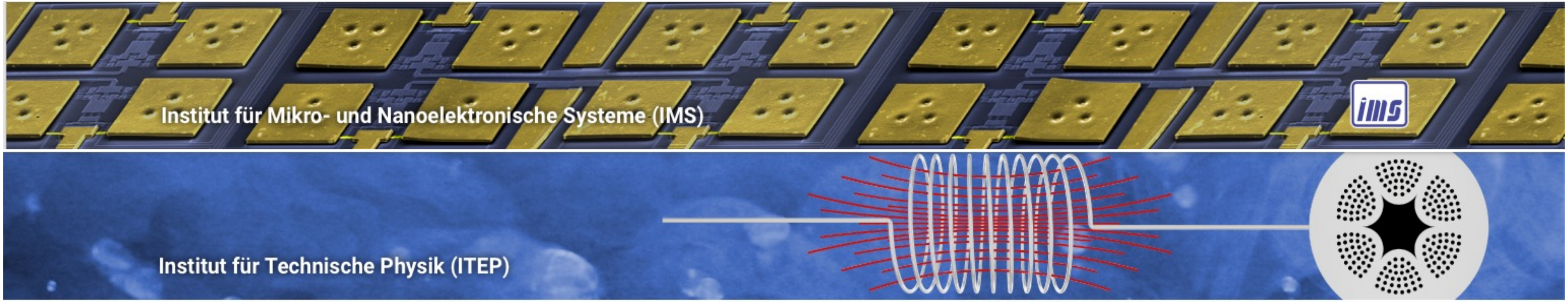
Superconductivity for Engineers

Prof. Dr. Sebastian Kempf, Prof. Dr. Bernhard Holzapfel

Summer term 2021



2 Superconducing Applications

2.1 General aspects

2.2 Magnet applications

2.3 Electronic applications

2.3.1 Biomedical applications

2.3.2 Field exploration in geology

2.3.3 Ultrasensitive microcalorimeters

2.4 Power applications

2.4.1 Fault Current limiter

2.4.2 Rotating machines (motor, generator)

2.4.3 Cables

General Aspects of Superconducting Applications

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Applications are based on :

- Dissipation free current flow in SCs (power applications)
- Macroscopic quantum effects in SCs (electronic applications)
- Highly non linear IV-curve of SC transition (power/electronic applications)

But :

- Refrigeration is needed (HT_c vs. LT_c)
- Costs ! Esp. HT_c´s are (still) expensive (important for power applications, „$/kAm“)
- Competition with well established technologies (important for electronics)

Real applications only if SC offers **unique** properties over existing technologies

General Aspects of Superconducting Applications

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- existing application,
- large volume

LT_c Magnets
(MRI, NMR, research)

- existing application,
- small volume

Special Applications
(cavities, current leads)

Electronics
(sensors, computing)

- demonstrated application,
- potential for very large volume

Electronics
(sensors, computing)

Magnet and Power Applications
(cable, FCL, rotating machines, magnets)

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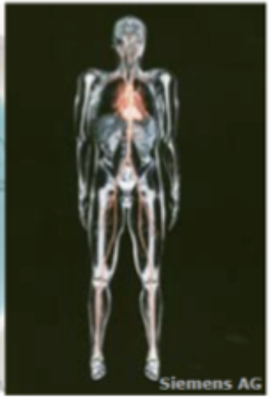
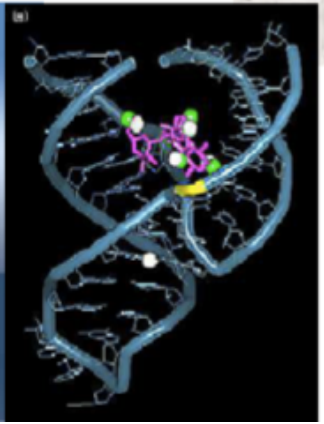
Existing Volume Applications of LTSC

Magnets for Medical and Analytical Applications

Medizintechnik

MRI Bildgebung
für weiches Gewebe
(Organe, Knorpel, Sehnen)
Weltmarkt > 3 Mrd € p.a.
> 3000 to NbTi p.a.





Analytik

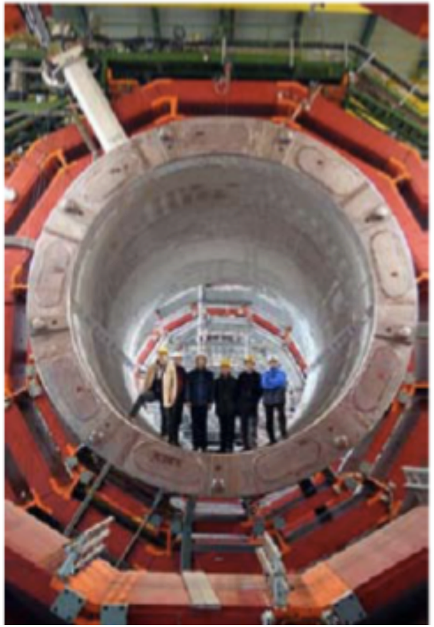
NMR Spektroskopie
Weltmarkt > 500 M€ p.a.
> 500 to Nb_3Sn p.a.

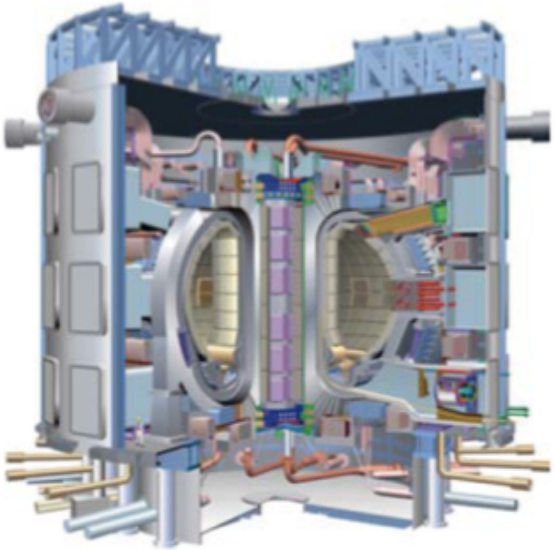
Existing Volume Applications of LTSC

Magnets for Large Scale Facilities

- Particle Accelerators
- Nuclear Fusion

Large Hadron Collider, LHC at CERN





International Thermonuclear Experimental Reactor, ITER

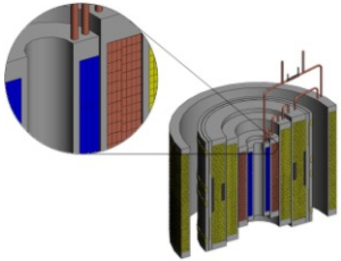
> 500 to Nb_3Sn

ITER Kabel

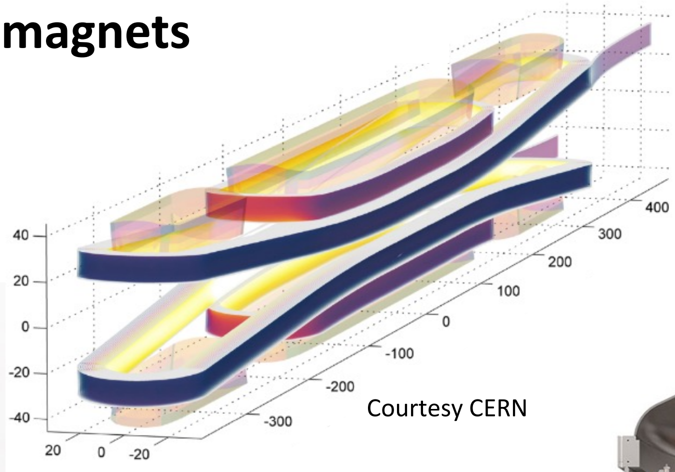
Upcoming applications of HTSC magnets

Ultra high field magnets beyond LTS

- **UHF NMR**



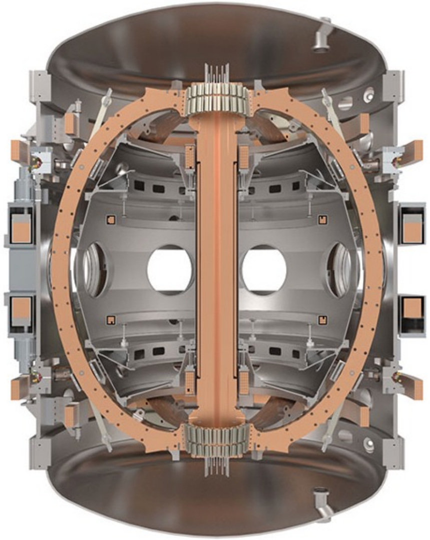
1.2 GHz ≙ 28.2 T
HTSC insert coil



Courtesy CERN

- **Next generation dipole magnets for particle accelerators (LHC, FCC)**

- **Compact nuclear fusion (e.g. tokamak energy)**



https://www.bruker.com/en/products-and-solutions/mr/nmr/ascend-ghz-class.html

https://www.tokamakenergy.co.uk/st40/

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Electronic Applications (SQUIDS)

- **B.D. Josephson** in 1962
  (nobel price with Esaki and Giaever in 1973)

