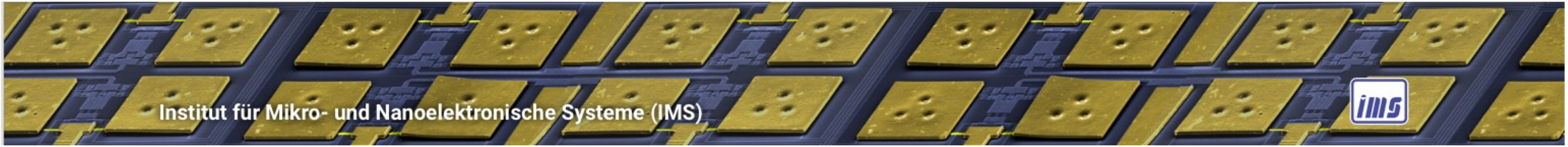
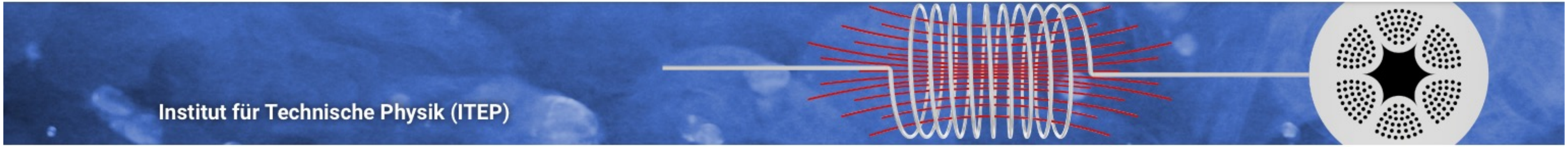
Karlsruher Institut für Technologie

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)**	**Critical currents, pinning and superconducting permanent magnets**
Lecture 12:	**(BH)**	**ac-losses, electrical stabilization and thermal aspects**
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

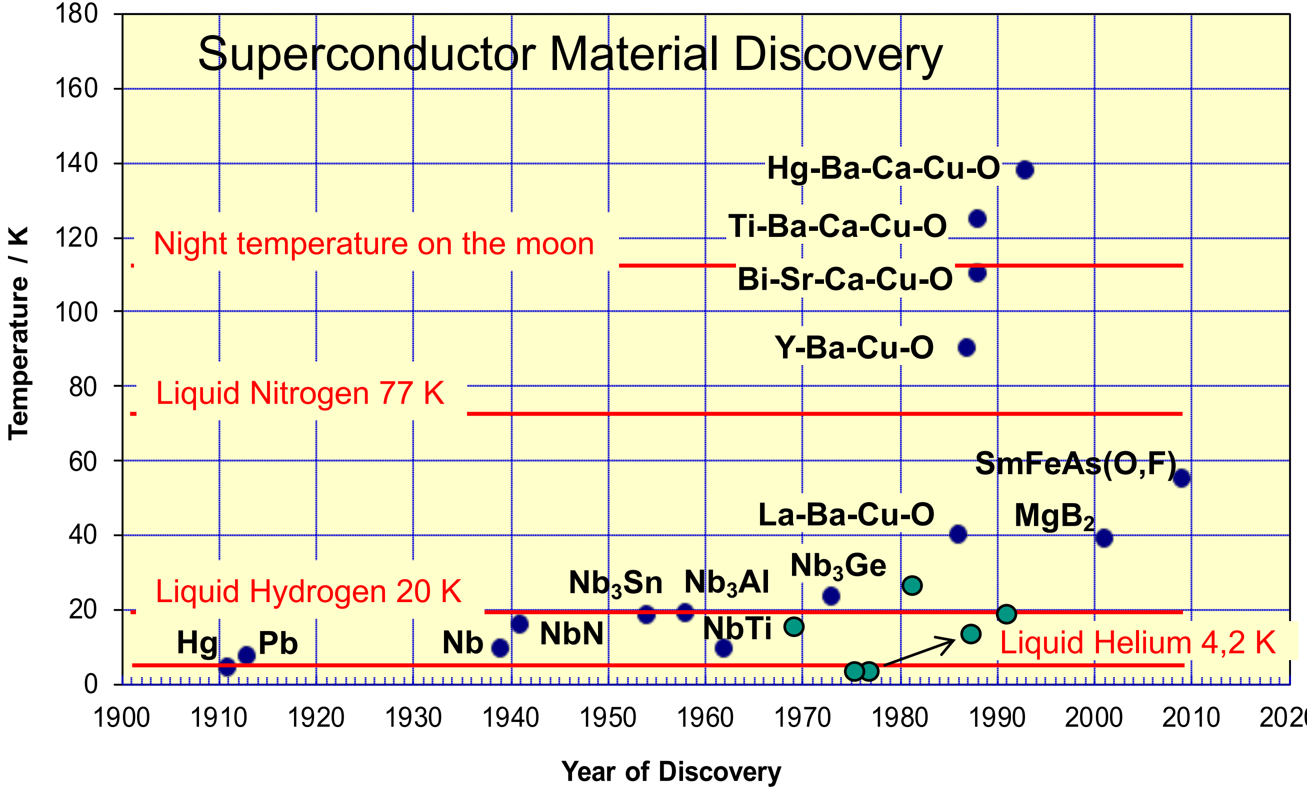
  Nb_3Sn

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

  Y123 Coated Conductor

  Y123 bulk
- **Magnesiumdiboride**

Historic Overview



Overview

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Technical relevant superconductors

Superconductor phase/family	Critical temperature	Critical Field B_{c2}	Year of discovery
NbTi	9,3 K	14,5 T	1962
Nb_3Sn	18,3 K	27,9 T	1954
MgB_2	39 K	8-16 T	2001
BSCCO 2223 BSCCO 2212	~ 110 K ~ 80 K	>80 T >80 T	1987 1987
(RE)BCO RE123	~ 90 K	> 100 T	1987
Fe-based SC	10 K-55 K	- 90 T	2008

