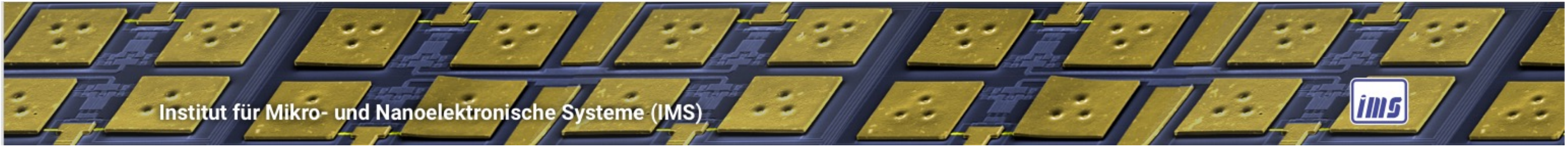
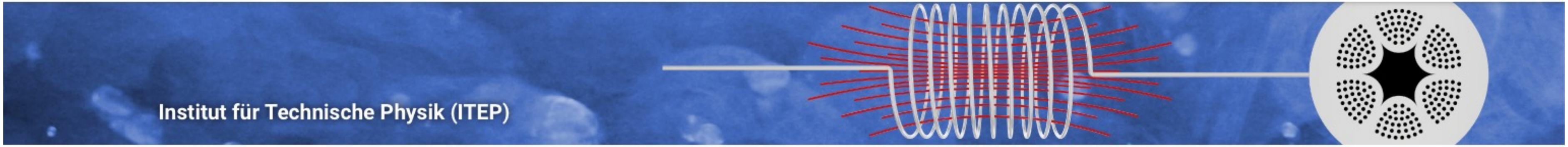
Karlsruher Institut für Technologie

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

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)**	**ac-losses, pinning in HTS**
Lecture 13:	(SK)	Josephson junctions and SQUIDs
Lecture 14:	(SK)	Josephson junctions and SQUIDs

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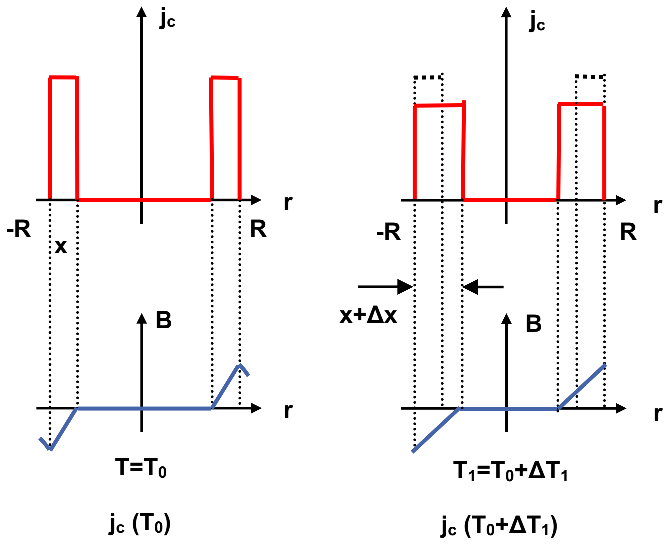
Stability of the sc state in sc wires

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

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

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

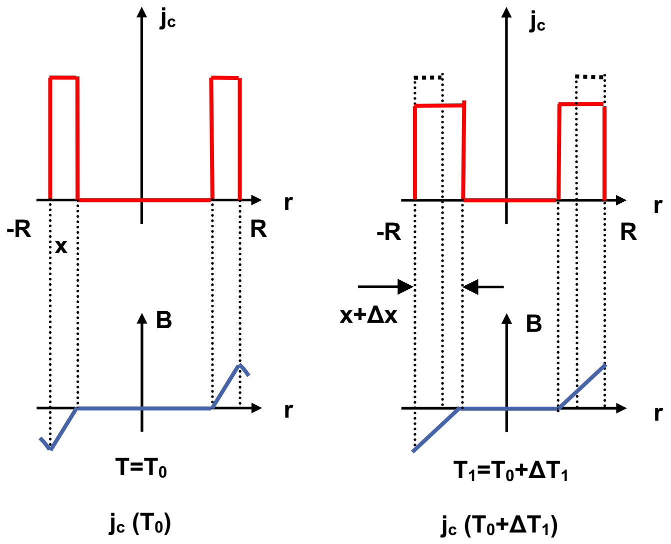
ΔQ results in a temperature increase ΔT_2 (adiabatisch)

