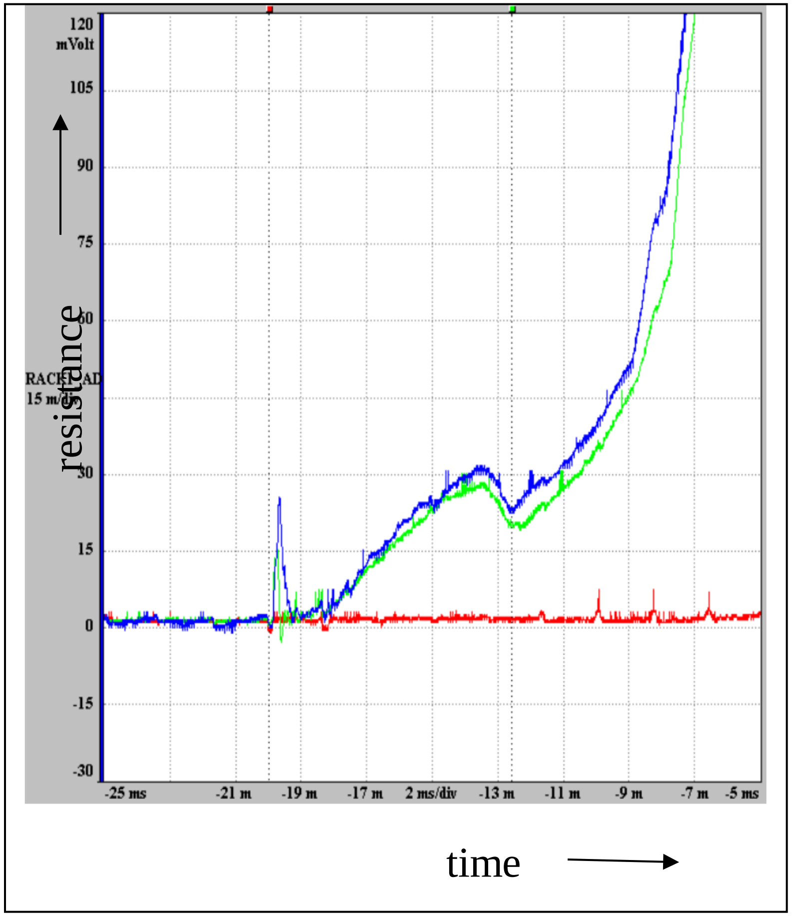
Lecture 2: Training and fine filaments

Degraded performance & Training

- load lines and expected quench current of a magnet
- causes of training - release of energy within the magnet
- minimum propagating zones MPZ and minimum quench energy MQE

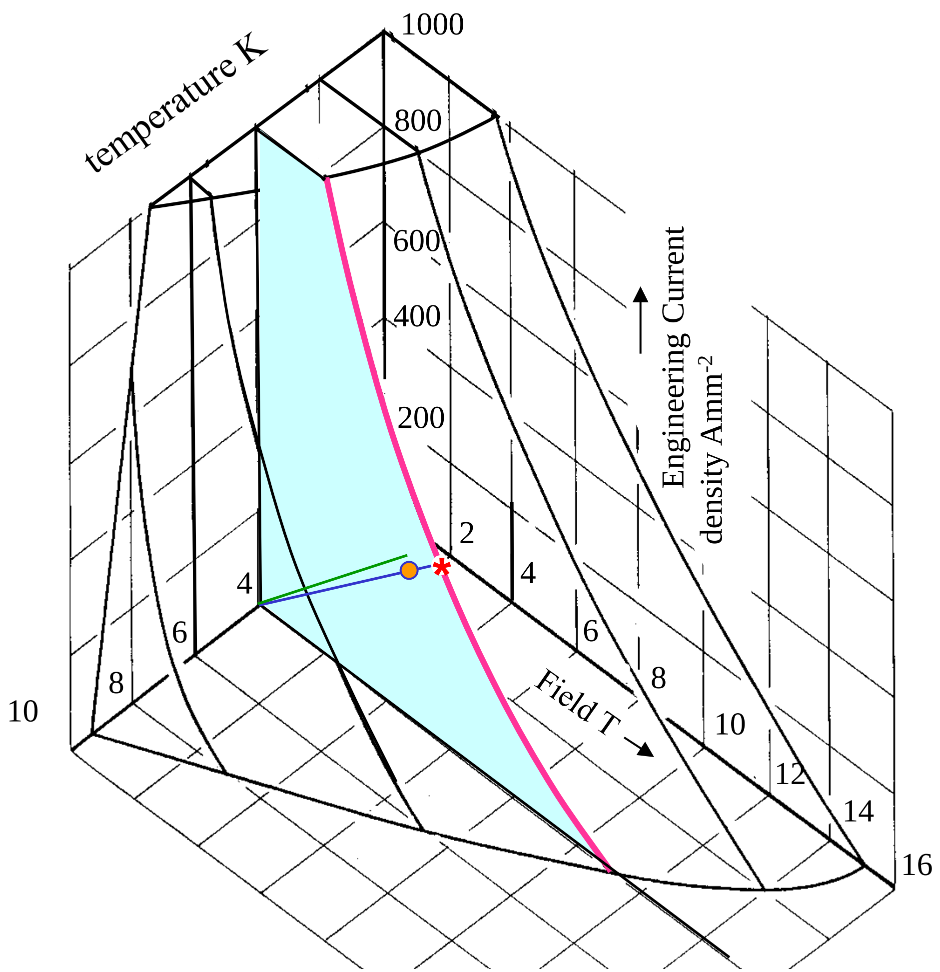
Fine filaments

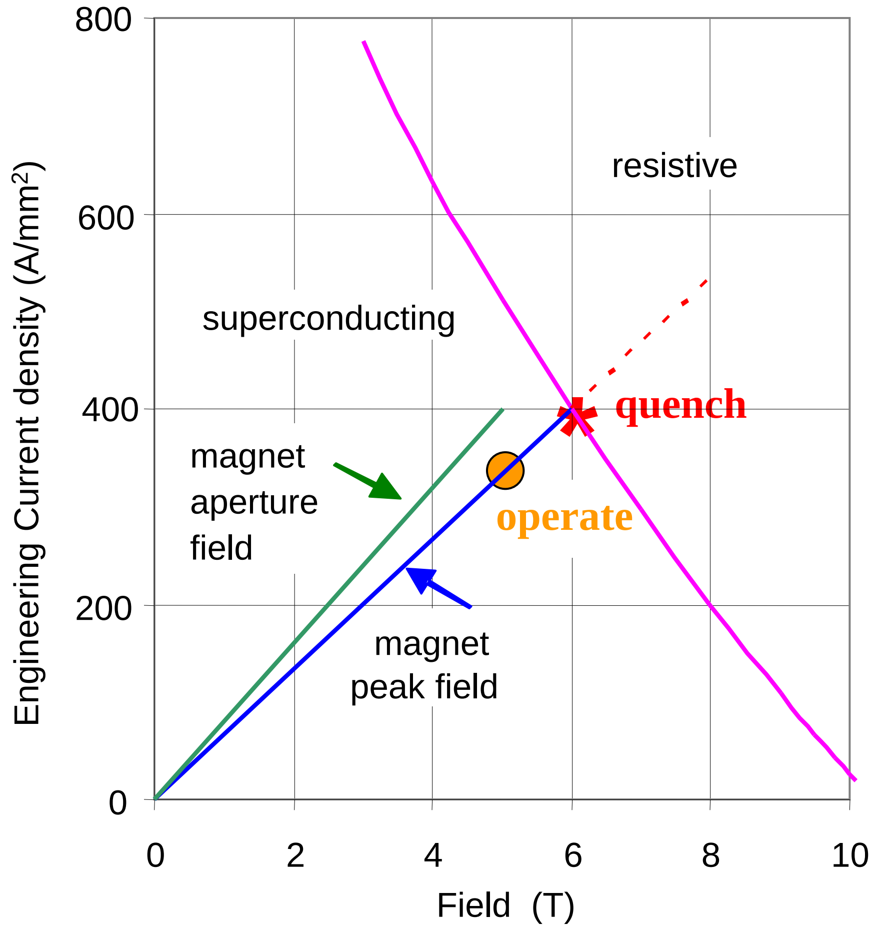
- screening currents and the critical state model
- flux jumping
- magnetization and field errors
- magnetization and ac loss



