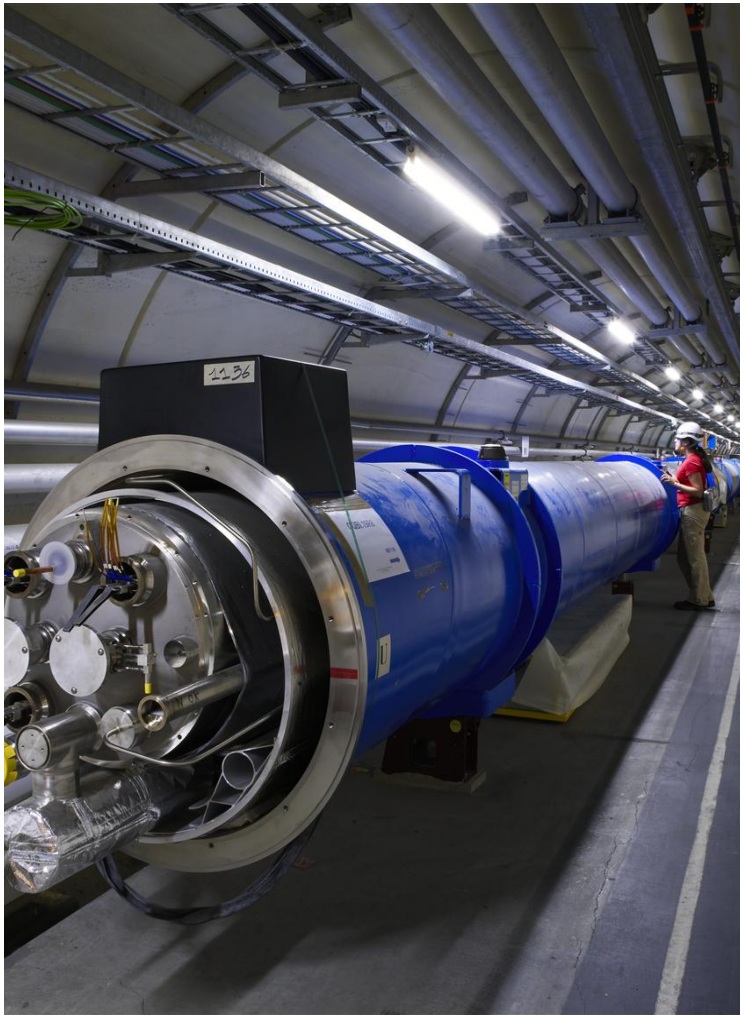
Superconductivity for accelerators – why bother?

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 ⇒ high fields
  (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: plan of the lectures

1 Introduction to Superconductors

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

2 Magnetization, Cables & AC losses

- superconductors in changing fields, critical state model
- filamentary superconductors and magnetization
- coupling between filaments ⇒ magnetization
- why cables, coupling in cables
- mini tutorial
- AC losses in changing fields

3 Magnets, ‘Training’ & Fine Filaments

- coil shapes for solenoids, dipoles & quadrupoles
- engineering current density & load lines
- degradation, training & minimum quench energy MQE
- flux jumping

4 Quenching and Protection

- the quench process
- resistance growth, current decay, temperature rise
- calculating the quench
- mini tutorial
- quench protection schemes

5 Cryogenics & Practical Matters

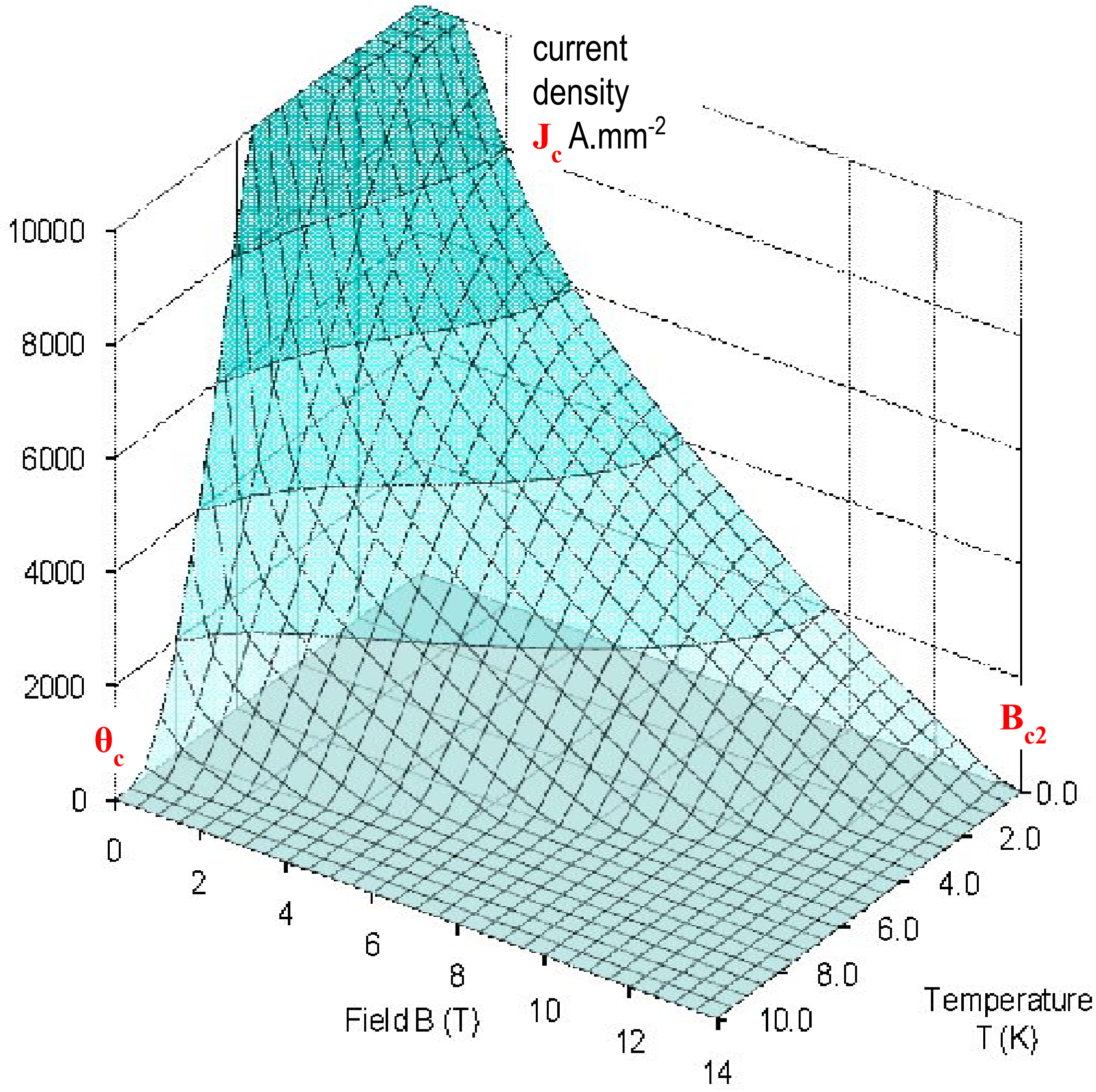
- working fluids, refrigeration
- cryostat design
- current leads
- accelerator magnet manufacture
- some superconducting accelerators

mini tutorials

get a feel for the numbers, bring a calculator

The critical surface of niobium titanium

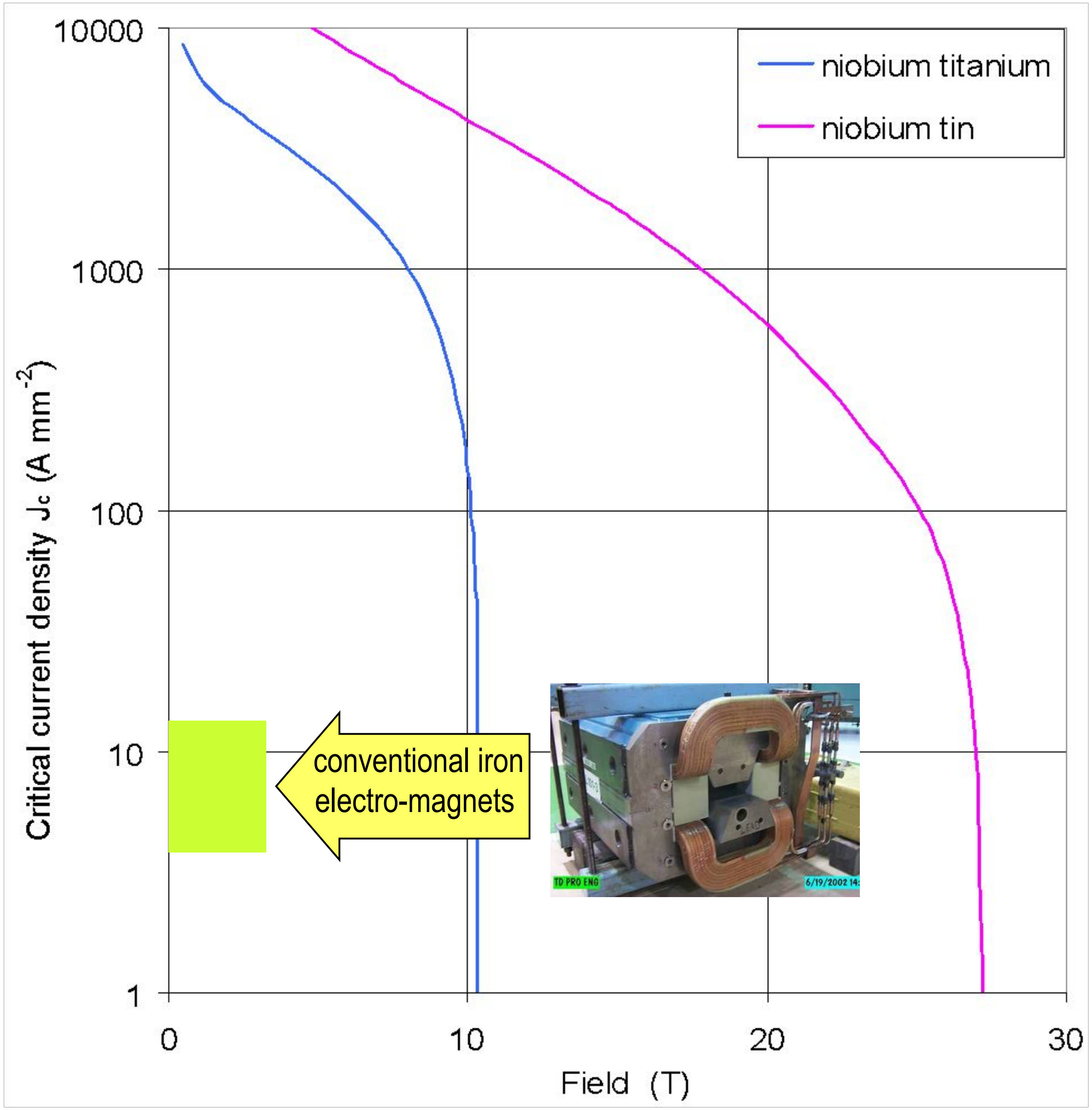
- **NbTi** is the standard commercial ‘work horse’ of the superconducting magnet business



- ***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

- keep it cold!

