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Leibniz-Institut for Solid State and Materials Research Dresden

High temperature superconductors: Properties and applications

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Outline

Introduction

- **High temperature superconductors (HTSC)**
  - ➢ which materials?
  - ➢ what are the basic properties?
- **Power applications of HTSC**
  - ➢ what are possible applications?
  - ➢ what are the requirements for application?
- **Development of conductor based on HTSC**
  - ➢ Powder-in-tube technology (PIT)
  - ➢ YBCO coated conductors
    - textured substrates: RABiTS
    - textured buffers: IBAD

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  - **which materials?**
  - **what are the basic properties?**
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Superconductivity

Discovery of Superconductivity

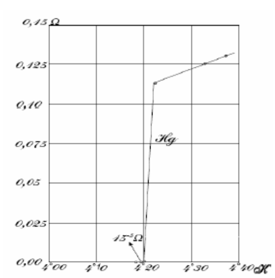
Liquification of Helium

H. Kamerlingh Onnes, Leiden (1908)

Discovery of „Superconductivity“: ideal conductivity

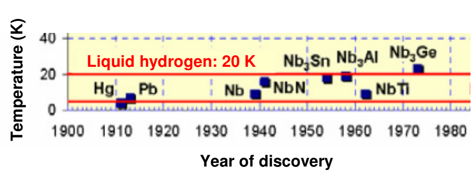
H. Kamerlingh Onnes, Leiden (1911)

Kamerlingh Onnes



Step in the electrical resistivity of Hg: critical temperature T_C

Many metals become superconducting at low temperatures

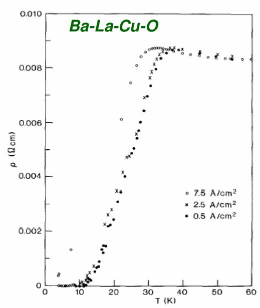


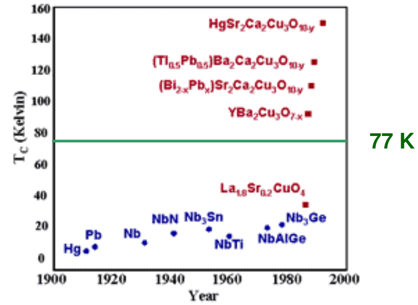
→ Current transport without losses possible

Cooling with liquid helium necessary

High temperature superconductors

Ba-La-Cu-O compound:
J. G. Bednorz, K. A. Müller, Z. Physik, B 64 (1986) 189





Cooling with liquid nitrogen possible

compound		T_C *(K)*
$YBa_2Cu_3O_{7-\delta}$	Y-123	92
$Bi_2Sr_2CaCu_2O_8$	Bi-2212	84
$Bi_2Sr_2Ca_2Cu_3O_{10}$	Bi-2223	110
$TlBa_2Ca_2Cu_3O_{10}$	Tl-1223	125
$HgBa_2Ca_2Cu_3O_{10}$	Hg-1223	133

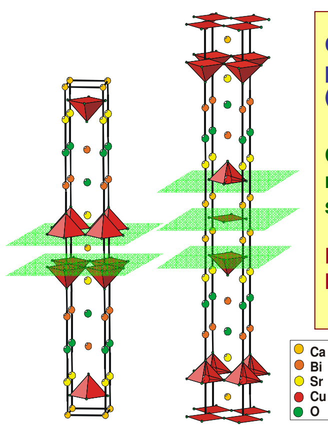
commercial potential (Y-123, Bi-2223)

High temperature superconductors

BiSCCO

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

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



T_C = 85 K ***T_C = 110 K***

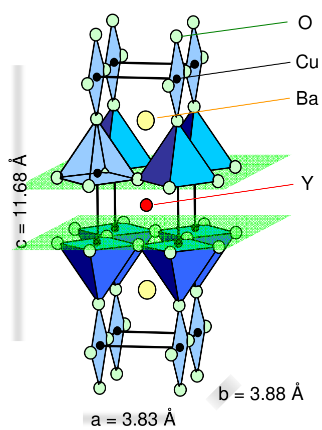
Ceramics: layered perovskite material (2-dimensionality)

CuO_2-planes responsible for superconductivity

Properties show high anisotropy

REBCO

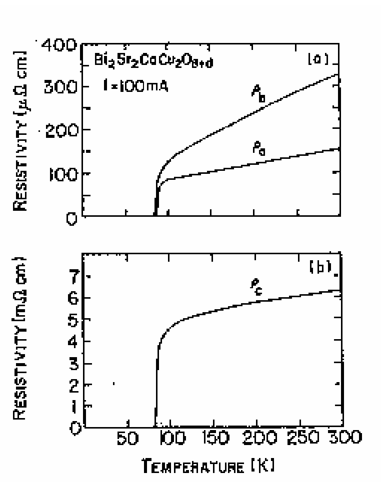
$REBa_2Cu_3O_{7-x}$
RE: Y, Nd, Er, Gd, Eu..