quench initiation in LHC dipole

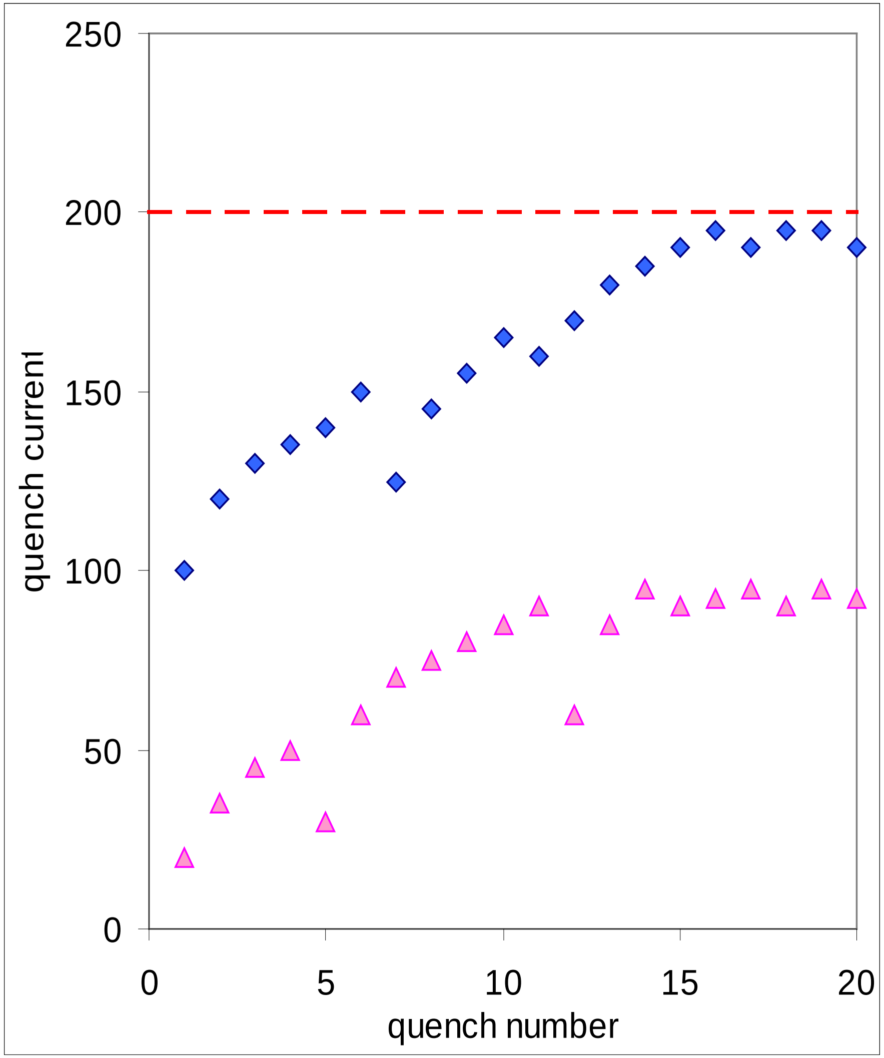
Critical line and magnet load lines





we expect the magnet to go resistive ***'quench'*** where the peak field load line crosses the critical current line *
usually back off from this extreme point and operate at

Degraded performance and 'training'

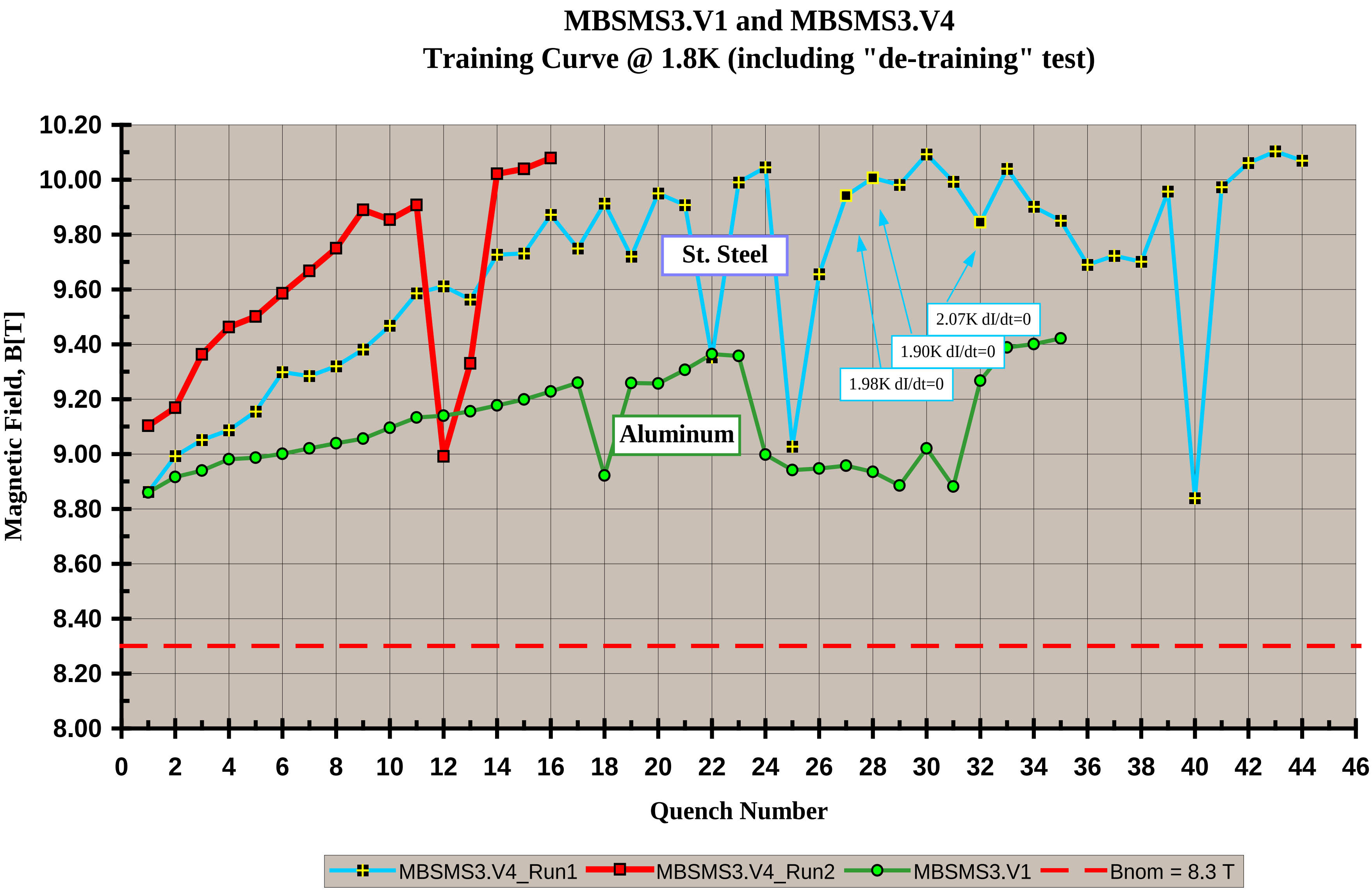


- an early disappointment for magnet makers was the fact that magnets did not go straight to the expected quench point, as given by the intersection of the load line with the critical current line
- instead the magnets went resistive - ***quenched*** - at much lower currents
- after a ***quench***, the stored energy of the magnet is dissipated in the magnet, raising its temperature way above critical