→ Cooper pairs can tunnel through thin insulating barrier

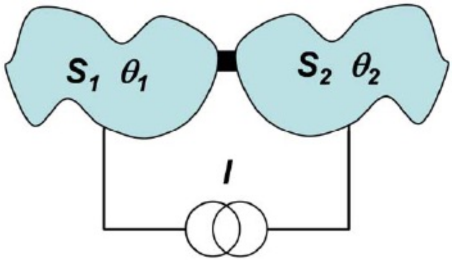
expectation:

- tunneling probability for pairs ≈ $(|T|^2)^2$

  → extremely small ≈ $(10^{-4})^2$

Josephson:

- tunneling probability for pairs ≈ $|T|^2$
- coherent tunneling of pairs (*tunneling of macroscopic wave function*



$$\psi(\mathbf{r}, t) = \psi_0(\mathbf{r}, t)\, e^{i\theta(\mathbf{r}, t)}$$

→ finite supercurrent at zero applied voltage

→ oscillation of supercurrent at constant applied voltage

} *Josephson effects*

1. Josephson equation: $J_s(\varphi) = J_c \sin\varphi$

- applications: - Josephson voltage standard
  - microwave sources

2. Josephson equation: $\frac{\partial\varphi}{\partial t} = \frac{2\pi}{\Phi_0} \int_1^2 \mathbf{E}(\mathbf{r}, t) \cdot d\mathbf{l}$

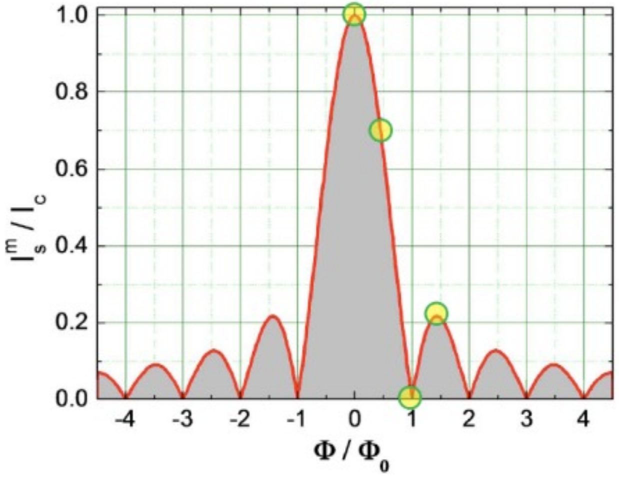
voltage drop

→ voltage controlled oscillator

Fraunhofer Pattern

- external magnetic field
  → **spatial** change of gauge invariant phase difference
  → **spatial** interference of macroscopic wave functions in JJ

→ **Fraunhofer diffraction pattern:**



Fraunhofer diffraction pattern:

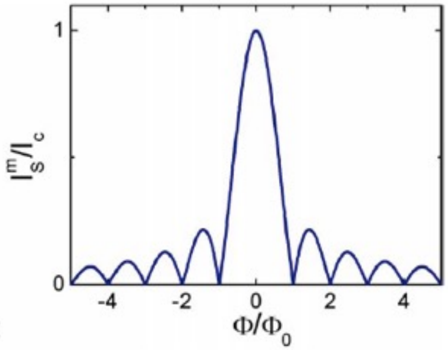
$$I_s^m(\Phi) = I_c \left| \frac{\sin \frac{\pi\Phi}{\Phi_0}}{\frac{\pi\Phi}{\Phi_0}} \right|$$

Electronic Applications (SQUIDS)

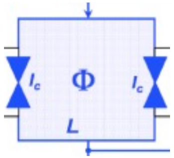
Superconducting Quantum Interference Devices = SQUID

single Josephson junction as can be used as *magnetic field sensor*: $I_s^m = I_s^m(B)$

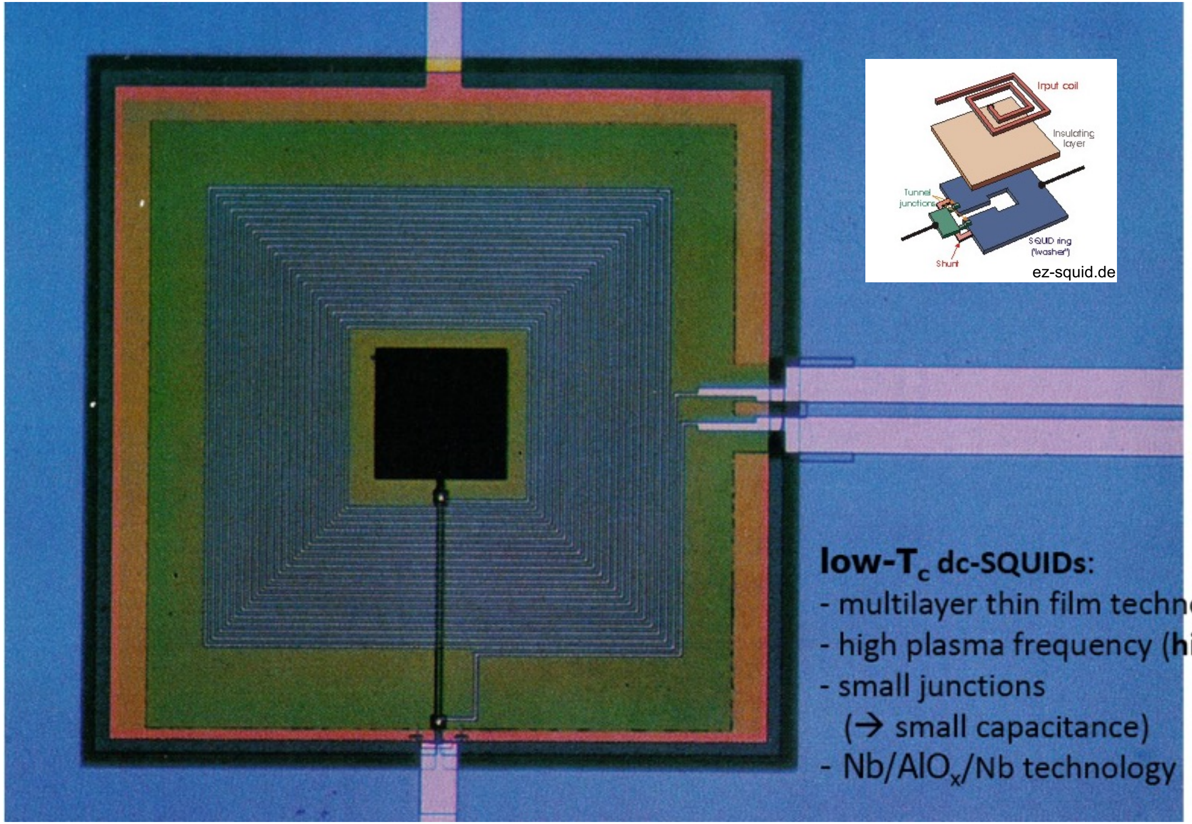
- **sensitivity**: $dI_s/d\Phi \approx I_s^m/\Phi_0 = I_s^m/B_0 t_B L$
→ increase $t_B L$ to increase sensitivity



- superconducting **loop** with one or more Josephson junctic
  → relevant **area**: loop area
- dual or multi beam interference:
  → **Superconducting Quantum Interference Devices** (SQUIDs)
- relevant physics:
  → **flux quantization** in superconducting loops and **Josephson effect**
- **SQUIDs = most sensitive** detectors for magnetic **flux**
- can detect every quantity that can be converted into magnetic flux:
  → magnetic field, field gradient, current, voltage, displacement, …
- most relevant types of SQUIDs:
  → **direct current (dc)** and **radio frequency (rf) SQUIDs**



dc-squid example



low-T_c dc-SQUIDs:
- multilayer thin film technology
- high plasma frequency (**high J_c**)
- small junctions
  (→ small capacitance)
- $Nb/AlO_x/Nb$ technology

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Magnetometer for Biomagnetic Signals

biomagnetic method:

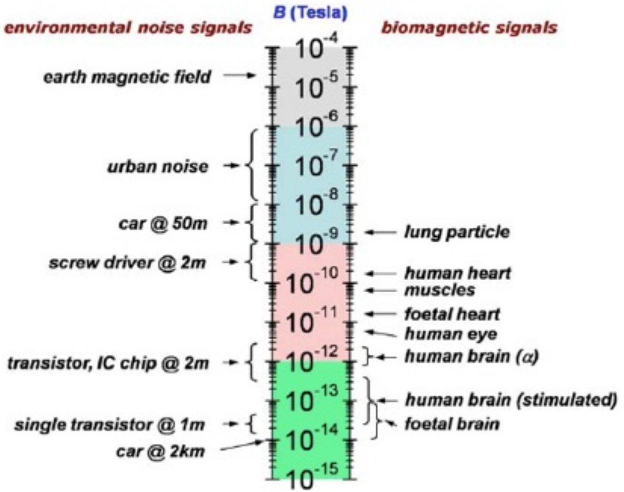
- non-invasive detection of magnetic signals from human body

biomagnetic imaging:

- field map of heart / brain activity → source location
  (only simple volume conductor models are needed)

