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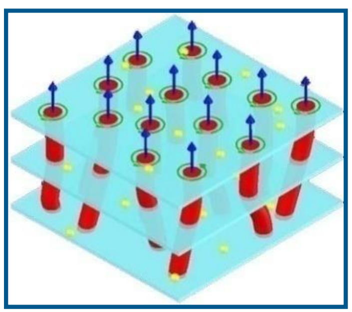
Superconductivity and its applications

Lecture 9



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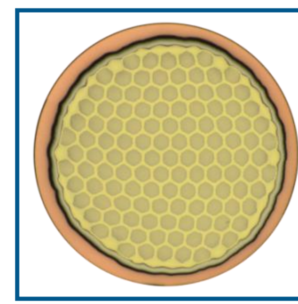
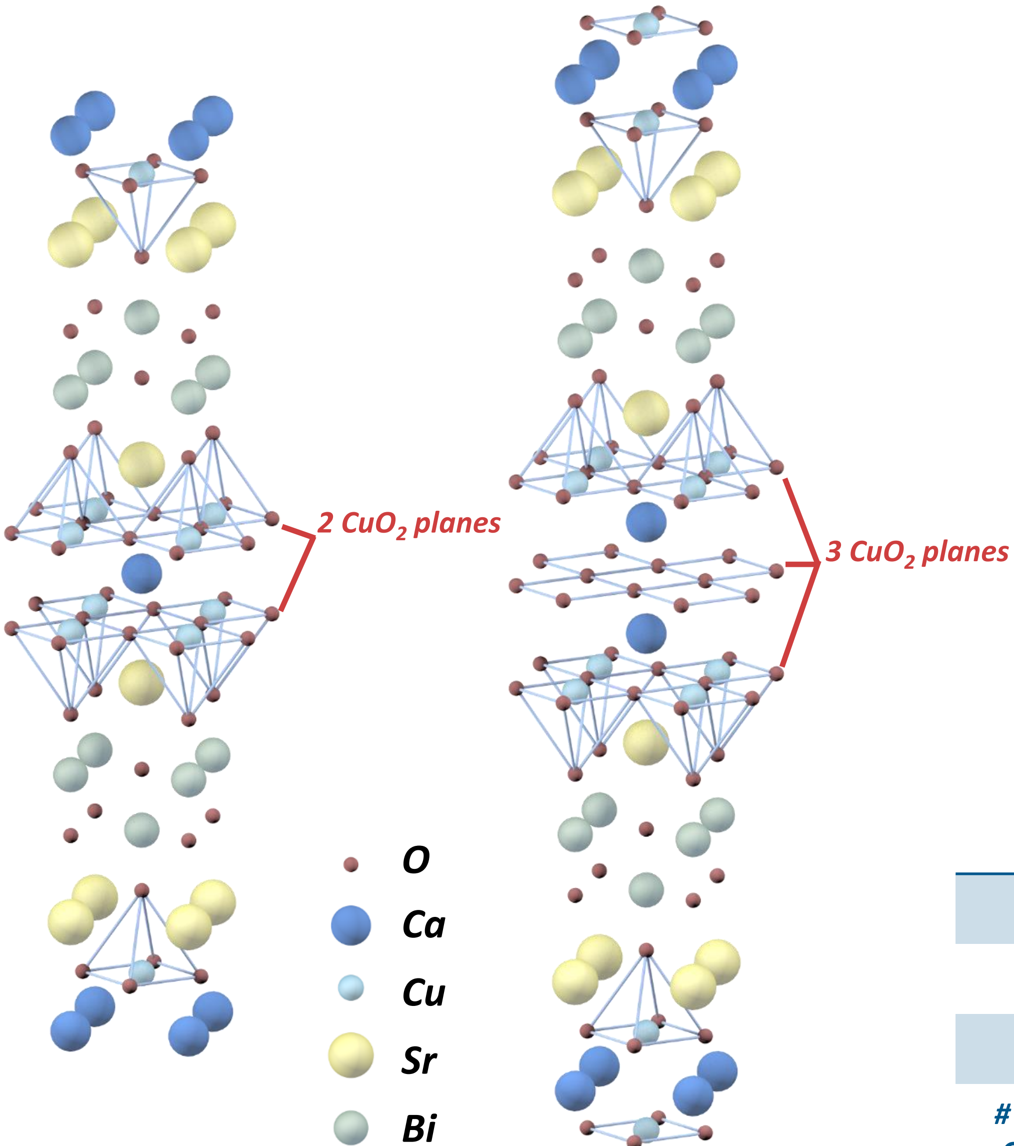


Previously, in lecture 8 - HTS materials for applications



Bi2212
$Bi_2Sr_2CaCu_2O_{8+x}$

Bi2223
$Bi_2Sr_2Ca_2Cu_3O_{10+x}$

	Bi2212	Bi2223
a [Å]	5.415	5.413
b [Å]	5.421	5.421
c [Å]	30.880	37.010
# of adjacent CuO_2 planes	2	3
T_c [K]	91	110

Previously, in lecture 8
HTS materials for applications

Copper oxides with highly anisotropic structures, texturing (grain orientation) is required in technical superconductors

	T_c [K]	texture	
Bi2223	110	c-axis	
Bi2212	91	c-axis (radial)	

Bi2223:
- Produced by Powder-In-Tube method
- Ag matrix material
- Tape geometry to achieve c-axis texturing
- I_c depends on the magnetic field orientation

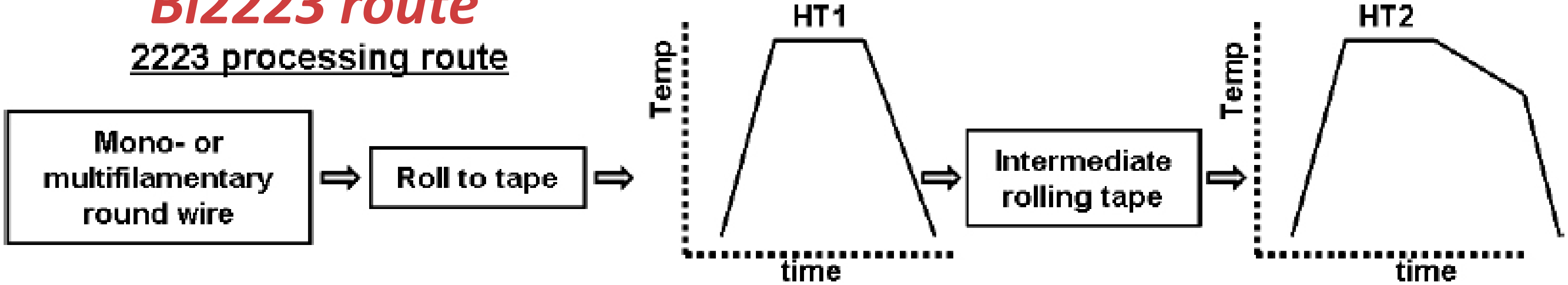
Bi2212:
- Produced by Powder-In-Tube method
- Ag matrix material
- Round wire, spontaneous radial texturing of the c-axis
- Isotropic properties of I_c

