HTS for accelerators –
Connections to Industry and Applications

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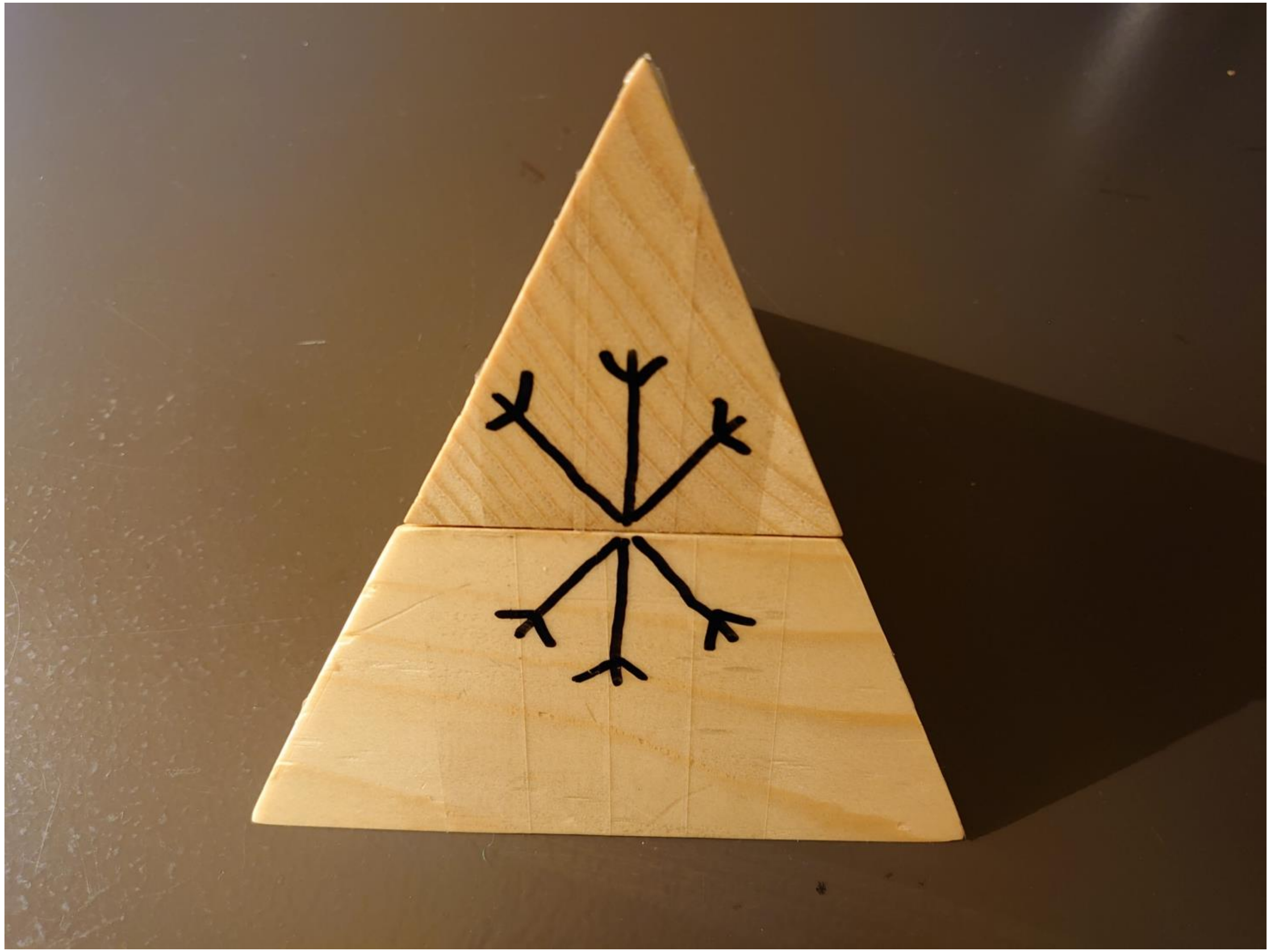
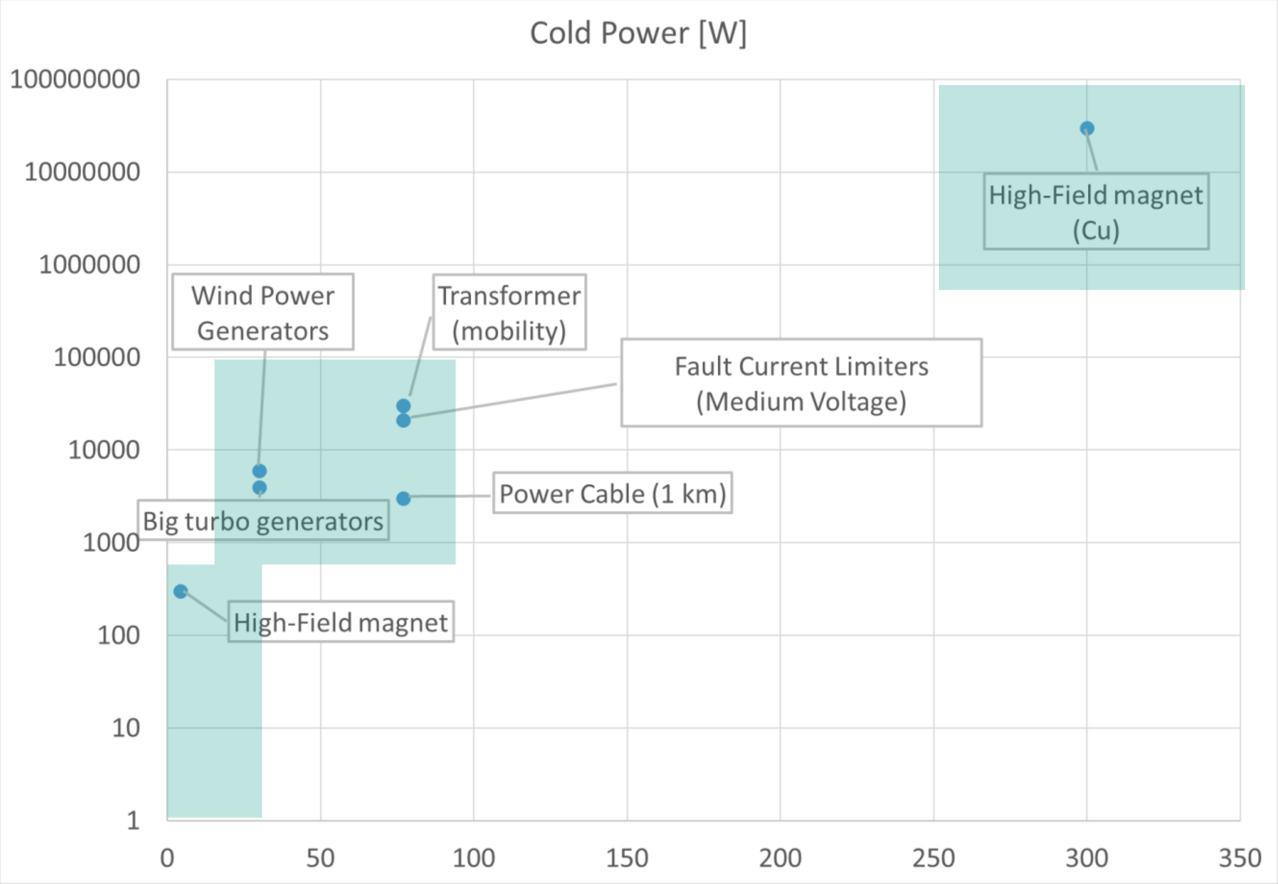
openECFA, CERN, 14.Nov.2019

