Superconducting Wires and Cables

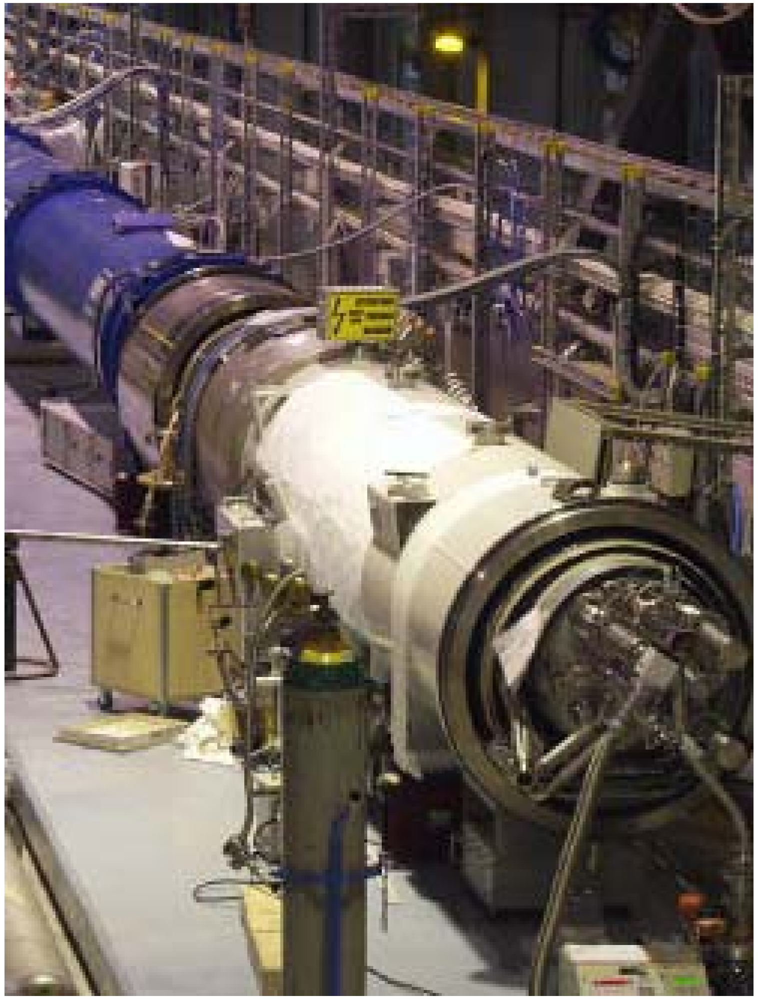
Who needs superconductivity anyway?

Abolish Ohm's Law!

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

Consequences

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

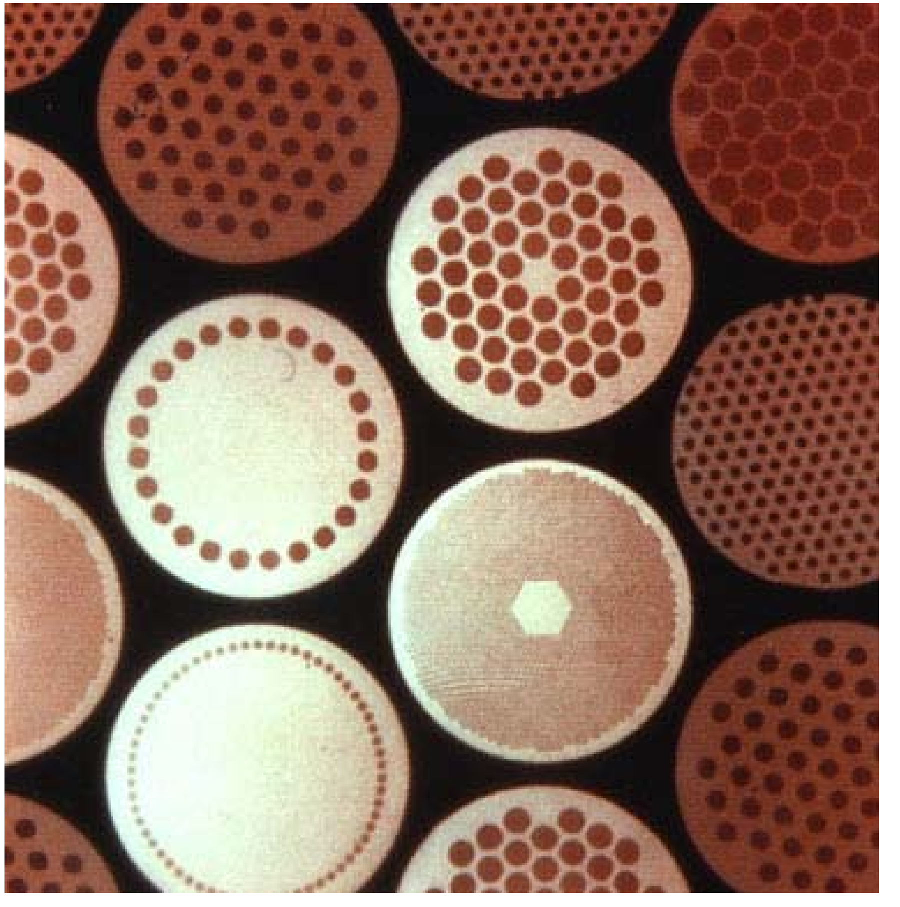


Superconducting Wires and Cables

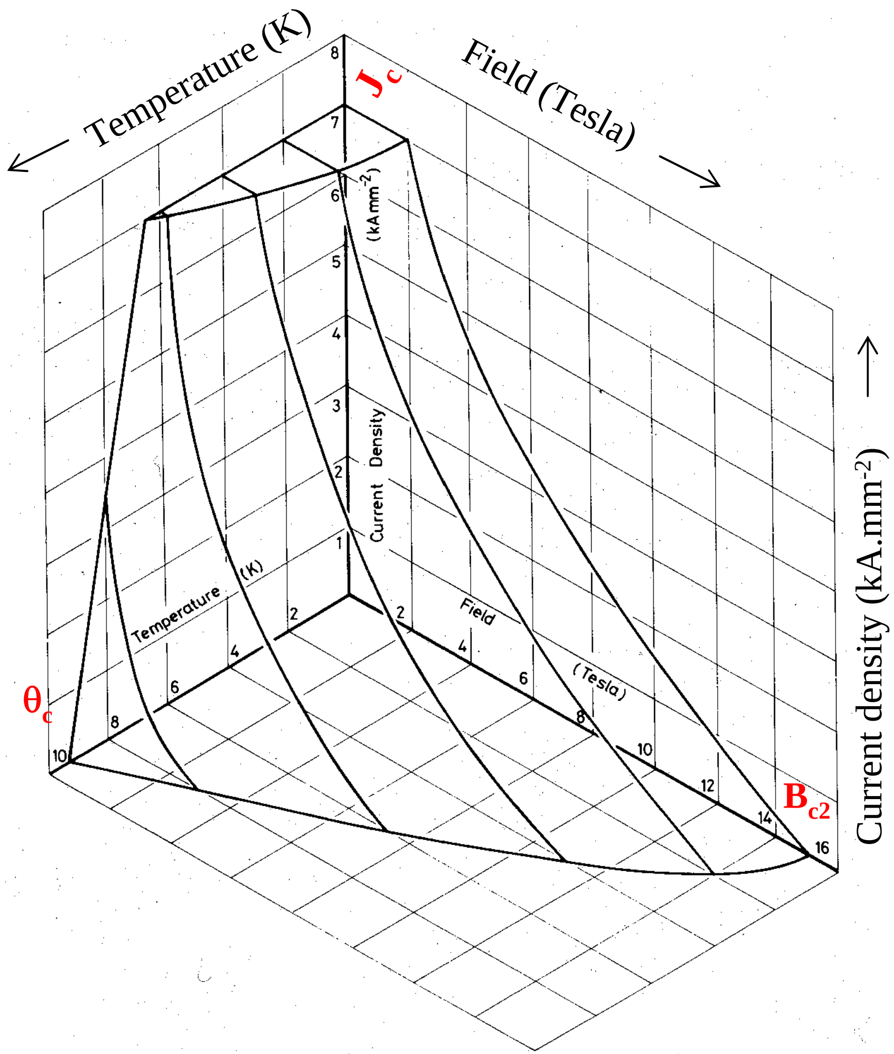
Martin N Wilson (Rutherford Lab ⇒ Oxford Instruments ⇒ CERN ⇒ consultant)

- properties of superconductors: critical surface of field, temperature and current density

- degradation and training
- minimum propagating zones MPZ and minimum quench energy MQE
- screening currents and the critical state model
- flux jumping
- magnetization and field errors
- filamentary composite wires: coupling and twisting
- why cables?
- coupling in cables

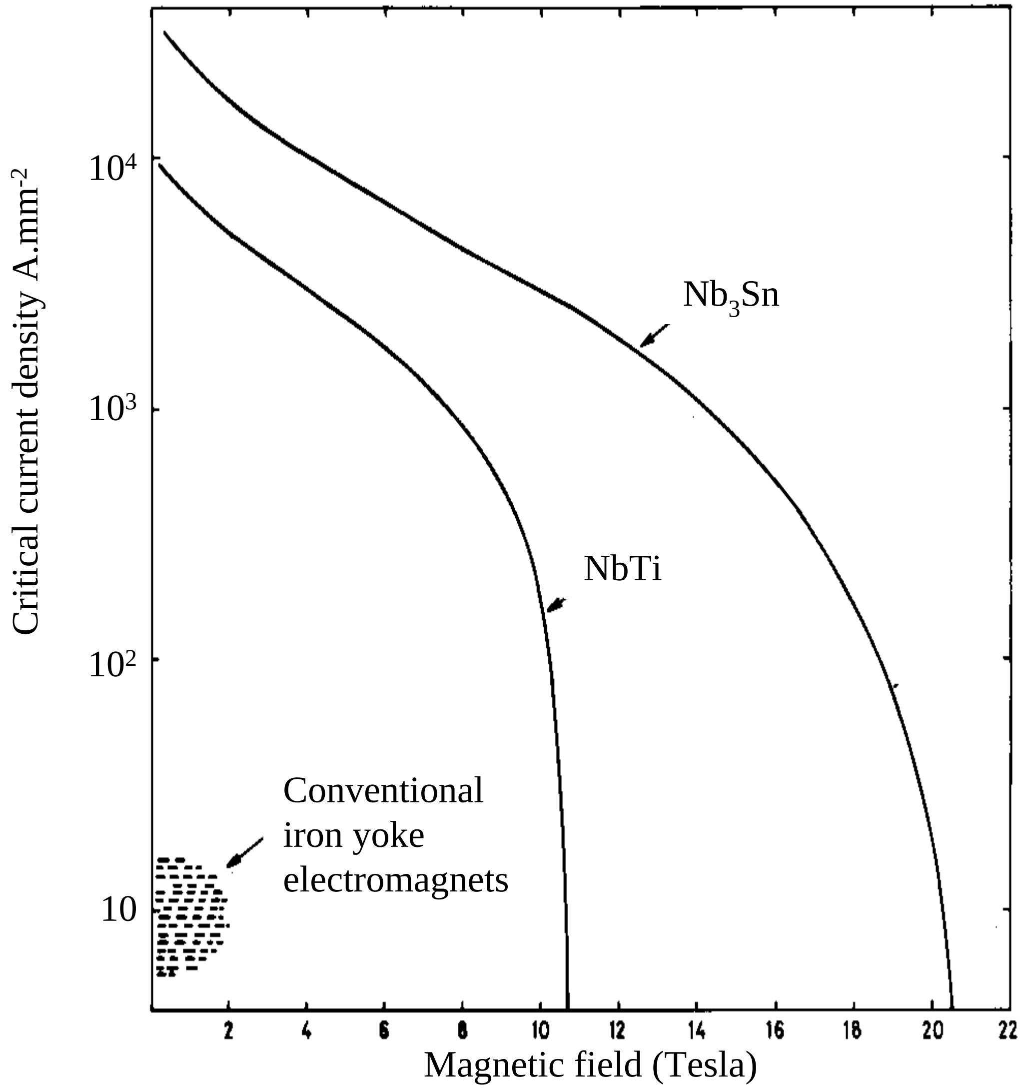


The critical surface of niobium titanium



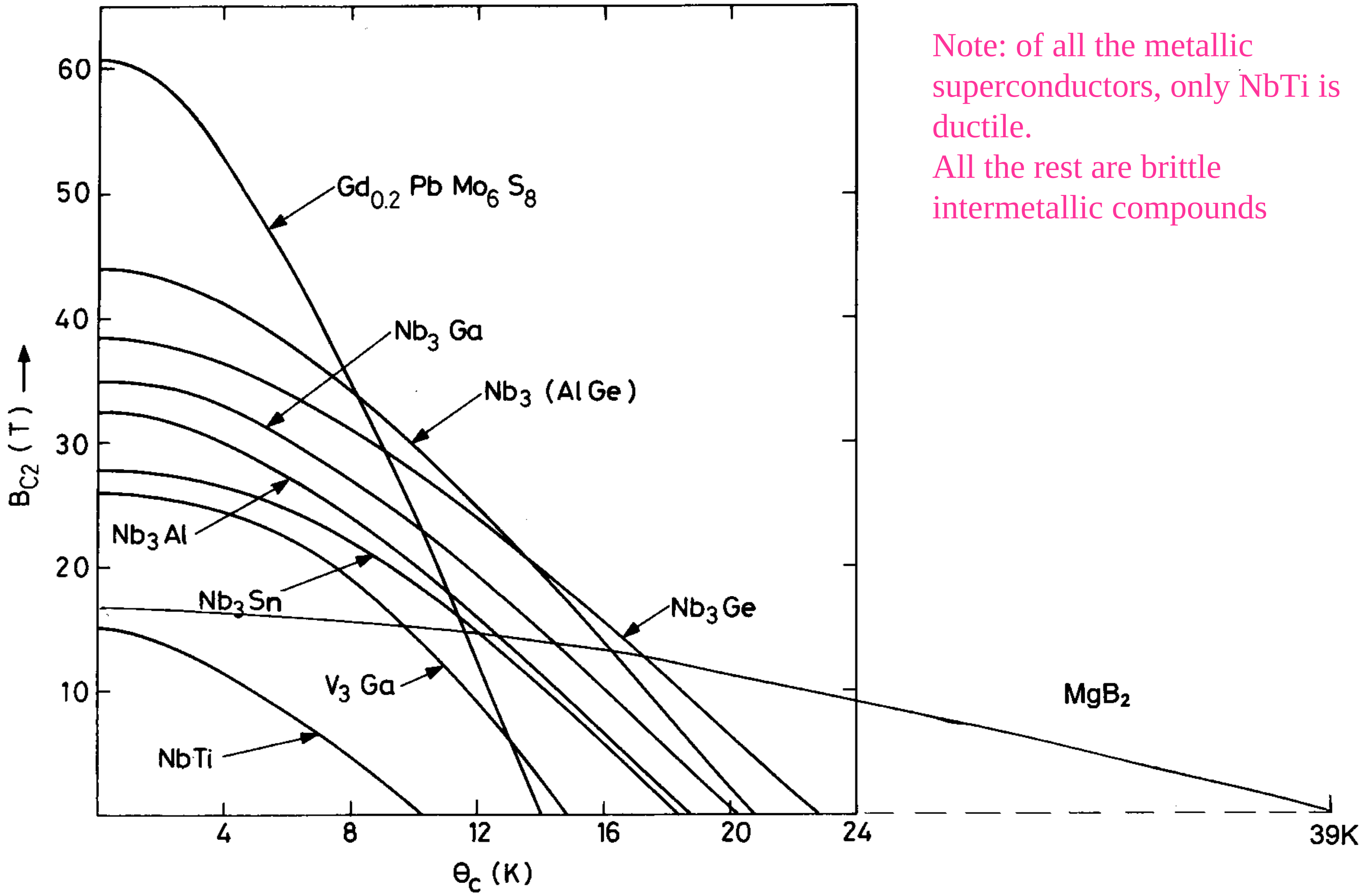
- Niobium titanium **NbTi** is the standard 'work horse' of the superconducting magnet business
- it is a ductile alloy
- picture shows the **critical surface**, which is the boundary between superconductivity and normal resistivity in 3 dimensional space
- superconductivity prevails everywhere below the surface, resistance everywhere above it
- we define an upper critical field $\mathbf{B_{c2}}$ (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 $\mathbf{J_c(B,\theta)}$ depends on processing