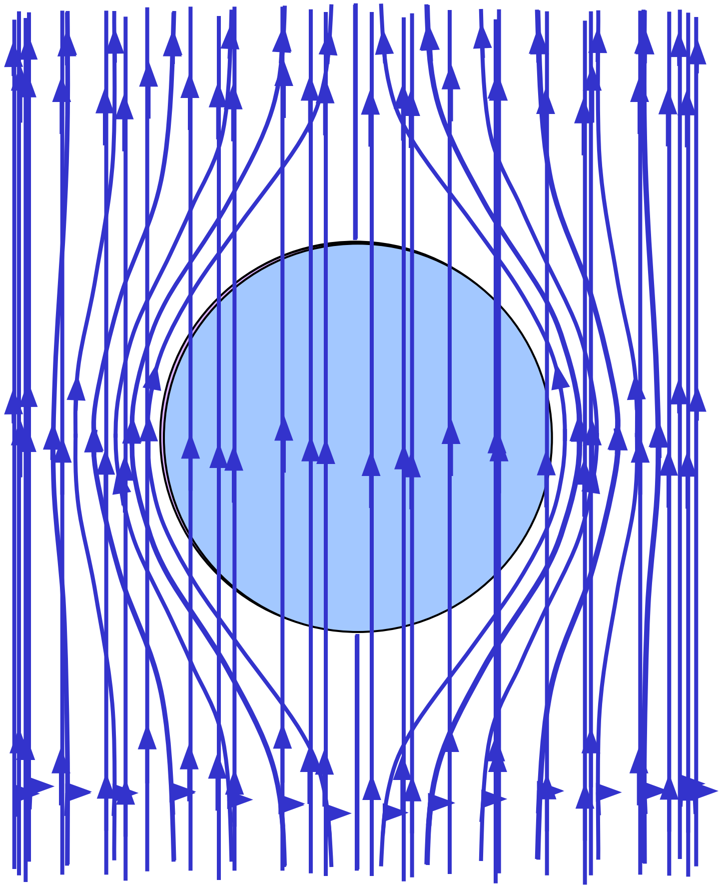
The critical line at 4.2K



- 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

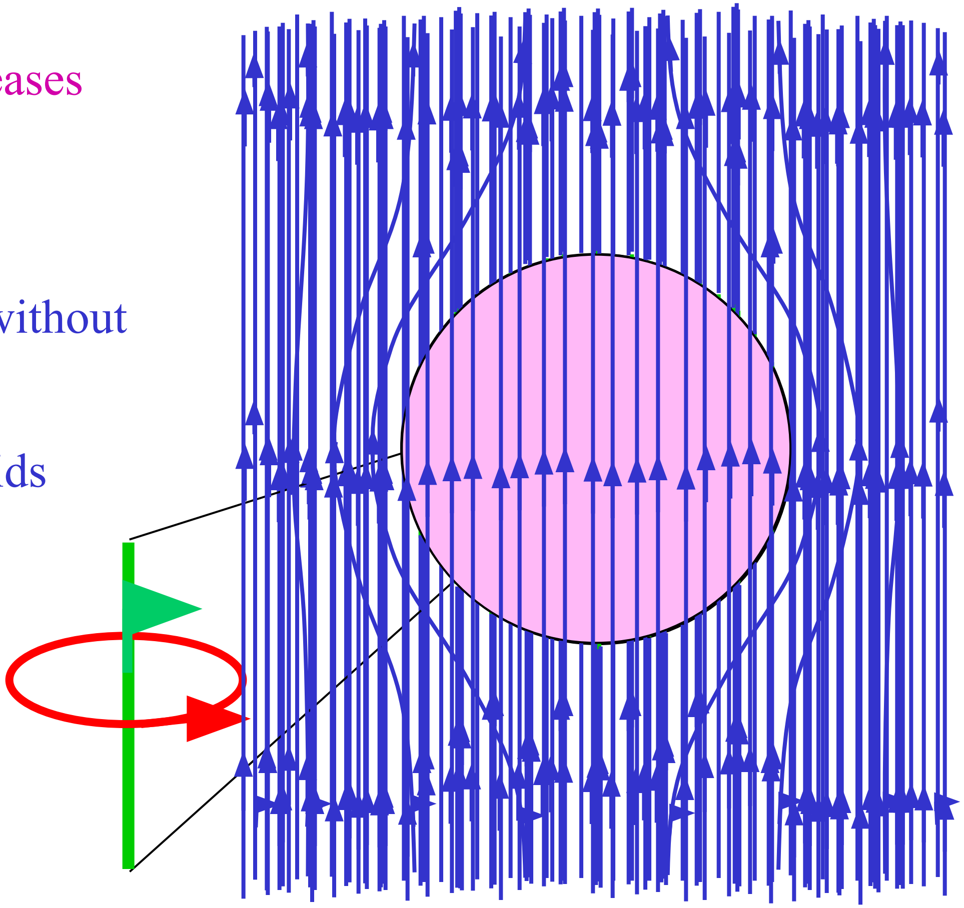
- the materials first discovered by Kammerlingh Onnes in 1911 - soft metals like lead, tin mercury
- sphere of metal at room temperature
- apply magnetic field
- reduce the temperature - resistance decreases
- reduce the temperature some more - resistance decreases some more
- at the critical temperature 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



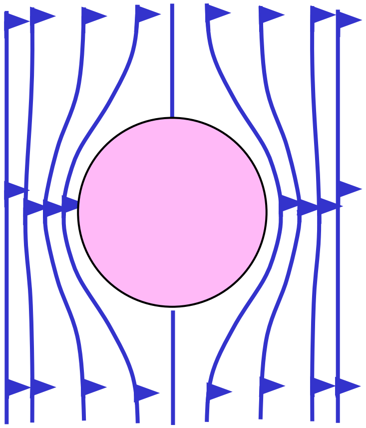
useless for magnets!

Two kinds of superconductor: type 2

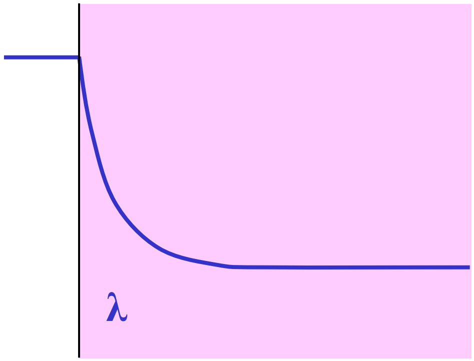
- apply magnetic field
- reduce the temperature - resistance decreases
- at the critical temperature θ_c the field is pushed out
- increase the field - field jumps back in without quenching superconductivity
- it does so in the form of quantized fluxoids
- lower critical field B_{c1}
- supercurrents 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}



Type 1 and type 2 superconductors

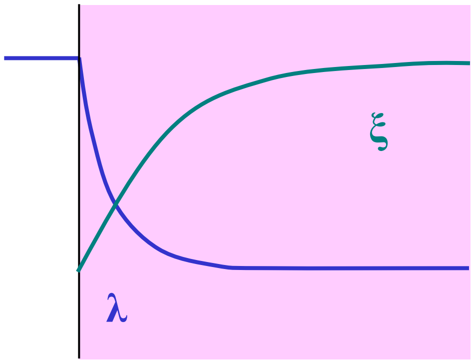


- Meissner effect is not total
- magnetic field penetrates a small distance *λ*
- the ***London Penetration Depth.***

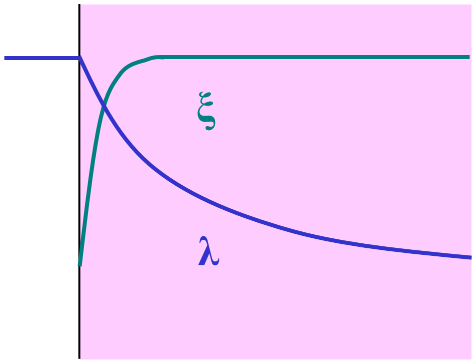


- another characteristic distance is the ***coherence length*** *ζ* - the minimum distance over which the electronic state can change from superconducting to normal
- theory of Ginsburg, Landau, Abrikosov and Gorkov **GLAG** defines the ratio $\kappa = \lambda / \xi$

if $\kappa < 1/\sqrt{2}$
material is
Type 1



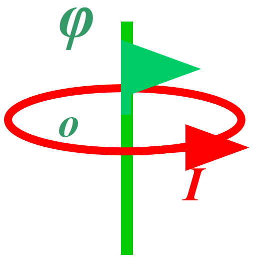
if $k > 1/\sqrt{2}$
material is
Type 2



Critical fields of type 2 superconductors

- recap thermodynamic critical field $\boldsymbol{B_c}$ *(slide 6)*
- lower critical field $\boldsymbol{B_{c1} = B_c / \kappa}$
- above $\boldsymbol{B_{c1}}$ magnetic field penetrates as discrete quantized ***fluxoids***

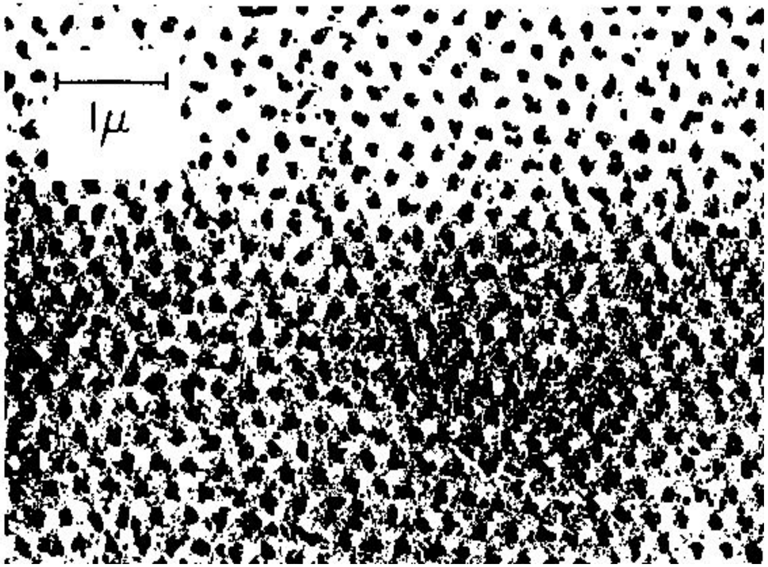
human hair in earth's magnetic field ~ 50 φ_o



a fluxoid encloses flux

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

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 $\boldsymbol{\rho_n}$ 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: γ ~ 900 J m^{-3} K^{-2} $\boldsymbol{\rho_n}$ ~ 65 x10^{-8} W m $\boldsymbol{\theta_c}$ = 9.3 K hence **B_{c2} ~ 18.5 T**

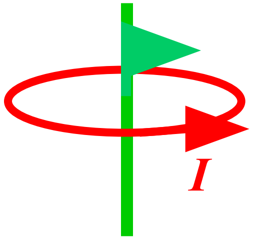
Sommerfeld coefficient of electronic specific heat $C_e = \gamma\theta$

Critical current density: type 2 superconductors

- a single fluxoid encloses flux

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

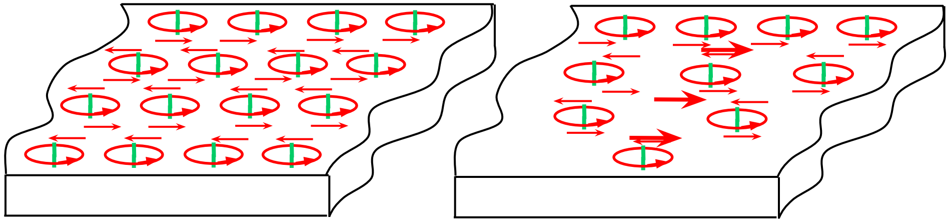
h = Planck's constant, e = electronic charge



human hair in Earth's field encloses 20 × φ_o

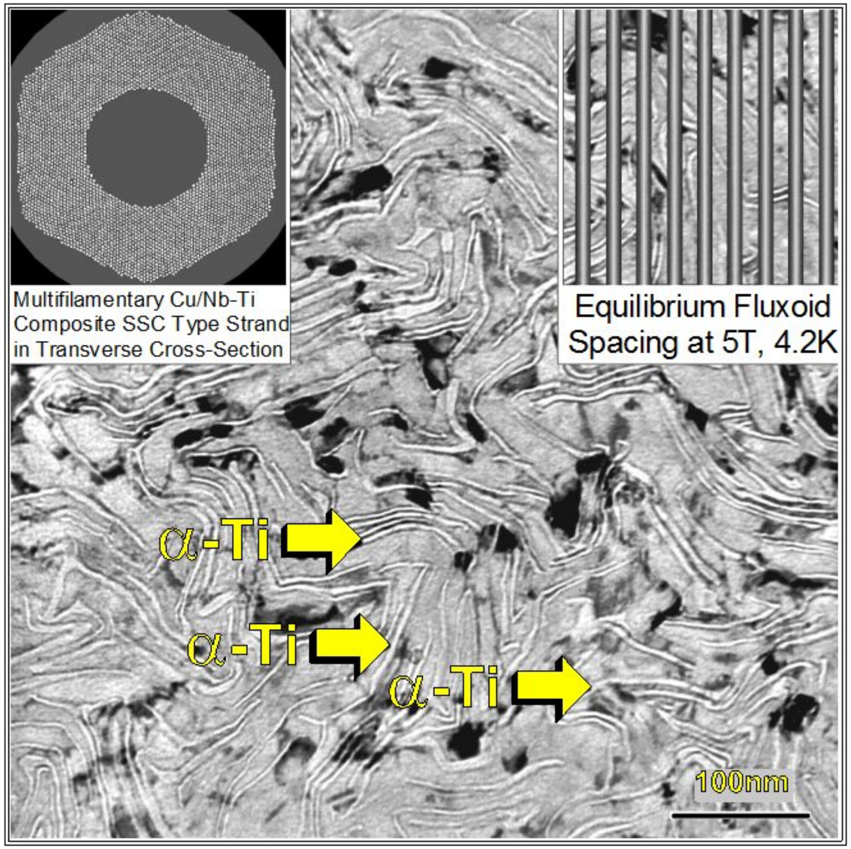
- so density of fluxoids ~ average field
  uniform density ⇒ uniform field
  ⇒ zero *J* (because *Curl B* = $\mu_o J$)

