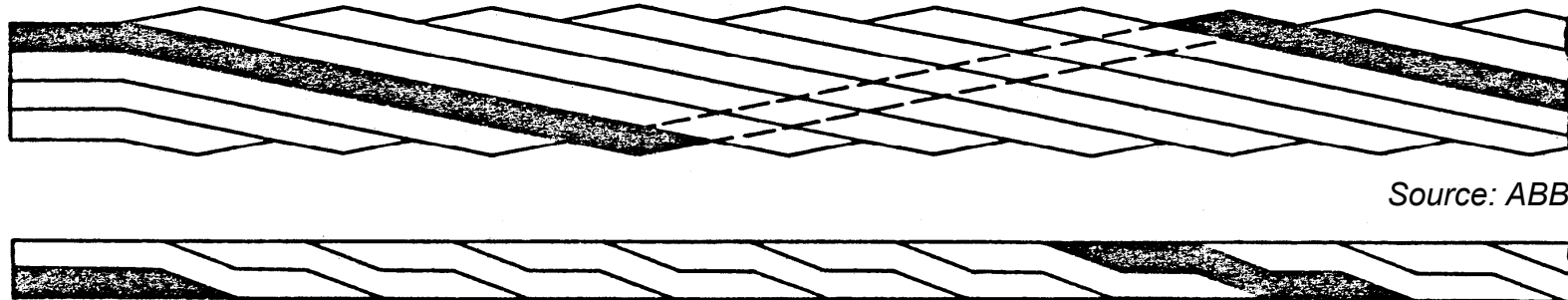
Insulation of one turn
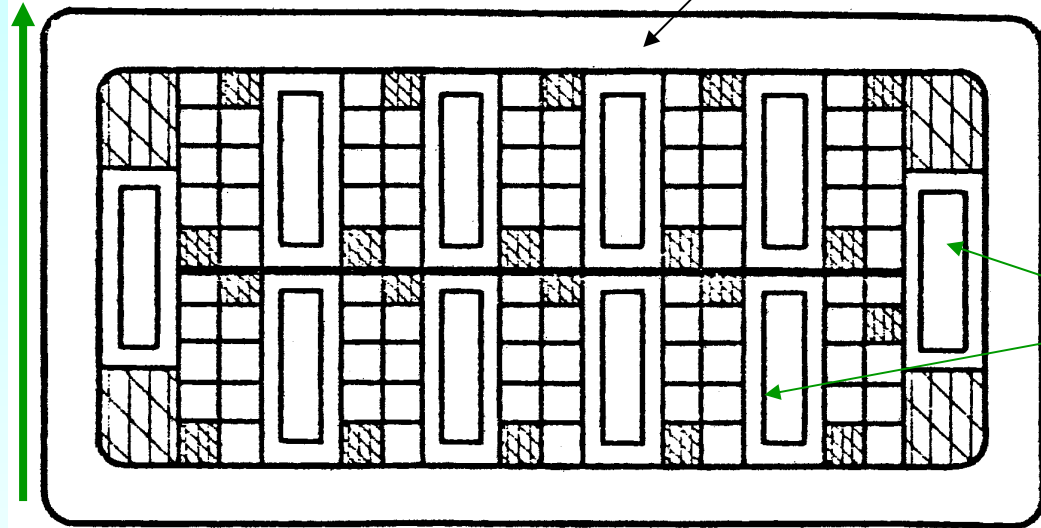
One turn = one top or bottom layer bar, which consists of 10 twisted parallel conductors

COOLANT FLOW

1 conductors consists of 8 twisted parallel Cu wires

Tangential field B_t

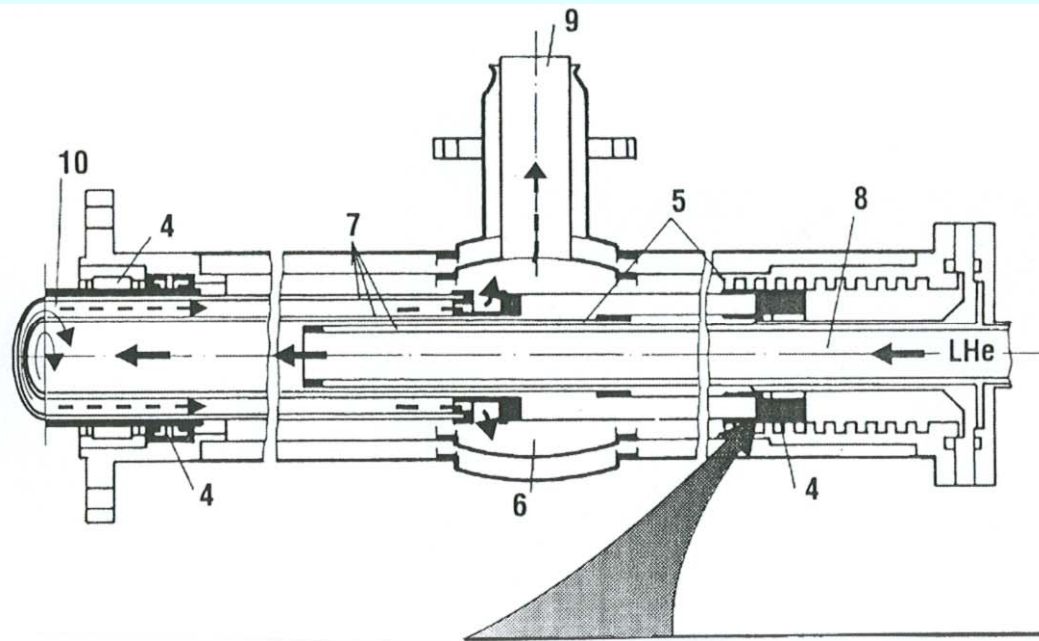**Cu wire**

Source: ABB; Switzerland

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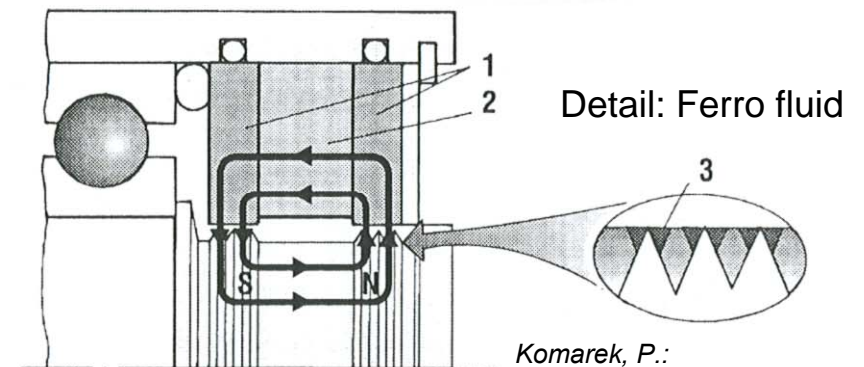
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He coolant feed into the hollow rotor shaft

1: Pole shoes
2: Permanent magnet,
3: Ferro fluid,
4: Auxiliary bearing,
5: Sealing location,
6: Annular slot for dispersing He warm gas,
7: Vacuum chambers (thermal insulation between 4.2 K-LHeI in-flow and warm gas out-flow),
8: LHeI entry,
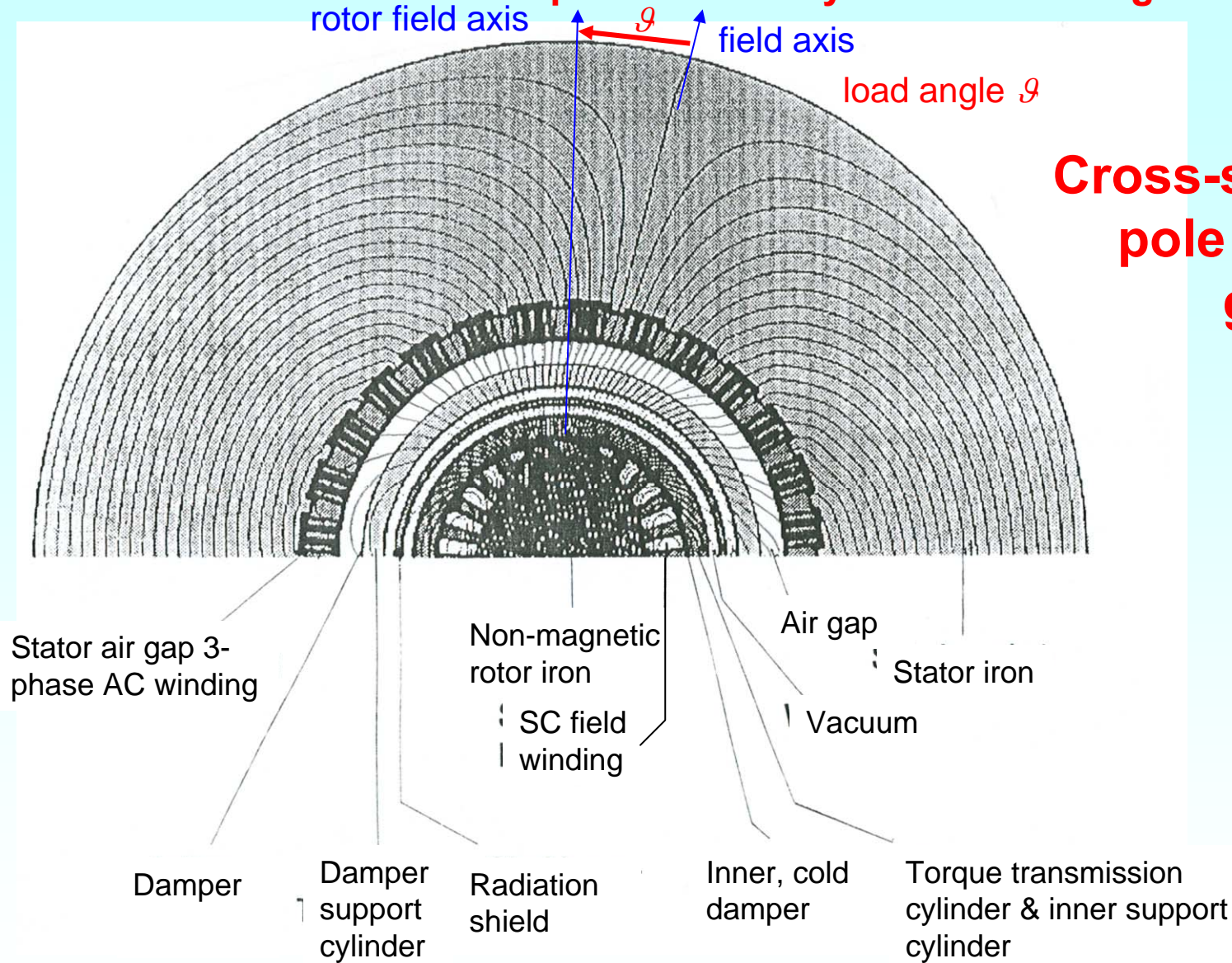9: He warm-gas exhaust, 10: He gas flow

Source: Siemens AG

Detail: Magnetic sealing

Detail: Ferro fluid

Komarek, P.: Teubner, Stuttgart, 1995

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rotor field axis

ϑ

field axis

load angle ϑ

Cross-section of a two-pole LTSC turbine generator

Source: Siemens AG

Stator air gap 3-phase AC winding

Non-magnetic rotor iron

SC field winding

Air gap

Stator iron

Vacuum

Damper

Damper support cylinder

Radiation shield

Inner, cold damper

Torque transmission cylinder & inner support cylinder

Komarek, P.: Teubner, Stuttgart, 1995

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Magnetic field (nominal point) of a 800 MW LTSC turbine generator

Stator iron yoke
(magnetostatic shield)

*Source: M. Liese,
Siemens AG*

field axis

rotor field axis

Air gap winding   non-magnetic rotor core   SC field winding

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**Institute of Electrical
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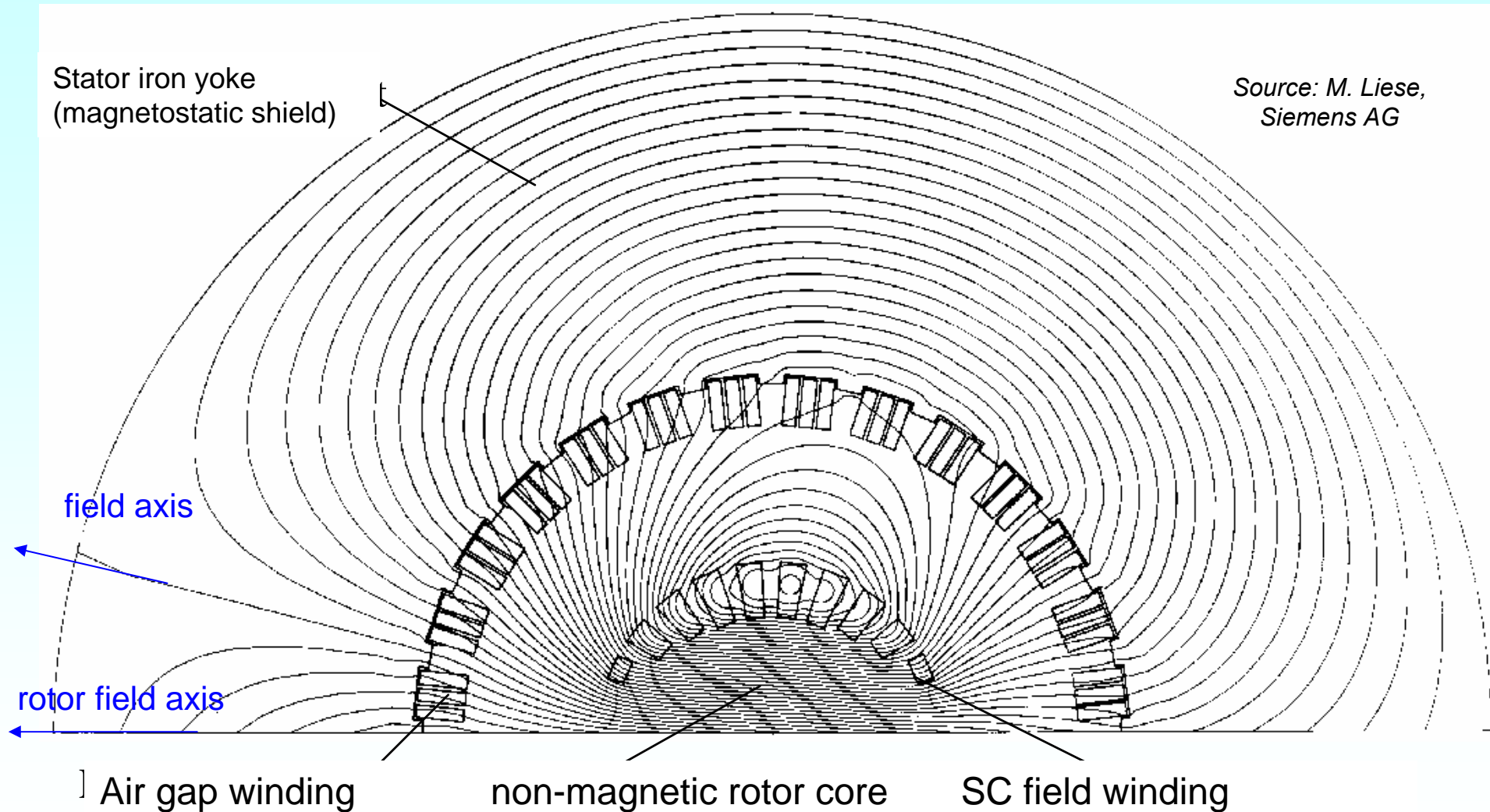
Magnetic no-load field ($I_s = 0$) of a 2-pole turbine generator with SC field winding

2-pole B- field

Stator iron yoke

$\mu_{Fe} \to \infty$

R

R_f

A_f

φ

r

SC rotor field winding
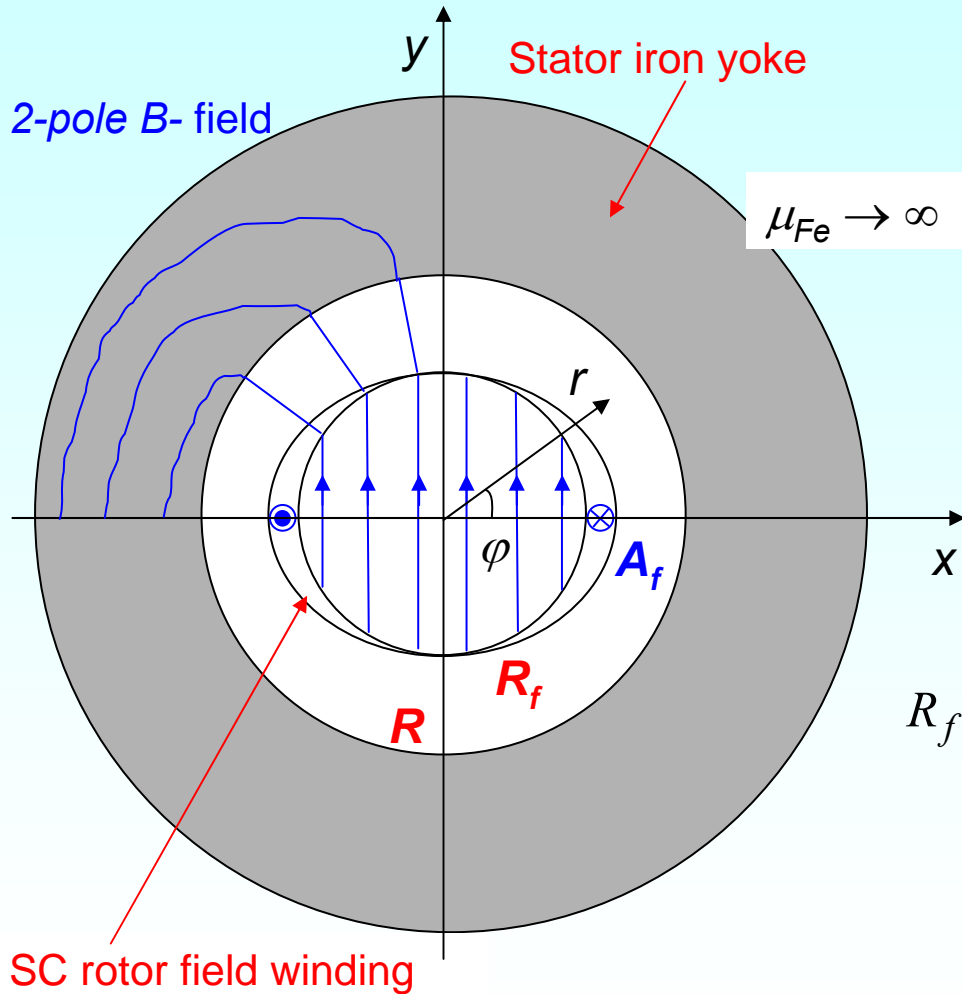
R: stator bore radius,
R_f: field winding radius
A_f: average field current loading

$$A_f = 2N_{f,pole}I_f / (\pi \cdot R_f)$$

Homogeneous inner field:

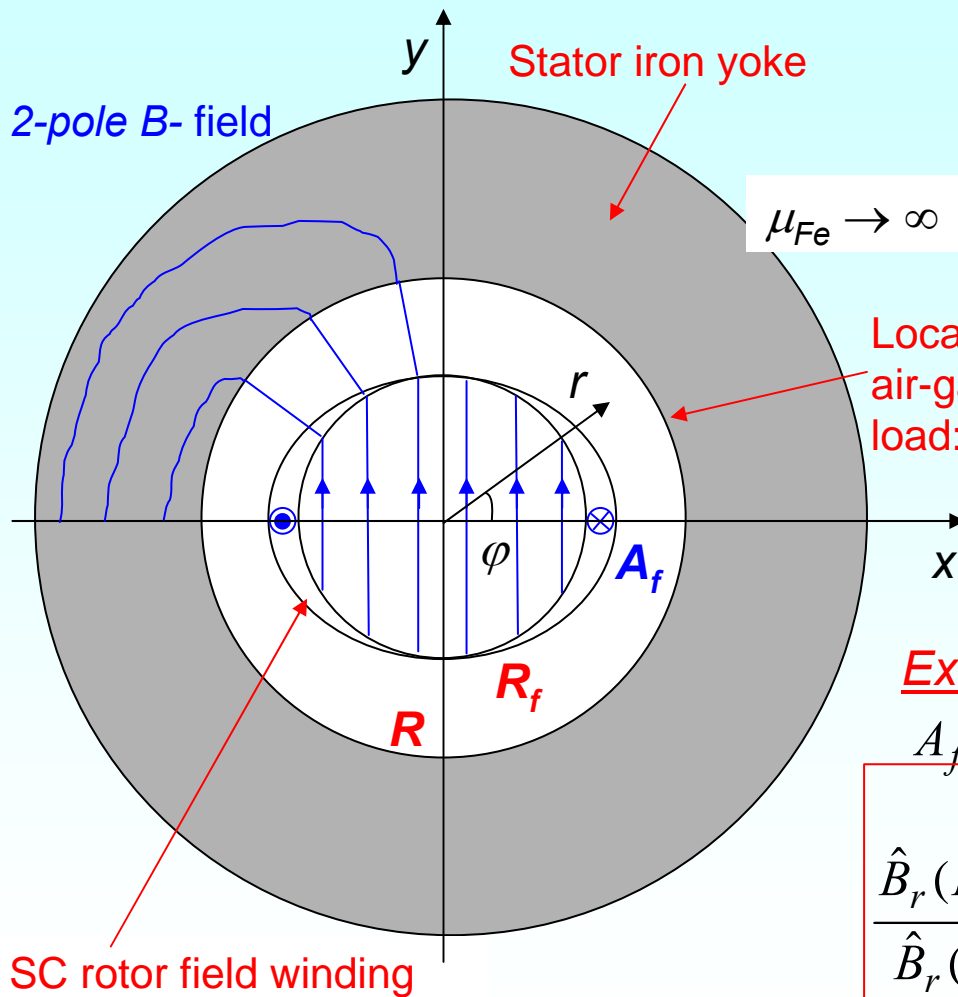$$0 \le r \le R_f : B_x = 0, \, B_y = \mu_0 A_f \frac{\pi}{4} \cdot \left(1 + \left(\frac{R_f}{R}\right)^2\right)$$

Sinusoidal distributed gap field:

$$R_f \le r \le R : B_r = \mu_0 A_f \frac{\pi}{4} \cdot \left(\left(\frac{R_f}{R}\right)^2 + \left(\frac{R_f}{r}\right)^2\right) \cdot \sin\varphi$$

$$B_\varphi = \mu_0 A_f \frac{\pi}{4} \cdot \left(\left(\frac{R_f}{R}\right)^2 - \left(\frac{R_f}{r}\right)^2\right) \cdot \cos\varphi$$

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Relation of magnetic no-load field at stator and rotor SC winding

2-pole B- field

Stator iron yoke

$\mu_{Fe} \to \infty$

y

r

φ

A_f

x

R_f

R

Location of stator AC air-gap winding (no-load: $I_s = 0$)

SC rotor field winding

Sinusoidal distributed no-load radial field at stator winding:

$$r = R : B_r = \mu_0 A_f \frac{\pi}{2} \cdot \left(\frac{R_f}{R}\right)^2 \cdot \sin\varphi$$

Field ratio at DC field winding and AC 3-phase winding:

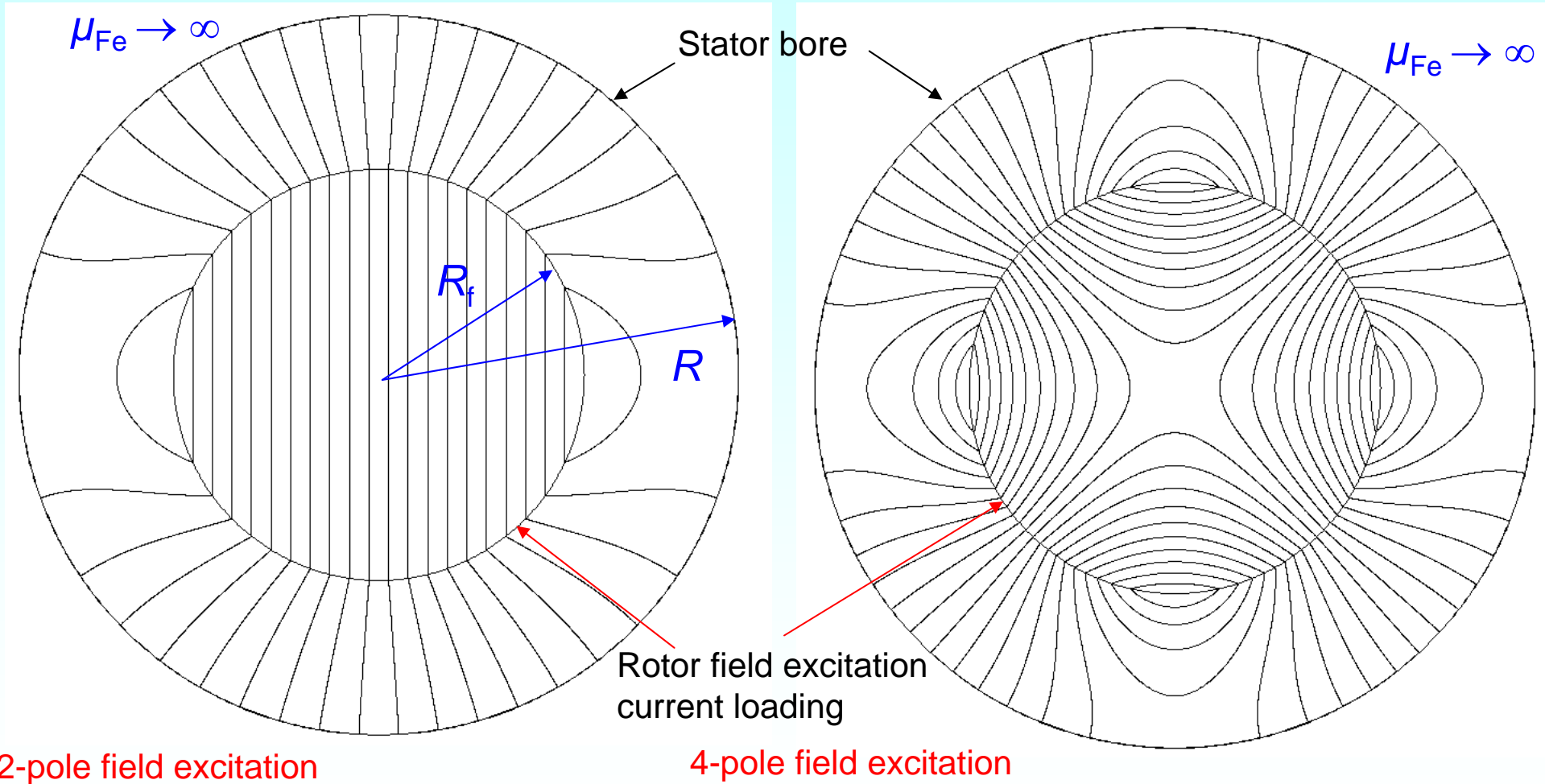$$\frac{\hat{B}_r(R_f, \varphi = \pi/2)}{\hat{B}_r(R, \varphi = \pi/2)} = \frac{\left(\frac{R}{R_f}\right)^2 + 1}{2}$$

Example:

$$A_f = 30000\,A/cm, R = 0.875m, R_f = 0.5m$$

$$\frac{\hat{B}_r(R_f, \varphi = \pi/2)}{\hat{B}_r(R, \varphi = \pi/2)} = \frac{3.92T}{1.93T} = \frac{\left(\frac{0.875}{0.5}\right)^2 + 1}{2} = 2.03$$

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Analytical calculation of the magnetic rotor no-load field in a SC synchronous machine ($I_s = 0$)

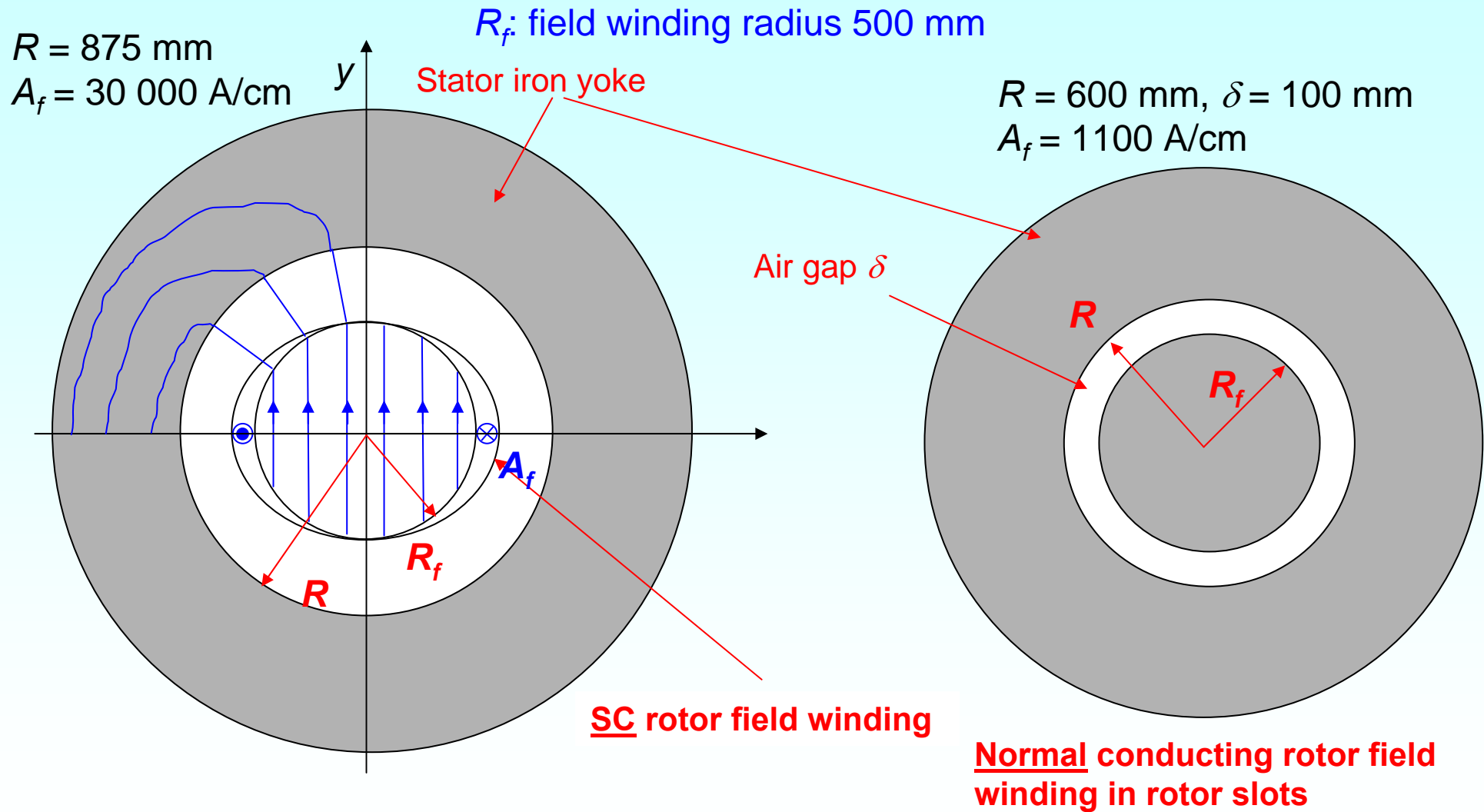$\mu_{Fe} \rightarrow \infty$

Stator bore

R_f

R

$\mu_{Fe} \rightarrow \infty$

Rotor field excitation current loading

2-pole field excitation

4-pole field excitation

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2-pole SC & normal conducting turbine generator geometry

R_f: field winding radius 500 mm

R = 875 mm
A_f = 30 000 A/cm

Stator iron yoke

R = 600 mm, δ = 100 mm
A_f = 1100 A/cm

Air gap δ

R

R_f

A_f

R_f

R

SC rotor field winding

Normal conducting rotor field winding in rotor slots

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Comparison: Normal-conductive and LTSC turbine generator (1)

● **Two-pole 600 MVA turbine generator:** (rough values)

| Turbine generator	LTSC turbogenerator	Normal-conductive (NC)
Air gap	$R - R_f = 375$ mm	$\delta_{mag} = 100$ mm
Field winding: Cooling	LHeI cooling	direct water-cooling
Field current loading	$A_f = 30\ 000$ A/cm	$A_f = 1100$ A/cm
Air-gap induction ($r = R_f$)	$B = 3.92$ T	$B = 1.44$ T
Air-gap induction ($r = R$)	$B = 1.93$ T $R = 875$ mm	$B = 1.2$ T $\quad R = 600$ mm

$$B(r = 0.875m) \approx \frac{0.5}{0.875} \cdot B(R_f) = 0.57 B(R_f) = 2.15T \ (R_f = 500 \text{ mm})$$

• At coil surfaces the field is maximum: at 6 T at the field coils, the field at the stator winding is only ca. 1.7 T $\Rightarrow B_{LTSC} = 1.5 \cdot B_{NC}$

• Utilization increases: $C \sim A \cdot B$: Air-gap winding: $A_{LTSC} = 2A_{NC}$

C_{LTSC} = ca. 3C_{NL}: **Superconducting generator ca. 3 times as much utilized.**

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Comparison: Normal-conductive and LTSC turbine generator (2)

Superconducting generator   Normally conducting generator
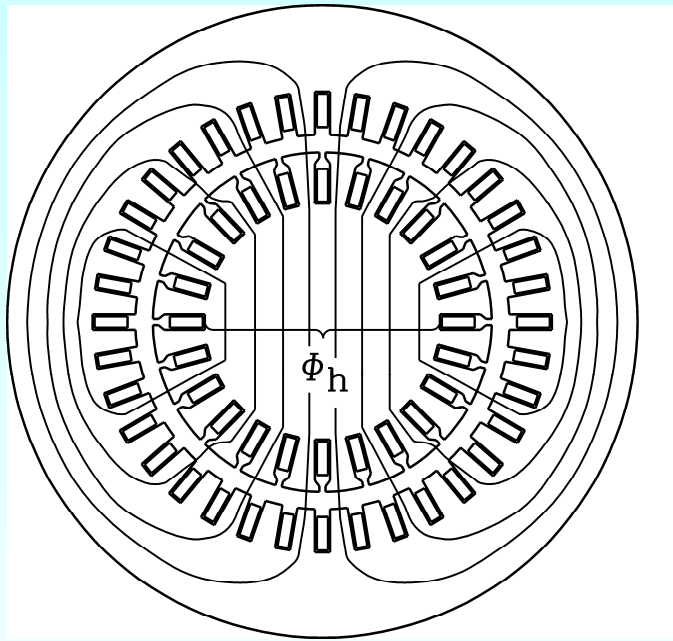
$$P \sim C \cdot d_{si}^2 l_{Fe}$$

l_{Fe}

d_{si}
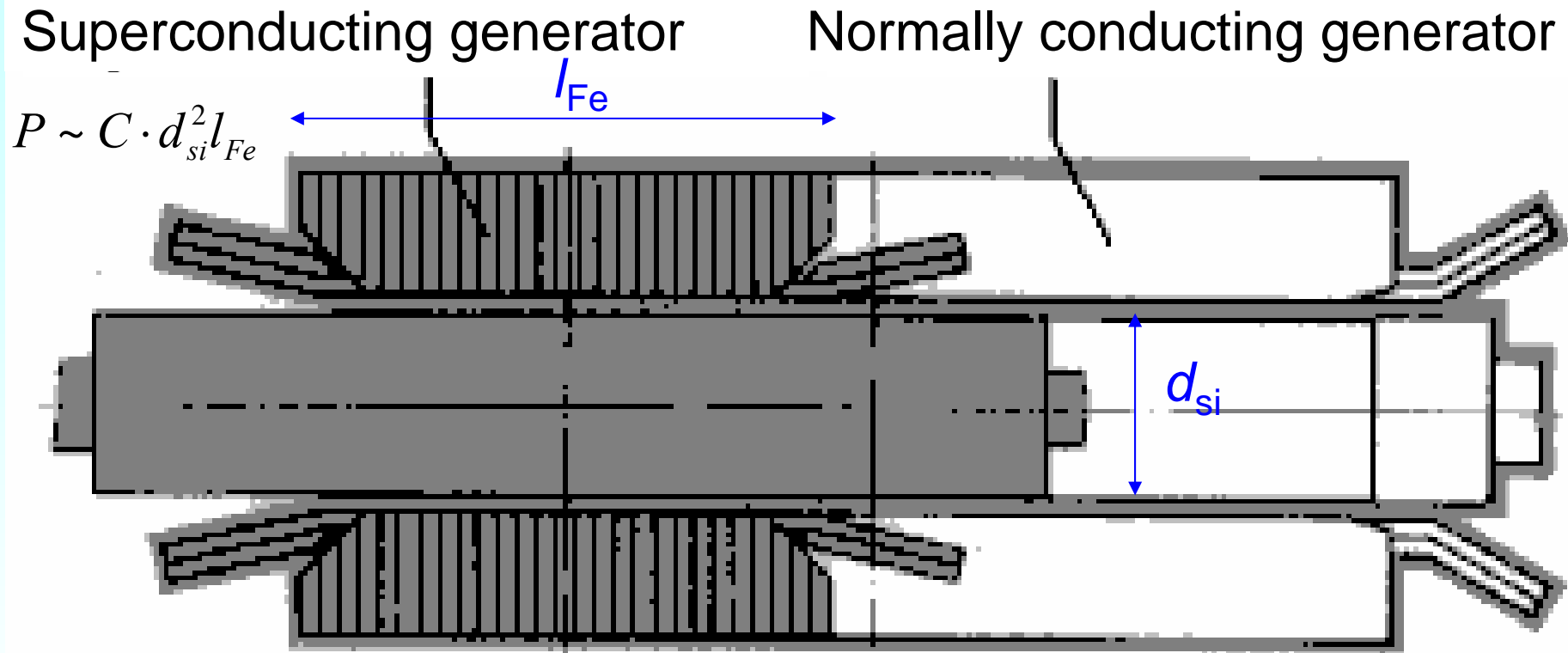
Source: M. Liese,
   Siemens AG

The active iron length l_{Fe} can (at equal bore diameter d_{si} of the stator) be **reduced to one third**.

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Magnetizing inductance of the stator winding L_h

$$L_h \sim \Phi_h$$

N_s: Number of turns per phase
   of the stator winding
k_{ws}: Winding factor due to
   distributed stator winding
m: Number of phases
R: Stator bore radius
l: Axial iron length
δ: Air gap

Φ_h

Φ_{hf}
Φ_{Dh}
Φ_h
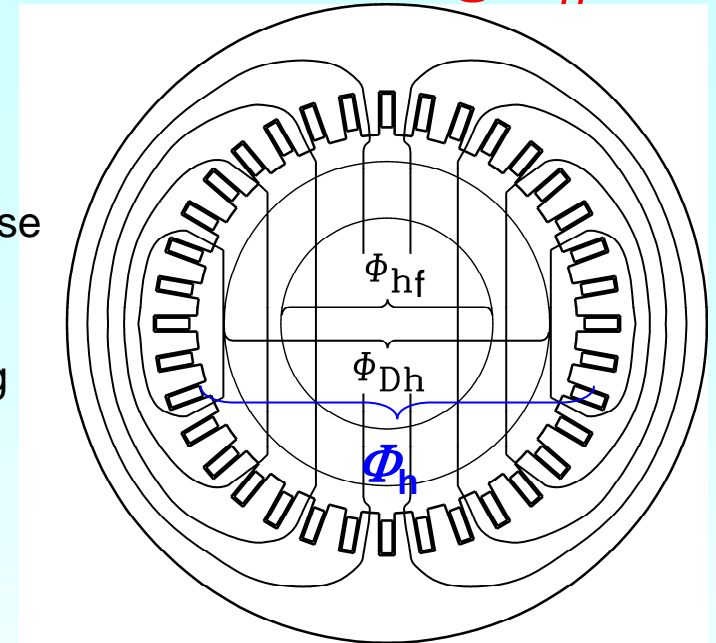
NC: Normally conducting machine

$$L_{h,\mu_{Fe} \to \infty} = \mu_0 \cdot (N_s k_{ws})^2 \cdot \frac{2m}{\pi} \cdot \frac{R \cdot l}{\delta}$$

2p = 2

SC: Super-conducting machine

$$L_{h,\mu_{Fe} \to \infty} = \mu_0 \cdot (N_s k_{ws})^2 \cdot \frac{2m}{\pi} \cdot l$$

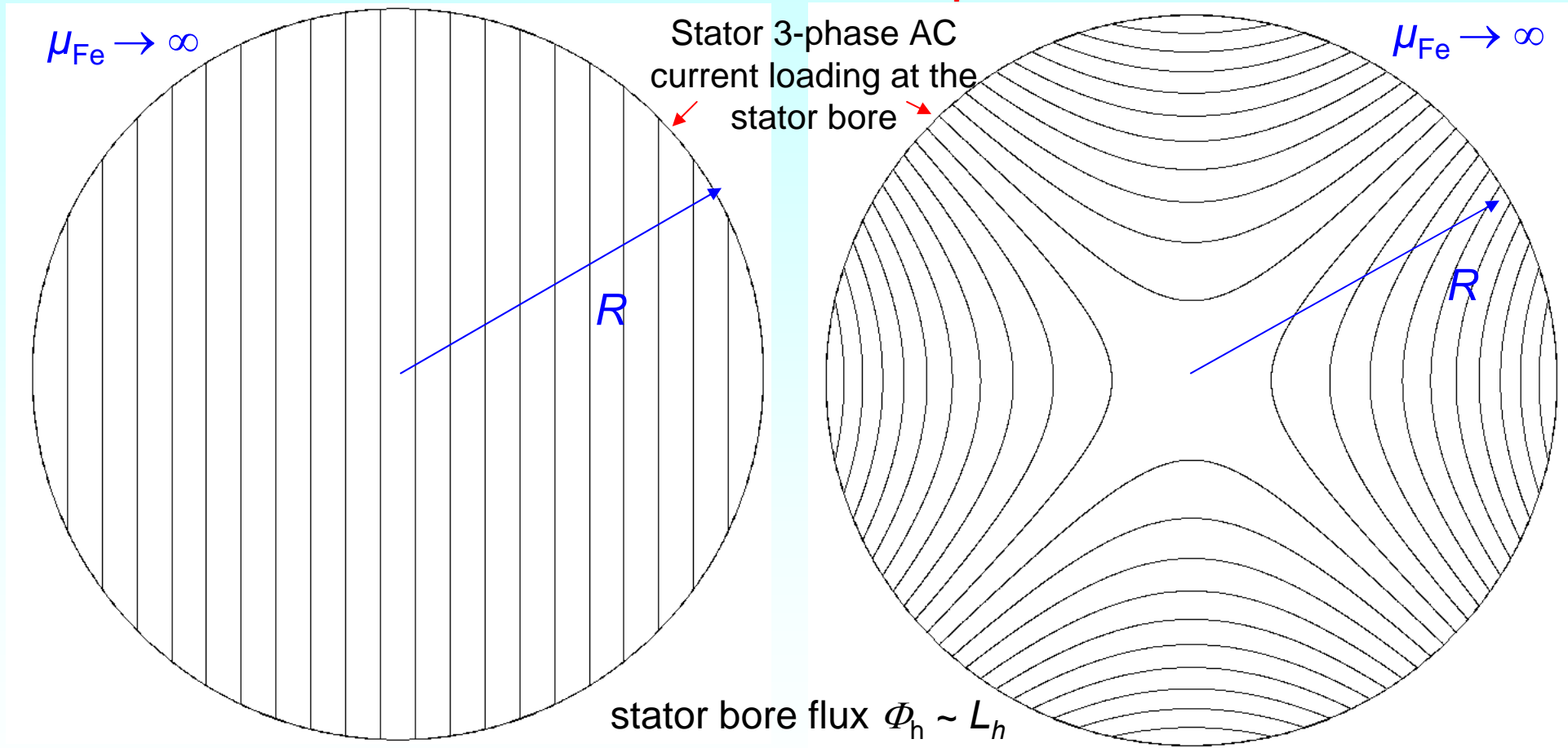Φ_{hf}: Coupled flux with field winding
Φ_{Dh}: Coupled flux with damper winding

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Analytical calculation of the stator magnetic field at unexcited rotor winding ($I_f = 0$)

$\mu_{Fe} \to \infty$

Stator 3-phase AC current loading at the stator bore

R

$\mu_{Fe} \to \infty$

R

stator bore flux $\Phi_h \sim L_h$

2-pole field excitation

4-pole field excitation

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Magnetizing inductance of the stator winding L_h
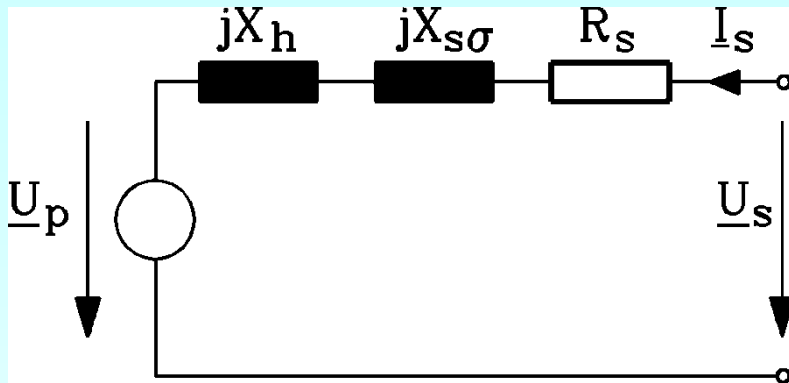
- $$L_h \sim \mu_0 N_s^2 \frac{R\pi}{\varDelta} l$$ Number of turns per winding phase: N_s

- SC: $\varDelta = R$ (austenitic rotor: non-magnetic), NC: $\varDelta = \delta_{mag}$

- Air-gap winding: $A_{SC} = 2A_{NC}$: $N_{SC} = 2N_{NC}$.

  SC: Super-conducting
  NC: Normally conducting

- Iron length $l_{SC} = l_{NC}/3$

  Example: SC: $R = 0.875$ m, NC: $R = R_f + \delta_{mag} = 0.5 + 0.1 = 0.6$ m

  $$\frac{L_{h,SC}}{L_{h,NC}} = \frac{N_{SC}^2 \cdot R_{SC} \cdot l_{SC} \cdot \Delta_{NC}}{N_{NC}^2 \cdot R_{NC} \cdot l_{NC} \cdot \Delta_{SC}} = \frac{4 \cdot 0.875 \cdot 0.33 \cdot 0.1}{1 \cdot 0.6 \cdot 1 \cdot 0.875} = 0.2$$

- The magnetizing inductance L_h of the stator winding of the SC generator is significantly smaller than the one of a NC generator of equal power.

- The "synchronous inductance" (sum of magnetizing and stator stray inductance) amounts to about 30% of the value of conventional turbine generators.