The critical line at 4.2K



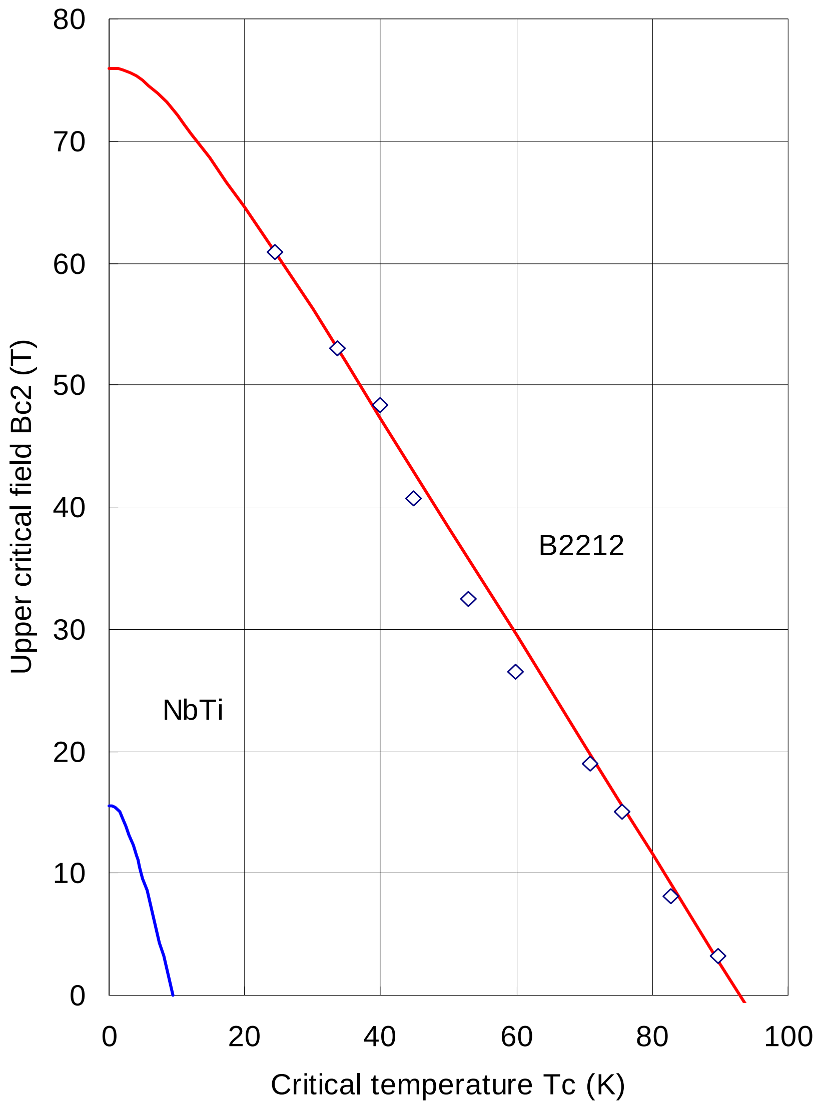
- because magnets usually work in boiling liquid helium, the critical surface is often represented by a curve of current versus field at 4.2K
- niobium tin Nb_3Sn has a much higher performance in terms of critical current field and temperature than NbTi
- but it is brittle intermetallic compound with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

Upper critical fields of metallic superconductors



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

High temperature superconductors

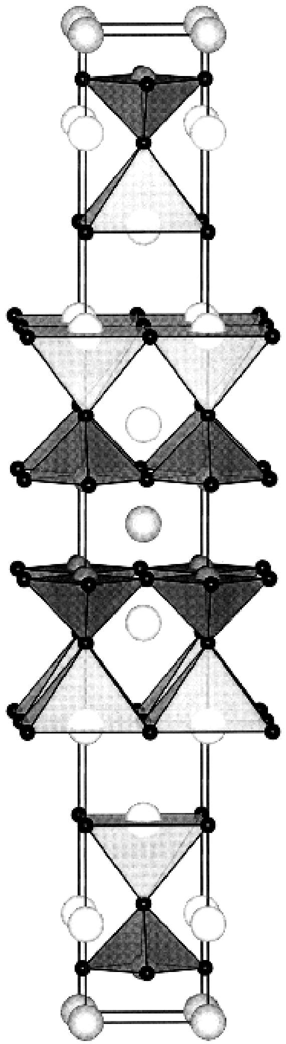


- many superconductors with critical temperature above 90K - BSCCO and YBCO
- operate in liquid nitrogen?
- trouble is that HTS do not carry much current in field at high temperature

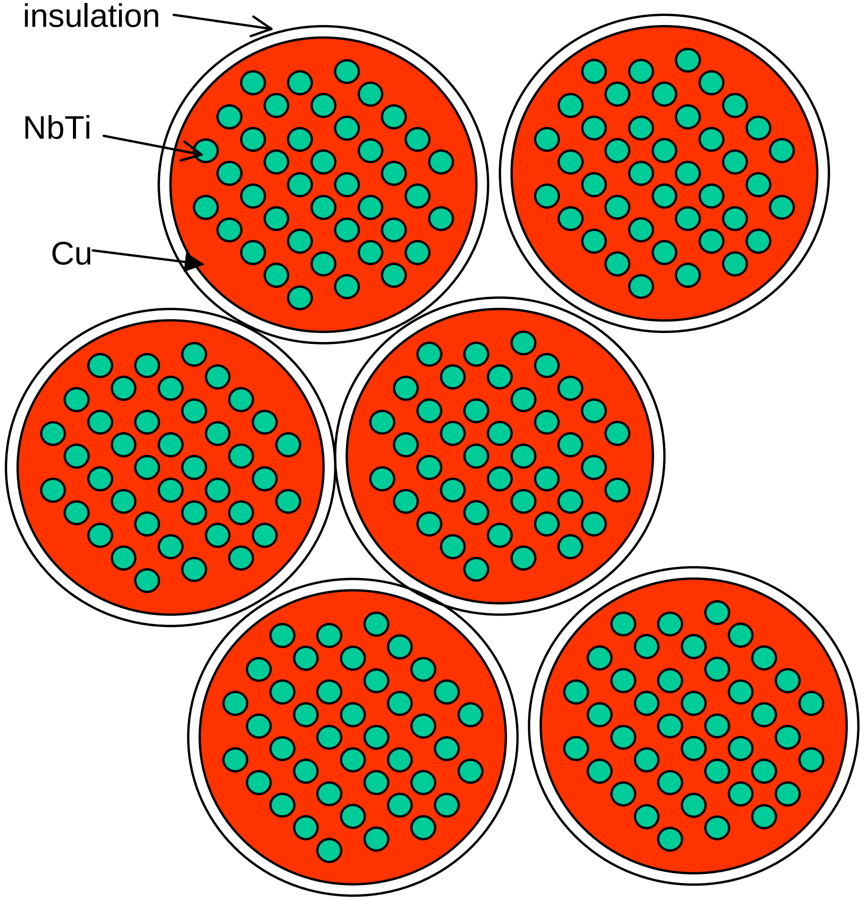
  - irreversibility line

  - melting of the fluxoid lattice

  - still superconducting but resistive to bulk current



Current density



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

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

fill factor $\lambda_{metal} = \frac{1}{(1+mat)}$

where *mat* = matrix : superconductor ratio

typically:

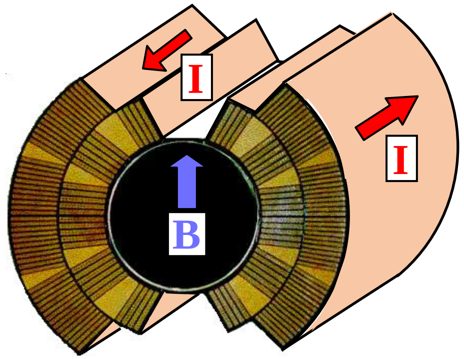
for NbTi *mat* = 1.5 to 3.0 ie λ_{metal} = 0.4 to 0.25

for 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

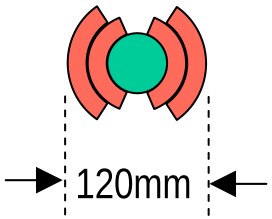
$\lambda_{winding}$ takes account of space occupied by insulation, cooling channels, mechanical reinforcement etc and is typically 0.7 to 0.8