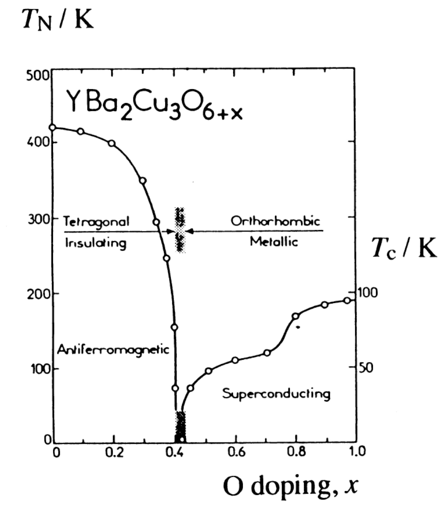
T_C = 92 K

High temperature superconductors

Anisotropy of the resistivity

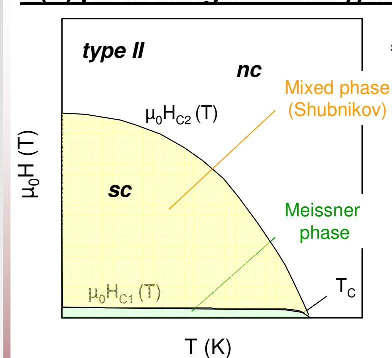


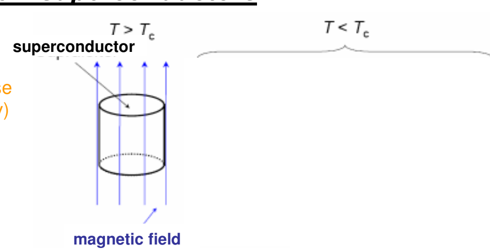
Dependence of the superconducting properties on O doping



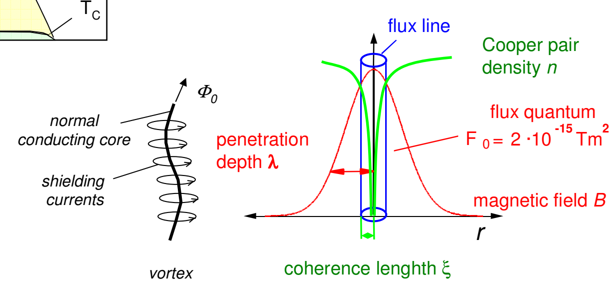
HTSC in magnetic fields

B(T) phase diagramm of type II superconductors





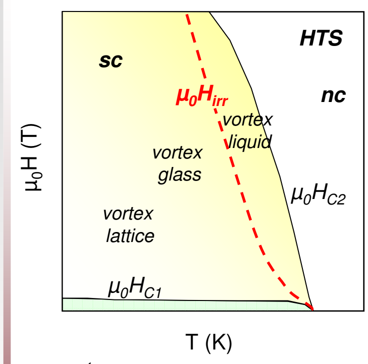
type II	*T_C (K)*	*μ_0H_{C2} (T)*
Nb	*9.3*	*0.3*
Nb_3Sn	*18.0*	*24.5*
Nb_3Ge	*23.2*	*38.0*
MgB_2	*39.0*	*17.0*
Y-123	*92.0*	*150*
Bi-2223	*110.0*	*108*

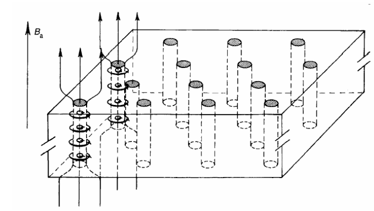


HTSC in magnetic fields

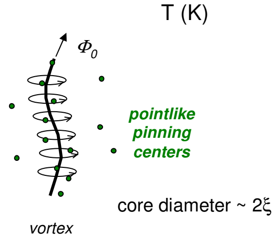
Basic properties of HTSC

B(T) phase diagram of superconductors: critical fields





applied magnetic field penetrates the superconductor in form of vortices

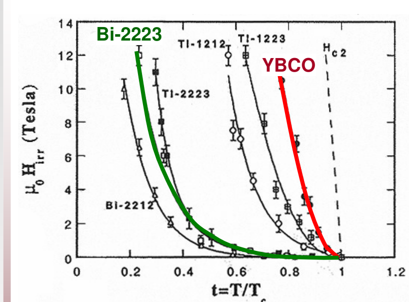


→ current leads to Lorenz force on vortex lines
→ movement of vortices leads to dissipation: Irreversibility line
→ pinning of the vortices necessary for high critical currents in magnetic fields
→ incorporation of nanoscaled pinning centres

HTSC in magnetic fields

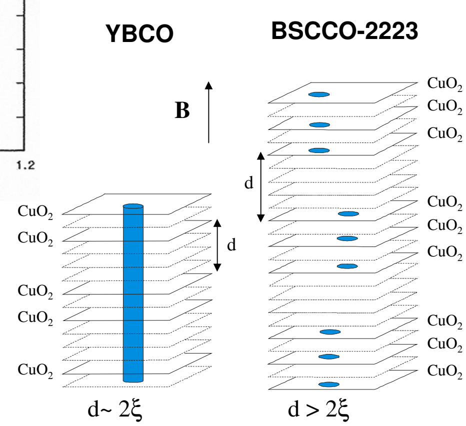
Basic properties of HTSC

Irreversibility line



Properties of the vortices are dependant on the crystal structure of the material

YBCO is the preferred material for applications at 77 K in higher magnetic fields