Previously, in lecture 8

Bi2212 & Bi 2223 conductor technology

Bi2223 route

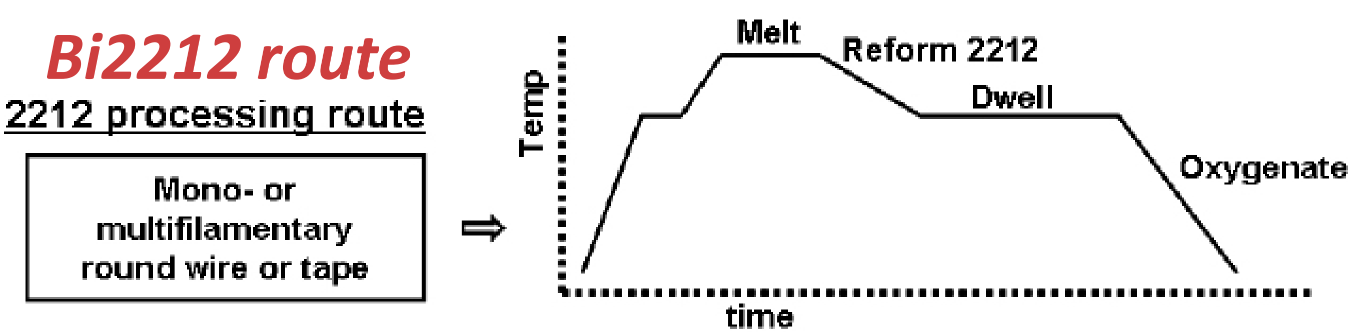
2223 processing route

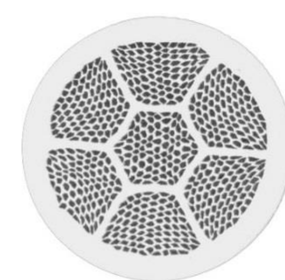


Bi2223 conductors are multifilamentary tapes

Bi2212 route

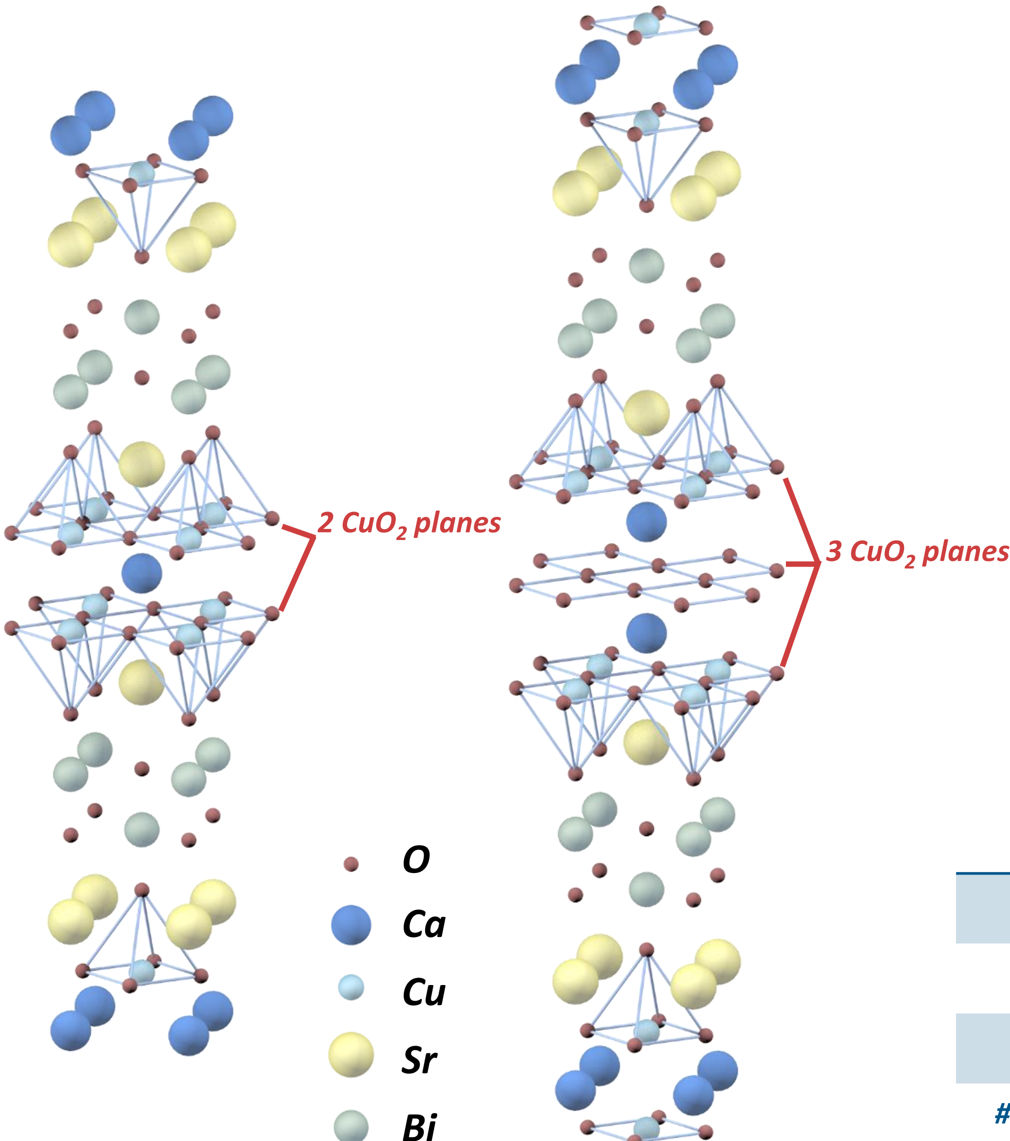
2212 processing route





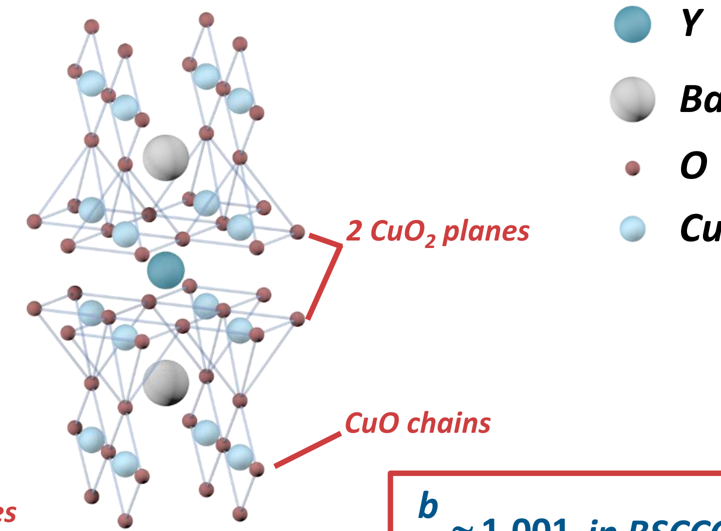
Bi2212 conductors are multifilamentary round wires

Previously, in lecture 8 - HTS materials for applications



Bi2212
$Bi_2Sr_2CaCu_2O_{8+x}$

Bi2223
$Bi_2Sr_2Ca_2Cu_3O_{10+x}$



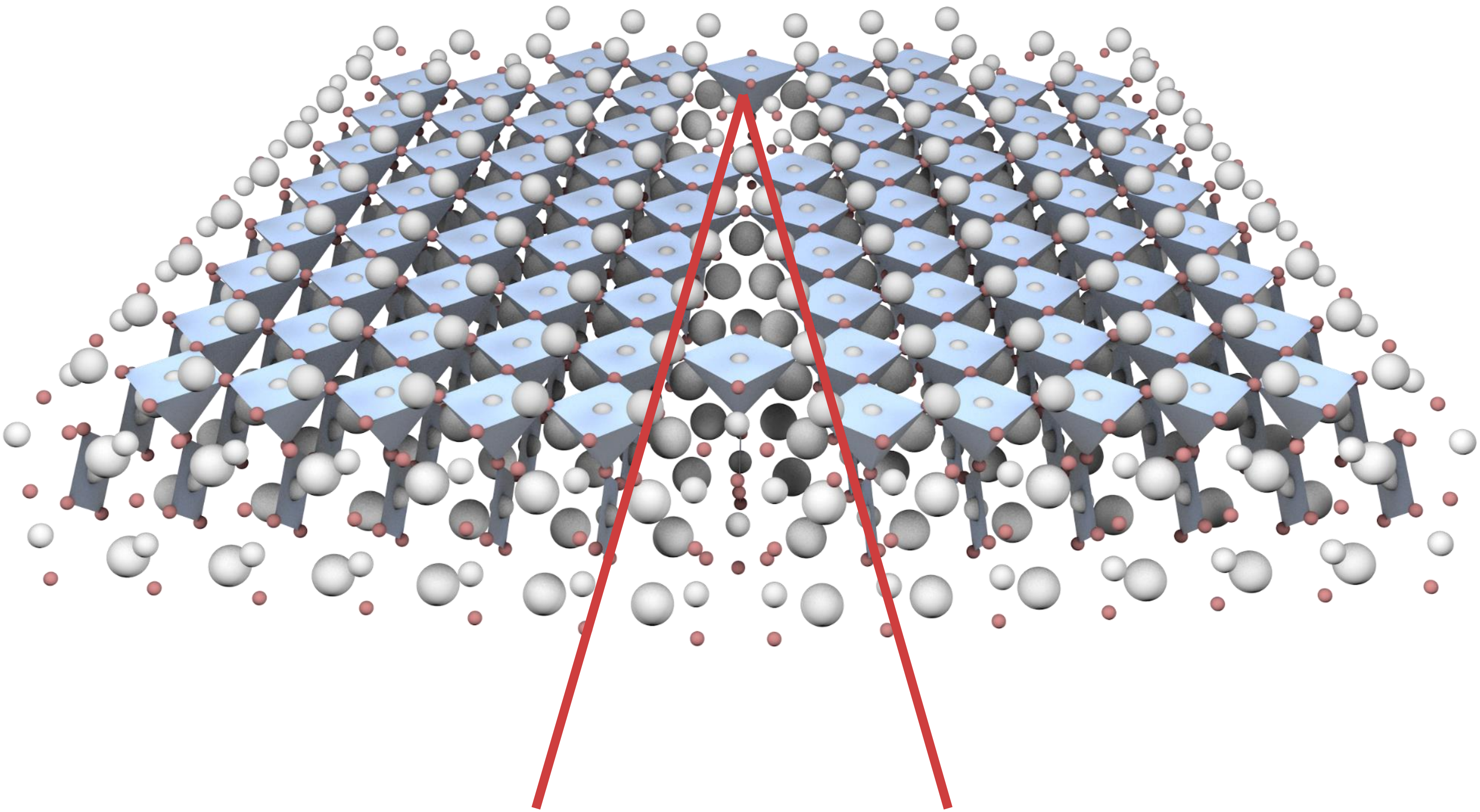
Y123
$YBa_2Cu_3O_{7-x}$

$\frac{b}{a} \approx 1.001$ *in BSCCO*

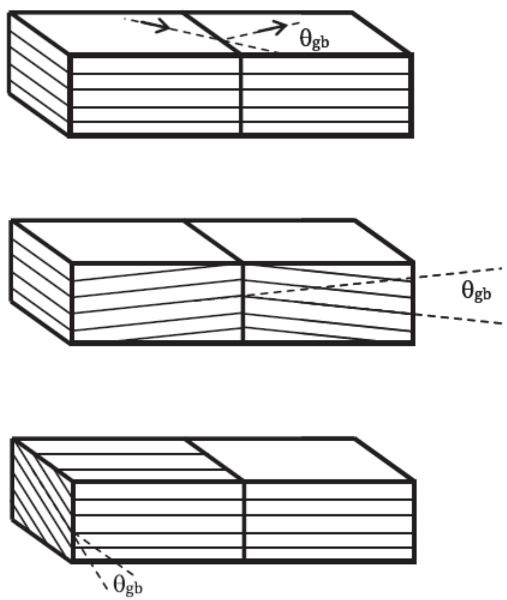
$\frac{b}{a} \approx 1.02$ *in YBCO*

	Bi2212	Bi2223	Y123
a [Å]	5.415	5.413	3.8227
b [Å]	5.421	5.421	3.8872
c [Å]	30.880	37.010	11.680
# of adjacent CuO$_2$ planes	2	3	2
T_c [K]	91	110	92