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

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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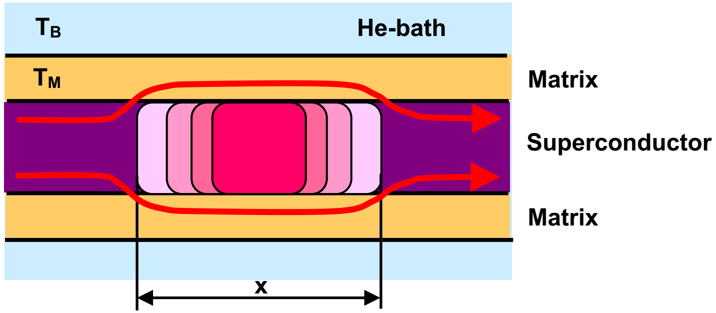
Stability of the sc state in sc wires

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

Stabilization by cooling



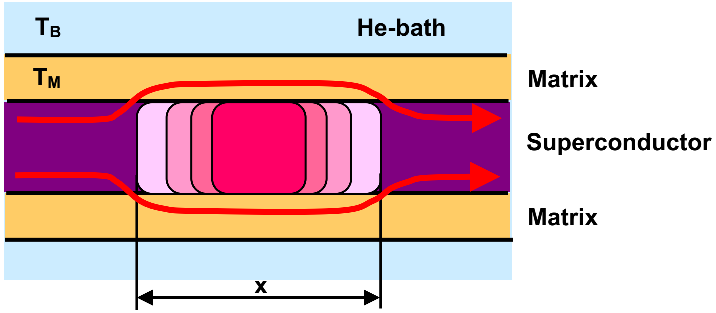
Area of Joule heating

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

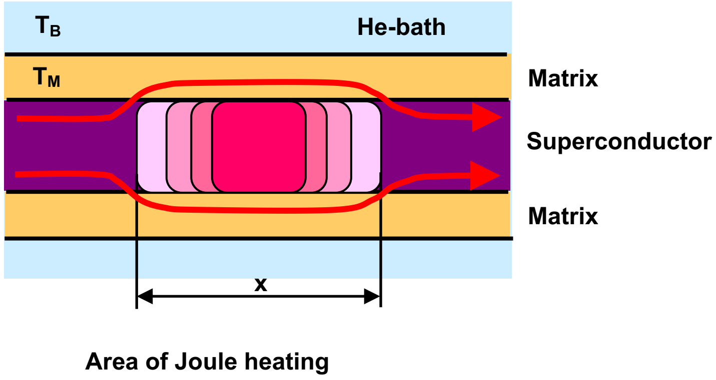
$$\alpha_{st} = \frac{I^2 \rho_M}{A_M \, u_M \, \alpha_{MB} \, (T_C(B, j_{SL}) - T_B)} < 1$$

