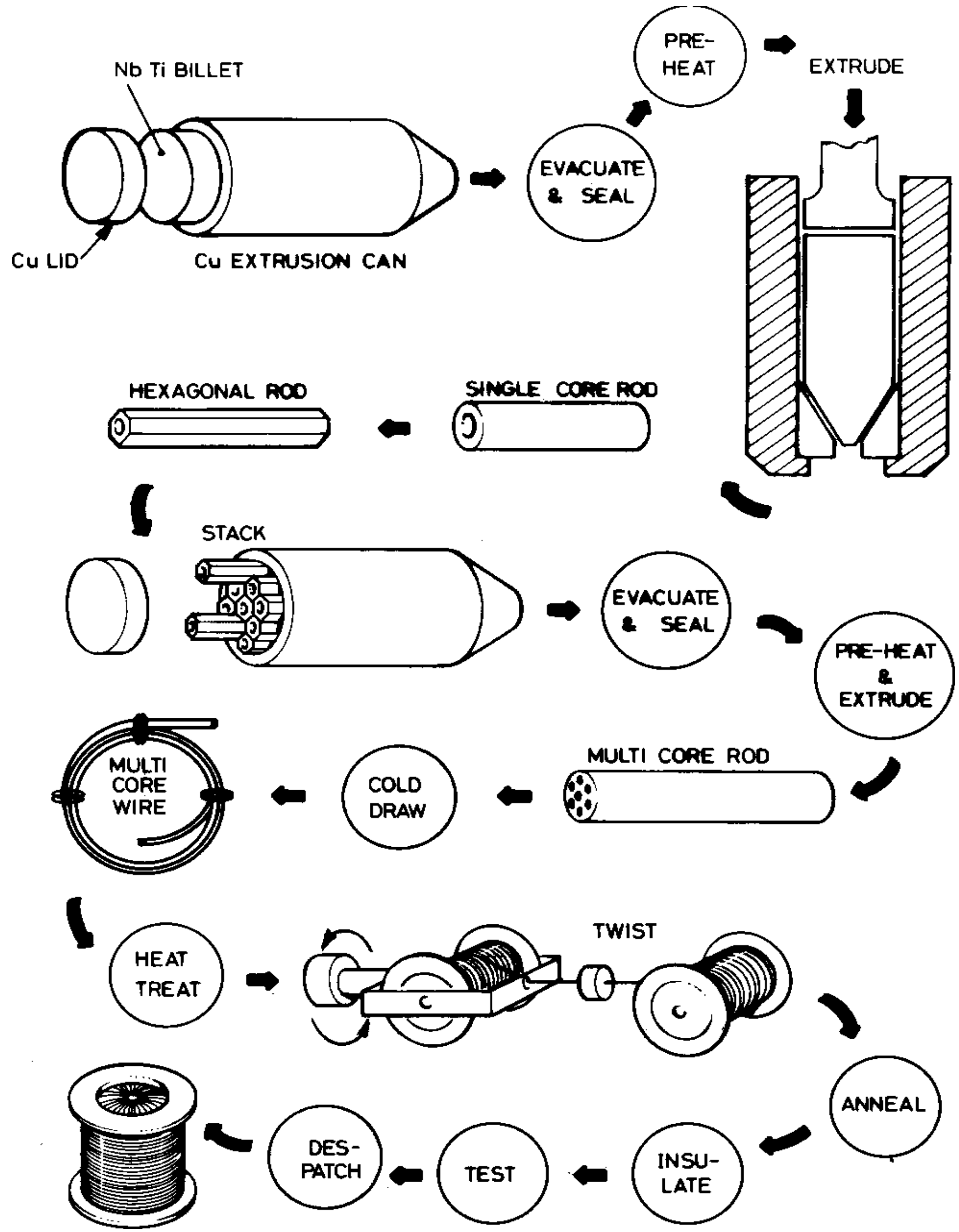
NbTi manufacture



- 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

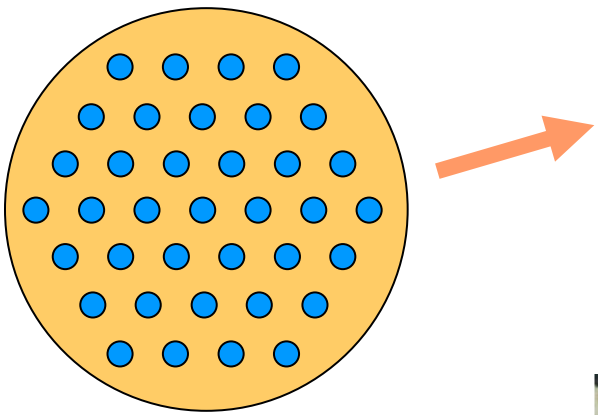
Filamentary Nb_3Sn wire via the bronze route

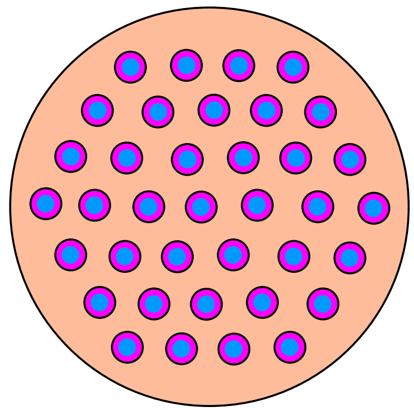
Nb_3Sn is a brittle material and cannot be drawn down.

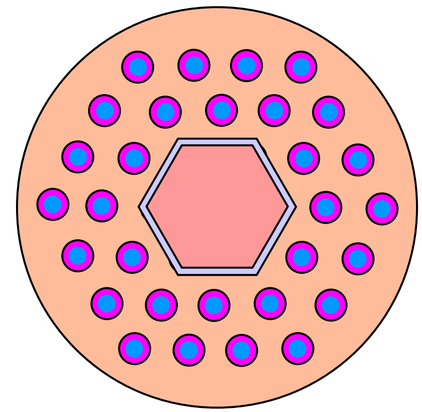
Instead must draw down pure niobium in a matrix of bronze (copper tin)

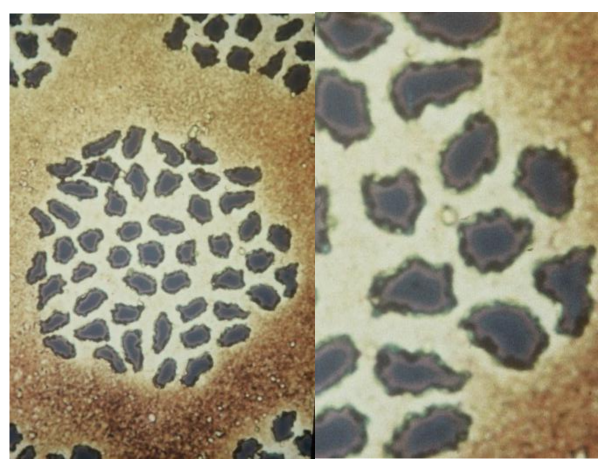
At final size the wire is heated (~700C for some days) tin diffuses through the Cu and reacts with the Nb to form Nb_3Sn