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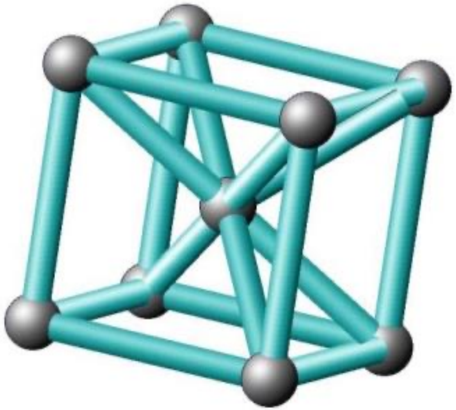
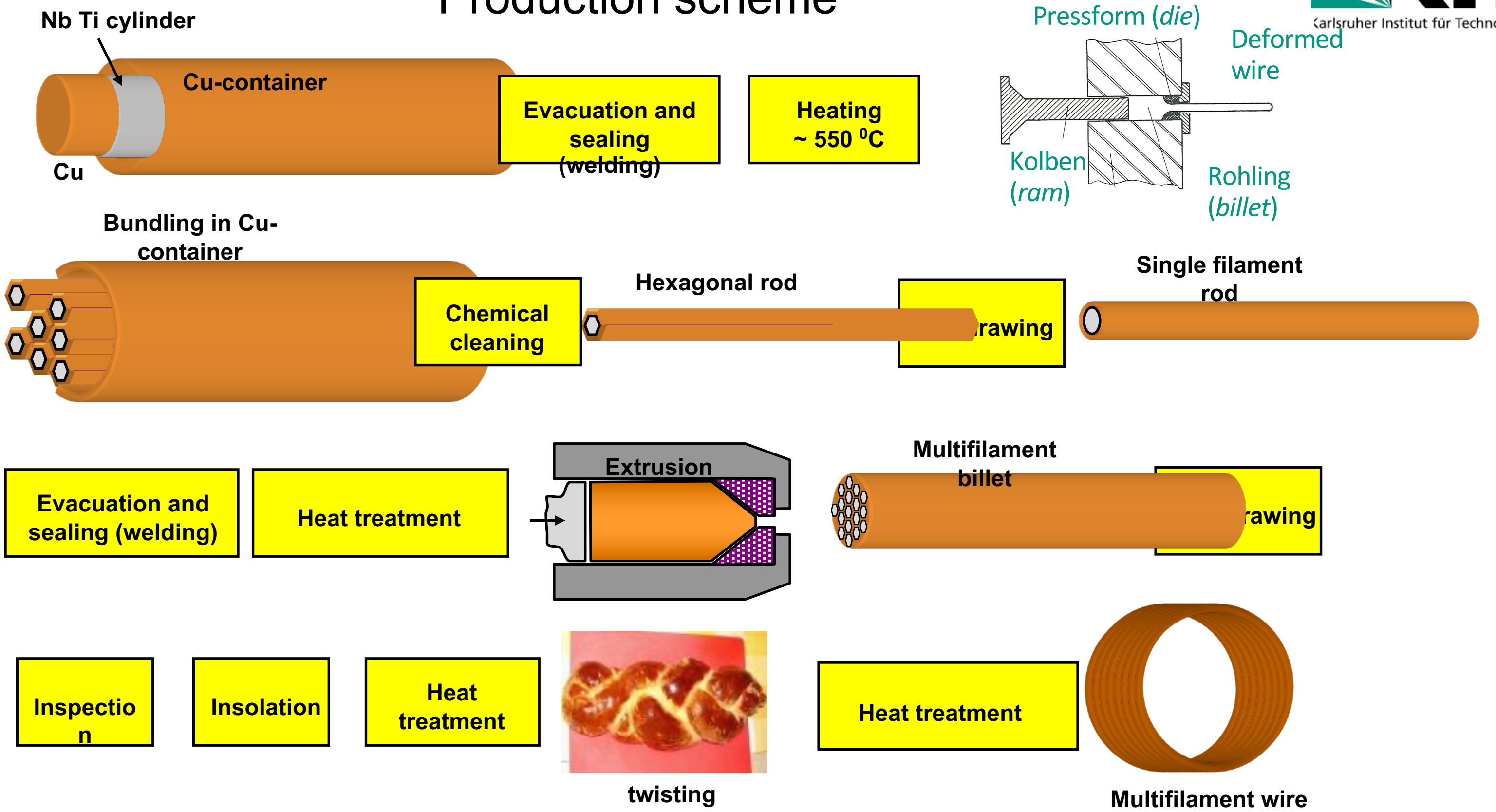
Nb-Ti

- Crystal Structure
  - body centered cubic (bcc)
  - lattice constant = 3.285 Å
  - Nb and Ti atoms statistically distributed over crystal sites
- $Nb_{0.6}Ti_{0.4}$: T_c = 9,8 K
  B_{c2} = 11,5 T
- Advantages:
  - Excellent strength and ductility
  - High current-carrying capacity
  - Low cost
  - React and wind possible
- Applications: MRI, NMR, laboratory magnets, particle accelerators, SMES, minesweeping, ore separation, levitated trains



