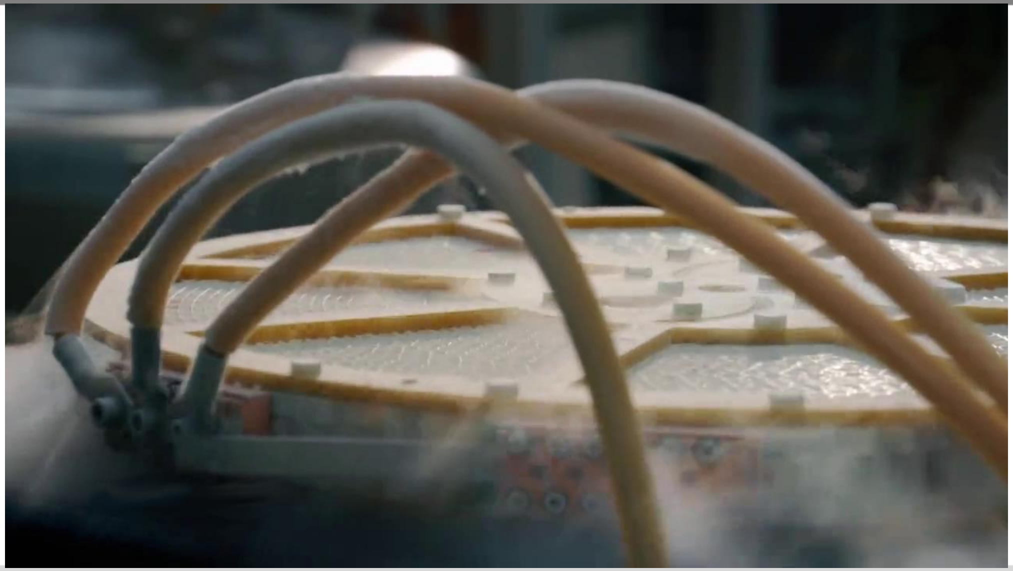
Superconducting Power Systems (2314011)

(Winter term 2022/2023)

#01 – Introduction and Motivation

Prof. Dr. Tabea Arndt

Institute for Technical Physics (ITEP)



Content

- House keeping
- Introduction
- KIT and ITEP– where, who, what?
- Lecture contents
- Let’s get started – why superconductors?

→ House keeping

House keeping

- News, documents, files, etc. (when sufficiently compact in data volume): →ILIAS
- Winter term 2022/2023: aiming for in person lectures
- Lectures:
  - as planned according itinerary
  - fall back in case of (rare) unavailability: recordings or MS TEAMS
- Exam:
  There is an (oral) joint exam of „Superconducting Magnet Technology (Summer Term)" & „Superconducting Power Systems (Winter Term)“
  This is a joint lecture and to best knowledge there is no option for a separate exam.
  Timeslots (weeks) for exams will be communicated later and usually near starting/ ending dates of lecture periods.

Introduction →

Introduction Tabea Arndt

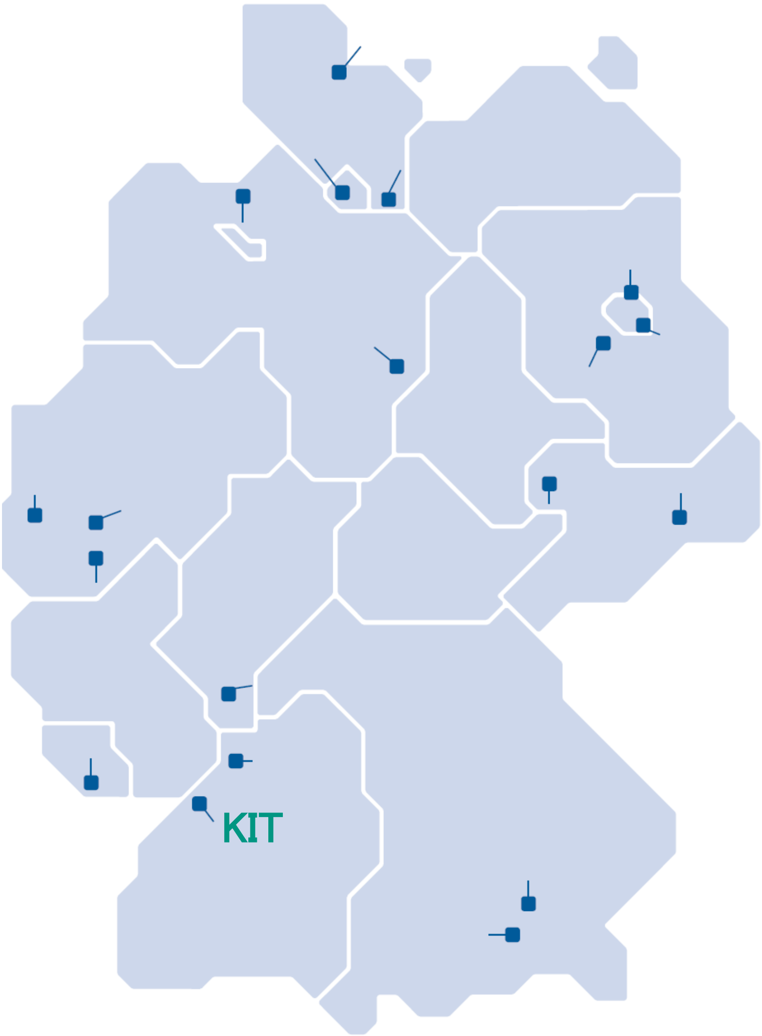
- grown-up in Niedersachsen, Germany
- Study, Diploma and PhD in Physics, University Karlsruhe (TH)
- Vacuumschmelze GmbH&Co.KG, Hanau
- ...different carve outs
- Bruker BioSpin
- Siemens Corporate Technology
- KIT ITEP

Tel.: 0721-608-23515

Email: Tabea.Arndt@kit.edu

Introduction to first lecturer.
Introduction large scale research/ HGF...