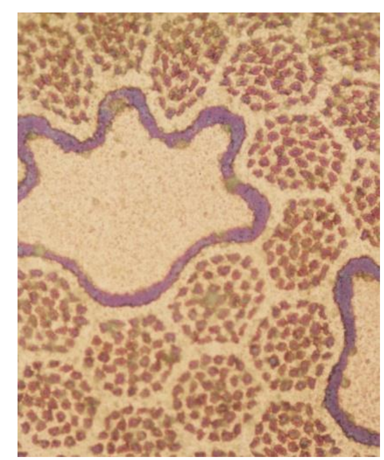
The remaining copper still contains ~ 3wt% tin and has a high resistivity ~ $6 \times 10^{-8} \Omega$m.
So include 'islands' of pure copper surrounded by a diffusion barrier







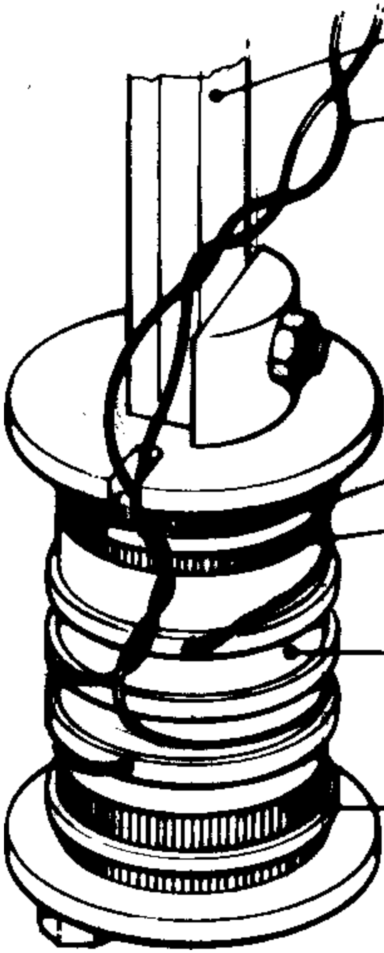




- *BUT maximum ductile bronze is ~13wt% tin,*
- *reaction slows at ~ 3wt%*
- *so low engineering J_c*

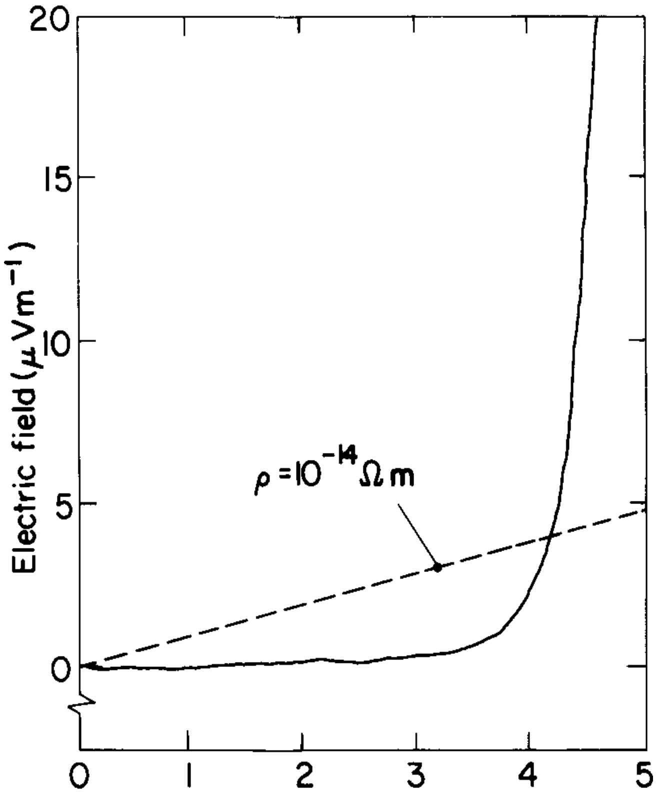
Measurement of critical current

- this sample holder is placed in the bore of a superconducting solenoid, usually in liquid helium boiling at 4.2K
- at each field level the current is slowly increased and voltage across the test section is measured



Resistive transition 1

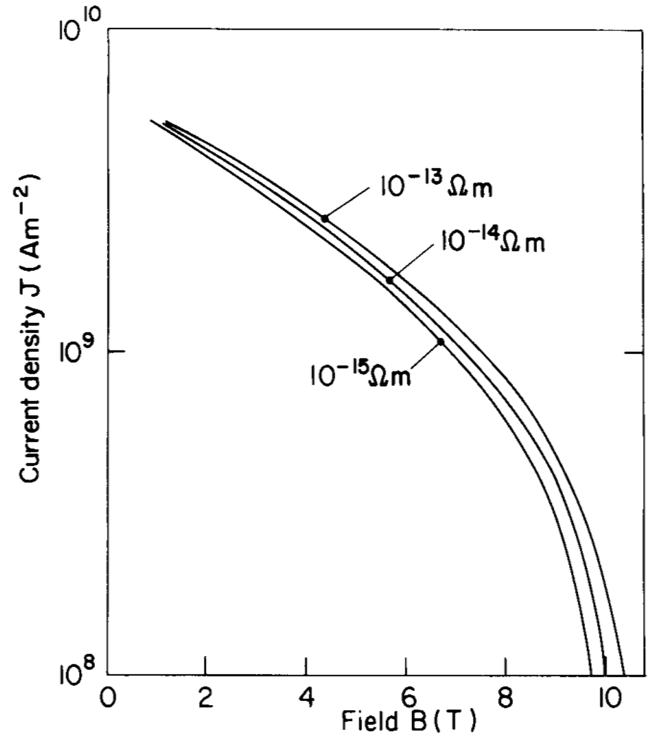
When measured sensitively, the boundary between superconducting and resistive states is not sharp, but slightly blurred.



