Superconducting magnets for Accelerators

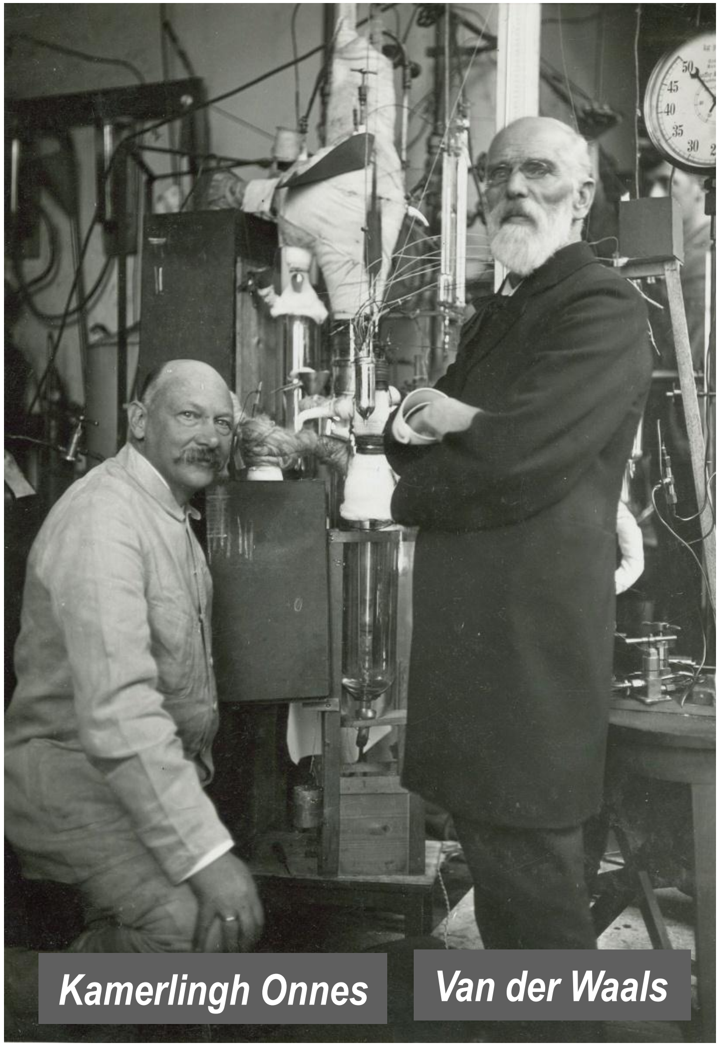
Martin N Wilson (Rutherford Lab ⇒ Oxford Instruments ⇒ CERN ⇒ OI ⇒ cons

101 years of superconductivity

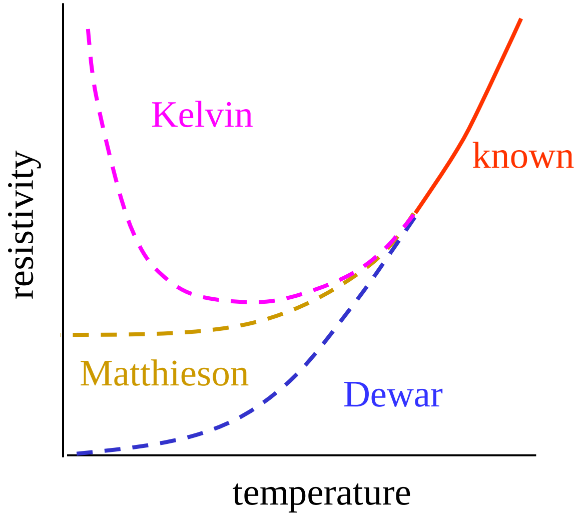
1908: Heike Kamerlingh Onnes liquefies helium

1911: HKO finds superconductivity

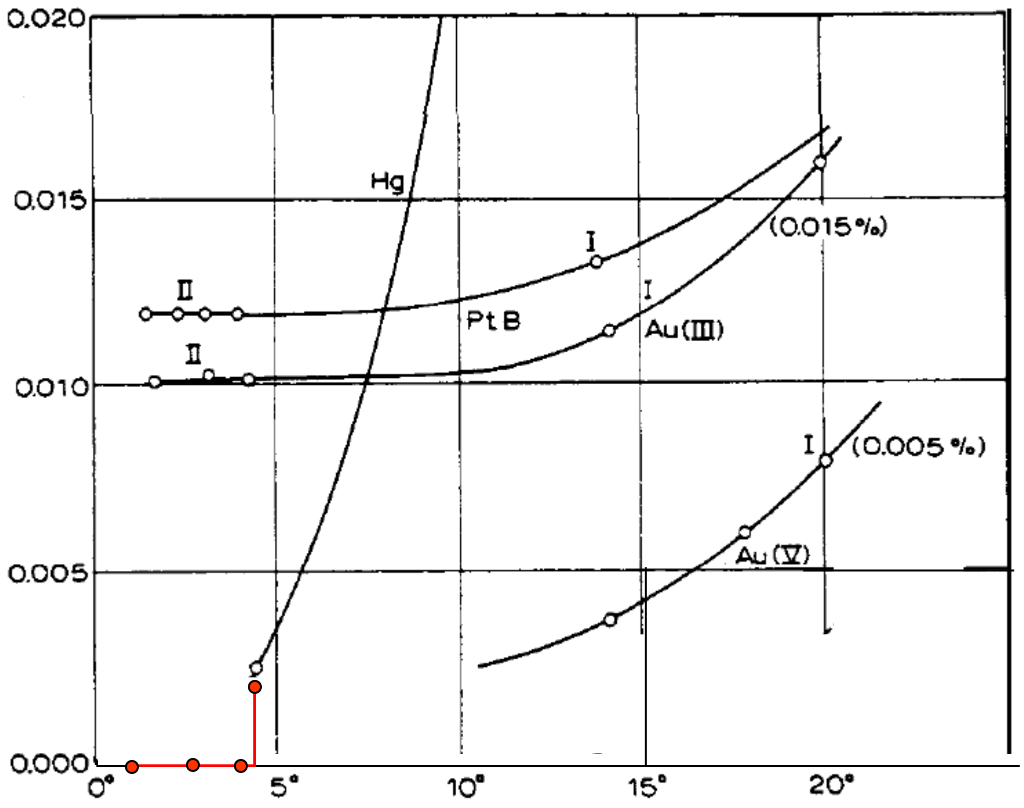
new science enabled by technology development



Resistivity at low temperature



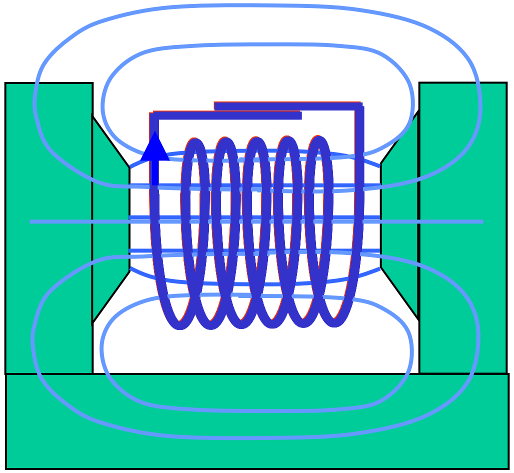
- very different predictions of what might happen

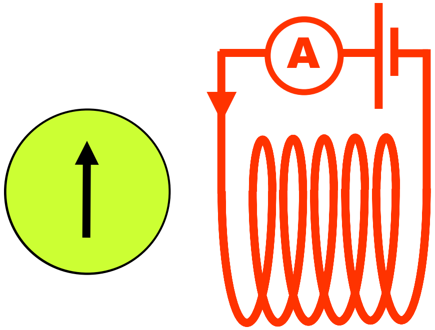


- need high purity to test different theories
- can make Hg very pure by multiple distillation
- *but nobody expected this!*

> *'Thus the mercury at 4.2 has entered a new state which ….. can be called the state of superconductivity'* (HKO Nobel lecture)

How low is the resistance?





coil of lead wire, with shorted terminals

impose magnetic field when warm

cool the coil

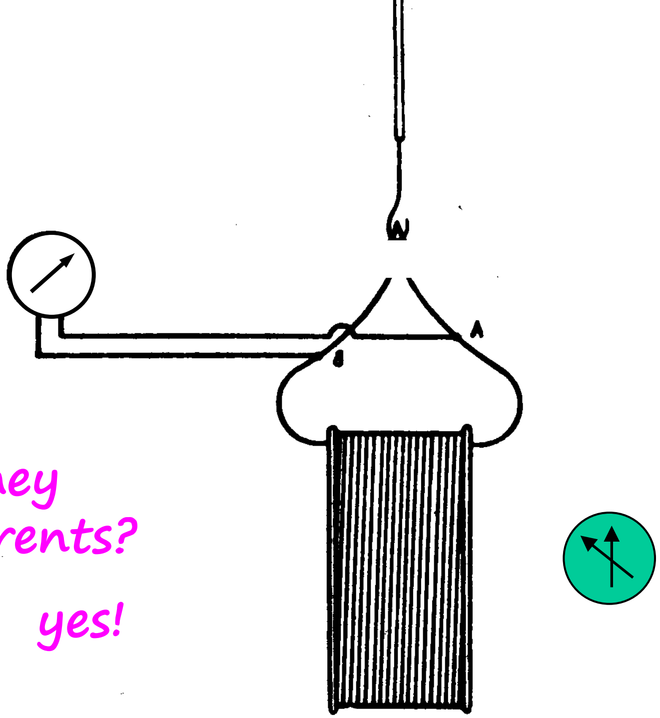
remove field - induces current

measure field from current

back off with a resistive coil

no change for hours - ***persistent current***

> 'It is uncanny to see .... You can feel, almost tangibly how the ring of electrons in the wire turns around, around, around – slowly and almost without friction'
>
> *P Ehrenfest*



but are they really currents?

yes!

Magnets

' ………. bearing on the problem of producing intense magnetic field ……a great number of Ampere windings can be located in a very small space without …….. heat being developed……'

Communication from the Physical Laboratory University of Leiden Sept 1913

' ……….. 100,000 Gauss could then be obtained by a coil of say 30 centimetres in diameter and the cooling with helium would require a plant which could be realized in Leiden with a relatively modest support………..'

Third International Congress of Refrigeration, Chicago Sept 1913

' ……… In field above this threshold value, a relatively large magnetic resistance arises at once…..'

'Thus an unexpected difficulty ………….. faced us. The discovery of the strange property which causes this made up for the difficulties involved.'

Nobel Prize Acceptance Lecture, Stockholm Dec 1913

Superconductivity for accelerators - why bother?

Abolish Ohm's Law

- no power consumption
  (although do need refrigeration power)
- high current density ⇒ compact windings, high gradients
- ampere turns are cheap, so 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

Plan of the Lectures

1 Introduction to Superconductors

- critical field, temperature & current
- superconductors for magnets
- manufacture of superconducting wires
- high temperature superconductors HTS

2 Magnets, 'Training' & Fine Filaments

- coil shapes for solenoids, dipoles & quadrupoles
- engineering current density & load lines
- degradation & training minimum quench energy
- critical state model & fine filaments

3 Magnetization, Cables & AC losses

- filamentary superconductors and magnetization
- coupling between filaments ⇒ magnetization
- why cables, coupling in cables
- AC losses in changing fields

4 Quenching and Cryogenics

- the quench process
- resistance growth, current decay, temperature rise
- quench protection schemes
- cryogenic fluids, refrigeration, cryostat design

5 Practical Matters

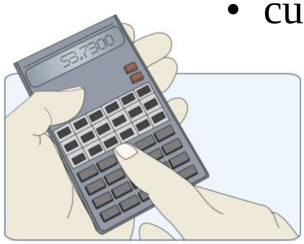
- LHC quench protection
- current leads
- accelerator magnet manufacture
- some superconducting accelerators