The Helmholtz association on Large Scale Research (HGF)



CISPA	Helmholtz-Zentrum für Informationssicherheit, Saarbrücken
DLR	Deutsches Zentrum für Luft- und Raumfahrt, Köln
FZJ	Forschungszentrum Jülich
KIT	Karlsruher Institut für Technologie
DKFZ	Deutsches Krebsforschungszentrum, Heidelberg
DESY	Deutsches Elektronen-Synchrotron, Hamburg
DZNE	Deutsches Zenrtrum für Neurodegenerative Erkrankungen e.V., Bonn und 9 Standorte
IPP	Max-Planck-Institut für Plasmaphysik, Garching (assoziiert)
GEOMAR	Ozeanforschung, Kiel
HMGU	Helmholtz Zentrum München-Deutsches Forschungszentrum für Gesundheit & Umwelt, Neuherberg
AWI	Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven
GSI	Gesellschaft für Schwerionenforschung, Darmstadt
UFZ	Helmholtz-Zentrum für Umweltforschung, Leipzig
MDC	Max-Delbrück-Centrum für Molekulare Medizin, Berlin
GKSS	Forschungszentrum Geesthacht
HZB	Helmholtz Zentrum Berlin für Materialien und Energie
GFZ	GeoForschungszentrum, Potsdam
HZI	Helmholtz-Zentrum für Infektionsforschung, Braunschweig
HZDR	Helmholtz-Zentrum Dresden-Rossendorf
HZG	Helmholtz-Zentrum Geesthacht Zentrum für Material- und Küstenforschung

ITEP-events on superconductivity...

ITEP-events (selected)

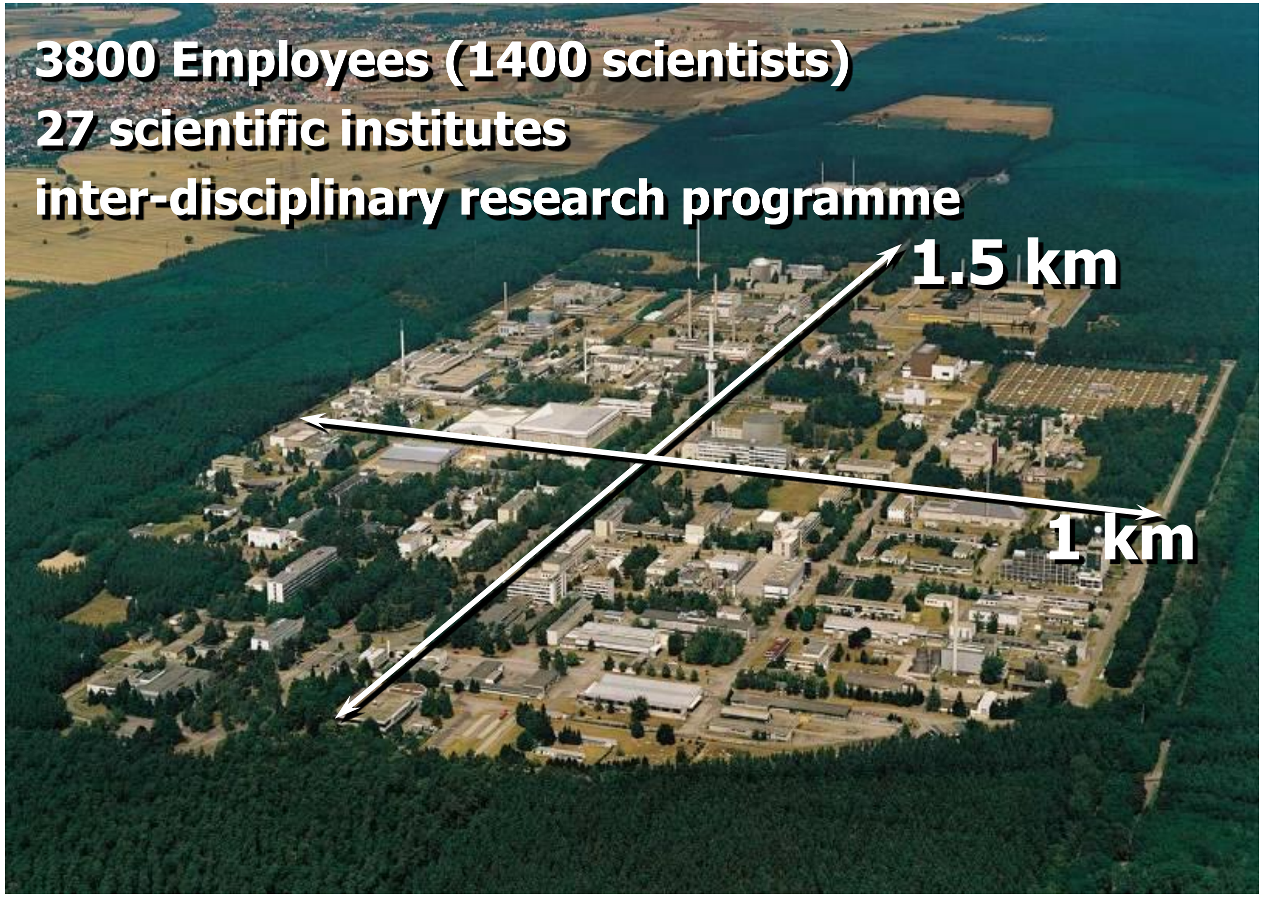
Karlsruhe Institute of Technology

Summer term	Title	Responsible	Faculty	Institute
2312698	Superconducting Magnet Technology	Prof. Arndt	ETIT	IMS (ITEP)
2312684	~~Projektmanagement für Ingenieure~~	~~Prof. Noe~~	~~ETIT~~	~~IMS (ITEP)~~
2312704	Superconductors for Energy Applications	Apl. Prof. Grilli	ETIT	IMS (ITEP)
2312687	Energy Storage and Network Integration	Apl. Prof. Grilli, de Carne	ETIT	IMS (ITEP)
2312691	Superconductivity for Engineers	Prof. Holzapfel Prof. Kempf	ETIT ETIT	IMS (ITEP) IMS
2312692	Tutorial for 2312691	Wünsch, Stefan	ETIT	IMS
2312696	Superconducting Materials Part II	Prof. Holzapfel	ETIT	IMS (ITEP)
2310542	Seminar on Applied Superconductivity	Prof. Arndt Prof. Holzapfel Prof. Kempf	ETIT	IMS (ITEP) IMS (ITEP) IMS

Winter term	Title	Responsible	Faculty	Institute
Seminar (one full day)	Netzwerken-Optionen schaffen Freiheiten	Prof. Arndt	HoC	ITEP
Seminar	Strategieableitung für Ingenieure	Prof. Arndt	ETIT	ITEP
Practise	Robotic Winding of superconductors	Prof. Arndt	ETIT	ITEP

Campus North...

Campus North



- The ITEP is located at CN as being part of the large scale research of Germany.

research at ITEP...

Research fields and topics at ITEP

Karlsruhe Institute of Technology

Superconductivity

Superconducting and Cryomaterials Holzapfel	Energy Applications Noe	Superconducting Magnet Technology Arndt	Fusion Fuel Cycle Technologies Day
Superconducting Materials	Superconducting Power Systems Components	Coil and Magnet Technology	Vacuum Technology and Process Development
Conductor Concepts and Technologies	Modelling of Superconductors and Components	High-Current Components for H_2 and Fusion	Rarefied Gas Dynamics
Materials for Cryogenic Applications	Real-Time System-Integration	Rotating Machines	Vacuum Hydraulics and Hydrogen Separation

Superconducting & Cryomaterials...