MEG: magneto**encephalo**graphy

MCG: magneto**cardio**graphy



extremely small fields:

brain: 100 fT (one neuron: 0.1 fT), **heart**: 10 pT

→ **highly sensitive** SQUID magnetometers

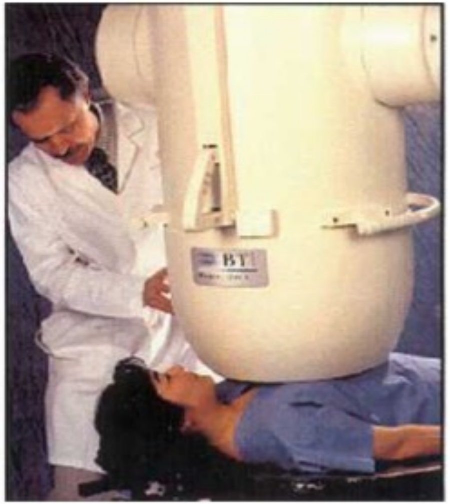
→ low 1/f noise

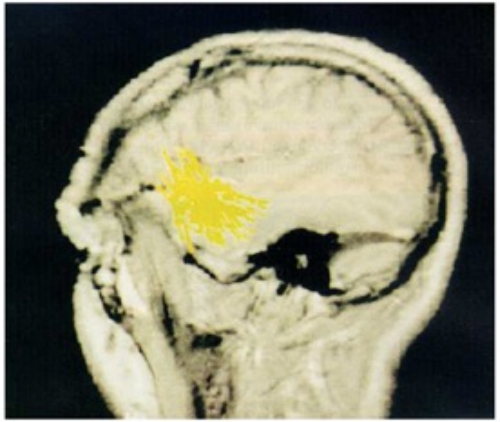
spatial and **temporal** magnetic field distribution:

array of SQUID sensors (**multichannel systems**)

(or scan single SQUID)

Biomagnetism





signal reconstruction

- current distribution cannot be calculated from measured field distribution

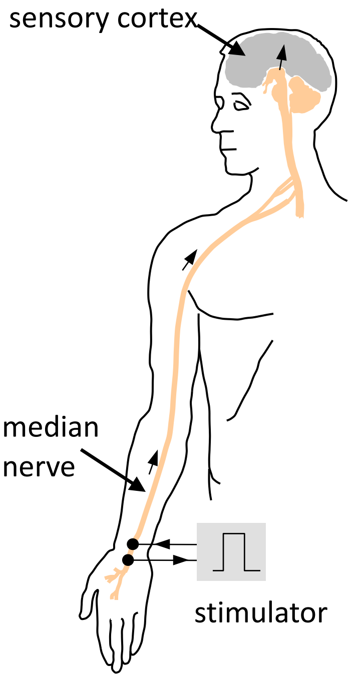
→ *inverse problem has no unique solution*

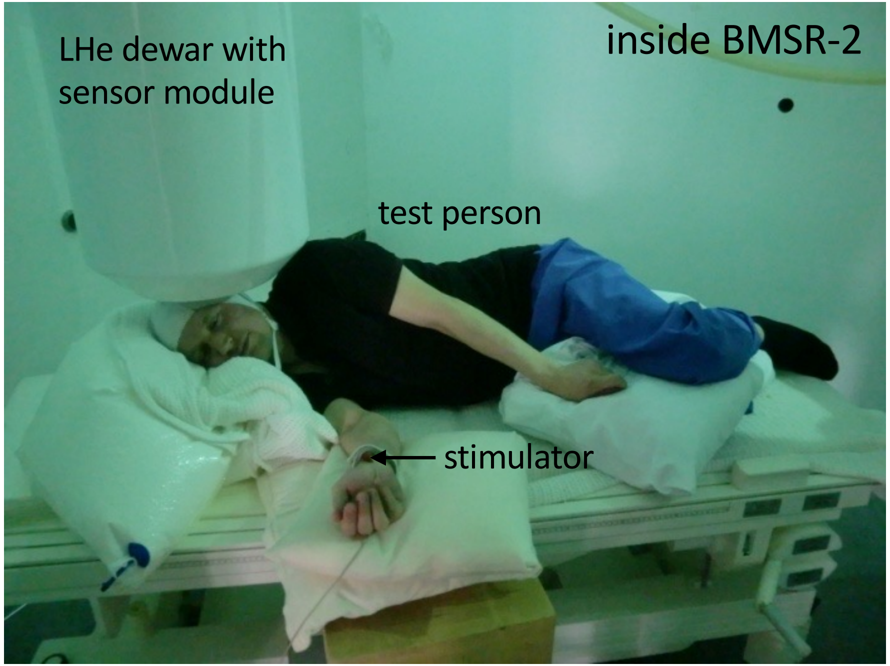
→ **model assumptions**

→ based on elementary current dipoles (= short localized conductor segments & volume backflow)

Magnetoencephalography

somatosensory evoked brain activity after electric stimulation of median nerve





courtesy of J. Beyer, PTB Berlin

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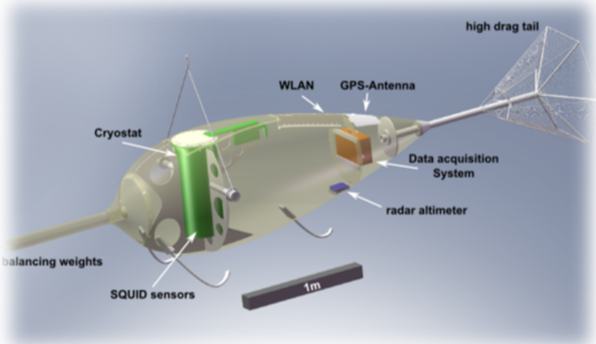
JeSSY STAR – FTMG instruments and platforms

