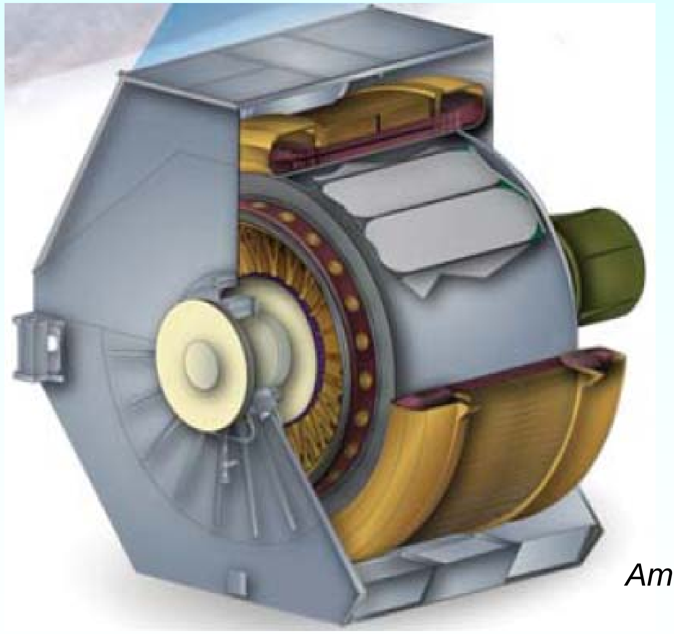
New technologies of electric energy converters and actuators

Andreas Binder



Source:

American Superconductor, USA

Lecturer

Prof. Dr.-Ing. habil. Dr. h.c. Andreas Binder
Institut für Elektrische Energiewandlung
TU Darmstadt
64283, Landgraf-Georg-Strasse 4, Darmstadt
tel.: +49-6151-16-24181 o. 24182
fax.:+49-6151-16-24183
e-mail: abinder@ew.tu-darmstadt.de

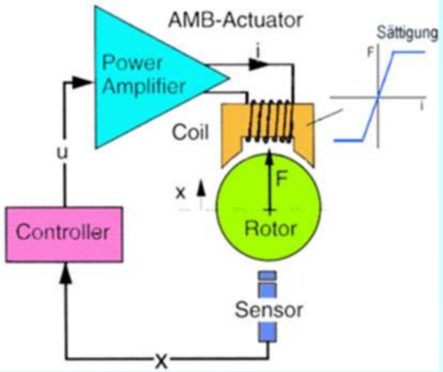
Tutorial

M. Sc. Gael Messager
Institut für Elektrische Energiewandlung
TU Darmstadt
64283, Landgraf-Georg-Strasse 4, Darmstadt
tel.: +49-6151-16-24181 o. 24182
fax.:+49-6151-16-24183
e-mail: gmessager@ew.tu-darmstadt.de

New technologies of electric energy converters and actuators

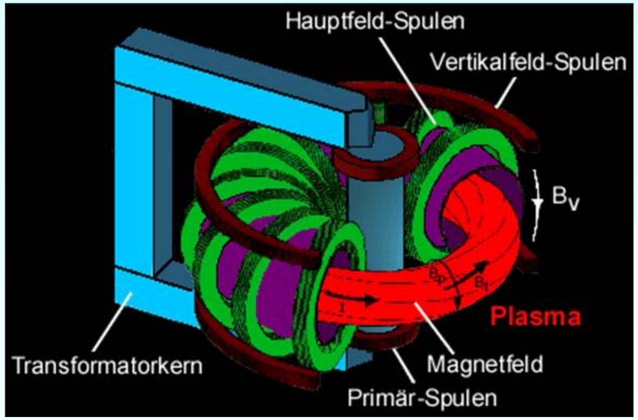
SS 2+1

Lecture contents :



Source: Internet

- Application of superconductors for electrical energy conversion
- Active magnetic bearings (“magnetic levitation”)
- Magneto-hydrodynamic energy conversion
- Fusion research



Source: Internet

Course language: German or English

Power point presentation (download)
Paper copy: text book
Tutorials, excursion to industry

Source:
Siemens AG

Type of examination

Written examination

1 hour

Six questions with about 10 min. per question

2 dates per year

List of questions: see text book

Learning outcomes

Understanding of

- basics of superconducting physics for power engineering
- applications of superconductivity in electrical power engineering
  i.e. fault current limiters, cables, storage devices, transformers, generators

Knowledge of active magnetic bearings,
electrodynamic levitation & superconductive levitation

- basics and applications in rotary machinery
- bearingless electrical machines
- application in high speed trains

Knowledge of basics in magnetohydrodyamics

- applications as generators and satellite propulsion

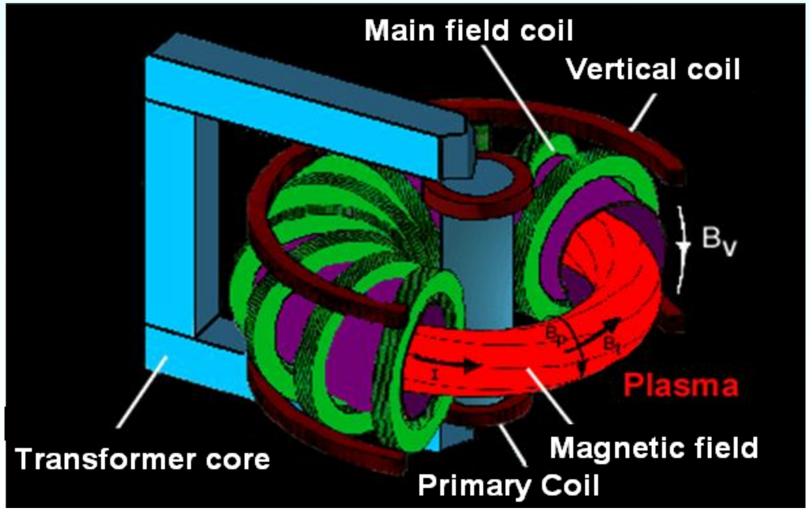
Understanding of basics in nuclear fusion for power generation

Calculation examples for self-training

New technologies of electric energy converters and actuators

Contents

1. Superconductors for power systems
2. Application of superconductors for electrical energy converters
3. Magnetic bearings („magnetic levitation“)
4. *Magneto-h*ydro*d*ynamic (MHD) energy conversion
5. Fusion research



Source: Internet

New technologies of electric energy converters and actuators

1. Superconductors for power systems

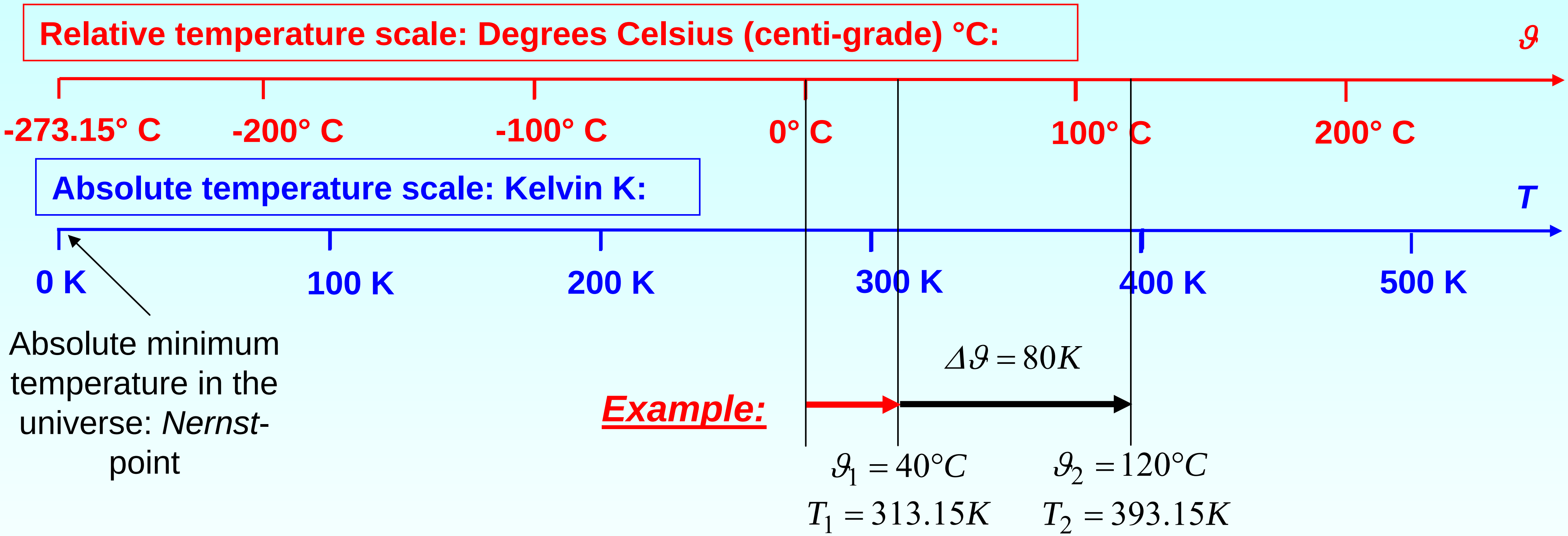
Used literature

Komarek, P.: Hochstromanwendung der Supraleitung, Teubner, Stuttgart, 1995
Buckel, W.: Supraleitung, VHC-Verlag, Weinheim, 1994
Buckel, W.; Kleiner, R.; Superconductivity, Wiley-VCH, 2004, Weinheim
Rödel, J.: Funktionswerkstoffe, Vorlesungs-Skript, TU Darmstadt, FB Materialwissenschaften, 1997
Wilson, M. N.: Superconducting Magnets, Oxford Science Publishing, Clarendon Press, 1998
Carlsaw, H. S.; Jaeger, J. C.: Conduction of Heat in Solids. Oxford Univ. Press, 1959
Brechna, H.: Superconducting Magnet Systems. Berlin, Springer, 1973
Bhattacharya, R. N.; Paranthaman, M. P. (ed.): High Temperature Superconductors, Wiley-VCH, 2010, Weinheim
Krabbes, G.; Fuchs, G.; Canders, W.-R.; May, H.; Palka, R.: High Temperature Superconductor Bulk Materials, Wiley-VCH, 2006, Weinheim

New technologies of electric energy converters and actuators

1. Superconductors for power systems

Temperature scales – Temperature rise



Relative temperature scale: Degrees Celsius (centi-grade) °C: ϑ

Absolute temperature scale: Kelvin K: T

Absolute minimum temperature in the universe: *Nernst*-point

Example:

$\Delta\vartheta = 80K$

$\vartheta_1 = 40°C$ $\quad$ $\vartheta_2 = 120°C$

$T_1 = 313.15K$ $\quad$ $T_2 = 393.15K$

Temperature rise $\Delta\vartheta$ = temperature difference: $\boxed{\Delta\vartheta = \vartheta_2 - \vartheta_1 = T_2 - T_1}$

(It is measured ALSO in K!)

Low-temperature superconductors – overview

- Good electrical "normal conductors" are NOT superconductors: Cu, Ag, Au, Al,...
- Ferromagnets are NOT superconductors: Fe, Ni, Co
- Superconductor 1st type: Pure elements (metals): Hg, Pb, Sn, Nb, Ta, V, La, Ga...

  - Below critical temperature T_c: *Meissner*-phase: interior B-field-free,

  - lossless current transport: for resistance unmeasurably small

- Superconductor 2nd type: Metal alloy (mixed crystal): Pb-In, Nb-Ti...

  - Below T_{c1}: *Meissner* phase;

  - above, up to T_{c2}: *Shubnikov* phase: interior not B-field-free, no lossless current transport, but considerably higher currents and magnetic fields

- "Hard" (technical) superconductors: artificial PINNING centres prevent fluxtube movement: lossless DC transport; but with AC losses

High-temperature superconductors – overview

- **Low-temperature superconductors:** Transition temperature T_c below 20 K, He cooling for high *B*-fields necessary
- **High-temperature superconductors:** ceramic (brittle) materials: LaCu oxide, BaCu oxide, Bi-Al-Ca-Sr-Cu oxide, YBaCu oxide, ...,

  - Transition temperature between 30 K and 160 K

  - Cooling with LN_2 and LH_2 possible
- **Ceramic material: Anisotropy** in crystal structure! In “preferred” axis about 5 times higher external field strength *B* possible!
- **High-temperature wire conductor:** Bi-Al-Ca-Sr-Cu oxide
- **High-temperature solid & tape conductor:** YBaCu oxide: Production as conductor tapes is promising future technology

Mobility law for “free” electrons in metal crystal lattice

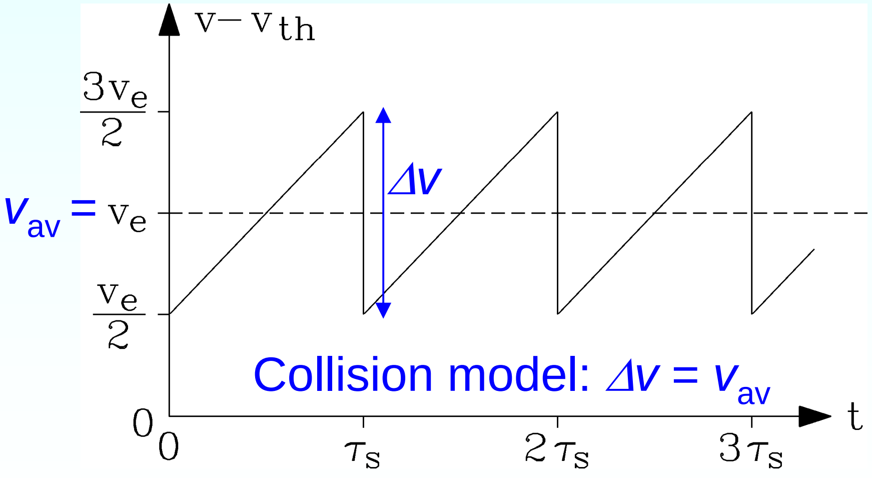
NEWTON´s law: $\vec{F} = m_e \cdot d\vec{v} / dt \Rightarrow (-e) \cdot \vec{E} = m_e \cdot d\vec{v} / dt$

P. DRUDE: Collisions with oscillating atoms of crystal: mean time τ_s between two collisions

$$\vec{F} = m_e \cdot d\vec{v} / dt \approx m_e \cdot \Delta\vec{v} / \tau_s = m_e \cdot \vec{v} / \tau_s = (-e) \cdot \vec{E} \quad \Rightarrow \quad \vec{v}_{av} = \vec{v}_e = \mu_e \cdot \vec{E}$$

$\boxed{\vec{v}_e = \mu_e \vec{E}, \quad \mu_e = (-e) \cdot \tau_s / m_e}$ **Free electron mobility**: $\mu_e < 0$

v_{th}: Average thermal velocity of the free electrons due to their kinetic energy $W_{kin} \sim k \cdot T$ at a given temperature T of the metal (k: BOLTZMANN´s constant)



Due to the collisions the force F is on average not proportional to the electron acceleration, but to (average) electron velocity! **This constitutes OHM´s law for metals!**

1.1 Fundamentals of superconductivity

OHM´s law for pure metals

- Current density of free electrons in the metal: $\vec{J}_e = (-e) \cdot n_e \cdot \vec{v}_e$ $\vec{J}_e \uparrow\downarrow \vec{v}_e$

  ***n_e*: number of free electrons/volume**

- OHM´s law: $\boxed{\vec{J}_e = (-e) \cdot n_e \cdot \vec{v}_e = (-e) \cdot n_e \cdot \mu_e \cdot \vec{E} = \kappa_T \cdot \vec{E} = \frac{1}{\rho_T} \cdot \vec{E}}$

Temperature dependent electrical conductivity κ_T determined by electron parameters:

$$\boxed{\kappa_T = \frac{1}{\rho_T} = \mu_e \cdot n_e \cdot (-e) = \frac{e^2 \cdot n_e \cdot \tau_s}{m_e}}$$

τ_s: Collision time = corresponds to „average free path of motion“ *l_s:*

$$v_e = l_s / \tau_s \Rightarrow l_s = v_e \cdot \tau_s \qquad \rho_T = \frac{m_e}{e^2 \cdot n_e \cdot \tau_s} = \frac{m_e \cdot v_e}{e^2 \cdot n_e \cdot l_s}$$

Facit:

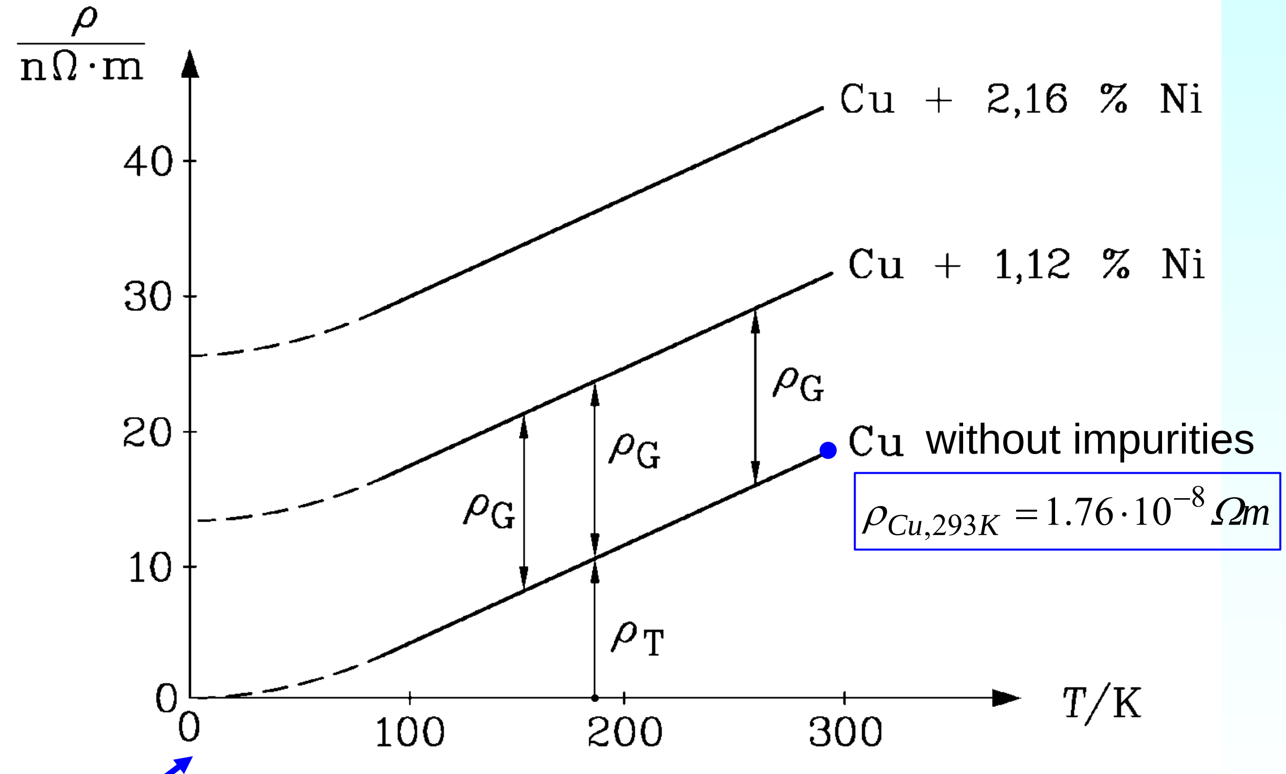
With increasing temperature the atoms oscillate more, yielding more collisions for a certain travel distance, hence the collision time reduces. So the specific resistivity increases in metallic conductors with increasing temperature!

1.1 Fundamentals of superconductivity

Temperature dependence of electrical specific resistance $\rho(T)$

***Mathiessen*-rule**: ρ has two components ρ_G and ρ_T: $\boxed{\rho(T) = \rho_G + \rho_T(T)}$

Source: Clausert, H.; Elektrotechnik



Nernst´s absolute zero temperature point $T = 0$

Resistance is collisions of free moving electrons in the metal crystal lattice (e.g. of Cu):

a) with crystal lattice defects such as impurities (e.g. Ni), constituting ρ_G (independent of T)

b) with the oscillating atoms of the crystal lattice, constituting ρ_T

Oscillations “ARE“ temperature T!

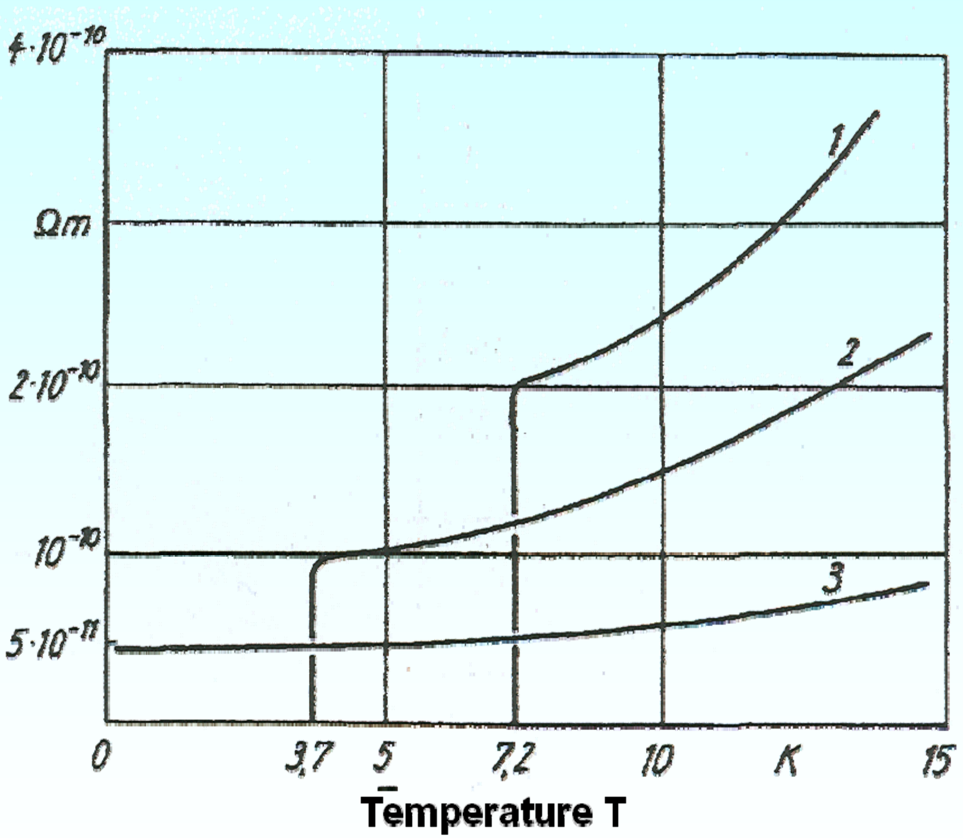
Hence: $T = 0 \Leftrightarrow$ NO oscillations $\Leftrightarrow$

No collisions $\Leftrightarrow \rho_T = 0$

1.1 Fundamentals of superconductivity

Superconductor 1^{st} type – Compared to "normal conductor" copper

- Function of the *specific electric resistance* in low-temperature area for Pb (1), Sn (2), Cu (3)



Rödel, J.: Funktionswerkstoffe, Vorlesungs-Skript, TU Darmstadt, FB Materialwissenschaften, 1997

Historic development and progress in superconductivity

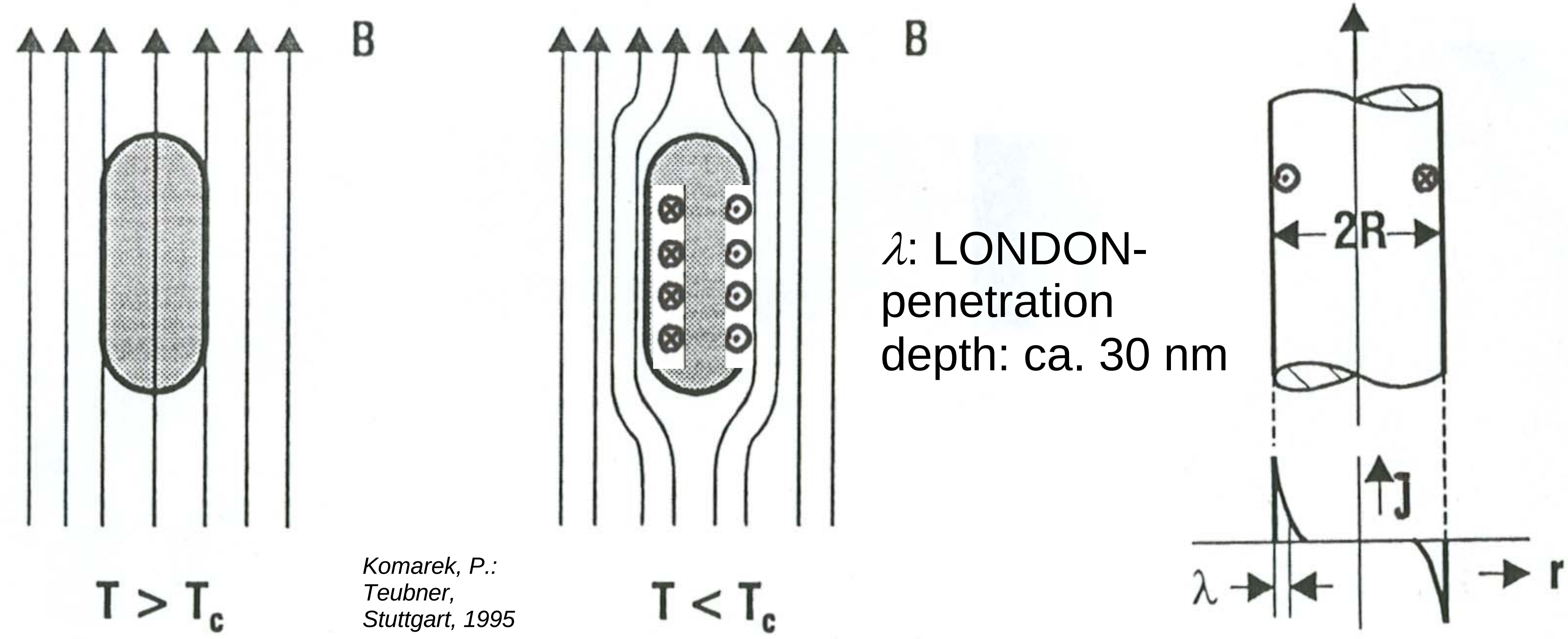
Year	Event	Material	T_c
1911	*Kammerlingh-Onnes* discovers superconductivity	Hg	4 K
1952	Niob-3-Tin material	Nb_3Sn	18 K
1957	*Bardeen, Cooper, Schrieffer*: quantum mech. superconductor theory		
1986	*Müller* and *Bednorz* discover "high-temperature superc." HTSC	$(La,Ba)_2Cu_2O_4$	30 K
1987	Material „YBCO“	$YBa_2Cu_3O_{7-\delta}$	93 K
1988	Material „BiSCCO“	Bi-Al-Ca-Sr-Cu-O	120 K
1993	(..) value: under pressure highest T_c	$HgBa_2Ca_2Cu_3O_{8+x}$	120 K (160 K)

BARDEEN-COOPER-SCHRIEFFER theory

- ***Cooper* pairs:** Two electrons with opposite *momentum* and *spin (angular momentum),* coupled together via phonon interaction below T_c.
- **BCS** valid for low-temperature SC
- **Lossless current transport** in ideal crystal
- **Separation of the pairs above T_c** because of too strong crystal lattice oscillation
- Superconductivity is a **macroscopically** observable **quantum-mechanical effect**

Meissner-Ochsenfeld effect

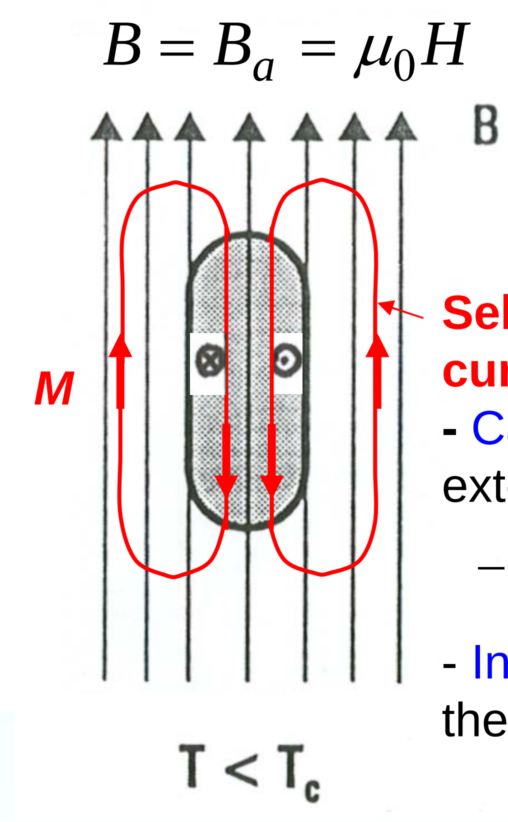
- **Field *displacement* from the inside of the SC 1st type**
- **Super current density *J* as shielding circulating current**



λ: LONDON-penetration depth: ca. 30 nm

Komarek, P.: Teubner, Stuttgart, 1995

Self-field of shielding currents

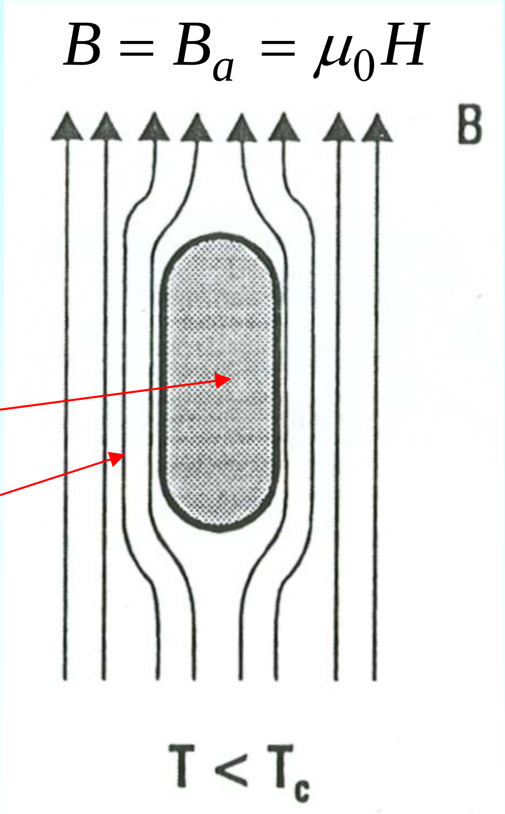


Self-field *M* of shielding currents:

- Cancels inside the SC the external field B_a

$$-\mu_0 M = \mu_0 H = B_a$$

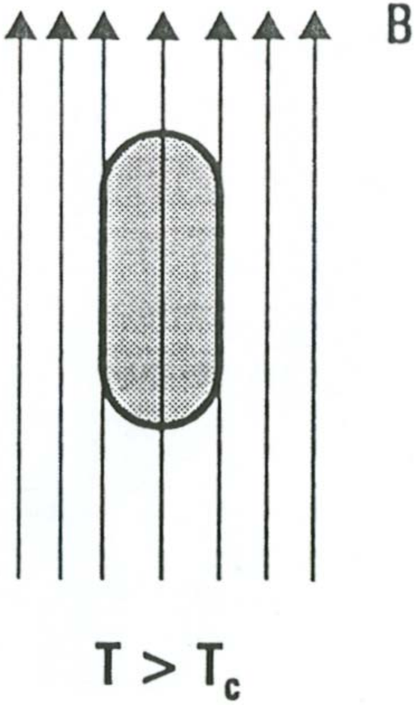
- Increases the outside field at the SC sides