Institute for Technical Physics (ITEP)

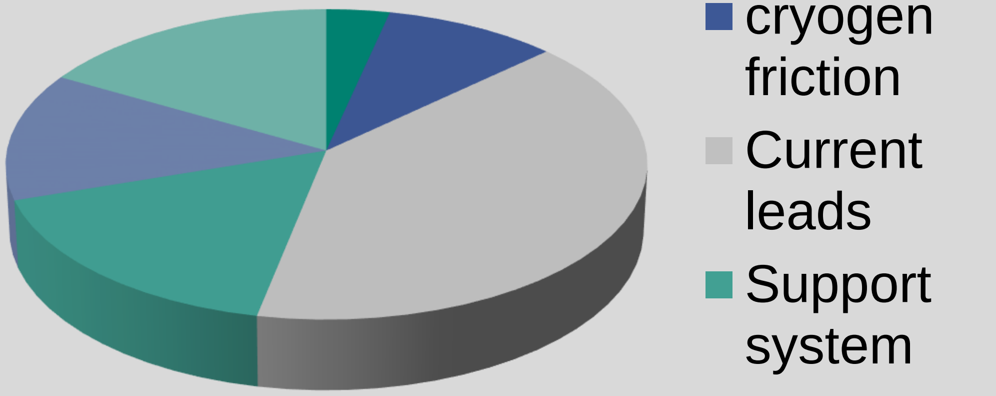
Cooling



Cooling – demand of selected applications



example: heat pie of HTS turbo generators



(total:
up to several 10 kW)

Cooling demand of Energy Applications much higher than for Magnets, but common challenges. Specific cooling technologies are crucial for industrialization...

Actually preferred cooling concepts (selected)

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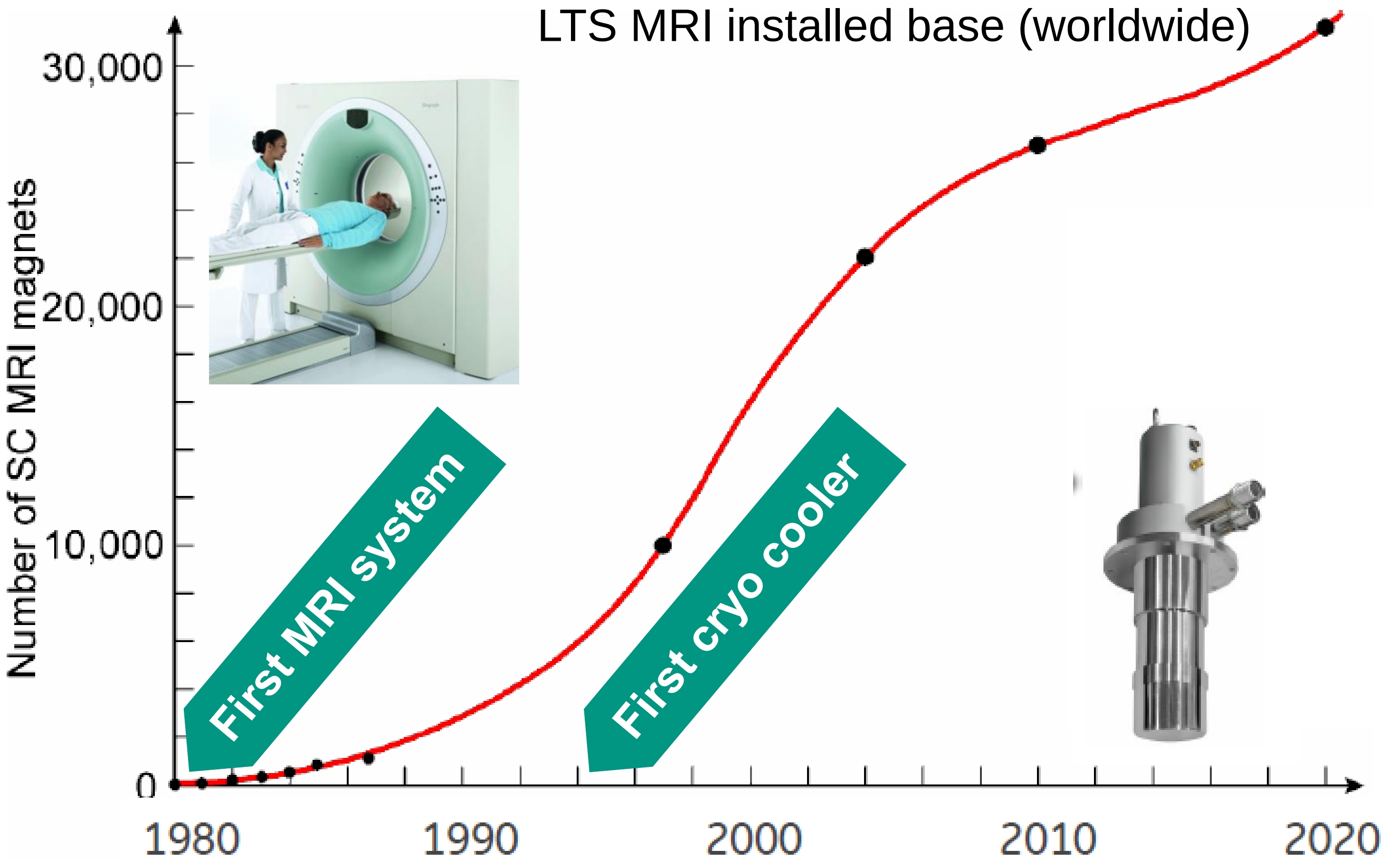
HTS devices	Cable	FCL	Trans-former	Magnet HEP, HF	Magnet MRI	Magnet NMR	Wind Geno	Hydro Geno	Turbo Geno	eAir Geno
LN_2-flow										
LN2-bath										
LN2-pressurized bath										
Conduction cooling								not yet		
Ne-Thermosiphon										
LHe (1.8…4.2 K)					LTS				LTS	LTS
LHe cooling loops					LTS				LTS	
GHe cooling										
H_2-evaporation										