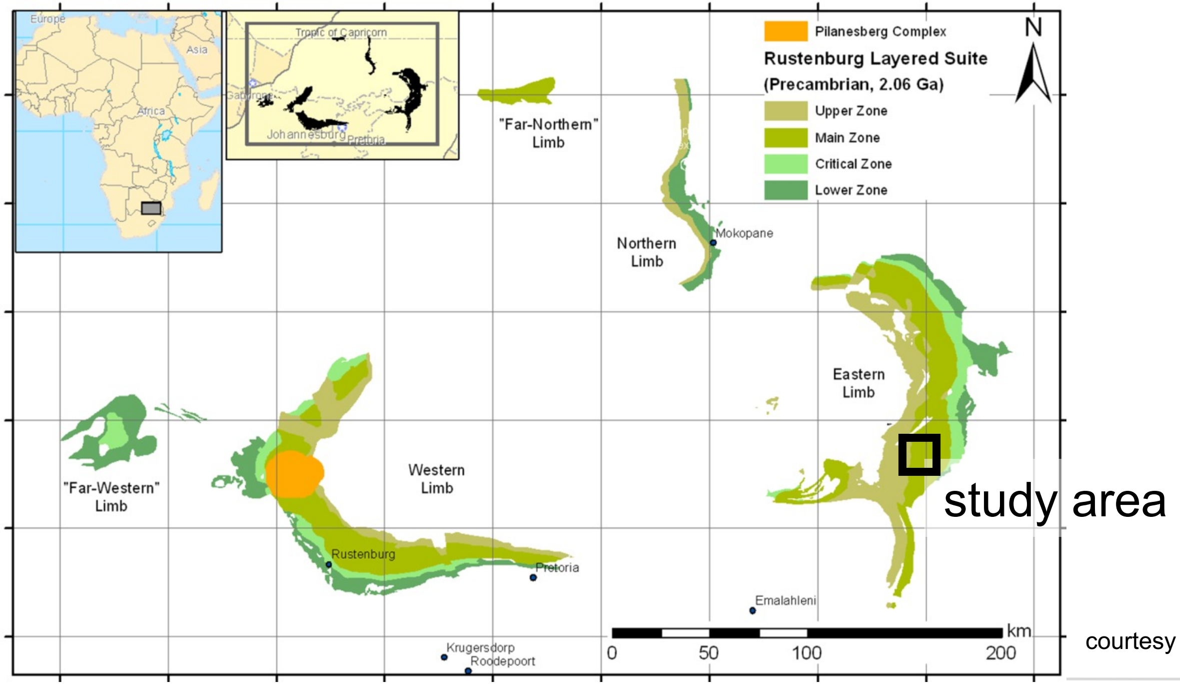


submarine

courtesy of R. Stolz, IPHT Jena

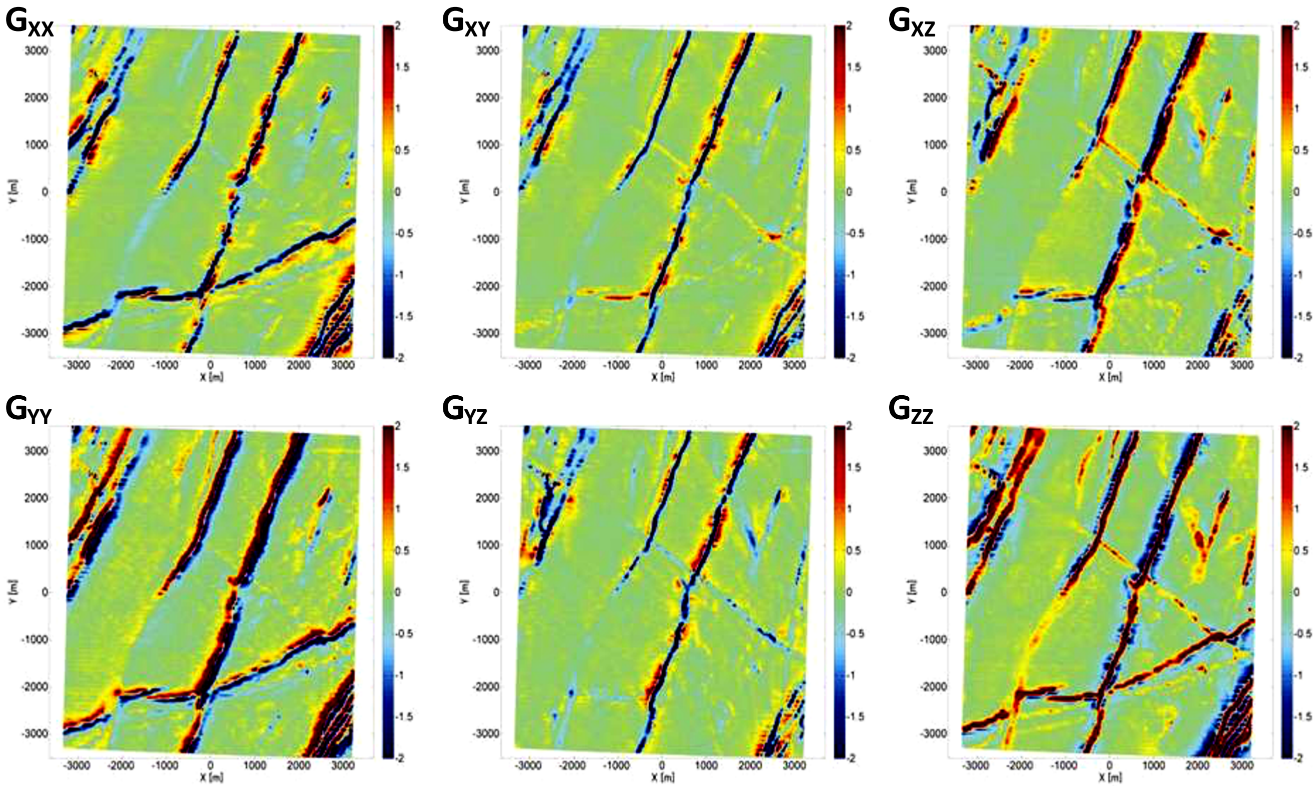
Survey in Republic of South Africa

- airborne operation survey for Anglo American Platinum in September 2006,
- focus: dyke deposits (platinum and chromatite layers) inside Bushveld Igneous Complex
- **selection of area: location of Merensky Reef and UG2 chromatite layer, *dolerite dyke swarms* (Holland 2014)**



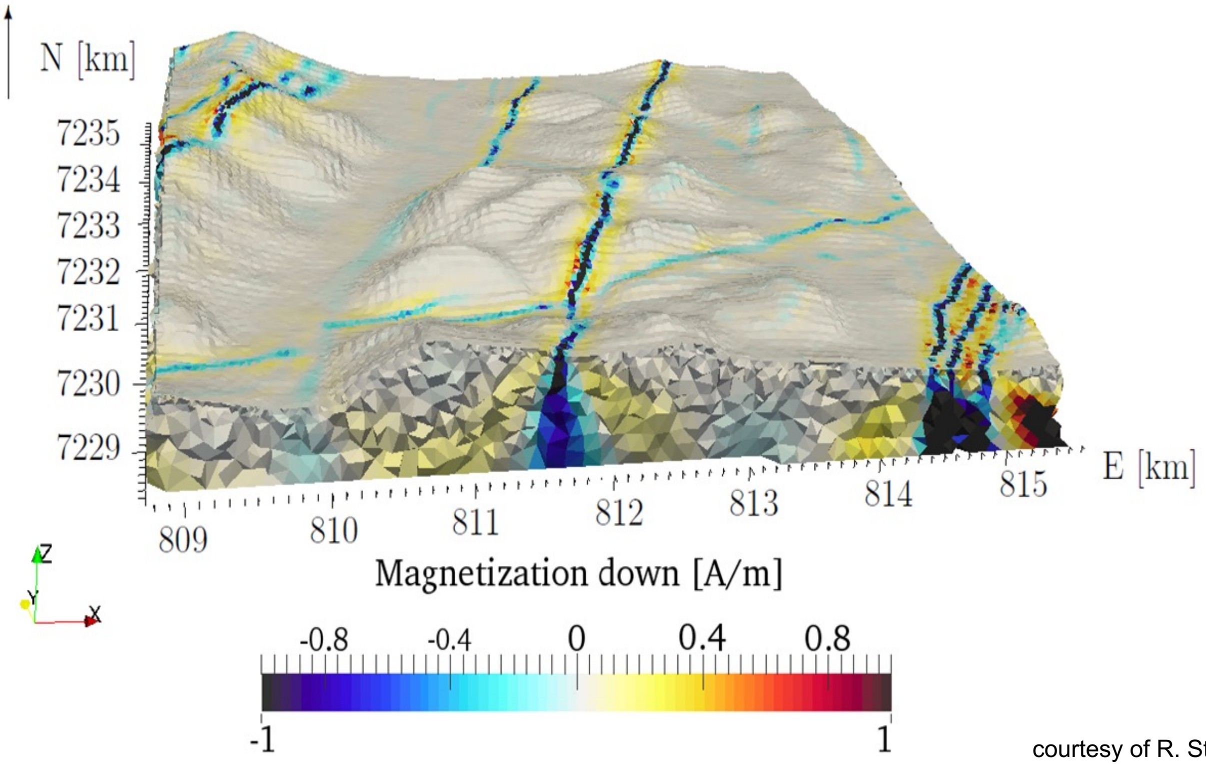
courtesy of R. Stolz, IPHT Jena

FTMG results – new quality of tensor data



courtesy of R. Stolz, IPHT Jena

3D inversion results



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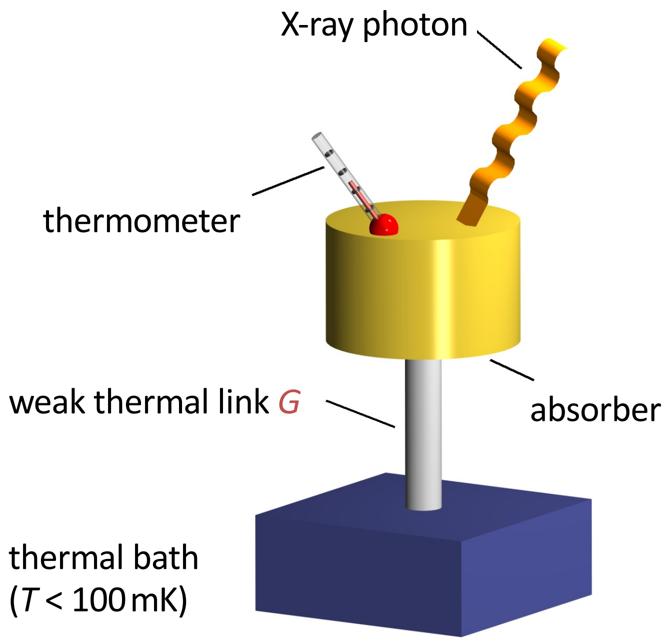
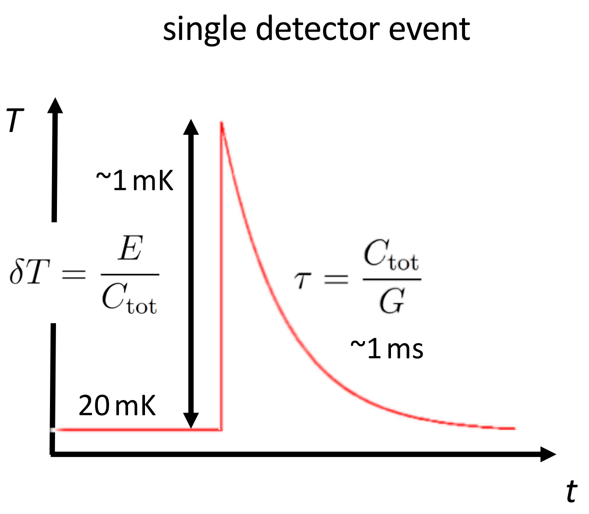
Concept of a cryogenic microcalorimeter





$$\delta T = \frac{E}{C_{\mathrm{tot}}} \qquad \tau = \frac{C_{\mathrm{tot}}}{G}$$

operation at low temperature ($T < 0.1$ K):

- small specific heat
- large temperature change
- small thermal noise

Thermometer concepts

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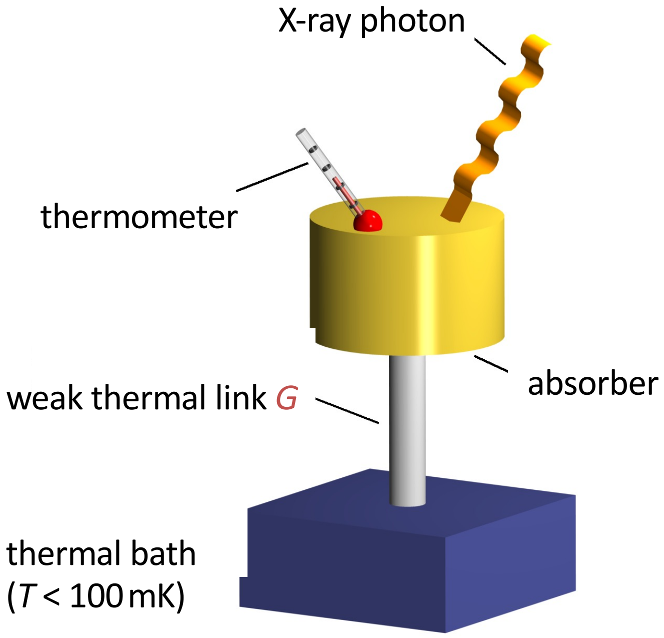
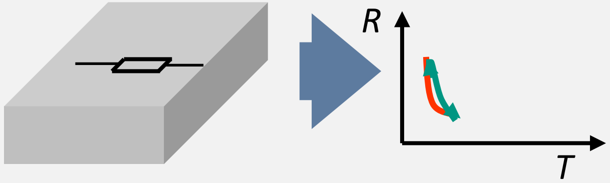
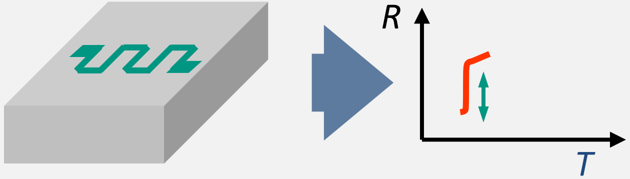