Komarek, P.:
Teubner,
Stuttgart, 1995

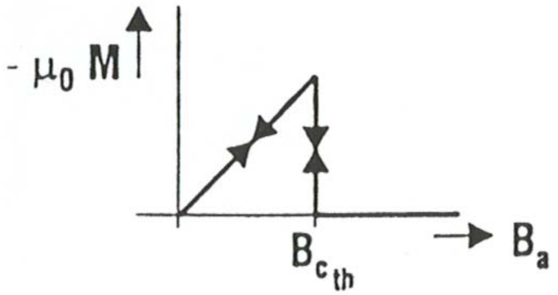
Ideal diamagnetism

$$B = B_a = \mu_0 H$$

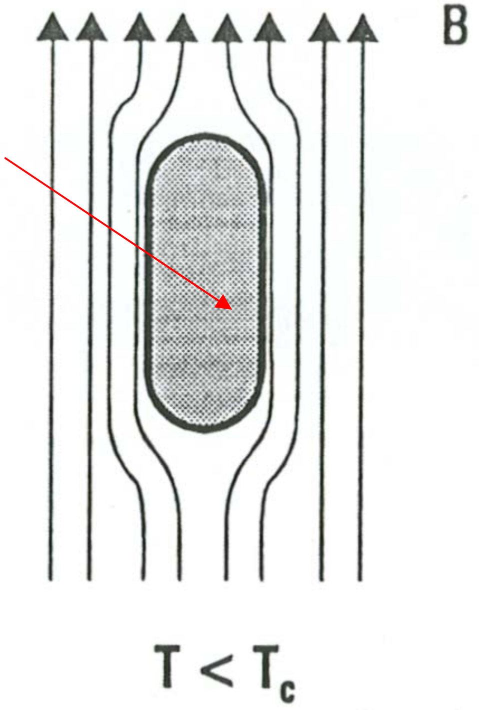


$$B_i = \mu_0 H + \mu_0 M = 0$$

$$\boxed{-\mu_0 M = \mu_0 H = B_a}$$



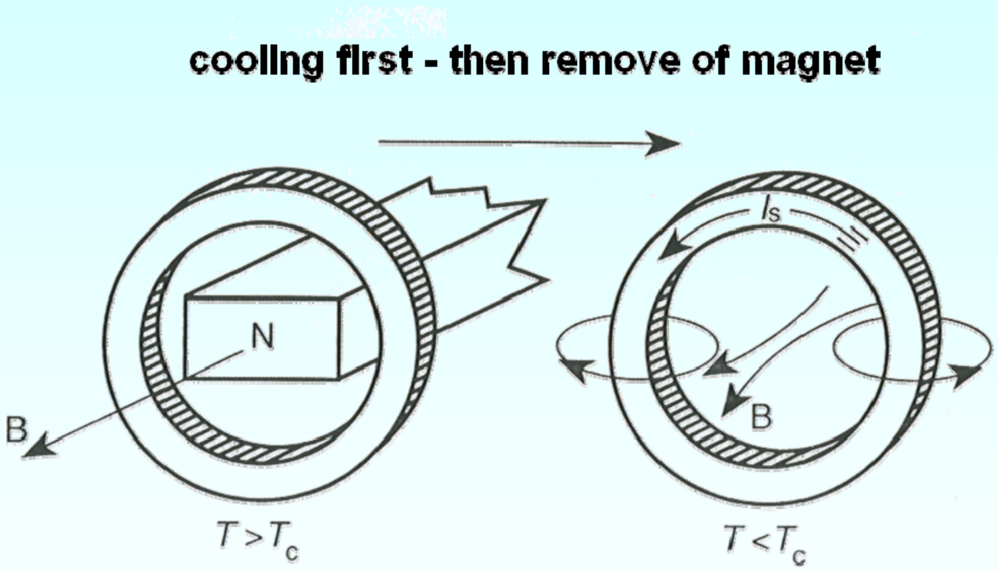
$$B = B_a = \mu_0 H$$



Komarek, P.:
Teubner,
Stuttgart, 1995

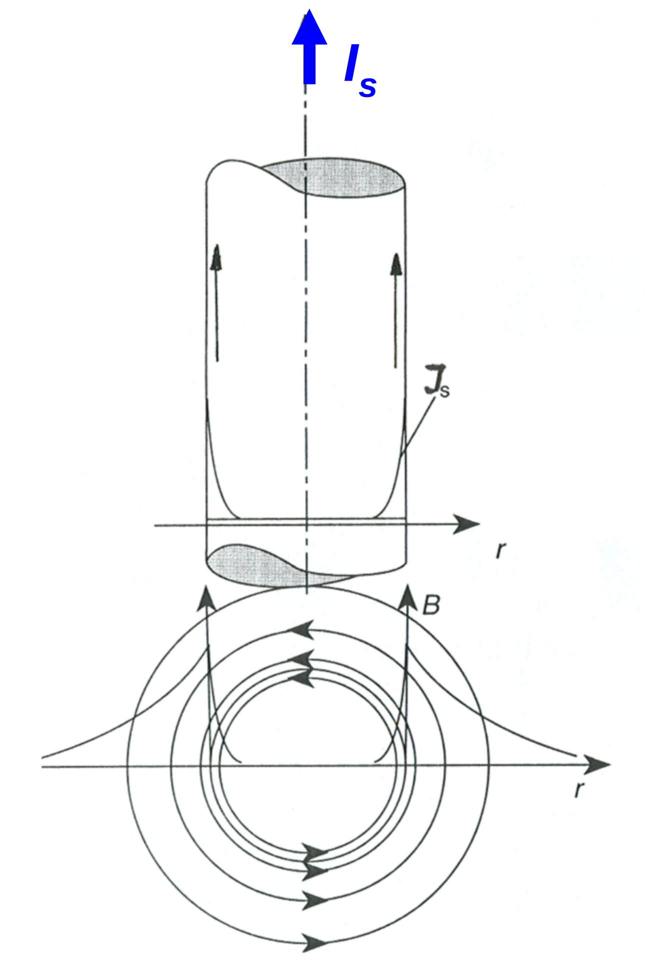
Meissner phase – transport current in SC 1^{st} type

- **Current flows in outer layer (ca. 30 nm), thus SC-interior *field-free***



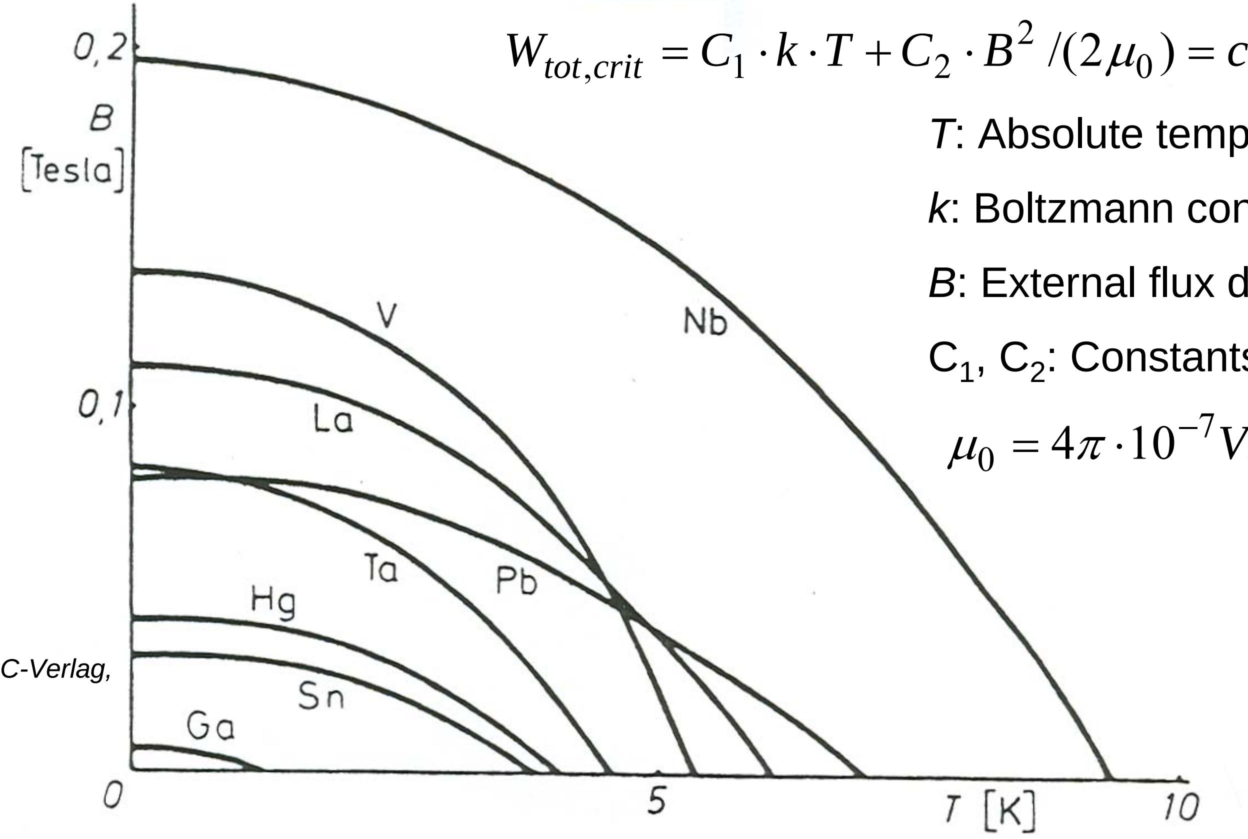
Normal conducting ring
Superconducting ring

Buckel, W.: Supraleitung, VHC-Verlag, Weinheim, 1994



Meissner phase – critical flux density B_c

- **In external field *B* the energy state of *Cooper* pairs is raised, hence the transition temperature decreases**



$$W_{tot,crit} = C_1 \cdot k \cdot T + C_2 \cdot B^2 / (2\mu_0) = const.$$

T: Absolute temperature

k: Boltzmann constant

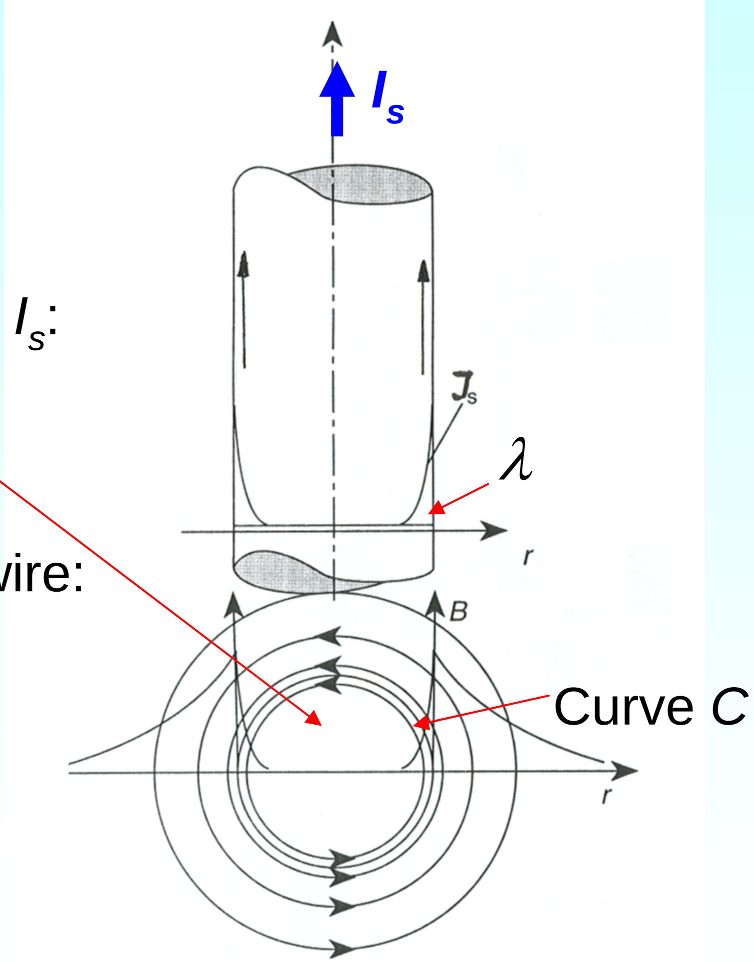
B: External flux density

C_1, C_2: Constants

$$\mu_0 = 4\pi \cdot 10^{-7} Vs/(Am)$$

Buckel, W.: Supraleitung, VHC-Verlag, Weinheim, 1994

Critical Current Density J_c (1)



SC wire: radius R, transport current I_s:
Interior within λ-depth: $B = 0$

$$\oint_C \vec{H} \bullet d\vec{s} = \Theta = 0 \rightarrow H = 0$$

Outside of SC wire: radius R, transport current I_s:

$$\oint_C \vec{H} \bullet d\vec{s} = H(r) \cdot 2\pi r = \Theta = I_s \rightarrow B(r) = \mu_0 H(r)$$

By I_s generated magnetic field B_0 on surface of wire:

$$B_0 = \frac{\mu_0 I_s}{2\pi R}$$

Buckel, W.: Supraleitung, VHC-Verlag, Weinheim, 1994

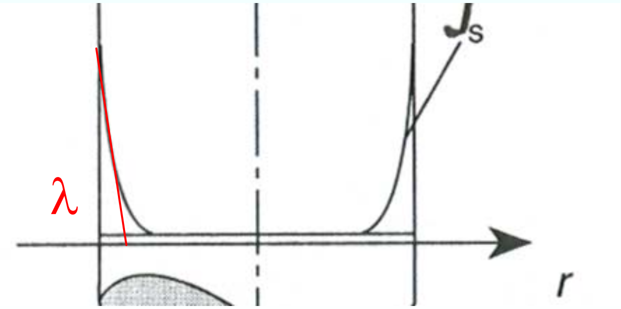
Critical Current Density J_c (2)

- **SC wire:** radius *R*, transport current I_s:
- $B_0 > B_c$: superconducting condition expires: $B_c = \frac{\mu_0 I_{s,c}}{2\pi R}$

  Corresponding super transport current density is

  critical current density J_c. $\boxed{J_{s,c} = I_{s,c}/(2R\pi\lambda)}$
- Superconducting operating area:

  three-dimensional diagram with the limits T_c, B_c, J_c



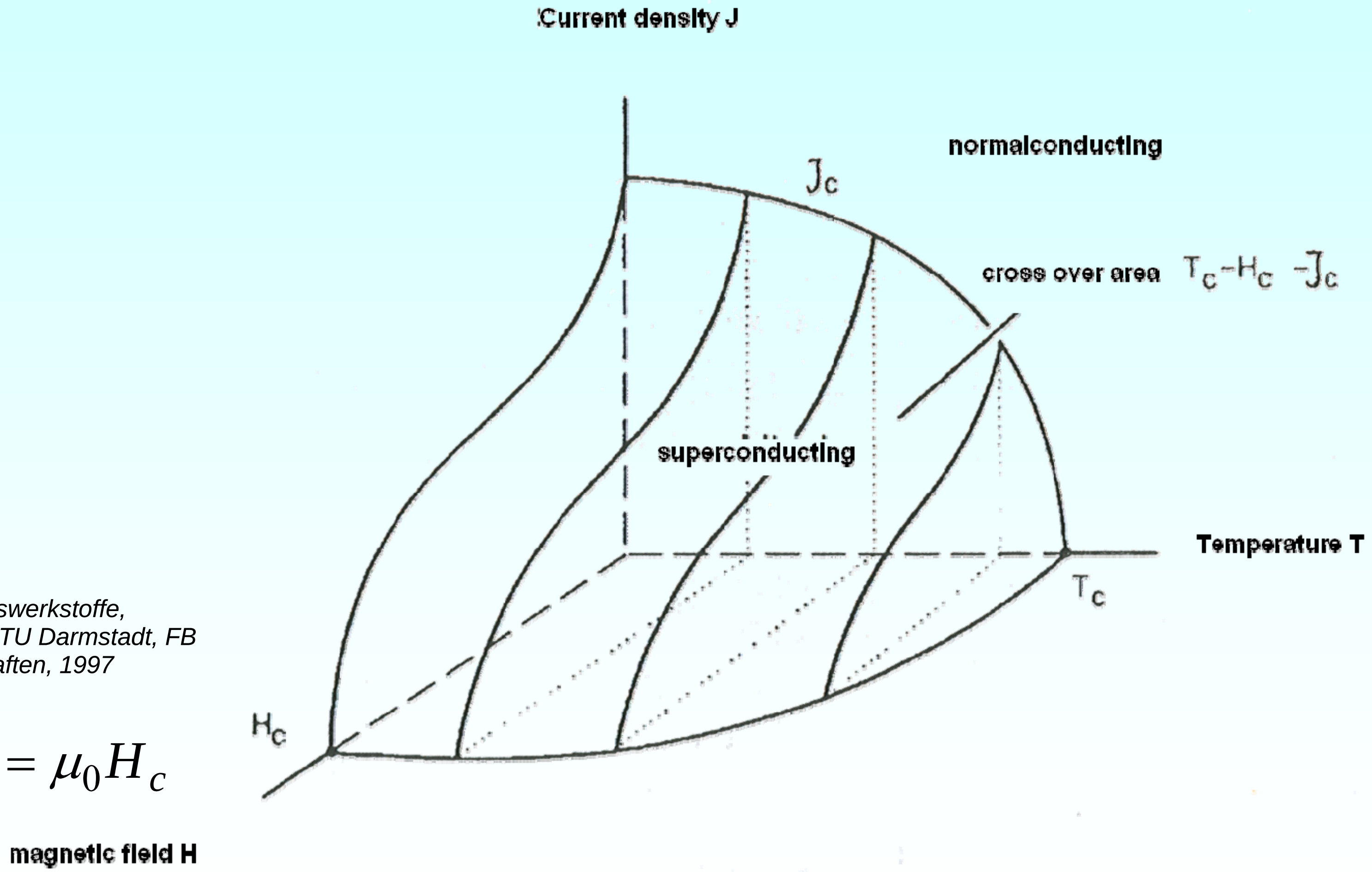
$$I_s = \int_A J_s(r,\varphi) \cdot r \cdot dr \cdot d\varphi = 2(R-\lambda/2)\pi \cdot \lambda \cdot J_s(R)$$

$$I_s \approx 2R\pi \cdot \lambda \cdot J_s(R)$$

Buckel, W.: Supraleitung, VHC-Verlag, Weinheim, 1994

Three-dimensional phase diagram of a super-conductor

Superconducting state is possible only within the T_c-B_c-J_c-area



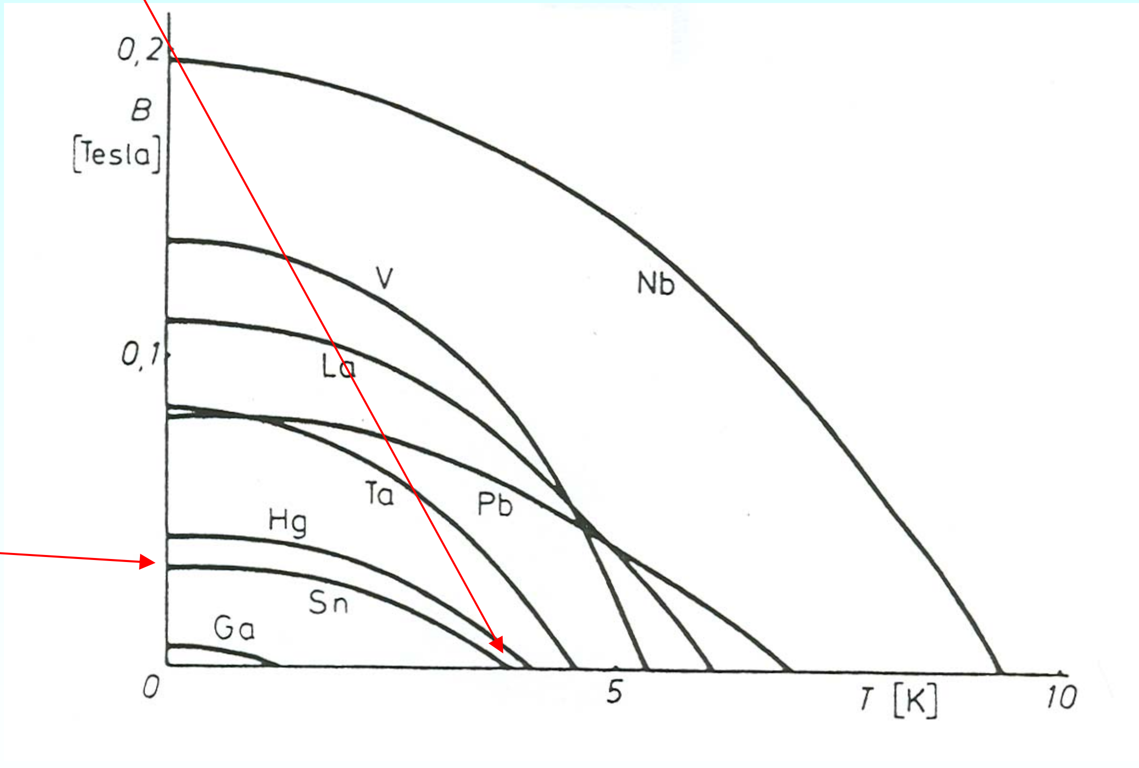
Rödel, J.: Funktionswerkstoffe, Vorlesungs-Skript, TU Darmstadt, FB Materialwissenschaften, 1997

$$B_c = \mu_0 H_c$$

Transport current in SC 1^{st} type

Example:

Tin wire, $R = 0.5$ mm, $T_c(B = 0, I_s = 0) = 3.8$ K, $B_c(T = 0\text{ K}) = 0.03$ T



$B_c(T = 0\text{ K}) = 0.03$ T

Transport current in SC 1st type

Example: Tin wire, R = 0.5 mm, T_c(B = 0, I_s = 0) = 3.8 K,

$B_c(T=0\text{K}) = 0.03$ T $\quad I_{sc} = 2\pi R B_c / \mu_0 = 75 A \quad \lambda = 30 nm$

$$J_c = I_{sc} / (2\pi R\lambda) = 7.9\cdot 10^{11} A/m^2 = 7.9\cdot 10^5 A/mm^2$$

Result:

For superconductors 1st type, the limits T_c, B_c, J_c are therefore too small to use these materials for lossless energy transport with high currents or the excitation of strong magnetic fields.

Remedy: Shubnikov phase:

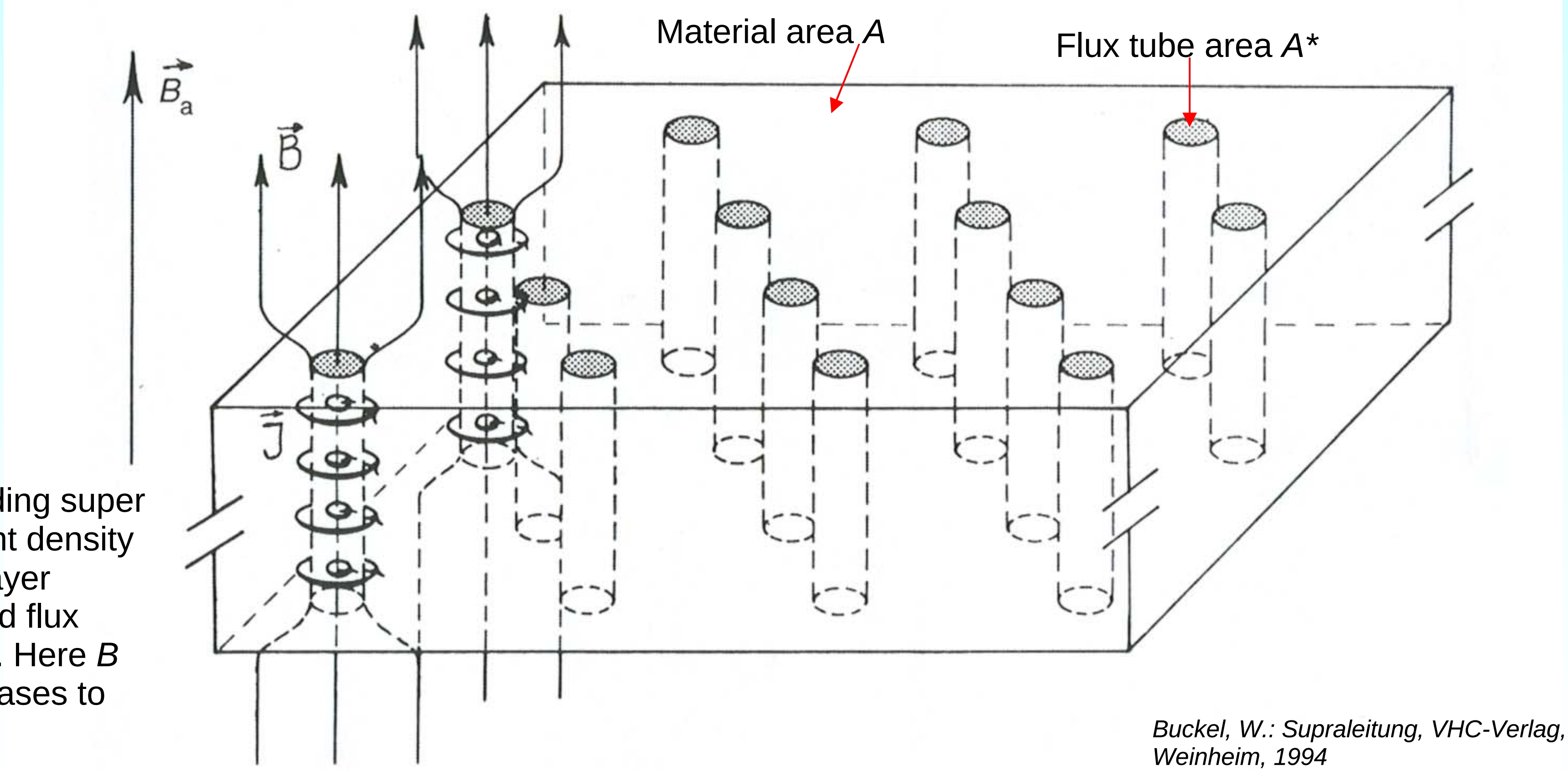
Superconductor 2nd type by means of metal alloy with base material of superconductors of 1st type

$B_{c1} < B < B_{c2}$: Magnetic field enters the interior of the superconductor as a periodical "**Flux tube"** pattern

Shubnikov phase

Magnetic field "tubes" and supercurrents:

Interior of the flux “tubes" is normal-conducting, so that flux penetration is possible.



Shielding super current density in λ-layer around flux tubes. Here *B* decreases to zero.

Buckel, W.: Supraleitung, VHC-Verlag, Weinheim, 1994

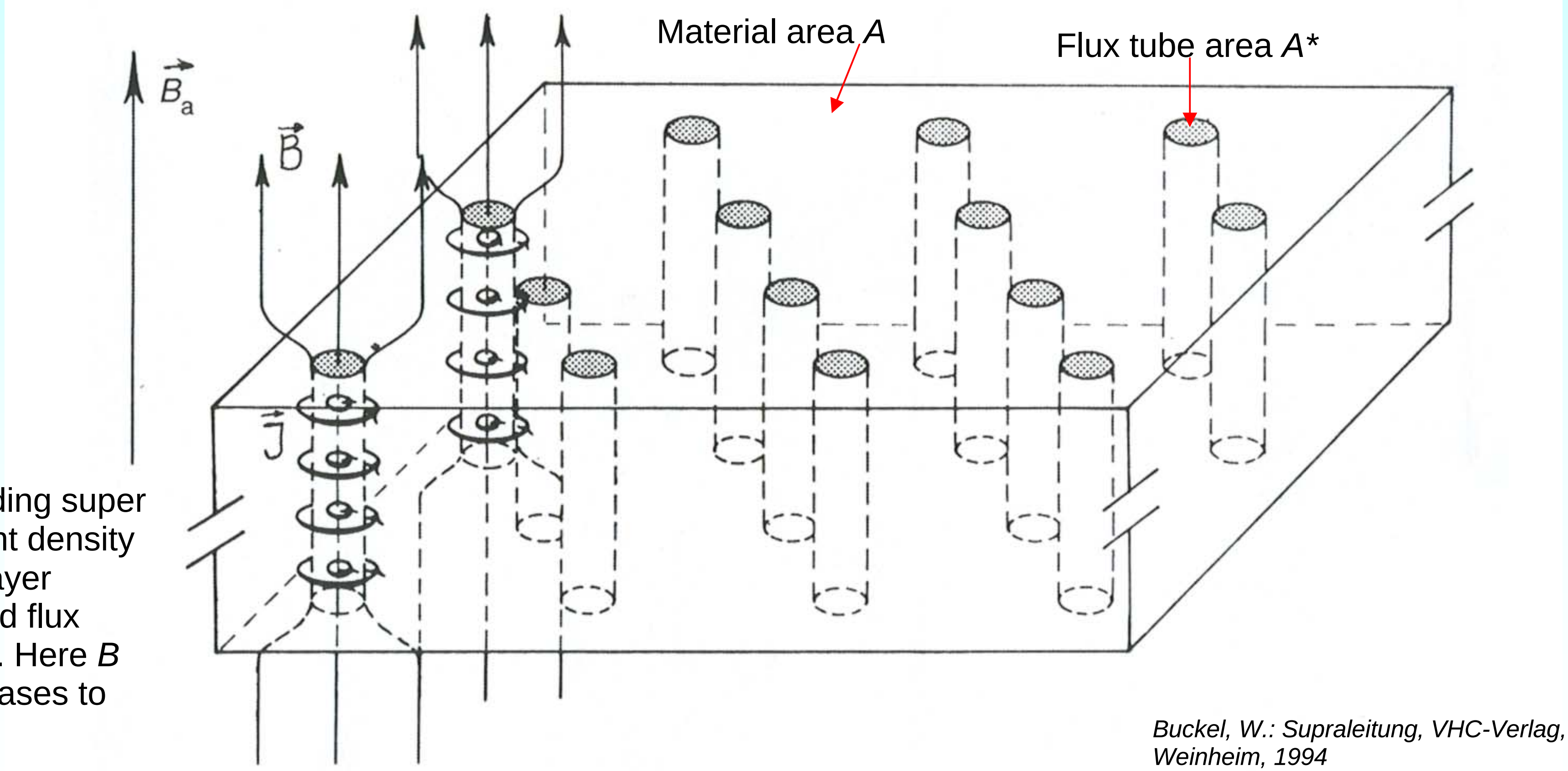
1.1 Fundamentals of superconductivity

Flux tubes

Flux tube is a quantum mechanical quantity: $\Phi^* = B \cdot A^*$

Total flux with n tubes: $\Phi = B_a \cdot A = n \cdot \Phi^*$

$$A^* = R^{*2} \pi$$



Material area A

Flux tube area A^*

Shielding super current density in λ-layer around flux tubes. Here B decreases to zero.

Buckel, W.: Supraleitung, VHC-Verlag, Weinheim, 1994

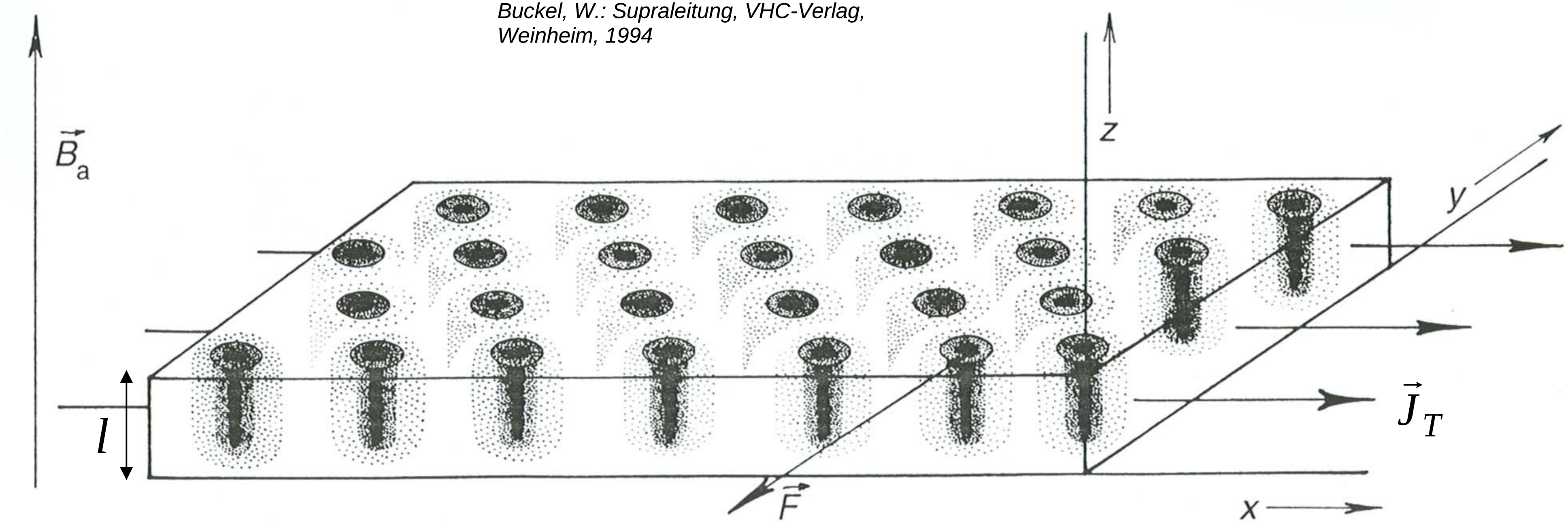
1.1 Fundamentals of superconductivity

Flux “tube" movement in *Shubnikov* phase

Transport current density J_T: Flux tubes shifted by *Lorentz force F*, pushing it into -*y*-direction ⇒ crystal “friction” loss ⇒ no lossless current transport

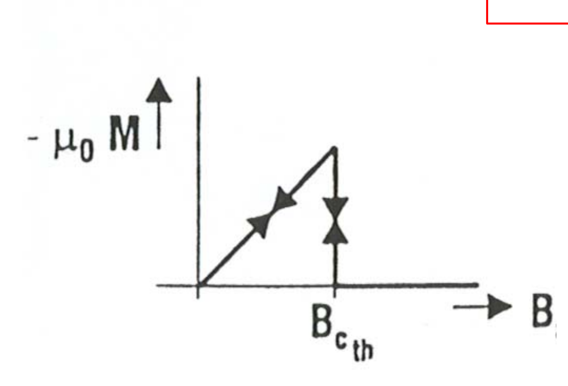
$$\vec{F} = \vec{J}_T \times \vec{B} \cdot \lambda \cdot 2\pi R^* \cdot l$$

Buckel, W.: Supraleitung, VHC-Verlag, Weinheim, 1994



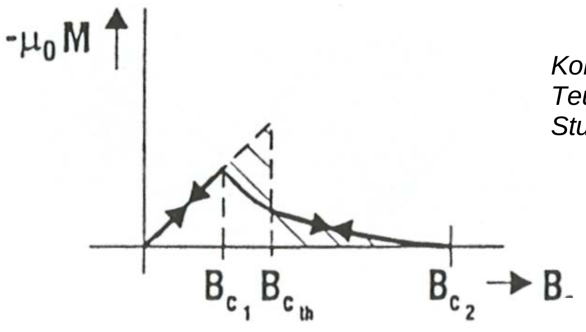
"Hard" (= technical) Superconductors

- Directed use of crystal defects: **pinning centre**
- Flux tubes get caught at pinning centres ⇒ losses disappear
  ⇒ lossless DC current transportation
- Magnetization *M*: $\boxed{\vec{B} = \mu_0 \vec{H} + \mu_0 \vec{M}}$



th: theoretical

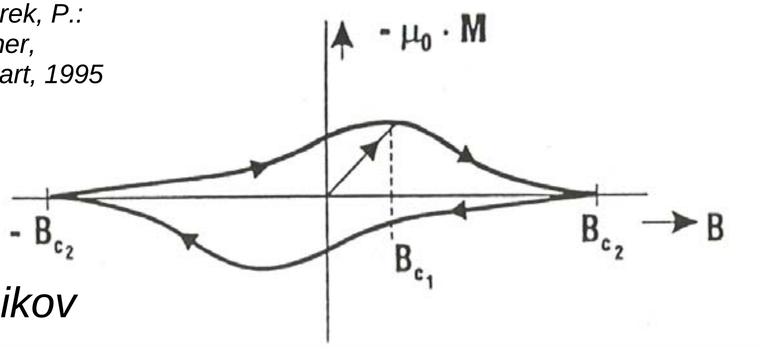
Superconductor 1st type
(ideal diamagnetism)



1: *Meissner* 2: *Shubnikov*

Pure SC 2nd type
(non-ideal diamagnetism)

Komarek, P.:
Teubner,
Stuttgart, 1995



"Hard" superconductor
(diamagnetism & Hysteresis)

"Hard" superconductor shows hysteresis due to pinning centres.
Their crystal energy results in crystal "friction" losses, when flux tubes move!