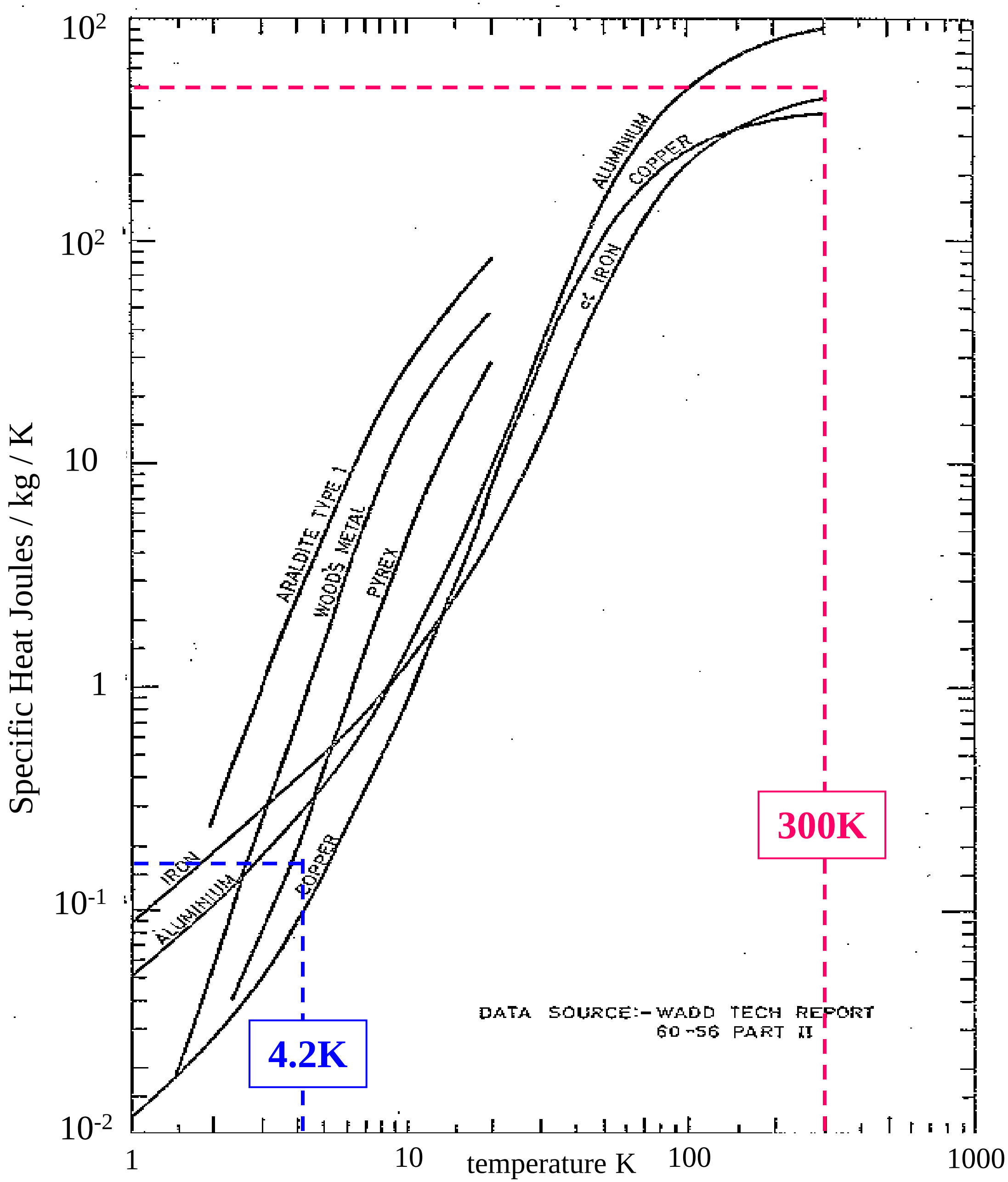
  - you must wait for it to cool down and then try again
- the second try usually quenches at higher current and so on with the third

  - known as ***training***
- after many training quenches a stable well constructed magnet (blue points) gets close to it's expected critical current, but a poorly constructed magnet (pink points) never gets there

Training of an early LHC dipole magnet



Causes of training: (1) low specific heat

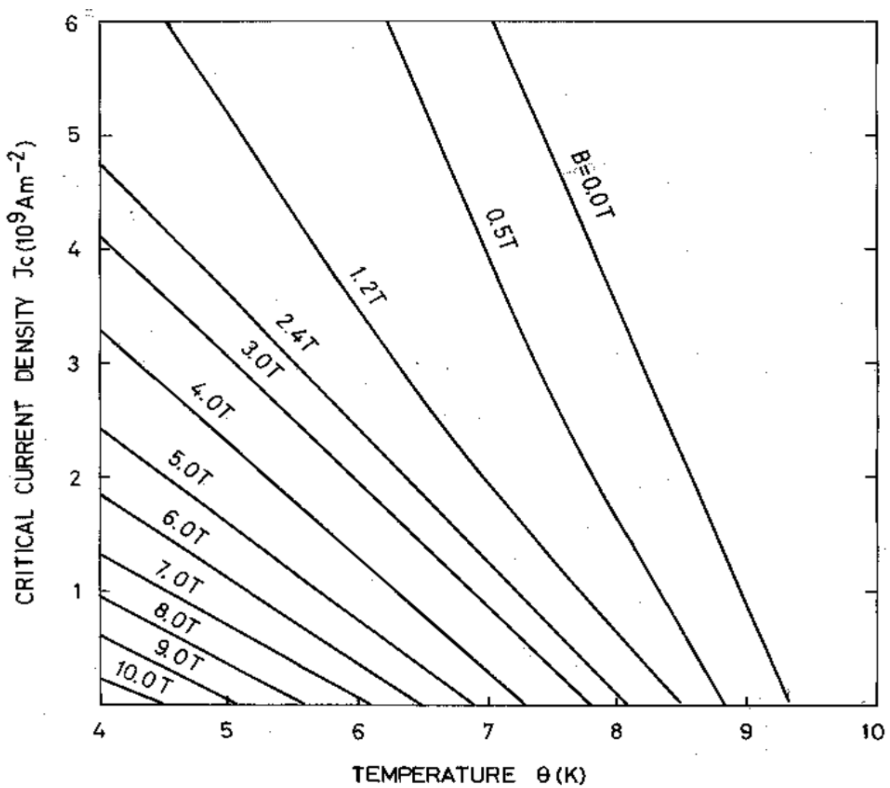


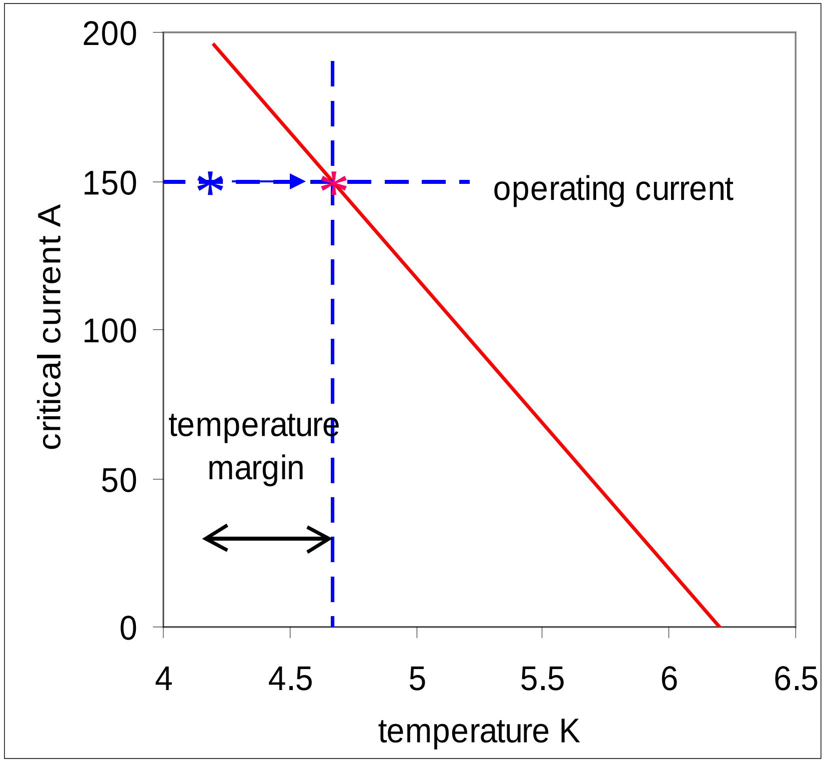
- the specific heat of all substances falls with temperature
- at 4.2K, it is ~2,000 times less than at room temperature
- a given release of energy within the winding thus produce a temperature rise 2,000 times greater than at room temperature
- the smallest energy release can therefore produce catastrophic effects