Research fields and topics at ITEP

Superconducting and Cryomaterials Holzapfel
Superconducting Materials
Conductor Concepts and Technologies
Materials for Cryogenic Applications
Superconducting Materials

Reel to reel chemical solution deposition

Ion beam assisted deposition chambers

YBCO Roebel cables

FBI cryogenic material tests

HTS CroCo (CrossConductor)

Development of ReBCO superconducting tapes

Investigation of cryogenic properties of structural materials

High current and low loss conductor and wire concepts

Energy Applications...

Research fields and topics at ITEP

Energy Applications

Noe

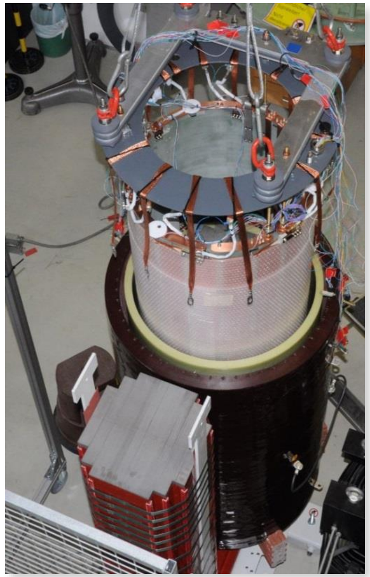
Superconducting Power Systems Components

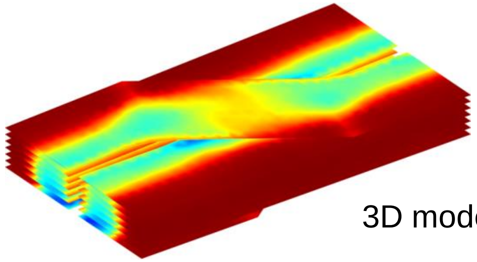
Modelling of Superconductors and Components

Real-Time System-Integration


HTS fault current limiter


HTS high current cable model


HTS transformer


3D modeling and simulation

Development of HTS Power System and new Applications (Cables, FCL, ….)

Simulation and modeling of HTS tapes and devices

Operation and development of large scale cyrogenic systems

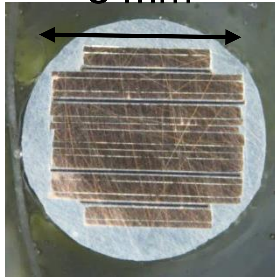
Development of real time system integration of new network technology

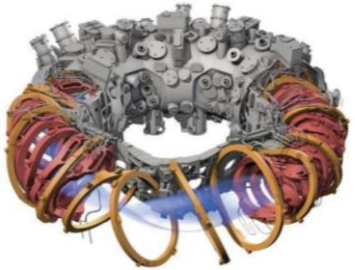
Superconducting Magnet Technology...

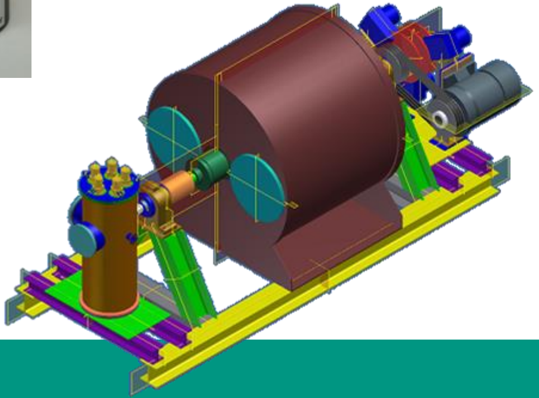
Research fields and topics at ITEP

Superconducting Magnet Technology Arndt
Coil and Magnet Technology
High-Current Components for H_2 and Fusion
Rotating Machines

3 mm







From Research Fields to (actual) projects...

Actual projects at ITEP (selected)

- AppLHy!
- COST
- Demo200
- (HighAmp)
- (Jp-PTL)
- MEESST
- SuperLink
- SupraGenSys
- several funded research projects in application (accelerators, Wind Power)
- several contract research projects (CERN, industrial players)
- SFB Hyperion: miniaturized NMR magnets

research → application
Contents of this lecture series...

Contents of lecture series

Date	Title	Lecturer	Remark
25.10.2022	Introduction & Motivation	Arndt	To raise interest
08.11.2022	Basics of Superconductivity	Grilli	Meissner-Ochsenfeld effect, Type 1 and type 2 superconductors, magnetization, losses, sc. wires
15.11.2022	Sc. Cables and Busbars 1(3)	Kottonau	AC cable types, operation parameters
22.11.2022	Sc. Cables and Busbars 2(3)	Kottonau	DC high current busbars, state-of-the-art
29.11.2022	Sc. Cables and Busbars 3(3)	Kottonau	Design example and comparison with conventional cables
06.12.2022	Sc. Transformers 1(2)	Fotler	Basic design, main parameters, operation behaviour, design equations, losses, state of the art
13.12.2022	Sc. Transformers 2(2)	Fotler	Design example for superconducting railway transformer
20.12.2022	Sc. Fault Current Limiters 1(3)	de Sousa	Motivation, resistive type, conceptual design, simulation tools, design task
10.01.2023	Sc. Fault Current Limiters 2(3)	de Sousa	Round of questions for design task
17.01.2023	Sc. Fault Current Limiters 3(3)	de Sousa	Presentation of design proposals
24.01.2023	Sc. Rotating Machines 1(2)	Schreiner	Basic design, operation parameters, synchronous machines, applications, state-of-the-art
31.01.2023	Sc. Rotating Machines 2(2)	Schreiner	Design example of DC wind power generator demonstrator
07.02.2023	Sc. Magnetic Energy Storage	Pham	Design and function, main parameters, operation behaviour, design equations, losses, state of the art
14.02.2023	Basics of Cryogenics	Pham	Cooling systems, cooling fluids and materials, basic design of cryostats, optimization of current leads, general design, basic design equations, state of the art

