Karlsruhe Institute of Technology

Introduction to Cryogenics and Superconductivity

Carolin Heidt, Juliane Raasch

KSETA- Workshop Freudenstadt 2013

INSTITUTE FOR TECHNICAL PHYSICS, INSTITUTE FOR TECHNICAL THERMODYNAMICS AND REFRIGERATION
INSTITUTE OF MICRO- AND NANOELECTRONIC SYSTEMS

Source:
Cern Website

Outline – Cryogenics

- Introduction
- Cold production
- Cryogenic Properties
  - Cryogenic fluids
  - Material Properties
- Cryostats
  - Dewar vessel
  - Thermal Insulation
  - Cern
  - Temperature measurement
  - Flow measurement
  - Safety

Source:
Cern Website

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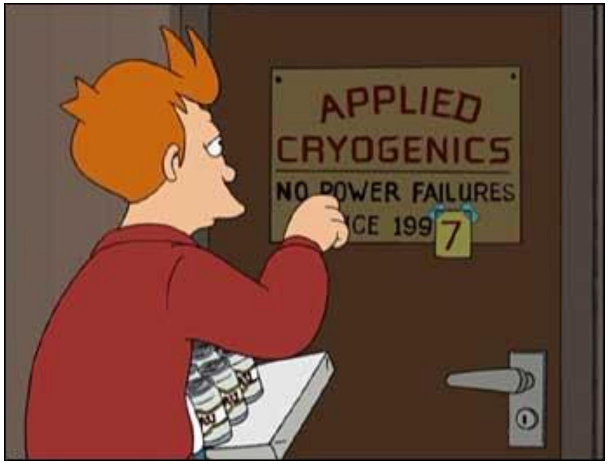
Introduction

- Cryogenics -> Greek: production of freezing cold
- Cryogenics -> Refrigeration at T<120K (definition since 1971)
- Cryogenics <-> Cryonics= preservation of the human body in LN2 after death



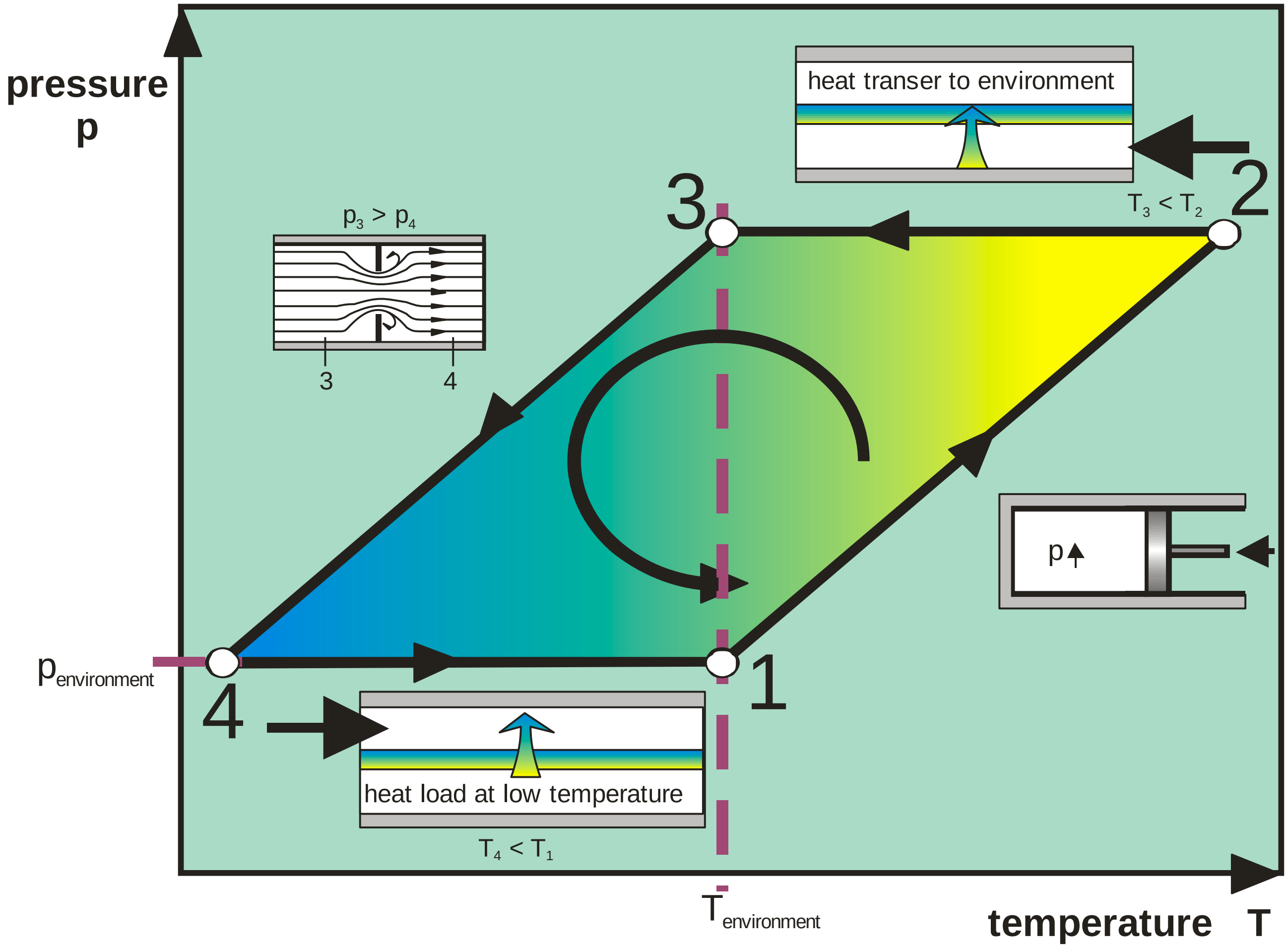
Source: http://www.dailygalaxy.com/my_weblog/2007/10/experimental-tr.html

Source: http://theinfosphere.org/images/cache/enwiki/f/fd/Cryogenic_Freezing_Chamber.html

Introduction

- Applications:
  - Condensation & liquefaction of gases
    - Air separation
    - Transport
    - Storage
  - Reduction of thermal noise and excitation
    - Particle accelerators
    - Particle detectors
  - Others
    - Food Freezing
    - Space flight technology
    - LH2 technology
    - Medical applications

Cold production (Basic)

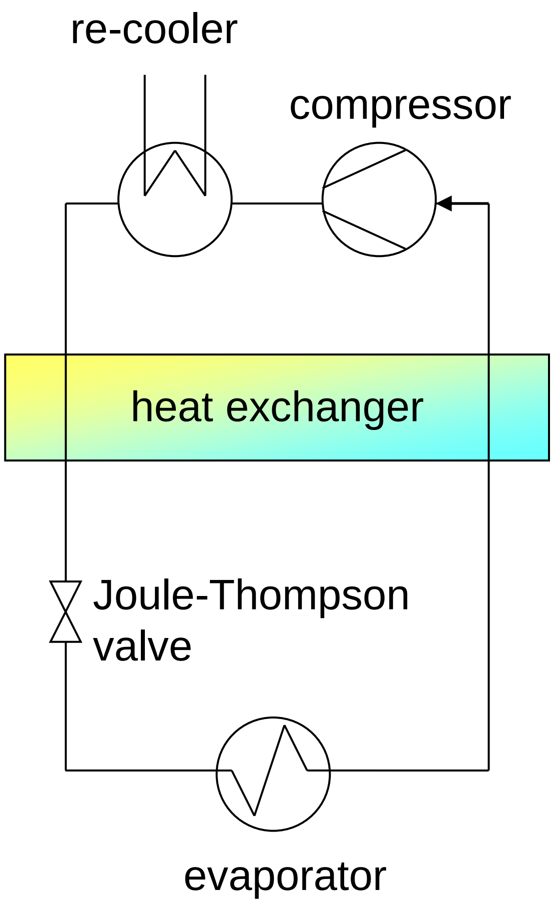


- Basic principle:
  - Compression
  - Heat transfer to ambient
  - Throttling/ expansion
  - Heat load at low temperature

Source:
H. Neumann, ITEP, KIT, 2013 ESAS Summer School

Cold production (Refrigeration Cycles)

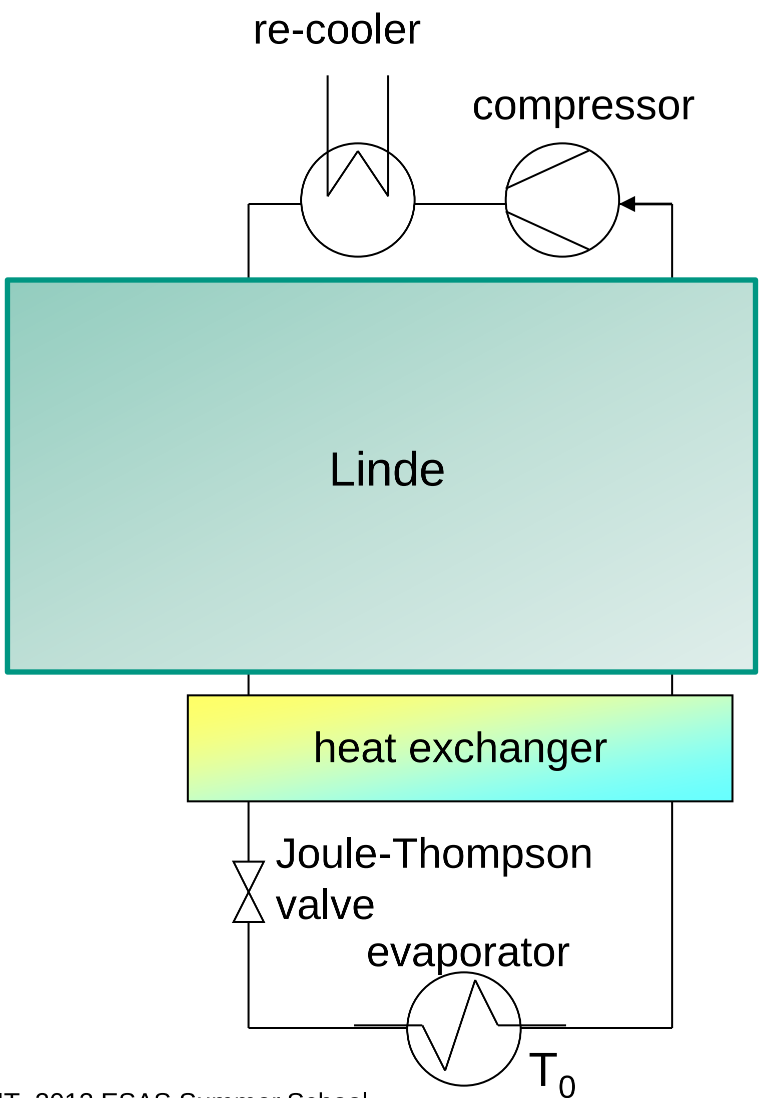
- Joule-Thompson-Process (Linde)
  - Simple, reliable
  - Low efficiency



Source:
H. Neumann, ITEP, KIT, 2013 ESAS Summer School

Cold production (Refrigeration Cycles)

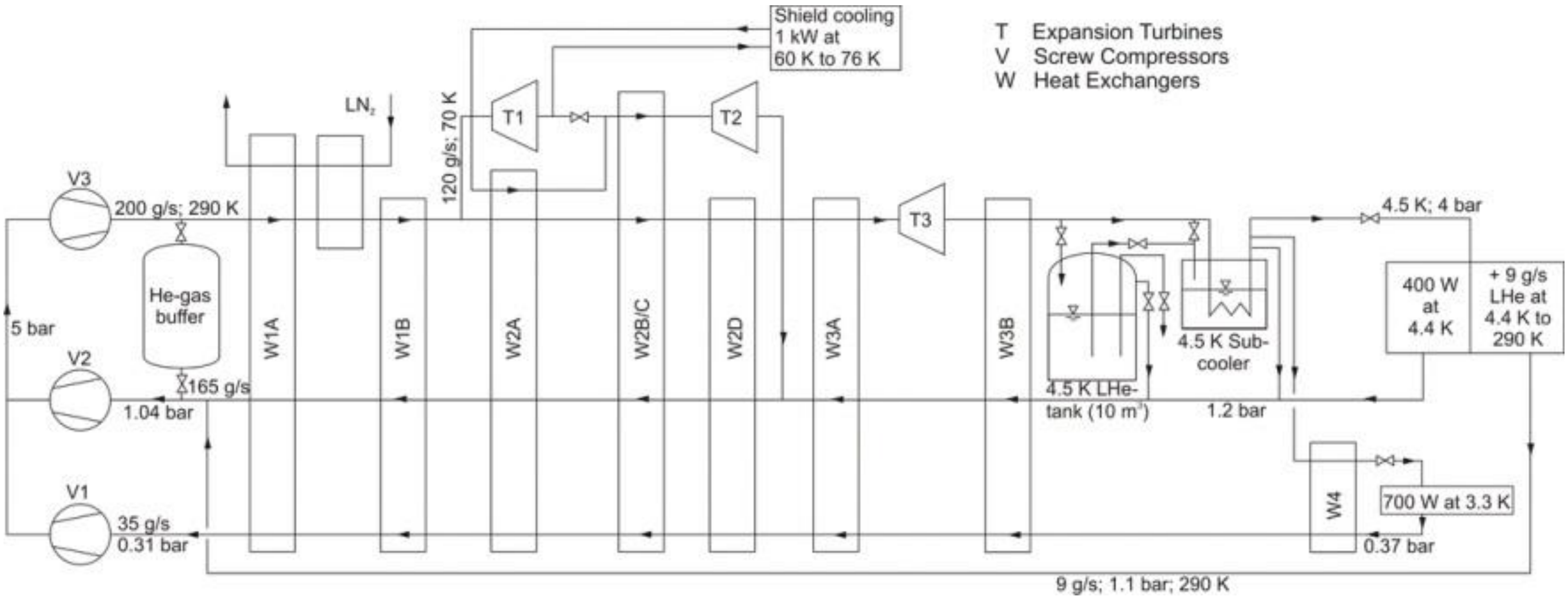
- Joule-Thompson-Process (Linde)
  - Simple, reliable
  - Low efficiency
- Claude-Process
  - Higher efficiency
    - Expansion of partial current for extra cooling
  - Less reliable
- Stirling Process
  - Compact
  - No liquefaction



Source:
H. Neumann, ITEP, KIT, 2013 ESAS Summer School

Cold production (Refrigeration Cycles)