Cooling – Learning from the past

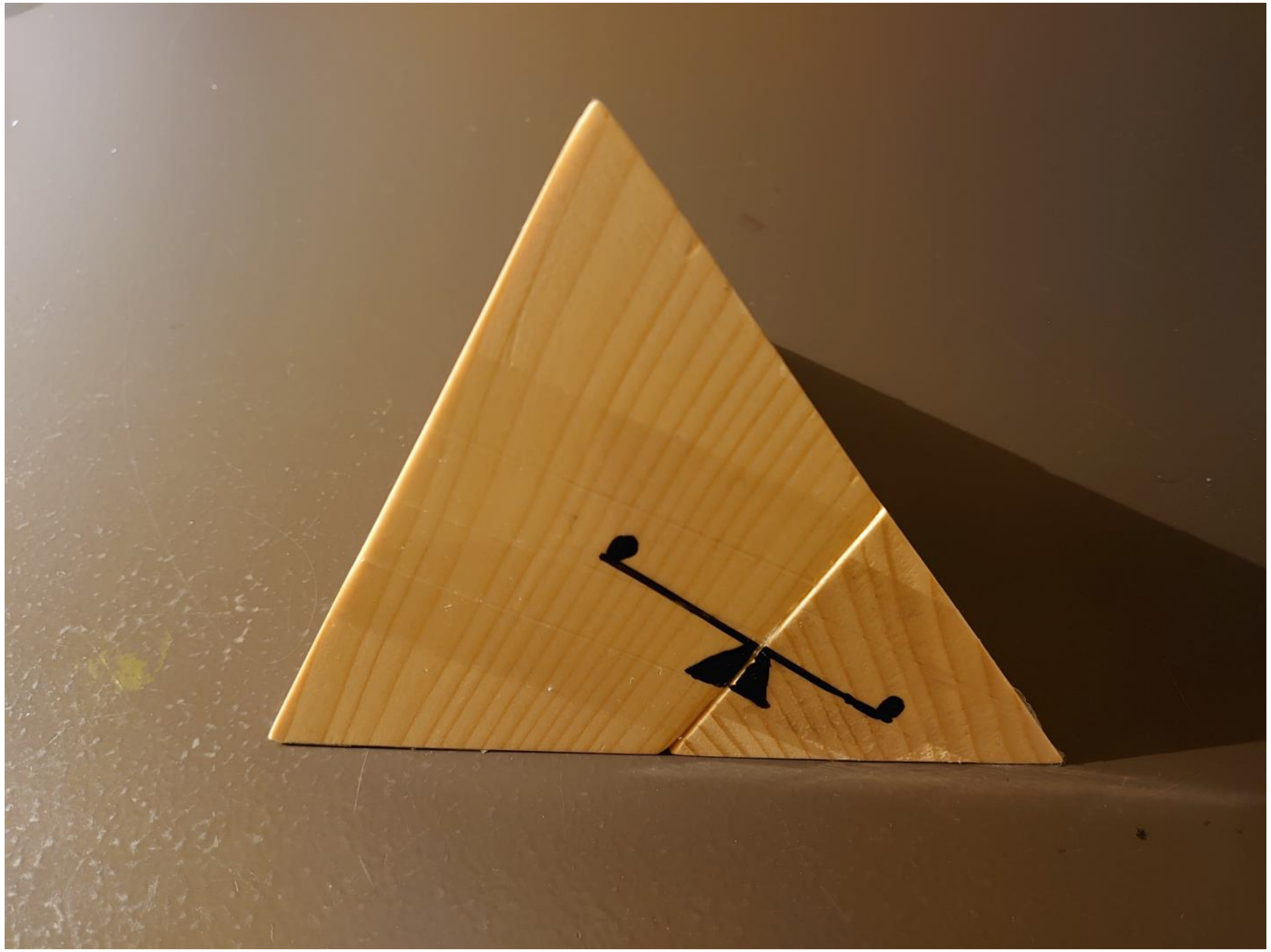


- Emerging business established „early“
- commercialization enablers followed 13 years later
→ widespread penetration & economy of scale

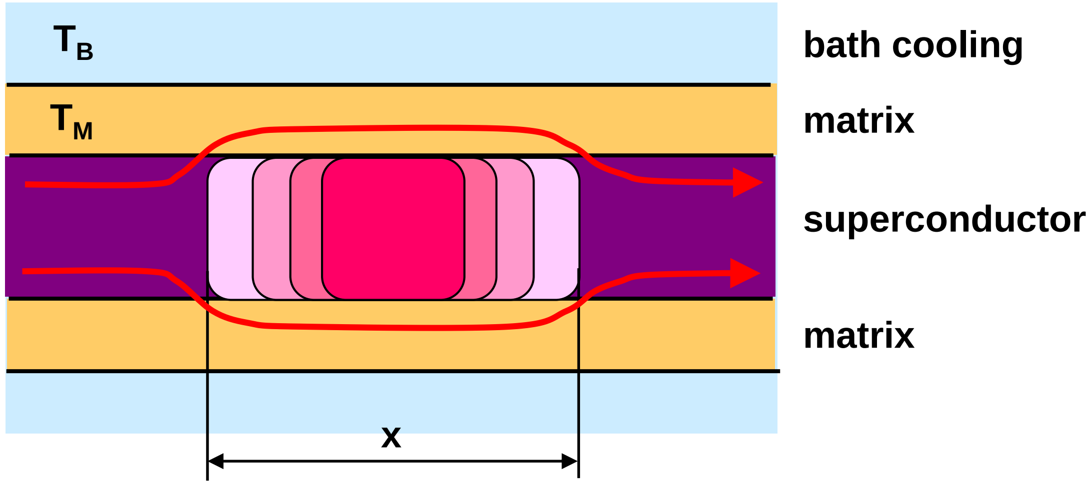
Data from W.Stautner – "Cooling systems for HTS equipment – overview and critical assessment", IWC-HTS 2015, Matsue, Japan

→Availability of specific industrial cooling technology paves the way for application!
Let's look at the next area...