3D flux line

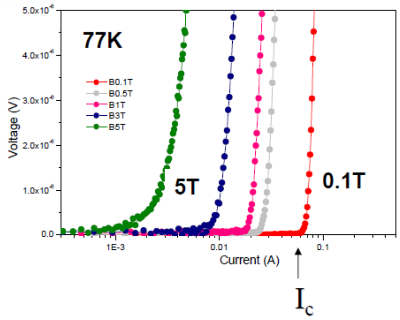
2D *pancake* vortices

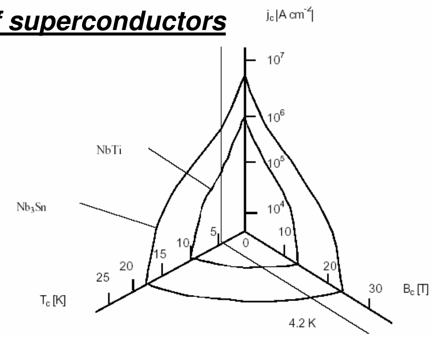
Critical current density

Basic properties of HTSC

Current-voltage characteristic of superconductors

$$U(I) = U_0 \left(\frac{I}{I_0} \right)^n$$





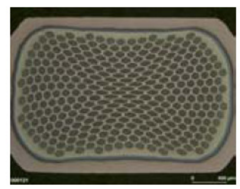
Critical current I_c is dependant on temperature and magnetic field

Critical current density J_c:

I_c divided by cross section of the superconductor

Engineering current density J_e:

I_c divided by cross section of complete conductor



Nb_3Sn

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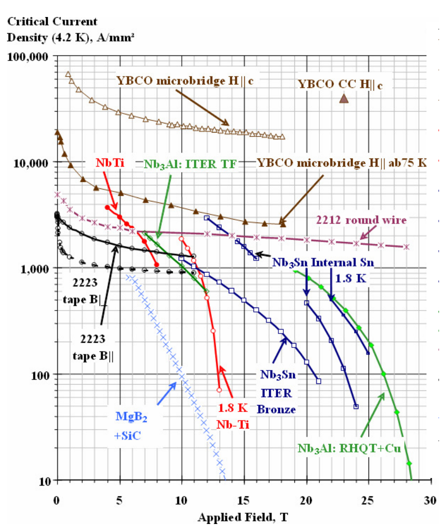
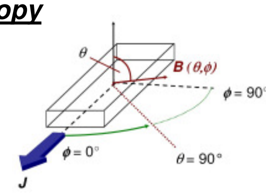
Critical current density

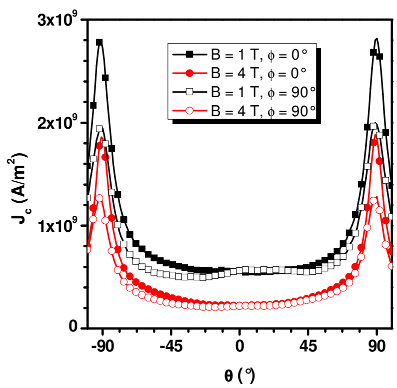
Basic properties of HTSC

Critical current density



Anisotropy





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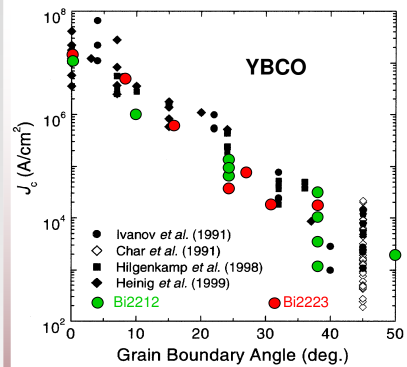
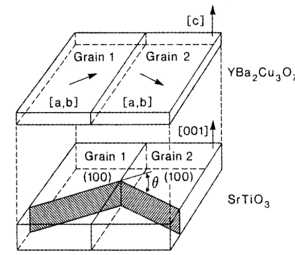
HTSC grain boundaries

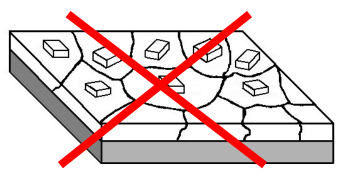


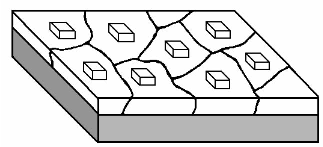
Measurement on bicrystals



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

➩ High J_c in polycrystalline materials require strong biaxial texture

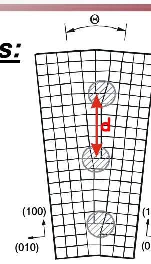




HTSC grain boundaries

Origin of J_c-limitation at grain boundaries:

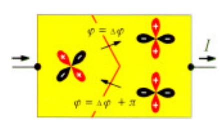
- **Microstructure:**
  - **Strain fields around dislocations,**
  - **Distorted areas in large angle grain boundaries**
- **Deviations from ideal stoichiometry**
  - **regions with oxygen vacancies**
  - **disorder**
  - **localised states**
- **Symmetry of the order parameter**
- **Band bending due to interface charging**
- **Direct suppression of pairing mechanism**
- **Reason:**
  Extremly short coherence length ξ and low charge carrier density in HTSC

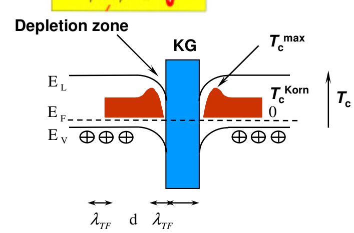


$d = b/2\sin(\Theta/2) \approx b/\Theta$

Für b=0.38nm

$\Theta = 8° \Rightarrow d = 2.7$nm





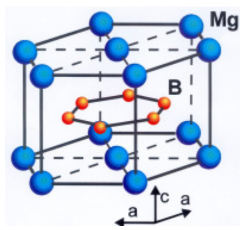
Hilgenkamp et al., Rev. Mod. Phys. 74 (2002) 485