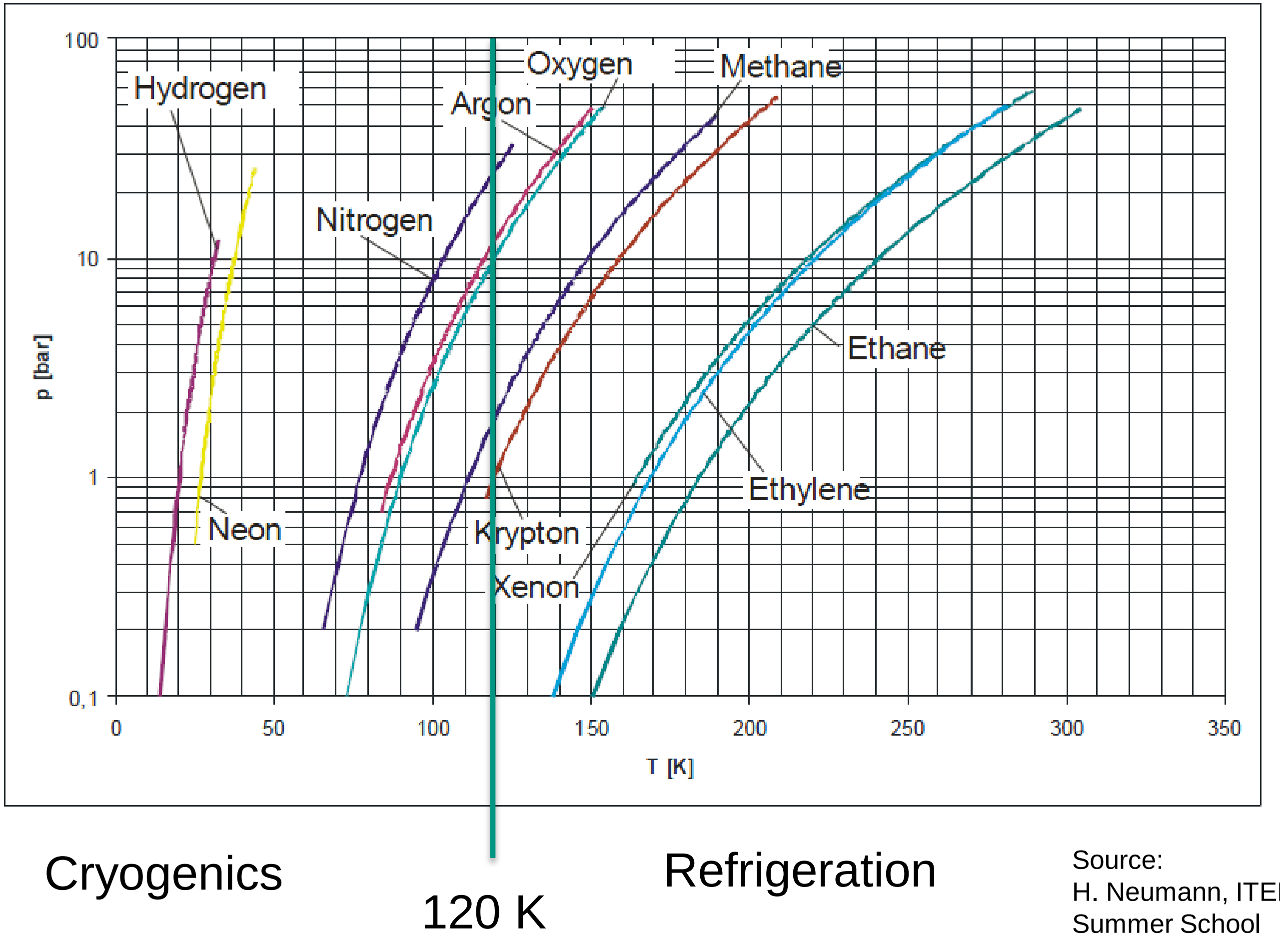
- Example: 2kW helium liquefier at ITEP



Source:
ITEP Homepage

Cryogenic fluids

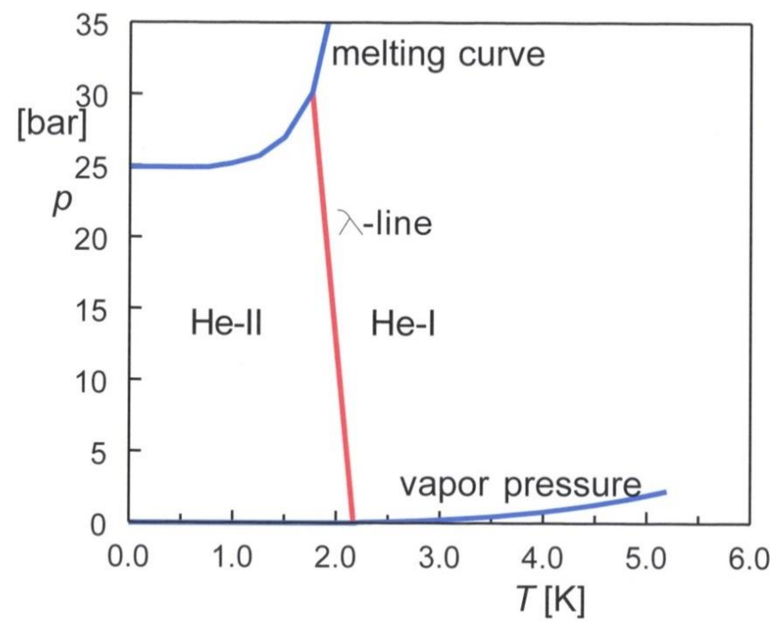
- Vapor-pressure curves



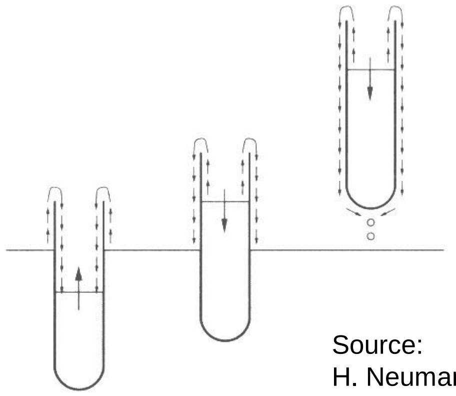
Source:
H. Neumann, ITEP, KIT, 2013 ESAS Summer School

Cryogenic fluids (Helium)

- Specifics of helium
  - λ –line separates
    - LHe I
    - LHe II (superfluid)
      - Very high thermal conductivity
      - No boiling
      - Onnes-effect



Source:
Wikipedia „Helium“



Source:
H. Neumann, ITEP, KIT, 2013 ESAS Summer School

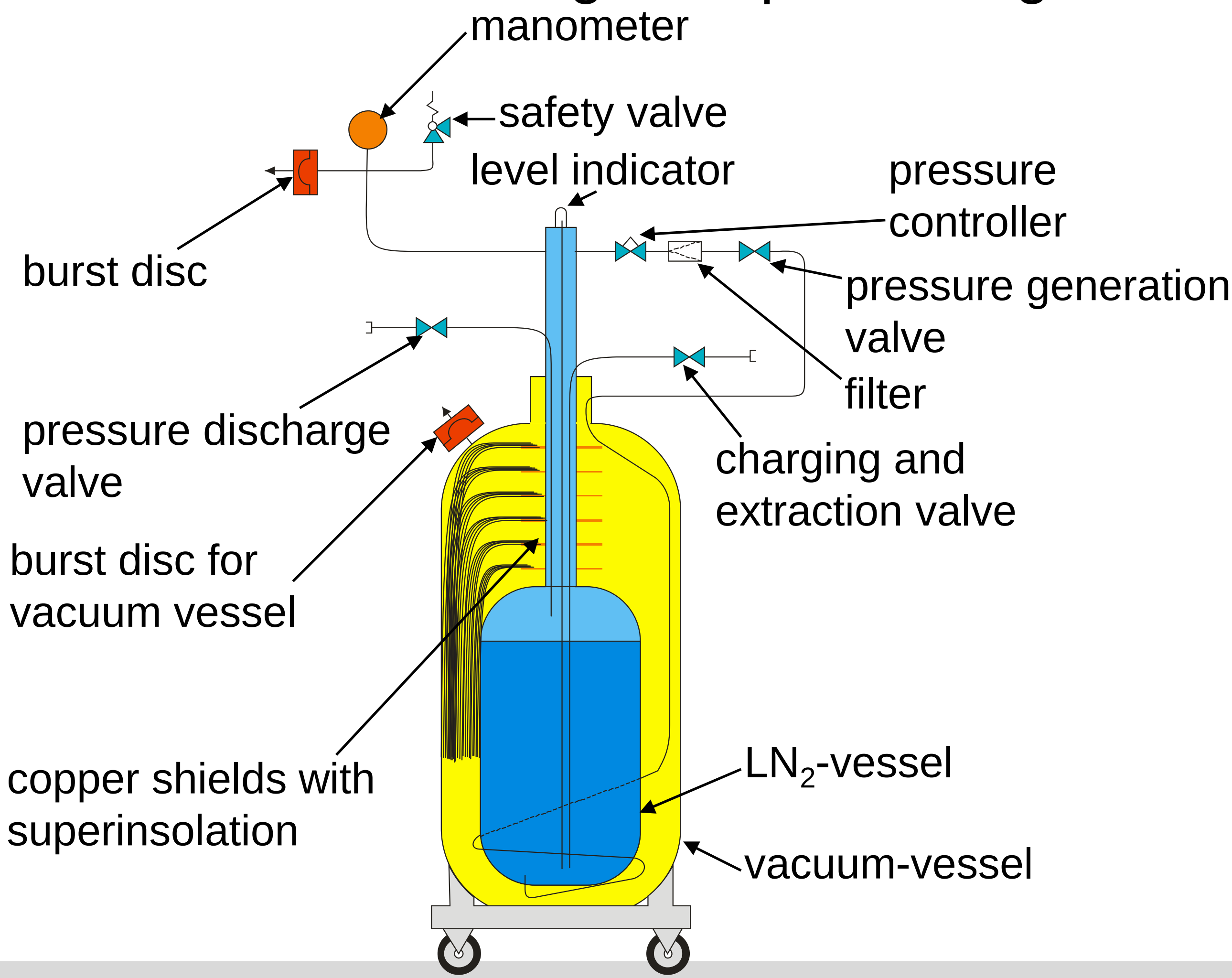
Material Properties

- To take into account:
  - Heat conductance
    - varies with decrease in T
  - Thermal contraction
    - different contractions of different materials
  - Mechanical characteristics
    - elastic limit and modulus increase ☺
    - ductility and plasticity decrease dramatically -> brittleness ☹
  - Consult AD 2000-W10 for materials at cryogenic temperatures

Source:
K.Weiss, ITEP meeting 2012

Cryostats (Layout)

- example: LN2-vessel with integrated pressure generation

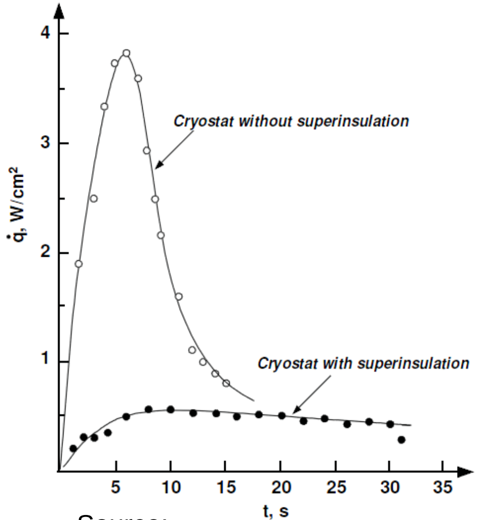


Cryostats (Insulation)

- Types of thermal insulation
  - Powders, foams, fibreglas,…
  - Vacuum Insulation

- MLI (Multi-Layer-Insulation) or SI (Super-Insulation)
  - high vacuum (prevents convection)
  - reflecting layers, e.g. Al foil (reduce radiation)
  - spacer elements,e.g. glas fibre (have low heat conductivity

Source: V. Chrz
http://indico.cern.ch/getFile.py/access?sessionId=3&resId=0&materialId=0&confId=90787



Source:
Lehmann/Zahn, 1978, Proc. CEC

Cryostats (CERN)

- Example: CERN, the largest cryogenic system in the world
  - 36,000 t of SC magnets (NbTi wires) operate at 1.9 K
  - Need of 136 t of helium (superfluid below 2.17K, very high thermal conductivity -> efficient heat conductor)
  - Closed LHe circuit, 27 km long
  - Entire cooling process takes weeks to complete

Source: Cern website
http://home.web.cern.ch/about/engineering/cryogenics-low-temperatures-high-performance

Cryostats (CERN)

Compressor unit of the 4.5 K refrigerator

Source: Cerncourier
http://cerncourier.com/cws/article/cern/54382

- 8 units in the complete system
- Each cryoplant consists of 3 stages
  1. RT-> 80 K
     using 10,000 t LN2 in HX (600 kW)
  2. 80 K -> 4.5 K
     using refrigerator with cooling capacity of 18 kW at 4.5 K
  3. 4.5 K ->1.9 K
     using refrigerator with cooling capacity of 2.4 kW at 1.8 K

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Cryostats (Temperature Measurement)

- **temperature measurement**
  - low temperature sensors (secondary temperature sensors)
    - ***resistive sensors***
      - *negative temperature coefficient (NTC)*
        - carbon - glas sensor (CG)
        - Cernox (CX1050)
        - carbon sensor (Allen Bradley C100)
        - germanium (Ge)
        - carbon composite (TVO)
      - *positive temperature coefficient (PTC)*
        - platinum sensor (Pt100)
        - rhodium - ferric - sensor (RhFe)

diodes

Si - diodes
GaAlAs - diodes

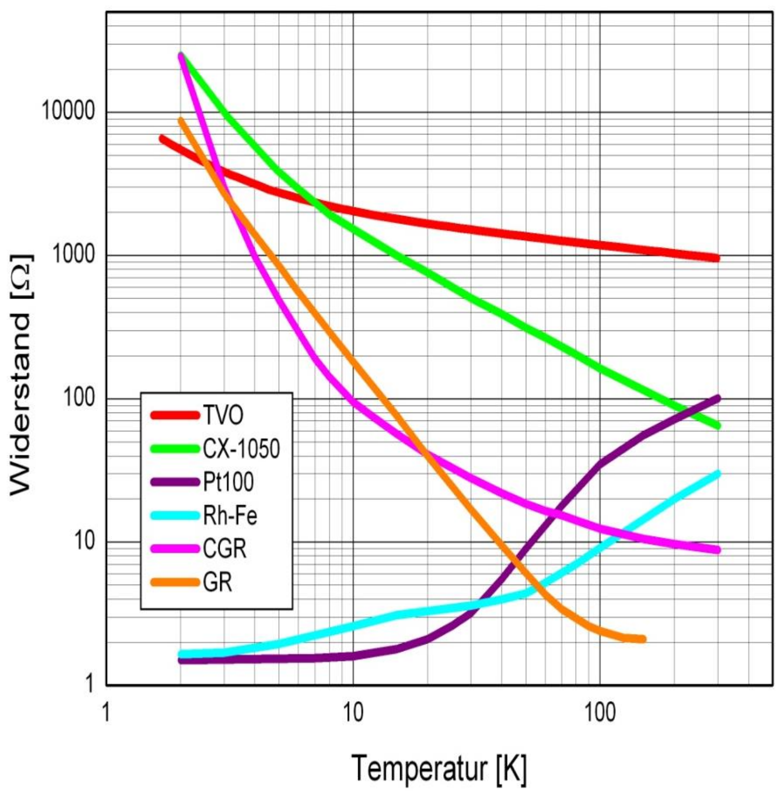
others

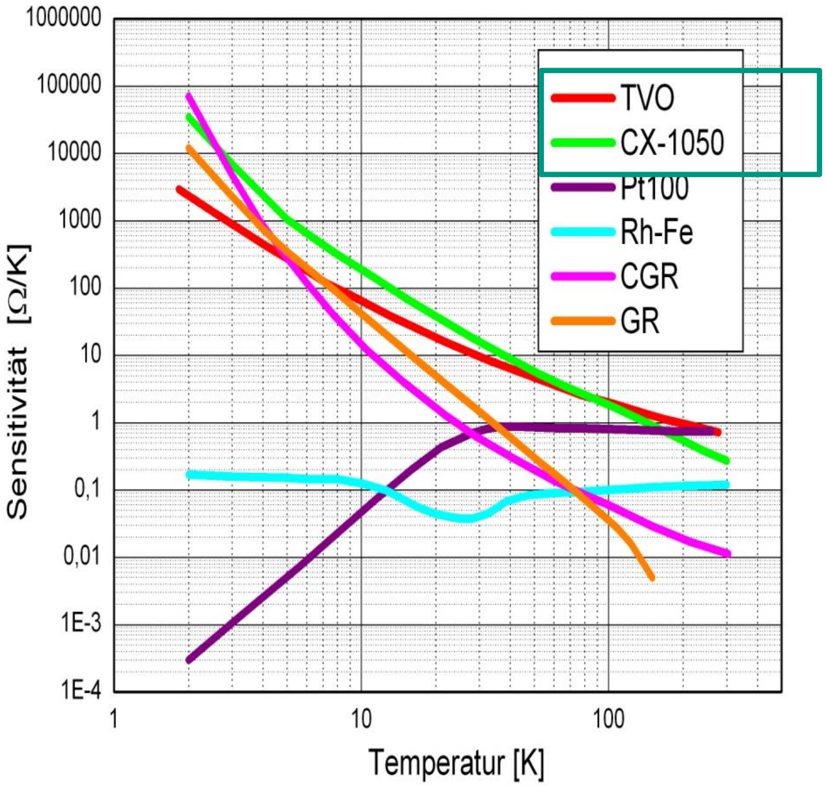
thermocouple (CuKo)
CLTS (Cryogenic Linear Temperature Sensor)
capacity thermometers