Stability



Stability – wires in magnets



x: regime of Joule heating by normal conducting matrix

Heat generation in matrix:

$$Q_{Joule} = \frac{I^2 \rho_M \, x}{A_M}$$

Heat transferred to bath along circumference u_{MB}:

$$Q_B = \alpha_{MB} \, (T_M - T_B) \, A_{MB} \ mit \ A_{MB} = u_{MB} \, x$$

No extension of normal zone if

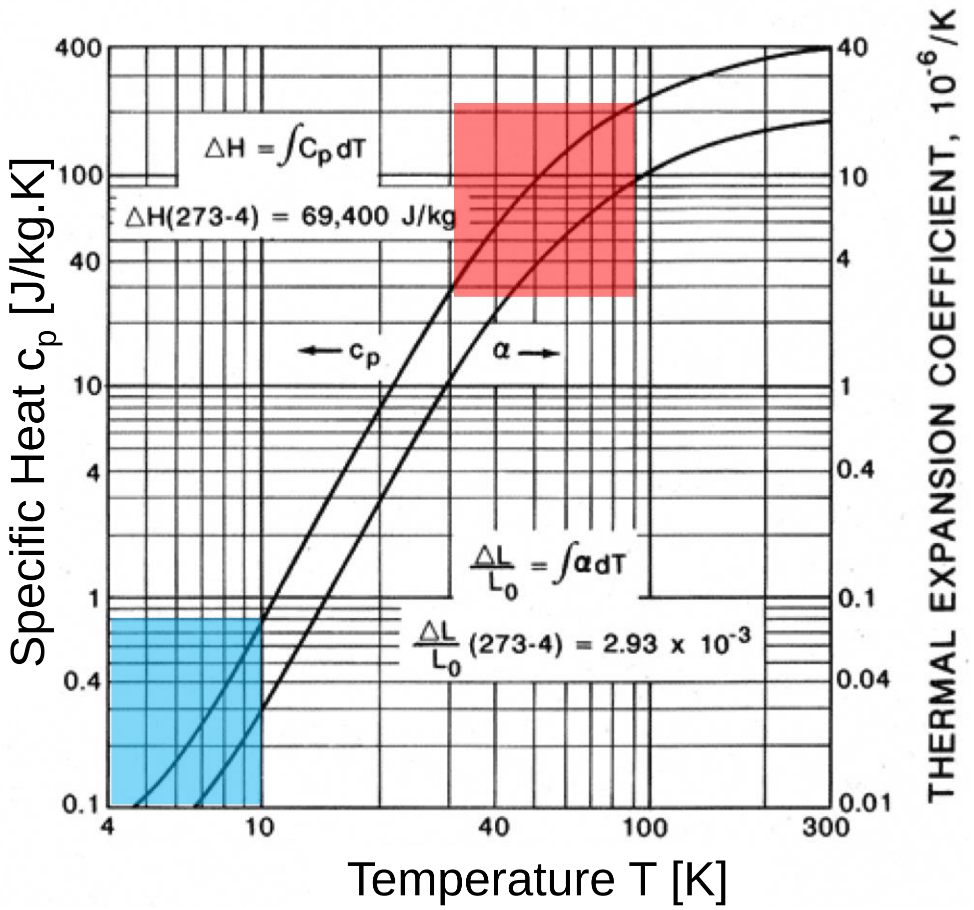
$$Q_{Joule} < Q_B \text{ and } T_M < T_C$$

Thus (Stekly parameter defining stability):

$$\alpha_{st} = \frac{Q_{Joule}}{Q_B} = \frac{I^2 \rho_M}{A_M u_{MB} \alpha_{MB} (T_C(B, j_{SL}) - T_B)} < 1$$

Bath cooling and heat transfer areas have to be designed carefully.
Let‘s compare the situation with applications in energy technology...

Stability



Low/ „high“ temperature aspects (Cu)

- T< 10 K: cp <0.8 J/kg.K
- T> 30 K: cp=30…200 J/kg.K

$$\frac{dT}{dQ} = \frac{1}{m \, c_p}$$

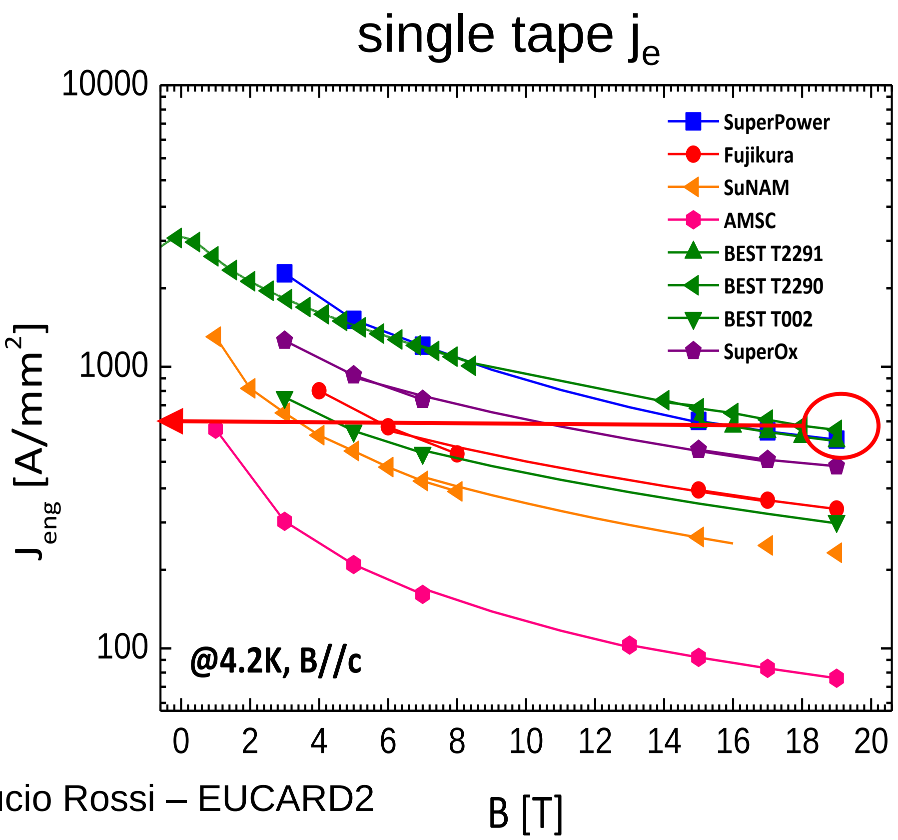
$$\frac{dT}{dQ} = (30 \ldots 200) \, \frac{dT}{dQ}$$

Source: C.A. Thompson, W. M. Manganaro and F.R. Fickett, NIST, Boulder, CO, July 1990.