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



- fluxoids like to distribute uniformly

- must impose a gradient by inhomogeneities in the material, eg dislocations or precipitates



precipitates of α Ti in Nb Ti

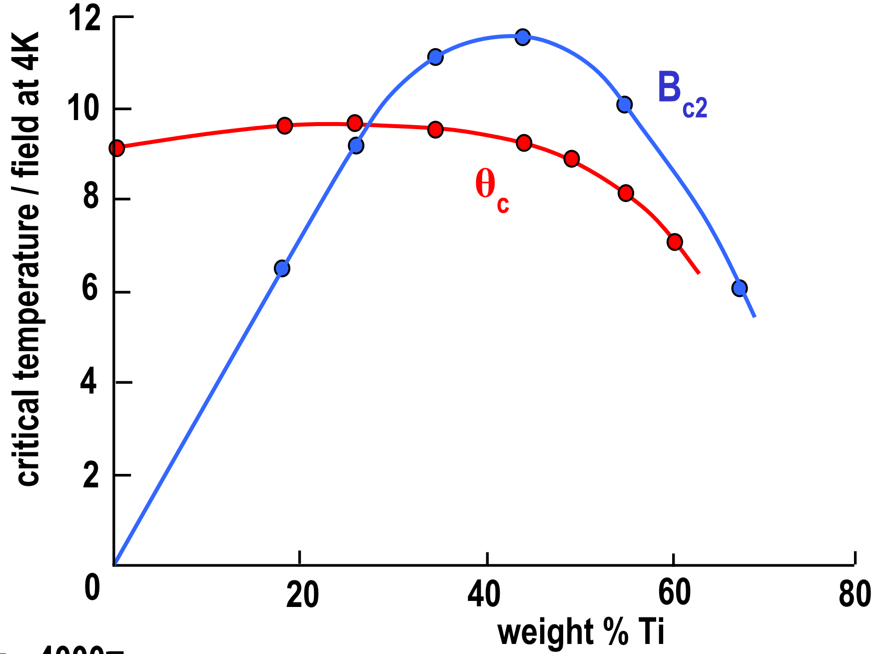
Meingast, P Lee and DC Larbalestier: J. Appl. Phys. 66, 5971

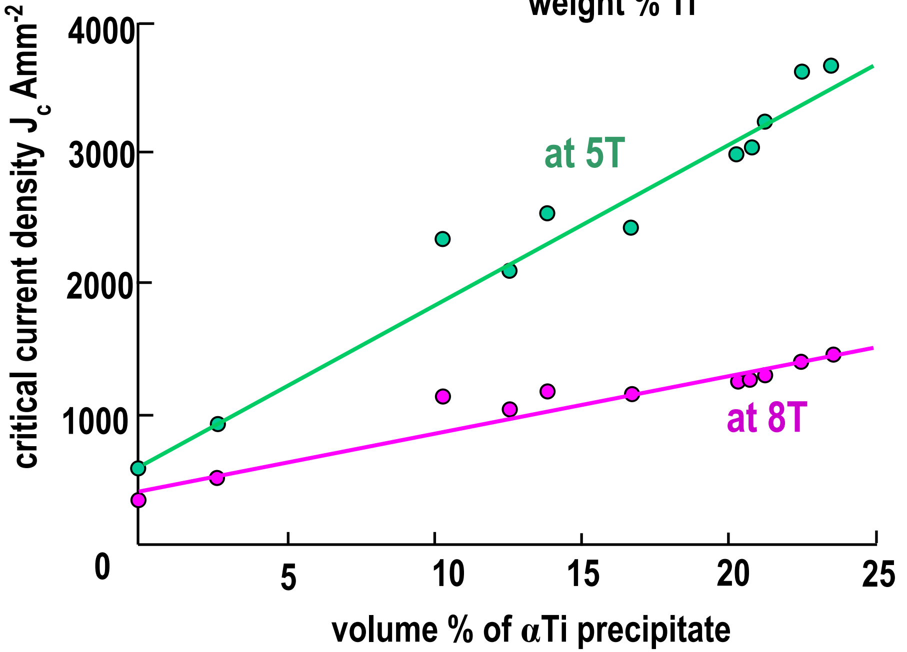
Critical properties

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

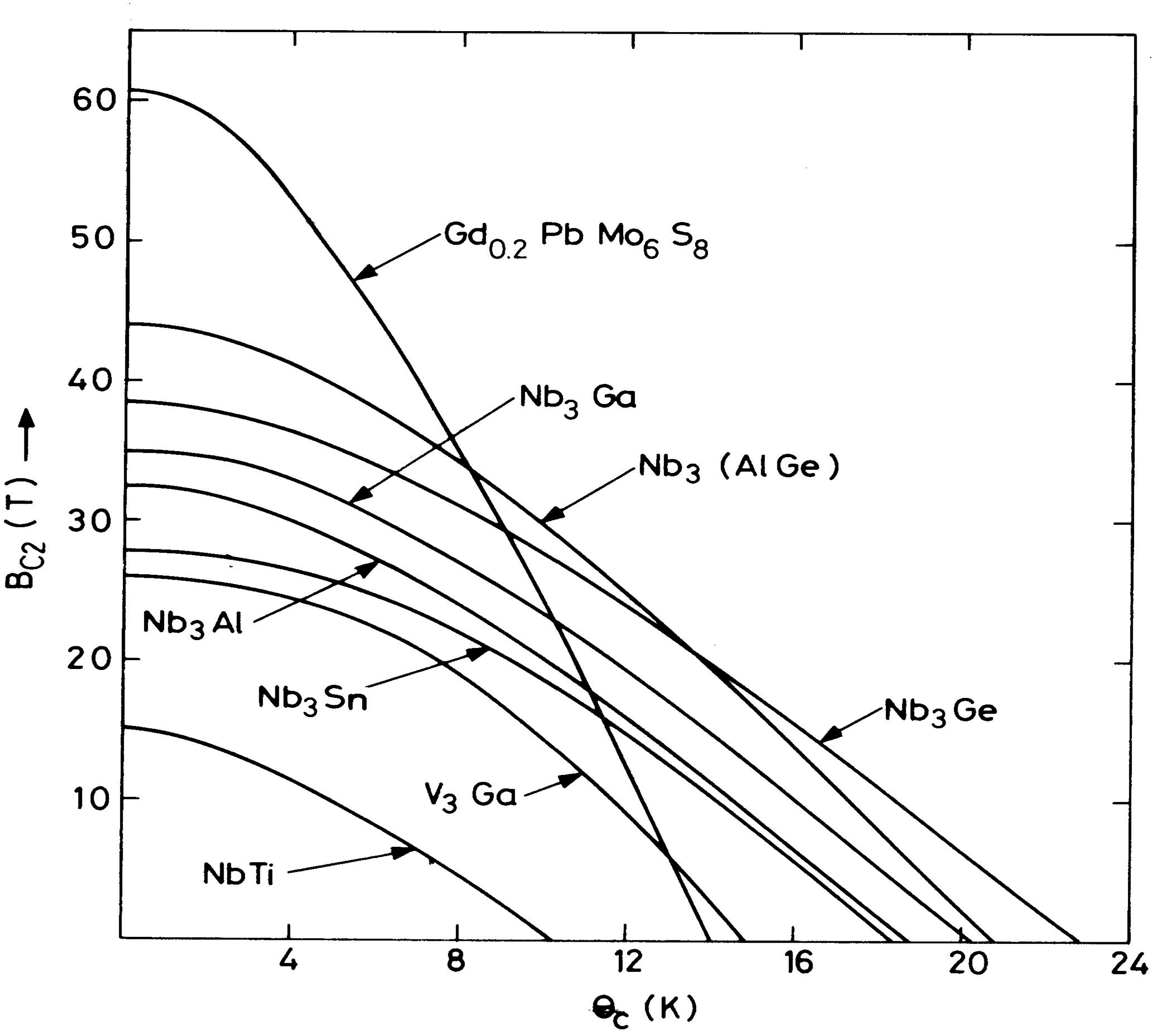
- **Upper Critical field B_{c2}**: choose a Type 2 superconductor with a high critical temperature and a high normal state resistivity
  property of the material

- **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 LTS

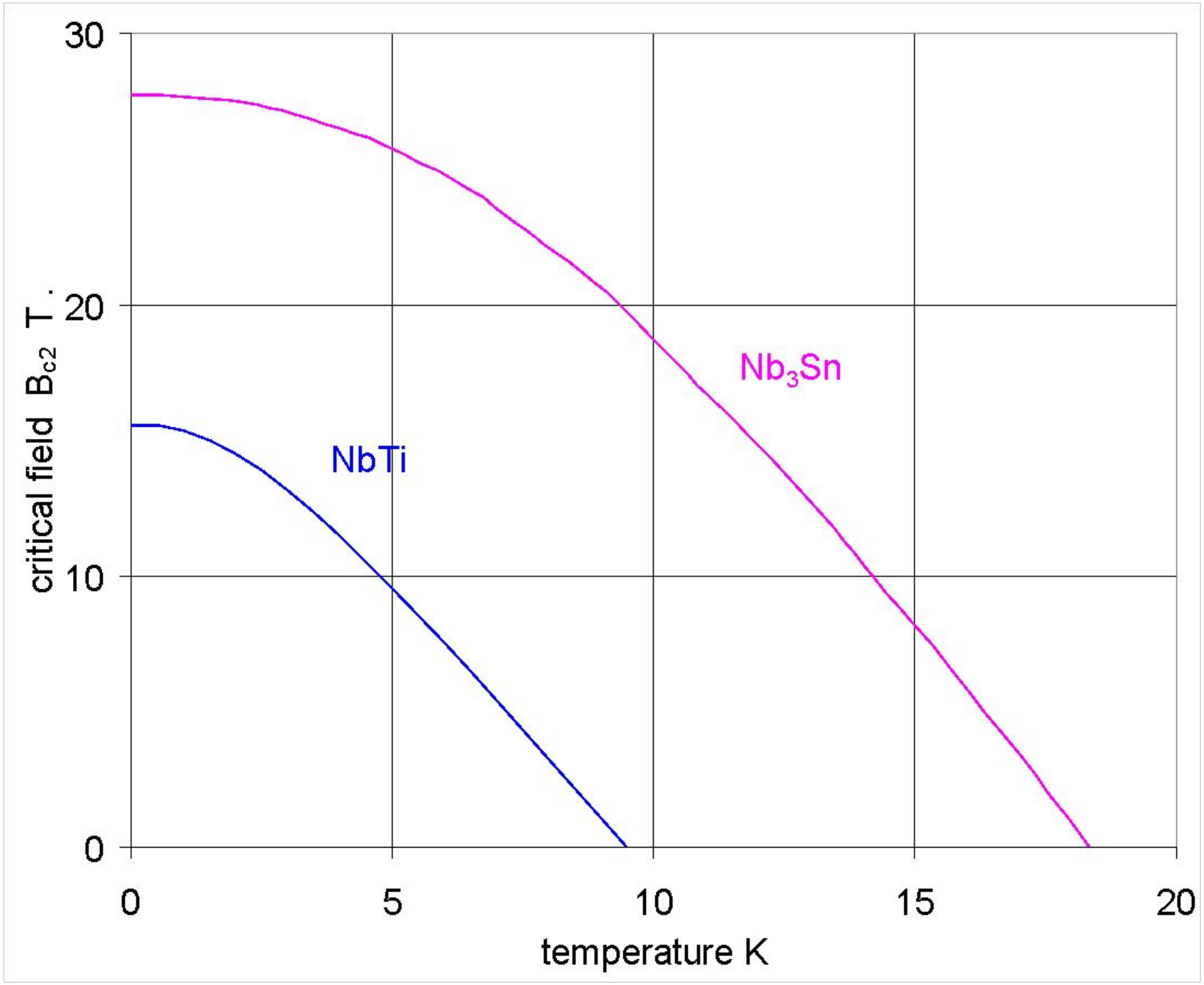


Low
Temperature
Superconductors

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

All the rest are brittle intermetallic compounds

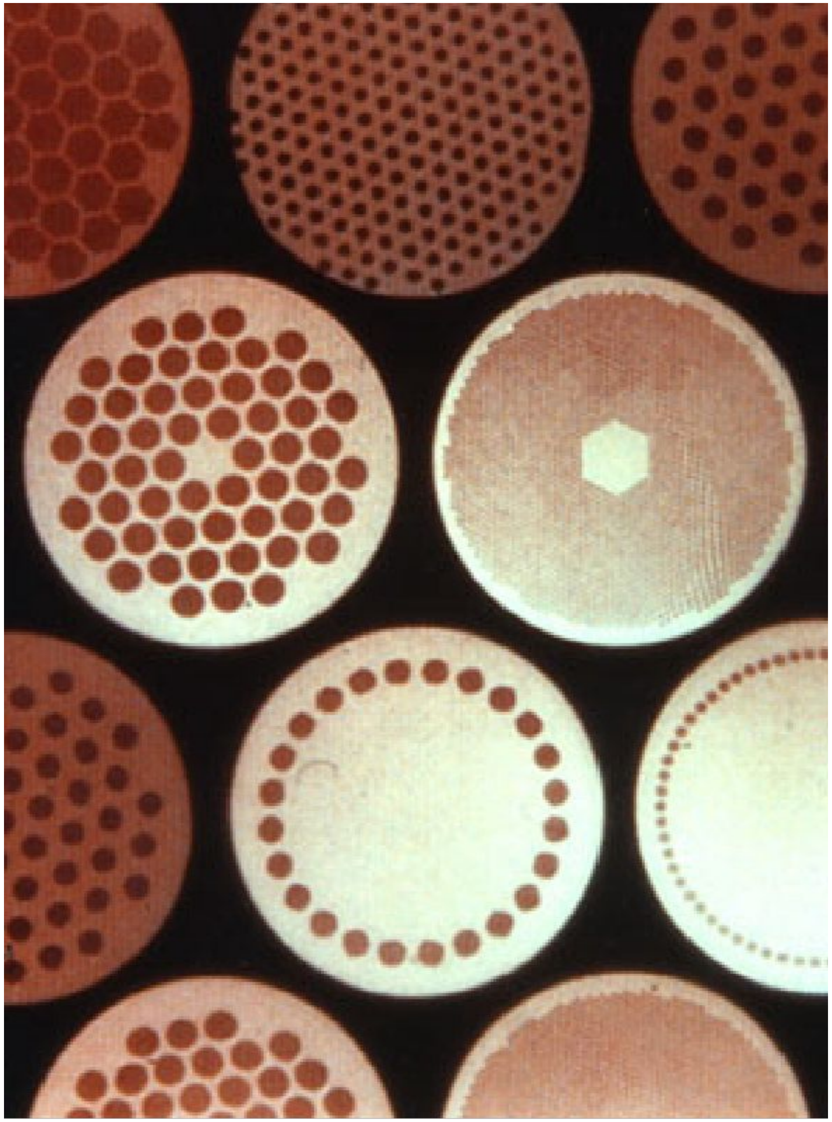
Critical field & temperature of LTS in accelerators (so far)



To date, all superconducting accelerators have used NbTi.