(by M. Süßer)

Cryostats (Temperature Measurement)

- Characteristic curves of resistive sensors

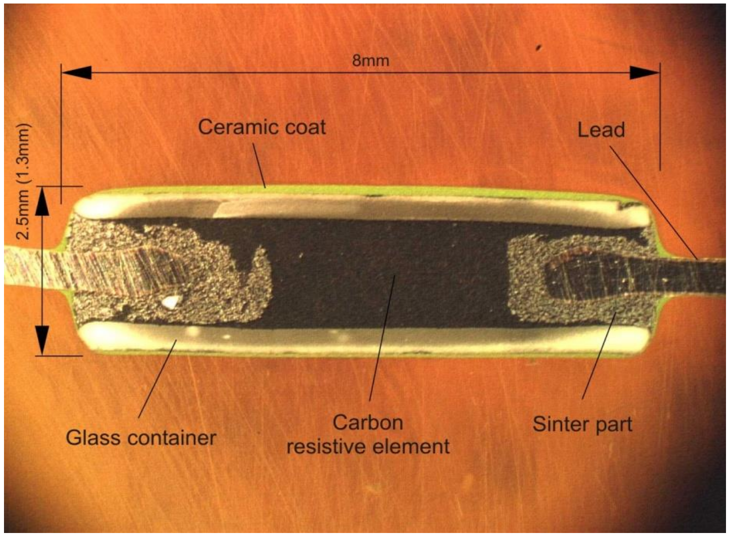




Source: M.Süßer, Einführung in die Tieftemperaturmesstechnik

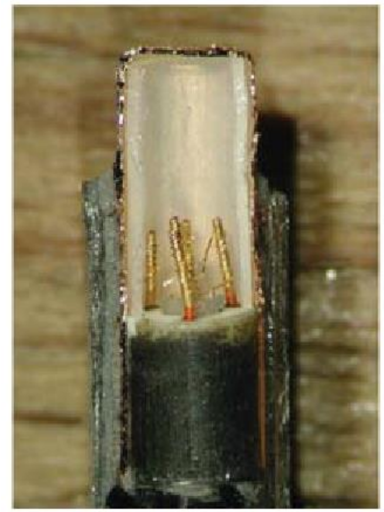
Cryostats (Temperature Measurement)

- TVO



  - Carbon- Al_2O_3 Compound
  - Calibration at ITEP
  - Costs ~ 400 €
  - Able to work under high pressure and stress

- Cernox

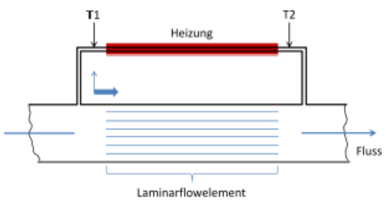


  - Zirconium-Nitrit-film on saphir body
  - Lakeshore
  - Costs ~650€

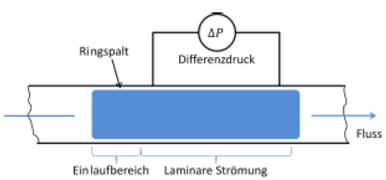
Source: M.Süßer, Einführung in die Tieftemperaturmesstechnik

Cryostats (Mass flow measurement)

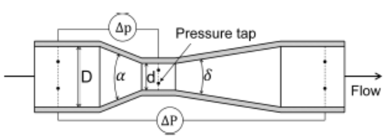
- Mass flow measurement



System	Einsatzgebiet	Messgröße
Thermischer Durchflussmesser	Prozesssteuerung	$q \sim \Delta T$



System	Einsatzgebiet	Messgröße
Laminarflow-element	Präzisionsmessung	$q \sim \Delta P$



System	Einsatzgebiet	Messgröße
Venturi-Rohr	Messung bei flüssig Helium Temperatur	$q \sim \sqrt{\Delta p}$

Source: M.Schrank, DKV-Tagung 2012

Cryostats (Safety)

- Safety standards:
  - DIN EN 13648
  - EN ISO 4126
  - AD 2000
  - To come: DIN SPEC 4683 „Überdruck-Absicherung von Helium-Kryostaten“

Sources

- Information on Cryogenics:
  - H. Neumann, ITEP, KIT, Talk at 2013 ESAS International Summer School oh Materials and Applications of Superconductivity, 1st August 2013
  - M.Schrank, Introduction to cryogenics, Vortrag beim Young Scientists Workshop 2013, Kristberg
- Information on Dewar vessels and MLI:
  - V. Chrz, Chart Ferox, http://indico.cern.ch/getFile.py/access?sessionId=3&resId=0&materialId=0&confId=90787 Information on Cryogenic Measurement
- Information on CERN Cryogenics :
  - http://cerncourier.com/cws/article/cern/54382
  - http://home.web.cern.ch/about/engineering/cryogenics-low-temperatures-high-performance
- Information on Cryogenic Measurement
  - M. Süßer, Einführung in die Tieftemperaturmesstechnik, Interner Bericht FE.5130.0013.0012/N
  - M. Schrank, Gasdurchflussmessung in der Kryotechnik, Vortrag bei der DKV-Tagung 2012, Würzburg
- Information on Helium Cryogenics Safety
  - W. Lehmann/ G. Zahn, Safety aspects for Lhe cryostats and Lhe transport cpntainers, Proc. ICEC, London, 1978, Vol. VII, 569-579

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Outline – Superconductors

- Phenomenology and electromagnetic description
- Classification
- Theory of superconductivity
- Applications of superconductors

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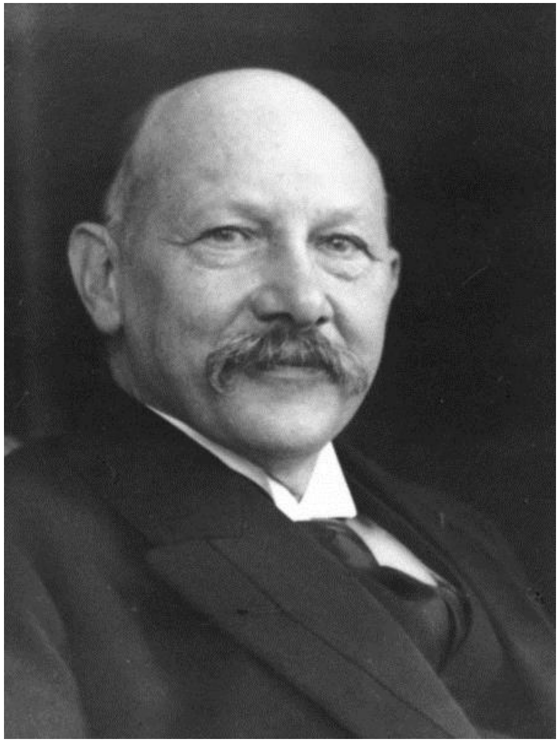
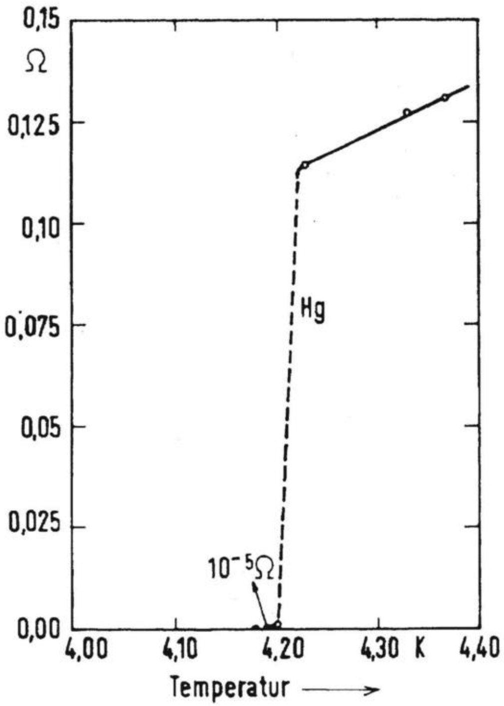
Discovery of the superconductivity



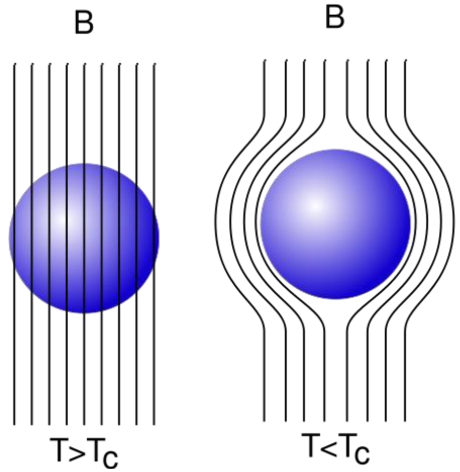


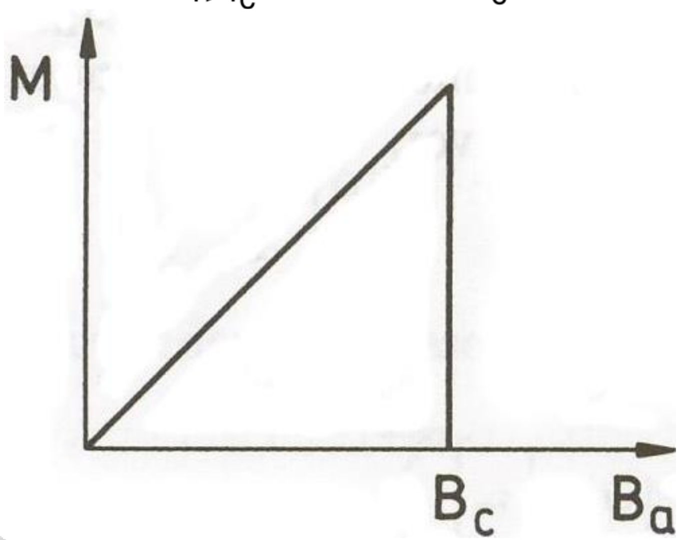
- 1908 Liquefaction of helium experiments at 1.5 K
- 1911 Discovery of superconductivity in mercury

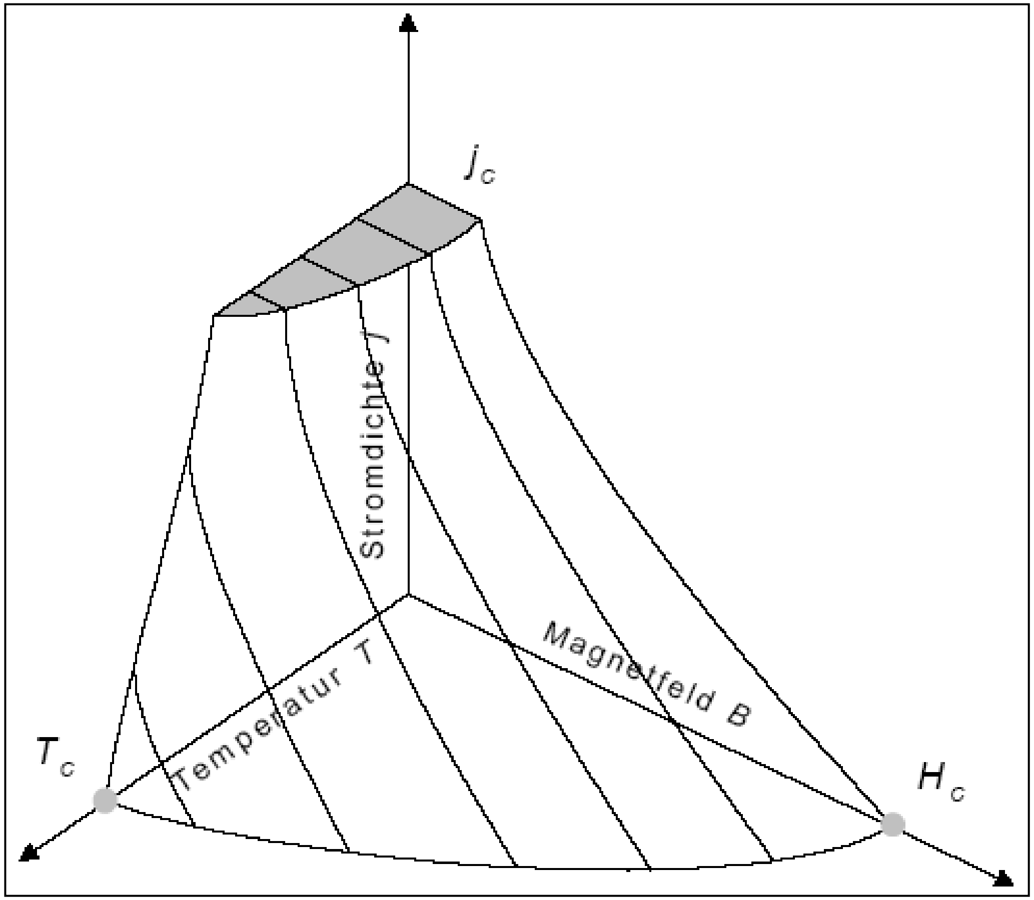
http://www.nobelprize.org, http://hoffman.physics.harvard.edu

Characteristics of Superconductivity

- 1933 Meissner effect







http://en.wikipedia.org

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London equations

- Behaviour of electromagnetic fields in superconductor:

$$\vec{j} = \sigma \vec{E}$$

  - 1st London equation: $$\frac{d\vec{j}_s}{dt} = \frac{1}{\mu_0 \lambda^2} \vec{E}$$
  - 2nd London equation: $$\text{rot } \vec{j}_s = -\frac{1}{\mu_0 \lambda^2} \vec{B}$$
  - London penetration depth: $$\lambda^2 = \frac{m_s}{\mu_0 n_s e_s{}^2}$$

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Meissner effect

4th Maxwell equation + 2nd London eqaution

$$\vec{j}_s = \frac{1}{\mu_0} \text{rot}\, \vec{B} \qquad \text{rot}\, \vec{j}_s = -\frac{1}{\mu_0 \lambda^2} \vec{B}$$

rot ⇓ ⇓

$$\text{rot}\, \vec{j}_s = \frac{1}{\mu_0} \text{rot rot}\, \vec{B} \quad \Rightarrow \quad -\frac{1}{\mu_0 \lambda^2} \vec{B} = \frac{1}{\mu_0} \text{rot rot}\, \vec{B}$$

$\text{rot rot}\, \vec{B} = \text{grad div}\, \vec{B} - \Delta \vec{B}$; 2nd Maxwell eq.: $\text{div}\, \vec{B} = 0$

$$\Rightarrow \boxed{\Delta \vec{B} - \frac{1}{\lambda^2} \vec{B} = 0} \xrightarrow{\vec{B} = B \cdot \vec{e}_z} \boxed{B(x) = B_a e^{-x/\lambda}}$$

