Superconducting 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
- higher rf electric fields (continuous)

Superconducting magnets for Accelerators

Plan of the Course

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1 Introduction

- properties of superconductors, critical field, critical temperature & critical current density
- superconducting rf cavities
- high field 'type 2 superconductors
- high temperature superconductors HTS
- magnetic fields and how to create them
- engineering current density
- where to find more information

2 'Training', fine filaments & cables

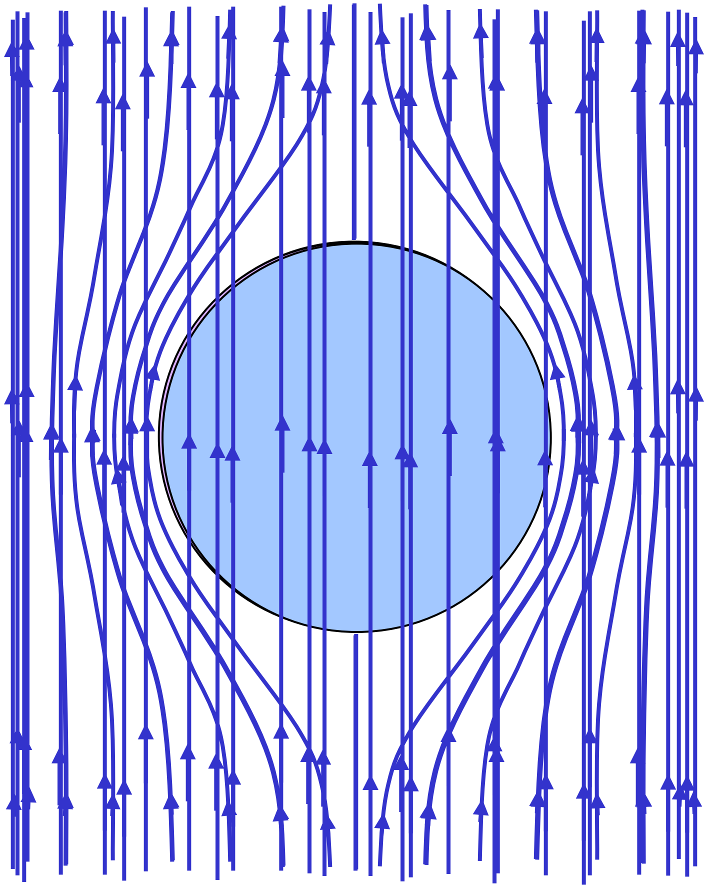
- load lines, quenching, degradation & training
- causes of training
- minimum propagating zones MPZ and minimum quench energy MQE
- screening currents and magnetization
- field errors and ac losses
- filamentary wires, coupling and cables

3 Quenching and hardware

- the quench process
- decay times and temperature rise
- quench protection schemes
- cryostats
- superconductor manufacture
- magnet manutacture
- some superconducting accelerators

Two kinds of superconductor: type 1

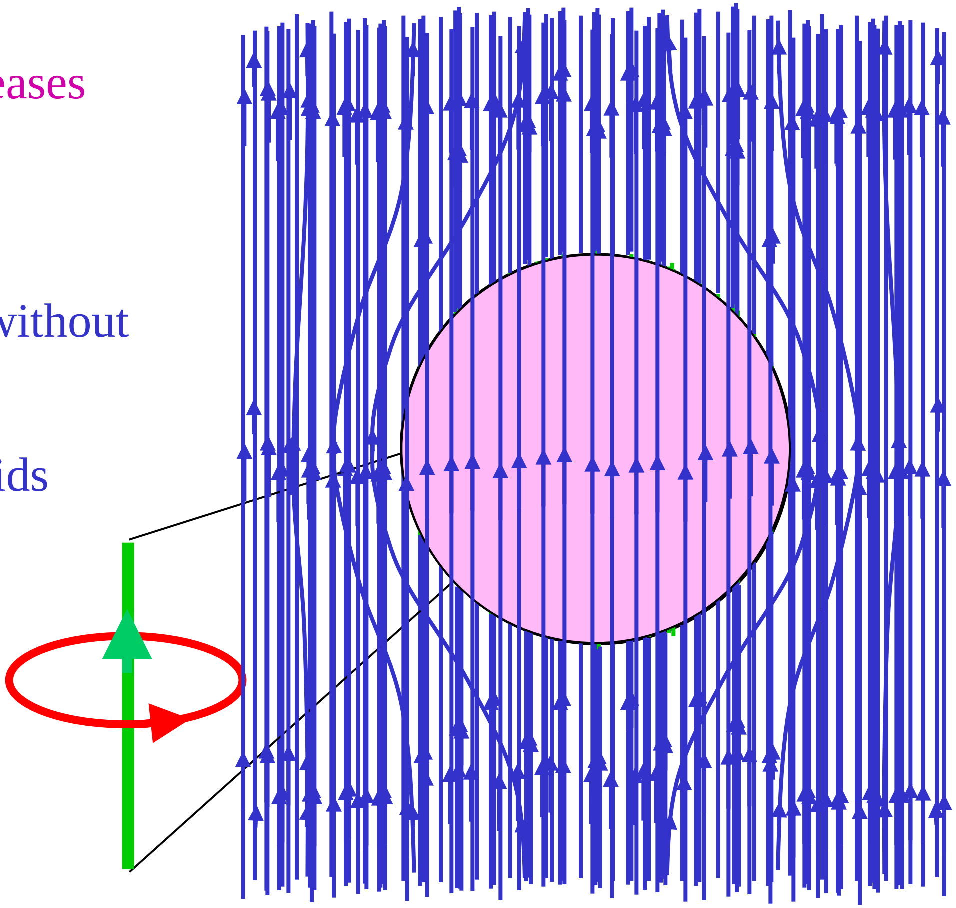
- the materials first discovered by Kammerlingh Onnes in 1911 - soft metals like lead, tin mercury
- sphere of metal at room temperature
- apply magnetic field
- reduce the temperature - resistance decreases
- reduce the temperature some more
  - resistance decreases some more
- at the critical temperature θ_c the field is pushed out - the **Meissner effect** - superconductivity!
- increase the field - field is kept out
  - by Maxwell there must be surface currents
- 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 - surface currents again
- 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}



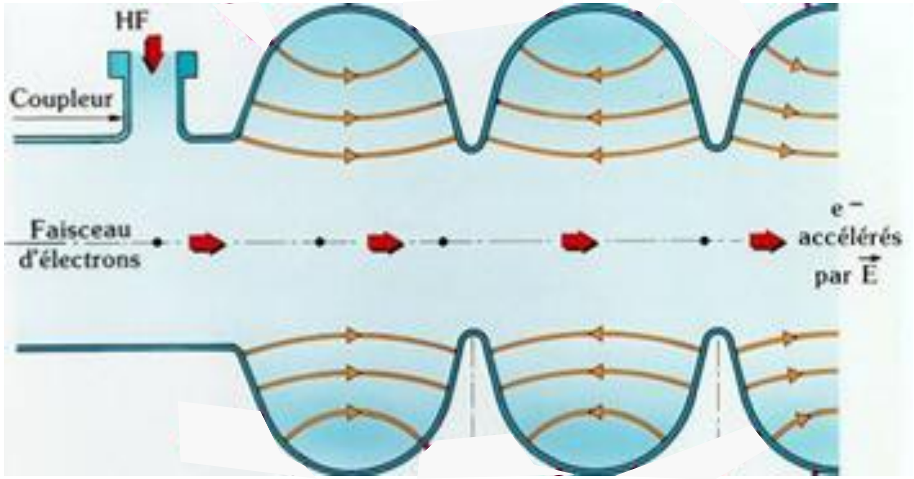
OK for magnets!

Superconductors below B_{c1} make great rf cavities

- particle acceleration needs electric field along direction of motion - rf cavity

- high Ohmic losses in copper make superconducting cavities attractive

- below B_{c1} the surface currents have very small ac loss (Type 1 or Type 2 at low field)



- loss usually expressed in terms of quality factor $Q = \omega U_{stored} / P_{dissipation}$

bell at middle C reverberates for 1 ½ years

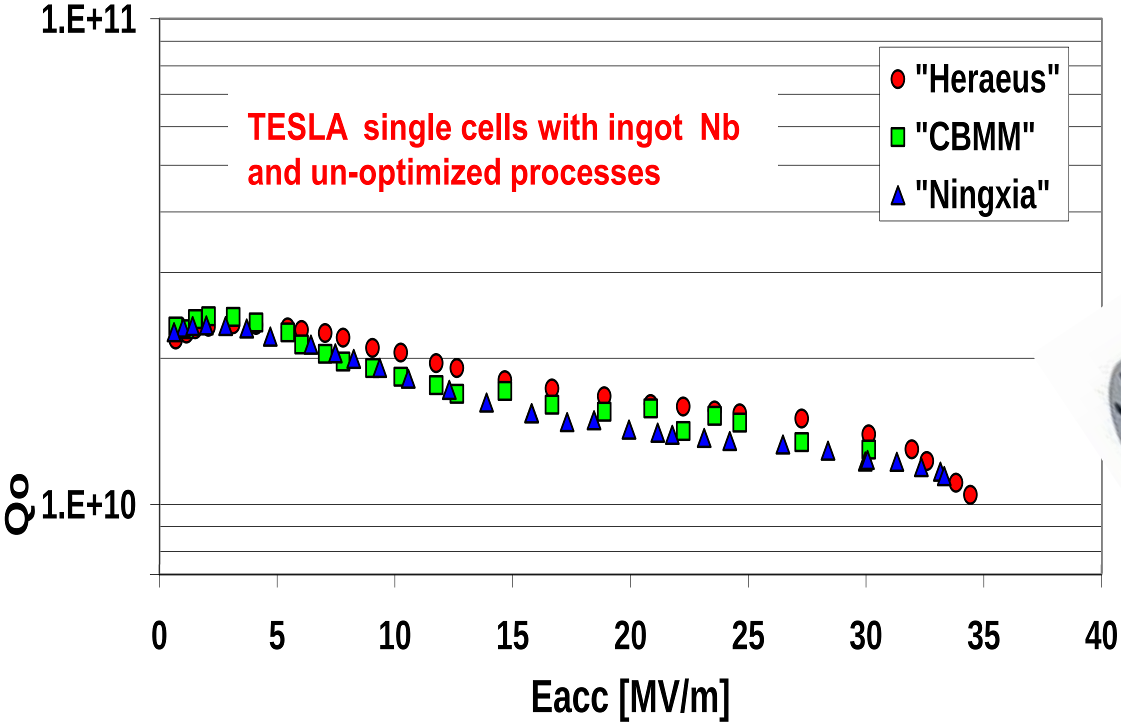
- at 1.3GHz, Q factors > 10^{10} achieved - a 'ringing time' of > 8 seconds!