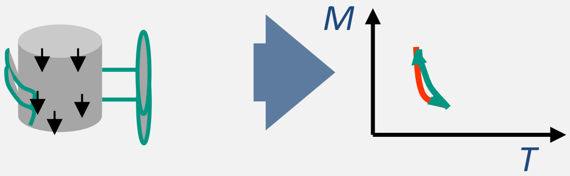
resistance of highly doped semiconductors



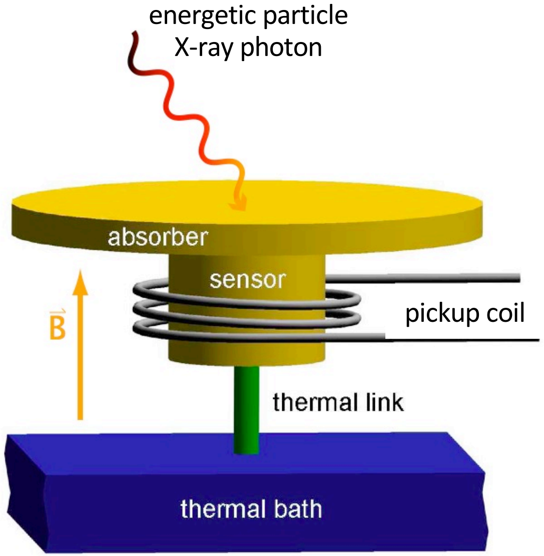
resistance at superconducting transition (TES)



magnetization of paramagnetic material



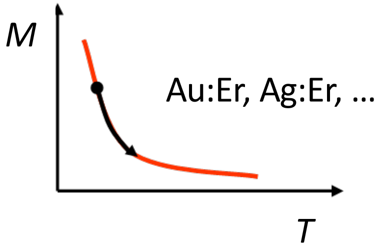
Metallic magnetic calorimeters



main difference to resistive thermometers:

- no power dissipation in the sensor
- no galvanic contact to readout circuit

paramagnetic sensor:



signal size:

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{ges}}}$$

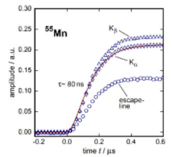
energy resolution:

$$\Delta E_{\mathrm{FWHM}} \simeq 2{,}36\sqrt{4k_{\mathrm{B}}C_{\mathrm{Abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$$

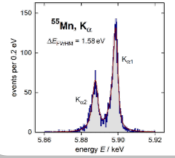
Key features of metallic magnetic calorimeters

metallic magnetic calorimeters

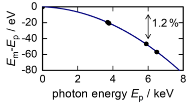
fast signal rise time



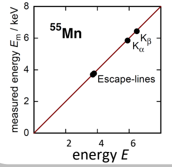
outstanding energy resolution



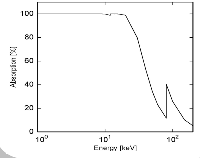
excellent linearity



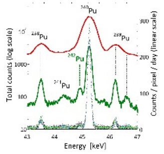
easy energy calibration



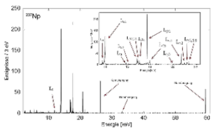
high quantum efficiency



reproducible detector



large energy bandwidth



Applications of metallic magnetic calorimeters

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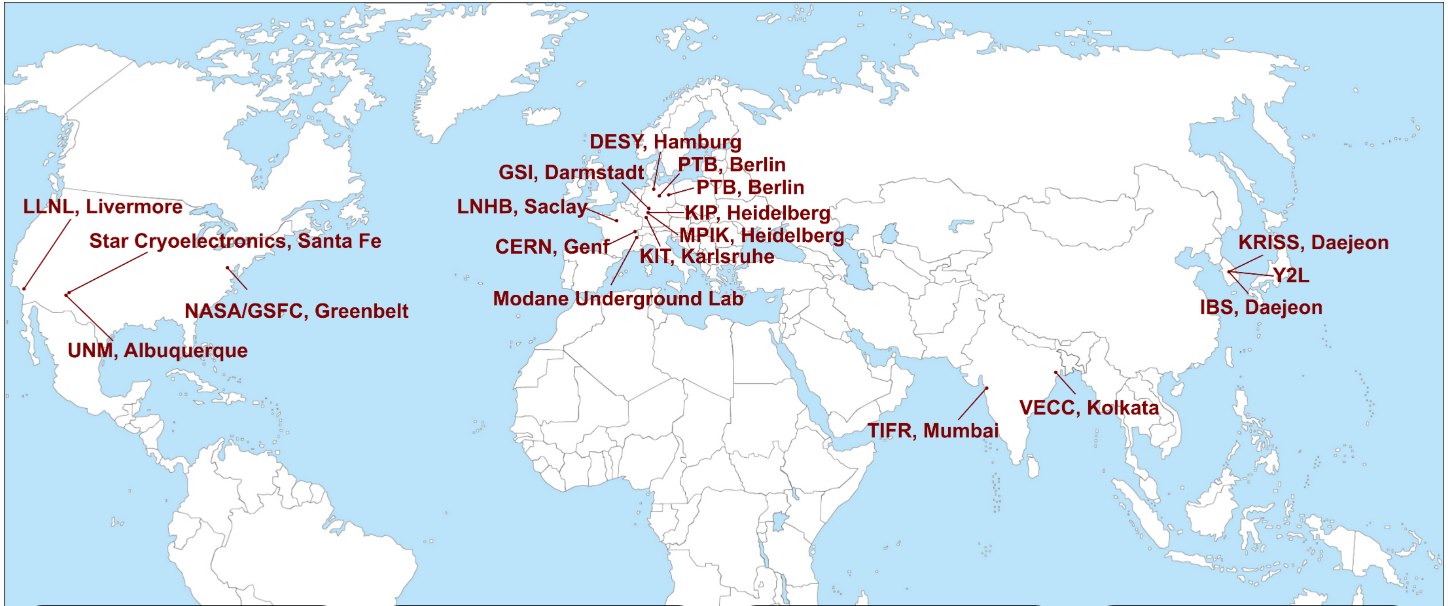

atomic/molecular physics
- X-ray spectroscopy
- highly-charged ions
- molecular ion chemistry
- Lamb-Shift measurements
- X-ray polarimetry

nuclear physics
- nuclear isomer state of ^{229}Th
- nuclear forensics
- nuclear safeguards
- gamma spectroscopy

metrology
- α–, β–, and γ–spectroscopy
- Q-value measurements
- measurements of EC spectra

particle physics
- neutrino mass determination
- search for $0\nu\beta\beta$
- dark matter searches

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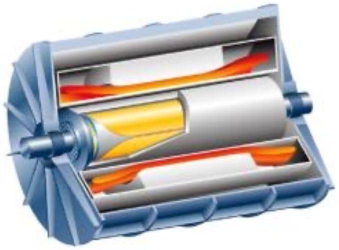
Power Applications