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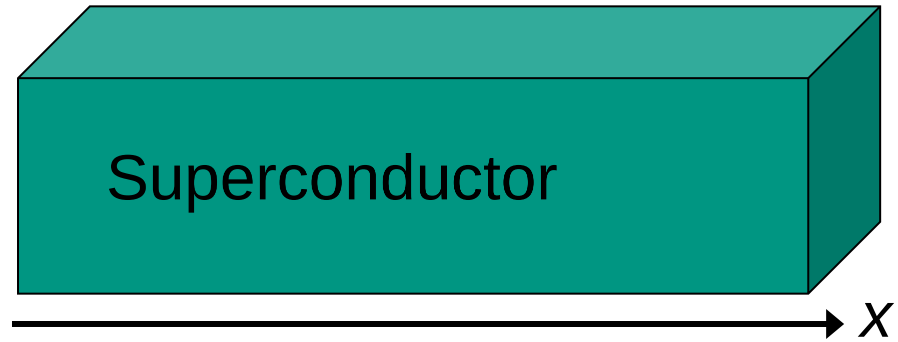
Critical current density



$$\vec{B} = B \cdot \vec{e}_z$$

$$\vec{j}_s = \frac{1}{\mu_0} \operatorname{rot} \vec{B}$$

$$B(x) = B_a e^{-x/\lambda}$$

$$\vec{j}_s(x) = \frac{1}{\mu_0} \operatorname{rot}\left(B_a e^{-x/\lambda} \cdot \vec{e}_z \right)$$

$$\vec{j}_s(x) = \frac{1}{\mu_0 \lambda} B_a e^{-x/\lambda} \cdot \vec{e}_y$$

- j_s → Screening current
- $j_s > j_c$ → break down of SC

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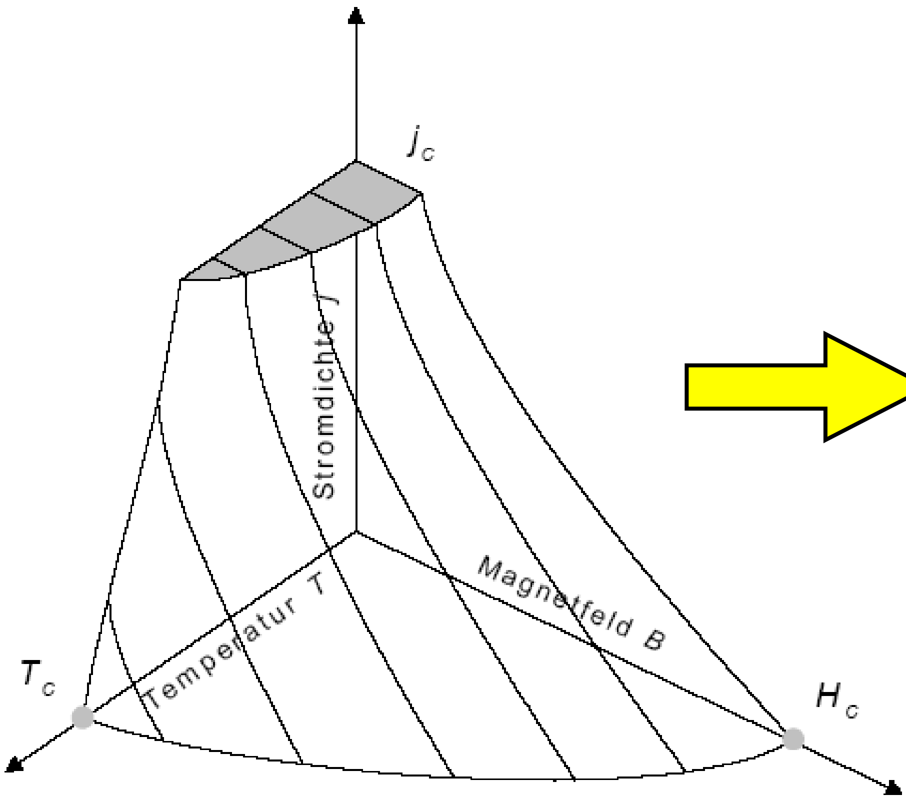
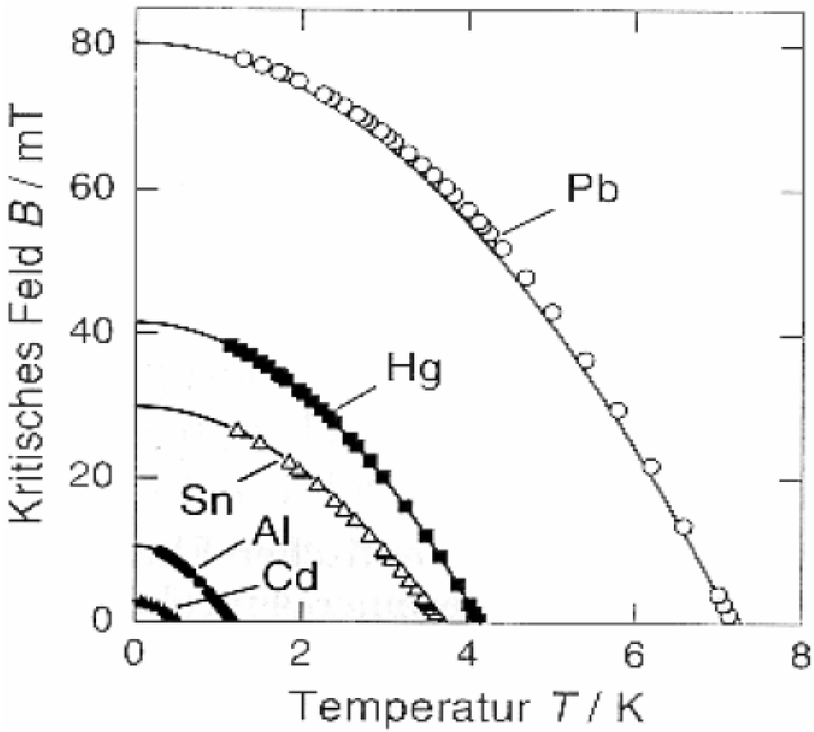
Classification – Type-I superconductors

- Phase diagram in *B*,*T*-plane:





$$B_c(T) = B_c(0)\left[1-\left(T/T_c\right)^2\right]$$

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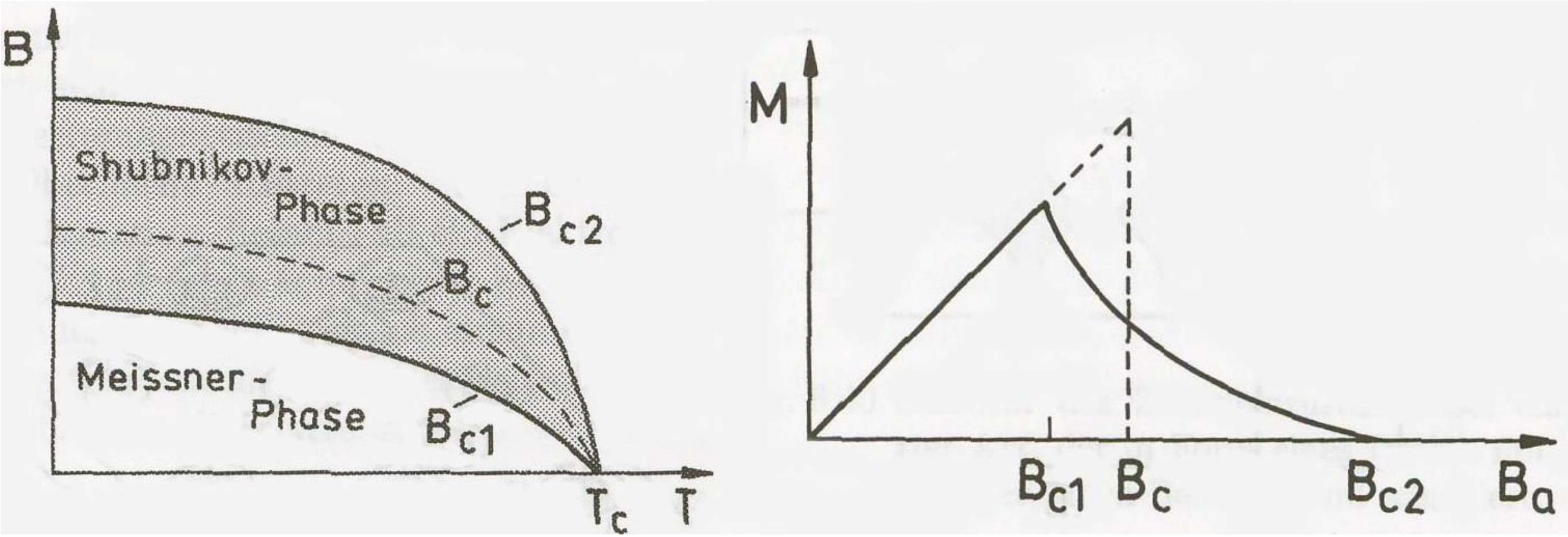
Classification – Type-II superconductors

- $B < B_{c1}$: Meissner phase
- $B_{c1} < B < B_{c2}$: Shubnikov phase
- $B_{c2} < B$: break down of SC



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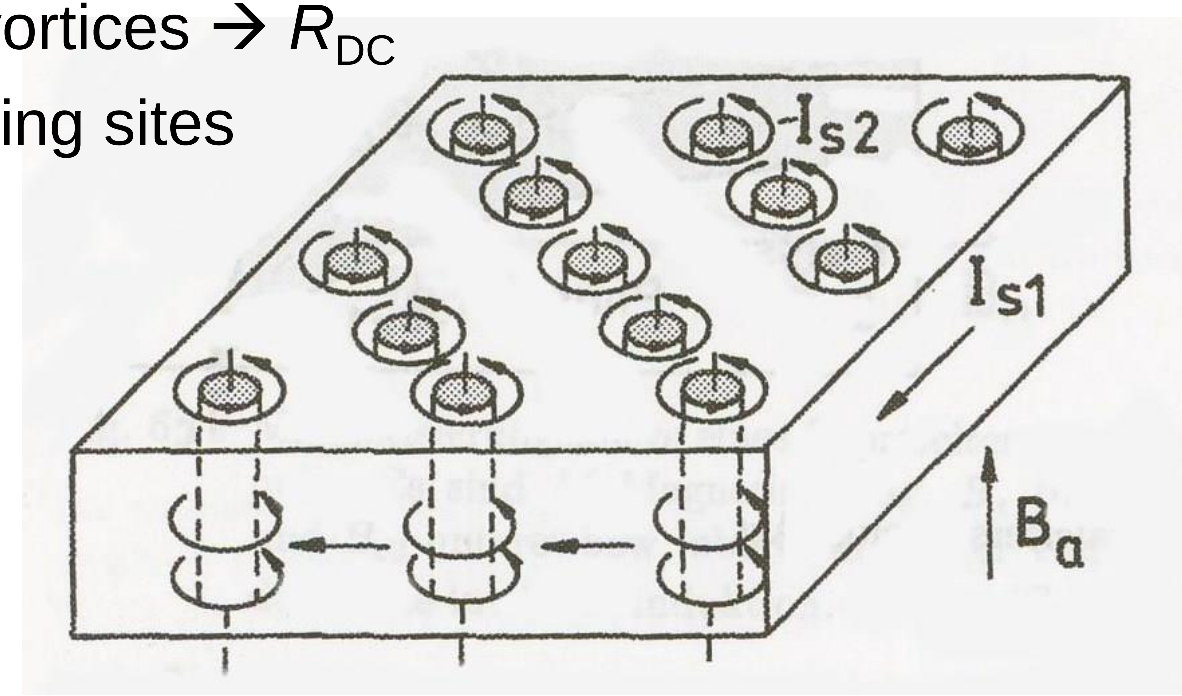
Classification – Type-II superconductors

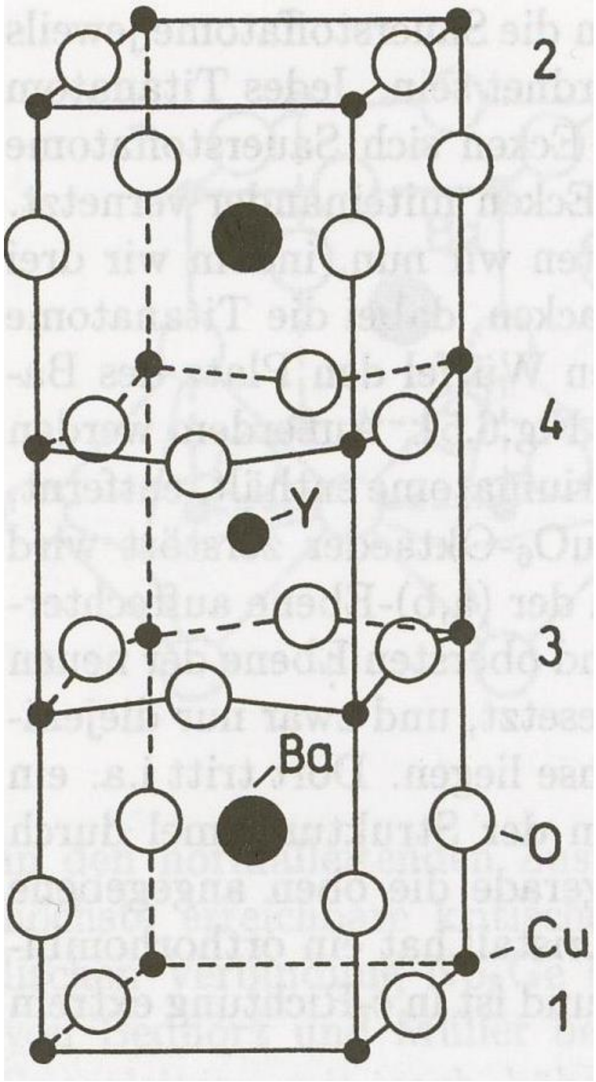
- $B_{c1} < B < B_{c2}$: Shubnikov phase
  - Vortices carry magnetic flux
  - Magnetic flux quantum Φ_0
  - Movement of vortices → R_{DC}
  - Defects = Pinning sites



Abrikosov vortex lattice

Classification – High temperature SC

- 1986 Bednorz & Müller
- Ceramics
  Cuprates: $YBa_2Cu_3O_{7-x}$
- T_c > 77 K
  Liquid nitrogen or cryogen free cooling
  Maximum: T_c ~ 135 K
- Lack of theory



Classification

	Material	T_c (K)	$B_{c(2)}$ (T)
Type-I SCs	Al	1,19	0,0099
	Hg	4,15	0,0412
	Pb	7,2	0,0803
Type-II SCs	Nb	9,2	0,27
	Ta	4,39	0,18
	Nb_3Ge	23	30
	$PbMo_6S_8$	15	45
HTSC	$YBa_2Cu_3O_7$	93	30 bis 60
	$Te_2Ca_2Ba_2Cu_3O_x$	135	100 bis 120

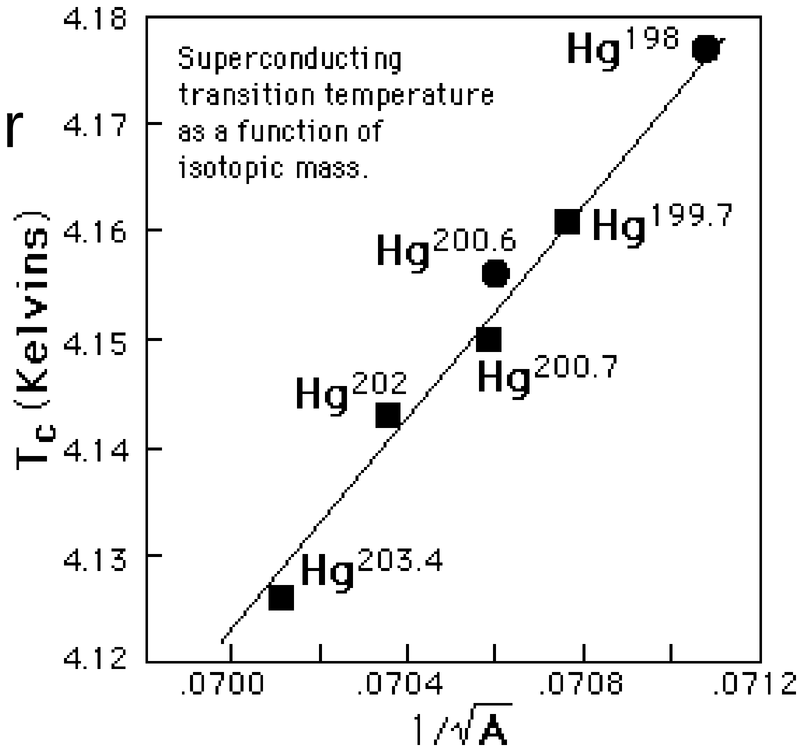
BCS theory (1)

- London equations: electromagnetic, phenomenologic
- Ginzburg-Landau theory: thermodynamic, phenomenologic