- accelerating voltages - up to 35 MV/m - a copper cavity at 5 MV/m ⇒ several MW/m

- however, when pulsed, copper cavities can do better ~ 100MV/m

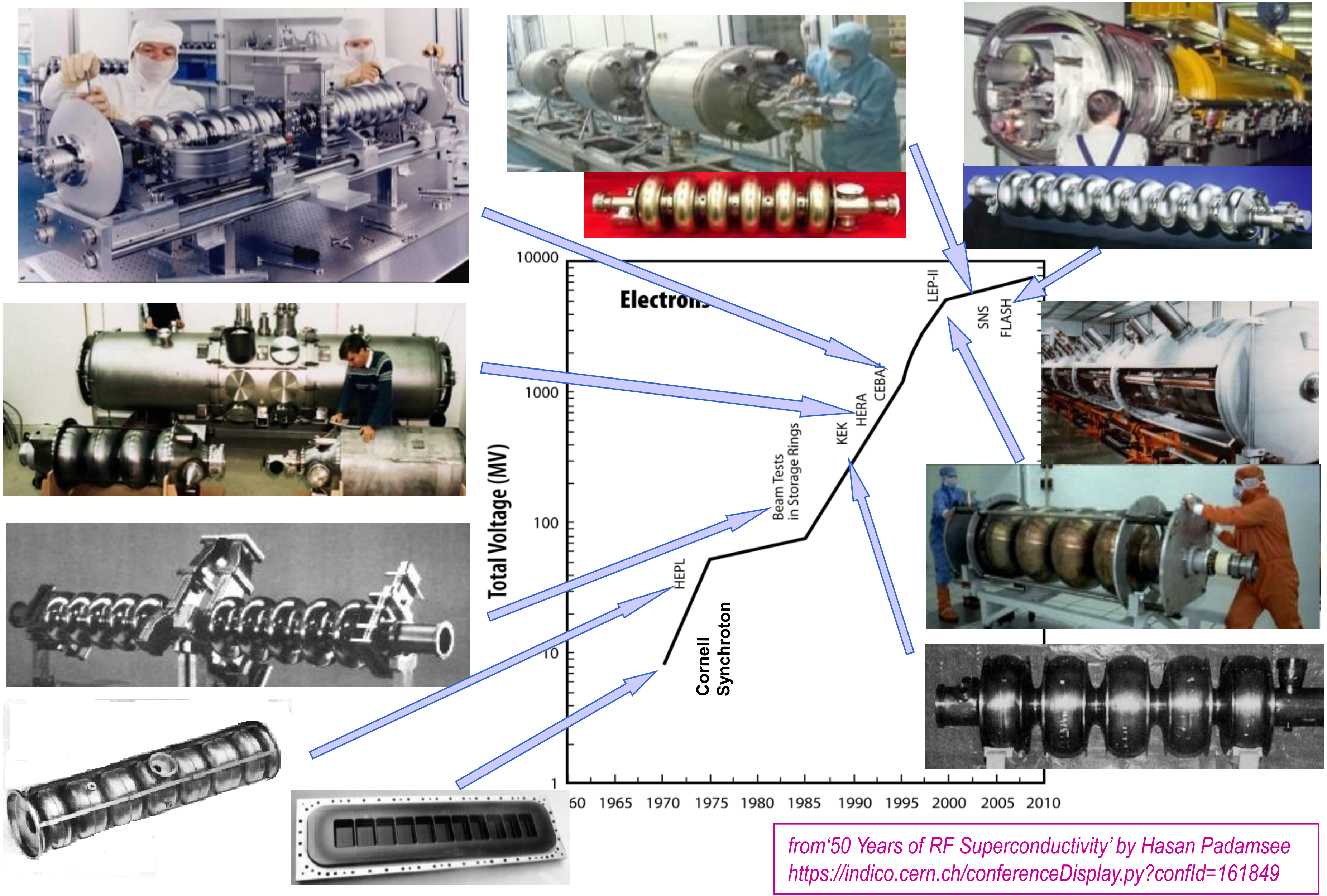
- because don't need to conserve power, s/c cavities can have a better shape - bigger beam hole

Accelerating voltage, quality factor & surface quality



Myneni et al at Jefferson lab have shown that the key to performance is eliminating hydrogen from grain boundaries - regular Nb is then OK

Superconducting RF Cavities: 50 years of progress



from'50 Years of RF Superconductivity' by Hasan Padamsee
https://indico.cern.ch/conferenceDisplay.py?confId=161849

Accelerator driven fission?

Energy efficient superconducting accelerators

⇒ sub critical fission reactors driven by spallation neutron source - inherently safe

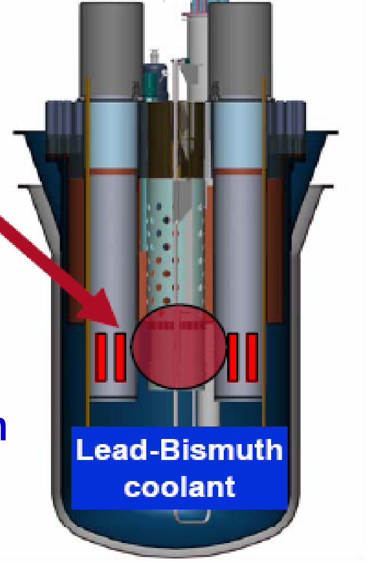
⇒ burn up the waste products

MYRRHA - project to build a subcritical research reactor at the Belgium nuclear research centre

Superconducting Proton Accelerator 600 MeV - 2.5mA = 1.8MW

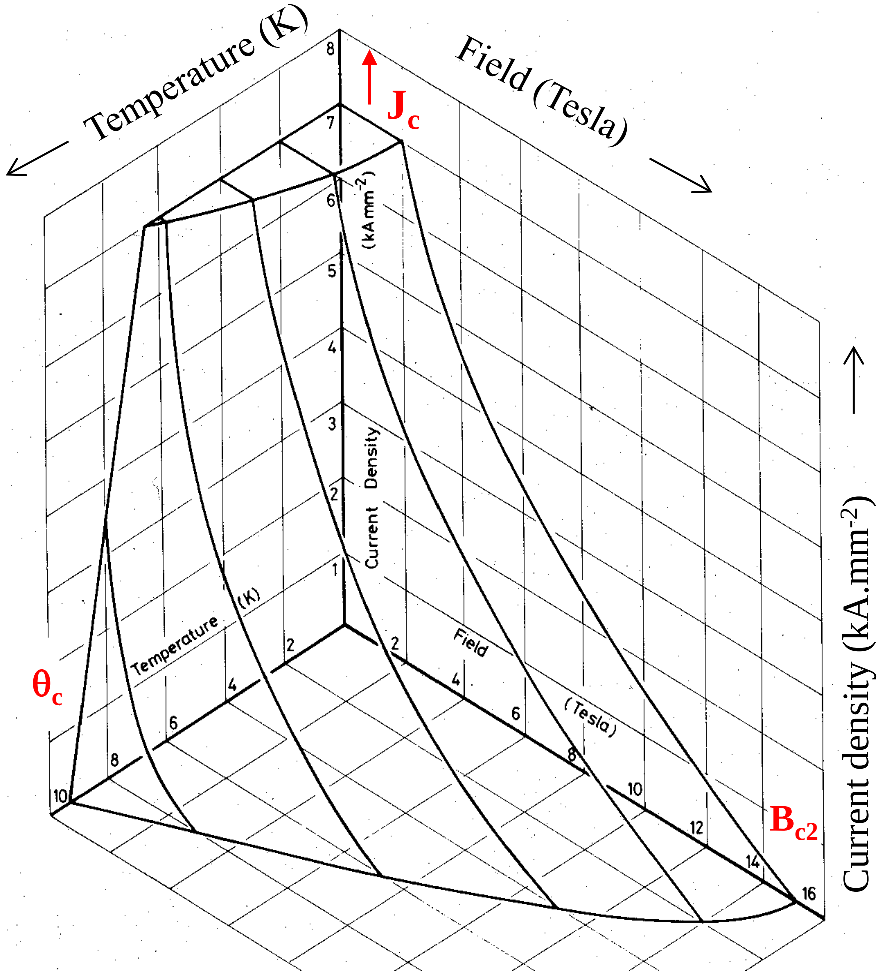
superconducting proton linac at ORNL

Spallation target
⇒ fast neutrons



Reactor 100MWth

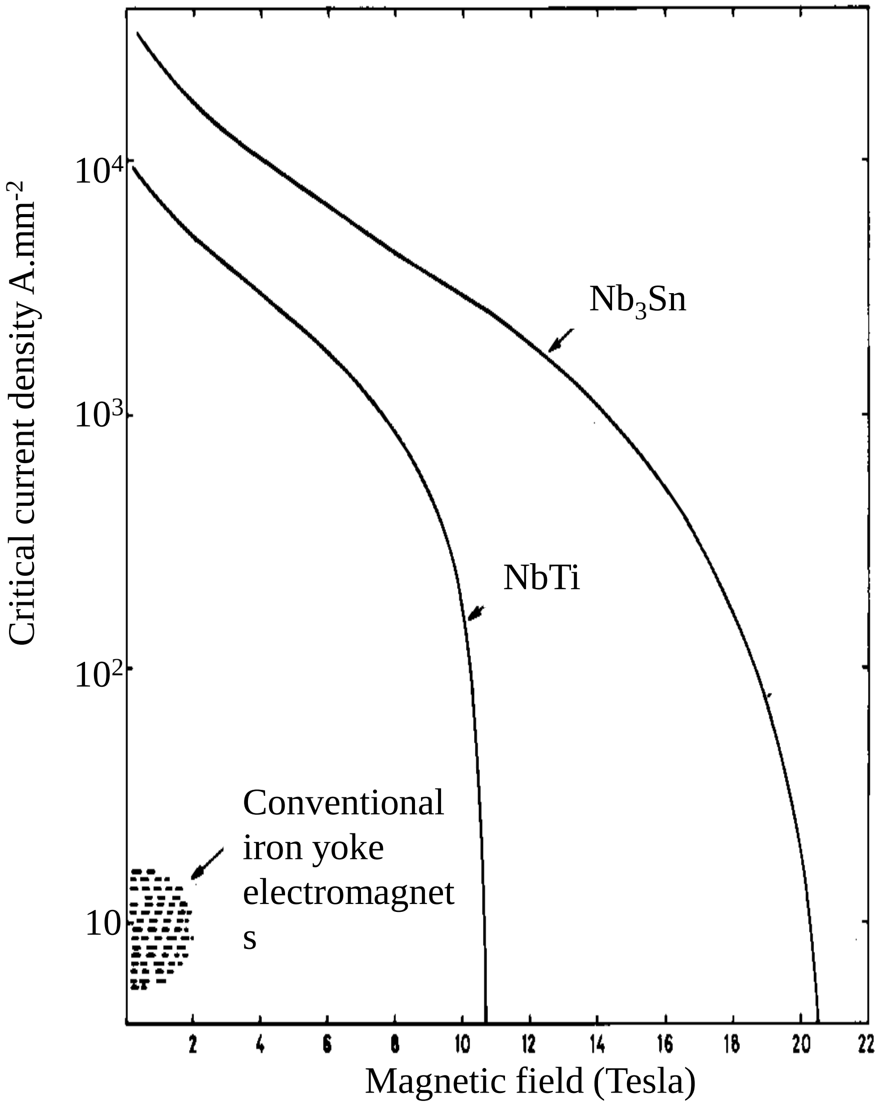
High field superconductors for magnets



The critical surface of niobium titanium

- Niobium titanium **NbTi** is the standard 'work horse' of the superconducting magnet business
- it is a ductile alloy
- 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