Grain Boundaries in Y123



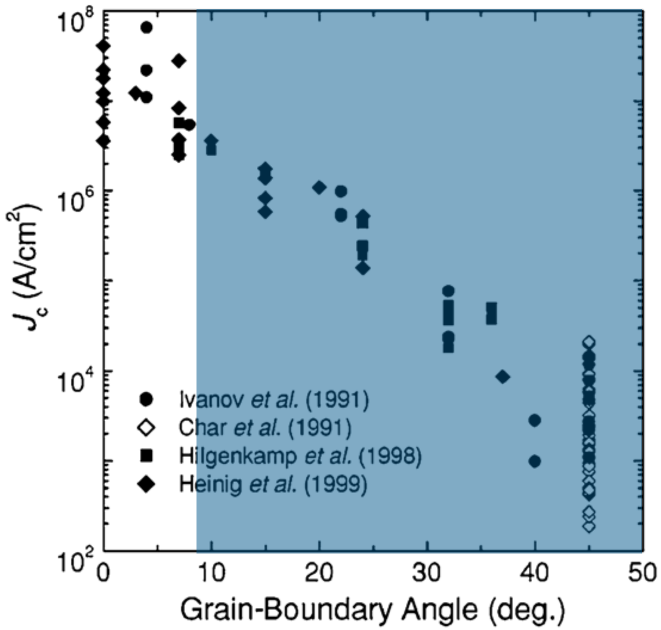
Grain boundaries in Y123



[001] tilt boundary

[100] tilt boundary

[100] twist boundary



Hilgenkamp and Mannhart, RMP 74 (2002) 485

For angles above 8-10°, the J_c^{GB} is reduced by a factor >100 !!

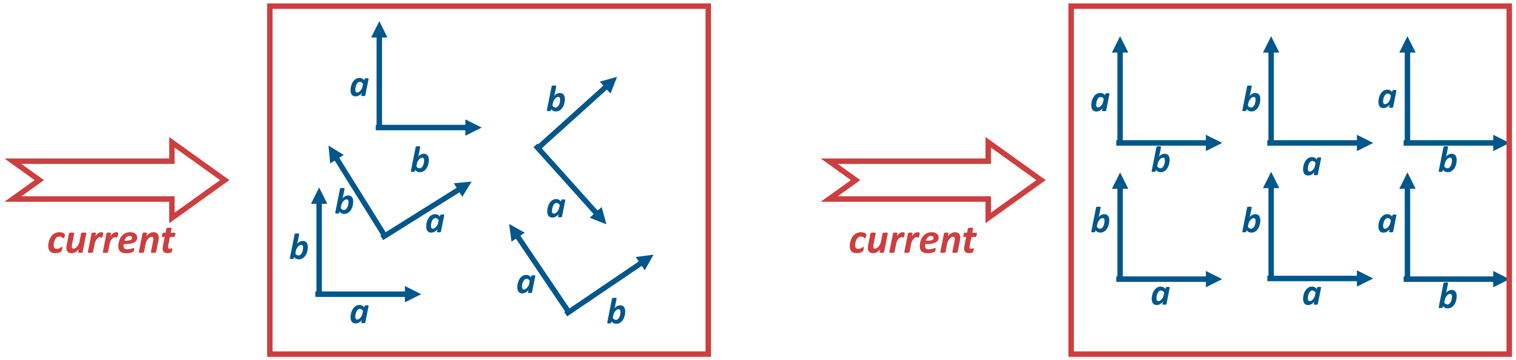
In order to get high J_c in the conductor, the c-axis texturing is not enough

We do need also texturing in the ab plane

HTS conductors: texturing in Bi2223 and Y123

Both in Bi2223 and Y123, c-axis texturing is required due to the anisotropy of the properties //ab and //c

Because of the J_c dependence on the GB angle in the ab plane, also in-plane texturing is required for Y123

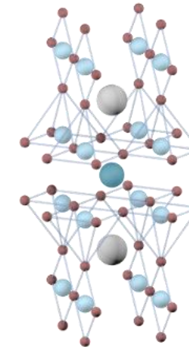


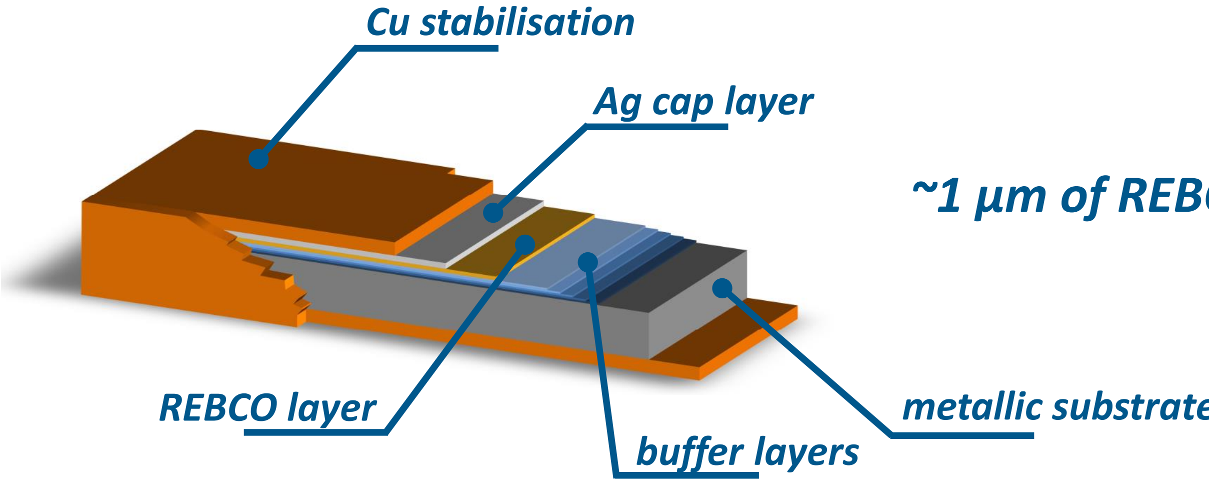
Bi2223 **Y123**

This biaxial texture is required over kilometers!!

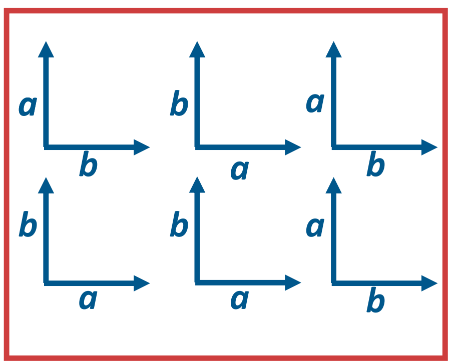
YBCO (REBCO) coated conductors

Iijima et al., APL 60 (1992) 769
Goyal et al., APL 69 (1996) 1795





~1 μm of REBCO in a ~100 μm thick tape



Looking from above

The template is a metallic substrate coated with a multifunctional oxide barrier

Biaxial texturing – within < 3° – is obtained

but with some also drawbacks:

- *pronounced anisotropic behaviour*
- *complex and expensive manufacturing process*

Presently produced by American Superconductor, BRUKER, Fujikura, SuNAM, SuperOx, SuperPower Inc. A Furukawa Company, STI, THEVA, Shanghai 上海超导 SHANGHAI SUPERCONDUCTOR, OXOLUTIA, deutsche nanoschicht, MetOx

The technology of REBCO coated conductors

Alternative approaches for growing epitaxial REBCO on flexible metallic substrates in km-lengths

Substrate texturing

- **RABiTS : Rolling-Assisted, Biaxially Textured Substrates**
  Texture is created in NiW by a rolling-and-recrystallization process
- **IBAD : Ion Beam Assisted Deposition**
  A biaxially textured MgO layer is grown on polycrystalline Hastelloy

REBCO layer deposition

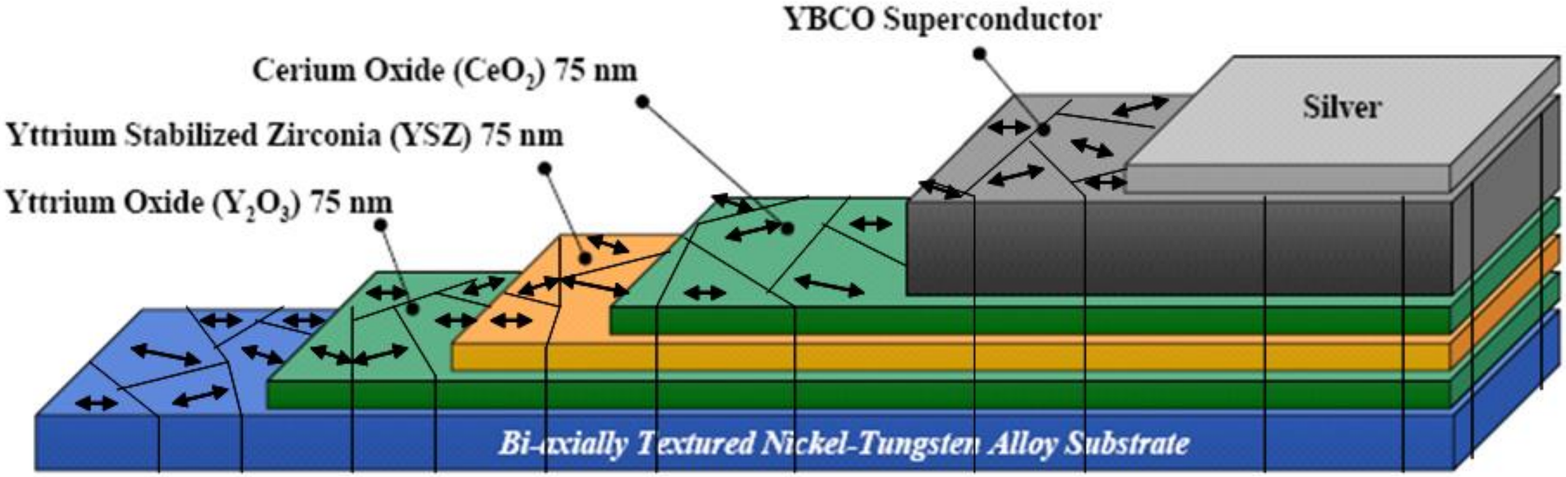
- **Physical routes**
  - **PLD** Pulsed Laser Deposition
  - **RCE** Reactive Co-Evaporation
- **Chemical routes**
  - **MOD** Metal-Organic Deposition
  - **MOCVD** Metal-Organic Chemical Vapor Dep.