„Heat tolerance“ increases dramatically for higher temperatures.
Let‘s look at the next area...

Amperage

Amperage – HTS accelerator dipole



Lucio Rossi – EUCARD2

Accelerator dipoles require:

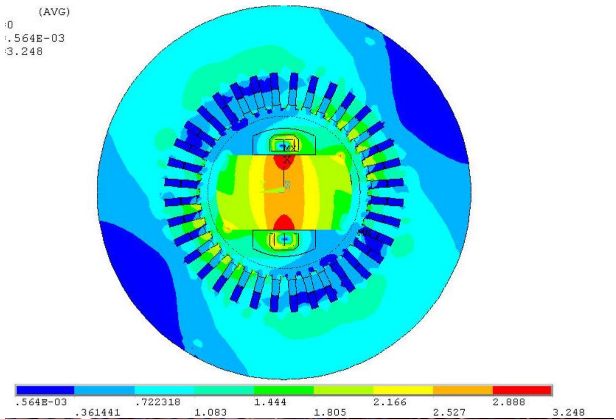
- overall current density j_e>400 A/mm² at 20 T, 4.2 K
- total current I=10...20 kA

Furthermore:

- homogeneity of magnetic field
- minimizing magnetization effects

High currents and homogeneity in field/ magnetization effects will ask for HTS stranded conductors. This holds not only for accelerators, but also for Energy applications...

Amperage – energy applications

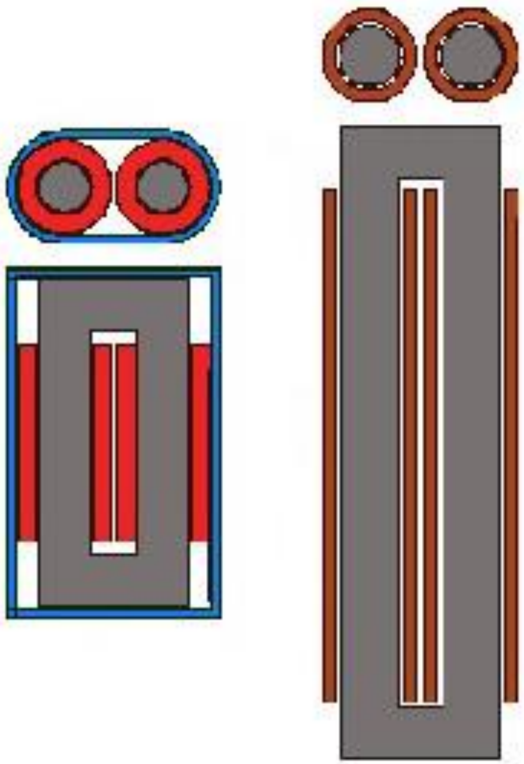


Dynamics spec. of turbo generators:

- Excitation currents in the range of kA (compatible to Cu-based design)
- single HTS-tape: ≈300 A
- Grid codes require short response time (determined by inductance, number of field winding turns)
- single HTS-tape: 3000 turns → 9 s
- Roebel-conductor: <300 turns → < 1 s

High currents/ low inductances/ transients might require HTS stranded conductors.
This holds not only for turbo generators, but also for...

Amperage – energy applications



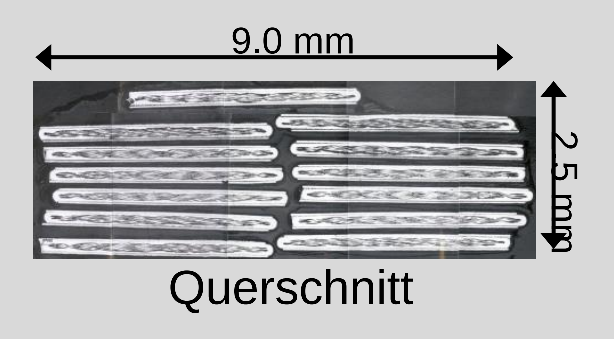
Aspects on transformers:

- High current winding in range of kA
  (compatible to Cu-based design)
- single HTS-tape: ≈300 A
- minimizing ac-loss requires transposed conductor

High currents/ low ac-loss require HTS stranded conductors.
Necessity clear, what‘s already on the table?

Amperage – energy applications

KIT Karlsruhe Institute of Technology

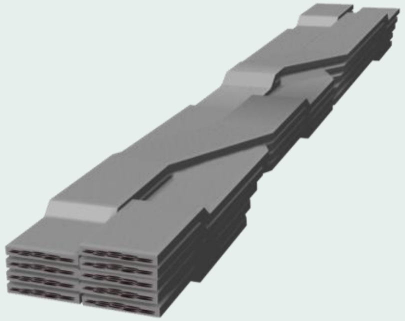


1G-HTS Roebel-conductor; cross section

1G-HTS Roebel-conductor sample

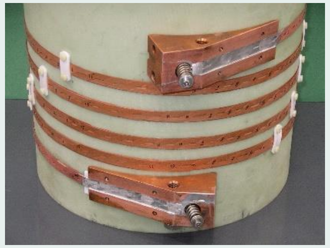
1G-HTS Roebel-conductor Storage spool (160 m)

