

Cooling and operating stationary & rotating superconducting arrangements: concepts of the past, special requirements, and recent developments

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5th IWC-HTS

University of Twente, 27.10.2026, 13:45-14:25



[Symbolic picture created by ChatGPT]

- Cryogenics
- Power Devices
- PTL & SFCL
- Rotating Machines
- Initial motivation & challenges
- Progress in operating current
- Other motivation of HTS
- Cooling options
- Further challenges
- TEC
- Thermosyphons in machines
- Coils and testing
- STAR-machine
- Conclusions

Cryogenic liquids and gases

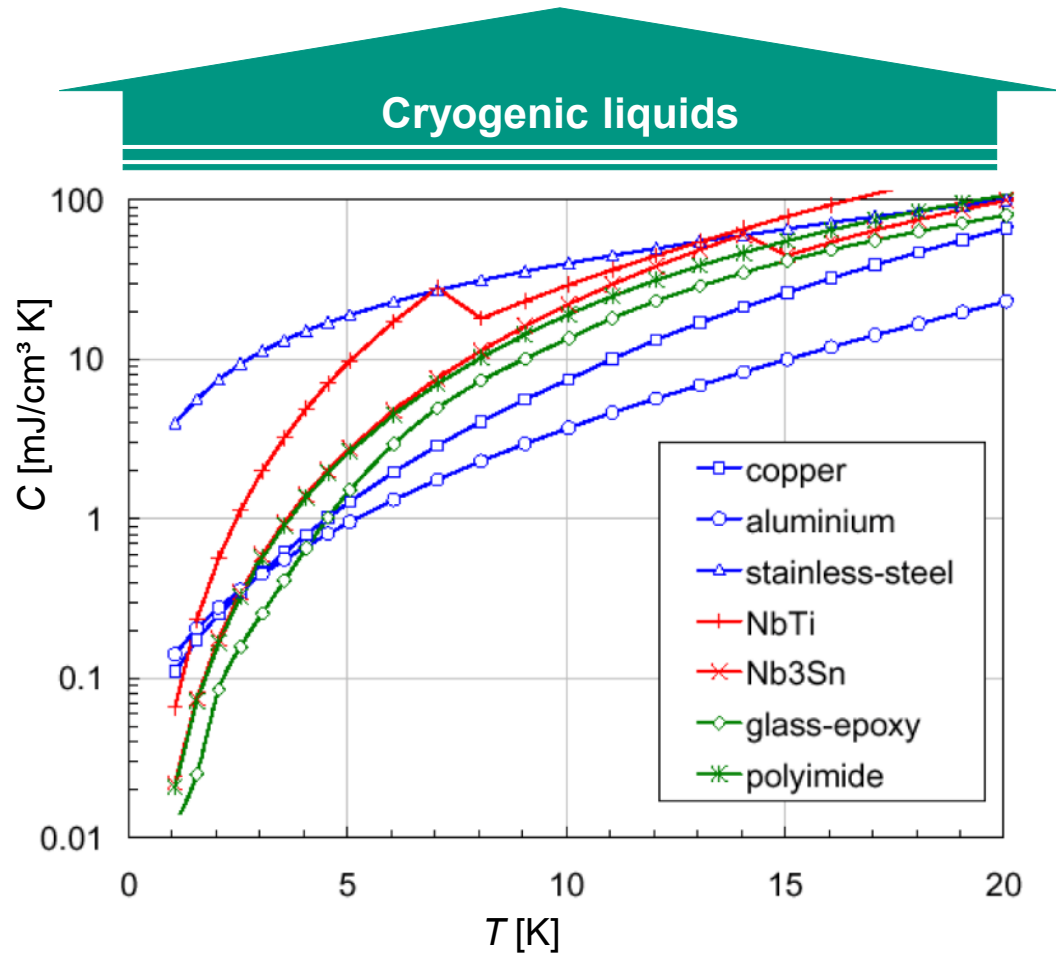
	Gas: liquid	Evaporation enthalpy	Spec. heat c_v	Boiling temperature
N ₂	692	0.199 kJ/g	1.084 J/g.K 874 mJ/cm³.K	77.4 K
He	750	0.021 kJ/g	2.412 J/g.K 301 mJ/cm ³ .K	4.2 K
Ar	840	0.161 kJ/g	0.536 J/g.K 748 mJ/cm ³ .K	87.3 K
H ₂	846	0.449 kJ/g	5.661 J/g.K 401 mJ/cm ³ .K	20.4 K
O ₂	857	0.213 kJ/g	0.929 J/g.K 1060 mJ/cm ³ .K	90.2 K
Ne	1438	0.086 kJ/g	0.894 J/g.K 1078 mJ/cm³.K	27.1 K

[CoolProp.py]

H₂ is champion, He second in c_v , Ne superior to H (volume), but challenging in expansion factor, N for elevated temperatures.
Value of cryogens and latent heat...

- Expansion requires
 - safety measures like valves, burst disks, big cross sections of boil-off/exhaust gas, buffer volumes
- 3(4) appealing cryogenic cooling media!
 - H₂: champion, but special!
 - He: second in c_p
 - N₂: high T and mid values
 - Ne: similar to N₂, but expansion higher

Specific heat of typical materials



Details:

- at low temperatures for metals:

$$c_e \propto T$$

$$c_{\text{phonons}} \propto T^3$$

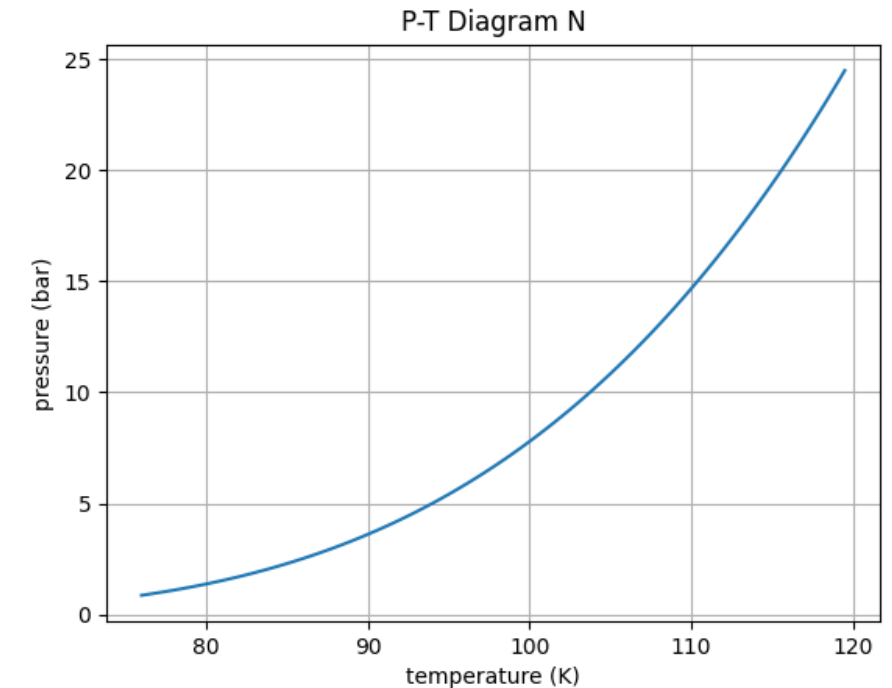
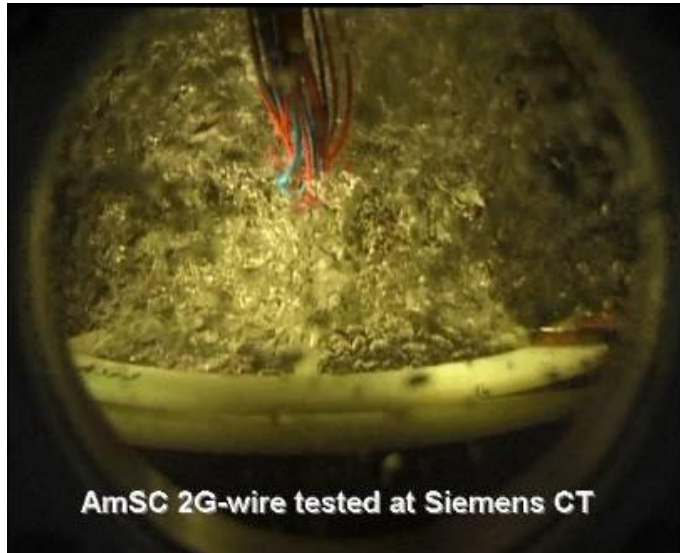
- Thus $c \rightarrow 0$ for $T \rightarrow 0$

Cryogenic liquids are very helpful, for solid material, the operating temperature should be chosen as high as possible.
What's the impact of SC and operating temperature on „operational safety margins“?

PTL & SFCL

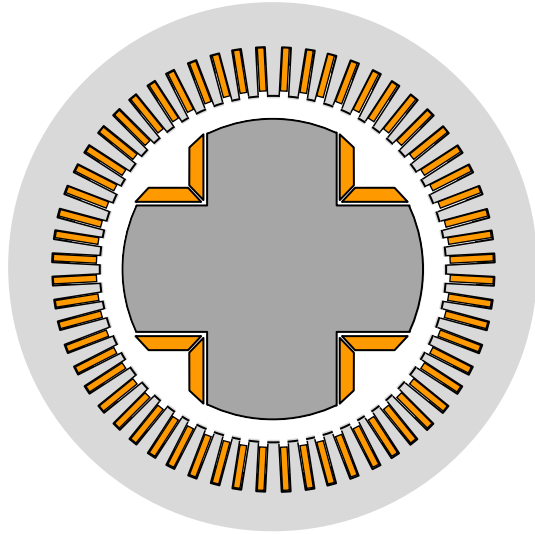


- AC applications in power devices
- AC loss prefers higher temperatures
- LN2 preferred due to boiling temperature and insulation properties
- Avoid bubbles for insulation purposes (higher pressures)



AC applications require higher operating temperatures and frequently rely on (pressurized) LN₂.
Rotating machines – initial motivation...

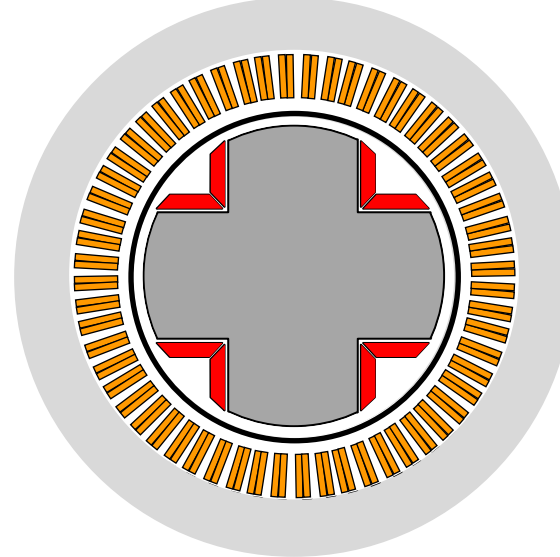
Conventional & (partial) superconducting machine cross section



stator: **Cu**, Iron

rotor: **Cu**, Iron

Balance of field, current and iron



stator: **Cu**, Iron

rotor: **HTS**, Iron

Field & Current might exceed saturation of iron

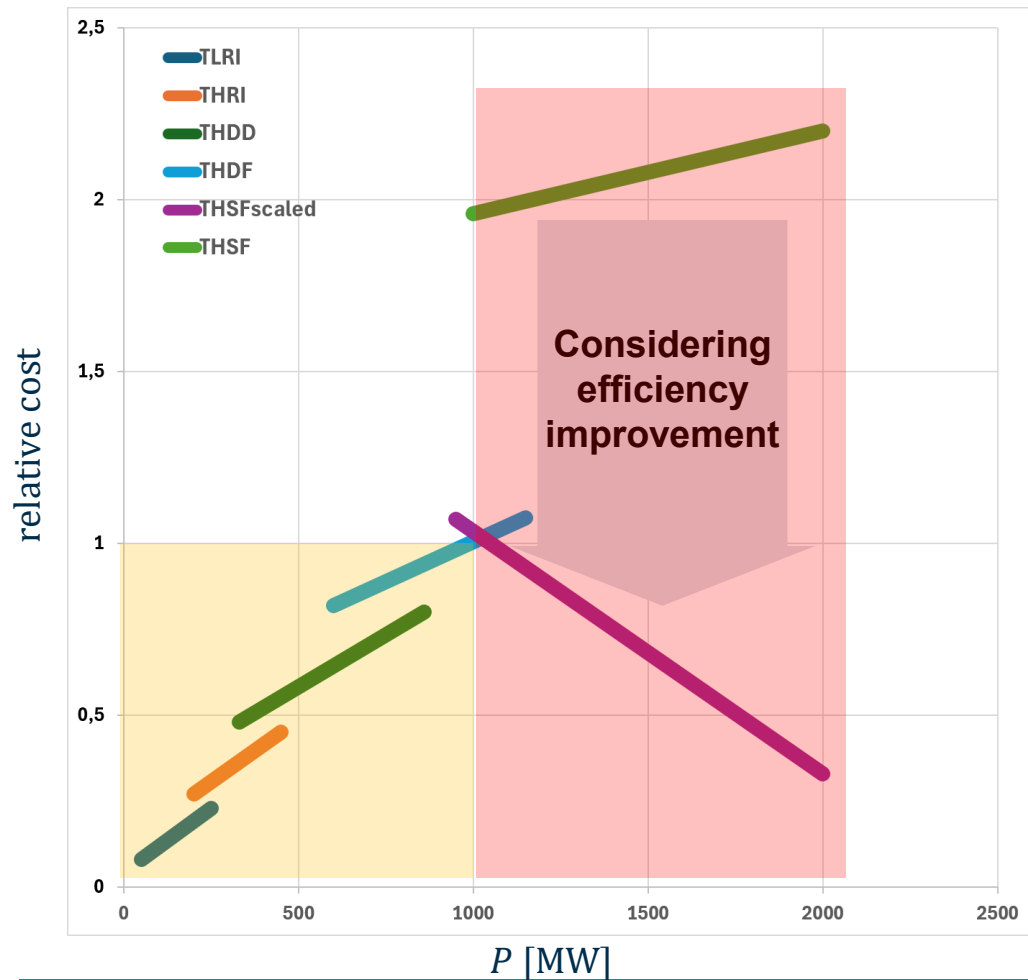
- Basic dimensioning:

$$P = \omega A B V = 2\pi \cdot n_{rot} \cdot A B V$$

- Rotor: SCs in field winding: higher I
→ higher B
- Stator: higher B
 B higher than saturation of iron core
→ use space of teeth for more copper
→ higher A
- Machine: higher A , B in same V
→ $P \mapsto 4 \cdot P$
- Furthermore, for **partially sc. machines**:
air-teeth and spatial needs of cryostat
→ increased efficient magnetic air-gap
→ reduced magnetic interaction of stator to rotor
→ reduced synchronous reactance

The most obvious entry point for SC is in the rotor – with some consequences.
Initial entry point of superconducting generators at LHe-temperatures...