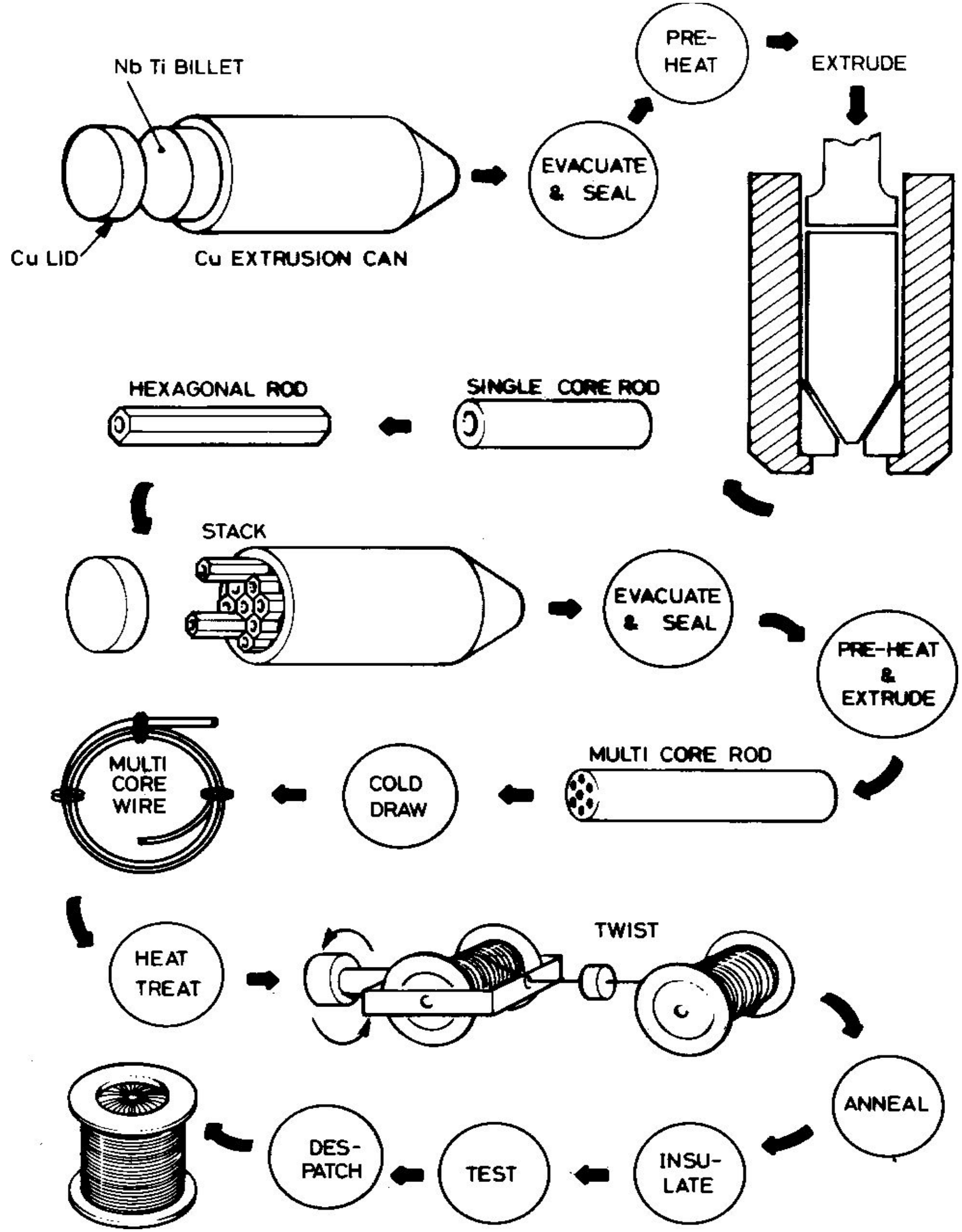
Of the intermetallics, only Nb_3Sn has found significant use in magnets

Practical wires for magnets



- ~ 50 years after its development, NbTi is still the most popular magnet conductor,
- Nb_3Sn used for special high field magnets and HTS for some developmental prototypes.
- superconducting materials always combined with a good normal conductor such as copper
- need intimate mixing between the two, so superconductor made as fine filaments in a matrix of copper
- typical dimensions:
  - wire diameter = 0.3 - 1.0mm
  - filament diameter = 5 - 50μm
- for electromagnetic reasons, the composite wires are twisted so that the filaments look like a rope (see Lecture 2)

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 brittle and cannot be drawn down.

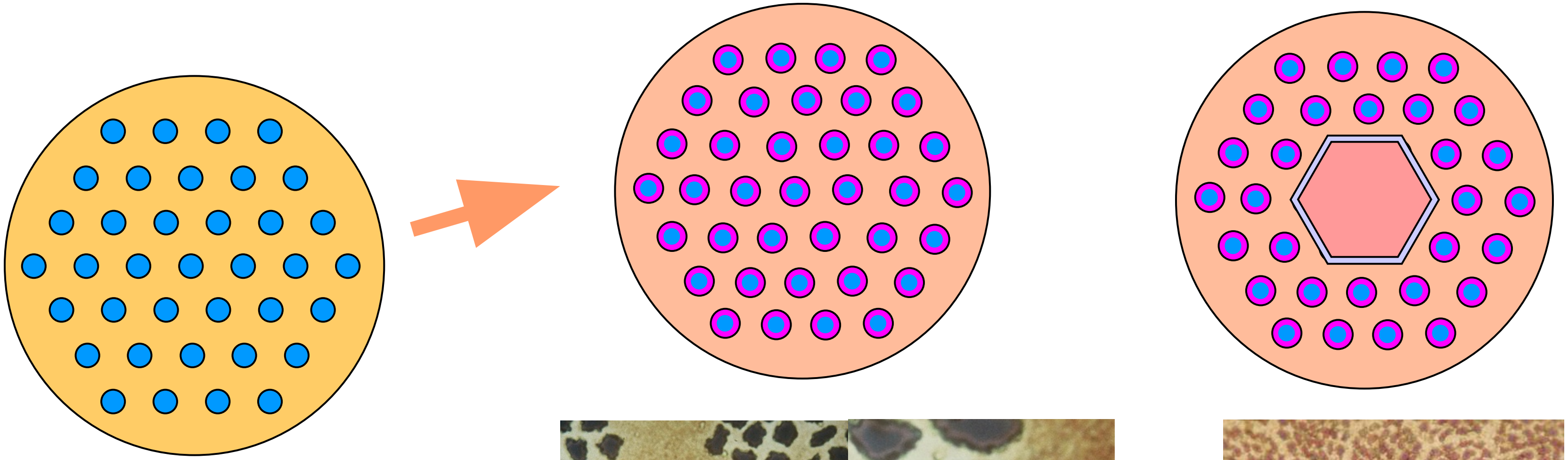
  so draw down pure niobium in a matrix of bronze (copper tin)

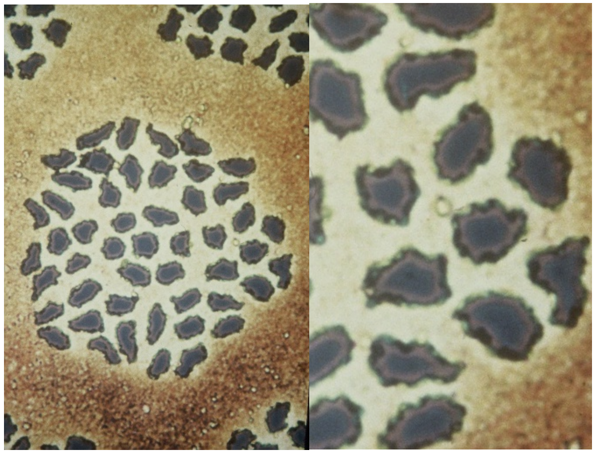
- At final size heat the wire (~700C for some days)

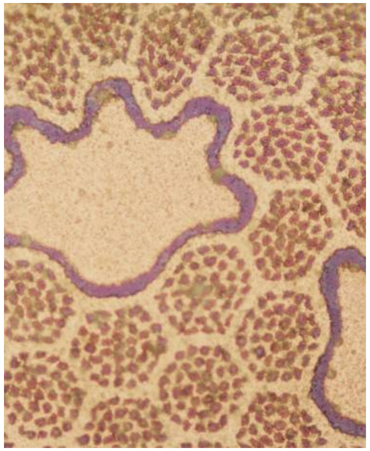
  Sn diffuses through Cu & reacts with Nb ⇨ Nb_3Sn

- Remaining copper still contains ~ 3wt% tin ⇨ high resistivity

  so add 'islands' of pure copper surrounded by a diffusion barrier



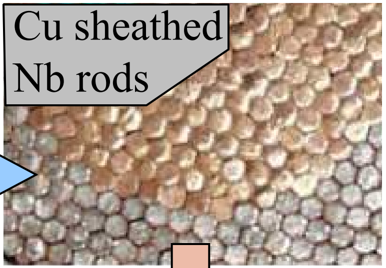




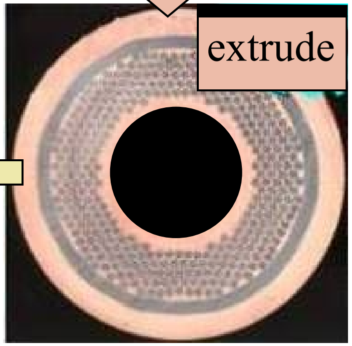
- *BUT maximum ductile bronze is ~13wt% tin,*
- *reaction slows at ~ 3wt%*
- *so low engineering J_c*

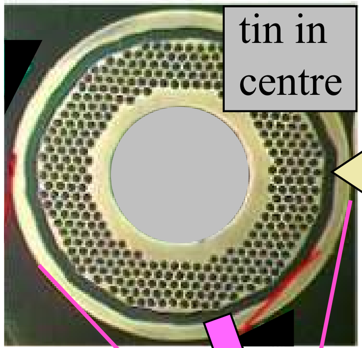
Nb_3Sn with higher engineering J_c

RRP®
Rod Restack Process
OXFORD INSTRUMENTS


Cu sheathed Nb rods

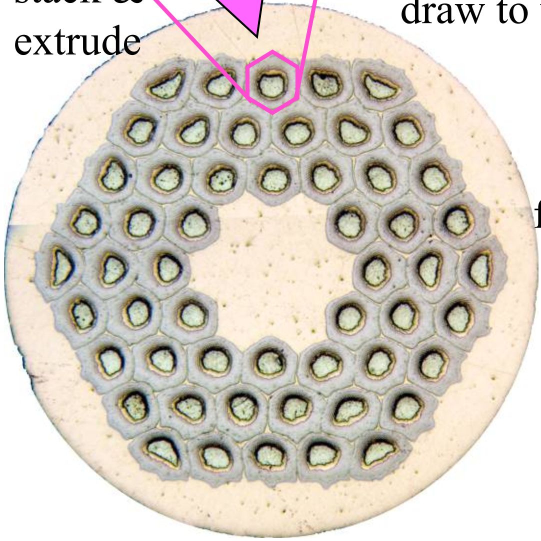
extrude



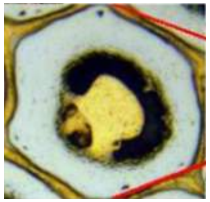

tin in centre

stack & extrude

draw to wire

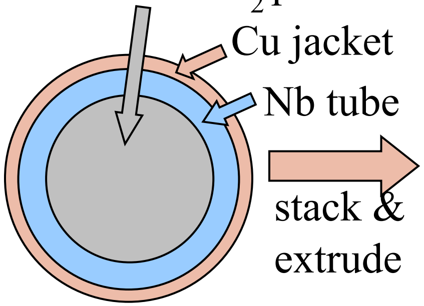


heat treat to form 'macro filaments' of Nb_3Sn

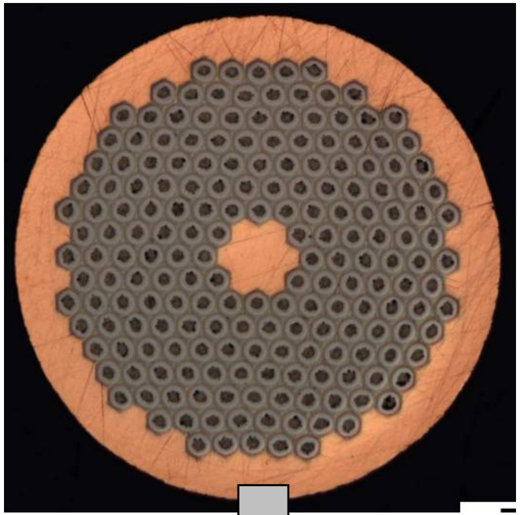


SMI
SHAPEMETAL INNOVATION B.V.