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



➷ Evaporation

For stable temperature $Q_M = Q_B$

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

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

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

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

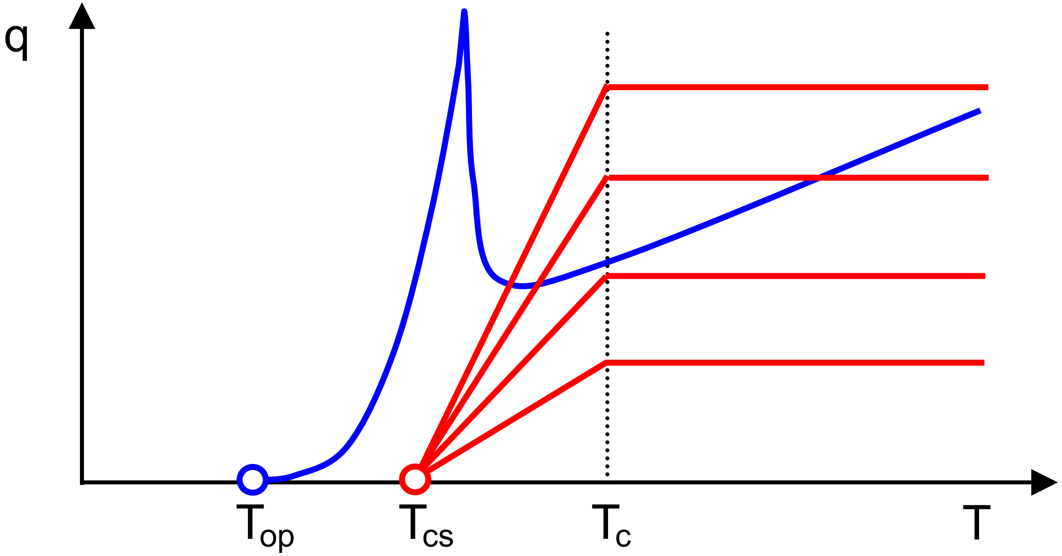
$$\rho_{Cu} = 1 \cdot 10^{-8}\,\Omega cm \;(4K)$$

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

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

Stabilization by bath cooling

- Cryostability



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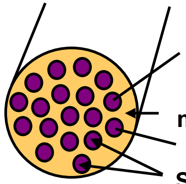
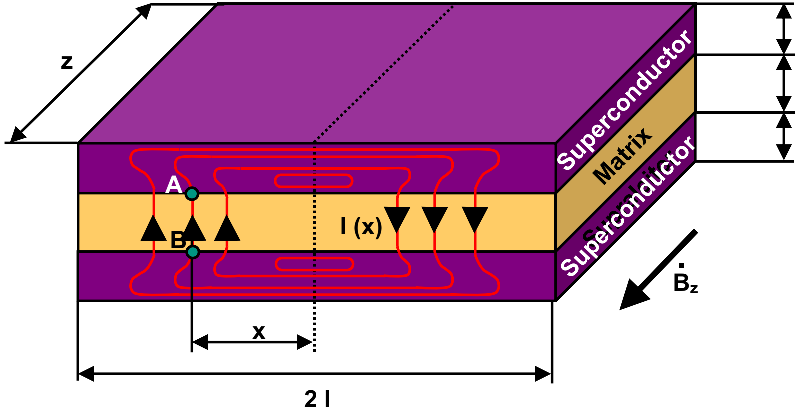
Losses in sc wires due to non stationary conditions

- Filament coupling
- AC-losses (hysteretic losses, eddy current losses)