Low-Temperature Superconducting Generator @ $T_{op} = 4.2 \text{ K}$



- Cost and cooling efficiency restrict the business case to machines $\geq 1000 \text{ MVA}$ for LTS.

Cu

LTS

TLRI: Turbo/Air/Rotor radial cooling/Stator indirect

THRI: Turbo/H₂/Rotor radial cooling/Stator indirect

THDD: Turbo/H₂/Rotor axial cooling/Stator direct gas

THDF: Turbo/H₂/Rotor axial cooling/Stator direct fluid

THSF: Turbo/H₂/Rotor supercond./Stator direct fluid

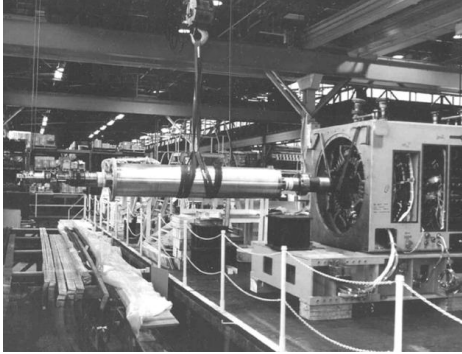
THSFscaled (including value of efficiency improvement)

Following [L. Ichtchar "Entwicklung supraleitender Turbogeneratoren", e&i, 109(1992)379]

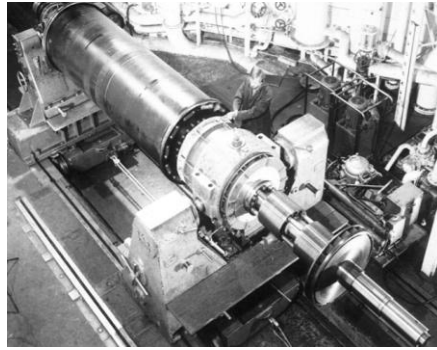
LTS economically viable only for high power ratings (>1000 MVA).

Selected examples for LTS turbo generators...

Extended power rating: NbTi Generator @ $T_{op} = 4.2\text{ K}$



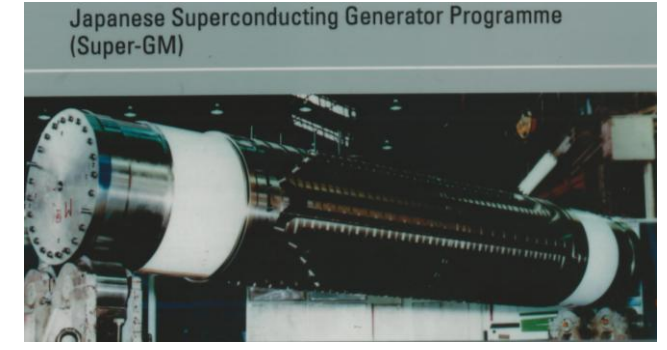
1979: USA (GE)
20 MVA NbTi generator



1981: France (Alstom)
Rotor of 250 MVA NbTi
experimental generator



1991: Germany (Siemens)
Rotor of 400 MVA NbTi
experimental generator



Japanese Superconducting Generator Programme
(Super-GM)
1997: Japan (Hitachi, Mitsubishi, Toshiba)
Super-GM project Rotor of >70 MVA NbTi
experimental generator (3 types)



Cold box produced in trial manufacture

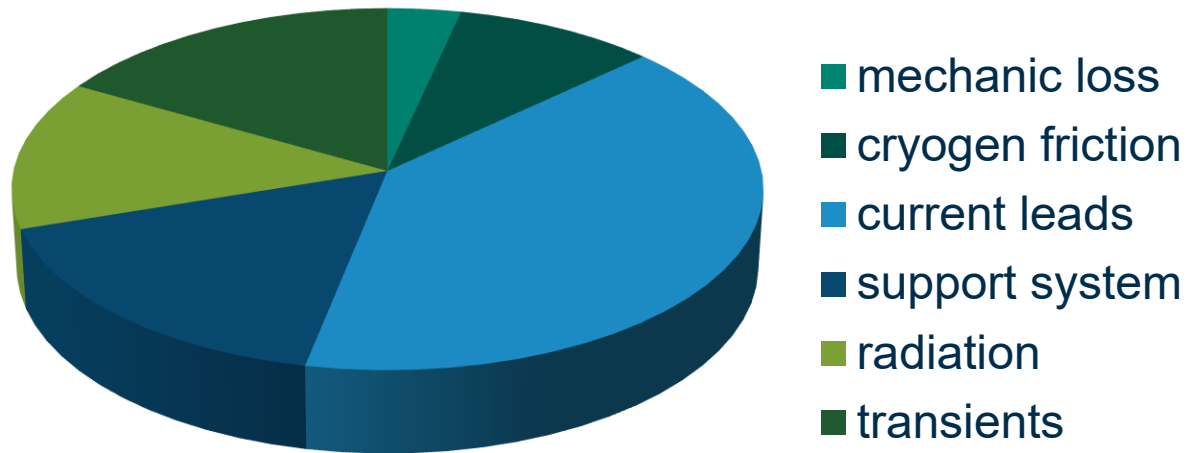
- Pros: improved efficiency, size & power rating
- Cons: increased complexity (some with active thermal shield) and cost

[Kalsi, S. S., K. Weeber, H. Takesue, C. Lewis, H. W. Neumueller, and R. D. Blaugher.
Proceedings of the IEEE 92, no. 10 (2004): 1688-704. <https://doi.org/10.1109/jproc.2004.833676>]

High-power LTS generators successfully realized – with complexity & extensive cooling equipment.

Complex cooling – which effort may be justified?...

Heat loads in superconducting rotating synchronous machines



Heat loads in superconducting rotors

Head loads in superconducting rotor:

1. Current leads
2. Transient operation
3. Support system
4. Radiation
5. Cryogenic friction
6. Mechanical loss

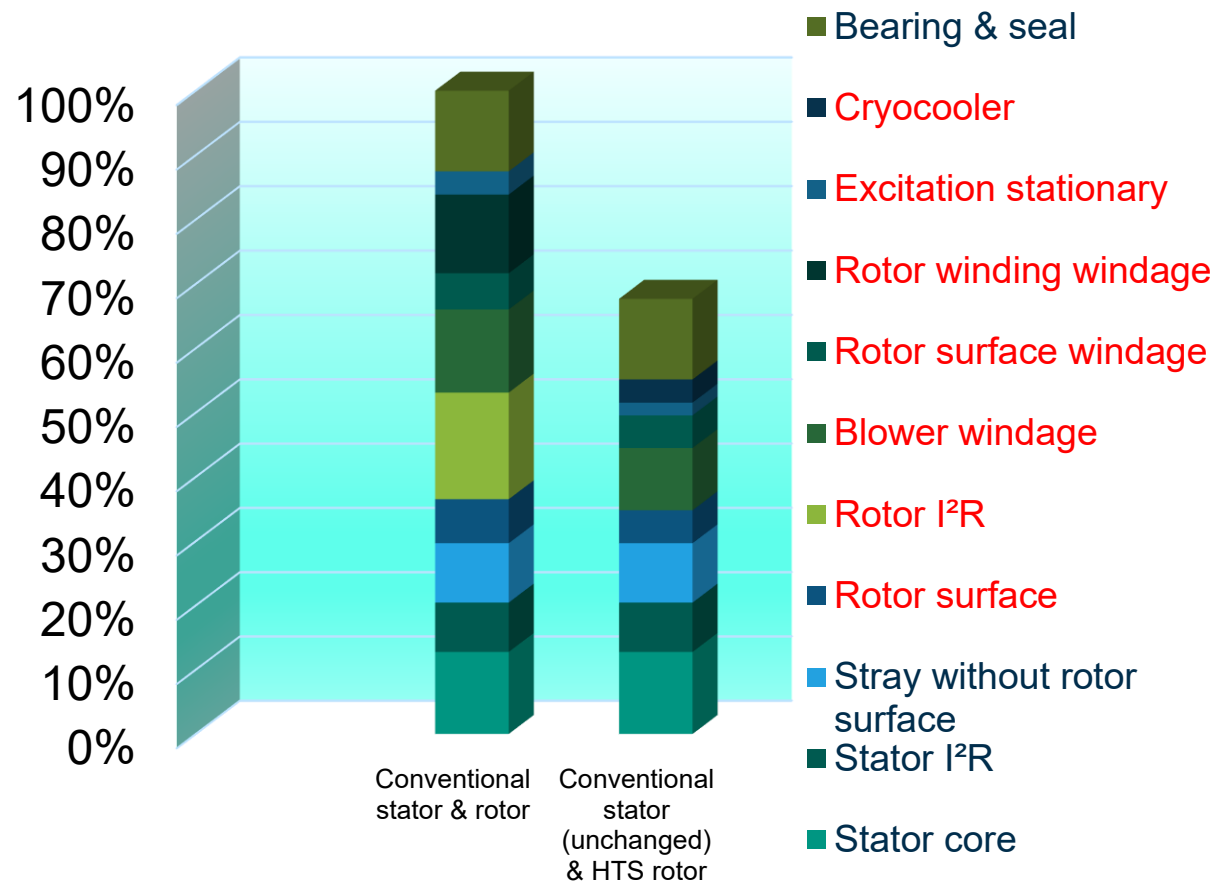
Heat loads in superconducting stator:

- Current leads
- AC loss
- Support system
- Radiation
- others

Current leads, AC & mechanical support are dominating the heat load.
Is there some margin to introduce cryogenic cooling?...

Justification of efficiency-based entry point – example 250 MVA turbo generator

Loss at rated load (250 MVA)



Loss balance:

Cu I²R-loss: -500 kW

T_{op}=30 K (CoP): x80 W/W

max. allowed loss: 500 kW/80= 6.3 kW

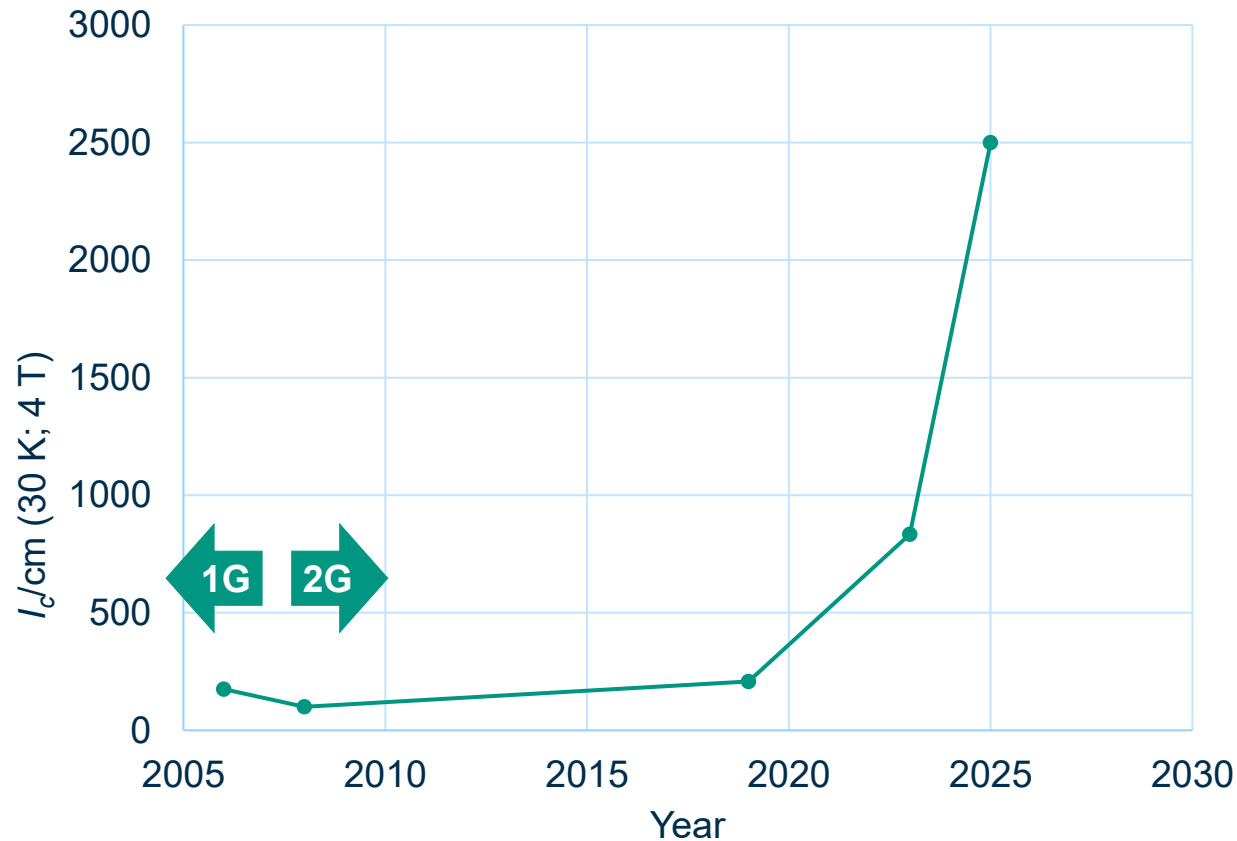
Very large cooling headroom for superconductors!

→ Very strong justification by efficiency
(not power rating anymore)!

Turbo generators show clear benefit in energy efficiency when applying HTS in the rotor (only) – even for low(er) power ratings!
Another motivation to consider HTS in generators...

HTS improvement of $I_{op}(30\text{ K}, 4\text{ T})$ vs. time for rotating machines (2026)

Improvement of x100 in 20 years!



HTS has improved dramatically and will in the future!
Another sweet spot for entry...