Importance of current density: (2) dipoles



LHC dipole

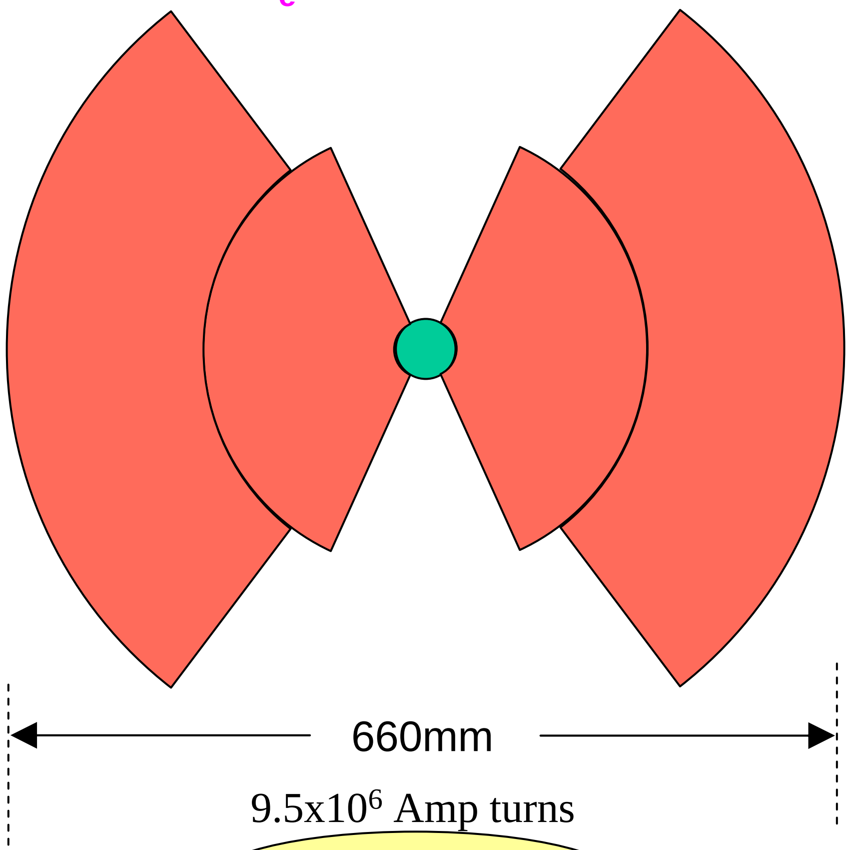
J_e = 375 Amm^{-2}



9.5x10^5 Amp turns

=1.9x10^6 A.m per m

J_e = 37.5 Amm^{-2}



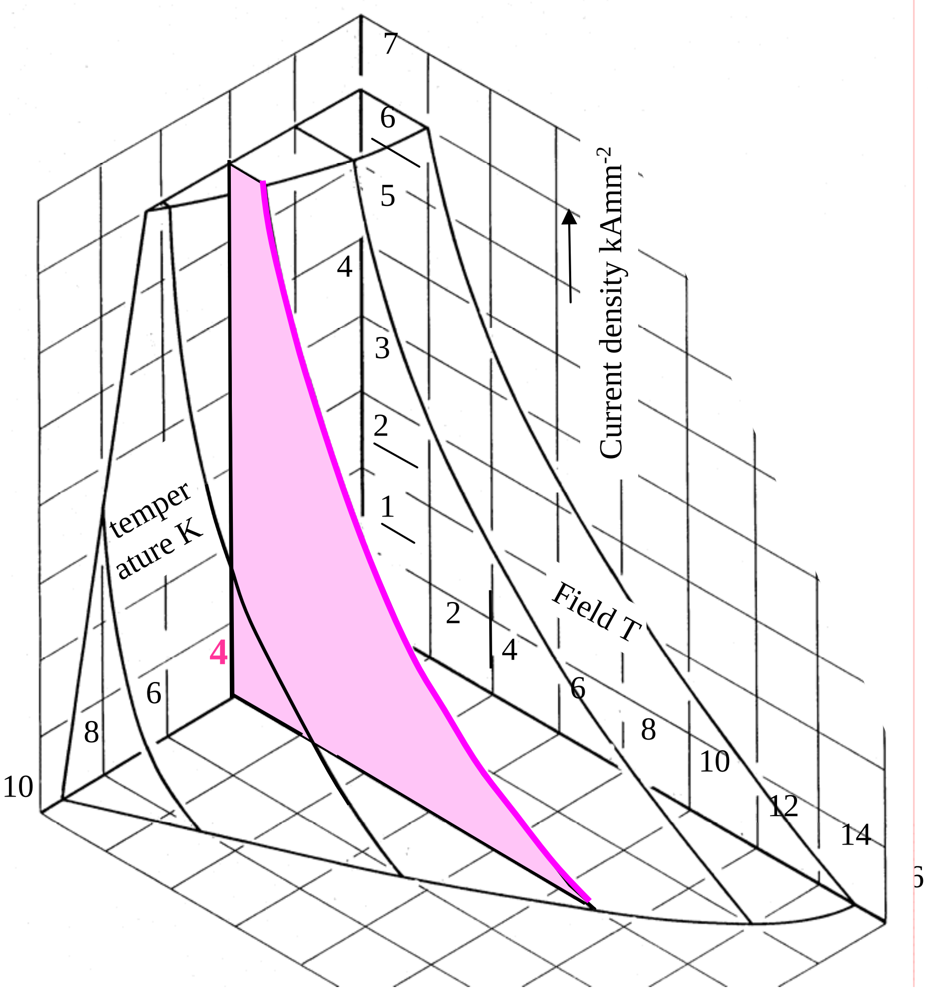
9.5x10^6 Amp turns

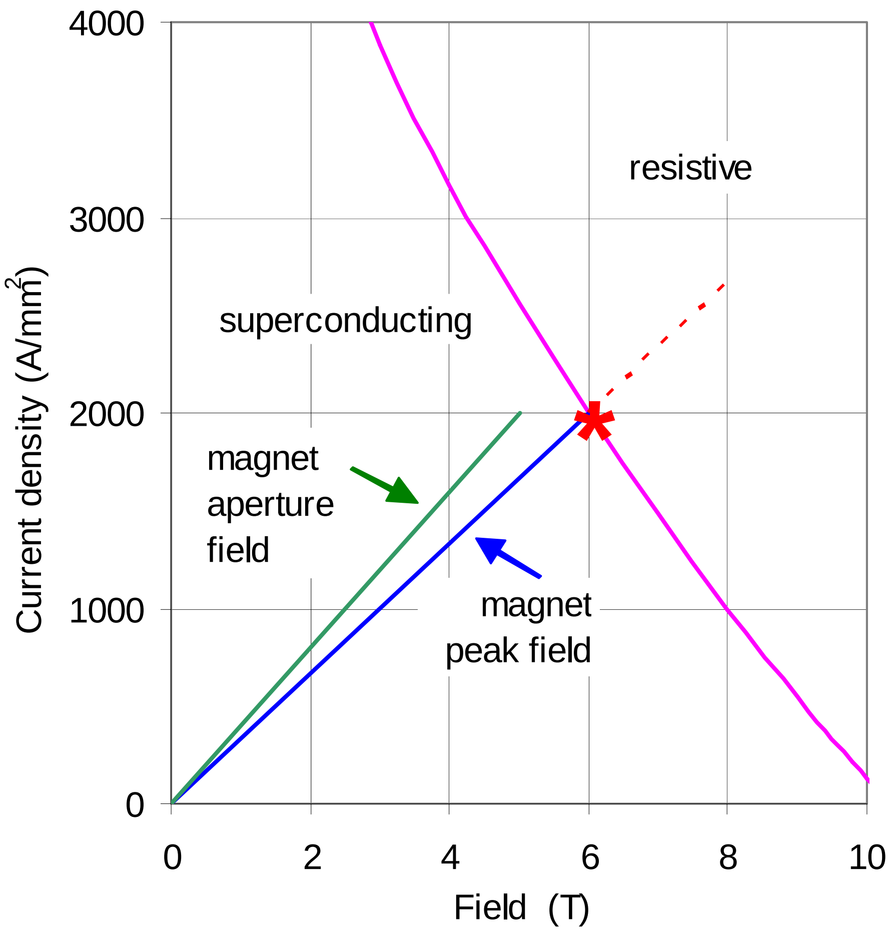
=1.9x10^7 A.m per m

field produced by a perfect dipole is

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

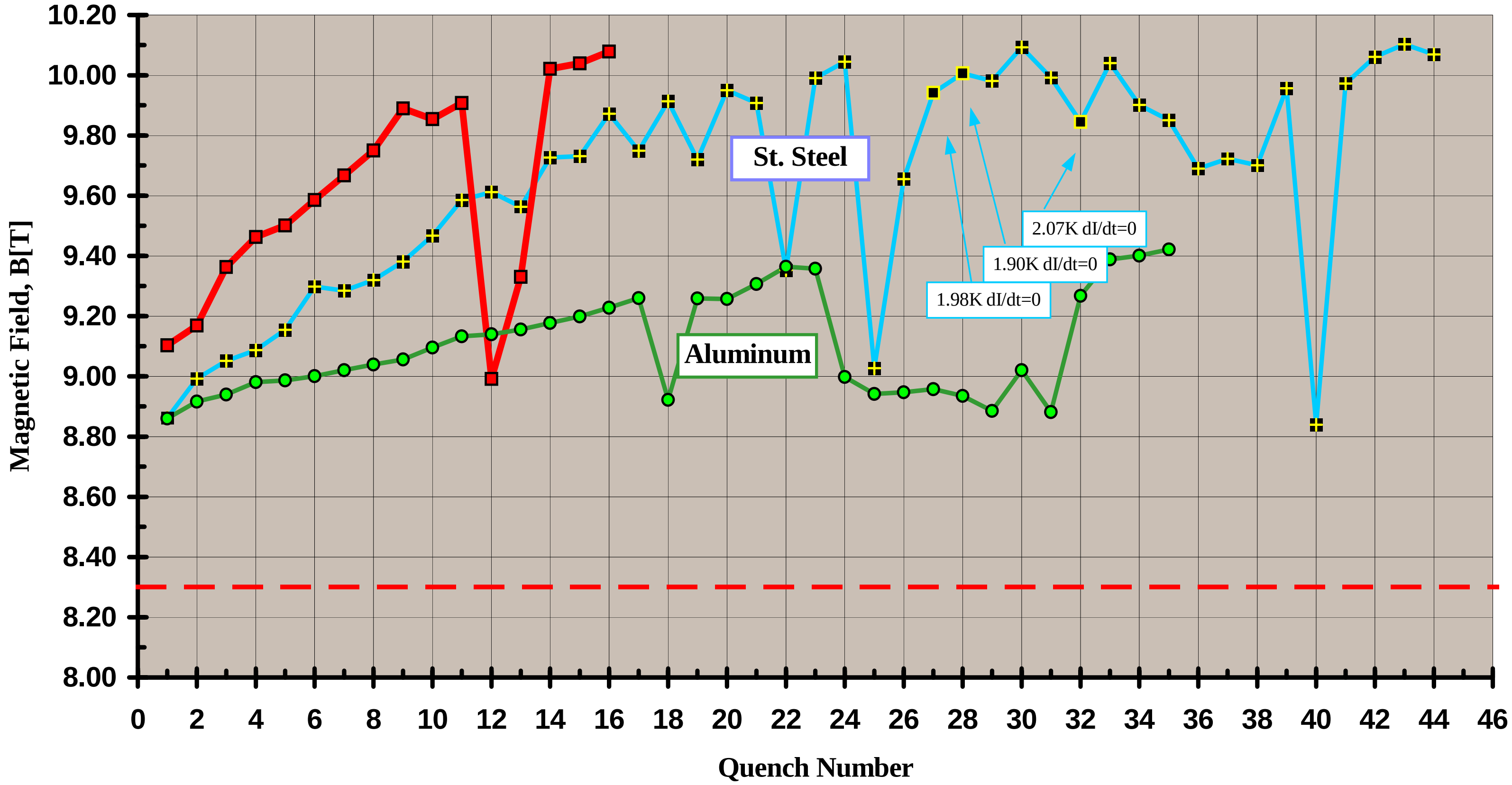
Critical line and magnet load lines





we expect the magnet to go resistive ***'quench'*** where the peak field load line crosses the critical current line *

Degraded performance and 'training'



LHC short model dipole training histories: data from Andrzej Siemko

- most magnets do not go straight to the expected quench point *, instead they go resistive - ***quench*** - at lower currents
- at ***quench***, the stored energy $\frac{1}{2}LI^2$ of the magnet is dissipated in the magnet, raising its temperature way above critical - must wait for it to cool down and then try again
- second try usually goes to higher current and so - known as ***training***

Causes of training: and some cures

Low Specific Heat: at 4.2K the specific heat of all substances is ~2,000 times less than at room temperature – so the smallest energy release can produce a catastrophic temperature rise.

Cure: work at higher temperatures – but HTS materials don't yet work in magnets

Jc decreases with temperature: so a temperature rise drives the conductor resistive.

Cure: there isn't one.

Conductor motion: $J \wedge B$ force makes conductor move, which releases heat by friction - even 10μm movement can raise the temperature by 3K:

Cures: i) make the coils fit together very tightly, pre-compress them
ii) vacuum impregnate with epoxy resin – **but**……………….

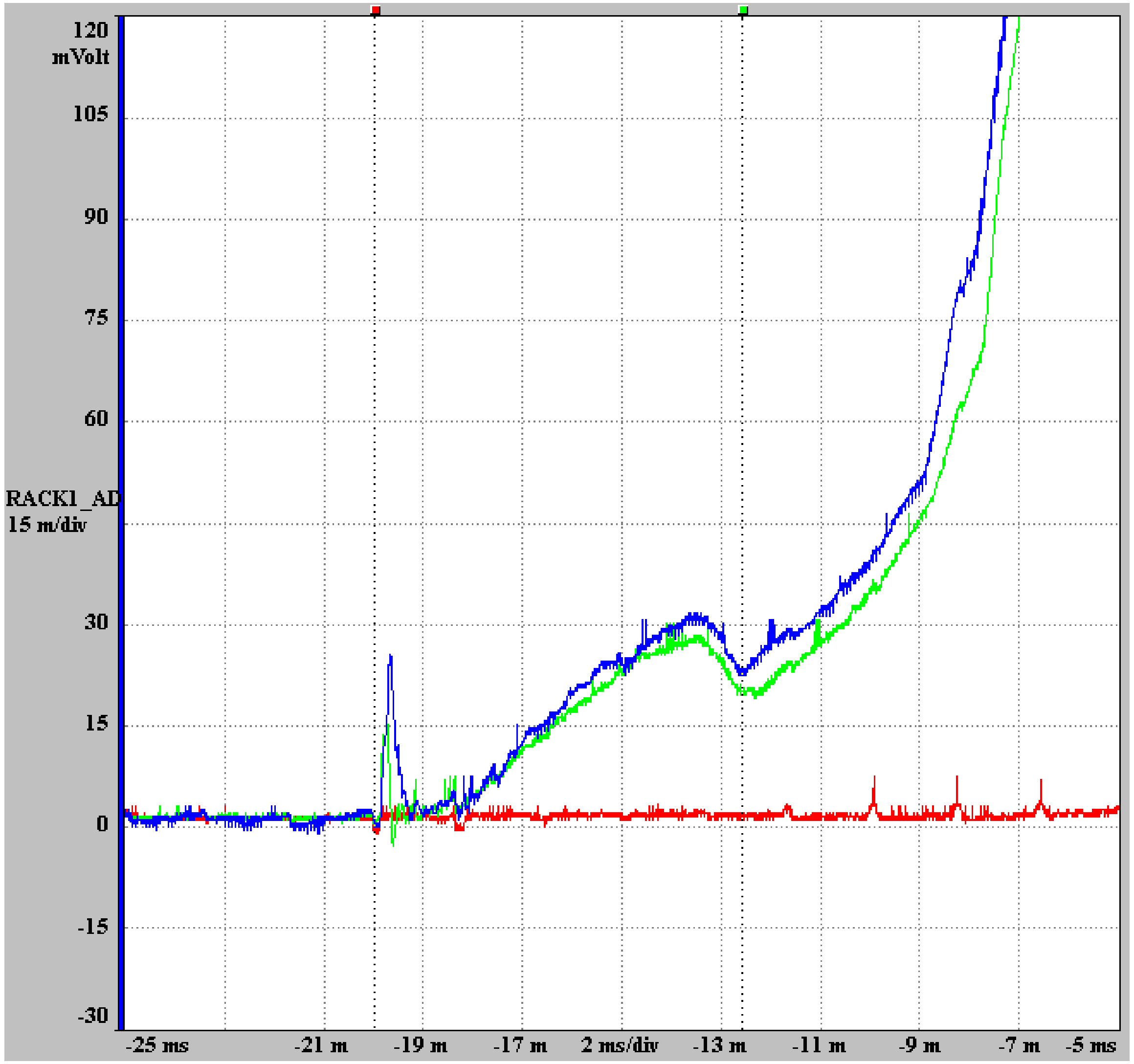
Resin cracks: organic materials become brittle at low temperature, because of differential thermal contraction they are often under tension – cracking releases heat.

Cure: fill the epoxy with low contraction (inorganic) material, eg silica powder or glass fibre.

Point quenching: even if only a very small section of conductor is driven resistive, the resistive zone will grow by Ohmic heating until it has quenched the magnet.

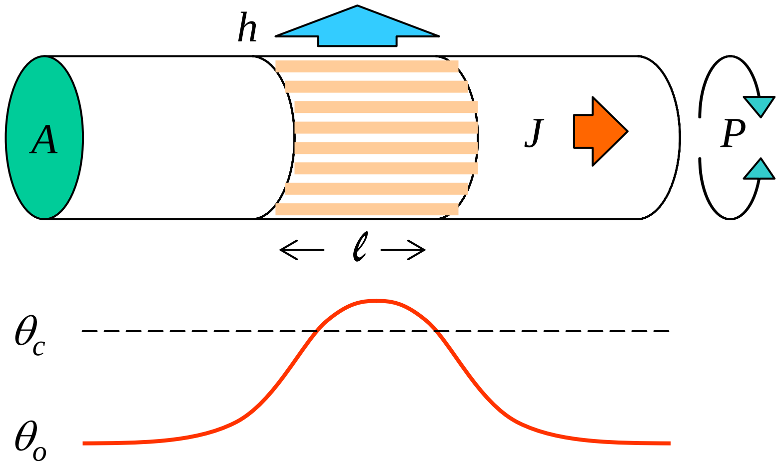
Cure: make the conductor such that a resistive zone will not grow until a large section has been driven resistive.

Quench initiation by a disturbance



- CERN picture of the internal voltage in an LHC dipole just before a quench
- note the initiating spike - conductor motion?
- after the spike, conductor goes resistive, then it almost recovers
- but then goes on to a full quench
- can we design conductors to encourage that recovery and avoid the quench?

Minimum propagating zone MPZ



- think of a conductor where a short section has been heated, so that it is resistive
- if heat is conducted out of the resistive zone faster than it is generated, the zone will shrink - vice versa it will grow.
- the boundary between these two conditions is called the minimum propagating zone *MPZ*
- for best stability make MPZ as large as possible

the balance point may be found by equating heat generation to heat removed.
Very approximately, we have:

$$\frac{2kA(\theta_c - \theta_o)}{l} + hPl(\theta_c - \theta_o) = J_c^2 \rho A l$$

$$l = \left\{ \frac{2k(\theta_c - \theta_o)}{J_c^2 \rho - \frac{hP}{A}(\theta_c - \theta_o)} \right\}^{\frac{1}{2}}$$

where: k = thermal conductivity ρ = resistivity A = cross sectional area of conductor