New technologies of electric energy converters and actuators

Summary:
Fundamentals of superconductivity

- Metallic low temperature superconductors are in *Meissner* phase
- Metallic alloy low temperature superconductors are in *Shubnikov* phase
- Pinning centres in metal alloys to create „hard“ superconductors
- „Hard“ (technical) superconductors allow big electric transport currents

New technologies of electric energy converters and actuators

1. Superconductors for power systems

1.1 Fundamentals of superconductivity

1.2 Technical design of superconductors

1.3 Superconductors for technical use

1.4 Cooling procedures

1.5 Cryostats

1.6 Cryogenic technology

Bean model: Current flow in technical superconductor

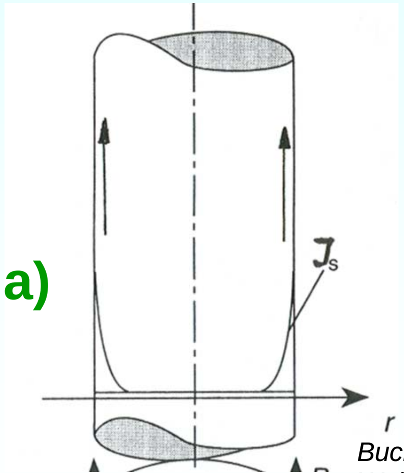
- Inside hard superconductor wire (radius *R*): Transport current I_s.

a) $I_s < I_{s,c1}$: *Meissner* phase; current flows in penetration depth λ = ca. 30 nm

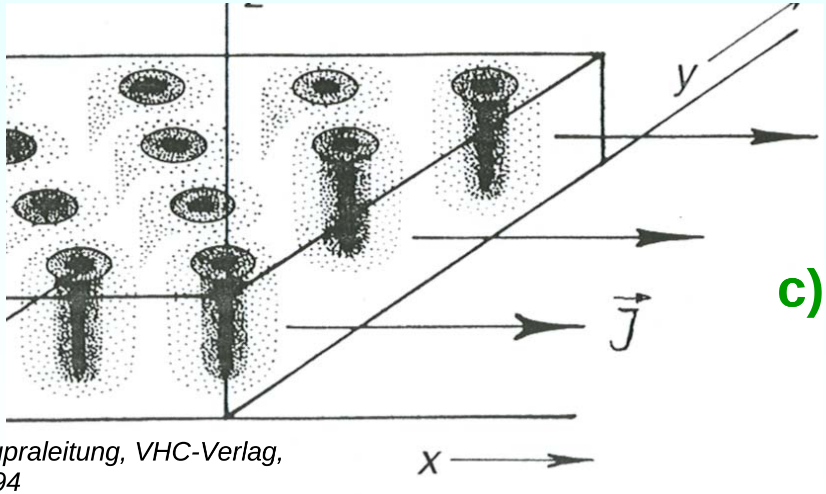
b) $I_{s,c1} < I_s < I_{s,cs}$: *Shubnikov* phase; Flux tubes get inside; current flows in λ -border area of each flux tube.

c) *Bean* model: Instead of b), an increased equivalent penetration depth *x* is defined at the material border, where the current flows with the critical current density $J_c(T, B)$

a)

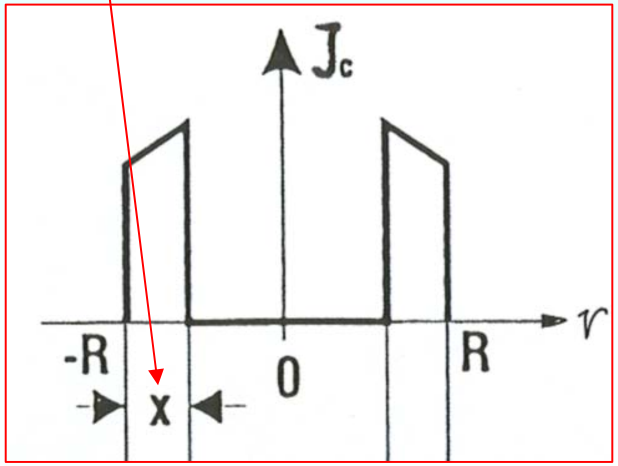


b)



Buckel, W.: Supraleitung, VHC-Verlag, Weinheim, 1994

c)



Bean model: Calculation for round wire, *T* = const.

1st step: **assumption: J_c independent of B:** $R - x \le r \le R : J_c = const.$

Transport current I_s: $I_s = J_c \cdot (R^2 - (R-x)^2) \cdot \pi$

Komarek, P.:
Teubner,
Stuttgart, 1995

Self-field B : $R - x \le r \le R$

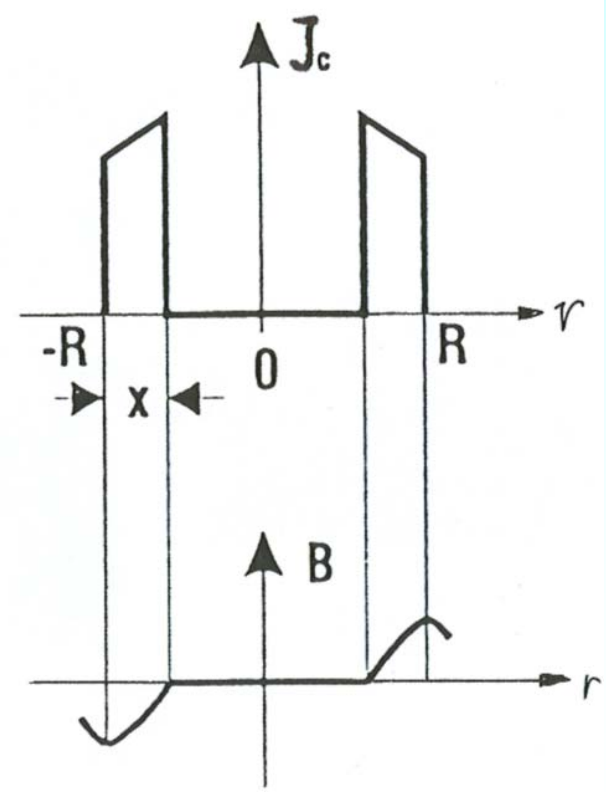
$$\oint_C \overrightarrow{H}(r) \cdot d\vec{s} = 2\pi r H(r) = \Theta = J_c \cdot \left[r^2 - (R-x)^2 \right] \cdot \pi$$

$$B(r) = \mu_0 \cdot J_c \cdot (r - (R-x)^2 / r) / 2$$

Result: B depends on r, therefore does $J_c(B(r))$ too!

2nd step: Inside of SC: B smaller, outside bigger, therefore $J_c(B)$ smaller than assumed.

3rd step: With $J_c(B)$ new calculation of bigger x for given transport current I_s.



Conduction of heat

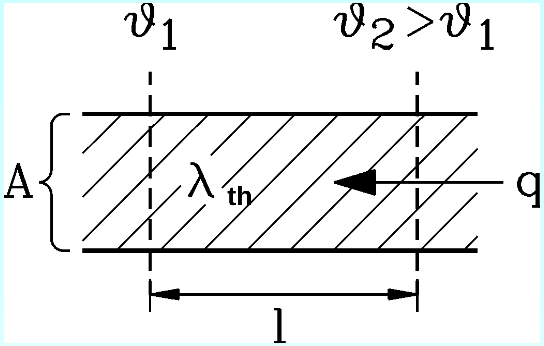
heat flow density $q = P_{th}/A$ [W/m^2]

Conduction of heat: ***Fourier´s law***

$$\boxed{\frac{P_{th}}{A} = \lambda_{th} \cdot (\vartheta_2 - \vartheta_1)/l}$$

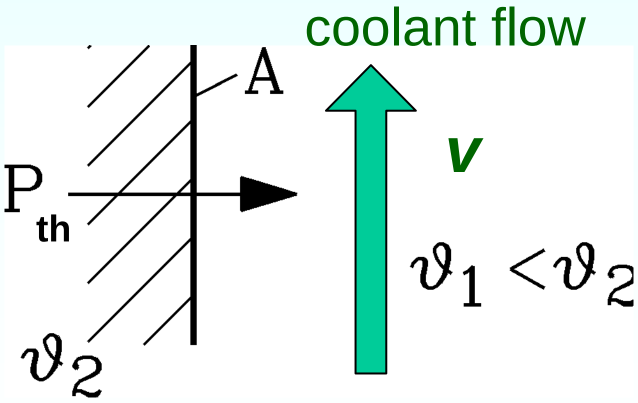
$\lambda_{th:}$ thermal conductivity (W/(m·K))

$P_{th:}$ thermal power (W)



Convection

Heat transfer coefficient α describes the cooling effect of flowing (”convection”) coolant, passing by a cooling surface *A* with the velocity *v*



$$\boxed{\frac{P_{th}}{A} = \alpha \cdot \Delta\vartheta}$$

α: heat transfer coefficient (W/(m^2·K))

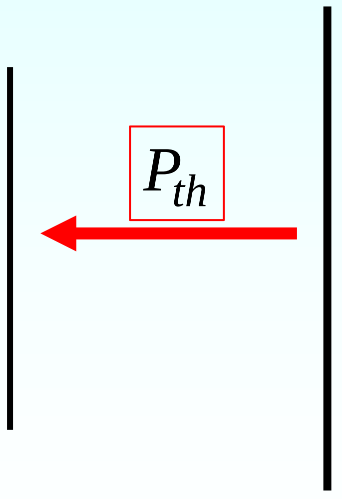
α: function of
- coolant velocity *v,*
- coolant parameters:
  mass density, thermal conductivity,
  heat capacity, viscosity

Radiation

Heat radiation does not need any medium to transport heat:

- Transferred heat P_{th} from hot (T_H) to cold ($T_K < T_H$) surface A
- T_K , T_H are absolute temperatures, measured in K
- **Heat radiation law** of *Stefan* and *Boltzmann*:
- "Black body" radiation: $\sigma_{SB} = 5.67 \cdot 10^{-8}$ W/(m^{2}K^4)

$$\boxed{\frac{P_{th}}{A} = \sigma_{SB} \cdot (T_H^4 - T_K^4)}$$



$$\boxed{P = A_K \cdot \frac{\sigma_{SB} \cdot (T_H^4 - T_K^4)}{\frac{1}{\varepsilon_K} - \frac{A_K}{A_H}\left(1 - \frac{1}{\varepsilon_H}\right)}}$$

$$\boxed{0 < \varepsilon_H , \varepsilon_K < 1}$$

Cold side:
area A_K
temperature T_K
absorption coefficient ε_K

Hot side:
area A_H
temperature T_H
absorption coefficient ε_H

Laminar (viscous) and turbulent flow

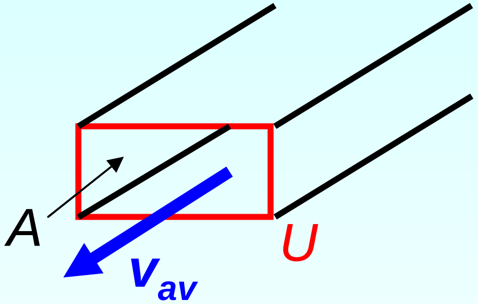
Flow in tubes :

a) Low velocity: "parallel" orbits of mass particles due to dominating inner viscous forces between particles = LAMINAR (VISCOUS) flow

b) High velocity: Orbits of different particles mingled in "chaotic" way = not only in flow direction, but also perpendicular: TURBULENT flow

Based on model parameters: ***REYNOLDS* number**

$$\boxed{\mathrm{Re} = \frac{v_{av} \cdot d}{\nu}}$$



v_{av}: average flow velocity

ν: kinematic viscosity

d: **hydraulic diameter of tube**

$d = 4A/U$ A,U Cross sectional area / circumference of tube

In *straight* tubes with smooth surface:

laminar flow: $Re < Re_{cr}$ (**critical *Reynolds* number $Re_{cr} = 2320$**)

turbulent flow: $Re > 3000$.

For good heat transfer: Turbulent flow is needed !

Bean model: Calculation for round wire, *T* variable

1st step: assumption: J_c independent of B:

$$I_s = J_c(T)\cdot(R^2-(R-x)^2)\pi = J_c(T)\cdot(2Rx-x^2)\pi$$

$$x = R-\sqrt{R^2-I_s/(J_c\pi)}$$

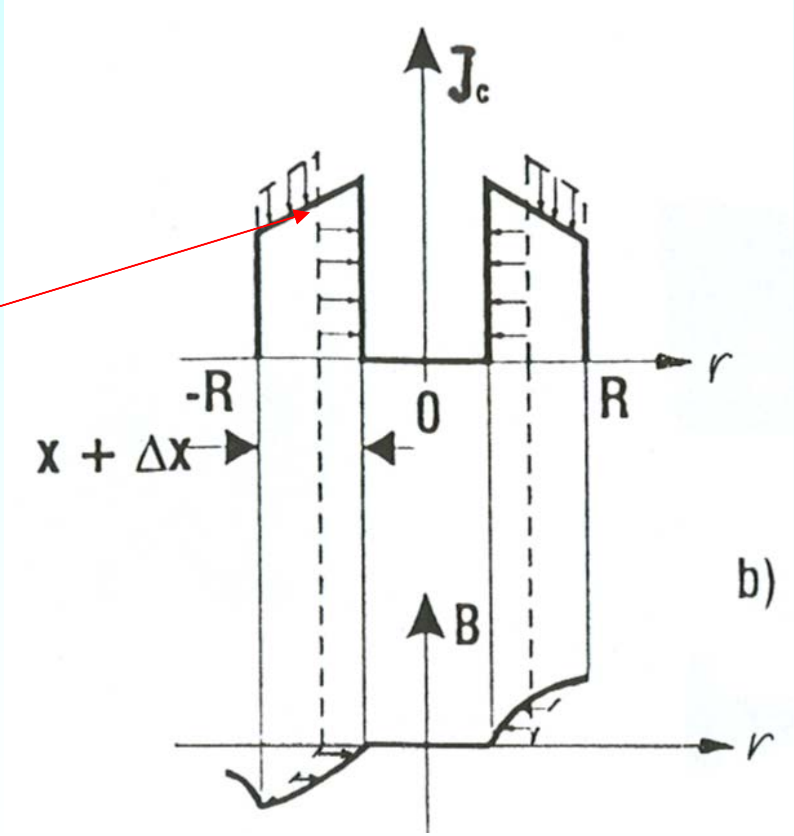
2nd step: If temperature *T* rises: J_c reduced, *x* must rise for a given I_s

3rd step: exact calculation with $J_c(T, B)$:

When *x* becomes equal to *R*, then the transport current limit is reached: $I_s = I_{s,cr}$.

At $I_s > I_{s,cr}$: Quenching into normal condition!

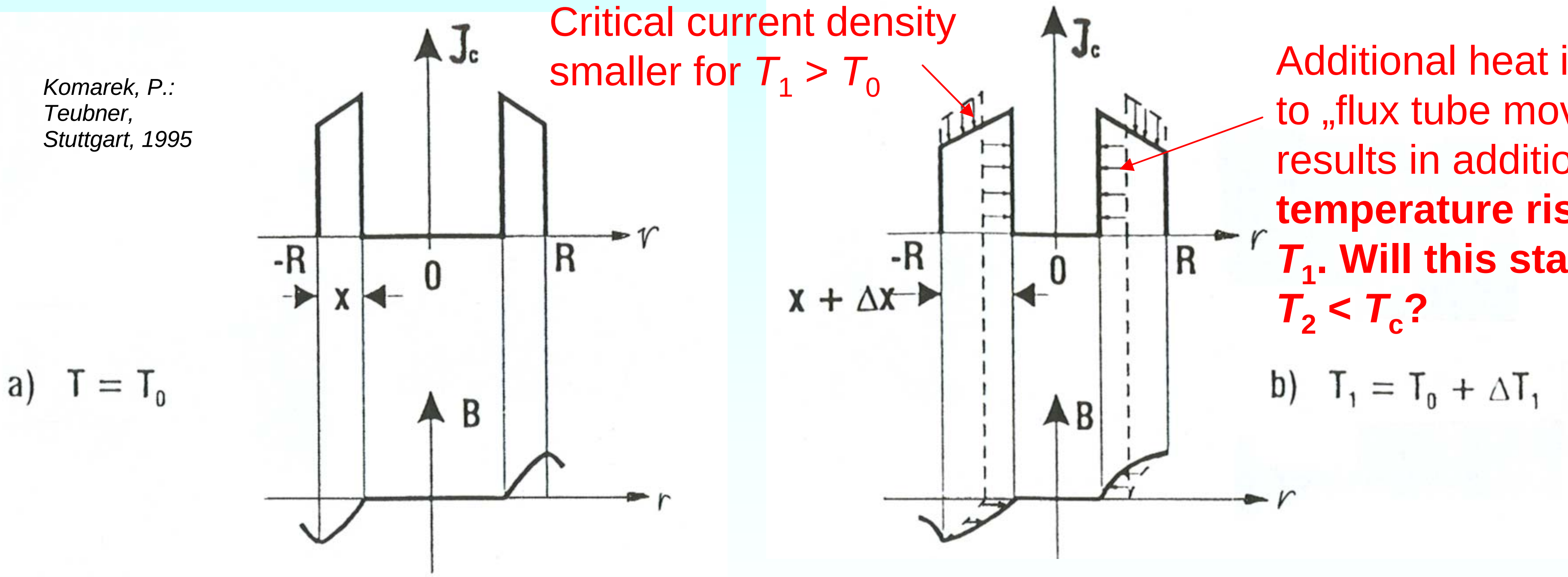
Komarek, P.:
Teubner,
Stuttgart, 1995



1.2 Technical design of Superconductors

How to attain thermal inherent stability ?

- Transport current density distribution in superconductor wire (radius R, penetration depth x), while raising temperature from a) T_0 to b) T_1



Komarek, P.: Teubner, Stuttgart, 1995

Critical current density smaller for $T_1 > T_0$

Additional heat input due to „flux tube movement" results in additional **temperature rise over T_1. Will this stabilize at $T_2 < T_c$?**

1.2 Technical design of Superconductors

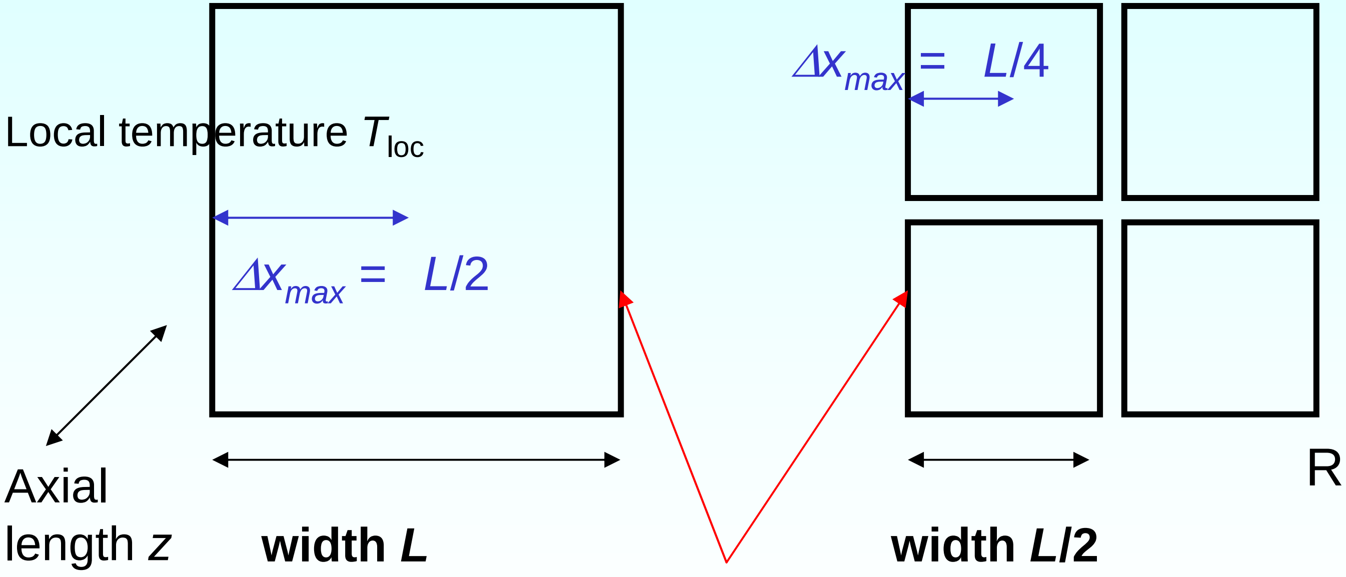
Filaments (length *z*) for thermal inherent stability

Very simplified comparison of thermal equilibrium temperature: Cases A & B:

Thermal equilibrium at loss power *P* & heat transfer coefficient α: $\boxed{P = \alpha \cdot A \cdot (T_{loc} - T_{amb})}$

$\Delta T = T_{loc} - T_{amb}$

Volume $V = L^2 z$



Case A:

1 conductor

Ambient temperature T_{amb}

Local temperature T_{loc}

$\Delta x_{max} = L/2$

Axial length *z*

width *L*

Case B:

1 conductor =

= 4 parallel filaments

$\Delta x_{max} = L/4$

width *L*/2

same heat transfer coefficient α

Flux tube movement ~ Δx

Power loss $P \sim \Delta x_{max} \cdot V$

$$P_A \sim L/2 \cdot (L^2 z)$$

$$P_B \sim (L/4) \cdot (L^2 z)$$

Cooling surface *A*:

$$A_A = 4L \cdot z$$

$$A_B = 4 \cdot (4 \cdot L/2) \cdot z$$

Ratio of temperature rise:

$$\boxed{\frac{\Delta T_B}{\Delta T_A} = \frac{P_B A_A}{P_A A_B} = \frac{1}{4}}$$

Inherent stability by filament wires

Arrange the SC as thin conductors (small radius), so that

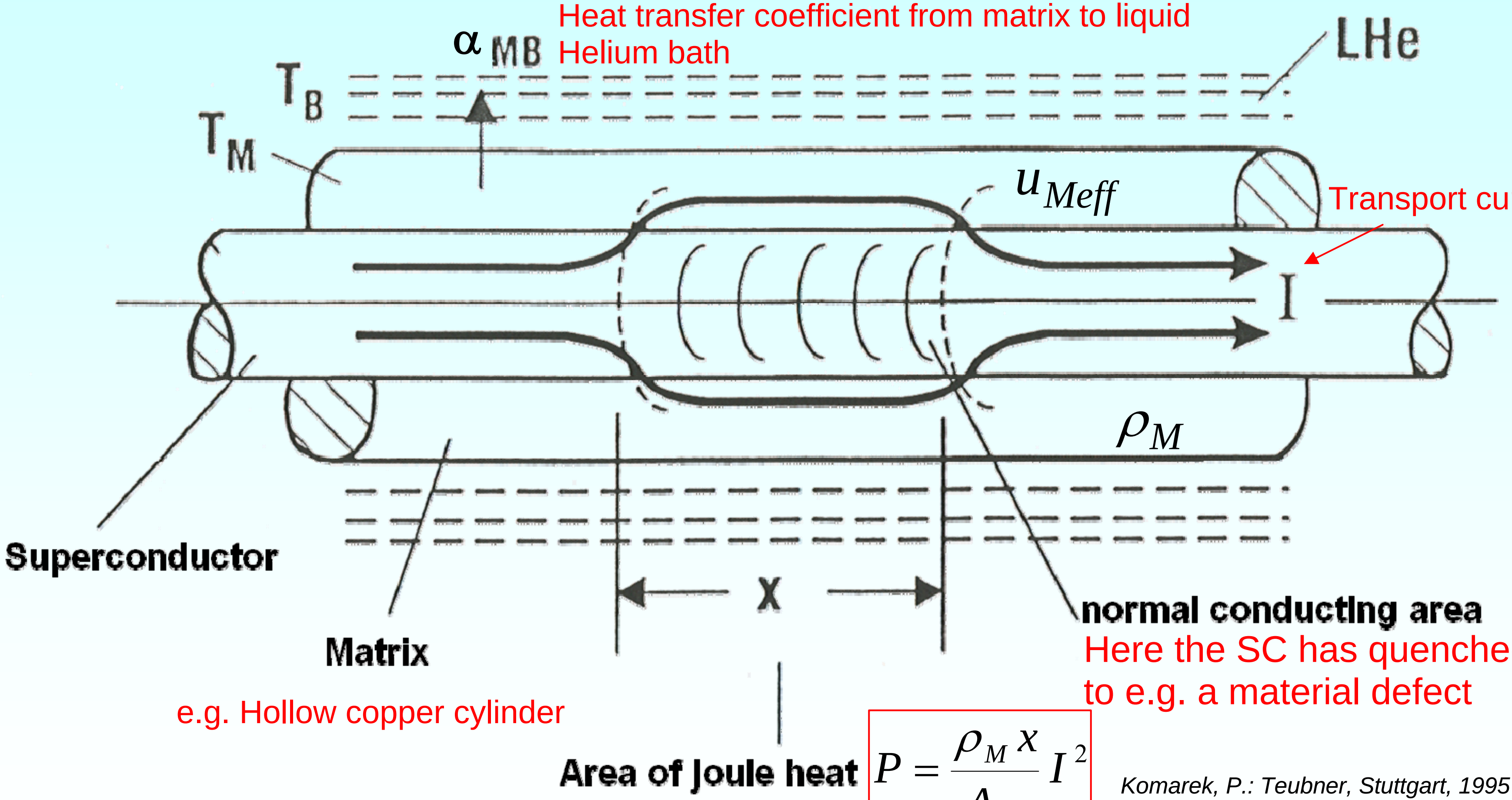
a) "flux movement" distances Δx are short and

b) the additional heat input is small.

Then the thermal stability criterion is fulfilled.

Hence: A separation in many parallel-positioned thin filaments is necessary.

How to scope with a local fault in a SC (quenching) at length *x*?



Heat transfer coefficient from matrix to liquid Helium bath

Transport current

Here the SC has quenched due to e.g. a material defect

e.g. Hollow copper cylinder

$$\boxed{P = \frac{\rho_M x}{A_M} I^2}$$

Komarek, P.: Teubner, Stuttgart, 1995

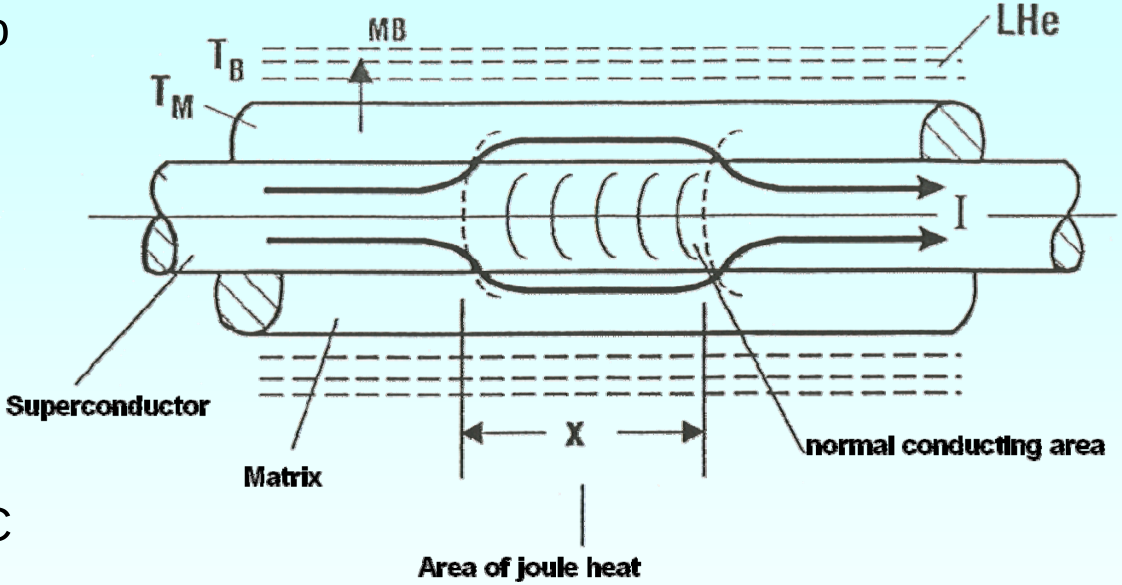
Cryogenic stabilisation of technical superconductors with enveloping normal conductor matrix

- If a local quenching occurs (e.g. due to a material defect), the resistivity of the then normally conducting SC is usually much higher than that of e.g. copper or aluminum.

- Hence a big local heat would melt the SC.

- Therefore a “matrix” (e.g. copper) by-pass as a hollow cylinder around the SC wire takes over the transport current.

- The matrix parameters must be chosen properly, so that the matrix Joule losses do not heat up the SC beyond the critical temperature, which otherwise would lead to a “quench” of the complete SC.



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Teubner,
Stuttgart, 1995

Cryogenic stabilisation with cooled matrix

- At partial “quenching“ at length *x*: Losses $P = \frac{\rho_M x}{A_M} I^2$ in matrix must be so small that we keep $T_M < T_c$!

- Hence the matrix resistivity ρ_M must be low and the matrix cross section A_M and the matrix circumference u_{Meff} big.

$\Rightarrow$ Heat removal via α_{MB} must be big enough, leading to the condition:

- $P = \frac{\rho_M x}{A_M} I^2 < \alpha_{MB}(T_c(B,J) - T_B) \cdot (x \cdot u_{Meff})$: *Stekly* parameter $\alpha_{St} < 1$

$$\boxed{\alpha_{St} = \frac{\rho_M I^2}{A_M \alpha_{MB}(T_c(B,J) - T_B) \cdot u_{Meff}} < 1}$$

- *The superconductor filament must be put into a highly conductive matrix (Cu, Al, Ag,...) of sufficiently large dimensions and good cooling conditions, to avoid that the quench fault length x increases along the superconductor*

AC operation: "Coupling" of SC filaments with eddy currents

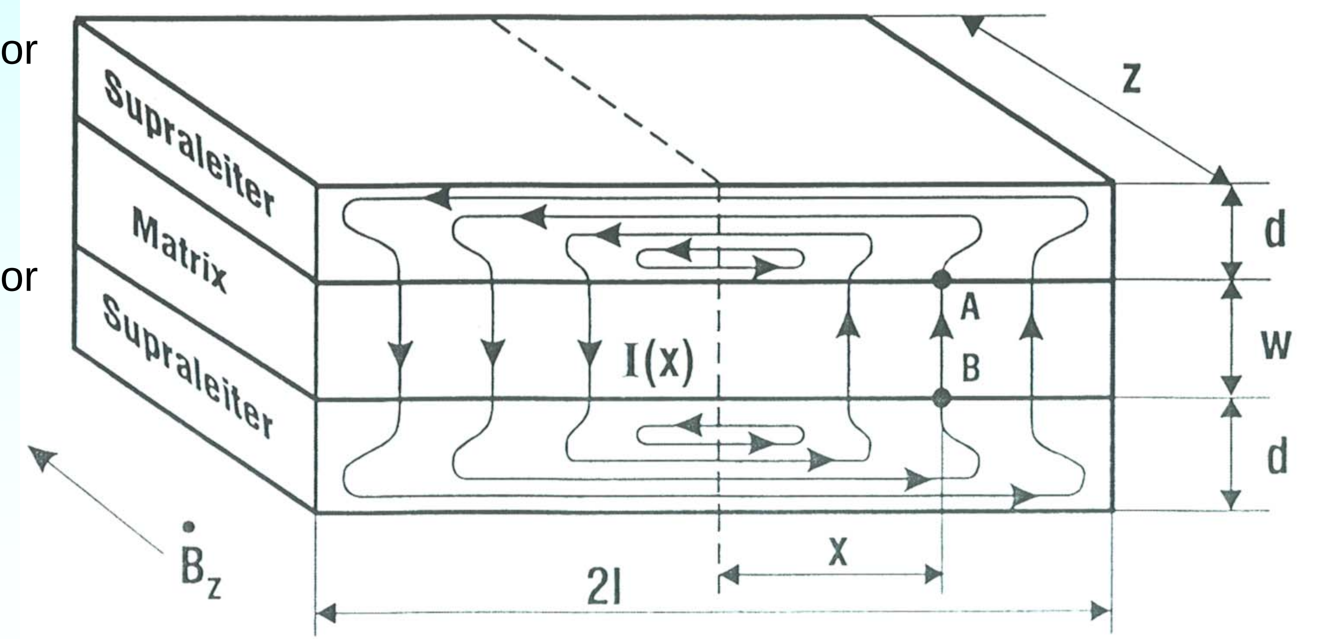
NbTi-SC in Cu matrix: SC: $d = 50\ \mu\mathrm{m}$, $J_c = 2\cdot10^9\ \mathrm{A/m}^2$, matrix: $\rho_M = 4\cdot10^{-10}\ \Omega\mathrm{m}$

External AC field with rate of change $dB_z/dt = 0.1$ T/s induces eddy currents $I(x)$.

