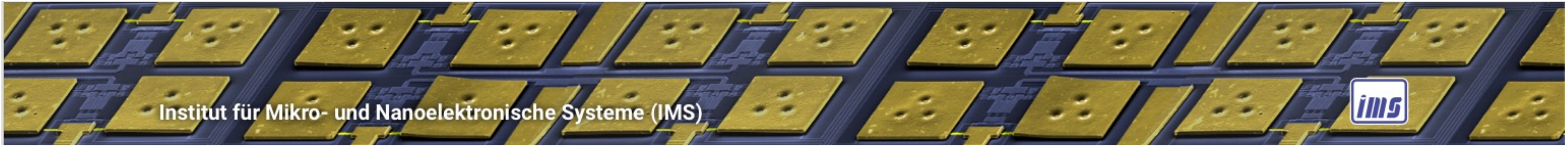
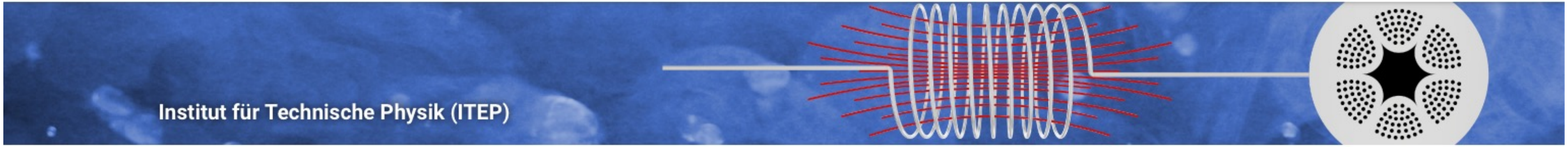
Karlsruher Institut für Technologie

Superconductivity for Engineers

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

Summer term 2021





(Preliminary) Schedule

	Day	Date	Lecture / Tutorial	Day	Date	Lecture / Tutorial
1	Mon	21-04-12	Lecture 1 (SK)	Wed	21-04-14	
2	Mon	21-04-19	Lecture 2 (BH)	Wed	21-04-21	
3	Mon	21-04-26	Lecture 3 (SK)	Wed	21-04-28	Tutorial 1 (IMS)
4	Mon	21-05-03	Lecture 4 (SK)	Wed	21-05-05	
5	Mon	21-05-10	Lecture 5 (SK)	Wed	21-05-12	~~Tutorial 2 (IMS)~~
6	Mon	21-05-17	Lecture 6 (SK)	Wed	21-05-19	Tutorial 2 (IMS)
7	Mon	21-05-24	---	Wed	21-05-26	
8	Mon	21-05-31	Lecture 7 (BH)	Wed	21-06-02	Tutorial 3 (IMS)
9	Mon	21-06-07	Lecture 8 (BH)	Wed	21-06-09	Tutorial 4 (ITEP)
10	Mon	21-06-14	Lecture 9 (BH)	Wed	21-06-16	
11	Mon	21-06-21	Lecture 10 (BH)	Wed	21-06-23	Tutorial 5 (ITEP)
12	Mon	21-06-28	Lecture 11 (BH)	Wed	21-06-30	
13	Mon	21-07-05	Lecture 12 (BH)	Wed	21-07-07	Tutorial 6 (ITEP)
14	Mon	21-07-12	Lecture 13 (SK)	Wed	21-07-14	
15	Mon	21-07-19	Lecture 14 (SK)	Wed	21-07-21	Tutorial 7 (IMS, ITEP)

(Preliminary) Lecture content

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Lecture 1:	(SK)	Introduction and overview
Lecture 2:	(BH)	Superconductor applications
Lecture 3:	(SK)	Normal metals and properties of the normal conducting state
Lecture 4:	(SK)	Perfect conductor, ideal diamagnetism, Two-Fluid-Model, London theory
Lecture 5:	(SK)	Disordered superconductors, Pippard theory, microwave properties
Lecture 6:	(SK)	BCS theory
Lecture 7:	**(BH)**	**Type-II superconductors, Current transport**
Lecture 8:	**(BH)**	**Bean Model, Ginzburg-Landau theory**
Lecture 9:	**(BH)**	**GL theory, intermediate state**
Lecture 10:	**(BH)**	**Superconducting Materials for applications**
Lecture 11:	**(BH)**	**Electrical stabilization and thermal aspects**
Lecture 12:	**(BH)**	**Critical currents, pinning, ac-losses,**
Lecture 13:	(SK)	Josephson junctions and SQUIDs
Lecture 14:	(SK)	Josephson junctions and SQUIDs