Filament Coupling in Multifilamentary Wires





Current between SC layers

$$I = \int_0^l j(x)\, z\, dx$$

from

$$\oint E\, ds = -\frac{d\phi}{dt}$$

results

$$U_{AB} = -x\, w\, \dot{B}_z = j(x)\, w\, \rho_M$$

and

$$j(x) = -\frac{x\, \dot{B}_z}{\rho_M}$$

Therefore

$$I = -\frac{\dot{B}_z\, l^2}{2\, \rho_M}\, z$$

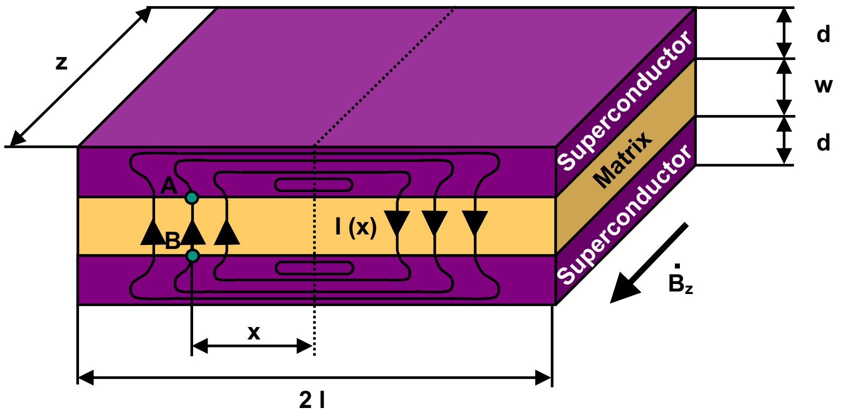
Maximal current at I_{max}=I_c

$$I_{\max} = I_C = j_c\, d\ z$$

Critical length l_c

$$l_c = \sqrt{2\, \rho_M\, j_c\, \frac{d}{\dot{B}_z}}$$

Filament Coupling in Multifilamentary Wires



$$l_c = \sqrt{2\,\rho_M\, j_c\, \frac{d}{\dot{B}_z}}$$ **Critical length l_c**

example for NbTi-conductor in copper matrix

$$j_c = 2 \cdot 10^9 \frac{A}{m^2}$$

$$d = 50\ \mu m$$

$$\dot{B} = 0{,}1 \frac{T}{s}$$

$$\rho_M = 4 \cdot 10^{-10}\ \Omega m$$

$$l_c = 2{,}8\, cm$$

Losses in sc wires due to non stationary conditions

- Filament coupling
- AC-losses (hysteretic losses, eddy current losses)

AC-losses in Superconductors

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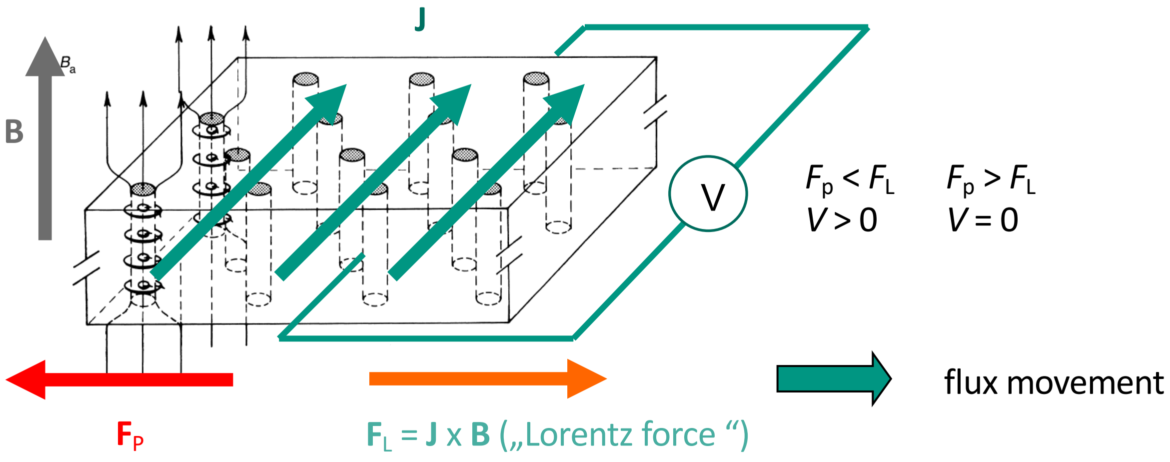
Reminder: curent transport in real type II Superconductors



Electrical current density j_T results in a Lorentz force F_L on each flux line

For $J > J_c$ (= $F_L > F_P$) flux lines move and dissipate energy

For AC-currents flux penetration changes periodically due to self field oszillation and shows hysteretic behaviour → "hysteresis losses" (see last tutorial)

AC-losses in Superconductors

Self field hysteresis losses

Assumption:

• Bean Modell (homogenous, $+j_c/-j_c$, J_c=const)

Hysteresis losses in J/m/period

elliptical conductor

$$P = \frac{I_c^2 \mu_0}{\pi} \left\{ (1-i)\ln(1-i) + i - \frac{1}{2} i^2 \right\} \qquad i = \frac{I_0}{I_c}$$