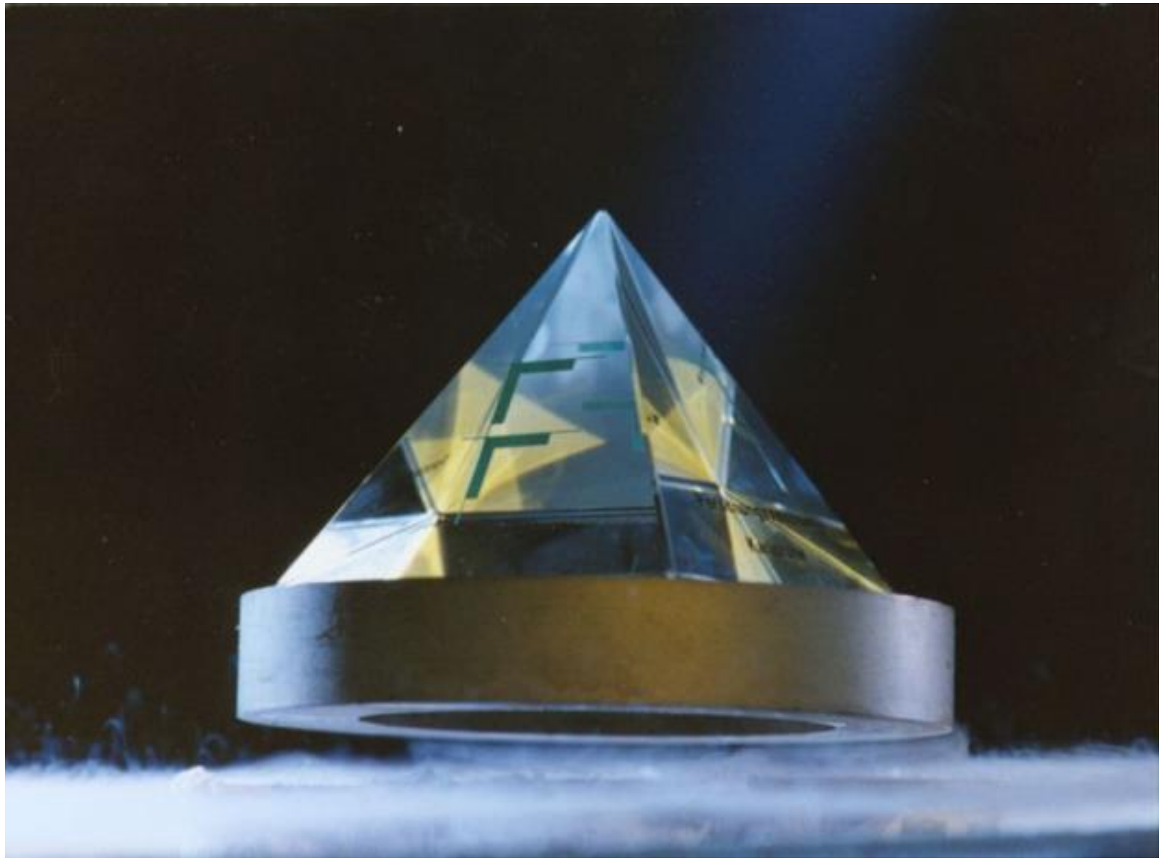
The topics in more detail...

Topic:
Introduction and Motivation

Just a teaser.

Basics...

Topic:
Basics of Superconductivity

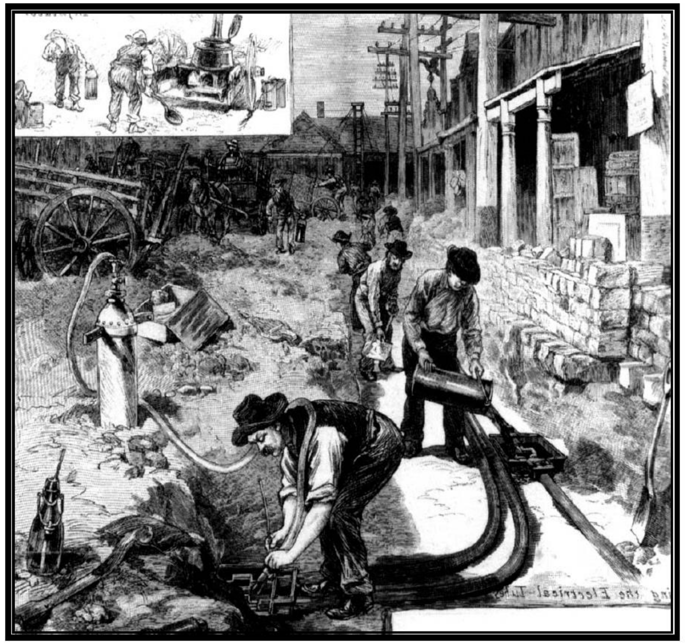


- Critical quantities
- Meissner-Ochsenfeld Effect
- Type 1 and Type 2 superconductors
- Magnetization
- Losses
- Superconducting wires
- Current transport

Foundation.

Cables...

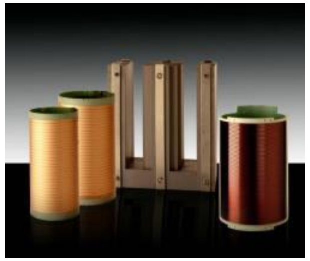
Topic:
Superconducting Cables

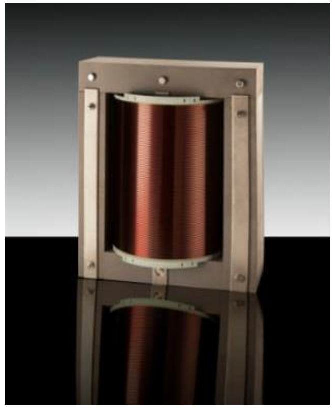


- Design
- Dielectric
- Cable types
- Operating parameters
- Transmission behavior
- Examples
- Cryogenics at high voltage levels

Efficient bulk transport of electric energy.
Transformers...

Topic
Superconducting Tranformer





- Design and operating principle
- Parameters
- Operating behavior
- Design equations
- Losses
- State of development

To taylor transmission and distribution.

Topic
Superconducing Fault Current Limiter (FCL)

- Conventional methods
- Types of superconducting FCL
- Functionality
- Current limiting behavior
- Possible applications
- Economic aspects

New approach: Problem oriented learning

- You hate the task to design a sc. FCL
- First lecture: introduction to topic and simulation tools (Matlab and Python)
- Second lecture: teacher is your coach and anwers your questions
- Third lecture: you present your design

To handle fault currents.

Incident...