Tutorial 1: Fine Filaments

- how filament size affects magnetization

Tutorial 2: Quenching

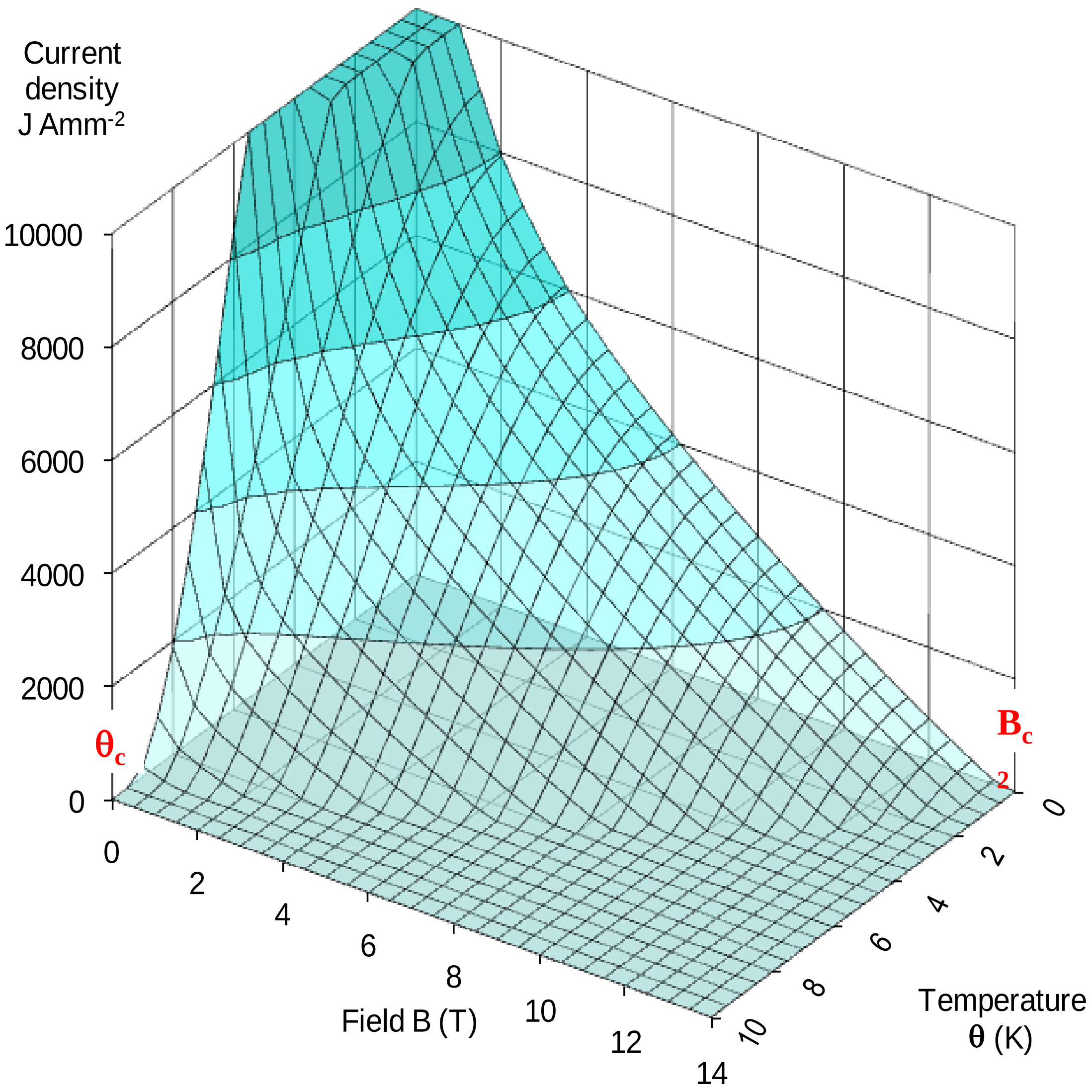
- current decay and temperature rise



get a feel for the numbers,
bring a calculator

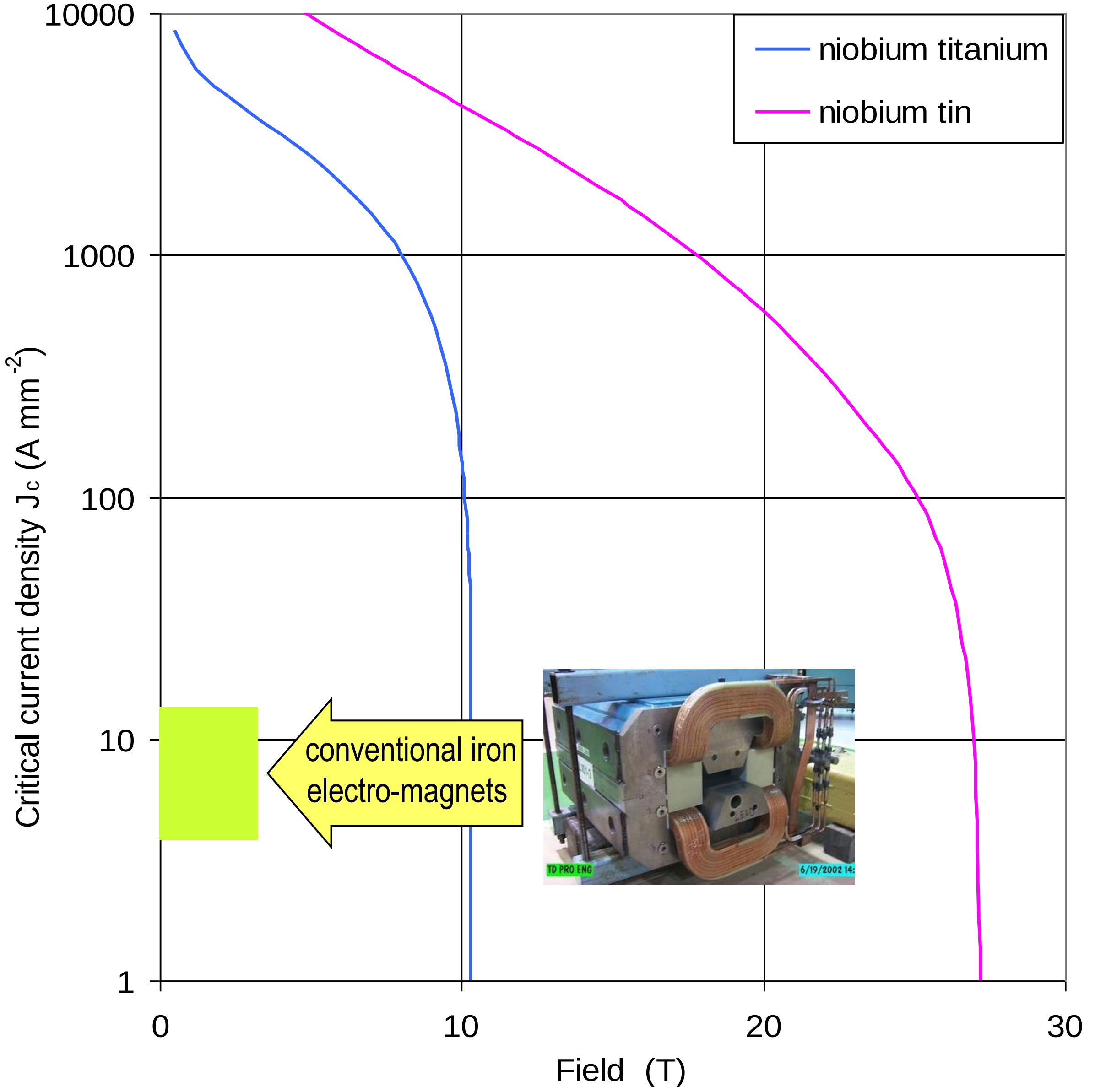
The critical surface of niobium titanium

- **NbTi** is the standard commercial ‘work horse’ of the superconducting magnet business



- ***critical surface*** is the boundary between superconductivity and normal resistivity in J, B, θ space
- superconductivity prevails everywhere below the surface, resistance everywhere above it
- upper critical field B_{c2} (at zero temperature and current)
- critical temperature θ_c (at zero field and current)
- B_{c2} and θ_c are characteristic of the alloy composition
- critical current density J_c depends on processing

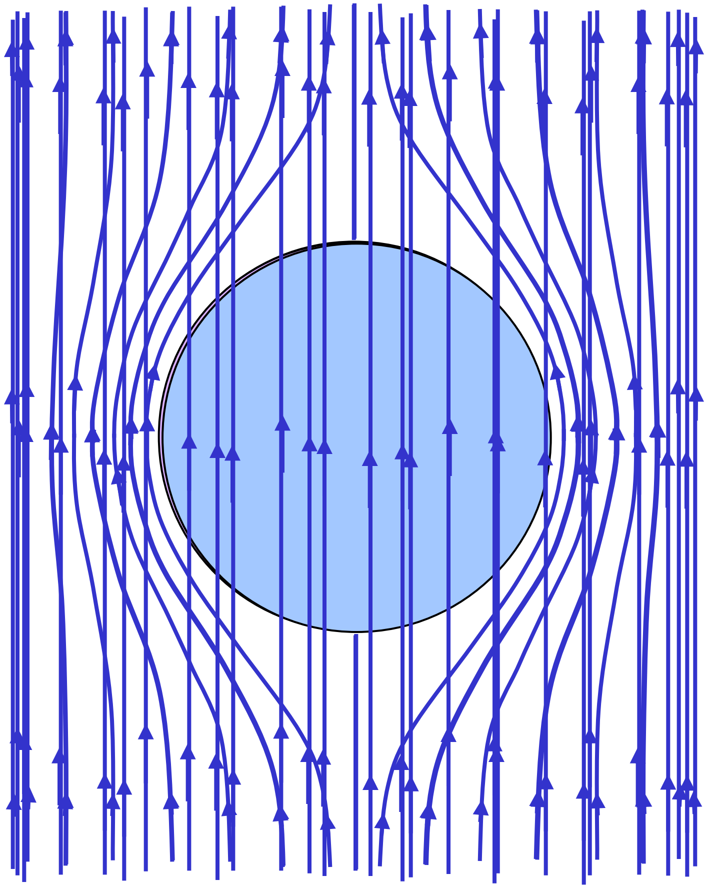
The critical line at 4.2K



- magnets usually work in boiling liquid helium, so the critical surface is often represented by a curve of current versus field at 4.2K
- niobium tin Nb_3Sn has a much higher performance than NbTi
- **but** Nb_3Sn is a brittle intermetallic compound with poor mechanical properties
- both the field and current density of both superconductors are way above the capability of conventional electromagnets

Two kinds of superconductor: type 1

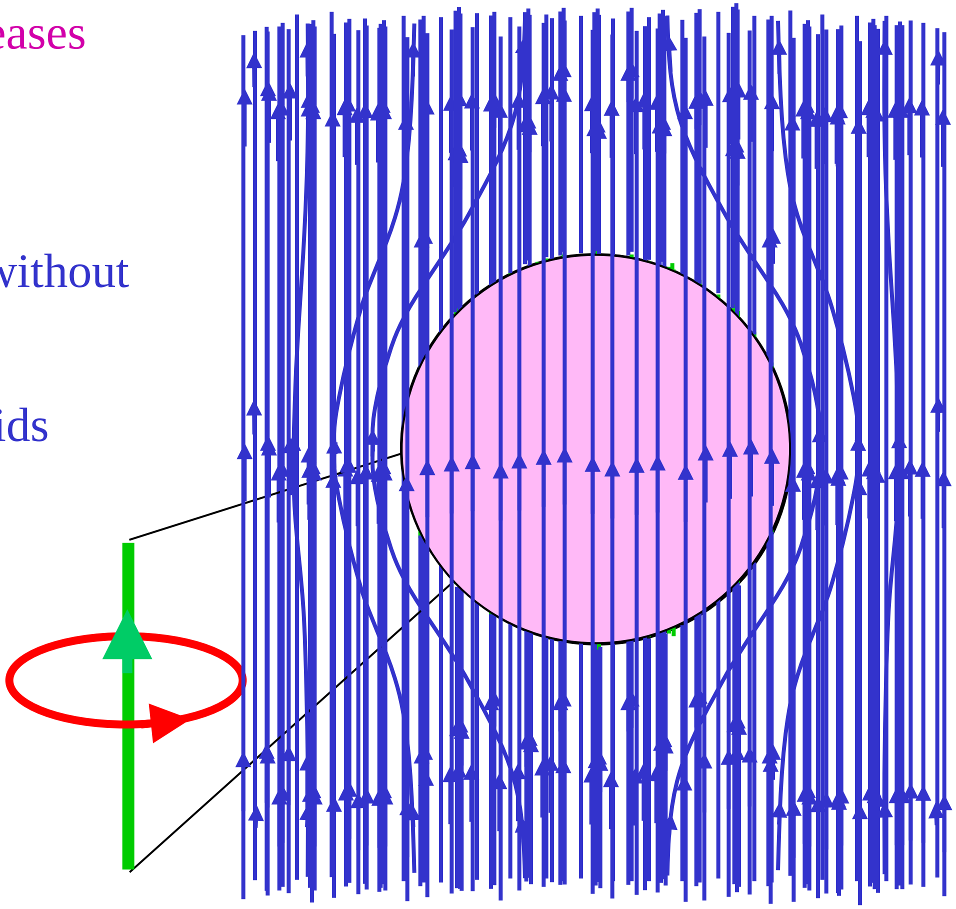
- the materials first discovered by Kammerlingh Onnes in 1911 - soft metals like lead, tin mercury
- sphere of metal at room temperature
- apply magnetic field
- reduce the temperature - resistance decreases
- reduce the temperature some more
  - resistance decreases some more
- at the critical temperature 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 is trade off between **reducing** energy via condensation to superconductivity and **increasing** energy by pushing out field ~ 0.1T



useless for magnets!