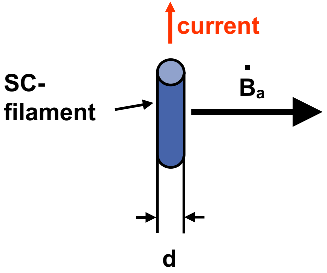
rectangle conductor

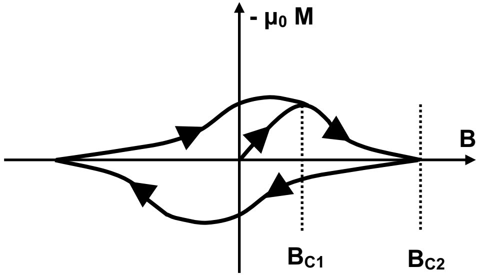
$$P = \frac{I_c^2 \mu_0}{\pi} \left\{ (1-i)\ln(1-i) + (1+i)\ln(1+i) - i^2 \right\} \qquad i = \frac{I_0}{I_c}$$

W. T. Norris. Calculation of hysteresis losses in hard superconductors carrying ac: isolated conductors and edges of thin sheets, J. Phys. D, vol. 3, 489-507, 1970

AC-losses in Superconductors

External field variations – hysteresis losses





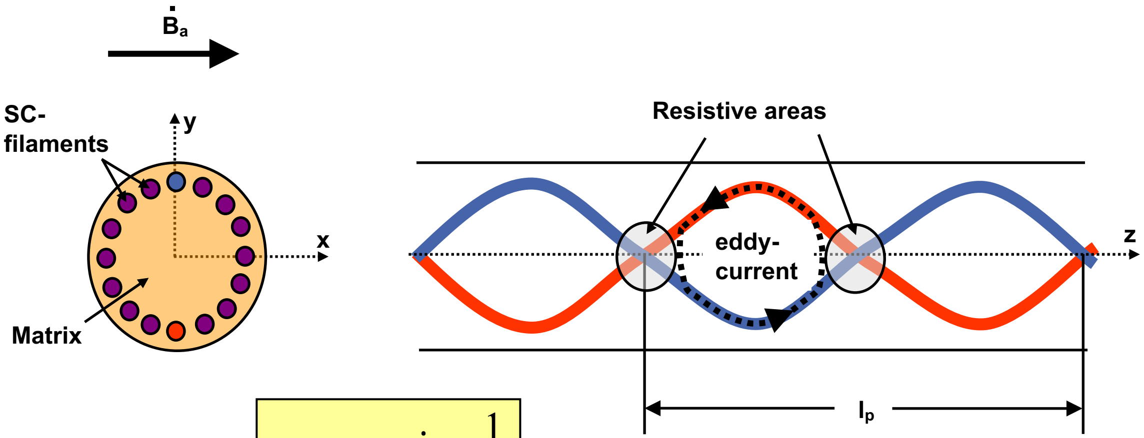
$$P_h \approx d \ \dot{B}_a \ j_c \ V$$

Reduction of hysteresis losses by

• thinner filaments (even thinner as necessary for stabilization)

AC-losses in Superconductors

External field variations – eddy current losses



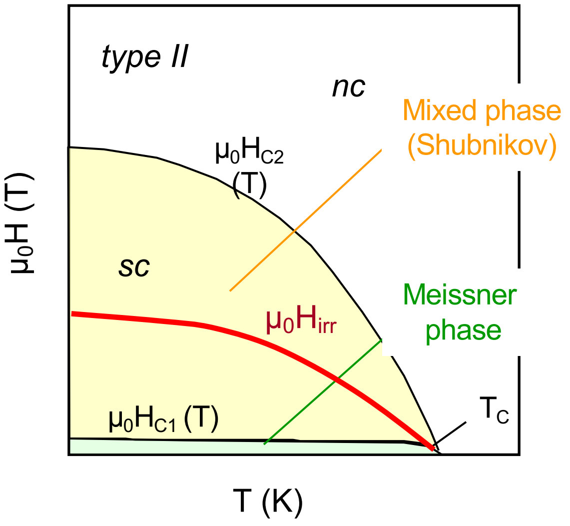
$$P_e \approx l_p \; \dot{B}_a \; \frac{1}{\rho_t}$$