Basic properties of HTSC

Other „new“ superconductors

MgB$_2$

- Phase known since the early 50‘s
  Jones et al., J. Am. Chem. Soc. 76 (1954) 1434
- Superconductivity discovered in 2001
  Nagamatsu et al., Nature 410 (2001) 63
- T_c = 39 K: highest T_c for binary superconductors



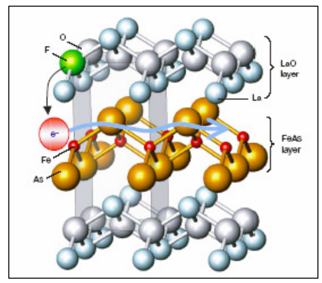
- no weak link behavior at grain boundaries in contrast to cuprates

large coherence length ξ_{ab} = 7-10 nm

Fe-pnictides and -chalcogenides

- Superconductivity discovered 2008
  Kamihara et al., J. Amer. Chem. Soc. 130 (2008) 3296

$LaO_{1-x}F_xFeAs$	T_c ~ 26 K
$GdO_{1-x}F_xFeAs$	T_c ~ 53 K
$SmO_{1-x}F_xFeAs$	T_c ~ 55 K
$Ba_{1-x}K_xFe_2As_2$	T_c ~ 38 K
$FeSe_{1-x}Te_x$	T_c ~ 15 K
…	



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Applications of superconductors

Outline

- High temperature superconductors (HTSC)
  - which materials?
  - what are the basic properties?
- **Power applications of HTSC**
  - **what are possible applications?**
  - **what are the requirements for application?**
- Development of conductor based on HTSC
  - Powder-in-tube technology (PIT)
  - YBCO coated conductors
    - textured substrates: RABiTS
    - textured buffers: IBAD

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Application of classical superconductors

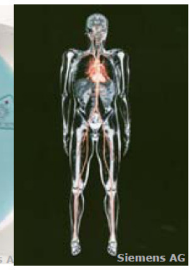
Applications of superconductors

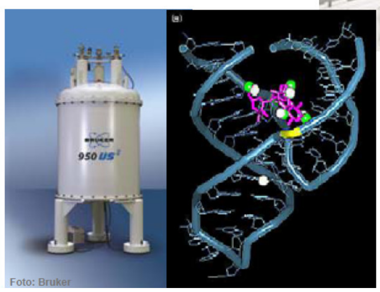
Application in medical and analytical devices

Medicine:

Magnetic Resonance Imaging (MRI) of soft tissues like organs, cartilages, tendons etc.

>3000 t NbTi per year





Analytics:

Nuclear Magnetic Resonance (MNR) spectroscopy

>500 t Nb_3Sn per year

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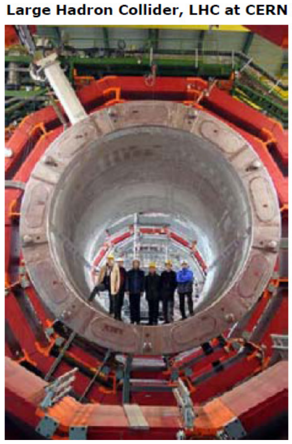
Application of classical superconductors

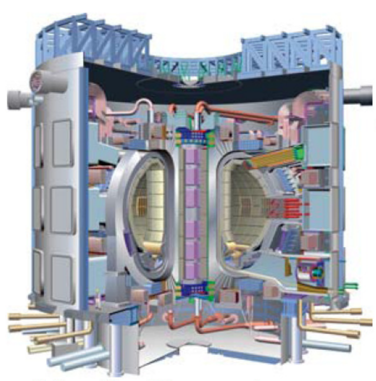
Applications of superconductors

Magnets for research devices

- **Accelerators in particle physics**
- **Reactors for nuclear fusion**

Large Hadron Collider, LHC at CERN





International Thermonuclear Experimental Reactor, ITER

> 500 to Nb_3Sn

ITER Kabel

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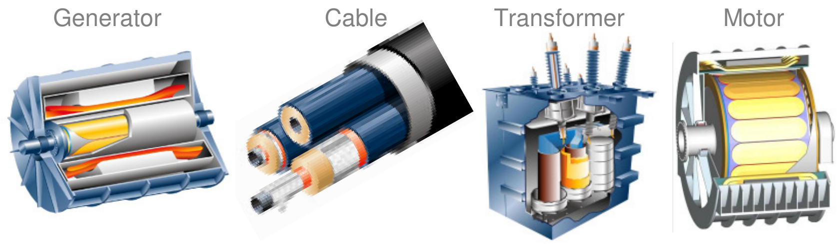
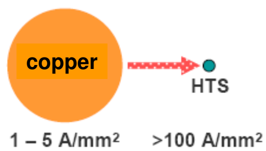
Power applications of HTSC



- Higher current density ⇨ lower weight @ same power
- Lower losses / higher efficiency
- Environmental friendly

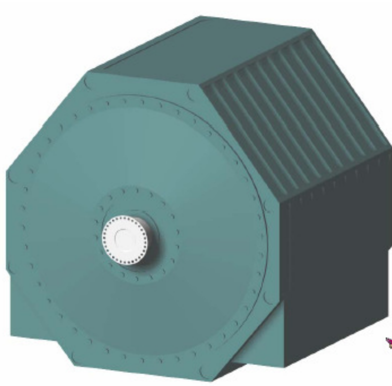


Power applications of HTSC

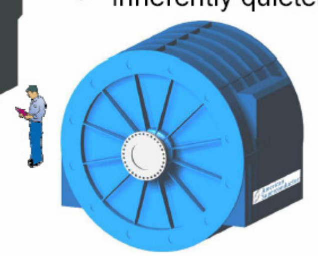
Applications of superconductors

Ship populsion motors

- Less than half the size
- Less than one-third the weight
- Higher net efficiency
- Equivalent prices
- Inherently quieter