Causes of training: (2) J_c decreases with temperature

at any given field, the critical current of NbTi falls almost linearly with temperature

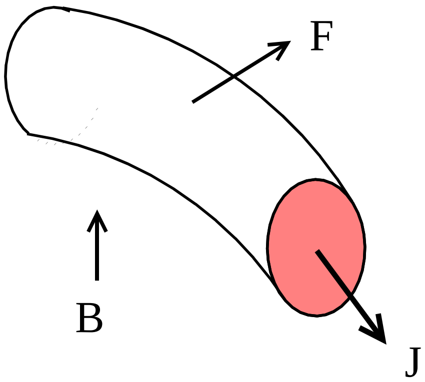
- so any temperature rise drives the conductor into the resistive state





but, by choosing to operate the magnet at * a current less than critical, we can allow a *temperature margin*

Causes of training: (3) conductor motion



Conductors in a magnet are pushed by the electromagnetic forces. Sometimes they move suddenly under this force - the magnet 'creaks' as the stress comes on. A large fraction of the work done by the magnetic field in pushing the conductor is released as frictional heating

work done per unit length of conductor if it is pushed a distance δz

$$W = F.\delta z = B.I.\delta z$$

frictional heating per unit volume

$$Q = B.J.\delta z$$

typical numbers for NbTi:

$B = 5T \quad J_{eng} = 5 \times 10^8 \, A.m^{-2}$

so if $\delta = 10 \, \mu m$

then $Q = 2.5 \times 10^4 \, J.m^{-3}$

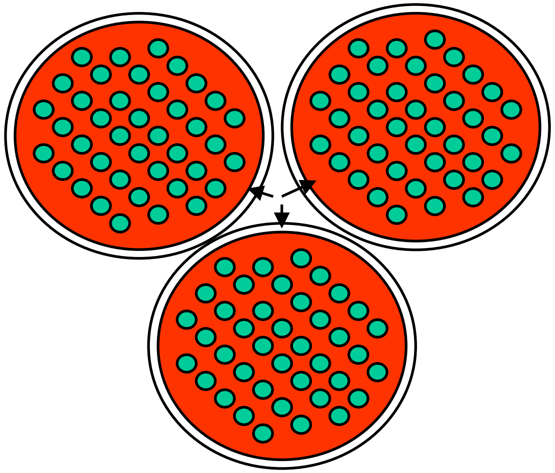
Starting from 4.2K $\theta_{final} = 7.5K$

can **<u>you</u>** engineer a winding to better than **10 μm?**

Causes of training: (4) resin cracking

We try to stop wire movement by impregnating the winding with epoxy resin. Unfortunately the resin contracts much more than the metal, so it goes into tension. Furthermore, almost all organic materials become brittle at low temperature. *brittleness + tension ⇒ cracking ⇒ energy release*

Calculate the stain energy induced in resin by differential thermal contraction



let: σ = tensile stress Y = Young's modulus
ε = differential strain ν = Poisson's ratio

typically: $\varepsilon = (11.5 - 3) \times 10^{-3}$ $Y = 7 \times 10^{9}$ Pa $\nu = {}^{1}/_{3}$

uniaxial strain $$Q_1 = \frac{\sigma^2}{2Y} = \frac{Y\varepsilon^2}{2}$$ $Q_1 = 2.5 \times 10^{5}$ J.m^{-3} $\theta_{final} = 16$K

triaxial strain $$Q_3 = \frac{3\sigma^2(1-2\nu)}{2Y} = \frac{3Y\varepsilon^2}{2(1-2\nu)}$$ $Q_3 = 2.3 \times 10^{6}$ J.m^{-3} $\theta_{final} = 28$K

an unknown, but large, fraction of this stored energy will be released as heat during a crack

Interesting fact: magnets impregnated with paraffin wax show almost no training although the wax is full of cracks after cooldown.
Presumably the wax breaks at low σ before it has had chance to store up any strain energy

How to reduce training?

1) Reduce the disturbances occurring in the magnet winding

- make the winding fit together exactly to reduce movement of conductors under field forces
- pre-compress the winding to reduce movement under field forces
- if using resin, minimize the volume and choose a crack resistant type
- match thermal contractions, eg fill epoxy with mineral or glass fibre
- impregnate with wax - but poor mechanical properties
- most accelerator magnets are insulated using a Kapton film with a very thin adhesive coating

2) Make the conductor able to withstand disturbances without quenching

- increase the temperature margin
  - operate at lower current
  - higher critical temperature - HTS?
- increase the cooling
- increase the specific heat

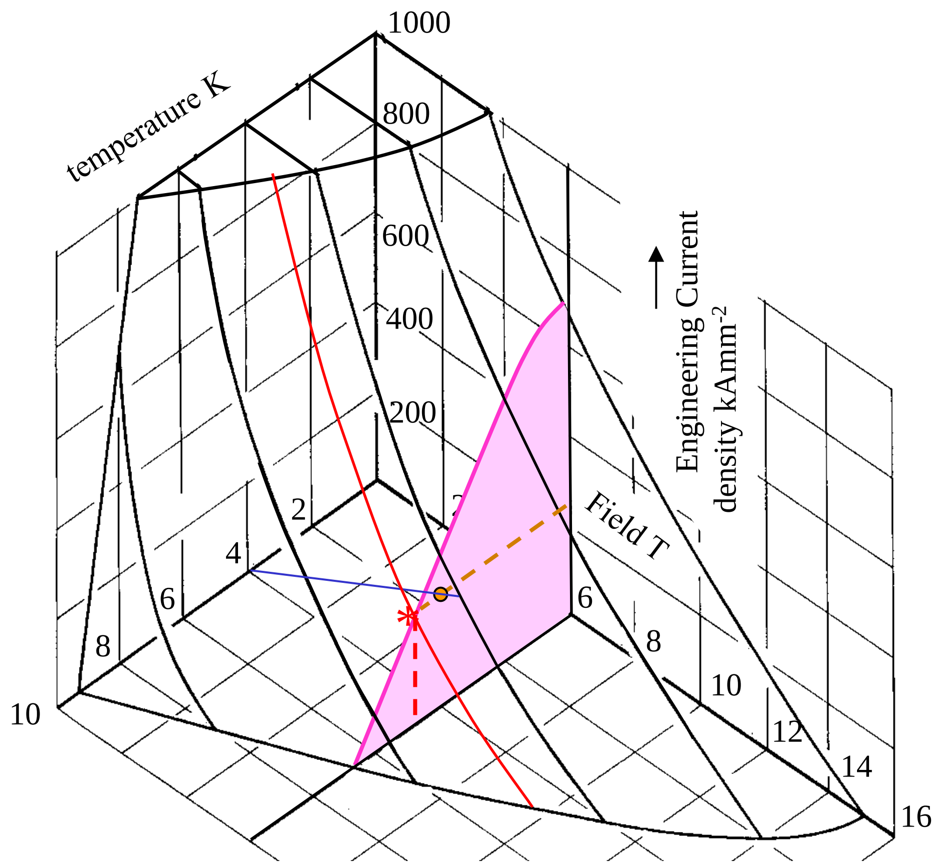
*most of **2)** may be characterized by a single number*