At a critical lenght $l_c = 2.8$ cm the eddy current density in the SC reaches the critical value J_c and quenches the SC filaments.

Superconductor filament

Superconductor filament



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AC operation: Induced eddy currents

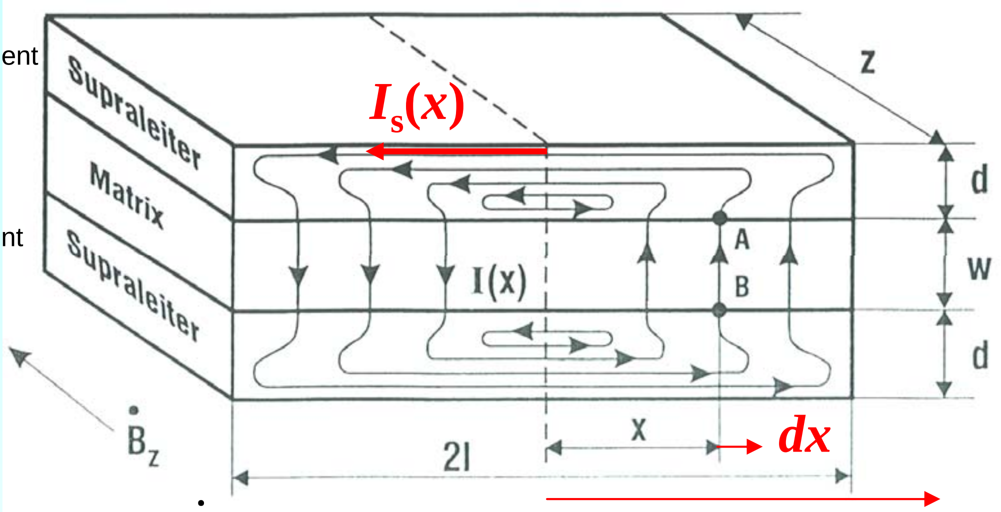
Flux: $\Phi(x,t) = B_z(t)\cdot w\cdot 2x$

Induced voltage:

$$u_i = -d\Phi(x,t)/dt = -\dot{B}_z(t)\cdot w\cdot 2x$$

Matrix coupling current (R_{SC} = 0!):

$$I(x) = \frac{u_i(x)}{2R_{M,AB}} = \frac{-\dot{B}_z(t)\cdot w\cdot 2x}{2\rho_M\cdot w/(dx\cdot z)}$$



Matrix coupling current density: $J(x) = \frac{I(x)}{dx\cdot z} = \frac{-\dot{B}_z(t)\cdot x}{\rho_M}$

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Eddy current in the SC filament and the limit of the critical current density:

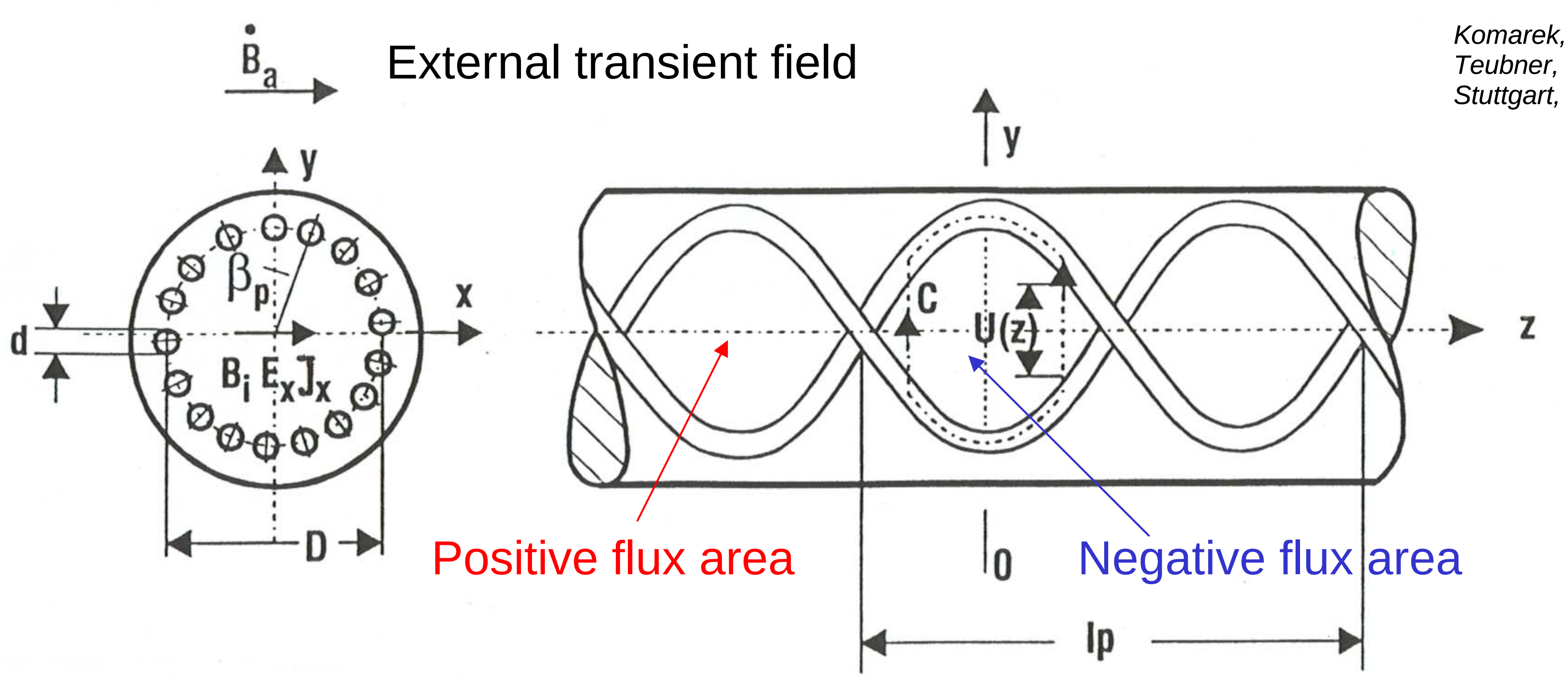
$$I_s(x) = -\int_0^x J(x)\cdot dx\cdot z = \frac{z\cdot\dot{B}_z(t)\cdot x^2}{2\rho_M} \qquad J_c\cdot d\cdot z = I_{s,c} = I_s(x=l_c) = \frac{z\cdot\dot{B}_z(t)\cdot l_c^2}{2\rho_M}$$

Maximum admissible SC filament half length:

$$\boxed{l_c = \sqrt{J_c 2\rho_M d/\dot{B}_z}} \qquad l_c = \sqrt{2\cdot 10^9\cdot 2\cdot 4\cdot 10^{-10}\cdot 50\cdot 10^{-6}/0.1} = 28mm$$

Twisting of superconductor filaments

Twisting of the superconductor filaments with a ***twist-length*** $\boldsymbol{l_p}$, *matched to the transient field dB/dt, is necessary, to avoid coupling of adjacent filaments and a "quench" by eddy currents.*



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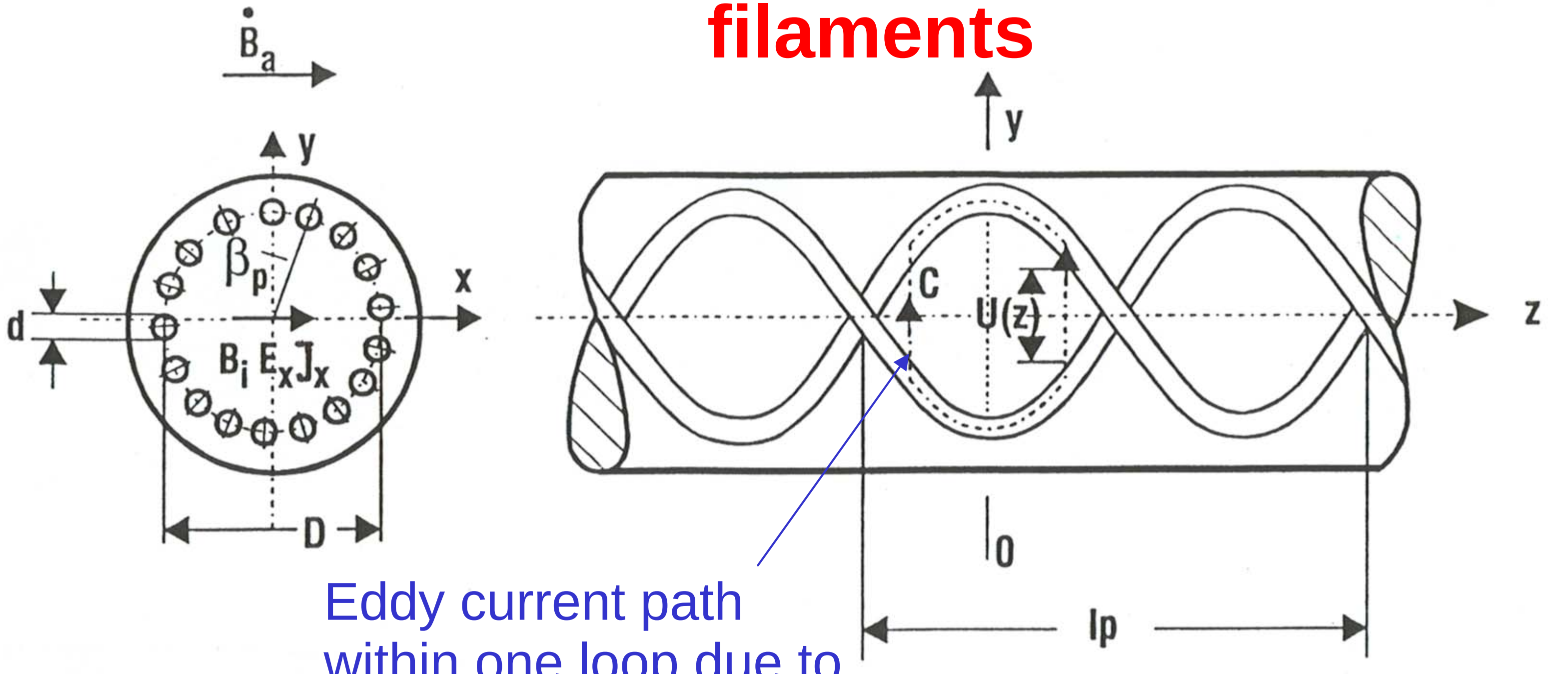
- Within l_p positive and negative flux areas cancel = no resulting induced voltage!

Eddy currents within one loop between two SC filaments



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Stuttgart, 1995

Eddy current path
within one loop due to
induced voltage *U*(*z*)

Eddy currents within one loop $I(z) = U(z)/R_M(z)$ cause eddy current losses (*Foucault* losses) in the matrix:

$$P_{Ft} = U^2 / R_M = (\omega \cdot B \cdot D \cdot l_p / 2)^2 / R_M \sim (\omega \cdot B \cdot l_p)^2 / \rho_M$$

SC alternating current losses

- **Eddy current losses** in the matrix: $P_{Ft} \sim (\omega B l_p)^2 / \rho_M$

  - Injection of **resistive barriers** (**mixed matrix**), CuNi-coating

  - Reducing the twist length l_p

- **Hysteresis loss in SC:** Partial Flux “tube" creep leads to hysteresis loop $M(B)$. P_{Hy} prop. to the area of the magnetic hysteresis loop $M(B)$.

  P_{Hy} ~ angular frequency ω & ~ SC filament wire diameter d

- *For especially low loss of superconductors in the alternating field, filaments should be very thin (small diameter d, being way thinner than it is necessary for thermal stabilising).*

New technologies of electric energy converters and actuators

Summary:
Technical design of superconductors

- Thin filaments for thermal stability
- Conductive matrix for quench take-over
- Much smaller filaments needed to reduce AC losses
- Twisted filaments for reduction of AC losses

New technologies of electric energy converters and actuators

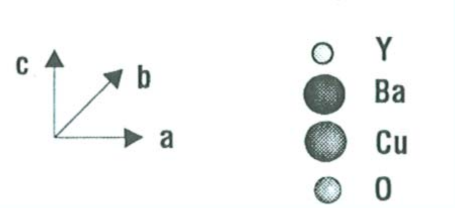
1. Superconductors for power systems

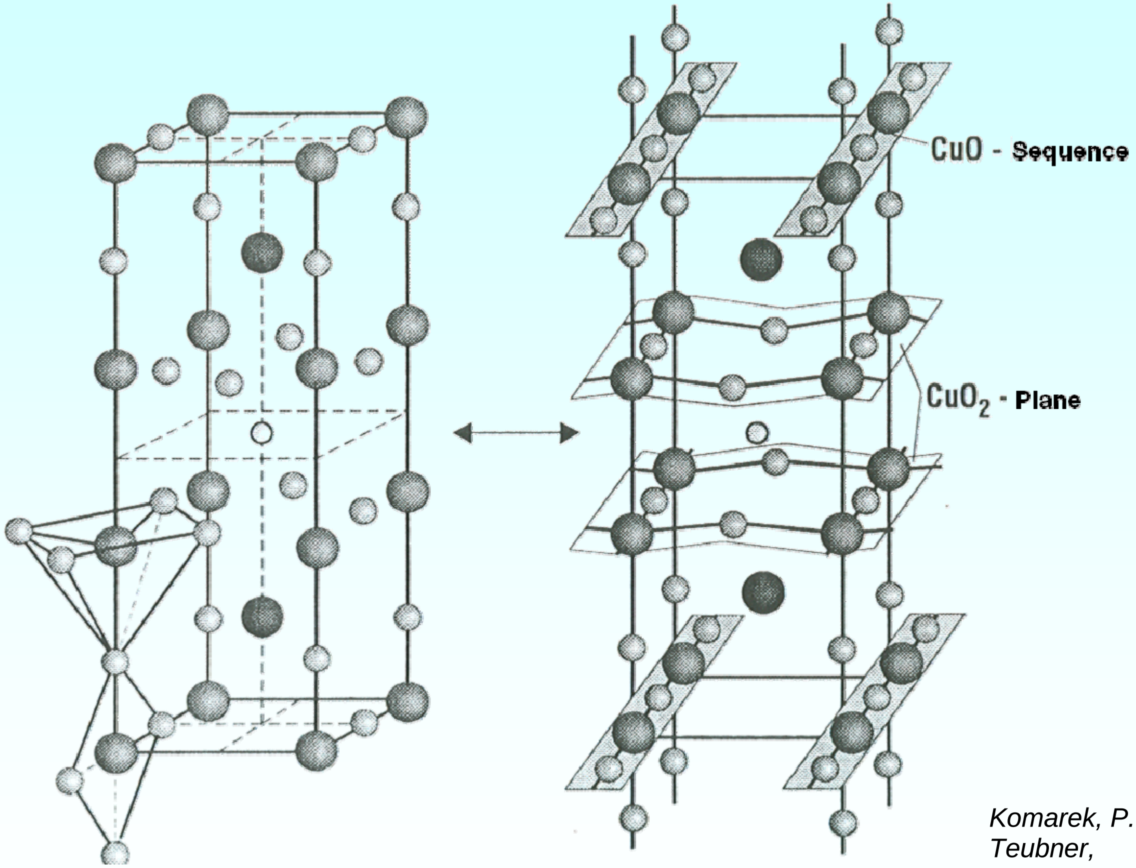
HTSC Superconductor *Yttrium-Barium-Copper oxide* $YBa_2Cu_3O_{7-x}$

Crystal structure:

Anisotrope behaviour

a- and b-axis: “easy” axis (preferred crystal axis)





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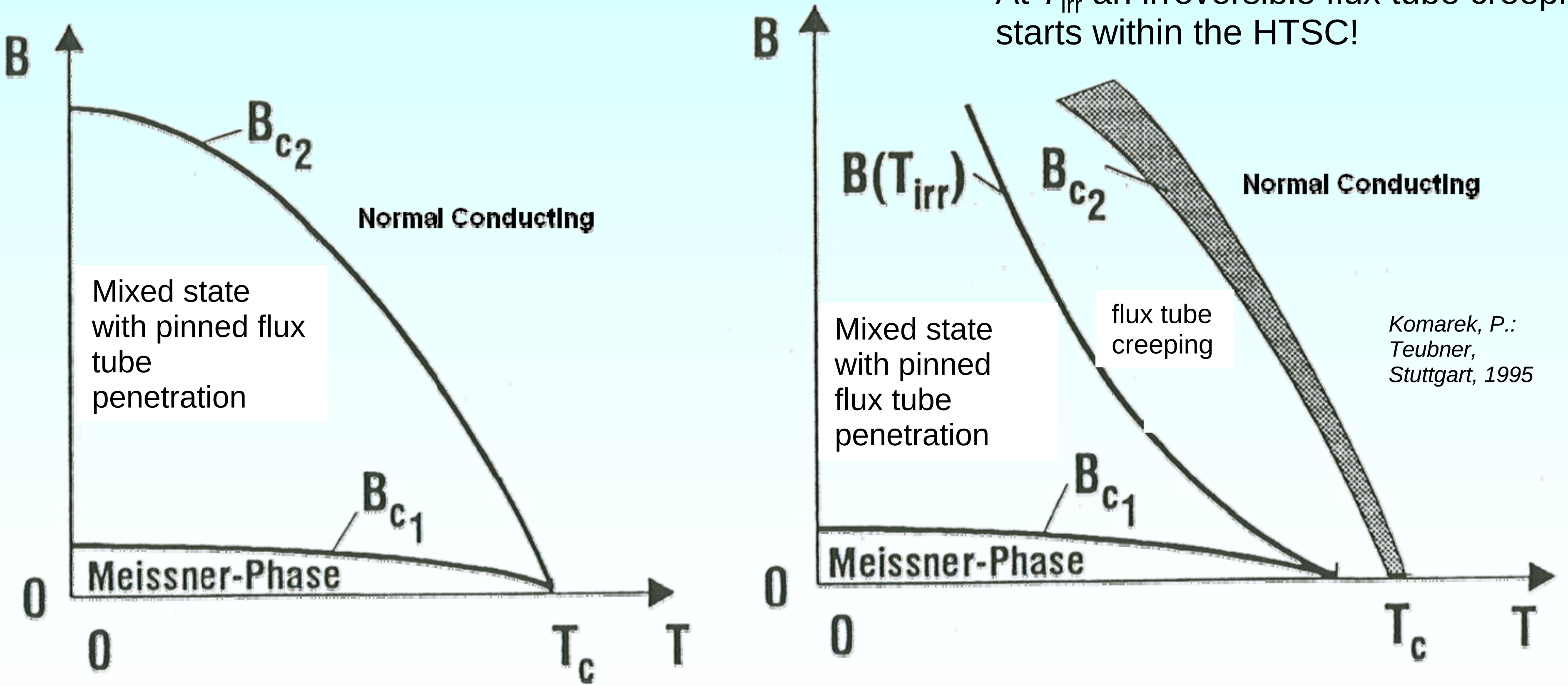
Limits of technical LTSC and HTSC superconductors

B(T) phase diagram



a) LTSC superconductor,

b) HTSC superconductor

At T_{irr} an irreversible flux tube creeping starts within the HTSC!

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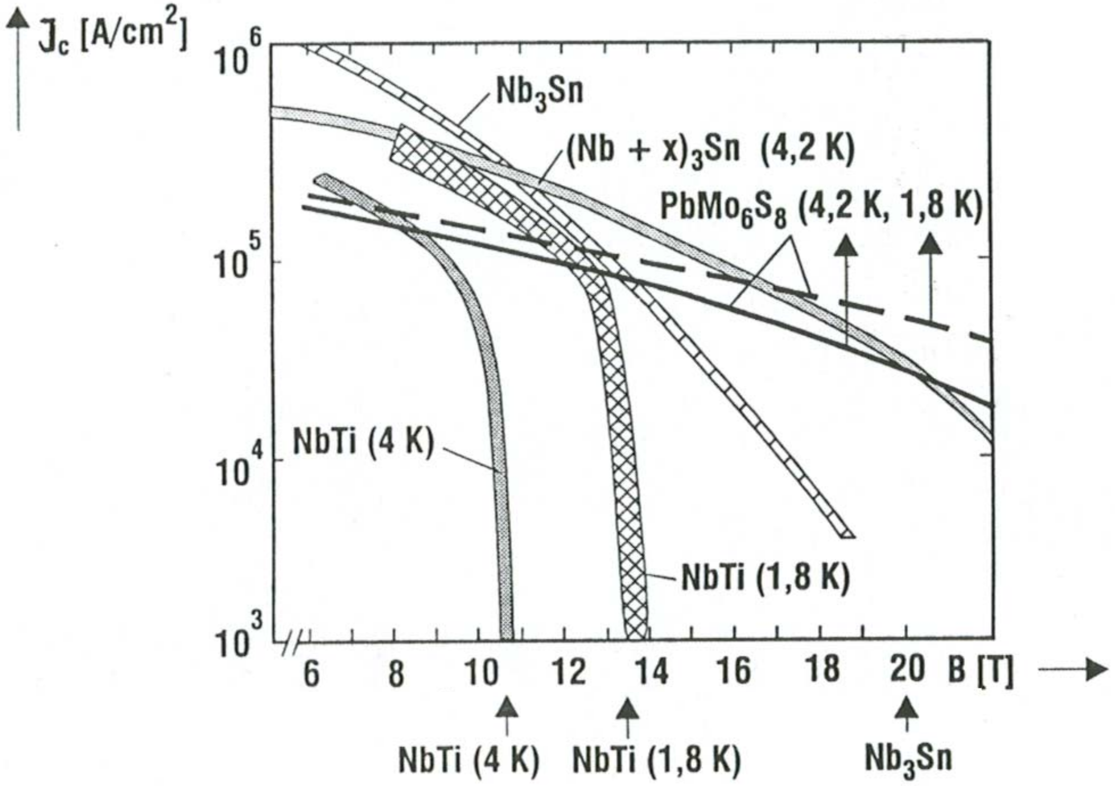
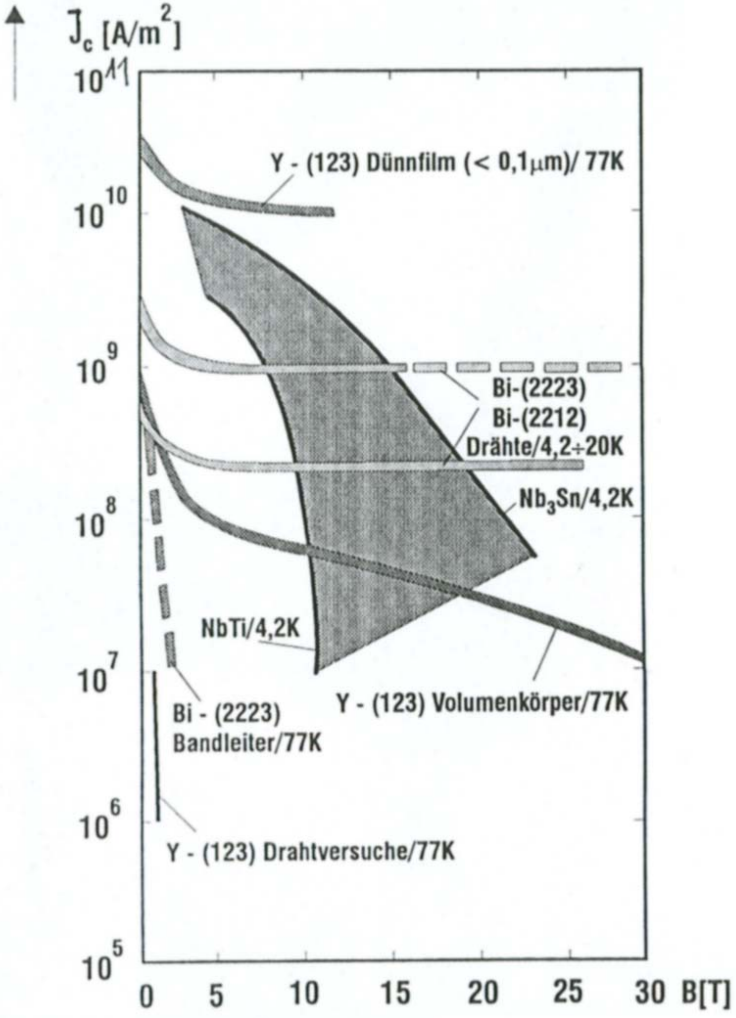
Operating Areas of LTSC and HTSC

Superconductor type	LTSC	HTSC
Meissner phase $B < B_{c1}$	Magnetic field does not enter SC, transport current flows without loss in the LONDON λ-layer	
Shubnikov phase	$B_{c1} < B < B_{c2}$	$B_{c1} < B < B(T_{irr})$
	Magnetic field enters SC as regular flux tube pattern, transport current flows in the entire conductor cross section (lossless DC, AC: eddy current and hysteresis losses)	
Thermally activated flux creeping	Occurs only very close to T_c, hence not relevant	$B(T_{irr}) < B < B_{c2}$ Through anisotropy and low pinning energy creeping of flux tubes: lossless DC not possible

1.3 Superconductors for technical use

Critical current density J_c and magnetic flux density B_{c2}





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Stuttgart, 1995

Parameters of LTSC and HTSC (1)

Material	T_c $(B = 0)$ / K	B_{c2} $(T = 0)$ / T	Application
NbTi (LTSC)	9.6	12 ... 14	Standard material für $B \leq 9$ T
Nb_3Sn (LTSC)	18	ca. 25	Standard material for high fields
Y(123) (HTSC)	ca. 90	>> 100 T *)	Magnet bearing, “Permanent” magnets, tape wire
Bi(2212)	ca. 80	> 20 T *)	Composite wire conductor
Bi(2223)	ca. 110	> 20 T *)	Composite wire conductor

(*) : parabolic extrapolated in 70 K–area) , in “easy” crystal axis for HTSC

$Bi_2Sr_2Ca_2Cu_3O_{8+x}$ = Bi(2223) $Bi_2Sr_2CaCu_2O_{8+x}$ = Bi(2212) $YBa_2Cu_3O_{7-x}$ = YBCO

Parameters of LTSC and HTSC (2)

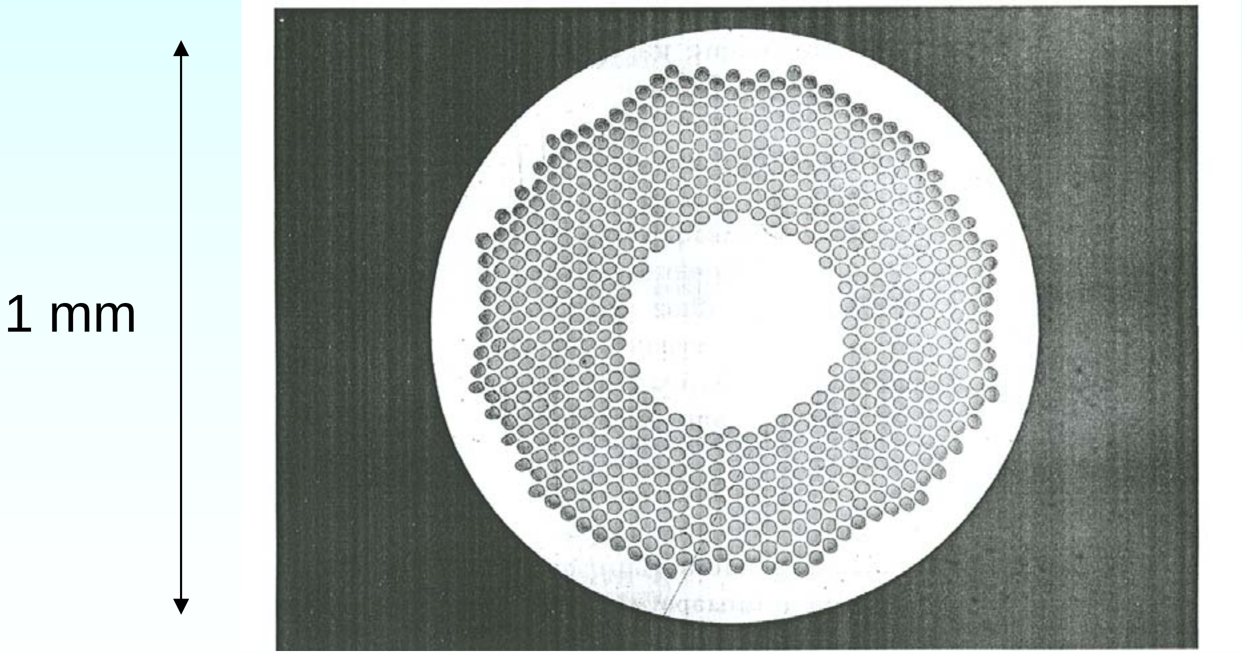
Material		Influence of mechanical load on critical current density: tensile stress σ and plastic deformation (elongation) ε
NbTi	LTSC	Small influence for $\sigma < 500$ MPa, $\varepsilon < 0.3$ %
Nb_3Sn	LTSC	Very sensitive, because brittle: decline of up to 50 %, at shear stress: filamentary break
Y(123)	HTSC	See: properties of HTSC tape conductors
Bi(2223)	HTSC	See: properties of HTSC wire conductors

1 Pa = 1 N/m^2,   500 MPa = 500 N/mm^2

NbTi-composite-round wire, Cu matrix, DC conductor

- Diameter 1 mm, 864 NbTi filaments, critical current I_c = 75 A (5 T, 4.2 K)
- Area: Wire overall: 0.785 mm^2, part of superconductor: 0.1 mm^2
- Area ratio matrix/superconductor = 7, J_c = 75/0.1 = 750 A/mm^2

“Engineering” current density: 75/0.785 = 96 A/mm^2



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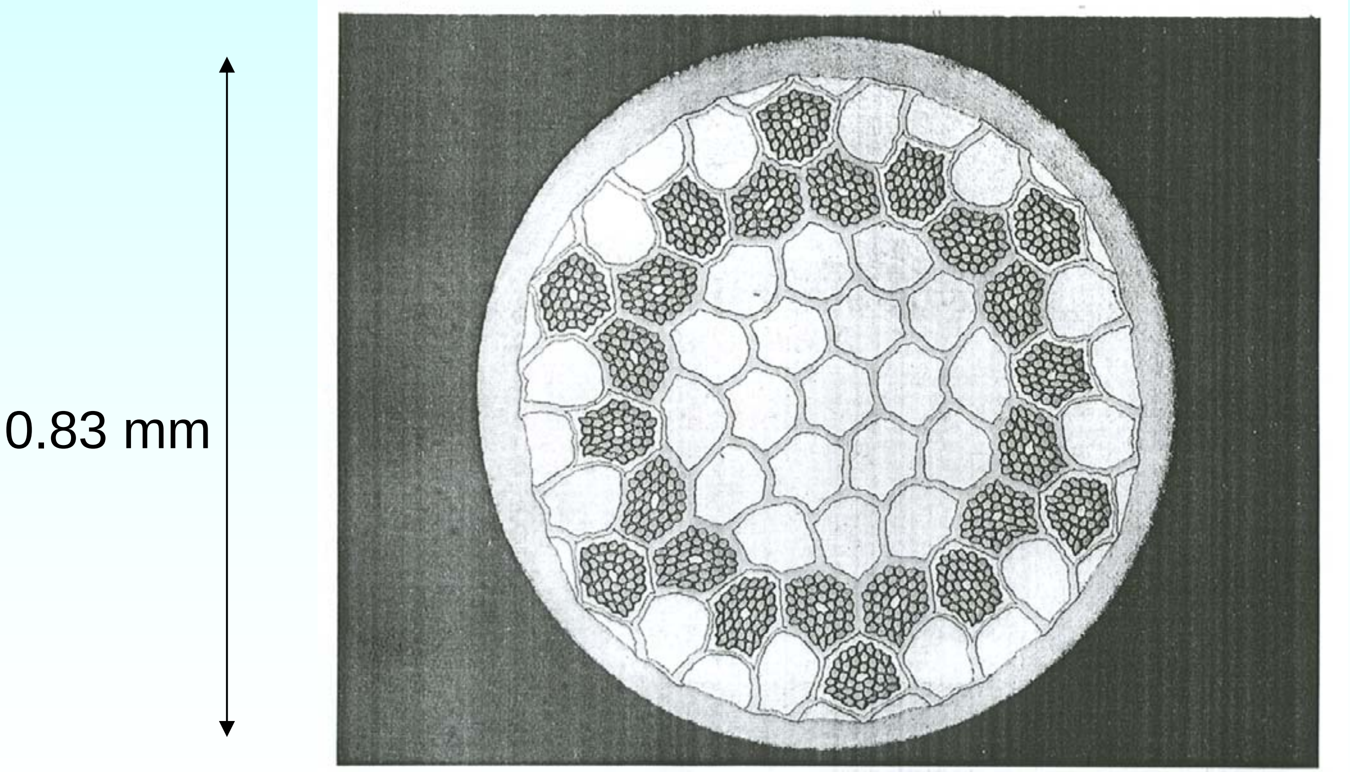
1.3 Superconductors for technical use