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

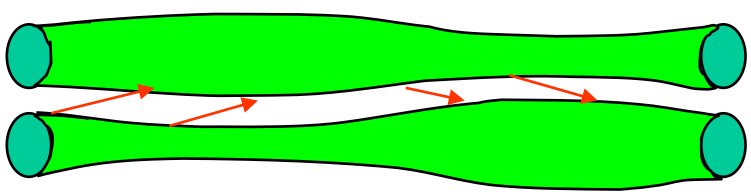
Resistive transition 2

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

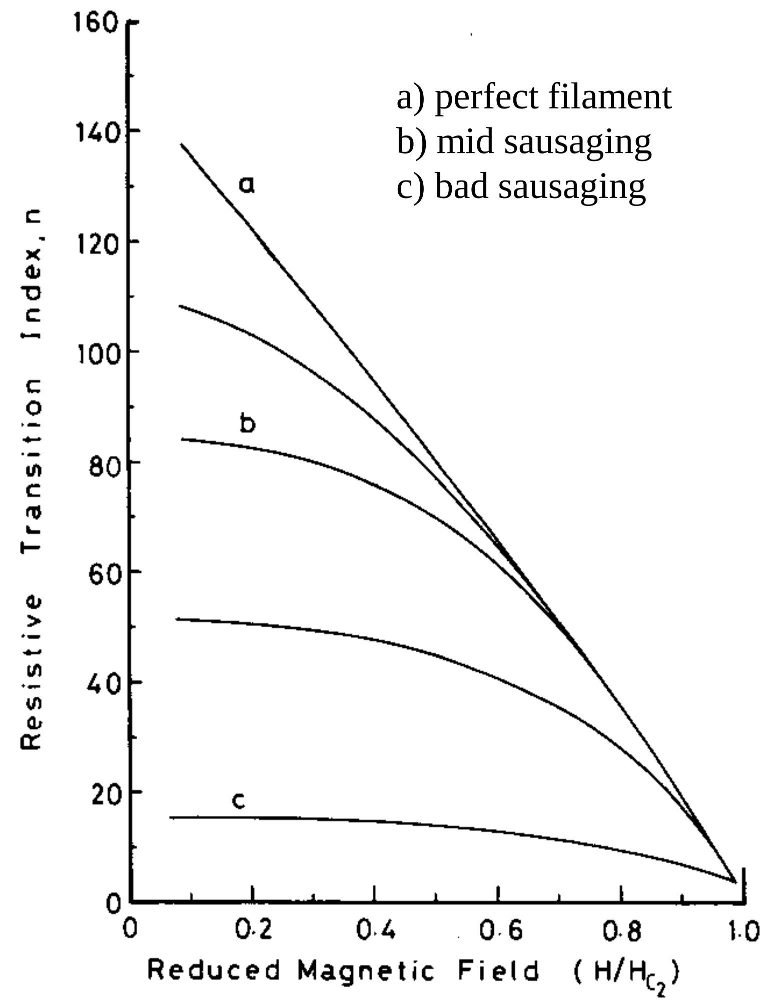
$$\rho(J) = \rho_o \left\{ \frac{J}{J_o} \right\}^n$$

where n is called the resistive transition index.

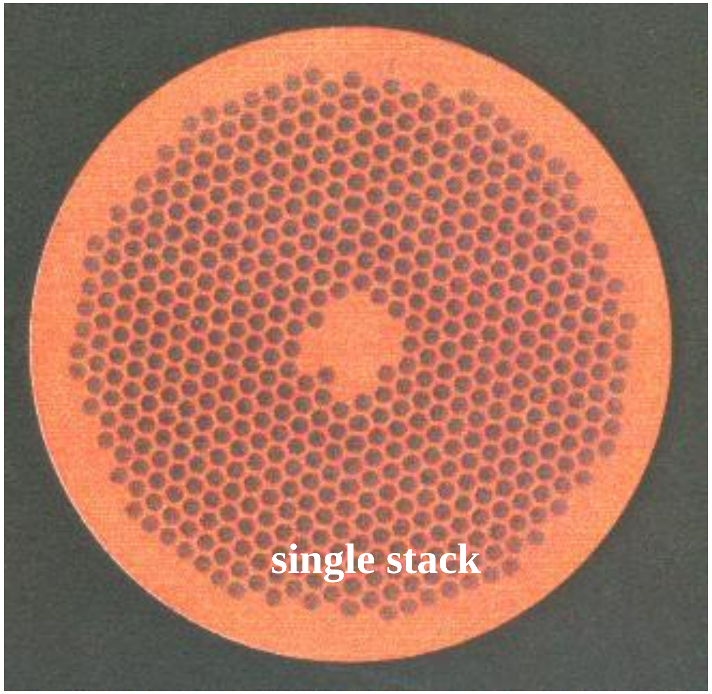
- the effect is partly within the filaments (flux flow) and partly between the filaments
- 'sausaging of the filaments, forces current to cross the copper matrix as critical current is approached.



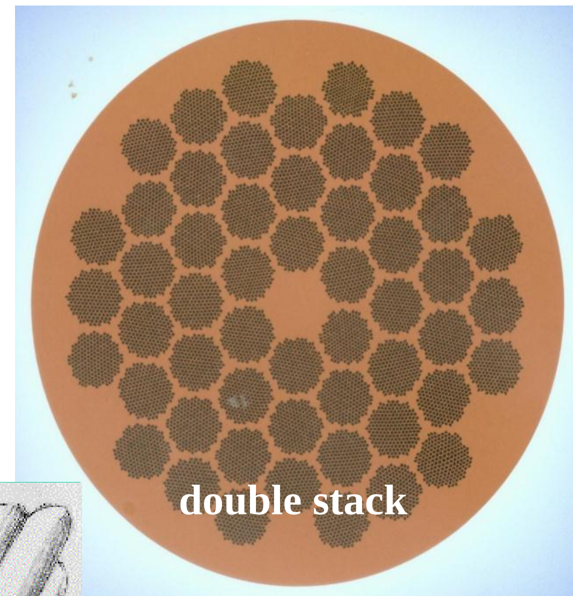
- resistive transition can be the main source of decay in persistent magnets
- 'n' is often taken as a measure of quality - look for n > 50
- HTS conductors so far have low n ~ 5 - 10

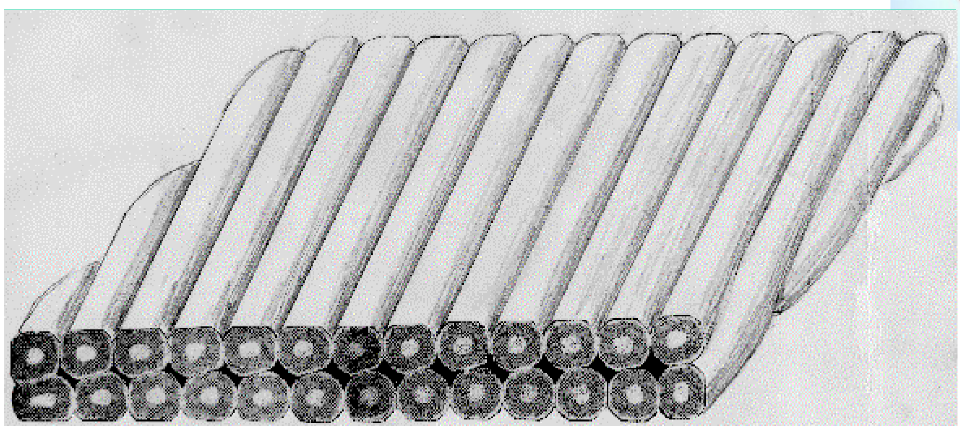


Conductors for accelerator magnets



- to date, all superconducting accelerators have used NbTi superconductor.
- to control field errors and ac losses, the filaments must be < 10μm diameter (lectures 2 & 3)