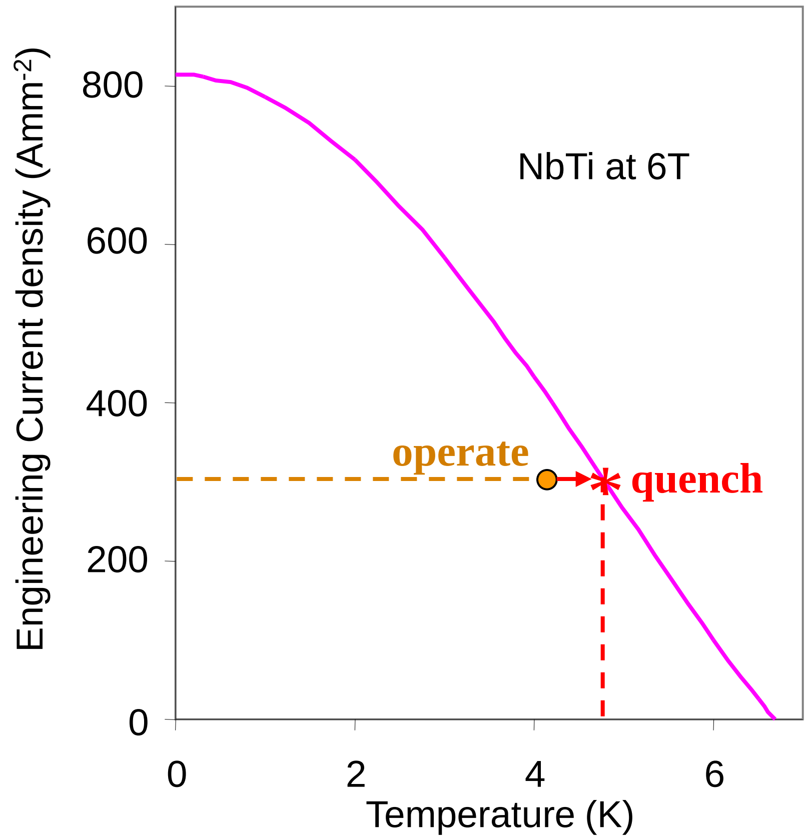
Minimum Quench Energy MQE

= energy input at a point which is just enough to trigger a quench

Temperature margin

- backing off the operating current can also be viewed in terms of temperature
  - for safe operation we open up a temperature margin

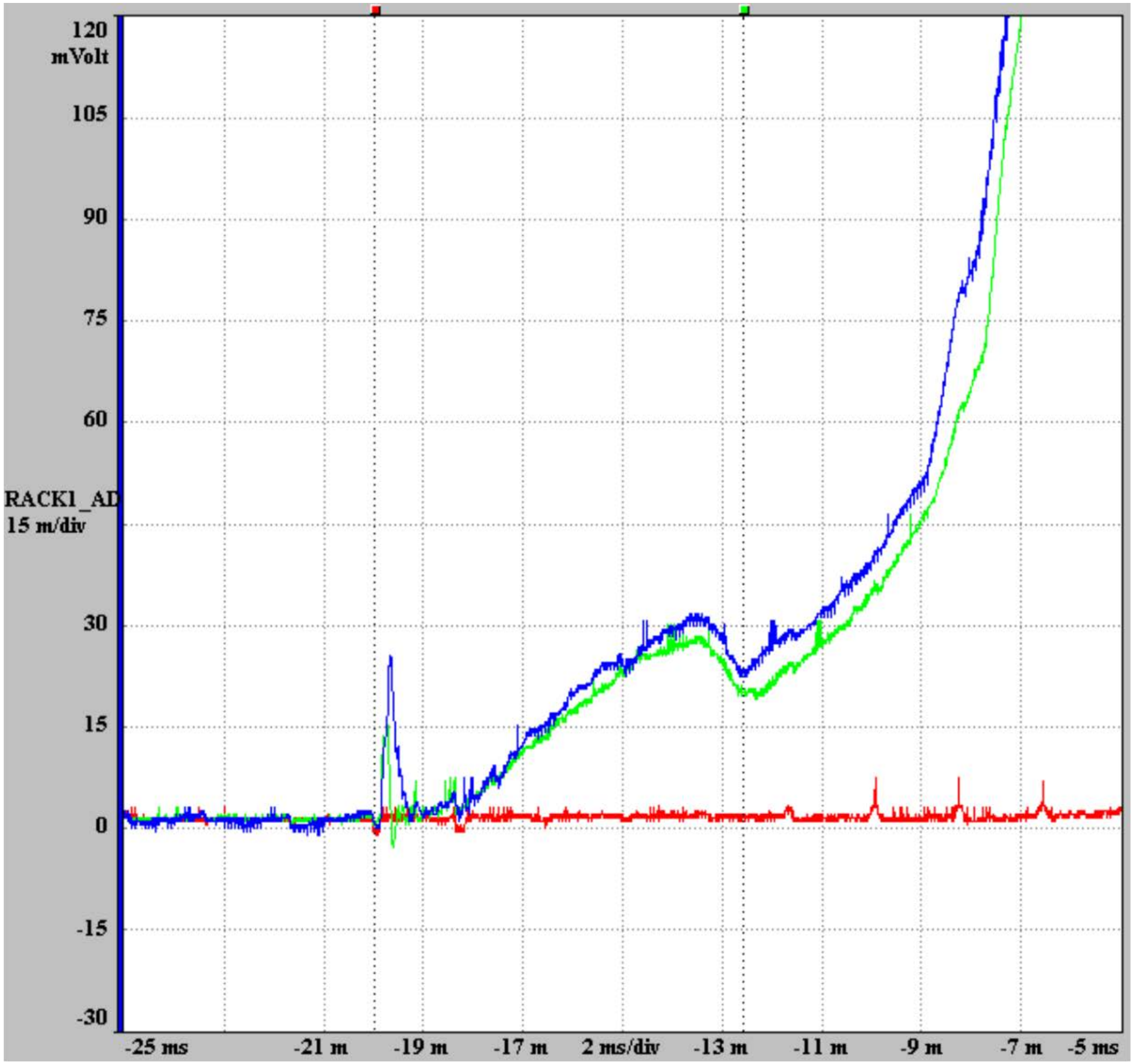




in superconducting magnets temperature rise may be caused by

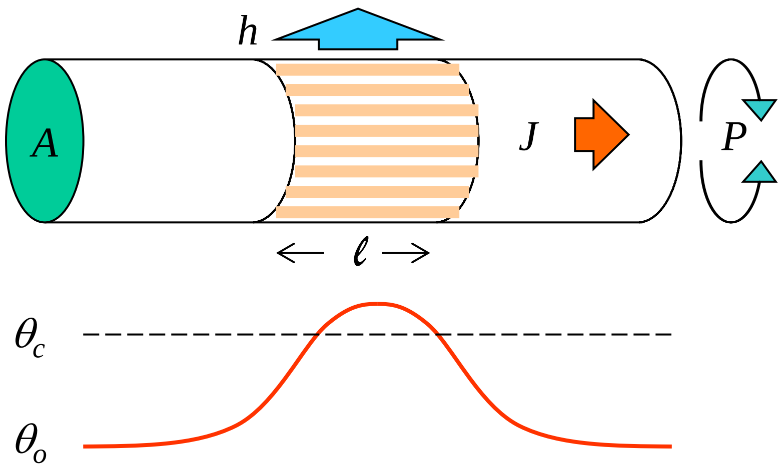
- sudden internal energy release
- ac losses
- poor joints
- etc, etc (lectures 2 and 3)

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.
<u>*Very*</u> 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