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2.2 Superconductivity in electrical engineering

$$\underline{U}_S = (R_S + j\omega L_{S\sigma} + j\omega L_h)\underline{I}_S + \underline{U}_p$$

Equivalent circuit of synchronous machines:
- Back *emf voltage* $\underline{U}_p$ ("controllable" by I_f)
- Winding resistance R_s
- Leakage- / Main reactance $X_{s\sigma} = \omega L_{s\sigma} / X_h = \omega L_h$
- Synchronous reactance: $X_d = X_{s\sigma} + X_h$

$U_p \cdot \sin\vartheta = X_d I_s \sin(\varphi - \frac{\pi}{2})$

- **Assumption $R_s = 0$: Then electrical and mechanical power are equal:** $\underline{P_e = P_m}$

$$P_e = 3U_s I_s \cos\varphi, \quad P_m = \Omega_m M_e = \Omega_{syn} M_e$$

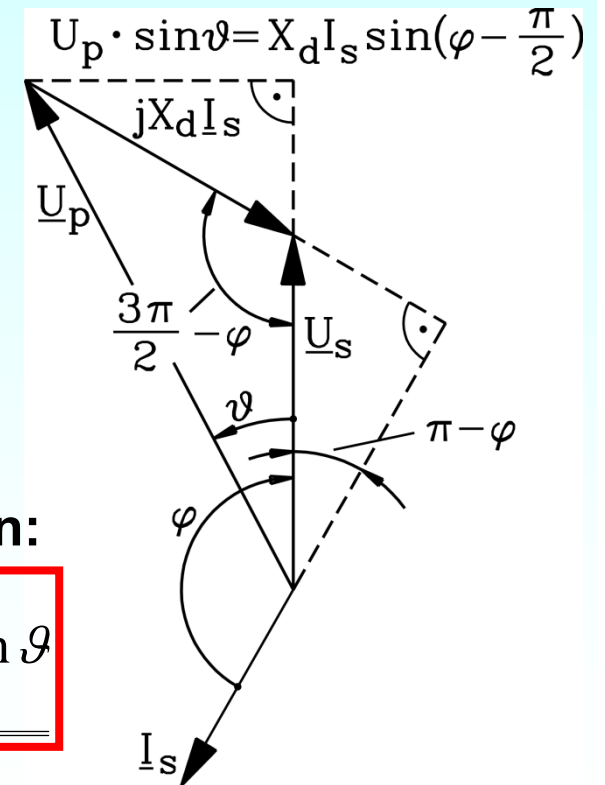- **Phasor diagram:**

$$U_p \sin\vartheta = X_d I_s \sin(\varphi - \frac{\pi}{2}) = -X_d I_s \cos\varphi$$

$$\underline{\underline{P_e}} = 3U_s \cdot \frac{-U_p \sin\vartheta}{X_d} = -\frac{3U_s U_p}{X_d}\sin\vartheta = \underline{\underline{P_m}}$$

Torque equation:

$$\underline{\underline{M_e = -\frac{3U_s U_p}{\Omega_{syn} X_d}\sin\vartheta}}$$

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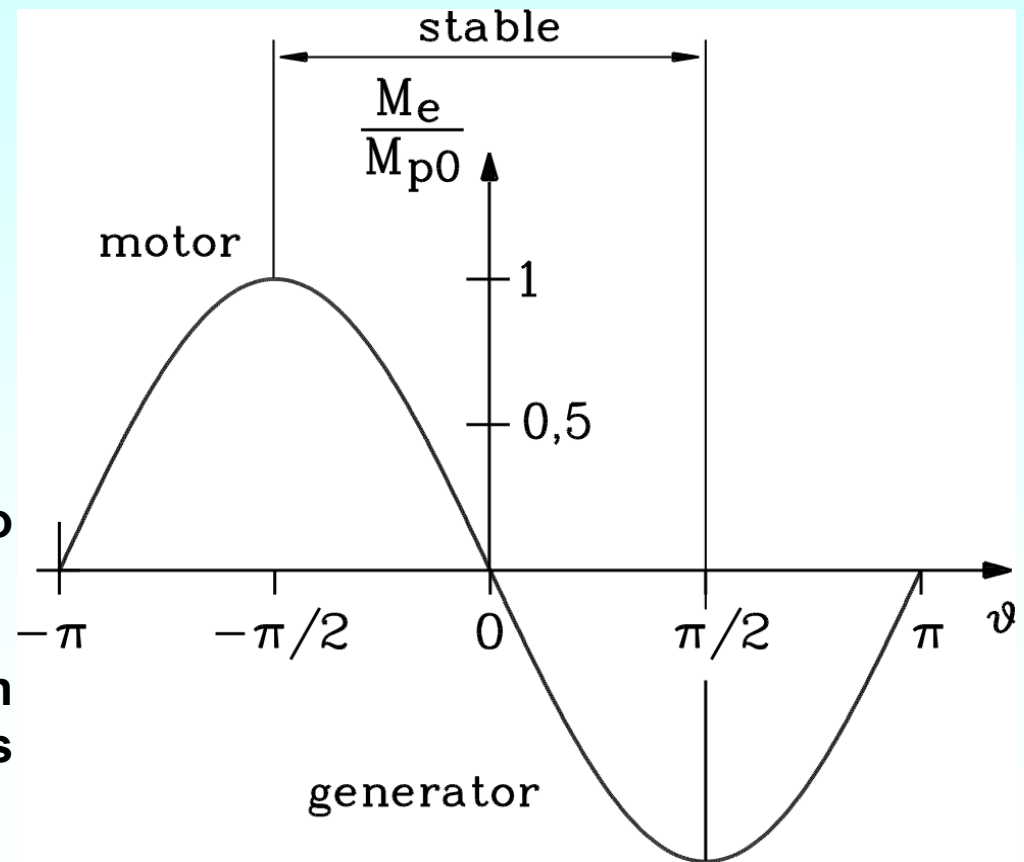
Electromagnetic torque vs. load angle

- **Machine produces maximum torque M_{p0} at load angle ±90°, where the "synchronous pull-out torque" occurs.**

$$M_e = -M_{p0} \sin \vartheta$$

$$M_{p0} = \frac{3 U_s U_p}{\Omega_{syn} X_d}$$

- **Increase of excitation current I_f leads to increase of U_p and pull-out torque**

- **Only for -90°< ϑ <90° a STABLE operation of the synchronous machine at the grid is possible.**

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Study: 1000 MVA LTSC synchronous generator

- <u>Data:</u> 27 kV line-to-line voltage, 15.6 kV & 21.4 kA phase voltage & current, Y connection of stator winding, stator frequency 50 Hz: $3U_sI_s = 3 \cdot 15.6 \cdot 21.4 = 1\text{GVA}$

- **Losses:**

  a) Conventional generator (NC): losses = ca. 10 MW: Efficiency 99 %

  $$x_d = x_{s\sigma} + x_{dh} = 1.7 \text{ p.u.}, \quad x_{s\sigma} = 0.4 \text{ p.u.}, \quad x_{dh} = 1.3 \text{ p.u.}$$

  b) LTSC generator: (LHeI cooling): - 40 % losses:

  Total losses = ca. 6 MW: Efficiency: 99.4 %

- **Reactance values:** $x_d = x_{s\sigma} + x_{dh} = 0.6 \text{ p.u.}, \quad x_{s\sigma} = 0.4 \text{ p.u.}, \quad x_{dh} = 0.2 \text{ p.u.}$

  related to nominal impedance $Z_N = U_{N,phase} / I_N = 0.73\Omega$

  $$x_d = \omega L_d / Z_N = 0.6 \Rightarrow L_d = 1.4mH \quad, L_h = 0.42 \text{ mH}, L_{s\sigma} = 0.98 \text{ mH}$$

Facit: Stray inductance $L_{s\sigma}$ higher than the magnetizing inductance L_h !

Very high synchronous pull-out torque yields very high overload capability!

$$\boxed{M_{p0} \sim 1/X_d}$$

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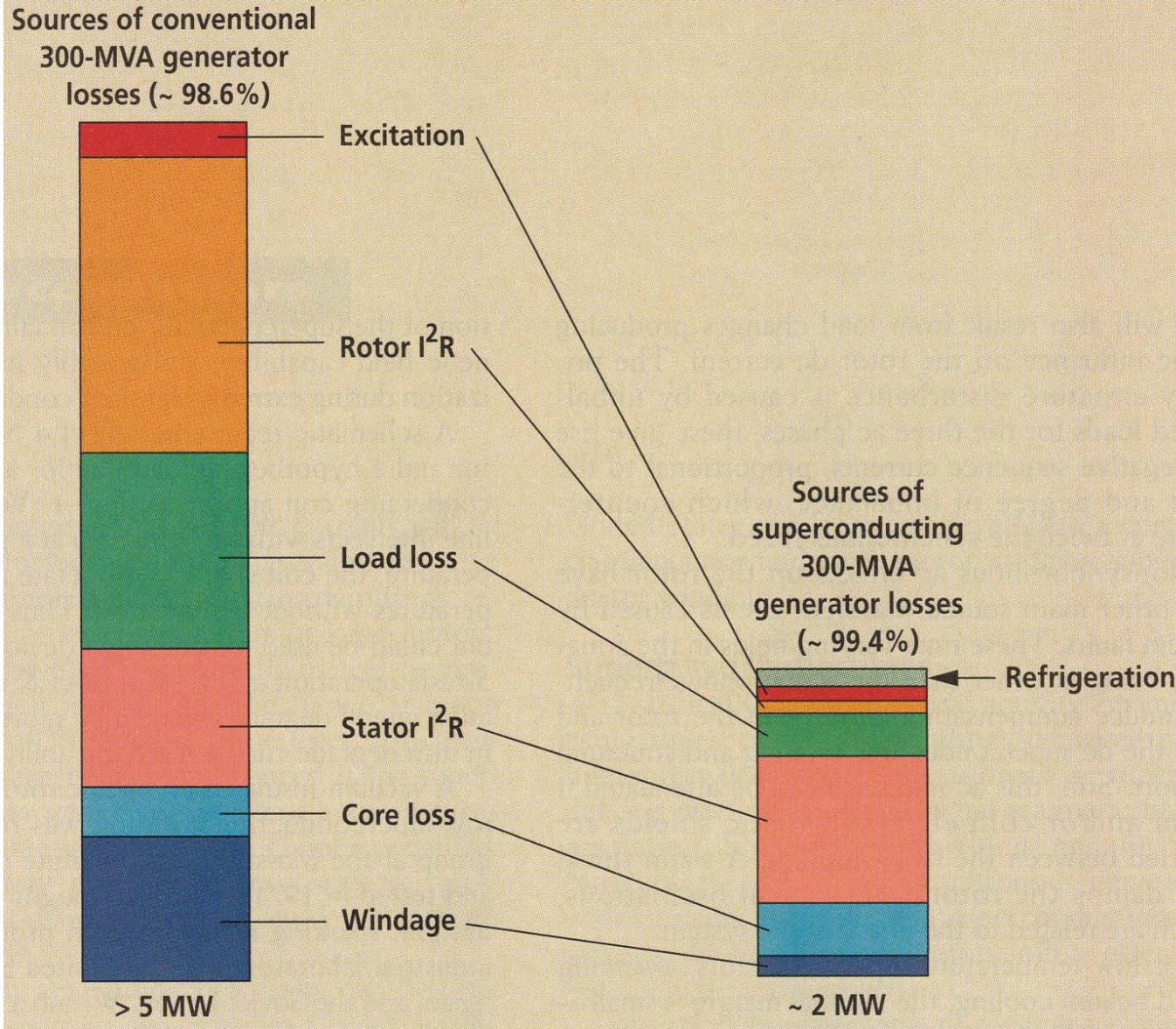
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Designed large SC generators 70 MVA, 2-pole, 60 Hz

● *Hitachi, Toshiba, Mitsubishi:* Feasibility study as pre-stage for 200-300 MW turbine generator
   - LTSC rotor (4.2 K LHeI cooling): LTSC multi-filament NbTi rotor field coils
   - Stator from *Hitachi*: normal-conducting Cu coils, Rotors: *Hitachi/Toshiba/Mitsubishi*

Generator 300 MW	NC: Rotor air-cooled	LTSC: NbTi, 4.2 K, LHeI
Total losses	4.3 MW	1.8 MW
Efficiency	98.6 %	99.4 %
Excitation equipment	160 kW	100 kW
Rotor field winding	1460 kW	50 W
Stator: Joule losses	710 kW	840 kW
Stator: Additional losses	960 kW	300 kW
Stator: Iron losses	300 kW	300 kW
Gas and bearing friction	710 kW	210 kW
Refrigeration power	-	50 kW

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Sources of conventional 300-MVA generator losses (~ 98.6%)
- Excitation
- Rotor I^2R
- Load loss
- Stator I^2R
- Core loss
- Windage

> 5 MW

Sources of superconducting 300-MVA generator losses (~ 99.4%)
- Refrigeration

~ 2 MW

Comparison:

Loss in 300 MVA synchronous machines

Left side:
normal-conducting

Right side:
LTSC excitation winding

From ca. 300 MW on the LTSC technology pays off!

Source: IEEE Energy Conversion Magazine

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Economical limit of SC synchronous machines

- Conclusion from the 300 MVA-generator study:
  Factor 1000:1 between refrigerating power and machine losses
  on SC side: Nevertheless the refrigerating power influences the
  total efficiency only by 0.017 % (50 kW/300 MW = 0.017%)

- Economical lower limit for LTSC generator:
  ca. 100 MW (optimistic) … 300 MW (realistic) nominal power

- HTSC synchronous machines: significantly cheaper, simpler and less cooling
  power (Factor 40:1 between refrigerating power and machine losses on SC side):
  Economical lower limit at ca. 4 MW (optimistic) … 10 MW (realistic).

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Availability of the SC generator

- **_Example:_** 300 MVA generator: 40 years lifespan

    - normal-conducting: Total loss 4.3 MW

    - superconductive: Total loss 1.8 MW

    Energy saving per annum: (4.3-1.8)·8760 = 21.9 GWh

- Assumption: Failure of SC generator 3 days per year more often than
        a NC generator:

Produced deficiency in output: 3·300·24 = 21.6 GWh = roughly the same as the
loss saving of an entire year = no advantage in energy production!

Facit:
The availability of the SC generator (whole system of generator, cryogenics,
excitation equipment, protection concept) must be at least as high as the one of
the NC generator.

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2. Application of superconductors for electrical energy converters

2.2 Superconductivity for electrical energy technology

2.2.5 Rotating electrical machines with superconductor winding

- Energy conversion

- Superconducting homo-polar machines

- Superconducting synchronous machines with electrical excitation

- Low-temperature superconductor excitation winding for synchronous machines

- High-temperature superconductor excitation winding for synchronous machines

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High-temperature superconductor excitation winding for synchronous machines

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Application of HTSC strip conductors in synchronous machines

- **Advantages:** - **Lower** cooling power necessary than for LTSC
  - Cooling system **simpler,** hence more reliable
  - **Reliability/availability** of the SC generators **increases**
  - Less sensitive to *B* and *T* change: Danger of quenching lowered

LTSC: Nb$_3$Sn: B$_{c2}$ at temperature T	*HTSC: BSCCO: B$_{c2}$ at temperature T*
5 T at 8 K	*) Worst-case: Cross field: 5.5 T at 8 K
4.5 T at 10 K	5 T at 10 K
0 T at 18 K	4.9 T at 20 K
-	3 T at 60 K
-	0 T at 120 K

- **Liquid hydrogen cooling** (LH$_2$) at ca. 20 K,
- **He or neon cold gas cooling** at ca. 20 ... 30 K, $P_T \sim P_d/\eta_{eff}(T)$
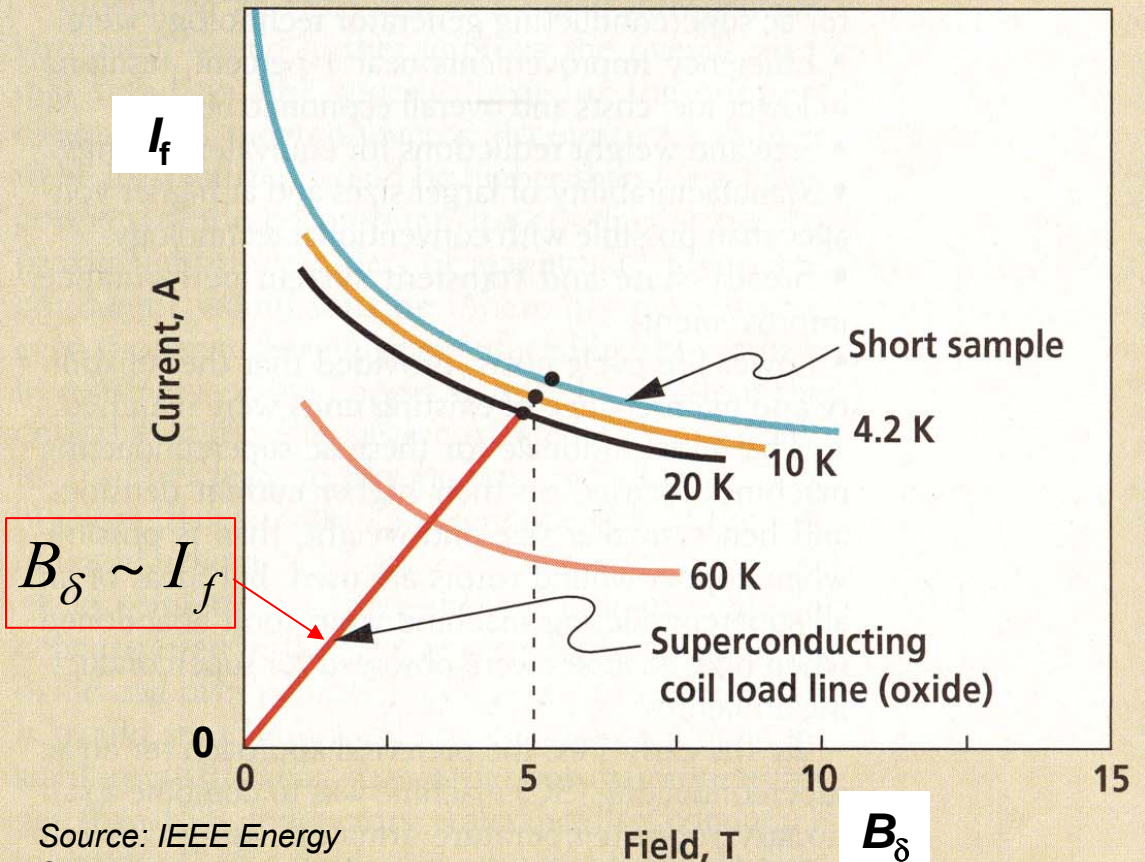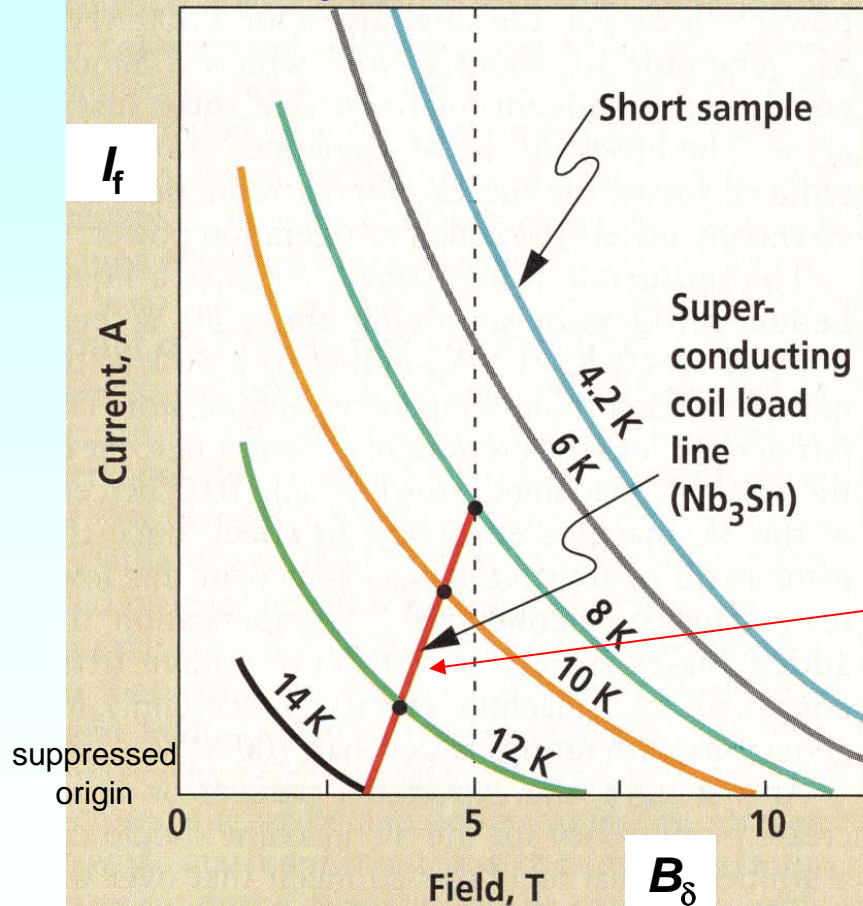- **Cooling power ratio** at *T* = 4.5 K/20 K/80 K: **P_T/P_{80K} = 40:8:1** ($1/\eta_c$ = 24:5:1)

- **Disadvantages:** - *) **Anisotropy** of HTSC reduces critical field strength
  - HTSC: **Brittle material:** maximum expansions 0.3%, precise stress design needed

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2.2 Superconductivity in electrical engineering
Superconductive field coils for synchronous motors/generators

LTSC Nb₃Sn: 5 T demand 8 K   **HTSC BSCCO: 5 T demand 20 K**

$$B_\delta \sim I_f$$

Source: IEEE Energy Conversion Magazine

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Comparison of NC with HTSC motors at 4 MW

- Normal-conducting asynchronous motor (measured):   Efficiency 96 %

- HTSC synchronous motor at 77 K (calculation):

  a) without refrigeration (cryo) losses: Efficiency 98 %
  b) with 140 W cryo loss: Factor 30: 140·30 = 4200 W: Efficiency 97.9%

- HTSC synchronous motor at 30 K (built: *Alstom, Siemens*):
    140 W cryo loss: Factor 90: 140·90 = 12.6 kW   Efficiency 97.7%

$$(\eta_{c,80K} / \eta_{c,30K} = 3{:}1)$$

Facit:

Despite the necessity of operating HTSC motors with BSCCO strip conductors at about 30 K currently, compared to normal-conducting machines, an efficiency advantage of ca. 1.7 % points is possible at 4 MW nominal power.

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Cost of superconductors and cooling

- **LTSC standard wires (strip conductor):**

NbTi:
DC: Cu matrix: 50 ... 100 Euro/kg, 3 ... 5 Euro/(kA und m) at 8 T
AC: Cu-Ni mixed matrix and thin filamentary SC conductors: up to 10 times more expensive!

For comparison: Cu wire (crude copper): ca. 10 Euro/kg

Nb_3Sn:
500 .... 1000 Euro/kg resp. 30 ... 60 Euro/(kA and m) at 13 T
Elaborate production process necessary, so more expensive!