NbTi composite wire, Cu-CuNi mixed matrix, AC conductor

- Wire diameter 0.83 mm, 636 NbTi filaments (diameter 20 μm)
- I_c = 430 A (5.5 T, 4.2 K), cross-sectional area: 0.54 mm^2, SC: 0.2 mm^2,
- Cu: 0.34 mm^2, ratio Cu/SC = 1.7, J_c = 430/0.2 = 2150 A/mm^2
  "Engineering" current density: 430/0.54 = 796 A/mm^2



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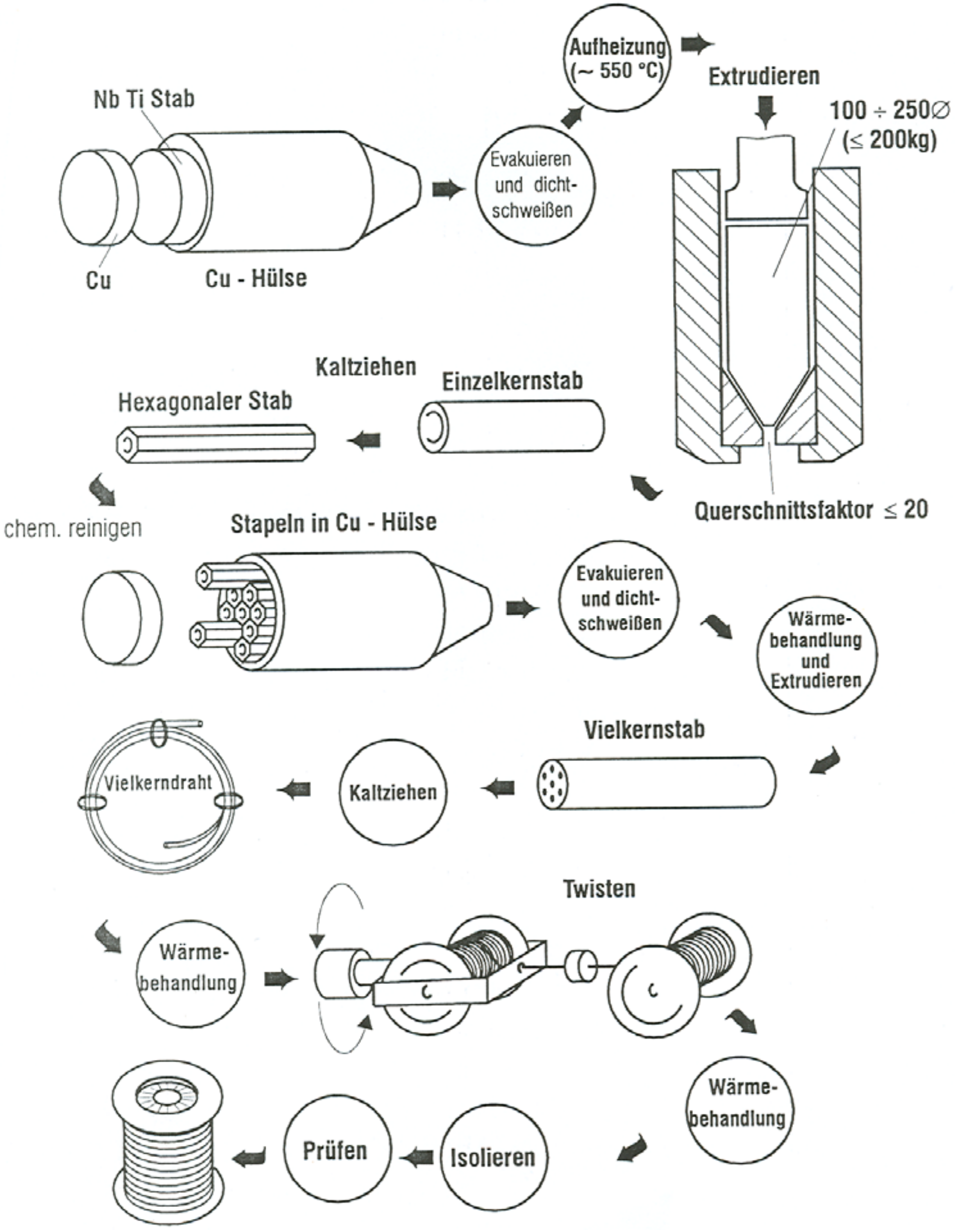
Teubner,
Stuttgart, 1995

1.3 Superconductors for technical use

Production of NbTi composite conductors



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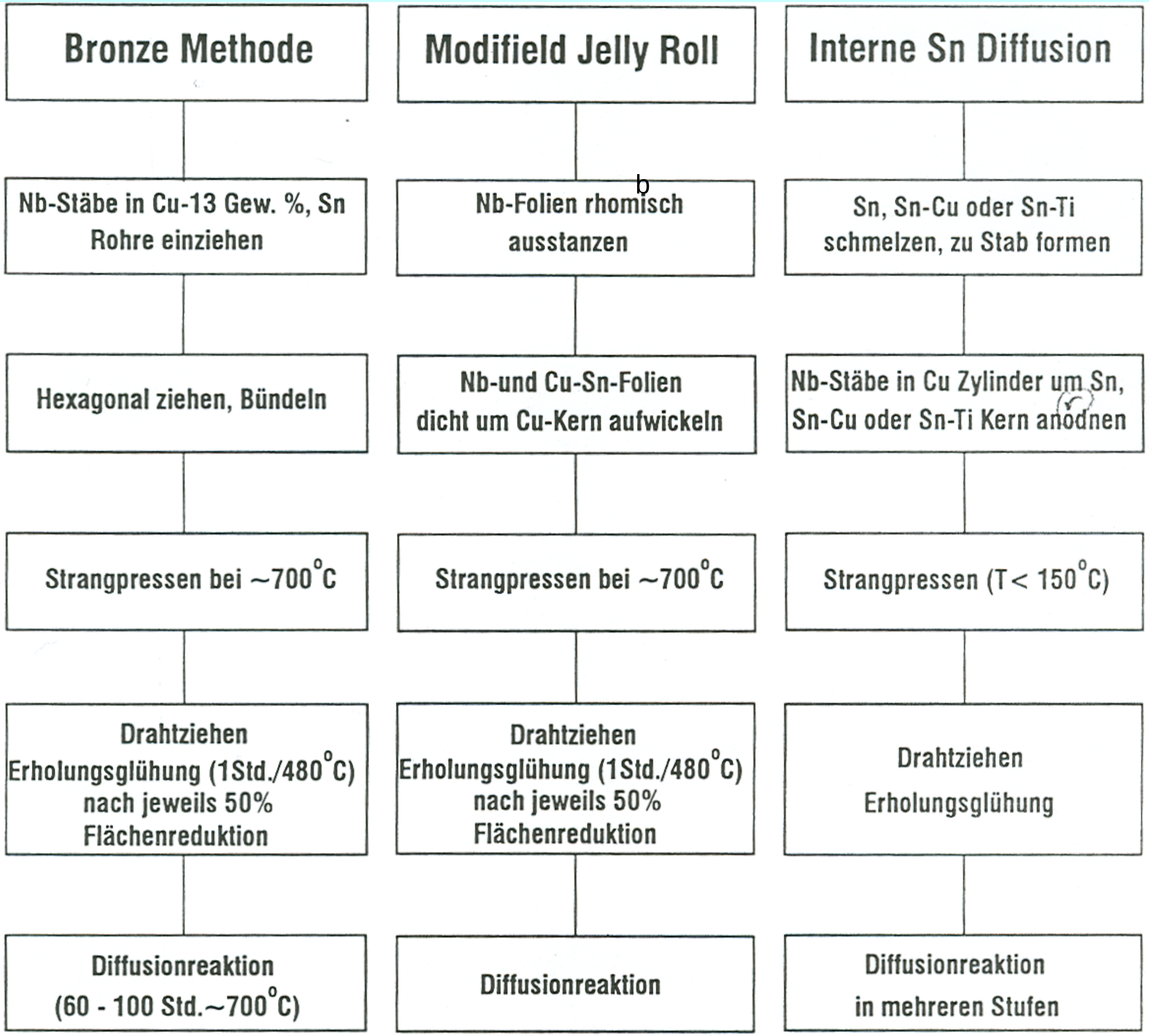
1.3 Superconductors for technical use

Different production procedures of Nb_3Sn composite conductors



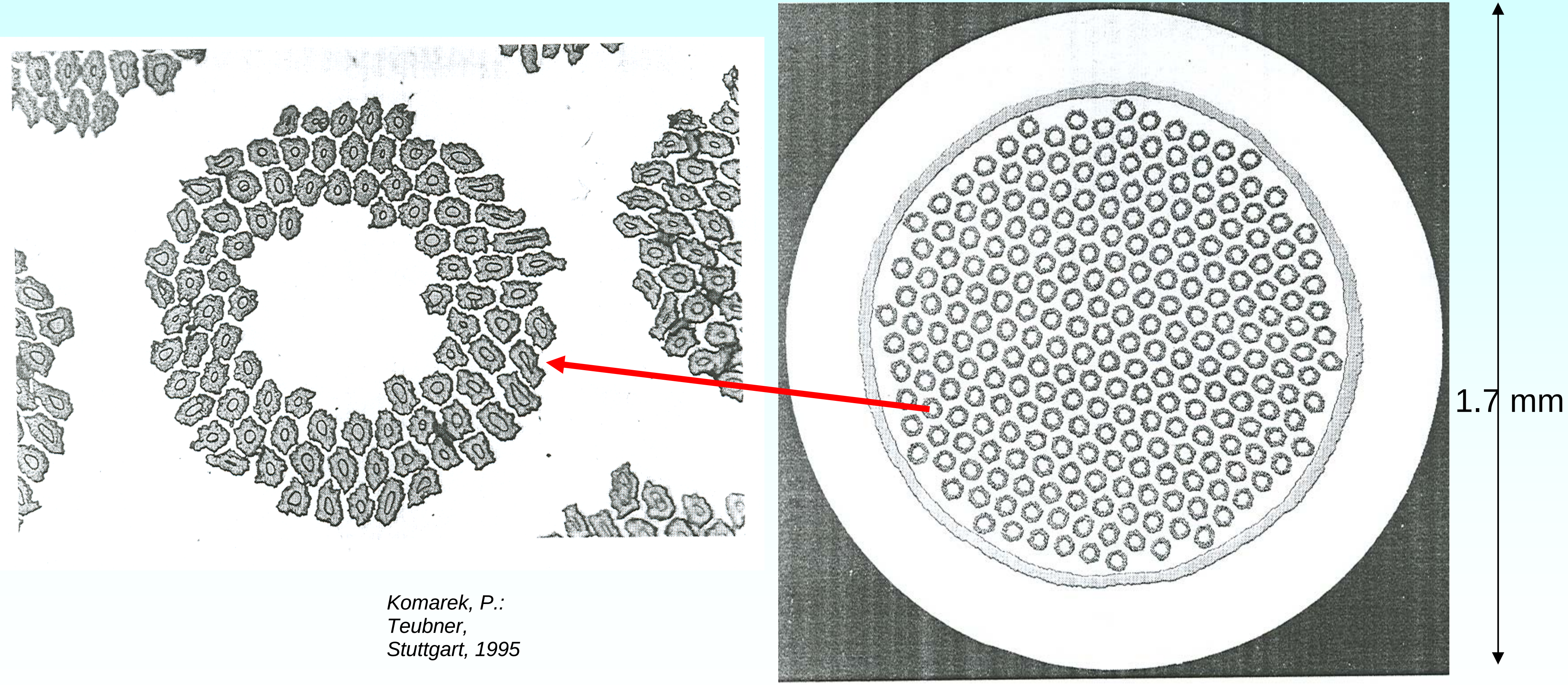
Bronze Methode	Modifield Jelly Roll	Interne Sn Diffusion
Nb-Stäbe in Cu-13 Gew. %, Sn Rohre einziehen	Nb-Folien rhombisch ausstanzen	Sn, Sn-Cu oder Sn-Ti schmelzen, zu Stab formen
Hexagonal ziehen, Bündeln	Nb-und Cu-Sn-Folien dicht um Cu-Kern aufwickeln	Nb-Stäbe in Cu Zylinder um Sn, Sn-Cu oder Sn-Ti Kern anodnen
Strangpressen bei ~700°C	Strangpressen bei ~700°C	Strangpressen (T< 150°C)
Drahtziehen Erholungsglühung (1Std./480°C) nach jeweils 50% Flächenreduktion	Drahtziehen Erholungsglühung (1Std./480°C) nach jeweils 50% Flächenreduktion	Drahtziehen Erholungsglühung
Diffusionreaktion (60 - 100 Std.~700°C)	Diffusionreaktion	Diffusionreaktion in mehreren Stufen

Komarek, P.:
Teubner,
Stuttgart, 1995

1.3 Superconductors for technical use

Nb_3Sn composite round wire

- Diameter 1.7 mm, 23000 Nb_3Sn filaments, critical current I_c = 750 A at 12 T and 4.2 K
- "Engineering" current density: $750/(1.7^2\pi/4) = 330\ \mathrm{A/mm^2}$



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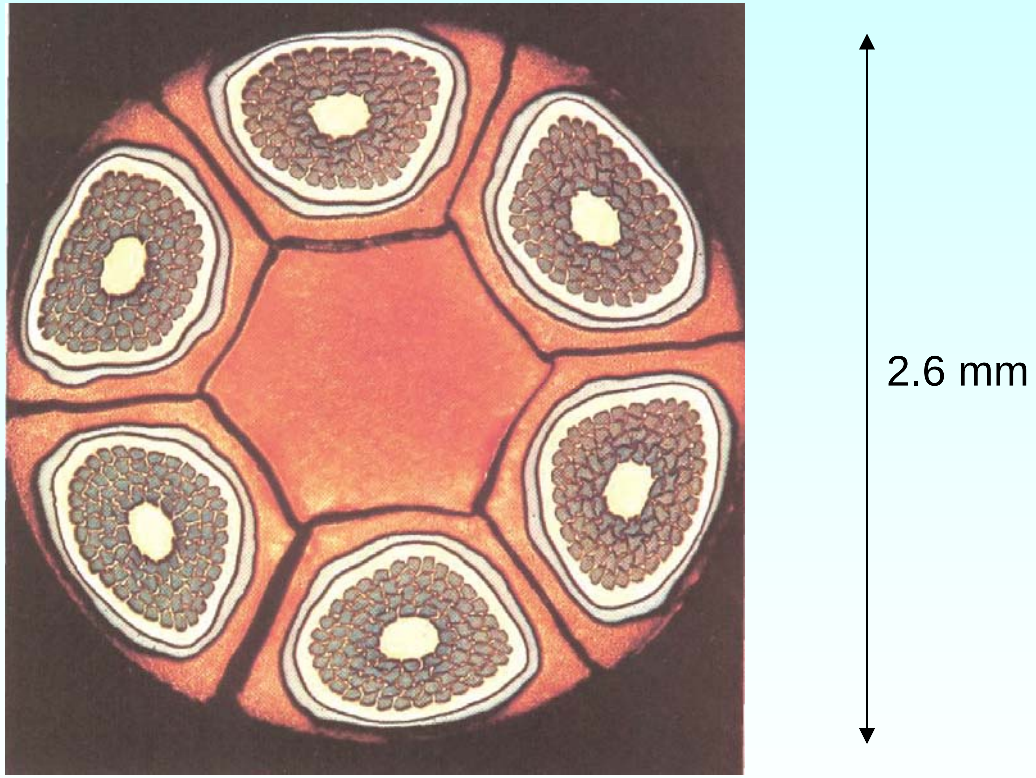
Nb_3Sn composite round wire

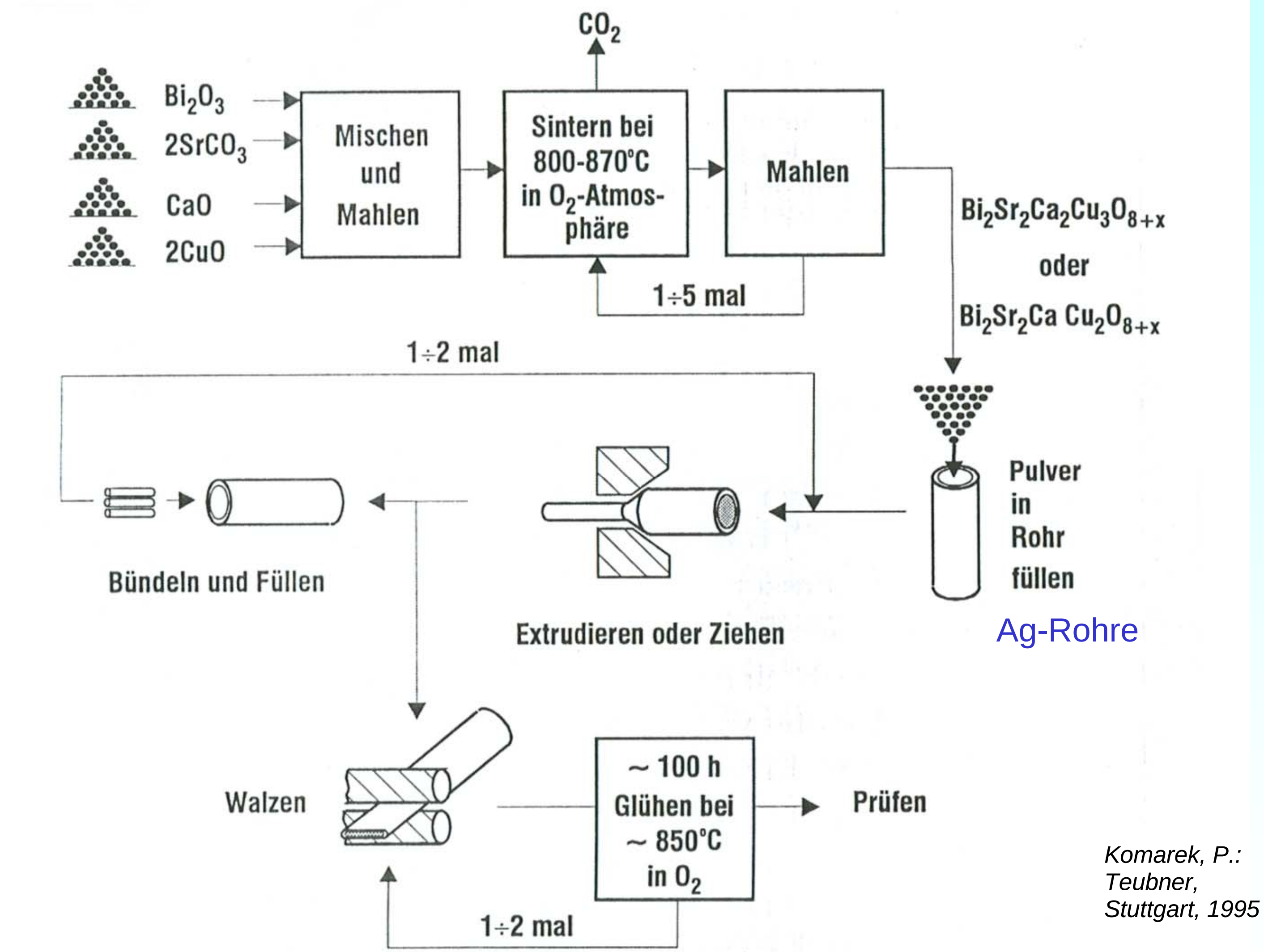
- Diameter 2.6 mm, 10000 Nb_3Sn filaments per conductor, 6 conductors in parallel, diameter 3 µm per filament, Cu-Sn-matrix material: copper-tin alloy



Source: Vacuumschmelze GmbH,
Hanau, Germany, 1983

1.3 Superconductors for technical use

Production of Bi-superconductor composite flat wires



Komarek, P.: Teubner, Stuttgart, 1995

1.3 Superconductors for technical use

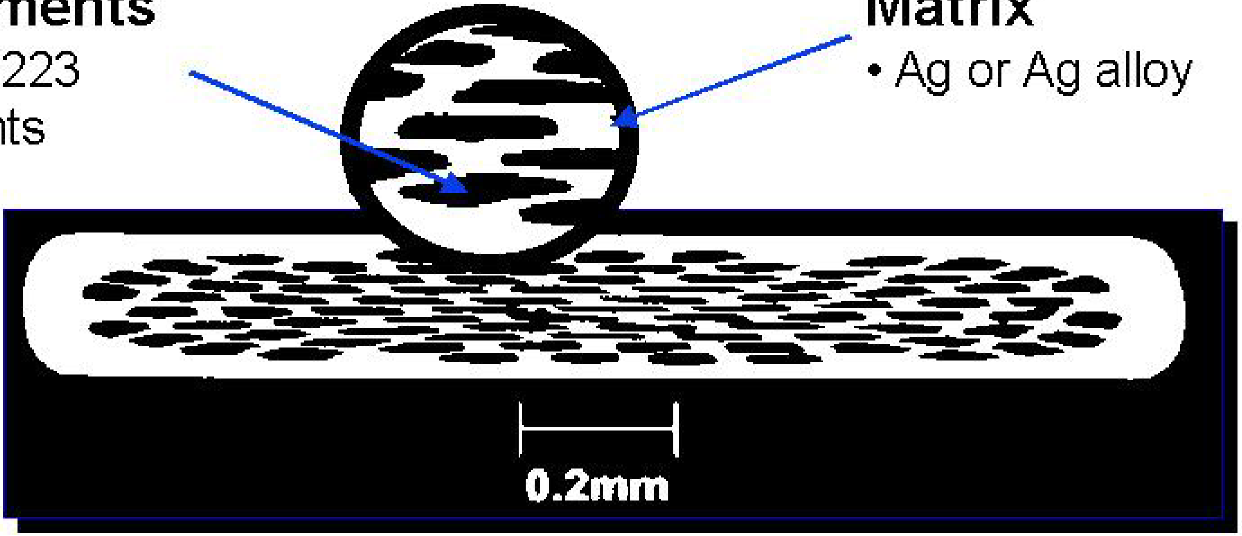
Cross section of a BiSCCO flat filament conductor

HTS Filaments

- BSCCO-2223
- 85 filaments

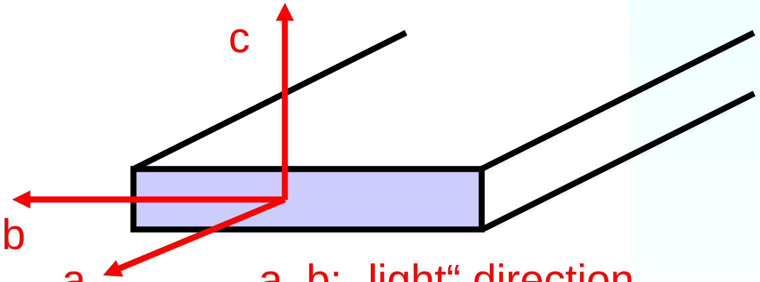
Matrix

- Ag or Ag alloy



Definitions:

- j_e = current density of entire tape
- j_c = current density of HTS filaments
- fill factor = j_e / j_c



a, b: „light“ direction

American Superconductor

REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY™

1.3 Superconductors for technical use

Winding up of HTSC BiSCCO flat filament conductors

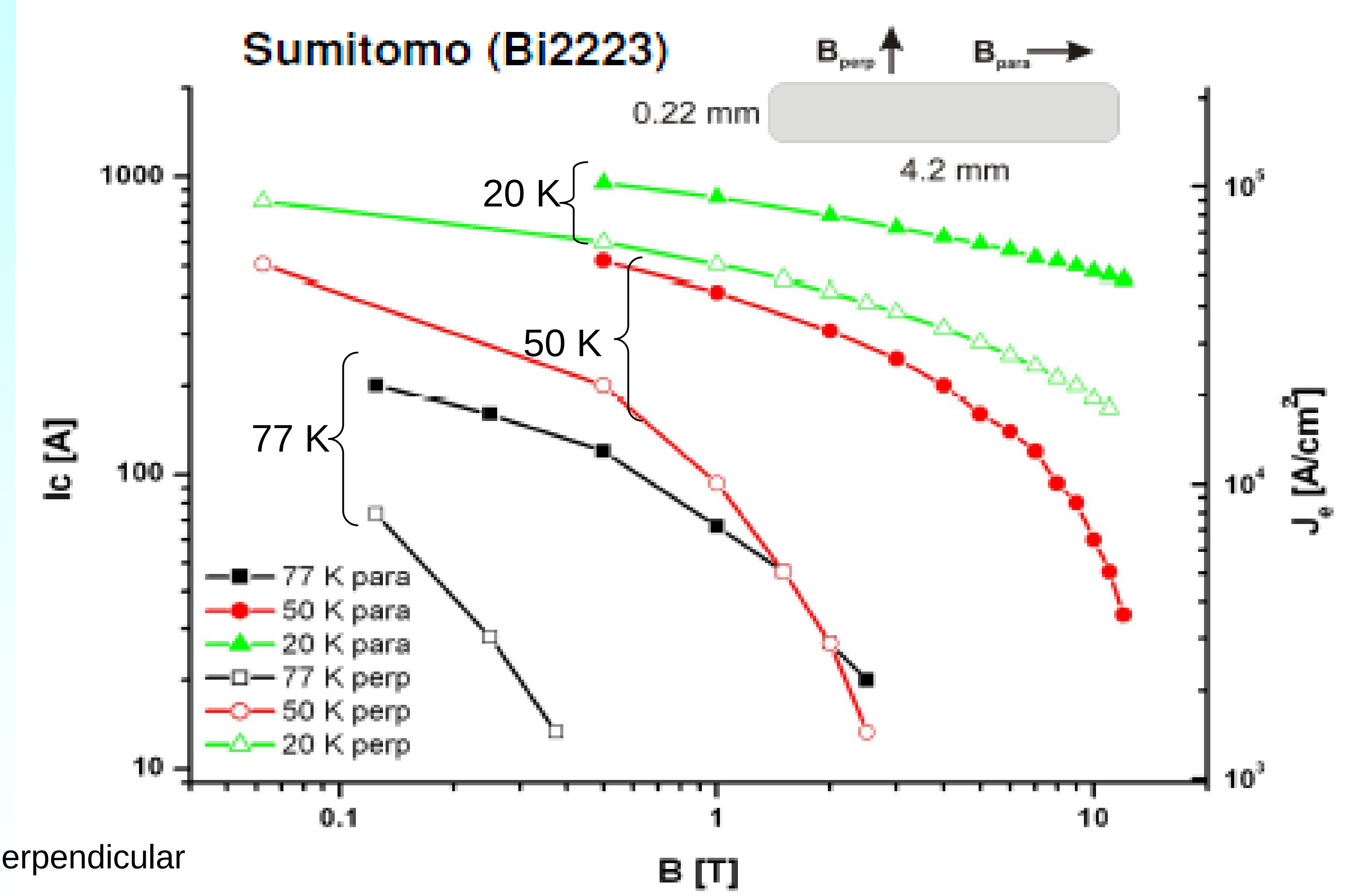
Source:

American Superconductor, USA

BSCCO-tapes: Cost per kA & m length = ca. 120 €/(kA·m) (2013)

Source: energiewirtschaft 112 2013, no.6

HTSC BSCCO anisotropic tapes for technical use



perp: perpendicular

para: parallel (higher critical values)

Source: DTU, Denmark

Technical data of YBCO tape conductors (Issue 2007)

Substrate: Non-magnetic stainless Cr-Ni-steel band: Thickness Δ = 0.05 … 0.1 mm
HTSC: $YBa_2Cu_3O_{7-x}$, Thickness d = 0. 5 … 3 μm depending on application
Cover layer: Silver, gold, copper: Thickness 0.1 … 40 μm
Band width: 4.0 … 40 mm, lengths 100 … 500 m

Cross section: e.g. 0.1 mm x 4.0 mm = 0.4 mm^2

Critical current (77 K, 0 T) in HTSC:
3 μm x 4 mm: 135 A; 3 μm x 40 mm: 1000 A
Critical current density (per HTSC cross section): 77 K, 0 T: 15 … 40 $\mathrm{kA/mm}^2$
Critical current density (per total cross section) = „Engineering“-current density:
at 77 K: 400 … 800 $\mathrm{A/mm}^2$ $\text{e.g.}: I_c / A = J_c \cdot d / \Delta = 40\,\mathrm{kA/mm}^2 \cdot (1\mu\mathrm{m} / 100\mu\mathrm{m}) = 400\,\mathrm{A/mm}^2$
at 65 K: 800 … 1600 $\mathrm{A/mm}^2$

Thermal conductivity (77 K, 3 μm YBCO): 25 W/(m·K)
Tensile strength (Zugfestigkeit): 650 MPa
Minimum admissible bending radius: 9 mm,
max. admissible torsion angle per cm: 30° at 4 mm band width

1.3 Superconductors for technical use

YBCO tape superconductors (Issue 2009)

HTS – Material: YBCO-Bandleiter vom AMSC,
Substrat: RABiTS NiW5%, 0.8 µm YBCO, Stabilisierung: 2 x 25 µm Edelstahl
4.4 mm breit, blank, I_c: ~85 A @ 77 K

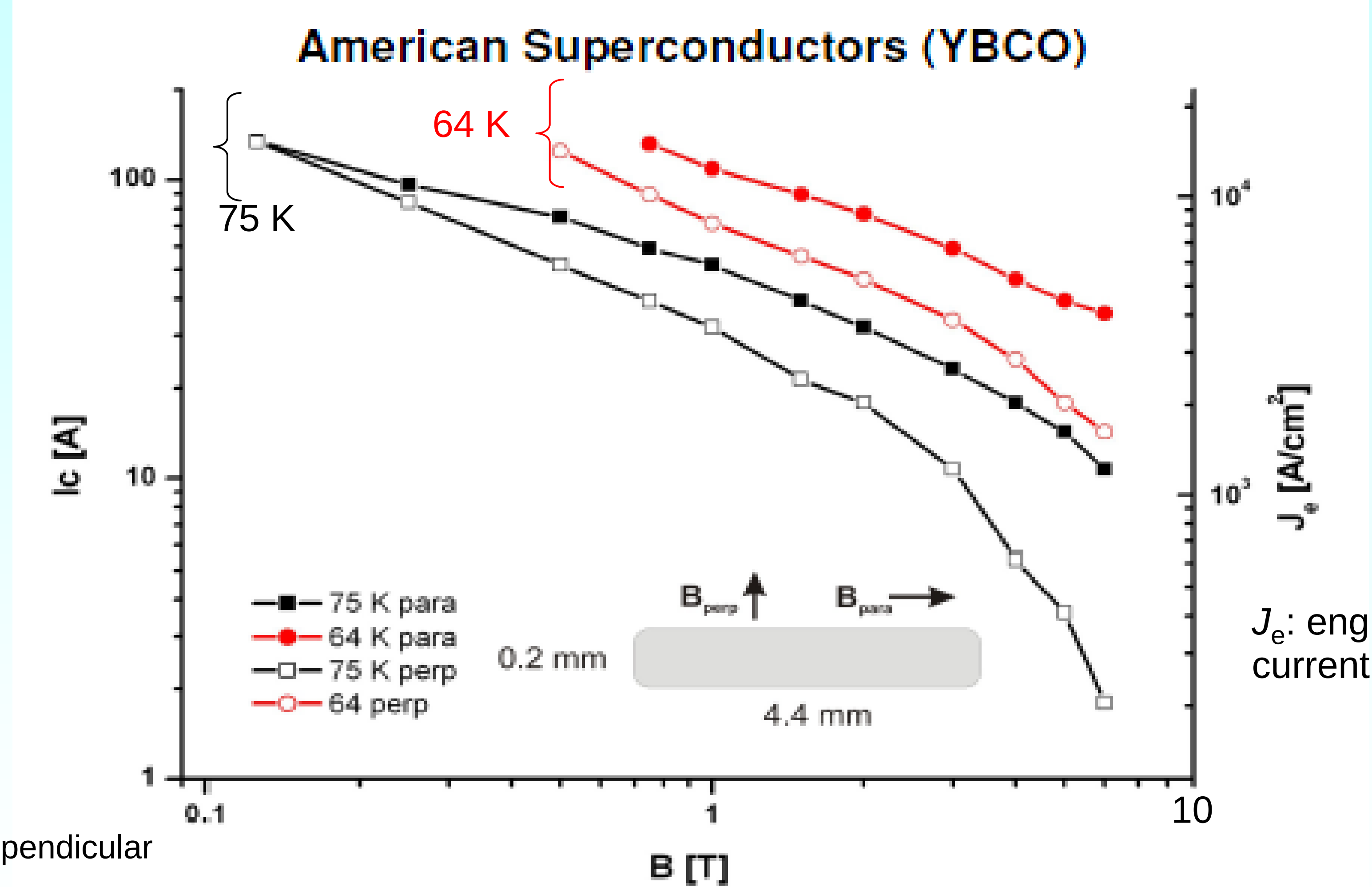
- HTS wire laminated on both sides with stainless steel for strength and stability
- Stainless steel lamination provides high resistance shunt
- High engineering current density
- Robust product with excellent mechanical strength and bend tolerance

Source:

American Superconductor, USA

344 superconductors are American Superconductor's new 3-ply, 4.4 mm wide second generation HTS wires.