Superconducting materials for power/magnet applications

- **Historic overview**
- **Low temperature superconductors (LTS)**

  NbTi

  Nb_3Sn

  NbTi/Nb_3Sn comparison
- **High temperature superconductors (HTS)**

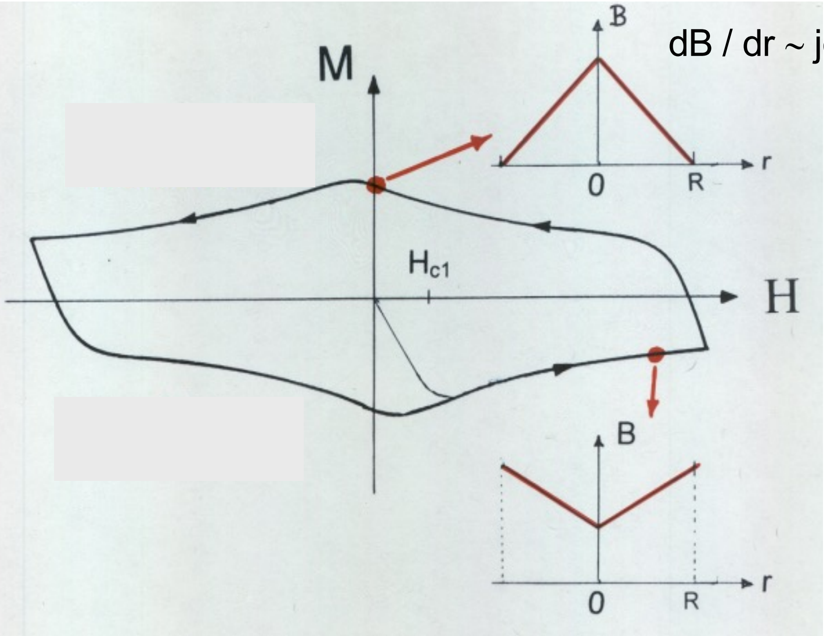
  Y123 Coated Conductor

  Y123 bulk
- **Magnesiumdiboride**

Melt textured bulk YBCO

Hysteresis of type II superconductors

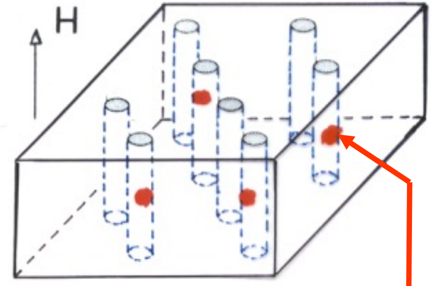
Magnetization and flux profile



dB / dr ~ jc

$H > H_{c1}$ ⇨ flux penetration

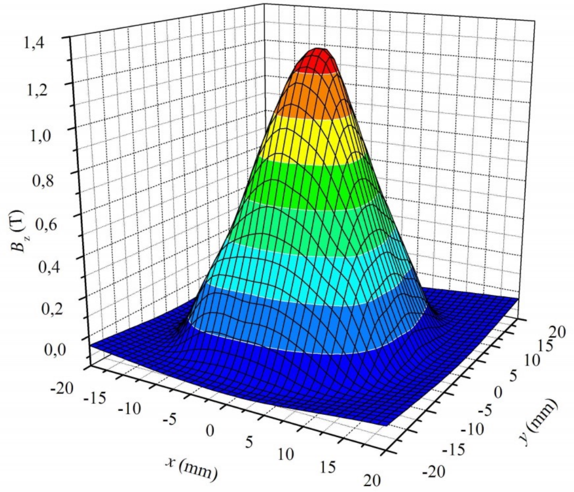
$\Phi_0 = 2*10^{-15}\ Tm^2$
$\xi\ = 1,8\ nm$



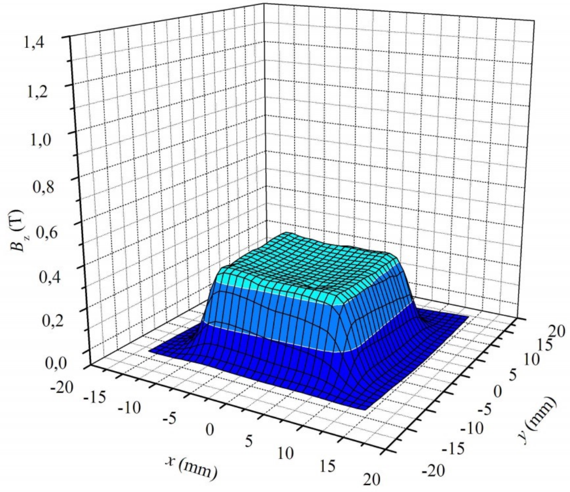
Pinning of flux lines by defects (pinningcenter)