- **HTSC-BSCCO strip conductor:**
  DC/AC: Ag matrix: ca. 2000 ... 3000 Euro/kg (prototype wire) $\Rightarrow$ 1000 Euro/kg expected

- **Coolant:**
  External purchase: LHel: 8 ... 15 Euro/Liter, LN_2: 0.1 ... 0.2 Euro/Liter
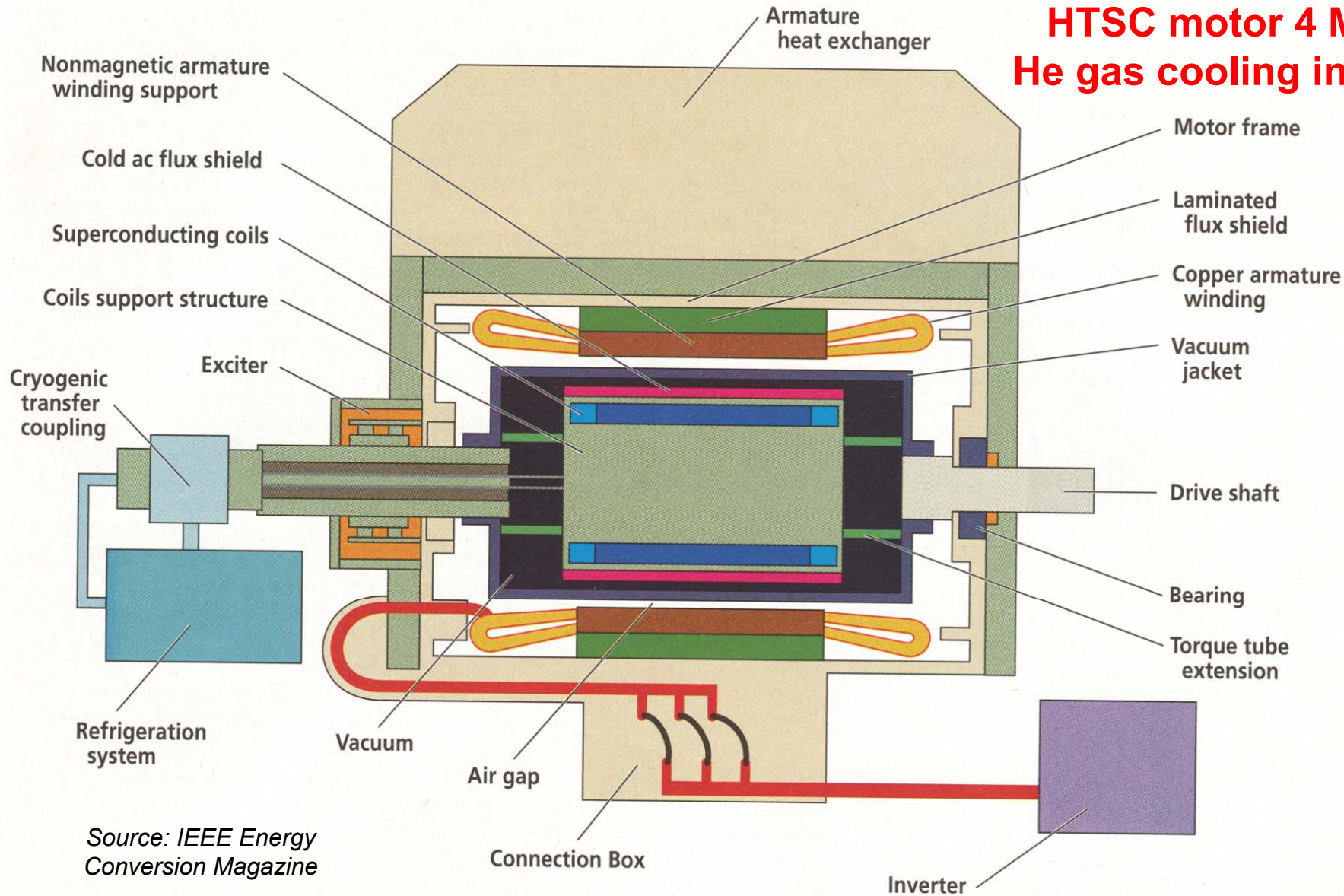 Per Wh "evaporation heat" (boiling bath cooling):
                    LHel: 10 ... 20 Euro/Wh, LN_2: 0.02 ... 0.05 Euro/Wh

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**HTSC motor 4 MW with
He gas cooling in the rotor**

Armature
heat exchanger

Nonmagnetic armature
winding support

Cold ac flux shield

Superconducting coils

Coils support structure

Exciter

Cryogenic
transfer
coupling

Refrigeration
system

Vacuum

Air gap

Connection Box

Motor frame

Laminated
flux shield

Copper armature
winding

Vacuum
jacket

Drive shaft

Bearing

Torque tube
extension

Inverter

*Source: IEEE Energy
Conversion Magazine*

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HTSC synchronous motor 149 kW with He gas cooling
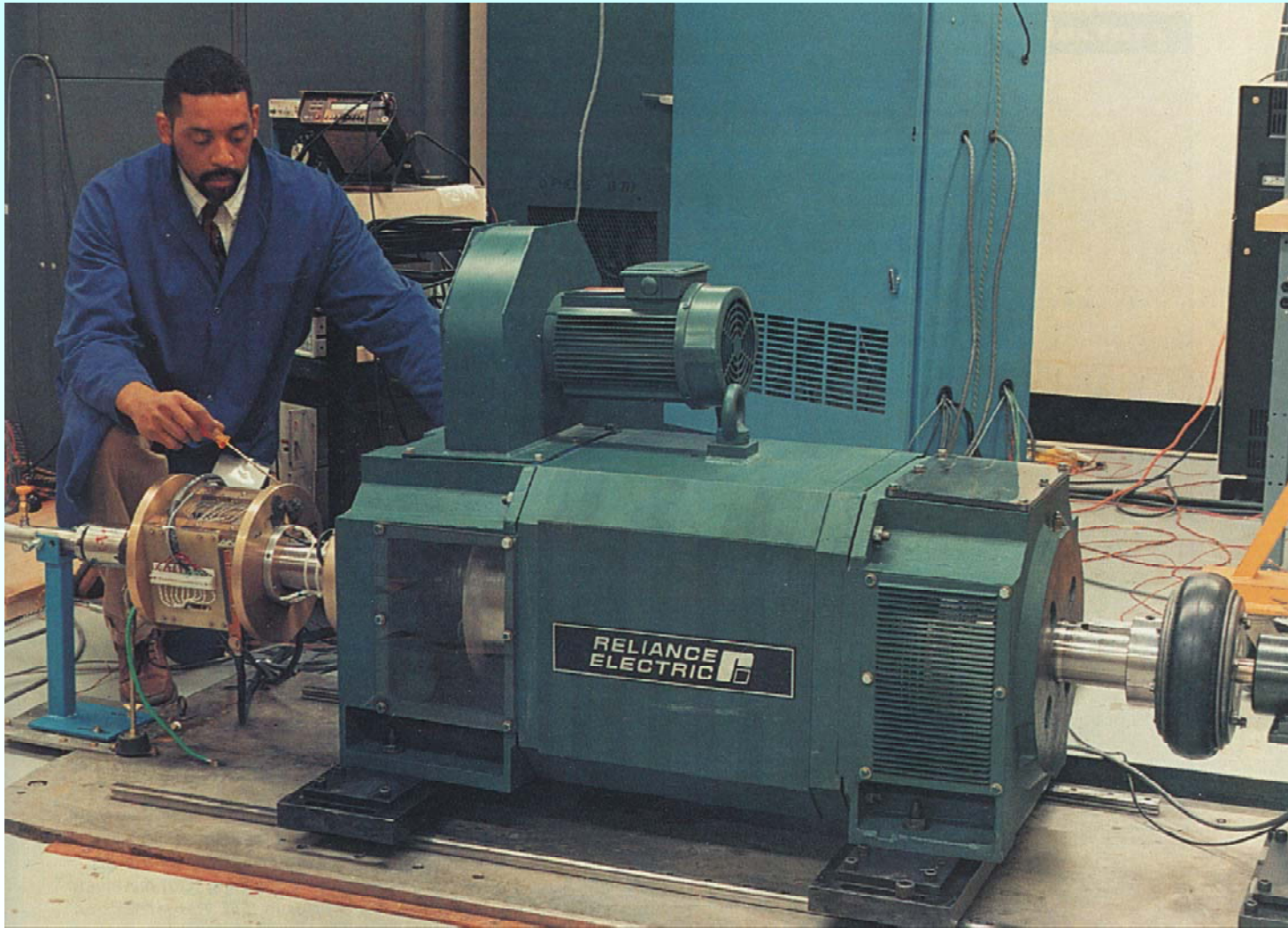
Source:
Reliance
Comp., USA

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Designed HTSC synchronous motor 380 kW *(Siemens AG)*

Rated power	P_N	kW	380
Rated voltage	U_N	V	400
Rated current	I_N	A	568
Power factor	$cos\varphi$	-	1.0
Field current	I_f	A	49
Rated speed	n_N	1/min	1500

- Four pole HTSC excitation winding (salient-pole machine), 2.5 T exciting field

- Three-phase current air-gap winding, twisted copper litz wires, forced-air cooling,
  1.1 T flux density at the stator bore, housing of the machine = frame size 350mm

- Operation of the motor tested a) at the 50 Hz grid and b) at the inverter

- Rotor cryostat: Neon gas cooling in a closed cooling circuit as thermal siphon cooling.
  Hollow rotor shaft for Ne supply at -249°C, *Gifford-McMahon* cooler, pre-cooling with LN_2,

- 10 km BSCCO wire (Company *NST, Denmark*), slip rings for excitation current

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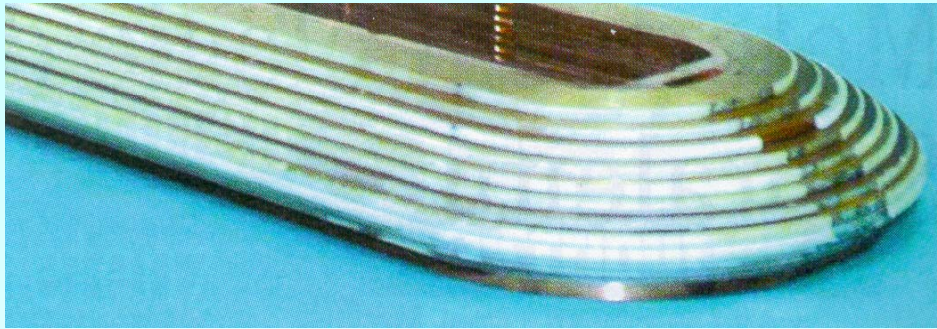# HTSC synchronous motor 380 kW in the test bay

Source:

Siemens AG, Nuremberg, Germany

- Closed neon cooling system with cold head in the foreground
- Fan for stator winding air cooling at the top, coupled load machine in the background

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HTSC synchronous motor 380 kW: Rotor construction

- HTSC field coil in graded design for optimum utilization of the winding space in the rotor

- The field coils are attached on the non-magnetic pole core with a bandage (mechanical fixation for coping with the centrifugal forces)

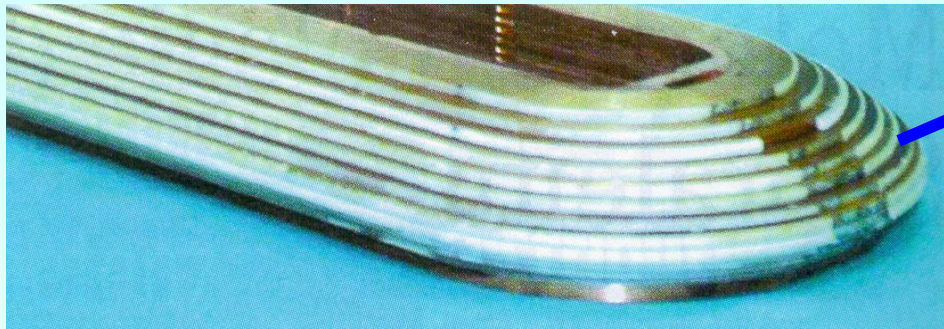Source: *Siemens AG, Nuremberg, Germany*

- An electrical damper cylinder is put over the bandage. The two ends of the shaft are designed as flanged shafts. On the right, the slip rings are visible.
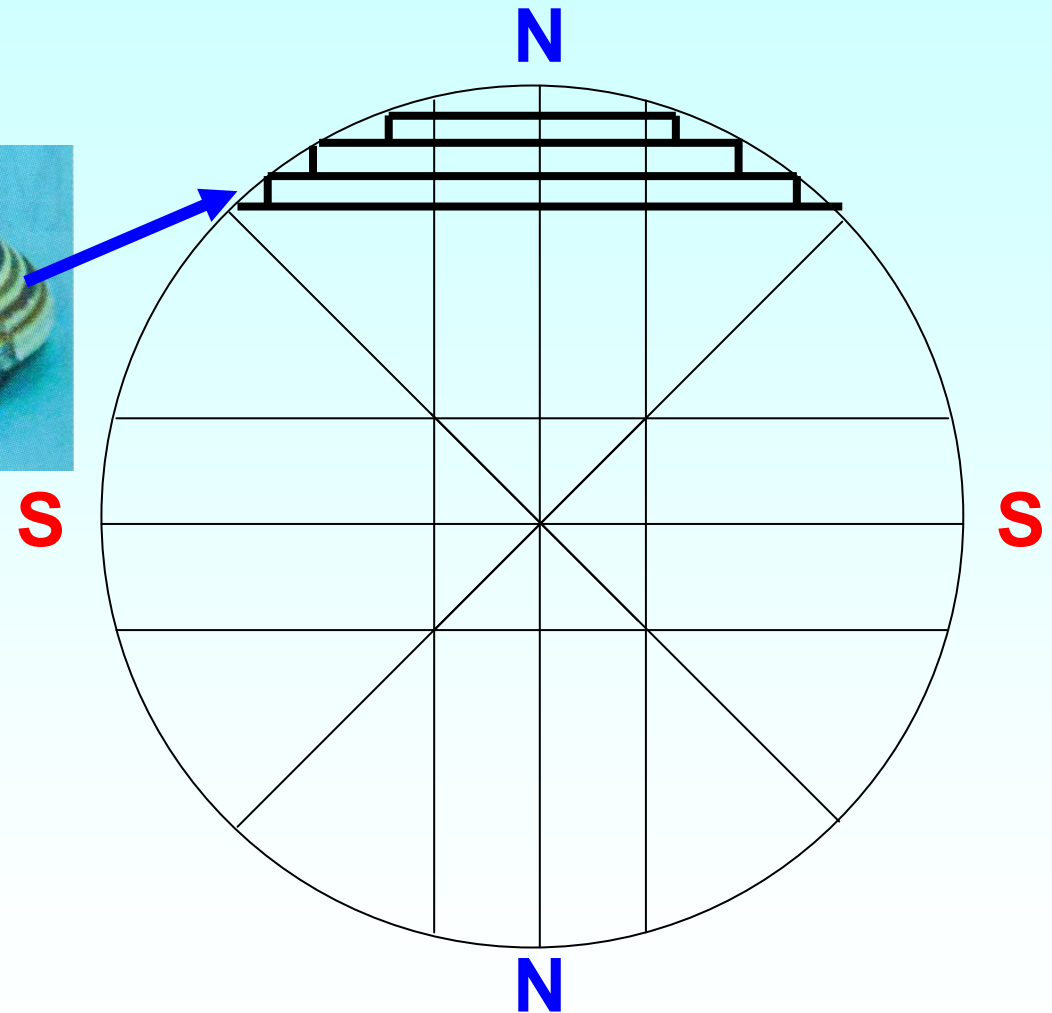
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Schematic of the rotor field coil of the HTSC synchronous motor 380 kW

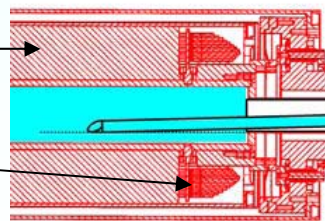Source: *Siemens AG, Nuremberg, Germany*

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380 kW-HTSC motor: Neon gas feeding to the rotor

Cold head with Neon gas feeding
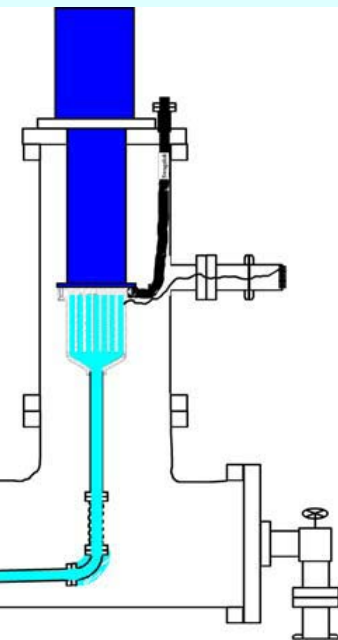
Stainless steel rotor

HTSC field winding

Source: *Siemens AG, Nuremberg, Germany*

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HTSC synchronous motor 380 kW:
Loss balance at sine operation at 50 Hz

Iron core iron losses	**1424 W**
Bearing friction losses	**150 W**
Separately driven fan losses	**1400 W**
Stator ohmic losses	**4309 W**
Rotor excitation losses	**0**
Cryo losses	**4173 W**
Brush contact losses	**98 W**
Additional losses stator	**411 W**
Eddy current losses in the stator winding	**562 W**
Total losses	**12527 W**
Efficiency	**96.8%**

Calculated efficiency at:

380 kW, Motor operation at 1500/min, 50 Hz, $\cos\varphi = 1$, 400 V, 568 A

Field excitation current: 49 A
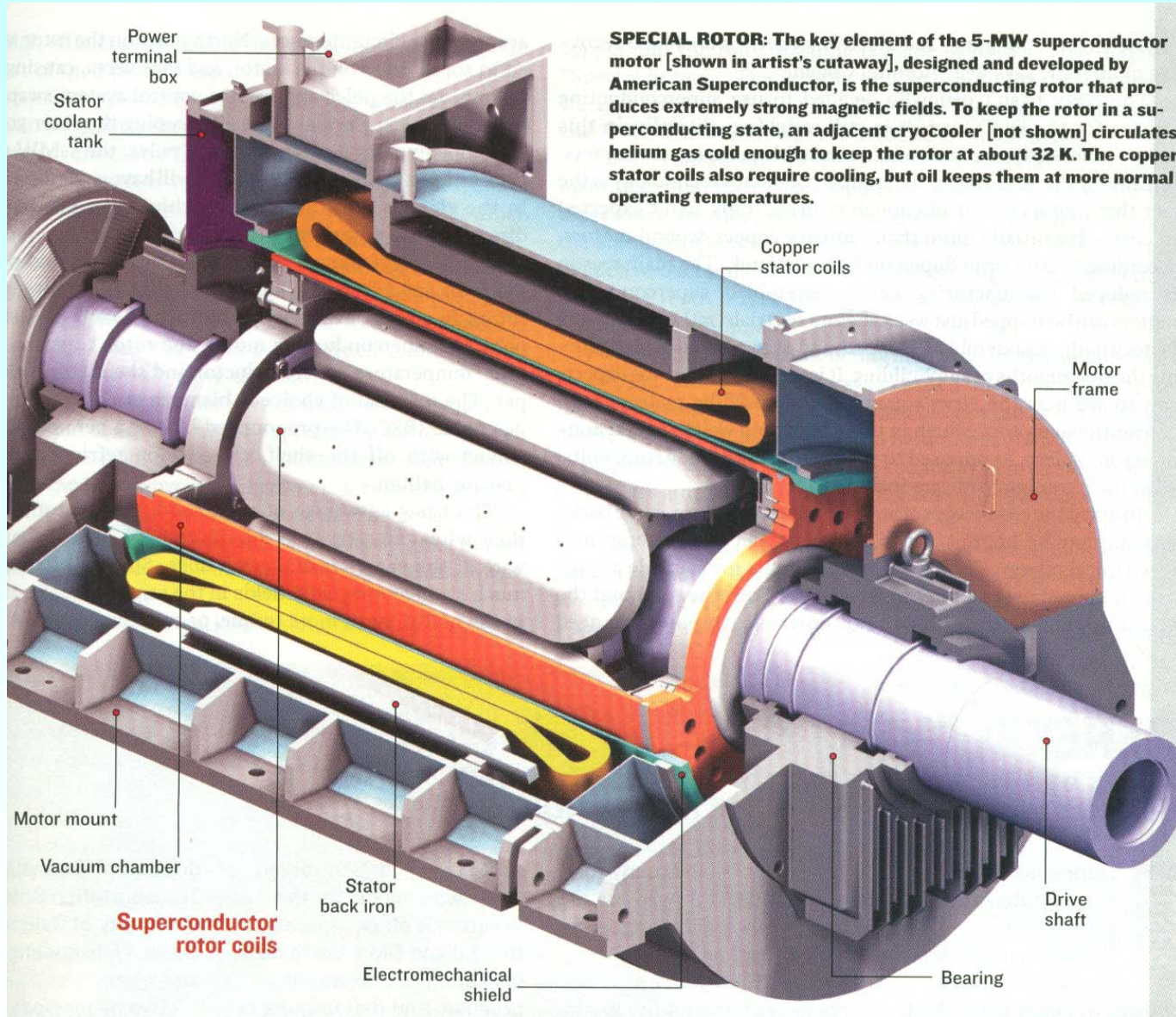
Source: Siemens AG

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HTSC synchronous motor 380 kW: Main electrical data

	SC	NC
Synchronous reactance x_d	0.15 p.u.	1 … 2 p.u.
Nominal load angle ϑ_N	8° el.	30 … 50° el.
Pull-out torque M_{p0}/M_N	7.0	1.5 … 2.0
Short-circuit current I_{sk}/I_{sN} (steady state, r.m.s.)	7.0	0.5 … 1.0
Harmonic content in the voltage THD	0.15 %	1 … 3 %

Source: Siemens AG

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SPECIAL ROTOR: The key element of the 5-MW superconductor motor [shown in artist's cutaway], designed and developed by American Superconductor, is the superconducting rotor that produces extremely strong magnetic fields. To keep the rotor in a superconducting state, an adjacent cryocooler [not shown] circulates helium gas cold enough to keep the rotor at about 32 K. The copper stator coils also require cooling, but oil keeps them at more normal operating temperatures.