Two kinds of superconductor: type 2

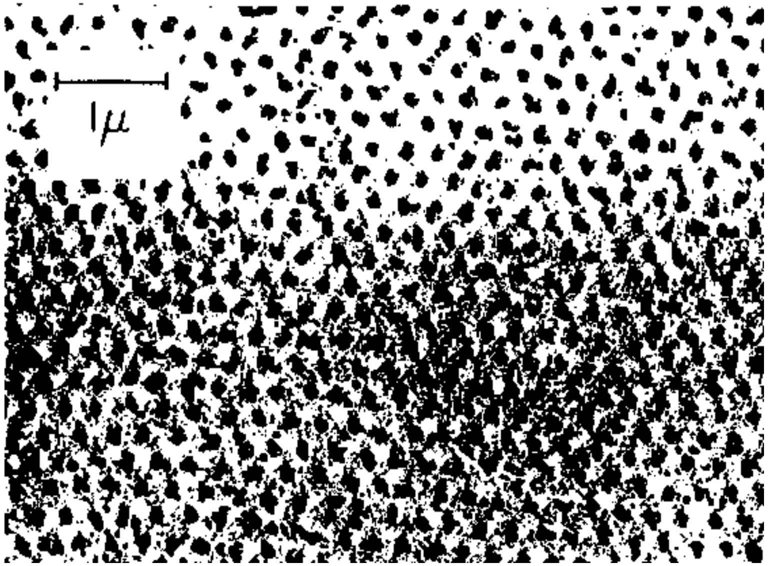
- apply magnetic field
- reduce the temperature - resistance decreases
- at the critical temperature θ_c the field is pushed out
- increase the field - field jumps back in without quenching superconductivity
- it does so in the form of quantized fluxoids
- lower critical field B_{c1}
- supercurrents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

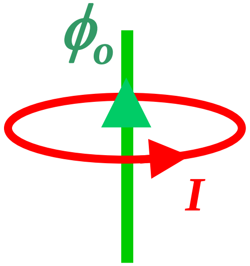


Critical field: type 2 superconductors

- 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

$$\phi_o = \frac{h}{2e} = 2 \times 10^{-15} Webers$$

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

upper critical field $B_{c2} = \sqrt{2} \kappa B_c$

in the 'dirty limit' $\kappa \approx 2.4 \times 10^{6} \gamma^{\frac{1}{2}} \rho_n$

where ρ_n is the normal state resistivity ***- best superconductors are best resistors!***

thus the upper critical field $B_{c2} = 3.1 \times 10^{3} \gamma \rho_n \theta_c$

for NbTi: $\gamma \sim 900$ J m $^{-3}$ K^{-2} $\rho_n \sim 65$ x10^{-8} W m $\theta_c = 9.3$ K hence **$B_{c2} \sim 18.5$ T**

Sommerfeld coefficient of electronic specific heat $C_e = \gamma\theta$

Critical current density: type 2 superconductors

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

  spacing between the fluxoids is:-

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

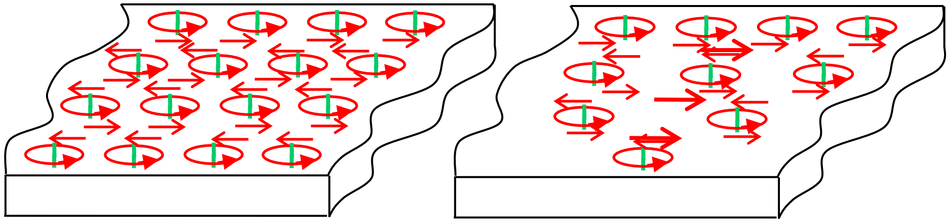
- each fluxoid carries one unit of flux,

  so density of fluxoids = average field

  uniform density ⇒ uniform field

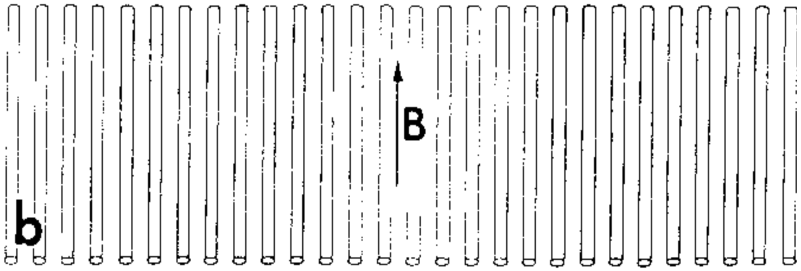
  ⇒ zero J (because $Curl\ B = \mu_o J$)

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



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

precipitates of α Ti in Nb Ti



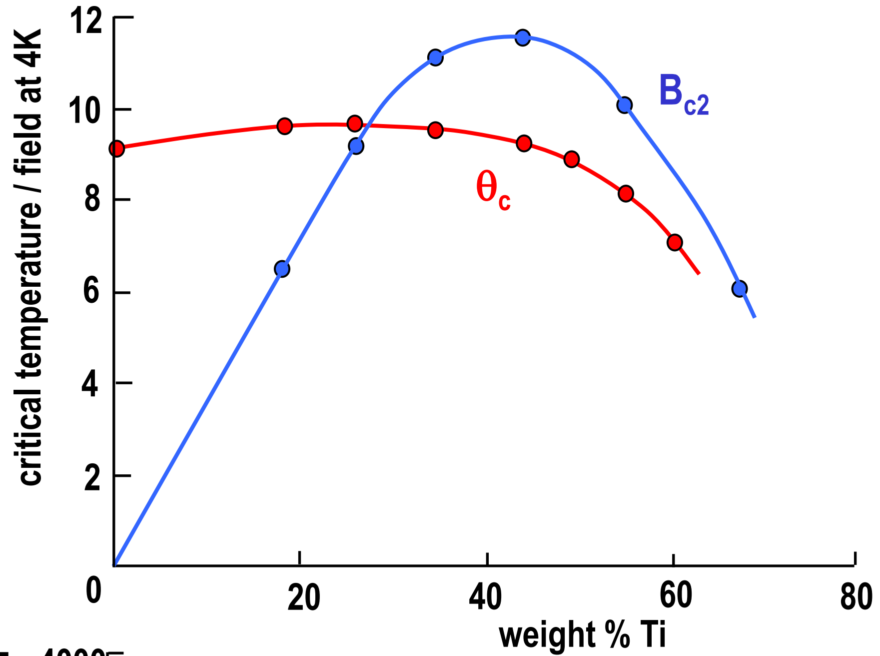
fluxoid lattice at 5T on the same scale

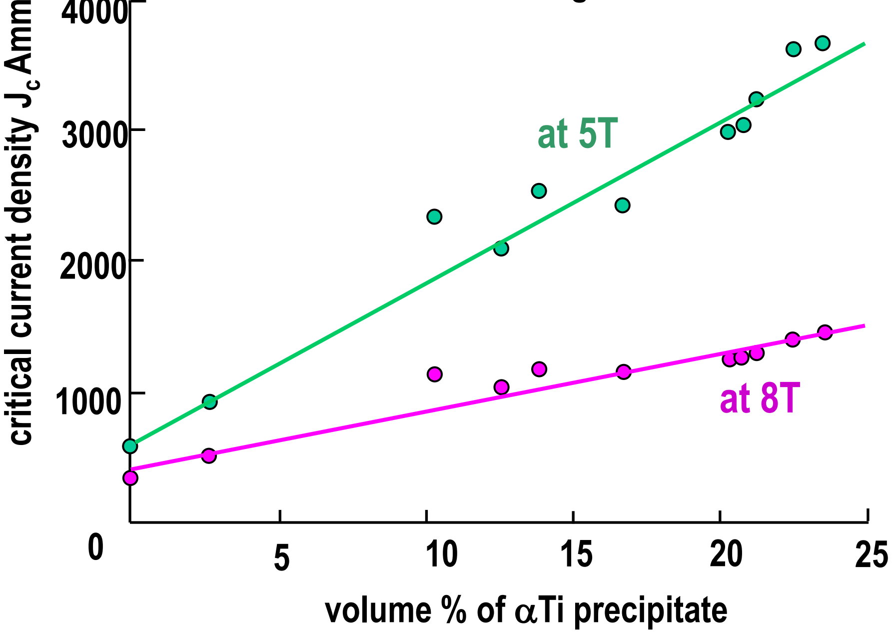
Critical properties

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

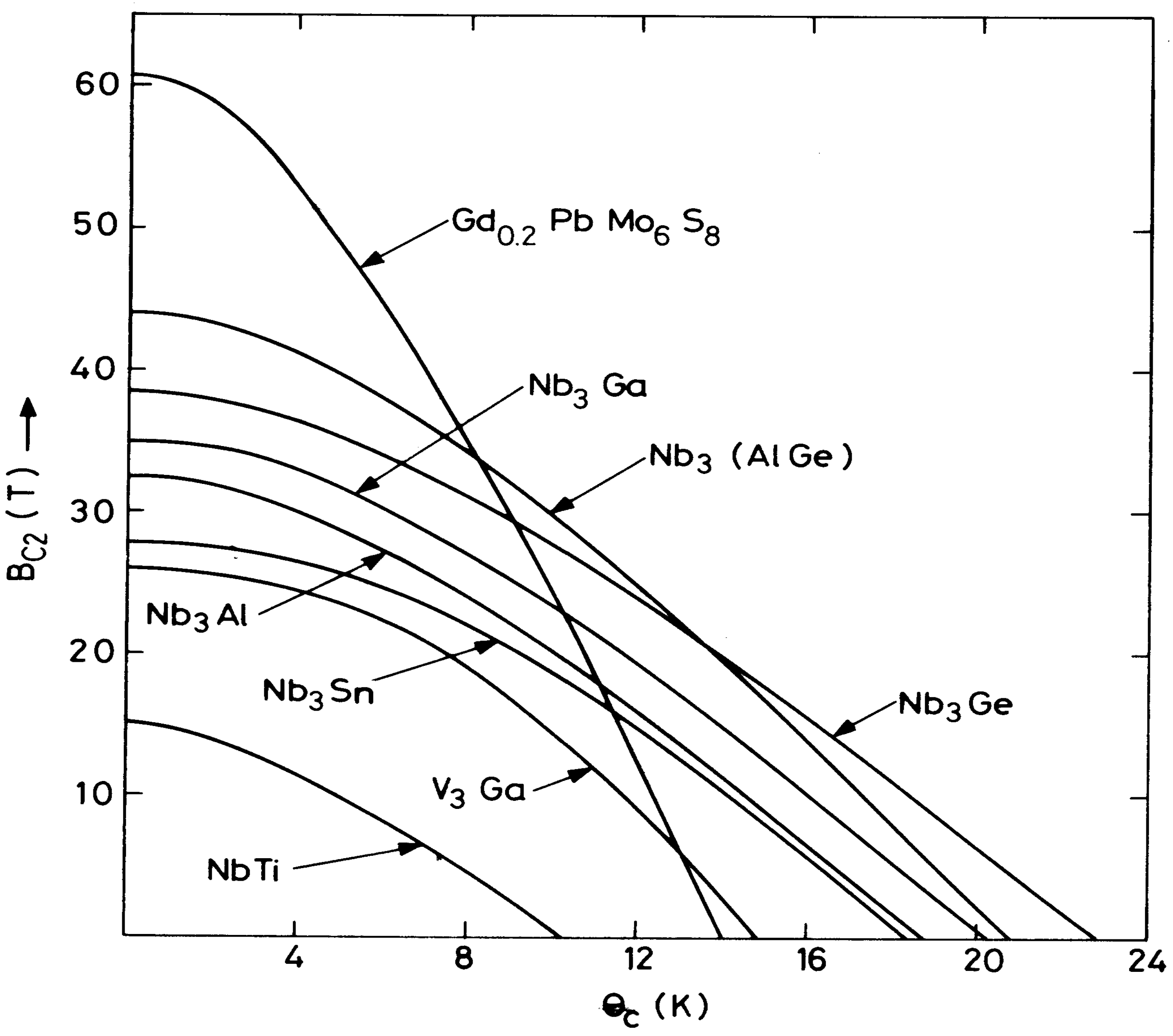
- **Upper Critical field B_{c2}:** choose a Type 2 superconductor with a high critical temperature and a high normal state resistivity
  property of the material