REBCO conductor technology: RABiTS template

RABiTS : Rolling-Assisted, Biaxially Textured Substrates

- *[100] cube texture is created in the NiW substrate by a rolling-and-recrystallization process*

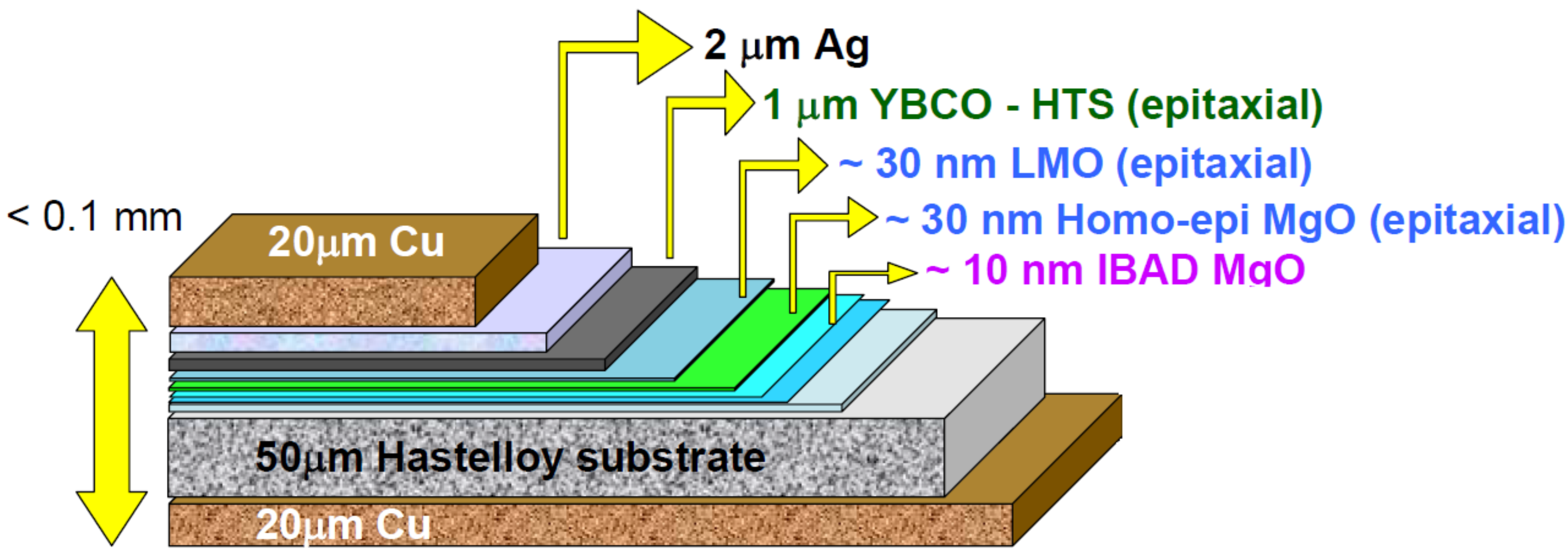
- *Several epitaxial buffer layers are needed to provide a lattice matched surface for growing the HTS layer*



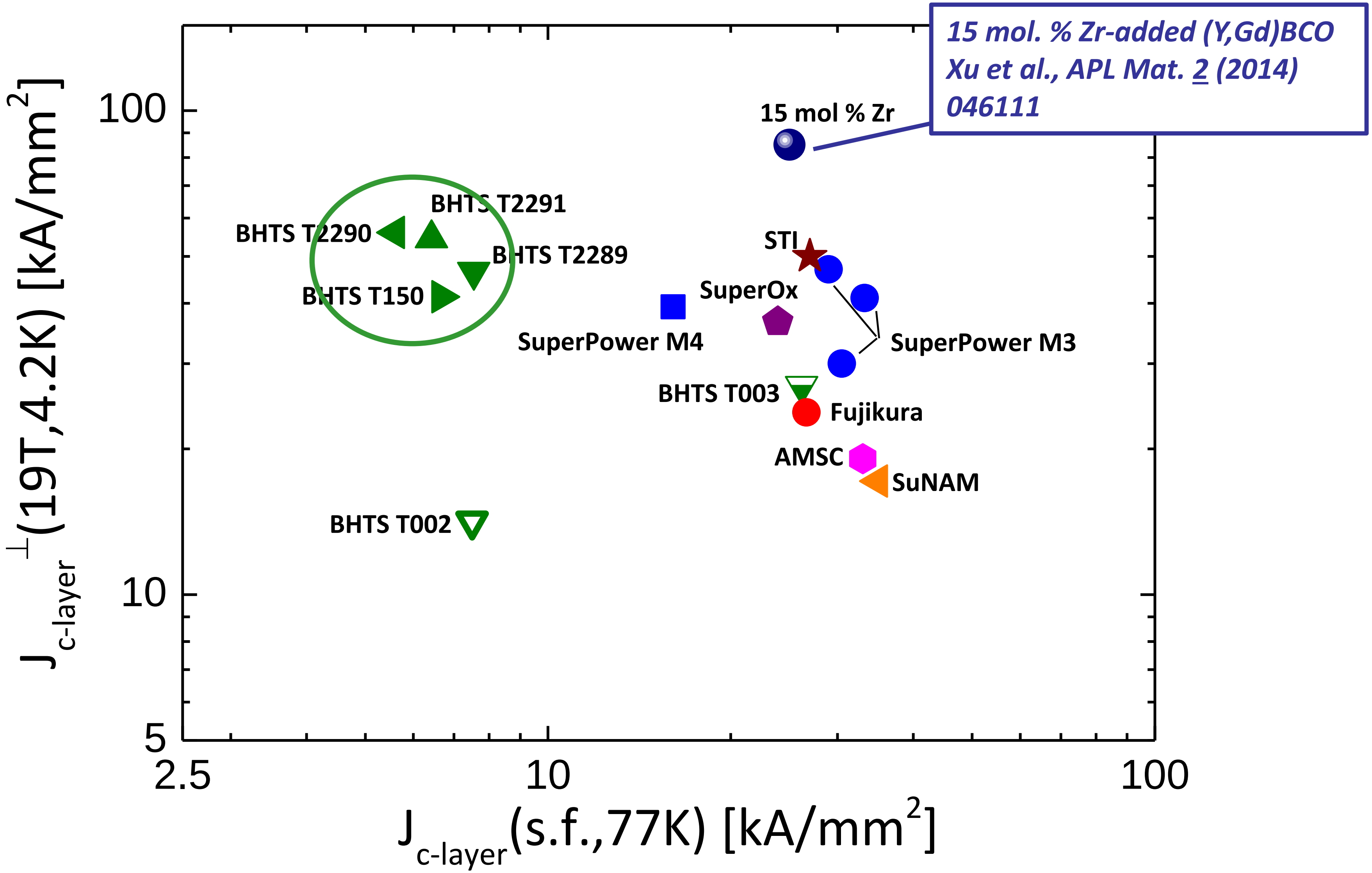
REBCO conductor technology: IBAD template

IBAD : Ion Beam Assisted Deposition

- *A biaxially textured MgO layer is grown on a polycrystalline Hastelloy tape*
- *Several other buffer layers are needed to provide a lattice matched surface for growing the HTS layer*



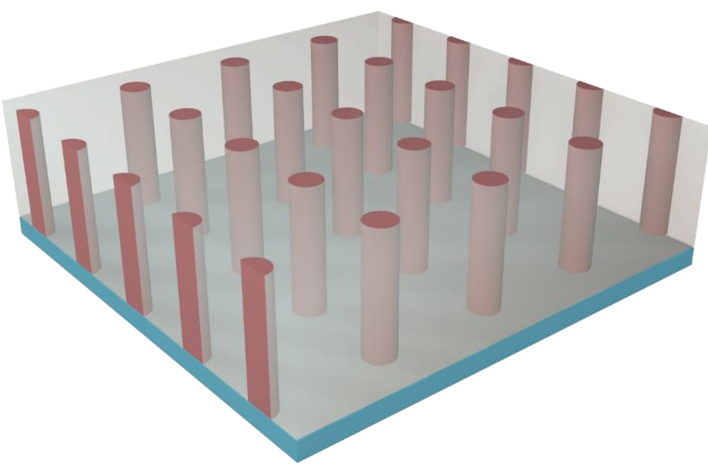
Performance overview: J_c(s.f.,77K) vs. $J_c^{\perp}$(19T,4.2K)