02.Sep.2022, Netherlands

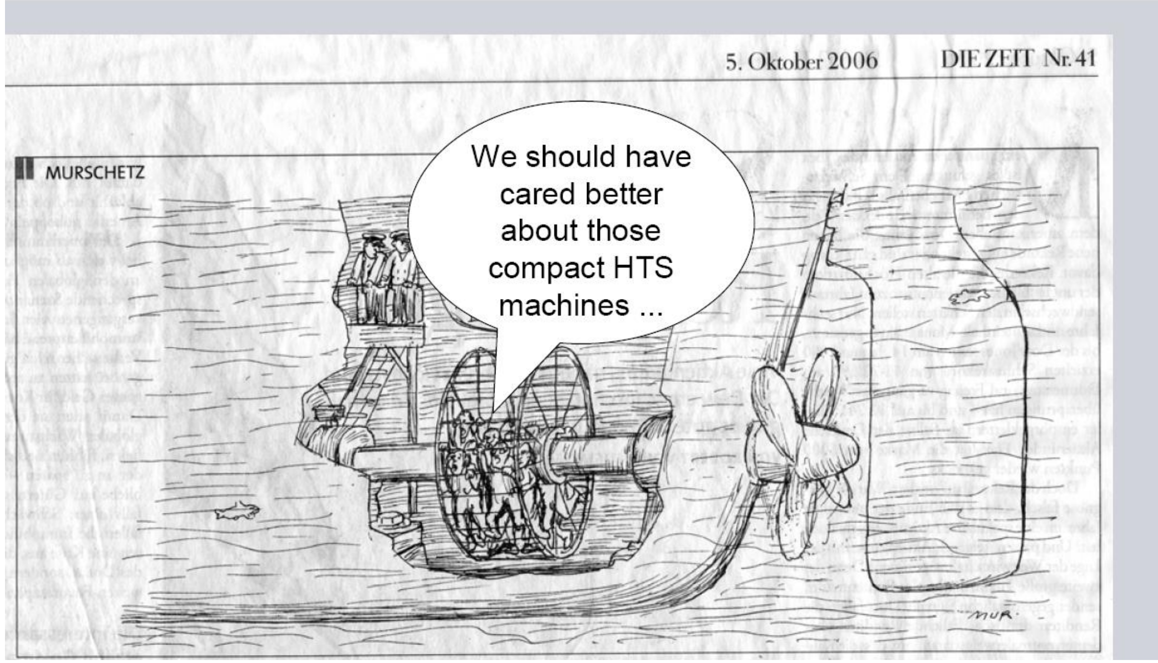
- Transformer caught fire/ explosion (conventional one)
- Unfortunately, the control equipment & safety measures have been destroyed by the explosion, too.
- High Fault currents flowing through the OH-Line for more than one minute
- Elongation of OH-Line
- Touching the railway track
- Damaging the railway track seriously

A recent arguing in favour of SFCL.
Rotating machines...

Topic:
Superconducting Rotating Machine

SIEMENS

Good Prospects for HTS Ship Propulsion



- Design
- Operating behavior
- Synchronous machine
- Homopolar motor
- Linear motor
- Reluctance motor
- Design parameters
- Applications
- State of development

Highly efficient and compact revolutions.

SMES...

Topic:
Superconducting Magnetic Energy Storage

- Overview of conventional energy storage systems
- Mode of operation
- Properties of SMES
- Basic equations
- Application examples

Short term energy storage for high power demand.
Basics of cryogenics...

Topic:
Basics of cryogenics

- Refrigeration
- Refrigerants (cryogens)
- Material properties at low temperatures
- Cryostats
- Safety

Keep it cold!

History of Superconductivity, the discovery...

