Superconducting magnets for Accelerators

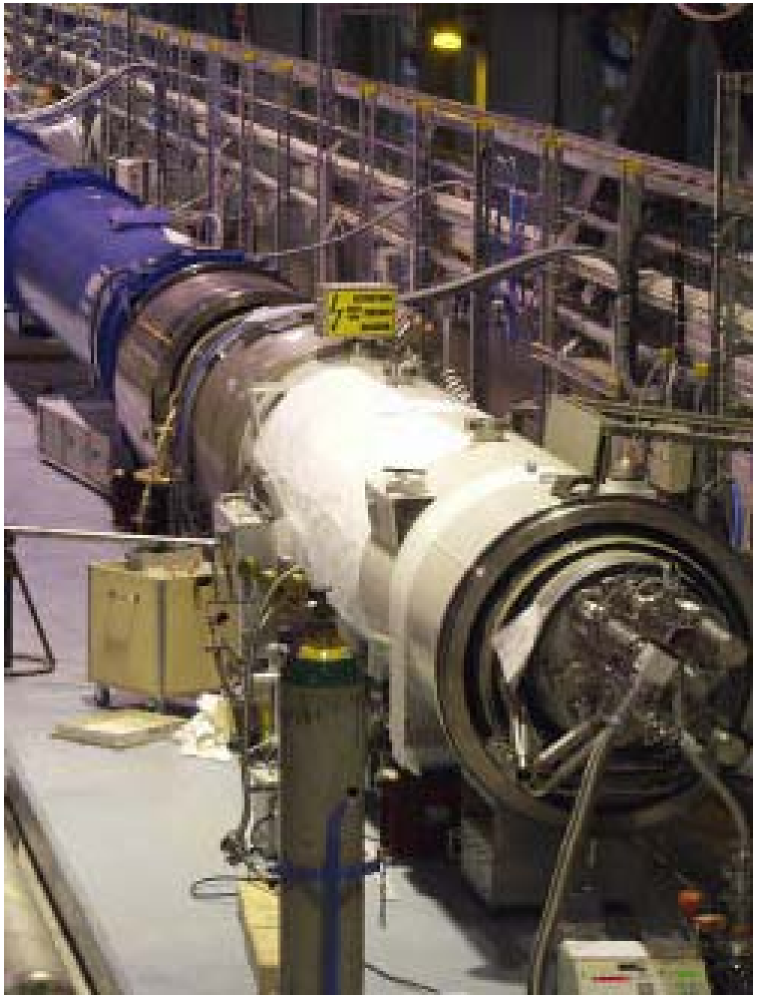
Who needs superconductivity anyway?

Abolish Ohm's Law!

- no power consumption
  (although do need refrigeration power)
- high current density ⇒ compact windings, high gradients
- ampere turns are cheap, so we don't need iron
  (although often use it for shielding)

Consequences

- lower power bills
- higher magnetic fields mean reduced bend radius
  - ⇒ smaller rings
  - ⇒ reduced capital cost
  - ⇒ new technical possibilities
    (eg muon collider)
- higher quadrupole gradients
  - ⇒ higher luminosity



Superconducting magnets for Accelerators

Plan of the Course

Martin N Wilson (Rutherford Lab ⇒ Oxford Instruments ⇒ consultant)

1 Introduction to Superconductors

- where to find more information
- critical properties: field, temperature & current
- low temperature superconductors LTS
- high temperature superconductors HTS
- manufacture of superconductors
- measurement of superconducting properties

2 Magnets, 'training' & fine filaments

- magnetic fields & how to create them
- load lines, degradation & training
- causes of training
- minimum quench energy MQE
- critical state model ⇒ screening currents
- flux jumping

3 Coupling, Cables & AC losses

- magnetization of filaments
- coupling between filaments ⇒ magnetization
- why cables? styles of cable
- coupling in cables ⇒ cable magnetization
- field errors caused by magnetization
- AC loss in terms of magnetization
- different components of AC loss

4 Quenching and protection

- the quench process, internal voltages
- decay times & temp rise
- propagation of the normal zone
- quench protection schemes, protection of LHC

5 Manufacturing and testing

- coil winding and curing
- forces, clamping, assembly, iron
- cryostats and current leads
- some examples of superconducting accelerators

Some useful references

Superconducting Magnets

- Superconducting Accelerator Magnets: KH Mess, P Schmuser, S Wolf., pub World Scientific, (1996) ISBN 981-02-2790-6
- High Field Superconducting Magnets: FM Asner, pub Oxford University Press (1999) ISBN 0 19 851764 5
- Case Studies in Superconducting Magnets: Y Iwasa, pub Plenum Press, New York (1994), ISBN 0-306-44881-5.
- Superconducting Magnets: MN Wilson, pub Oxford University Press (1983) ISBN 0-019-854805-2
- Proc Applied Superconductivity Conference: pub as IEEE Trans Applied Superconductivity, Mar 93 to 99, and as IEEE Trans Magnetics Mar 75 to 91
- Handbook of Applied Superconductivity ed B Seeber, pub UK Institute Physics 1998

Cryogenics

- Helium Cryogenics Van Sciver SW, pub Plenum 86 ISBN 0-0306-42335-9
- Cryogenic Engineering, Hands BA, pub Academic Press 86 ISBN 0-012-322991-X
- Cryogenics: published monthly by Butterworths
- Cryogenie: Ses Applications en Supraconductivite, pub IIR 177 Boulevard Malesherbes F5017 Paris France

Materials Mechanical

- Materials at Low Temperature: Ed RP Reed & AF Clark, pub Am. Soc. Metals 1983. ISBN 0-87170-146-4
- Handbook on Materials for Superconducting Machinery pub Batelle Columbus Laboratories 1977.
- Nonmetallic materials and composites at low temperatures: Ed AF Clark, RP Reed, G Hartwig pub Plenum
- Nonmetallic materials and composites at low temperatures 2, Ed G Hartwig, D Evans, pub Plenum 1982
- Austenitic Steels at low temperatures Editors R.P.Reed and T.Horiuchi, pub Plenum1983

Superconducting Materials

- Superconductor Science and Technology, published monthly by Institute of Physics (UK).
- Superconductivity of metals and Cuprates, JR Waldram, Institute of Physics Publishing (1996) ISBN 0 85274 337 8
- High Temperature Superconductors: Processing and Science, A Bourdillon and NX Tan Bourdillon, Academic Press, ISBN 0 12 117680 0
- **www.superconductors.org** website run by an enthusiast; gives some basic info and links.

Materials data web sites

- Cryogenic properties (1-300 K) of many solids, including thermal conductivity, specific heat, and thermal expansion, have been empirically fitted and the equation parameters are available free on the web at **www.cryogenics.nist.gov**.
- Plots and automated data-look-up using the NIST equations are available on the web for a fee from **www.cpia.jhu.edu**.
- Other fee web sites that use their own fitting equations for a number of cryogenic material properties include: **www.cryodata.com** (cryogenic properties of about 100 materials),

  and **www.jahm.com** (temperature dependent properties of about 1000 materials, many at cryogenic temperatures).
- Commercially supplied room-temperature data are available free online for about 10 to 20 properties of about 24,000 materials at **www.matweb.com.**

thanks to Jack Ekin of NIST for this information

Cryodata Software Products

GASPAK
properties of pure fluids from the triple point to high temperatures.

HEPAK
properties of helium including superfluid above 0.8 K, up to 1500 K.

STEAMPAK
properties of water from the triple point to 2000 K and 200 MPa.

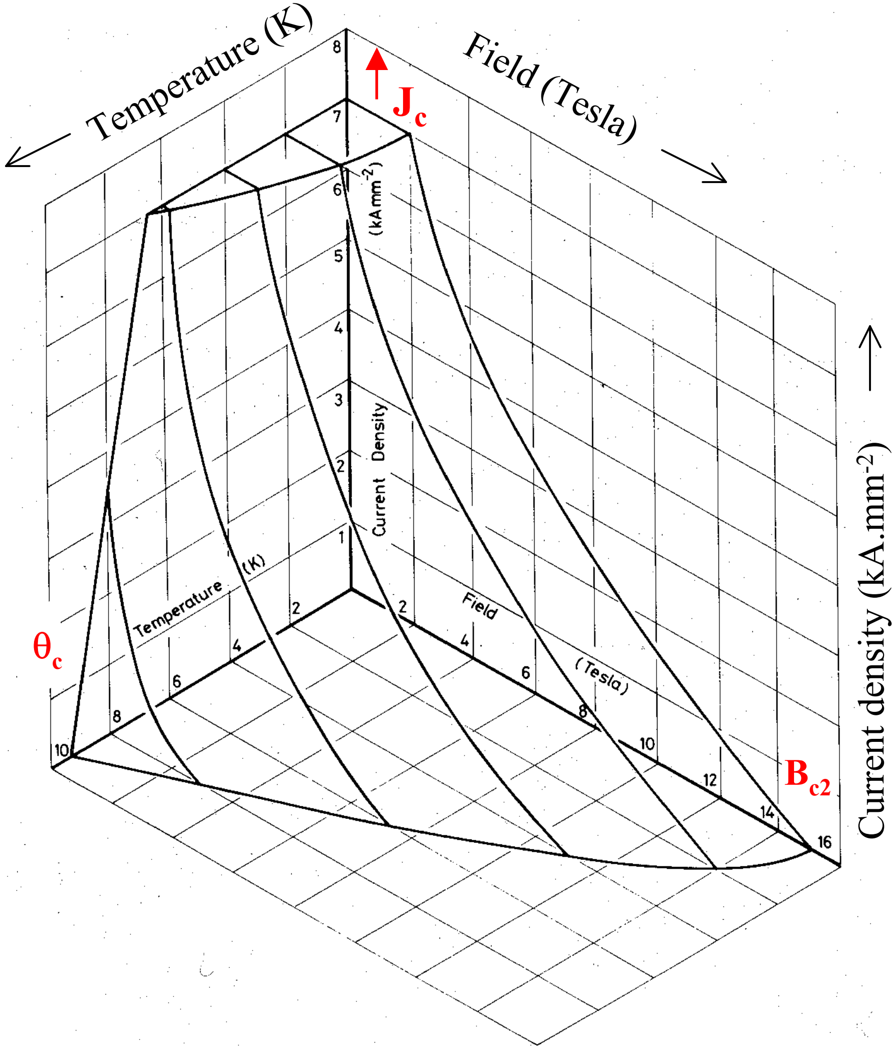
METALPAK, CPPACK, EXPAK
reference properties of metals and other solids, 1 - 300 K.

CRYOCOMP
properties and thermal design calculations for solid materials, 1 - 300 K.

SUPERMAGNET
four unique engineering design codes for superconducting magnet systems.

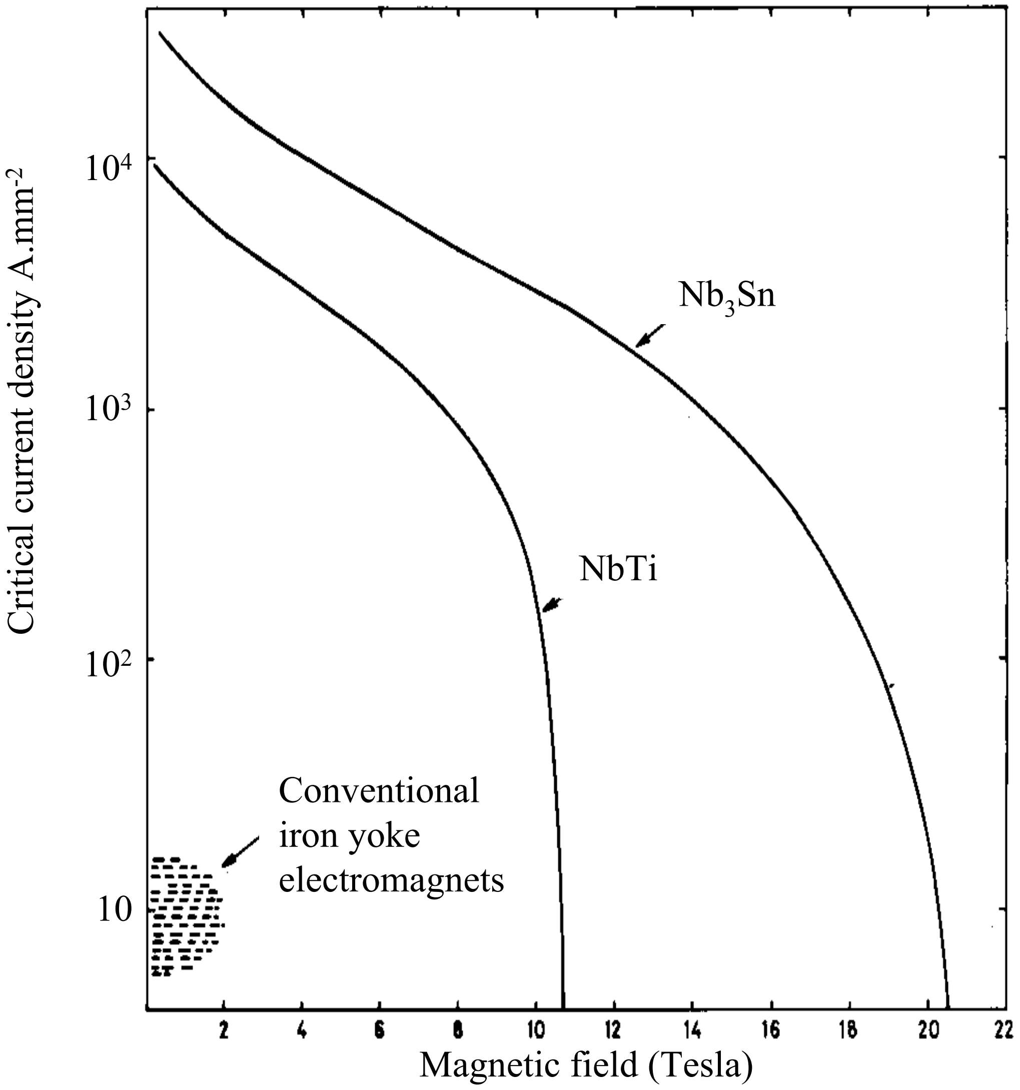
KRYOM
numerical modelling calculations on radiation-shielded cryogenic enclosures.