- Quantum mechanics?
- 1957 Bardeen, Cooper, Schrieffer
- Postulation of Cooper pairs
  - Attractive force between 2 electrons

$$T_C \propto \frac{1}{\sqrt{M}}$$

M – atomic mass



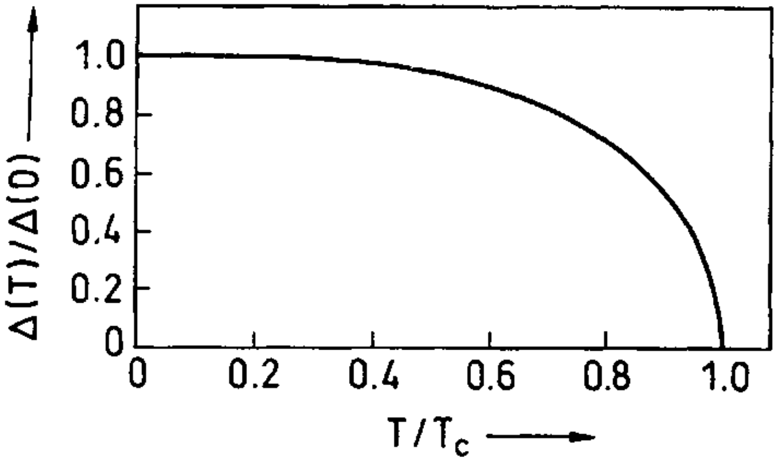
http://hyperphysics.phy-astr.gsu.edu

BCS theory (2)

- Postulation of Cooper pairs
  - (**k**,↑) and (-**k**,↓) → spin and momentum zero
  - Bosonic macroscopic state

$$\psi = \sqrt{n_s} \cdot e^{i\varphi}$$

  - Binding energy of Cooper pair: 2Δ
  - No DC resistance below excitations of 2Δ



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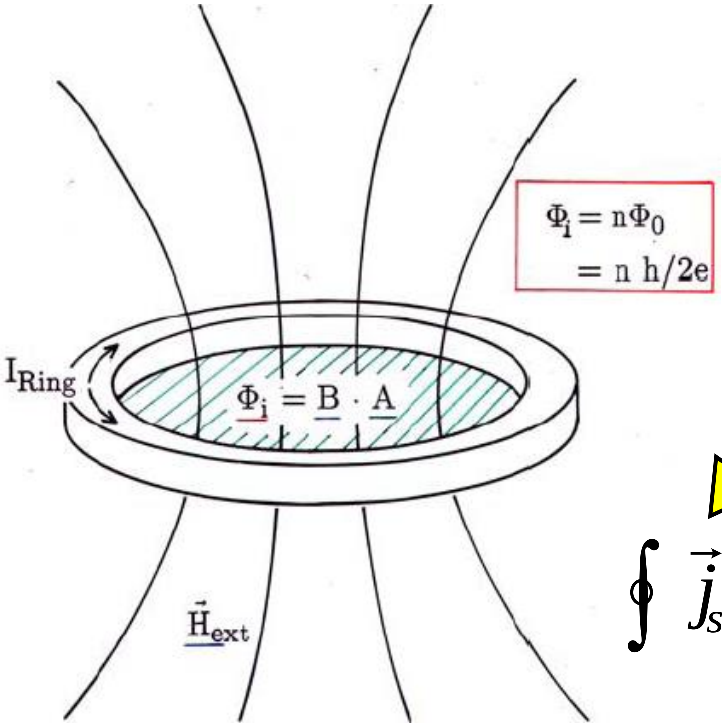
Flux quantisation



$$\mu_0 \lambda^2 \vec{j}_s = \frac{\hbar}{e_s} \operatorname{grad} \varphi - \vec{A}$$

no current inside the ring

$$\oint \vec{j}_s \, d\vec{s} = 0$$

ψ uniformly continuous

$$\oint \operatorname{grad} \varphi \, d\vec{s} = 2\pi n$$

Stokes

$$\oint \vec{A} d\vec{s} = \int_A \vec{B} d\vec{A} = \Phi_A$$

$$\Phi_A = {h \over e_s}\, n = n\,\Phi_0$$

Φ_0 = h/2e = 2,0678 10^{-15} Tm^2

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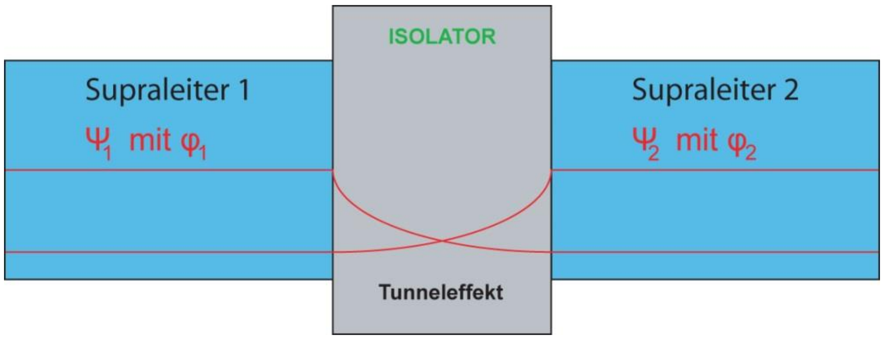
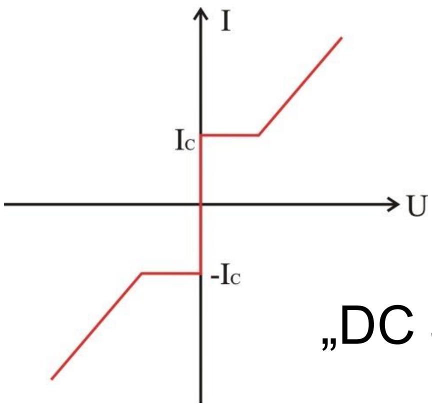
Josephson devices

- 1st Josephson equation

$$I_S = I_C \cdot \sin(\varphi_2 - \varphi_1)$$



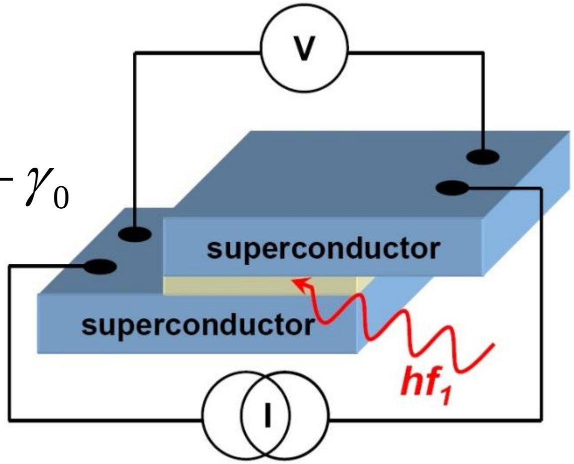


„DC Josephson effect“

- 2nd Josephson equation

$$\frac{d}{dt}(\varphi_2 - \varphi_1) = \frac{2\pi}{\Phi_0} \cdot U \quad \Rightarrow \quad \varphi_2 - \varphi_1 = \left(\frac{2\pi}{\Phi_0} U\right) \cdot t + \gamma_0$$

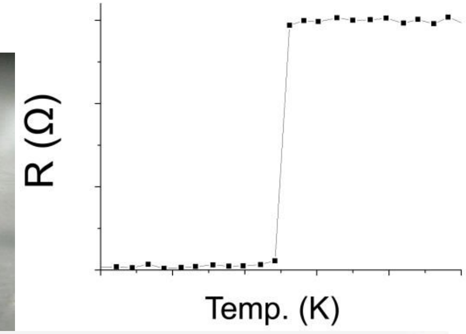
$$I_S = I_C \cdot \sin\left(\frac{2\pi}{\Phi_0} U \cdot t + \gamma_0\right) \quad \Rightarrow \quad f = \frac{2e}{h} \cdot U$$

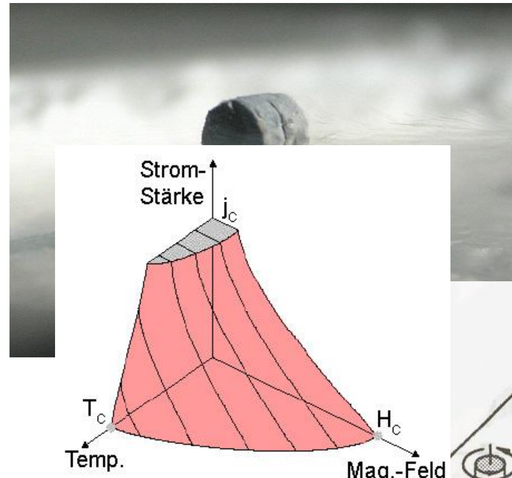


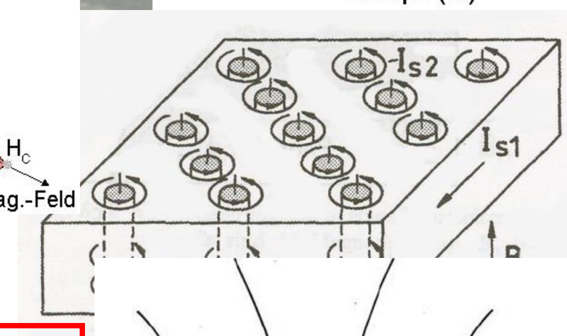
„AC Josephson effect“

Summary of superconductor basics

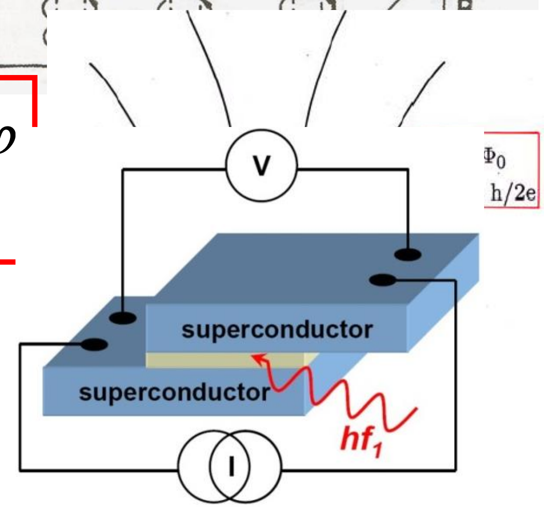
- R_{DC} = 0 & Meissner effect
- Critical values: T_c, j_c, B_c
- Type-I & Type-II SCs
- BCS theory: Cooper pairs
- Flux quantisation
- DC and AC Josephson effect







$$\psi = \sqrt{n_s} \cdot e^{i\varphi}$$



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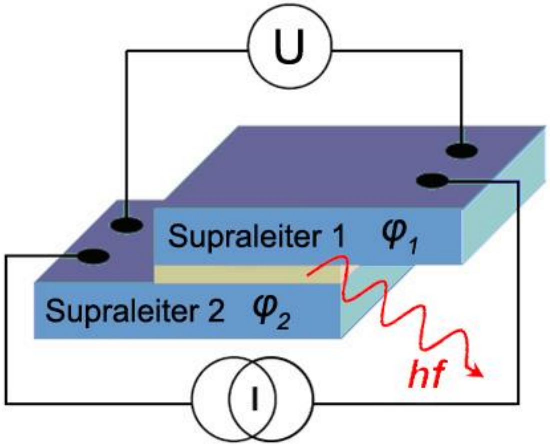
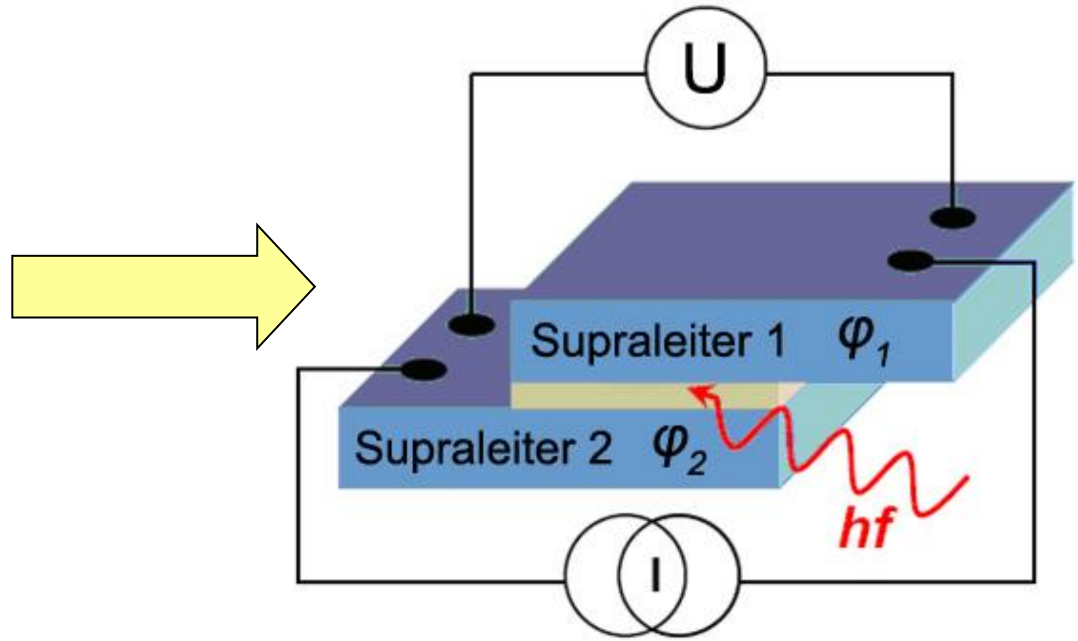
Quantum electronics: Voltage standard

- AC Josephson effect





„Inverse Josephson effect“

$$K_{J-90} = \frac{2e}{h} = 483{,}5979 \frac{GHz}{mV}$$

Quantum electronics: Single Photon Detection

Dark | Timing ...ter | Maximum count rate (s^{-1}) | Energy resolution $E/\Delta E$

PM (Ham...

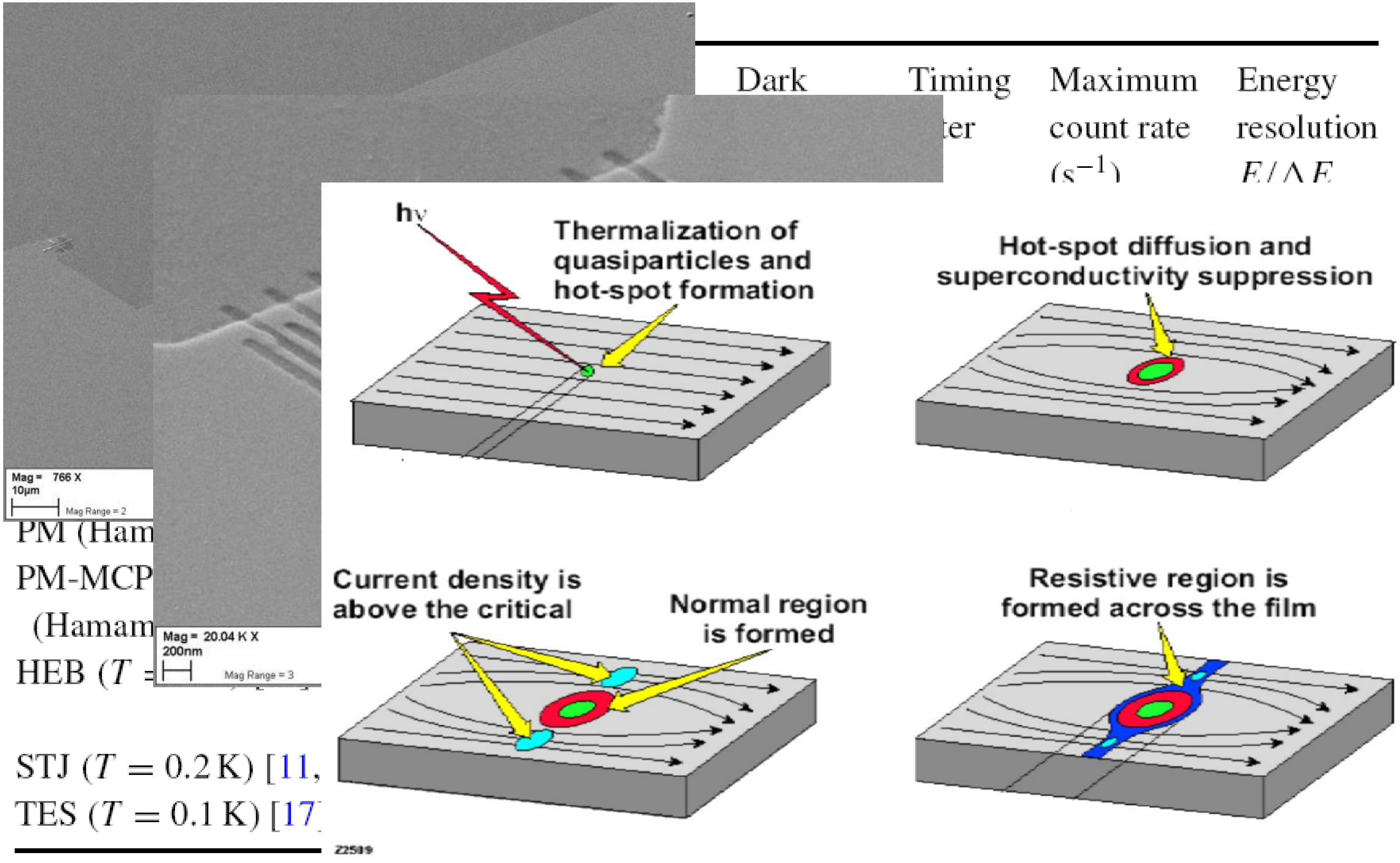
PM-MCP

(Hamam...