h = heat transfer coefficient to coolant – if there is any in contact

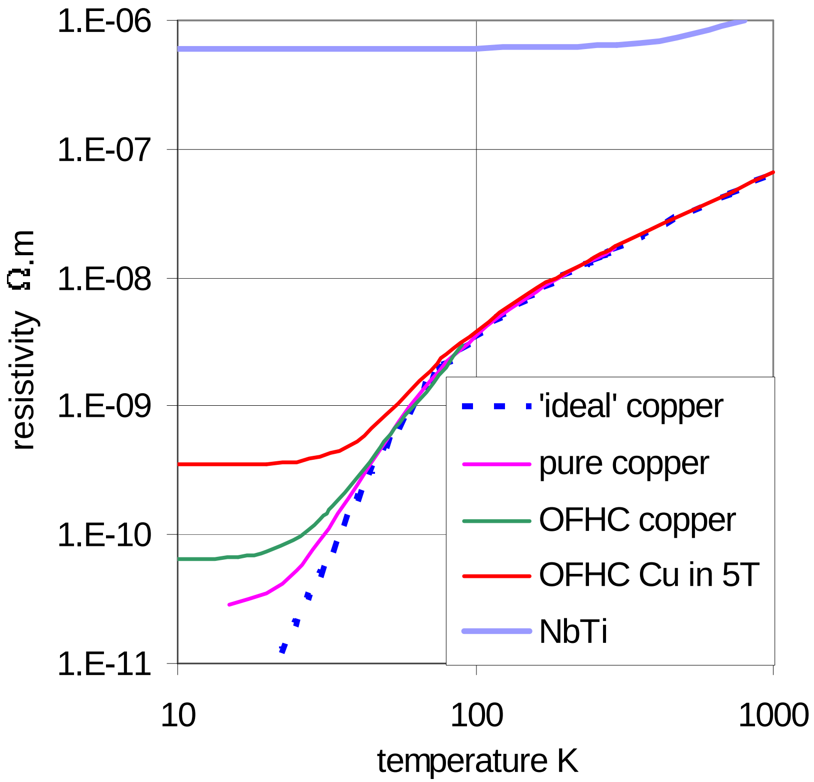
P = cooled perimeter of conductor

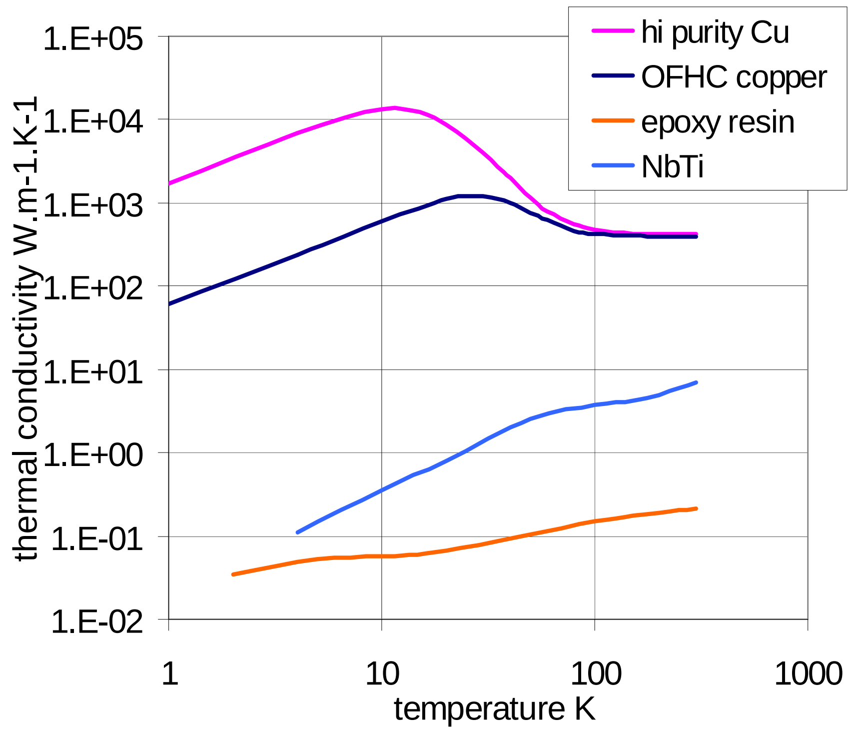
Energy to set up MPZ is called the Minimum Quench Energy *MQE*

How to make a large MPZ and MQE

$$l = \left\{ \frac{2k(\theta_c - \theta_o)}{J_c^2 \rho - \frac{hP}{A}(\theta_c - \theta_o)} \right\}^{\frac{1}{2}}$$

- make thermal conductivity k large
- make resistivity ρ small
- make heat transfer ***hP/A*** large (but $\Rightarrow$ low J_{eng})

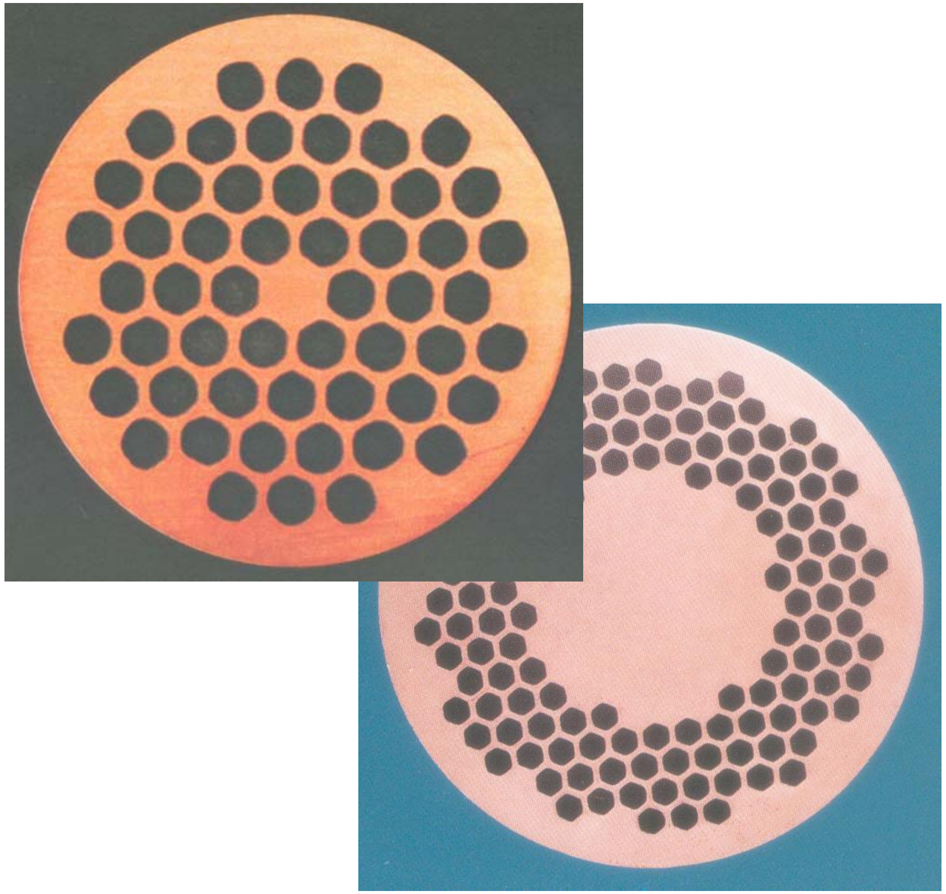




Large MPZ ⇒ large MQE ⇒ less training

$$l = \left\{ \frac{2k(\theta_c - \theta_o)}{J_c^2 \rho - \frac{hP}{A}(\theta_c - \theta_o)} \right\}^{\frac{1}{2}}$$

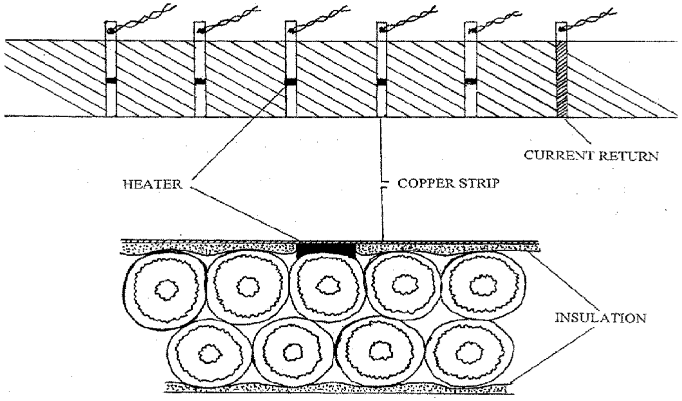
- make thermal conductivity k large
- make resistivity ρ small
- make heat transfer term *hP/A* large



- NbTi has high ρ and low k
- copper has low ρ and high k
- mix copper and NbTi in a filamentary composite wire
- NbTi in fine filaments for intimate mixing
- maximum diameter of filaments ~ 50μm
- make the windings porous to liquid helium
  - superfluid is best
- fine filaments also eliminate flux jumping
  (see later slides)

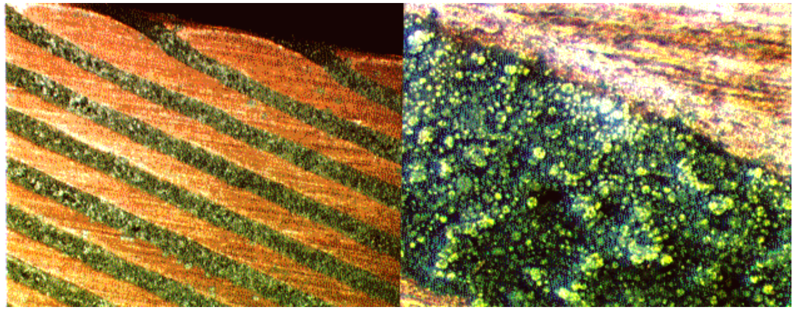
Measurement of MQE

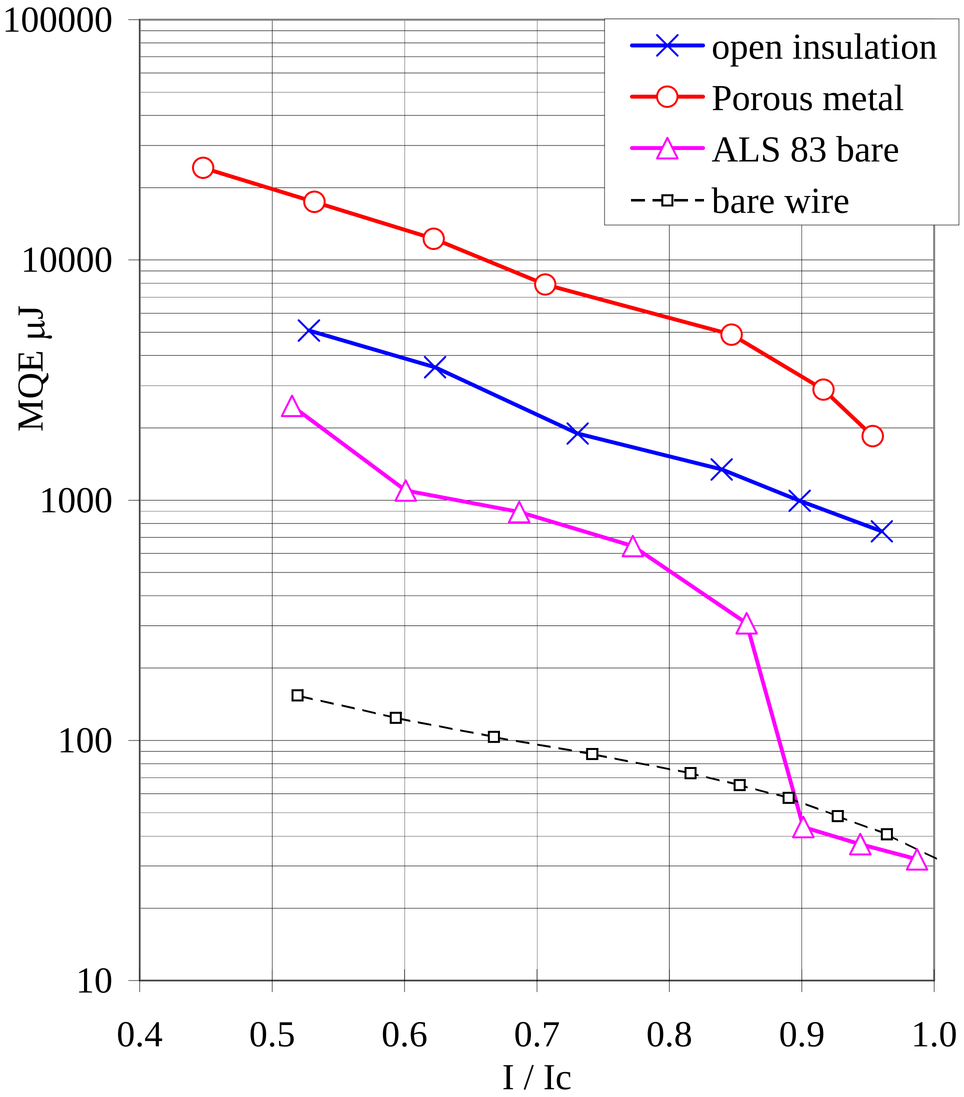
measure MQE by injecting heat pulses into a single wire of the cable



good results when spaces in cable are filled with porous metal

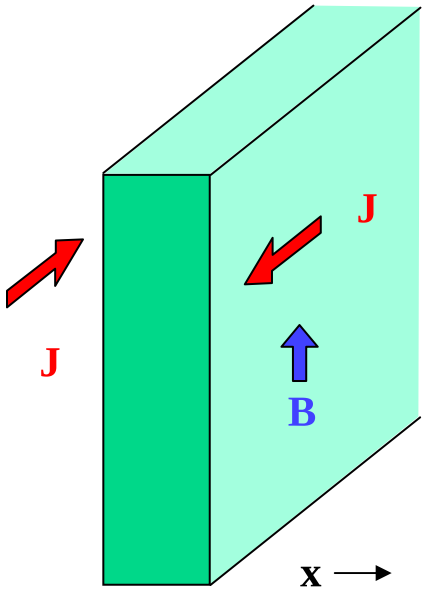
- excellent heat transfer to the helium





Another cause of training: flux jumping

- when a superconductor is subjected to a changing magnetic field, screening currents are induced to flow
- ***screening currents*** are in addition to the ***transport current***, which comes from the power supply
- they are like eddy currents but, because there is no resistance, they don't decay

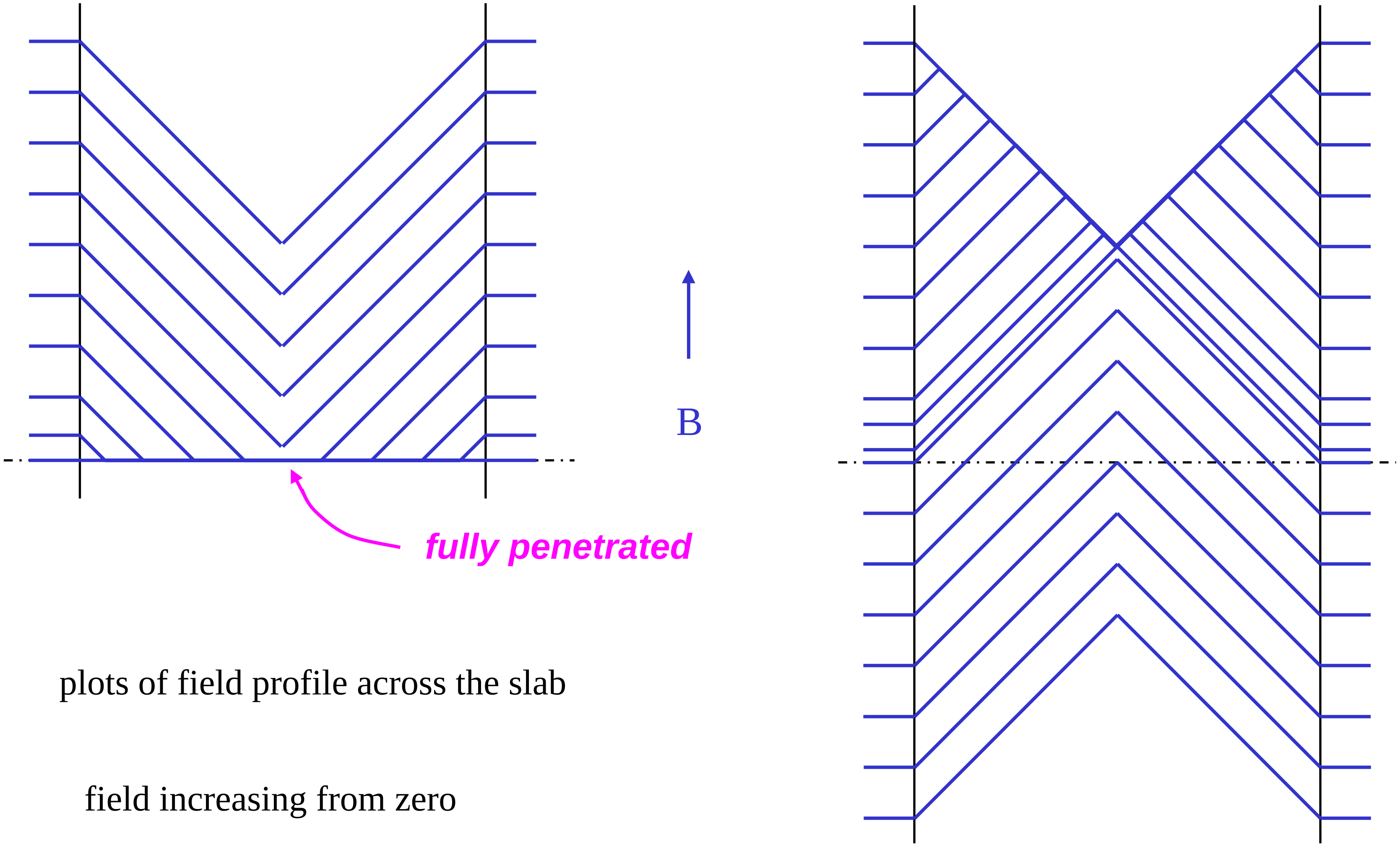


- usual model is a superconducting slab in a changing magnetic field $\boldsymbol{B_y}$
- assume it's infinitely long in the *z* and *y* directions - simplifies to a 1 dim problem
- ***dB/dt*** induces an electric field E which causes screening currents to flow at critical current density $\boldsymbol{J_c}$
- known as the ***critical state model*** or ***Bean model***
- in the 1 dim infinite slab geometry, Maxwell's equation says

$$\frac{\partial B_y}{\partial x} = -\mu_o J_z = \mu_o J_c$$

- so uniform $\boldsymbol{J_c}$ means a constant field gradient inside the superconductor