Labels in figure: Power terminal box · Stator coolant tank · Copper stator coils · Motor frame · Motor mount · Vacuum chamber · Superconductor rotor coils · Stator back iron · Electromechanical shield · Drive shaft · Bearing
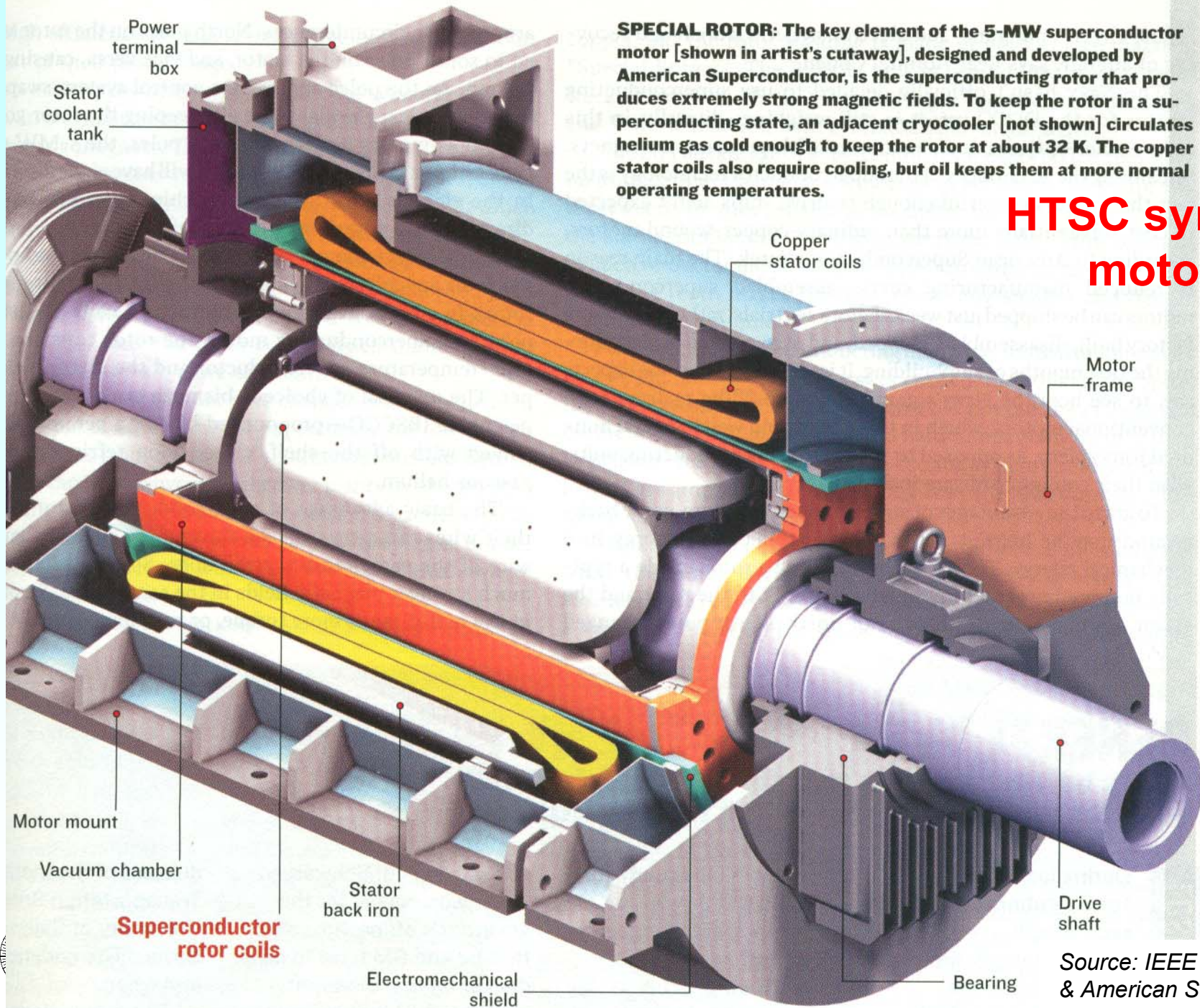
HTSC synchronous motor 5 MW

- 6-pole motor for ship drive project *US Navy*

- Rotor: He gas cooled at 32 K

- NC stator copper winding oil-cooled

- Oil-lubricated sleeve bearings
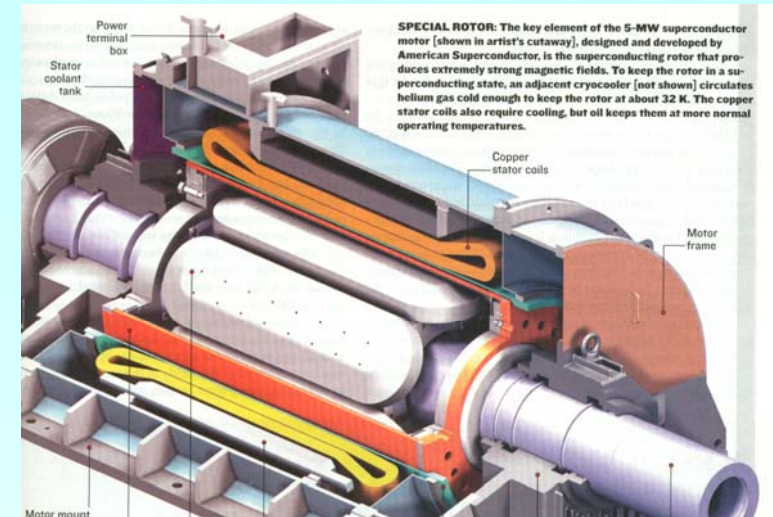
Source: IEEE IAS Magazine & American Superconductor

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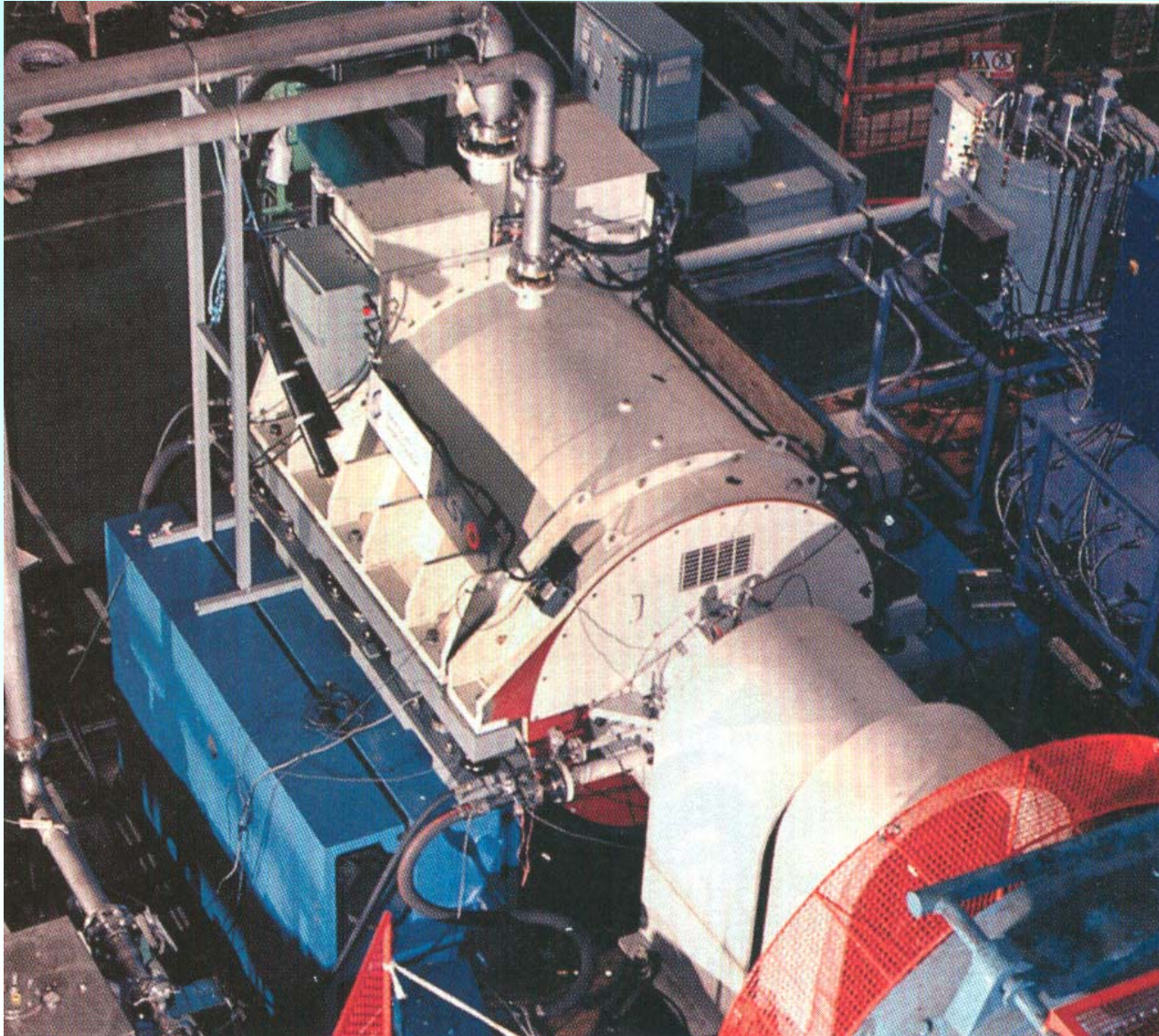
SPECIAL ROTOR: The key element of the 5-MW superconductor motor [shown in artist's cutaway], designed and developed by American Superconductor, is the superconducting rotor that produces extremely strong magnetic fields. To keep the rotor in a superconducting state, an adjacent cryocooler [not shown] circulates helium gas cold enough to keep the rotor at about 32 K. The copper stator coils also require cooling, but oil keeps them at more normal operating temperatures.

HTSC synchronous motor 5 MW

Power terminal box

Stator coolant tank

Copper stator coils

Motor frame

Motor mount

Vacuum chamber

Stator back iron

Superconductor rotor coils

Electromechanical shield

Drive shaft

Bearing

HTSC synchronous motor 5 MW

SPECIAL ROTOR: The key element of the 5-MW superconductor motor [shown in artist's cutaway], designed and developed by American Superconductor, is the superconducting rotor that produces extremely strong magnetic fields. To keep the rotor in a superconducting state, an adjacent cryocooler [not shown] circulates helium gas cold enough to keep the rotor at about 32 K. The copper stator coils also require cooling, but oil keeps them at more normal operating temperatures.

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Source: IEEE IAS Magazine & American Superconductor

HTSC synchronous motor 5 MW

- Motor for ship drive on the test rig at *Rugby, UK*

- Nominal torque: 208 kNm

- Nominal speed: 230 /min

- *US Navy* tested the machine in *Florida, USA,* afterwards successfully
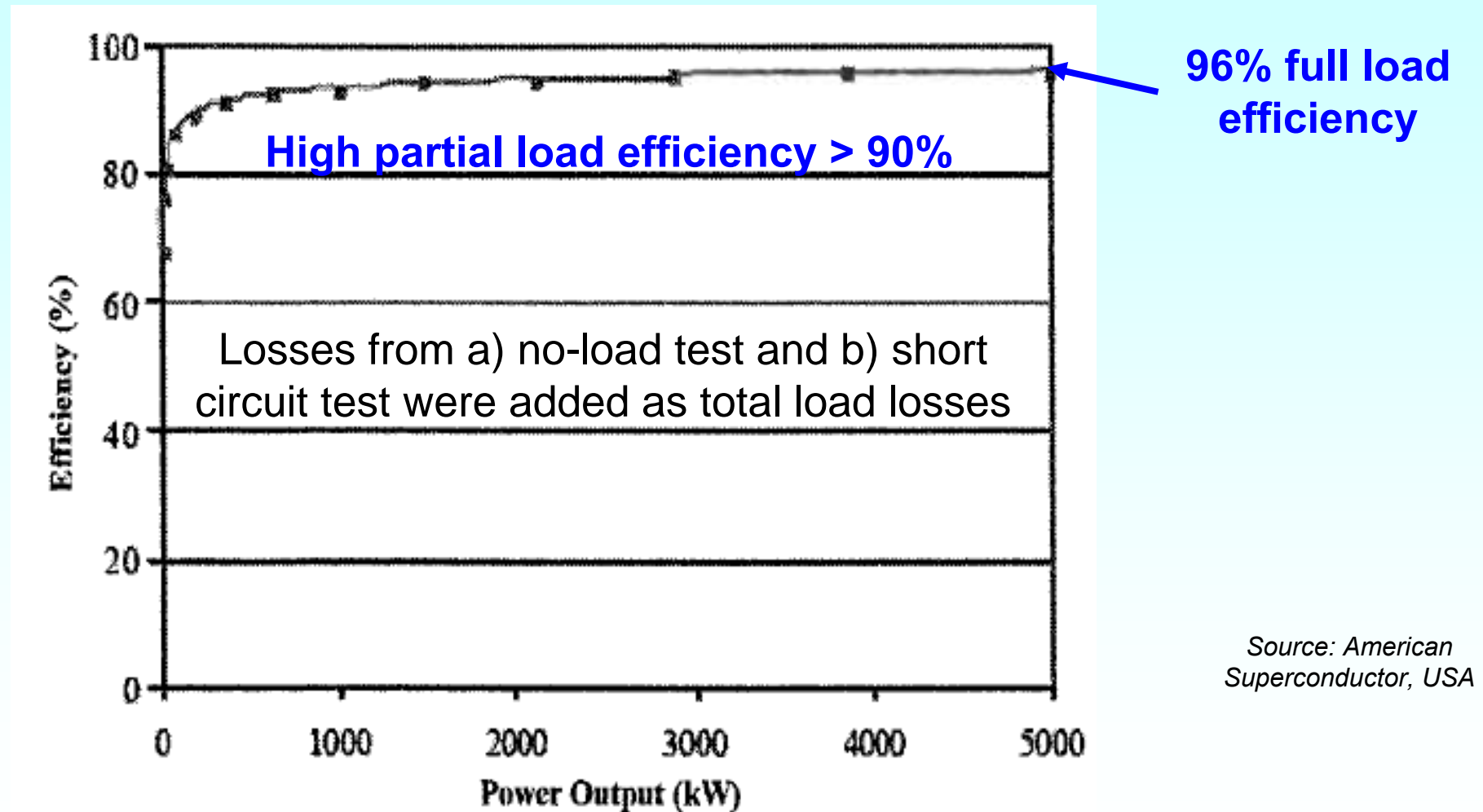
$$P = 2\pi n \cdot M$$

$$5\mathrm{MW} = 2\pi \frac{230}{60} \cdot 208 \frac{\mathrm{kNm}}{\mathrm{s}}$$

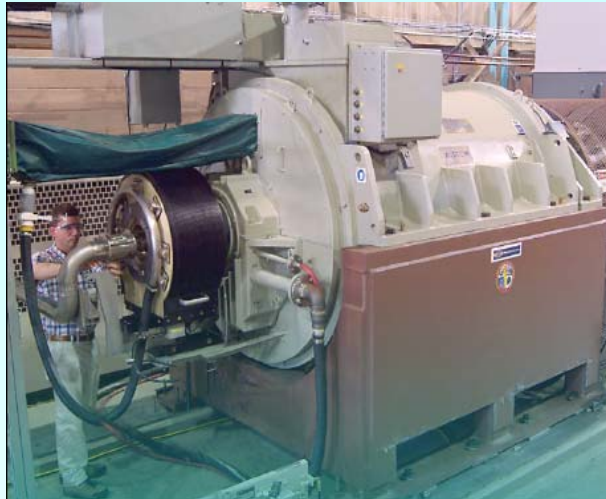*Source: IEEE IAS Magazine, American Superconductor, Alstom*

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Florida test results of the *U.S. Navy*: Measured efficiency: 6-poles HTSL- Synchronous motor 5 MW

96% full load efficiency

High partial load efficiency > 90%

Losses from a) no-load test and b) short circuit test were added as total load losses

Source: American Superconductor, USA

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Sudden short circuit – test: HTSC synchronous motor 5 MW

- **Synchronous reactance x_d = 0.32 p.u.**

- **Transient reactance x'_d = 0.24 p.u.**

- **Sub-transient reactance x''_d = 0.16 p.u.**

- **Stator time constant T_a = 69 ms (Armature time constant)**

- **Sub-transient short circuit time constants:**
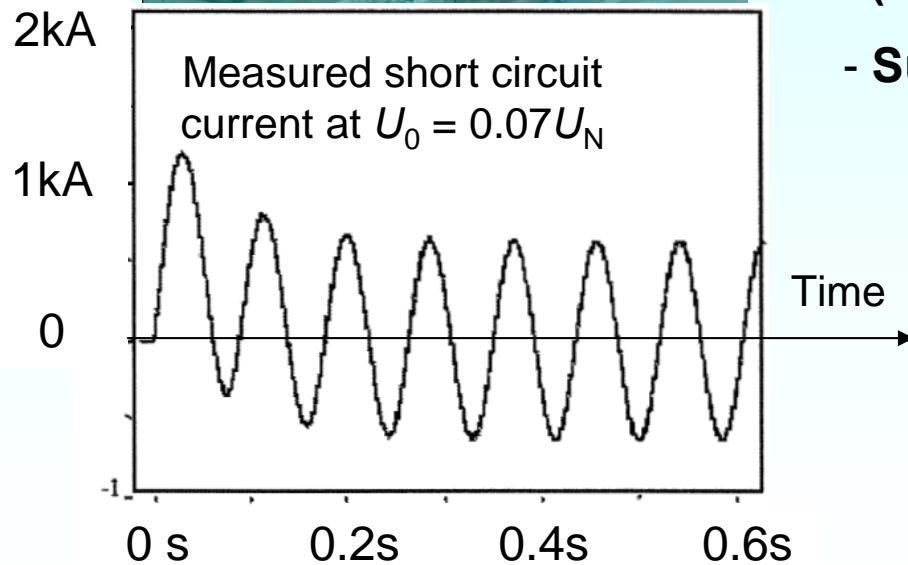
  d-axis: T''_d = 20 ms

  q-axis: T''_q = 28 ms

  Source: American Superconductor, Alstom

Measured short circuit current at $U_0 = 0.07 U_N$

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Synchronous motors with superconductors excitation field windings for ship propulsion

Source: American Superconductor

Rated power	5 MW (6 700 hp)	36.5 MW (49 000 hp)
Speed/Stator frequency	230/min / 11.5 Hz	120/min / 16 Hz
Efficiency	96%	97%
Pole / Phase count	6 / 3	16 / 9
Rated voltage line-to-line	4.16 kV	6.0 kV
Rated current per phase	722 A	1270 A
Power factor	1	1
Total mass	23 t	75 t
Dimensions L x B x H	2.5 m x 1.9 m x 1.9 m	3.4 m x 4.6 m x 4.1 m
Manufacturer	*Alstom/ UK*	*Northrop Grumman/USA*
Test date	2003	2008

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16-poles HTSC synchronous motor 36.5 MW (49000 hp)

- Synchronous motor with HTSC rotor excitation field winding for ship propulsion (*US Navy Frigate DDG-1000*)

- Manufacturers *Northrop Grumman & American Superconductor*

- Motor for ship propulsion with high-voltage inverter supply 6 kV

- *Speed range: 0 … 120/min, Rated torque: 2905 kNm*

- *Nominal efficiency 97%*

- *Oil liquid-cooling of the nine phases stator winding (Copper): 6 kV*

- *Stator electrical data: $U_{N,ph}$ = 3 kV, $I_{N,ph}$ = 1270 A, $\cos\varphi$ = 1*

- *Motor mass: 47 Tons (total < 75 Tons), l x b x h = 3.4 m x 4.6 m x 4.1 m*

- *Comparison to a NC motor, which has ca. double masses und volumes*

Source: American Superconductor, USA

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9-phase stator winding
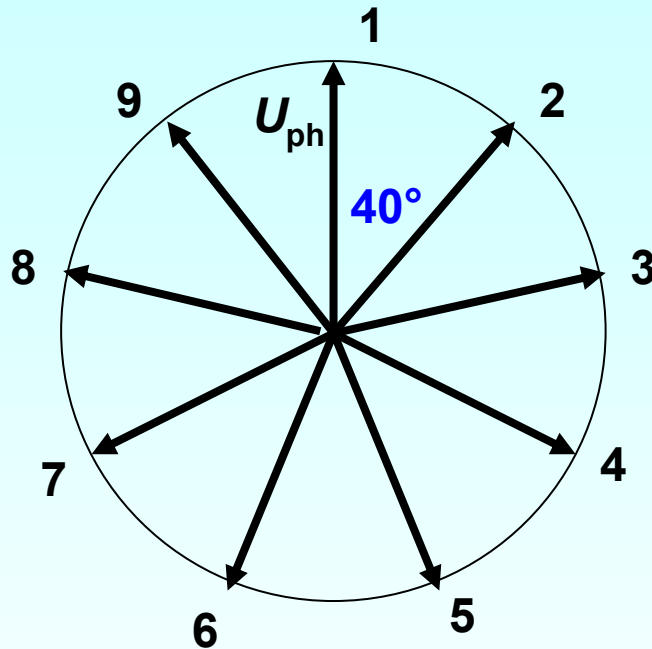
Maximum line-to-line voltage: e.g.: $U_{1\text{-}5}$: nearly:

$$U_{LL,\max} \approx 2 \cdot U_{ph} = 2 \cdot 3000 = 6\text{kV}$$

$$P_e = m \cdot U_{ph} I_{ph} \cos \varphi = 9 \cdot 3000 \cdot 1350 \cdot 1 = 34.3\text{MW}$$

$$P_{m,N} = 2\pi n \cdot M \Rightarrow M = 36500000/(2\pi 120/60) = 2905\text{kNm}$$

Source: American Superconductor, USA

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16-pole HTSC-Synchronous motor 36.5 MW
(49000 hp): Assembly in *Philadelphia* at *US Navy* Test Center

Rotor pole (DC-excitation)

HTSC-rotor   16-poles stator

16-poles HTSC-rotor

Before assembly

November 2008

Source: American Superconductor, USA

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36.5 MW-HTSC-synchronous motor on the test bench with the cryostat
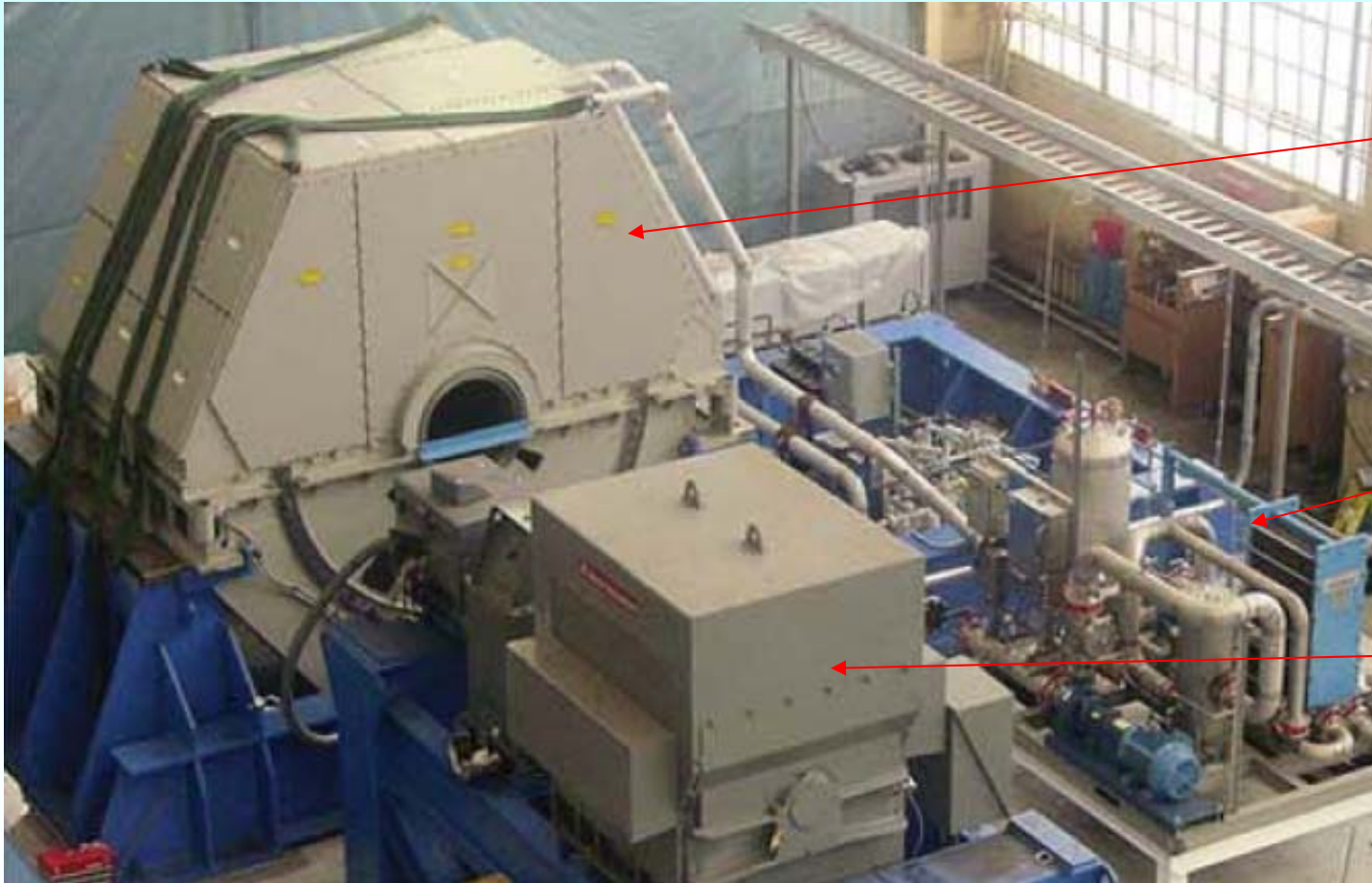
36.5 MW-HTSC-synchronous motor

cryostat

NC machine for driving the HTSC machine as a generator for no-load and short-circuit test