36.5 MW Conventional
(300 tons)



36.5 MW HTS
(75 tons)

Power applications of HTSC

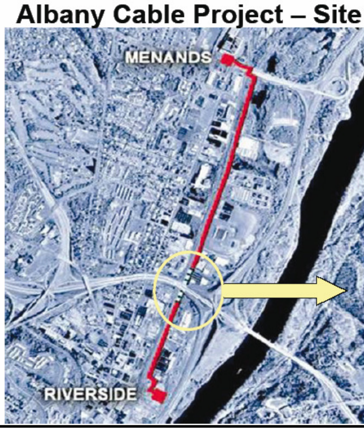
Applications of superconductors

Superconducting cable

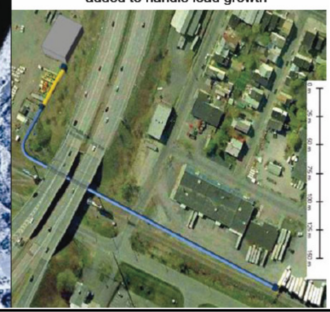
350 m long cable at 34.5 kV and 800 A in real network
Made form BiSCCO and YBCO based conductors

SuperPower · SUMITOMO ELECTRIC · BOC · Niagara Mohawk

Albany Cable Project – Site Layout



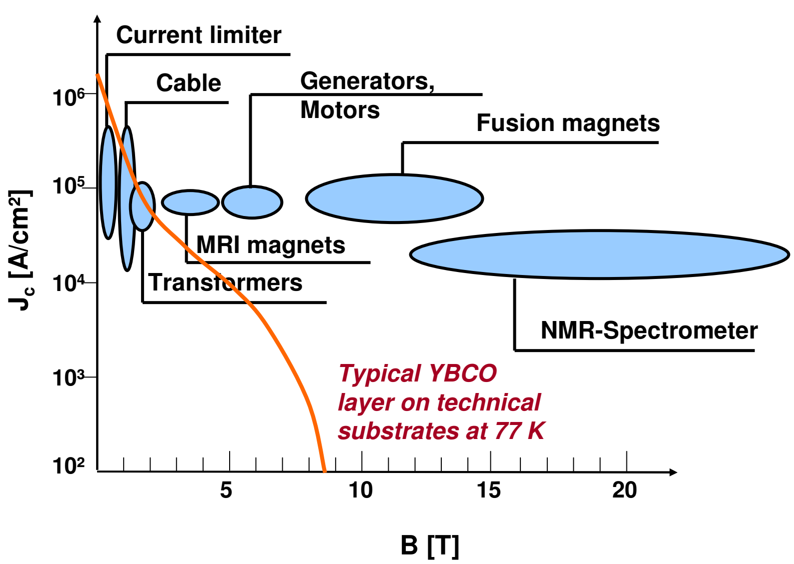
Installed between two Niagara Mohawk substations
- Riverside-Menands
- Parallels new 34.5kV installation
- added to handle load growth



Power applications of HTSC

Applications of superconductors

Required properties for different power applications



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Applications of superconductors

Application of HTSC

Main requirements on HTSL conductors for application

• Mechanical flexible conductor (for coils etc.)
→ metal-ceramic heterostructure

• High current transport capability at:
- highest application temperature (above 77 K)
- highest magnetic fields
→ strongly textured superconductors
→ defined incorporation of pinning centres

• Availability in long length
(several km necessary for demonstrators)

• Cheap production of long length necessary
→ robust and fast methods
→ low cost materials

• Other requirements for certain application:
- low ac-losses
- high mechanical strength
- reduced anisotropy

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Preparation of HTSC conductors

Outline

• High temperature superconductors (HTSC)
  - which materials?
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• **Development of conductor based on HTSC**
  - **Powder-in-tube technology (PIT)**
  - **YBCO coated conductors**
    - **textured substrates: RABiTS**
    - **textured buffers: IBAD**

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Powder-in-Tube (PIT) Technology

Preparation of BiSCCO and MgB_2 conductors

Precursor

Mixture of Base Compounds

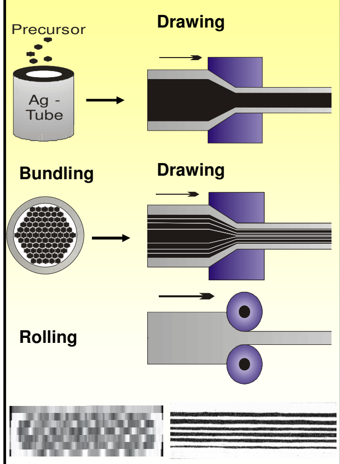
➯

- Sol-gel methods
- Mechanical alloying

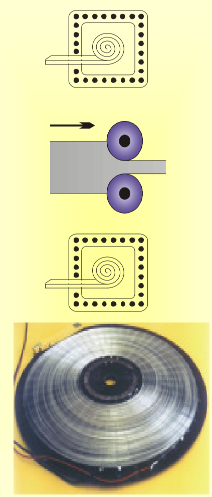
➯

e.g Bi-Pb-Sr-Ca-Cu-O powder with Bi-2223 composition or Mg, B mechanically alloyed precursor