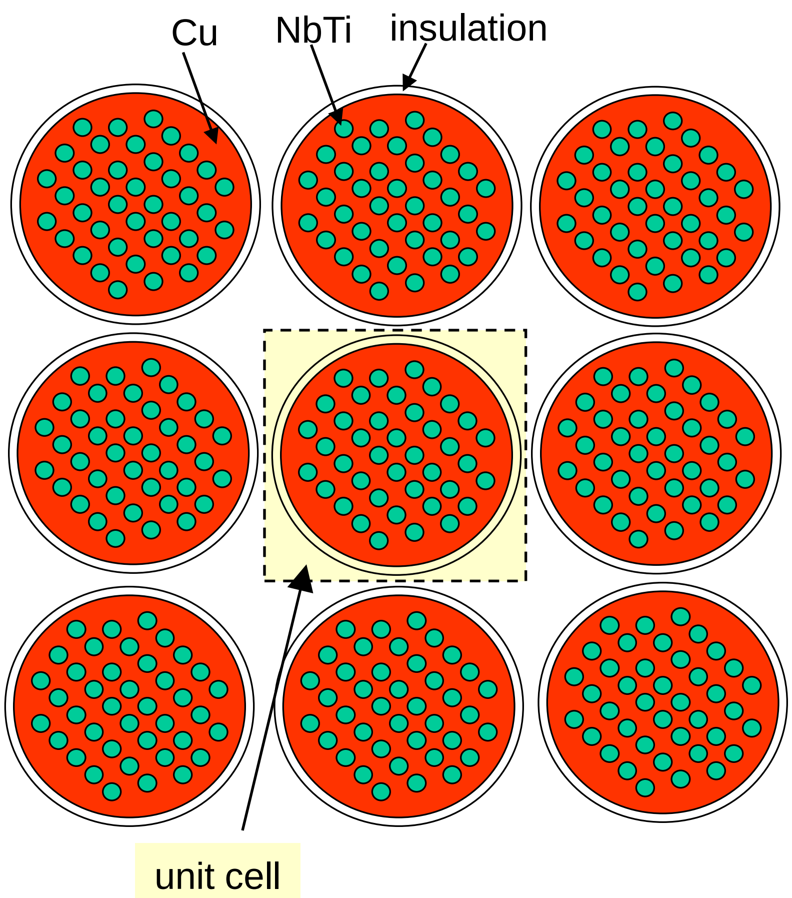


- to get the necessary high operating currents, many wires must be cabled together (lecture 3)

Engineering current density

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

$$J_{eng} = \frac{current}{unit\ \ cell\ \ area} = J_{sup} \times \lambda_{sup}$$



fill factor within the wire $\lambda_{wire} = \frac{1}{(1+mat)}$

where *mat* = matrix : superconductor ratio

typically:

for NbTi *mat* = 1.5 to 3.0 ie λ_{sup} = 0.4 to 0.25

for Nb_3Sn *mat* ~ 3.0 ie λ_{sup} ~ 0.25

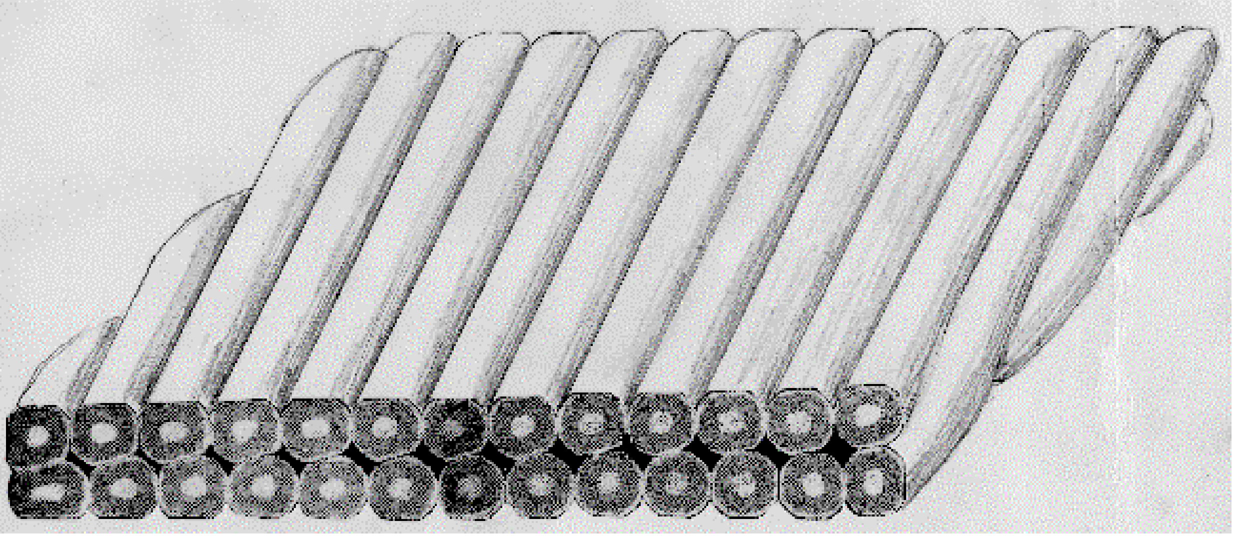
for B2212 *mat* = 3.0 to 4.0 ie λ_{sup} = 0.25 to 0.2

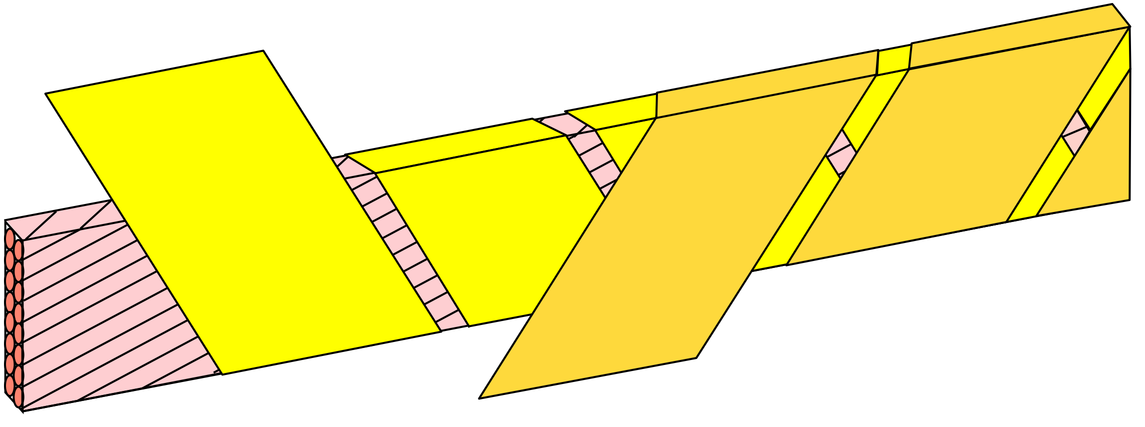
$\lambda_{winding}$ takes account of space occupied by insulation, cooling channels, mechanical reinforcement etc and is typically 0.7 to 0.8