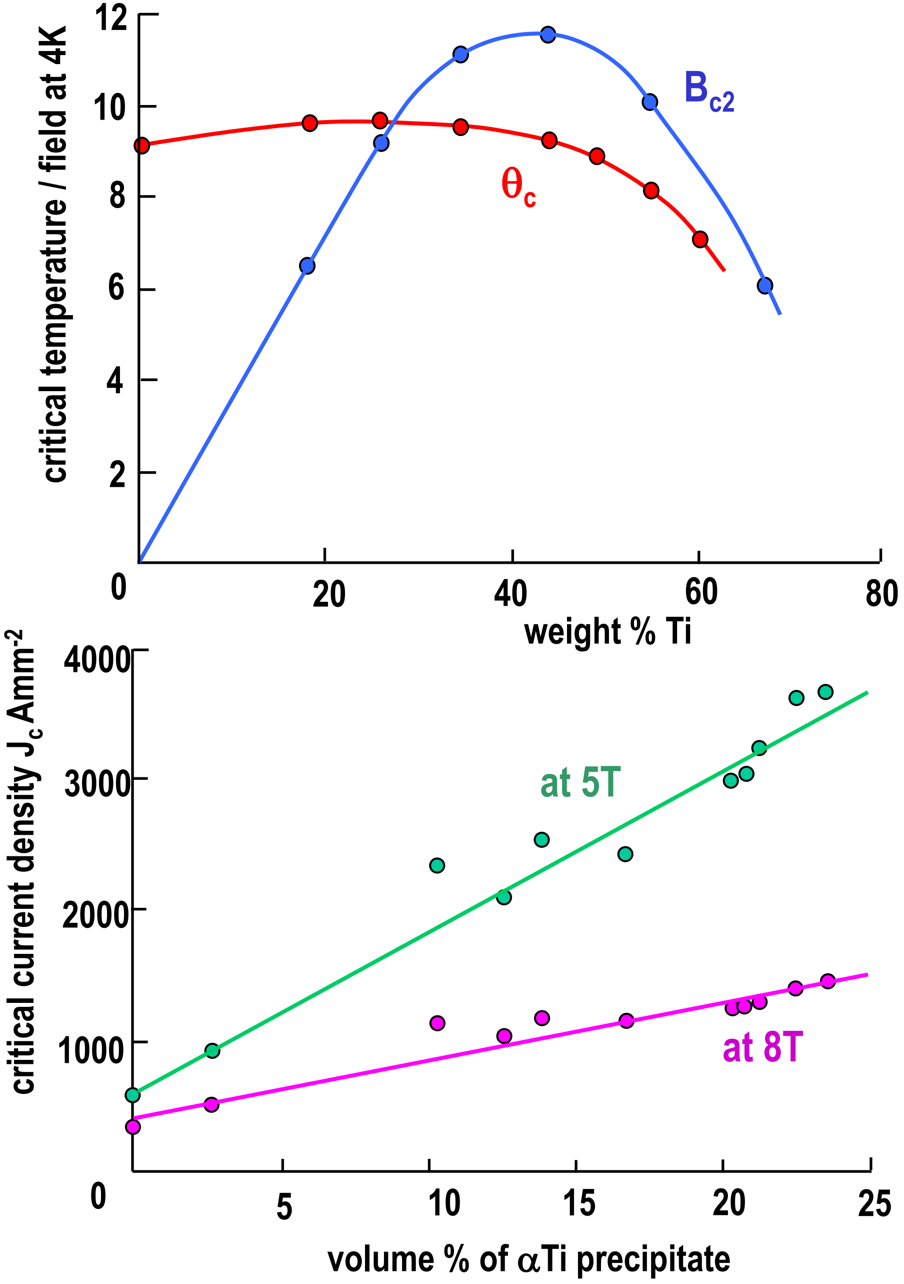
The critical line at 4.2K



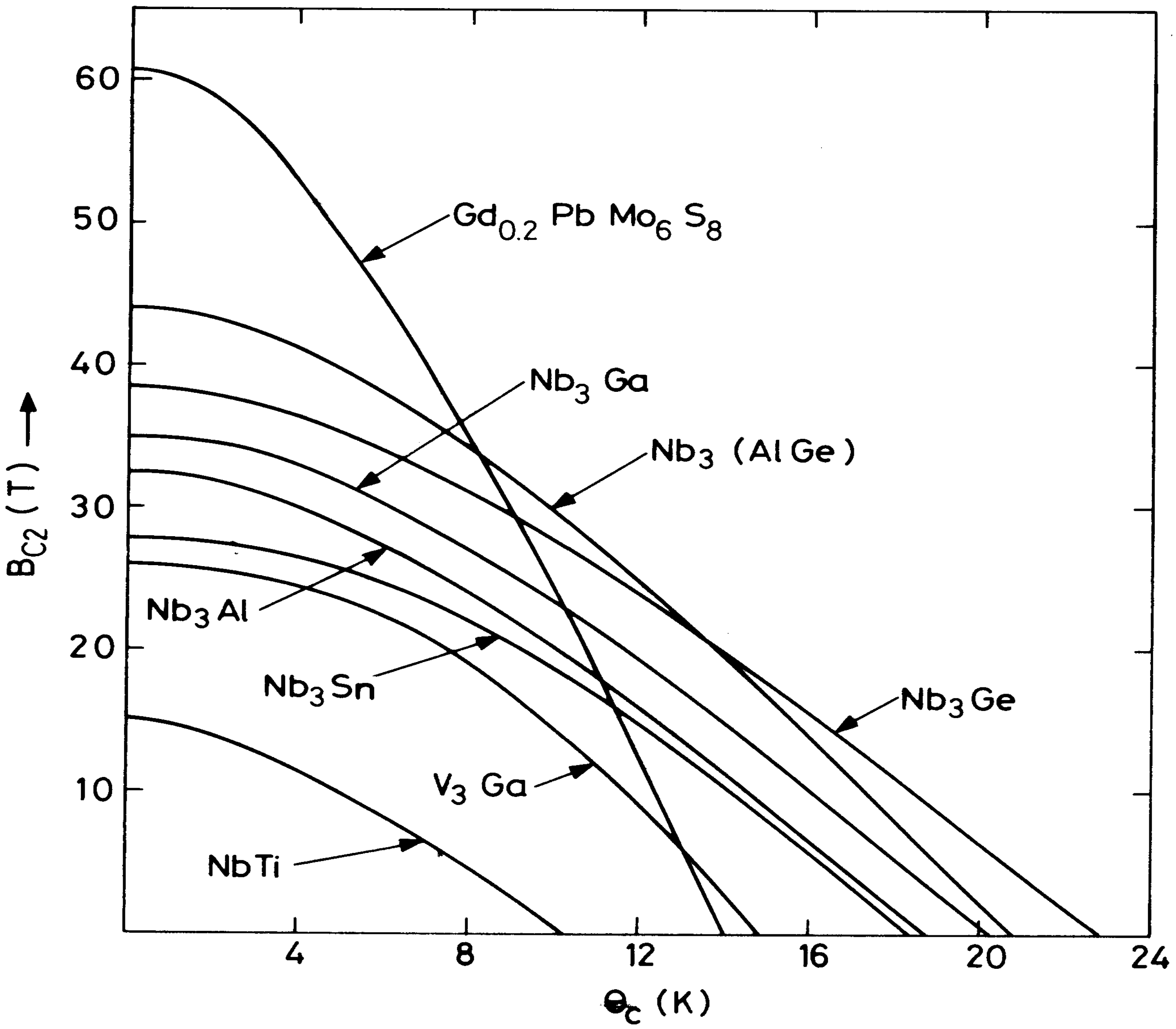
- because magnets usually work in boiling liquid helium, the critical surface is often represented by a curve of current versus field at 4.2K
- niobium tin Nb_3Sn has a much higher performance in terms of critical current field and temperature than NbTi
- but it is brittle intermetallic compound with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

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



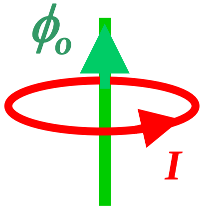
Critical field & temperature of metallic superconductors



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

All the rest are brittle intermetallic compounds

Critical current density in type 2 superconductors



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

  spacing between the fluxoids is:-

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

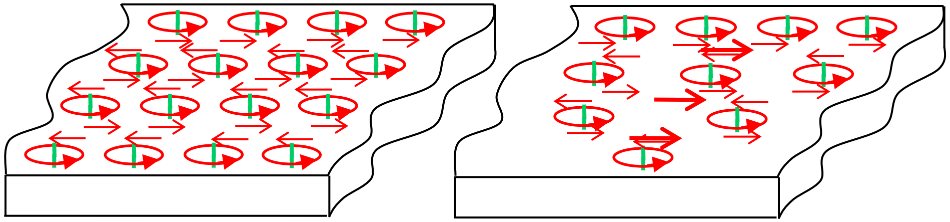
- each fluxoid carries one unit of flux,

  so density of fluxoids = average field

  uniform density ⇒ uniform field

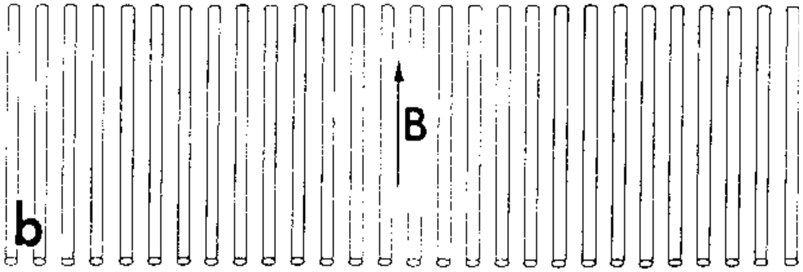
  ⇒ zero J (because $Curl\ B = \mu_o J$)