The critical surface of niobium titanium



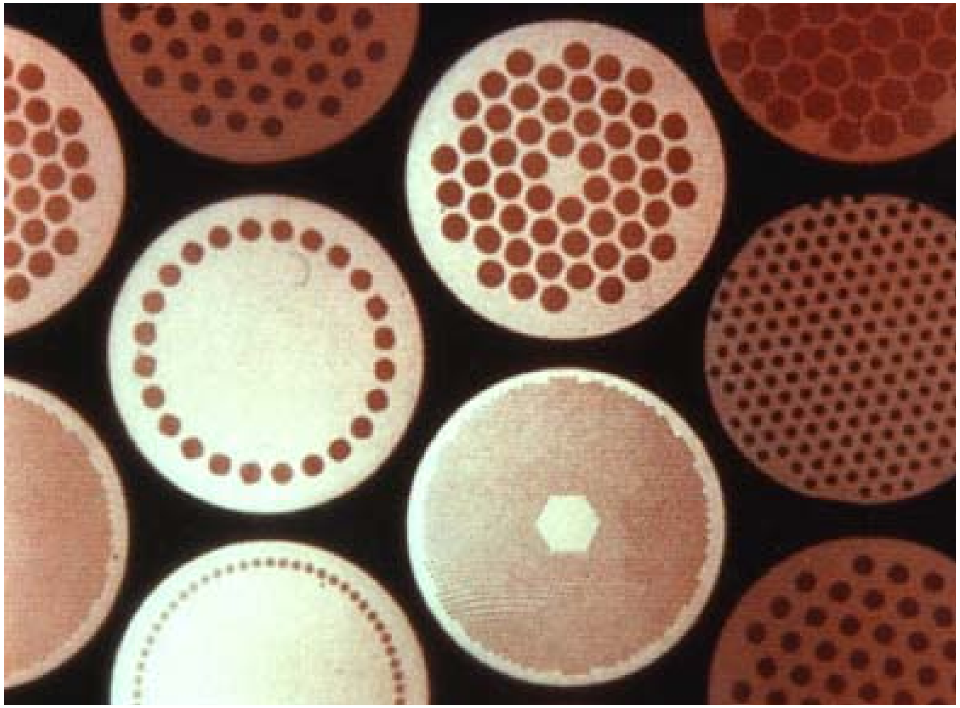
- Niobium titanium **NbTi** is the standard ‘work horse’ of the superconducting magnet business
- a low temperature superconductor LTS
- picture shows the **critical surface**, which is the boundary between superconductivity and normal resistivity in 3 dimensional space
- superconductivity prevails everywhere below the surface, resistance everywhere above it
- we define an upper critical field B_{c2} (at zero temperature and current) and critical temperature θ_c (at zero field and current) which are characteristic of the alloy composition
- critical current density $J_c(B,\theta)$ depends on processing

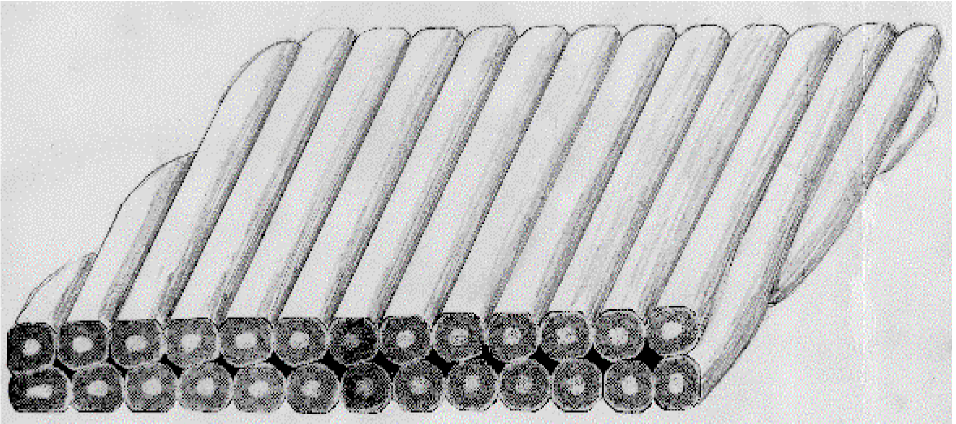
The critical line at 4.2K



- because magnets usually work in boiling liquid helium, the critical surface is often represented by a curve of current versus field at 4.2K
- niobium tin Nb$_3$Sn has a much higher performance in terms of critical current field and temperature than NbTi
- but it is brittle intermetallic compound with poor mechanical properties
- note that both the field and current density of both superconductors are way above the capability of conventional electromagnets

Practical superconductors for magnets





- for reasons that will be described later, superconducting materials are always used in combination with a good normal conductor such as copper

- to ensure intimate mixing between the two, the superconductor is made in the form of fine filaments embedded in a matrix of copper

- typical dimensions are:

  - wire diameter = 0.3 - 1.0mm

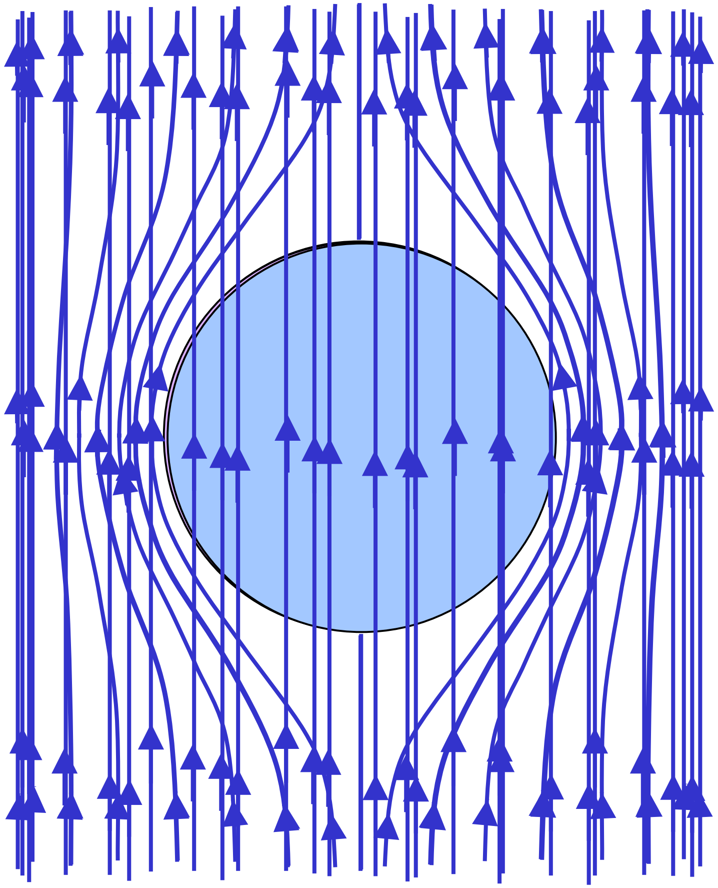
  - filament diameter = 10 - 60μm

- for electromagnetic reasons, the composite wires are twisted so that the filaments look like a rope (see Lecture 3)

- for accelerators, many wires are combined in a cable (see Lecture 3)

Two kinds of superconductor: type 1

- the materials first discovered by Kammerlingh Onnes in 1911 - soft metals like lead, tin mercury
- sphere of metal at room temperature
- apply magnetic field
- reduce the temperature - resistance decreases
- reduce the temperature some more
  - resistance decreases some more
- at the critical temperature θ_c the field is pushed out - the **Meissner effect** - superconductivity!
- increase the field - field is kept out
- increase the field some more - superconductivity is extinguished and the field jumps in
- thermodynamic critical field B_c



Type 1 superconductors: critical properties

- superconductivity is a condensation to a lower energy state
- the electrons form ***Cooper pairs*** with a binding energy Δ also called the ***energy gap***
- at the critical temperature the thermal energy breaks these pairs apart

$$3.5 k_B \theta_c = 2\Delta(0)$$

where k_B is Boltzmann's constant and $\Delta(0)$ is the energy gap at $\theta = 0$

- it costs energy to push the field out.
- at ***critical field*** the energy penalty of keeping the field out just exceeds the condensation energy of the superconducting state

$$\frac{B_c^{\,2}}{2\mu_o} = G_n - G_s$$

where G is the ***Gibbs Free Energy*** of the normal & superconducting states, calculated from the Bardeen Cooper Schriefer theory as

$$G_n(0) - G_s(0) = \frac{1}{2} N_F \left(\Delta(0)\right)^2$$

where N_F is the ***density of states*** at the Fermi surface of metal in normal state - calculated from:

$$\gamma = 2/3\pi^2 N_F k_B^{\,2}$$

where γ is Sommerfeld coefficient of electronic specific heat $C = \gamma\theta + A\theta^3$

putting it all together

$$B_c(0) = \left\{\frac{3\mu_0}{2}\right\}^{\frac{1}{2}} \frac{3.5}{2\pi} \gamma^{\frac{1}{2}} \theta_c = 7.65x10^{-4} \gamma^{\frac{1}{2}} \theta_c$$

'thermodynamic critical field' B_c

so like θ_c, $\boldsymbol{B_c}$ is defined by the 'chemistry'

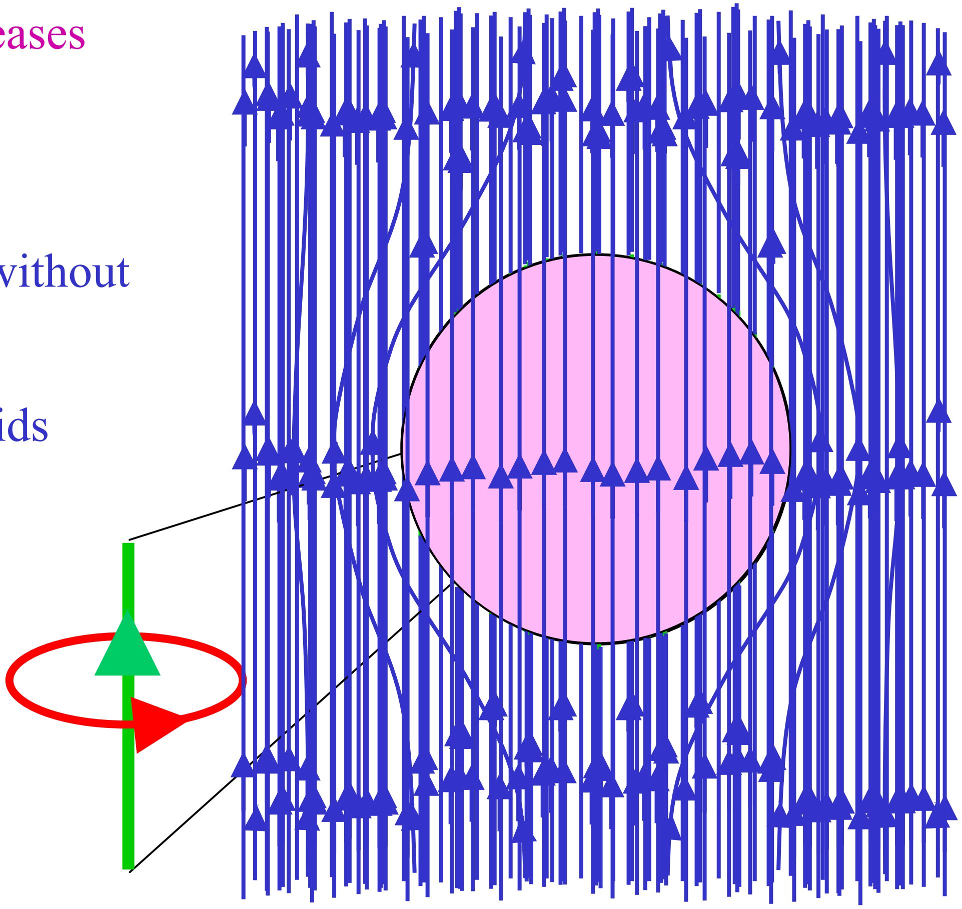
for NbTi $\gamma \sim 10^3$ J m^{-3} K^{-1} and $\theta_c = 10$ K

$\Rightarrow$ **B_c = 0.24T**

Conclusion: **Type 1 superconductors are useless for magnets!**

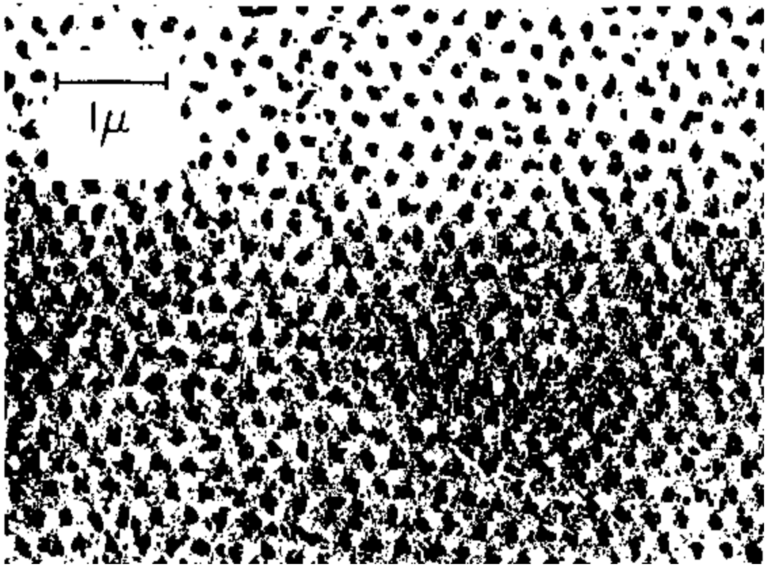
Two kinds of superconductor: type 2

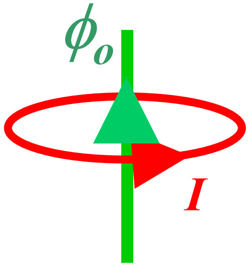
- apply magnetic field
- reduce the temperature - resistance decreases
- at the critical temperature θ_c the field is pushed out
- increase the field - field jumps back in without quenching superconductivity
- it does so in the form of quantized fluxoids
- lower critical field B_{c1}
- supercurrents encircle the resistive core of the fluxoid thereby screening field from the bulk material
- higher field $\Rightarrow$ closer vortex spacing
- superconductivity is extinguished at the (much higher) upper critical field B_{c2}



Critical field: type 2 superconductors

- Meissner effect is not total, the magnetic field actually penetrates a small distance λ the ***London Penetration Depth.***
- another characteristic distance is the ***coherence length*** ζ - the minimum distance over which the electronic state can change from superconducting to normal
- theory of Ginsburg, Landau, Abrikosov and Gorkov **GLAG** defines the ratio $\kappa = \lambda / \xi$
- if $\kappa > 1/\sqrt{2}$ material is ***Type 2***
- magnetic field penetrates as discrete ***fluxoids***





a single fluxoid encloses flux

$$\phi_o = \frac{h}{2e} = 2\times10^{-15}\,Webers$$

where h = Planck's constant,
e = electronic charge

upper critical field $B_{c2} = \sqrt{2}\kappa B_c$ in the 'dirty limit' $\kappa \approx 2.4\times10^6 \gamma^{\frac{1}{2}} \rho_n$ where ρ_n is the normal state resistivity