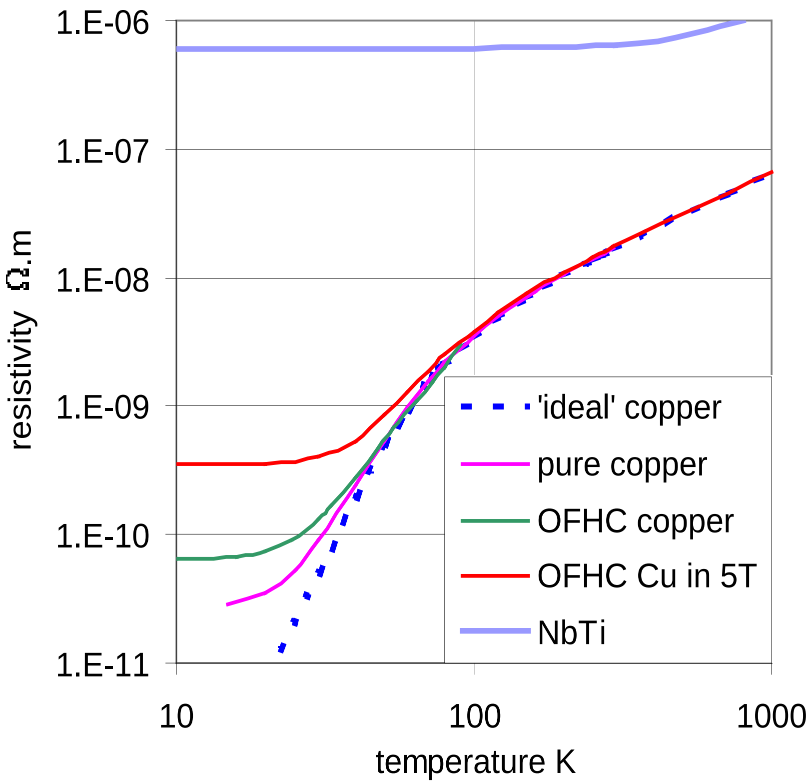
P = cooled perimeter of conductor

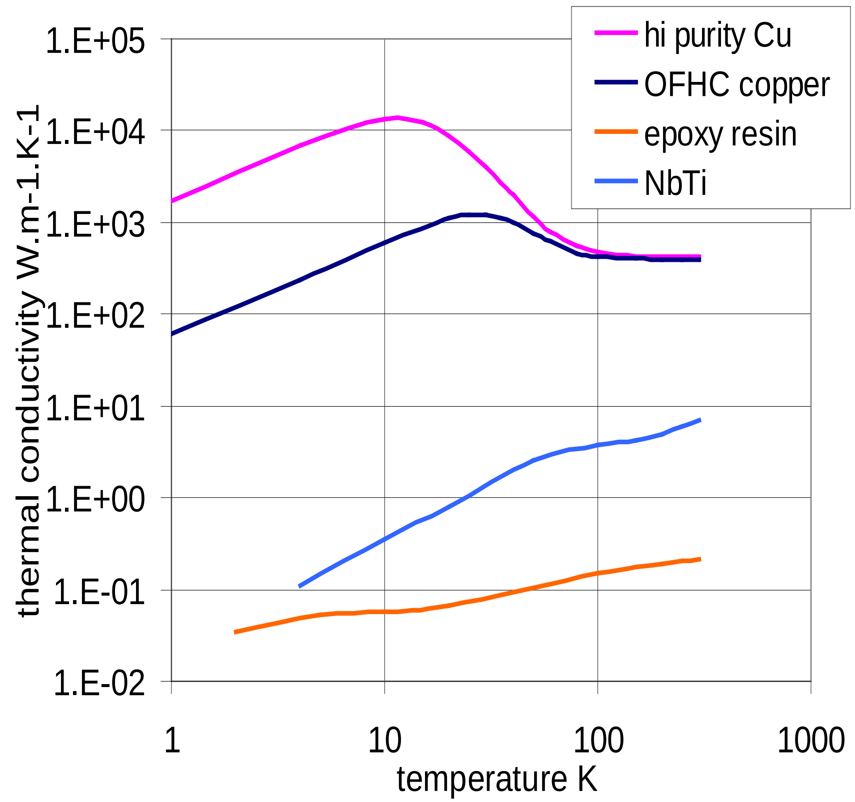
Energy to set up MPZ is called the Minimum Quench Energy *MQE*

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})



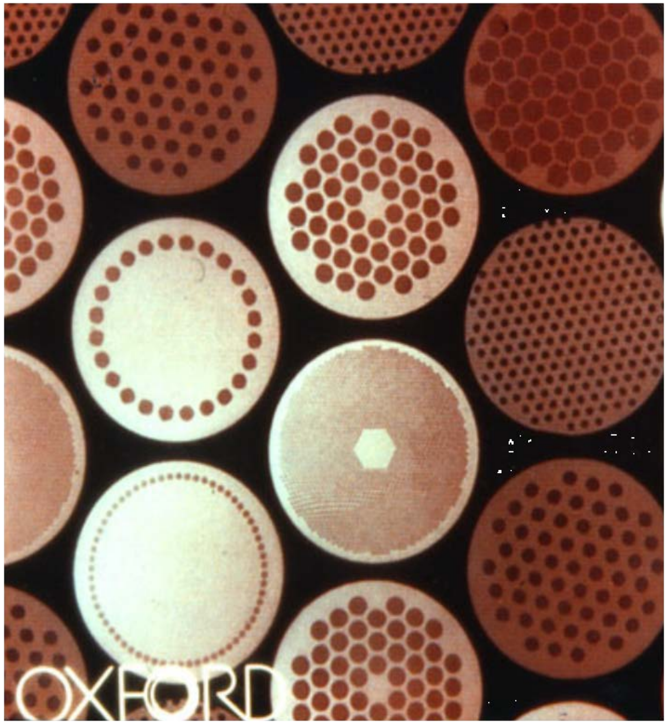


Large MPZ ⇒ large MQE ⇒ less training

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

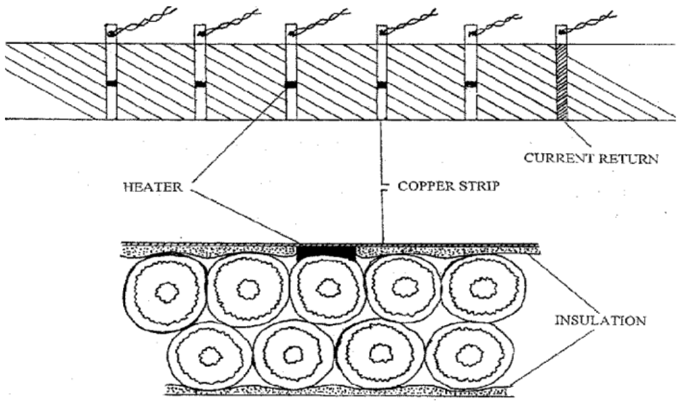
- make thermal conductivity k large
- make resistivity ρ small
- make heat transfer term *hP/A* large

- NbTi has high ρ and low k
- copper has low ρ and high k
- mix copper and NbTi in a filamentary composite wire
- make 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)