Demo 1G-HTS-Roebel coil



2G-HTS Roebel-conductor

2G-HTS Roebel-conductor sample

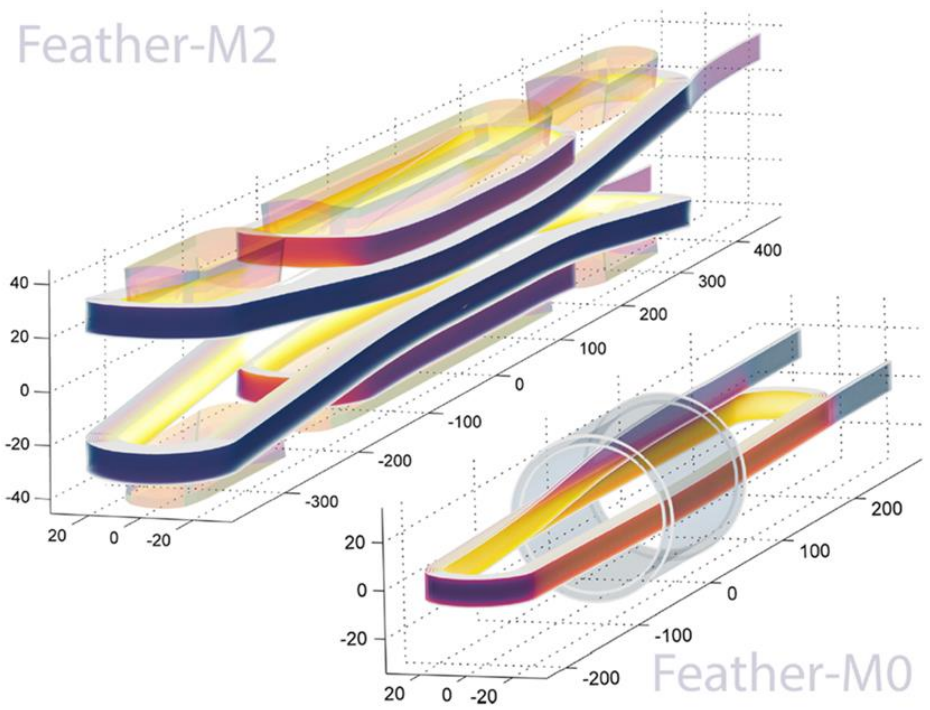


2G-HTS Roebel-conductor on drum

2G-HTS Roebel-racetrack coil (1.5 m x 1 m)

Quite a history and experience in HTS Roebel conductors and windings in industry.
How about the situation in accelerators?

Amperage - accelerators



Current, magnetization, field quality require stranded HTS conductor (different to energy applications)
How to get the high amperage into the system?

Amperage creates „common challenges“

9x4 stacks of
7 single 1G-HTS tapes

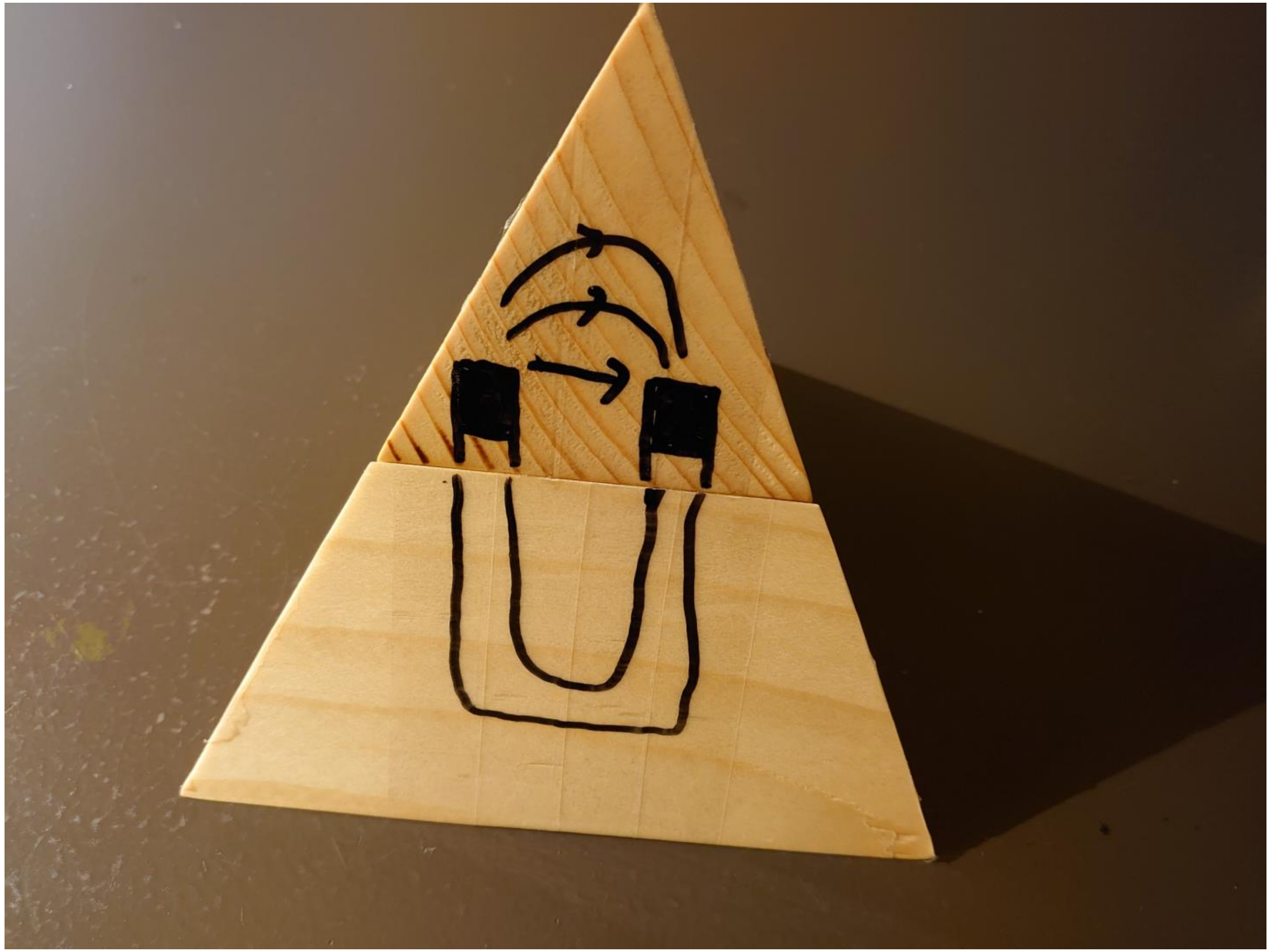
(Courtesy of CERN)

Example for „common challenge“:

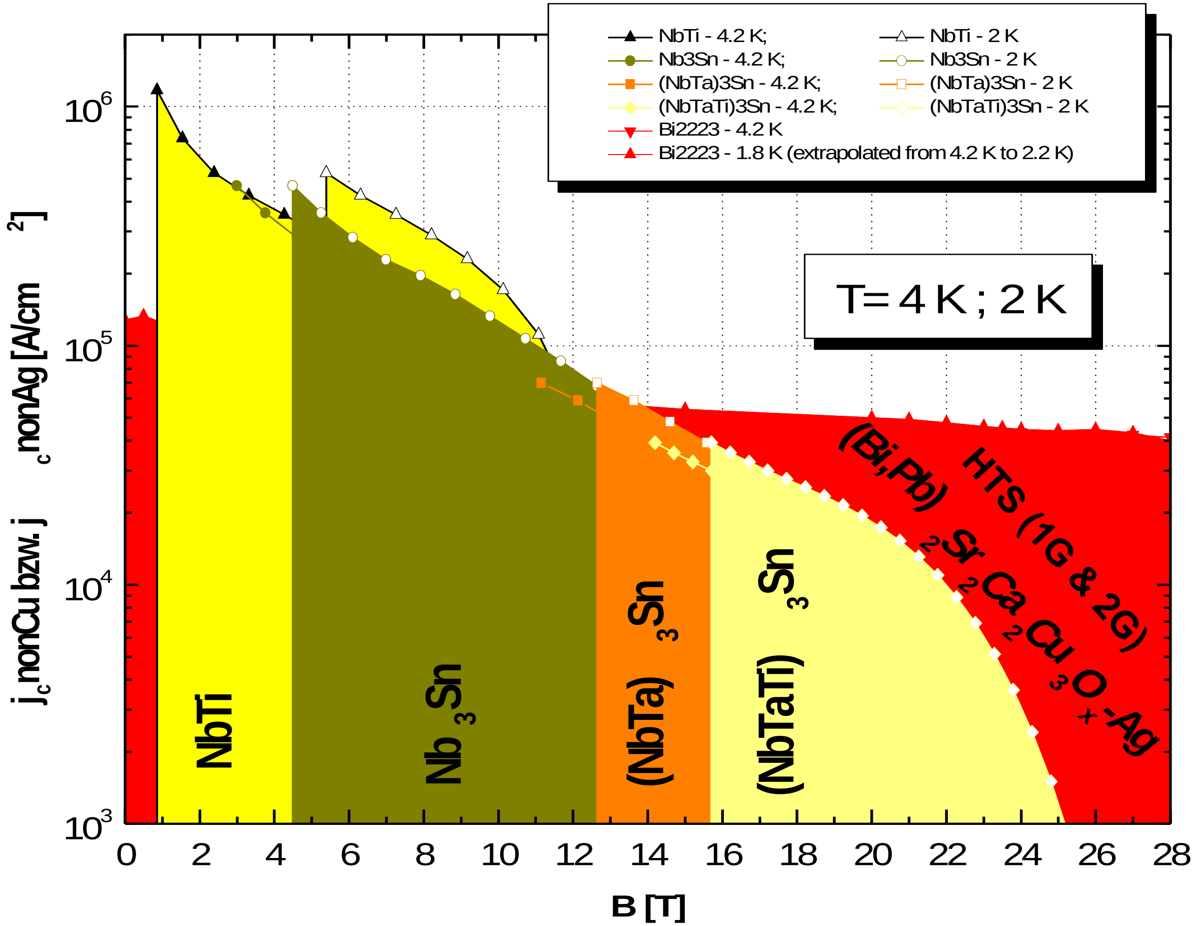
- 13 kA HTS current leads for LHC
- Energy applications will require high-amperage
  (ac, multi-phase) current leads, too

Current leads are a common challenge and new approaches highly welcome.
How about the magnetic field produced by such high currents? The next area...

Magnetic flux density



Magnetic flux density – low T applications



T≤ 4.2 K

- The higher the magnetic field B,
  the more complex the superconductor
  (& production)

High currents in high magnetic fields are paid with complexity.
How about B-requirements in industrial applications? What‘s the driver?

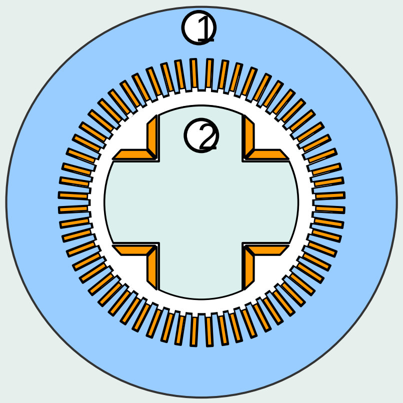
Magnetic flux density - NMR magnets

- NMR magnets are a driver in industry for high magnetic fields
- Push on wire development
- Most advanced systems have to use 2G-HTS
- 1.2 GHz (28.2 T) is ready to come

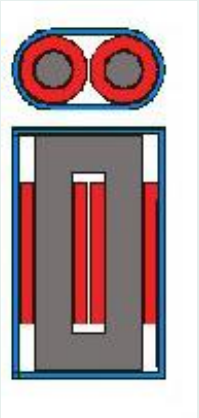
- but: low (wire) volume market

NMR magnets are demanding, but a kind of a „premium application segment“.
How about B-requirements in other industrial applications? What are the keys?

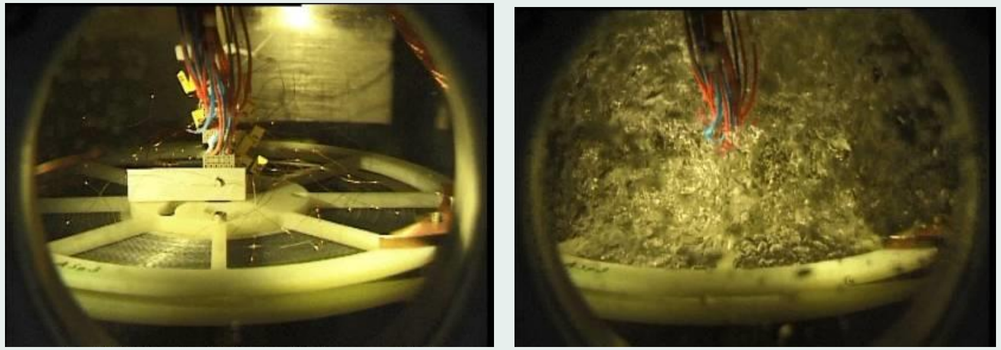
Magnetic flux density – energy applications



Rotating Machine



Transformer



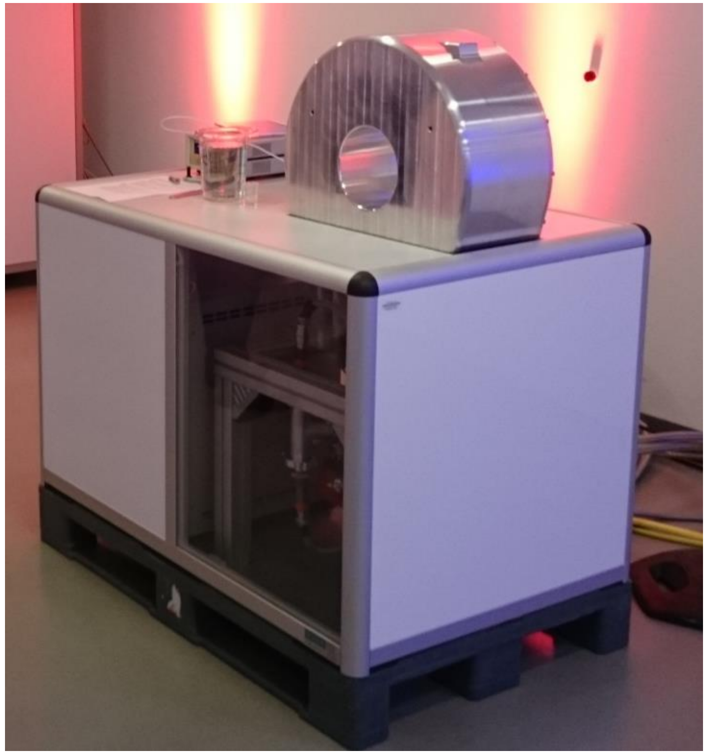
Switching Module for sc. Fault Current Limiter