Artificial pinning to enhance REBCO performance

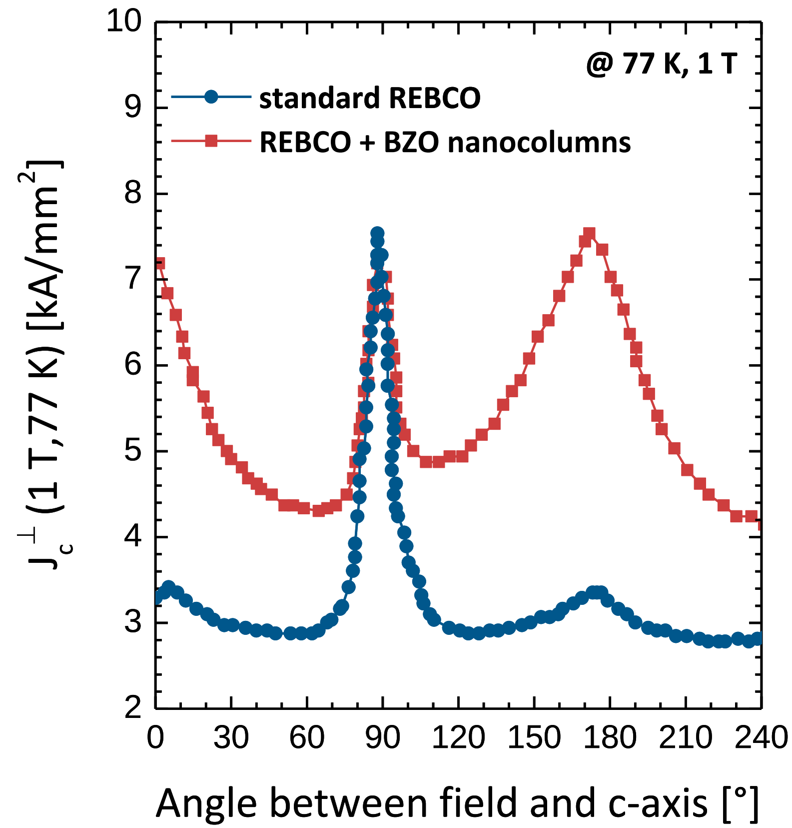
Introduction of artificial nano-defects to control vortex pinning, reduce anisotropy and enhance performance

$BaZrO_3$ (BZO) precipitates are in form of nano-columns oriented along the c-axis