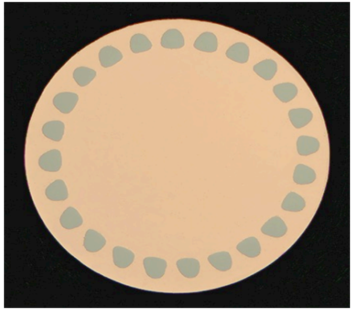
NbTi-Wires

Production scheme

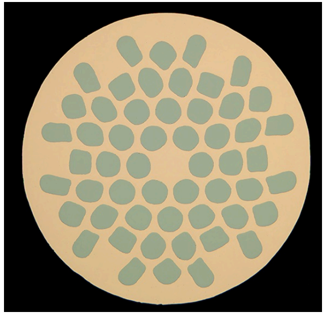


NbTi: Monolithic Conductors

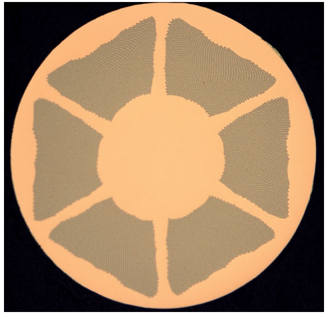
F24-6.5



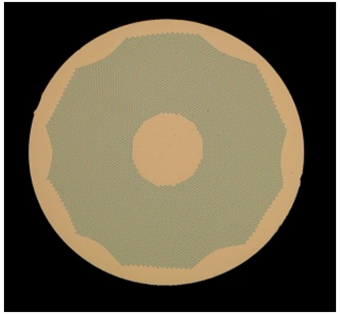
F54-1.35

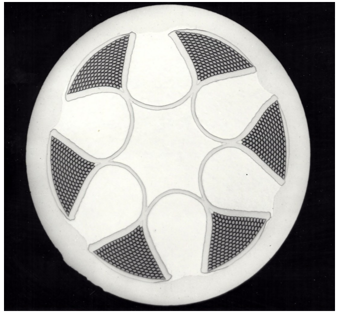


F12000

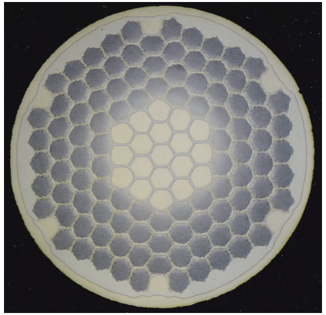


F6200 MQY

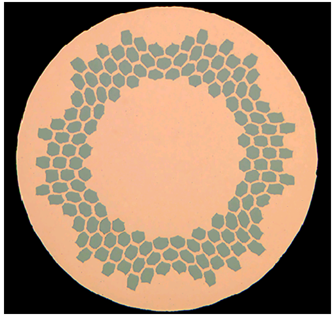




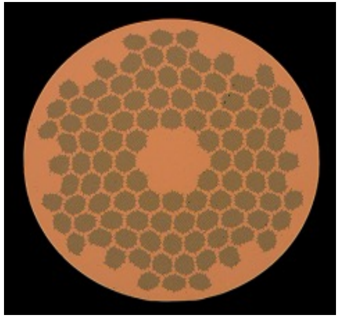
Poloidal field conductor



SC Generator CuNi matrix

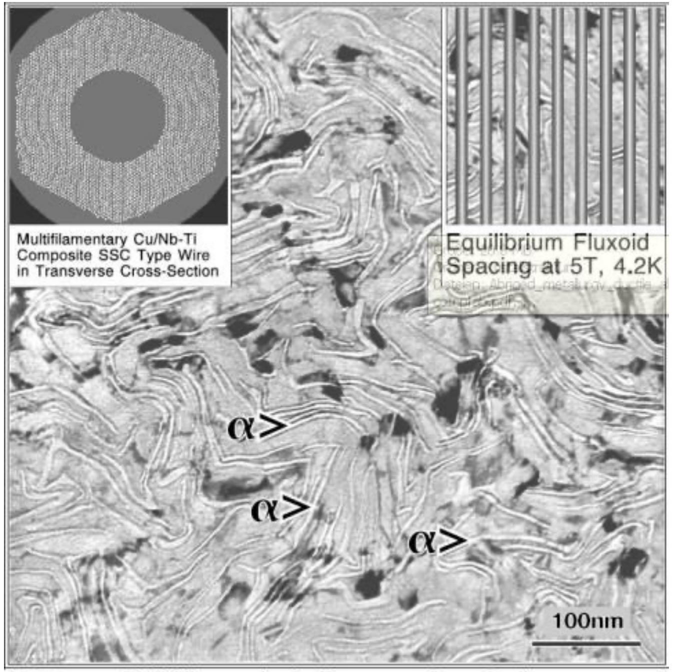


F144-2.6 Wendelstein



F8670 LHC dipole strand

NbTi: Pinning Centres



TEM Micrograph of a Transverse Cross-Section of a Nb-47wt.%Ti Filament at Peak Final Strain

Flux line distance comparable with distance of α-Ti-precipitates

Courtesy of P. Lee

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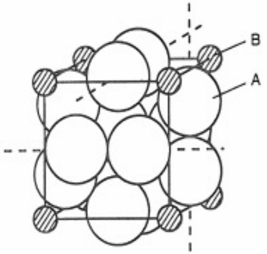
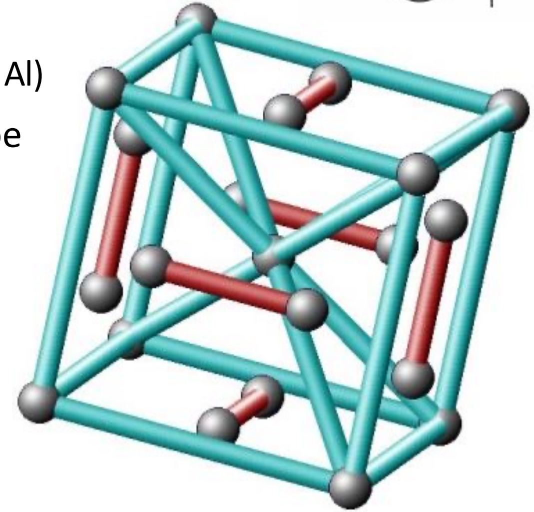
  Y123 bulk
- **Magnesiumdiboride**

The A15-phase (A_3B, β-Wolfram)

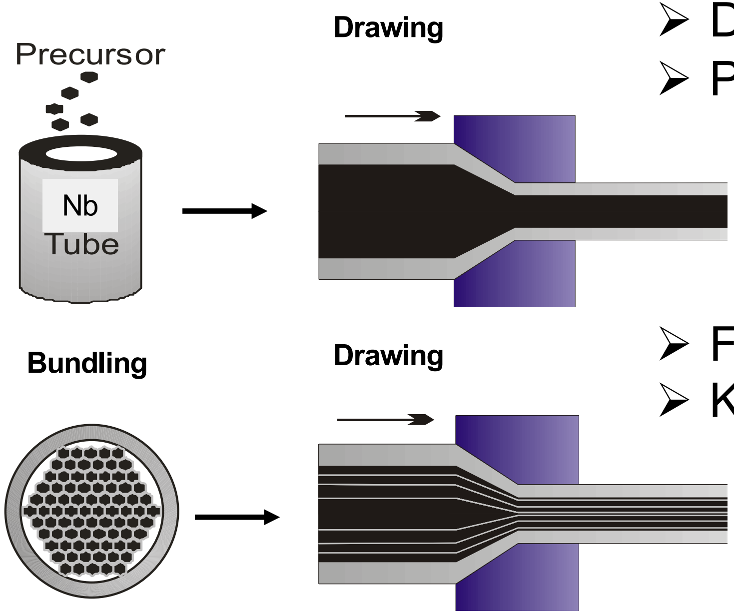
- Example: Nb_3Al, Nb_3Ga, Nb_3Ge, Nb_3Sn, V_3Ga, V_3Si
- General stoichiometry: A_3B,
  - A: transition metal (V, Nb)
  - B: metal, semiconductor (Si, Sn, Ga, Ge, Al)
- B-atoms in bcc-lattice, + 2 A-atoms on cube faces
- Very brittle
- Nb_3Sn : T_c = 18 K; B_{c2} (4.2K) = 18 T
- With Ga- rsp. Ta-addition : B_{c2}(4.2K) up to 25 T