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





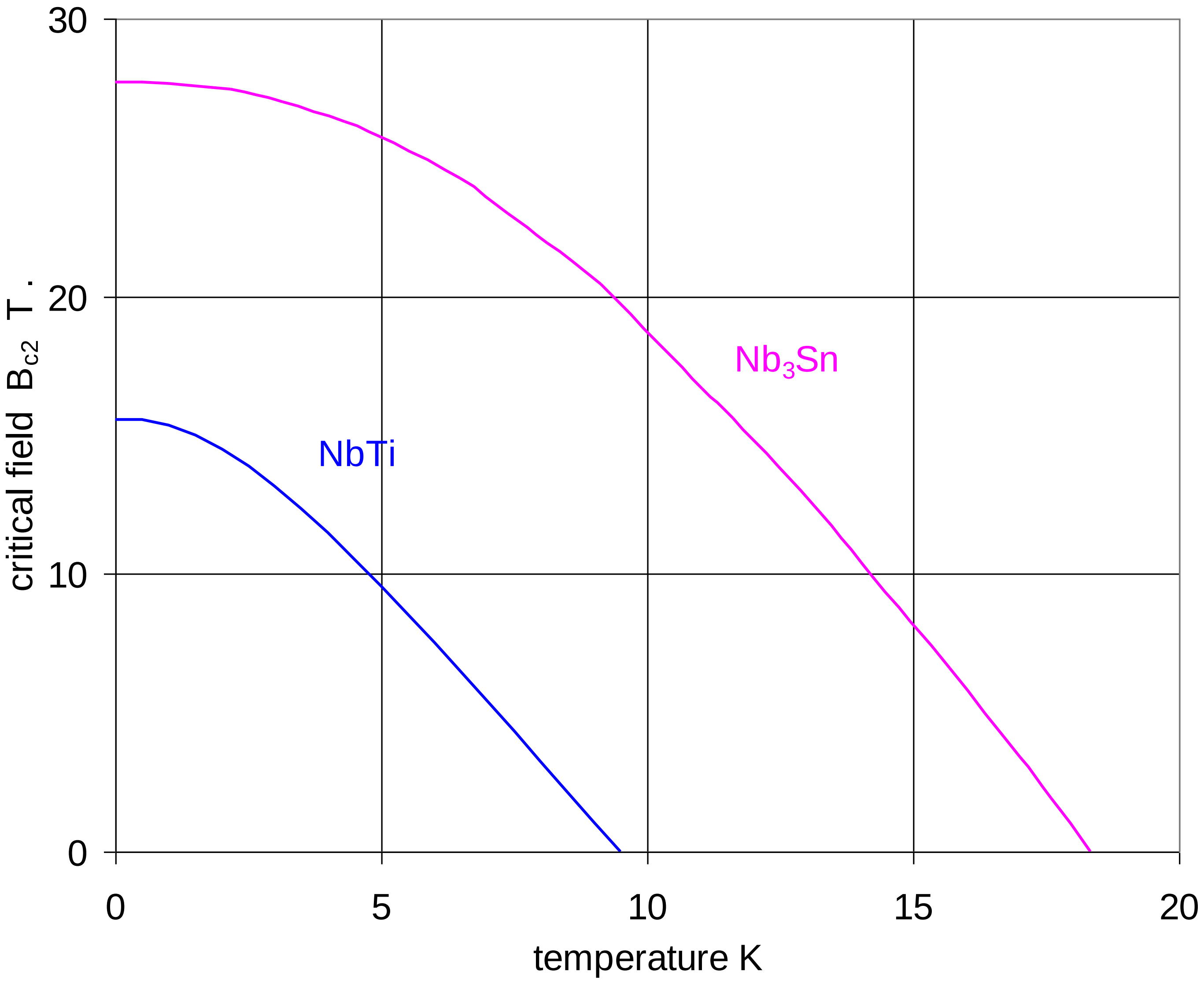
Critical field & temperature of metallic superconductors



Note: of all the metallic superconductors, only NbTi is ductile.

All the rest are brittle intermetallic compounds

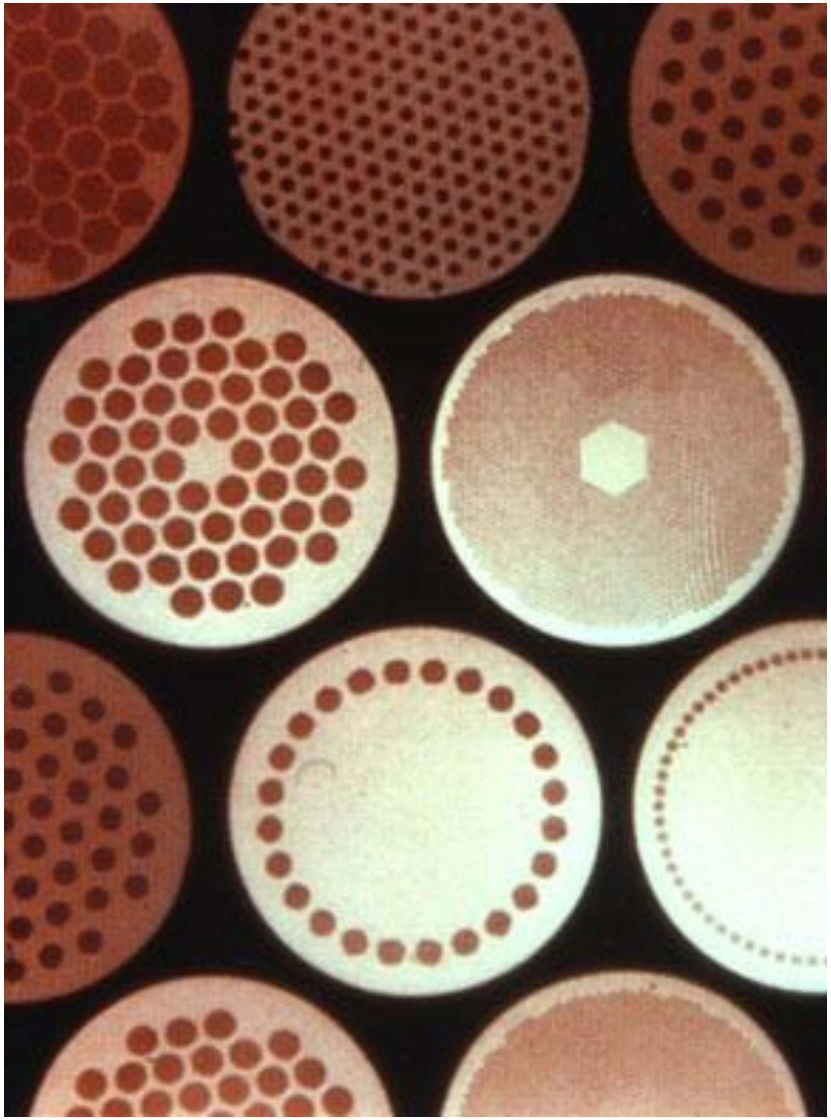
Critical field & temperature of metallic superconductors



To date, all superconducting accelerators have used NbTi.

Of the intermetallics, only Nb_3Sn has found significant use in magnets

Practical wires for magnets



- some 40 years after its development, NbTi is still the most popular magnet conductor, with Nb_3Sn being used for special high field magnets and HTS for some developmental prototypes.

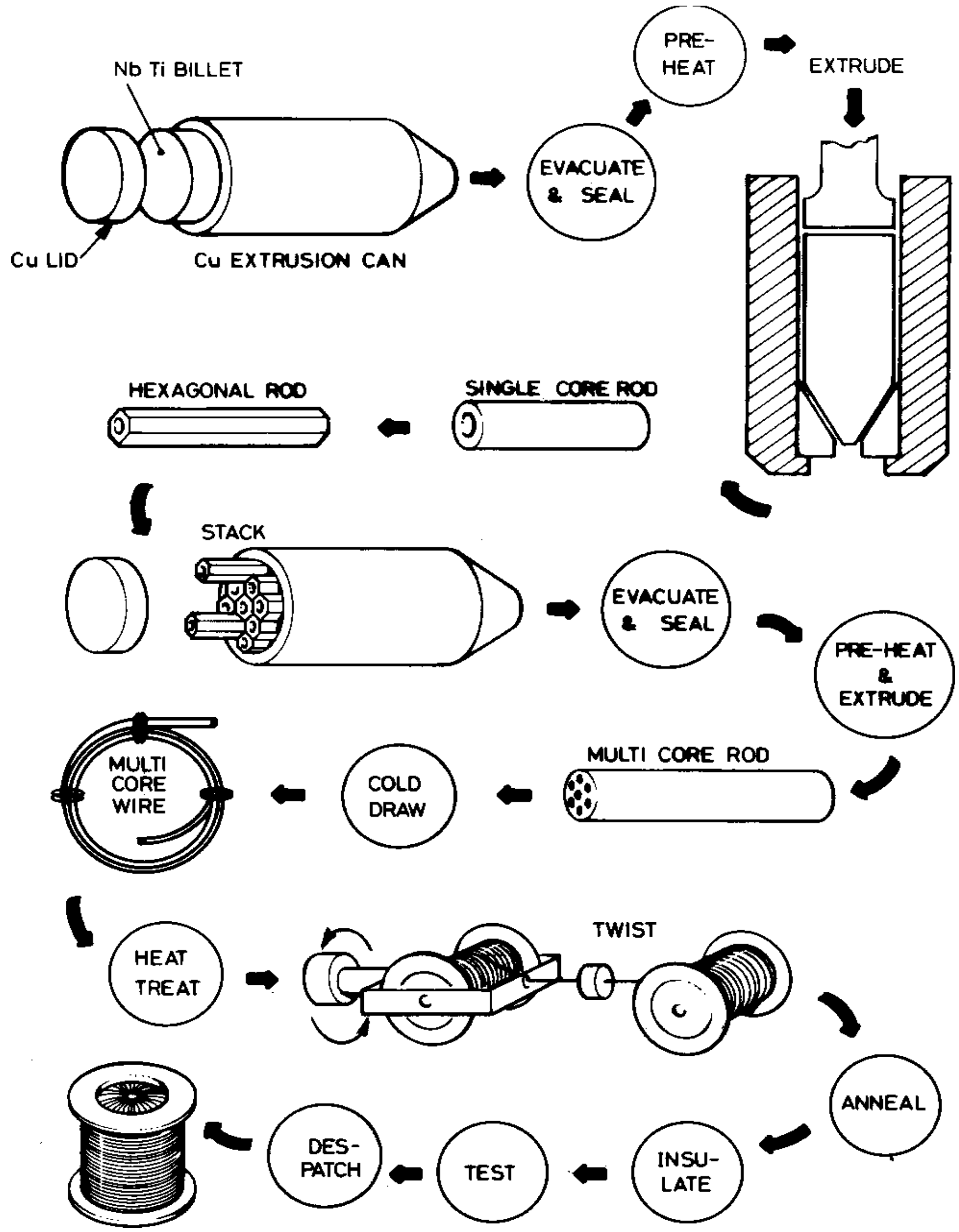
- for reasons that will be described later, superconducting materials are always used in combination with a good normal conductor such as copper

- 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)

NbTi manufacture

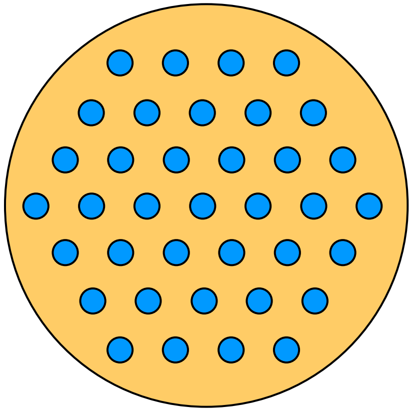


- vacuum melting of NbTi billets
- hot extrusion of the copper NbTi composite
- sequence of cold drawing and intermediate heat treatments to precipitate αTi phases as flux pinning centres
- for very fine filaments, must avoid the formation of brittle CuTi intermetallic compounds during heat treatment
  - 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

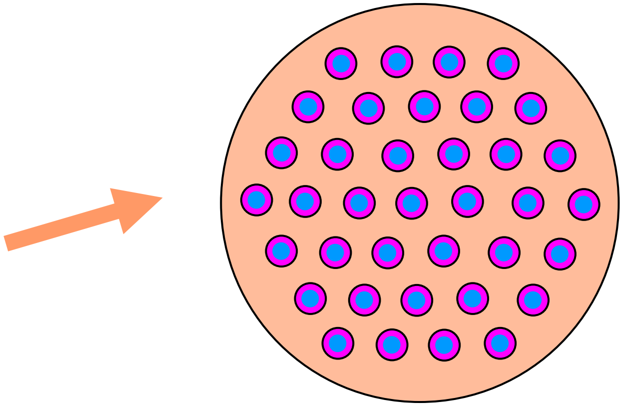
Nb_3Sn is a brittle material and cannot be drawn down.