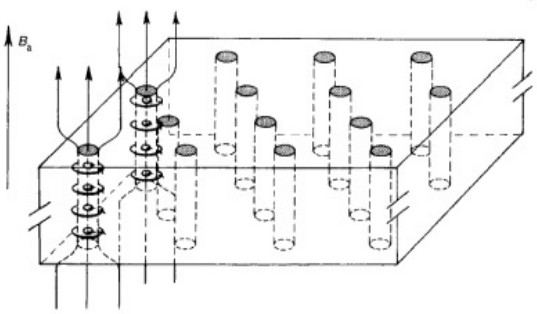
Reduction of eddy current losses by

- matrix with barriers to realize high transversal specific resistance ρ_t
- small twist length l_p

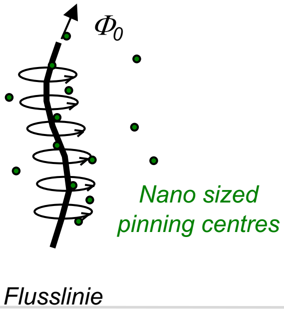
Irreversibility field of HTS

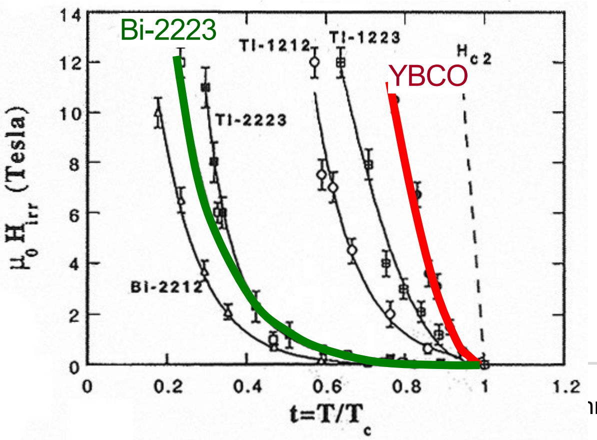
B(T) phase diagram



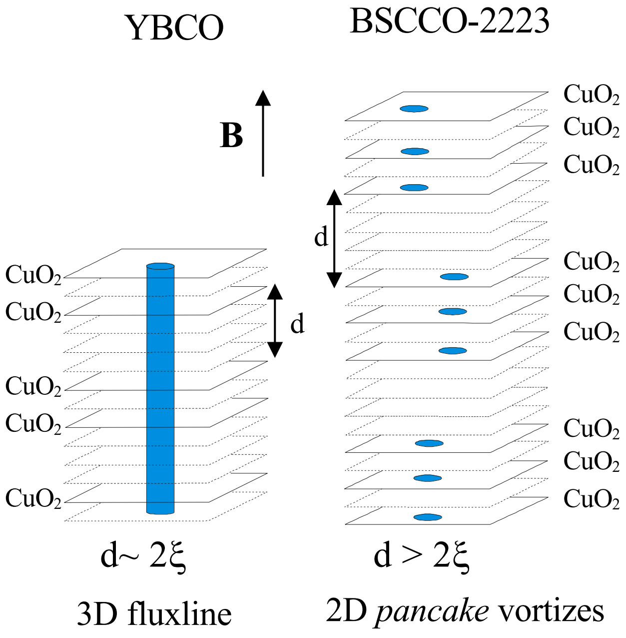


Irreversibility field limits applicability

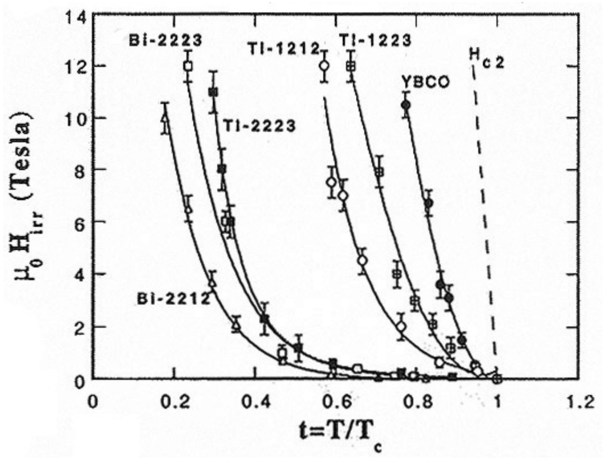




Irreversibility field of HTS



Irreversibility fields



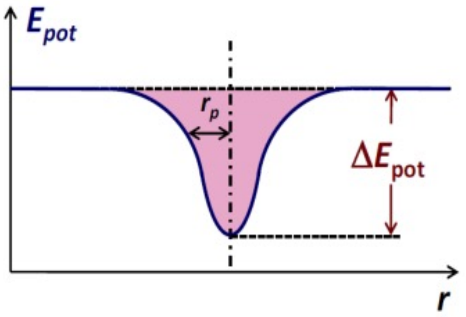
Very small coherence length in cuprates (few nm) + $\xi_c < \xi_{ab}$!