unit cell

Powder-in-Tube-Process

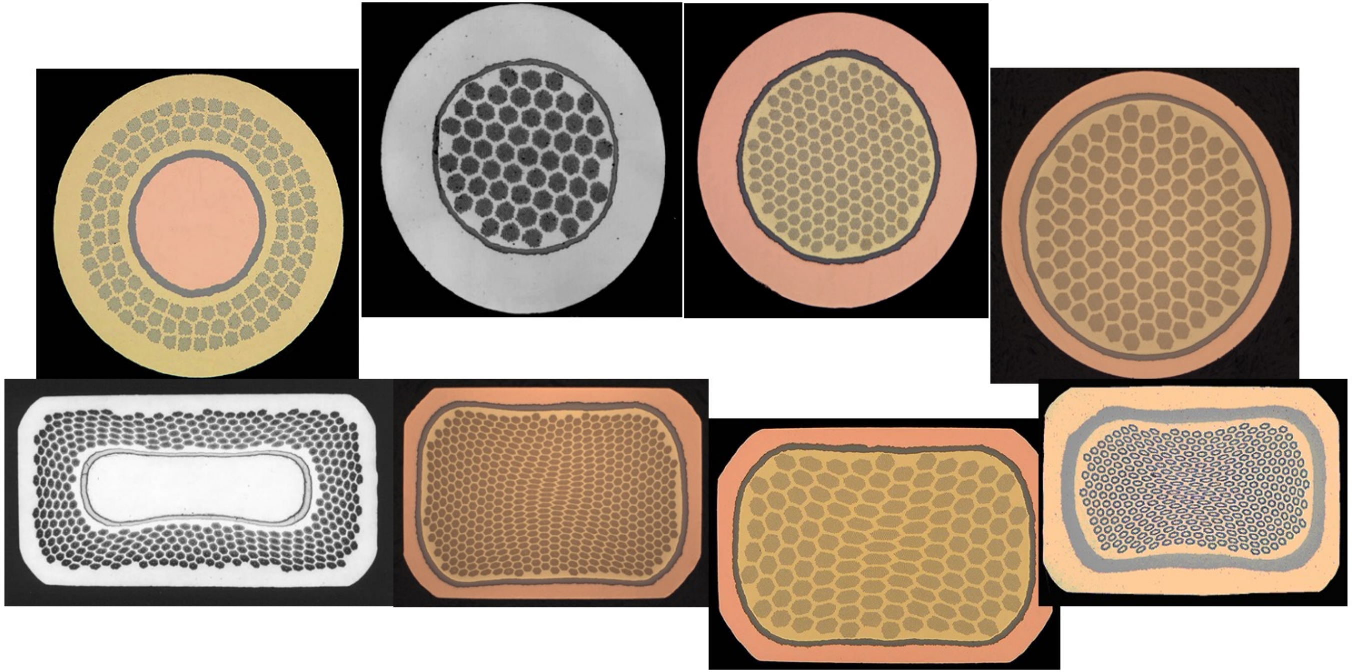


- Sn-powder in Nb/Cu tube
- Deformation + Bundling
- Phase formation (>930°C)

- First high field magnet
- Kunzler et al. 1961

Nb_3Sn-conductor

Examples (Bronze-Route) – European Advanced Superconductors



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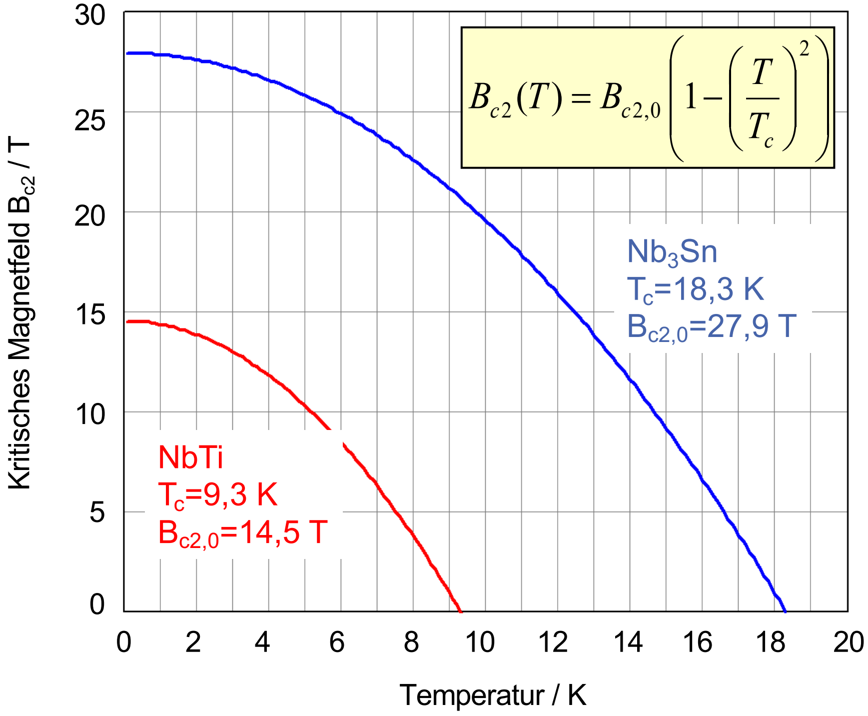
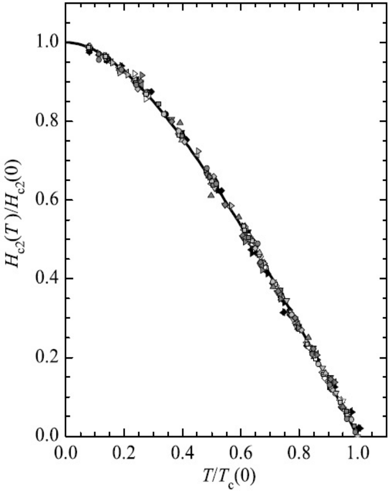
NbTi and Nb_3Sn comparison

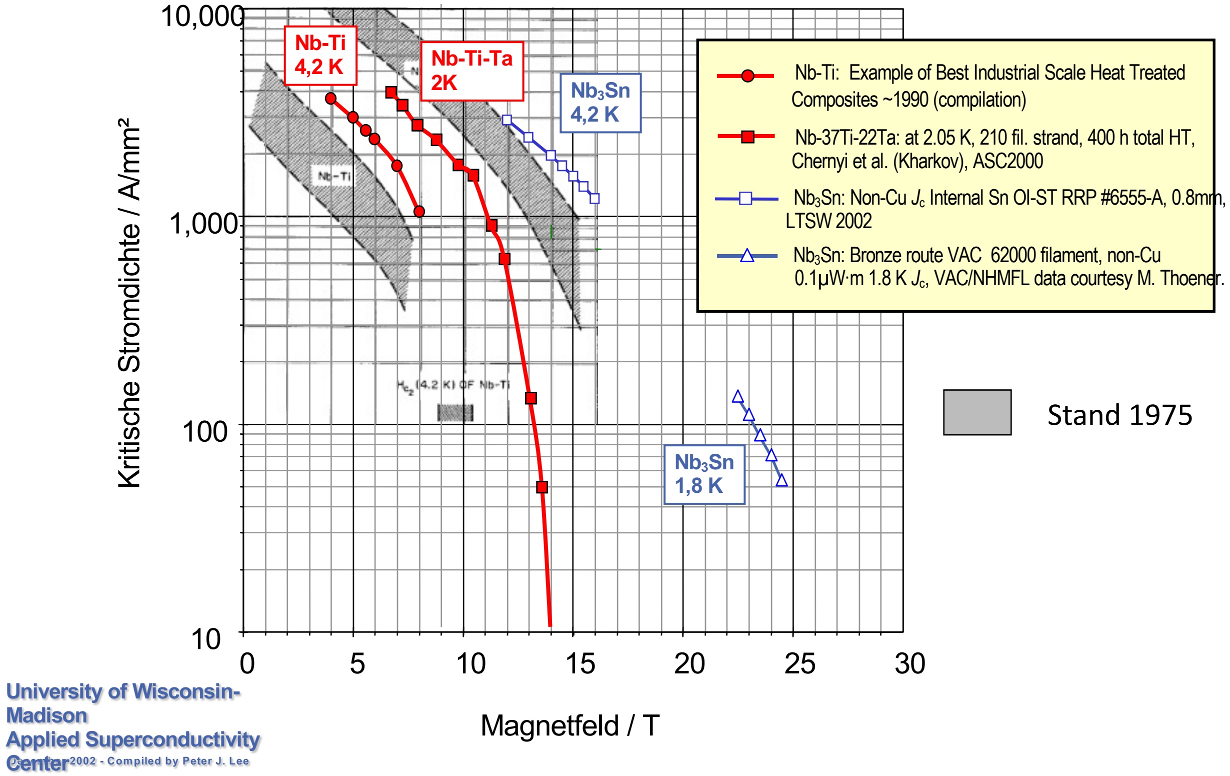
Temperature dependence of the upper critical fields