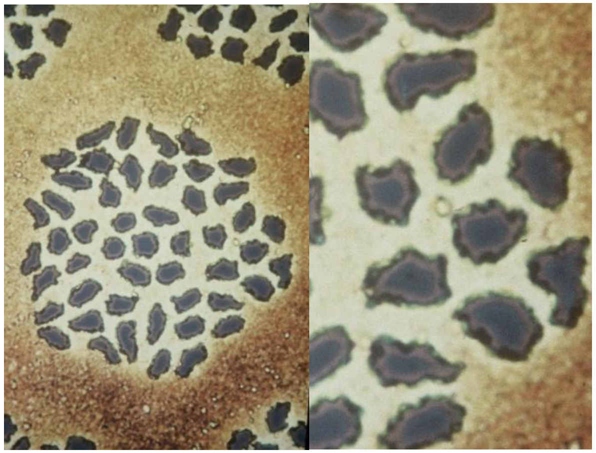
Instead must draw down pure niobium in a matrix of bronze (copper tin)



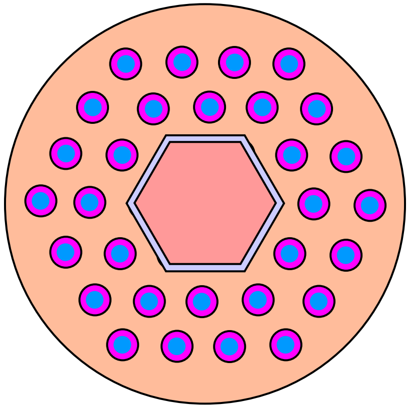
- *BUT maximum ductile bronze is ~13wt% tin,*
- *reaction slows at ~ 3wt%*
- *so low engineering J_c*

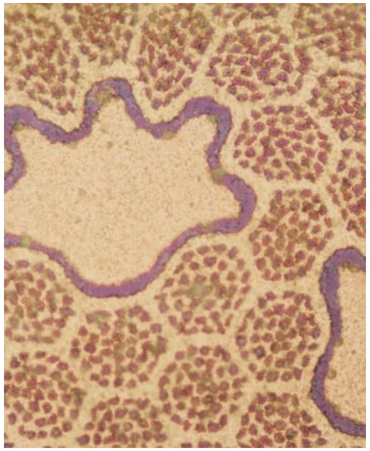
At final size the wire is heated (~700C for some days) tin diffuses through the Cu and reacts with the Nb to form Nb_3Sn





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

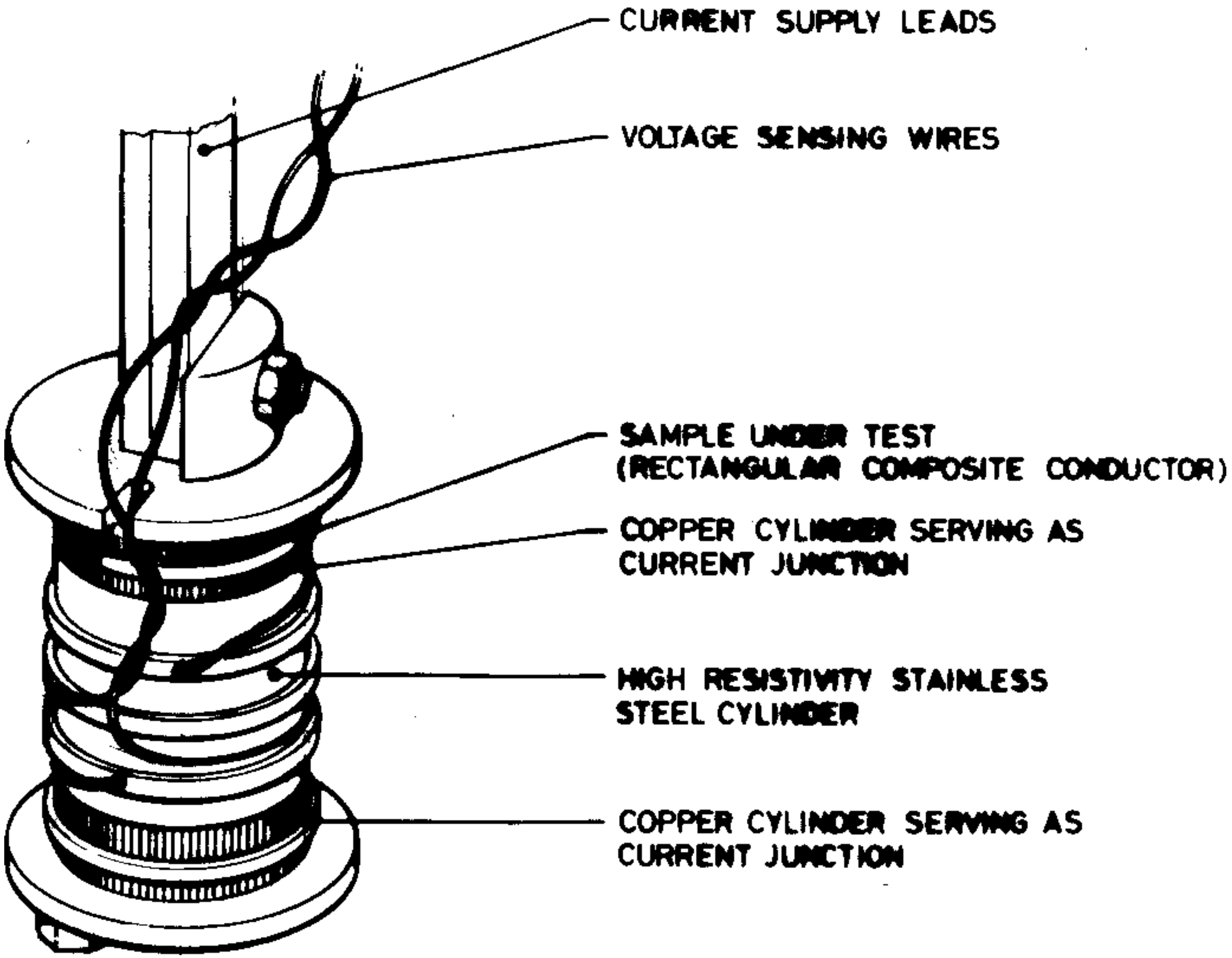




Measurement of critical current

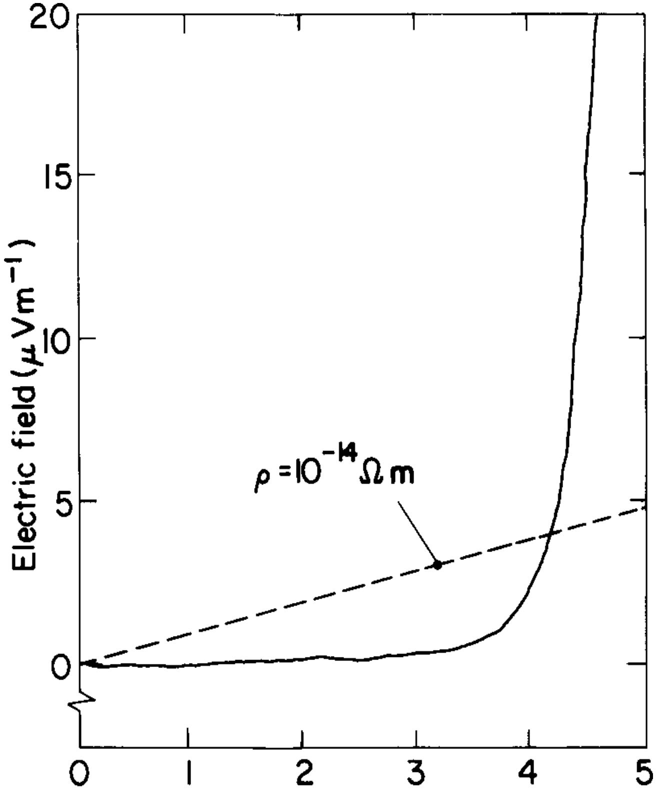
- this sample holder is placed in the bore of a superconducting solenoid, usually in liquid helium boiling at 4.2K

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



Resistive transition 1

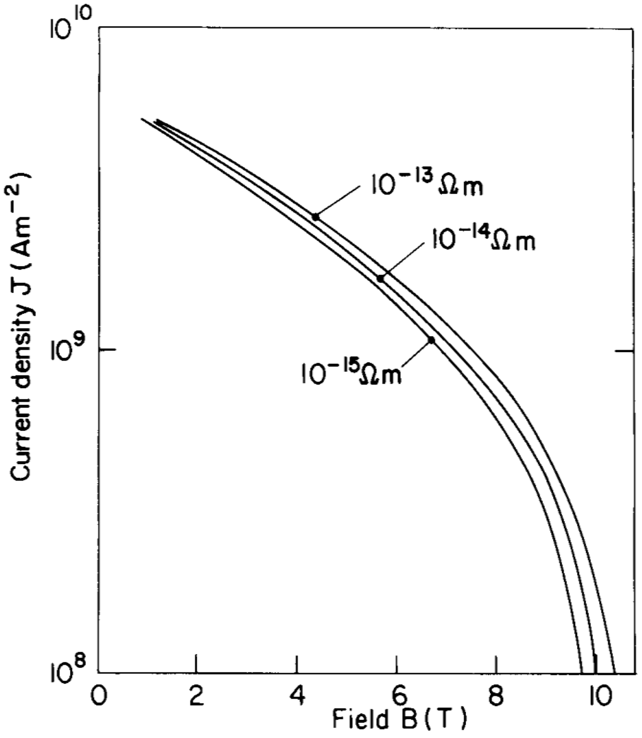
When measured sensitively, the boundary between superconducting and resistive states is not sharp, but slightly blurred.



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

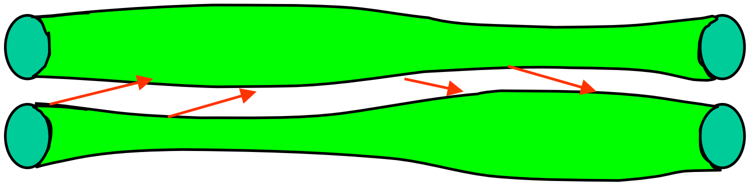
Resistive transition 2

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

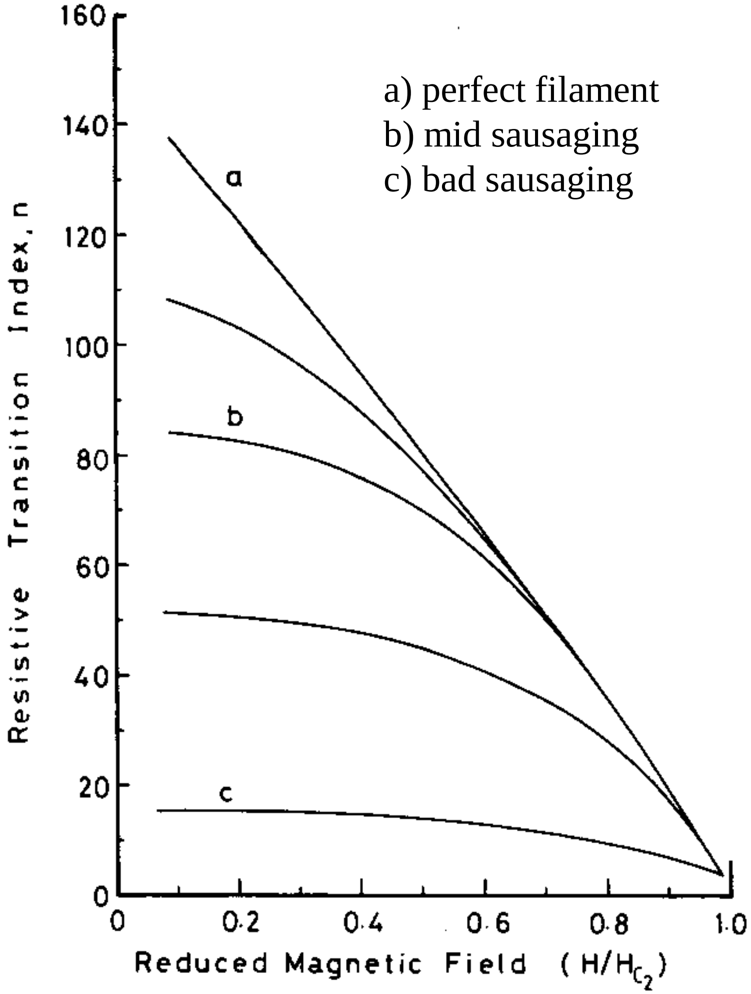
$$\rho(J) = \rho_o \left\{ \frac{J}{J_o} \right\}^n$$

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.