The flux penetration process



plots of field profile across the slab

field increasing from zero

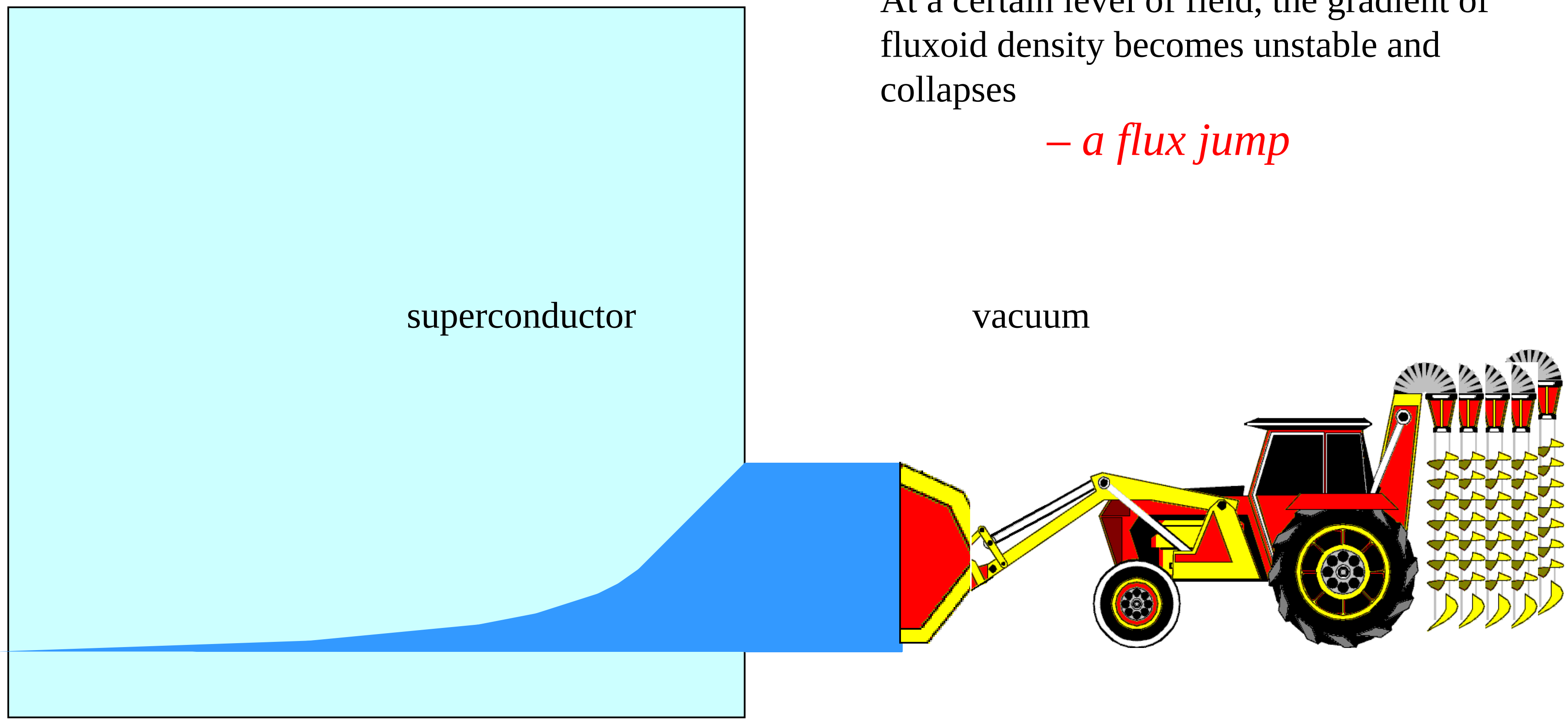
field decreasing through zero

Flux penetration from another viewpoint

Think of the screening currents, in terms of a gradient in fluxoid density within the superconductor. Pressure from the increasing external field pushes the fluxoids against the pinning force, and causes them to penetrate, with a characteristic gradient in fluxoid density

At a certain level of field, the gradient of fluxoid density becomes unstable and collapses

– a flux jump



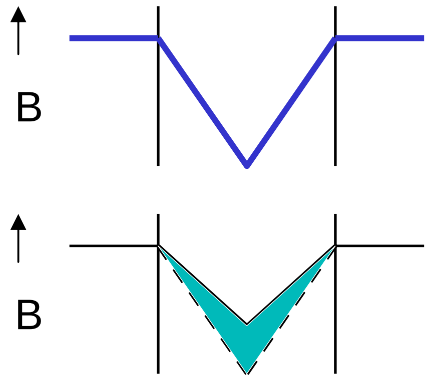
Flux jumping: why it happens

Unstable behaviour is shown by all type 2 and HT superconductors when subjected to a magnetic field

It arises because:-

magnetic field induces screening currents, flowing at critical density J_c

*** reduction in screening currents allows flux to move into the superconductor**

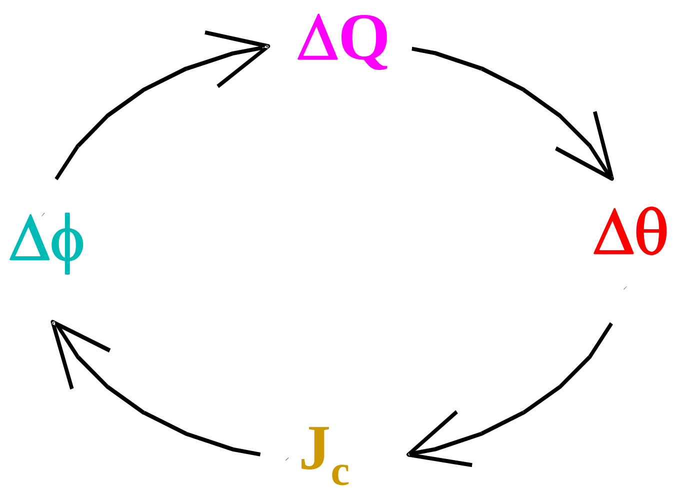


flux motion dissipates energy

thermal diffusivity in superconductors is low, so energy dissipation causes local temperature rise

critical current density falls with increasing temperature

go to *



Cure flux jumping by making superconductor in the form of fine filaments – weakens $\Delta J_c \Rightarrow \Delta\phi \Rightarrow \Delta Q$

Flux jumping: the numbers for NbTi

criterion for stability against flux jumping

a = half width of filament

$$a = \frac{1}{J_c}\left\{\frac{3\gamma\, C(\theta_c - \theta_o)}{\mu_o}\right\}^{\frac{1}{2}}$$

typical figures for NbTi at 4.2K and 1T

J_c *critical current density* = $7.5 \times 10^9\ Am^{-2}$

γ *density* = $6.2 \times 10^3\ kg.m^3$

C *specific heat* = $0.89\ J.kg^{-1}K^{-1}$

θ_c *critical temperature* = 9.0K

so a = 33μm, ie 66μm diameter filaments

Notes:

- least stable at low field because J_c is highest
- instability gets worse with decreasing temperature because J_c increases and C decreases
- criterion gives the size at which filament is just stable against infinitely small disturbances
  - still sensitive to moderate disturbances, eg mechanical movement
- better to go somewhat smaller than the limiting size
- in practice 50μm diameter seems to work OK

Flux jumping is a solved problem ✓

Magnetization

When viewed from outside the sample, the persistent currents produce a magnetic moment.

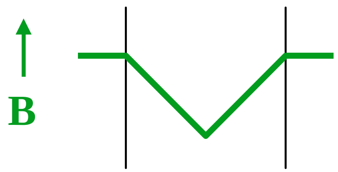
Problem for accelerators because it spoils the precise field shape

We can define a magnetization (magnetic moment per unit volume)

$$M = \sum_V \frac{I.A}{V}$$

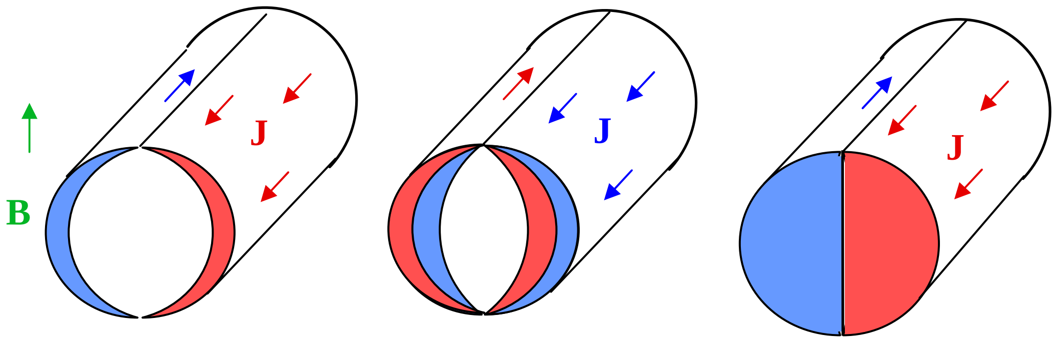
NB units of H

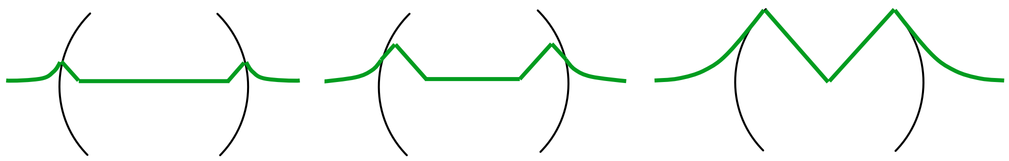
for a fully penetrated slab



$$M = \frac{1}{a}\int_0^a J_c.x.dx = \frac{J_c.a}{2}$$

for **cylindrical** filaments the inner current boundary is roughly elliptical (controversial)