HEB (T =...

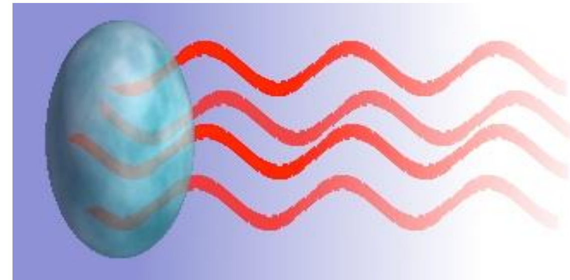
STJ ($T = 0.2\,K$) [11,

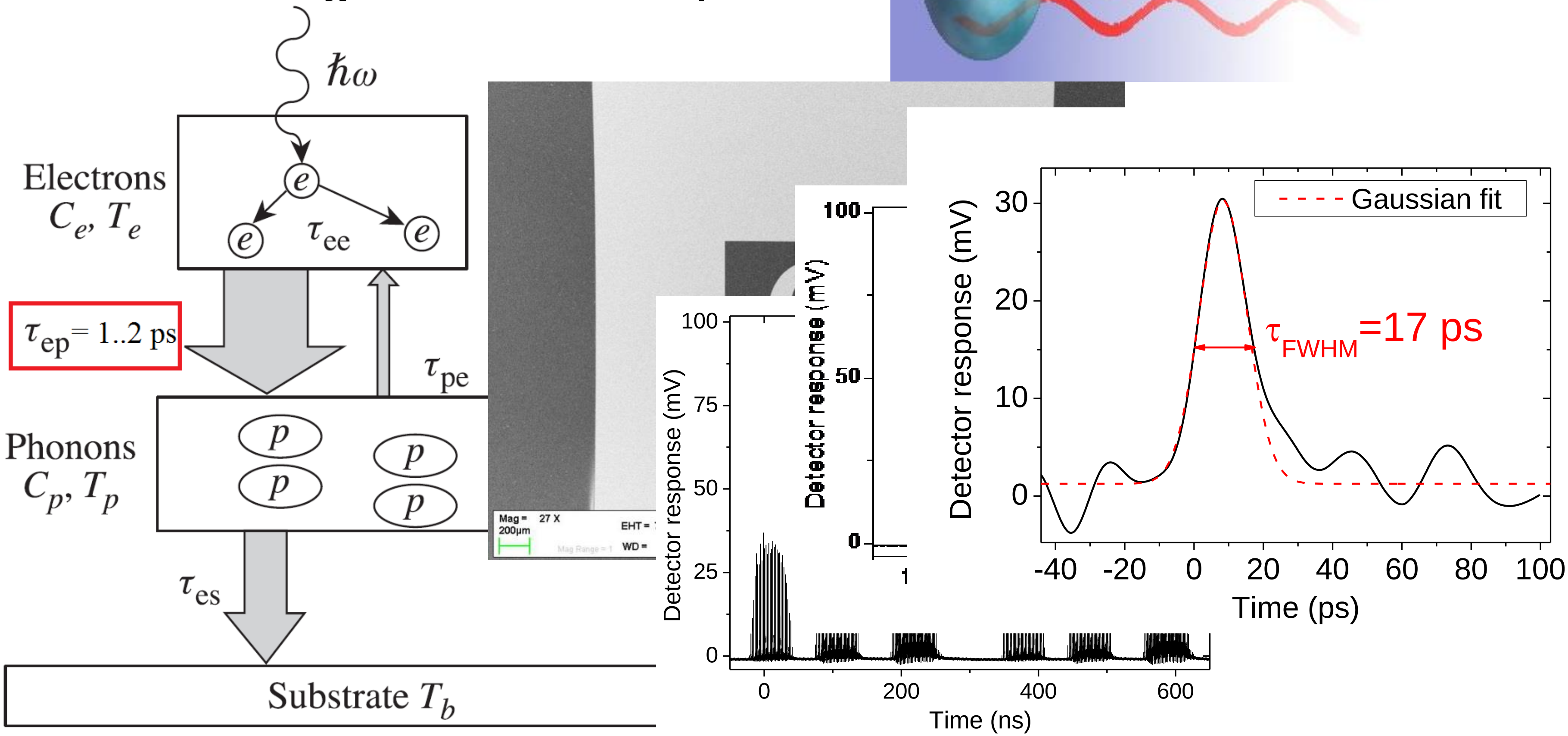
TES ($T = 0.1\,K$) [17



Ultra-fast THz detection with $YBa_2Cu_3O_{7-x}$

- Coherent Synchrotron Radiation bunch lenghts down to 1 ps





M. Klein, Studies of Bunch Distortion in the Generation of Coherent THz-Radiation at the ANKA Storage Ring, DPG 2009

A.D. Semenov, G.N. Gol'tsman, R. Sobolewski, Supercond. Sci. Technol. 15, R1 (2002)

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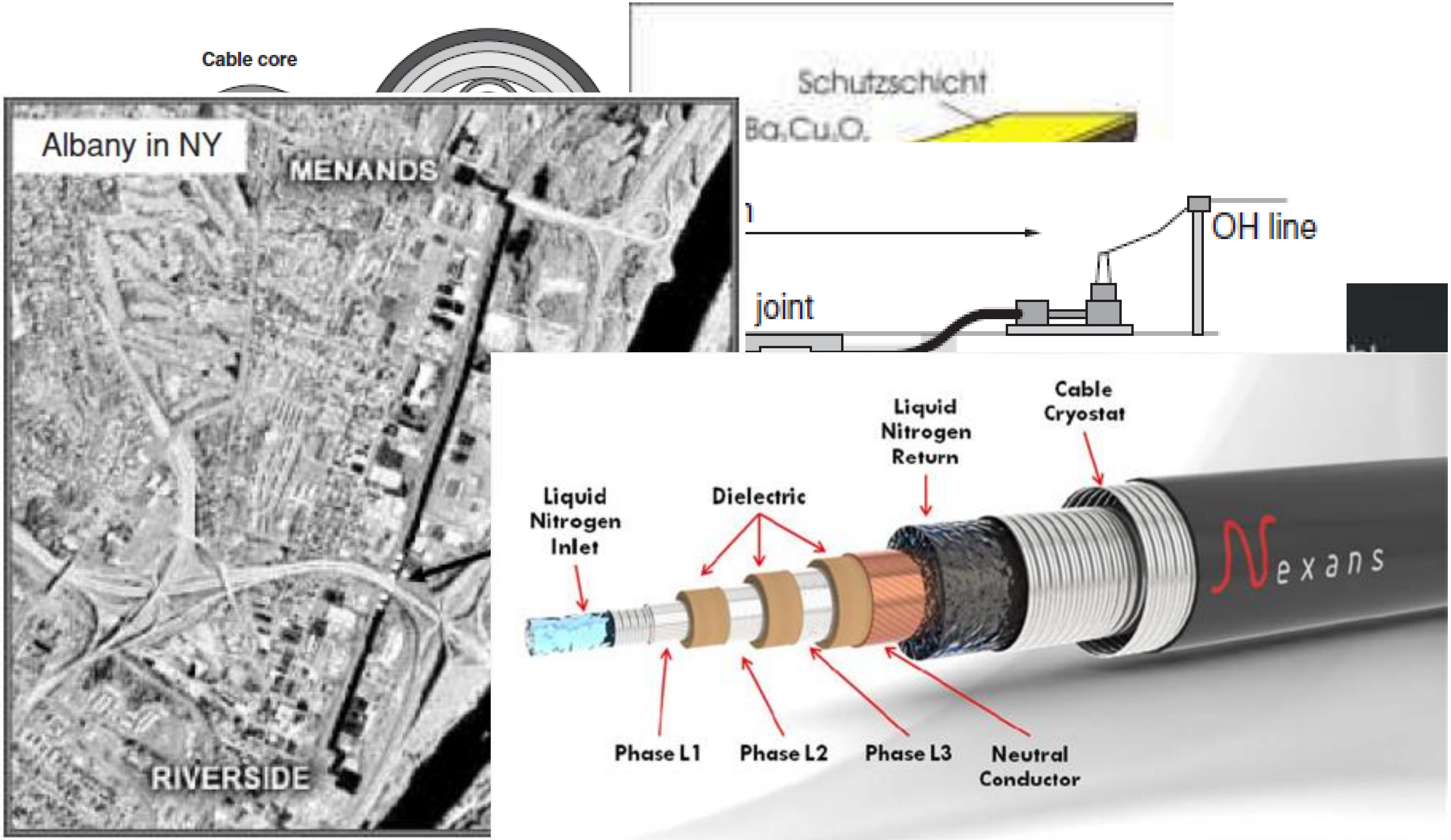
Magnetic Levitation Systems

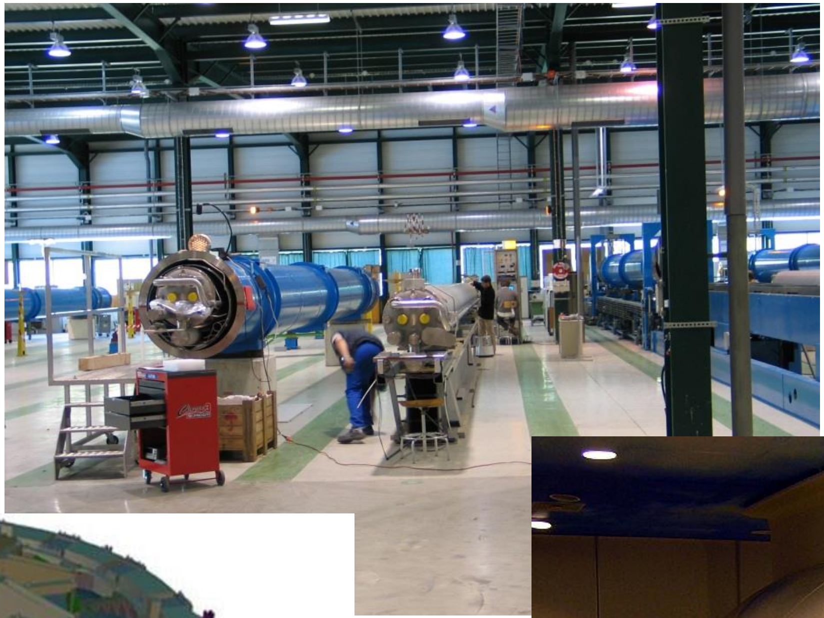
http://en.wikipedia.org

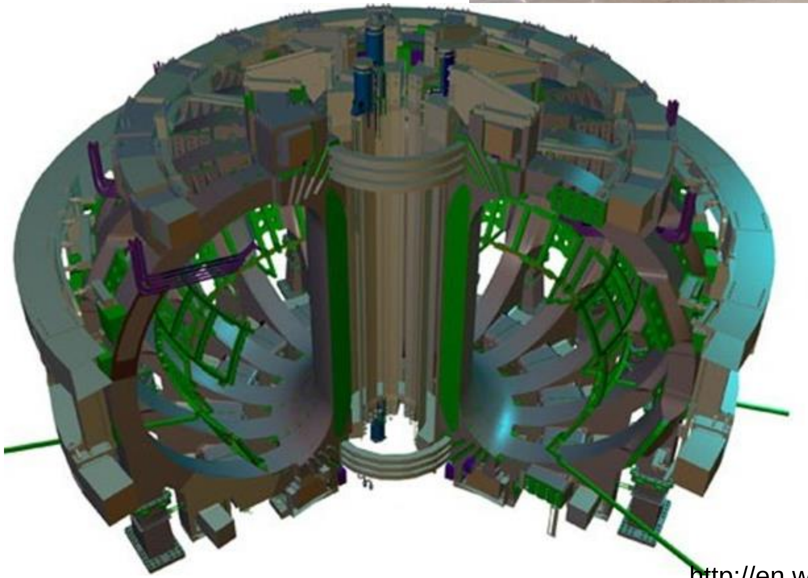
Low-loss power cables



T. Masuda et al., High-temperature superconducting cable technology and development trends
http://www.nexans.de, http://www.itep.kit.edu/66.php

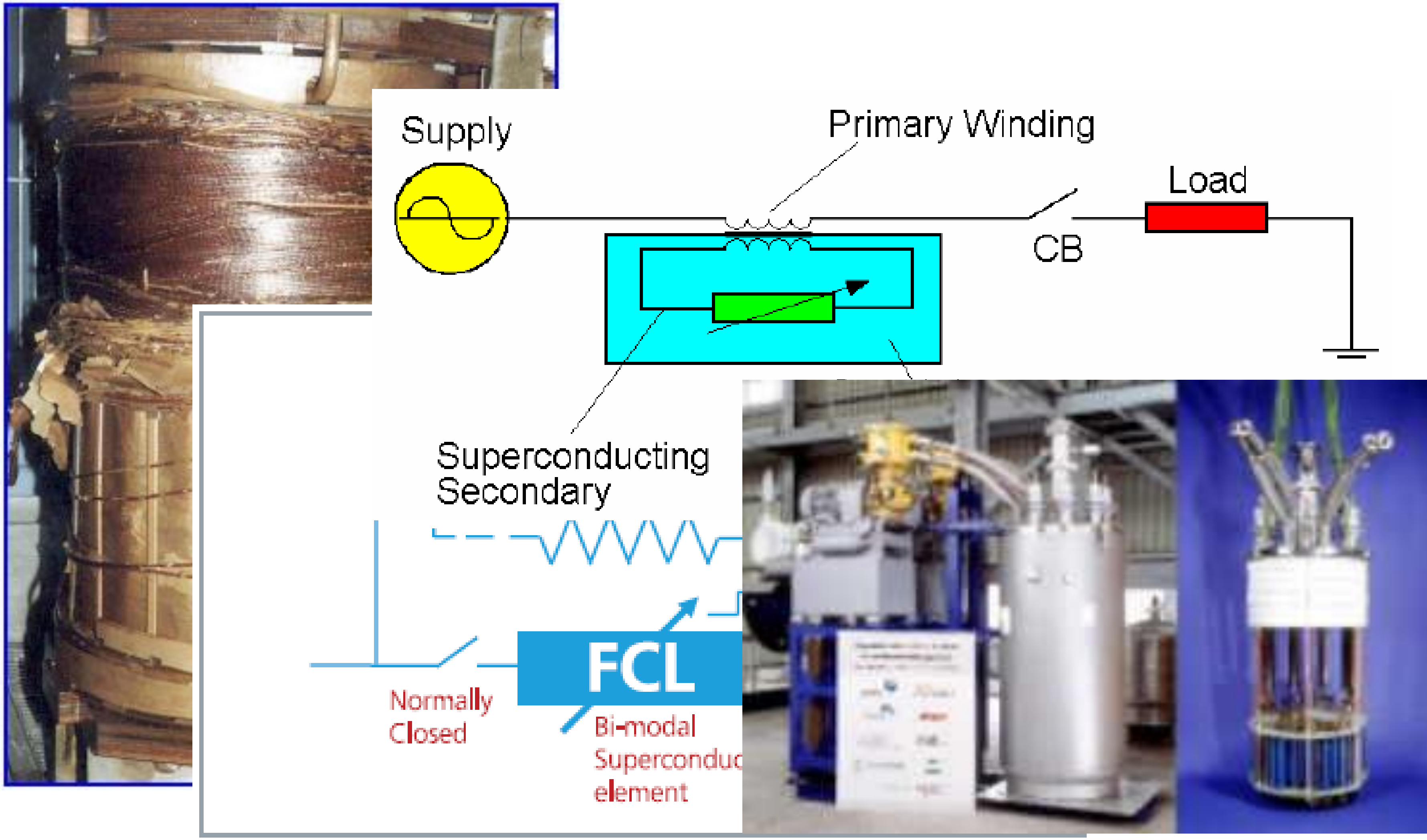
Superconducting Coils





http://en.wikipedia.org, http://www.iter.org/mach/magnets, http://lhc-machine-outreach.web.cern.ch

HTS Fault Current Limiters



F. Mumford, Inductive and Resistive HTS Fault Current Limiters: Prototyping, Testing, Comparing
http://www.amsc.com, http://www.itep.kit.edu/21.php

Thank you for your Attention

Great thanks to H. Neumann, M. Süßer, M. Schrank
and to C. Kaiser, M. Meckbach
for their contribution to this talk

Natur der anziehenden WW

Zwei e^- stoßen sich eigentlich ab (Coulomb-Kraft)

Im Festkörper:

- Durch **Atomgitter** kann effektive Anziehung entstehen
- Erklärung 1: Austausch von virtuellem Phonon
- Erklärung 2: Polarisation des Gitters
- Bindungsenergie im meV-Bereich

⇨ Cooper-Paare können nur in FK auftreten!