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

Rutherford cable

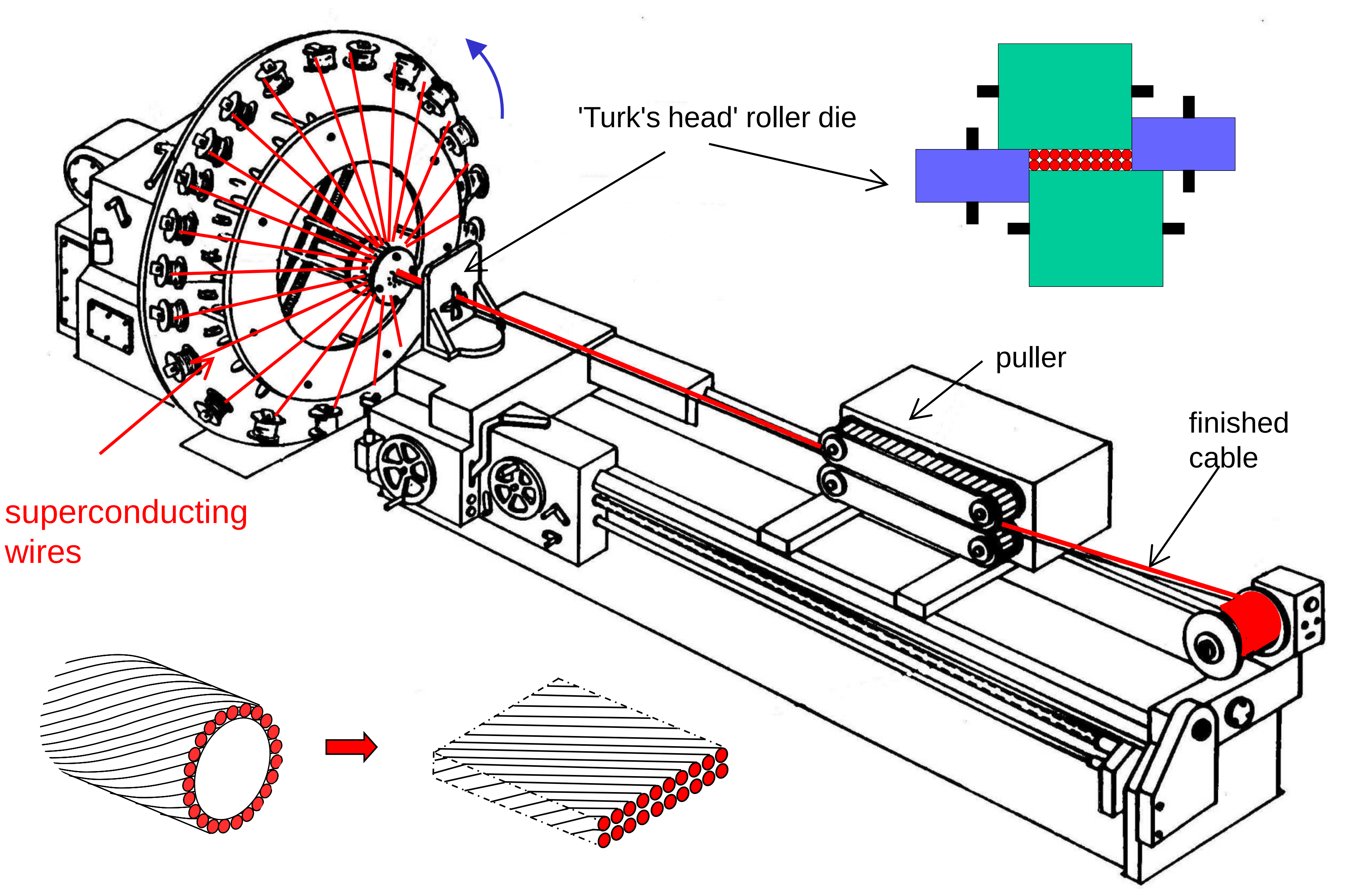
- for high current applications, such as accelerators, we need many wires in parallel
- the most popular way of doing this is the Rutherford cable (see lecture 3)