when fully penetrated, the magnetization is

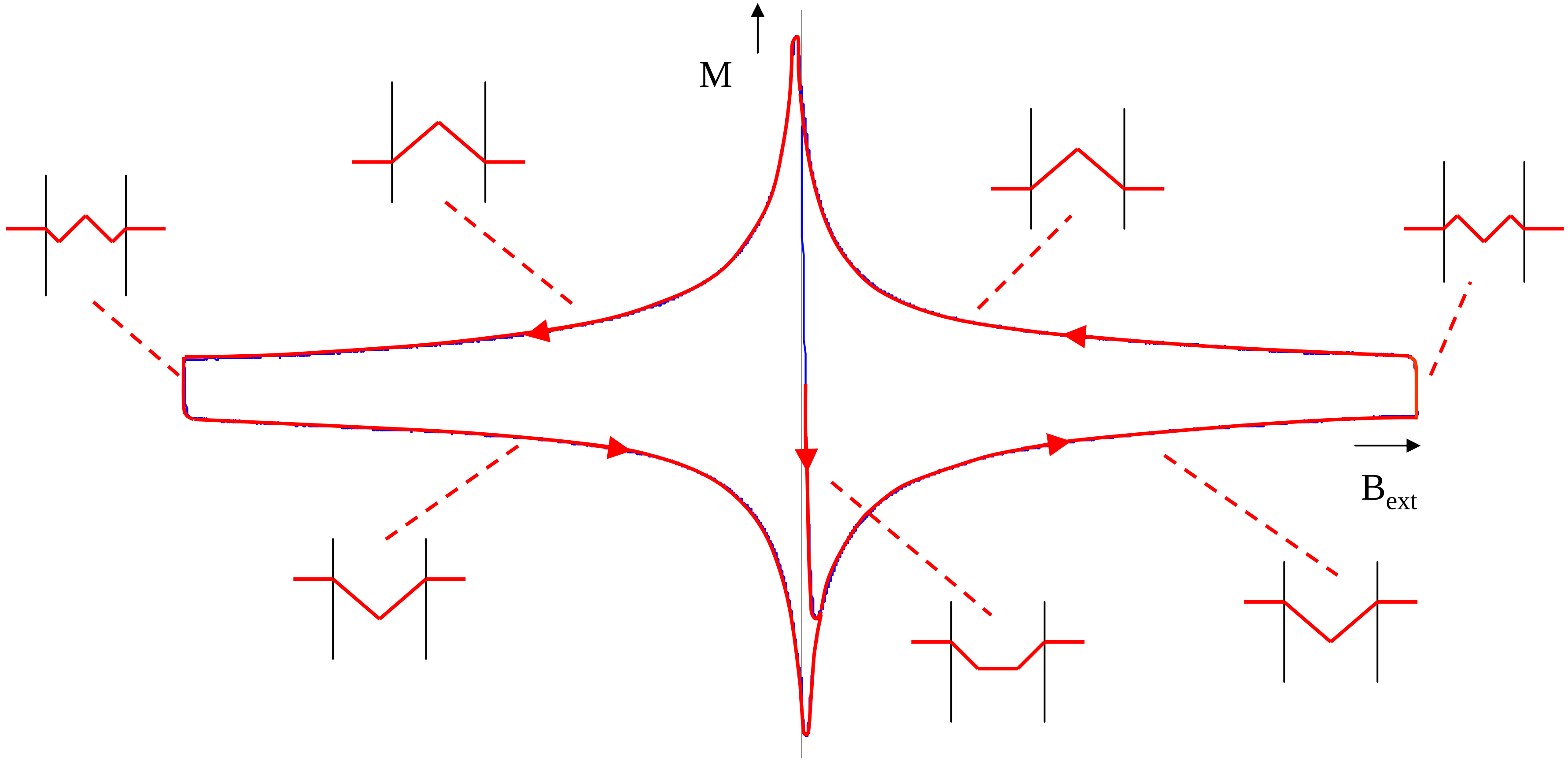
$$M = \frac{4}{3\pi} J_c\, a$$

where a = filament radius

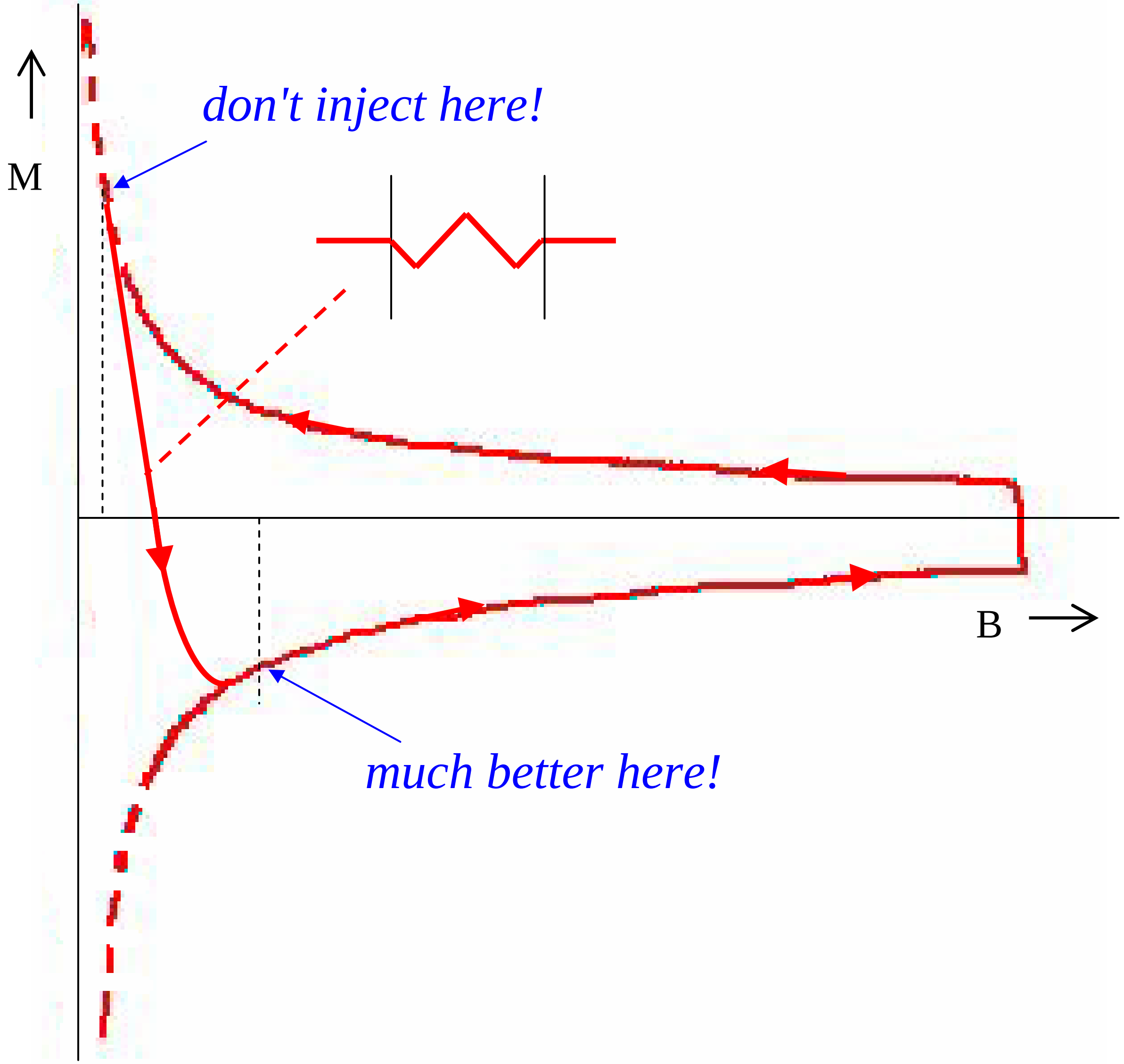
Note: M is here defined per unit volume of NbTi filament

Magnetization of a superconductor

The induced currents produce a magnetic moment and hence a magnetization
= magnetic moment per unit volume



Synchrotron injection



synchrotron injects at low field, ramps to high field and then back down again

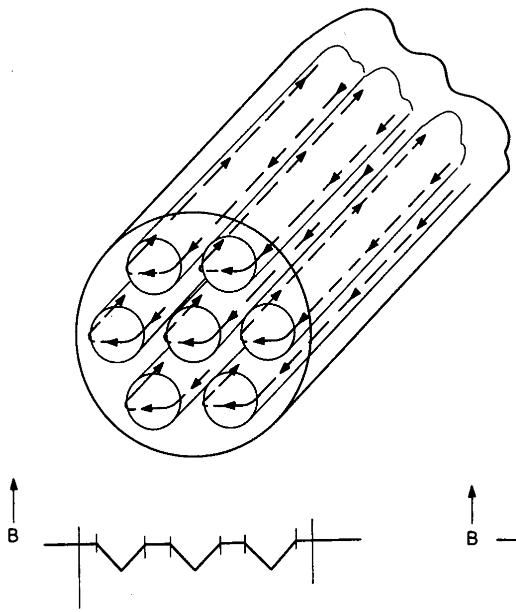
note how quickly the magnetization changes when we start the ramp up

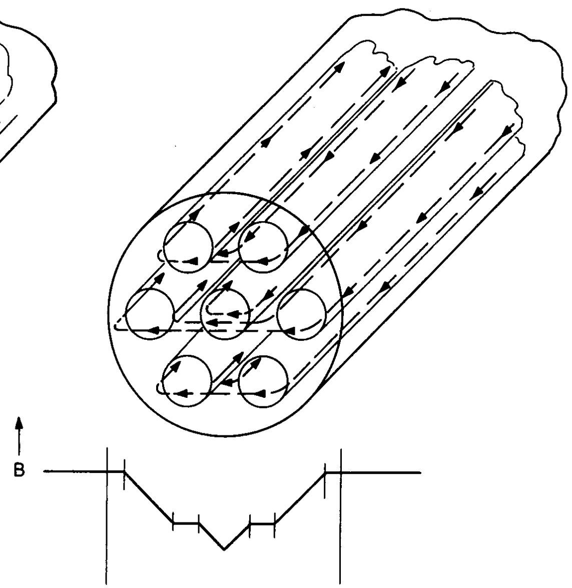
so better to ramp up a little way, then stop to inject

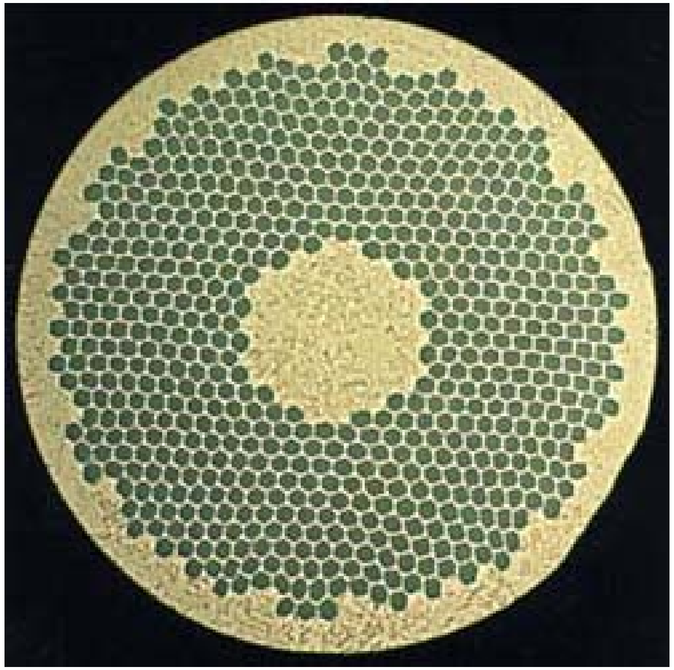
Coupling between filaments

recap $$M = \frac{4}{3\pi} J_c\, a$$

We can reduce M by making the superconductor as fine filaments. For ease of handling, an array of many filaments is embedded in a copper matrix







Unfortunately, in changing fields, the filament are coupled together; screening currents go up the LHS filaments and return down the RHS filaments, crossing the copper at each end.
In time these currents decay, but for wires ~ 100m long, the decay time is years!
So the advantages of subdivision are lost

Twisting

coupling between the filaments may be reduced by twisting the wire

magnetic flux now diffuses along the twist pitch P with a time constant τ

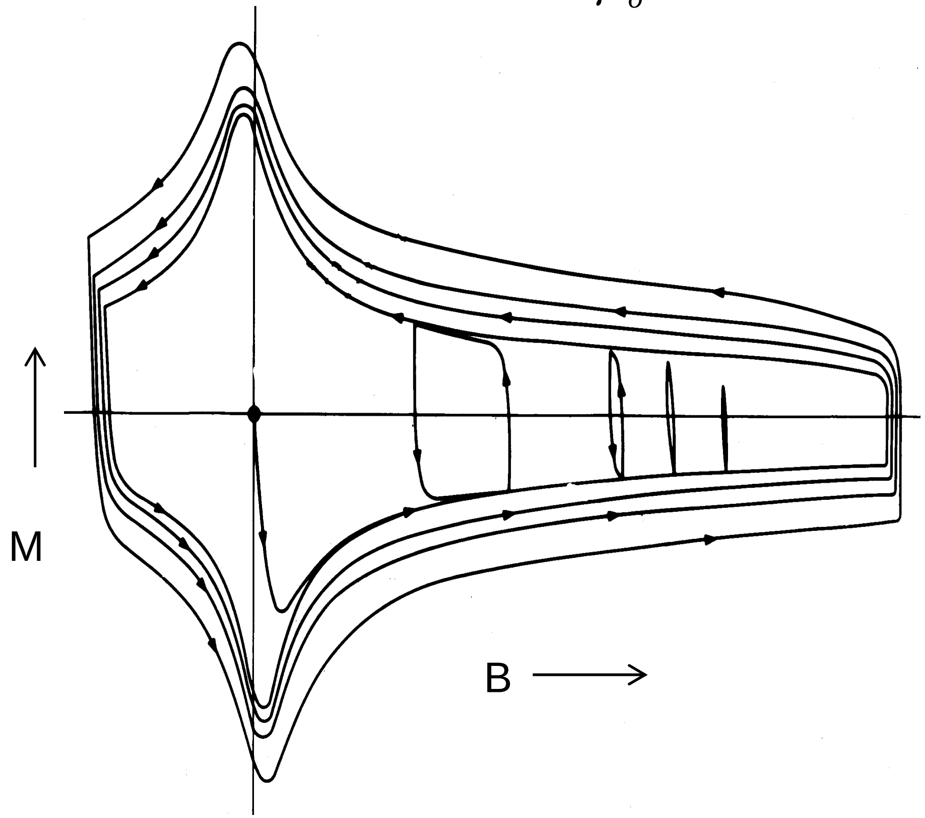
$$\tau = \frac{\mu_0}{2\rho_t}\left[\frac{P_w}{2\pi}\right]^2$$

where ρ_t is the transverse resistivity across the composite wire

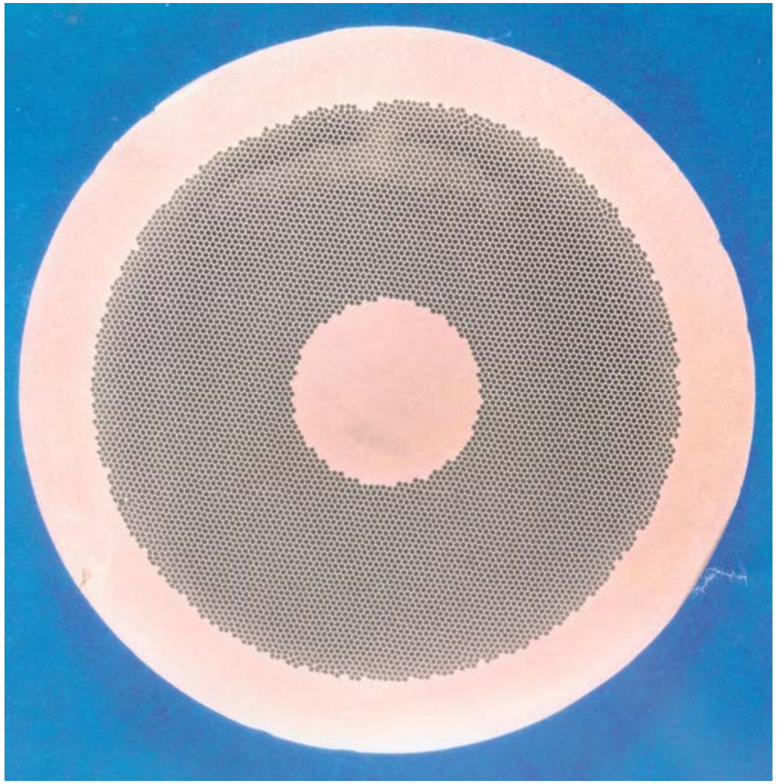
just like eddy currents - but the characteristic dimension is the twist pitch - not the wire diameter

extra magnetization due to coupling

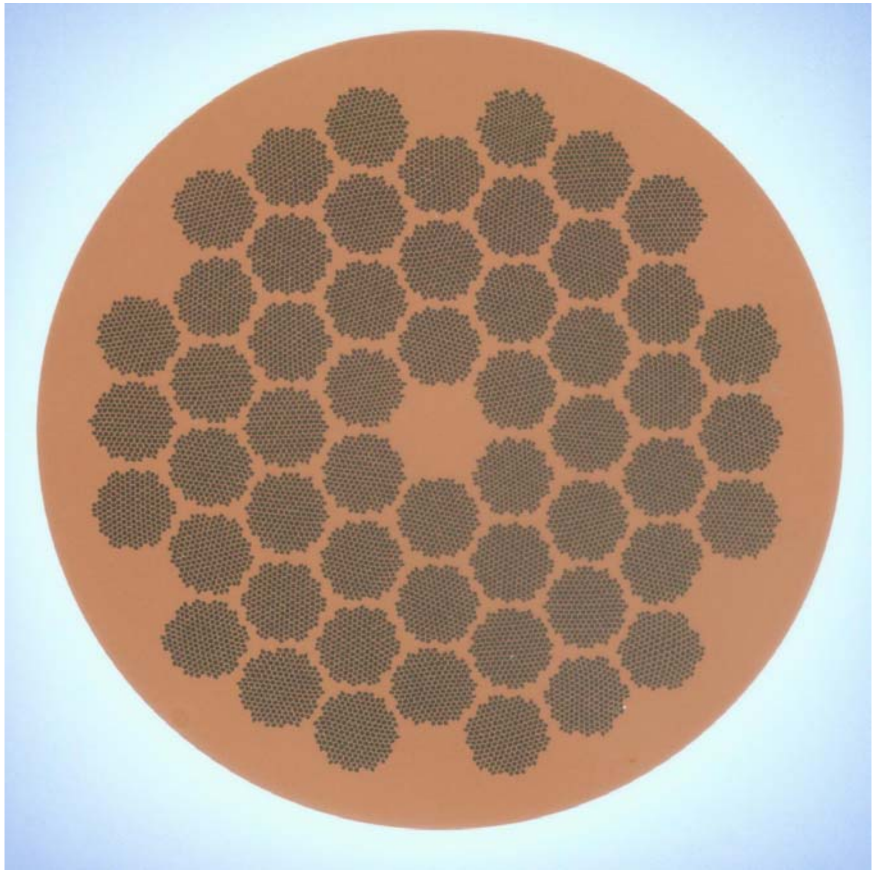
$$M_w = \frac{2}{\mu_o}\frac{dB}{dt}\tau$$



Fine filaments for low magnetization



- the finest filaments are made for accelerator magnets, mainly to keep the field errors at injection down to an acceptable level.