NbTi and Nb_3Sn comparison

Critical Current Density



NbTi and Nb_3Sn comparison

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Summary

Nb_3Sn shows higher stability

+ higher temperature tolerance (T_c = 18 K, NbTi: 10 K)

+ less need for Cu stabilization

+ higher B_{c2}

+ B_{c2} improvement by alloying

Disadvantages of Nb_3Sn

- mechanically brittle

- j_c depends on mechanical stress/strain

- quite expensive !

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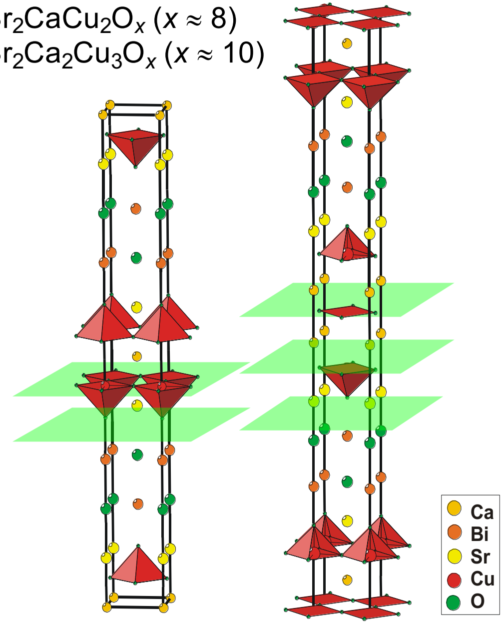
High temperature superconductors (HTS)

Bi(Pb)-2212 Bi(Pb)-2223

2212 ≈ $(Bi,Pb)_2Sr_2CaCu_2O_x$ ($x \approx 8$)
2223 ≈ $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ ($x \approx 10$)

BSCCO



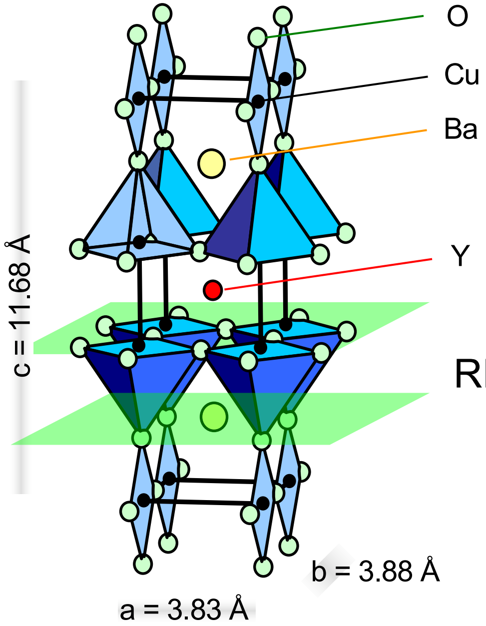
T_c = 85 K T_c = 110 K

Ceramics with complex layered unit cell (2-dimensional)

CuO_2-Ebenen responsible for superconductivity

Strong anisotropic properties

Very small coherence length (< 1nm)