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



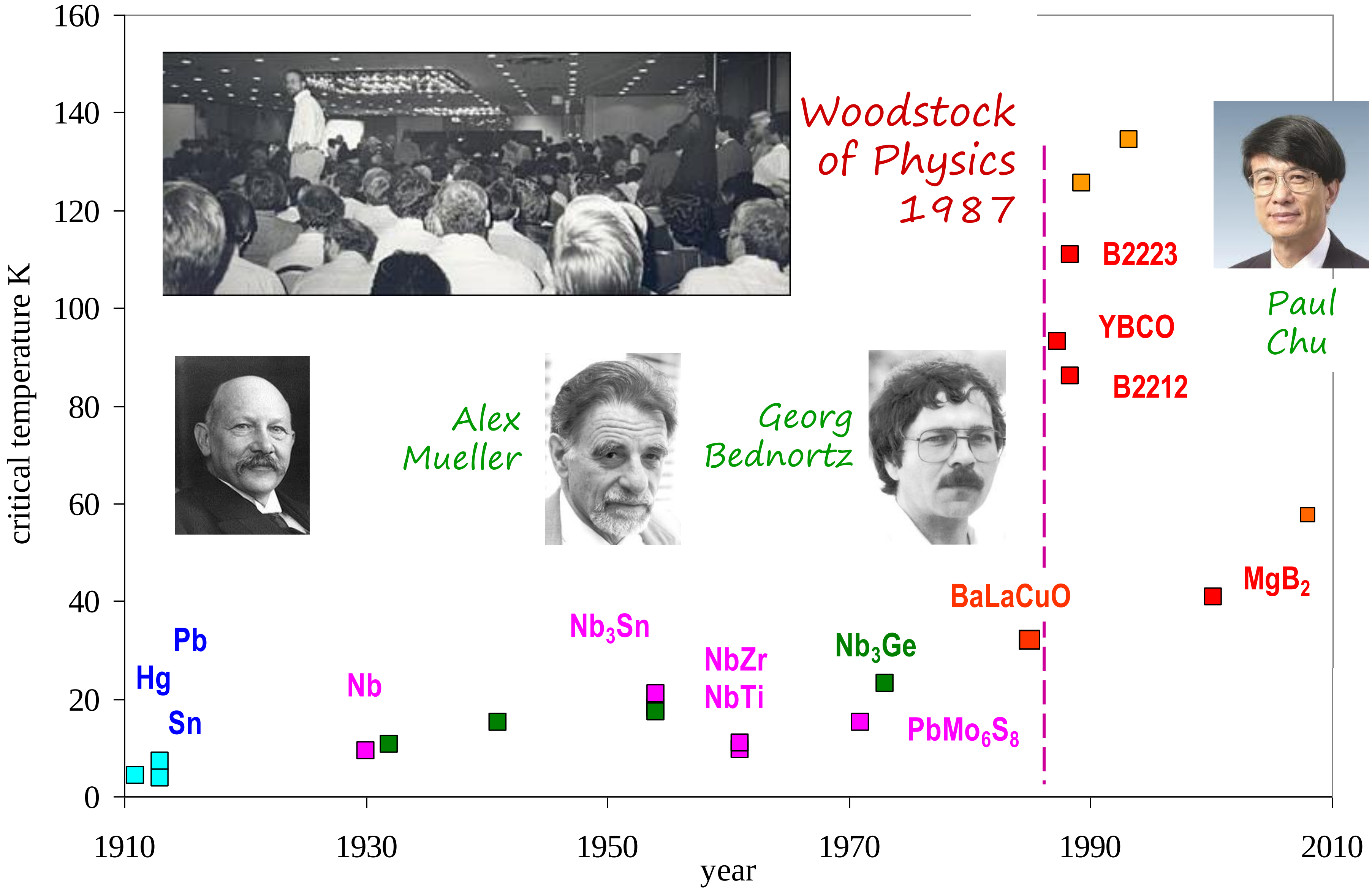
- fluxoids like to distribute uniformly
- so we must impose a gradient by inhomogeneities in the material, eg dislocations or precipitates