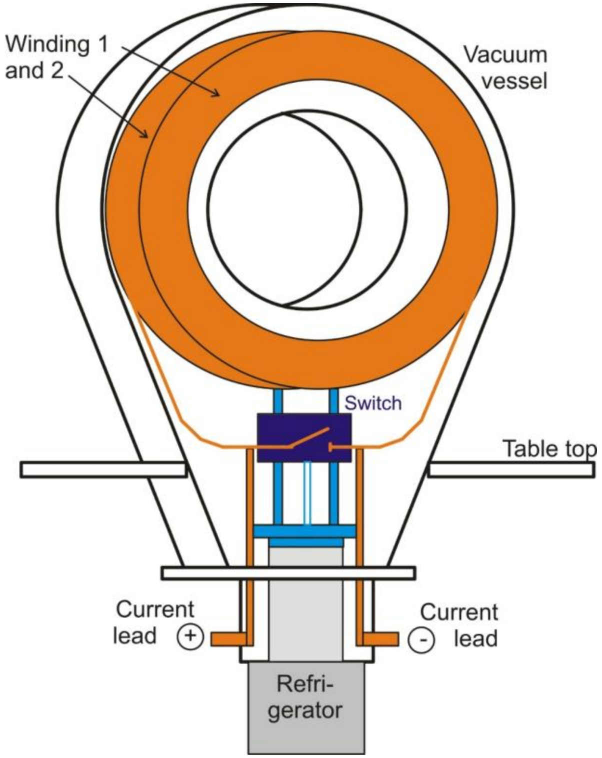
- HTS more expansive than iron
- Use iron to reduce HTS amount
- Saturation of iron at ≈2 T
- Maximum meaningful field at HTS-tape: ≈4 T

- When HTS beneficial in €/T, than ironless/ ironfree applications will become viable
  →innovative device designs needed
- some HTS-applications depict low fields only.

Iron limits high field ambitions in industry applications (for now)
But there are exceptions to that, not only SFCL and power cables...

Special MRI magnets (demonstrator 2G-HTS)





Demo-magnet

- Design field 1.4 T @ ≈25 K
- 2G-HTS
- Persistent mode operation (500 h)
- Switch
- Single GM coldhead for all components.
  cooling power: 1x 100W@25 K
- MLI, but no shield
- Aux: power, cooling water

HTS enable powerful plug-and-play magnets – robust high magnetic fields as a table-top.
Ready to prepare sum-up...

Applications vs. requirements

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	Cable	FCL	Trans-former	Magnet HEP, HF	Magnet MRI	Magnet NMR	Wind Geno	Hydro Geno	Turbo Geno	eAir Geno
Bread Down Voltage	+++	+++	++	+	+	++	O	O	+	+
Current leads	+	++	++	+	+	+	++	++	+	O
AC-loss	++	+	+++	O	+	+	+	+	++	+
Mechanical robustness	O	+	O	+++	+	+++	+	+	+++	+++
Total heat removal	+++	+	++	+	+	+	++	++	++	O
Thermal stability	+	O	O	++	+++	+++	+	+	+	O
Currents	++	++	+++	+++	++	++	++	++	+++	+++
Magn.fields	O	O	+	+++	++	+++	++	++	++	+++

LTS dominated (Magnet HEP, HF; Magnet MRI; Magnet NMR)

preferably by HTS (red entries)

Conclusion

- Cooling, stability, amperage and high magnetic field are important for HTS applications in accelerators and in industry – with varying aspects.
- More intense exchange of experts in accelerators and in industry would speed-up developments by
  - exchange of lessons learned
  - creating easily "critical mass" to push developments
- Other common challenges:
  - insulation/ voltages
  - mechanical forces
  - etc.
- Further improvement of HTS performance might enable concepts for established devices (e.g. ironfree).

FLUTE short-pulse accelerator test facility

Technical platforms at KIT

- Accelerator test facilities (electron storage ring and short-pulse linac)
- Characterization facilities for superconducting magnets and insertion devices
- Cryogenics and cooling test facilities
- Superconducting magnet winding and impregnation laboratories
- Characterization facilities for permanent and normal conducting accelerator magnets
- Test stations for RF, microwave and pulsed power technology
- Test facility for energy systems and electrical networks
- Characterization facilities for materials development (HTS, surfaces)
- Fabrication and characterization facilities for nano- and micro technology
- Electronics interconnect and packaging center

The Accelerator Technology Platform (ATP) at KIT

The ATP is a central access-point to accelerator-relevant technologies and know-how at the Karlsruhe Institute of Technology (KIT). About 300 scientists and technical staff operate the infrastructure and pursue advanced research. ATP covers a wide range of technologies, from superconducting magnets and materials to high-throughput beam diagnostics and imaging. The technology facilities at KIT have been involved in various Research Infrastructure projects such as:

- BESSY
- Dafne
- ELBA/TELBE
- ESS
- European X-FEL
- FCC
- FLASH
- GSI Fair
- High-Luminosity LHC
- ATHENA
- IFMIF
- JT-60SA
- LHC
- SOLEIL

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Innovation success story

Bilfinger Noell and KIT: Brilliant light from in-series produced superconducting undulators

The Challenge
Today's and future light sources require industrial-grade, high-performance, flexible while compact and radiation-resistant insertion devices.

The Solution
With its industrial partner BilfingerNoell, KIT initiated the development of superconducting undulators from the laboratory to industrial in-series production. Access to KIT's magnet characterization facilities allows fast-turnaround prototyping and quality assurance.

The Benefits
Bilfinger Noell developed the technology for manufacturing superconducting undulators. The community profits from the availability of high-performance, industrial-grade x-ray light sources for storage rings and FEL as commercial products.


CASPER II cryogen-free superconducting magnet test stand


PICARD cryogenics test facility


Gyrotron test facility


COLDDIAG


TRANSFLOW transition flow facility


KARA accelerator test facility


TIMO model pump test facility for ITER


FCC-hh chamber prototype in KARA

Thank you – questions?