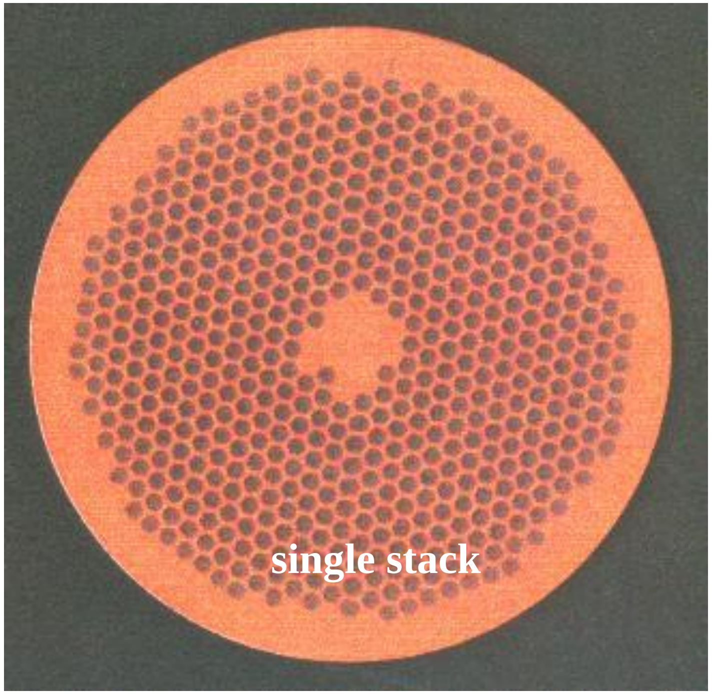


- resistive transition can be the main source of decay in persistent magnets
- 'n' is often taken as a measure of quality - look for n > 50
- HTS conductors so far have low n ~ 5 - 10

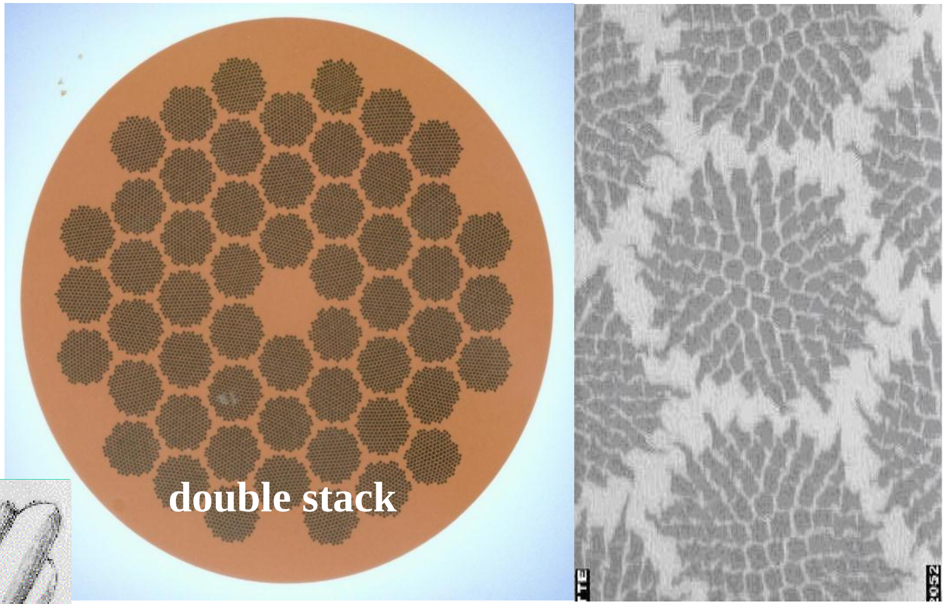


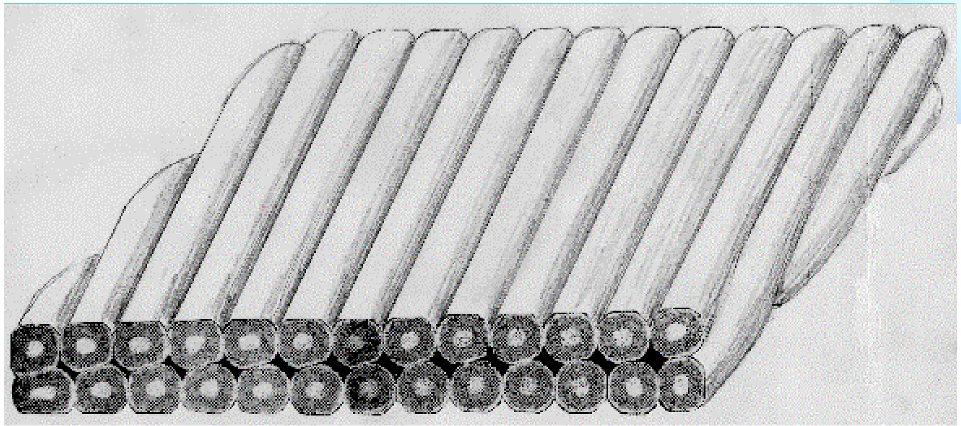
a) perfect filament
b) mid sausaging
c) bad sausaging

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)



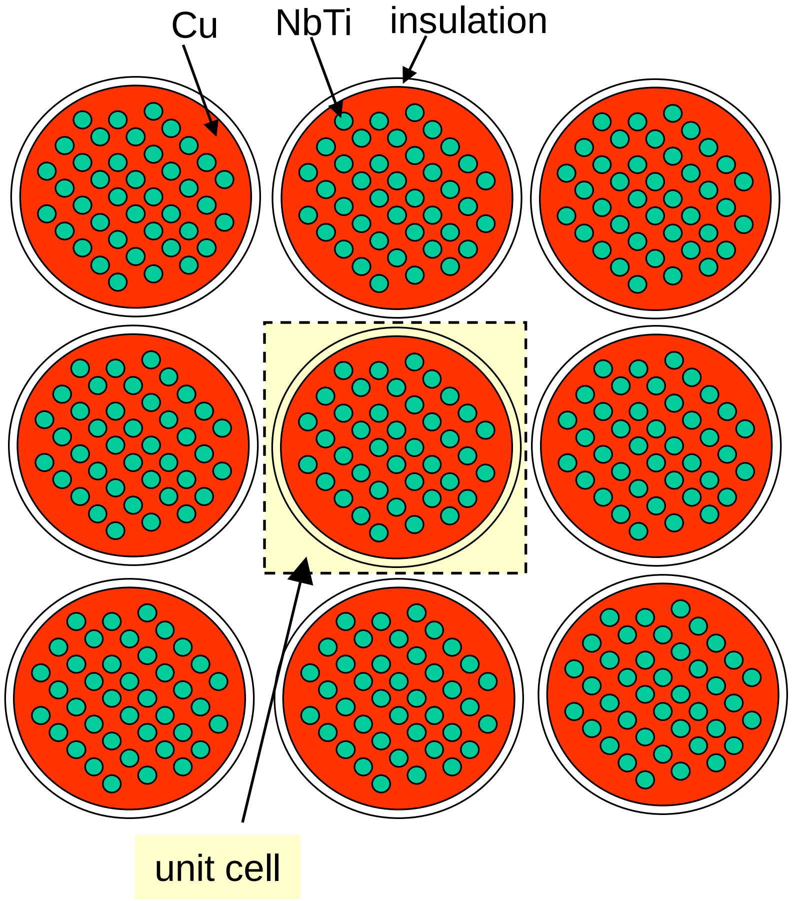


- to get the necessary high operating currents, many wires must be cabled together (lecture 3)

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

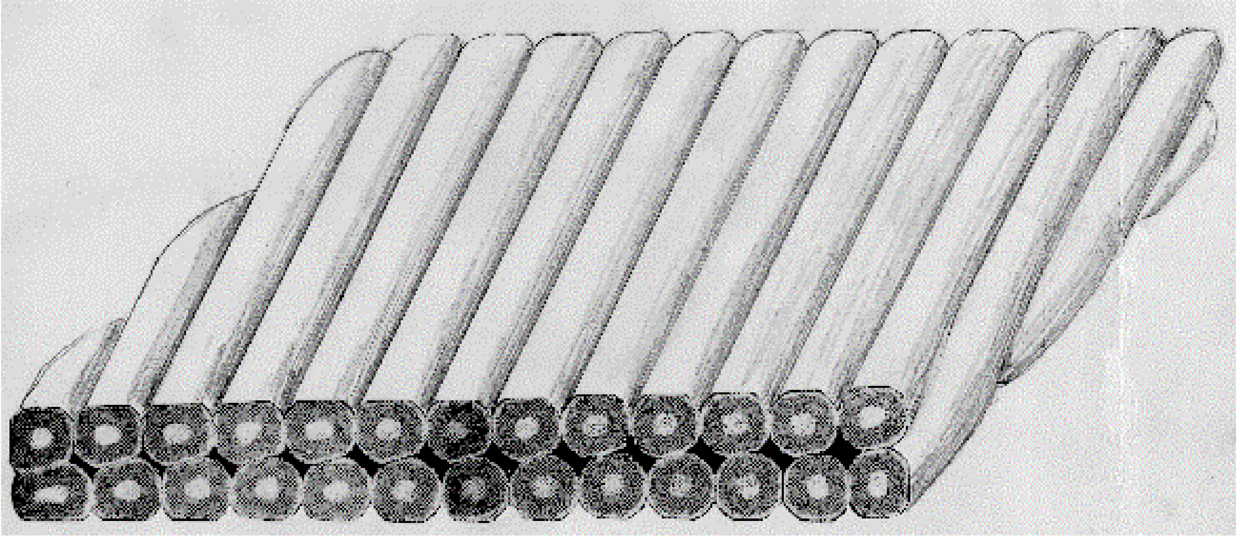
for B2212 *mat* = 3.0 to 4.0 ie λ_{sup} = 0.25 to 0.2

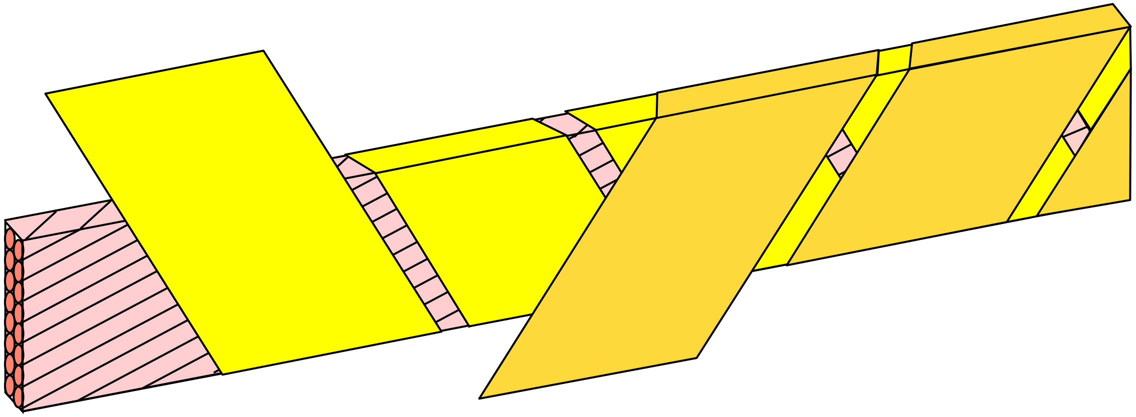
$\lambda_{winding}$ takes account of space occupied by insulation, cooling channels, mechanical reinforcement etc and is typically 0.7 to 0.8