- best superconductors are best resistors!

thus the upper critical field $B_{c2} = 3.1\times10^3 \gamma\rho_n\theta_c$

for NbTi: $\gamma \sim 900$ J m $^{-3}$ K $^{-2}$ $\rho_n \sim 65\text{ x}10^{-8}$ W m $\theta_c = 9.3$ K hence $B_{c2} \sim 18.5$ **T**

Critical current density: type 2 superconductors

- fluxoids consist of resistive cores with supercurrents circulating round them.

  spacing between the fluxoids is:-

$$d = \left\{ \frac{2}{\sqrt{3}} \frac{\phi_o}{B} \right\}^{\frac{1}{2}} = 22nm \quad at\ 5T$$

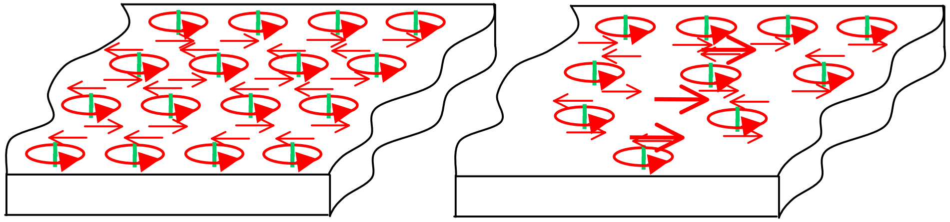
- each fluxoid carries one unit of flux,

  so density of fluxoids = average field

  uniform density ⇒ uniform field

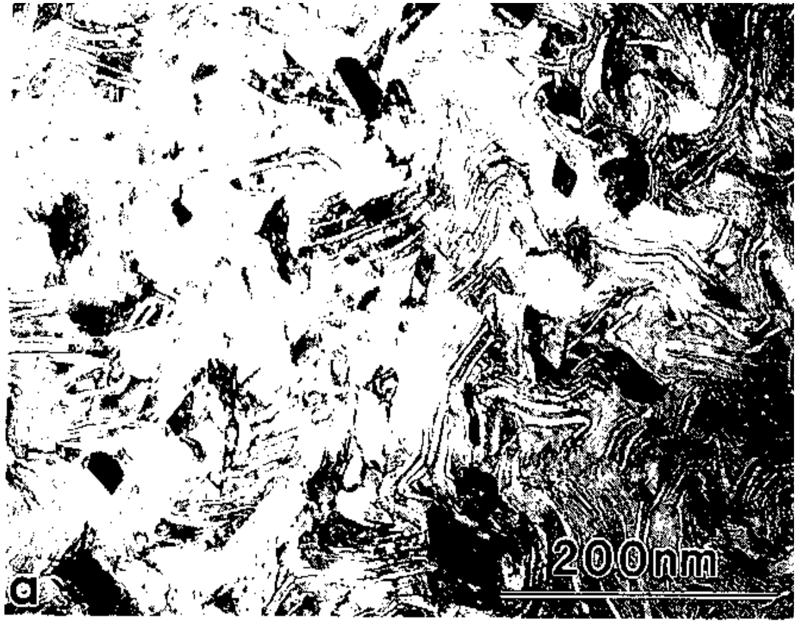
  ⇒ zero J (because $Curl\ B = \mu_o J$)

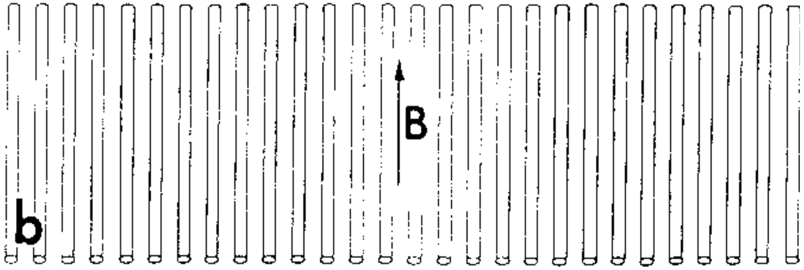
- to get a current density we must produce a gradient in the density of fluxoids



- fluxoids like to distribute uniformly
- so we must ompose a gradient by inhomogeneities in the material, eg dislocations or precipitates

precipitates of α Ti in Nb Ti





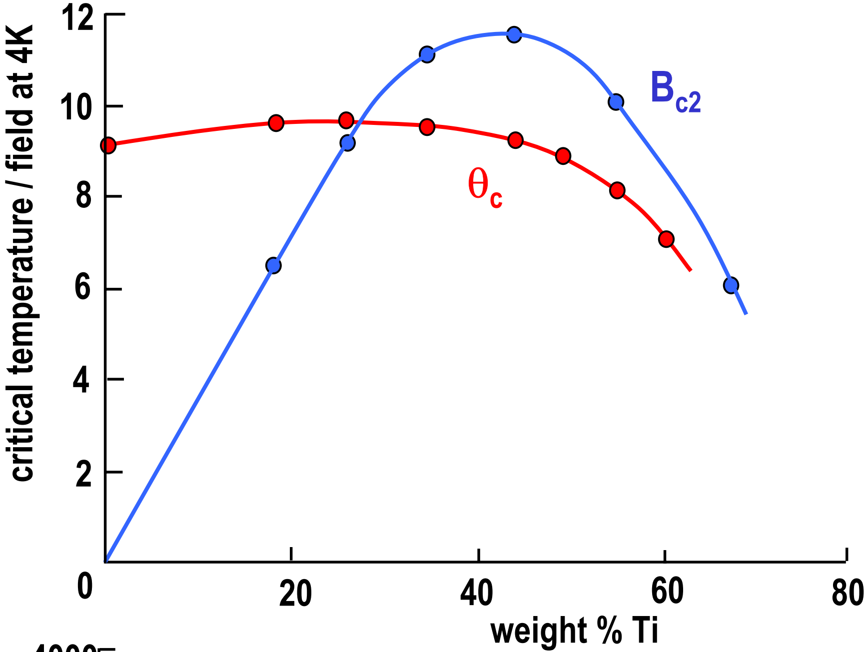
fluxoid lattice at 5T on the same scale

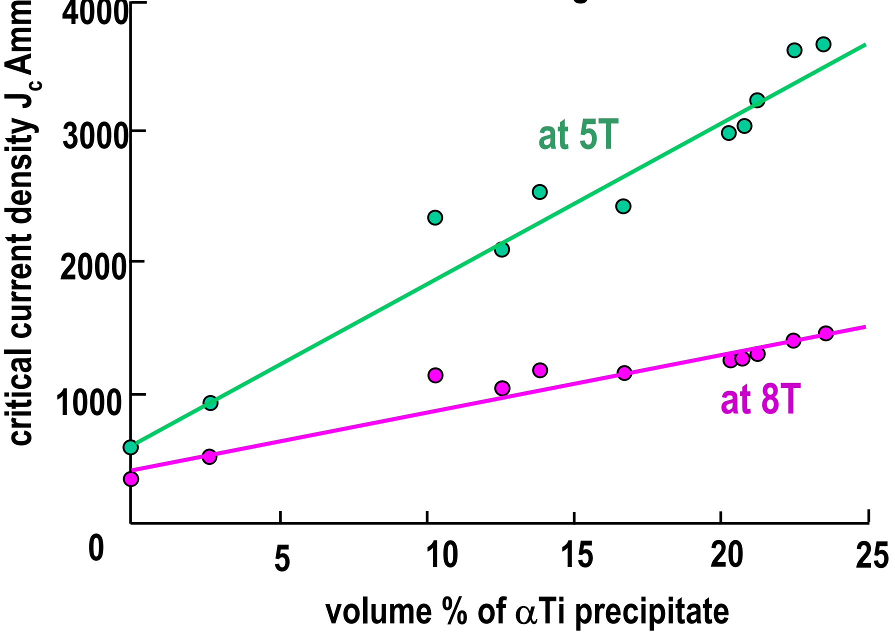
Critical properties

- **Critical temperature** θ_c: choose the right material to have a large energy gap or 'depairing energy'
  property of the material

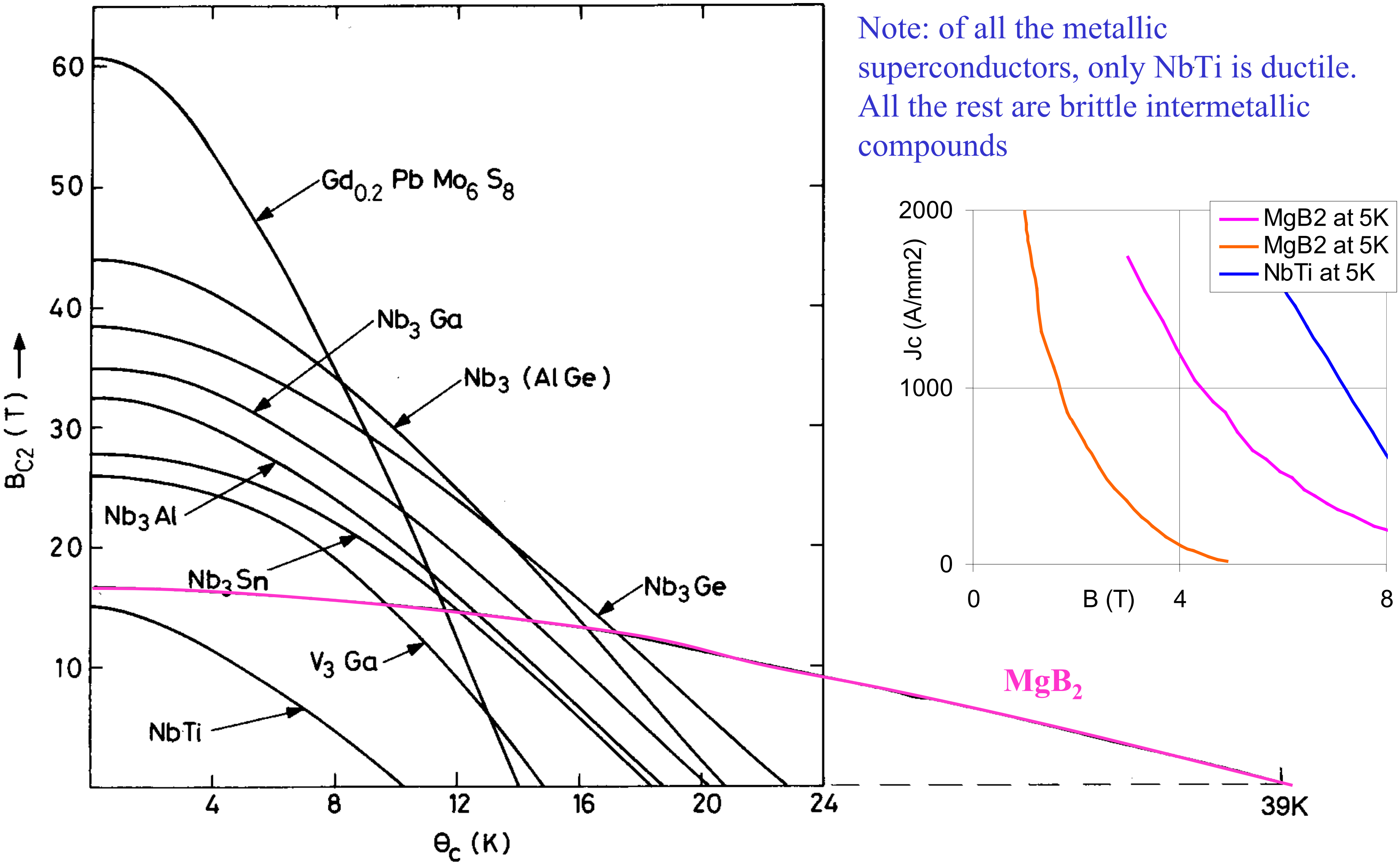
- **Upper Critical field** B_{c2}: choose a Type 2 superconductor with a high critical temperature and a high normal state resistivity
  property of the material

- **Critical current density** J_c: mess up the microstructure by cold working and precipitation heat treatments
  hard work by the producer



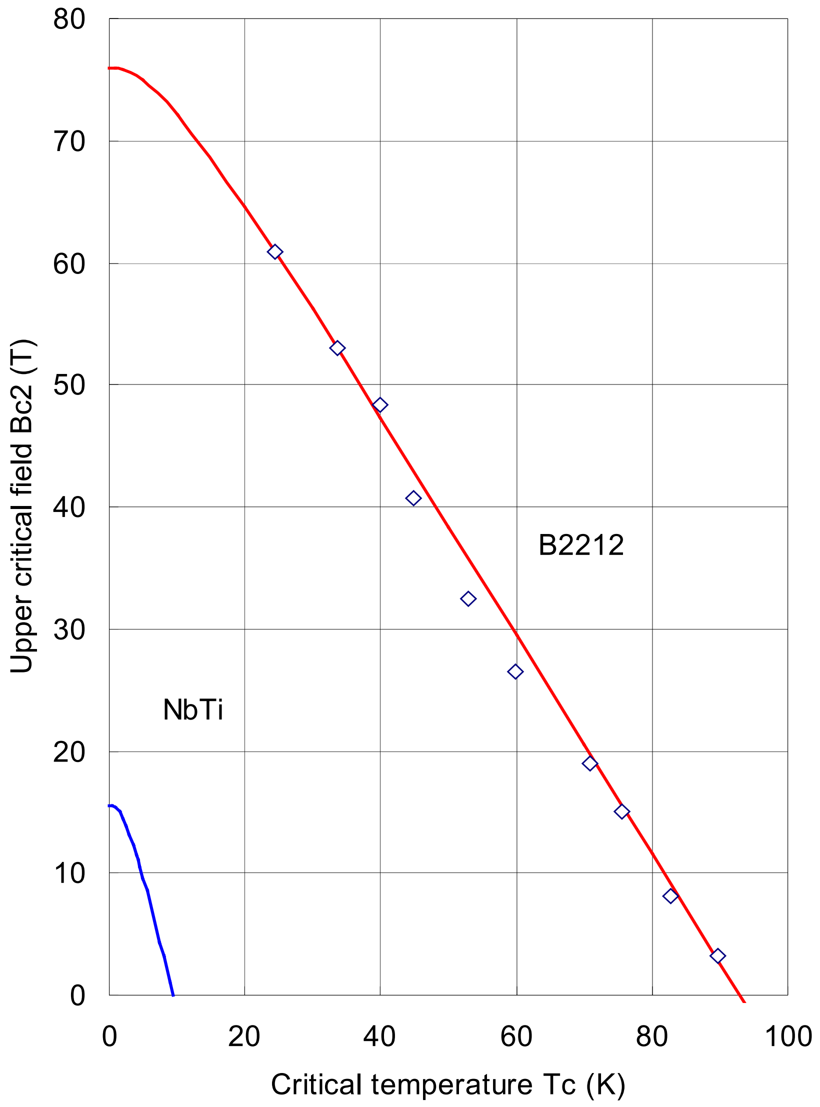


Upper critical fields of metallic superconductors



Note: of all the metallic superconductors, only NbTi is ductile. All the rest are brittle intermetallic compounds