Powder in tube PIT

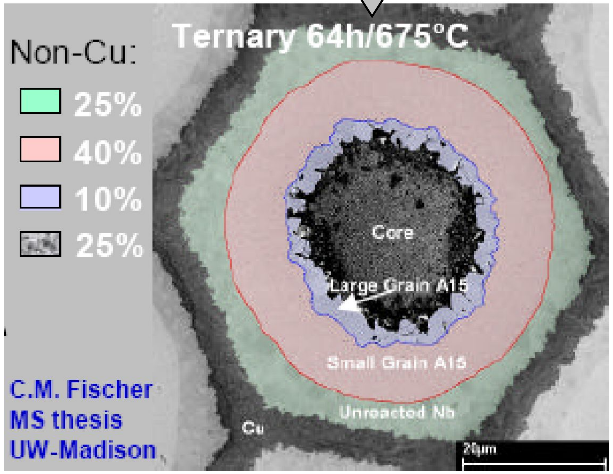


stack & extrude



draw to wire

heat treat



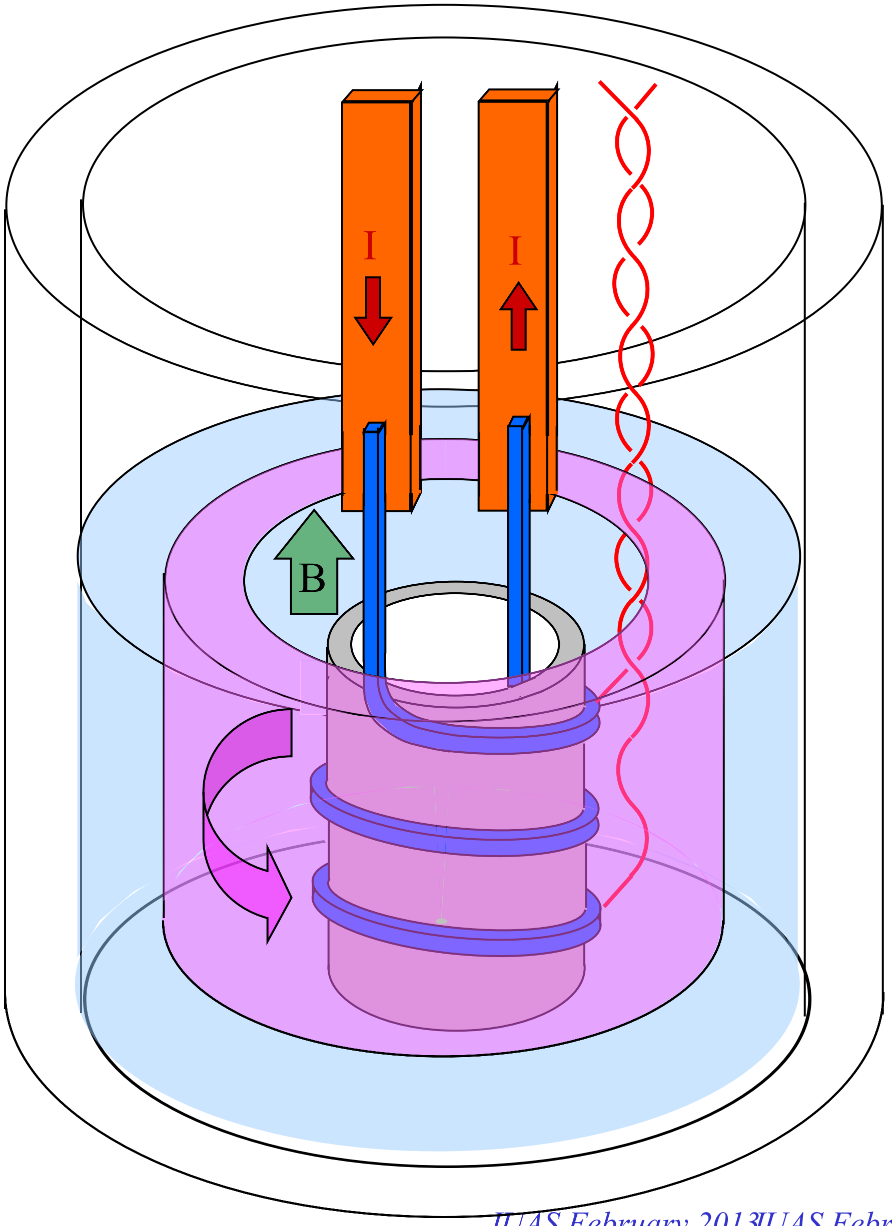
C.M. Fischer
MS thesis
UW-Madison

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

***but** large filaments*

Measurement of critical current

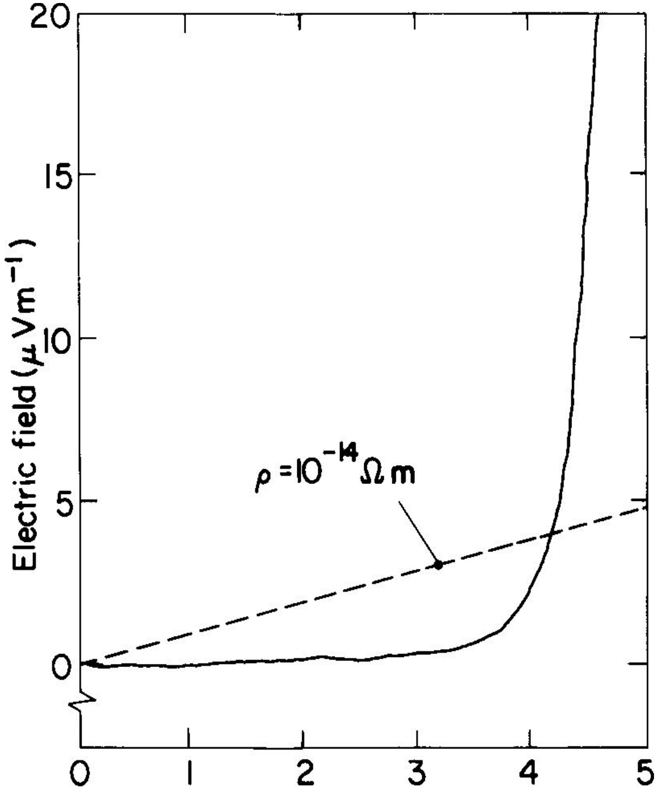
- spiral sample with current leads and voltage taps
- place in the bore of a superconducting solenoid
- put in cryostat
- immerse in liquid helium
- at each field level slowly increase the current and measure the voltage across the test section



Martin Wilson Lecture 1 slide 17 JUAS February 2015

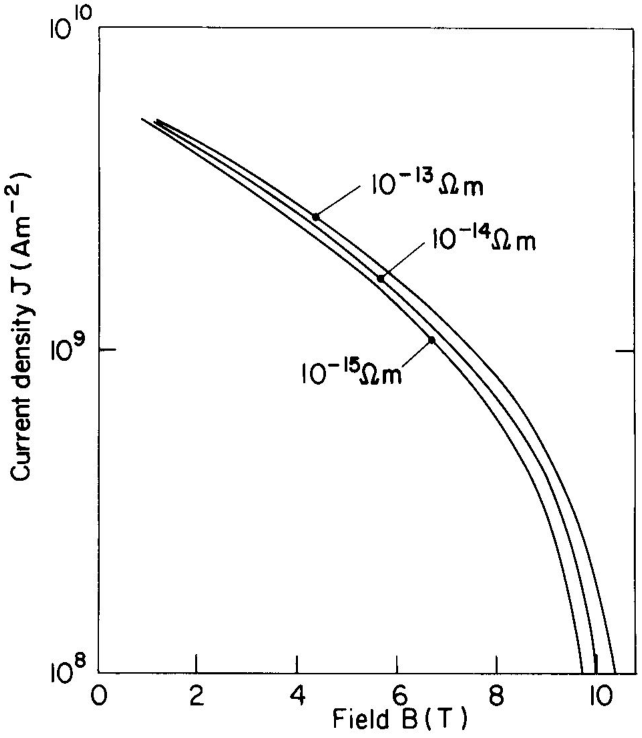
Resistive transition 1

- measured boundary between superconducting and resistive states is not sharp, but gradual.



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

- measure J_c with voltage taps across sample
- see voltage rise gradually.
- define J_c at a given electric field or effective resistivity.



- common definitions are **ρ = 10^{-14} Ωm or E = 1 μV.m^{-1}**
- this level is about the critical current expected in a resin impregnated winding
  - at higher current self heating

    ⇨ temperature rise ⇨ reduced critical current

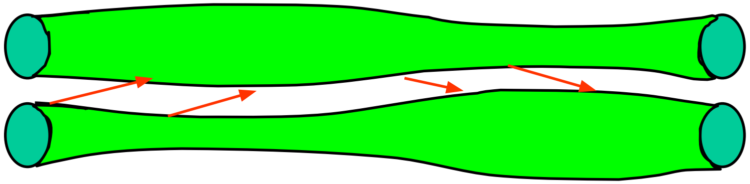
Resistive transition 2

- empirically find that resistive transition follows a power law

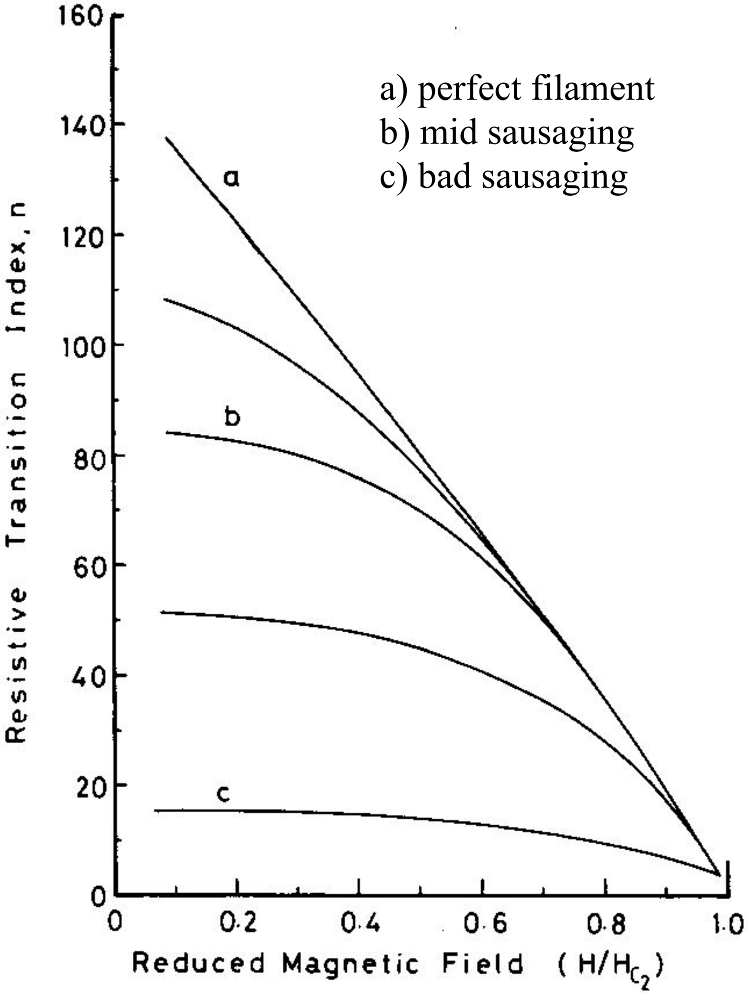
$$\rho(J) = \rho_o \left\{ \frac{J}{J_o} \right\}^n$$

where n is called the resistive transition index.