Discovery of superconductivity – electrical resistance vs. temperature

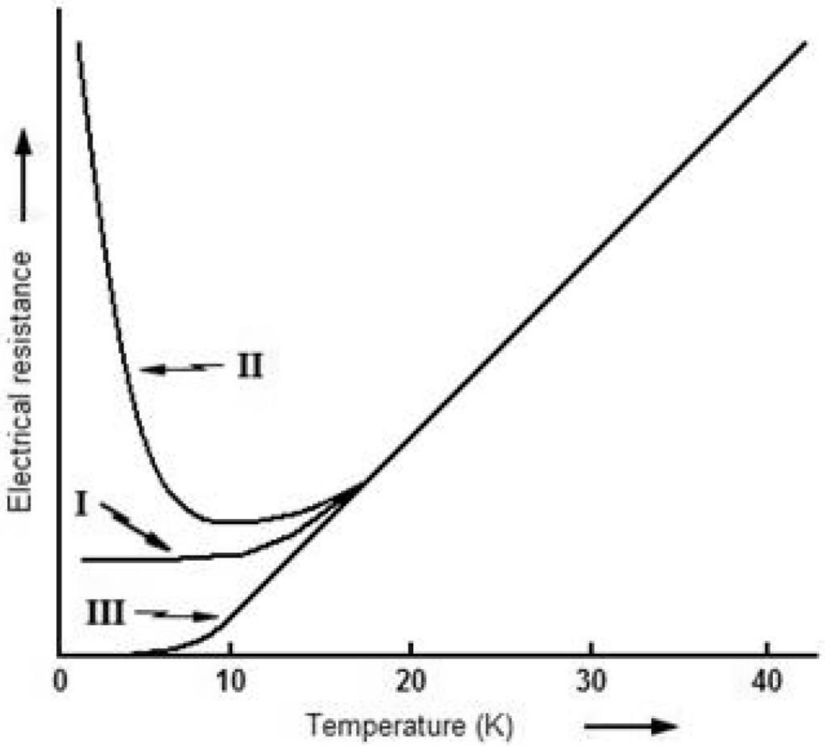


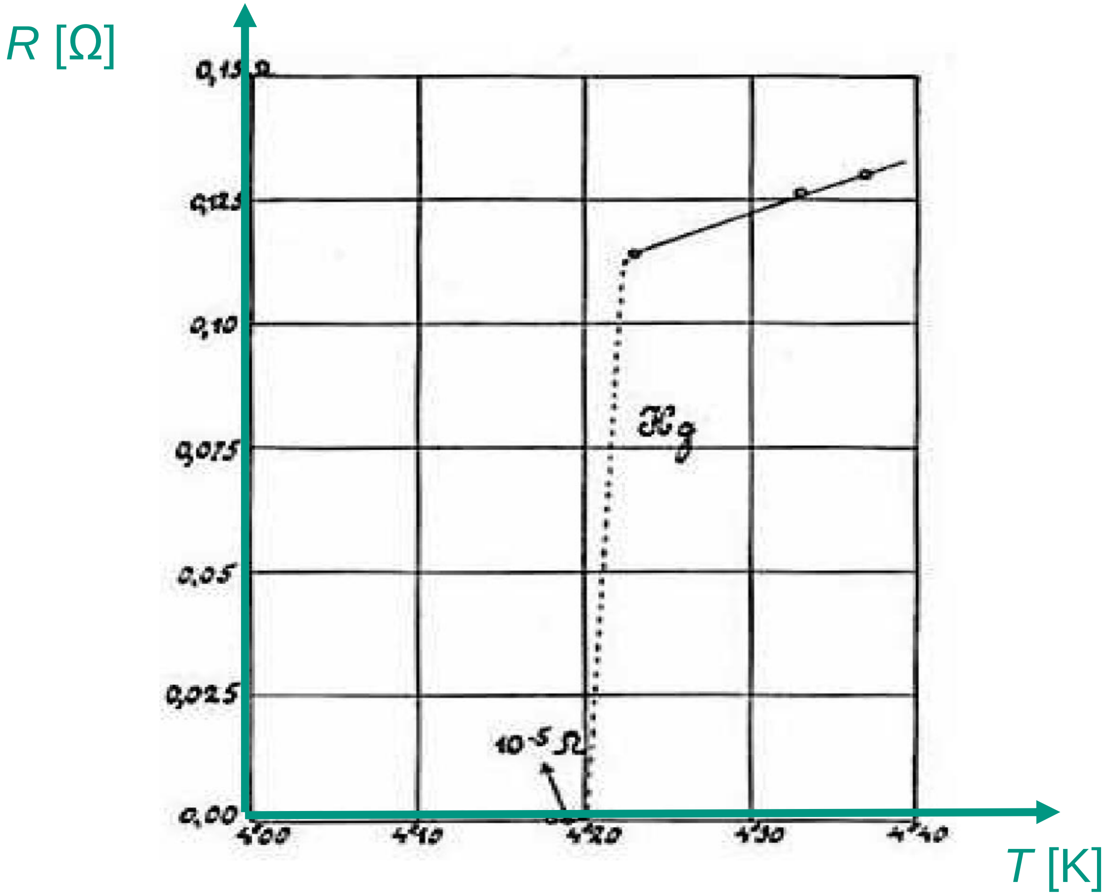
Figura 8 - Possible (qualitative) forms of temperature variation of electric resistance.

- I: impurities
  (Matthiessen 1864)
- II: freezing of charge carriers
  (Thompson/ Lord Kelvin 1902)
- III: freezing of collisions
  (Dewar 1904)

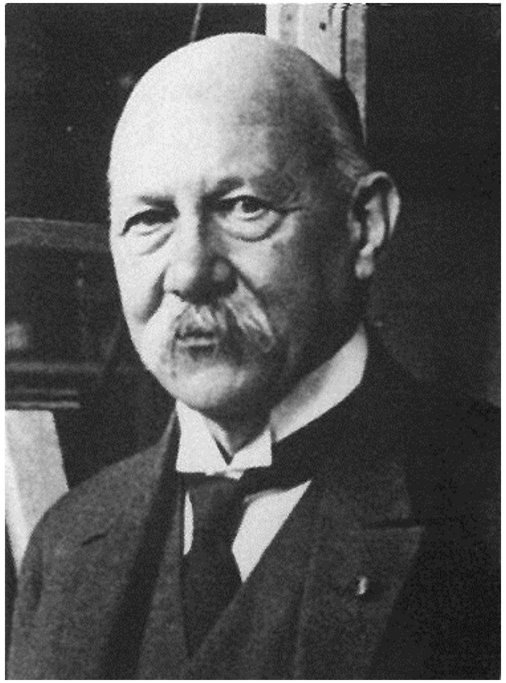
e.g. discussed for Pt and Au, taken from
[S. Reif-Acherman-Rev.Br.Ens.Fisica 33(2011)2601]

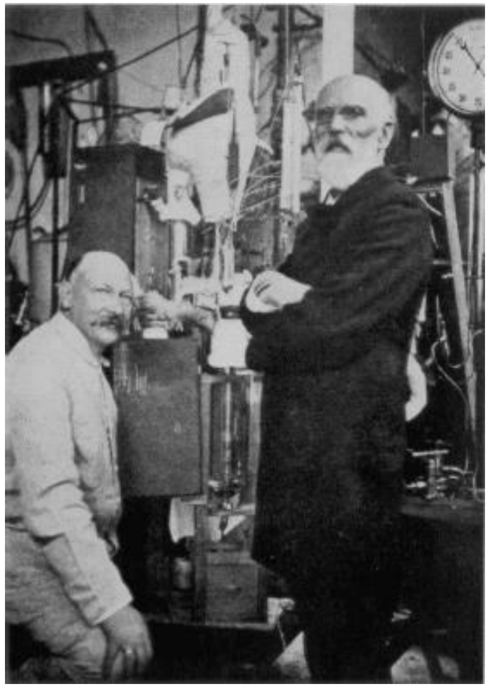
3 possible scenarios for the low temperature behaviour were considered.
Experimental observation...

Experiment of H.K. Onnes (1911) in liquid helium



- Electric resistance drops for temperatures *T*< ≈4.2 K not slowly with a slope, but abruptly (no data points) to very small values!





"Thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity"

Nobel prizes  in the field of superconductivity

Heike Kamerlingh Onnes

John Bardeen

Leon Neil Cooper

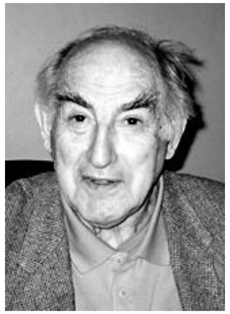
John Robert Schrieffer

Brian D. Josephson

J. Georg Bednorz

K. Alexander Müller

Alexei A. Abrikosov



Vitaly L. Ginzburg

1913-Low-temperature physics (e.g. superconductivity of Hg)