precipitates of α Ti in Nb Ti



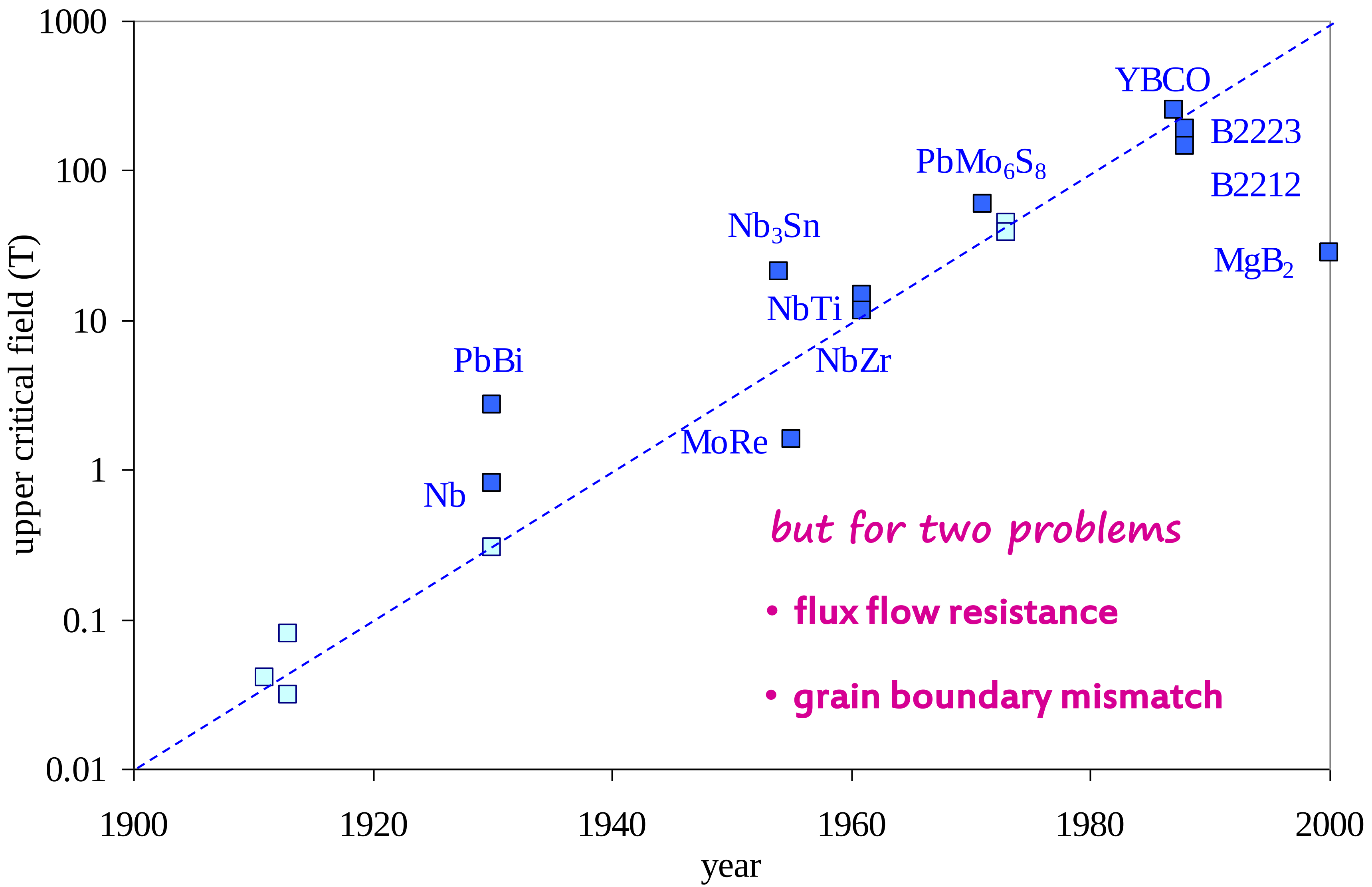
fluxoid lattice at 5T on the same scale

High temperature superconductors



Martin Wilson Lecture 1 slide 14

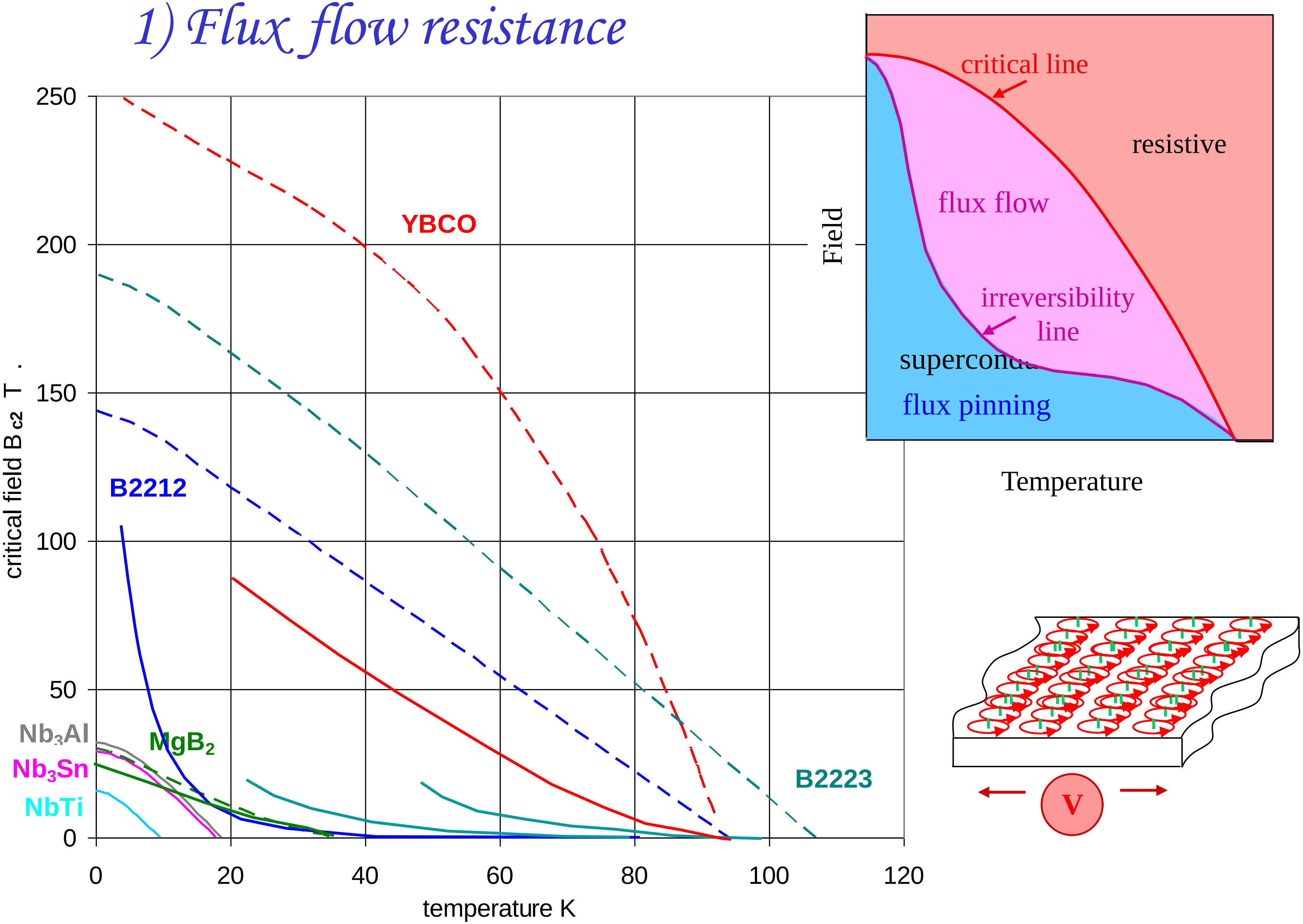
Wonderful materials for magnets



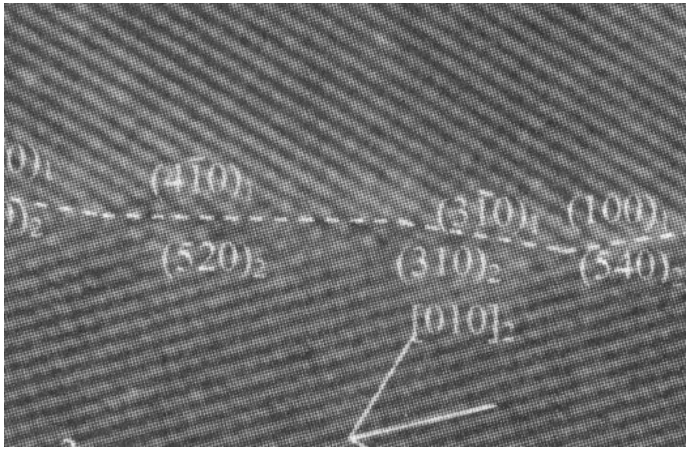
but for two problems

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

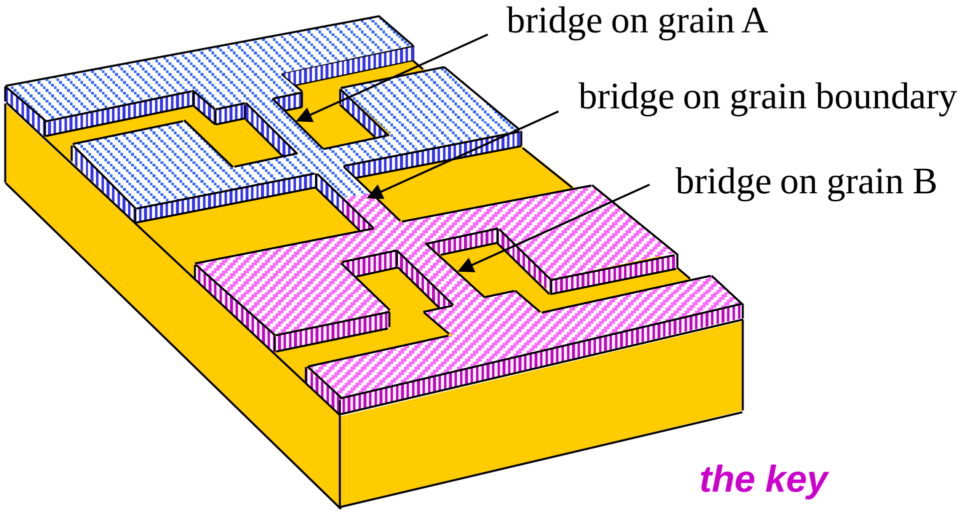
1) Flux flow resistance



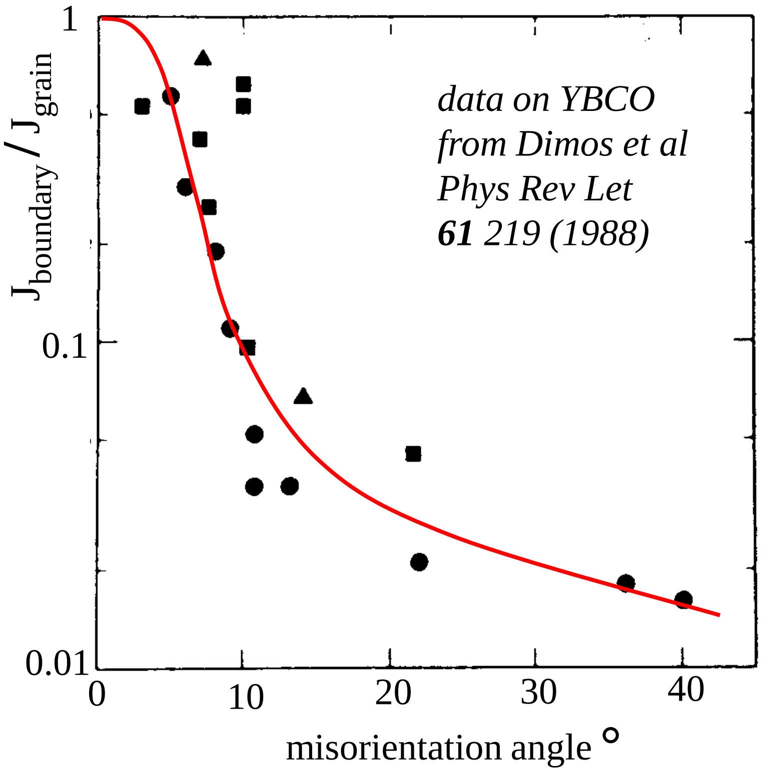
2) Grain boundary mismatch



- 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

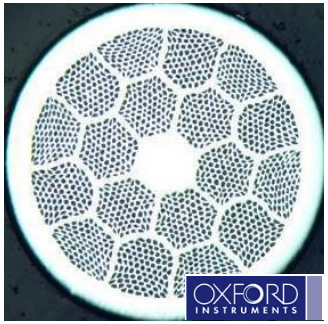


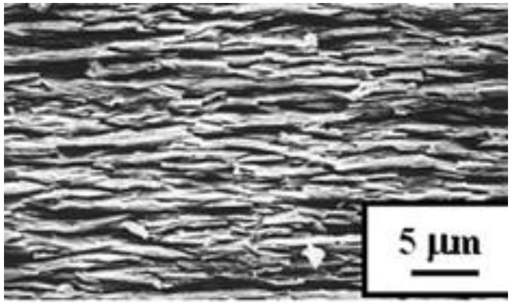
data on YBCO from Dimos et al Phys Rev Let ***61*** *219 (1988)*

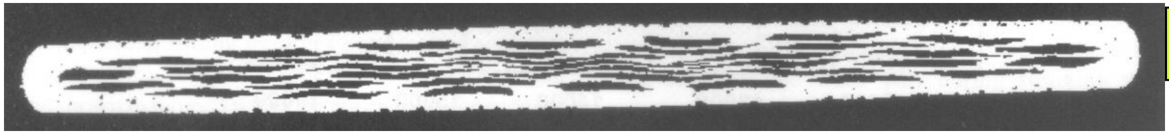
Practical HTS conductors

BSCCO wire and tapes

- processed in silver
- grains align during processing
- but low irreversibility field



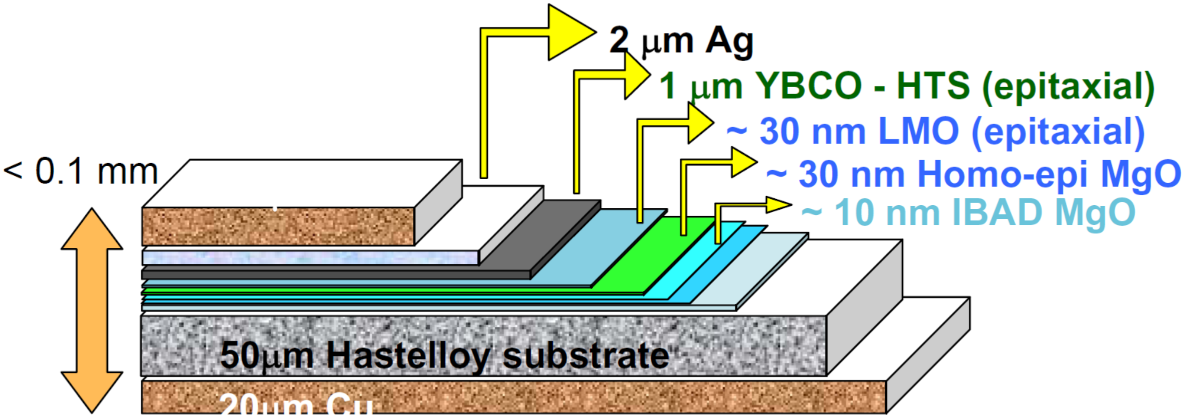




NST

YBCO tapes

- high irreversibility field
- but complex processing needed to align the grain boundaries



$2\ \mu m$ Ag

$1\ \mu m$ YBCO - HTS (epitaxial)

~ 30 nm LMO (epitaxial)