Driscoll et al., Nat. Mat. 3 (2004) 439

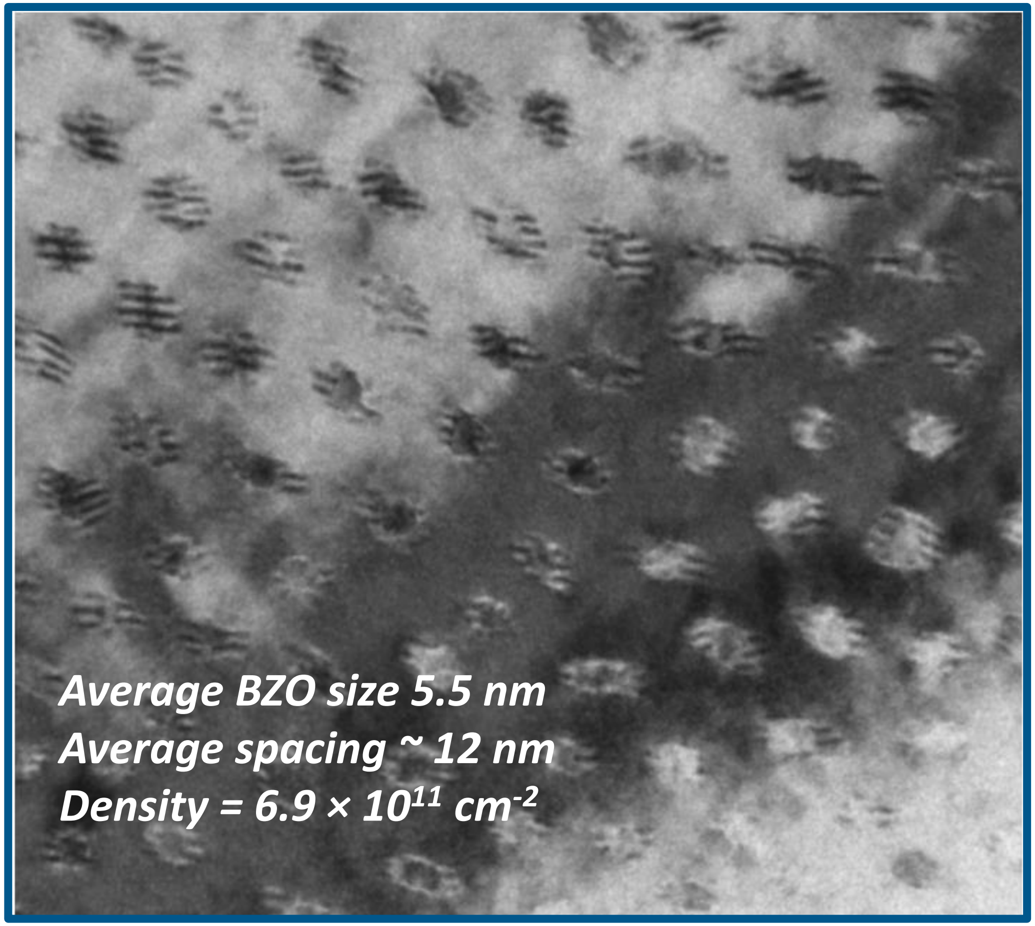
Goyal et al., SuST 18 (2005) 1533

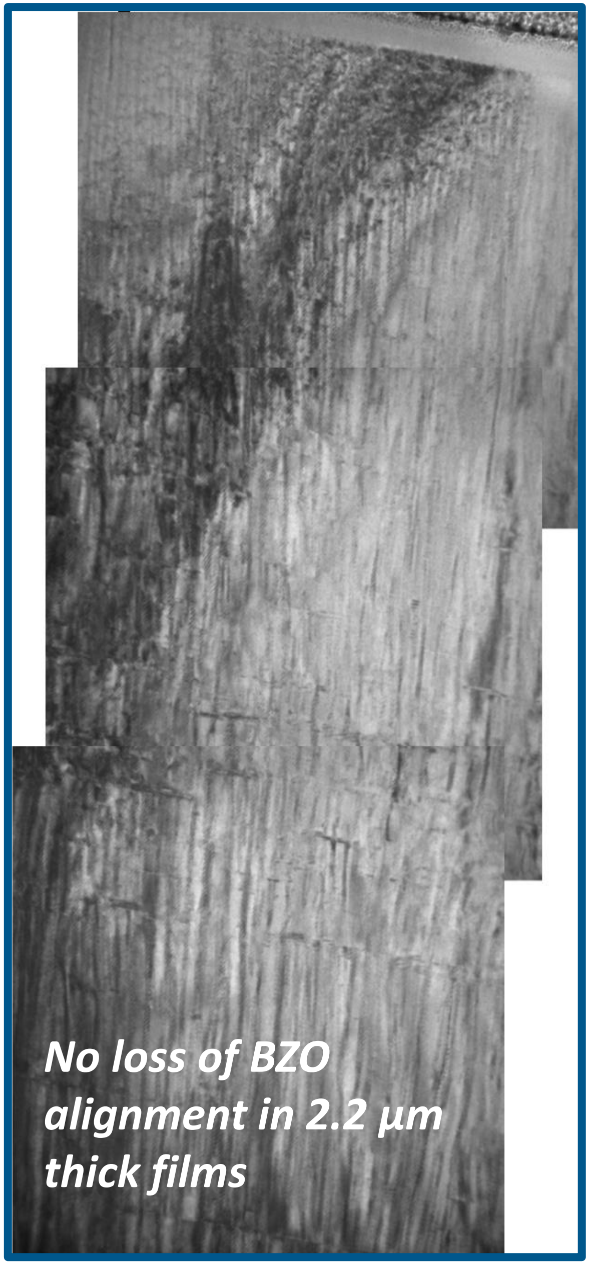


Selvamanickam et al., IEEE TAS 21 (2011) 3049

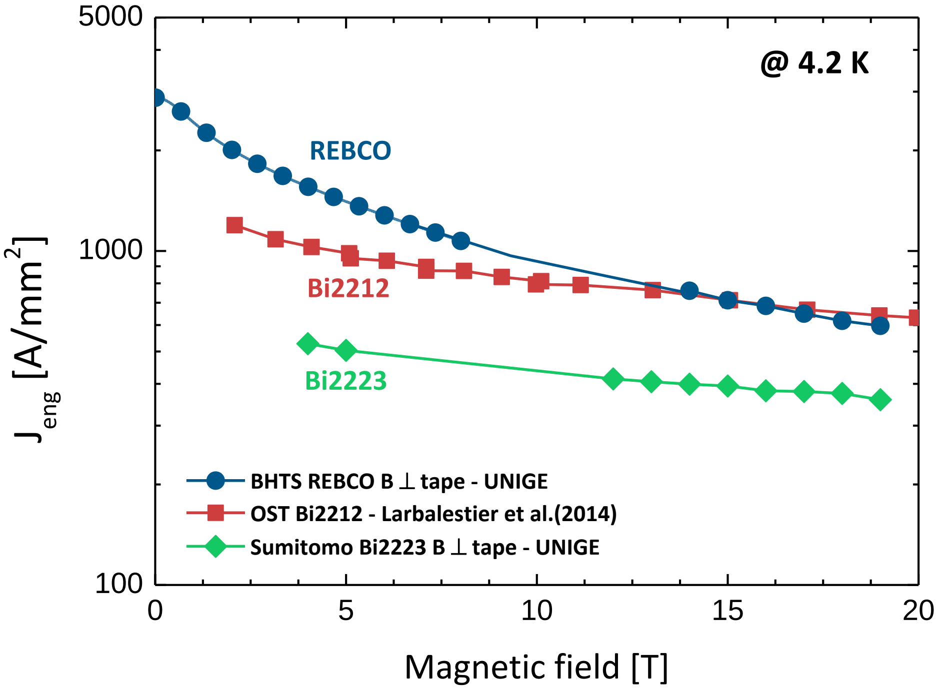
On the BZO nanorods morphology

Selvamanickam el al., APL 106 (2015) 032601

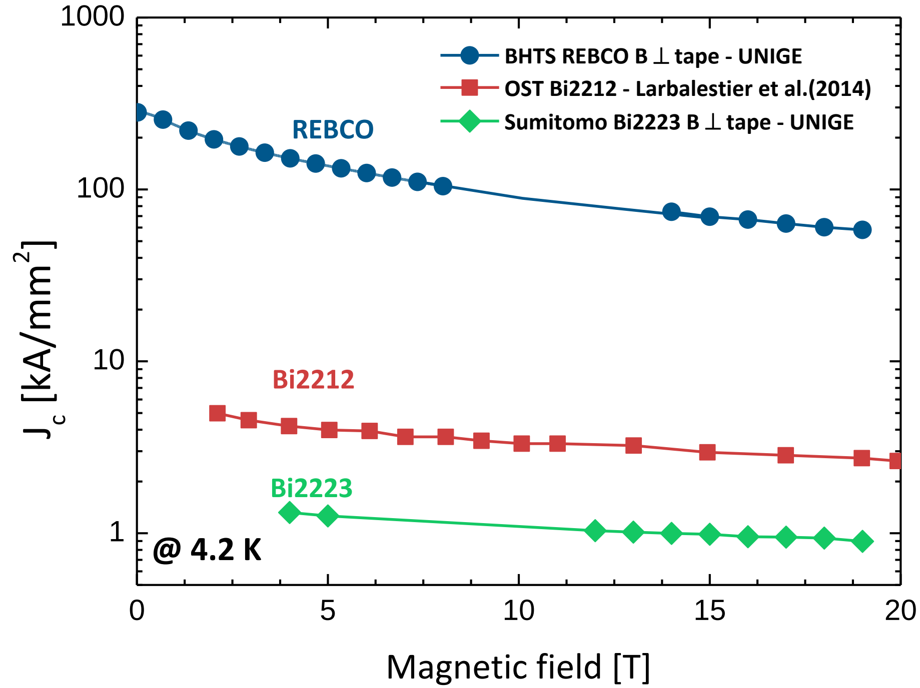




Engineering vs. superconducting layer performance



Engineering current density



Critical current density

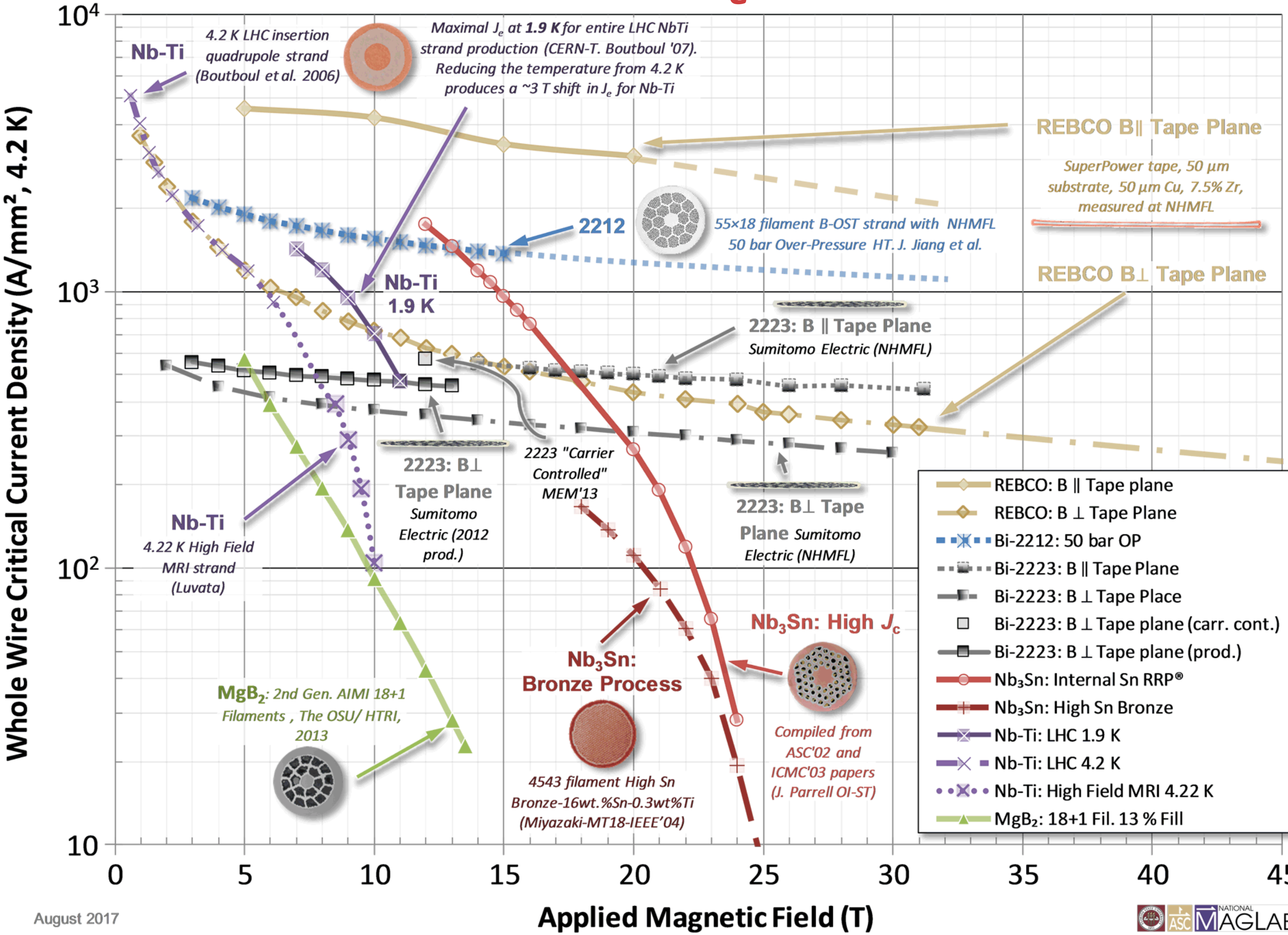
***REBCO and Bi2223** tapes retain the **anisotropic properties** of the superconductor*

Data shown here correspond to the unfavorable orientation wrt the field

The in-field properties of Bi2212 wires are fully isotropic

Industrial superconductors: J_e Comparison

$$J_e = \frac{I_c}{S_{tot}}$$

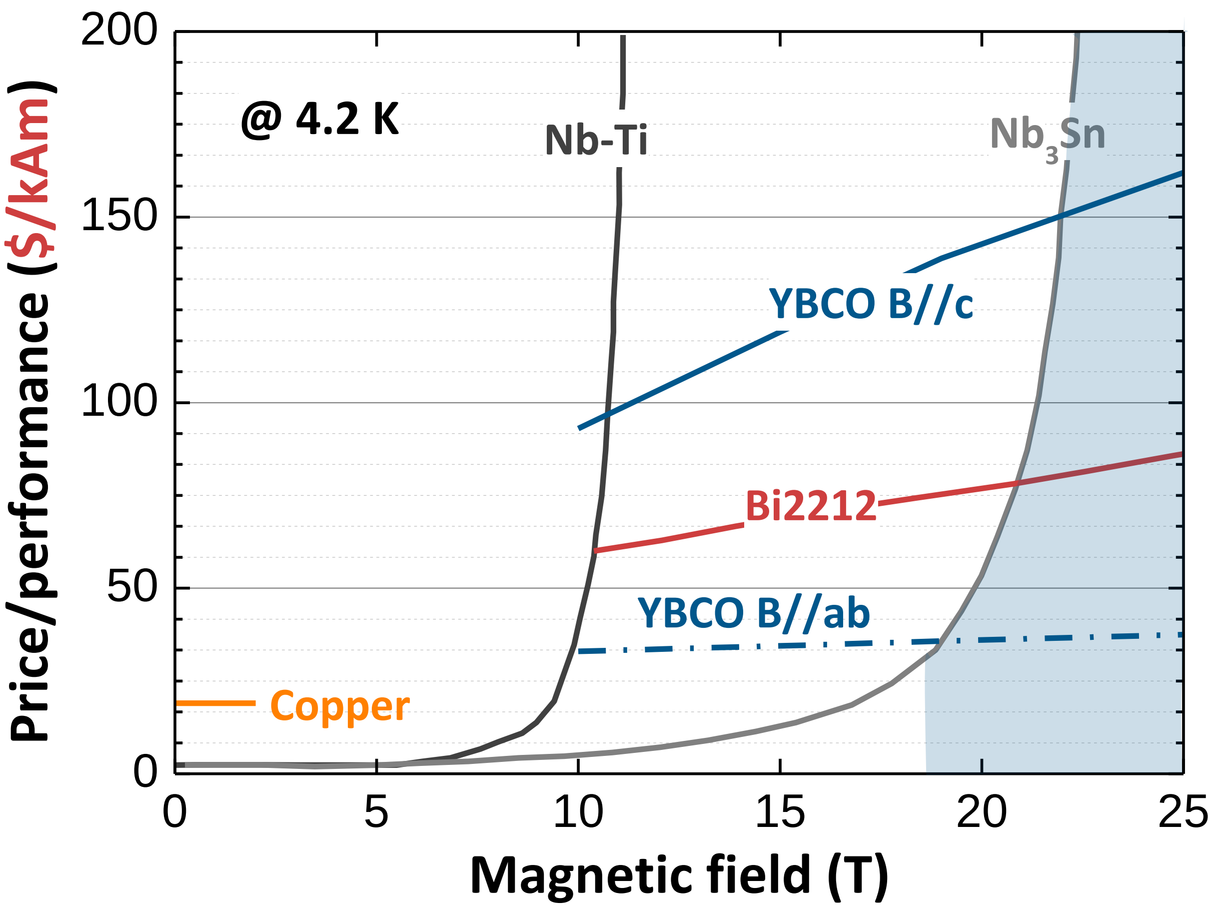


http://fs.magnet.fsu.edu/~lee/plot/plot.htm

Industrial superconductors React&Wind vs Wind&React

React&Wind	Wind&React
NbTi	Nb_3Sn
ex situ MgB_2	in situ MgB_2
Bi2223	IMD MgB_2
Y123	Bi2212