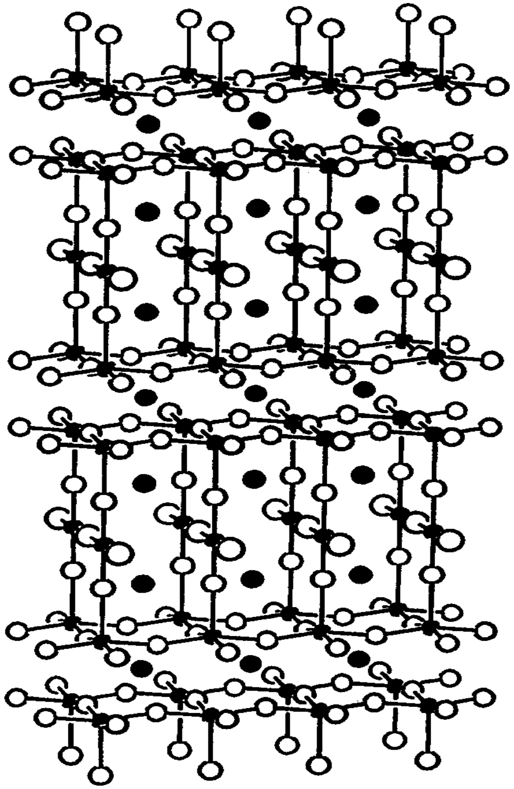
High temperature superconductors



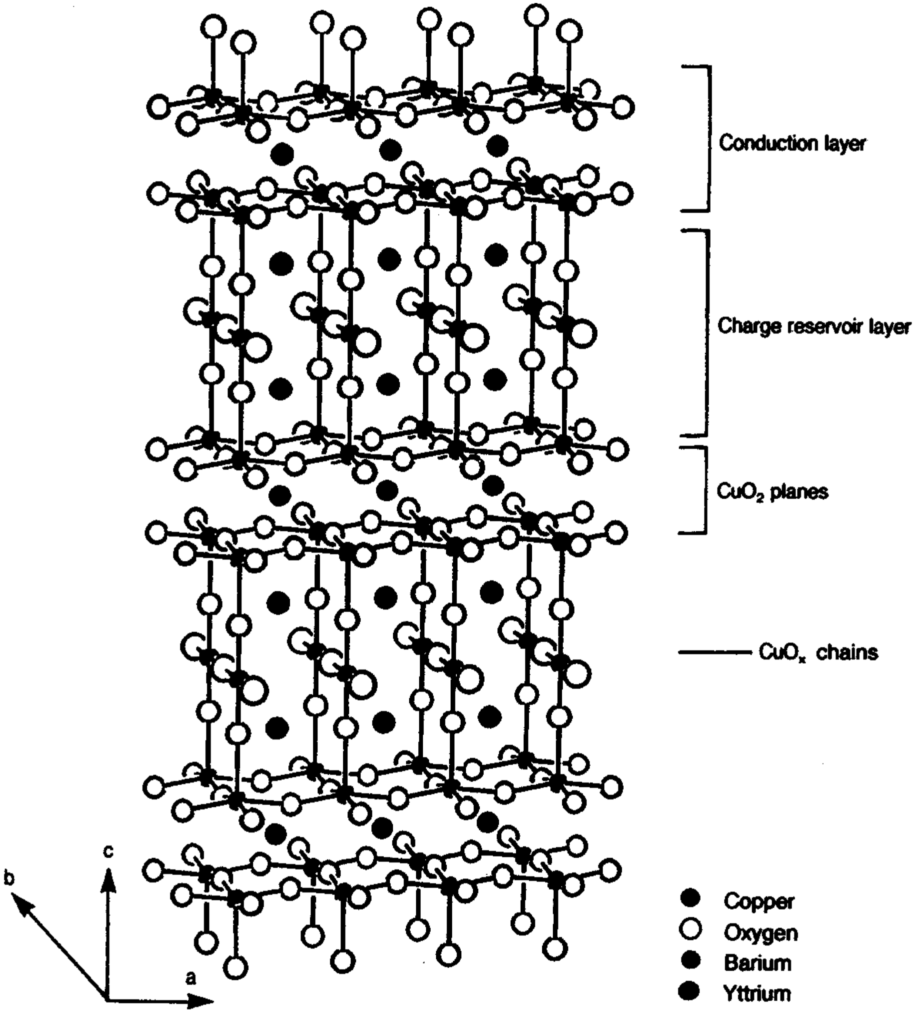
- many superconductors with critical temperature above 90K - BSCCO and YBCO
- operate in liquid nitrogen?

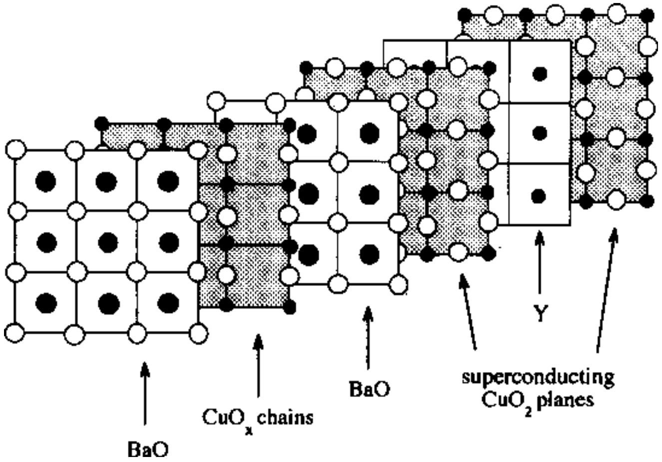
$YBa_2Cu_3O_7$

'YBCO'



High temperature superconductors





YBCO structure

Conduction layers consist of two CuO_2 layers separated by yttrium atoms.

The charge layer consists of copper, barium and oxygen atoms

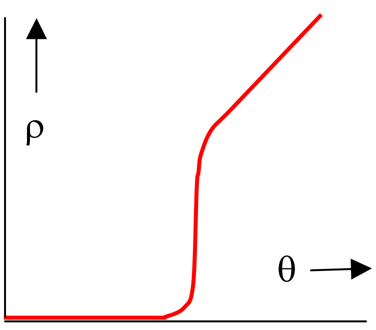
Note: this structure makes the properties highly anisotropic

Irreversibility line - a big disappointment

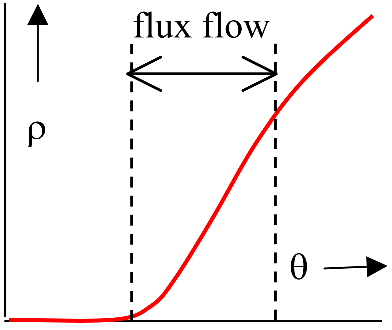
Unlike the metallic superconductors, HTS do not have a sharply defined critical current.

At higher temperatures and fields, there is an **'flux flow'** region, where the material is resistive - although still superconducting

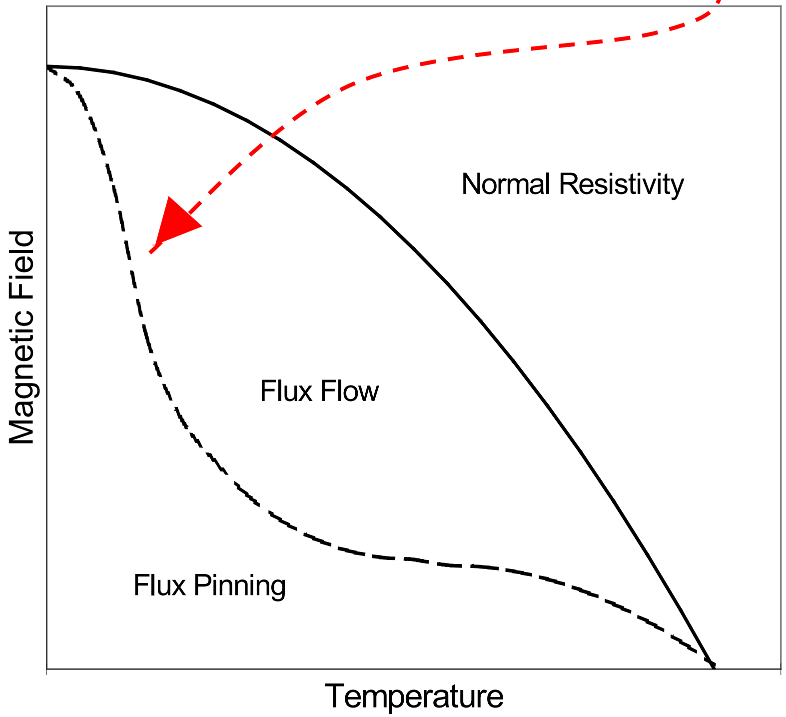
The boundary between flux pinning and flux flow is called the **irreversibility line**

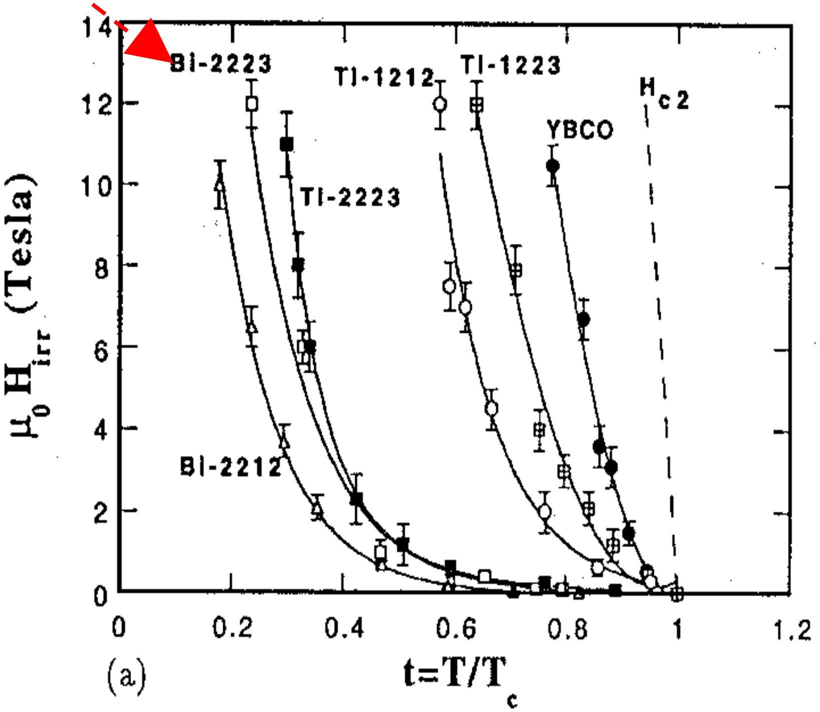


metallic

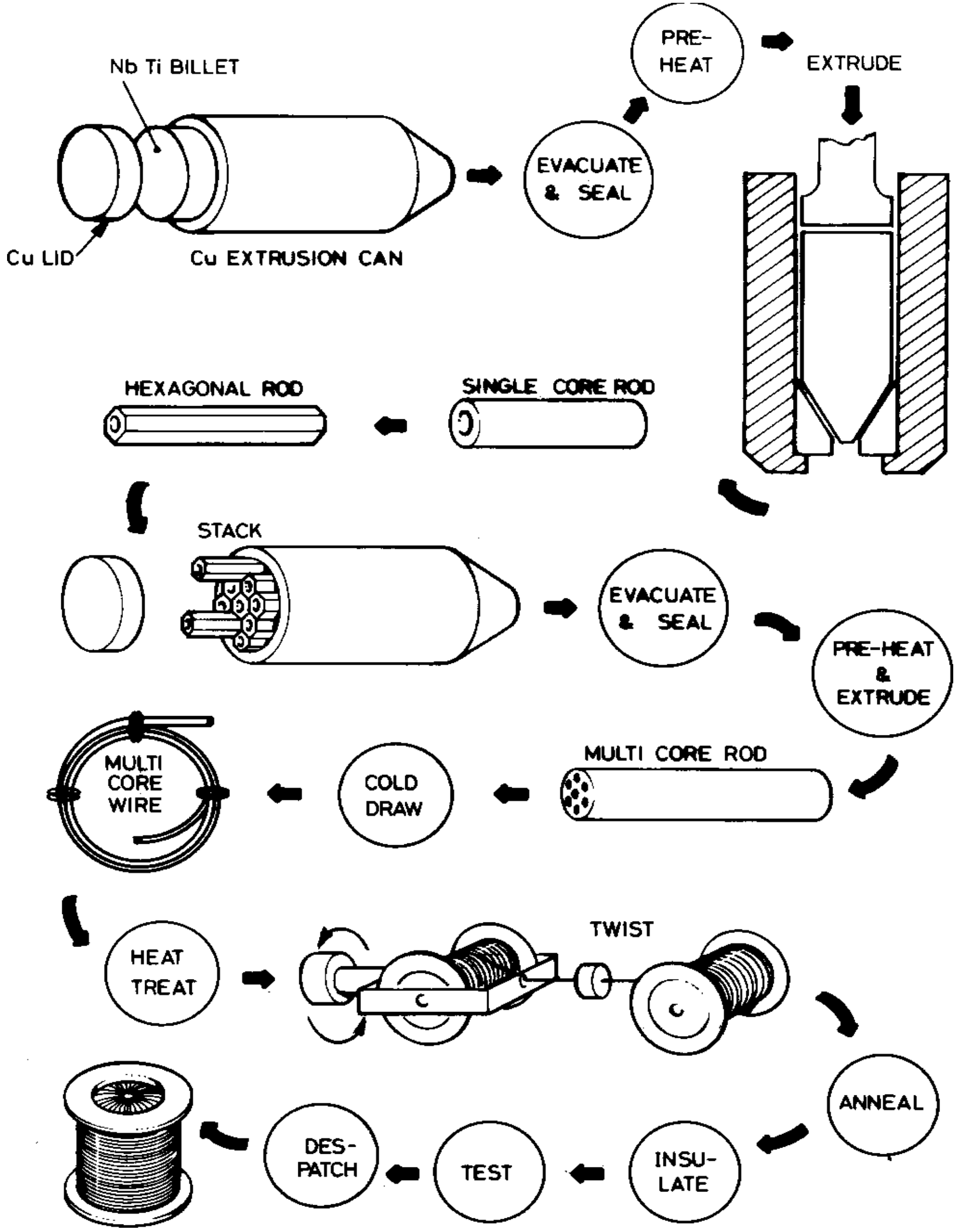


Oxide HTS





Manufacture of NbTi

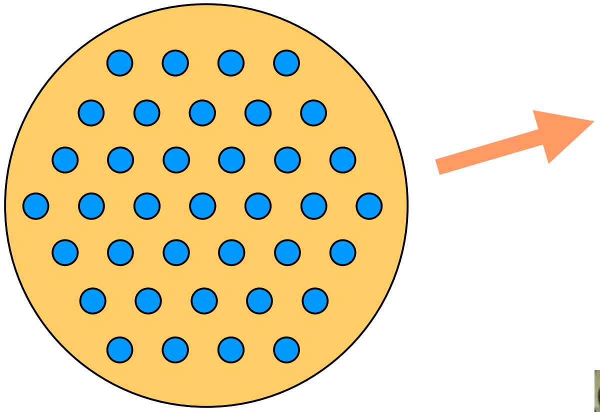


- vacuum melting of NbTi billets
- hot extrusion of the copper NbTi composite
- sequence of cold drawing and intermediate heat treatments to precipitate αTi phases as flux pinning centres
- for very fine filaments, must avoid the formation of brittle CuTi intermetallic compounds during heat treatment
  - usually done by enclosing the NbTi in a thin Nb shell
- twisting to avoid coupling - see lecture 2