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

Rutherford cable

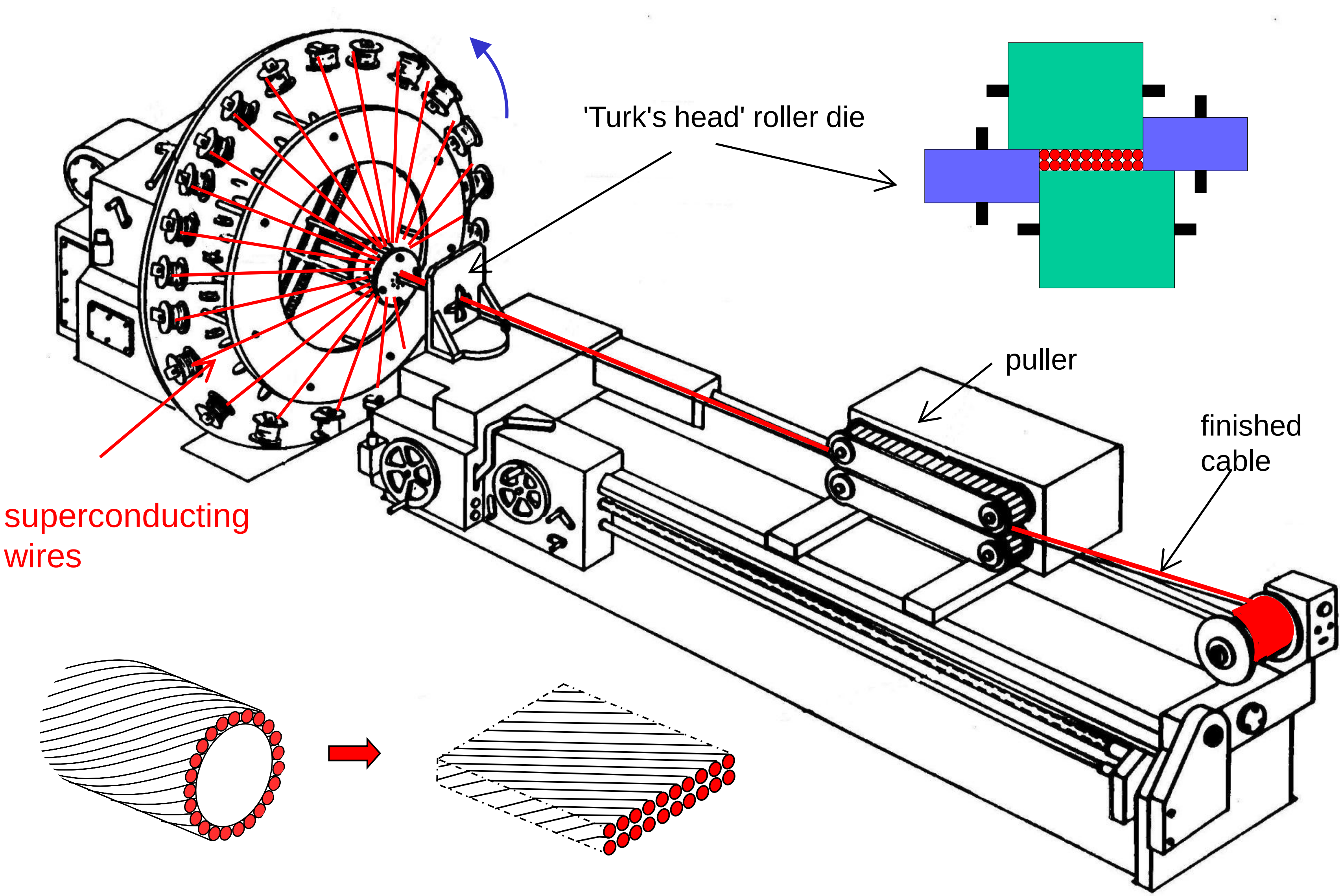
- for high current applications, such as accelerators, we need many wires in parallel
- the most popular way of doing this is the Rutherford cable (see lecture 3)