HTSC YBCO anisotropic tapes for technical use



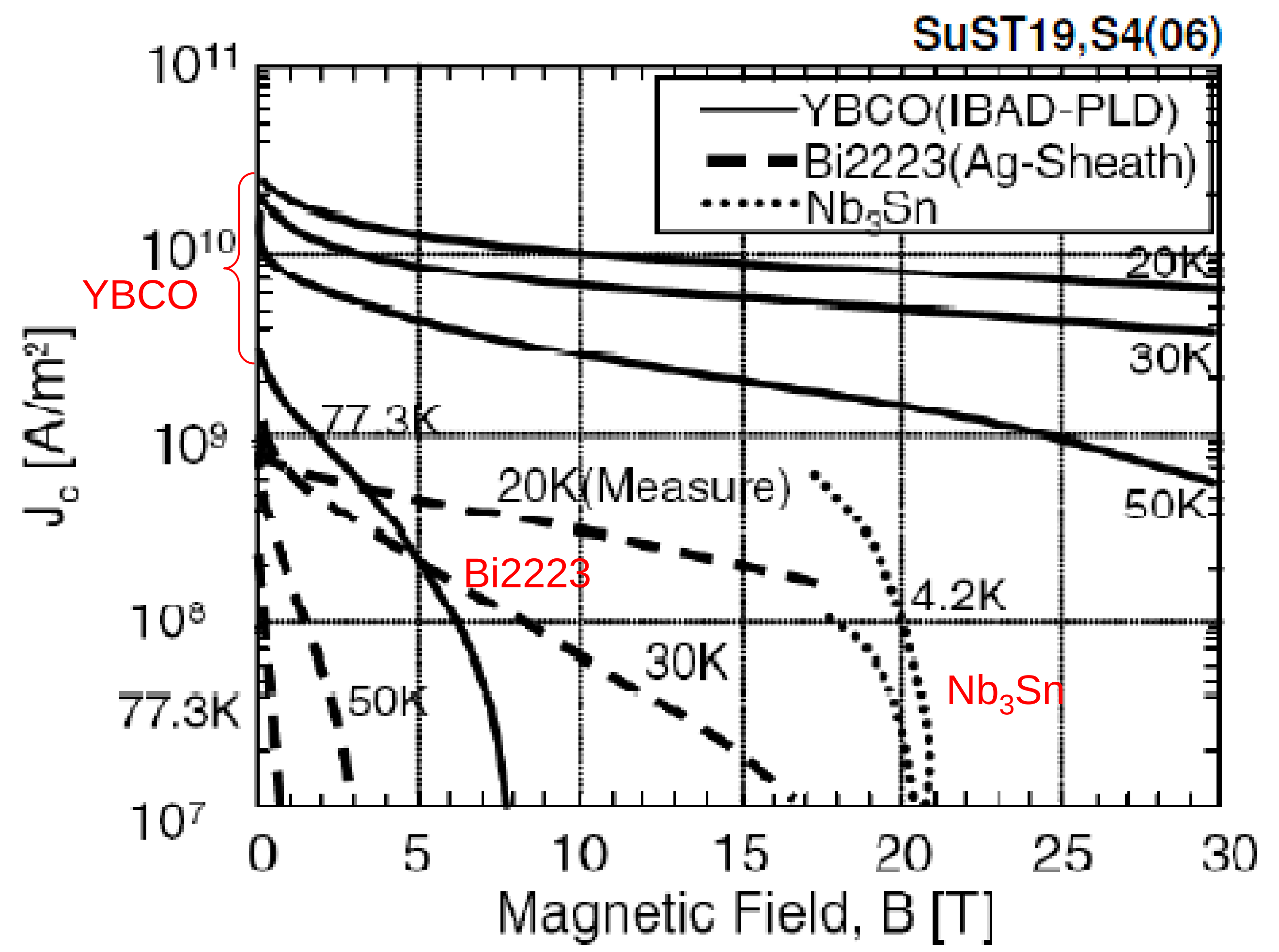
J_e: engineering current density

perp: perpendicular

para: parallel (higher critical values)

Source: DTU, Denmark

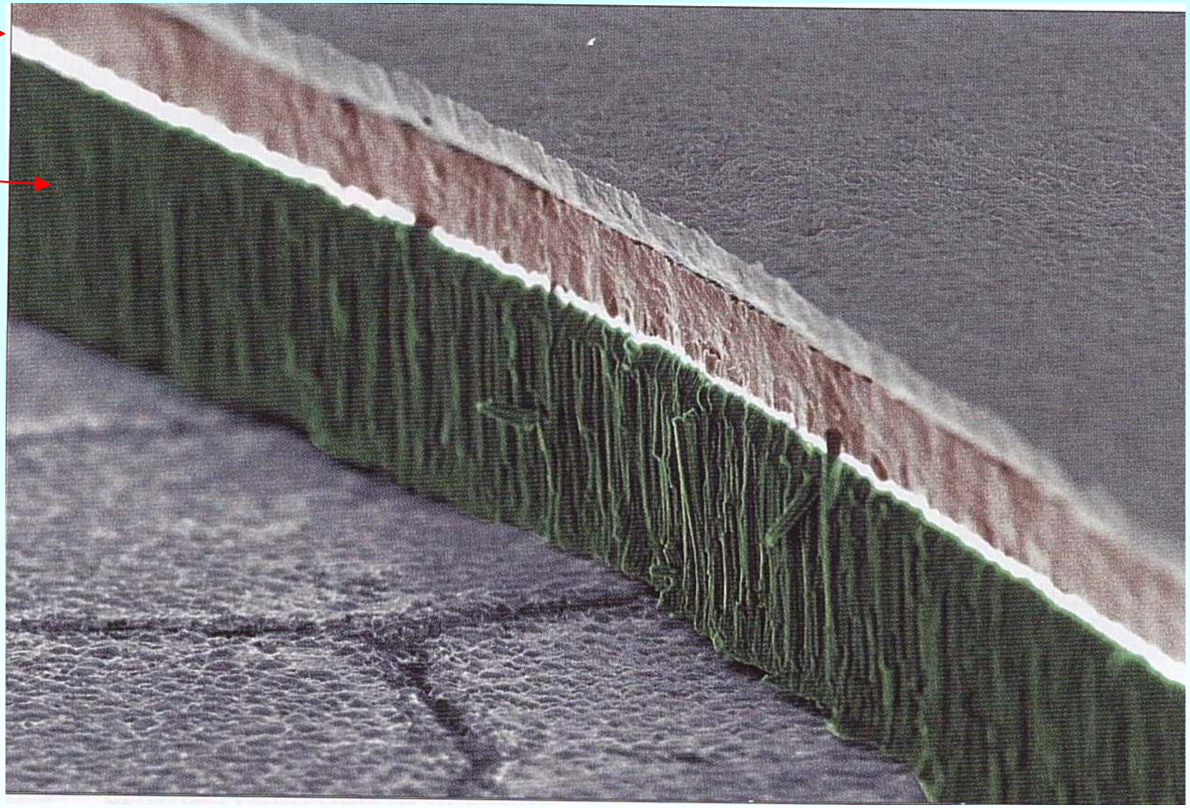
Comparison of HTSC anisotropic tape conductors with LTSC Nb_3Sn



Source:
DTU, Denmark

1.3 Superconductors for technical use

YBCO tape superconductors (Issue 2013)



YCBO layer ca. 1 … 3 μm

Stainless steel carrier tape
ca. 0.1 mm

Typical data:

- 500 A per cm tape width = 400 A/mm^2
  "engineering" current density at 77 K
- Tape width 4 … 12 mm
- Cost per kA & m length = 250 €/(kA·m)
  4-times of copper conductor (2013)
  Aim: 2016: 60 €/(kA·m)
- Different manufacturing methods:
  e.g.: Metal Organic Chemical Vapor
  Deposition MOCVD

Source: Theva Dünnschichttechnik GmbH, Ismaning, D,
Published in: energiewirtschaft 112, 2013, no. 6

$$\text{e.g.: } A = 10\text{mm} \cdot 0.12\text{mm} = 1.2\text{mm}^2$$

$$J_c = I_c / A = 500A / 1.2\text{mm}^2 = 400\text{A/mm}^2$$

New technologies of electric energy converters and actuators

Summary:
Superconductors for technical use

- Low temperature metallic superconductors:
  NbTi and Nb_3Sn: isotropic behaviour
- High temperature ceramic copper oxide superconductors:
  Ba- and Y-cuprates, anisotropic behaviour
- Ba-cuprates as thin flat wires with silver matrix
- Y-cuprates as massive conductors below ca. 5 … 10 cm or
  as flat band conductor strips

New technologies of electric energy converters and actuators

1. Superconductors for power systems

1.1 Fundamentals of superconductivity

1.2 Technical design of superconductors

1.3 Superconductors for technical use

1.4 Cooling procedures

1.5 Cryostats

1.6 Cryogenic technology

Coolants

Coolant	Melting point	Boiling point (1 bar)
He	-	4.2 K
H_2	14 K	20.4 K
N_2	63 K	77.3 K

- *Helium for cooling:*

a) **liquid Helium** LHe I near boiling point S

b) **“super-critical"** liquid Helium

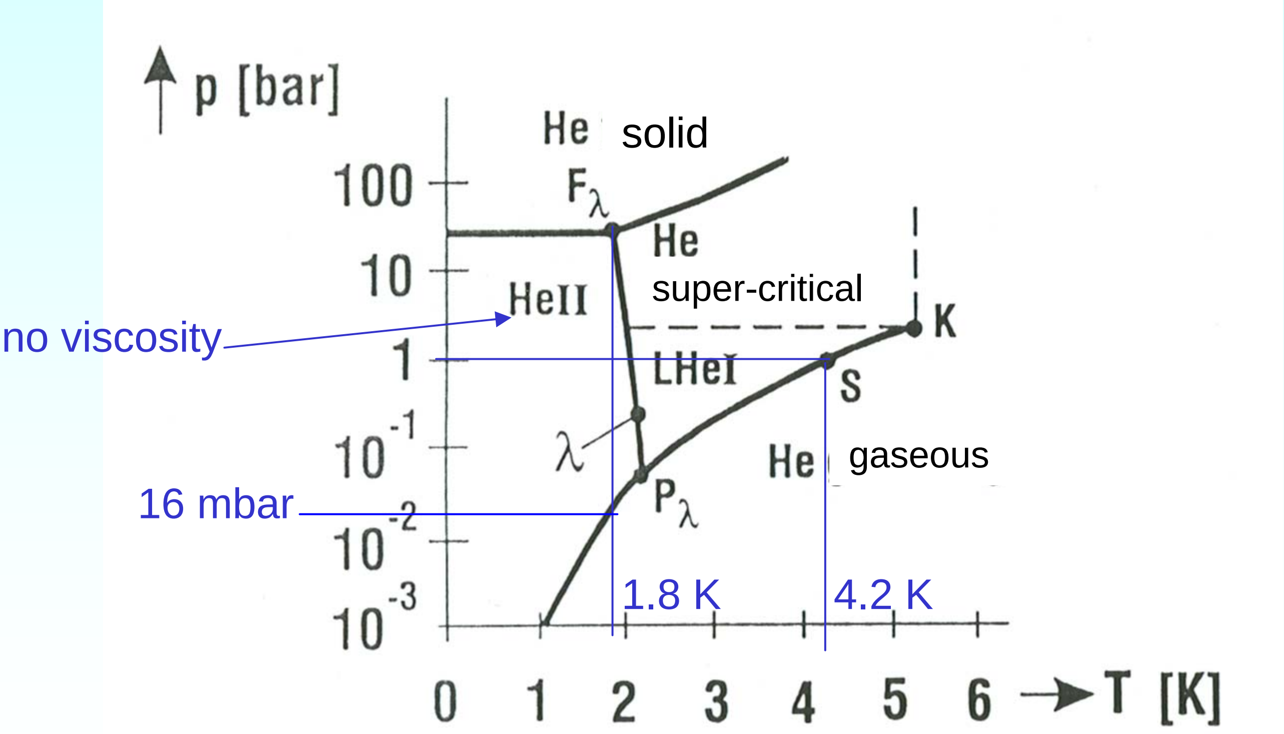
c) **superfluid** liquid Helium He II near 1.8 K

("superfluid" = very low viscosity)

- *Property of Helium a), b), c) different*

Pressure (p)-Temperature (T) phase diagram of Helium

- K: critical point 5.2 K, 2.26 bar, S: boiling point 4.2 K at 1 bar
- λ: $p(T)$-separation line between LHe I (L: liquid) and HeII ("superfluid" Helium)
- P_λ (2.17 K, 0.049 bar)...F_λ (1.76 K, 29.7 bar): crossover gaseous - solid



Komarek, P.:
Teubner,
Stuttgart, 1995

Helium bath cooling

q: heat flow density
P: losses
α: heat transfer coefficient
ΔT: temperature difference
A: cooling surface

0....A: convective heat transfer at liquid Helium LHe I

A...B: Evaporation of LHe I (blister evaporation)

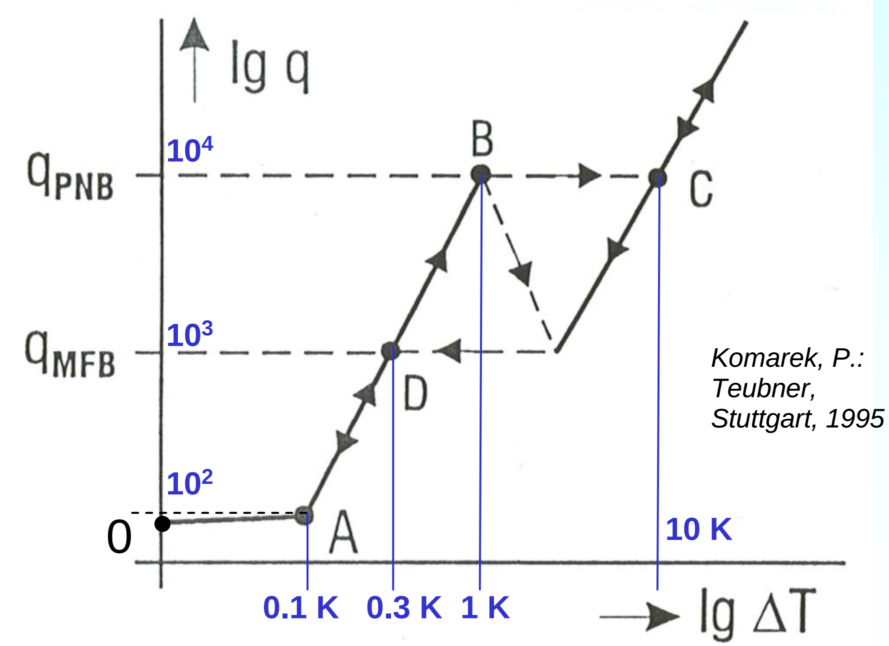
B: The blister evaporation creates an enclosed vapour skin

B...C...D: Thermally instable range between blister- and skin evaporation

above C: pure skin evaporation

$$\boxed{P/A = q = \alpha \cdot \Delta T}$$

	q / W/m²	ΔT / K	α / W/(m²K)
A	10^2	0.1	1000
B	10^4	1	10000
C	10^4	10	1000
D	10^3	0.3	3300



Komarek, P.: Teubner, Stuttgart, 1995

1.4 Cooling procedures

Heat Transfer: Forced flow of super-critical He

- Flowing super-critical He (4.2 K, 3 bar): *Reynolds* number e.g. 10^5 or 10^6 resp.

- q_{PNB}: Boiling bath cooling LHe I with blister evaporation (1 bar)

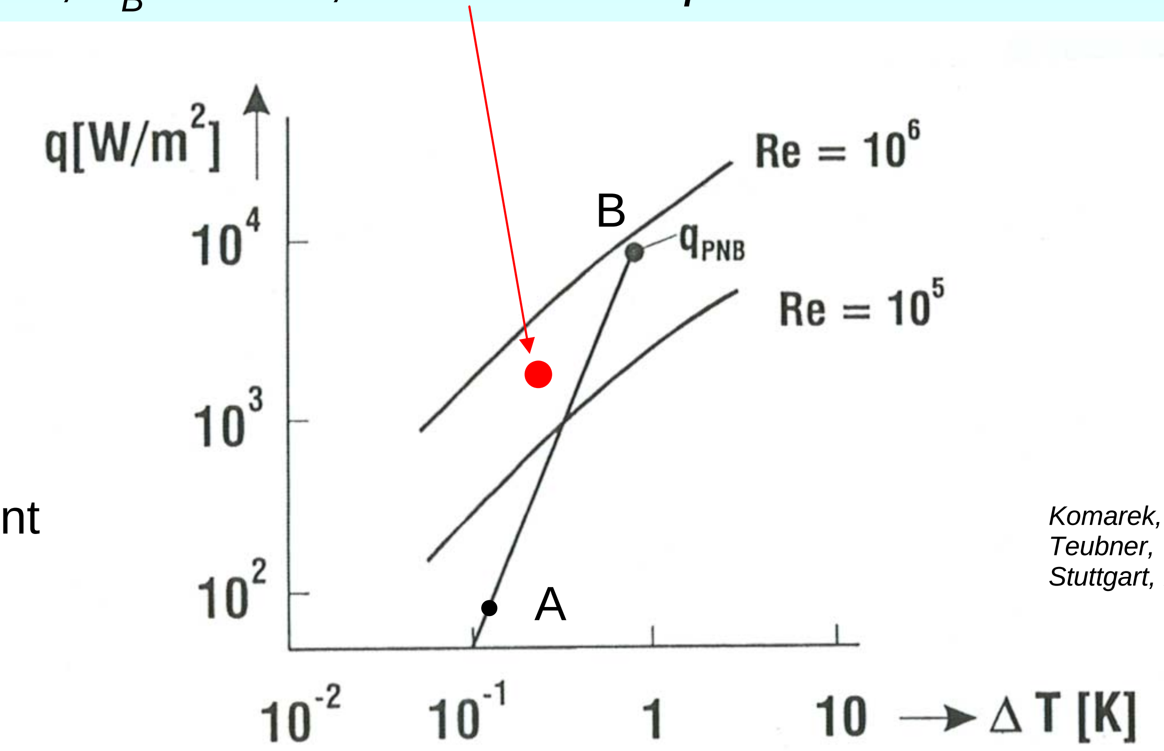
- Superfluid He II: $T_M = 2.16$ K, $T_B = 1.8$ K, $\Delta T = 0.36$ K: $q = 2100$ W/m^2

Re: Reynolds number

$$\mathrm{Re} = v_c \cdot d / \nu$$

v_c: coolant velocity
d: diameter of cooling pipe
ν: kinematic viscosity of coolant
T_M: matrix temperature
T_B: coolant temperature

$\Delta T = T_M - T_B$



Komarek, P.: Teubner, Stuttgart, 1995

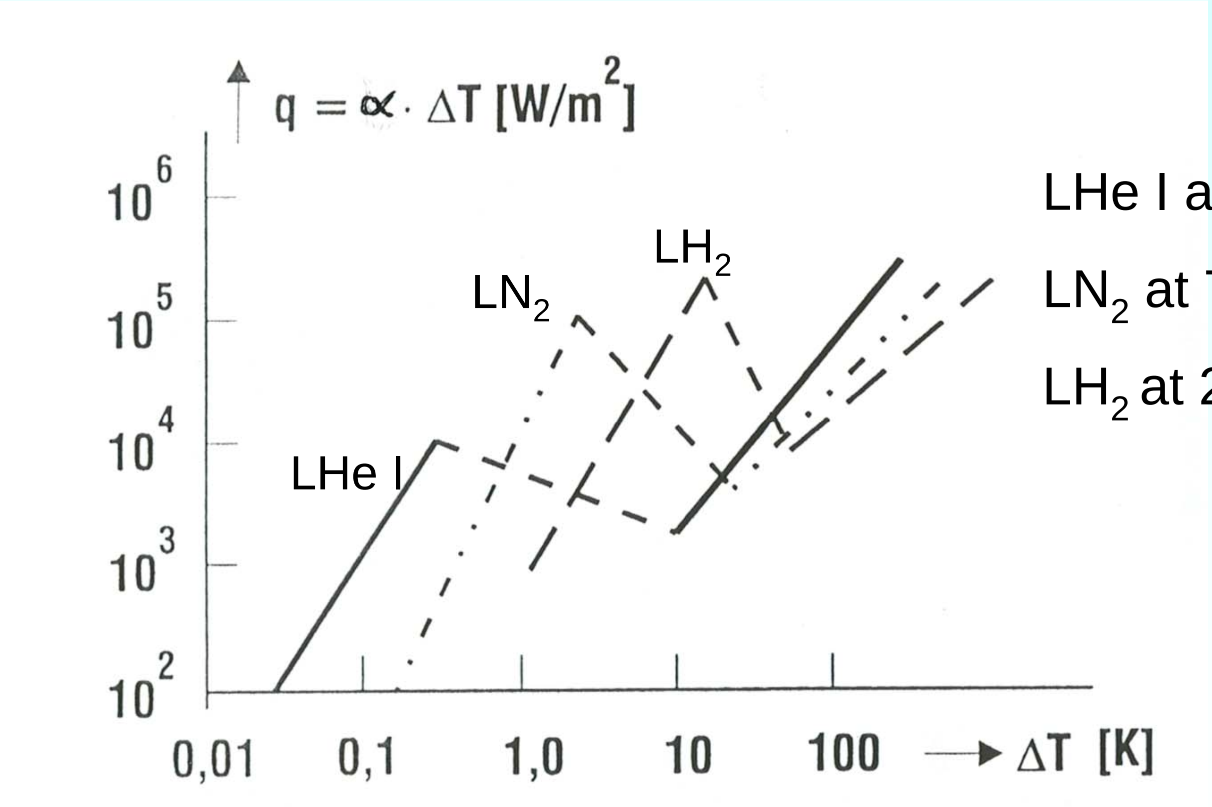
Boiling bath cooling: Nitrogen LN_2 and Hydrogen LH_2

- Compared: LHe I, LH_2 and LN_2 (p = 1 bar) (L: liquid)
- Blister cooling, unstable transition and skin cooling

———————— : LHe I

-- ··-- ··-- : LN_2

------------ : LH_2



Komarek, P.:
Teubner,
Stuttgart, 1995

New technologies of electric energy converters and actuators

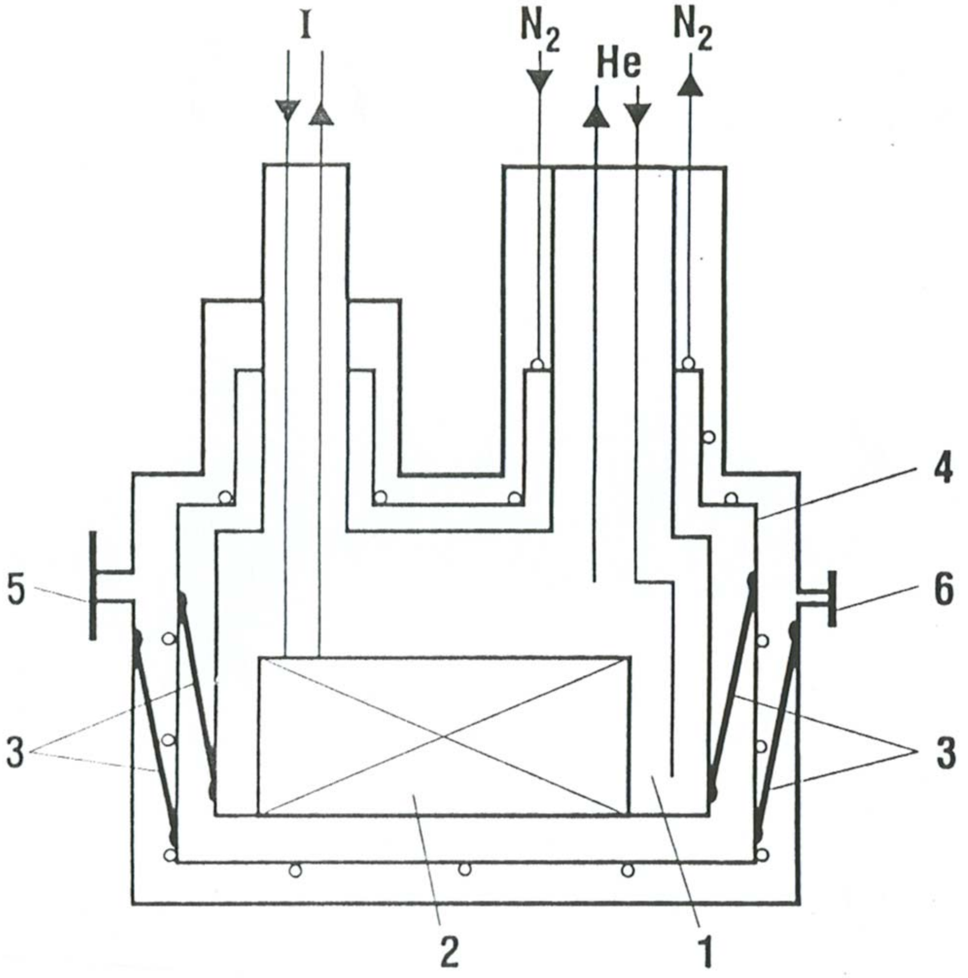
Summary:
Cooling procedures

- Low temperature superconductors: Liquid Helium cooling below 4 K
- Boiling bath cooling
- liquid pressurized He cooling
- superfluid He cooling at very low temperatures below 2 K
- High temperature superconductors:
  Liquid Nitrogen cooling or gaseous rare gas cooling, below 77 K

New technologies of electric energy converters and actuators

1. Superconductors for power systems

Cryostat: Schematic design



1: 4 K-He space

2: Superconductor magnet

3: Suspensions

4: Radiation shield cooled to 80 K with LN_2

5: Bursting disc

6: Evacuating system connection

I: Current leads

He: LHeI-Helium supply and He-exhaust gas

N_2: Shield cooling with LN_2 supply and N_2-exhaust gas

Komarek, P.:
Teubner,
Stuttgart, 1995

Thermal input to cryostats by heat conduction

a) Heat conduction by mechanic fixation rods from warm to cold side:

Fourier law: $q = \lambda \cdot \Delta T / \Delta x$

λ: Thermal conductivity for conduction of heat

Usually AUSTENITIC Cr-Ni-doped steel (non-magnetic) is used,

which can be used also at very low temperatures without getting brittle!

Heat flow is typically $\lambda \Delta T$ = 416 W/m per length of a steel rod!

Thermal input to cryostats by radiation

b) Thermal radiation from warm to cold areas:

$$\boxed{P = A_K \cdot \frac{\sigma_{SB} \cdot (T_H^4 - T_K^4)}{\frac{1}{\varepsilon_K} - \frac{A_K}{A_H}\left(1 - \frac{1}{\varepsilon_H}\right)}}$$

(Stefan-Boltzmann law , combined with Kirchhoff law)

$\sigma_{SB} = 5.67 \cdot 10^{-8}$ W/(m^{2}K^4) ***Stefan-Boltzmann* constant**

Absorption coefficient of radiation: ε_K (at cold side), ε_H (at hot side): $0 \le \varepsilon_K, \varepsilon_H \le 1$

ε_K should be small!

Radiating surface: A_K (at cold side), A_H (at hot side)

Surface temperature: T_K (at cold side), T_H (at hot side)

Note:
At $\varepsilon_H = 1$: $P \sim \varepsilon_K$

Radiated power: P

Note: At $\varepsilon_K = 1$, $\varepsilon_H = 1$, $A_K = A_H = A$: we get *Stefan-Boltzmann* law alone: $P = A \cdot \sigma_{SB} \cdot (T_H^4 - T_K^4)$

Thermal input to cryostats by “convection”

c) Heat convection by He-gas as residual gas in vacuum:

Residual He-gas molecules transport heat (= kinetic molecular energy) !

All other residual molecules (H_2, O_2, N_2, …) are frozen at the cold side!