~ 30 nm Homo-epi MgO

~ 10 nm IBAD MgO

< 0.1 mm

$50\mu m$ Hastelloy substrate

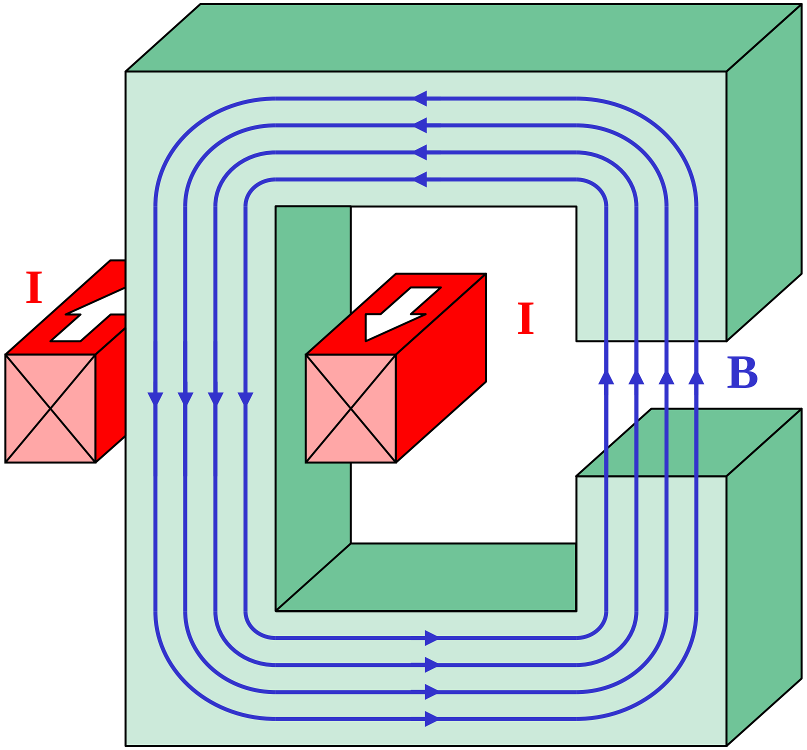
$20\mu m$ Cu

Magnetic Fields and ways to create them: (1) Iron

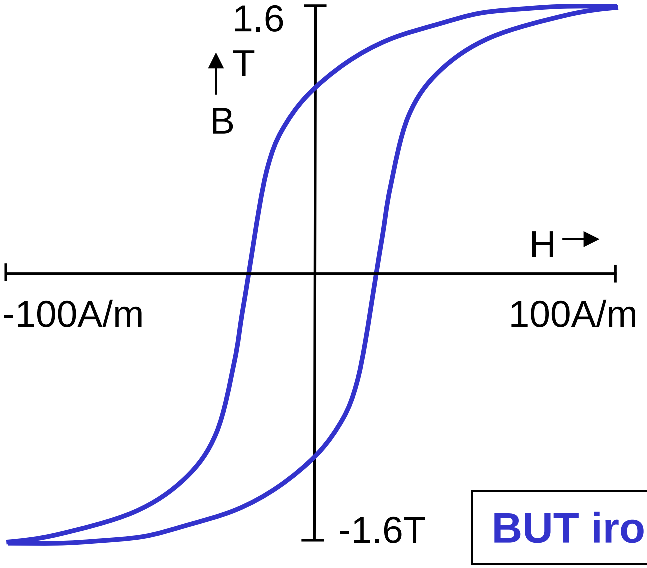
- Conventional electromagnets
- iron yoke reduces magnetic reluctance

  ⇒ reduces ampere turns required

  ⇒ reduces power consumption
- iron guides and shapes the field



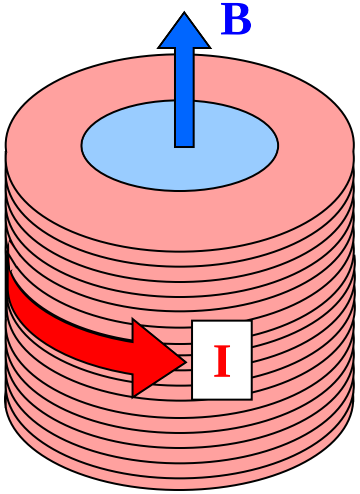
Iron electromagnet
– for accelerator, HEP experiment
transformer, motor, generator, etc



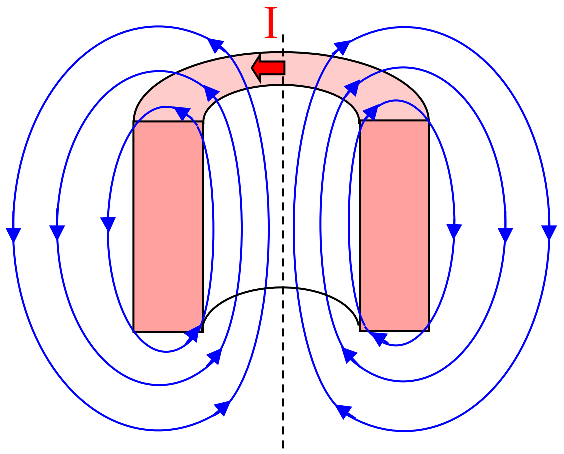
BUT iron saturates at ~ 2T

Magnetic Fields and ways to create them: (2) solenoids

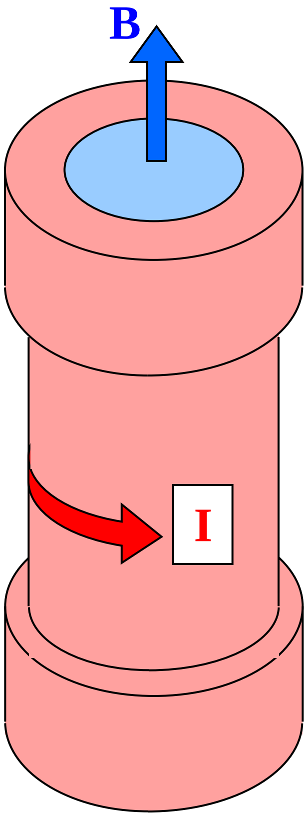
- no iron – field shape is set solely by the winding
- cylindrical winding
- azimuthal current flow
  - eg wire wound on bobbin
- axial field



- field lines curve outwards at the ends
- this curvature produces non uniformity of field
- very long solenoids have less curvature and more uniform field



- can also reduce field curvature by making the winding thicker at the ends
- this makes the field more uniform



- more complicated winding shapes can be used to make very uniform fields

Superconducting solenoids

small superconducting solenoids for research applications

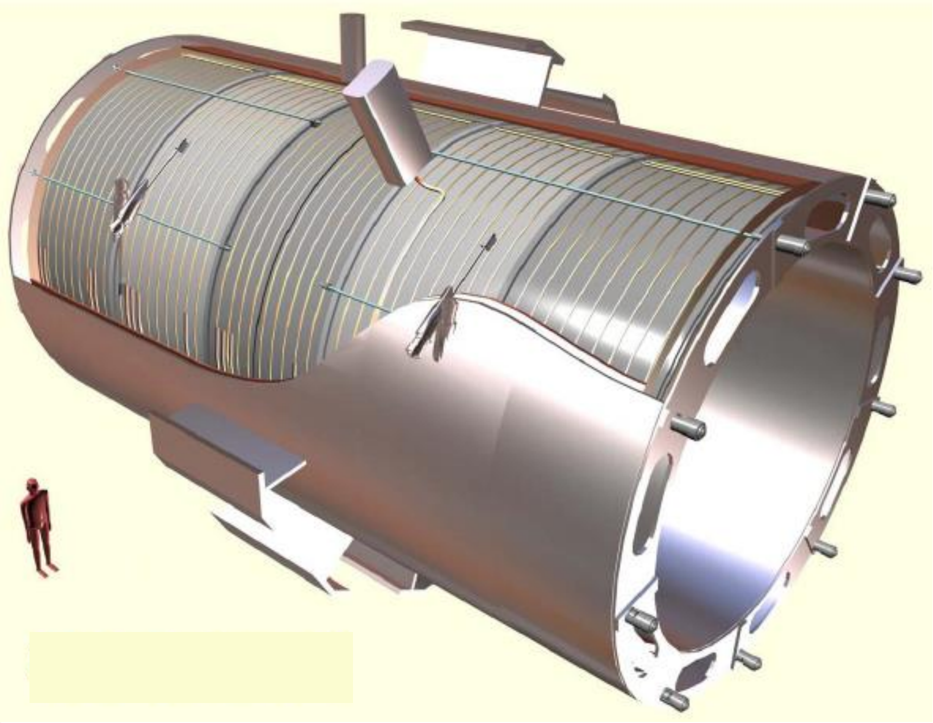
a large solenoid in routine commercial operation for the magnetic separation of Kaolin (china clay)

(was the) World's largest: Delphi superconducting so

Solenoids are not much used in accelerators. They are however frequently used in detectors, where the magnet field provides momentum analysis of the reaction products.

Delphi
1.2T
5.5m dia
6.8m long
110MJ

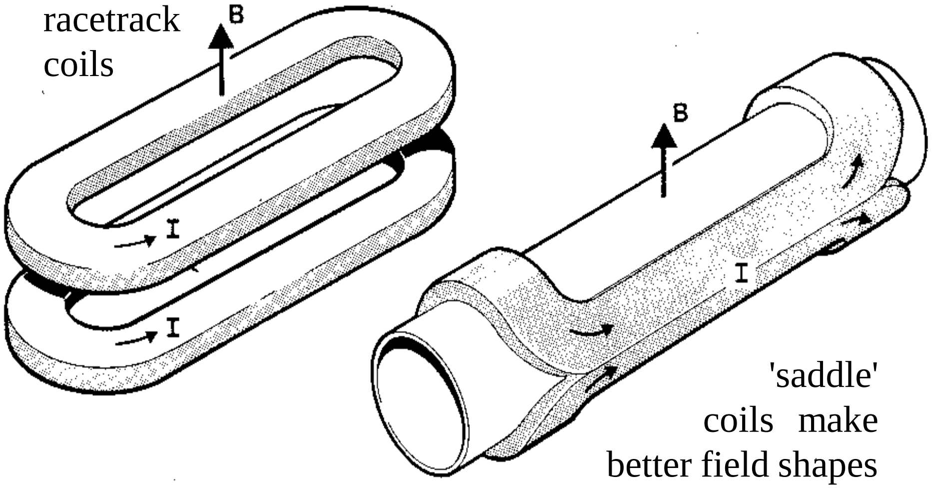
World's largest: CMS superconducting solenoid



CMS solenoid
4T at 20,000A
6 m diameter   12.5m long
stored energy 27000MJ

Magnetic Fields and ways to create them: (3)