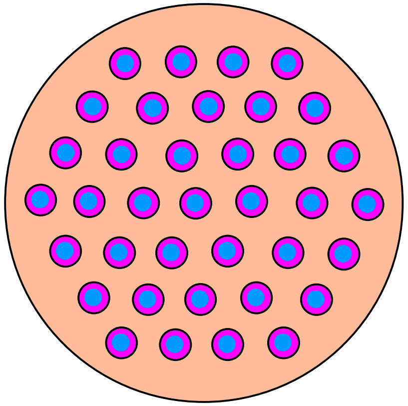
Filamentary Nb_3Sn wire via the bronze route

Nb_3Sn is a brittle material and cannot be drawn down.

Instead must draw down pure niobium in a matrix of bronze (copper tin)

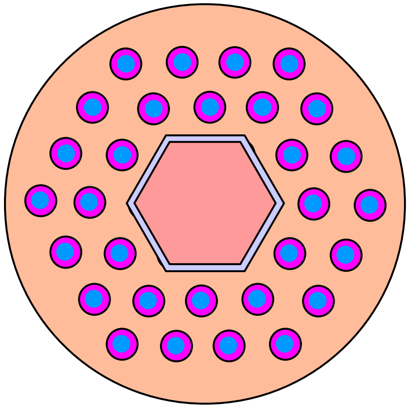


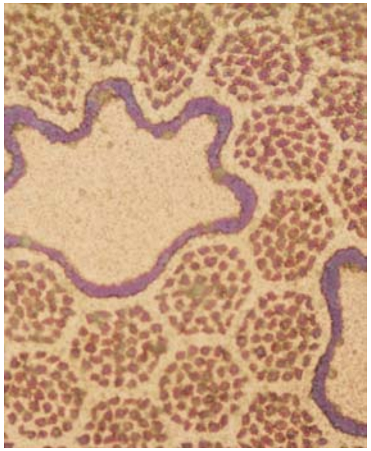
At final size the wire is heated (~700C for some days) tin diffuses through the Cu and reacts with the Nb to form Nb_3Sn



The remaining copper still contains ~ 3wt% tin and has a high resistivity ~ $6\times10^{-8}\Omega$m.

So include 'islands' of pure copper surrounded by a diffusion barrier

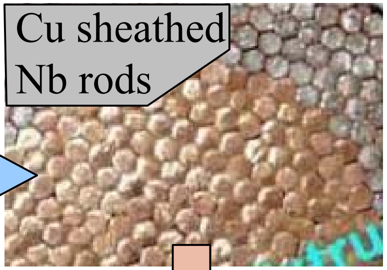




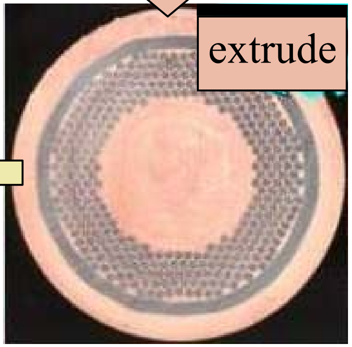
- *BUT maximum ductile bronze is ~13wt% tin,*
- *reaction slows at ~ 3wt%*
- *so low engineering J_c*

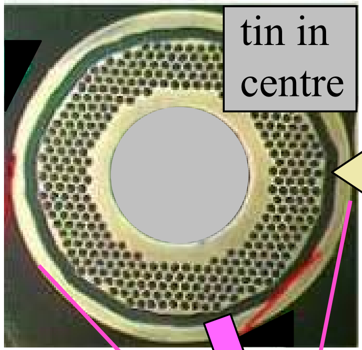
Nb_3Sn with higher engineering J_c

RRP®
Rod Restack Process
OXFORD INSTRUMENTS


Cu sheathed Nb rods

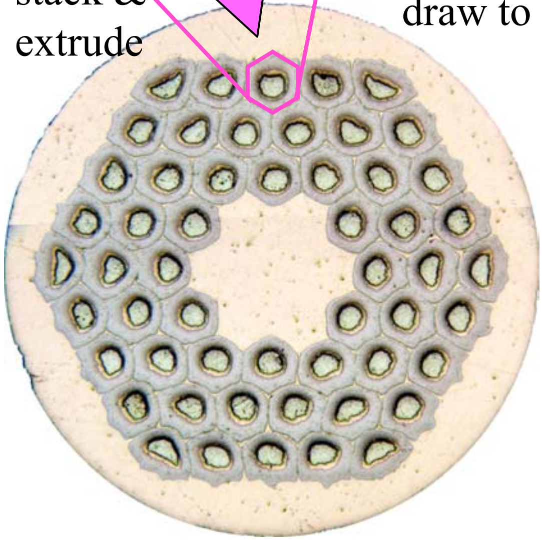
extrude



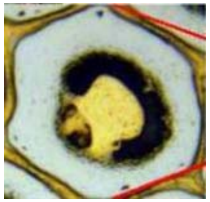

tin in centre

stack & extrude

draw to wire

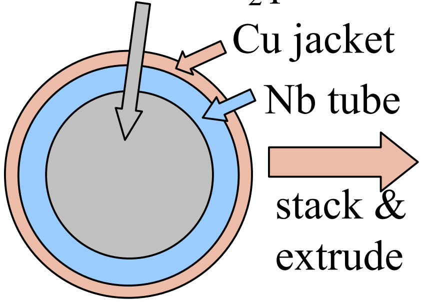


heat treat to form 'macro filaments' of Nb_3Sn

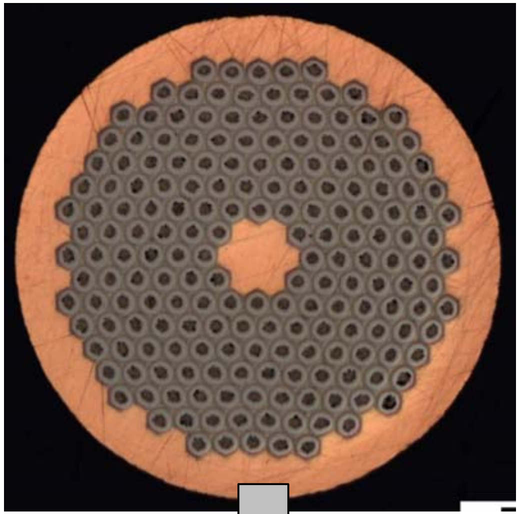


SMI
SHAPEMETAL INNOVATION B.V.

Powder in tube PIT

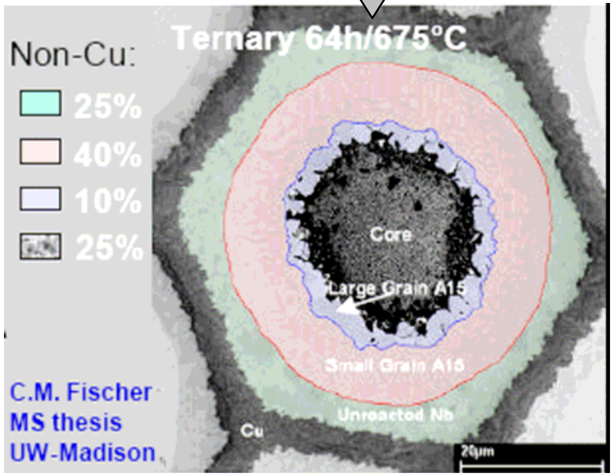

$NbSn_2$ powder
Cu jacket
Nb tube

stack & extrude



draw to wire

heat treat



C.M. Fischer
MS thesis
UW-Madison

both make high J_{eng}
(RRP is the highest)

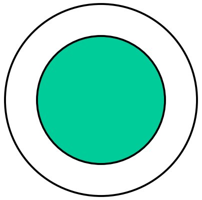
but large filaments

Manufacture of BSCCO HTS tapes

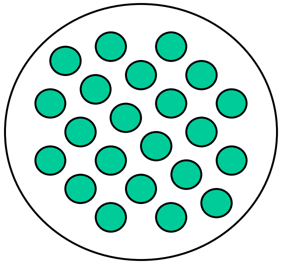
(Bismuth Strontium Calcium Copper Oxide)

1) Oxide powder in tube OPIT

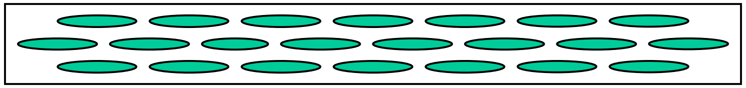
draw down
BSCCO powder
in a silver tube



stack many drawn wires
in another silver tube and
draw down again



roll the final wire to tape and heat treat at 800 - 900C in oxygen to melt the B2212

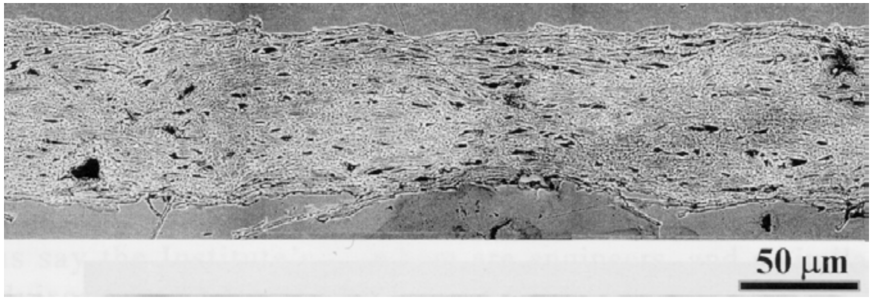


- for B2223, a special sequence of rolling and heat treatments must be used.
- the important feature of silver is that it is transparent to oxygen at high temperature, but does not react with it

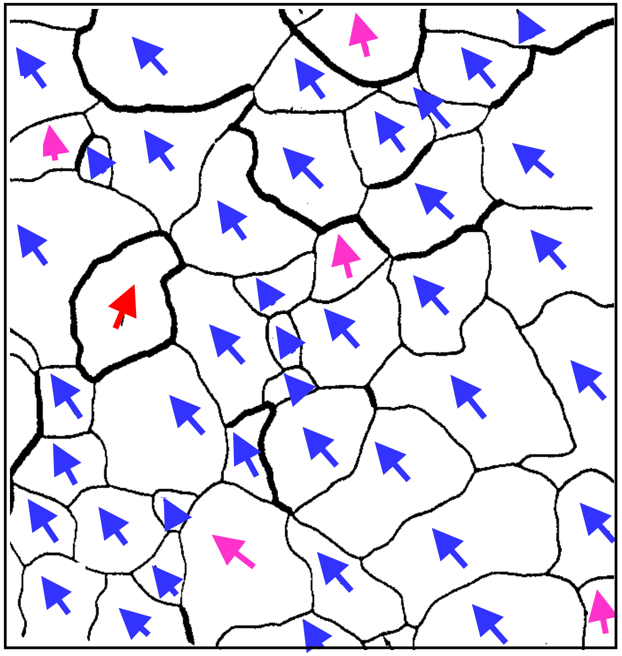
2) Dip coating

coat a silver tape with B2212 powder in an organic binder
heat treat to just melt the B2212

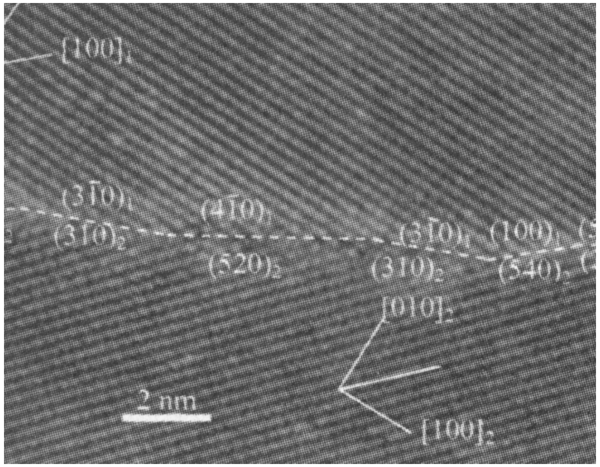
must achieve a good texture in the BSCCO layer
- silver is essential