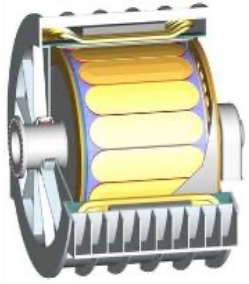
Generator



Cable

Transformer

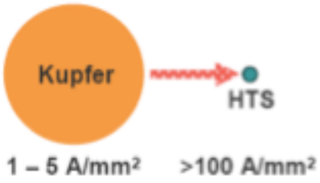
Motor



Advantages of HTSC for power applications

High power density
more
smaller
lighter

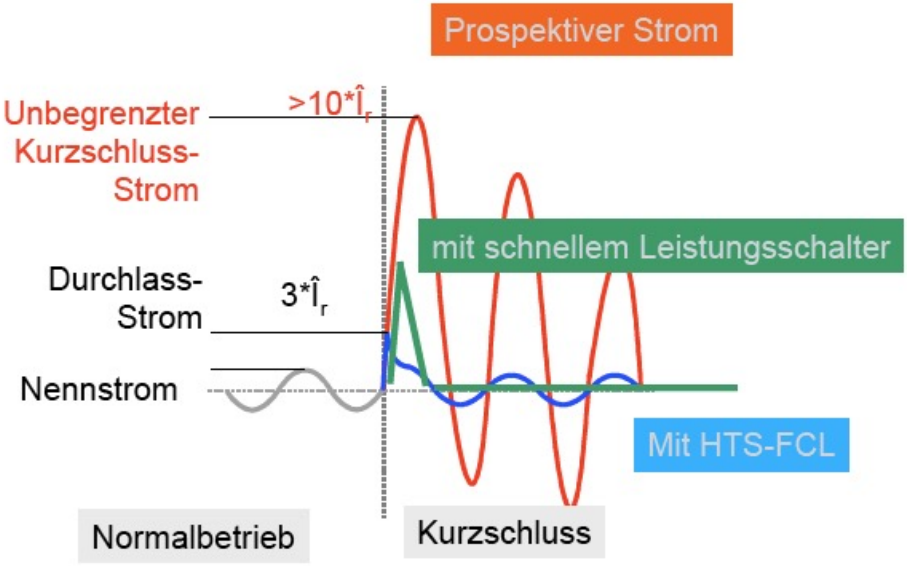
Low el. losses
higher efficiency

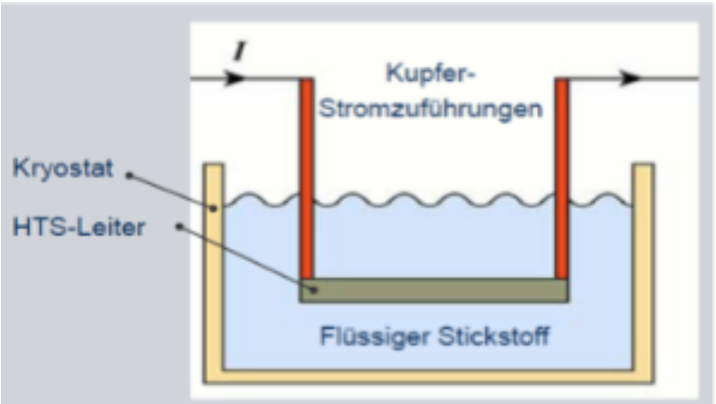


„green"
no oil cooling
fire safe

Fault Current Limiter (FCL)

- Fast SC - NC transition when overcurrent appears
- Leads to current limitation
- Fast, „self-healing“, limitation not cut-off, saves transformers





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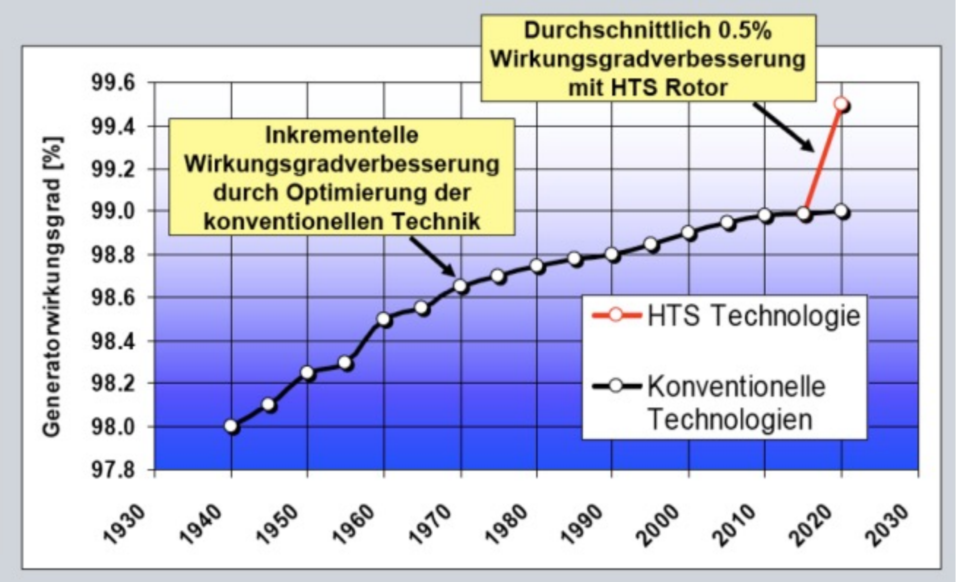
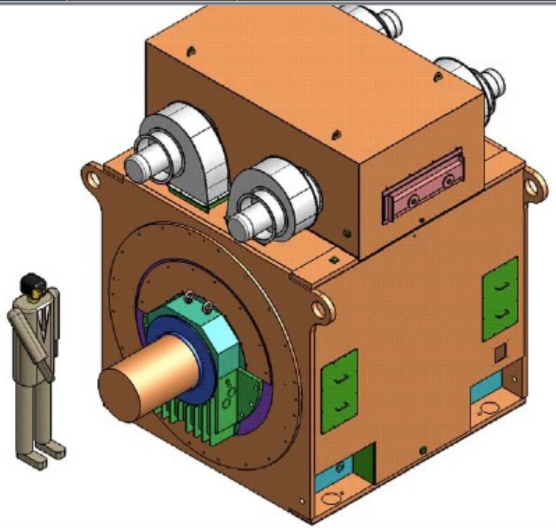
Generators and Motors



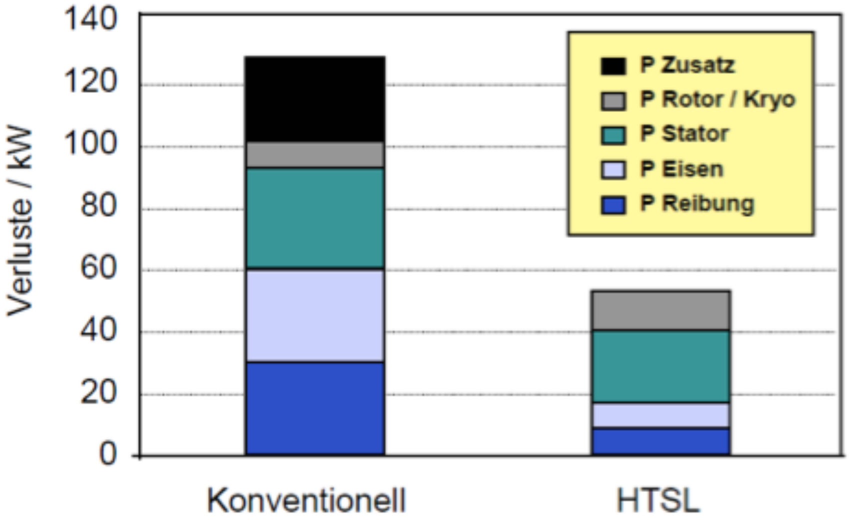
4MW Generator and Motor

	HTS	Comparison to conventional syn. machine
Power	4 MW	Same
Torque	> 300 kNm	Same
Weight	< 40 to	Reduction by more than 1/3
Volume	< 40 m^3	Reduction by more than 1/3
Efficiency	> 96%	< 95% for conventional



HTSC Generators for ships

4 MW Synchrongenerator



Verluste reduziert um mehr als 50 %

Bild: Siemens

Wirkungsgrad bei Nennbetrieb

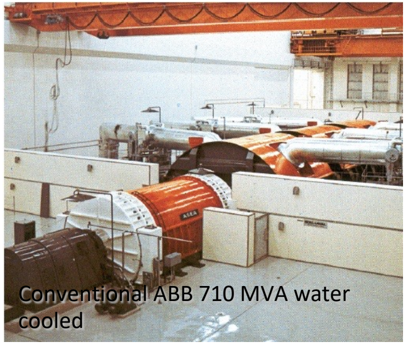
cos φ	Konv.	HTSL
0,8	96,1 %	98,4
1,0	97 %	98,7

+ significant mass- and space reduction

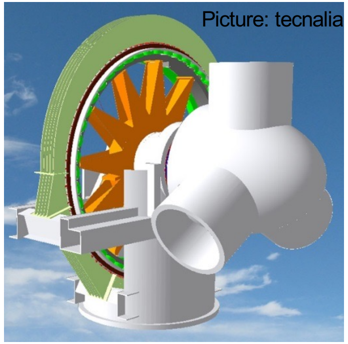
Quelle: Klaus et. al. „Design Challenges and Benefits of HTS Synchronous Machines
IEEE Trans. Appl. Supercond. 2007

Opportunities of Superconducting Machines

Power Generators



Wind Generators

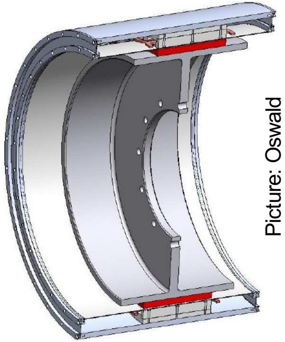


Hydro Generators

Picture: GE (Converteam)