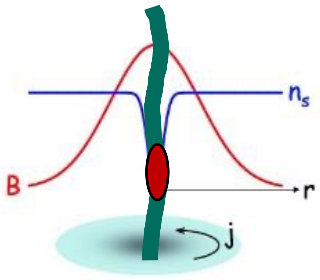
Low anisotropy vs. high T_c
at and below 77K YBCO has highest H_{irr} !

Pinning aspects

Pinning means always the preferred presence of flux lines at positions, where their local potential energy is reduced

$$F_p = -\frac{\partial E_{pot}(r)}{\partial r} \approx -\frac{\Delta E_{pot}}{r_p}$$



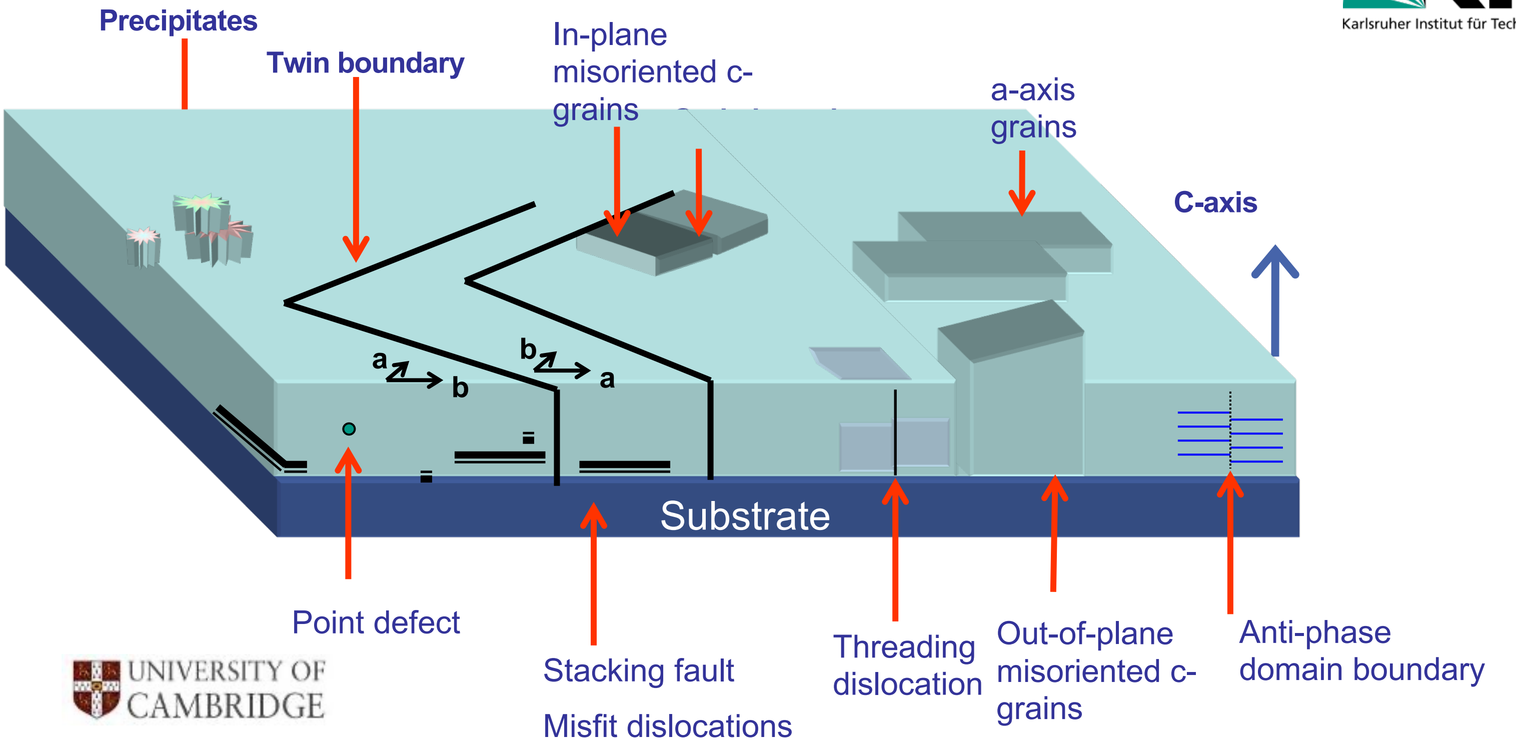


<u>E.g. core- pinning:</u>
Flux line pinned by normal conducting precipitates
$\rightarrow$ less Cooper pairs need to be broken

$\rightarrow$ reduction of condensation energy penalty at flux line core
Maximum pinning force, if $\varnothing \sim \xi \rightarrow$ nanotechnology