⇨ Beleg für Rolle des Atomgitters: Isotopieeffekt:

$T_c \sim M^{-\alpha}$, M = Atommasse

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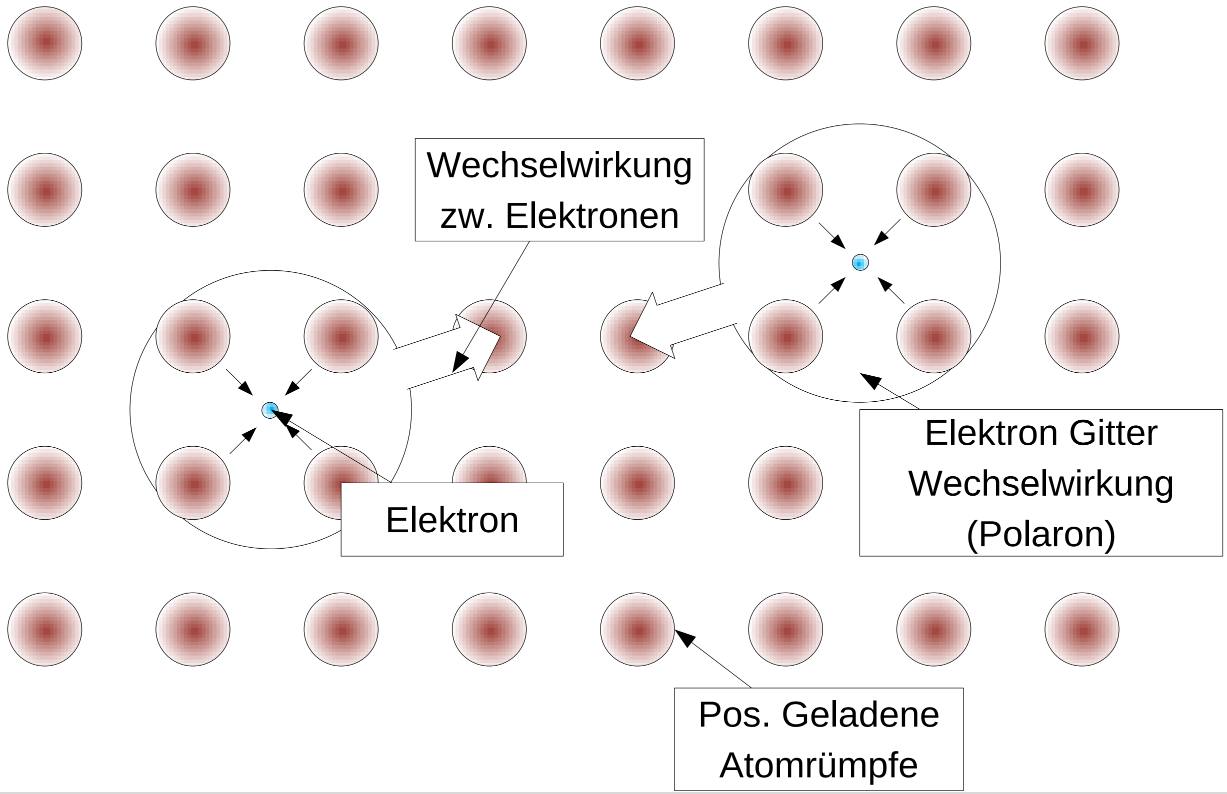
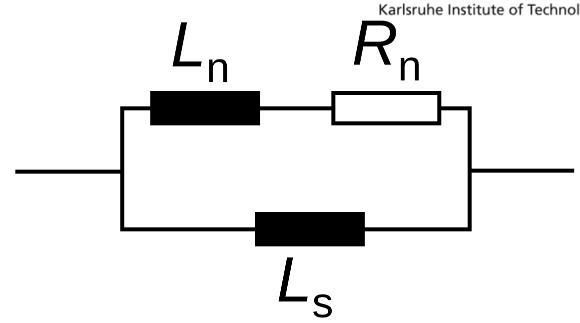
Bildung der Cooper Paare in einem Kristall

- Das 1. Elektron zieht die positiven Atomrümpfe zusammen. Das Elektron bewegt sich schneller als die Atomrümpfe, es bildet sich eine lokale Polarisation die das 2. Elektron anzieht



HF-Eigenschaften

Hochfrequenzverhalten von SL:



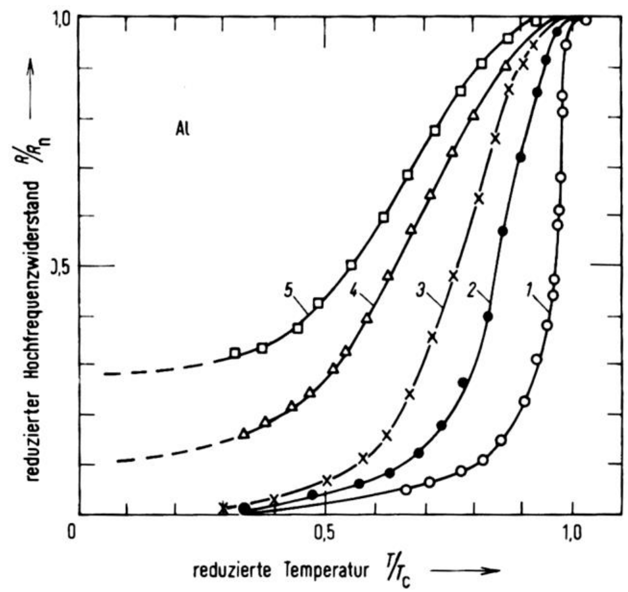
- Zwei-Flüssigkeits-Modell

  a) CP: haben Masse, d.h. Trägheit
  ⇨ Müssen beschleunigt werden → $L_s \neq 0$

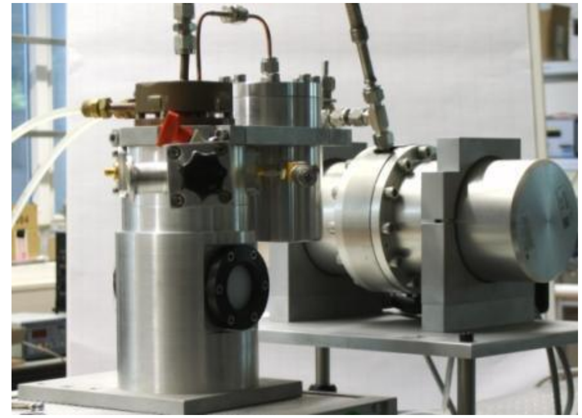
  b) Quasiteilchen (QT): R_n, L_n
  ⇨ Je mehr QT, desto höher R_{HF}

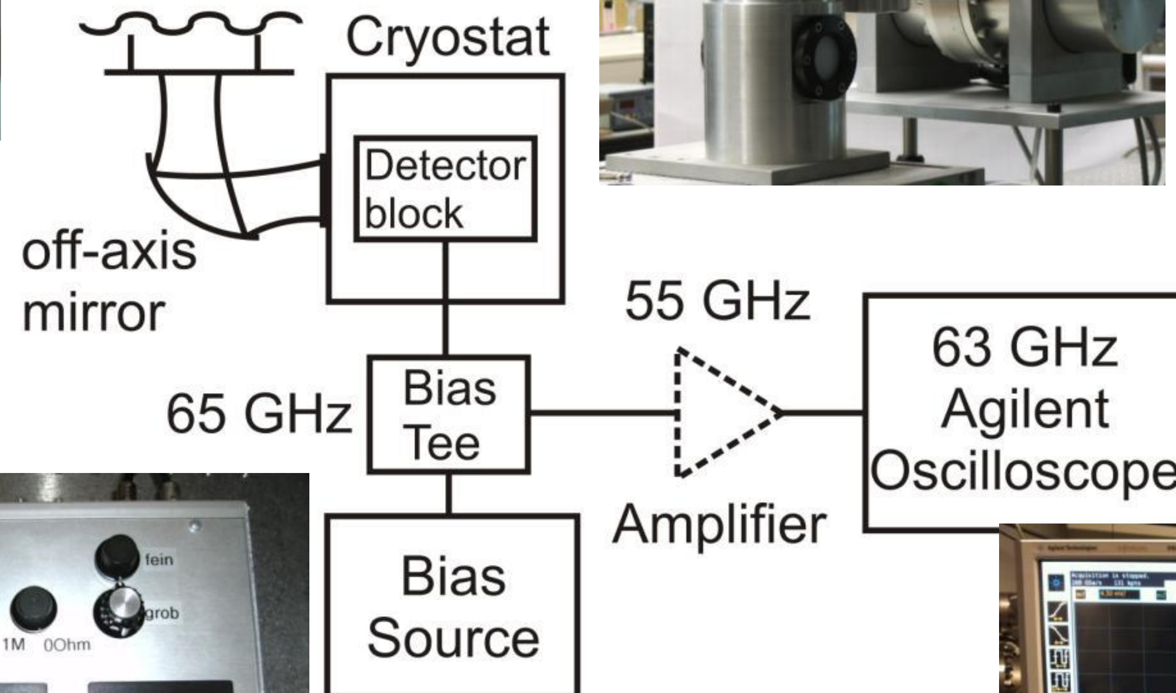
- Frequenzen $hf > 2\Delta$:
  (Fast) wie Normalleiter

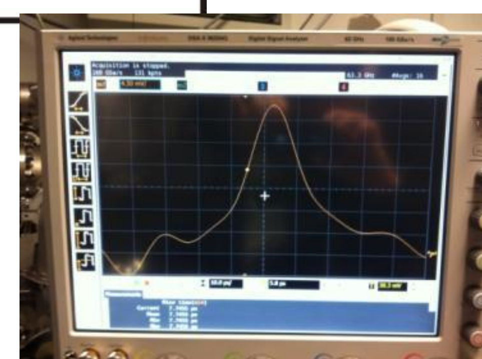
⇨ Vortrag von Herrn Brengartner!



YBCO THz measurements at ANKA, MLS and UVSOR-II







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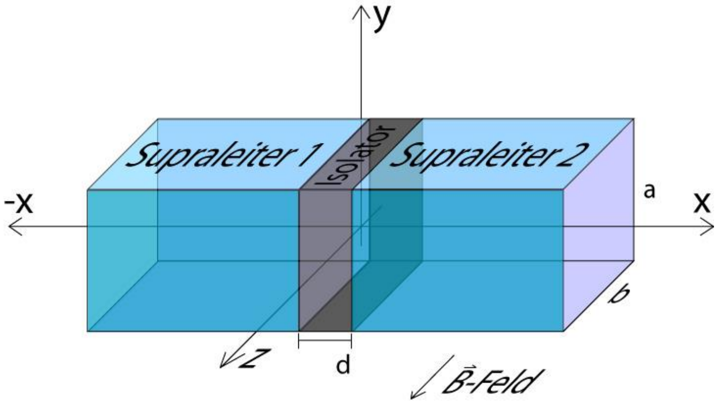
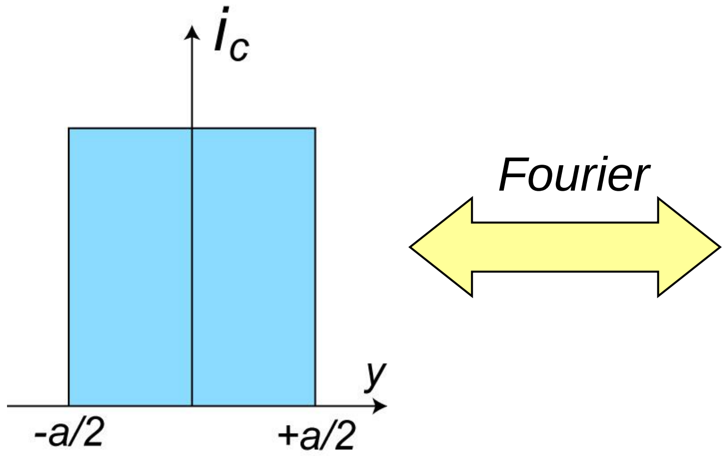
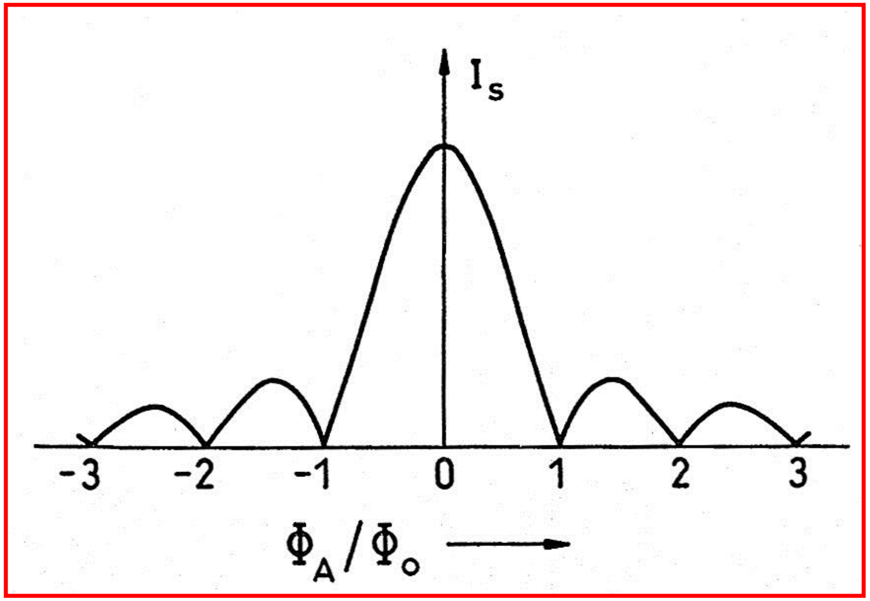
Quantum electronics: SQUIDs

- **S**uperconducting **QU**antum **I**nterference **D**evice
- Josephson junction in magnetic field



$$I_S = I_C \cdot \sin(\gamma_0) \cdot si\left(\pi \frac{\Phi_A}{\Phi_0}\right)$$