How to choose the superconductor: Performance vs Cost



$$\frac{\$}{kA \cdot m} = \left(\frac{\rho}{J_{eng}} \right) \times \frac{\$}{kg}$$

Adapted from B. Seeber, IEEE TASC 28 (2018) 6900305

Superconductor Technology

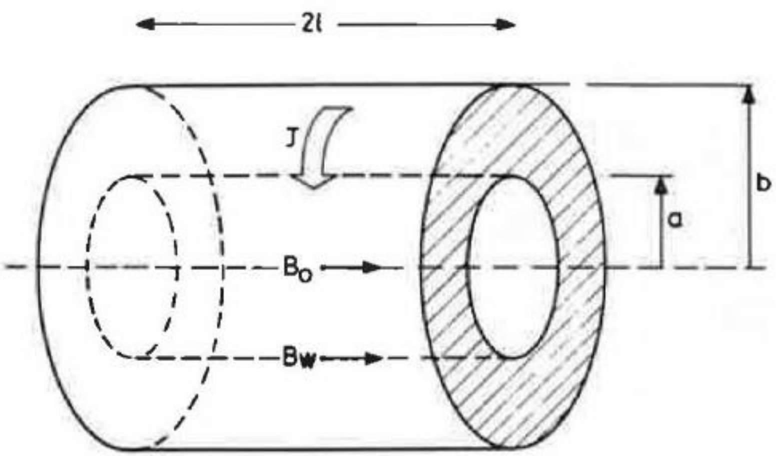
Basic design and operation issues of a superconducting device

Superconducting magnets, field shapes and winding configurations

- *Solenoids (NMR, MRI and laboratory magnets)*
- *Transverse fields (particle accelerators)*
- *Toroids (fusion magnets)*

Solenoids: concepts and design

Biot-Savart law $\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_C \frac{I d\vec{l} \times \vec{r}}{|r^3|}$



In the case of a solenoid

$$B_0 = JaF(\alpha,\beta)$$

where

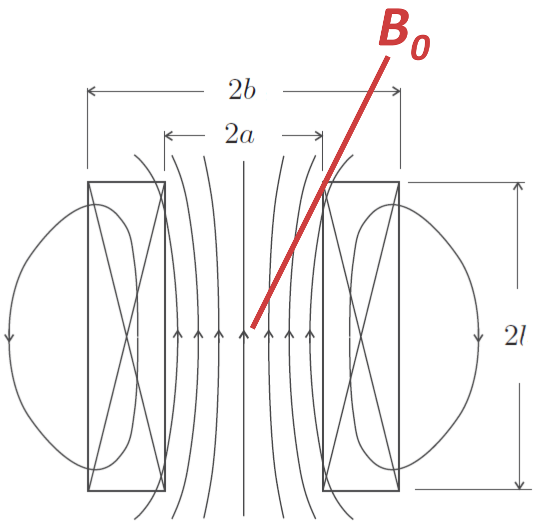
$$J = \frac{NI}{2l(b-a)} \quad *$$

$$F(\alpha,\beta) = \mu_0 \beta \ln\left[\frac{\alpha + \sqrt{\alpha^2+\beta^2}}{1+\sqrt{1+\beta^2}}\right]$$

with $\alpha = \frac{b}{a}$ **and** $\beta = \frac{l}{a}$

* Overall current density, normalized to the winding section including wire matrix and insulation