Deformation



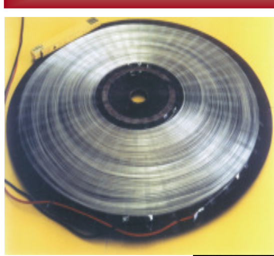
Thermal Treatment



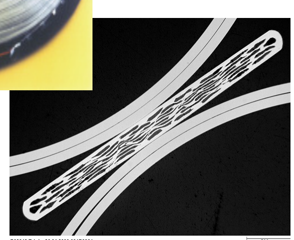
PIT conductors

BiPbSrCaCuO (2223) PIT conductor

- available in long length
- moderate performance (J_c < 60kA/cm^2)
  not applicable in magnetic fields at 77 K
  too expensive (Ag)



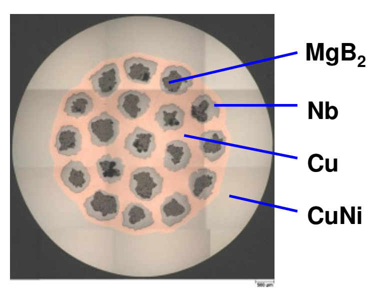
600 m long BSCCO tape



Cross section of BSCCO tape with 61 filaments

MgB_2 PIT conductor

- first long length available
- potential application at ~ 20 K (boiling point of hydrogen)
  → combined with hydrogen technology



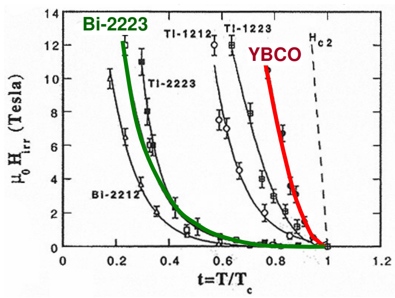
MgB_2 multifilamentary conductor

YBCO coated conductors

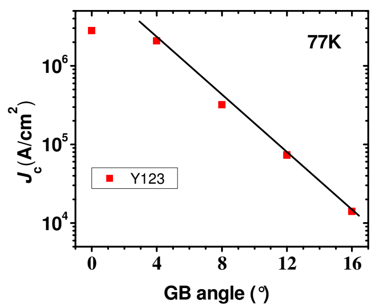
YBCO coated conductors

Application of YBCO for HTSC conductors

Advantage: high irreversibility fields at 77 K



Challenge: grain boundaries



- Powder-in-tube technology does not work for YBCO
- Long length of highly textured YBCO conductors required

Growth of epitaxial YBCO on a textured template: coated conductors

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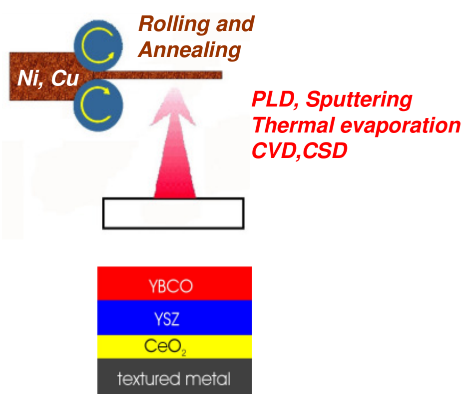
Preparation of YBCO coated conductors

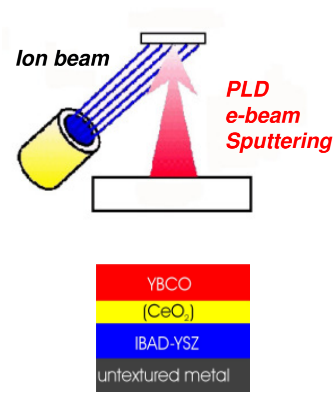
YBCO coated conductors

Major processing routes for YBCO coated conductors

Rolling Assisted Biaxially Textured Substrates (RABiTS)



Ion Beam Assisted Deposition (IBAD)



Based on biaxially textured substrates

Based on biaxially textured buffer layers

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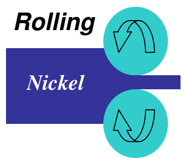
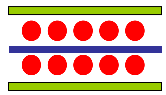
RABiTS Approach

Rolling Assisted Biaxially Textured Substrates (RABiTS)

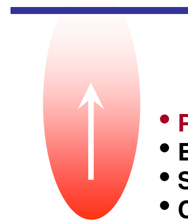
Rolling



Recrystallization

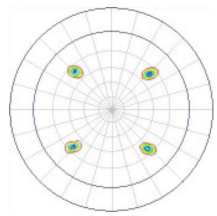


Epitaxial Film Deposition



- Cold deformation >95%
- Pure Ni
- Microalloyed Ni :
  Ni-0.1at%Mn
- Alloyed Ni :
  Ni-5at%W
  Ni-7.5at%W
  Ni-9at%W
  Ni-9at%V
  Ni-13at%Cr
- Composites :
  Ni-W/Ni-Cr
  Ni-W/Ni-W

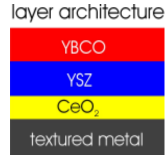
- Typical 900°C/1h
- Ar/H_2-atmosphere



(111)-pole figure of Ni-5at%W

- PLD
- E-beam
- Sputtering
- CVD
- CSD

layer architecture



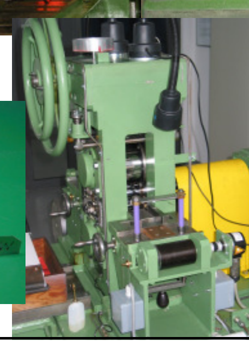
Tape Processing I

Induction furnace

Hot rolling

Intermediate Ni bars

Final tape (up to 100 m)