D-Project “Speedy_HTS”: HTS - Unrivalled performance in wind power

$D \approx 12\text{ m}$



14 MW direct drive
RE-PM generator

RE-mass: > 1500 kg

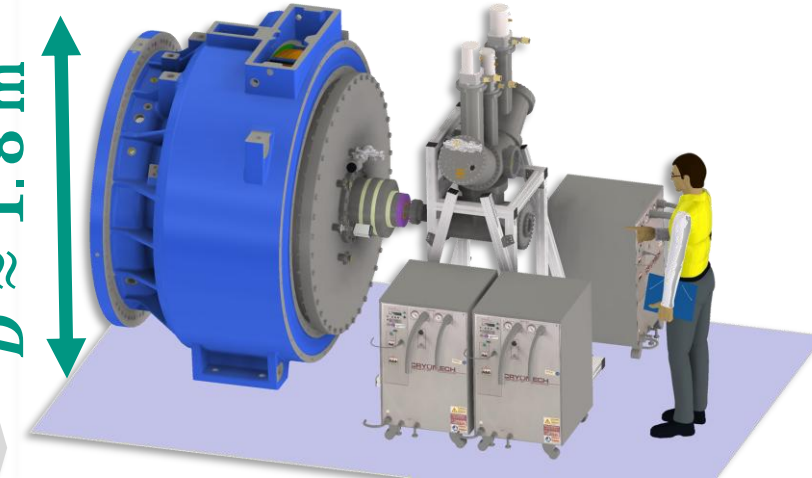
(RE: rare earth)



14 MW hybrid
RE-PM generator
max. efficiency: 98.4%
RE-mass: > 150 kg

(scaled product)

$D \approx 1.8\text{ m}$



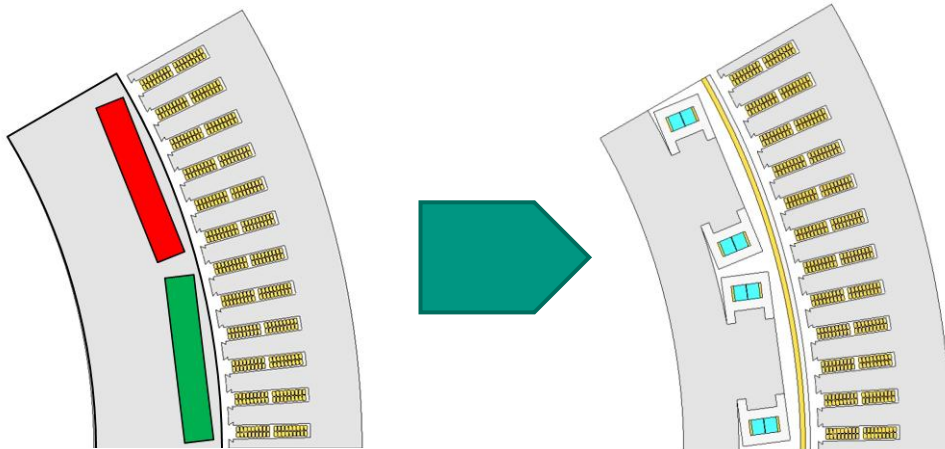
14 MW medium speed
HTS generator (test stand)
max. efficiency: 97%
RE-mass: < 40 g
Invention for integration of pitch
shaft

HTS: champion in energy & material efficiency!
What is maintained, what is special in this approach?...

Basic design equation

$$P = 2\pi \cdot n_{rot} \cdot \hat{A} \hat{B} \cos \delta V$$

P	power	[W]
n_{rot}	rotational speed	[1/s]
A	current loading	[A/m]
B	air gap magnetic field [T]	
V	volume	[m ³]
$\cos \delta$	internal power factor	



part of cross section of conventional PM-machine (left)
and HTS field-winding-excited machine (right)

Aspects:

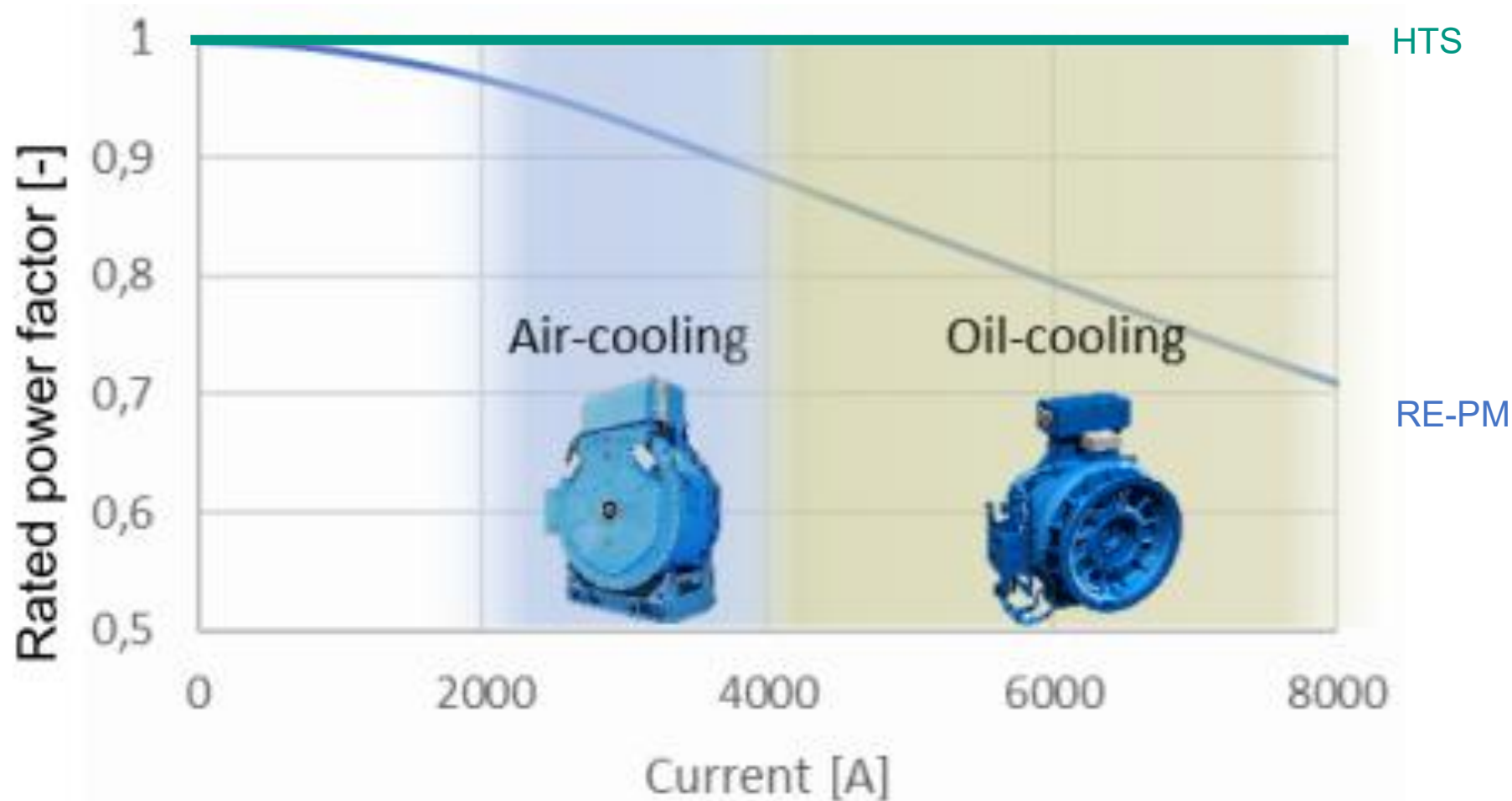
- Stator is fixed (by conventional product).
- Rotational speed is fixed.
- Option to change the air-gap magnetic field by replacing RE-PM with HTS coils (& option to change the excitation)
- Unfortunately, limited due to the need to stay close to the conventional magnetic circuit.
(using iron in the rotor, not using air-gap stator windings)

Approach:

- Keep the magnetic circuit,
but benefit from adjustable excitation

Machine keeps an “iron-copper dominated” high-current Cu-stator – not fully optimized for HTS.
Where is the magic in this approach?...

Conventional mid-speed wind power generator with high-current n.c. stator



Improving the current capacity/ loading in a stator may not be helpful for some machines! Partially sc. machines provide a workaround!
Cost situation direct-drive vs. mid-speed WP genos...

Cost situation

Direct drive generator (realistic(?))

$$L_{HTS} = 200.000 \text{ m}$$

$$\Delta\eta = +0.5\%$$

$$P = 10 \text{ MW}$$

$$\Delta P = 0.05 \text{ MW}$$

$$c_{MWh} = 500 \frac{\text{€}}{\text{MWh}}$$

$$t = 8600 \text{ h/a}$$

$$\text{benefit} = 500 \cdot 0.05 \cdot 8600 \text{ €/a} \\ = 215.000 \text{ €/a}$$

$$c_{HTS} = 20 \frac{\text{€}}{\text{m}}$$

$$c_{HTS, total} = 200.000 \cdot 20 \text{ €} = 4.000.000 \text{ €}$$

Direct drive generator (optimistic)

$$L_{HTS} = 20.000 \text{ m}$$

$$\Delta\eta = +0.5\%$$

$$P = 10 \text{ MW}$$

$$\Delta P = 0.05 \text{ MW}$$

$$c_{MWh} = 500 \frac{\text{€}}{\text{MWh}}$$

$$t = 8600 \text{ h/a}$$

$$\text{benefit} = 500 \cdot 0.05 \cdot 8600 \text{ €/a} \\ = 215.000 \text{ €/a}$$

$$c_{HTS} = 20 \frac{\text{€}}{\text{m}}$$

$$c_{HTS, total} = 20.000 \cdot 20 \text{ €} \\ = 400.000 \text{ €}$$

Mid-speed generator (Speedy_HTS)

$$L_{HTS} = 2.500 \text{ m}$$

$$\Delta\eta = +0.0\%$$

$$P = 14 \text{ MW}$$

$$c_{HTS} = 20 \frac{\text{€}}{\text{m}}$$

$$c_{HTS, total} = 2.500 \cdot 20 \text{ €} = 50.000 \text{ €}$$

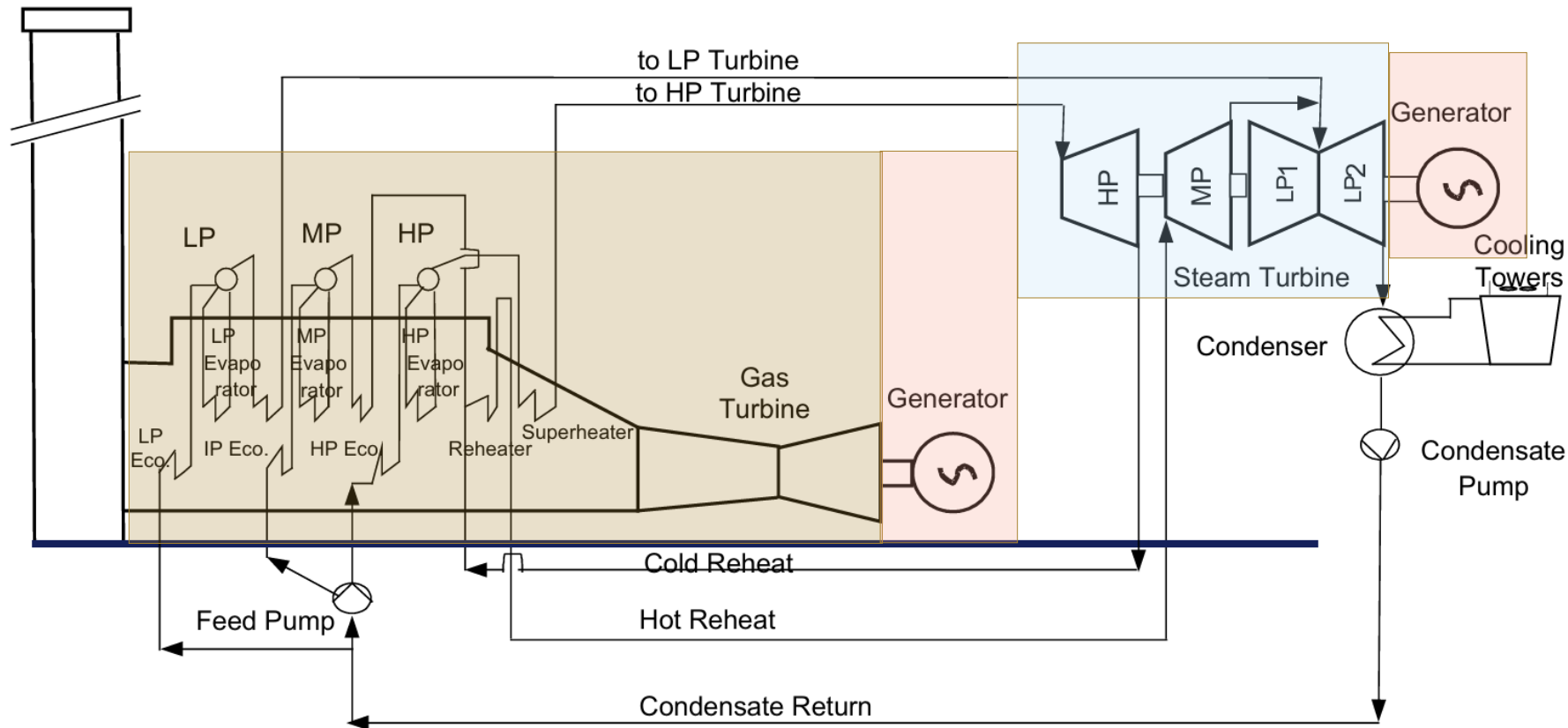
Cost fully covered by

- increase of $\cos \varphi$ and
- savings in rare earth magnets,
- savings in power electronics and
- savings in connections to the wind park grid.

Viable approach of mid-speed HTS genos (when accepting a 3-stage gearbox).

Challenges by application(s) (genos)...

Challenges (combined cycle power plants)



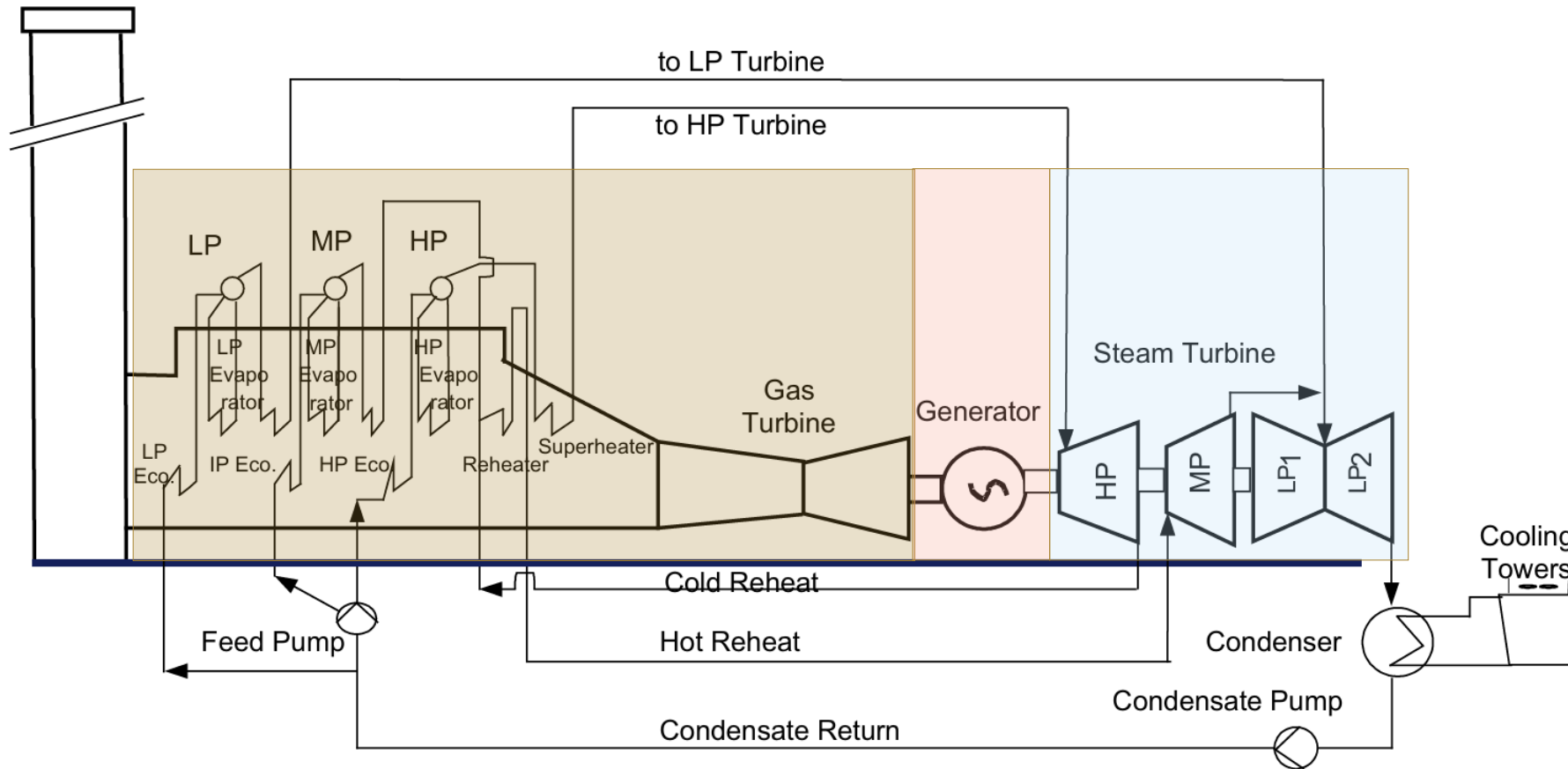
Multi-shaft configuration

- GT + ST on separate shafts
- 2 generators incl. grid connections
- Turbines coupled thermo-molecular (steam generation)

[Edris, M. (2010). Comparison between single-shaft and multi-shaft gas fired 800 MWe combined cycle power plant. Applied Thermal Engineering, 30(16), 2339-2346 <https://doi.org/10.1016/j.applthermaleng.2010.05.011>]

Multi-shaft configuration: coupling only “by pneumatics”, not by mechanics → free end access to gens (two).
Single shaft configuration...