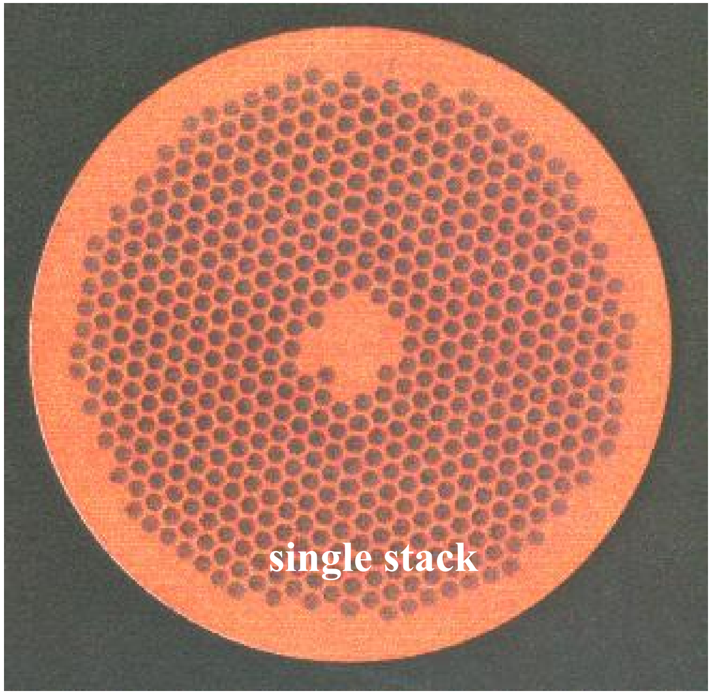
- effect is partly within filaments (flux flow) and partly between filaments
- 'sausaging of filaments, forces current to cross the copper matrix as critical current is approached.



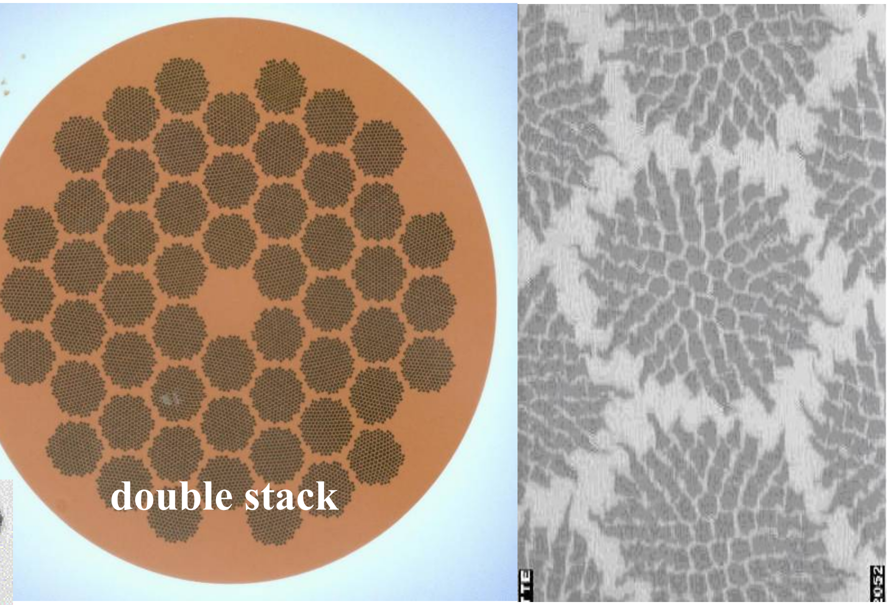
- resistive transition can be the main source of decay in persistent magnets
- 'n' is often taken as a measure of quality - look for n > 50
- HTS conductors so far have low n ~ 5 - 10

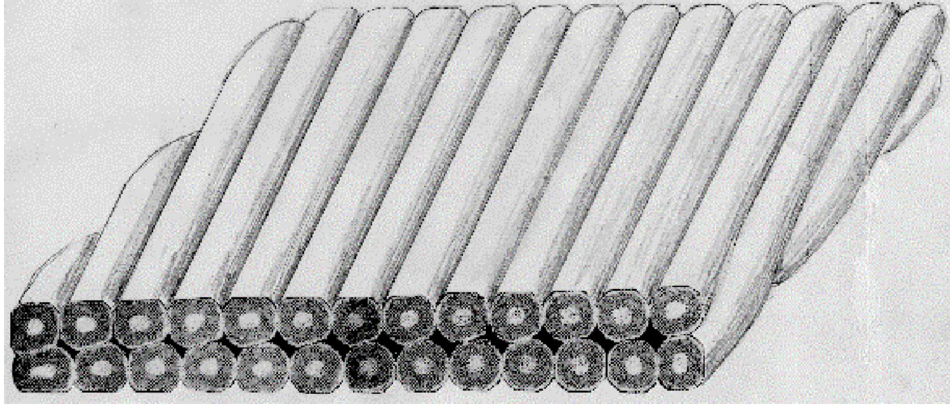


Conductors for accelerator magnets



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

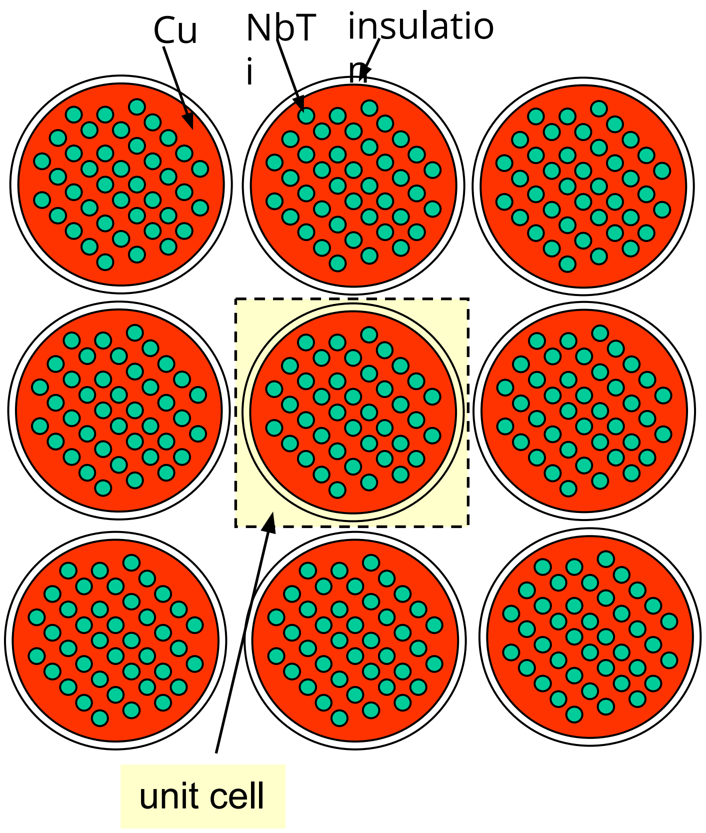




- to get high operating currents, many wires must be cabled together.

Engineering current density and filling factors

In magnet design, what really matters is the overall 'engineering' current density **J_{eng}**



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

filling factor of superconductor in unit cell $\lambda_{su} = \lambda_{sw} \times \lambda_{wu}$

λ_{sw} *filling factor superconductor in the wire* $\lambda_{sw} = 1\ /\ (1+mat)$

where *mat* = matrix : superconductor ratio, typically:

for NbTi $mat = 1.2$ to 3.0 ie $\lambda_{sw} = 0.45$ to 0.25

for Nb_3Sn $mat = 2.0$ to 4.0 ie $\lambda_{sw} = 0.33$ to 0.2

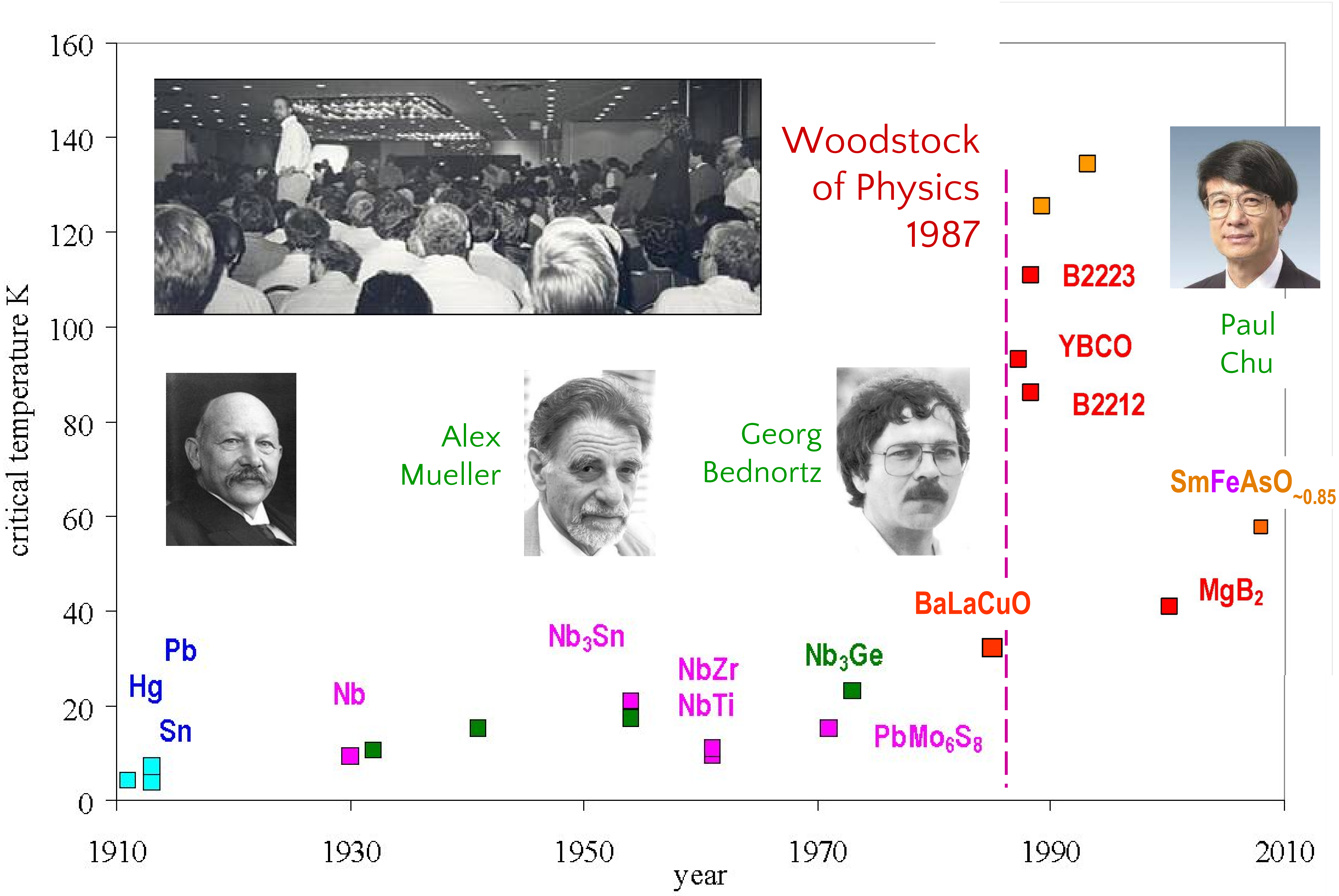
for B2212 $mat = 3.0$ to 4.0 ie $\lambda_{sw} = 0.25$ to 0.2

For Nb_3Sn and B2212 the area of superconductor is not well defined, so often define J_{sup} over ‘non matrix’or ‘non Cu’ area, which is greater than superconductor area.