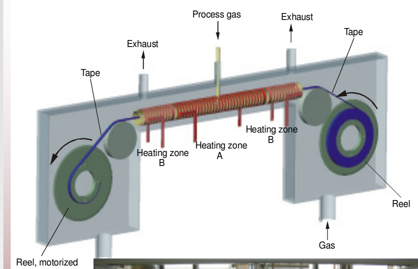


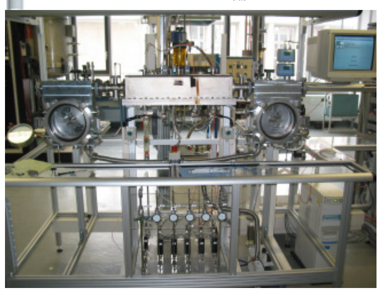
Special 4-high mill

Tape Processing II

YBCO coated conductors

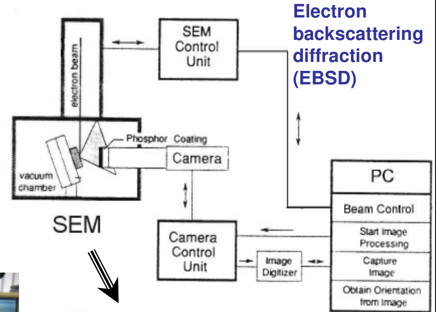
Continuous tape annealing



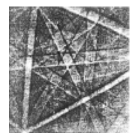


Characterisation

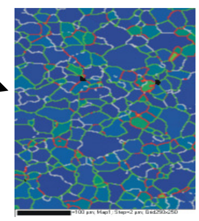
Electron backscattering diffraction (EBSD)



„Kikuchi pattern“



Local texture information „Texture maps“



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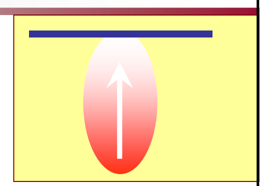
YBCO coated conductors on RABiTS

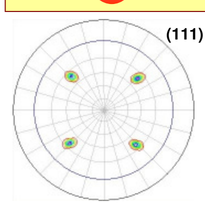
YBCO coated conductors

Epitaxial deposition of buffer layers and YBCO

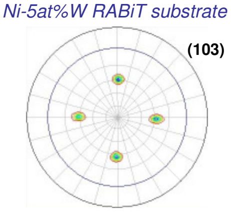
Necessary function of buffer layers:

- **Suppression of Ni diffusion into YBCO (Ni degrades superconductivity)**
- **Suppression of uncontrolled O diffusion to substrate (may lead to cracks and peeling off)**
- **Texture transfer from substrate to superconductor (cube textured YBCO)**

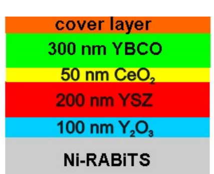




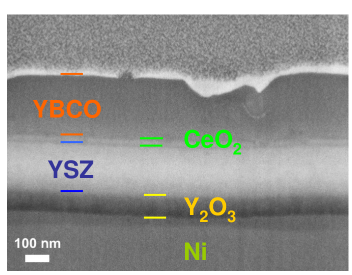
Ni-5at%W RABiT substrate



YBCO layer



YBCO coated conductor architecture



Cross section of coated conductor

Hühne, R. et al., Supercond. Sci. Technol. 20 (2007) 709

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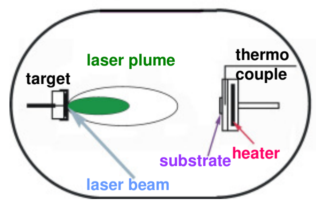
YBCO coated conductors on RABiTS

YBCO coated conductors

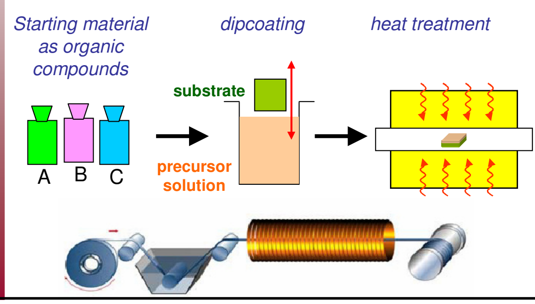
Pulsed laser deposition - PLD



- high quality of layers
- flexible method
- small substrates (typical 10 x 10 mm²)
- vacuum equipment necessary
- high costs

→ ideal for research and development

Chemical solution deposition - CSD



- no vacuum necessary
- easily scalable on long length
- high yield achievable
- large coating areas possible

→ ideal for industrial processing

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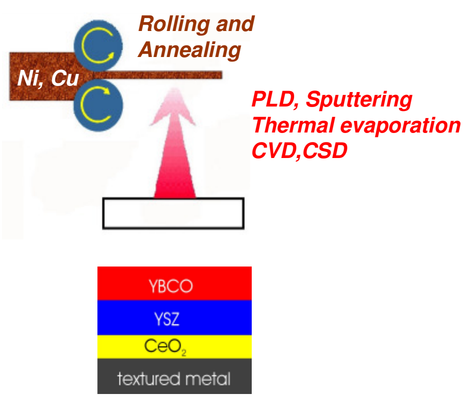
Preparation of YBCO coated conductors