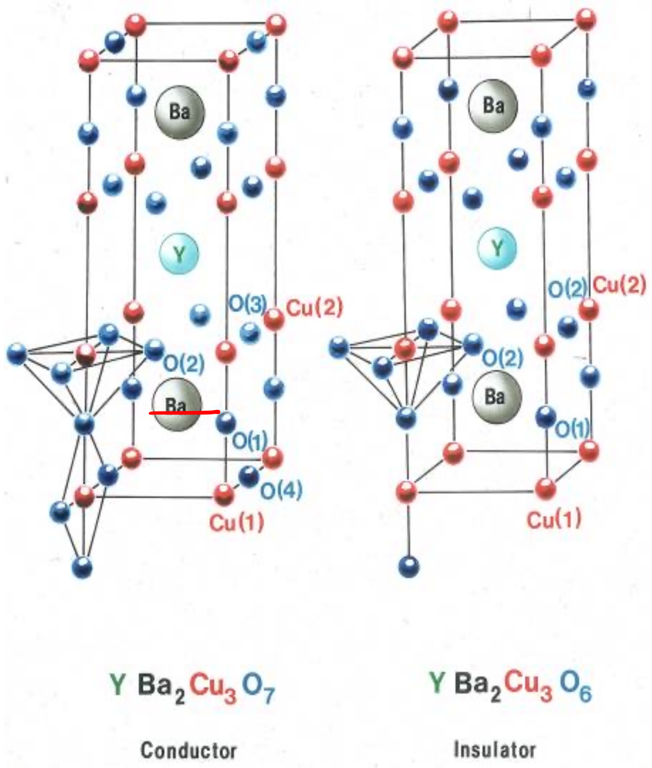
REBCO/RE123

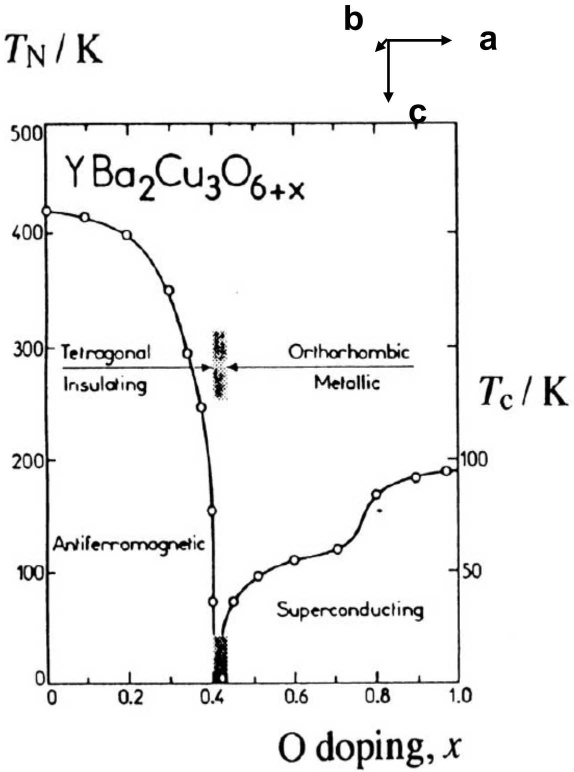
$REBa_2Cu_3O_{7-x}$

RE: Y, Nd, Er, Gd, Eu…

T_c = 92 K

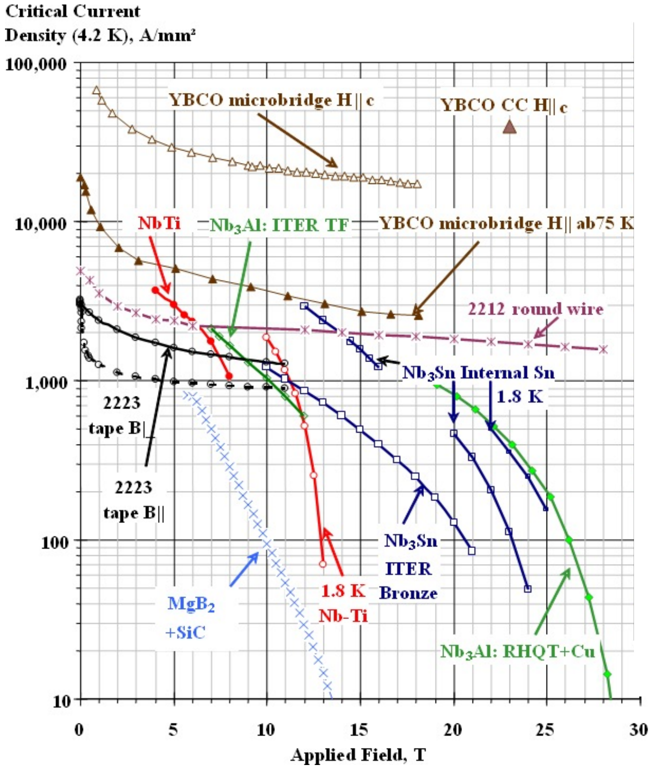
Yttrium Barium Copper Oxide (YBCO/Y123)