Very strong magnets compared with conventional permanent magnets

B_{max} = 1.3 T



B_{max} = 0.4 T



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Superconducting materials for power/magnet applications

- **Historic overview**
- **Low temperature superconductors (LTS)**

  NbTi

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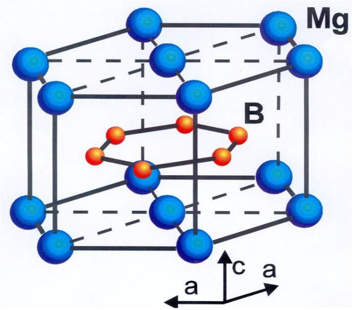
  NbTi/Nb_3Sn comparison
- **High temperature superconductors (HTS)**

  Y123 Coated Conductor

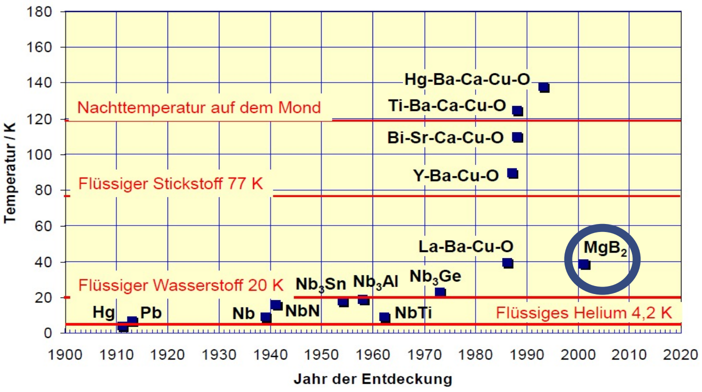
  Y123 bulk
- **Magnesiumdiboride**

Why is MgB_2 special ?



- Highest T_c for binary systems (39 K)
- Low material costs and easy to synthesize
- Refrigeration based cooling possible

- Hexagonal crystal structure (AlB_2-structure)
- Large coherence length
  (no weak-link-prperties of grain boundaries)
- Multiband superconductor
- Anisotropic critical fields



PIT-Technology: *wire examples*

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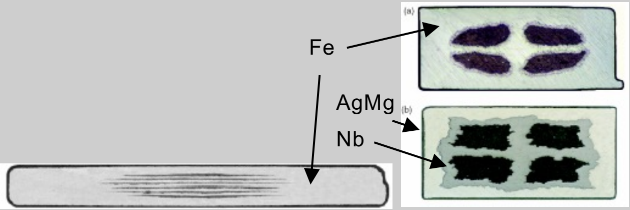
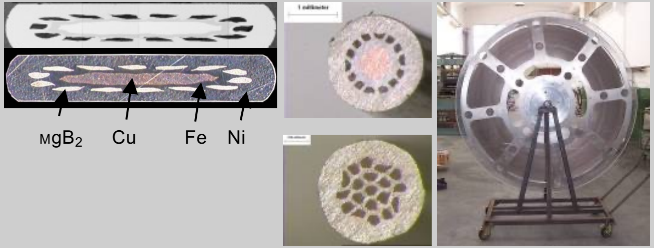
HyperTech Research Inc., USA

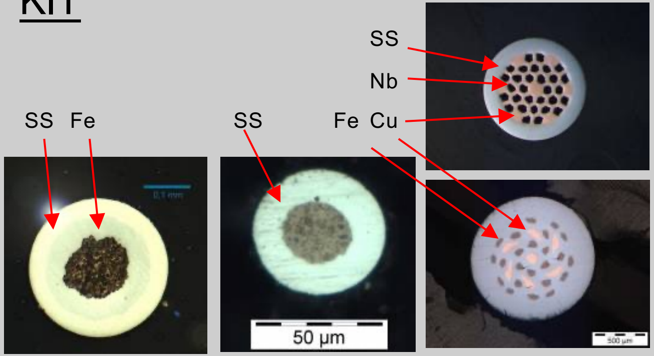
IEE, Bratislava



Columbus Superconductors srl, Genoa:



KIT



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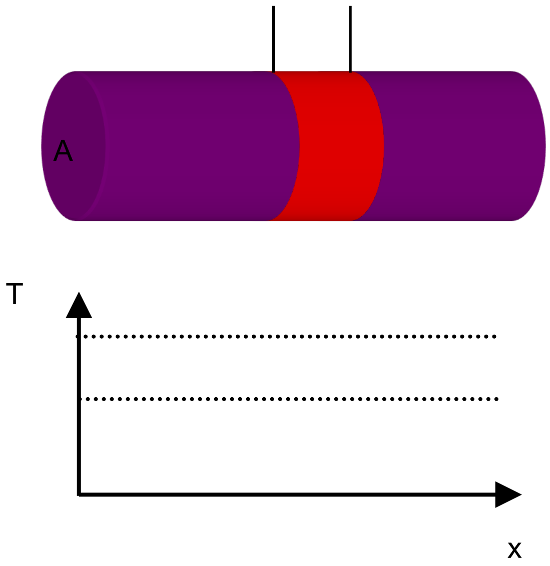
Stability of the sc state in sc wires

- Thermal balance
- Current sharing
- Intrinsic filament stability
- Electric stability with cooling

Motivation



Thermal balance

Basic thermal balance equation

$$c_p(T)\gamma V \frac{\partial T}{\partial t} = Q_{ext} + Q_{Joule} + \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)A_q - \alpha(T)A_o\left(T - T_{Cool}\right)$$

$\alpha(T)$: Heat transfer coefficient [W/(m^2 K)]

c_p (T): Specific heat capacity [J/(kg K)]

$\lambda(T)$: Thermal conductivity [W/(m K)]

T_{Cool} : Temperature of surrounding cooling liquid

γ : density [kg/m³]

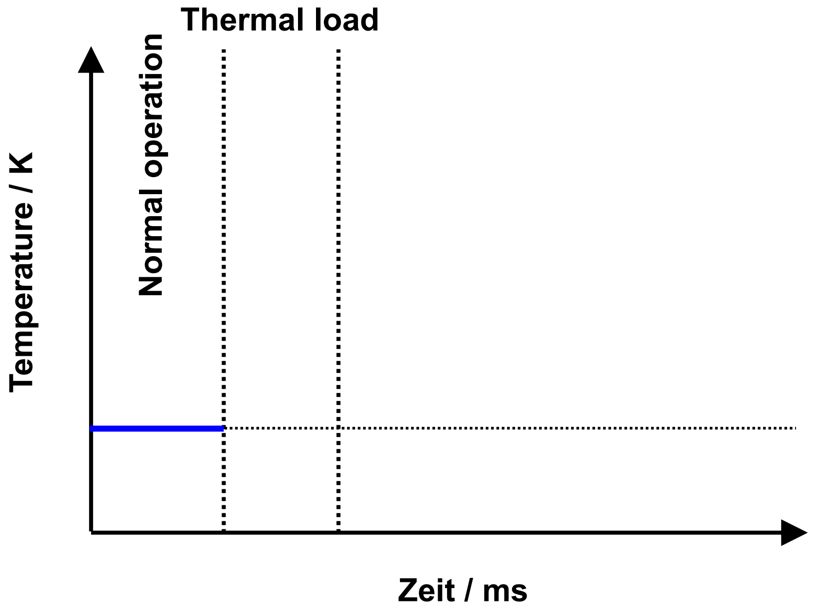
V : Volume [m³]

A_0 : Cooling surface [m²]

A_q : Wire cross section [m²]

Thermal balance

Temperature stability after disturbance



Instability:
Heat development > Cooling

Stability:
Heat development < Cooling

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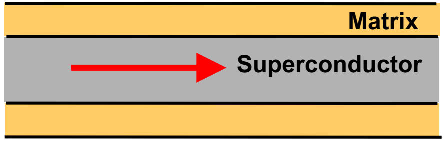
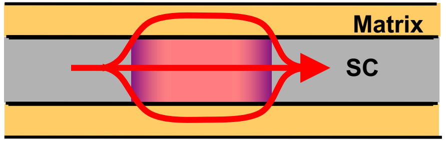
Current sharing