transverse uniform fields

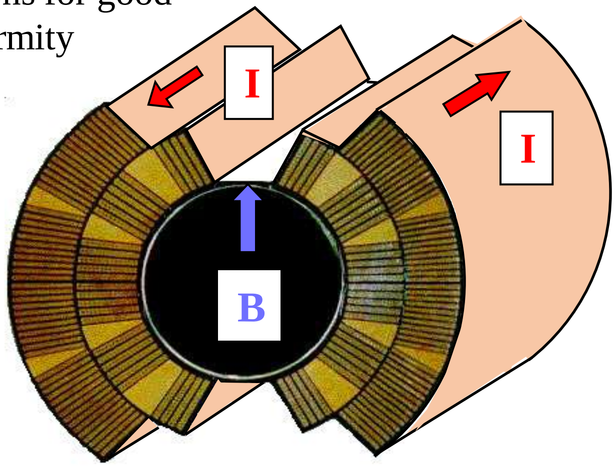


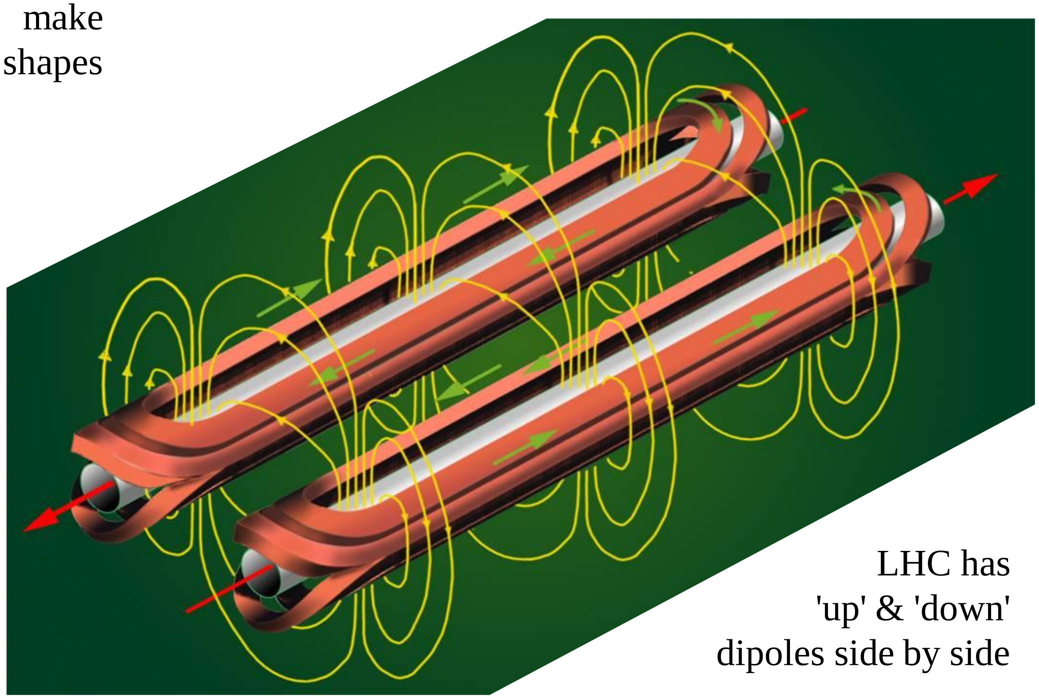
racetrack
coils

'saddle'
coils make
better field shapes

- some iron - but field shape is set mainly by the winding
- used when the long dimension is transverse to the field, eg accelerator magnets
- known as ***dipole*** magnets (because the iron version has 2 poles)

special winding cross
sections for good
uniformity



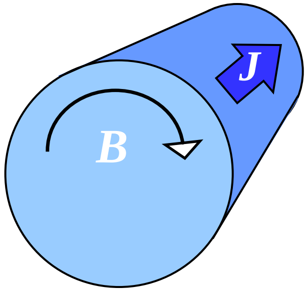


LHC has
'up' & 'down'
dipoles side by side

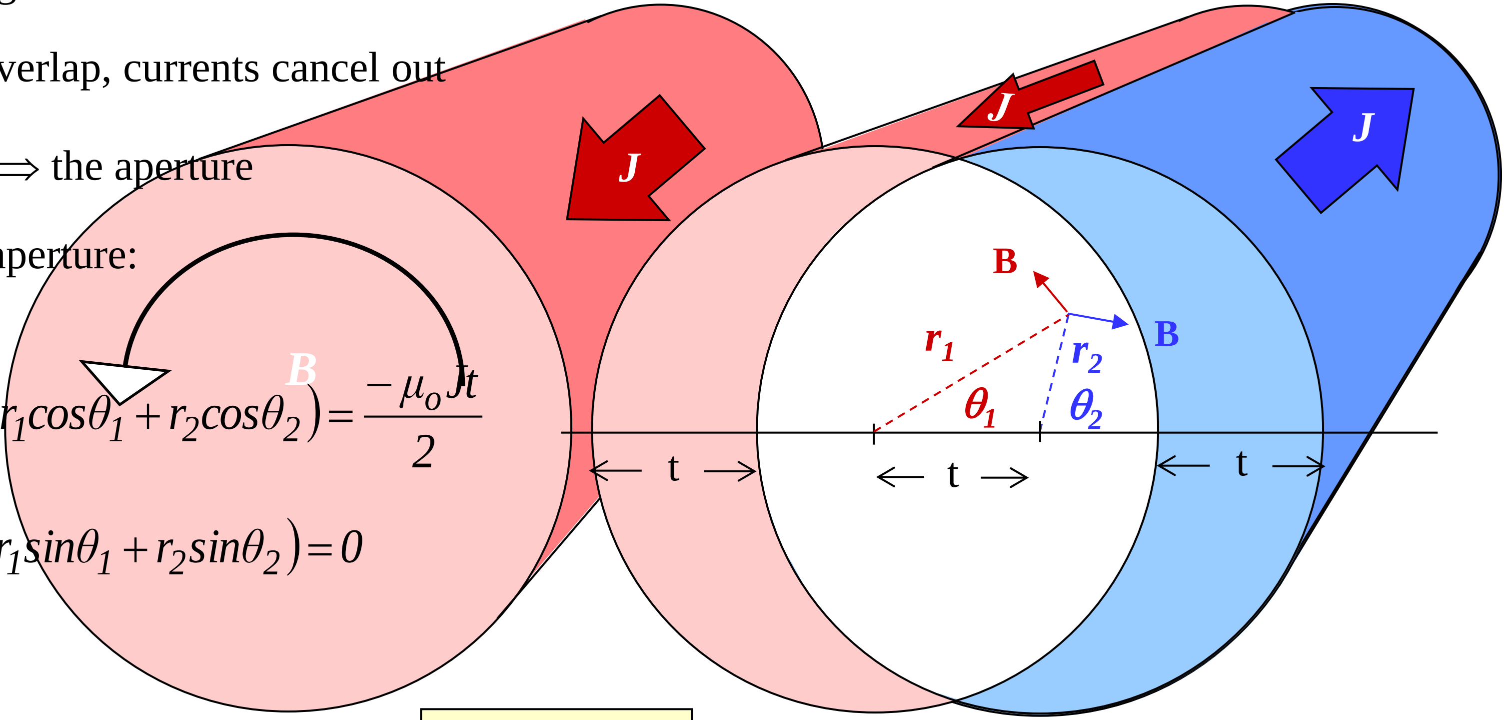
Dipole field from overlapping cylinders

Ampere's law for the field inside a cylinder carrying uniform current density

$$\oint B.ds = 2\pi r B = \mu_o I = \mu_o \pi r^2 J \qquad B = \frac{\mu_o J r}{2}$$



- two cylinders with opposite currents
- push them together
- where they overlap, currents cancel out
- zero current ⇒ the aperture
- fields in the aperture:



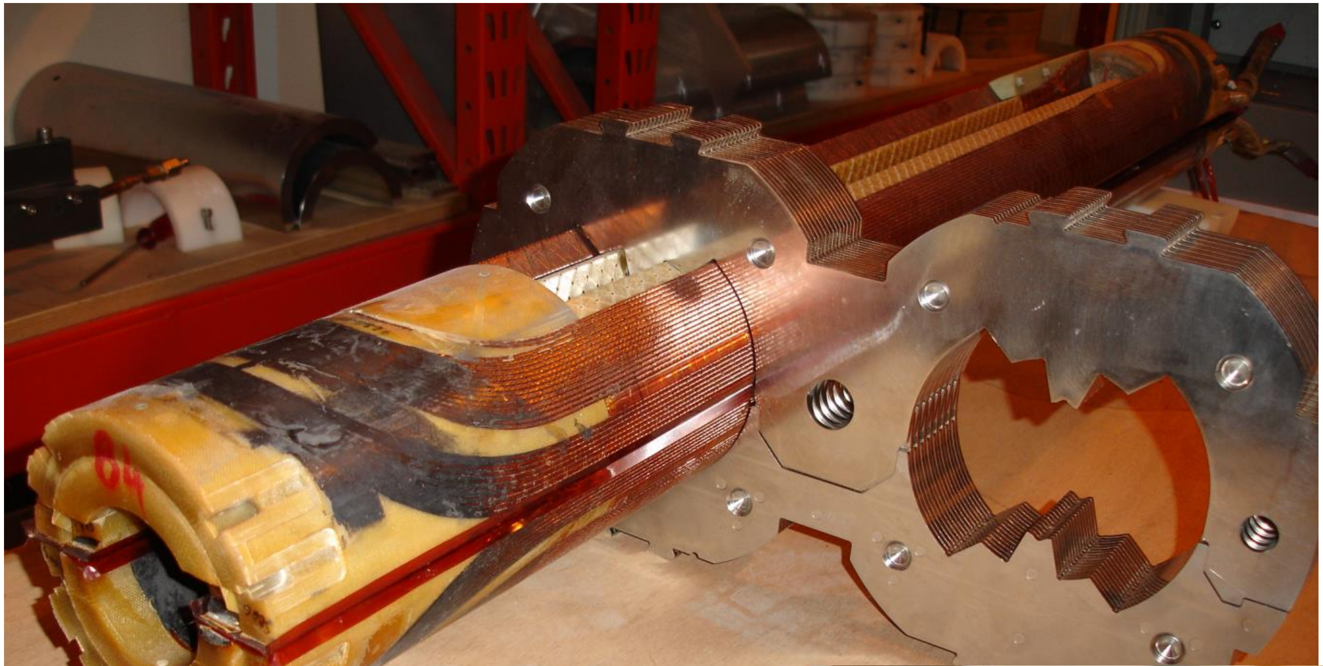
$$B_y = \frac{\mu_o J}{2}\left(-r_1 cos\theta_1 + r_2 cos\theta_2\right) = \frac{-\mu_o J t}{2}$$

$$B_x = \frac{\mu_o J}{2}\left(-r_1 sin\theta_1 + r_2 sin\theta_2\right) = 0$$

- thus the two overlapping cylinders give a perfect dipole field

$$\boxed{B_y = \frac{-\mu_o J_e t}{2}}$$

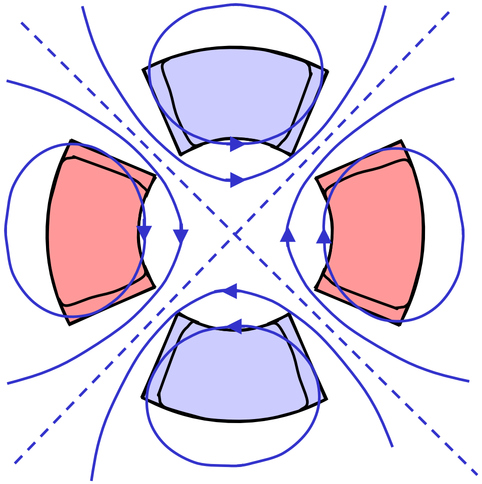
Dipole Magnets

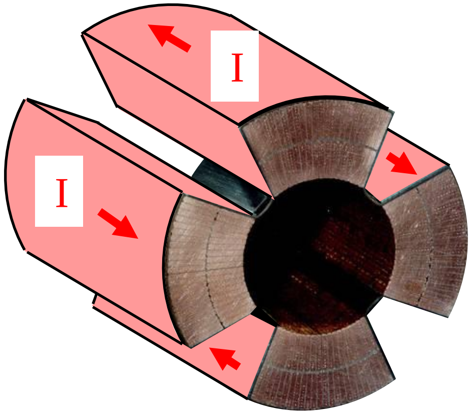


- made from superconducting cable
- winding must have the right cross section
- also need to shape the end turns