Source: American Superconductor, USA

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Size comparison of ship motors:
21 MW, 150/min (normal conductors) vs. 36.5 MW, 120/min (HTSC)

Copper Motor
21 MW, 150rpm, 4KV
183 tonnes

Source:

American Superconductor, USA

HTS Motor
36.5 MW, 120rpm, 6.6KV
<75 tonnes

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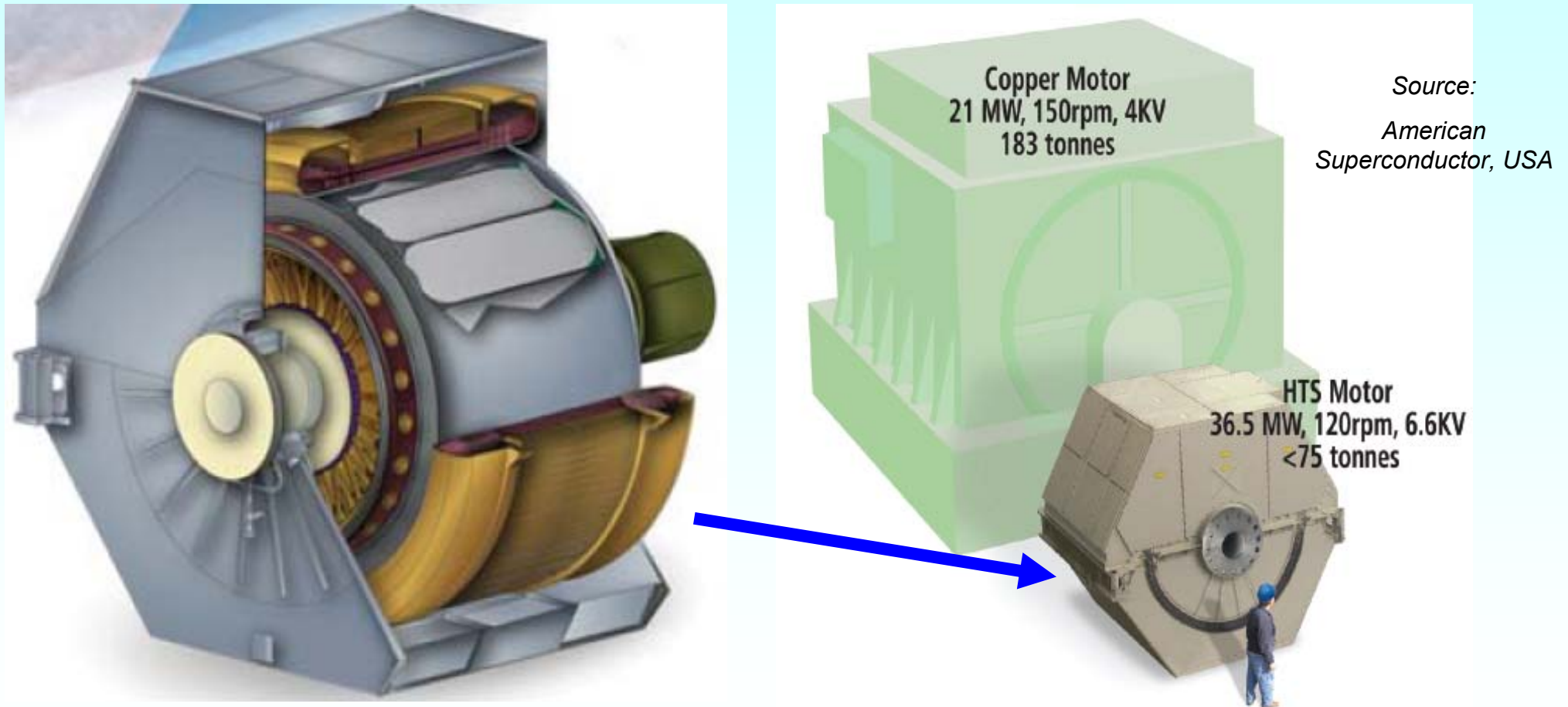
HTSC – 2-pole 4 MW synchronous generator 3600/min, 60 Hz, 6.6 kV, cosφ = 0.8 o.e. for ships in system test bay, *Nuremberg*

Source:

Siemens AG, Nuremberg. Germany

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4-MW-HTSC generator: Schematic Design of Motor and Rotor Cooling

Ambient temperature

RT

4000 kVA

6600 V, 60 Hz

$2p$ = 2, 3600/min

T = 25...30 K

Magnetic air gap

Source:

Siemens AG
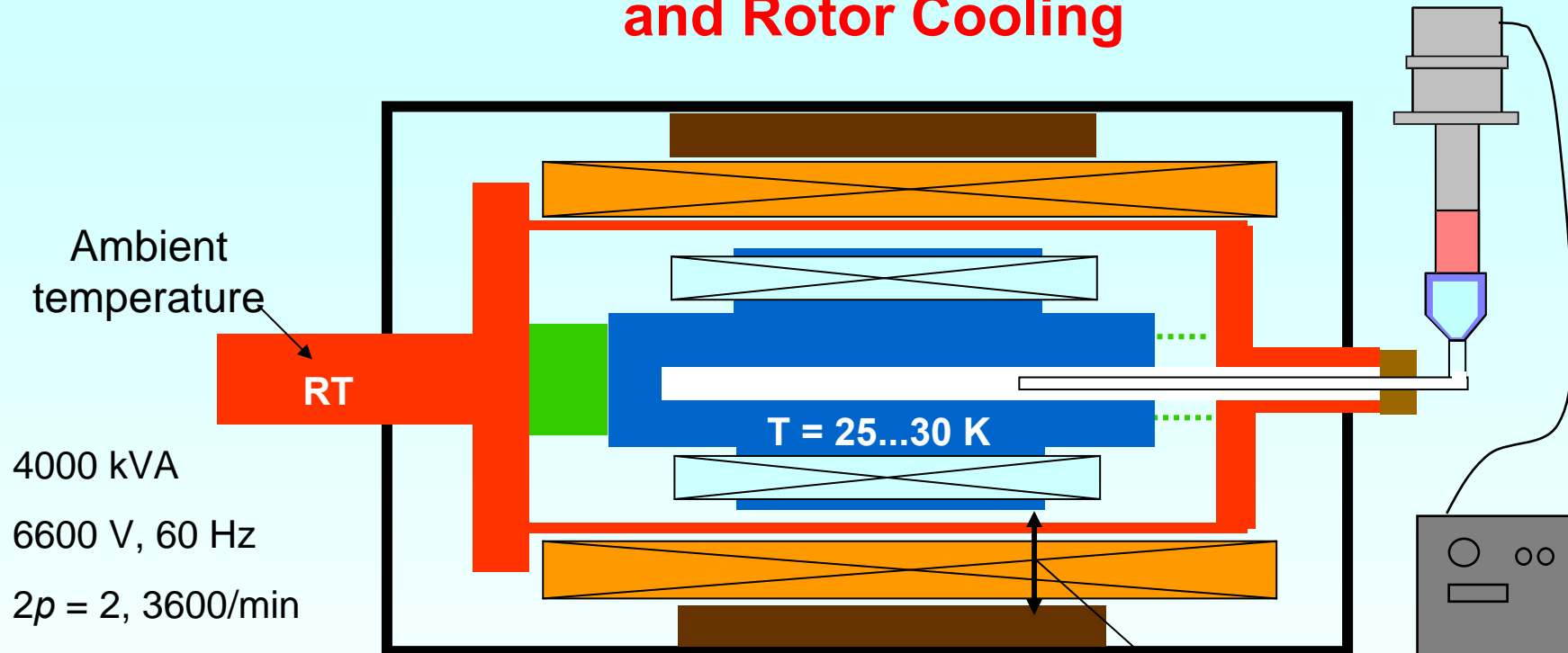
- **Rotor** = Cryostat
- **Torque transmission** (causes heat inflow)
- **Neon gas cooling through the hollow shaft** (cryogen transfer coupling -246°C)
- **Refrigeration system** (closed loop cooling system)
- **Stator without iron teeth, air-gap stator winding**

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4-MVA-HTSC generator: HTSC rotor pole coil

Source:

Siemens AG

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4 MW synchronous generator for ships: Comparison of the 2-pole HTSC prototype with a conventional 4-pole generator
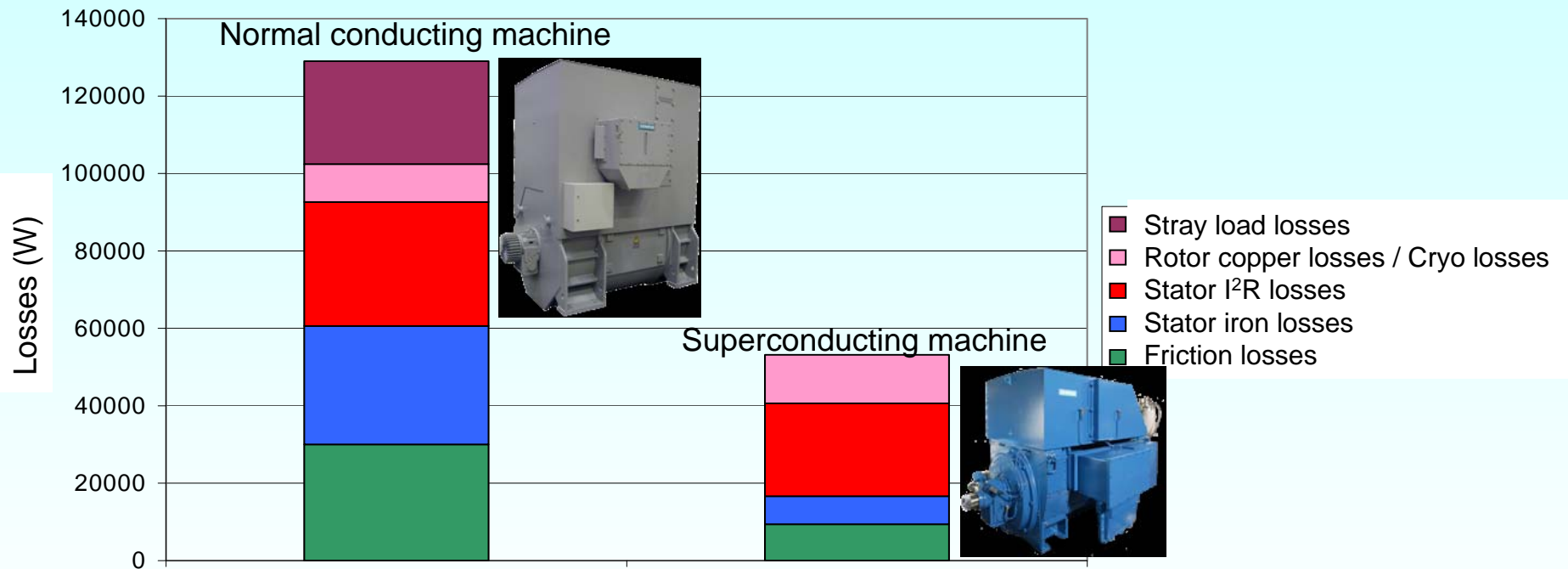
Smaller size and weight for the HTSC generator

2-pole 4 MVA HTS generator compared to **conventional 4-pole 4 MW generator**

2700

11 t

7 t

1800

Source:

Siemens AG

2600

3700

2200

1900

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Long term test of the 4-MVA-HTSC 2-pole prototype at 50 Hz, 3000/min as a phase-shifter (compensator) at *Siemens, Nuremberg*

Operation since 2008, compensates as over-excited machine with a capacitive load angle the inductive reactive power of the Siemens NMA manufacturing site
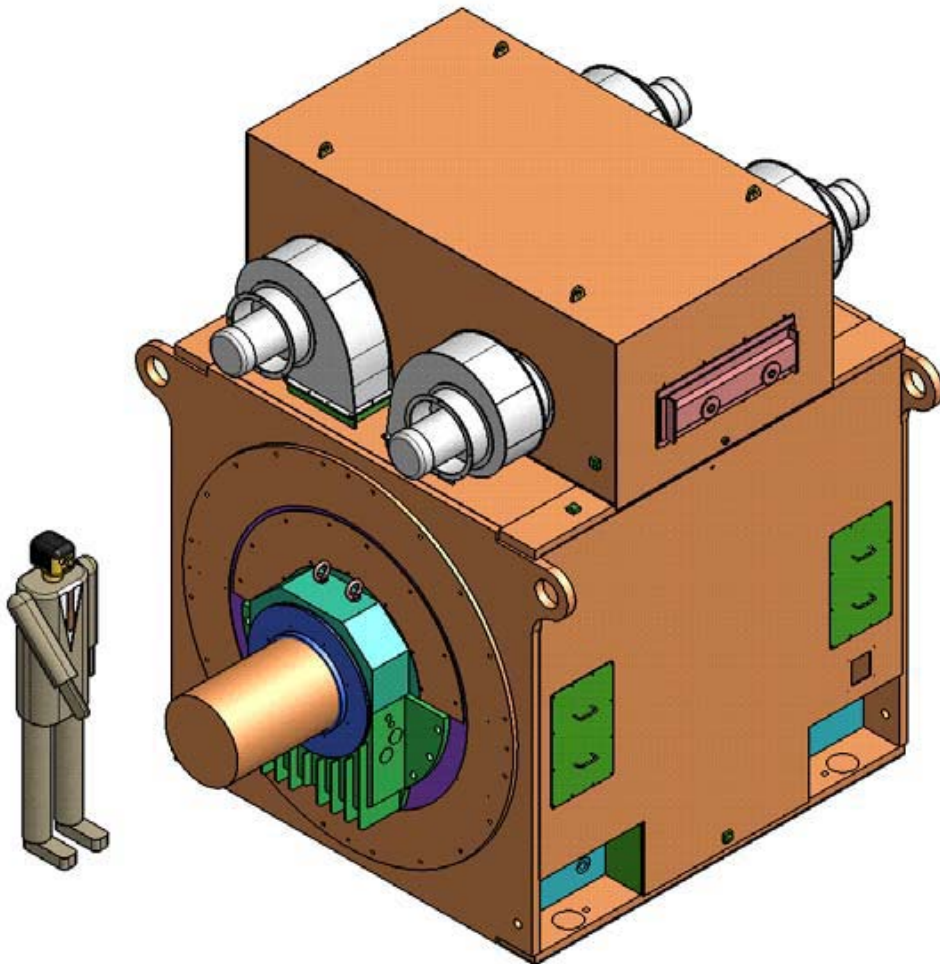
Source:

Siemens AG

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4 MW/120 min⁻¹ HTSC synchronous motor for ship propulsion

4000 kW, 3300 V, 8 Hz, M = 318.3 kNm

$2p$ = 8, 120/min, inverter operation, 36 t

$$f = n \cdot p = (120/60) \cdot 4 = 8 Hz$$

Source: Siemens AG

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**Institute of Electrical
Energy Conversion**

4 MW/120 min^{-1} HTSC synchronous motor for ship propulsion: Design data

Motor operation	Full rotor field		Field weakening
	Low speed	**Nominal**	**High speed**
Speed (1/min)	30	120	190
Power (kW)	1000	4000	4000
Torque (kNm)	318	318	200
Phase voltage (r.m.s.) (V)	775	3100	3100
Fundamental frequency (Hz)	2	8	12.67
Stator phase current (r.m.s) (A)	774	774	774
Power factor	1	1	1
Rotor excitation current (A)	75.8	75.8	49.4
Efficiency (%)		96.3	

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Institute of Electrical Energy Conversion

HTSC synchronous motor 4 MW: Dynamic electrical design data

Synchronous reactance x_d	**0.36 p.u.**
Transient reactance x'_d	**0.19 p.u.**
Subtransient reactance x''_d	**0.15 p.u.**
Transient time constant T'_d	**217 s**
Subtransient time constant T''_d	**0.06 s**
Stator time constant T_a	**0.07 s**

Measured: **0.30 p.u.**

Source: Siemens AG

Very long transient time constant shows, that the induced currents in the rotor field winding need very long to decay, as there are nearly no losses and hence no damping!

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4 MW/120 min^{-1} HTSC synchronous motor for ship propulsion

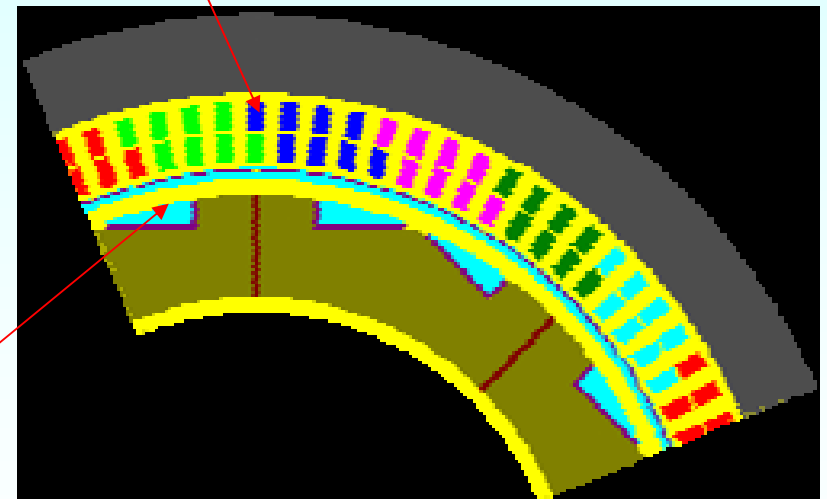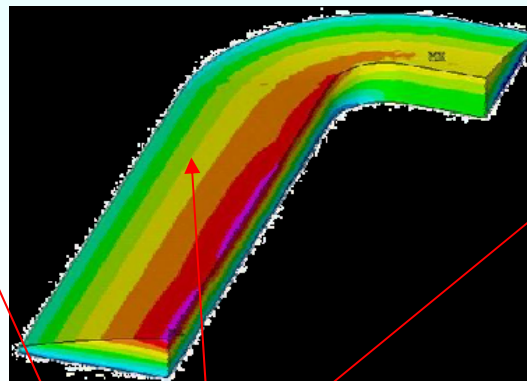*Source: EHTS, Bruker, Alzenau, Germany*

HTSC field winding: Wire with BSCCO filaments and PEEK insulation

Stator two-layer air-gap winding, 3 phases, $q = 4$ coils per pole and phase, coil pitch 11/12

Stator iron yoke
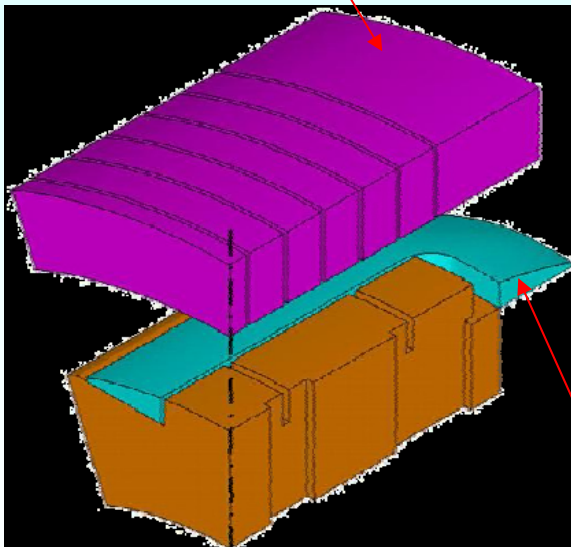
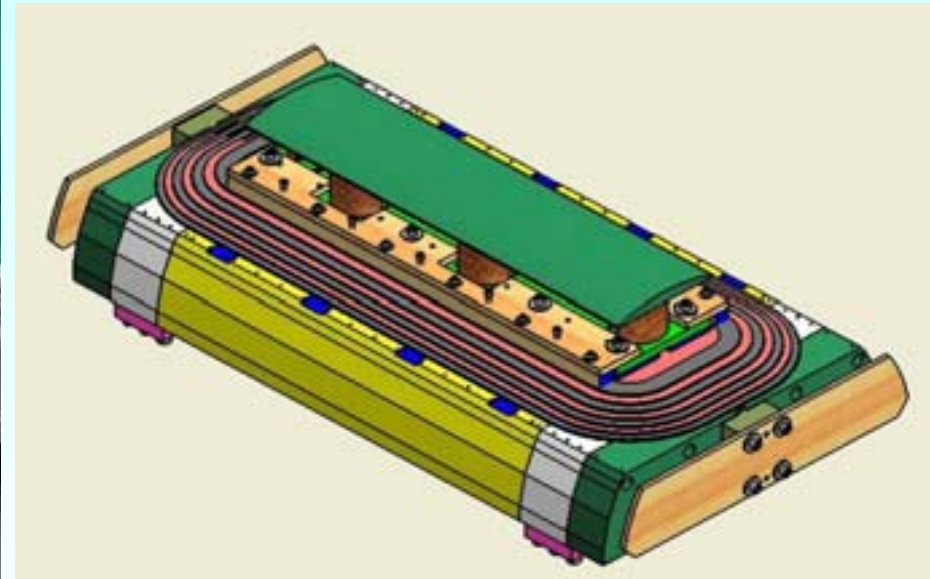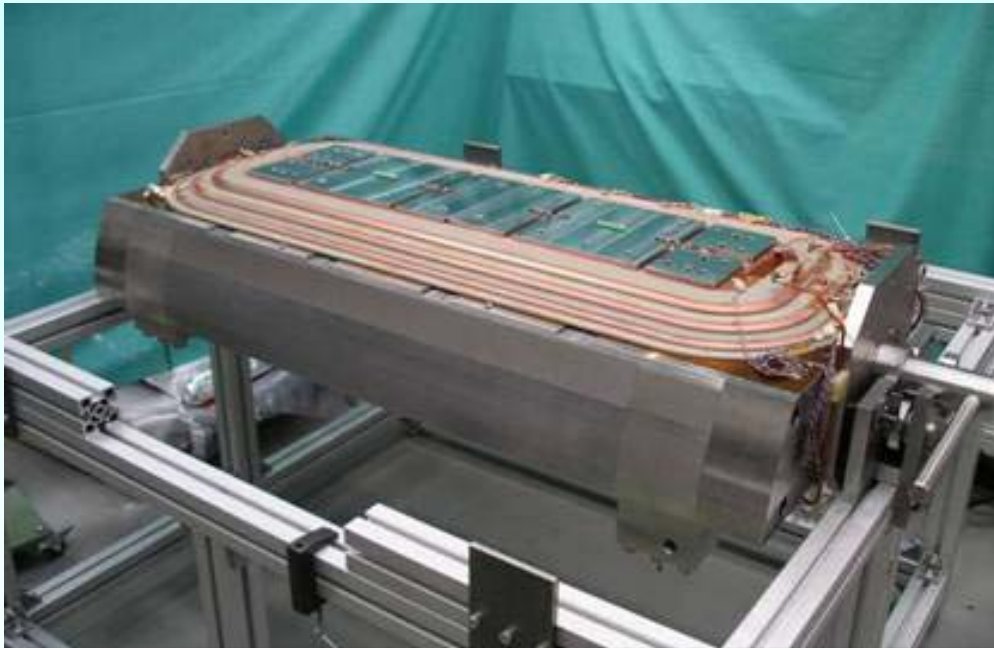Magnetic field distribution in the rotor HTSC coil