Challenges (combined cycle power plants)



Single-shaft configuration

- GT + ST on same shaft
- 1 generator in the middle
- Turbines coupled thermo-molecular (steam generation) and mechanically (clutch?)

[Edris, M. (2010). Comparison between single-shaft and multi-shaft gas fired 800 MWe combined cycle power plant. Applied Thermal Engineering, 30(16), 2339-2346. <https://doi.org/10.1016/j.applthermaleng.2010.05.011>]

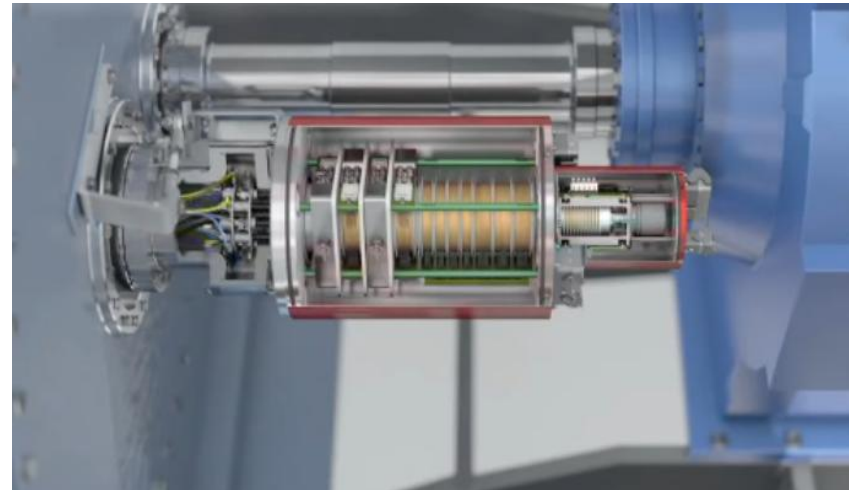
Single-shaft configuration: coupling by pneumatics and mechanics → no end access to single geno!
Other applications with restricted axial access/ end access?...

Present: wind power



Central pitch control in hub

- The **pitch control** is fed through the main shaft.
- For direct-drive WP drivetrains, this is the one and only shaft.
- The rotor must facilitate a **warm feedthrough** of the pitch control system (hydraulics or electric).



pitch control power slip rings on central shaft of bladders

[https://www.youtube.com/watch?v=0ZU5AMlx_38]

Hard to provide an off-axis cooling access.
Cooling concepts...

Cooling options

Stationary compressors & stationary cold heads



[Siemens HTS2-Generator 4 MVA]

Cold power: 3x 100 W

Pros

- Full access to cooling equipment
- Low-pressure rotating joints
- Scalable/ extendable

Cons

- Thermosyphon or gas circuit needed
- Risk of leaks (?)

Stationary compressors & rotating cold heads

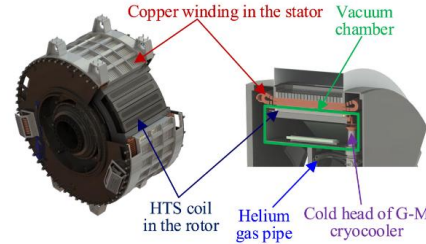


Fig. 1. A schematic view of the HTS generator in the EcoSwing project.

[Song et al., IEEE Transactions on Energy Conversion 35, no. 2 (2020): 757-64. <https://doi.org/10.1109/tec.2019.2960255>]

Cold power: 9x 30W

Pros

- Access to compressors

Cons

- Low-/High-pressure rotating joints needed
- Risk of leaks (?)
- Maintenance on cold heads difficult

Rotating compressors & rotating cold heads

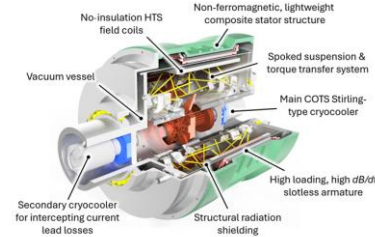


Fig. 1. CAD model of the general partially SC motor topology implemented in both CHEETA and CRUISE.

[T. Balachandran et al., IEEE TAS 35, no. 5 (2025): 1-5. <https://doi.org/10.1109/tasc.2025.3538003>]

Cold power: 3.3 W (?)

Pros

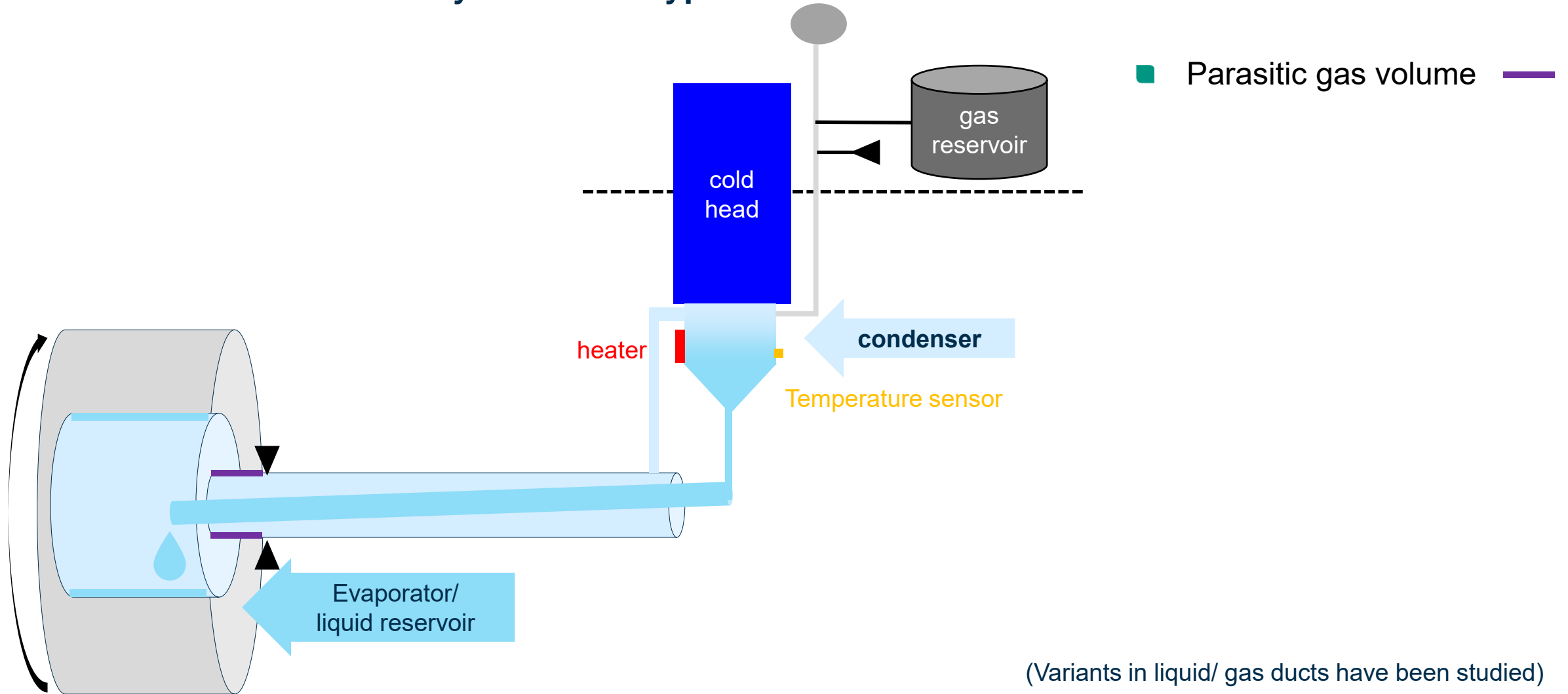
- Only electrical supply needed
- “invisible” cooling system

Cons

- Maintenance on cooler difficult
- Not scalable/ extendable
- Slip rings required

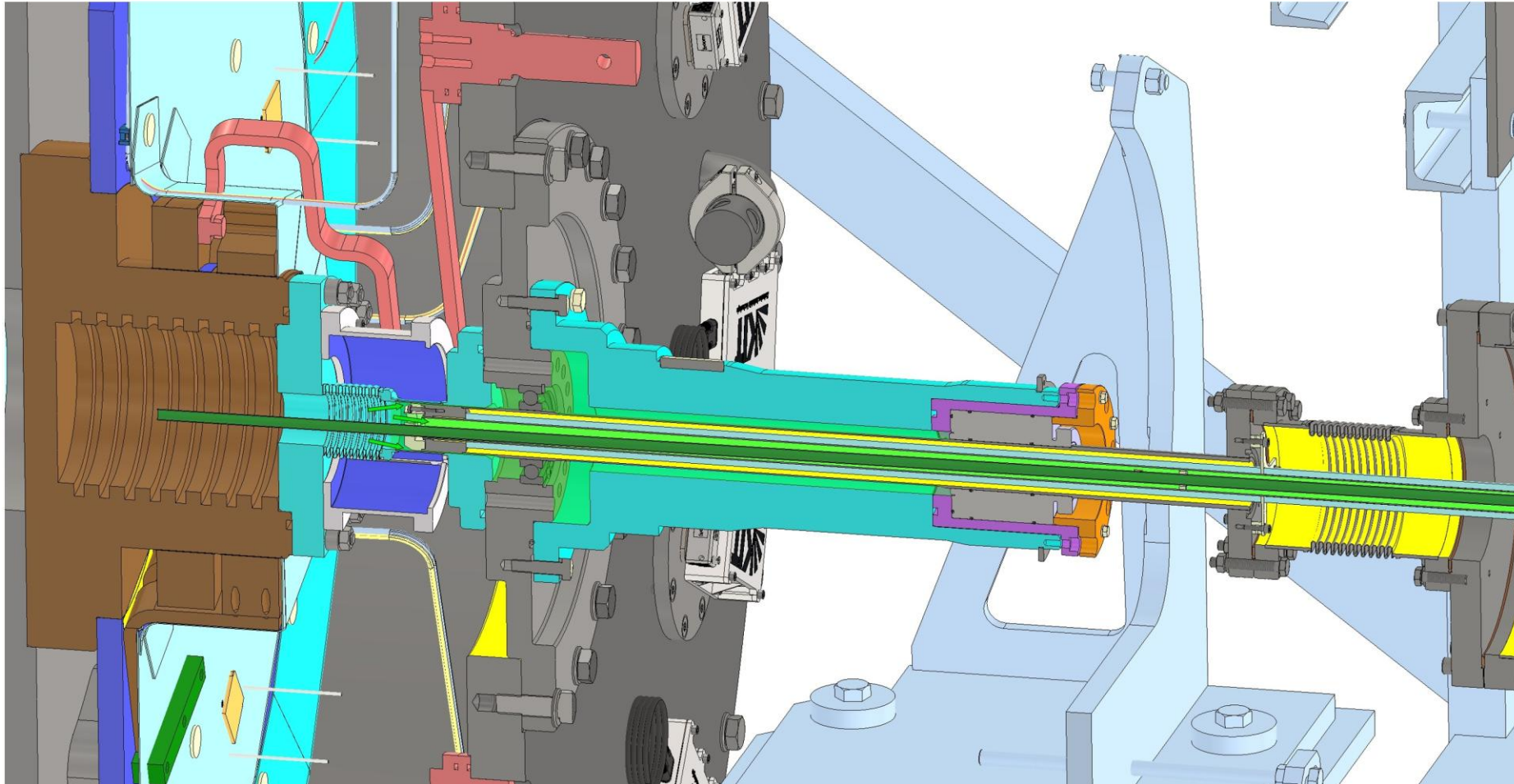
3 options to provide thermal anchors and cooling in the rotor.
Let's focus on the (most stationary) thermosyphon approach...