Other ways to pin FL: Magnetic interaction, strain/stress, T_c oder κ fluctuations, collective pinning of flux line bundles, intrinsic pinning of layered crystal structure ...

Native Defects in HTS Films

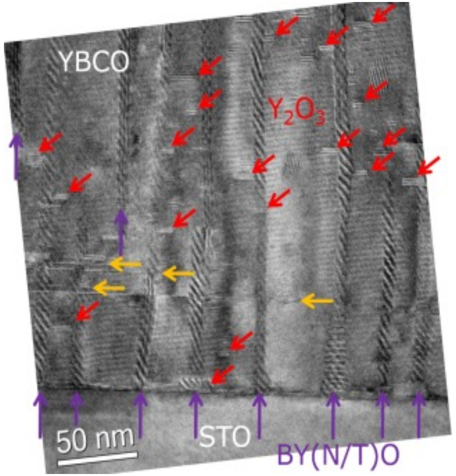


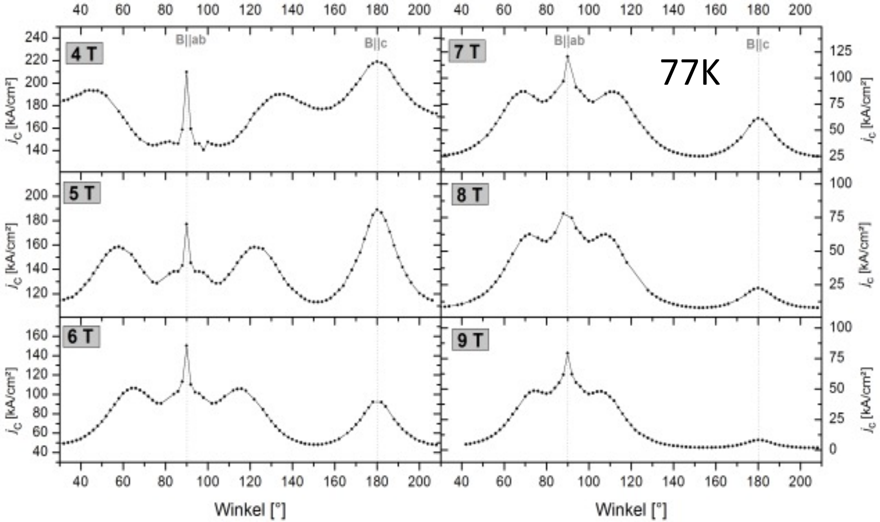
Isotropic: nanodots, strain, disorder, point defect,…

Anisotropic: dislocations (thread., misfit, partial), TB, sGB, strain, SF, APB, buckling, intrinsic, nanopillars,…

Complex pinning landscapes in HTSC

Pinning Engineering through incorporation of various defect structures (here Ba_2YNbO_6/Ba_2YTaO_6-Nanocolumns, Y_2O_3-Nanoparticles, stacking defects) within the superconducting matrix (YBCO)





→ Very complex and variable J_c angular dependence in HTSC