$\boxed{P = A_K \cdot \alpha \cdot (T_H - T_K)}$ $\alpha = K_W \cdot a_{AK} \cdot p_{Pa}$ (α: heat transfer coefficient)

K_W: gas constant (He: $2 \cdot 10^5$ W/($m^2 \cdot$K$\cdot$bar))

a_{AK}: Accommodation coefficient (He: 0.4), p_{Pa}: Partial pressure of residual gas

Example: Thermal input to cryostats

a) Austenitic rod fixation: Temperature difference

$\Delta T = 80 - 4 = 76$ K, rod cross section $A = 1$ cm^2, rod length $\Delta x = 50$ cm :

$$P = A \cdot \lambda \cdot \Delta T / \Delta x = 10^{-4} \cdot 416/(50 \cdot 10^{-2}) = 80 mW$$: $P = 80$ mW

b) Radiation: $\sigma_{SB} = 5.67 \cdot 10^{-8}$ W/(m^{2}K^4) ***Stefan-Boltzmann* constant**

Cold side: well polished metal surface: $\varepsilon_K = 0.05$, 4.2 K

Hot side: oxidised (dead) plate: $\varepsilon_H = 0.5$, 80 K

$A_H \sim A_K$: $P/A_K = q = 0.11$ W/m^2

c) He-residual gas: Partial pressure 10^{-5} mbar in vacuum container

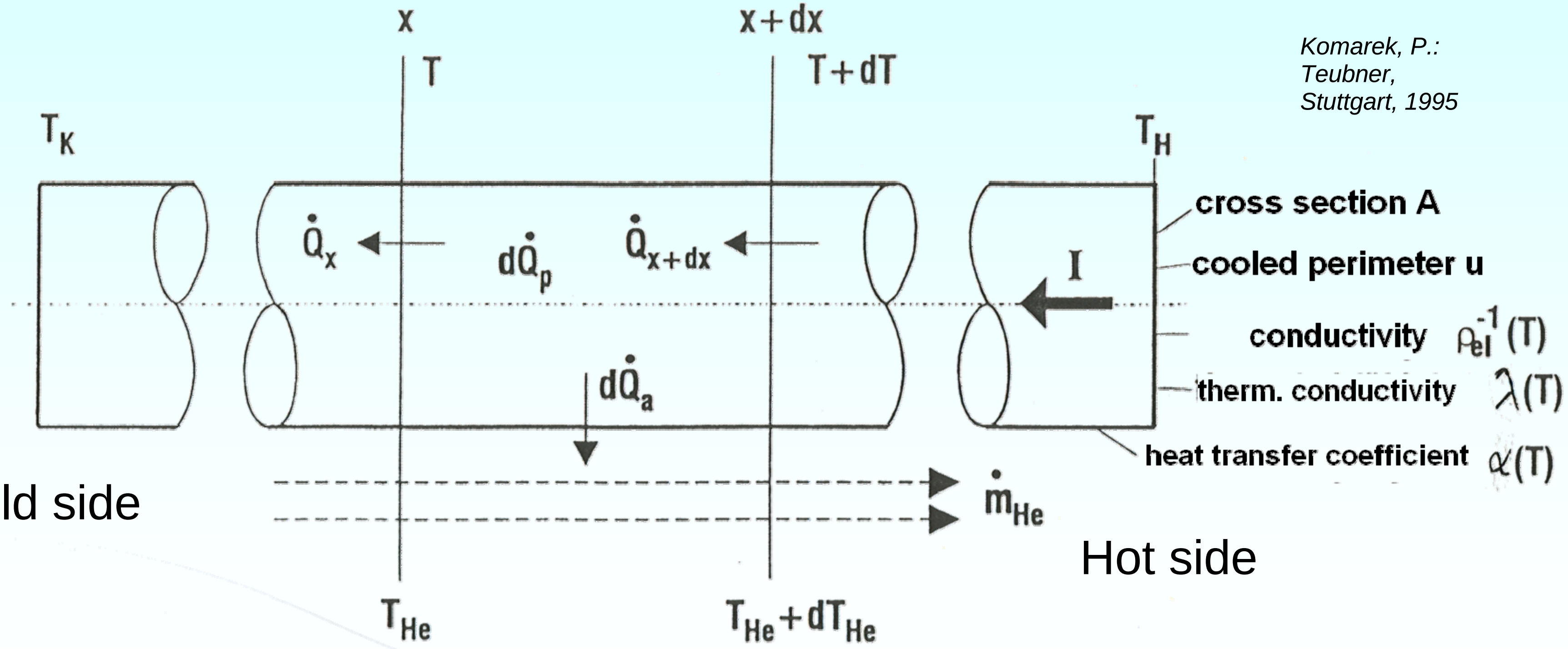
$T_H = 80$ K, $T_K = 4.2$ K, $P/A_K = 2 \cdot 10^5 \cdot 0.4 \cdot 10^{-8} \cdot (80 - 4.2) = 0.06 W/m^2$

$q = 0.06$ W/m^2

$$\boxed{\text{e.g.}: A_K = 1\text{m}^2 : P = (q_{b)} + q_{c)}) \cdot A_K = (0.11 + 0.06) \cdot 1 = 0.17 = 170\text{mW}}$$

Heat balance in cooled current feed

- Q: Heat energy, heat flow density $q = (\mathrm{d}Q/\mathrm{d}t)/A$ in gas cooled current feed
- Coolant flow rate $\mathrm{d}m_{He}/\mathrm{d}t$, current flow I
- Q_p: Heat by RI^2 $\quad$ Q_a: energy export by cooling



Cold side

Hot side

Komarek, P.:
Teubner,
Stuttgart, 1995

Heat inflow in non-cooled current feed

- *Joule* losses per volume $P/V = \rho_{el}(T)J^2$
- *Wiedemann-Franz-Lorenz law*: $\lambda(T)\rho_{el}(T) = L_0 T$ $L_0 = 2.445 \cdot 10^{-8}$ W·Ω/K²
- *Fourier* heat conducting law: Heat flow density: $q(x) = -\lambda(T) \cdot dT/dx$
- Heat flow balance: $A \cdot dq(x) = A \cdot (q(x+dx) - q(x)) = A \cdot dx \cdot \rho_{el}(x)J^2$
- HEAT CONDUCTION-equation: $$\frac{d}{dx}\left(\lambda(x) \cdot A \cdot \frac{dT}{dx}\right) + \frac{\rho_{el}(x)}{A} I^2 = 0$$
- Boundary condition: Copper bar: $x = 0,\ T = T_H;\ x = L,\ T = T_K$
- Solution: $$q = P/A = \frac{1}{A}\int_0^L \rho_{el}(x)J^2 A dx = \left(\frac{I}{A}\right)^2 \int_0^L \rho_{el}(x)dx = \frac{I}{A}\sqrt{2\int_{TK}^{TH} \lambda(T)\rho_{el}(T)dT}$$

$$\int_{TK}^{TH} \lambda(T)\rho_{el}(T)dT = \int_{TK}^{TH} L_0 T dT = L_0 \frac{T_H^2 - T_K^2}{2} \qquad \boxed{\Rightarrow q = \frac{I}{A}\sqrt{L_0(T_H^2 - T_K^2)}}$$

Example: **Non-cooled current feed**

- Copper-current feed: $T_K = 4.2$ K, $T_H = 290$ K (17°C at hot side)
- $I = 1000$ A Transport current: $P = q \cdot A = I\sqrt{L_0(T_H^2 - T_K^2)}$

$$P = q \cdot A = 1000\sqrt{2.445 \cdot 10^{-8}(290^2 - 4.2^2)} = \underline{\underline{45.3W}}$$

45 W: much too high !

- **Such simple built current feeds CANNOT be used!**

- If $T_H = 290$ K, $T_K = 77$K: $\underline{P = 43.7\ \mathrm{W}}$ would be somewhat smaller.

- *Current feeds **must be cooled**, so heat loss can be removed via a cooling gas and cannot flow to cold side.*

Technically realised current feeding

a) Exhaust gas cooled current feed:

He-Boiling-bath cooling: vaporized He passes as cooling gas past current feed

b) HTSC superconductor as current feed:

He cold gas cooling: critical temperature below the limit for HTSC ⇒
Cold side LTSC: (Nb_3Sn), intermediate conductor: HTSC (Bi(2212)),
Hot side: copper as conductor.

c) Removable current feed for "current short circuit" operation:
e.g. in computer tomographs (MRI), SMES:

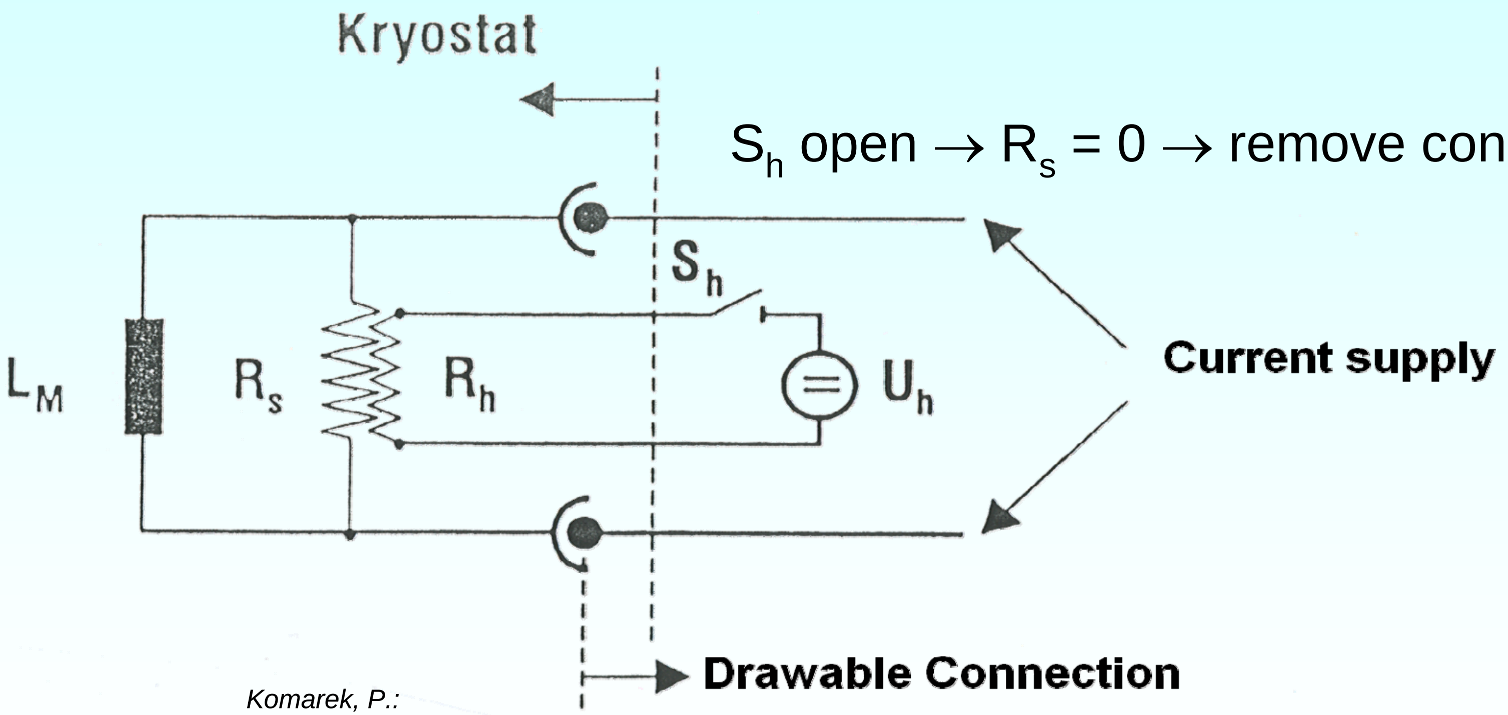
DC current needed for exciting a DC magnetic field for long time:

- Cold end: plug-in connection,
- Super-conducting short circuit switch for SC winding,

⇒ No loss due to heat conduction via current feed

Removable current feed for SC-magnet

- Continuous DC current operation with superconducting short circuit switch R_s
- L_M: magnet coil inductivity, R_h–S_h–U_h: heating circuit



S_h open → $R_s = 0$ → remove connections

Komarek, P.:
Teubner,
Stuttgart, 1995

New technologies of electric energy converters and actuators

Summary:
Cryostats

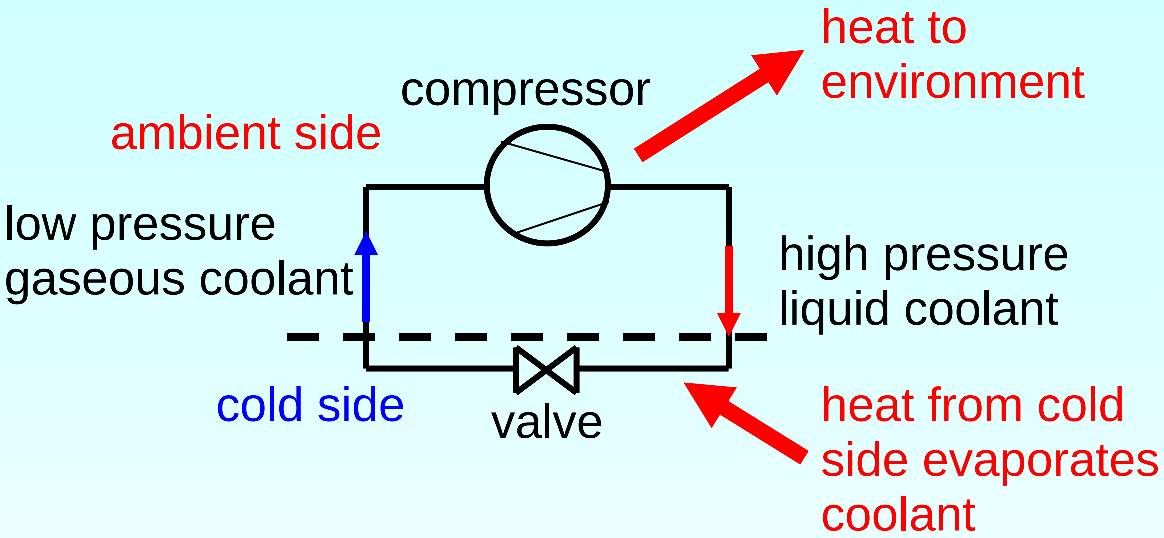
- Low temperature tank vessels
- Needed for maintaining a space at very low temperature
- Vacuum thermal insulation
- Radiation shields at intermediate temperature 77 K for 4 K operation

New technologies of electric energy converters and actuators

1. Superconductors for power systems

Cryogenic properties of He and N_2	**Helium**	**Nitrogen**
Boiling point T_s at 1 bar	4.22 K	77.35 K
Critical point p_K/T_K : Pressure / Temperature	2.3bar /5.22K	33.9bar/126K
Vaporizing heat w	20.8 kJ/kg	199 kJ/kg
Heat conductivity λ: boiling liquid	0.027 W/(m·K)	0.14 W/(m·K)
Heat conductivity λ: Gas at 300 K (about 27°C)	143 W/(m·K)	24 W/(m·K)
Heat flow density q for blister vaporization at 1 bar	0.8 W/cm^2	$\leq$ 12 W/cm^2
Specific heat c_p of boiling liquid, J/(kg·K)	4.41	2.03
Specific heat c_p of gas (at 0°C, 1 bar), kJ/(kg·K)	5.23	1.04
Density ρ **of boiling liquid**	124.8 kg/m^3	804.2 kg/m^3
Density ρ **of gas (at 0 °C, 1 bar)**	0.178 kg/m^3	1.25 kg/m^3
Relative permittivity ε_r / **loss factor** $tg\delta$	1.05 / $2\cdot10^{-6}$	1.43 / $>1\cdot10^{-5}$
Breakdown field strength E_D for boiling liquid, kV/cm	200...400	300...600
Breakdown field strength E_D for gas (at 1°C, 1 bar)	4.7 kV/cm	3.3 kV/cm
Pressure influence ***(Paschen law)***: $E_{D,min}$ **(kV/cm)** p^*	1.7 @ p^*= 50mbar	0.3 @ p^*= 10mbar

Cold vapour process (1)



- Refrigeration machine: Thermodynamic cycle process
- Cryogen (coolant, CN) operated between "liquid" and "gaseous“ state.

CN: Low boiling point, vapour heat is extracted from the cooled object.

CN: Afterwards liquefaction via compression $\Rightarrow$ The critical temperature of cryogen must be higher than the condenser temperature, otherwise no liquefaction of the gas under pressure possible.

Cold vapour process (2)

- Applications: Compressor fridge, heat pump (reversed operation to fridge)
- Special design: absorber fridge
- *To create very low temperatures (< -100 °C) the cold vapour process cannot be used for technical reasons:*

  - "cold" compressor causes technical problems (bearings!),
  - sealing problems,
  - freezing lubricant in bearings etc.

Cold gas process

- Cryogen (coolant) in gaseous state

1) Stirling process

In the ***Stirling* cycle process** the cryogen (He gas) is used in a closed thermal cycle and removes heat from chilled goods.

2) Adiabatic expansion (Q = const.)

An (ideal) gas is expanded in an expansion machine (e.g. piston engine,...) (= the pressure drops). The delivered work from the gas to the machine decreases the heat energy in gas, which is cooled.

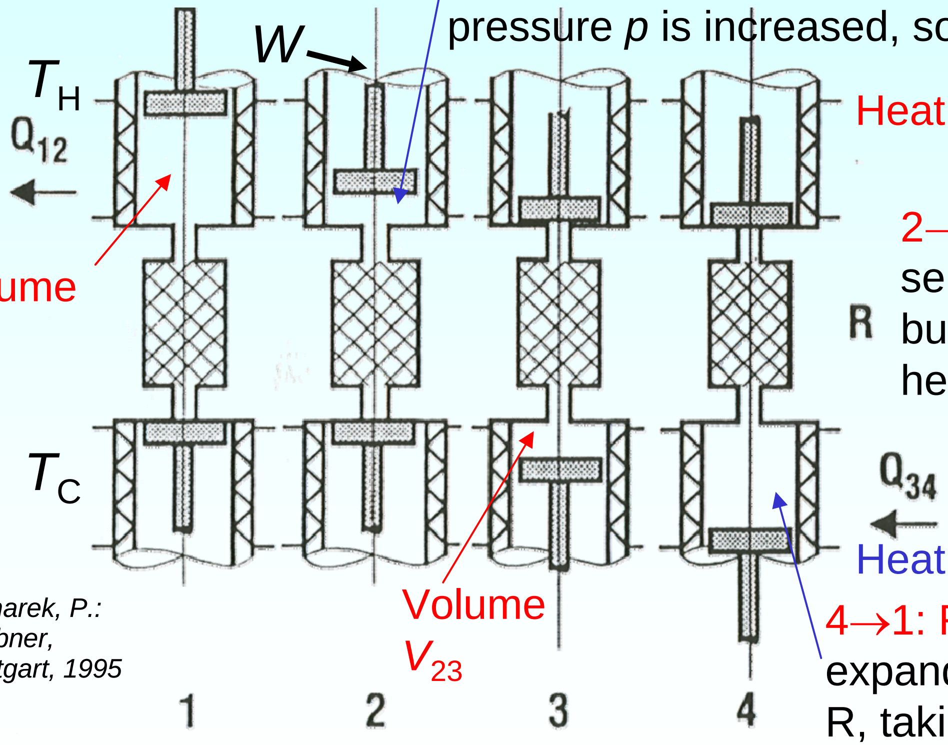
3) Joule-Thomson expansion

Expansion of a **real** gas via flowing through a throttle valve: Temperature falls in the gas (due to gas work against the attracting *van der Waals* forces).

1.6 Cryogenic technology

Stirling cooling process

- Inverse *Stirling*-motor cycle with regenerator R for heat storage: e.g. He-gas as coolant
  Q_{34}: Removed heat at cold side (cold temperature T_C),
  Q_{12}: Heat output on hot side (hot temperature T_H),
  $W = Q_{12} - Q_{34}$: Ideal work of piston engine



1→2: Gas compression by motor work W heats coolant, dissipated heat Q_{12} is transferred to the environment via heat exchanger, T_H is kept constant; gas pressure p is increased, so that gas may pass porous regenerator R

Heat exchanger

Volume V_{41}

2→3: Coolant passes regenerator R = porous separation of hot and cold side; allows coolant flow, but is thermally insulating and stores most of the gas heat, so cooled gas enters lower piston

3→4: Inflow of heat Q_{34} to cold gas: Coolant expands, keeping temperature constant T_C

Heat exchanger = "cold head"

Volume V_{23}

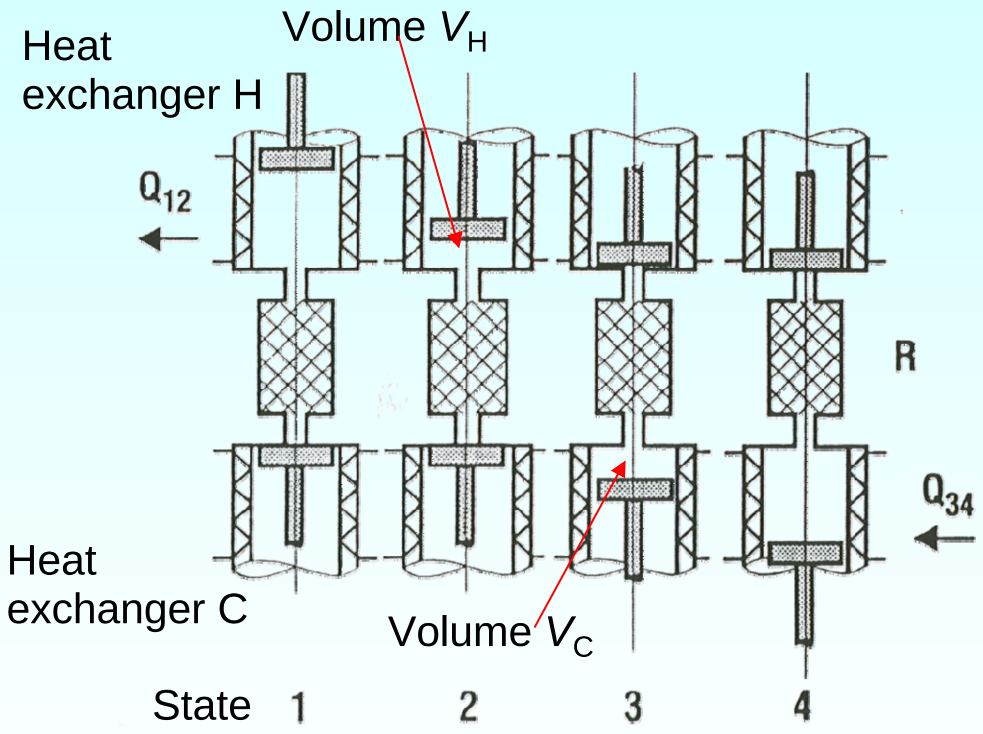
4→1: Rotating mass inertia reverses motion: Cold expanded gas flows back to upper piston via regenerator R, taking over the stored heat of R, being heated up to T_H

Komarek, P.: Teubner, Stuttgart, 1995

1.6 Cryogenic technology

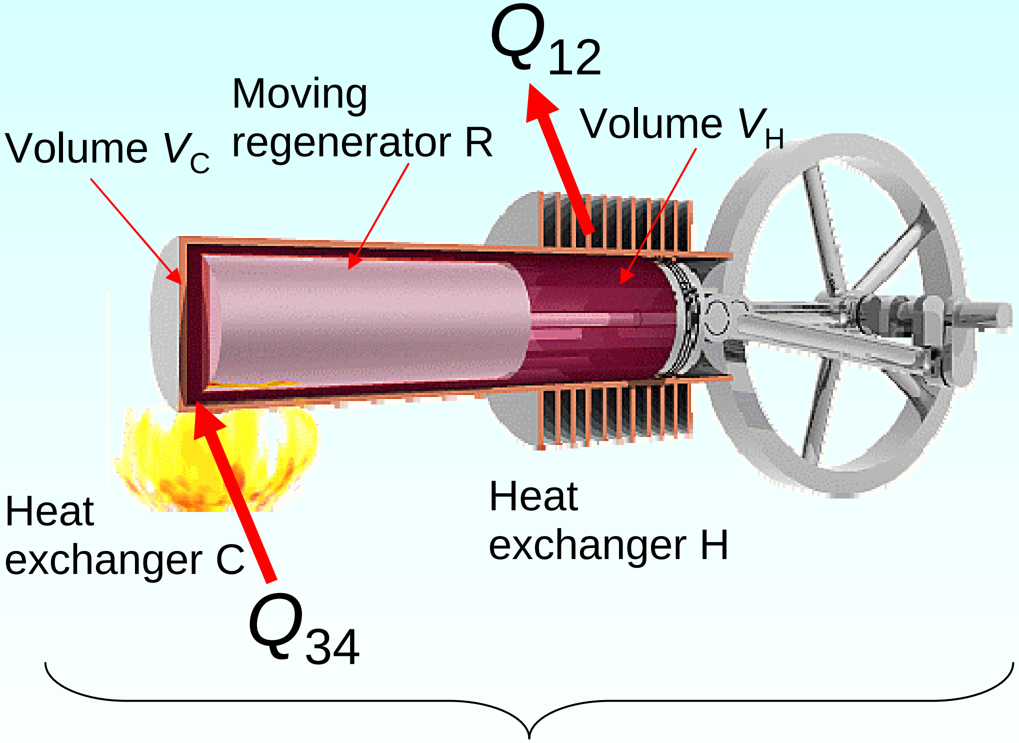
Stirling cooling machine

Moving pistons



Source: Komarek, P.: Teubner, Stuttgart, 1995

Moving regenerator



Source: Wikipedia, 2014

Stirling machine in State 1

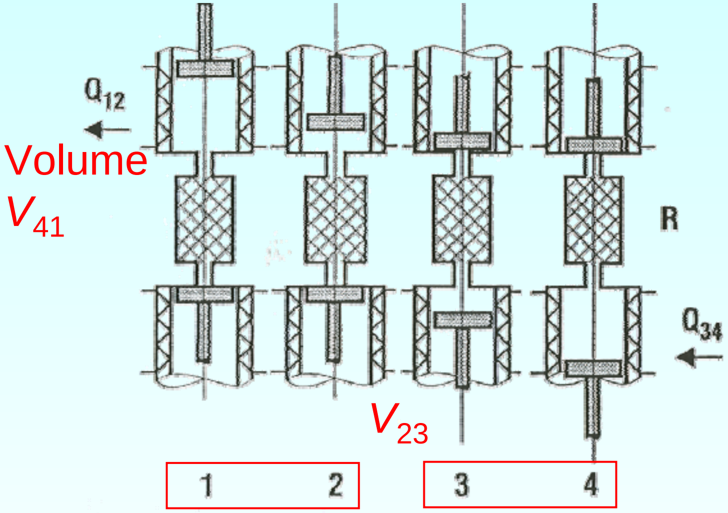
1.6 Cryogenic technology

Stirling cooling process: *T-s*-Diagram

Komarek, P.:
Teubner,
Stuttgart, 1995

- Temperature-entropy: *T(s)*-diagram of the coolant medium

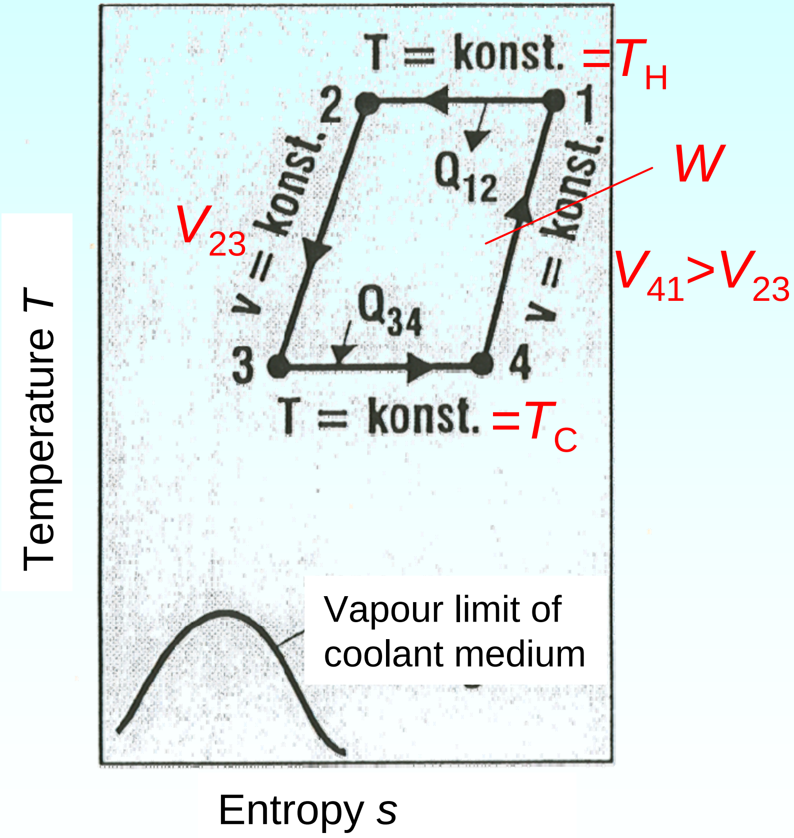
Entropy change: $ds = dQ/T$; enclosed area = necessary work W for cooling



$$s_4 - s_3 = \Delta s = \frac{Q_{34}}{T_C}$$

$$s_2 - s_1 = -\Delta s = -\frac{Q_{12}}{T_H}$$

$Q = m \cdot c \cdot T$: At m, c const.: $\Delta s_{12} = -\Delta s_{34}$



1.6 Cryogenic technology

Stirling cooling process: Theoretical efficiency

- Calculation of work *W* from *T(s)*-diagram

$$W = \int_{1-2-3} T(s)\cdot ds - \int_{1-4-3} T(s)\cdot ds = \int_{1-2-3} \frac{dQ}{ds}\cdot ds - \int_{1-4-3} \frac{dQ}{ds}\cdot ds =$$

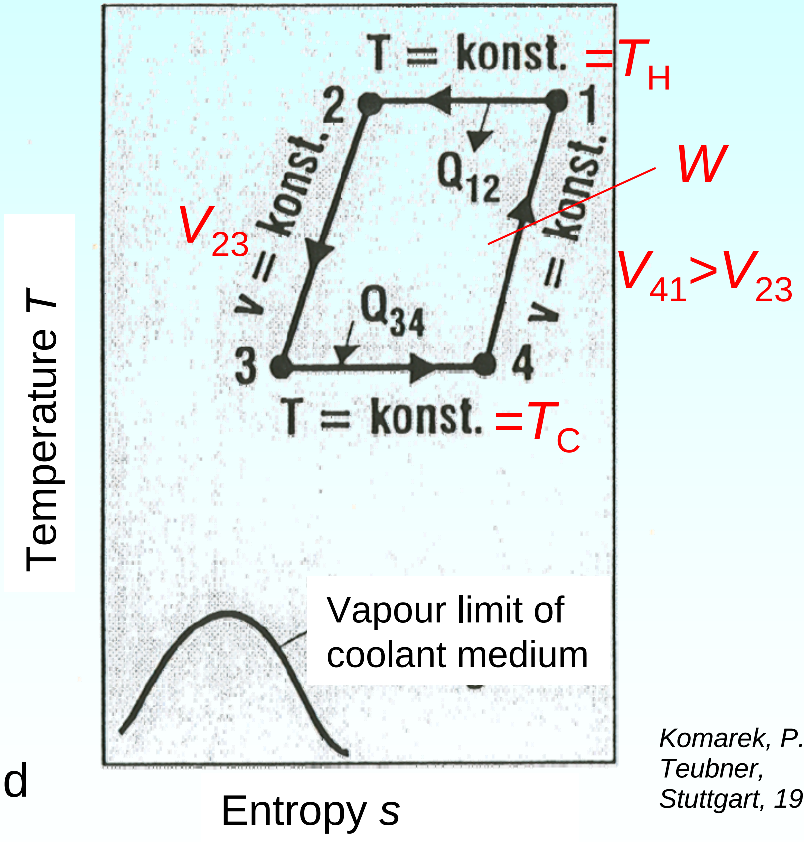
$$= \int_{1-2-3} dQ - \int_{1-4-3} dQ = \int_{1-2} dQ - \int_{4-3} dQ = Q_{12} - Q_{34}$$

$$\boxed{W = Q_{12} - Q_{34}}$$

- Ideal efficiency of the cooling process η :

$$\eta = \frac{Q_{34}}{W} = \frac{Q_{34}}{Q_{12} - Q_{34}} = \frac{\Delta s\cdot T_C}{\Delta s\cdot T_H - \Delta s\cdot T_C} = \frac{T_C}{T_H - T_C}$$

$$\boxed{\eta = \frac{T_C}{T_H - T_C}}$$



Komarek, P.: Teubner, Stuttgart, 1995

Facit: The ideal efficiency of the *Stirling* cooling process is identical with the CARNOT-efficiency and therefore maximum!

Adiabatic expansion (*Q* = const.)

- Ideal gas: Gas particles have no volume (“points”), but mass, and have no interacting forces

- Ideal gas: $p \cdot V = n \cdot R \cdot T$ *n*: number of mol = N/N_A, *N*: particle number
  $N_A = 6.022 \cdot 10^{23}$ *Avogadro´s* number

- Inner energy of an ideal gas:

$$U = N \cdot (f/2) \cdot k \cdot T$$

f: number of degrees of freedom per particle

$$U = n \cdot (f/2) \cdot N_A \cdot k \cdot T = n \cdot (f/2) \cdot R \cdot T$$

- Change of inner energy by work *W* or heat *Q*: $dU = \delta W + \delta Q$

- Adiabatic change of state: No heat exchange: $\delta Q = 0$: $dU = \delta W$

Ideal gas is expanded e.g. in a piston engine, the gas works against the piston. The delivered work $\Delta W < 0$ from the gas to the piston decreases the inner gas energy, hence its temperature *T* drops.

$$\Delta W = \Delta U = n \cdot (f/2) \cdot R \cdot \Delta T = n \cdot (f/2) \cdot R \cdot (T_2 - T_1) < 0 : T_2 < T_1$$

$p_1 \cdot V_1 \sim T_1 > p_2 \cdot V_2 \sim T_2$: pressure drops via expansion: $p_2 < p_1$

Ideal gas versus real gas

- Ideal gas: Gas particles have
  - no volume ("points"), but mass,
  - no interacting forces
- Real gas: Gas particles have
  - volume ("NO ideal points") and mass,
  - interacting forces (electrostatic ***van der Waals* forces**)

Joule-Thomson expansion

- Expansion of a real gas: Flowing through a throttle valve:

A) There are ***van der Waals* forces** between the gas molecules, against which the expanding gas performs work, which is covered by its heat content (inner energy U): **T falls.**

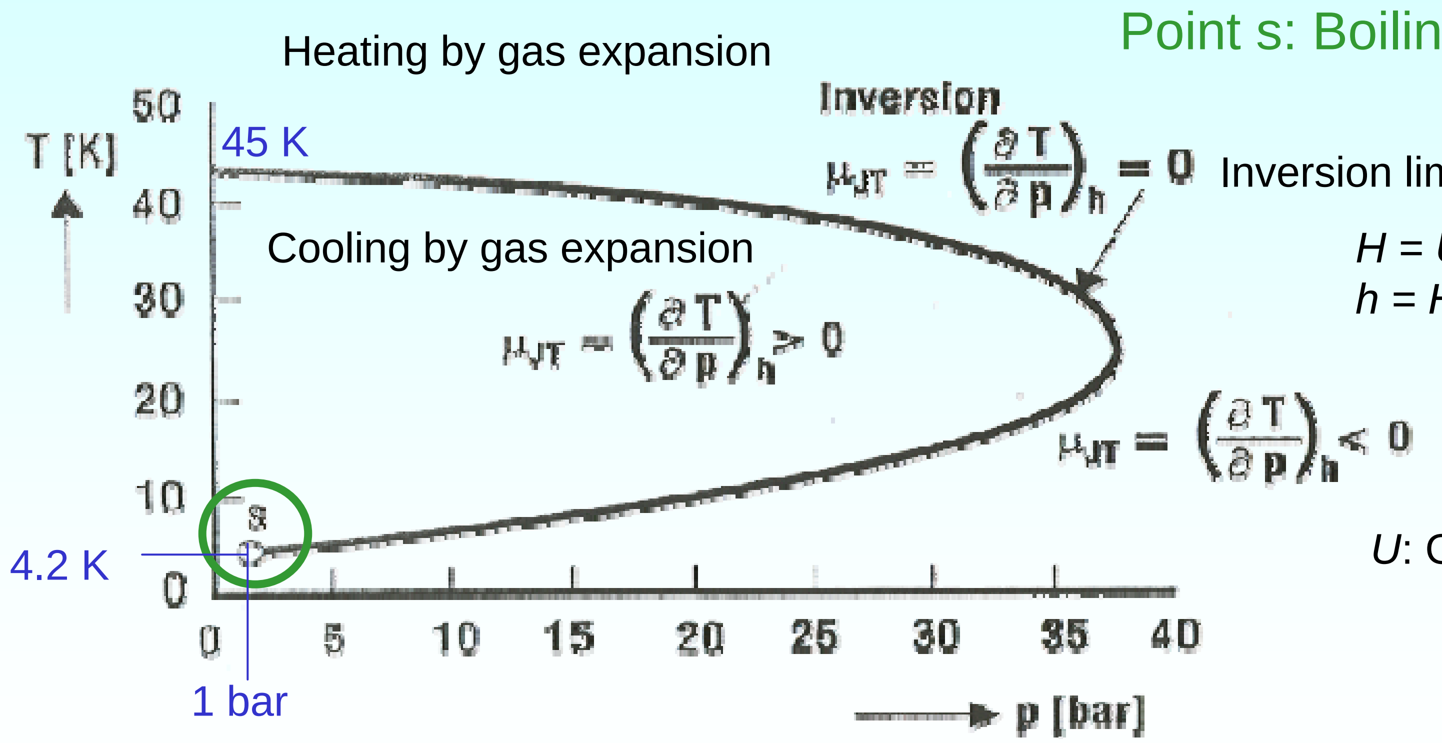
B) Gas-molecules have **finite volume**, which narrows the space for molecule movement (kinetic energy $U \sim kT$) . Gas, limited to small volume V, has lower U than in bigger volume $\Rightarrow$ expansion: **T rises**

- If A dominates over B: Temperature falls at expansion: at low T (U small)
- If B dominates over A: Temperature rises at expansion: at high T (U big)
- The temperature, at which the effect changes its sign, is called **inversion-temperature T_i**. It depends on the pressure p in the gas.