Scheme of heat removal by a thermosyphon



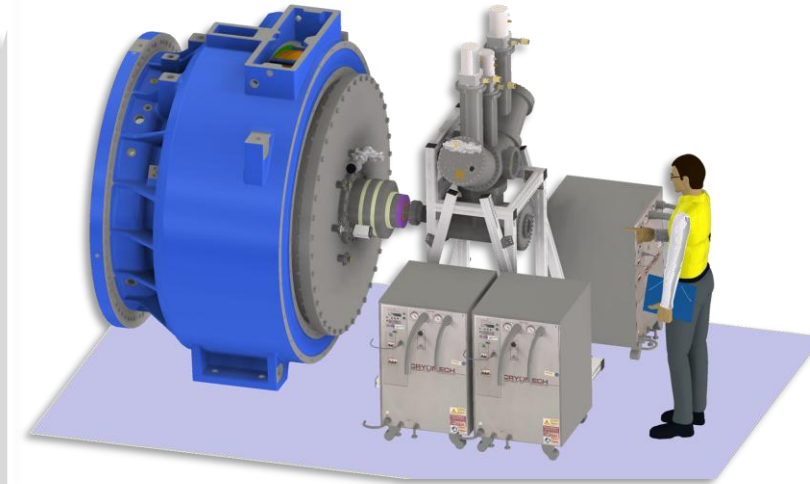
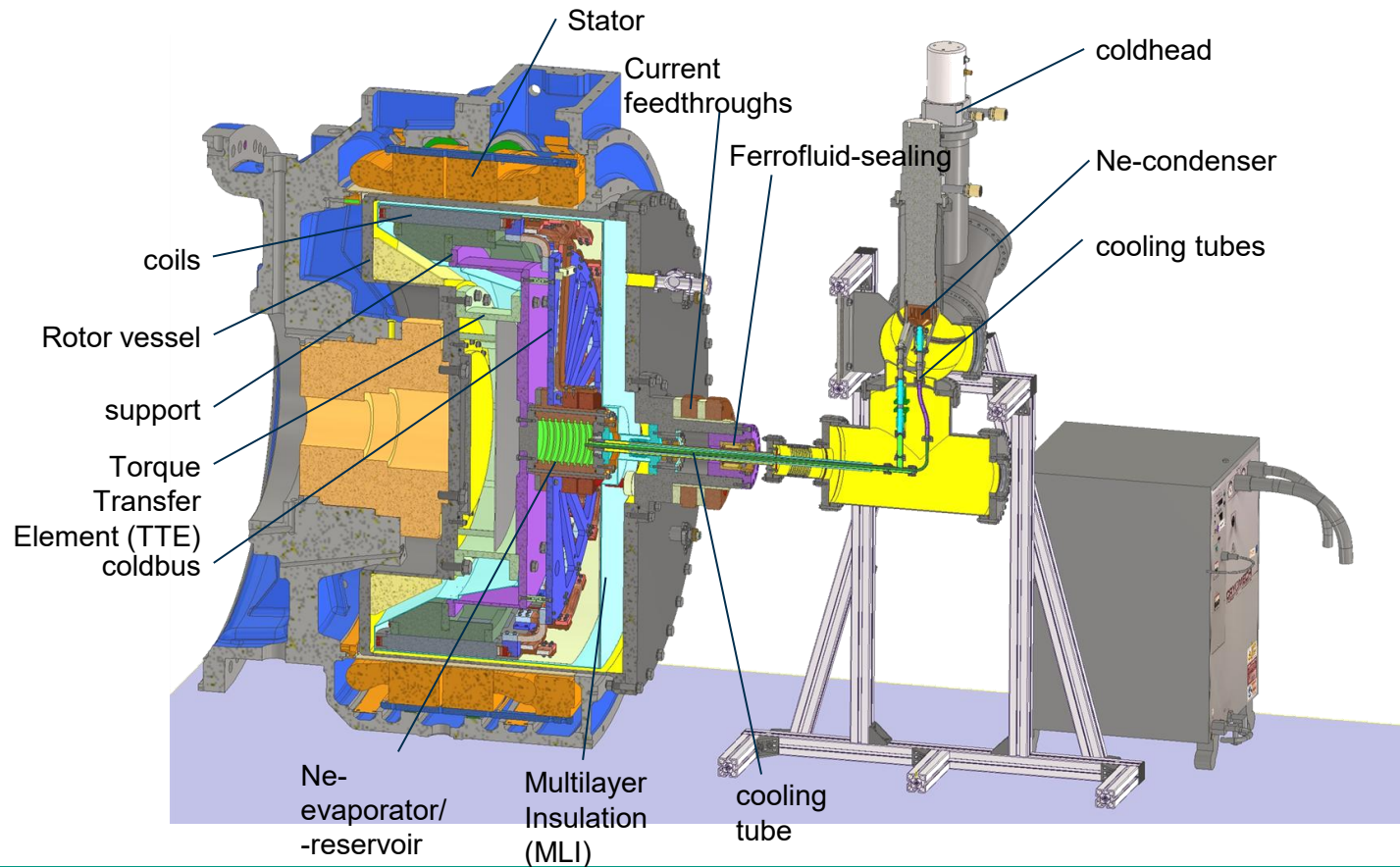
A thermosyphon provides a thermal anchor in the central part of the rotor.
More detailed drawings...

Drawings of Ne-feeding system



Liquid and gaseous neon phases have separated ducts enclosed by vacuum and providing the thermal anchor/ reservoir in the rotor.
The overall cooling system...

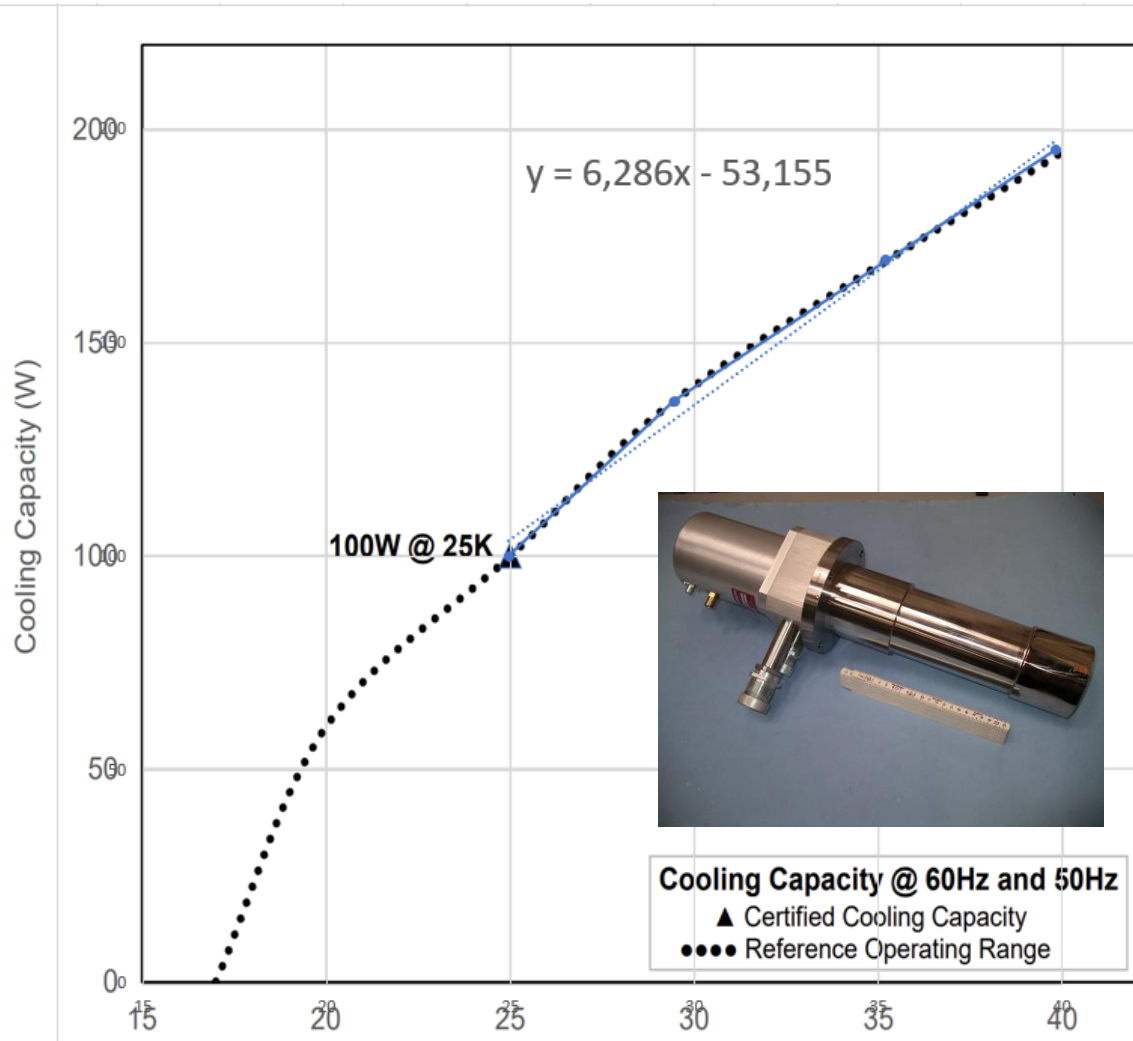
SPEEDY_HTS - Test stand setup



14 MW medium speed
HTS generator
max. efficiency: 98.7%
RE-mass: < 40 g

Yoke, HTS-coils, coldbus, thermosiphon, current feeds, TTE designed and partly purchased.
Thermal equivalent circuit...

Thermosiphon – Cooling power by cold head – linearization approach



A fit/ linearization around an operating temperature $T_{op} \approx 30$ K yields the expression:

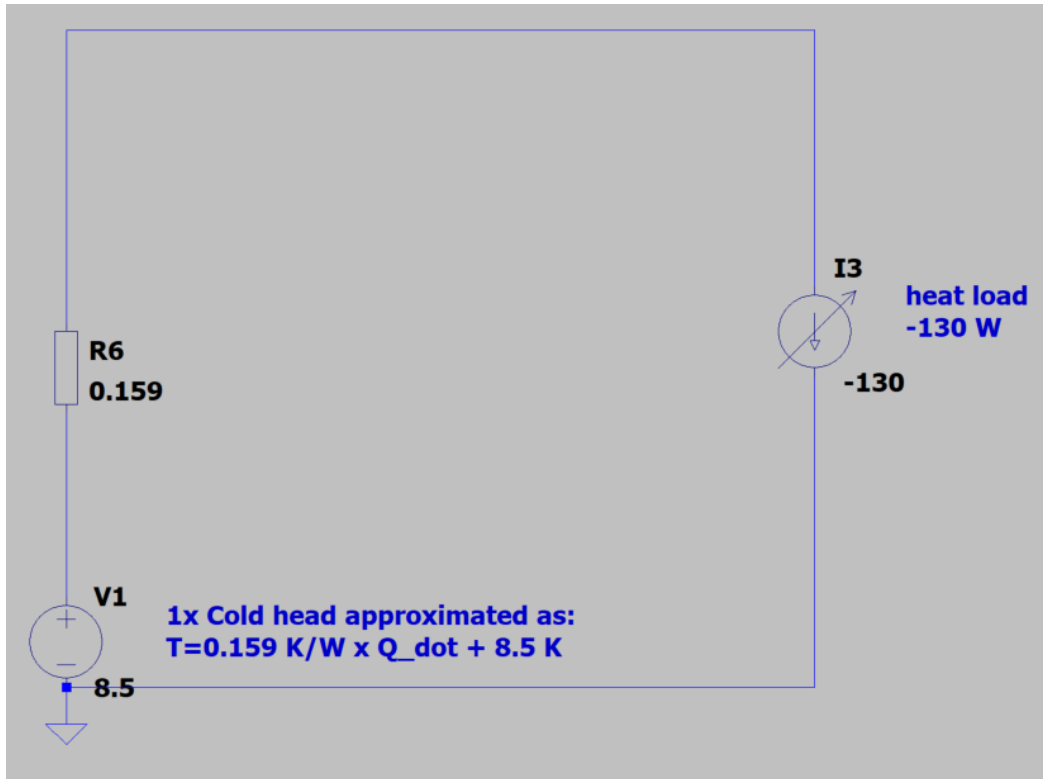
$$P = -53.155 \text{ W} + 6.286 \frac{\text{W}}{\text{K}} \cdot T \quad (.1)$$

Or –when considering the heat flow- for the temperature:

$$T = 8.5 \text{ K} + 0.159 \frac{\text{K}}{\text{W}} \cdot \dot{Q} \quad (.2)$$

Linearization of coldhead at operating temperature.
The cold head as a “real temperature source”...

Thermal equivalent circuit (coldhead)



(Remark: you might connect I3 directly to ground – and not via V1.

V1 is an “ideal voltage source”, this is just aesthetics, but perhaps more “intuitive” as R6 is creating a “real voltage source” out of V1)

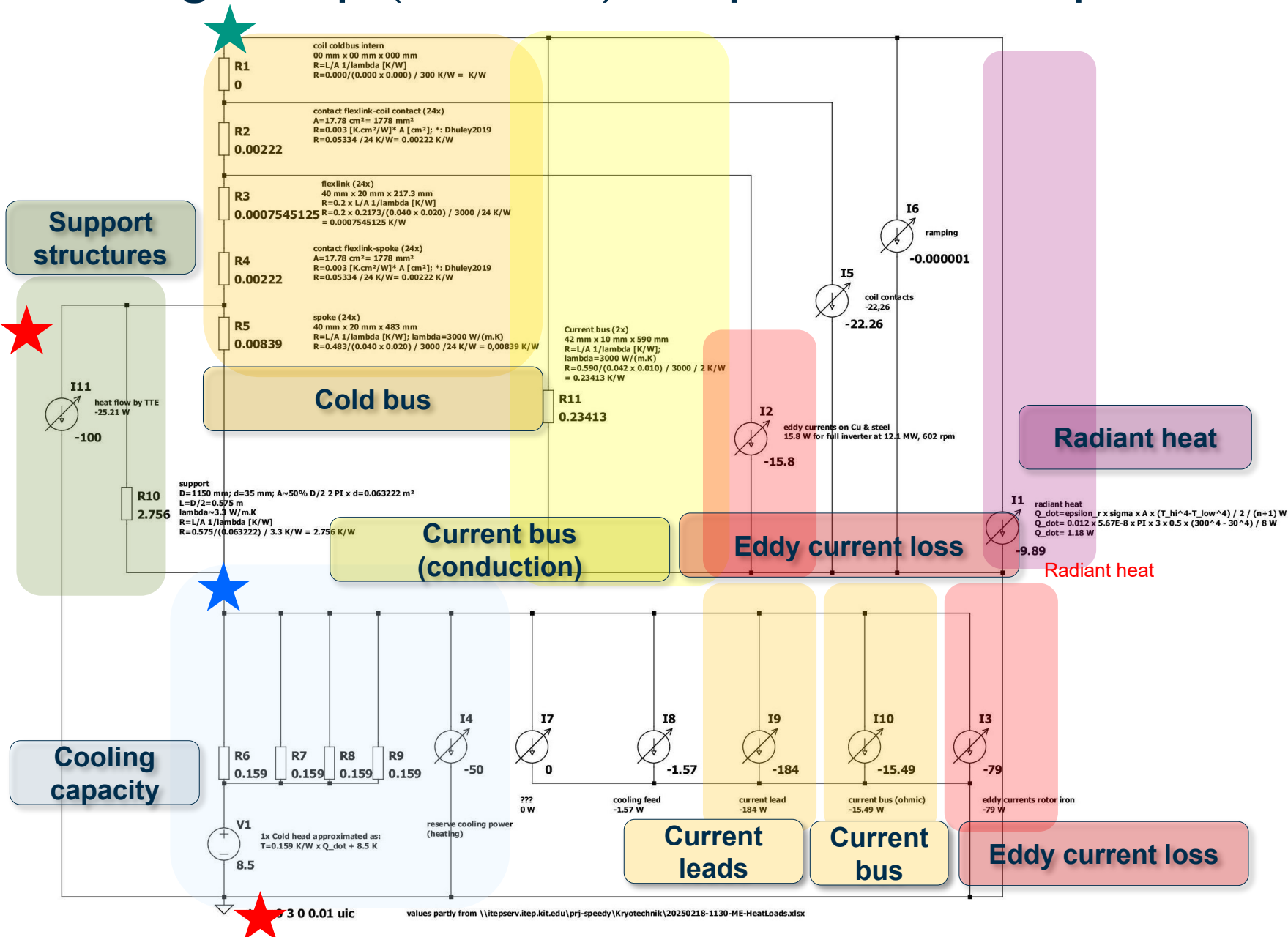
$$T = 8.5 \text{ K} + 0.159 \frac{\text{K}}{\text{W}} \cdot \dot{Q} \quad (.2)$$