Quantum electronics: SQUIDs

- **S**uperconducting **QU**antum **I**nterference **D**evice

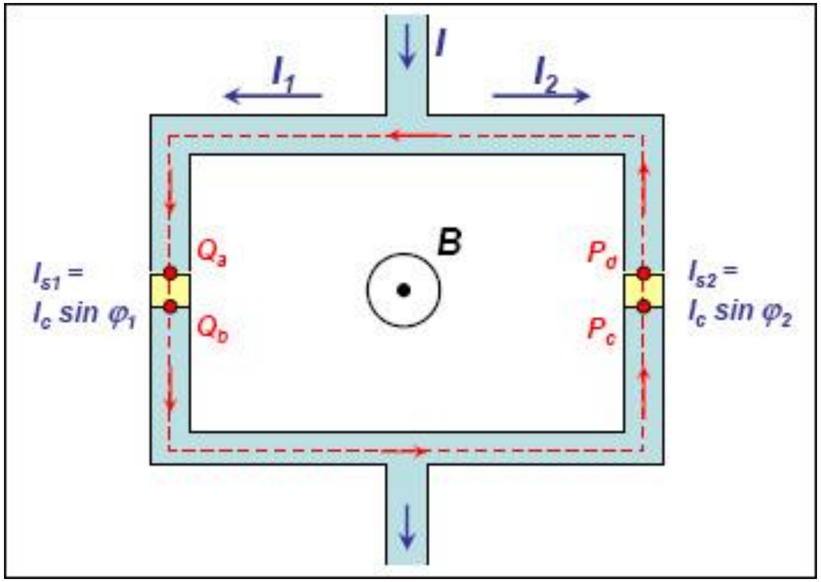
$$I_S = I_C \sin\gamma_1 + I_C \sin\gamma_2$$

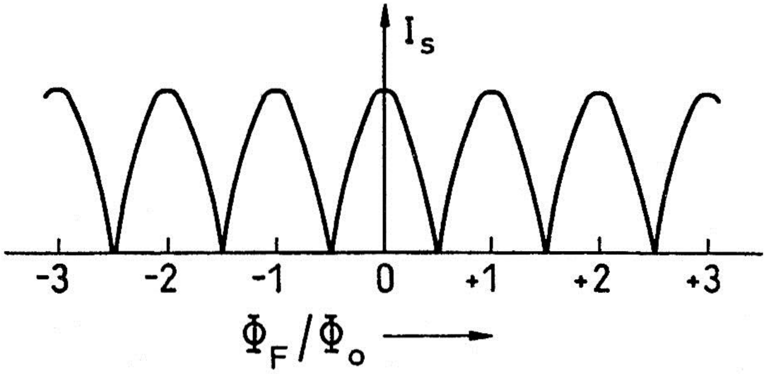
$$I_S = 2I_C \cos\left(\frac{\gamma_1 - \gamma_2}{2}\right) \cdot \sin\left(\frac{\gamma_1 + \gamma_2}{2}\right)$$

$$\Rightarrow \gamma_2 - \gamma_1 = 2\pi \cdot n + 2\pi \frac{\Phi_F}{\Phi_0}$$

$$I_S = \underbrace{2I_C \cos\left(\pi \frac{\Phi_F}{\Phi_0}\right)}_{\tilde{I}_C} \cdot \sin\underbrace{\left(\gamma_1 + \pi \frac{\Phi_F}{\Phi_0}\right)}_{\tilde{\gamma}}$$

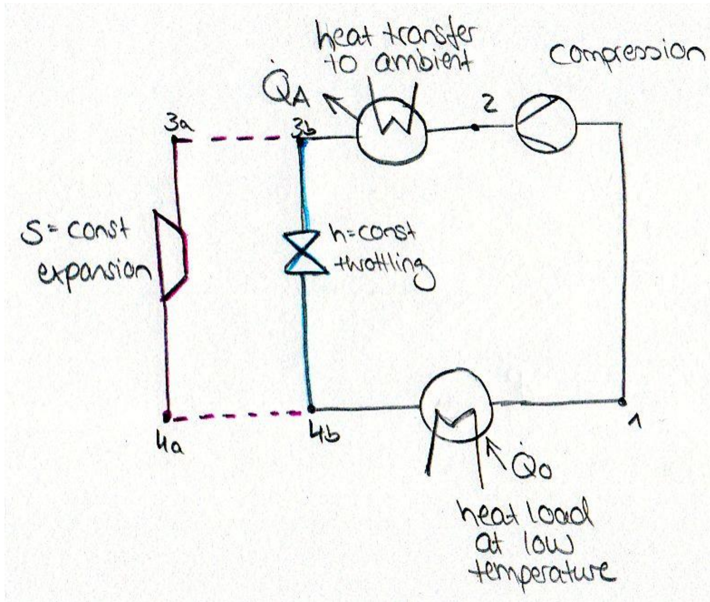
$$\Rightarrow \boxed{I_S = \tilde{I}_C \cdot \sin\tilde{\gamma}}$$



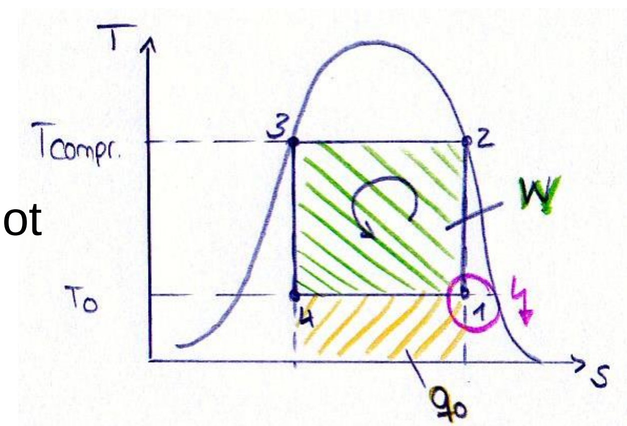


Cold production (Basic)

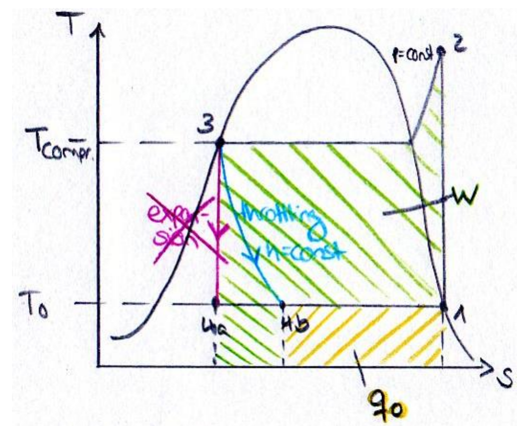
- Basic principle:
  - Compression
  - Heat transfer to ambient
  - Throttling/ expansion
  - Heat load at low temperature
- Carnot:
  - Ideal process (best q_0/w)
  - Liquid yields problem for compressor & turbine



Carnot



Clausius Rankine



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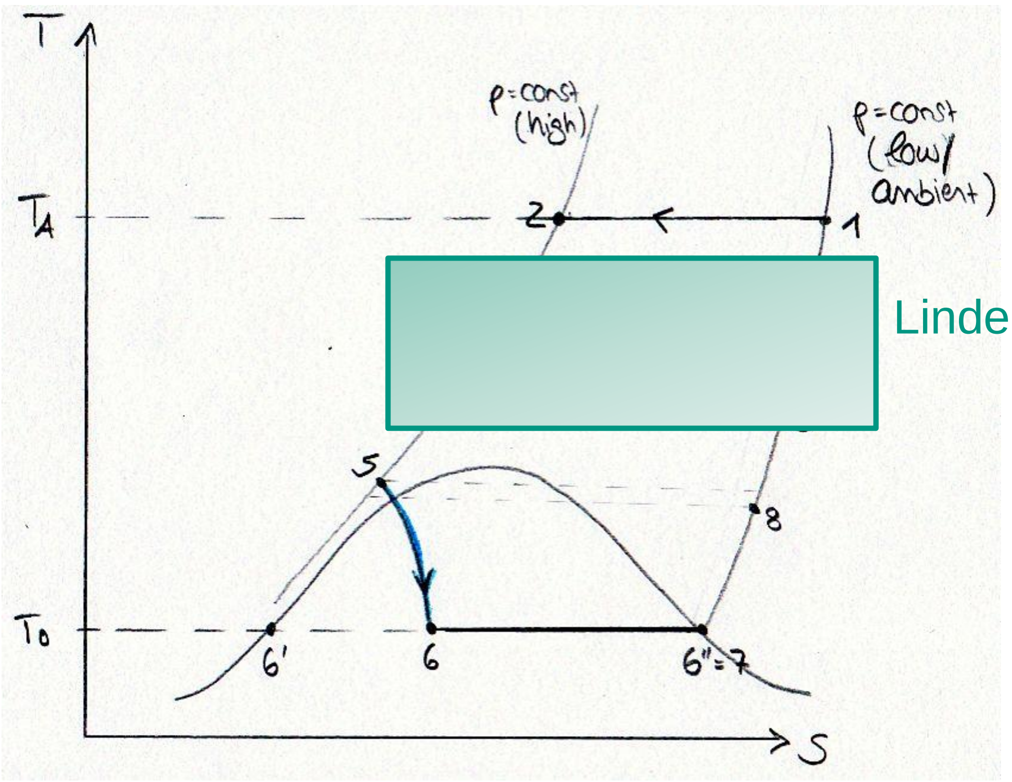
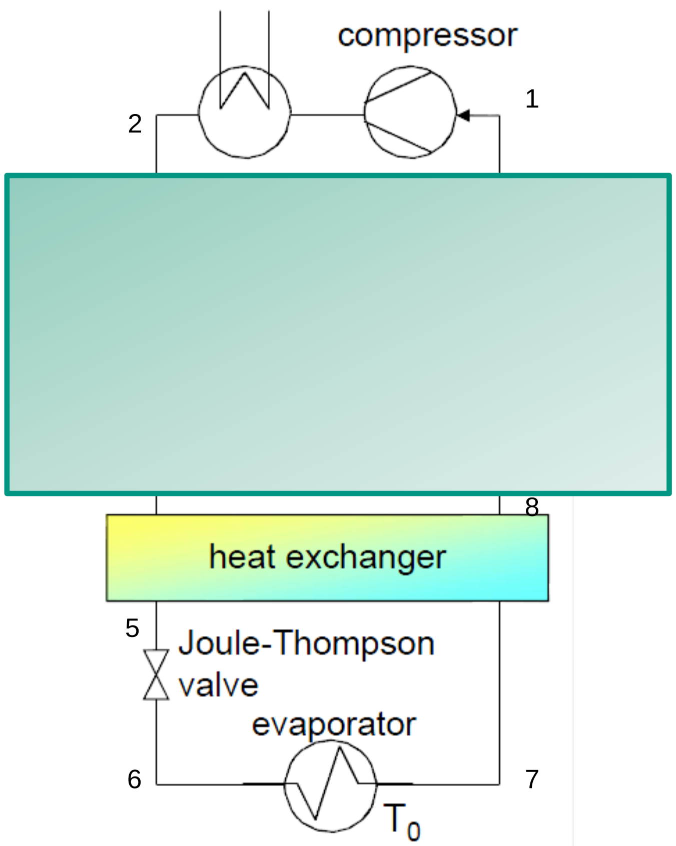
Cold production (Refrigeration Cycles)

- Claude / Linde-Process

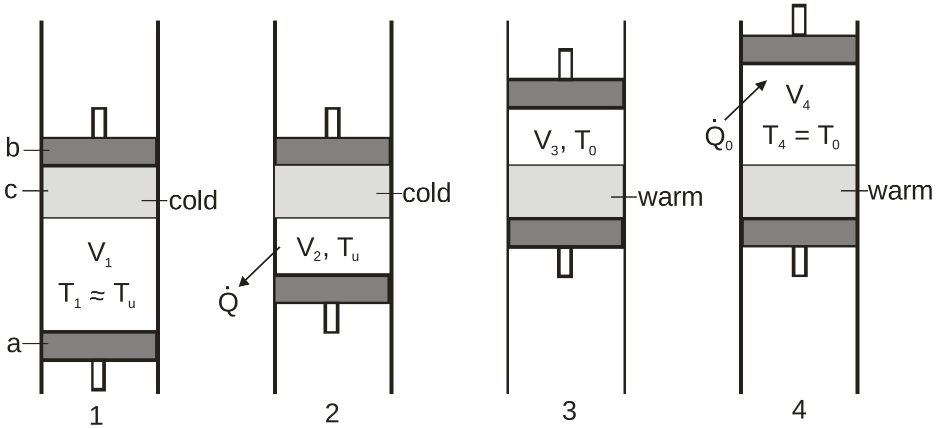




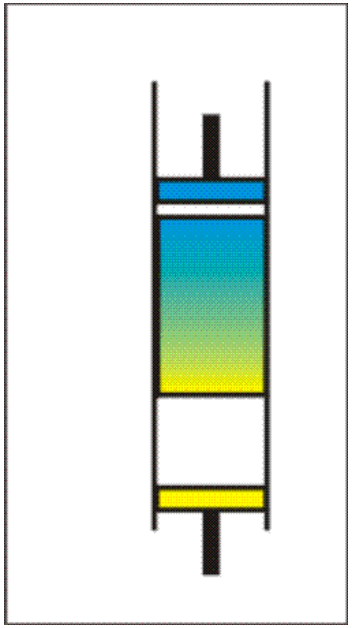
Source:
H. Neumann, ITEP, KIT, 2013 ESAS Summer School

Cold production (refrigeration / liquefaction)

- **Refrigeration cycle**
  - Stirling-process
    - **Advantages**
      - high efficiency
      - compact
    - **Disadvantages**
      - no liquefaction
      - mechanical movements in cold part
      - additional cold cycles are needed to transport the refrigeration power to consumer far away



a: piston on warm side; b: piston on cold side; c: regenerator



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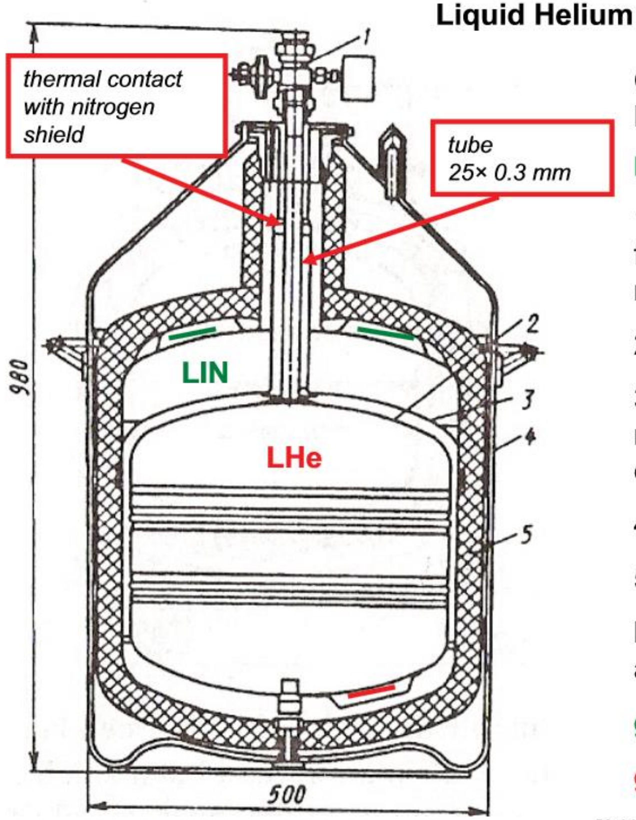
Cryostats (Dewars)

- Dewar vessel



Liquid Helium Dewar vessel with LIN shielding

Capacity: 40 liters
Liquid helium volume: **28 Nm3**

Remember: 700 liters gas from 1 liter liquid

1 – valve head with thread connections for liquid fill and gas withdrawal, manometr and safety membrane.

2 – inner vessel (12Cr18Ni1.0T)

3 – nitrogen vessel (12Cr18Ni1.0T) with nitrogen shield (copper – high thermal conductivity for uniform temperature)

4 - outer jacket

5 – multilayer vacuum insulation

high vacuum between the inner vessel and the nitrogen shield

getter at nitrogen temperature

getter at helium temperature

[Arkharov et all., Cryogenic Systems]

Source: V. Chrz
http://indico.cern.ch/getFile.py/access?sessionId=3&resId=0&materialId=0&confId=90787

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