$T < T_{cs}$

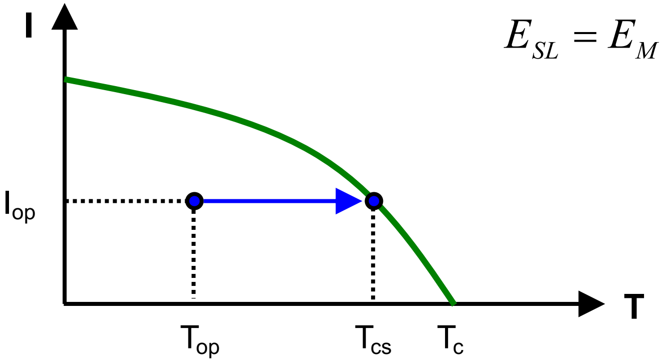


$$E_{SL} = E_M = 0$$

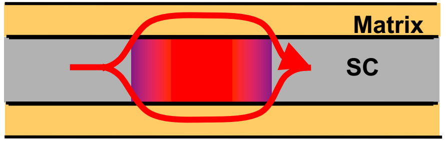
$T_{cs} < T < T_c$



$$E_{SL} = E_M = I_M \frac{\rho_M}{A_M}$$

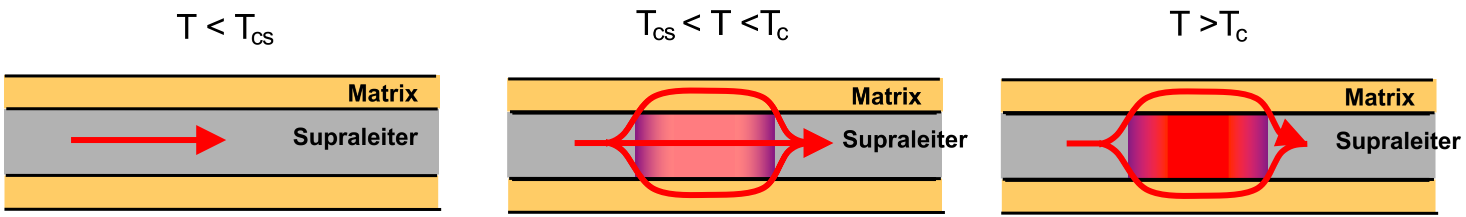


$T > T_c$



$$E_{SL} = E_M = I_{op} \frac{\rho_M}{A_M}$$

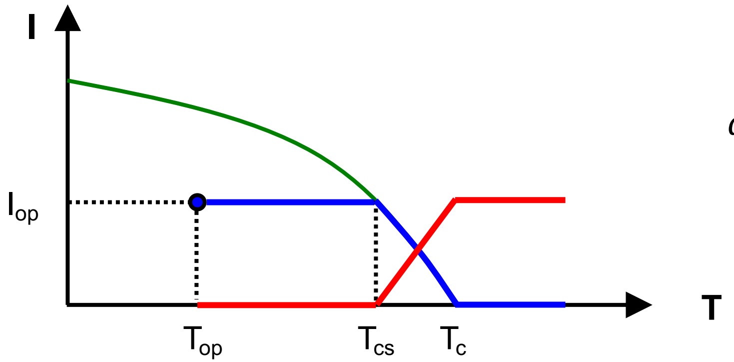
Current sharing



$$E_{SL} = E_M = 0$$

$$E_{SL} = E_M = I_M \frac{\rho_M}{A_M}$$

$$E_{SL} = E_M = I_{op} \frac{\rho_M}{A_M}$$



$$q_{Joule} = 0$$

$$q_{Joule} = \frac{EI_M}{A_{ges}} = \frac{\rho_M I_M (I_{op} - I_c)}{A_M A_{ges}}$$

$$q_{Joule,\max} = \frac{E\, I_{op}}{A_{ges}} = \frac{\rho_M\, I_{op}^2}{A_M\, A_{ges}}$$

Current sharing

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linear approximation of I_c by