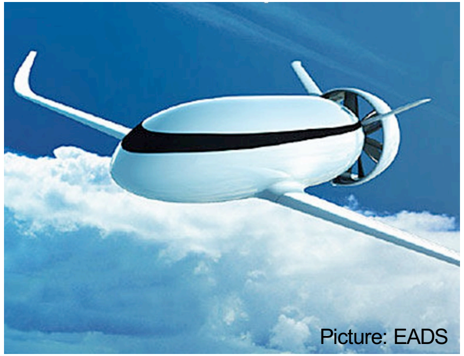
Ship Propulsion

High Torque Motors



Picture: Oswald

Others



2 Superconducing Applications

2.1 General aspects

2.2 Magnet applications

2.3 Electronic applications

2.3.1 Biomedical applications

2.3.2 Field exploration in geology

2.3.3 Ultrasensitive microcalorimeters

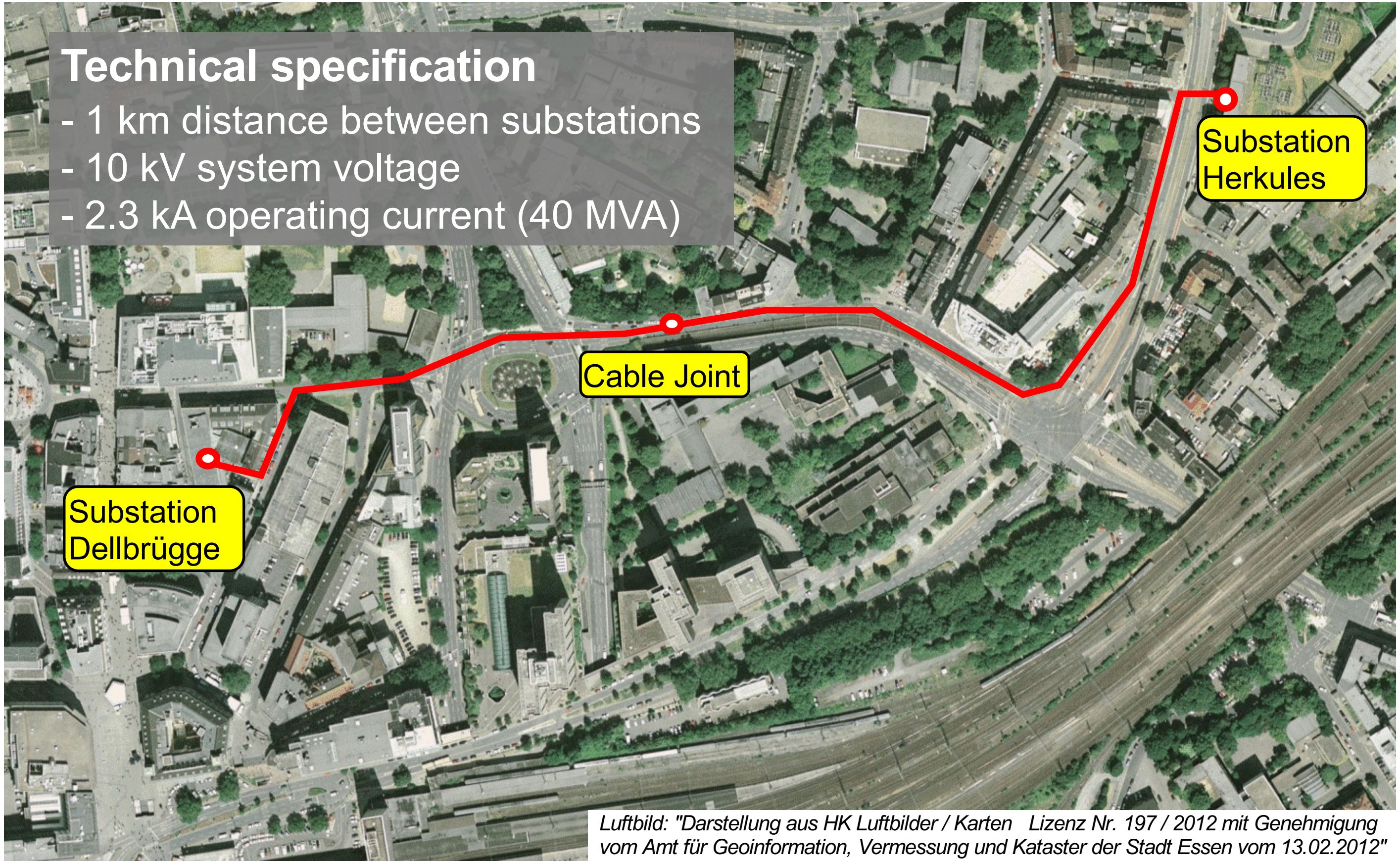
2.4 Power applications

2.4.1 Fault Current limiter

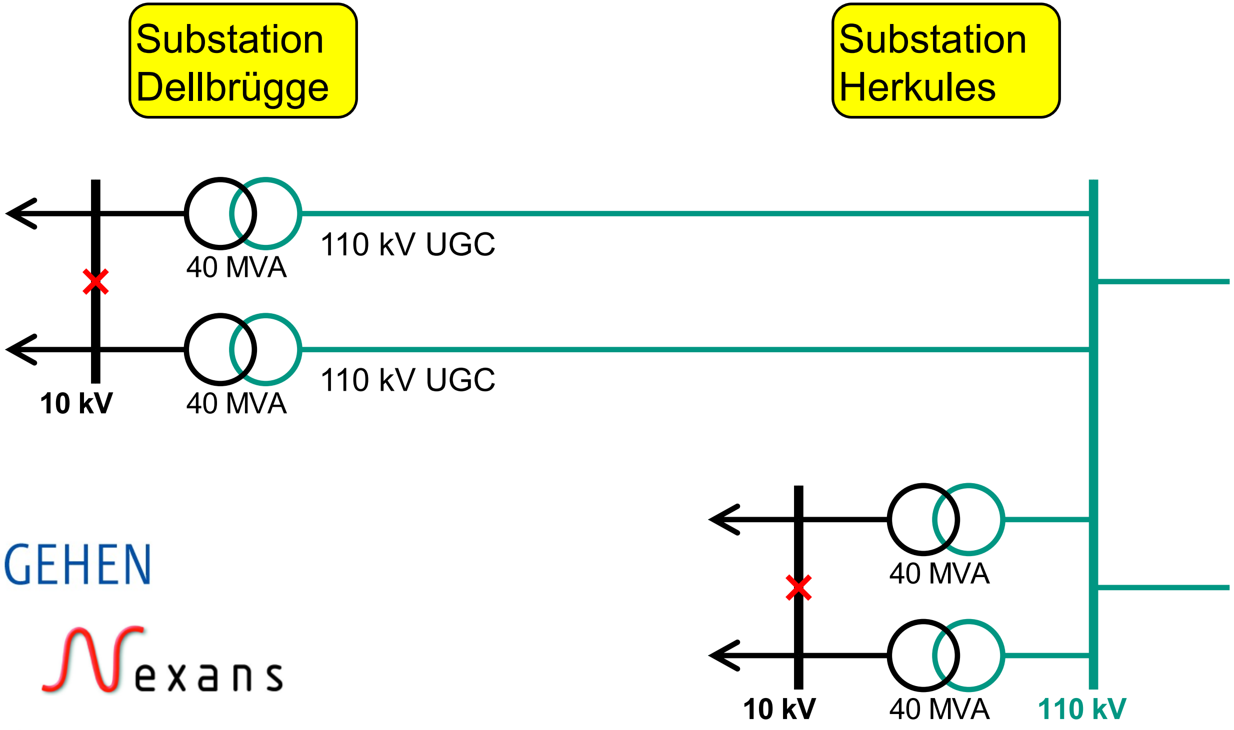
2.4.2 Rotating machines (motor, generator)