1972-BCS-Theory

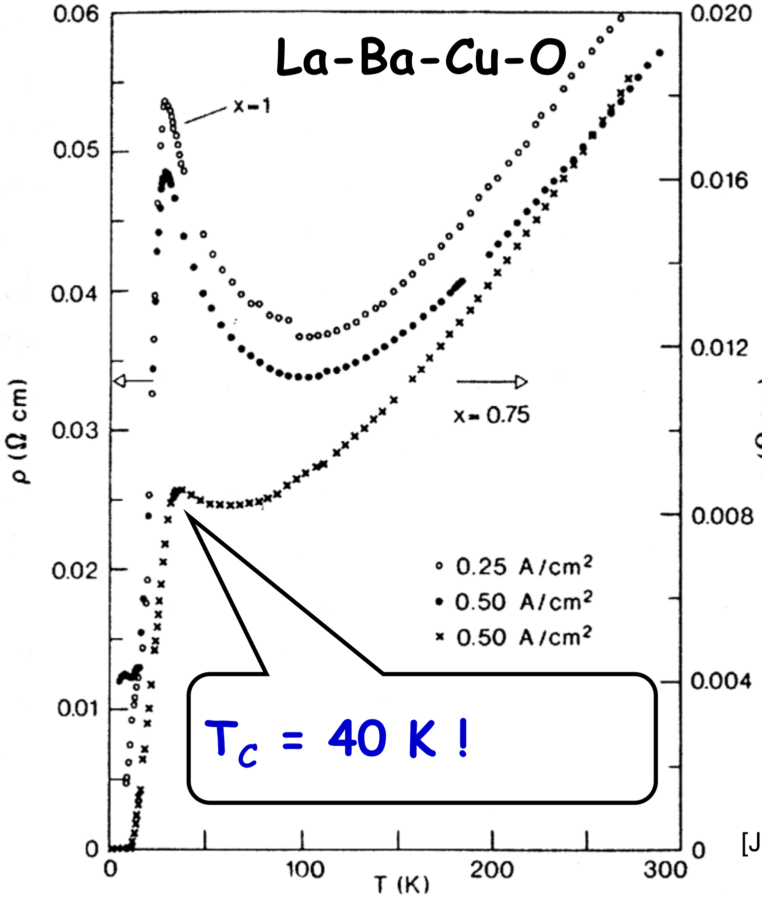
(1973-Josephson-Effect)

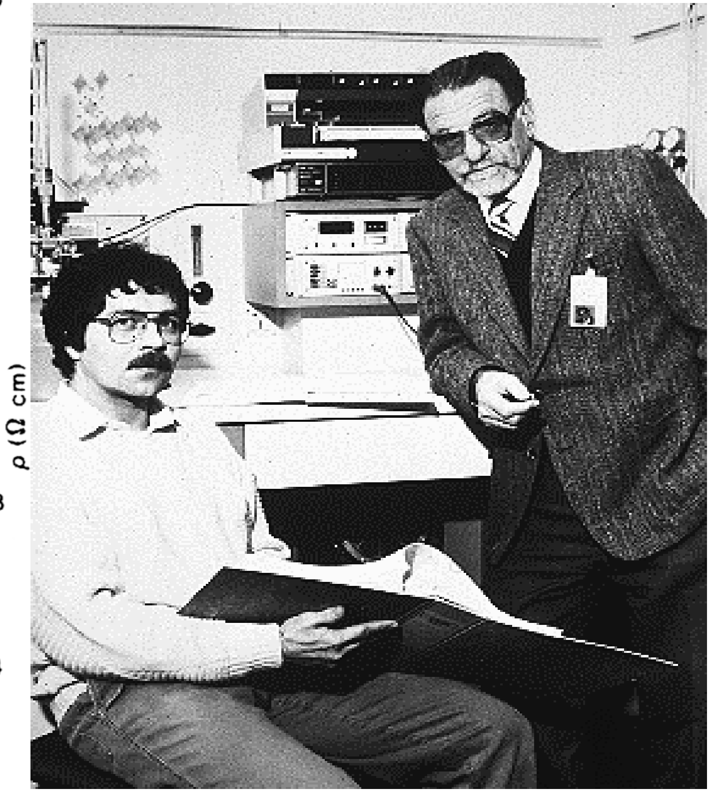
1987-High-Temperature Superconductors

2003-Theory of Superconduct‘s

The discovery of High-Temperature Superconductors (HTS)...

Discovery of high-temperature superconductivity by Bednorz and Müller (IBM, Zürich, 1986)





[J.G. Bednorz, K.A. Müller, „Possible High Tc Superconductivity in the Ba-La-Cu-O System, Z. Physik B., Condensed matter 64, 189-193 (1986)]

- First, $T_c \approx 40\ \mathrm{K}$
- Lateron, $T_c > 77\ \mathrm{K}$, so cooling with LN_2 instead of LHe possible

New prospects for energy technology!

Historical development of HTS...

Historical development of HTS (selected)

Karlsruhe Institute of Technology

- 1986 Discovery of high-temperature superconductivity by Bednorz and Müller: $(La, Sr)_2CuO_4$ with T_C = 30...40 K.
- 1987 Discovery of Y1Ba2Cu3O(7-X) (YBCO) with TC = 92 K.
- 1987 until now: Discovery of new materials and development of materials and applications e.g.:
  Bi2Sr2CaCu2O8 (BSCCO 2212 or Bi 2212) TC = 92 K
  Bi2Sr2Ca2Cu3O10 (BSCCO 2223 or Bi 2223) TC = 110 K
- 1996 in October: world‘s first inductive HTS FCL (10 kV, 60 A, 3 phase) in long-term test, Löntsch power station, CH
- 1997 in March: Grid operation of the world‘s first 3 phase HTS transformer with 630 kVA & 18.7 kV/420 V, Löntsch
- 2001 Discovery of MgB_2 with T_c = 39 K.
- 2004 in April: world‘s first resistive HTS FCL (10 kV, 600 A) in grid operation at RWE in Netphen (Germany)
- 2005 First commercial availability of YBCO 2G-HTS tapes
- 2008 Discovery of FeAs compounds with T_c = 55 K
- 2014 World‘s longest HTS cable in Essen, Germany (AmpaCity)
- 2018 World‘s first field test of HTS wind turbine (Ecoswing)
- and ongoing...

Many developments improved maturity to high TRLs.

Why HTS in power engineering?...

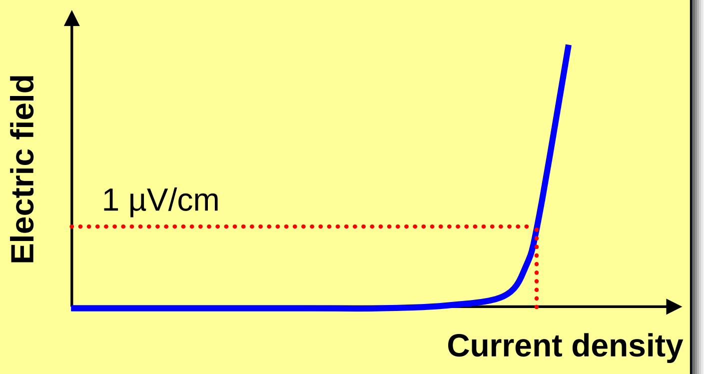
Why superconductors? (HTS in power engineering)

Karlsruhe Institute of Technology

Highest current densities

Current density in superconductors: 100 - 10000 A/mm^2

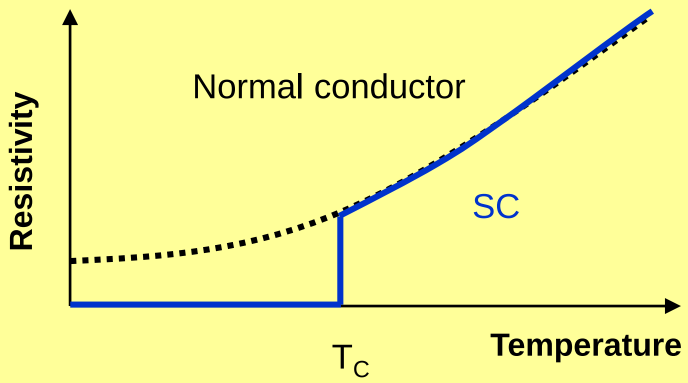
(in copper: 1 - 5 A/mm^2)



Negligible el. resistance

Below the critical quantities the DC resistance of superconductors is nearly zero

(Resistivity of copper: 0,0175 Ω mm^2/m)



Superconductivity improves conventional technology and enables new applications!
What does that mean in electrodynamics?...