$$I_c(T) \approx I_{op} \frac{(T_c - T)}{(T_c - T_{cs})}$$

therefore

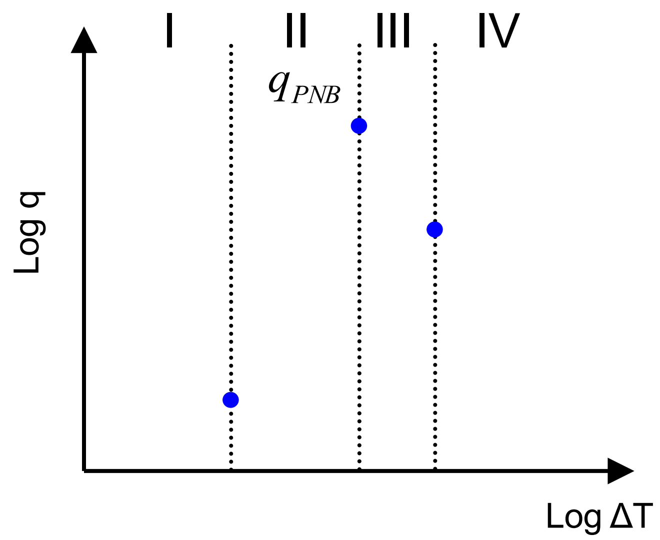
$$q_{Joule} = 0 \qquad T < T_{cs}$$

$$q_{Joule} = q_{Joule,max} \frac{(T - T_{cs})^2}{(T_c - T_{cs})^2} \qquad T_{cs} < T < T_c$$

$$q_{Joule,\max} = \frac{E\, I_{op}}{A_{ges}} = \frac{\rho_M\, I_{op}^2}{A_M\, A_{ges}}$$