Rotor HTSC coil per pole

Source: Siemens AG

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4 MW/120 min⁻¹ HTSC synchronous motor for ship propulsion: Rotor HTSC coil test set-up

Source: Siemens AG

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Institute of Electrical Energy Conversion

4 MW/120 min^{-1} HTSC synchronous motor for ship propulsion: Completing of the HTSC rotor

Stainless steel rotor pole core for 8 poles
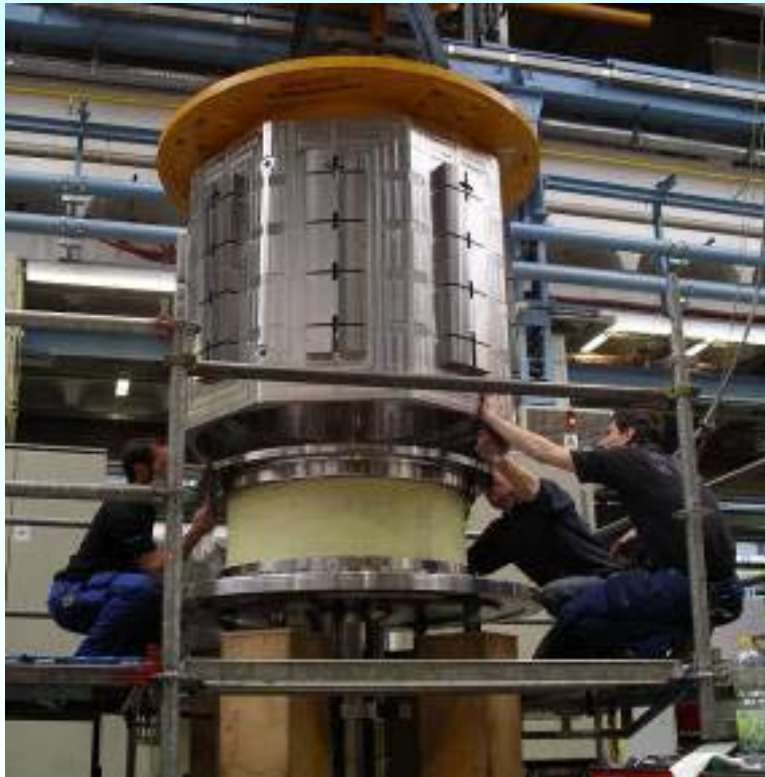
Source: Siemens AG

Mounting of the cryostat cylinder on the pole core

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4 MW/120 min^{-1} HTSC synchronous motor for ship propulsion: Finishing of the bearing seat surfaces

Source: Siemens AG

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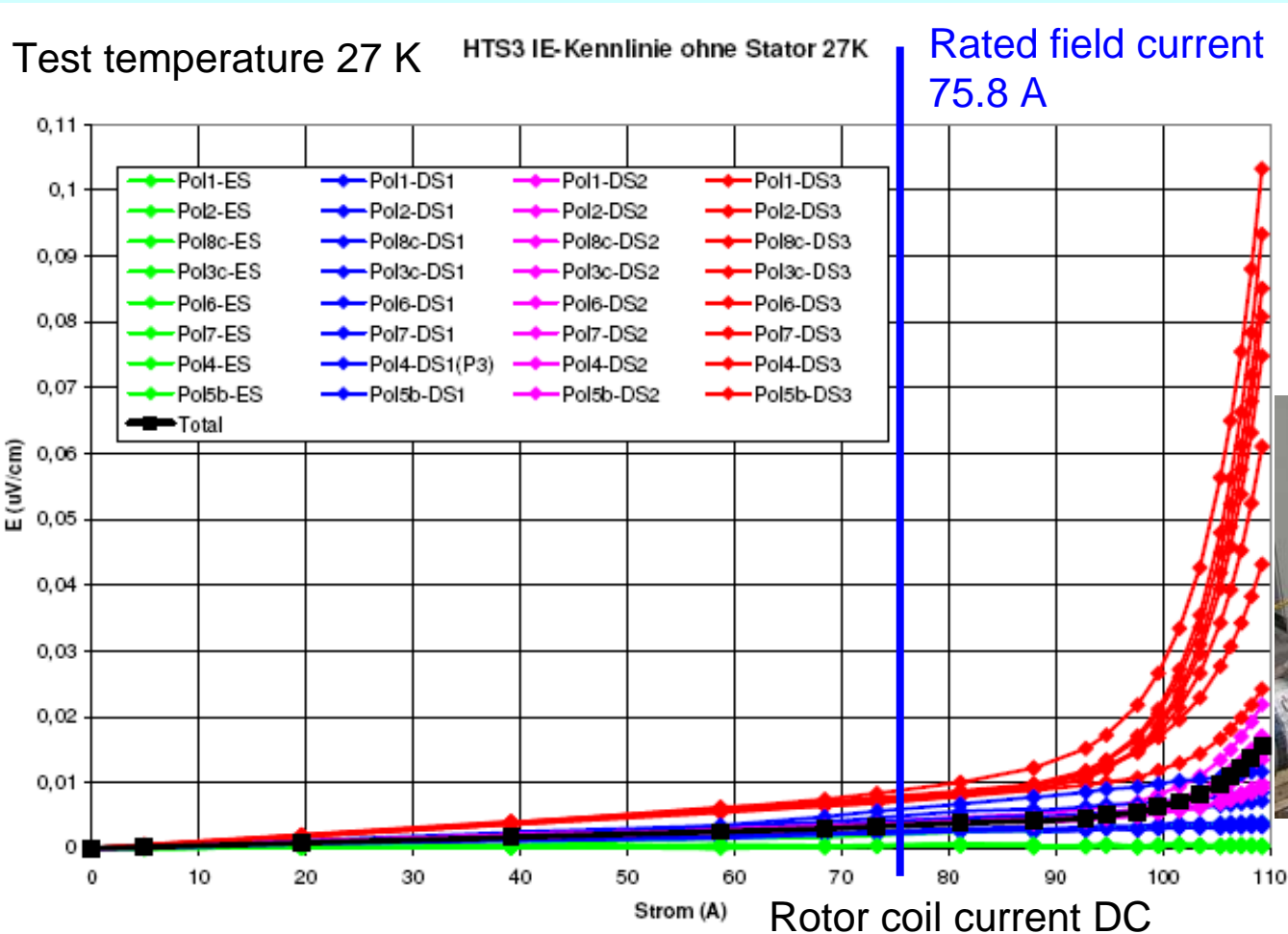**Prof. A. Binder : New technologies of electric energy converters and actuators**

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Institute of Electrical Energy Conversion

4 MW/120 min⁻¹ HTSC synchronous motor for ship propulsion: Testing the *U*-*I*-curves of the 8 rotor pole HTSC coils

Test temperature 27 K

HTS3 IE-Kennlinie ohne Stator 27K

Rated field current 75.8 A

$$E = U / l$$
Electrical field strength

Source:

Siemens AG

Rotor coil current DC

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HTSC synchronous motor 4 MW: Rotor losses at inverter operation

Operation	Rotor excitation current (DC)	Rotor losses
1. Rotor at stand-still (n = 0)	0 A	80 W
2. Rotor rotates (n = 120/min), no-load motor inverter operation ($I_s \approx 0$ A)	73 A	98 W
3. Rotor rotates (n = 103/min), loaded motor inverter operation (I_{sN} = 774 A) (Stator winding temperature: ca. 160°C)	75 A	115 W

- The losses were measured via the input and output temperature of the coolant (Neon gas) and the coolant mass flow ("calorimetric" method)!

- Inverter operation: The stator current has a ripple with double switching frequency! The ripple is nearly independent from load. The stator magnetic field component, which is excited by that ripple, pulsates with that frequency and induces the rotor. The damper shields most of the ripple field. But a small part reaches the rotor HTSC winding and causes AC losses.

Source: Siemens AG

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New technologies of electric energy converters and actuators

Summary:
Rotating electrical machines with superconductor winding

- Mainly 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 field
- Large generators at reduced mass and increased efficiency and stiffness possible, but expensive
- Reliability issue of total cryostat system is crucial for power generation
- Ship propulsion motors for (military) vessels of interest due to reduced size

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2. Application of superconductors for electrical energy converters

2.2 Superconductivity for electrical energy technology

2.2.1 Fault current limiter

2.2.2 Superconducting power cables

2.2.3 Superconducting magnetic energy storage (SMES)

2.2.4 Superconducting power transformers

2.2.5 Rotating electrical machines with superconductor winding

2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

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2. Application of superconductors for electrical energy converters

2.2 Superconductivity for electrical energy technology

2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

- Cryo-machines

- Superconducting hysteresis machines

- Superconducting synchronous reluctance machines

- Superconducting permanent magnet synchronous machines

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2.2.6 Cryogenic machines

- **Operation in liquid nitrogen LN$_2$:** **Boiling bath cooling:** T = 77 K

- **Decrease of R(T) allows** **at equal I^2R an increase of electric loading A.**

- **Eddy current losses & additional losses P_Z are prop. to U^2/R_{Fe}.**
  These losses increase, since $R_{Fe}(T)$ decreases with decreasing T.

- **Friction losses P_R are** **in liquid nitrogen higher than in air.**

Copper winding: Resistance in-/decrease:

$$77K - 273.15°C = -196.15°C, \quad -196.15°C + 23K = -173.15°C$$

Standard motor: **80 K temperature increase at** $\dfrac{235 + 80 + 40}{235 + 20} = 1.39$
40 °C ambient temperature:

Cryogenic motor: **23 K temperature increase at** $\dfrac{235 - 173}{235 + 20} = 0.24$
-173°C ambient temperature:

The resistance of the copper winding drops from 120°C (Thermal Class B operation) to -173°C by the factor 0.24/1.39 = 1/5.7 ≈ 1/6.

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Utilization of cryogenic induction machines (ASM)

- **Total iron losses P_{Fe} are increased at –196°C, compared to 80 °C:**
    - **Hysteresis losses P_{Hy} are by T only minor influenced**
    - **Eddy current losses $P_{Ft} \sim B^2/R_{Fe}$ increase, because R_{Fe} drops. Increase of only 40% at transition from ca. 80 °C iron temperature to 77 K by addition of Si.**
    - **Resulting total iron losses (at 50 Hz):**
    $P_{Hy} / P_{Fe} \approx$ 0.75, $P_{Ft} / P_{Fe} \approx$ 0.25. Increase by 1.4·0.25 + 0.75 = 1.1 = 110%

- **Increase of the motor utilization at:** $I^2 R = const.$ **: Current increase:** $\sqrt{6} = 2.5$

    ASM: $\cos\varphi = 0.83$ **: Active current I_w/I_N = 83%, reactive current I_B/I_N = 56%.**

    Flux Φ = const. $\Rightarrow I_B$ = const.: Active current increase: $\sqrt{2.5^2 - 0.56^2} = 2.43$
    $\Rightarrow$ Torque increase by 2.43/0.83 = 2.94 (= ca. 3).

For cryogenic asynchronous motors, at equal ohmic losses an increase of the power at 77 K compared to 120°C (Th. Cl. B) by nearly a factor 3 is possible.

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Cryogenic machines: *Example 1*

- **TEFC standard asynchronous motor as "cryogenic" motor, LN$_2$ cooling**

<u>**Standard motor data:**</u> **4 kW, 380 V, Y, 9 A, cosφ = 0.83, 1450/min, Th. Cl. B**

d_{sa}/d_{si} **= 180/114.5 mm,** l_{Fe} **= 100 mm, air gap 0.3 mm,** $R_{20°C}$ **= 1.339 Ohm,**

$P_{in} = \sqrt{3}UI\cos\varphi$ **= 4916 W, air-gap induction** B_δ **= 0.97 T,**

Electric loading: A **= 250 A/cm, stator current density** J **= 7.3 A/mm²,**

Slip s **= 3.3%**

Slip depends   a) on rotor resistance $R_r(T)$**:** R_r**(77 K) =** R_r**(120°C)/5.7,**
**   b) on the load torque:** $s \sim M$ **in the nominal slip range**

- *Result:*

- At 4 kW and 77 K: Slip s **drops ~** $R_r(T)$ **:** $s(T)$ **= 3.3/5.7 = 0.58 %.**

- Increase of torque M **by 2.94:** s **increases prop.** M **to** s **= 2.94·0.58 = 1.72 %.**

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Cryogenic machines: *Example 2*

	Standard induction motor	Cryogenic induction motor
I_N / P_{out}	9 A / 4000 W	22.5 A / 12000 W
M_N / n_N	26.4 Nm / 1450 /min	26.4·2.94 = 77.6 Nm / 1475 /min
$P_{Cu,s} / P_{Fe}$	452 W (120°C) / 200 W	495 W (100 K) / 220 W
Rotor losses ~ s	140 W	140·**(22.5/9)**^{2}/5.7 = 154 W
$P_R + P_z$	ca. 50 W	ca. 100 W
P_d / η	842 W / 82.6 %	969 W / 92. 5 %

- *Total losses 969 W as cryogenic power require*
  ca. (20 ... 30) x 969 = 19 ... 29 kW electrical cooling power
- *Pays off only, where more compact dimensions of the total drive unit are desired*
  (e.g. driving motor for a LN$_2$ liquefaction compressor, which operates within the
  compressor unit without any sealing)

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2. Application of superconductors for electrical energy converters

2.2 Superconductivity for electrical energy technology

2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

- Cryo-machines

- Superconducting hysteresis machines

- Superconducting synchronous reluctance machines

- Superconducting permanent magnet synchronous machines

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Cooling of "small" HTSC motors (1)

- A separate cryostat for a rotor or a stator is generally too expensive, so the total motor is submerged in liquid nitrogen (bath cooling at 77 K). Hence such motors are preferably used as built-in motors in large LN_2-liquefaction machines, where they can substitute the induction cryo motors.

- In LN_2 submerged cryo motors or HTSC motors are much smaller than air-cooled conventional motors. So they reduce space significantly. They operate inside the cryo compressor and avoid the sealing problem.

- For the same output power the losses $P_{d,c} = P_{d,NC}/3$ of a cryo motor are 1/3 of the conventional air-cooled motor. The LN_2-cooling of these losses needs an additional cooling power by a typical factor 20: $\Delta P_{cooling} = 20P_{d,NC}/3 = 6.6P_{d,NC}$.

- Submerged motors pay off only, where more compact dimensions of the total drive unit and the avoiding of seals are desired, and where the total plant power P is much bigger than $\Delta P_{cooling}$.

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Concepts for "small" HTSC motors (2)

- Operation shall be done at 77 K to be a cheap solution.

- At 77 K bigger critical magnetic field values are possible for YBCO bulk material than for BSCCO wires. Therefore first attempts were made with YBCO bulk material in hysteresis and later in synchronous reluctance motors.

- For reluctance motors a higher "Torque/Current ratio" is achieved than for hysteresis motors, but still too low to be economical.

- With the advent of YBCO tapes it is possible to manufacture SC three-phase AC windings for operation at 77 K with rather low AC losses.

- Therefore PM synchronous motors with tooth-coil AC windings from YBCO tapes are under investigation.

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Hysteresis motors: Torque generation

- **Hysteresis torque:** **Hysteresis losses of the rotor material cause a phase shift between rotor field and stator field, causing an asynchronous torque generation**

$$\boxed{P_{Hy}/V = w_{Hy} \cdot f}$$ w_{Hy} : **Area of the *B(H)* loop, *V*: Hysteresis material volume**

- **Energy balance of the rotor at asynchronous run with slip *s* :**

$$P_{\delta} = 2\pi n_{syn} M_e = s \cdot P_{\delta} + (1-s) \cdot P_{\delta} = P_{Hy} + P_m = P_{Hy} + 2\pi n M_e$$

Rotor frequency $f_r = s \cdot f_s$, hysteresis torque M_e

$$P_{Hy} = w_{Hy}V \cdot f_r = w_{Hy}V \cdot |s|f_s = s \cdot 2\pi \frac{f_s}{p} M_e \qquad \boxed{\Rightarrow M_e = \frac{p}{2\pi} w_{Hy}V \frac{|s|}{s}}$$

- ***Hysteresis torque is independent from speed. At 1 > s > 0 it acts driving, at s < 0 it is braking. At s = 0 the rotor is in a magnetized state due to the remanence and acts as permanent magnet. At asynchronous operation s ≠ 0, due to eddy current losses in the conductive rotor, an additional eddy-current torque M_w occurs.***

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Characteristic of the torque of a hysteresis motor

- M_{Hy}: Hysteresis torque, M_w: Eddy current torque

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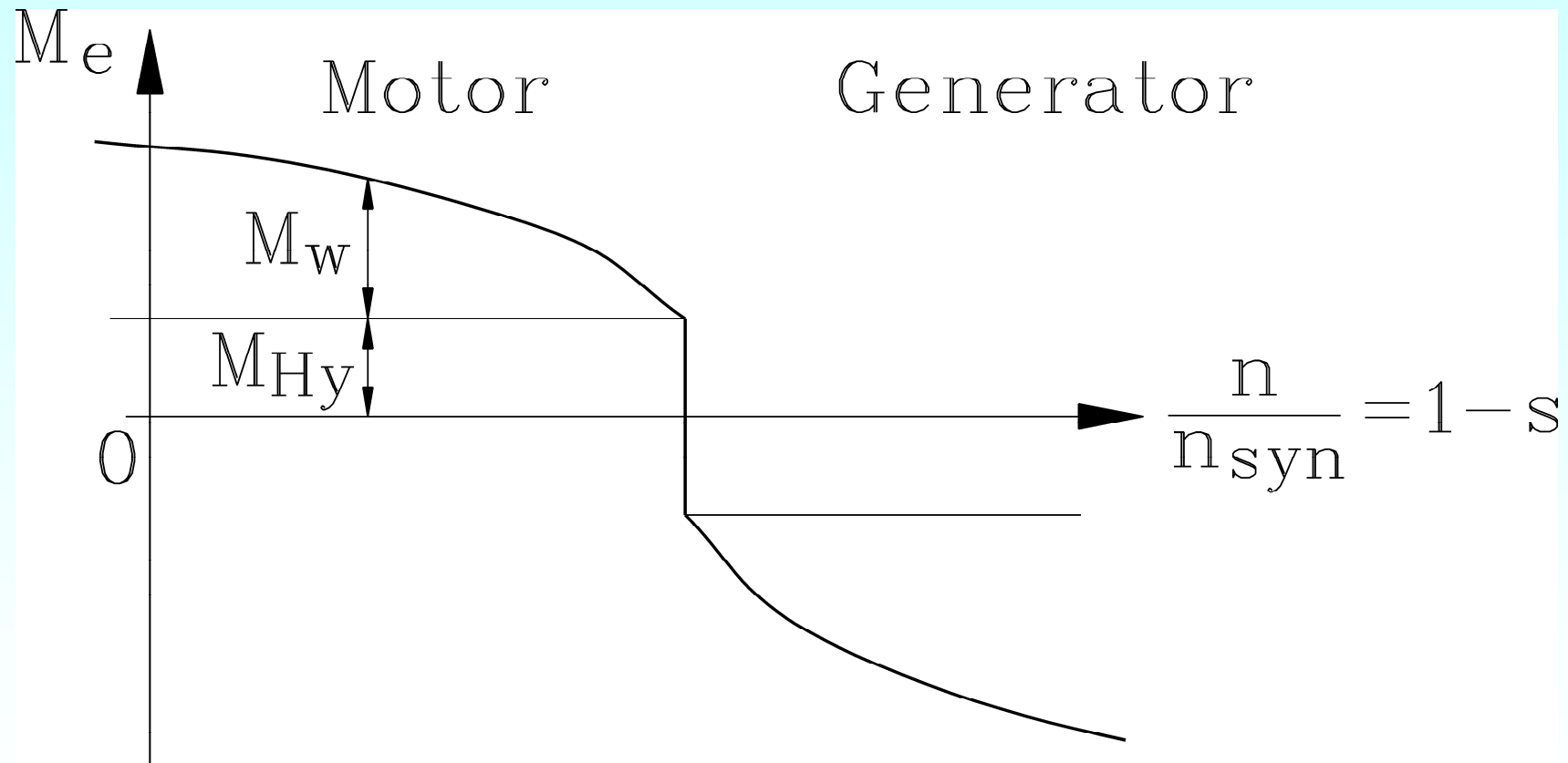
Example: Built HTSC hysteresis motor

Three-phase copper winding in the stator
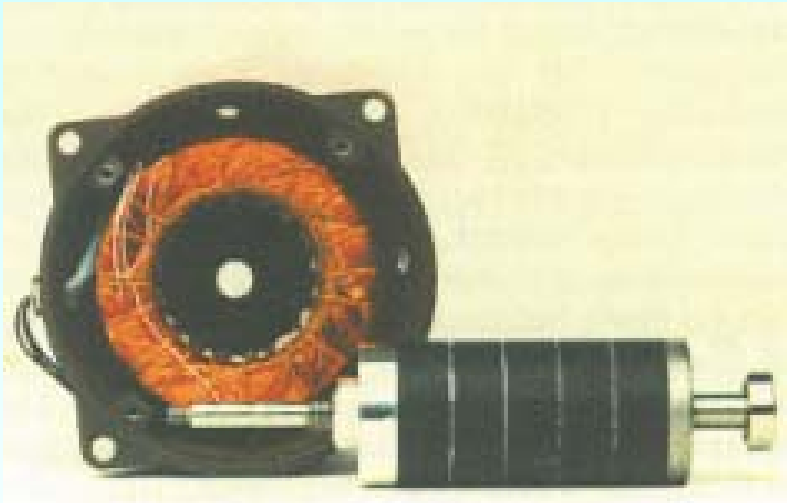
YBCO rings on the rotor as hysteresis material

Source: Gutt/Grüner, Univ. Stuttgart, 1998

Phase voltage U / V	127
Phase current I / A	15.4
Power P_m / W	720
Power factor cos φ	**0.19**
Efficiency η	63 %
Specific tangential thrust (r.m.s.)	0.66 bar

Low power factor due to diamagnetic rotor core: $\mu_r = 0.5$!

Big reactive stator current already for $B = 0.25$ T with big I^2R-losses = low efficiency

No favourable motor type!

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2. Application of superconductors for electrical energy converters

2.2 Superconductivity for electrical energy technology

2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

- Cryo-machines

- Superconducting hysteresis machines

- Superconducting synchronous reluctance machines

- Superconducting permanent magnet synchronous machines

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Reluctance motors

- The rotor is magnetically anisotropic:

  Direct axis (*d*-axis):   air gap very small,

  Quadrature axis (*q*-axis):   air gap much larger.