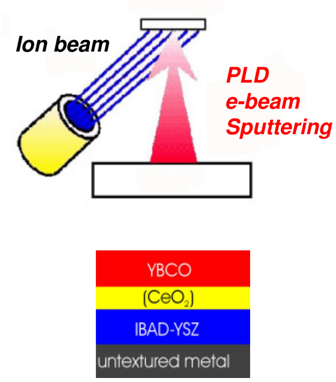
YBCO coated conductors

Major processing routes for YBCO coated conductors

Rolling Assisted Biaxially Textured Substrates (RABiTS)



Ion Beam Assisted Deposition (IBAD)



Based on biaxially textured substrates

Based on biaxially textured buffer layers

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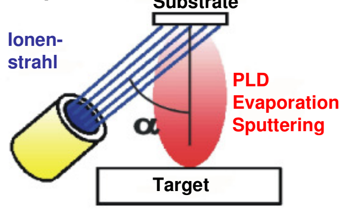
IFW

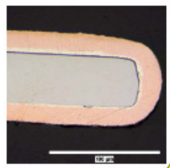
Ionenstrahlunterstützte Deposition (IBAD)

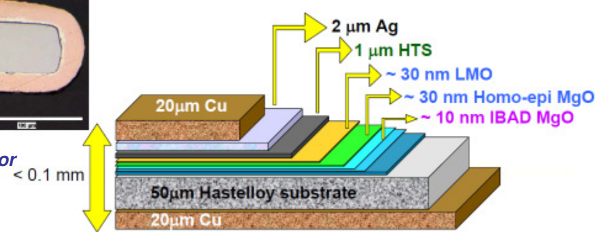
YBCO coated conductors

Principle:



Preparation of textured buffer layers





Typical IBAD coated conductor architecture Superpower Inc. (USA)

Available in length of > 1 km

Comparison to RABiTS approach

- all kind of substrates possible
- smaller grains and sharper textures compared to RABiTS → higher J_c
- extremely fast texturing process for IBAD-MgO or IBAD-TiN (within 10 nm!)

- complex process
- smooth (polished) substrates necessary
- vacuum equipment and on-line control necessary

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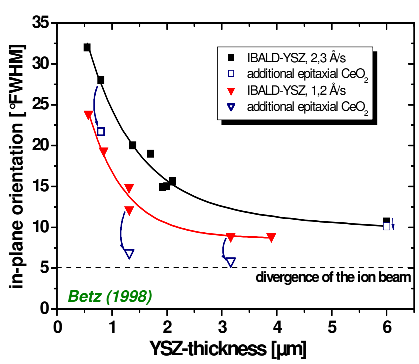
IFW

Ion-beam assisted deposition (IBAD)

YBCO coated conductors

Materials for the IBAD process:

⇨ YSZ, CeO_2, Pr_6O_{11}, $Gd_2Zr_2O_7$...

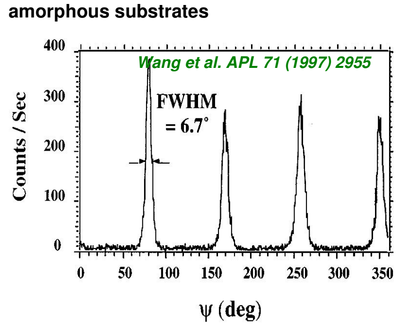


Ion beam improves in-plane texture through a *growth selection process*

⇨ Slow process

⇨ MgO, TiN...

Cube texture in 10 nm thick IBAD-layers on amorphous substrates



Ion beam influences already the *nucleation*

⇨ Very fast process

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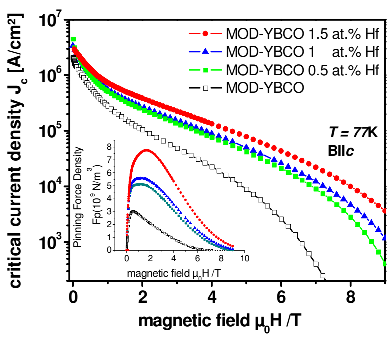
Optimization of YBCO coated conductors

Artificial pinning centres

- improvement of the critical current density J_c in magnetic fields
- incorporation of nanosized pinning sites:
  - non-superconducting particles
  - growth defects through islands on the substrate
  - magnetic nanoparticles



Engel, S. et al., Appl. Phys. Lett. 90 (2007) 102505

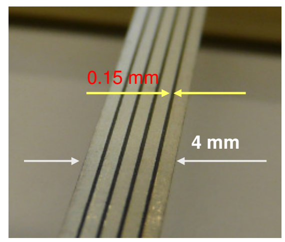
Reduction of ac-losses

- losses due to magnetization change of ferromagnetic substrates

  → development of RABiTS with reduced ferromagnetism

- hysteretic losses in YBCO due to conductor geometry

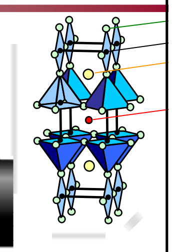
  → filamentation of conductors



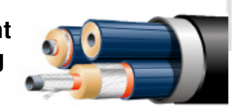
- coupling losses in multilayer systems

Summary

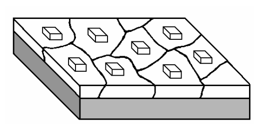
- HTSC are highly anisotropic, ceramic superconductors



- HTSC are potential materials for different applications using liquid nitrogen cooling



- Main challenge is to prepare flexible conductors with high critical current densities in higher magnetic fields on long length



- Different approaches were developed to realize such conductors:

  - ➢ Powder-in-tube technology
  - ➢ Coated conductors