$$q_{Joule} = q_{Joule,\max} \qquad T > T_c$$

Heat transfer with direct contact to an He bath



I

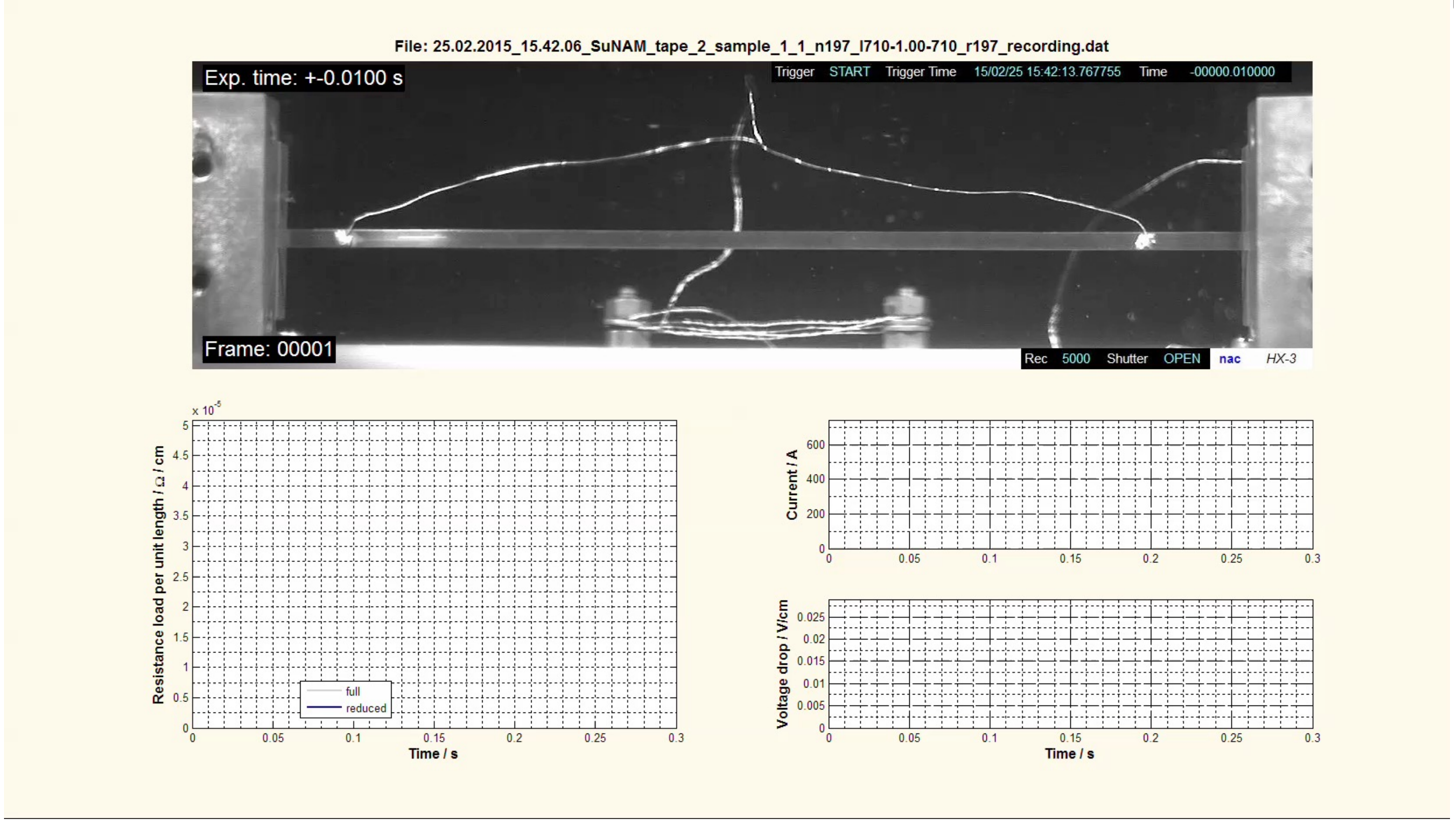
II

III

IV

$$q = \alpha(p)\Delta T^{2...3}$$

„Quench“ of a YBCO Coated Conductor



Stability of the sc state in sc wires

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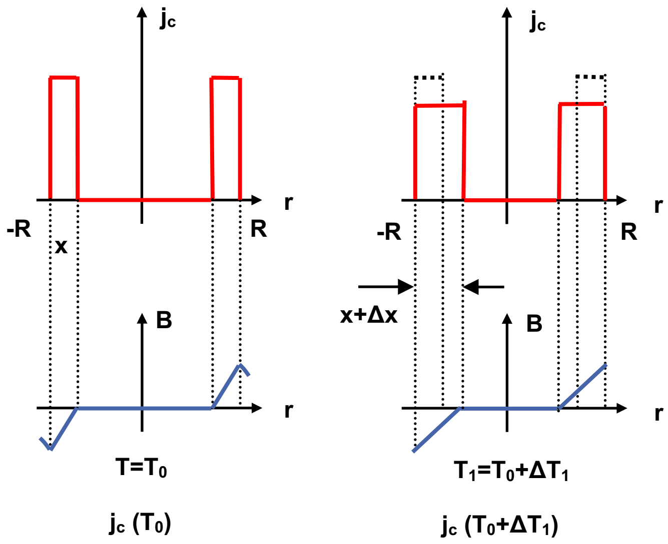
Requirement for thermal stability



Macroscopic flux penetration depth

$$x = \frac{B}{\mu_0 \, j_c}$$

Penetration depth change Δx upon temperature rise ΔT_1

$$\Delta x = -\frac{B}{\mu_0 \, j_c^{\,2}} \Delta j_c \quad mit \;\; \Delta j_c = \frac{dj_c}{dT} \Delta T_1$$

Energy dissipation due to flux motion ΔQ

$$\Delta Q = const \; j_c \, B \, \Delta x$$

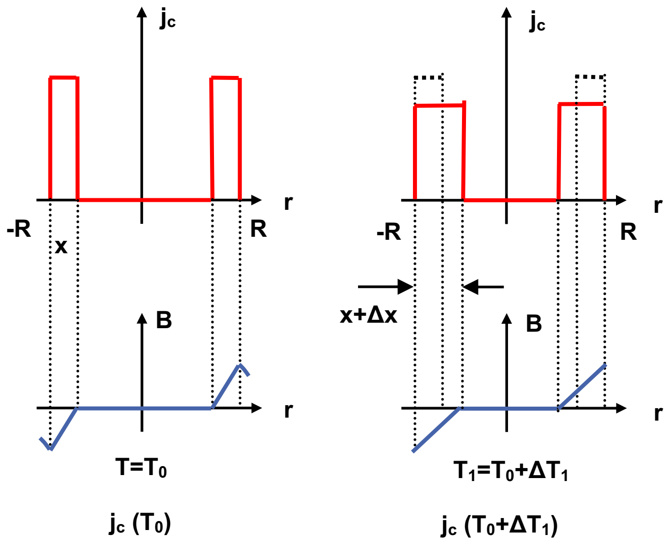
ΔQ results in a temperature increase ΔT_2 (adiabatisch)

$$\Delta T_2 = \frac{\Delta Q}{\rho_{SL} \, c_{SL}}$$

Thermal stability only if

$$\frac{\Delta T_2}{\Delta T_1} < 1 \qquad \Rightarrow \; x < j_c^{-1} \sqrt{\frac{3 \, \rho_{SL} \, c_{SL}}{\mu_0} T_0}$$

Intrinsic stability



Thermal stability only if

$$\frac{\Delta T_2}{\Delta T_1} < 1 \quad \Rightarrow \quad x < j_c^{-1} \sqrt{\frac{3\,\rho_{SL}\,c_{SL}}{\mu_0} T_0}$$