Download:

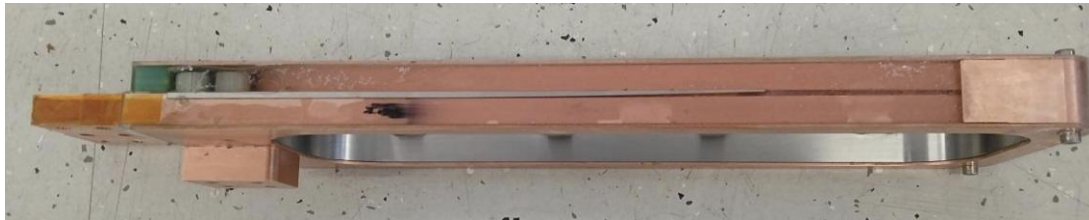
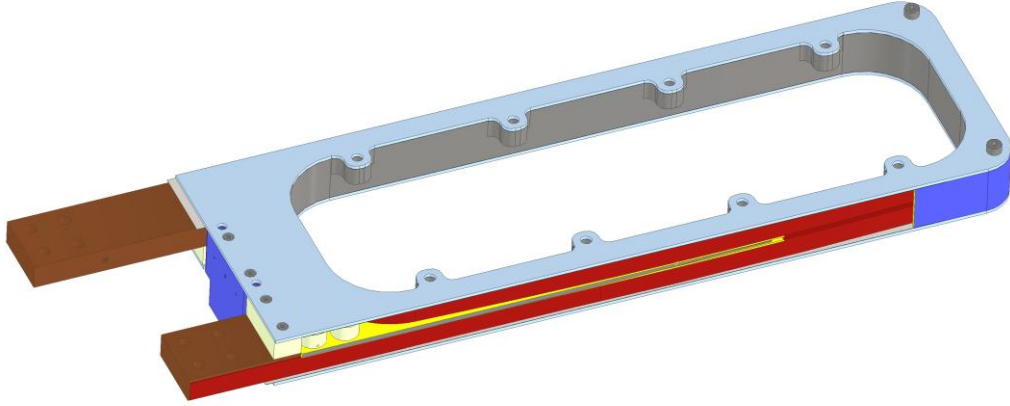
<https://www.analog.com/en/resources/design-tools-and-calculators/ltspice-simulator.html>

The linearization might be used to determine nicely dependencies and temperatures at arbitrary points.
The full TEC of the rotor...

Cooling concept (test stand)– simplified thermal equivalent circuit (draft)



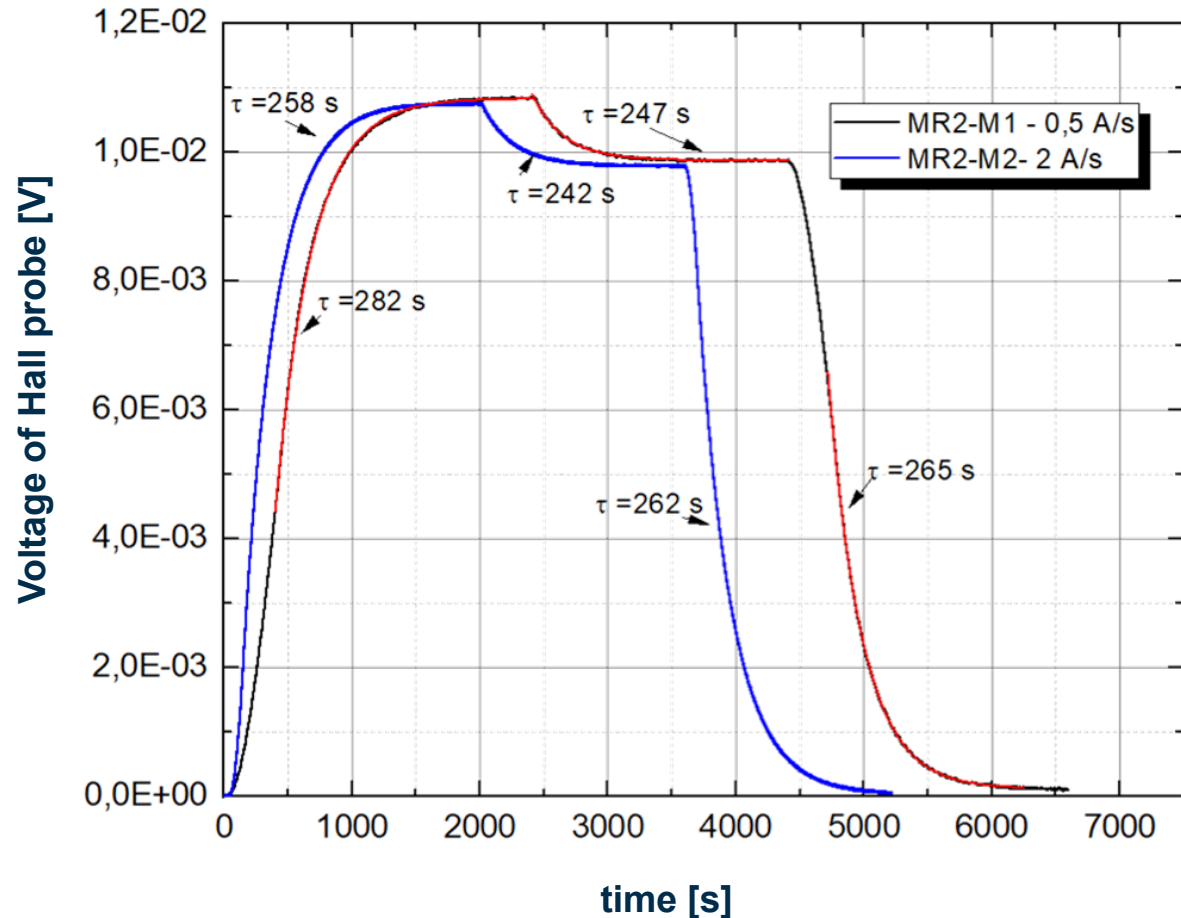
2G HTS poles: VPI double coil NI-windings



Quantity	Symbol	Value	Unit
Number of turns	n_{turns}	2x 37	n.a.
Nominal current	I_n	1000	A
Nominal temperature	I_n	30	K
Number of poles	n_{poles}	24	n.a.
Axial length of coils	l_{tot}	440	mm
Azimuthal width of coils	w_{tot}	146	mm

First sets of rotor coils produced.
Dynamics of coils...

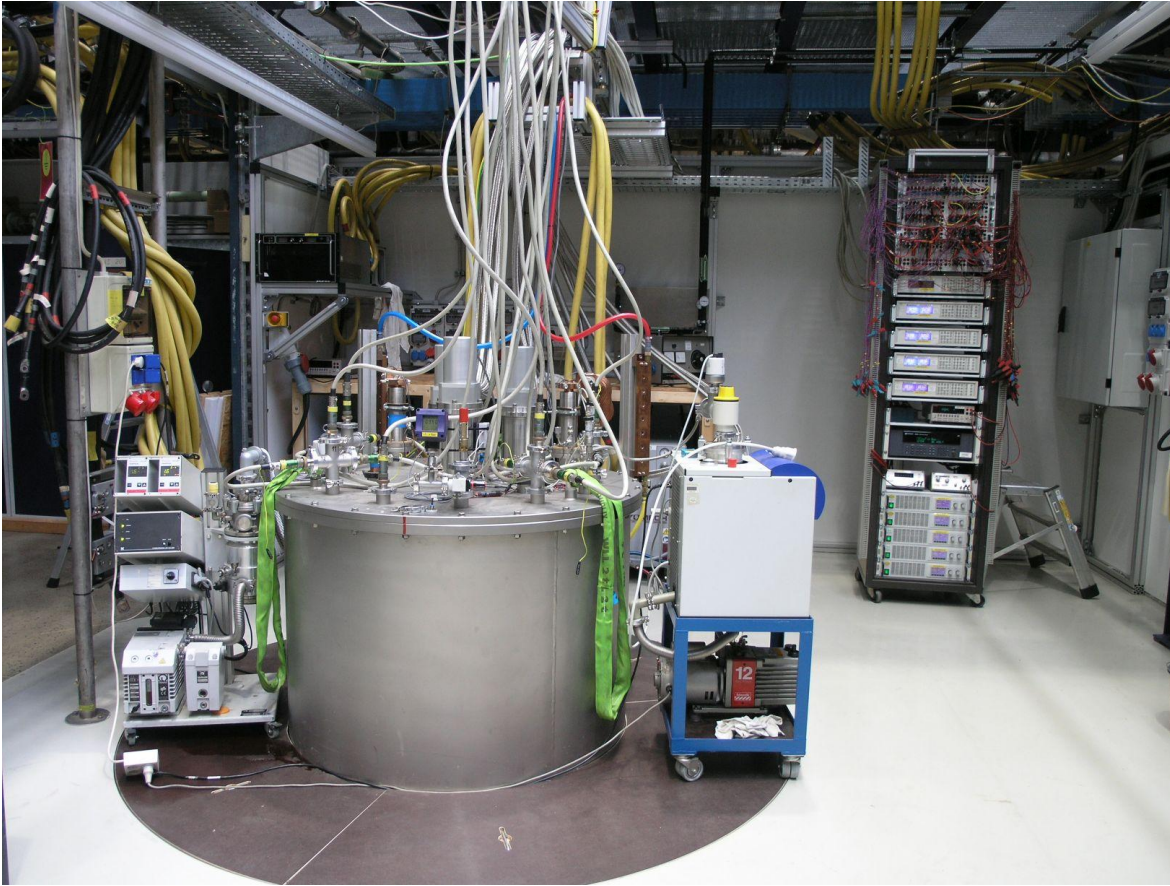
Current ramping at T=77 K



- Evaluation of the transient signal of the Hall probe yields a time constant $\tau \approx 250$ s.
- Sufficient to meet the dynamic requirements in a wind turbine.

NI-VPI coils are sufficiently “agile” to meet the wind turbine specs.
Testing of the double coils at operating conditions...

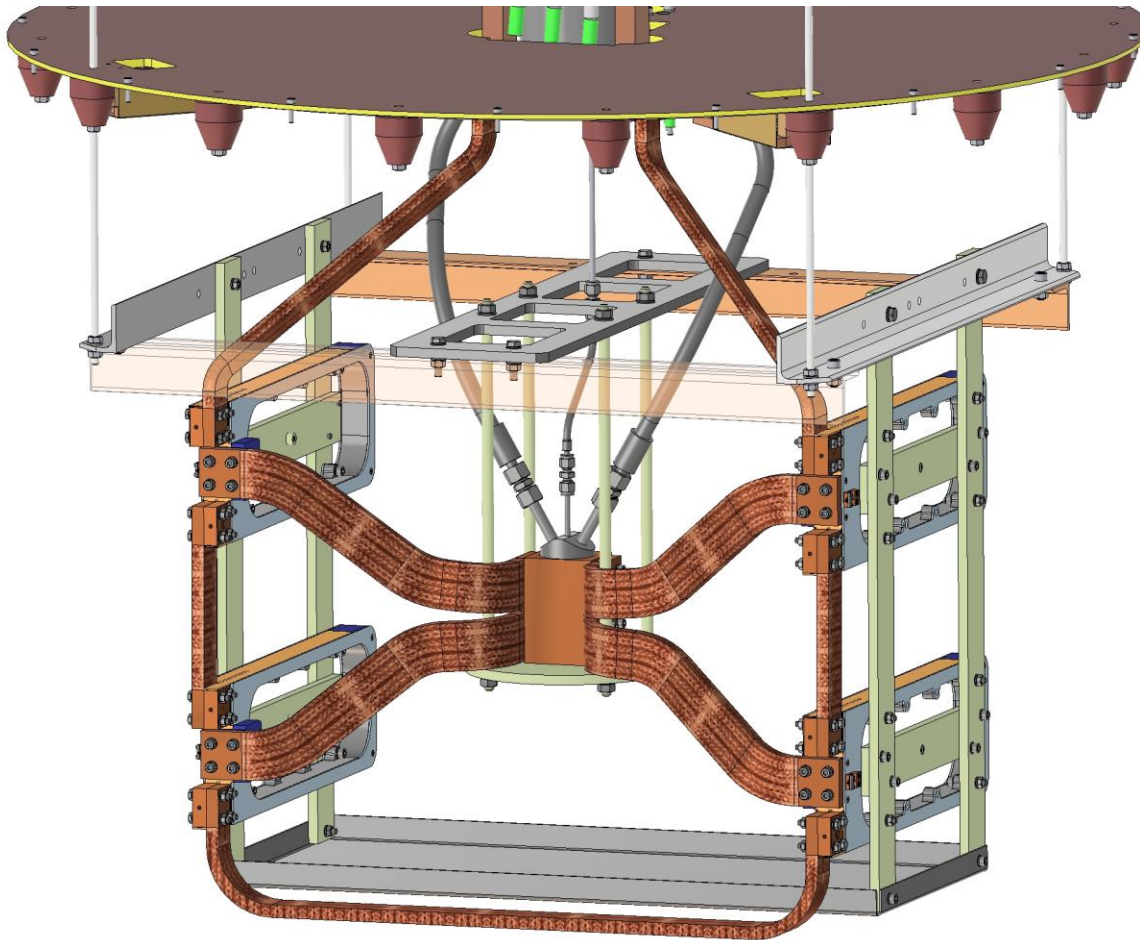
Characterization of coils



- Big vacuum vessel
- Several cold heads
- Simultaneous testing of several coils

Installations available for testing.
Sample holder...