  Rotor tries to align itself in the stator's rotary field such that the *d*-axis coincides with the pole axis of the stator's rotary field = RELUCTANCE TORQUE

- Magnetic axes: Stator inductance in direction of *d*-axis higher than in direction of *q*-axis: $L_d > L_q$. At load, rotor is shifted from the *d*-axis with the load angle ϑ, until as maximum the static pull-out torque M_{p0} is reached.

$$M_e = -\frac{3p}{2\pi f_s} \cdot U^2 \cdot \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \cdot \sin(2\vartheta) = -M_{p0} \sin(2\vartheta) \qquad R \approx 0,\ X = 2\pi f_s L$$

- In the quadrature axis: Y(123)-HTSC bulk material is inserted in the gaps: *B* > 0.1 T: HTSC in the *Shubnikov* phase: Diamagnetic effect: Partial flux displacement from the pole gap ⇒ quadrature inductance L_q REDUCED = Pull-out torque M_{p0} increased ! *HTSC reluctance motor has a significantly higher pull-out torque than a conventional reluctance motor.*
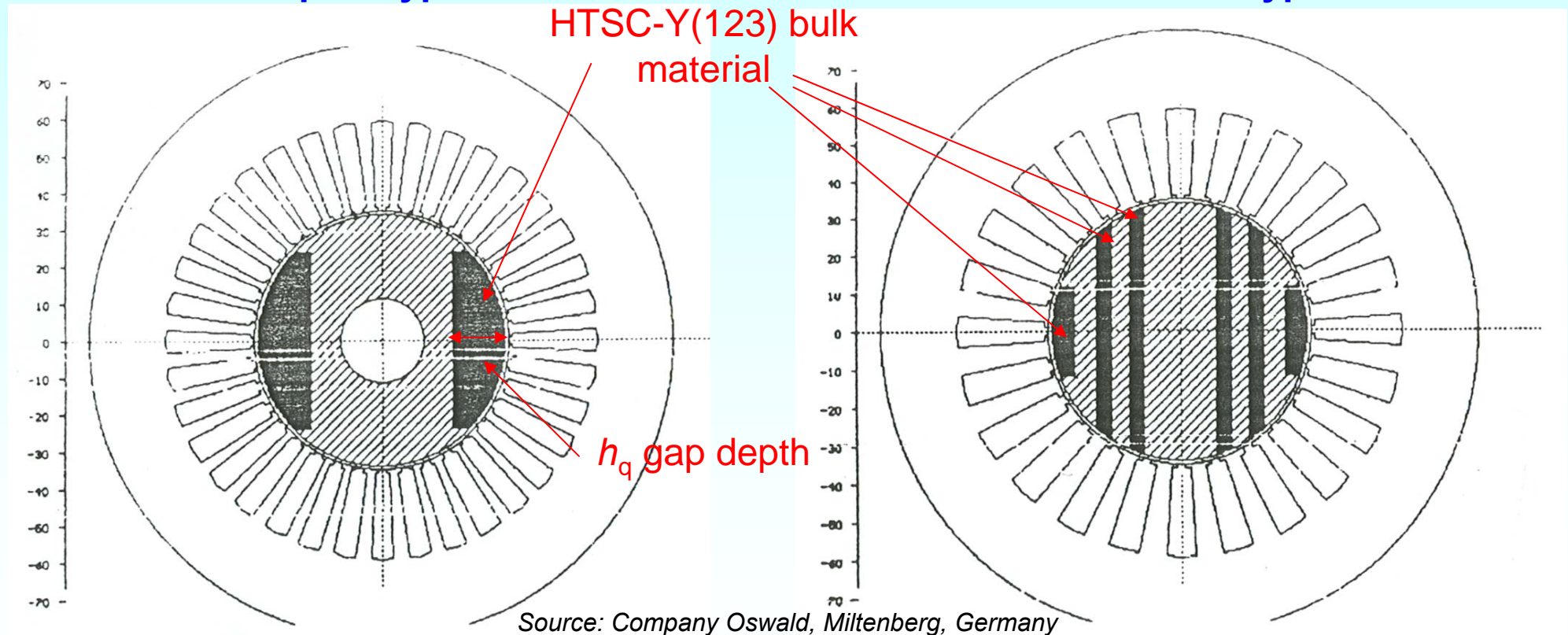
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Two-pole HTSC reluctance motors (axial cut-view)

● **In the pole gaps HTSC-Y(123) bulk material is inserted**

Salient-pole type   **"Zebra" type**

HTSC-Y(123) bulk material

h_q gap depth

Source: Company Oswald, Miltenberg, Germany

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Two-pole HTSC reluctance prototype motor

400 kW

3000 … 8000/min

LN_2 bath cooling

- Low power factor < 0.5

- Big reactive stator current with big I^2R-losses = low efficiency

- No favourable motor type!

Source: Company Oswald, Miltenberg, Germany

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2. Application of superconductors for electrical energy converters

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2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

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Permanent magnet synchronous motor with HTSC stator winding
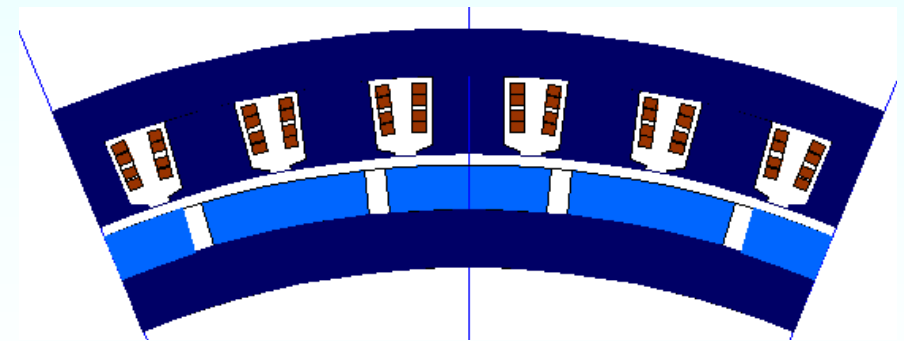
Example: Permanent magnets: 2*p* = 16 poles
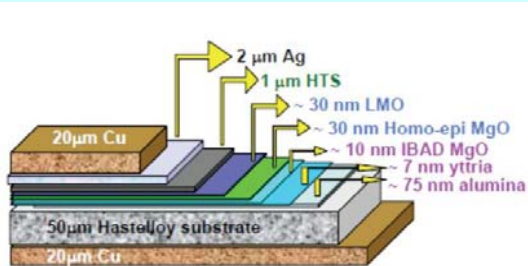
Fig.1. Structure of SuperPower's IBAD MgO-based HTS wire
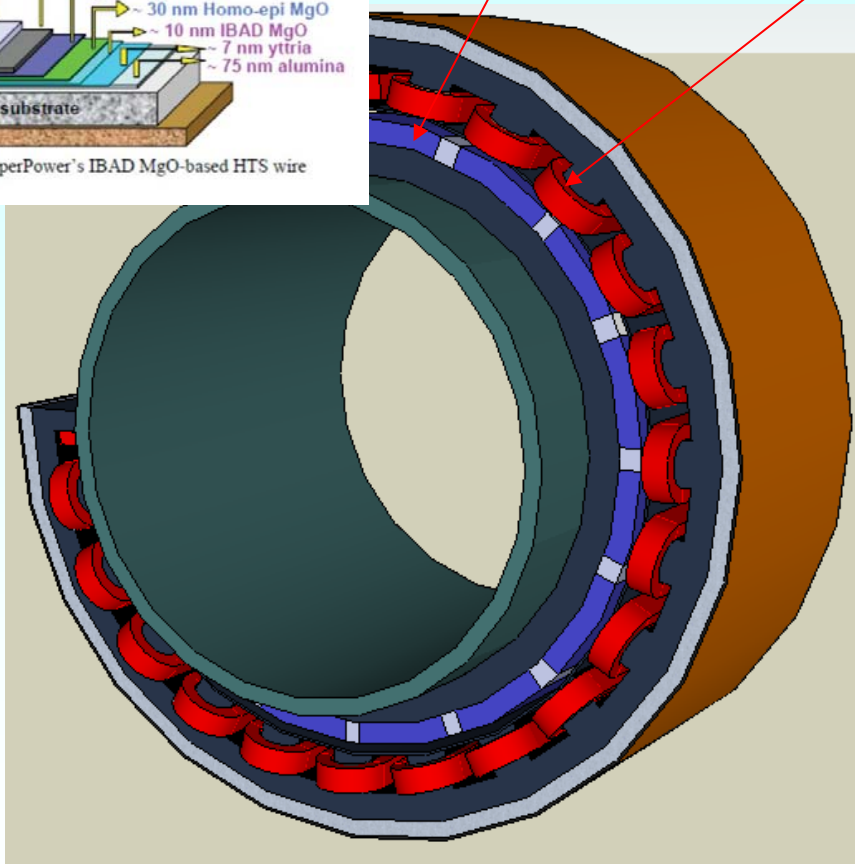
- YBCO tapes for SC three-phase AC winding for operation

- High torque, low speed operation = low AC fundamental frequency = low AC losses

- High pole count 2*p* = low frequency and high torque at low speed $f = n \cdot p$

- Two-layer tooth coil winding with *q* = ½ slots per pole and phase

Source: Company Oswald, Miltenberg, Germany

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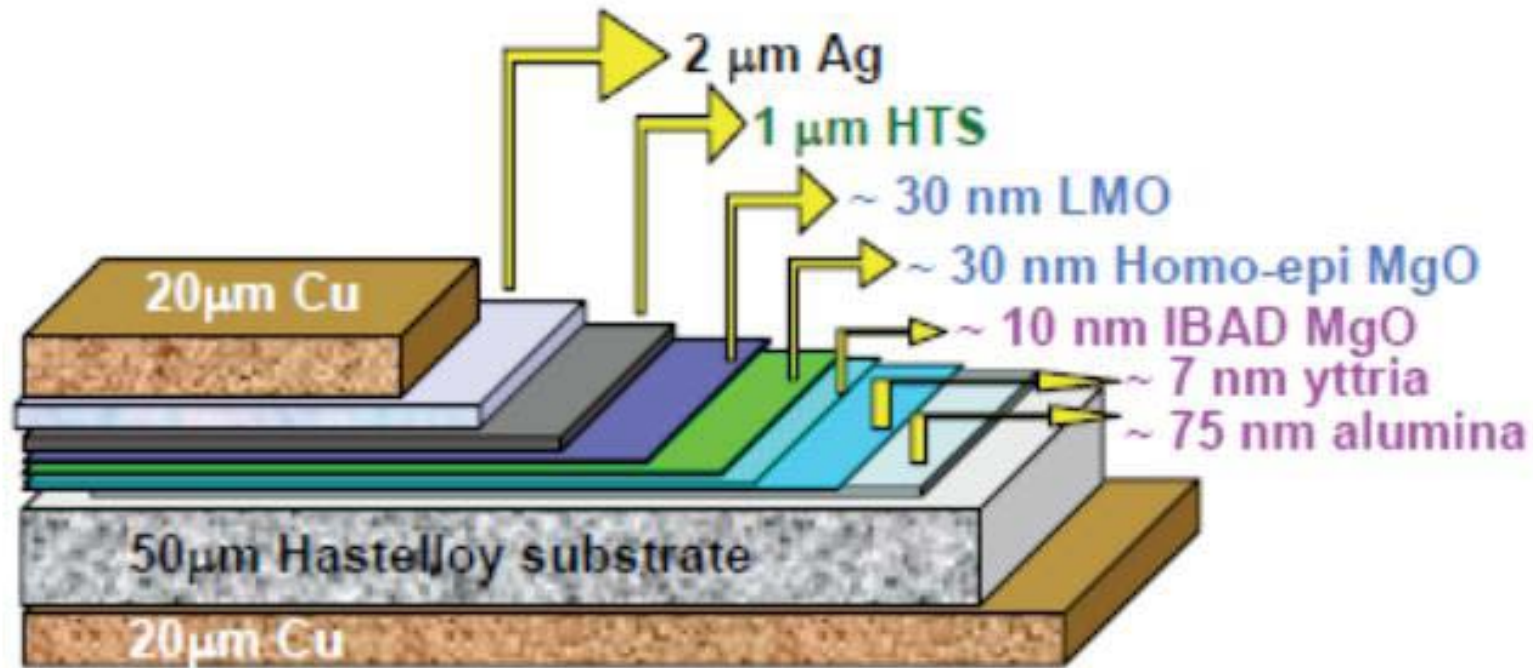# YBCO-tape (HTS) for stator winding of PM synchronous motor

Fig.1. Structure of SuperPower's IBAD MgO-based HTS wire

Source: Company Oswald, Miltenberg, Germany

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HTSC tooth-coil three-phase AC winding

Stator with slots

M.M.F. $V(x)$

Fundamental M.M.F. $V_1(x)$

(Case shown: $i_U = 0$, $i_V = -i_W = I$)
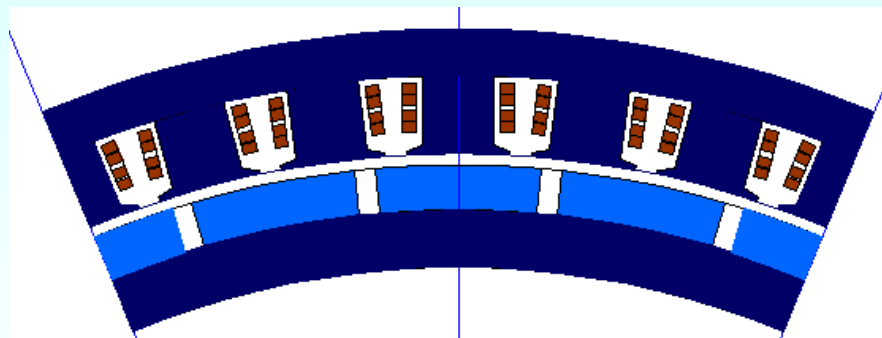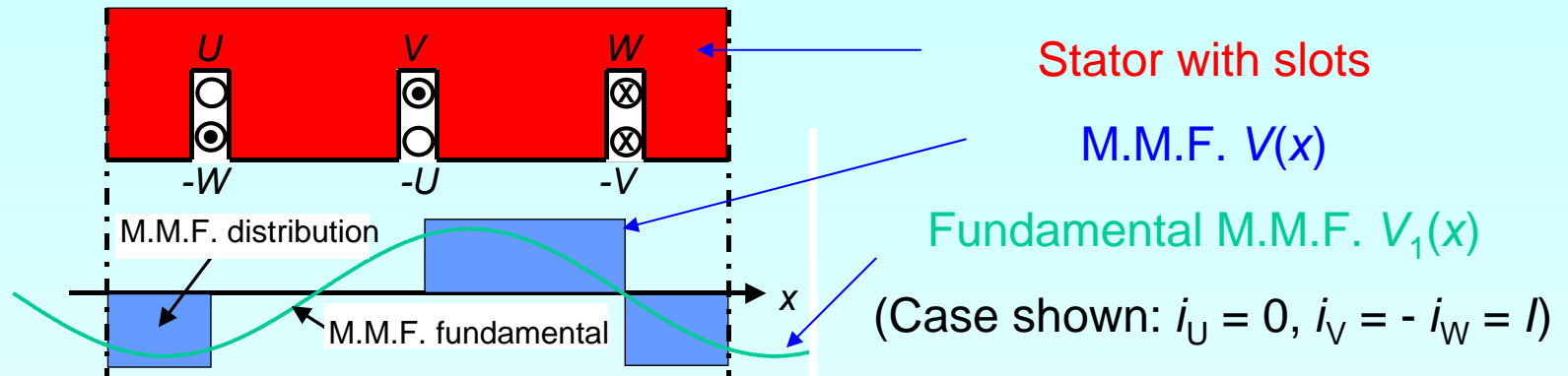
Prototype geometry of 4 poles

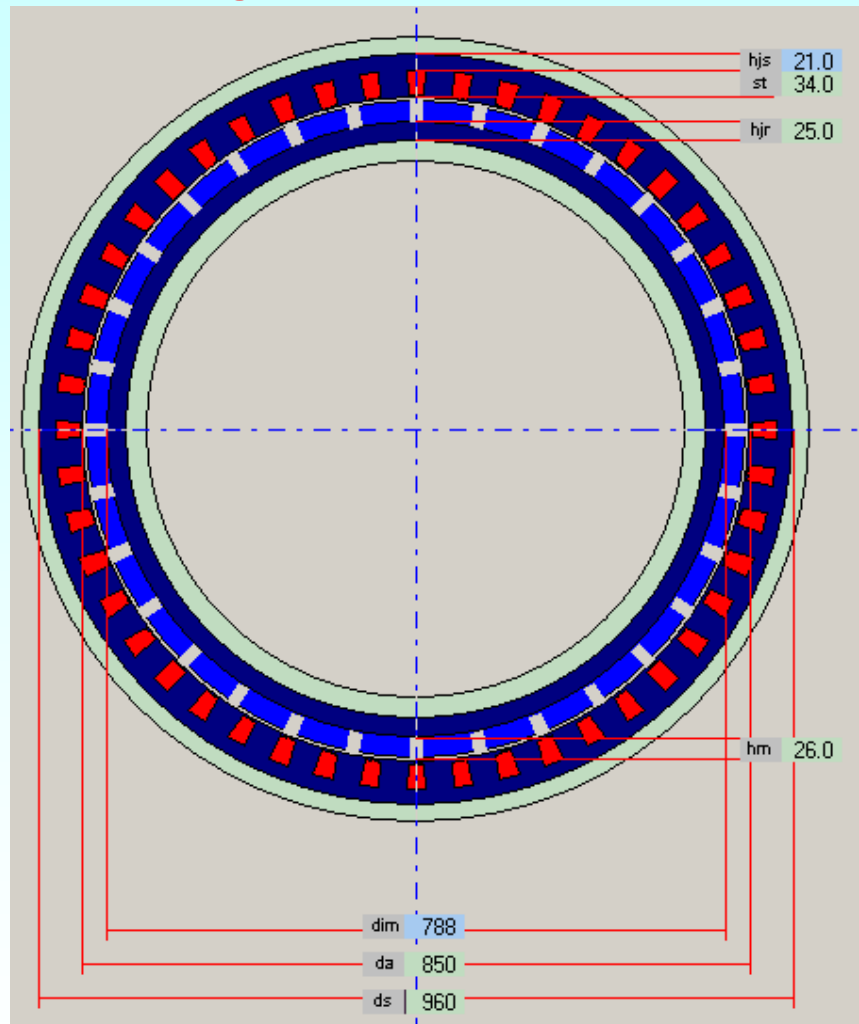*Source: Company Oswald, Miltenberg, Germany*
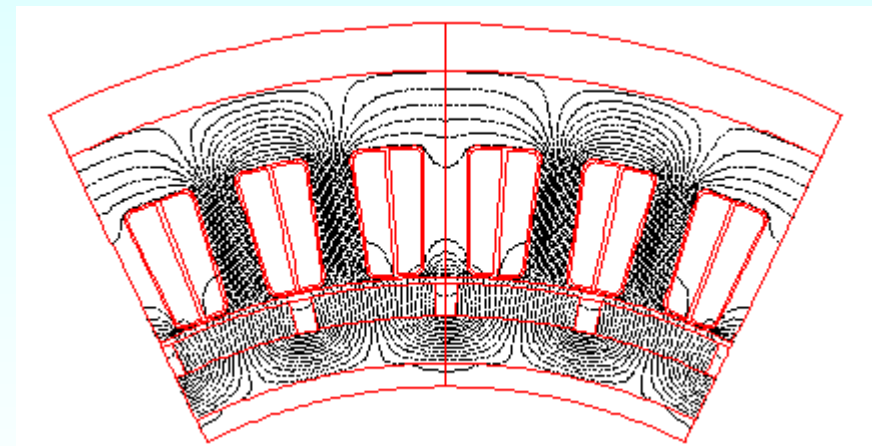
No-load field of permanent magnets

With unsaturated iron stator teeth the main flux is guided via the teeth, hence the external transversal field is low

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PM synchronous motor prototype with HTSC stator winding

380 V, 315 A, 26 kNm, 2p = 32 poles

0 … 56 … 100/min

0 … 154 … 154 kW

26 … 26 … 14.6 kNm

0 … 16 … 28.6 Hz

Power factor 0.74 at sine wave operation

Torque/motor mass = 24 Nm/kg

(NC-Torque motor: 8 Nm/kg)

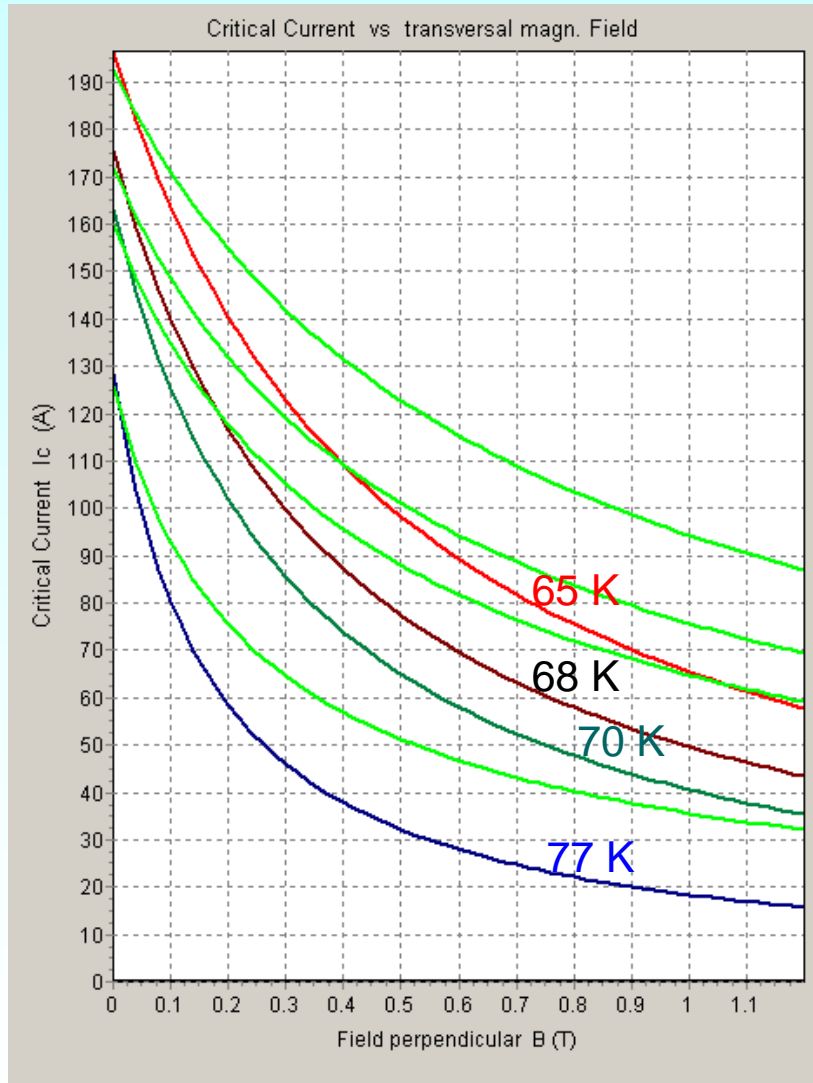*Source: Company Oswald, Miltenberg, Germany*

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Tooth-coil HTSC YBCO tape stator winding

Critical Current vs transversal magn. Field

Critical current per coil conductor vs. external transversal magnetic

I_c at $B = 0$ T	T
A	K
195	65
176	68
163	70
130	77

With unsaturated iron stator teeth the main flux is guided via the teeth, hence the external PM transversal field is low

Maximum slot transversal flux density:
(in the prototype calculated)

0 A	26 mT
124 A	213 mT
247 A	386 mT

Source: Company Oswald, Miltenberg, Germany

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New technologies of electric energy converters and actuators

Summary:
Cryo-machines and rotating electrical machines with massive superconductors

- Induction cryo-machines e.g. in liquid nitrogen (or air) are state of the art
- Y-bulk high temperature SC in hysteresis and reluctance motors only as basic research, but no commercial future due too low power factor
- Y-band conductor high temperature SC as AC tooth coil windings in PM machines as prototypes investigated for high torque application

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