Electrodynamics: Maxwell Equations and Ohm's law for normal-conducting materials

Gauß' law	$\nabla \cdot \mathbf{E} = \frac{\rho_e}{\varepsilon_0}$	The electric flux leaving a volume is proportional to the enclosed charge. "The Charge is source of the electrical Field"
Gauß' law for magnetic fields	$\nabla \cdot \mathbf{B} = 0$	The total magnetic flux leaving a closed surface vanishes. "There are no sources of the magnetic field"
Faraday's law	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	The rate of change of the magnetic field leads to an electric vortice field.
Ampere's law	$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$	Electric currents including the discplacement currents lead to a magnetic vortice field.

Ohm's law	$\mathbf{j} = \sigma \mathbf{E}$	Electrical current and electric field are proportional. (constant is the electrical conductivity)

Frequently written as	$j = \frac{ne^2\tau}{m} E$	n: density of charge carrier, e: elementary charge, τ: mean free path, m: masse of charge carrier

Maxwell is universal, Ohm is for material class.
And how about superconductors?

"Superconducting electro dynamics" – Maxwell stays, but "London replaces Ohm".

Karlsruhe Institute of Technology

Gauß' law	$\nabla \cdot \mathbf{E} = \frac{\rho_e}{\varepsilon_0}$	The electric flux leaving a volume is proportional to the enclosed charge. "The Charge is source of the electrical Field"
Gauß' law for magnetic fields	$\nabla \cdot \mathbf{B} = 0$	The total magnetic flux leaving a closed surface vanishes. "There are no sources of the magnetic field"
Faraday's law	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	The rate of change of the magnetic field leads to an electric vortice field.
Ampere's law	$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$	Electric currents including the discplacement currents lead to a magnetic vortice field.
London-equation	$\vec{j} = \frac{ne\hbar}{m} \nabla S - \frac{ne^2}{m} \vec{A}$	Electrical currents result from the local variation of the wave function and from the vector potential of the magnetic field.

Or in the form	$\frac{\partial}{\partial t} j = \frac{e^2 n}{m} E$ $\nabla \times j = -\frac{e^2 n}{m} B$	n: density of charge carriers, e: charge, m: mass of charge carriers

Superconductors: „London replaces Ohm"
The new technical opportunities and impacts in detail...

Why superconductors? (HTS in power engineering)

Highest current densities with almost zero DC resistance ad high magnetic fields

Impact on energy technology:

- Increased energy efficiency=reduced loss →

Application examples	Loss reduction
Generators (several MVA) Generators (> 100 MVA)	30-40 % 40-50 %
Transformators stationary mobile	 ~ 50 % 80-90 %
Induction heating	~ 50 %
Magnetic separator	> 80 %
HTS current leads	70-80 %
HTS high field magnets	> 90 %

Increased energy efficiency!

Why superconductors? (HTS in power engineering)

Karlsruhe Institute of Technology

Highest current densities with almost zero DC resistance ad high magnetic fields

Impact on energy technology:

- Increased energy efficiency=reduced loss
- Higher energy density →

Volume and weight reduction	
Generators	30-50 %
Transformators	30-50 %
Cable	> 50 %

Increased energy density!

Why superconductors? (HTS in power engineering)

Highest current densities with almost zero DC resistance ad high magnetic fields

Impact on energy technology:

- Increased energy efficiency=reduced loss
- Higher energy density
- New technology and applications

→

Superconductivity offers

- Superconducting fault current limiter
- Current limiting systems
- Superconducting magnetic energy storage

New technology and applications!

Why superconductors? (HTS in power engineering)

Karlsruhe Institute of Technology

Highest current densities with almost zero DC resistance ad high magnetic fields

Impact on energy technology:

- Increased energy efficiency=reduced loss
- Higher energy density
- New technology and applications
- Improved grid quality →

Higher grid quality

- Lower impedance of the equipment
- High short circuit power with current limiters
- Fast compensation of interferences with magnetic energy storage

Improved grid quality!

Why superconductors? (HTS in power engineering)

Highest current densities with almost zero DC resistance ad high magnetic fields

Impact on energy technology:

- Increased energy efficiency=reduced loss
- Higher energy density
- New technology and applications
- Improved grid quality
- Environmentally friendly →

Liquid nitrogen

- as coolant and electric insulation
- broadly available
- not flammable

More friendly to nature!

References/ further studies

- Werner Buckel – **Supraleitung**, VCH, 1994 (or later)
- P. Komarek – **Hochstromanwendung der Supraleitung** (Teubner 1995 – no reprint!)
- J.D. Doss – Engineer‘s guide to high-temperature superconductivity, John Wiley, 1989
- Wilson – **Superconducting Magnets**, Clarendon-Press, 1983
- H. Brechna – **Superconducting Magnet Systems**, Springer, 1973
- J.C. Phillips – Physics of high-Tc superconductors, Academic Press, 1989
- Bernd Seeber – Handbook of Applied Superconductivity, Vol. 1 and 2, IOP 1998
- David A. Cardwell (Eds.) - Handbook of Superconducting Materials
- Rosenberg – Low Temperature Solid State Physics, Clarendon Press (1965)
- R.D. Parks – Superconductivity, CRC Press, 1969
- Frey, H., Haefer,R.A.; Eder, F.X. (Ed.) – „Tieftemperaturtechnologie“, VDI-Verlag GmbH, 1981
- Jousten, K. – „Handbuch Vakuumtechnik“, Springer Vieweg, 2018

Learning objectives...

Learning objectives

- Motivation to use superconductors
- Difference in electrodynamics (Maxwell vs. Material laws)
- Most prominent applications for HTS in power engineering
- Benefits for HTS in power engineering

Thank you!