Topology for performance test of 4 double-coils ($T = 30$ K; $B = s.f.$)



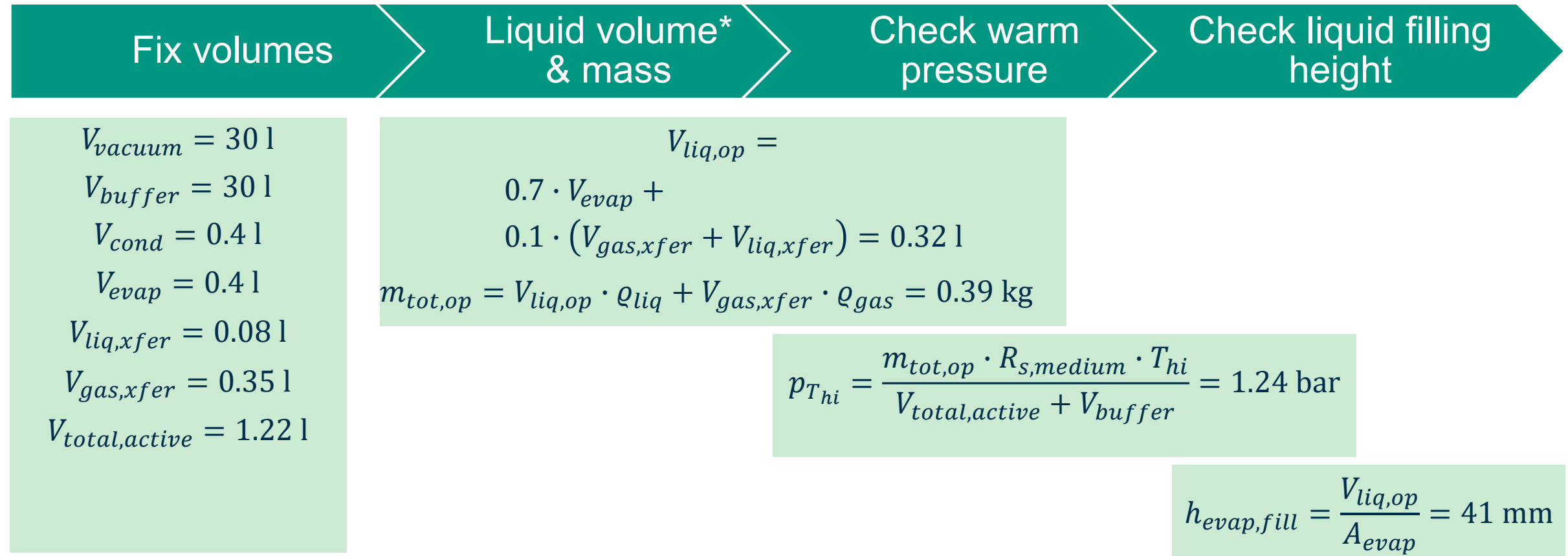
Representing the environment in the machine
(thermosyphon & Cu-cold bus)

Instrumentation:

- 8 T -sensors (2 per double coil)
- 4 U -signals
- 4 Hall probes
- T -control at evaporator (T -sensor & heater)
- Operating current 1000 A
- Including failure test (rupture of current bus)

Stationary vacuum vessel to provide T-environment for 4 double-coils in series.
“Thermosyphon for Dummies”...

Thermosyphon design “for dummies” – an example



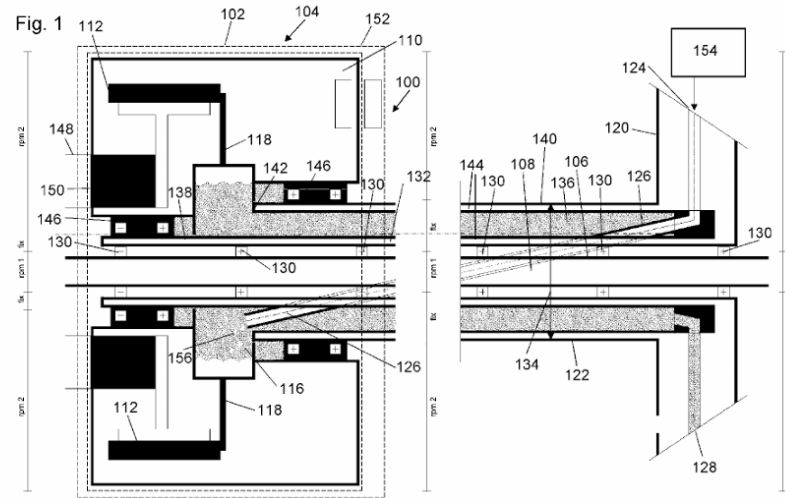
* rule of thumb, may be checked for cooling power compatibility

Quantities depend on medium (properties), geometries and required cooling power.
Coming back to the warm shaft challenge...

Cooling off-axis – invention and WO patent application (published)

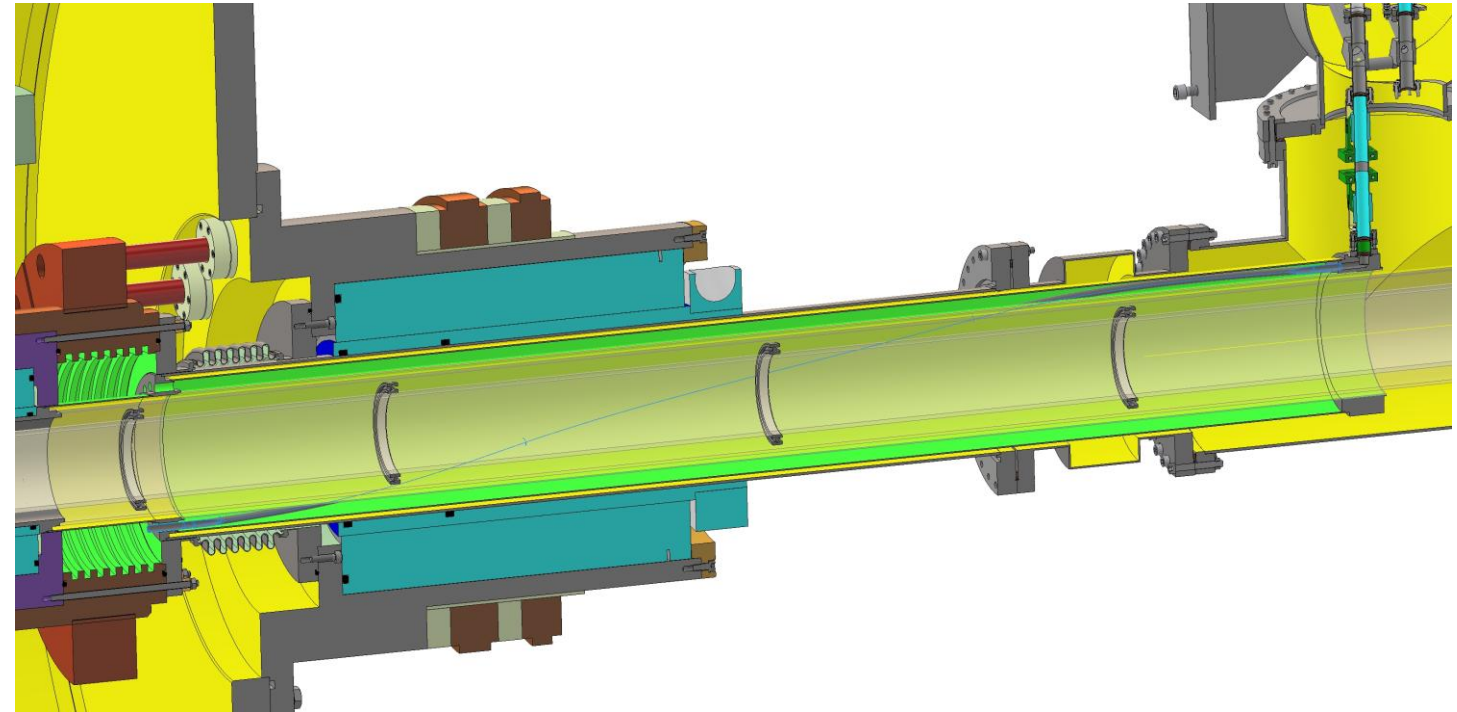
(54) Title: COOLING SYSTEM FOR A ROTOR, ROTOR AND ELECTRIC MACHINE

(54) Bezeichnung: KÜHLSYSTEM FÜR EINEN ROTOR, ROTOR UND ELEKTRISCHE MASCHINE



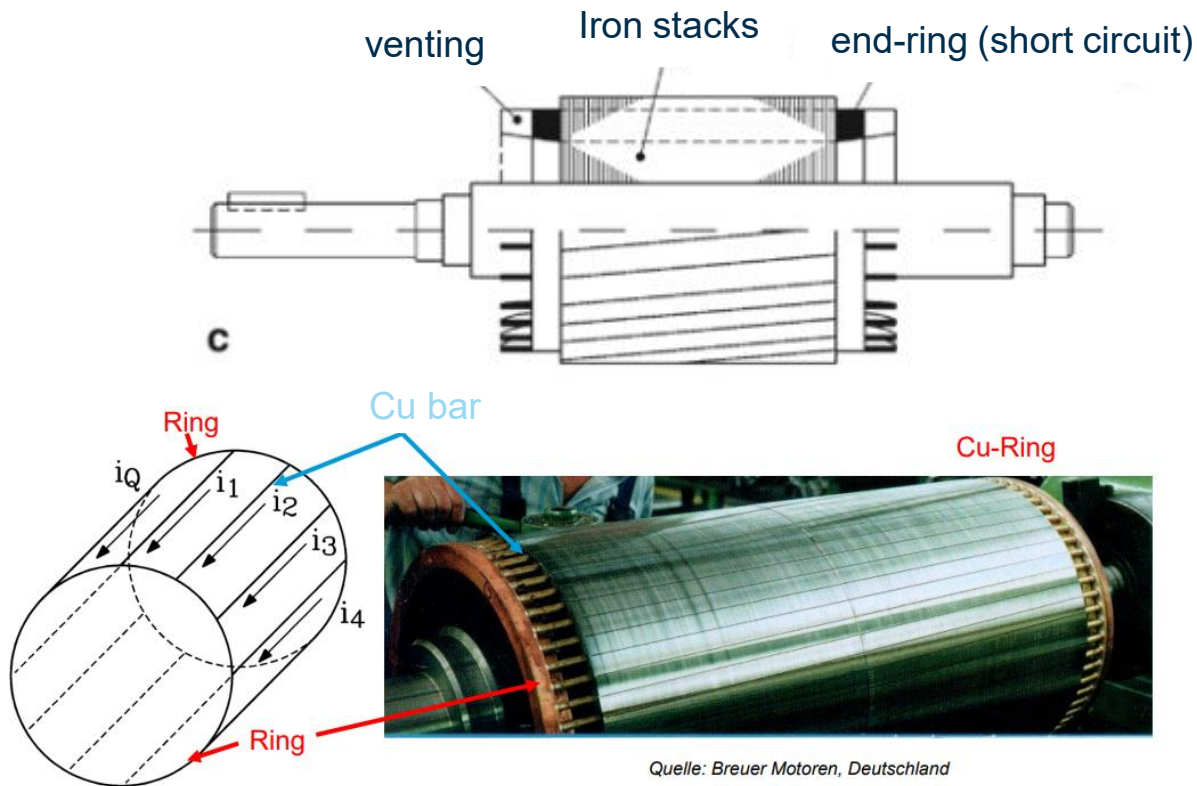
(57) Abstract: A cooling system (100) for a rotor (102) is proposed. The cooling system (100) comprises a first vacuum chamber (110), wherein the first vacuum chamber (110) is designed to be arranged so as to be rotatable relative to a central shaft (106) and is subjected to a negative pressure with respect to atmospheric conditions, wherein electrical coils (112) are arranged in the first vacuum chamber (110), a refrigerant reservoir (116), wherein the refrigerant reservoir (116) is arranged and rotatable in the first vacuum chamber (110), wherein the refrigerant reservoir (116) is connected to the coils (112) in a thermally conductive manner, and a housing (120) having a cylindrical housing projection (122), wherein the housing (120) has a refrigerant inlet (124), a refrigerant channel (126) and a refrigerant outlet (128), wherein the refrigerant inlet (124) and the refrigerant outlet (128) are formed in the housing (120), wherein the refrigerant

- Ring-shaped transfer space
- Half-spiral liquid neon feed
- Central warm “space” for whatever is needed.



Solution filed as patent – enabler for a warm central space, shaft, feedthrough,...
→STAR-machine...

Conventional asynchronous/ induction/ squirrel cage machine



Features

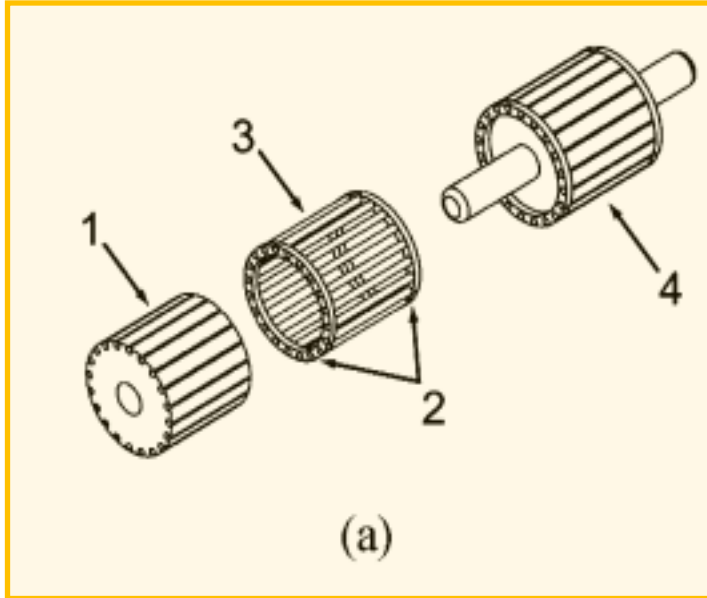
- Cu- or Al-bars connected by end-rings to form induction loops.
- Fit of the number of loops to the stator configuration
- No current leads needed for excitation of the rotor

[A. Binder, TU Darmstadt, IEE, „Elektrische Maschinen und Antriebe“]

Simple architecture and operation of conventional asynchronous squirrel cage machines.
Historic efforts to rebuild with HTS...

ISM machine

Cu-based squirrel cage



HTS-based squirrel cage

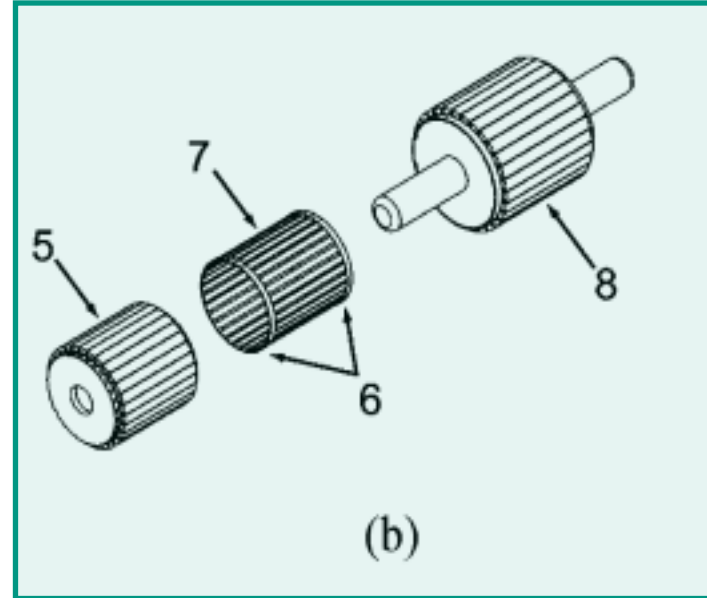


Fig. 2. Squirrel cage rotor of the induction motor. (a) Conventional motor (b) HTS motor 1, 5: rotor core 2,6: short ring 3, 7: bar 4, 8: assembled rotor.