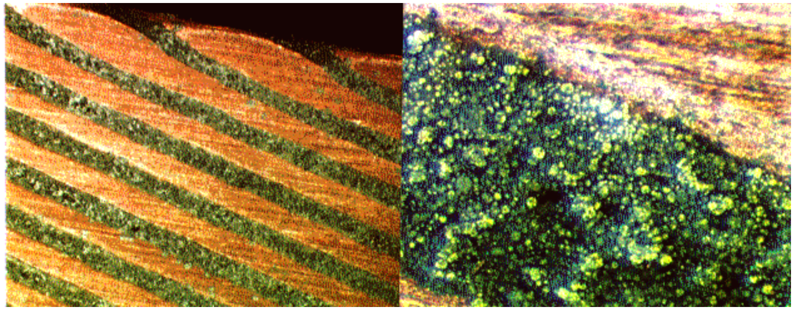


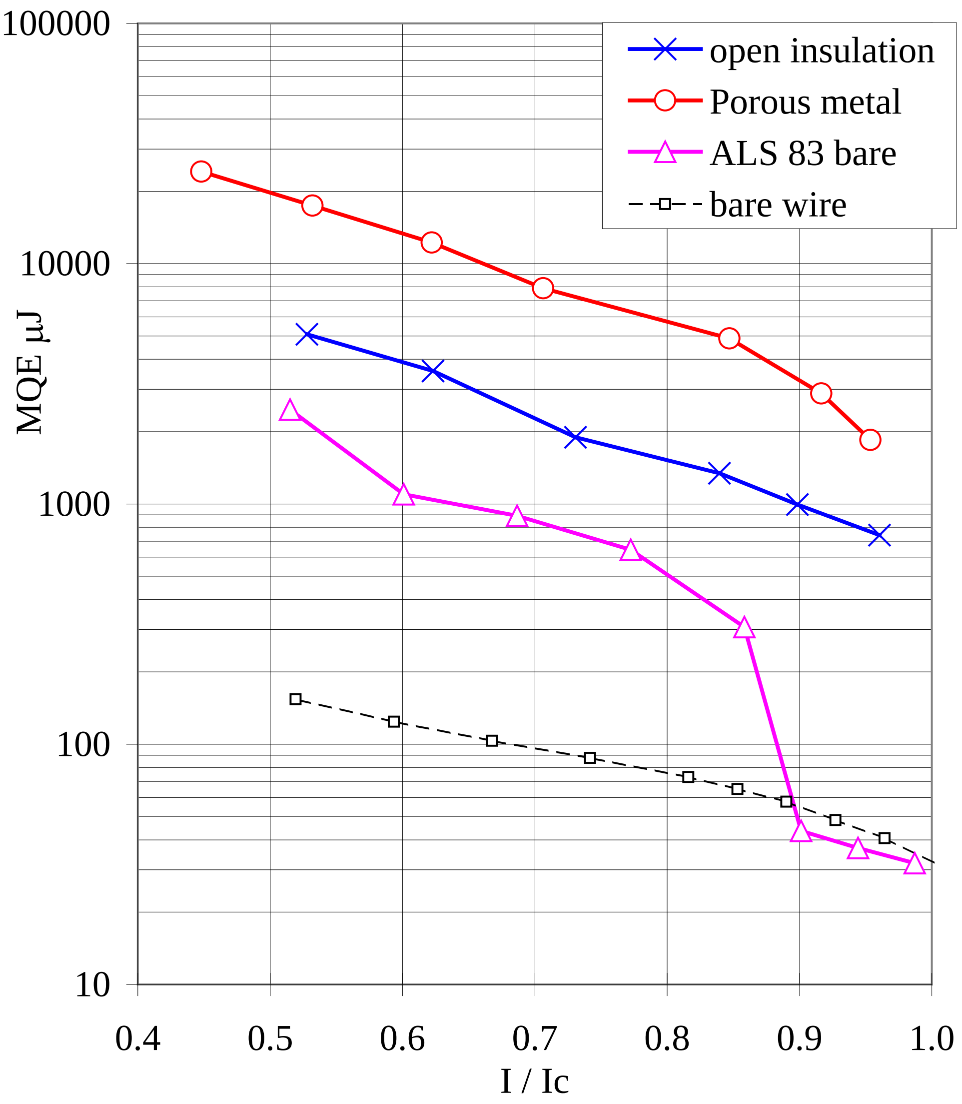
Measurement of MQE

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



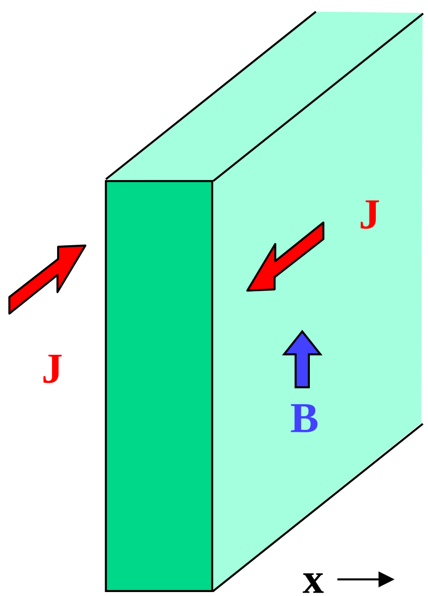
good results when spaces in cable are filled with porous metal
- excellent heat transfer to the helium





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



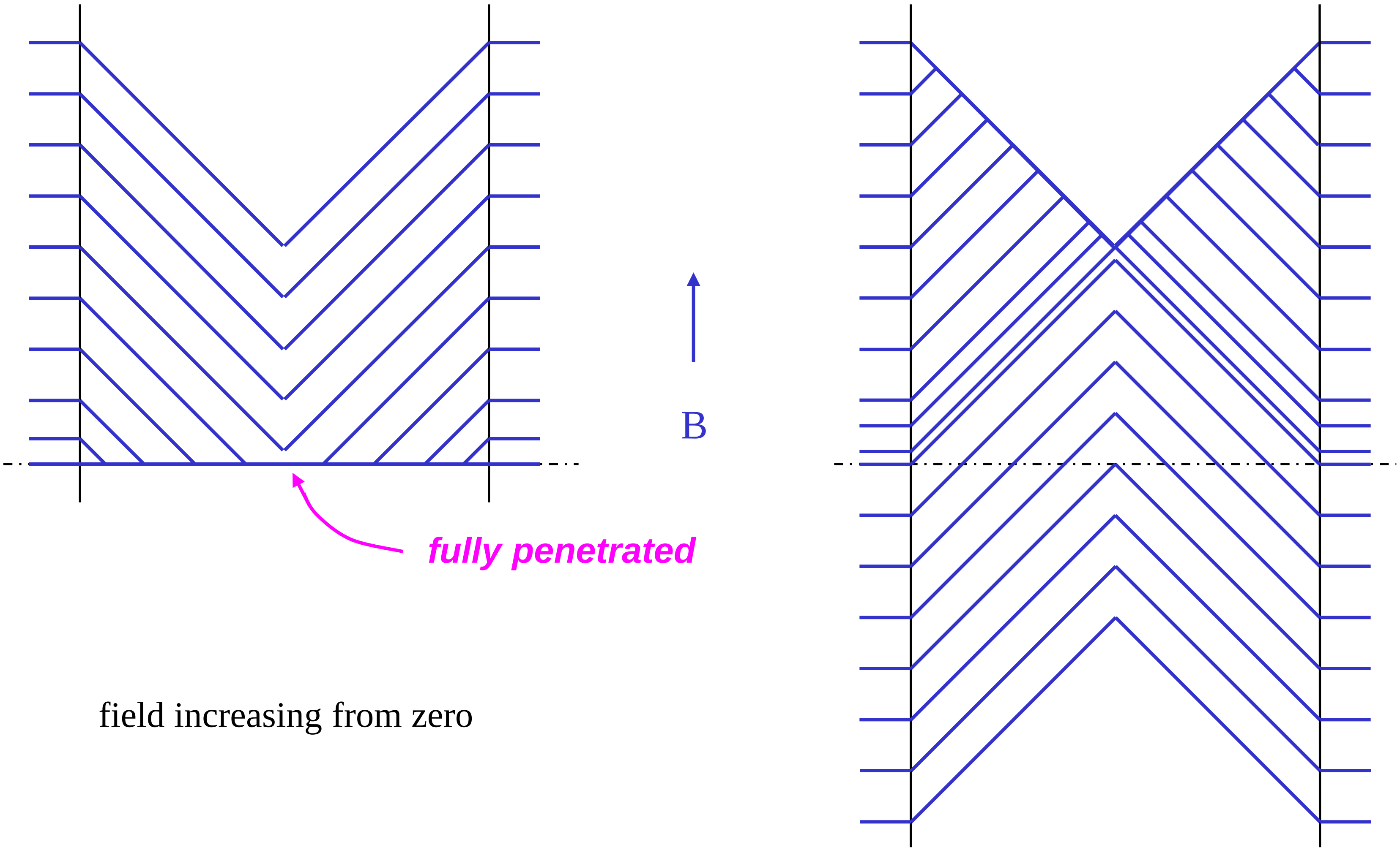
- usual model is a superconducting slab in a changing magnetic field B_y
- assume it's infinitely long in the *z* and *y* directions - simplifies to a 1 dim problem
- ***dB/dt*** induces an electric field E which causes screening currents to flow at critical current density J_c
- known as the ***critical 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 J_c means a constant field gradient inside the superconductor