2.4.3 Cables

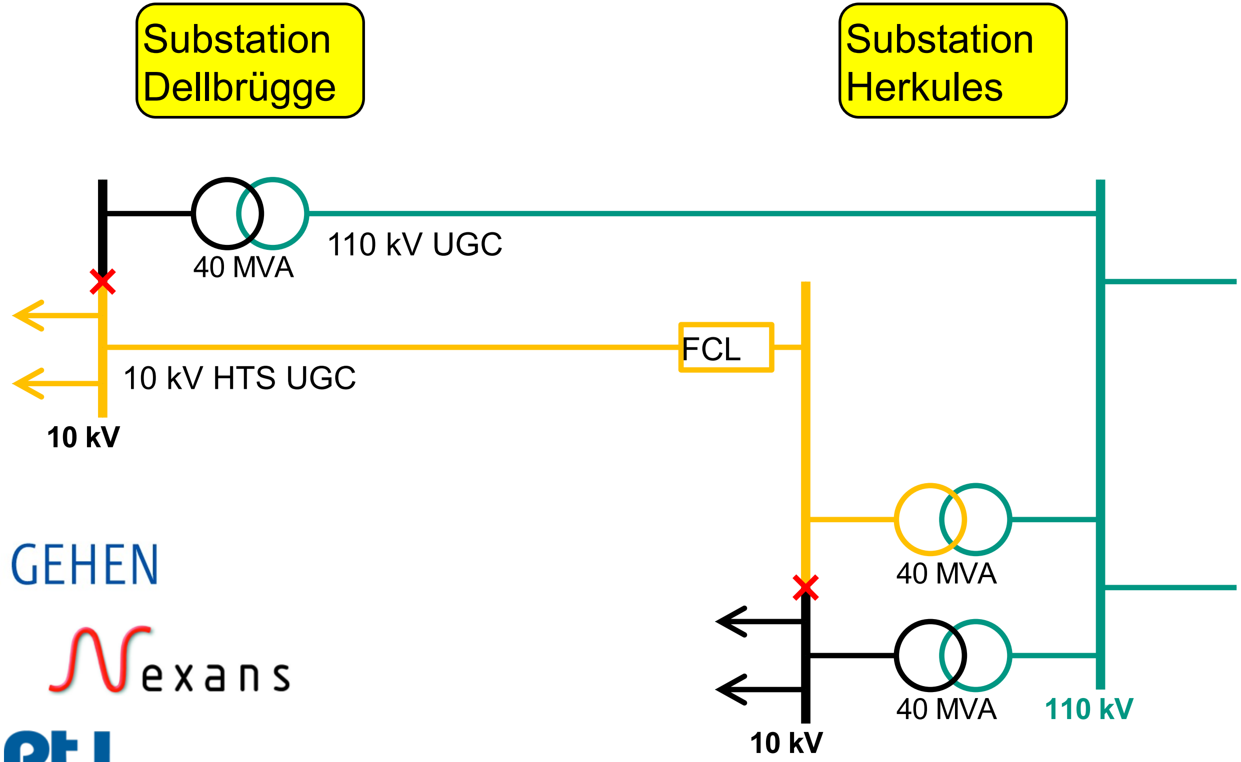
AmpaCity Installation in Essen, Germany



Present Electrical Configuration



Electrical Configuration with HTS System



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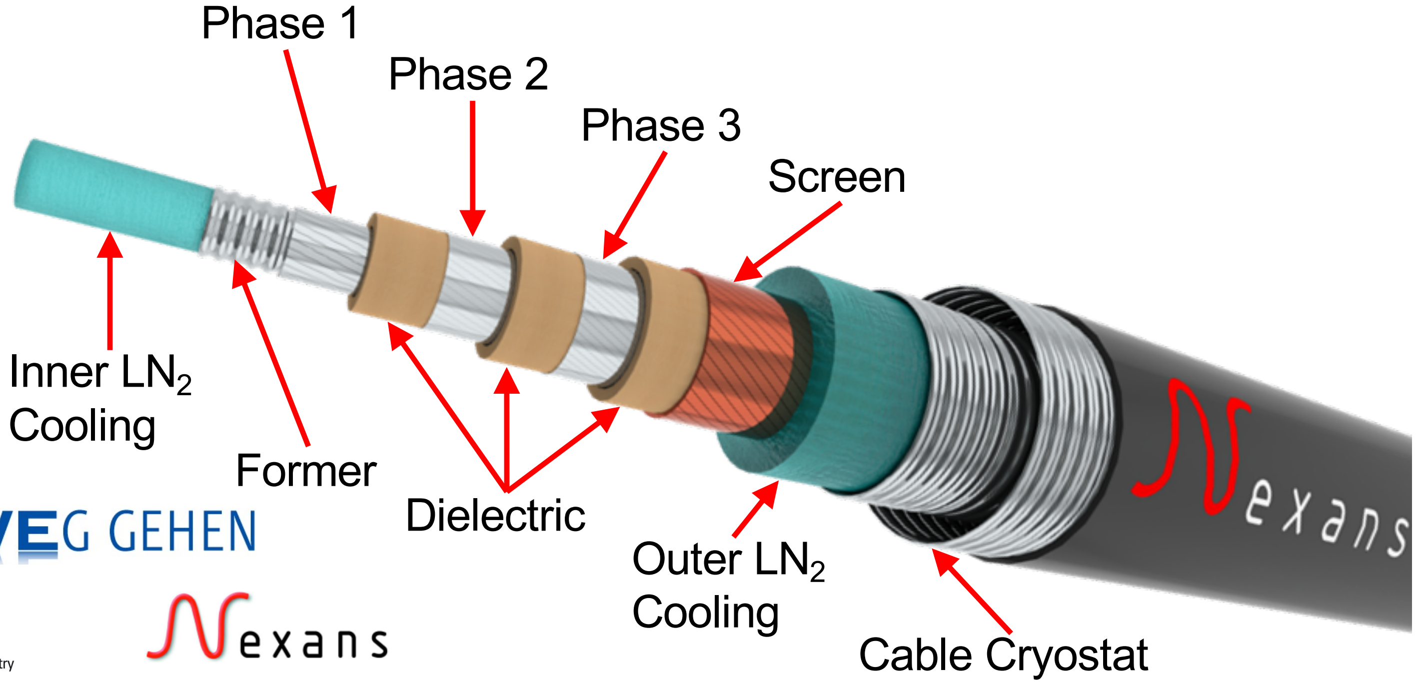
Cable Design



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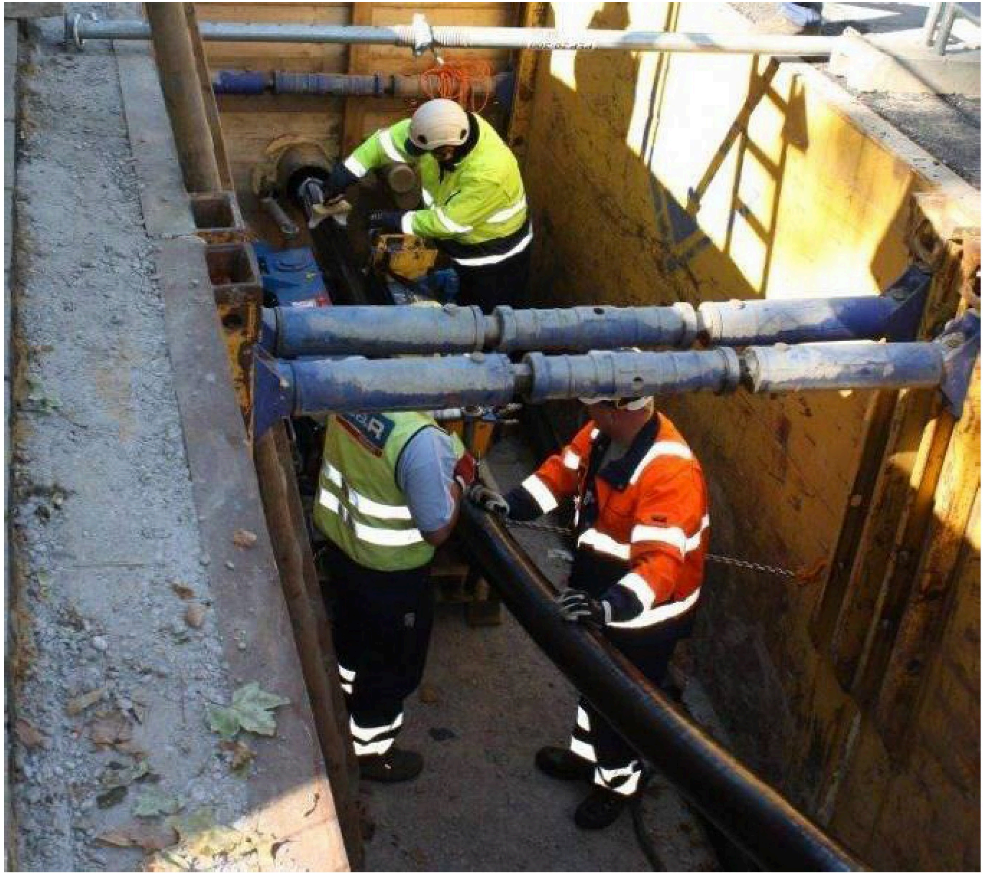
Cable installation (2014)



Cable installation at Dellbrügge

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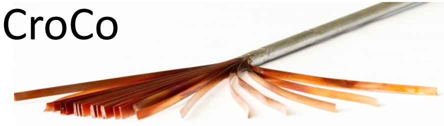
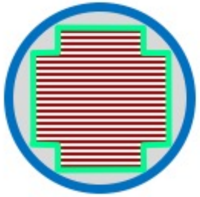
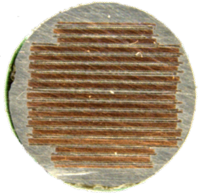
HTSC cable 2.0 – combined LH_2 + power transport

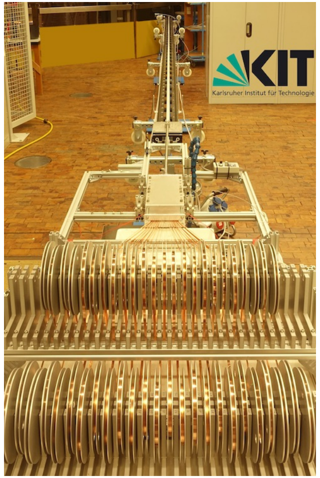
HTSC CroCo







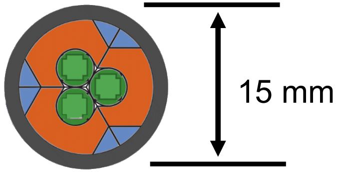
50 m long HTS CroCos fabrication demonstrated @ ITEP



35 kA lossless current transfer demonstrated with 12 CroCos at 77 K (Ø130 mm)

→

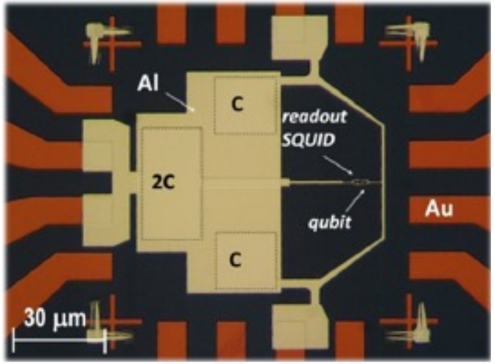
At LH_2 temperature (21 K) a small CroCo-Triplett could carry a DC current of 30 kA without losses



Use of LH_2 + superconductors opens a wide range of promising applications

And much more ....

Karlsruher Institut für Technologie



Levitation

Qubits

Magnetic levitation

SC Bearings

Bolometers

THz-detection

Single photon counting

Magnetic separation

Current leads

SMES