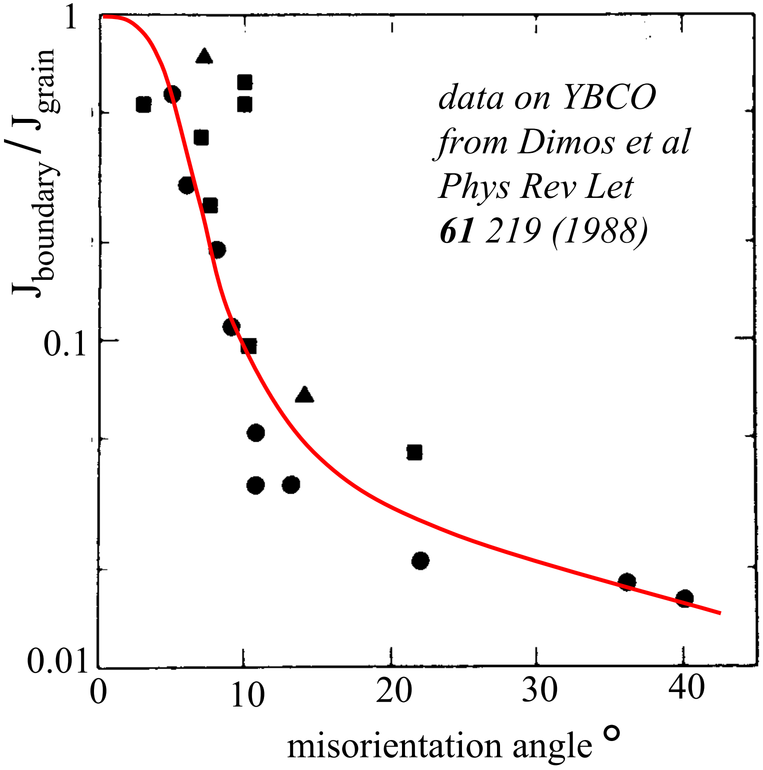


Transport current flow

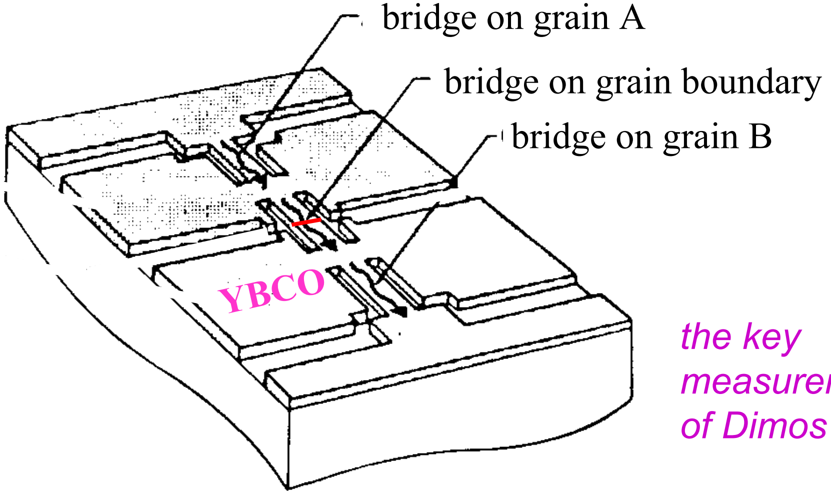


- real polycrystaline materials are made up of grains
- the crystal planes in different grains point in different directions
- critical currents are high within the grains
- across the grain boundary J_c depends on the misorientation angle





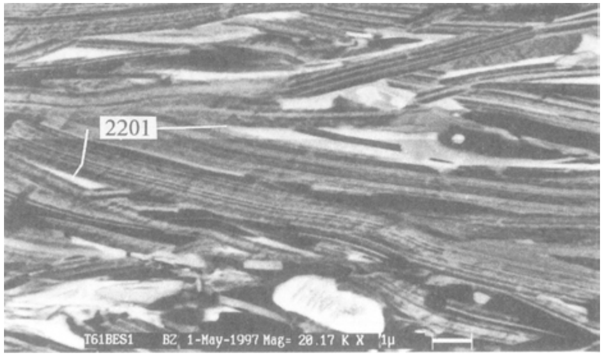
data on YBCO from Dimos et al Phys Rev Let ***61*** *219 (1988)*

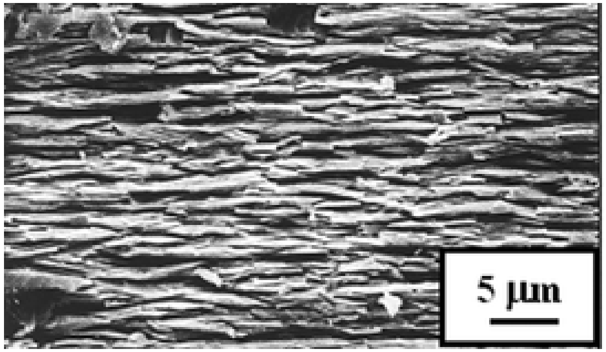


the key measurement of Dimos et al

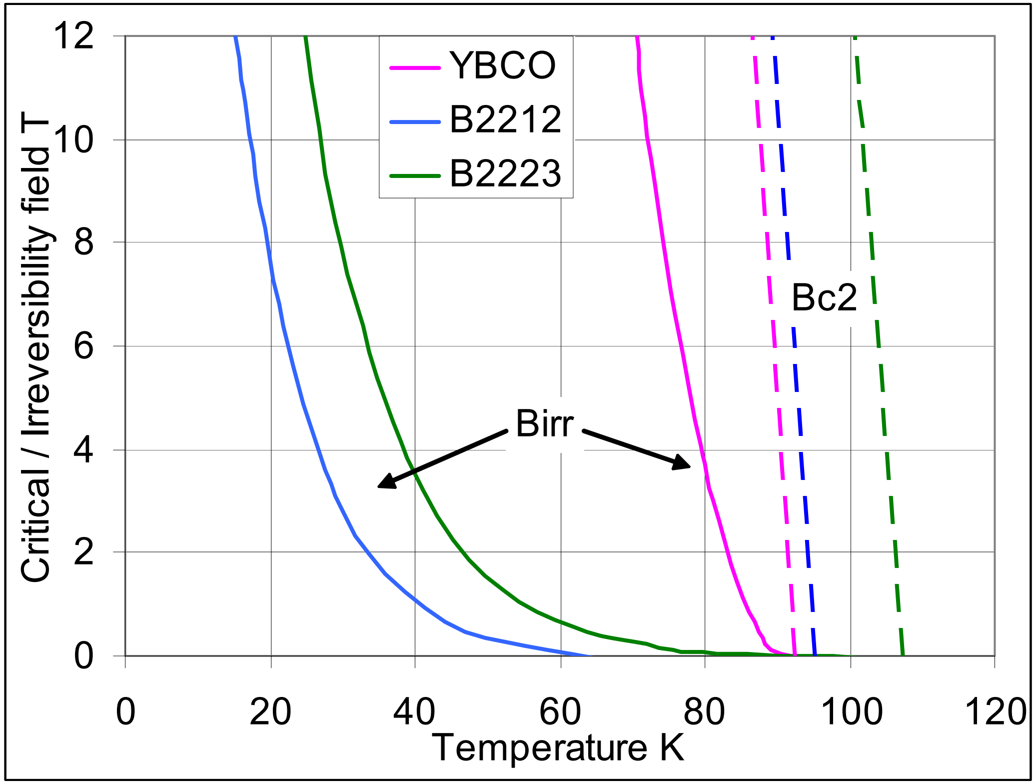
Grain alignment - texture

- Grains of BSCCO tend to line up when in contact with silver
- BSCCO is not as sensitive as YBCO to misalignment





- grains of YBCO do not line up
- **BUT** YBCO has much better irreversibility line ⇒
- so for magnets at higher temperatures we need YBCO
- if it is to carry current, we need to line up the grains



Production of textured YBCO tape

YBCO has a much better irreversibility line than BSCCO but, unlike BSCCO, the grains do not align during processing. If grains are not aligned the supercurrent cannot jump between them

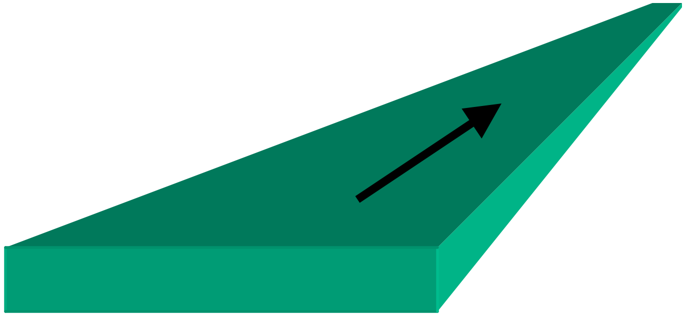
- so we must force the grains to align via a texturing process

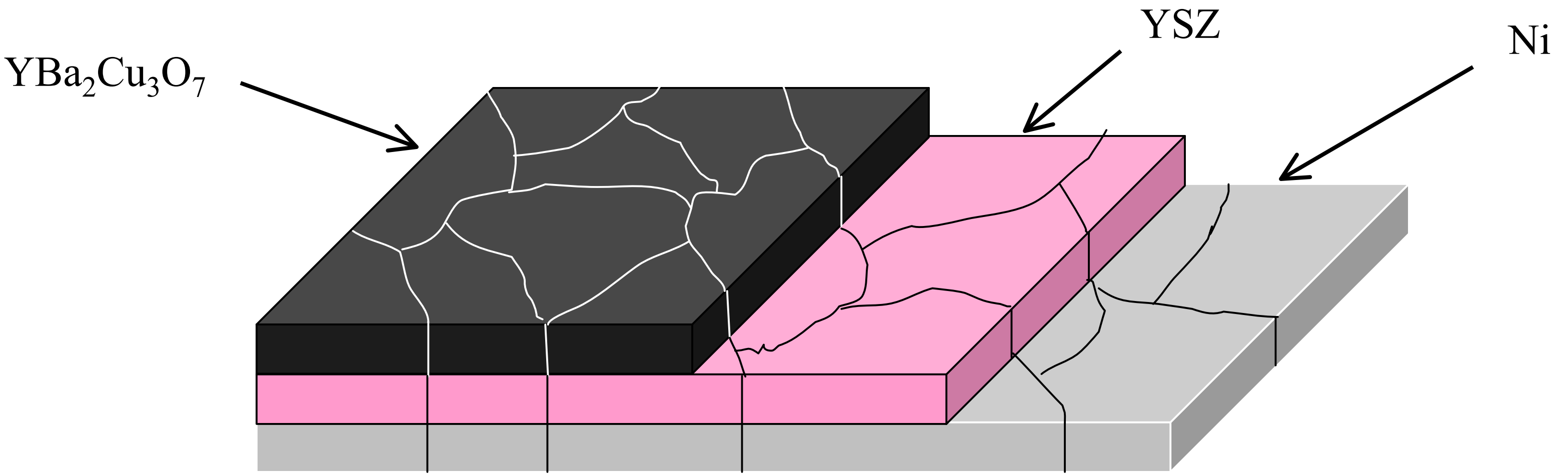
1) Produce a rolled nickel tape with an aligned texture

RABiTS Rolled And Biaxially Textured Substrate

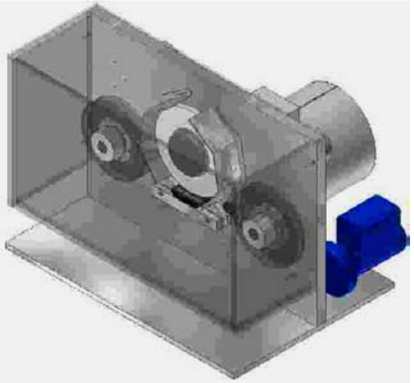
2) Coat the tape with a buffer layer, eg Ce_2O_3 such that the texture of the buffer follows that of the substrate

3) Coat the buffer with a layer $YBa_2Cu_3O_7$ such that the texture of the YBCO follows that of the buffer and substrate

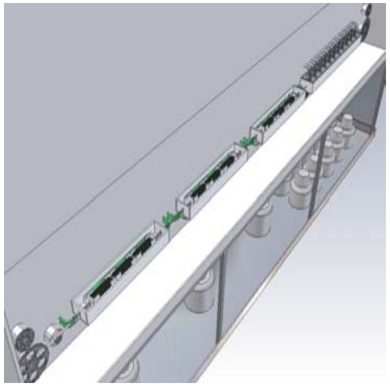




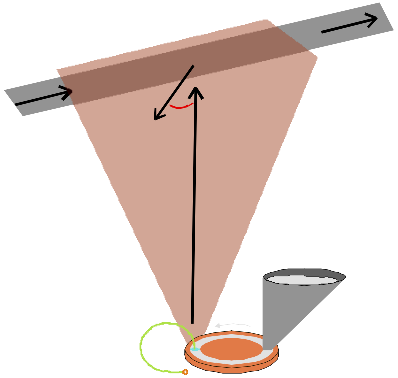
Manufacturing process for textured YBCO tape