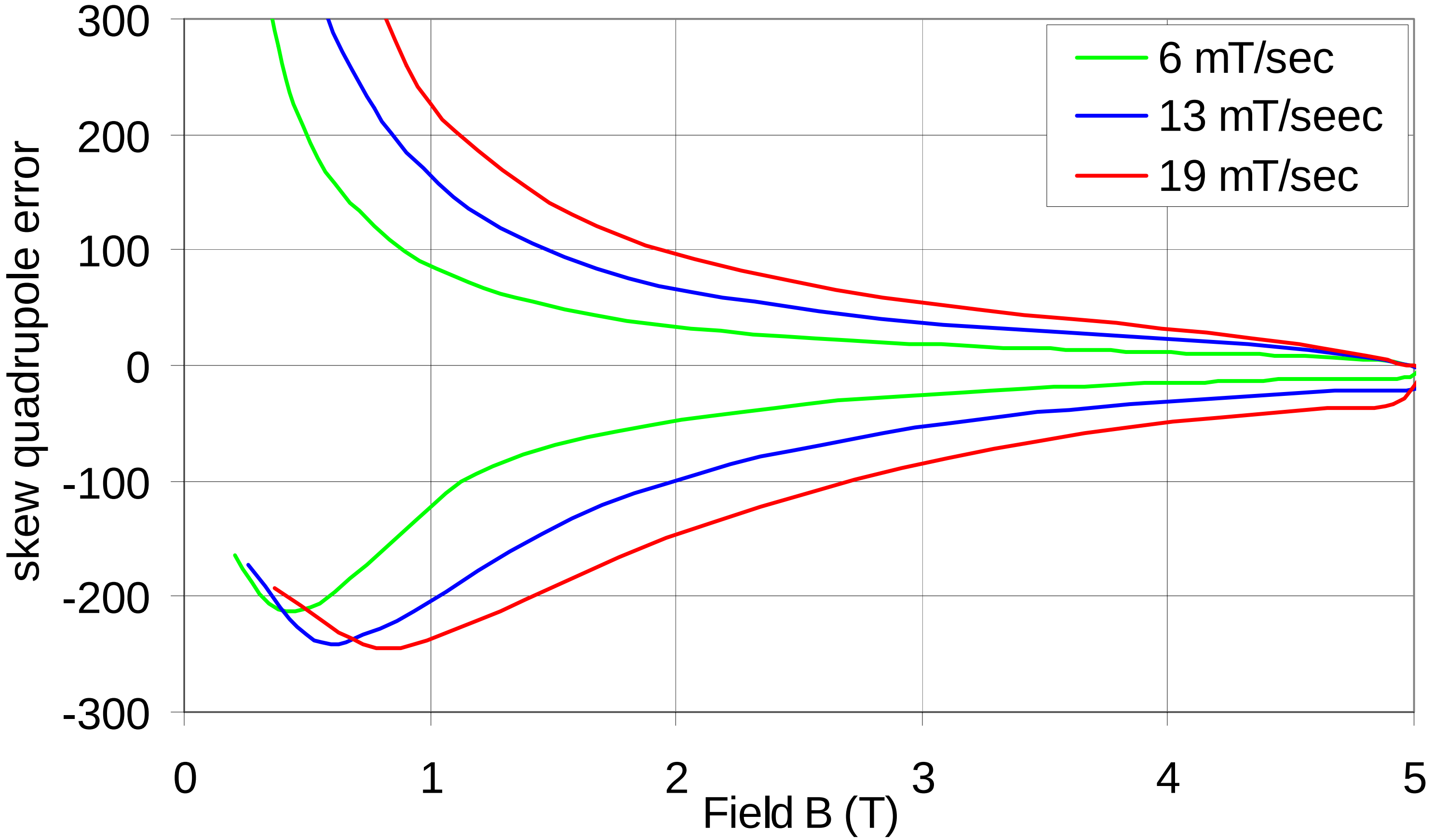
- typical diameters are in the range 5 - 10μm
  - compare with flux jumping < 50μm

- fine filament also give low ac loss
  - important for fast ramping accelerators like FAIR

Magnetization and field errors

Magnetization is important in accelerators because it produces field error. The effect is worst at injection because

- $\Delta B/B$ is greatest
- magnetization, ie ΔB is greatest at low field



skew quadrupole error in Nb_3Sn dipole which has exceptionally large coupling magnetization (University of Twente)

Why cables?

- for good tracking we connect synchrotron magnets in series
- if the stored energy is *E*, rise time *t* and operating current *I* , the charging voltage is

$$E = \frac{1}{2} L I^2 \qquad\qquad V = \frac{L\,I}{t} = \frac{2\,E}{I\,t}$$

RHIC E = 40kJ/m, t = 75s, 30 strand cable

cable I = 5kA, charge voltage per km = 213V

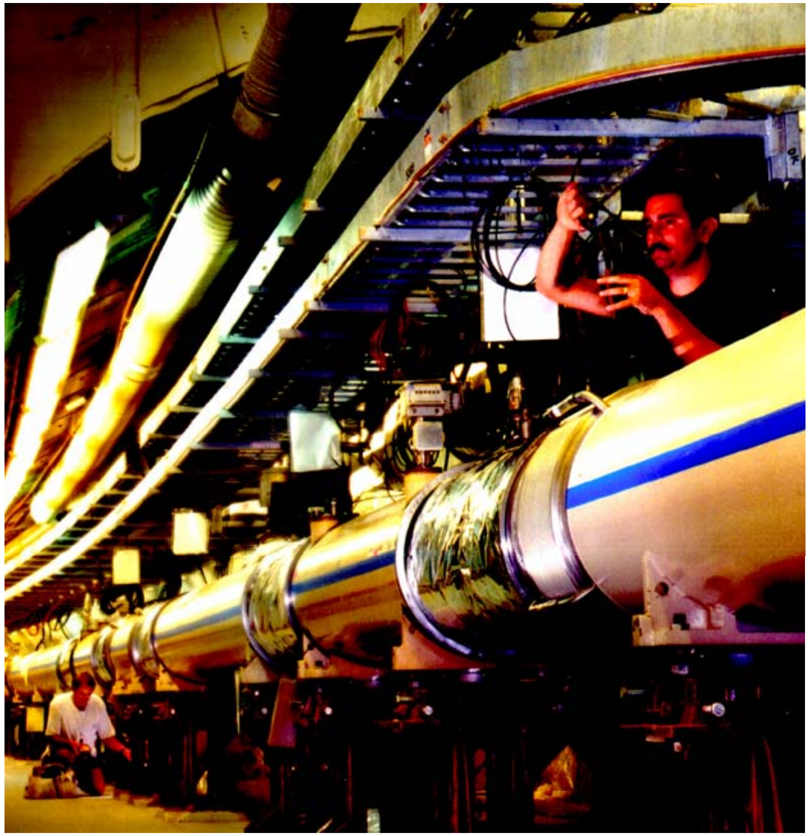
wire I = 167A, charge voltage per km = 6400V

FAIR at GSI E = 40kJ/m, t = 4s, 30 strand cable

cable I = 5kA, charge voltage per km = 4kV

wire I = 167A, charge voltage per km = 120kV

- so we need high currents!

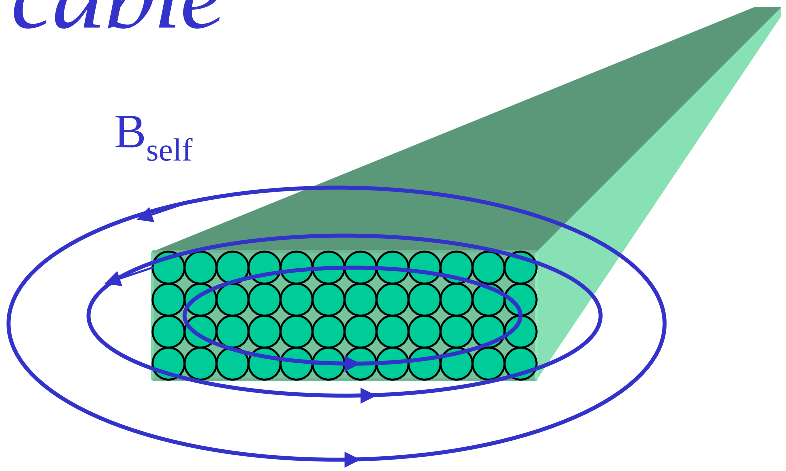


the RHIC tunnel

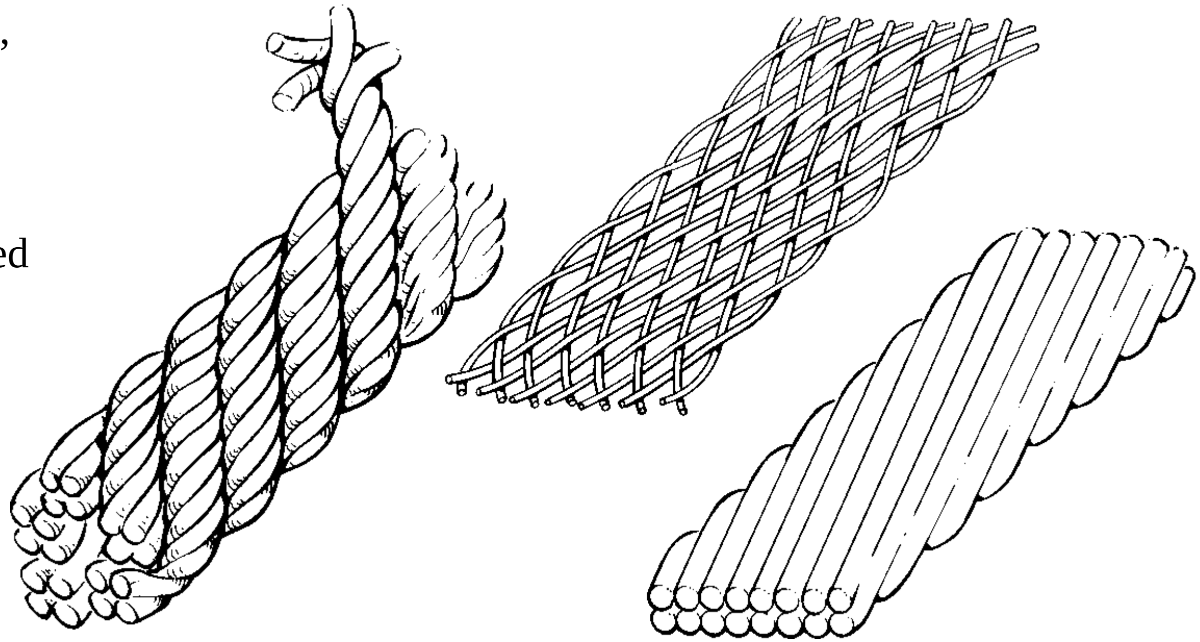
- a single 5μm filament of NbTi in 6T carries 50mA
- a composite wire of fine filaments typically has 5,000 to 10,000 filaments, so it carries 250A to 500A
- for 5 to 10kA, we need 20 to 40 wires in parallel - a cable

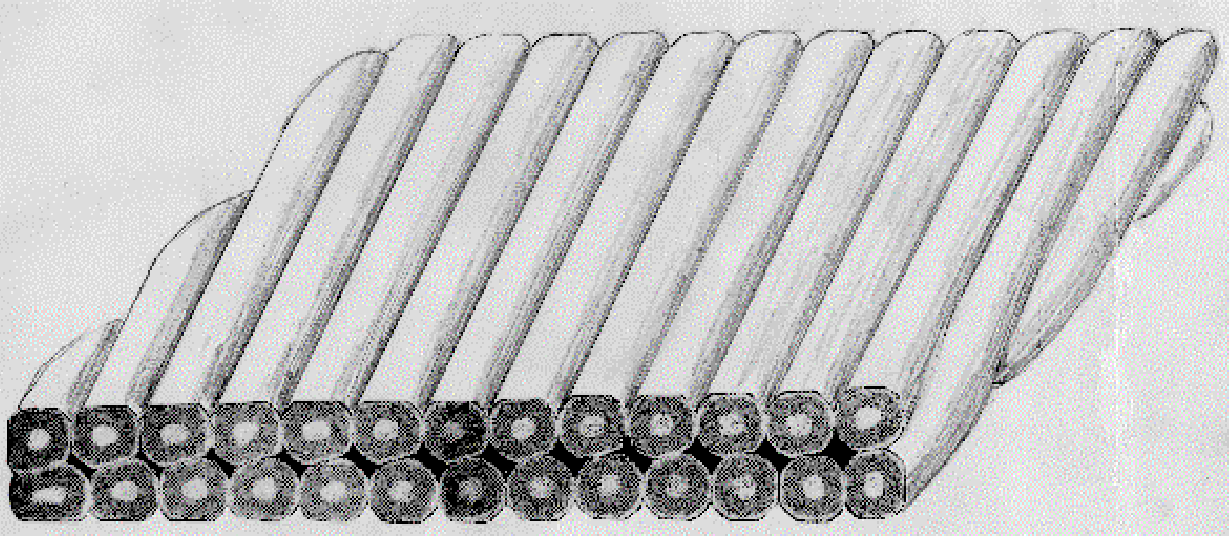
Types of cable

- like the filaments in composite wires, cables must be twisted to reduce coupling
- because cables are so large, they generate a significant **self field** and it is necessary to 'twist' against this self field,
- note how in this cable there are flux linkages between the inner and outer wires ⇒



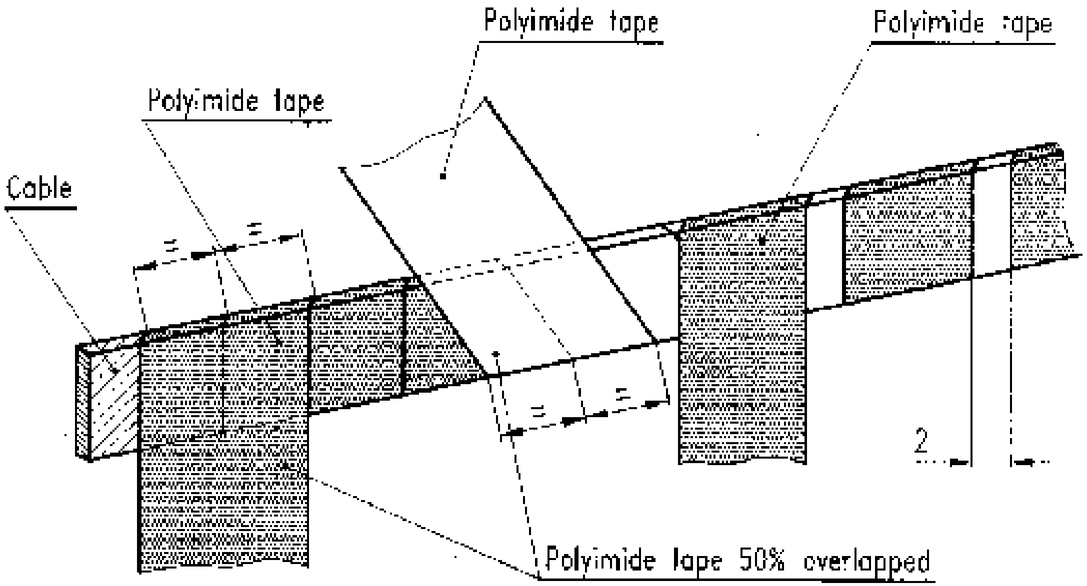
- thus it is necessary for the wires to be fully **transposed**, ie every wire must change places with every other wire along the length of the cable
- three types of fully transposed cable have been tried in accelerators
  - rope
  - braid
  - Rutherford