Example for NbTi

$$j_c = 3 \cdot 10^9 \frac{A}{m^2} \quad bei\ ca.\ 4T$$

$$\rho_{SL} = 6{,}2 \cdot 10^3 \frac{kg}{m^3}$$

$$c_{SL} = 0{,}89 \frac{Ws}{kg\,K}$$

$$T_0 = 4\,K$$

$$x < 76\,\mu m$$

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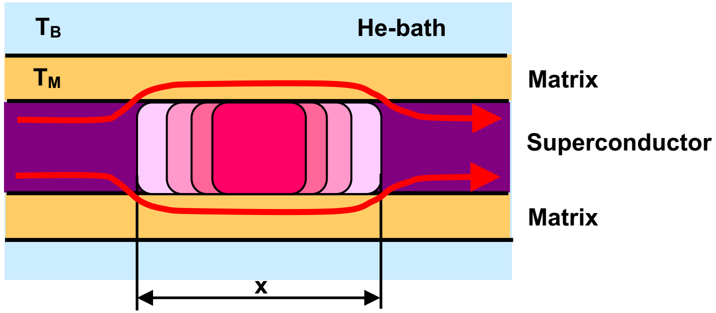
Stabilization by cooling



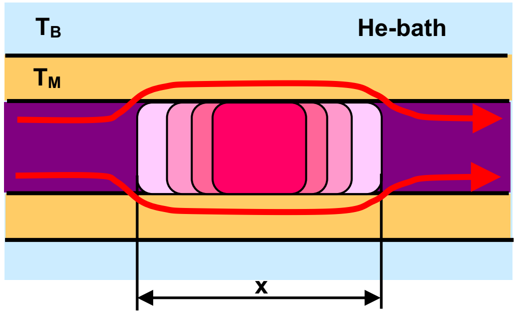
Area of Joule heating

Assumptions:

- Within the normal conducting zone current flows only through matrix
- No contact resistance between SC and matrix
- No axial heat transfer
- Stationary conditions d/dt=0
- No external heat sources

$$c_p(T)\rho V\frac{\partial T}{\partial t}=Q_{ext}+Q_{Joule}+\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)A_q-\alpha(T)A_o\left(T-T_{Kühl}\right)$$

Stabilization by cooling



Area of Joule heating

Resistive heating within the matrix

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

Heat transfer to cooling bath

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

No extension of the normal conducting area if

$$Q_{Joule} < Q_B \; und \; T_M < T_C$$

Therefore

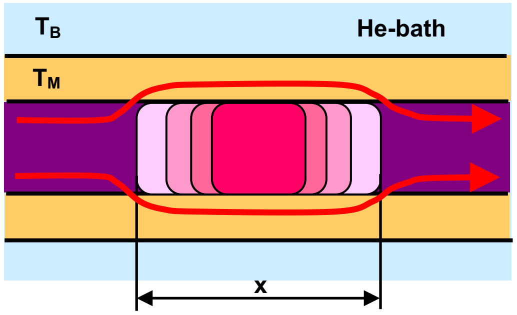
$$\alpha_{st} = \frac{I^2 \rho_M}{A_M \, u_M \, \alpha_{MB} \, (T_C(B, j_{SL}) - T_B)} < 1$$

For stable temperature Q_M=Q_B

$$\frac{I^2 \rho_M}{A_M} = \alpha_{MB}(T_C(B, j_{SL}) - T_B) \, u_{MB}$$

Stekly, Zar, Stable superconducting coils, IEEE Transactions on Nuclear Science, 1965

Stabilization by cooling



For stable temperature $Q_M=Q_B$

$$\frac{I^2 \rho_M}{A_M} = \alpha_{MB}(T_C(B, j_{SL}) - T_B)u_{MB}$$

↳ **Evaporation**

Example for NbTi wire without matrix

$$I = 50\,A \text{ bei } 5T$$

$$d = 0{,}25\,mm$$

$$\rho_{SL} = 1\cdot 10^{-4}\,\Omega cm$$

$$\alpha_{MB} = 0{,}7\frac{W}{cm^2\,K}$$

$$\Delta T = T_{SL} - T_B = 9200\,K$$

Example for NbTi wire with matrix

$$I = 50\,A \text{ bei } 5T$$

$$d_{CU} = 0{,}125\,mm$$

$$\rho_{Cu} = 1\cdot 10^{-8}\,\Omega cm\ (4K)$$

$$\alpha_{MB} = 0{,}7\frac{W}{cm^2\,K}$$

$$\Delta T = T_{SL} - T_B = 0{,}4\,K$$

Stabilization by bath cooling

- Kryostability