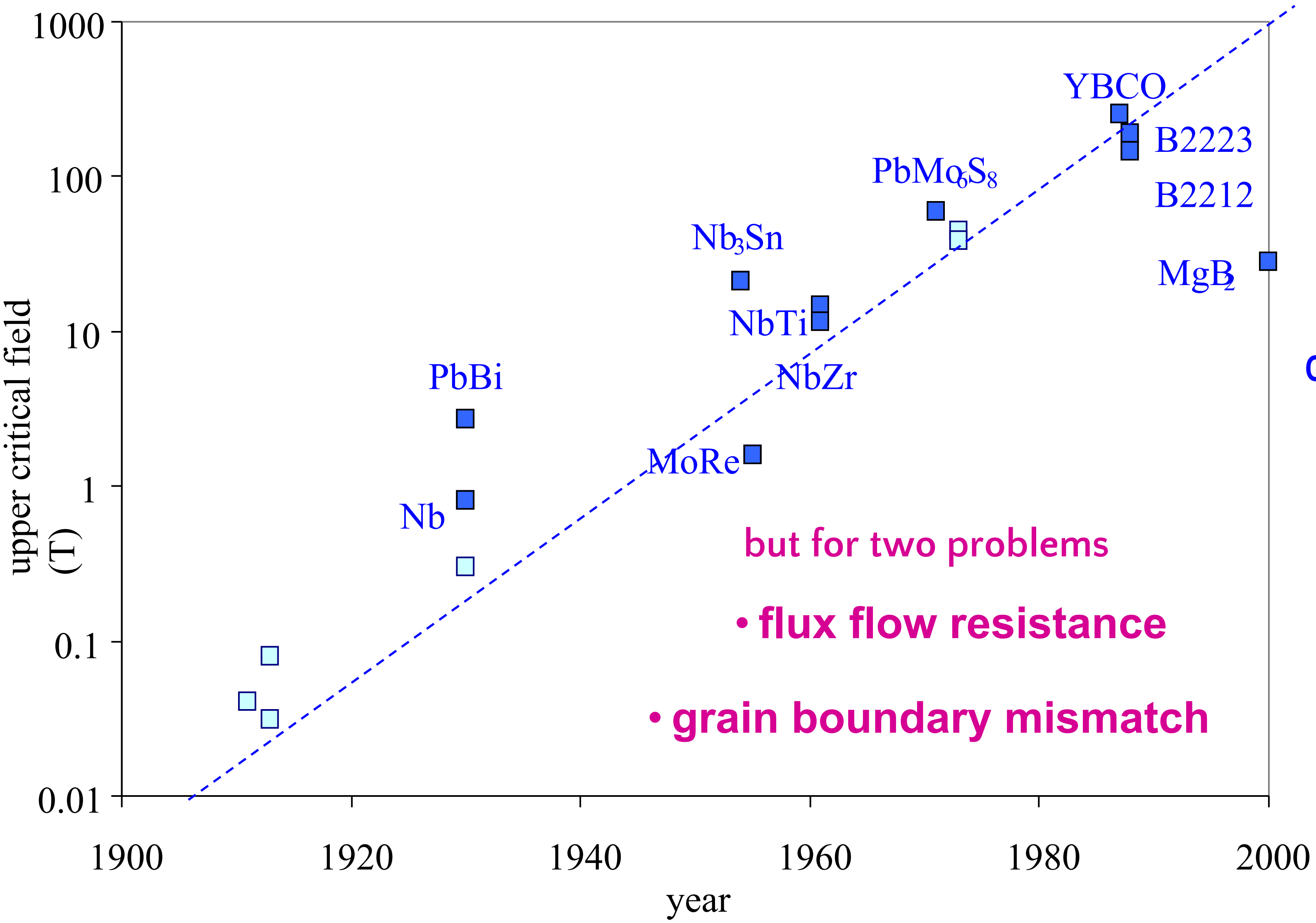
λ_{wu} fraction of wire in unit cell taking account of space occupied by insulation, cooling channels, reinforcement etc: typically $\lambda_{wu} \sim 0.7$ to 0.8

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

A century of critical temperatures



Wonderful materials for magnets



but for two problems

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

Yttrium Barium Copper Oxide

$YBa_2Cu_3O_7$

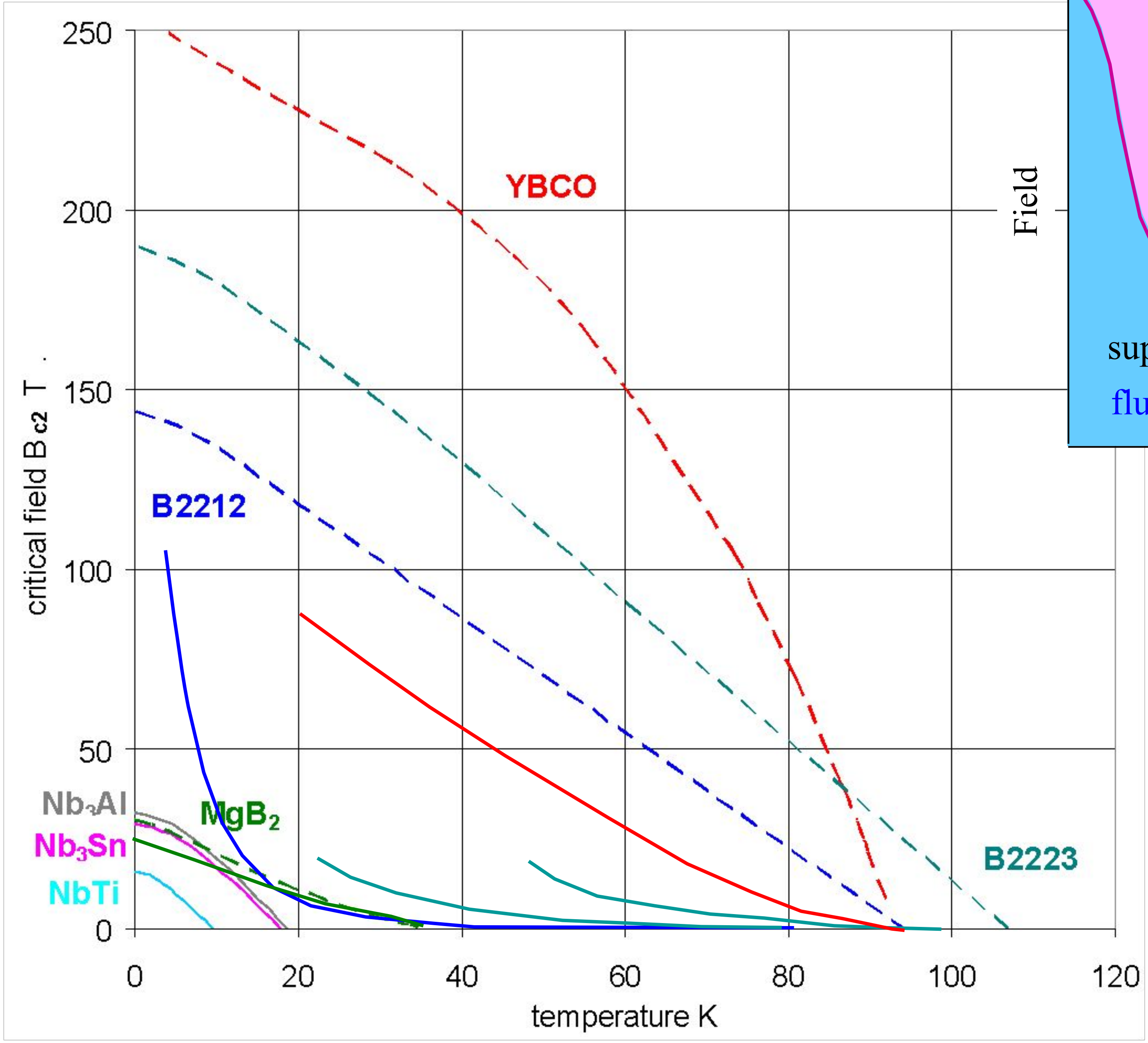
Barium Strontium Calcium Copper Oxide BSCCO