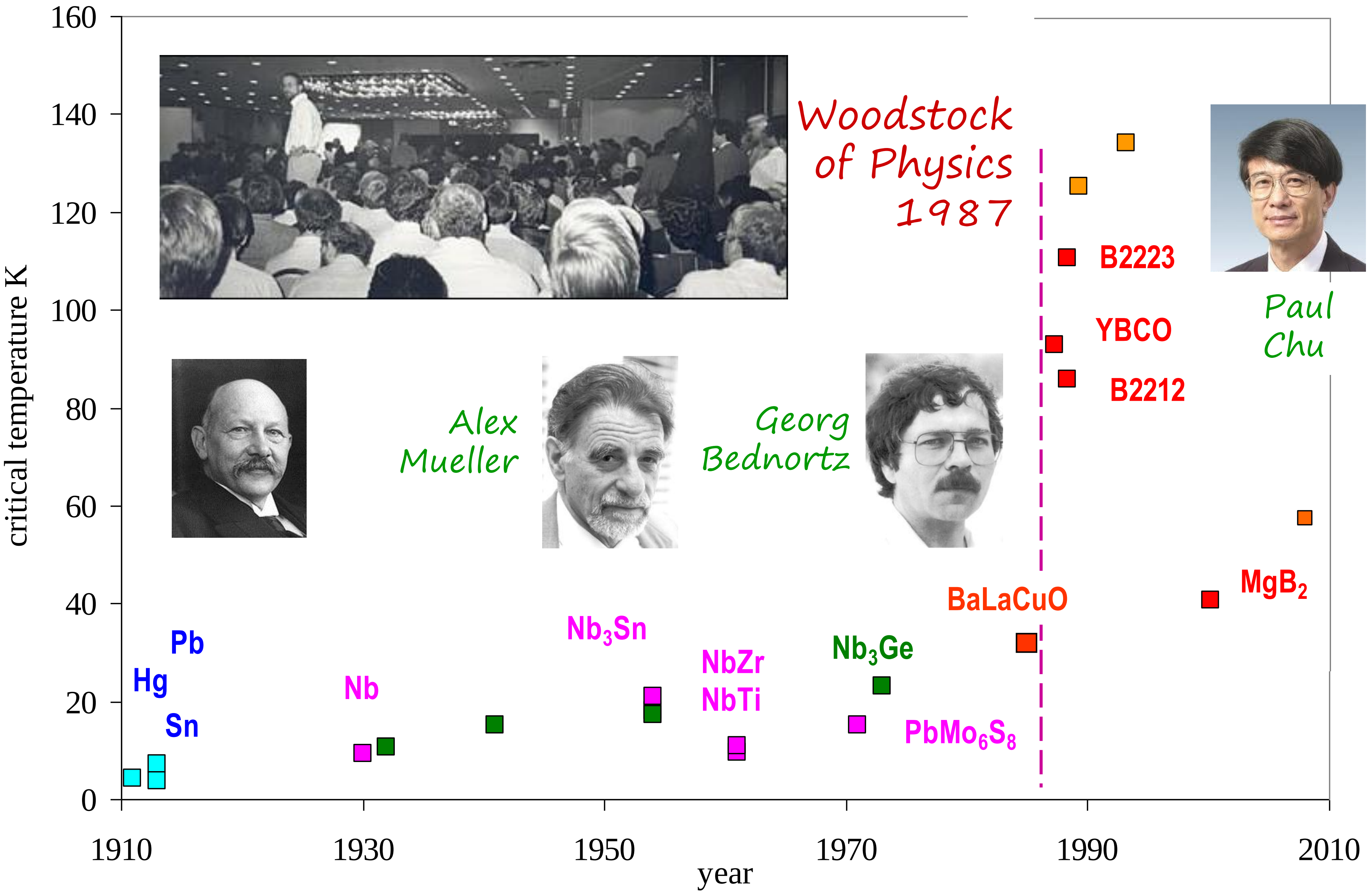


- Rutherford cable is usually insulated by wrapping it with Kapton tape

Manufacture of Rutherford cable

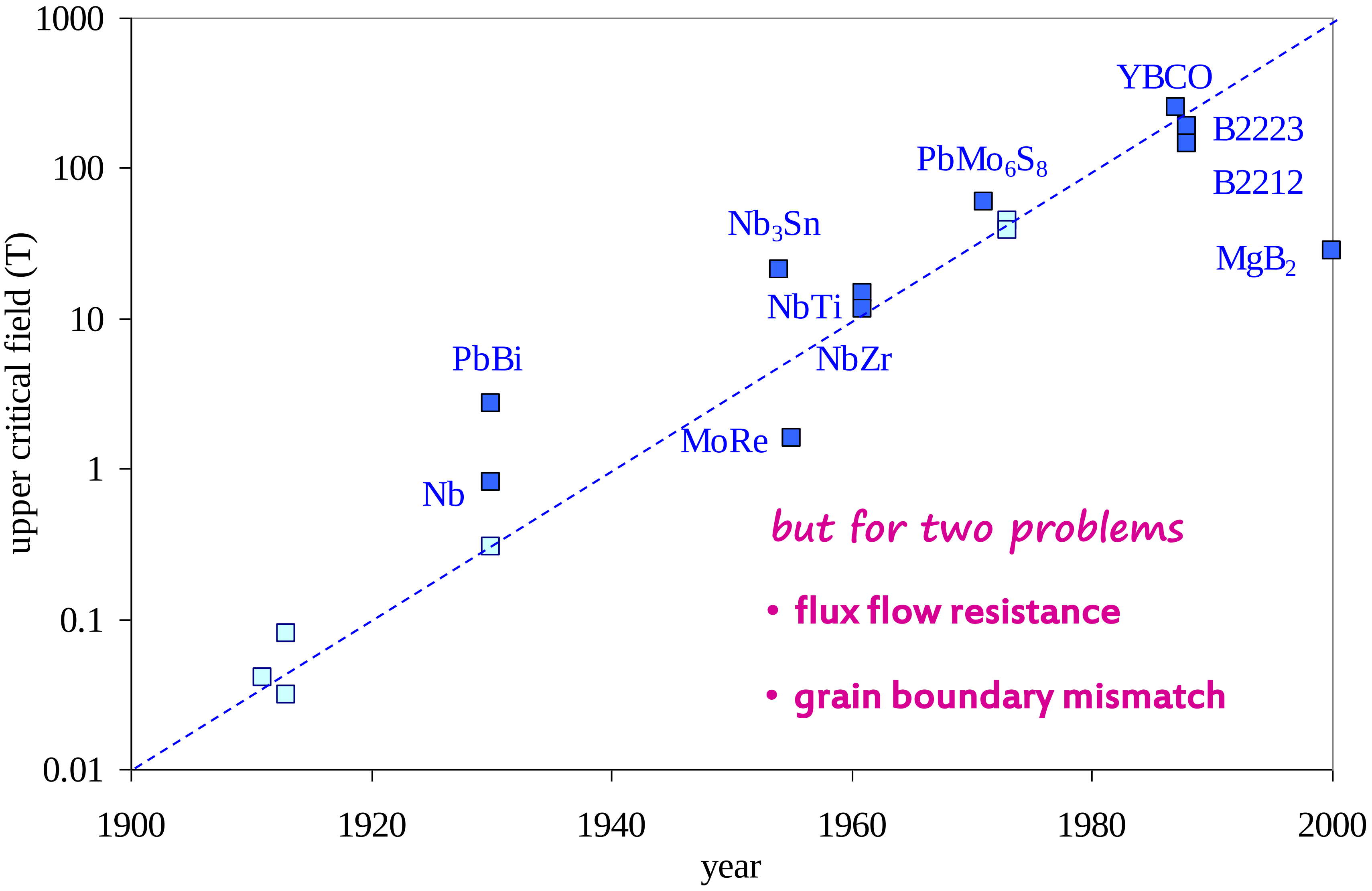


A century of critical temperatures



Woodstock
of Physics
1987

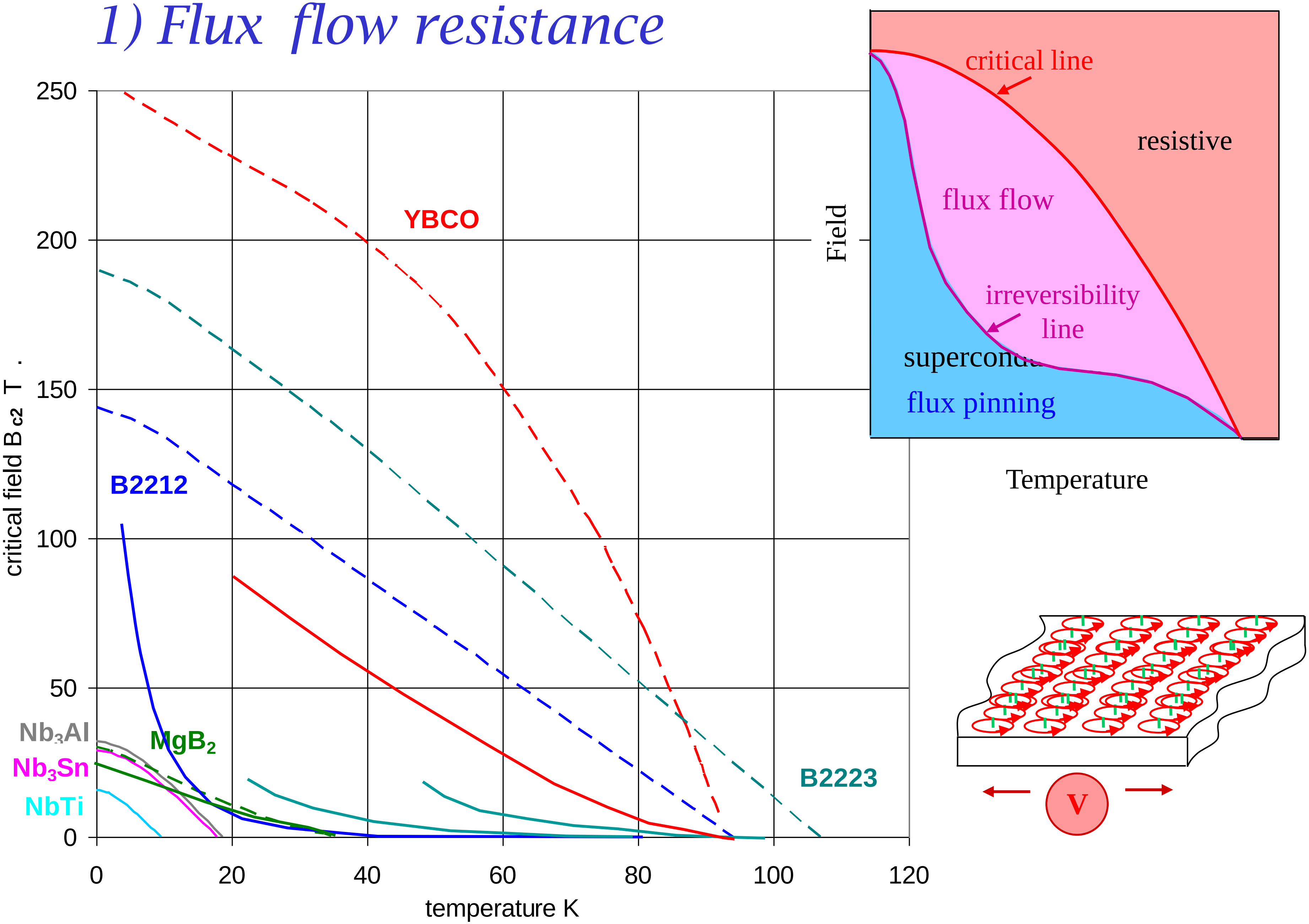
Wonderful materials for magnets



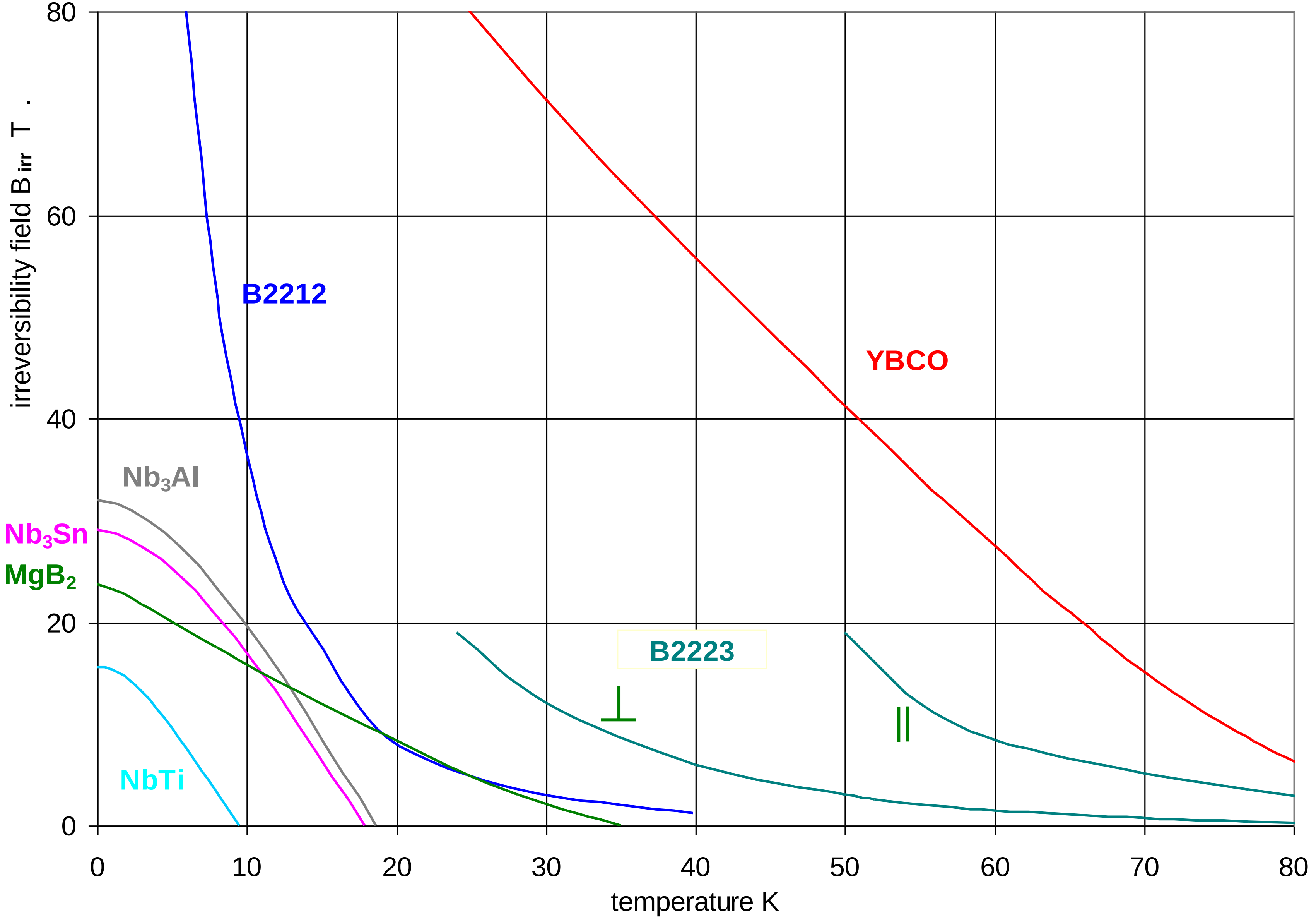
but for two problems

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

1) Flux flow resistance

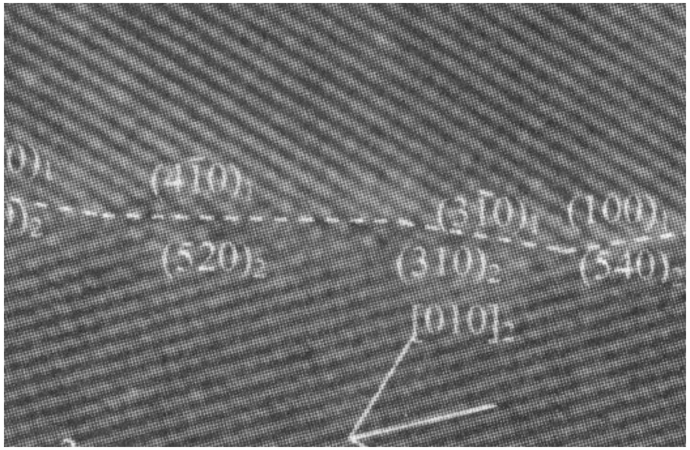


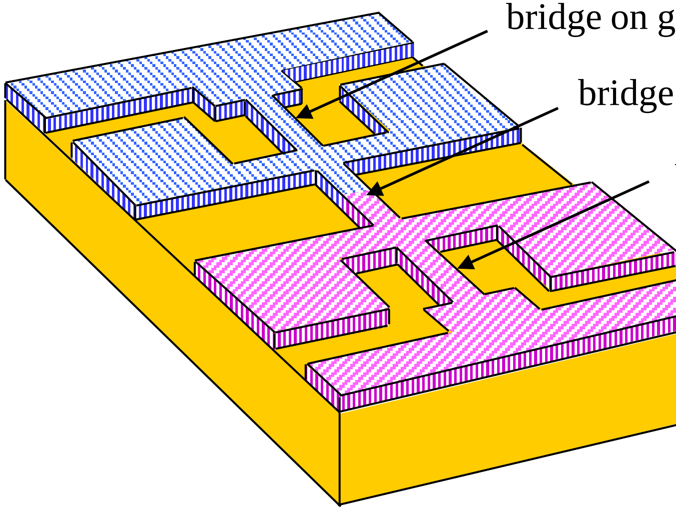
Accessible fields for magnets



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



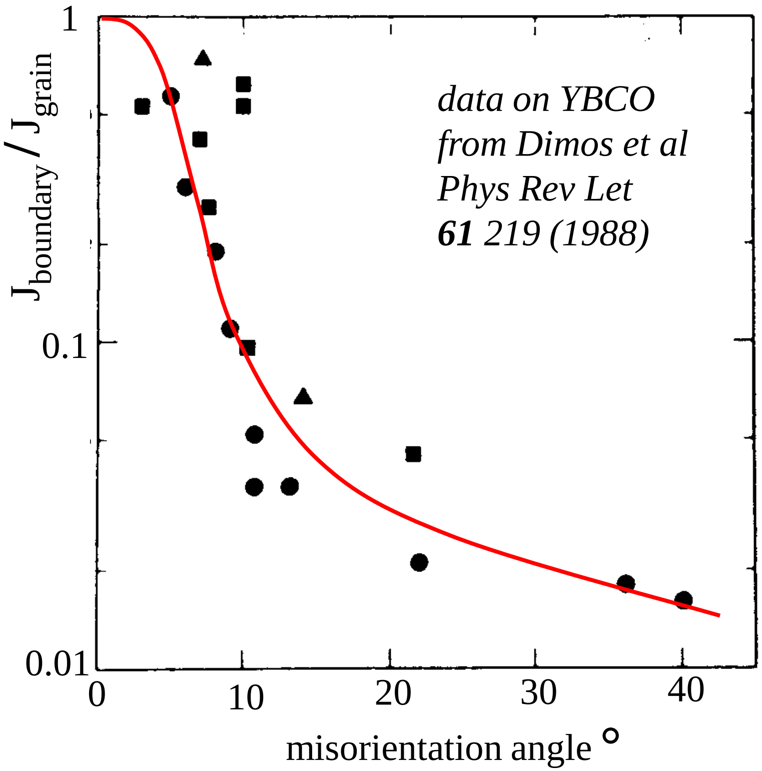


bridge on grain A

bridge on grain boundary

bridge on grain B

the key measurement of Dimos et al

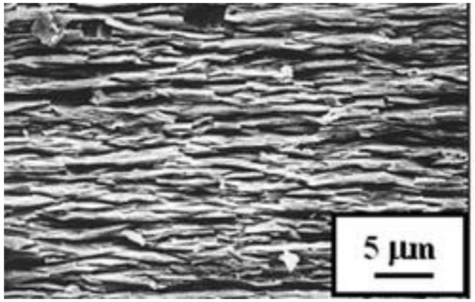


*data on YBCO from Dimos et al Phys Rev Let **61** 219 (1988)*

Practical HTS conductors

B2212 & B2223

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



- OK in high field at low temperature

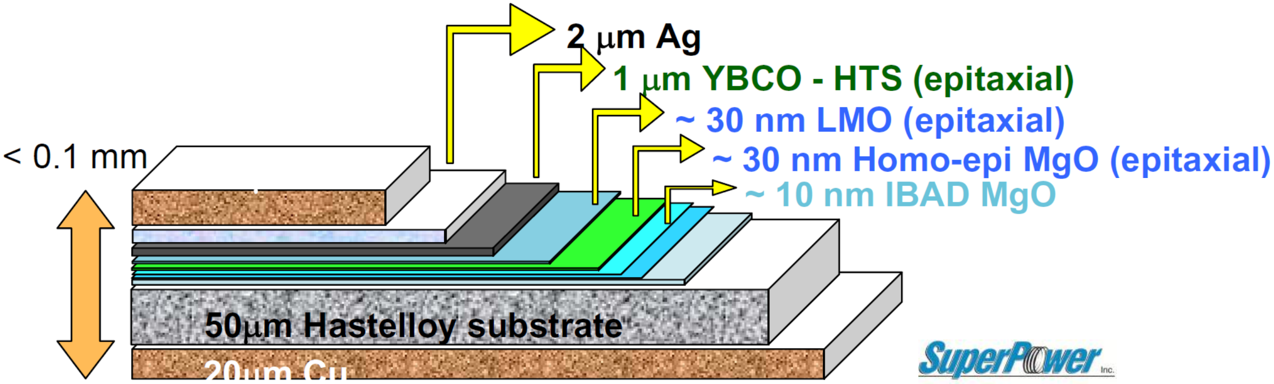
– high field inserts

- 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

  ⇒ fields higher than iron saturation (but still use iron for shielding)
- performance of all superconductors described by the critical surface in $\boldsymbol{B\ J\ \theta}$ 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