[Sim, J., K. Lee, G. Cha, and J. K. Lee.,
IEEE Transactions on Applied Superconductivity 14, no. 2 (2004): 916-19.
<https://doi.org/10.1109/tasc.2004.830317>.]

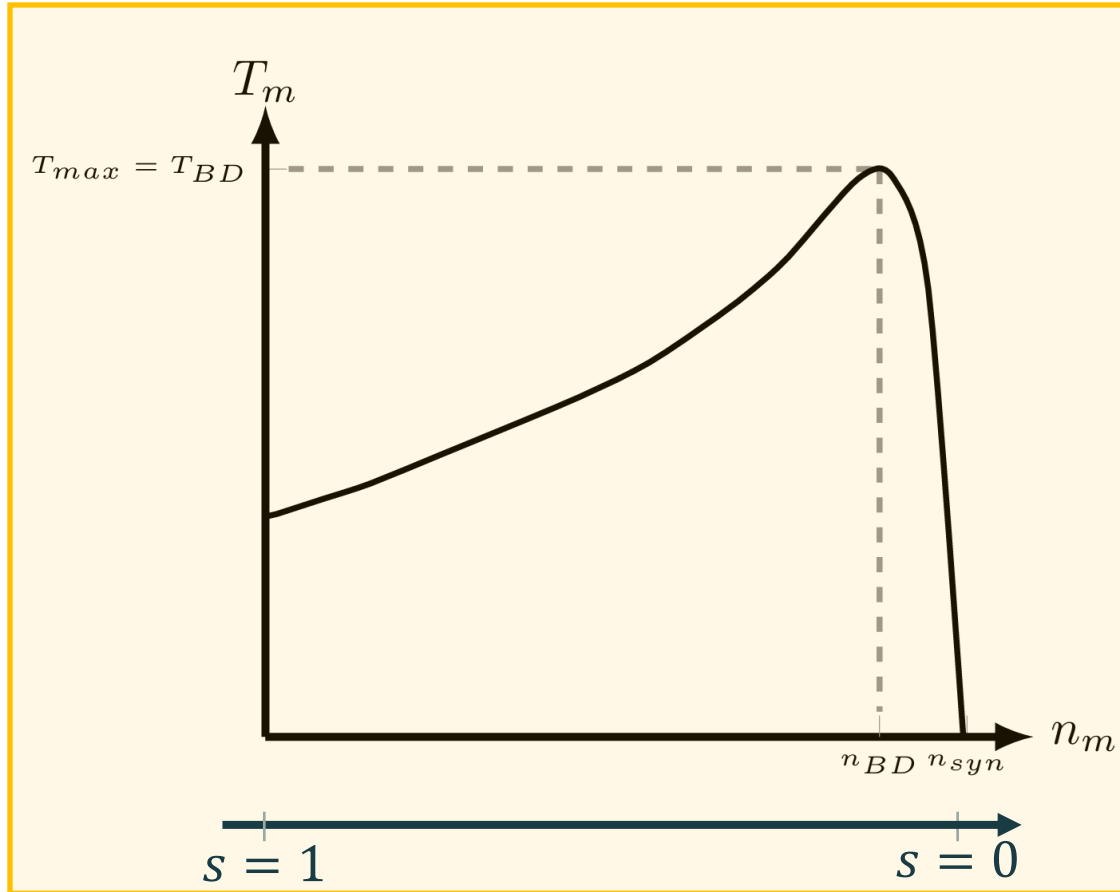
Approach:

- Engineers replaced **copper** by **HTS** (partly) in machine designs following established e-machine theory.
- **NEW:** HTS machine may be operated in **asynchronous** as well as in **synchronous** mode!
- ISM=„Induction Synchronous Machine“

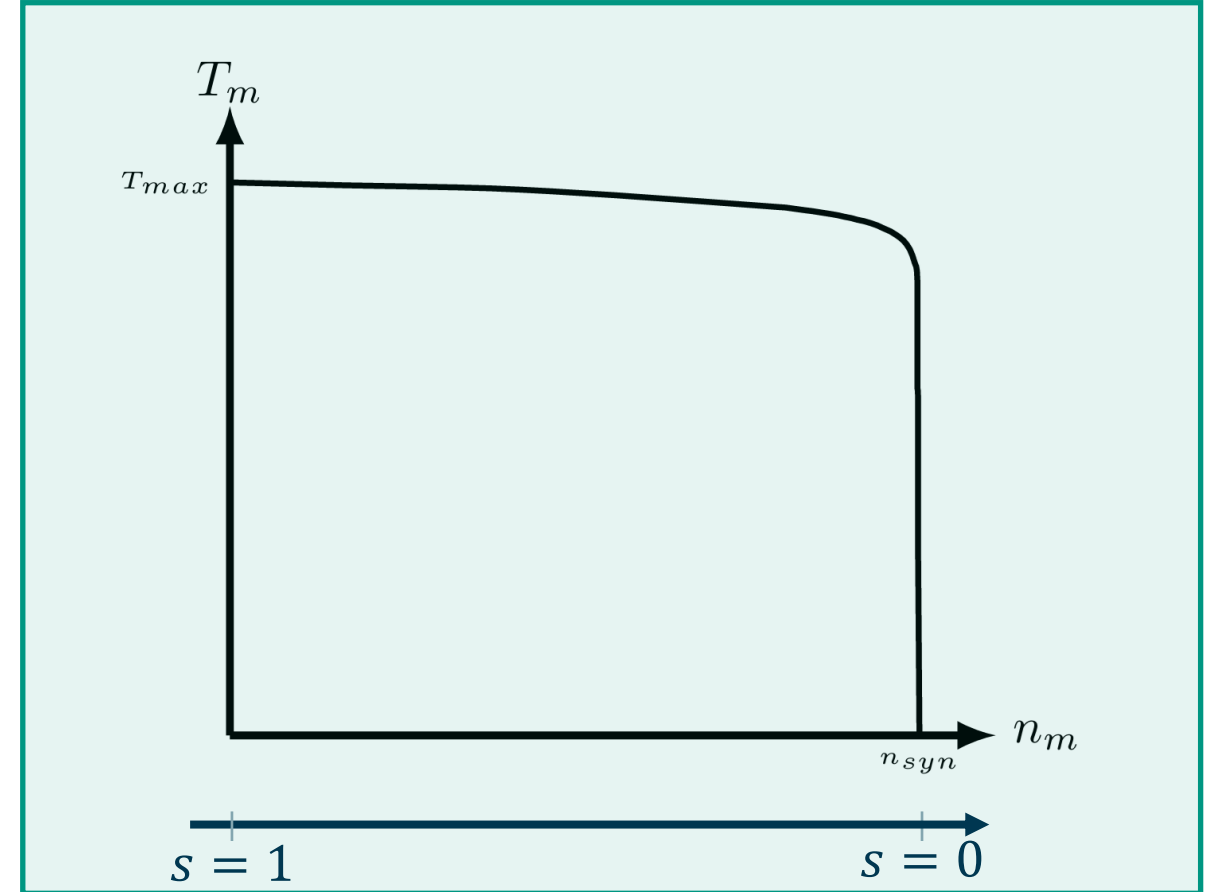
Replacing copper by HTS adds new functionality.
Torque-speed characteristics...

Performance torque vs. speed

conventional squirrel cage induction machine

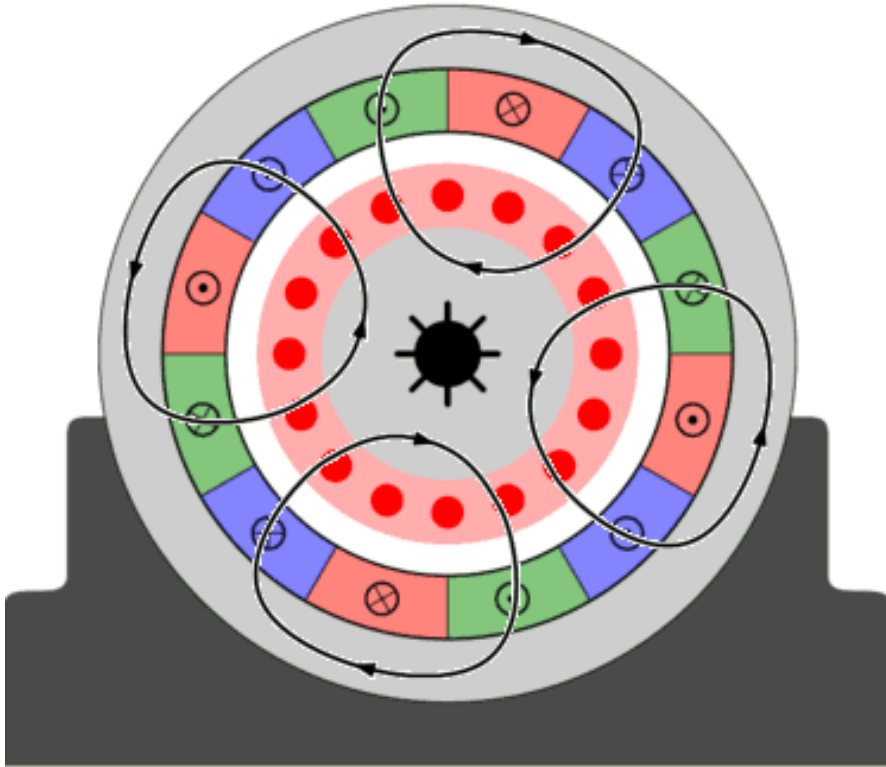


HTS squirrel cage machine (more than induction)



HTS-machine works with higher torque even for $s \rightarrow 0$ (as synchronous machine).
Motivation for end rings & number of bars...

Conventional 3-phase 4 pole induction motor (with squirrel cage)



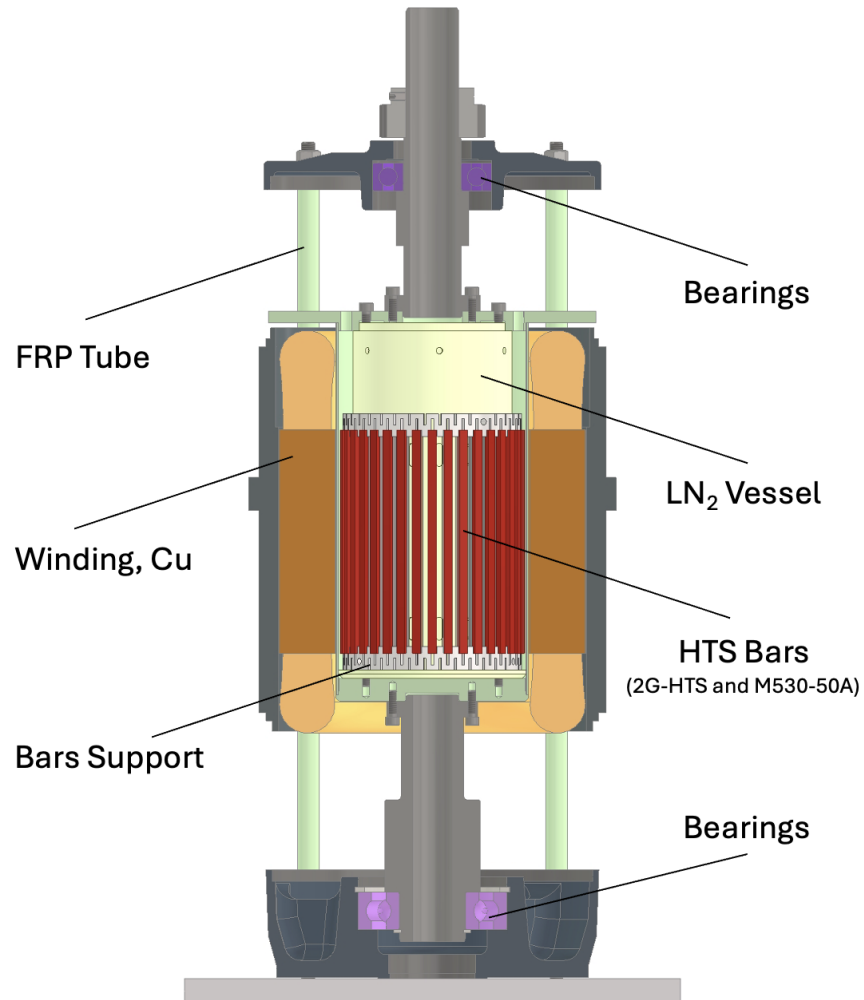
Details:

- Stator: Distributed winding 12 slots
- Rotor: Squirrel cage 16 bars, 2 end rings

[CC BY 3.0: https://en.wikipedia.org/wiki/Induction_motor#/media/File:Asynchronmotor_animation.gif]

Motor theory: end rings are required to form induction loops sufficiently large along the rotor perimeter to act according to Lenz's law.
Novel approach of the STAR-machine ...

Test stand (schematic)



Rotor

- Only hollow **FRP-body** (filled with LN2)
- **HTS bars** glued to FRP-body (epoxy)
- No ohmic contacts, **no ohmic currents**
- Only **supercurrents**

Teststand

- **No cryostat** included in the proof-of-concept design
- **Vertical position** for the sake of simple cooling by LN2
- **Spatial separation** of bearing shields to ensure thermal „decoupling“

[R. Oliveira, T. Arndt, A. Yenes, M. Eisele, M. Kläser.
"A Novel Type of Jointless HTS Induction Machine—Proof-of-Principle."
IEEE Transactions on Applied Superconductivity 36, no. 8 (2026): 5206010-10.
<https://doi.org/10.1109/tasc.2026.3711020>]

Very simple test stand to proof the concept.
Closing...

Conclusions

- Superconducting rotating machines have been **developed for decades** – even with LTS using LHe
- HTS enable **new business opportunities** (simplified cooling) even for lower power ratings
- HTS machine's main benefits:
 - Increased **air-gap magnetic field**, allows **high stator current loadings**
 - Larger air-gap, smaller X_s , high power factor
 - **Thermosyphon** allows **simple** and **flexible cooling** with **thermal anchors** in the rotor
 - **ISM concept** with enlarged torque range & eliminating current leads
 - **STAR-machine(?)**
- Main challenges:
 - **HTS wire**: stabilization, quench handling, current feeding
 - **Rotor**:
 - TTE: heat load vs. torque transmission
 - Cooling: COP of sized equipment, Off-axis-concept, closed, maintenance
 - Excitation: dynamics vs. NI-coils, heat-load/ efficiency & HTS dynamo
 - **Armature**:
 - AC-losses, cold inverters(?), distributed windings, I_c

Thank you!
QnA...

Questions?



Thank you!