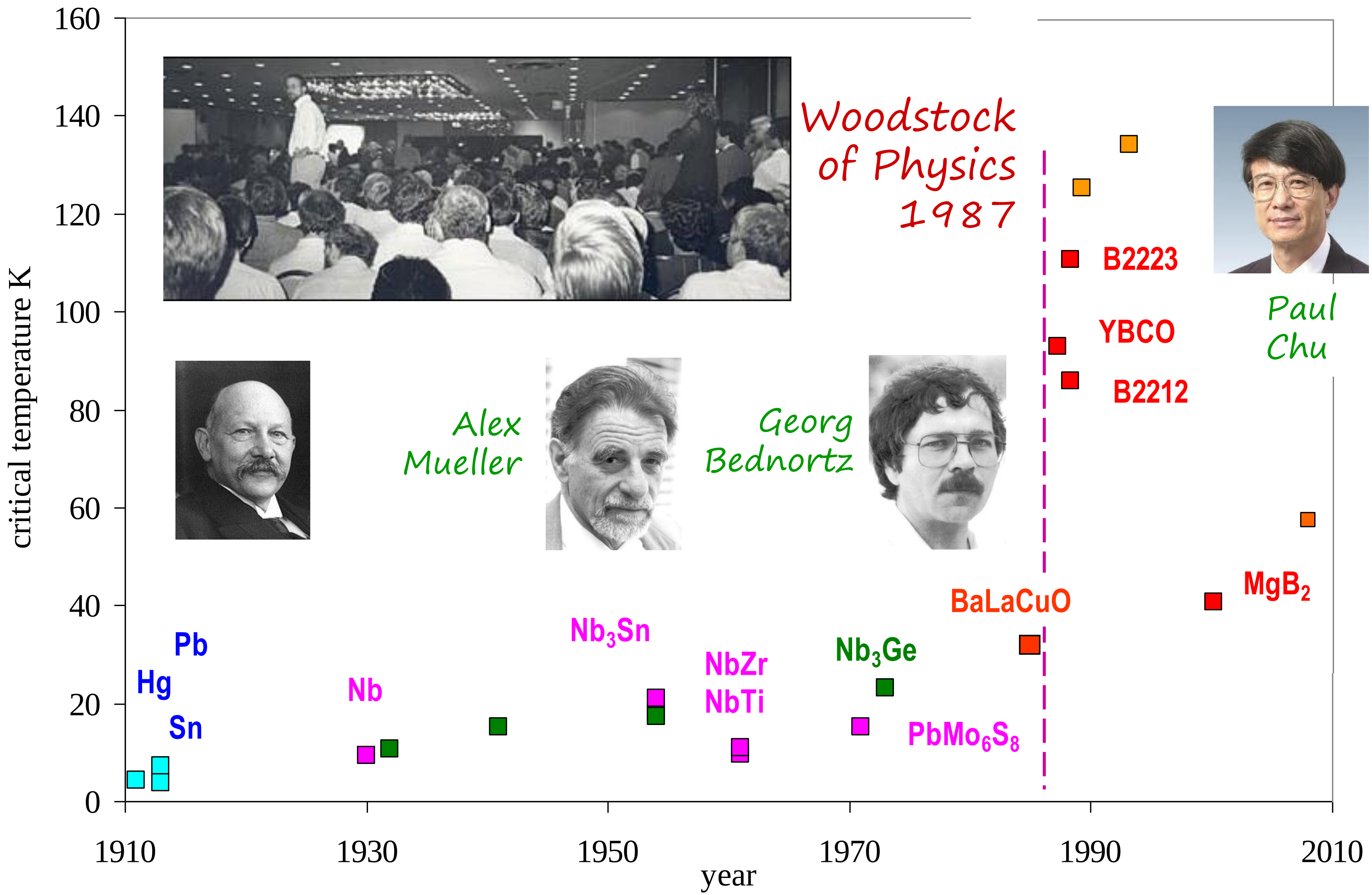


- Rutherford cable is usually insulated by wrapping it with Kapton tape

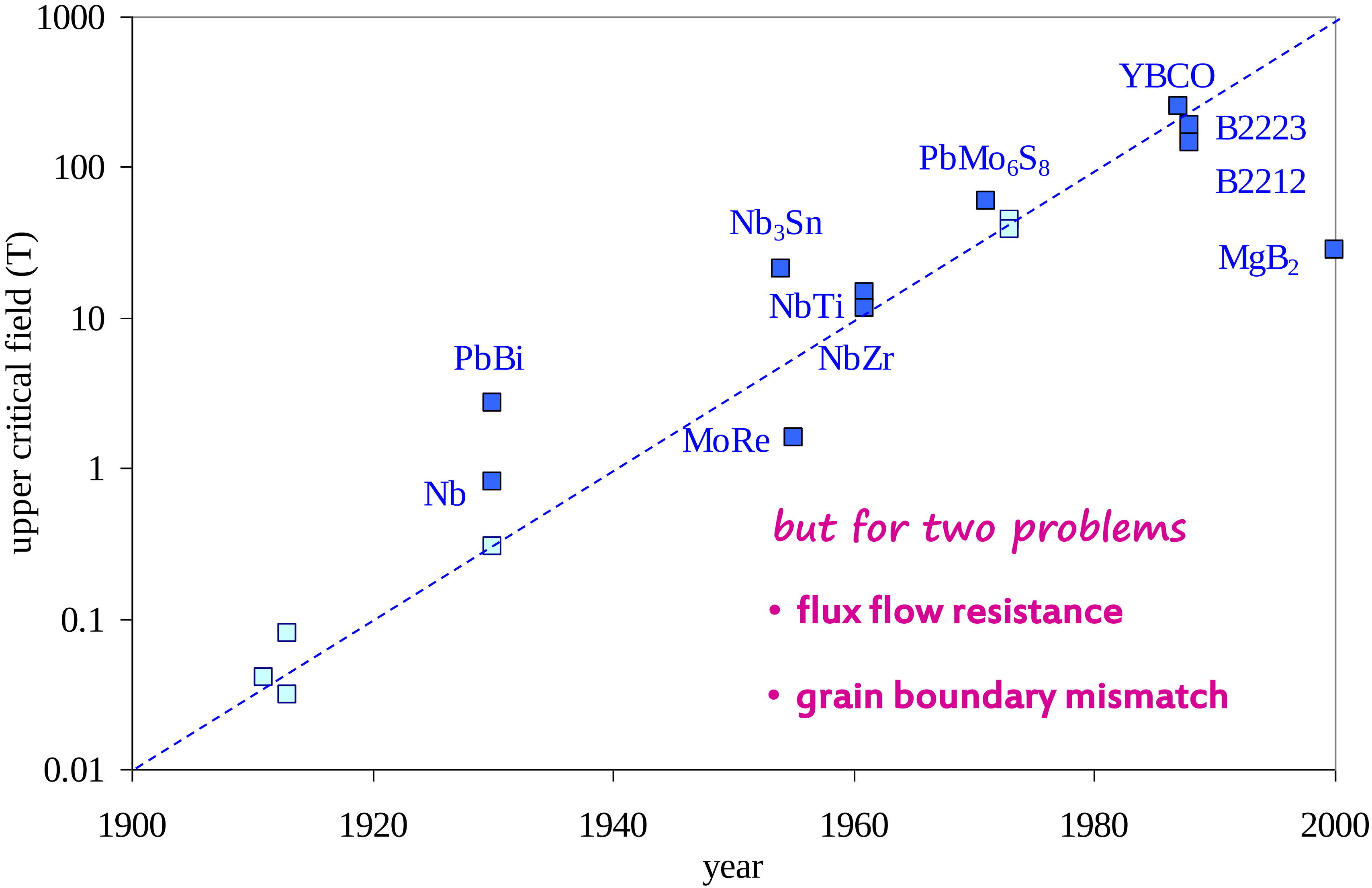
Manufacture of Rutherford cable



A century of critical temperatures



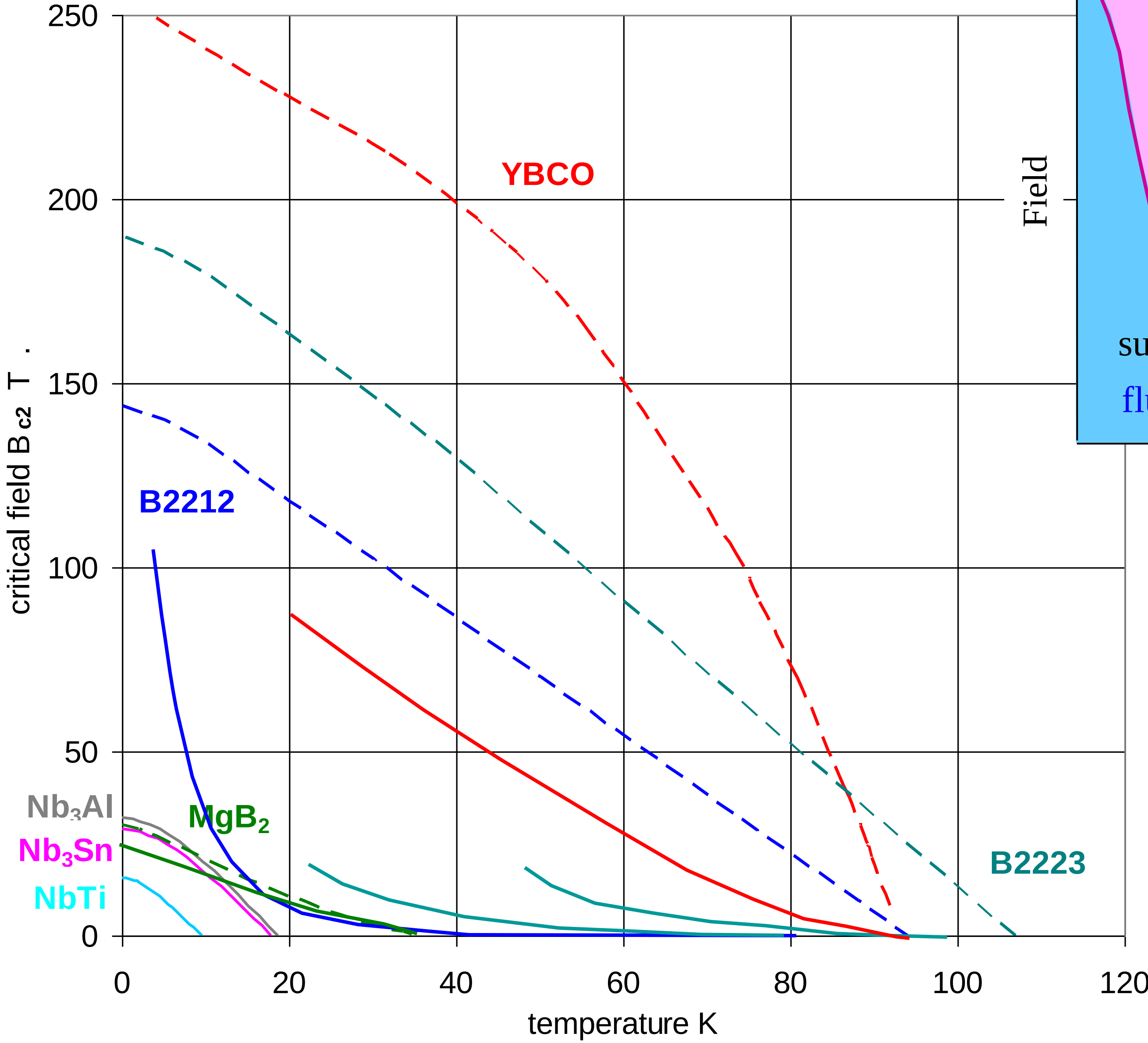
Wonderful materials for magnets

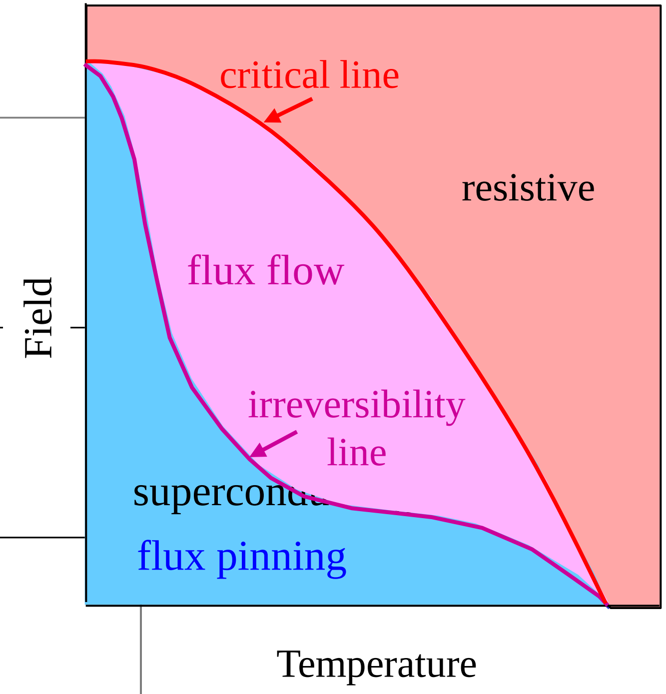


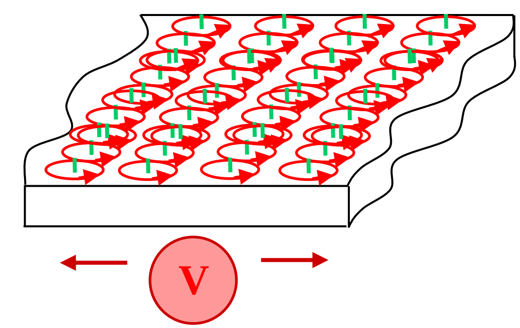
but for two problems

- **flux flow resistance**
- **grain boundary mismatch**

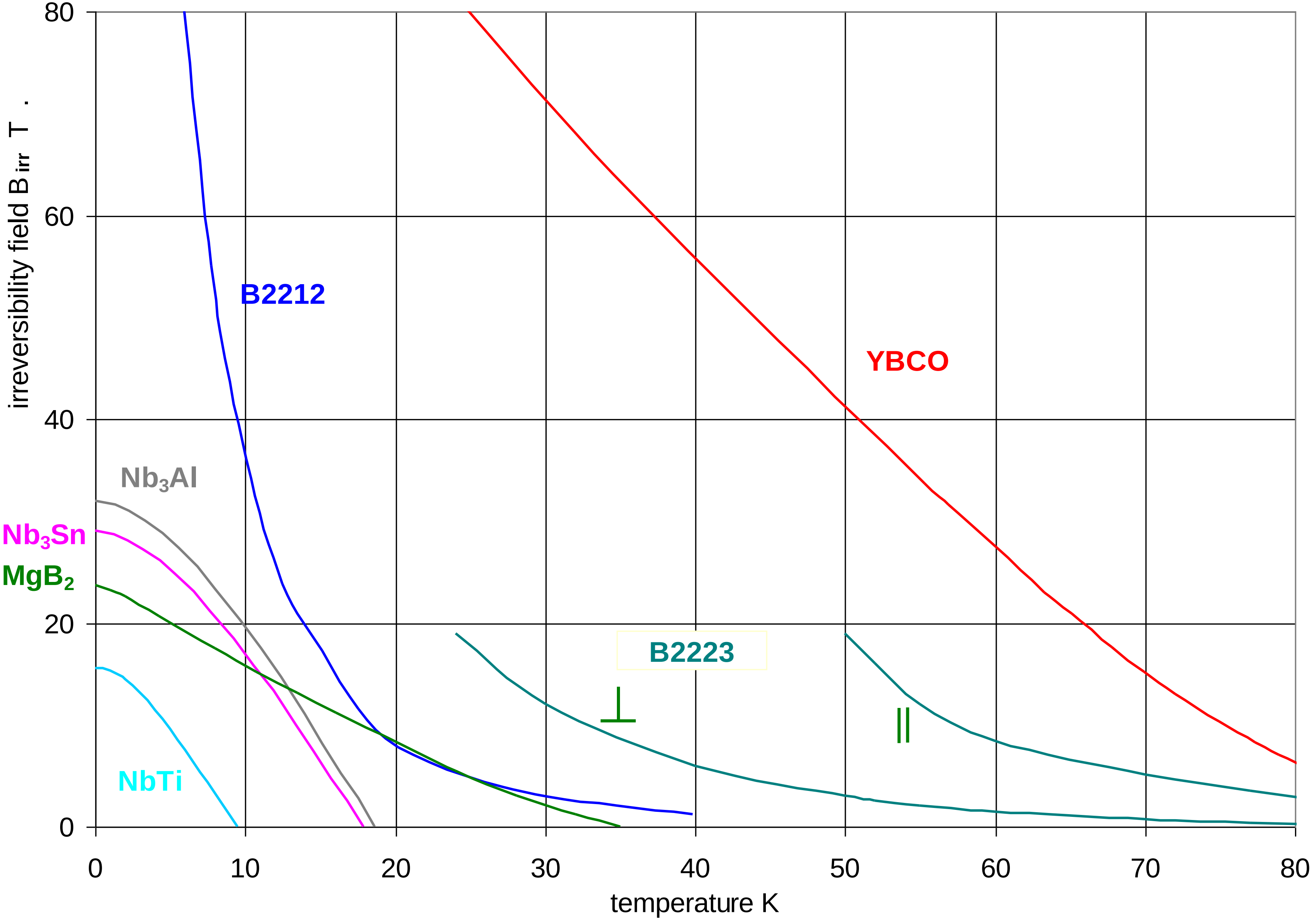
1) Flux flow resistance





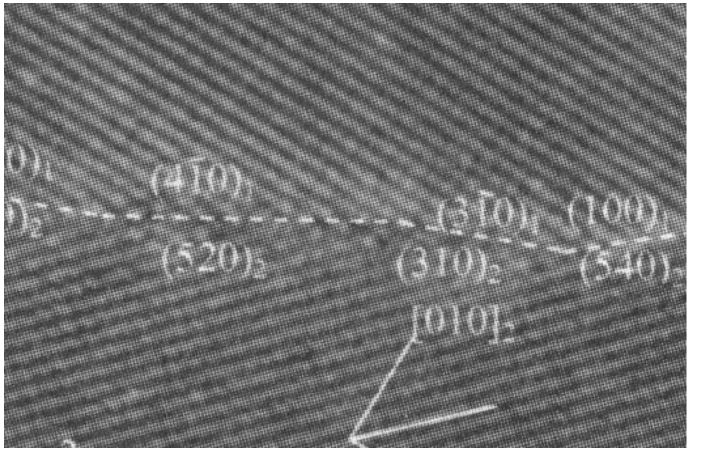