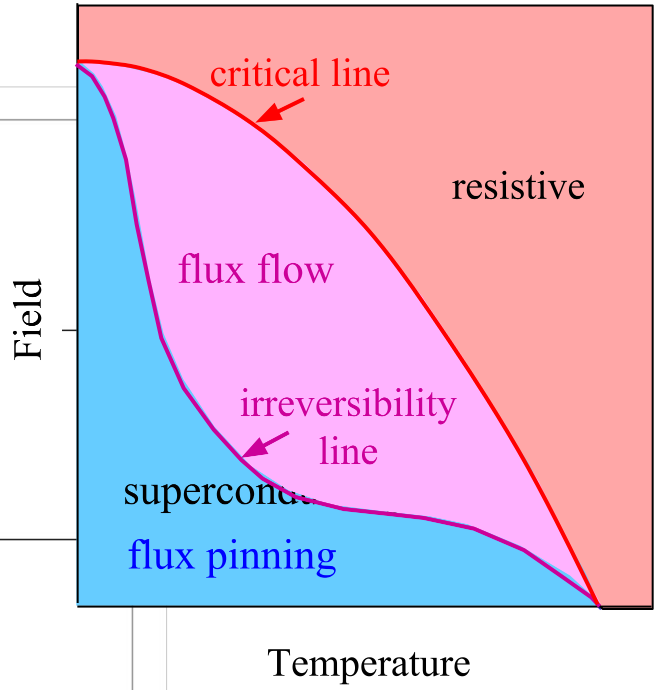
$Bi_2Sr_2CaCu_2O_8$ B2212

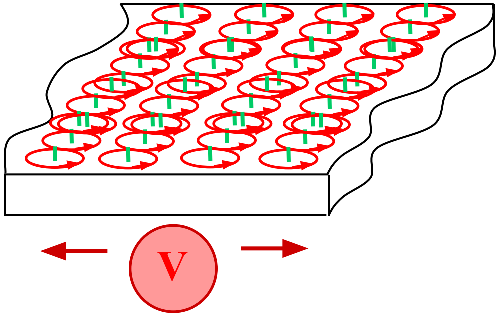
$Bi_2Sr_2Ca_2Cu_3O_6$ B2223

Magnesium Diboride MgB_2

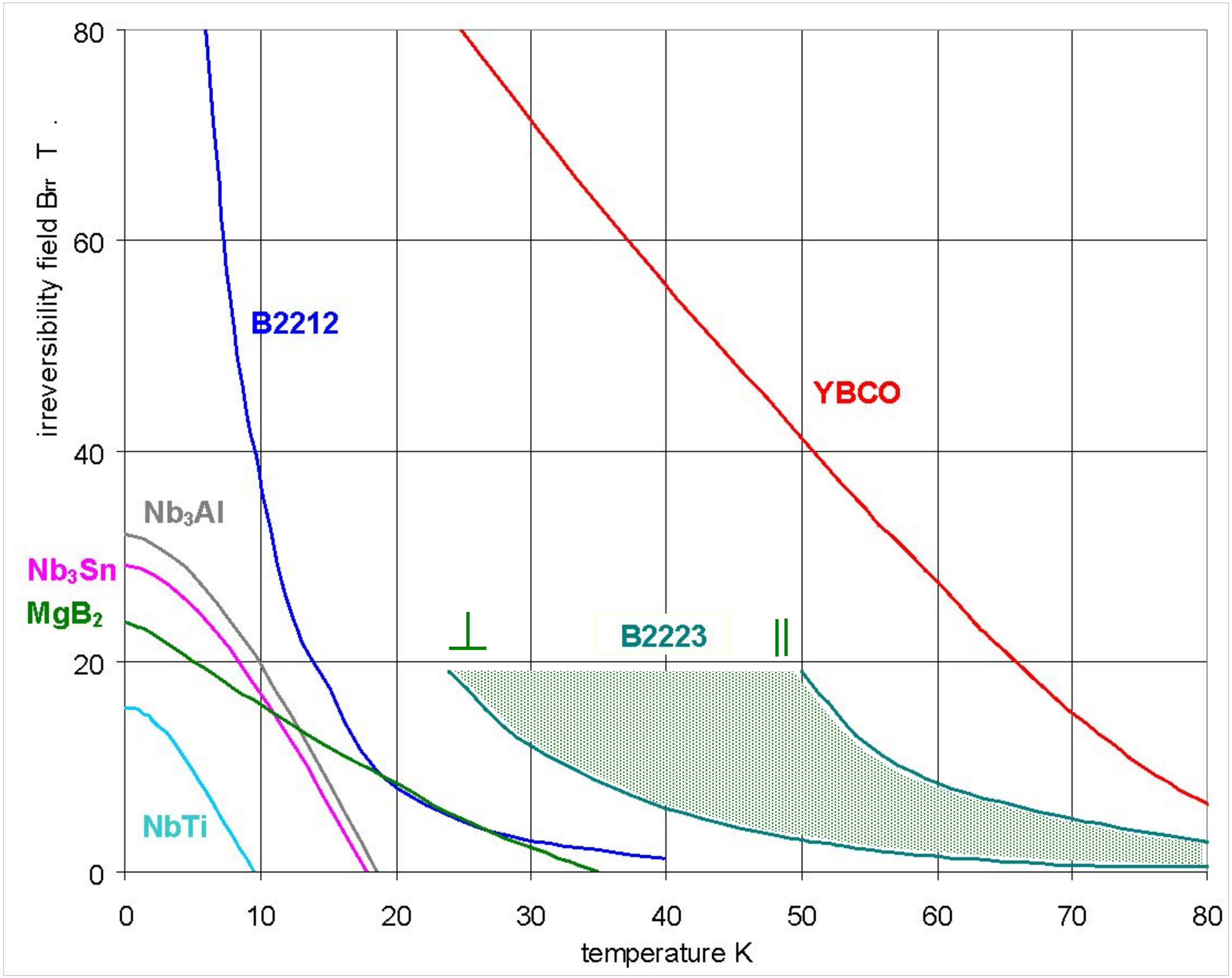
1) Flux flow resistance







Accessible fields for magnets

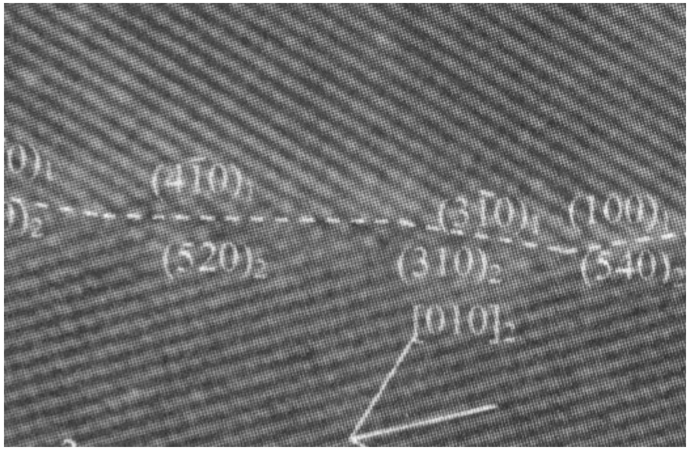


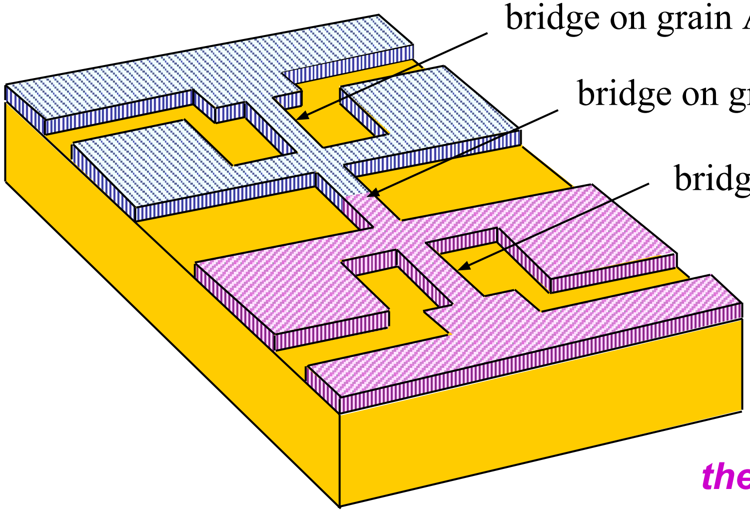
so here's the parameter space for future magnets

and we still need to work on the current density

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



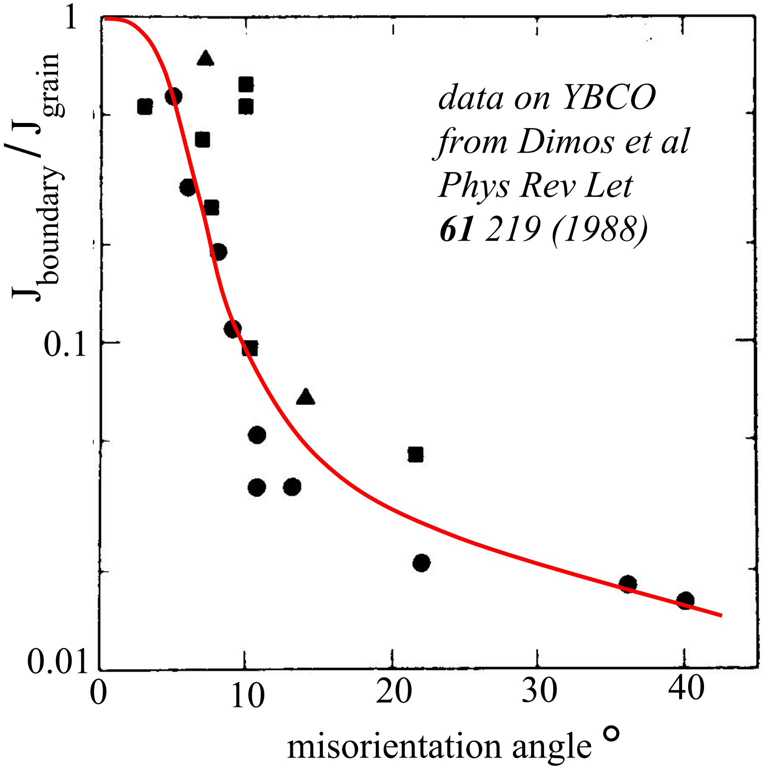


bridge on grain A

bridge on grain boundary

bridge on grain B

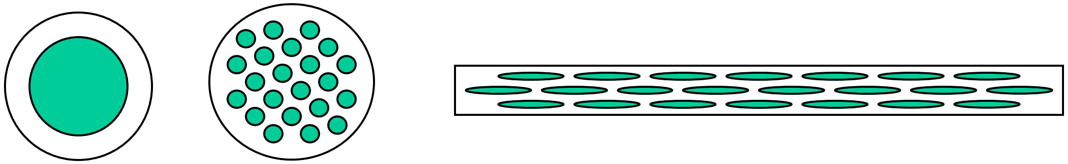
the key measurement of Dimos et al



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

BSCCO conductors

- BSCCO powder in silver matrix
- silver is transparent to oxygen
- grains tend to line up during processing in contact with silver
- but low irreversibilty field



$Bi_2Sr_2Ca_2Cu_3O_6$ B2223

- θ_c ~110 K ⇨ 77 K use
- complex thermo-mechanical fabrication route to produce uniaxial texture
- reaction of 2212 + stuff to 2223 occurs primarily in the solid state at ~840°C
- texture requires pressing to a large aspect ratio tape (4 x 0.2 mm)
- anisotropic J_c
- mature conductor – semi commercial production for > 10 years

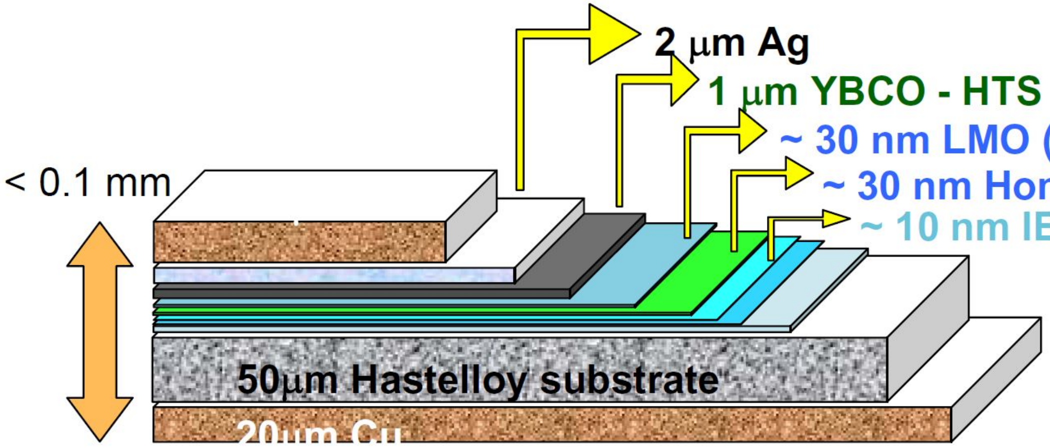
$Bi_2Sr_2CaCu_2O_8$ B2212

- θ_c ~ 85 K
- produced by <u>melting</u> B2212 powder inside silver matrix
- round filaments in round wires
- Isotropic and high J_c, but originally only in short length
- recently achieved high J_c in long lengths by heat treatment under high pressure O_2
- engineers like round wire
- can make Rutherford cables

Coated YBCO tape

- YBCO has the best irreversibility field, but it is very sensitive to grain boundary misalignment
- the grains do not line up naturally - they must be persuaded
- deposit YBCO on a substrate where the grains are aligned and the lattice roughly matches YBCO

OK high field **and** high temperature



2 µm Ag

1 µm YBCO - HTS (epitaxial)

~ 30 nm LMO (epitaxial)

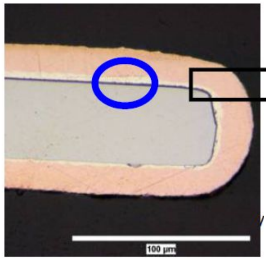
~ 30 nm Homo-epi MgO (epitaxial)

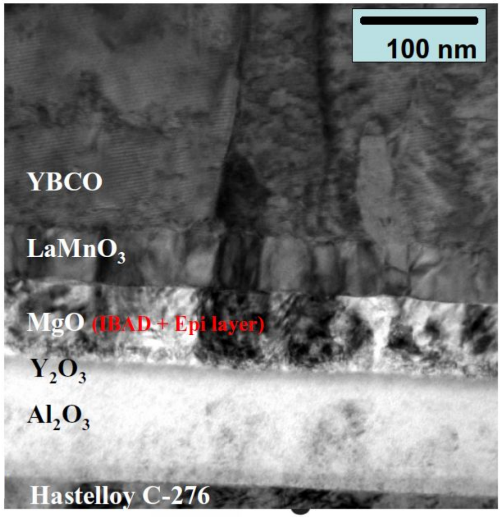
~ 10 nm IBAD MgO

< 0.1 mm

50µm Hastelloy substrate

20µm Cu





SuperPower Inc.

SuperPower Inc.

YBCO coated tape at SuperPower Inc.


IBAD

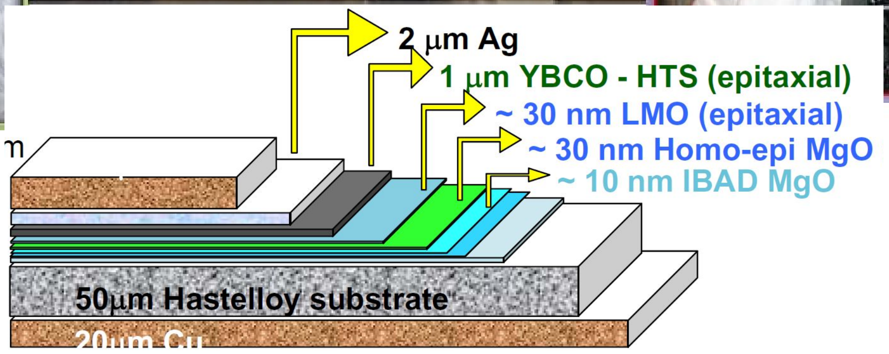

MOCVD


IBAD


Ag sputtering


Buffer


Buffer


2 μm Ag

1 μm YBCO - HTS (epitaxial)

~ 30 nm LMO (epitaxial)

~ 30 nm Homo-epi MgO

~ 10 nm IBAD MgO

50μm Hastelloy substrate

20μm Cu

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
    – accelerators will probably settle for low temperature to get high field and current density
- NbTi is still the most common superconductor - standard commercial product
- 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 - prototype commercial production
- measure I_c to check specification, the index n indicates quality
- Accelerators to date are (almost) all NbTi, usually in Rutherford cables

Some useful references

Superconducting Magnets

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- Superconducting Magnets: MN Wilson, pub Oxford University Press (1983) ISBN 0-019-854805-2
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- Superconductivity: A Very Short Introduction by Stephen J. Blundell: Oxford University Press (2009) ISBN978-0-19-954090-7

Materials Mechanical

- Materials at Low Temperature: Ed RP Reed & AF Clark, pub Am. Soc. Metals 1983. ISBN 0-87170-146-4
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- 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

Cryogenics

- Experimental Techniques for Low-temperature Measurements: J. W. Ekin Pub. Oxford University Press, ISBN 978-0-19-857054-7
- 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

on the Web

- **Lectures on Superconductivity** http://www.msm.cam.ac.uk/ascg/lectures. A series of lectures produced for SCENET by Cambridge University: fundamentals, materials, electronics, applications. Also available as a DVD
- **Superconducting Accelerator Magnets** http://www.mjb-plus.com. A course developed from SSC experience, available from website for $20
- www.superconductors.org website run by an enthusiast; gives some basic info and links
- **Superconductivity Course** at the (UK) Open University. http://openlearn.open.ac.uk/course/view.php?id=2397 Good coverage of basics.
- **Wikipedia** on Superconductivity http://en.wikipedia.org/wiki/Superconductivity Good on basics with lots of references and links.
- **European Society for Applied Superconductivit**y http://www.esas.org/ News, events and people in the area of applied superconductivity
- **CONECTUS** Consortium of European Companies determined to use Superconductivity http://www.conectus.org/
- **IEEE Council on Superconductivity** http://www.ewh.ieee.org/tc/csc/ News, events and people in the area of applied superconductivity (US based)

Materials data on the Web

- 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**
- Thermodynamic properties of gases (and liquids) available free as a programme which you can interrogate for your own temperature interval etc. **http://webbook.nist.gov/chemistry/fluid/**
- 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 and Charles Monroe 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.