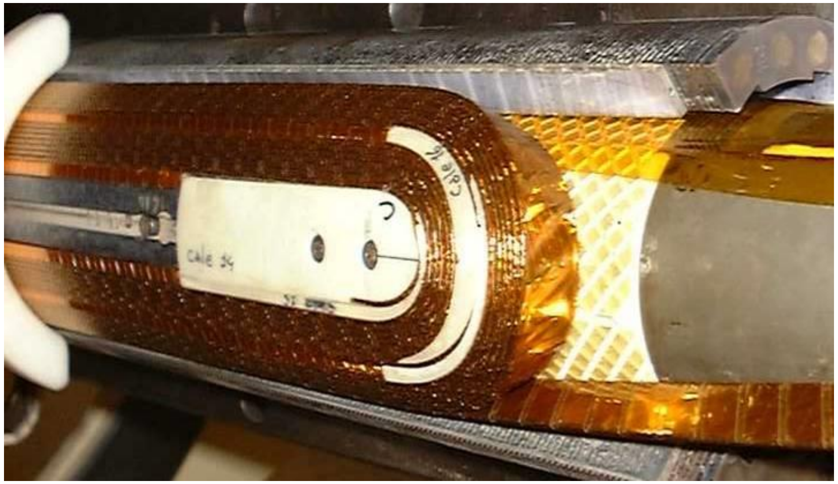
Fields and ways to create them: (4) transverse gradient fields

- gradient fields produce focussing
- quadrupole windings





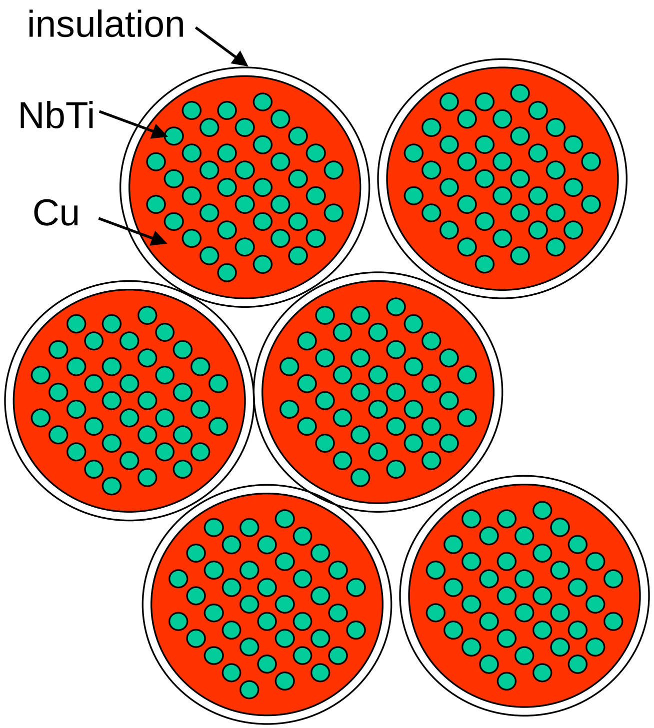
$B_x = ky$ $B_y = kx$



Engineering current density

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

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



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 λ_{metal} = 0.4 to 0.25

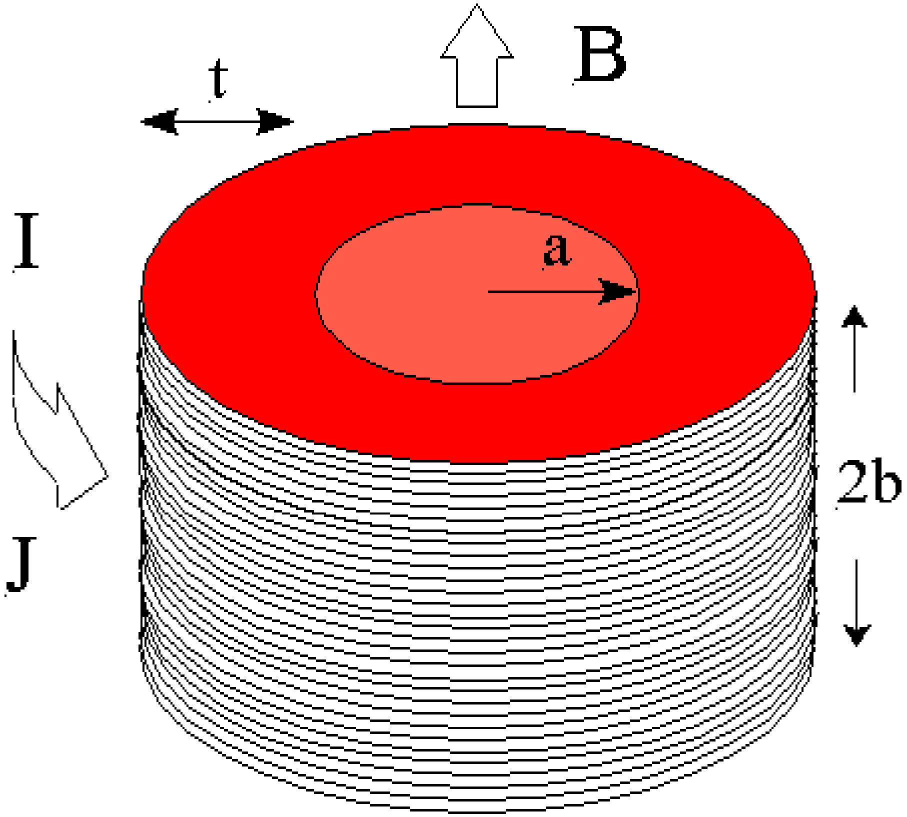
for $\mathrm{Nb_3Sn}$ *mat* ~ 3.0 ie λ_{metal} ~ 0.25

for B2212 *mat* = 3.0 to 4.0 ie λ_{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 $\boldsymbol{J_{supercon}}$

Importance of (engineering) current density: (1) solenoids



- the field produced by an infinitely long solenoid is

$$B = \mu_o J_e t$$

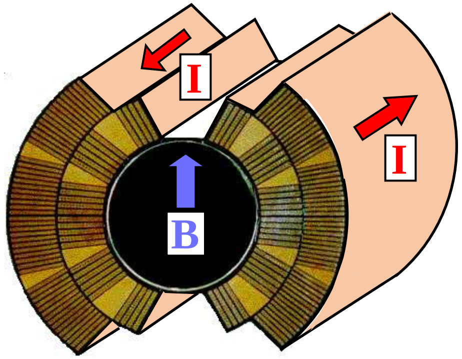
- in solenoids of finite length the central field is

$$B = \mu_o f J_e t$$

where f is a factor less than 1, typically ~ 0.8

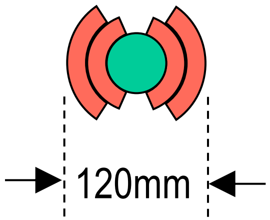
- so the thickness (volume, cost) of a solenoid to produce a given field is inversely proportional to the engineering current density J_e

Importance of (engineering) current density: (2) dipoles



LHC dipole

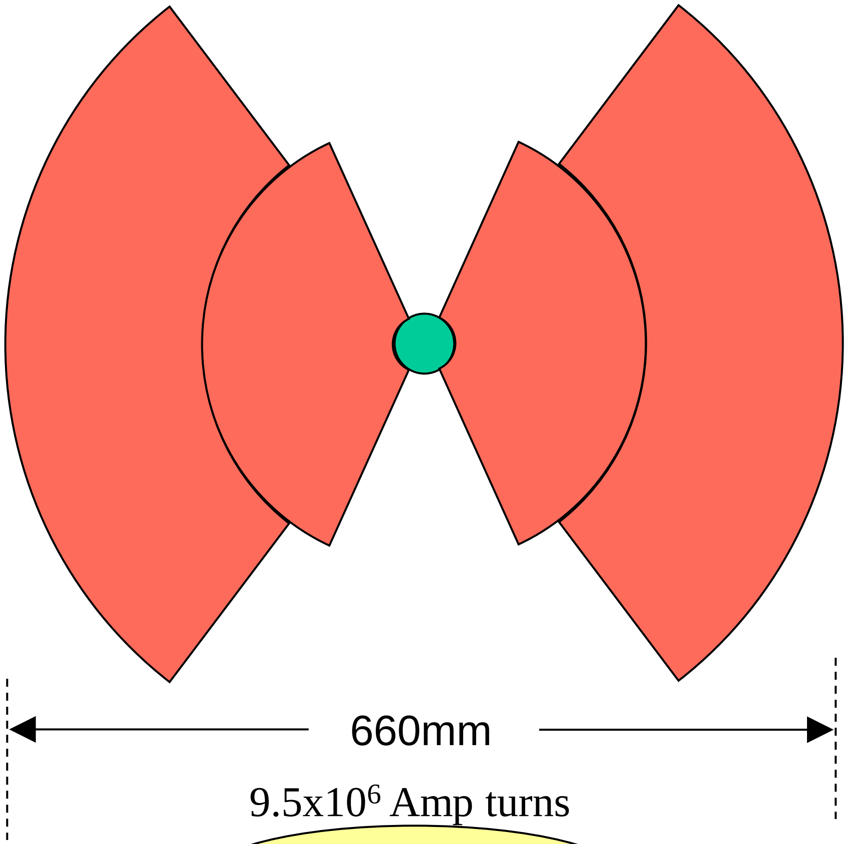
J_e = 375 Amm^{-2}



9.5x10^5 Amp turns

=1.9x10^6 A.m per m

J_e = 37.5 Amm^{-2}



9.5x10^6 Amp turns

=1.9x10^7 A.m per m

field produced
by a perfect
dipole is

$$B = \mu_o J_e \frac{t}{2}$$

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**: unsuitable for high field
  - **type 2**: good for high field - but must work hard to get current density
  - **HTS**: good for high field & temperature - but current density still a problem in field
- superconducting rf cavities use type 1 superconductors or type 2 below B_{c1}
- superconducting magnets use Type 2 or HTS conductors
- all superconducting accelerators to date use **NbTi** (45 years after its discovery)
- field shape of superconducting magnets is set by the winding shape (unlike iron yoke magnets)
- different field shapes need different windings
  - simplest is the solenoid,
  - transverse field for accelerators
- engineering current density is a crucial factor in magnet design and economy

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
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- Proc Applied Superconductivity Conference: pub as IEEE Trans Applied Superconductivity, Mar 93 to 99, and as IEEE Trans Magnetics Mar 75 to 91
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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
- Superconductivity: A Very Short Introduction by Stephen J. Blundell: Oxford University Press (2009) ISBN978-0-19-954090-7

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 Superconductivity** 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**.
- 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.