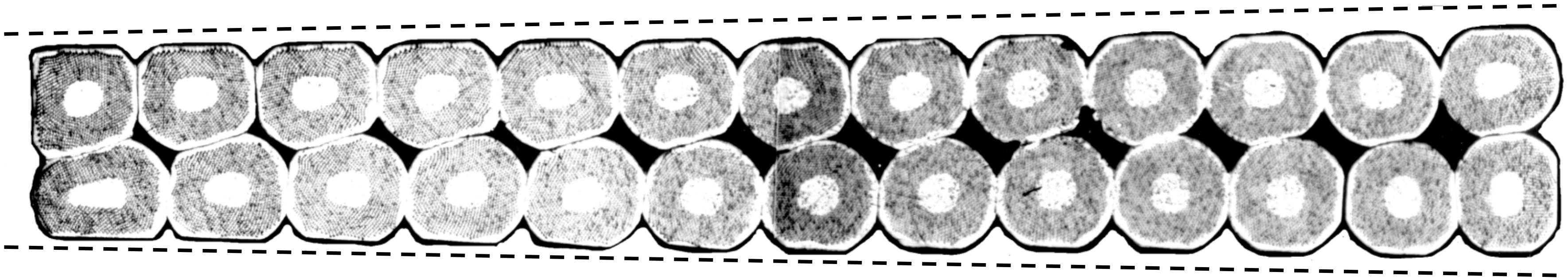


Rutherford cable

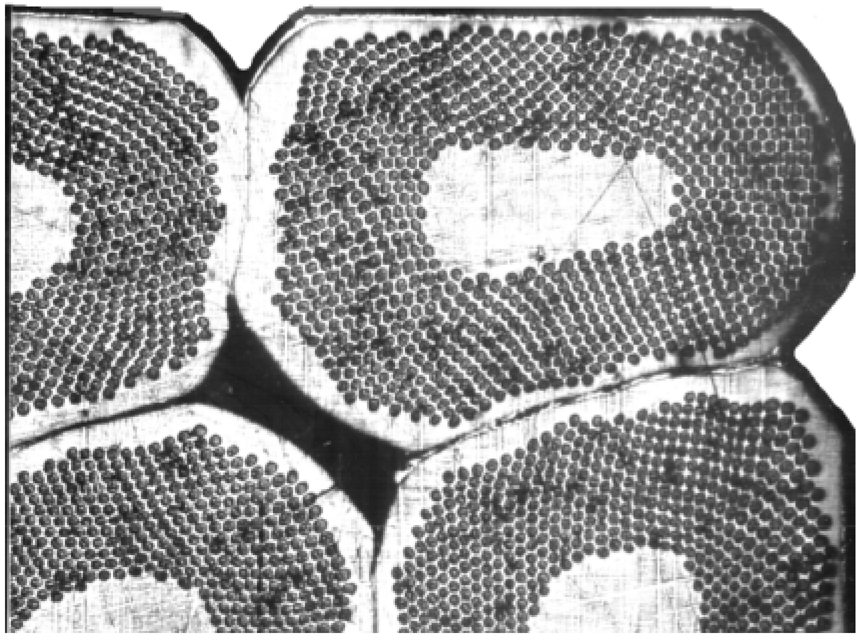
- the cable is insulated by wrapping 2 or 3 layers of Kapton. The outer layer is treated with an adhesive layer for bonding to adjacent turns.
- Note the adhesive faces outwards, do no bond to the cable (avoid energy release by bond failure, which could quench the magnet)



Rutherford cable



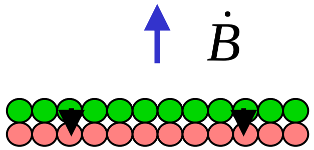
- The main reason why Rutherford cable succeeded where others failed was that it could be compacted to a high density (88 - 94%) without damaging the wires. Furthermore it can be rolled to a good dimensional accuracy (~ 10mm).
- Note the 'keystone angle', which enables the cables to be stacked closely round a circular aperture



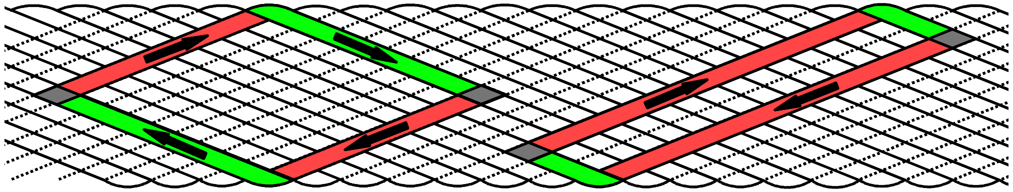
Coupling in Rutherford cables

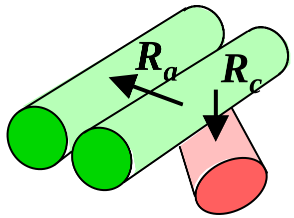
Changing fields induce coupling currents between the wires in a cable
- just like coupling between filaments in a wire, but the geometry is different

- Field transverse
  coupling via crossover resistance R_c

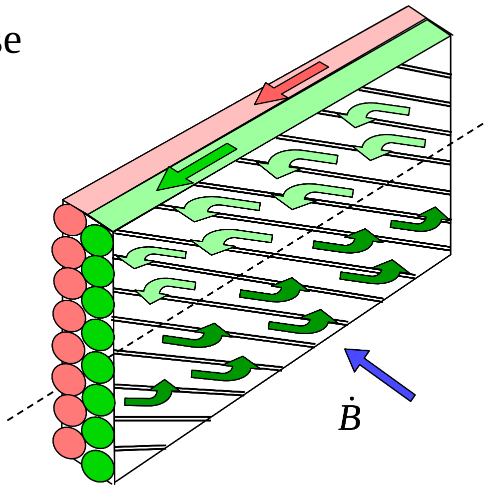


crossover resistance *Rc*
adjacent resistance *Ra*

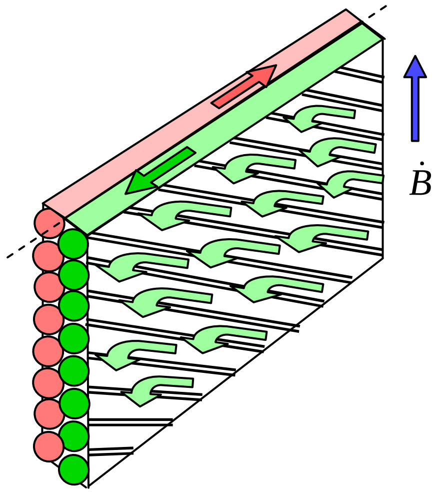




- Field transverse
  coupling via adjacent resistance R_a

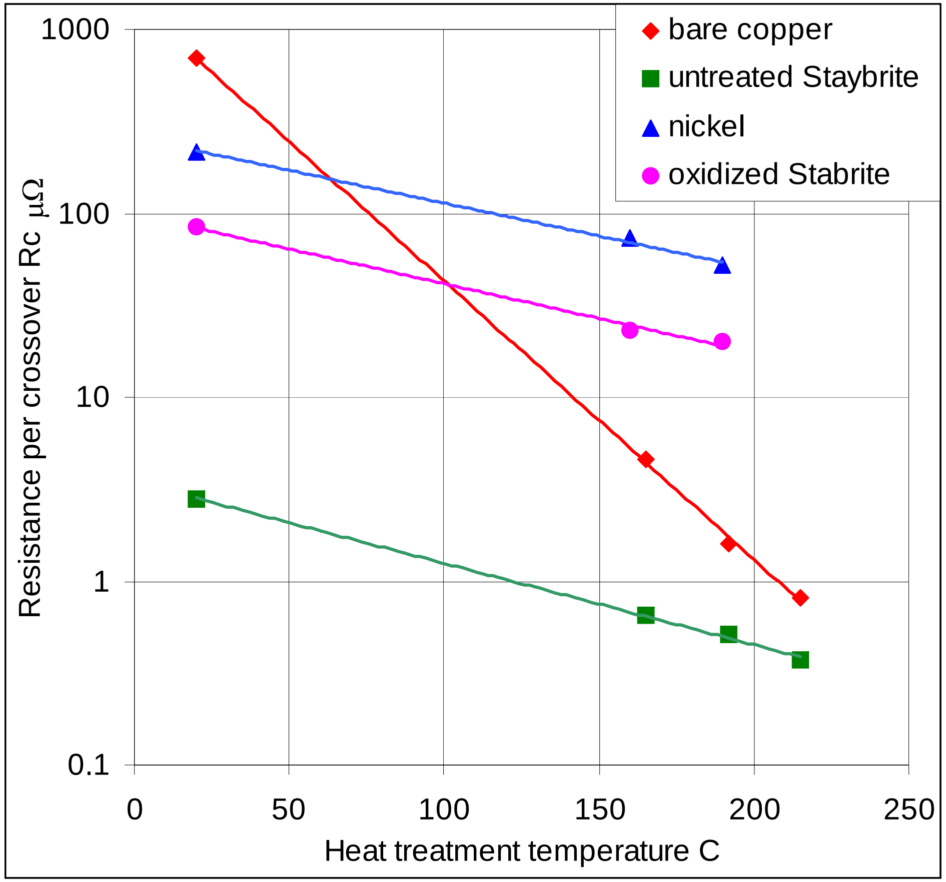


- Field parallel
  coupling via adjacent resistance R_a



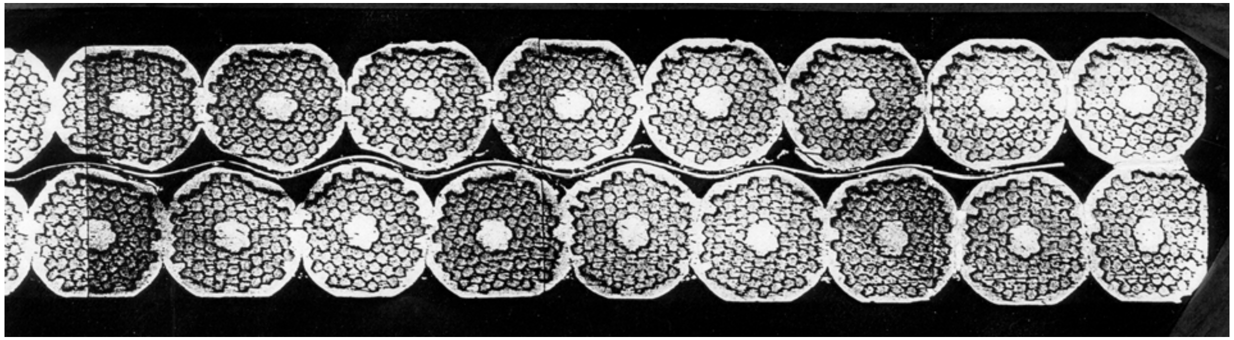
Controlling Ra and Rc

- coupling currents in cables depend on the inter-strand contact resistances R_c and R_a
- surface coatings on the wires are used to adjust R_c and R_a
- the values obtained are very sensitive to pressure and heat treatments used in coil manufacture (to cure the adhesive between turns)
- *data from David Richter CERN*



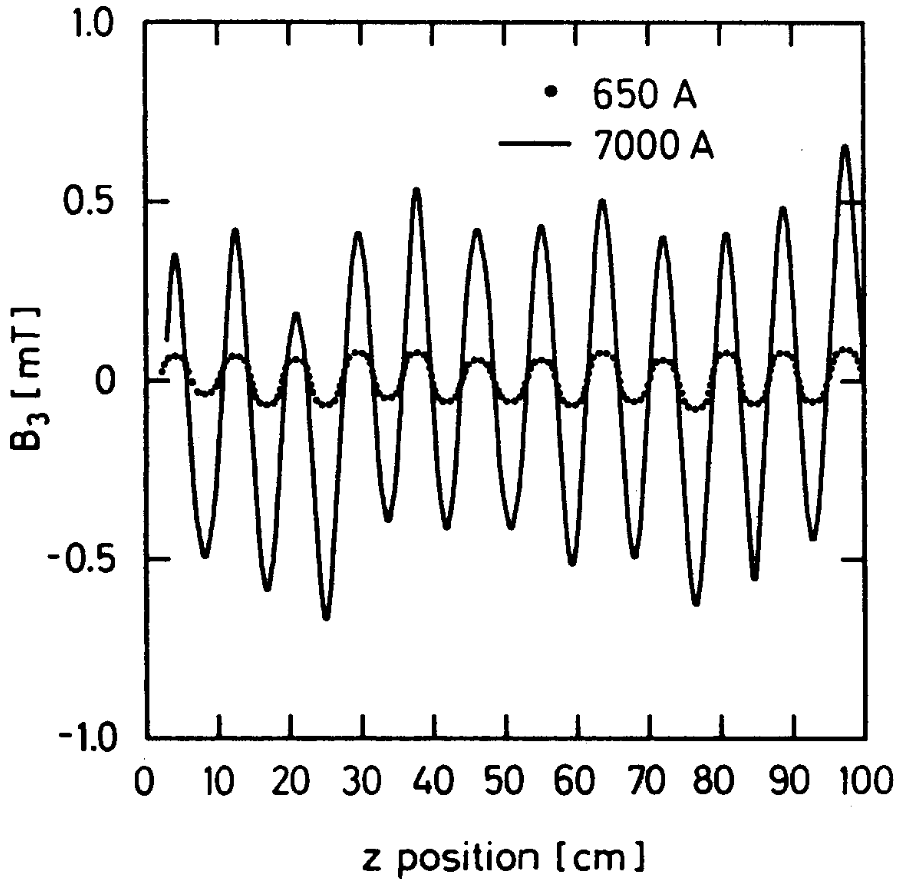
Cored Cables

- using a resistive core allows us to increase Rc preferentially
- not affected by heat treatment



Long range coupling: BICCs

- measuring the field of an accelerator magnet along the beam direction, we find a ripple
- wavelength of this ripple exactly matches the twist pitch of the cable
- thought to be caused by non uniform current sharing in the cable
- Verweij has called them 'boundary induced coupling currents' **BICCs**
- they are caused by non uniform flux linkages or resistances in the cable, eg at joints, coil ends, manufacturing errors etc.
- wavelength is << betatron wavelength so no direct problem, but interesting secondary effects such as **'snap back'.**



sextupole measured in SSC dipole at injection and full field

Concluding remarks: Superconducting wires & cables

- all superconducting accelerators to date still use **NbTi** (45 years after its discovery)
- performance of superconductors is described by the critical surface in $\boldsymbol{B\ J\ \theta}$ space,
- magnet performance is often degraded and shows ‘training’
- minimum quench energy MQE is the energy needed to create a minimum propagating zone MPZ
  - large MPZ $\Rightarrow$ large MQE $\Rightarrow$ harder to quench the conductor
- make large MQE by making superconductor as fine filaments embedded in a matrix of copper
- magnetic fields induce persistent screening currents in superconductor
- flux jumping occurs when screening currents go unstable $\Rightarrow$ quenches magnet
  - avoid by fine filaments - solved problem
- screening currents produce magnetization $\Rightarrow$ field errors
  - reduce by fine filaments
- in changing fields, filaments become coupled $\Rightarrow$ increased magnetization
  - reduce by twisting
- accelerator magnets need high currents $\Rightarrow$ cables
  - cables must be fully transposed
  - Rutherford cable used in all accelerators to date
- can get coupling between strands in cables
  - causes additional magnetization $\Rightarrow$ field error
  - control coupling by oxide layers on wires or resistive core foils