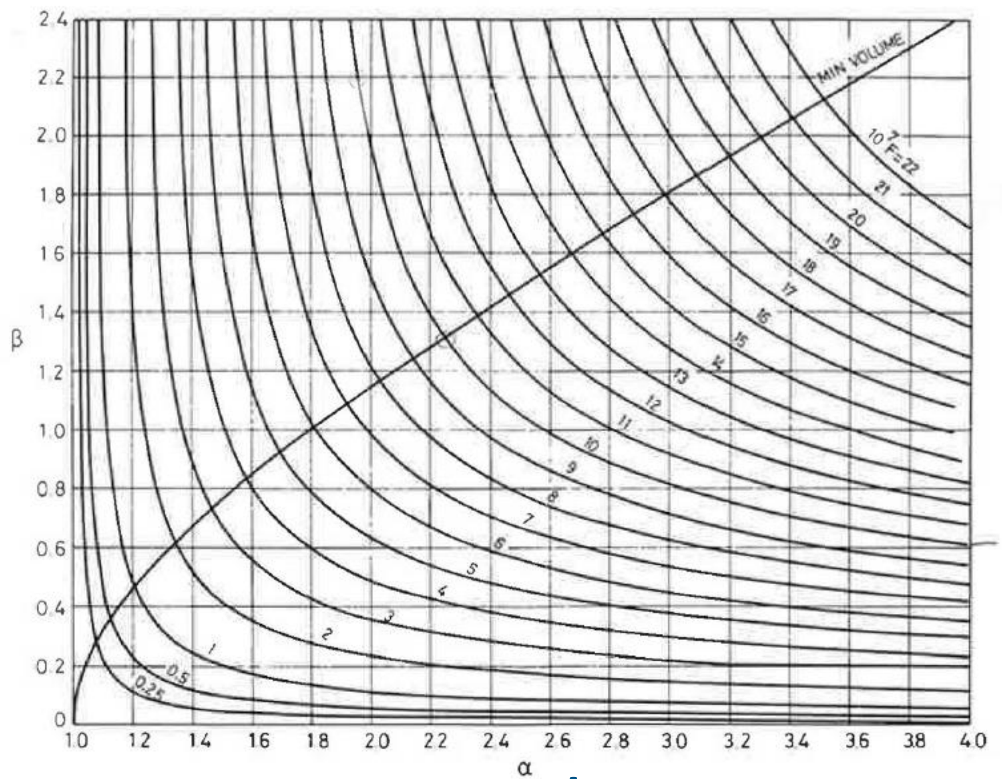
Coil geometry and shape factor



$$B_0 = JaF(\alpha,\beta)$$

A given field can always be made by a short fat coil or a long thin one

$$\beta = \frac{l}{a}$$



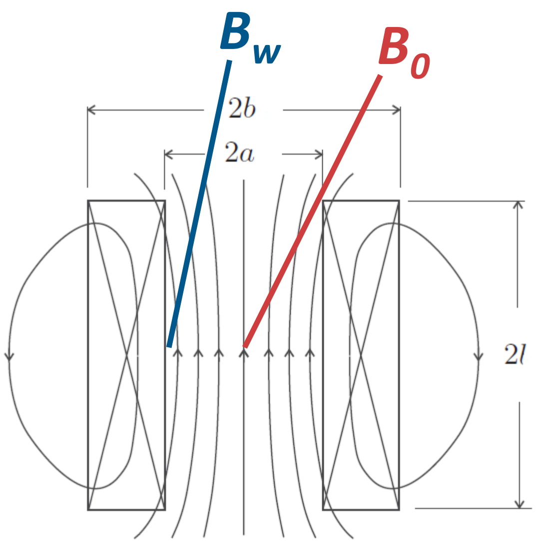
$$\alpha = b / a$$

$$V = 2\pi\, l(b^2 - a^2)$$

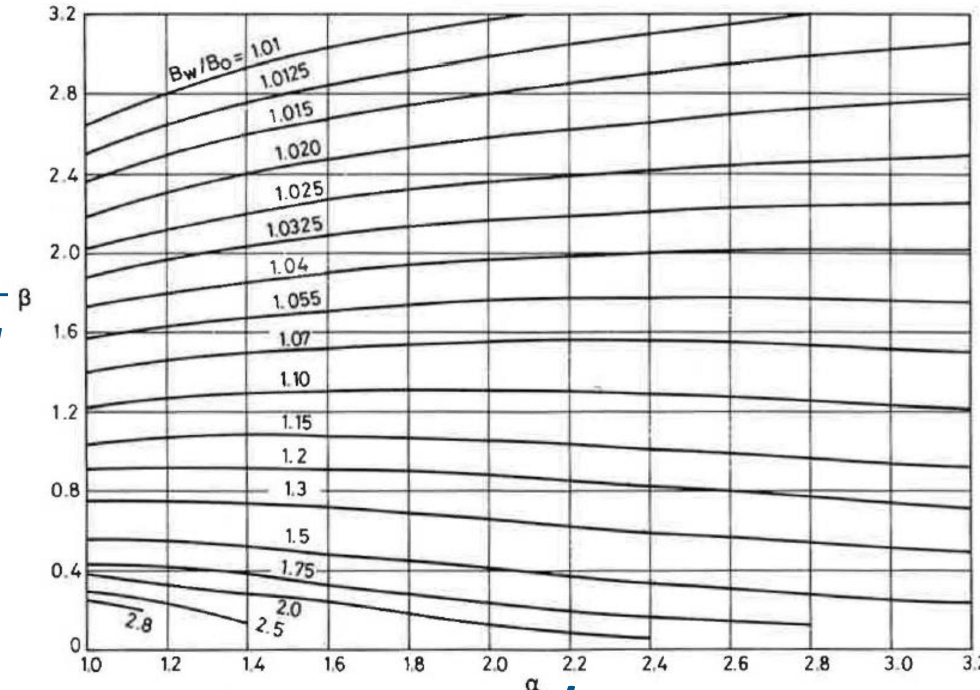
$$= 2\pi\, a^3(\alpha^2 - 1)\beta$$

Maximum field on the winding

α and β have an influence on the field uniformity



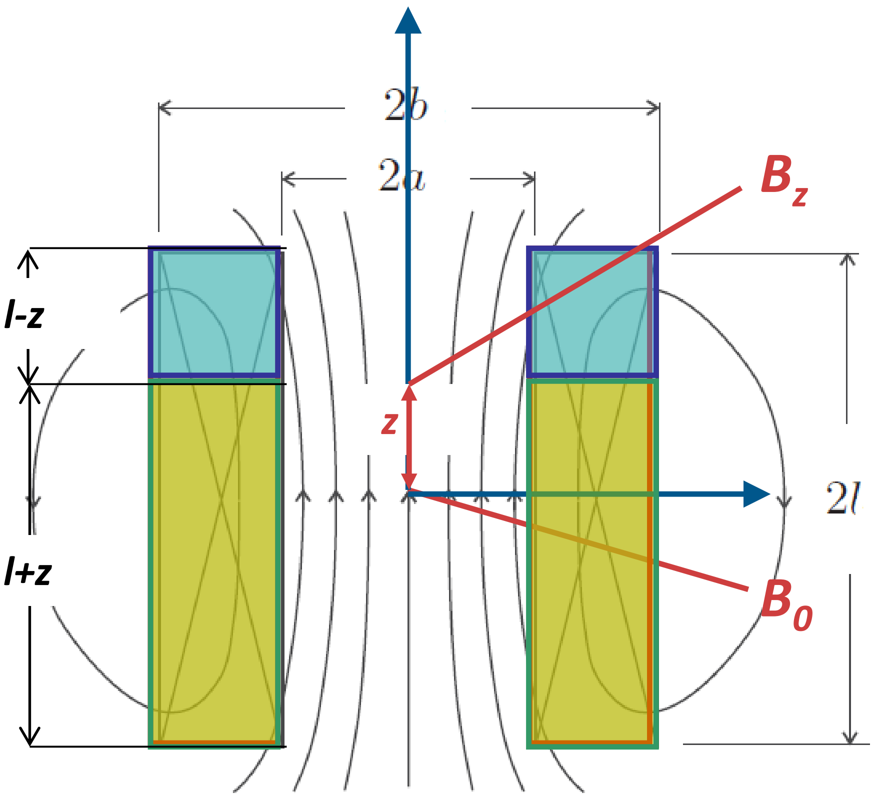
$$\beta = \frac{l}{a}$$



$$\alpha = \frac{b}{a}$$

At the exercise session: how to choose α and β when designing a solenoid

Homogeneity of the field along z



$$B_0 = JaF(\alpha, \beta)$$

$$\text{where} \quad \alpha = \frac{b}{a} \quad \text{and} \quad \beta = \frac{l}{a}$$

How to calculate the variation of field along the axis of a solenoid

$$B_z = \frac{1}{2} JaF(\alpha, \beta_1) + \frac{1}{2} JaF(\alpha, \beta_2)$$

$$\beta_1 = \frac{l+z}{a} \qquad \beta_2 = \frac{l-z}{a}$$

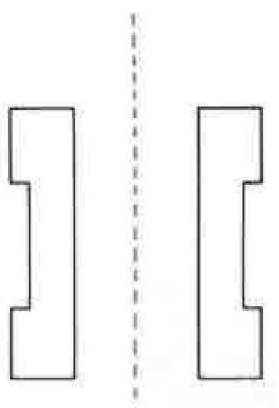
Homogeneity of the field along z

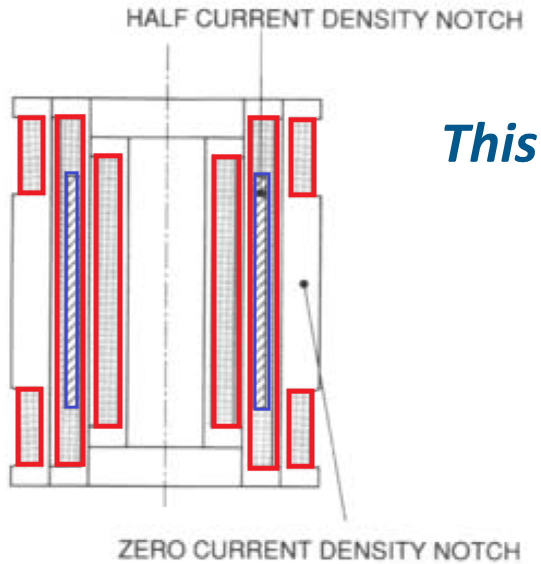
Along the solenoid axis

$$E_{2n} = \frac{1}{B_0}\frac{1}{(2n)!}\frac{d^{2n}B_z}{dz^{2n}}$$

$$B_z = B_0\left[1 + E_2\left(\frac{z}{a}\right)^2 + E_4\left(\frac{z}{a}\right)^4 + E_6\left(\frac{z}{a}\right)^6 + \ldots\right]$$

By suitable adjustment of coil shape, one may reduce an error coefficient to zero

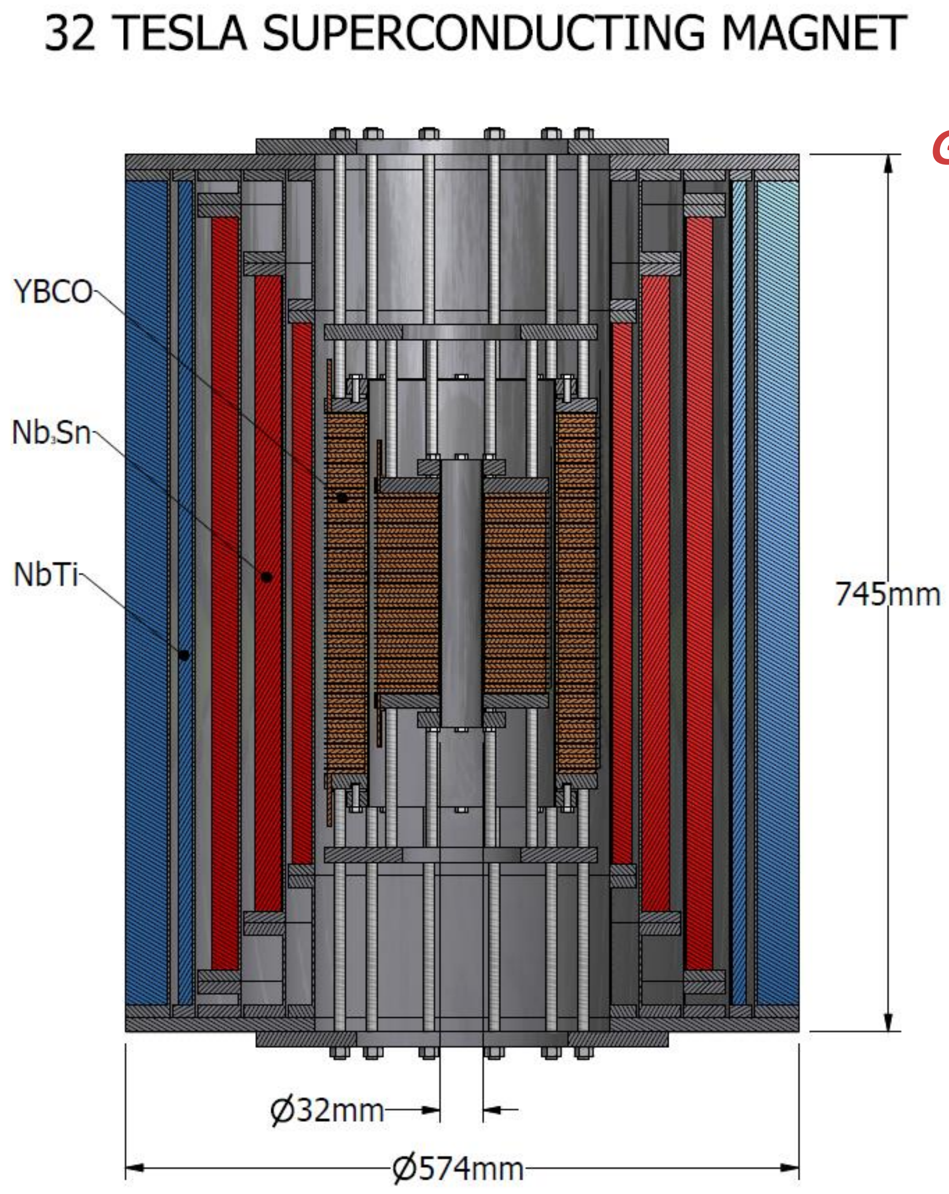




This notched solenoid is of sixth order

$$E_2 = E_4 = 0$$

A 32 T all-superconducting magnet at NHMFL, US



General guidelines for magnet design

Subdivide the winding into a number of concentric sections to improve the efficiency of superconductor utilization

All sections take the same current, but each section has its own J, α and β

Each section operates at the maximum current density allowed by the local field level

Bibliography

Rogalla & Kes
100 Years of Superconductivity
Chapter 11 Section 5 (Y123)

Wilson
Superconducting Magnets
Chapter 3

Papers cited in the slides