mechanical grinding

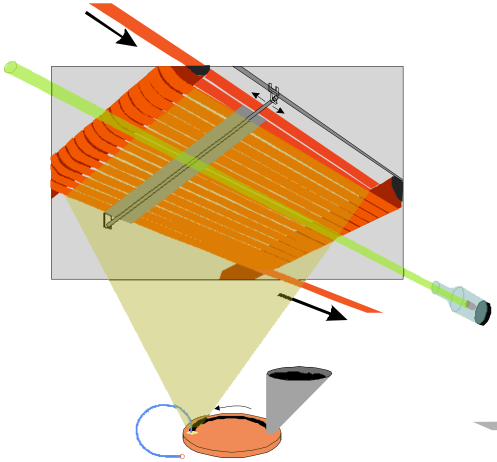


electro-polishing

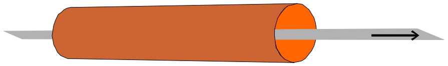


oriented buffer

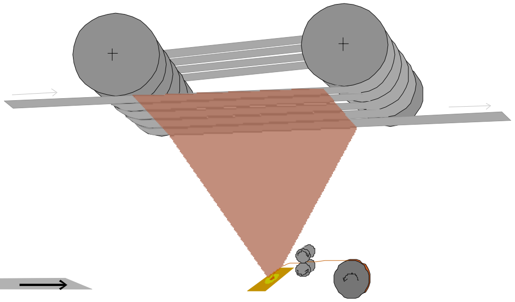
enhance buffer



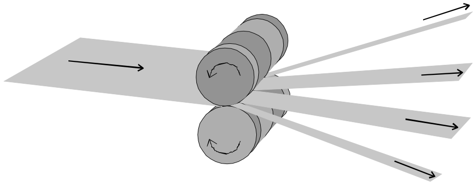
HTS coating



O_2 - anneal



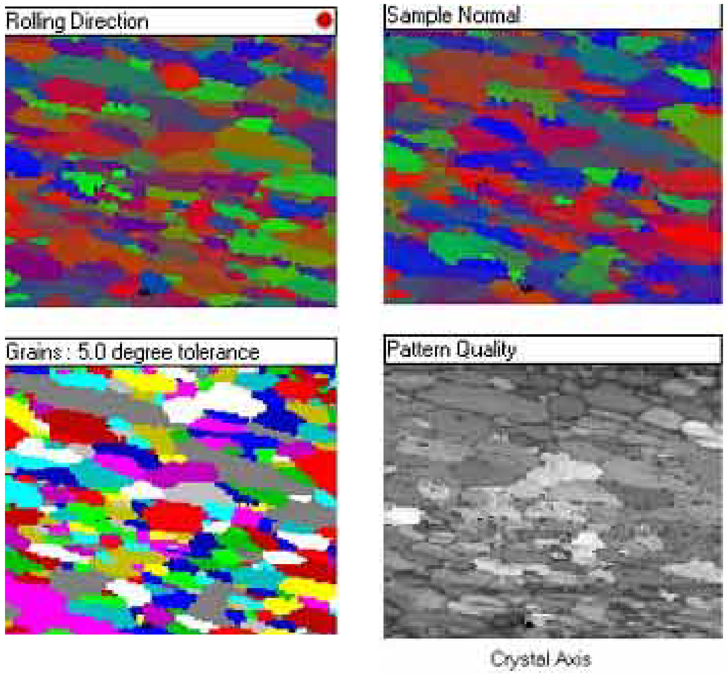
metal coating



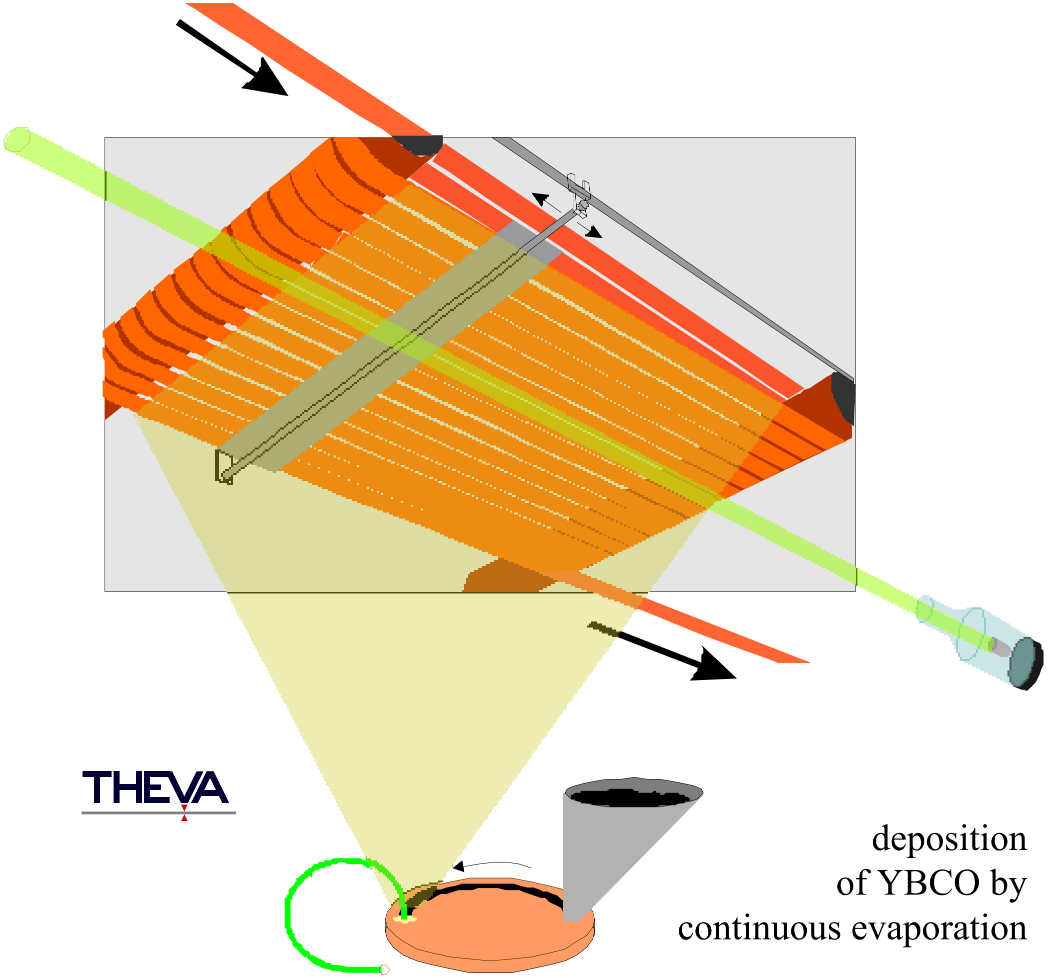
slicing

THEVA

Tape production

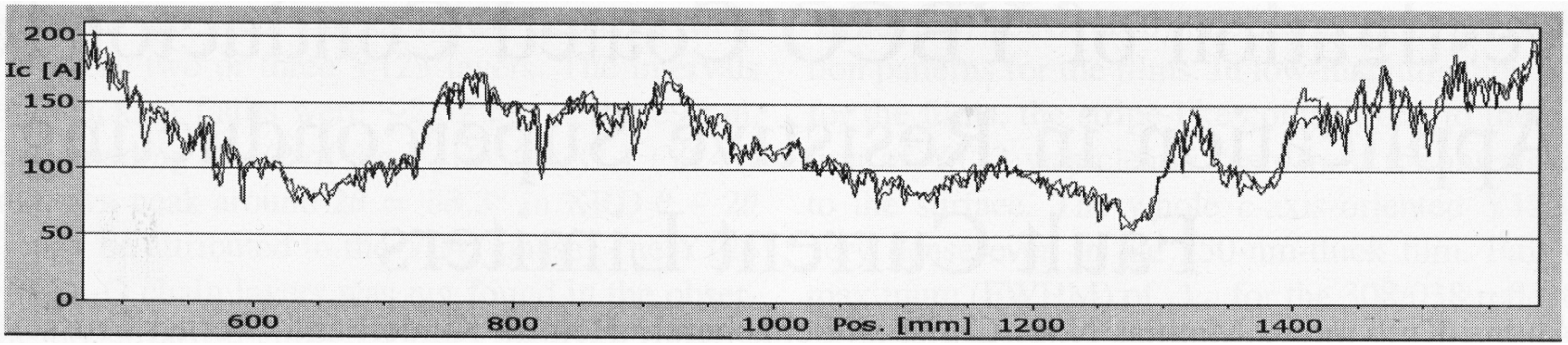


grain orientation map by Electron Backscatter Diffraction (EBSD) in a scanning electron microscope (SEM).



deposition of YBCO by continuous evaporation

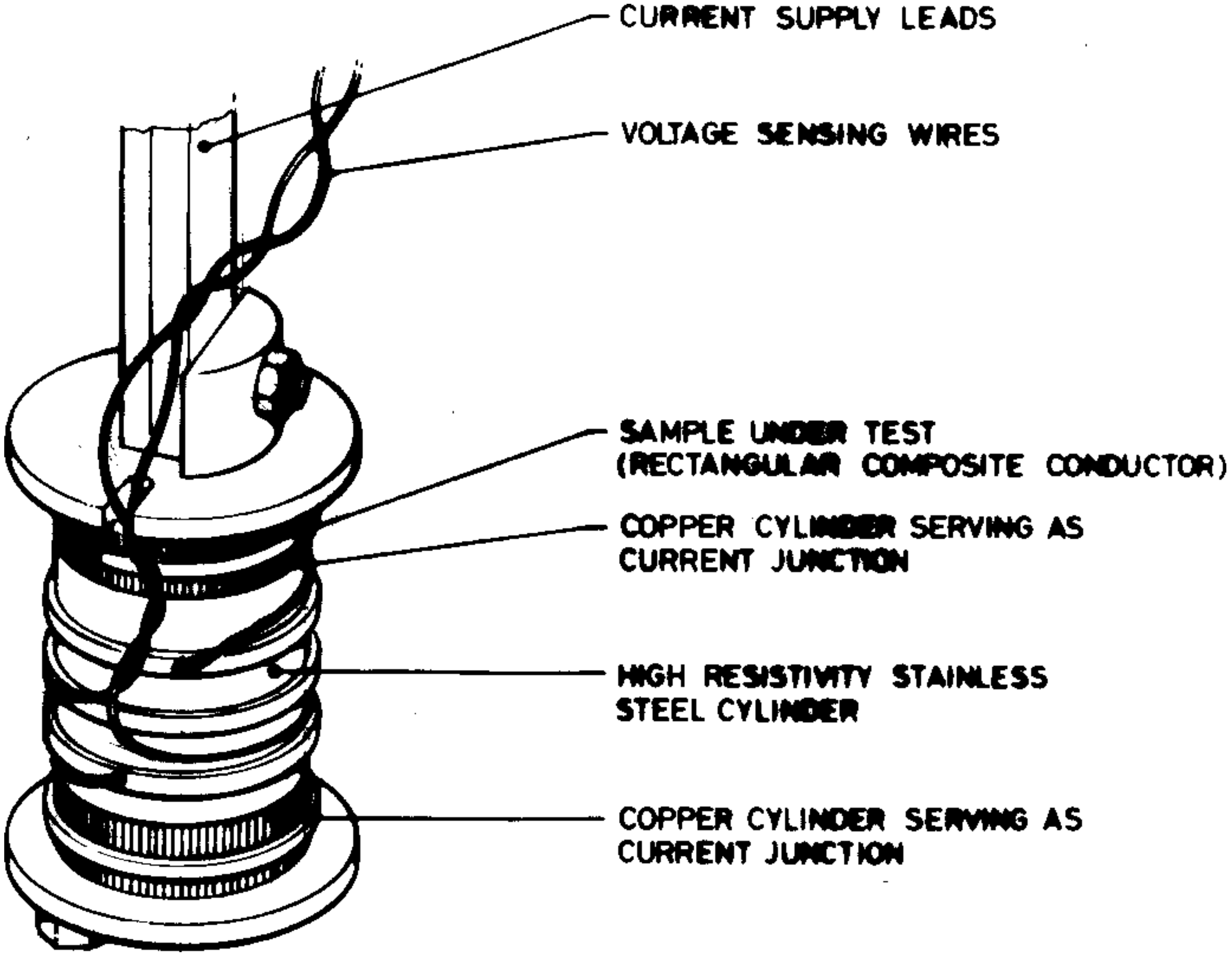
plot of critical current along the tape



Measurement of critical current

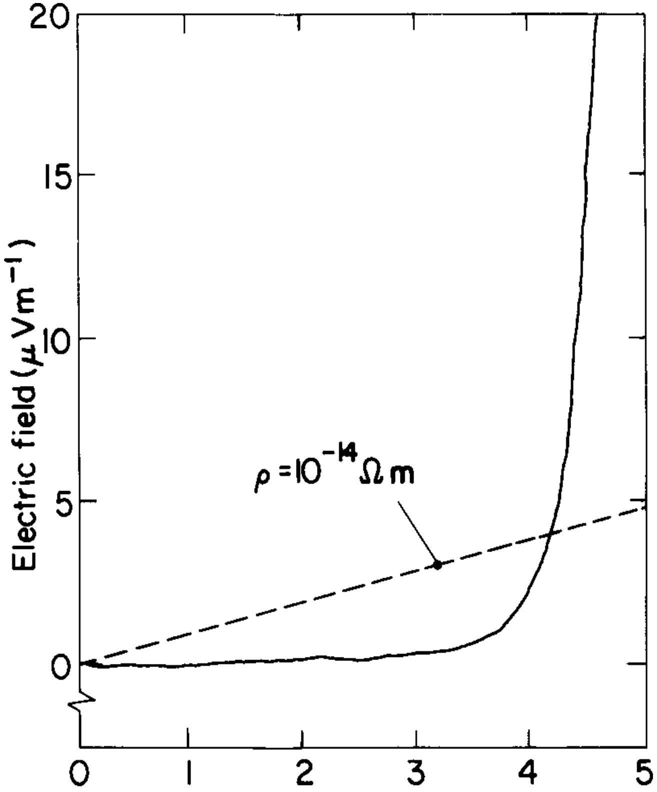
his sample holder is placed in the bore of a superconducting solenoid, usually in liquid helium boiling at 4.2K

t each field level the current is slowly increased and voltage across the test section is measured



Resistive transition 1

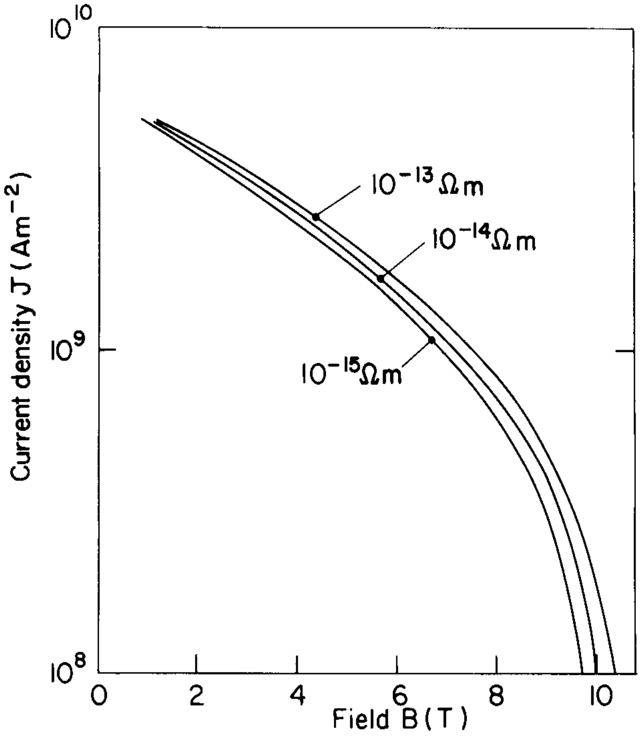
When measured sensitively, the boundary between superconducting and resistive states is not sharp, but slightly blurred.



Overall Current density 10^{8} A.m^{-2}

If we measure J_c with voltage taps across the sample, we see that the voltage rises gradually.

To define Jc, we must therefore define a measurement sensitivity in terms of electric field or effective resistivity.