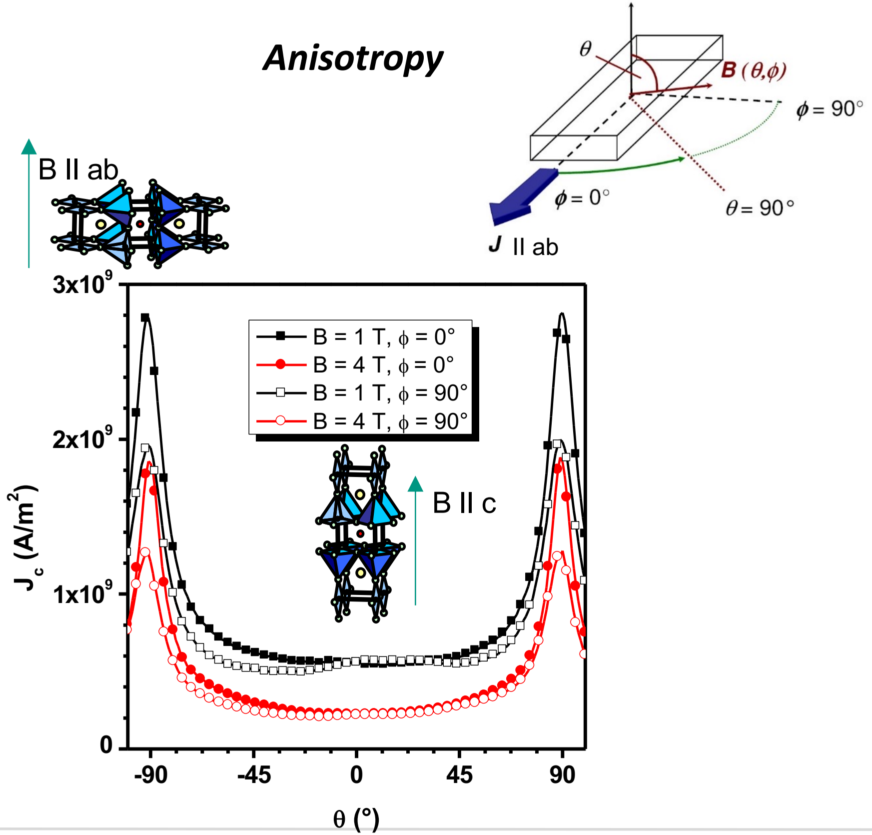


Critical current density

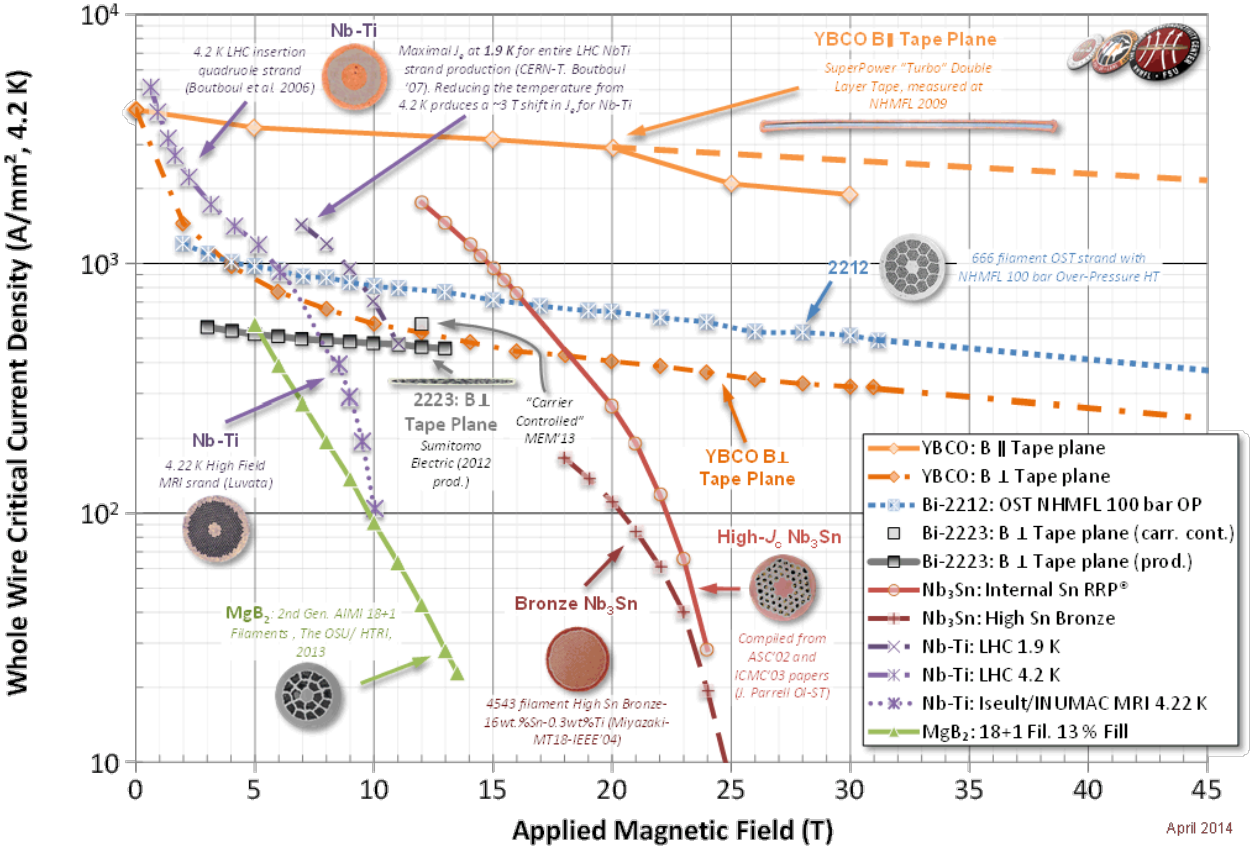
Basic properties of HTSC



Anisotropy



J_c comparison



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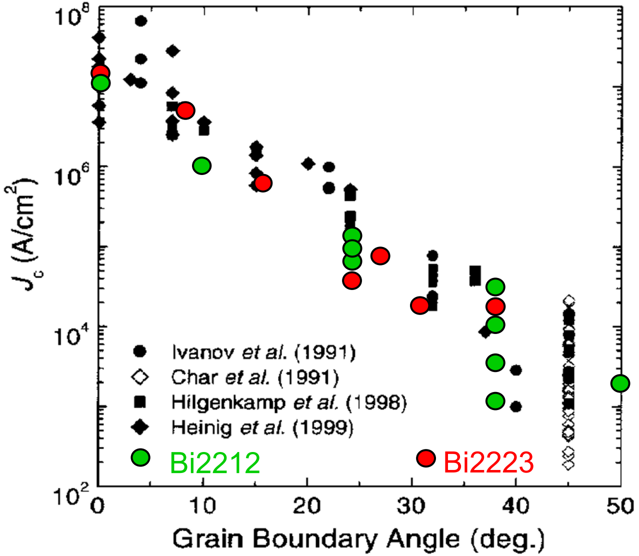
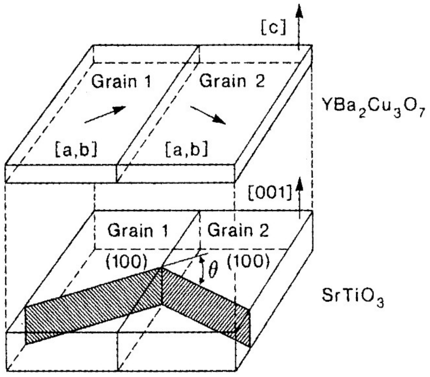
HTSC grain boundaries

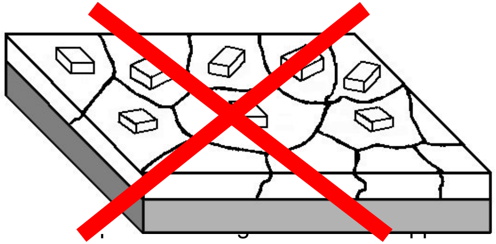


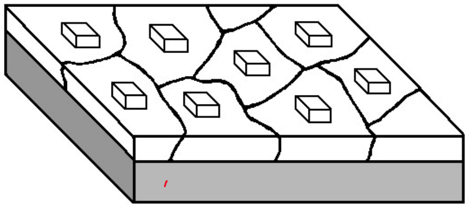
Measurement on bicrystals



Hilgenkamp et al., Rev. Mod. Phys. 74 (2002) 485

➯ High J_c in polycrystalline materials require strong biaxial texture





YBCO-tapes (Coated Conductors)

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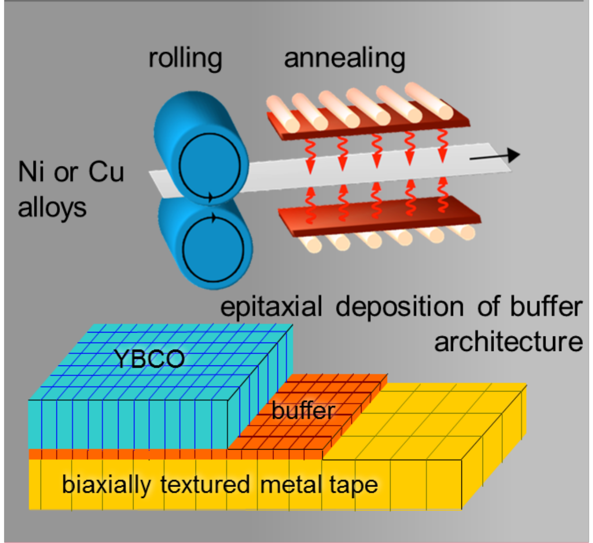
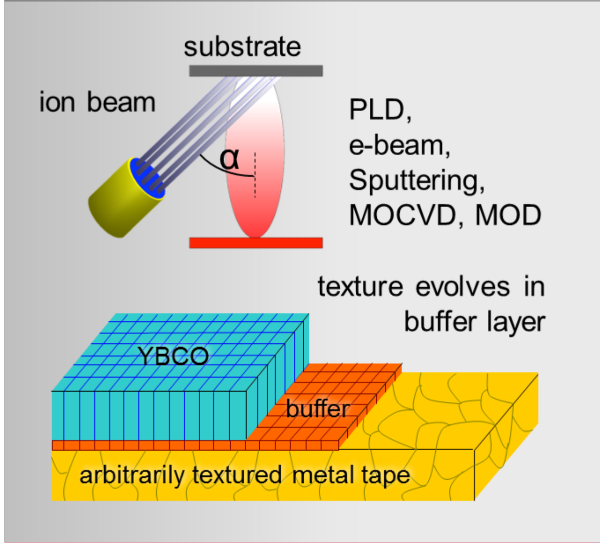
Rolling Assisted Biaxially Textured Substrates (RABiTS)



Based on biaxially textured substrates

Ion Beam Assisted Deposition (IBAD)