1.6 Cryogenic technology

Helium-inversion temperature T_i

- $T_i(p)$: Inversion curve: He-Gas: T_i = 45 K (0 bar), T_i max. at p_{min}
- Inside inversion curve: Expansion by a throttle valve ⇒ cooling effect



Point s: Boiling Point

Heating by gas expansion

45 K

$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h = 0$ Inversion limit curve

Cooling by gas expansion

$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h > 0$

$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h < 0$

4.2 K

1 bar

$H = U + p.V$: Enthalpy
$h = H/m$: Enthalpy per mass

Komarek, P.:
Teubner,
Stuttgart, 1995

U: Gas inner energy

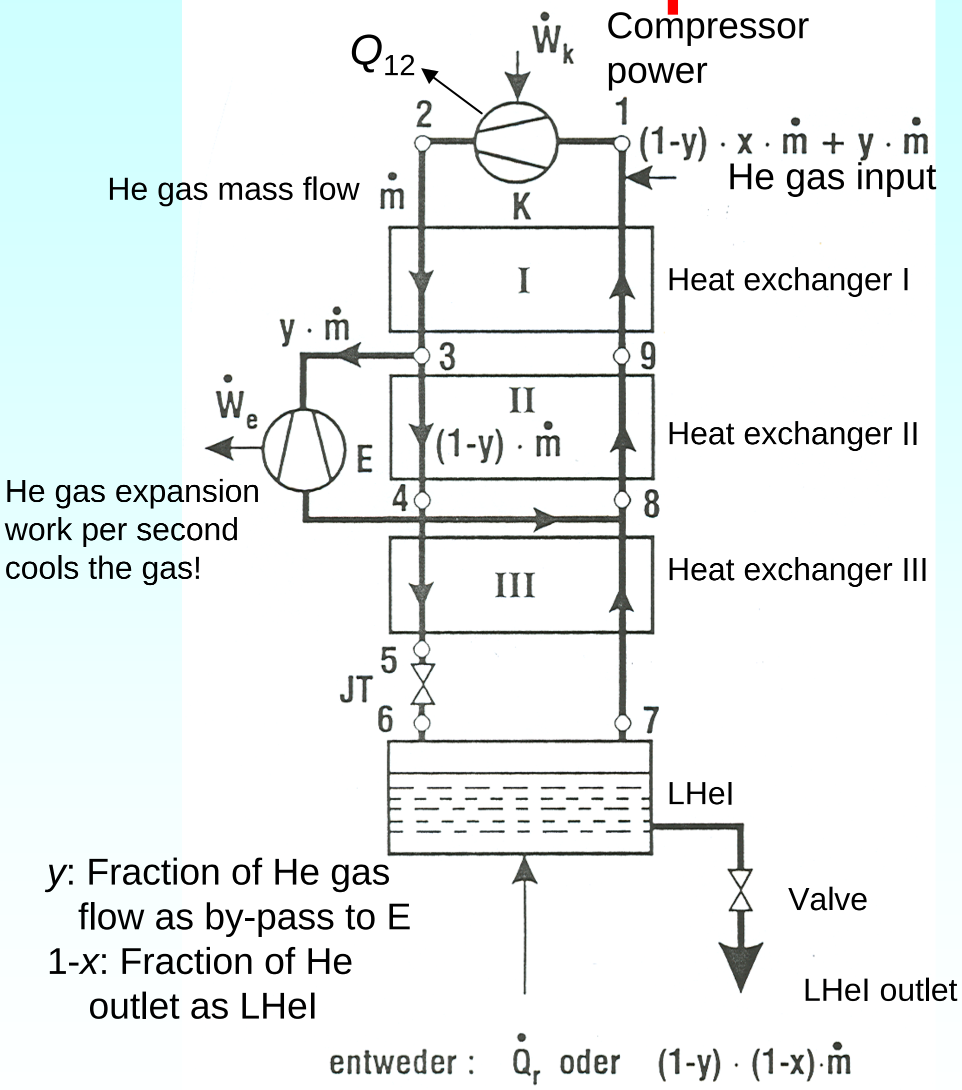
Inversion temperature *T* of gases He, H_2, N_2

- $p = 0$ bar:

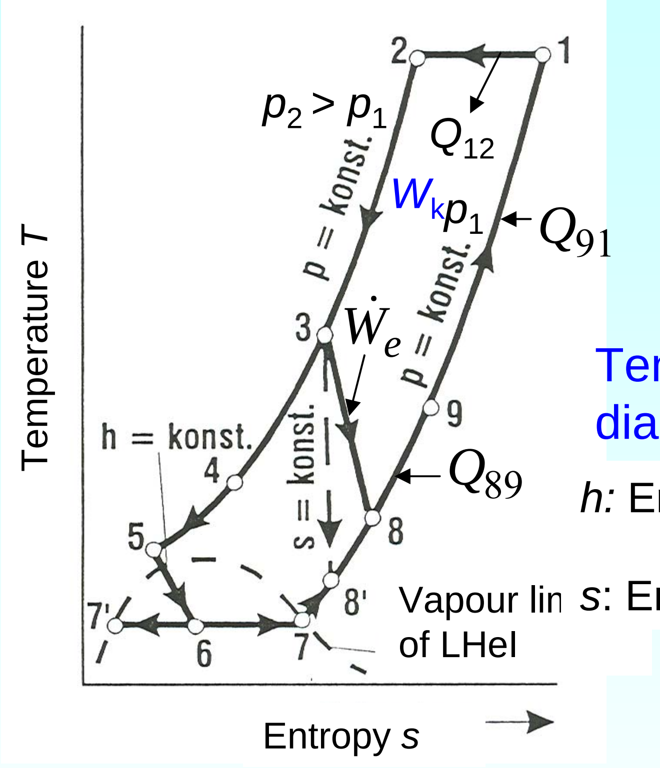
Gas	Helium	Hydrogen	Nitrogen
Inversion temperature	45 K	205 K	621 K

- *Joule-Thomson* effect can be used for N_2 in all cooling ranges from room temperature 293 K (20°C) downwards.
- He and H_2-Gas: Until reaching inversion temperature, it must be pre-cooled by other effects. Multistep cooling processes are necessary.
- Using the *Joule-Thomson* effect:
  e. g. *Claude* process: LHeI-liquefaction, *Linde* process: N_2-liquefaction

Claude process for He I liquefaction



y: Fraction of He gas
flow as by-pass to E
1-*x*: Fraction of He
outlet as LHeI



Temperature-entropy diagram *T(s)*

h: Enthalpy per mass

s: Entropy: $ds = dQ/T$

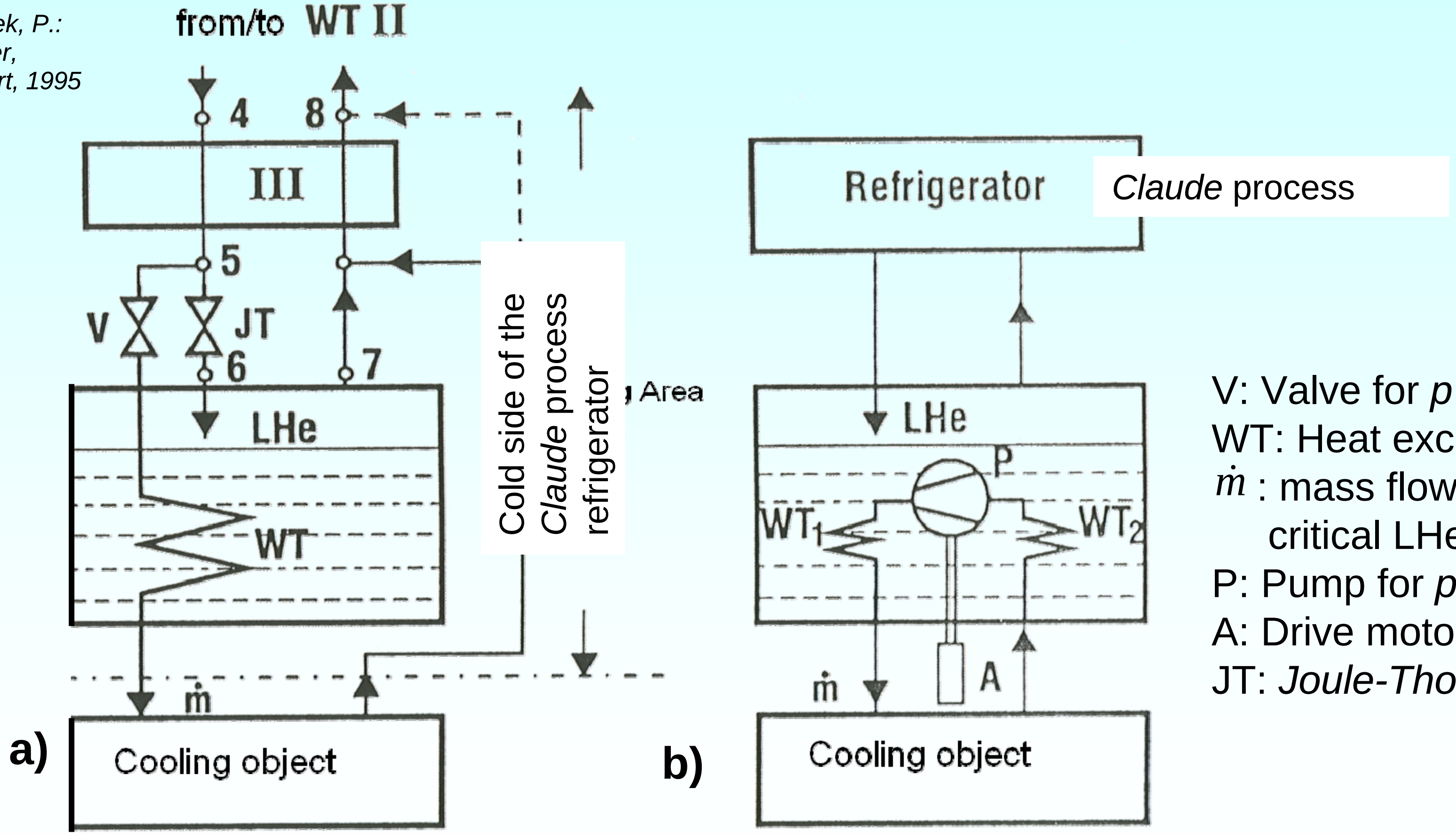
K: Compressor
I, II, III: Heat exchanger
E: Expansion machine
JT: *Joule-Thomson* throttle
$\dot{Q}_r$: Refrigerator power

Komarek, P.:
Teubner,
Stuttgart, 1995

Production of super-critical He (*p* > 2.26 bar)

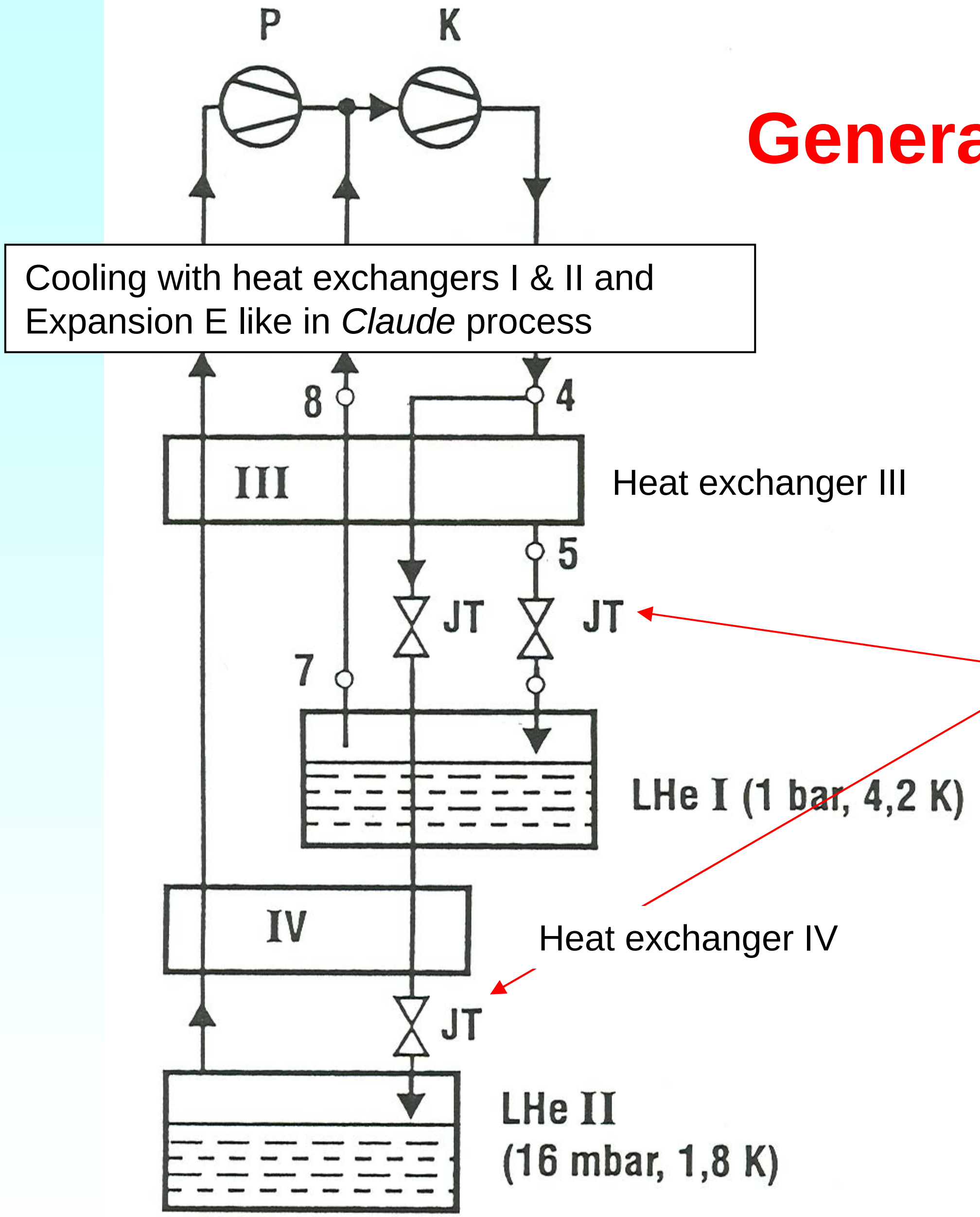
a) Directly from *Claude* process refrigerating machine for LHeI,
b) Via enclosed cooling secondary circuit inside the LHeI bath

Komarek, P.:
Teubner,
Stuttgart, 1995



V: Valve for *p* > 2.26 bar
WT: Heat exchanger
$\dot{m}$: mass flow of super-critical LHe
P: Pump for *p* > 2.26 bar
A: Drive motor for pump
JT: *Joule-Thomson* throttle

Generation of superfluid He II



Cooling with heat exchangers I & II and Expansion E like in *Claude* process

Heat exchanger III

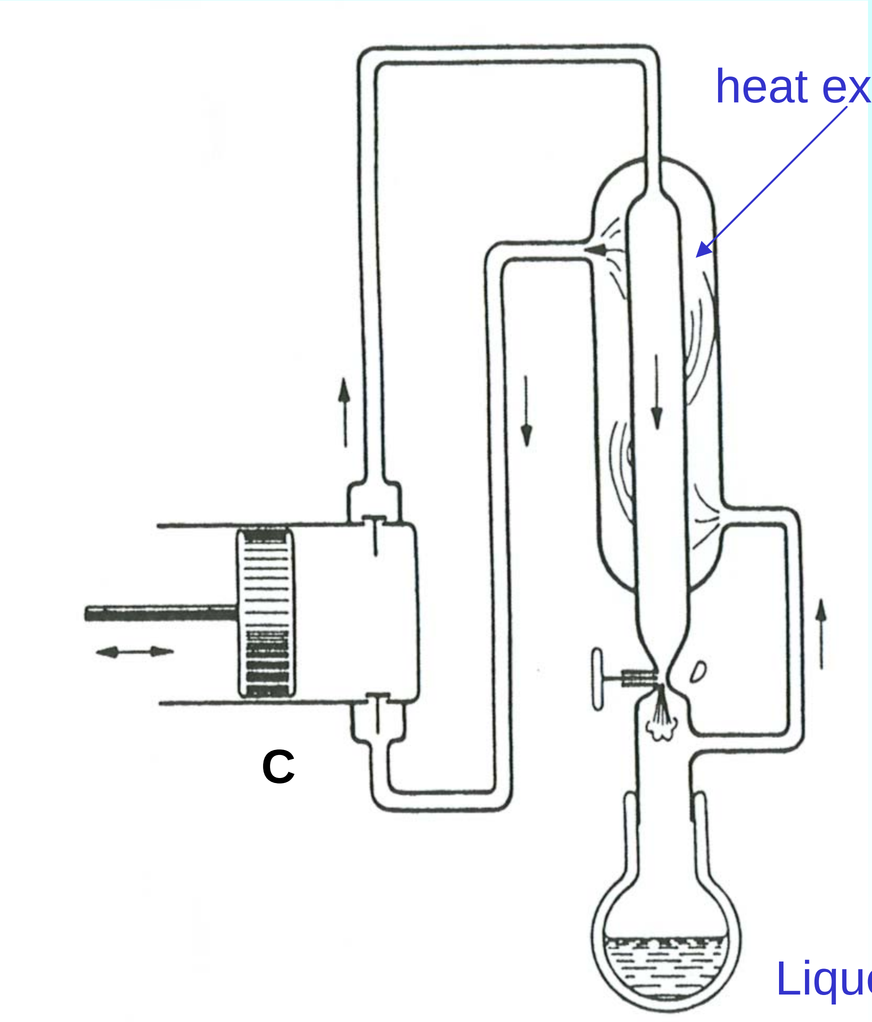
Heat exchanger IV

- Pump P for circulating the He
- Compressor K for build-up of pressure difference
- *Joule-Thomson* throttle JT for sequential cooling

Komarek, P.:
Teubner,
Stuttgart, 1995

1.6 Cryogenic technology

Linde cycle for air and LN_2-liquefaction



heat exchanger

Liquefied air or N_2

- C: Piston compressor:
  Gas compression to 200 bar
- *Joule-Thomson* throttle D: Gas expansion to
  20 bar,
- Resulting gas cooling of about 45 K
- Cooled gas cools in a reverse flow via heat exchanger the gas inflow!
- Cyclic repetition leads to continued gas cooling, until liquefaction occurs!

Westphal, W.:
Physik, Springer,
Berlin

Method of N_2 (and H_2) liquefaction

a) *Linde* cycle: large scale application

b) **Small cooling systems:** temperature range 20 K (LH_2) ... 80 K (LN_2)

***Stirling* cycle** and ***Gifford-McMahon* cycle.**

b1) *Stirling* cycle:

For most N_2-liquefiers for lab purpose (80 K, small devices), because of its simple and robust design.

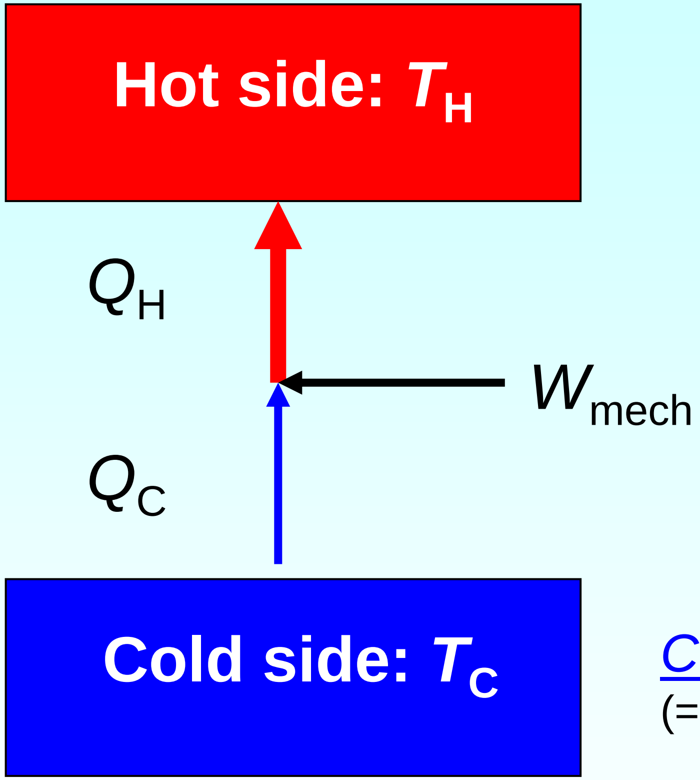
b2) *Gifford-McMahon* cycle:

For most small cooling systems for temperature range down to about 20 K (LH_2-liquefiers):

$$\left.\begin{array}{l}\text{1. Isothermal compression } (p \text{ increased, } V \text{ reduced, } T = \text{const.})\\ \text{2. Isobaric compression } (p = \text{const., } V \text{ reduced, heat } Q_{12} \text{ removed as } Q_{12} \text{ output})\end{array}\right\} \text{Work } W \text{ needed}$$

3. Isentropic expansion (s = const., V increased)
4. Isobaric expansion (p = const., V increased, heat Q_{34} inflow as Q_{34} input)

Efficiency of thermal cyclic processes



Heat energy (J): $Q = m \cdot c \cdot T$

Q_H: Heat energy output to hot side

Q_C: Heat energy withdrawn from cold side

W_{mech}: Mechanical work of refrigerator

$$\boxed{\eta_{Cooling} = \frac{Q_C}{W_{mech}} = \frac{Q_C}{Q_H - Q_C} = \frac{T_C}{T_H - T_C} \begin{cases} <1 \\ >1 \end{cases}}$$

Compare: Efficiency of a thermal cyclic machine
(= reversed cycle to cooling process):

$$\eta_{Motor} = \frac{P_{mech}}{P_{in}} = \frac{W_{mech}}{Q_H} = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{T_C}{T_H} < 1$$

Example:
T_H = 300 K, T_C = 77 K: $\eta_{Motor} = \frac{300-77}{300} = 74.3\%$, $\eta_{Cooling} = \frac{77}{300-77} = 34.5\%$

Example: Ideal efficiency of cooling systems

- *Carnot* efficiency η_c: Ideal η :

$$\eta_{Cooling} = \frac{T_C}{T_H - T_C} = \eta_c$$

- T_H = 300 K:

a) N_2 liquefaction: T_C = 77 K:

$$\eta_c = \frac{77}{300-77} = 34.5\%$$

b) He liquefaction: T_C = 4.2 K:

$$\eta_c = \frac{4.2}{300-4.2} = 1.4\%$$

- *For each Watt of heat power that is to be removed from the superconductor, you ideally need for LHe 1/0.014 =* ***71 W as*** *compressor power, but for* LN_2 *only 1/0.345 =* ***3 W*** *!*

$$\boxed{71:3 = 24(!)}$$

Real energy input for cooling with He and N_2

- The big imbalance 24 : 1 (N_2 : He-liquefaction) shows enormous technical potential of HTSC technology, which can operate with LN_2.

- Rise of losses due to compressor engine friction, loss of pressure due to friction e.g. in tubes, driving motor losses, heat exchanger losses,..

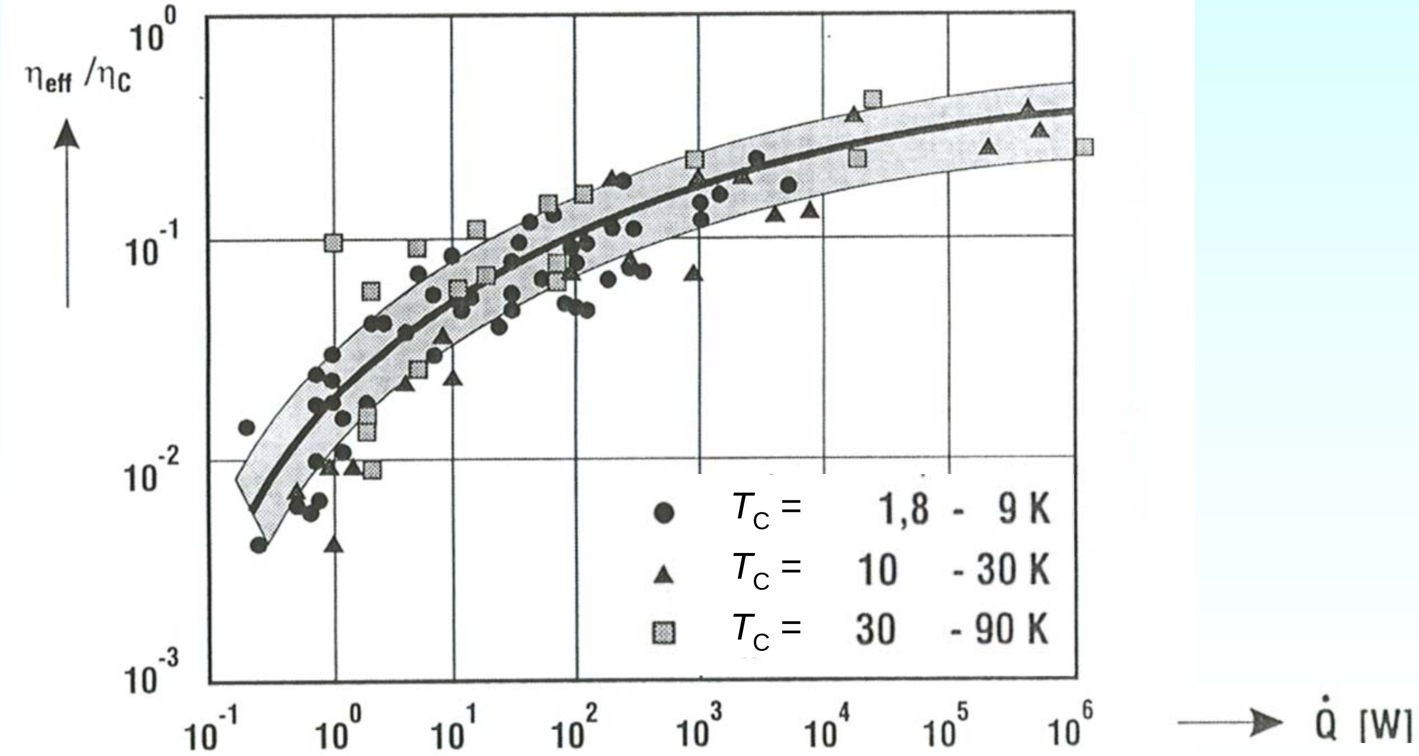
$\Rightarrow$ Real cooling systems have a significantly lower efficiency η_{eff} compared to η_c .

Result:

*A real cooling system with **100 W** cooling power has typically a **1/10** smaller efficiency than the ideal Carnot cooling system. For 1 W cooling power that is to be removed from the superconductor, you need about 700 W electric driving power for the compressor drive at 4.2 K (LTSC), at 77 K (HTSC) it´s "only" 30 W.*

Efficiency of cooling systems

- Measured efficiency η_{eff} of real cooling systems
- Comparison to ideal *Carnot* efficiency η_c
- η_{eff}/η_c depends on: - system size (removed power $\dot{Q}$ from cold side),
  - cold side temperature T_C



Komarek, P.:
Teubner,
Stuttgart, 1995

Portable small *Gifford-McMahon*-refrigerator

Cooling power:

$\dot{Q}$ = 1 W at T_C = 4 K

$\dot{Q}$ = 40 W at T_C = 50 K

Compressor drive electric input power P_e: 7.5 kW

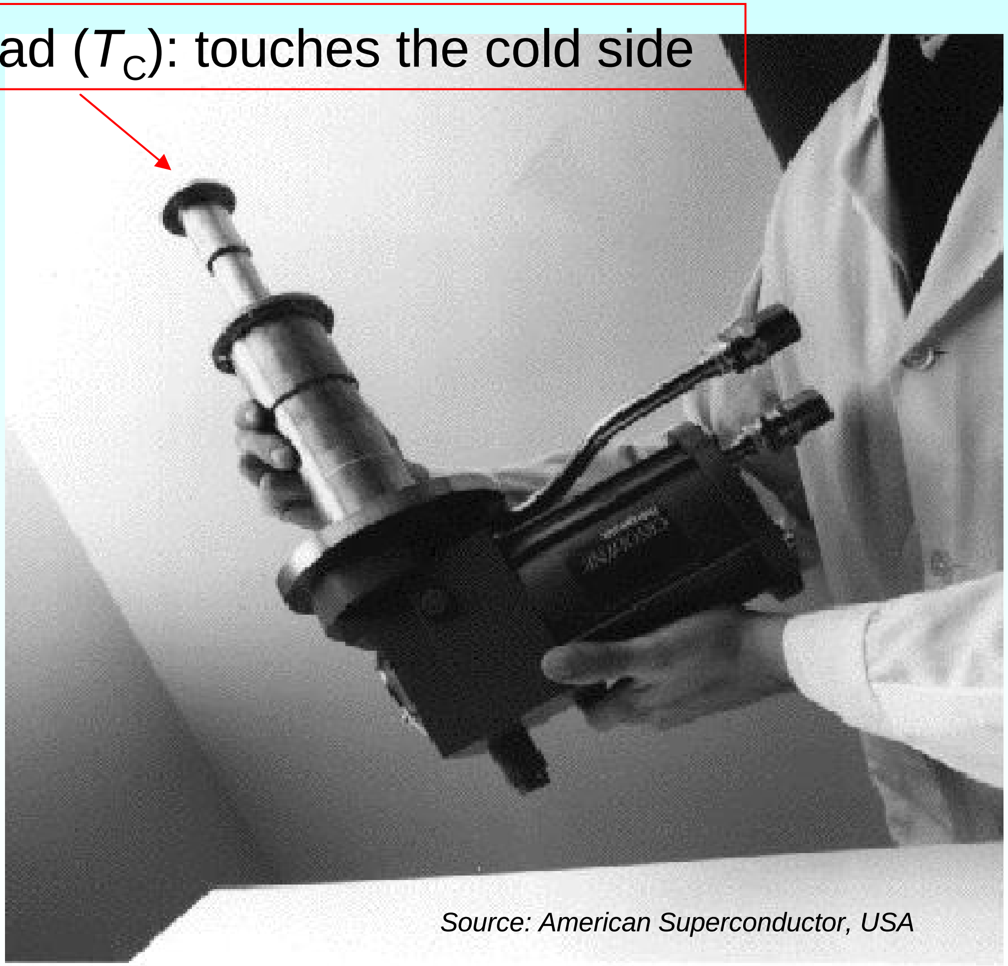
20 000 hours MTBF
(Mean time between failure)

$$1W\big|_{T_C=4K,\eta_c=0.014} \Rightarrow \frac{1W}{0.014} = 71.4W$$

$$\Rightarrow \frac{\eta_{eff}}{\eta_c} = \frac{71.4}{7500} = 0.01$$

$$40W\big|_{T_C=50K,\eta_c=0.2} \Rightarrow \frac{40W}{0.2} = 200W$$

$$\Rightarrow \frac{\eta_{eff}}{\eta_c} = \frac{200}{7500} = 0.027$$



Cold head (T_C): touches the cold side

Source: American Superconductor, USA

New technologies of electric energy converters and actuators

Summary:
Cryogenic technology

- Liquefaction of He or nitrogen needed for cooling
- Cold vapour process only for limited cooling, as seals are freezing
- Cold gas process via cycle processes (e.g. *Stirling* or *Gifford-McMahon*)
- Cold gas process via adiabatic expansion or *Joule-Thomson*-expansion
- For He liquefaction a two-stage Claude cooling process is needed
- Much higher amount of energy needed for He liquefaction than for nitrogen