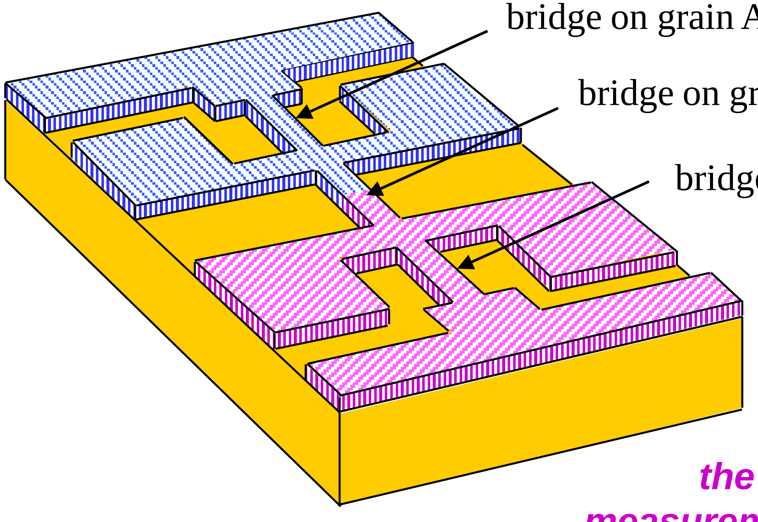
Accessible fields for magnets



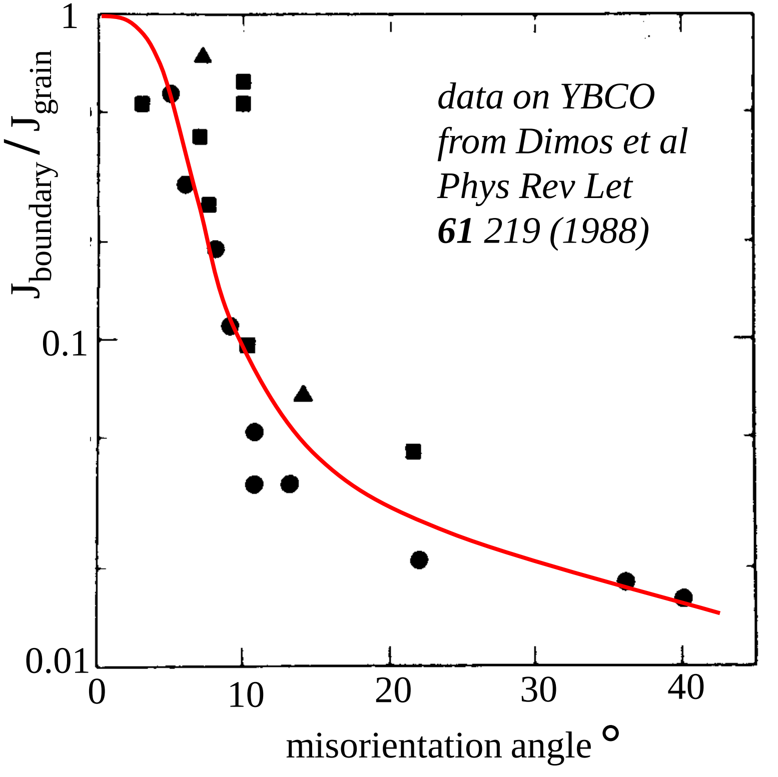
2) Grain boundary mismatch

- crystal planes in grains point in different directions
- critical currents are high within the grains
- J_c across the grain boundary depends on the misorientation angle
- For good J_c must align the grains to within a few degrees





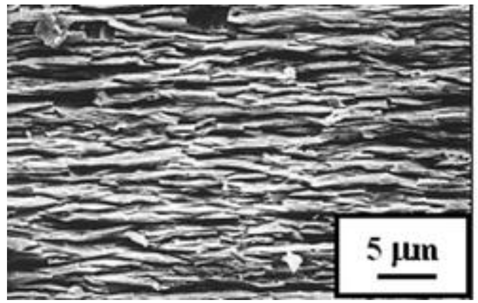
the key measurement of Dimos et al



Practical HTS conductors

B2212 & B2223

- grains tend to align when processed with silver