Commonly used definitions are **$\rho = 10^{-14}\,\Omega$m or E = 1 μV.m^{-1}**

Critical current defined at this level is about what you would expect the conductor in a resin impregnated solenoid to achieve. At higher resistivity, self heating starts to raise the internal temperature and reduce the critical current

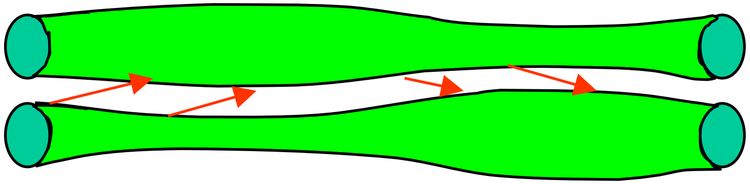
Resistive transition 2

It has been found empirically that the resistive transition may be represented by a power law

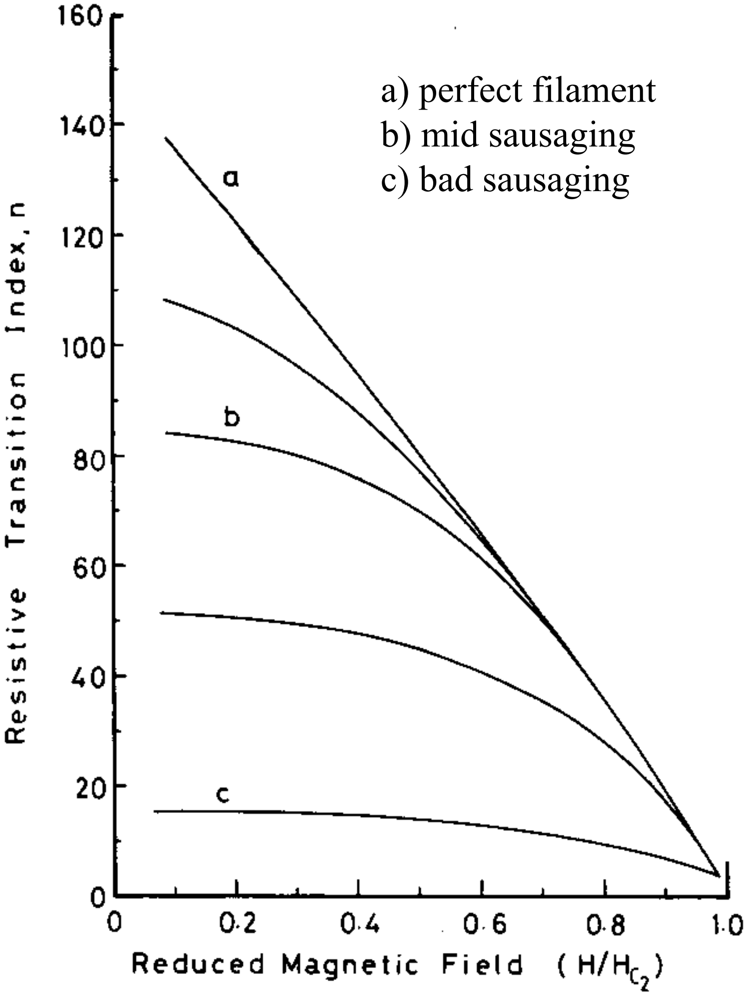
$$\rho(J) = \rho_o \left\{ \frac{J}{J_o} \right\}^n$$

where n is called the resistive transition index.

- the effect is partly within the filaments (flux flow) and partly between the filaments
- 'sausaging of the filaments, forces current to cross the copper matrix as critical current is approached.



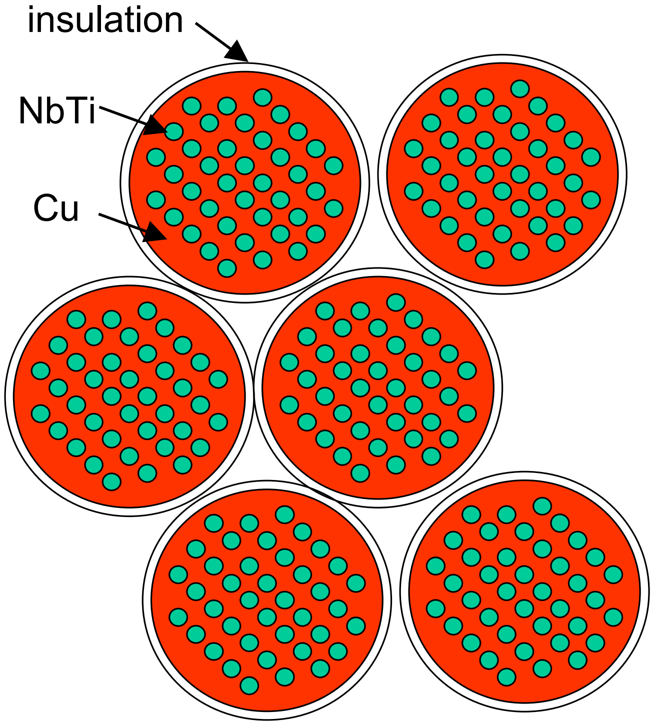
- resistive transition can be the main source of decay in persistent magnets
- 'n' is often taken as a measure of quality - look for n > 50
- HTS conductors so far have low n ~ 5 - 10



Engineering current density

In designing a magnet, what really matters is the overall 'engineering' current density $\boldsymbol{J_{eng}}$

$$J_{eng} = \frac{current}{unit\ \ cell\ \ area} = J_{supercon} \times \lambda_{metal} \times \lambda_{winding}$$



fill factor in the wire $\lambda_{metal} = \dfrac{1}{(1+mat)}$

where *mat* = matrix : superconductor ratio

typically:

for NbTi *mat* = 1.5 to 3.0 ie $\lambda_{\mathrm{metal}} = 0.4$ to 0.25

for Nb_3Sn *mat* ~ 3.0 ie $\lambda_{\mathrm{metal}} \sim 0.25$

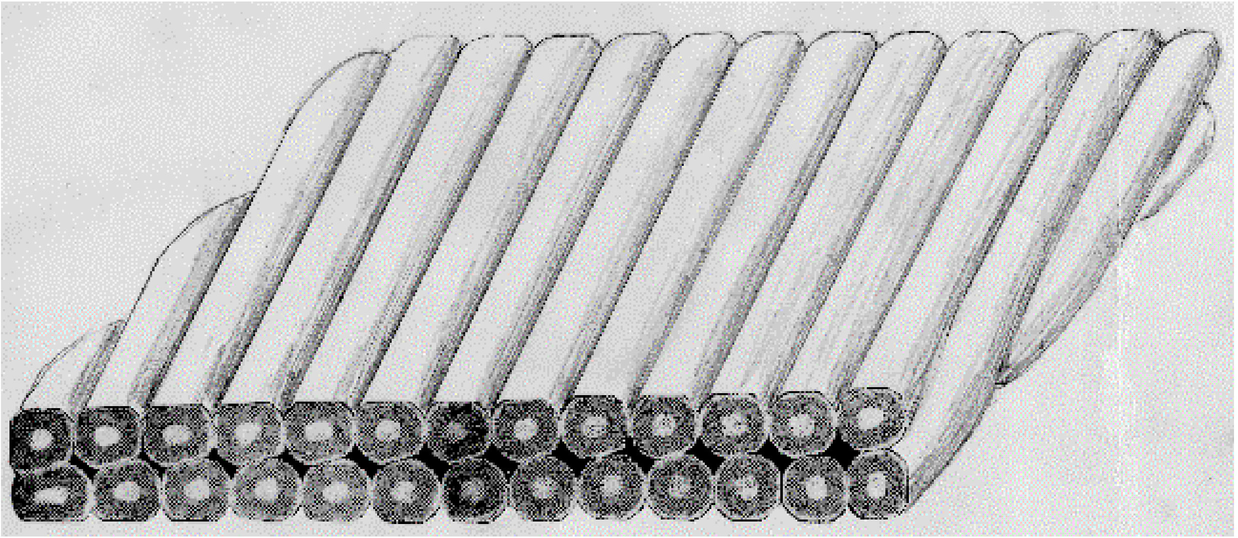
for B2212 *mat* = 3.0 to 4.0 ie $\lambda_{\mathrm{metal}} = 0.25$ to 0.2

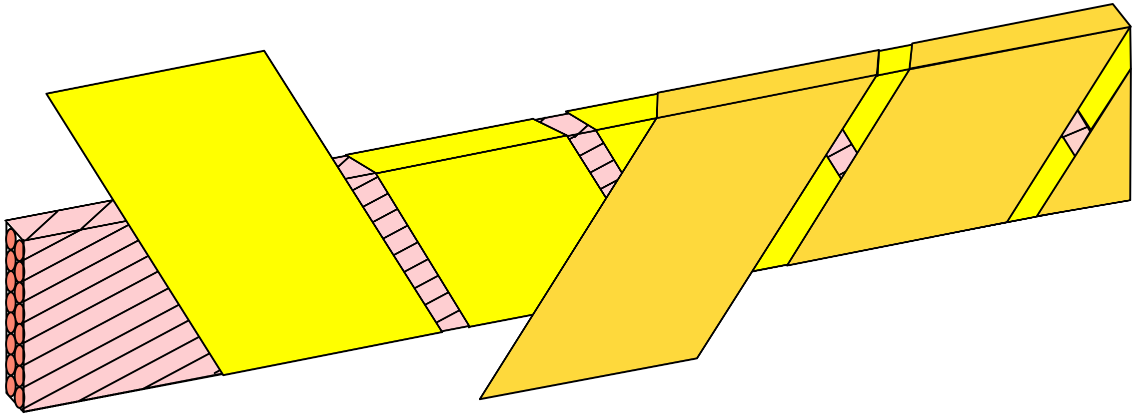
$\lambda_{\mathrm{winding}}$ takes account of space occupied by insulation, cooling channels, mechanical reinforcement etc and is typically 0.7 to 0.8

So typically $\boldsymbol{J_{eng}}$ is only 15% to 30% of $\boldsymbol{J_{supercon}}$

Rutherford cable

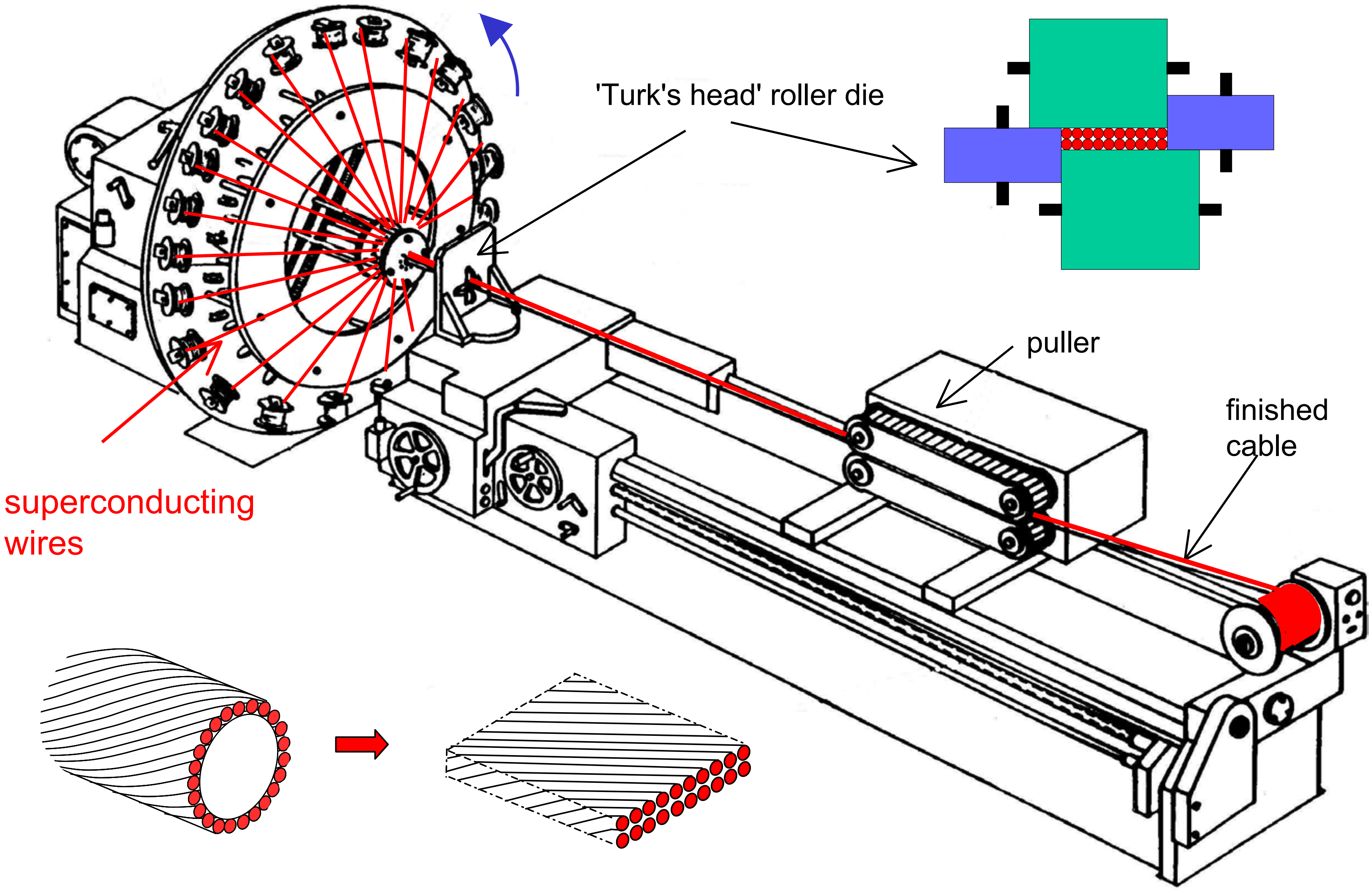
- for high current applications, such as accelerators, we need many wires in parallel
- the most popular way of doing this is the Rutherford cable (see lecture 3)





- Rutherford cable is usually insulated by wrapping it with Kapton tape

Manufacture of Rutherford cable



Lecture 1: concluding remarks

- superconductors allow us to build magnets which burn no power (except refrigeration)
- ampere turns are cheap, so don't need iron

  ⇒ fields higher than iron saturation (but still use iron for shielding)
- performance of all superconductors described by the critical surface in ***B J θ*** space,
- three kinds of superconductor
  - **type 1**: low temperature, unsuitable for high field
  - **type 2**: low temperature, good for high field - but must create flux pinning to get current density
  - **HTS**: high temperature, high field - but current density is still a problem
- NbTi is the most common commercial superconductor - standard production process
- Nb_3Sn has higher critical field & temperature - specialized commercial production
- BSCO high temperature **or** high field, but not both - prototype commercial production
- YBCO high temperature **and** high field, but must align the grains - research production
- measure I_c to check specification, the index n indicates quality
- for accelerators, so far it's only been NbTi, often in Rutherford cables