Based on biaxially textured buffer layers

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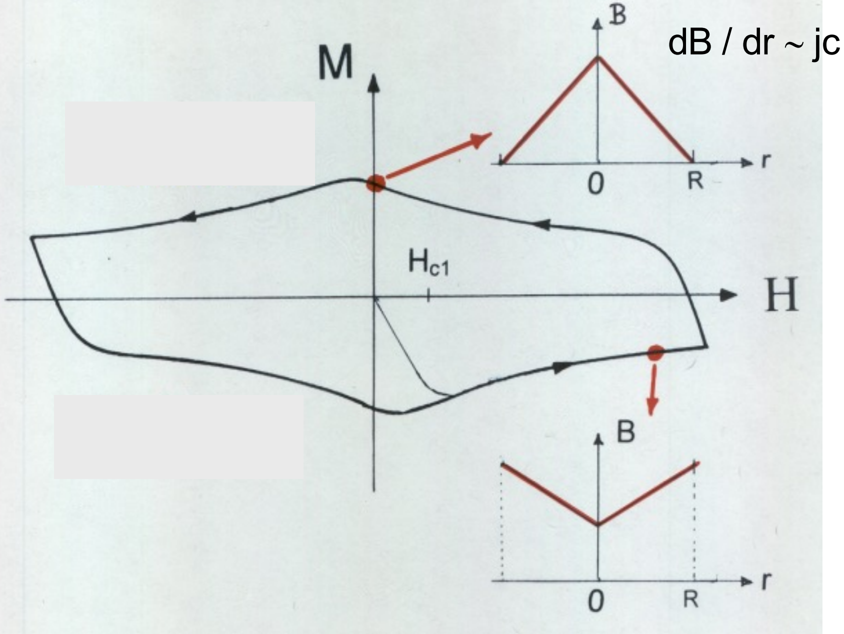
Melt textured bulk YBCO

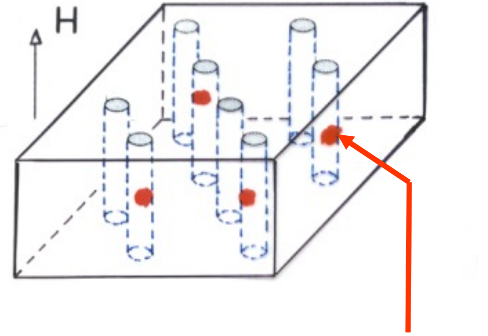
Hysteresis of type II superconductors

Magnetization and flux profile



$H > H_{c1}$ ⇨ flux penetration

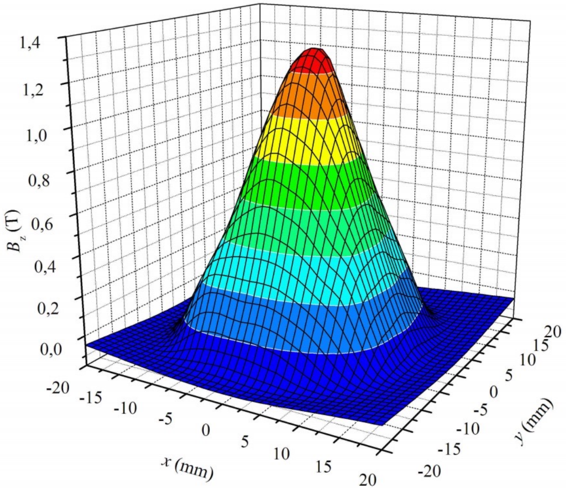
$\Phi_0 = 2{*}10^{-15}\ Tm^2$
$\xi\ = 1{,}8$ nm



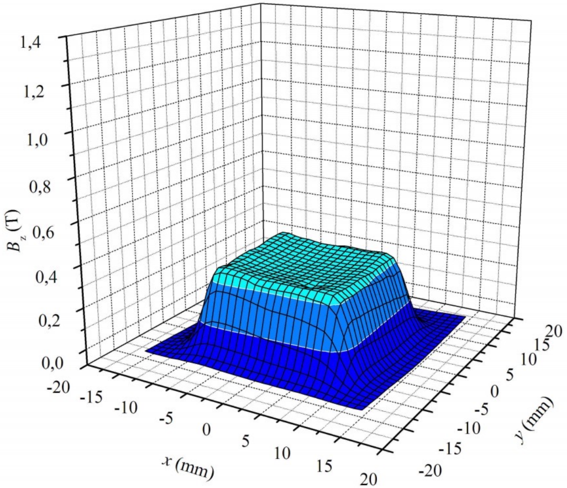
Pinning of flux lines by defects (pinningcenter)

Very strong magnets compared with conventional permanent magnets

B_{max} = 1.3 T



B_{max} = 0.4 T



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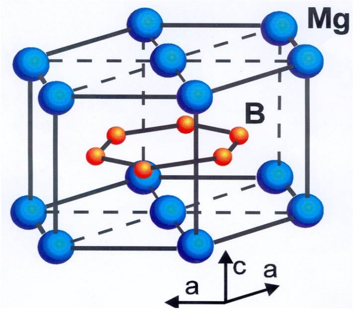
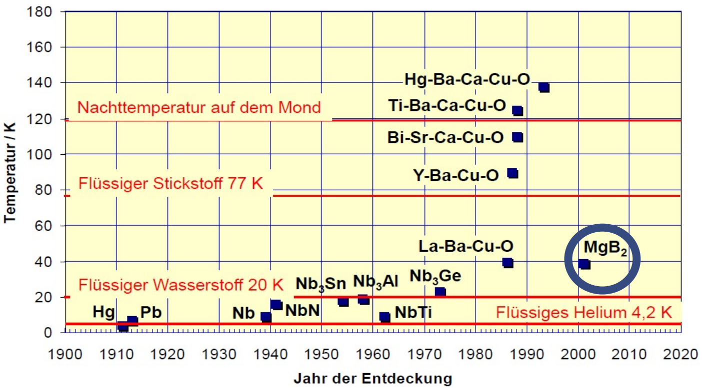
Why is MgB_2 special ?



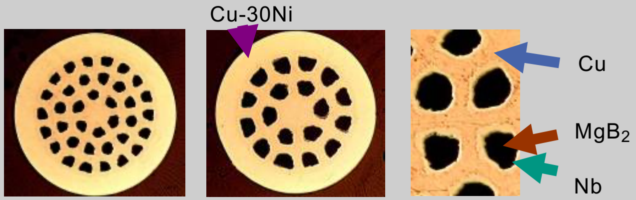
- Highest T_c for binary systems (39 K)
- Low material costs and easy to synthesize
- Refrigeration based cooling possible

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

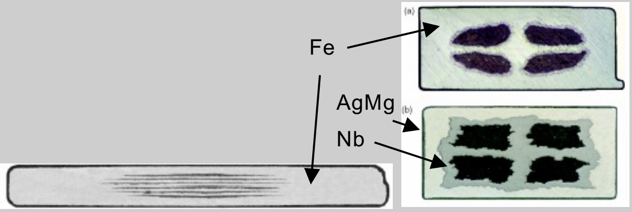


PIT-Technology: *wire examples*

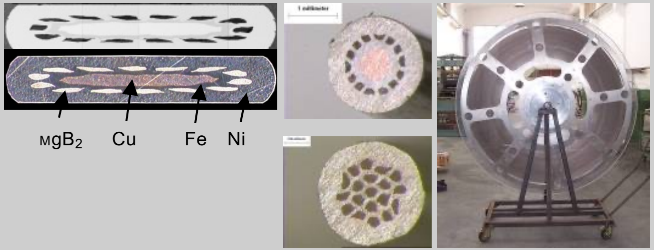
HyperTech Research Inc., USA



IEE, Bratislava



Columbus Superconductors srl, Genoa:



KIT