- but low irreversibility field



- OK in high field at low temperature

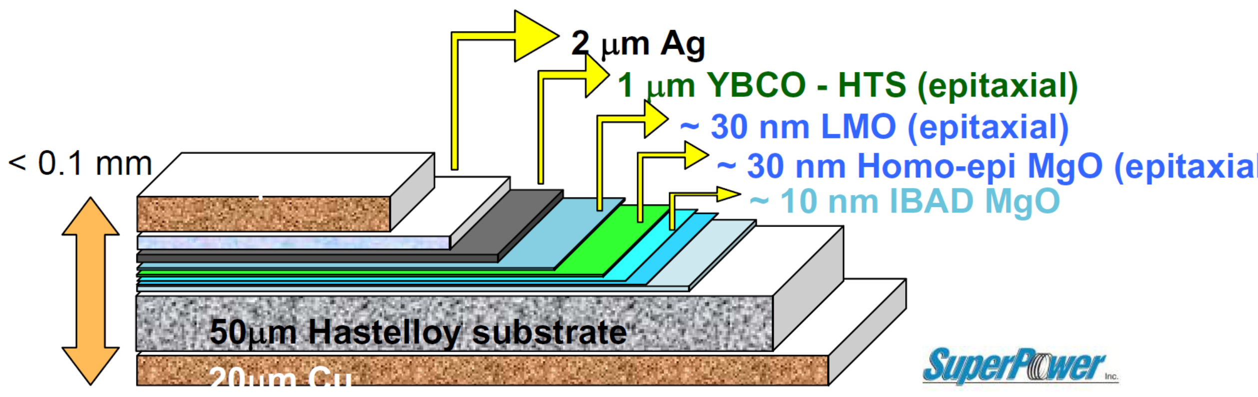
- high field inserts

- OK in low field at high temperature

- power transmission cables

YBCO

- best irreversibility field
- very sensitive to grain boundary misalignment
- grains do not line up naturally
- deposit YBCO film on aligned substrate



- OK in high field **and** at high temperature

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
  $\Rightarrow$ 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, usually in Rutherford cables