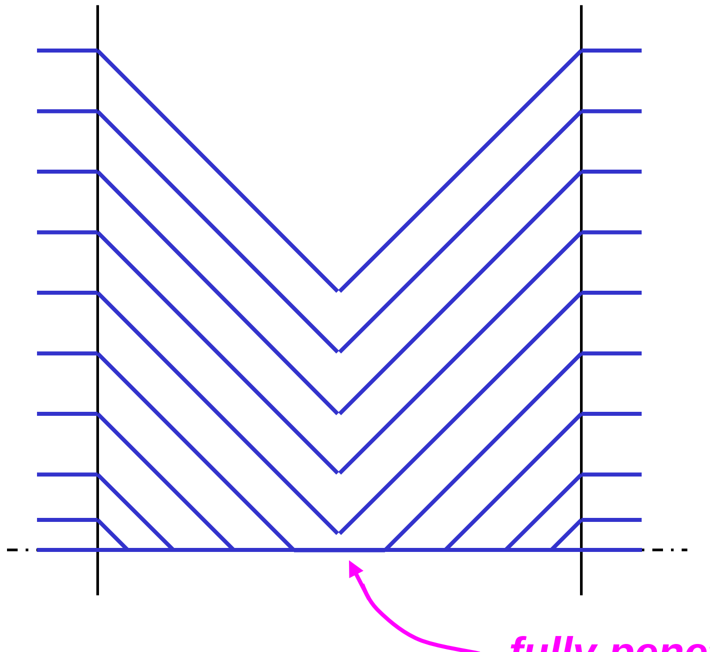
The flux penetration process

plot field profile across the slab



The flux penetration process

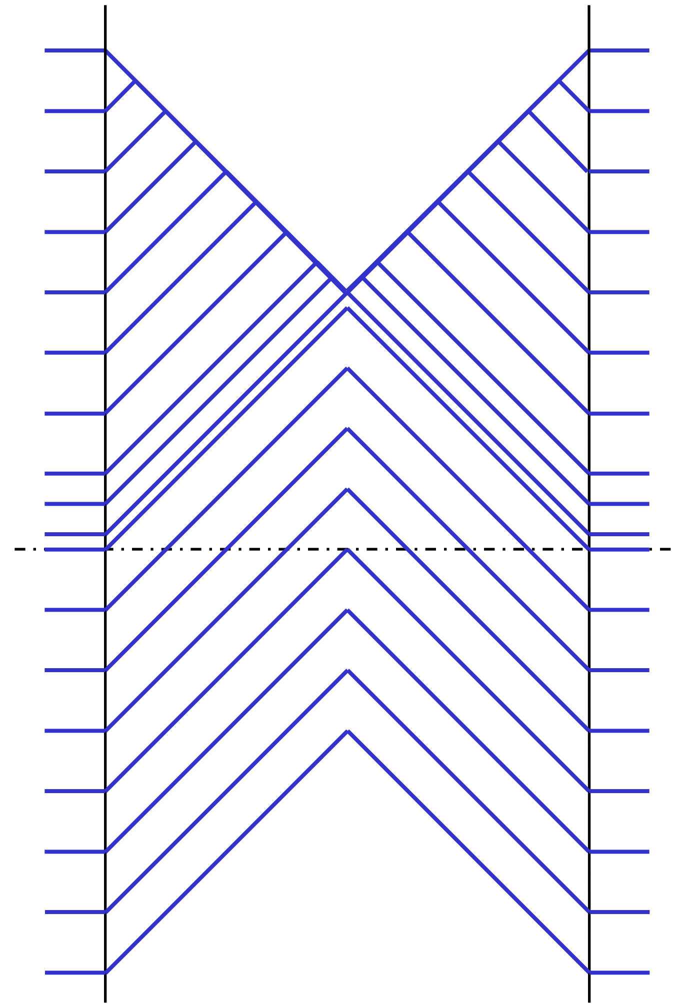
plot field profile across the slab



fully penetrated

field increasing from zero

B



field decreasing through zero

Bean critical state model

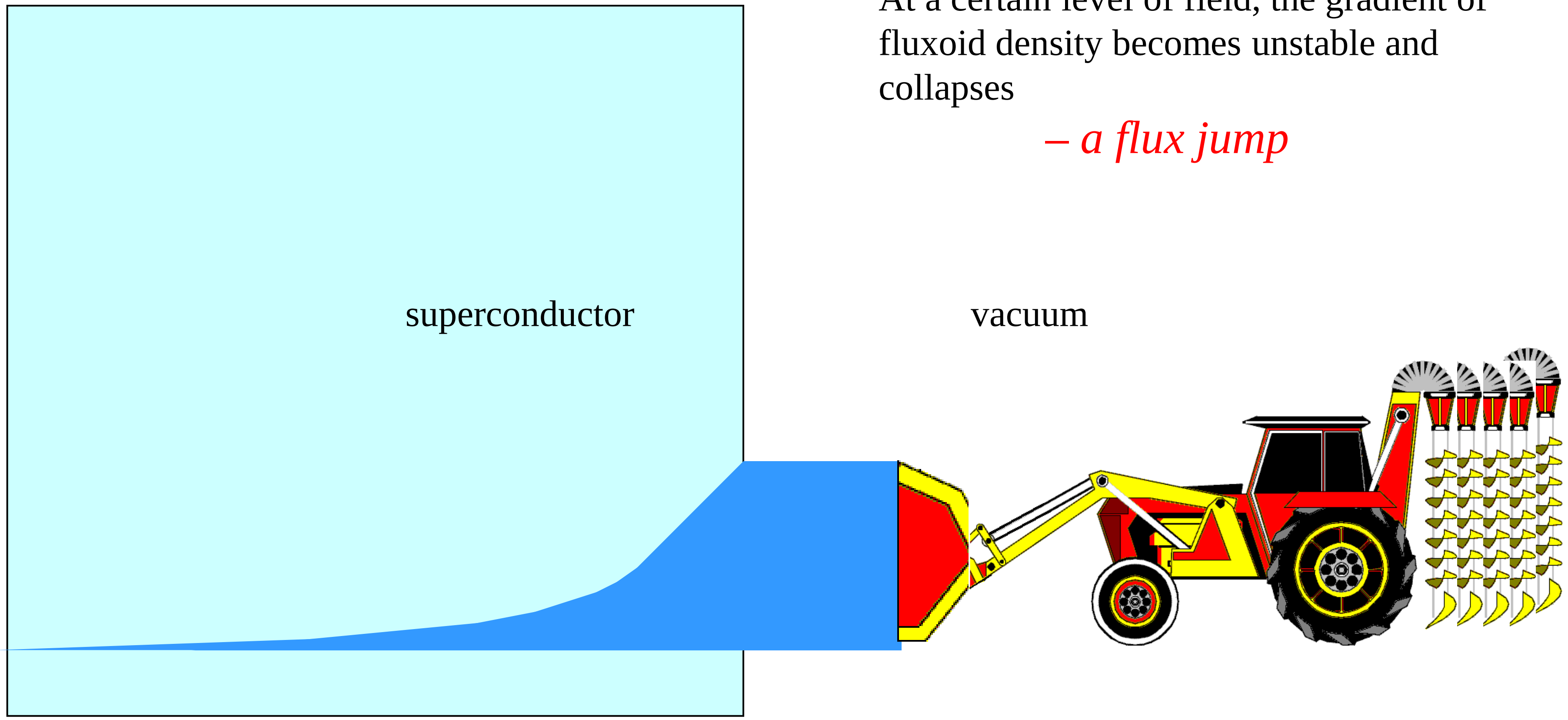
- **current density everywhere is $\pm J_c$ or zero**
- **change comes in from the outer surface**

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

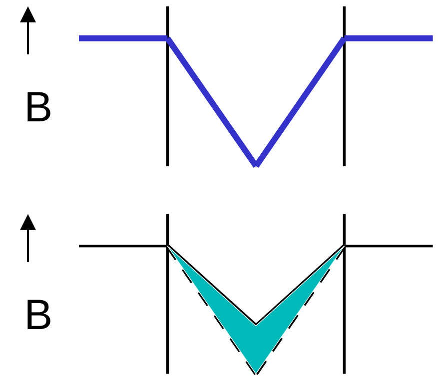
– a flux jump



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

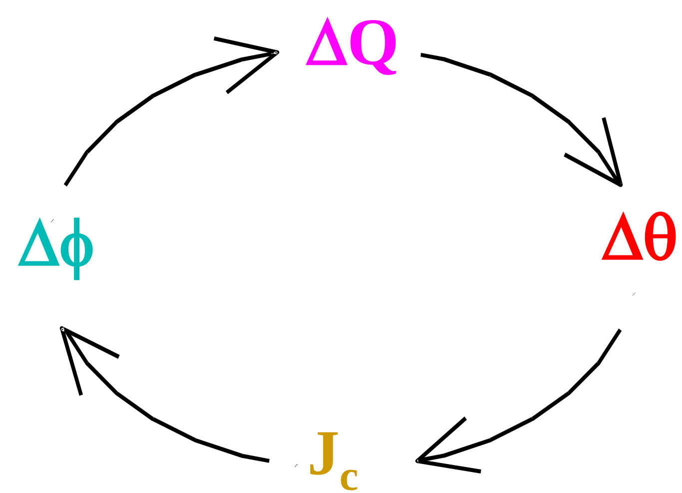
*** reduction in screening currents allows flux to move into the superconductor**

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 x 10* ^{9} *Am* $^{-2}$

γ *density = 6.2 x 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 of the Superconductor

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

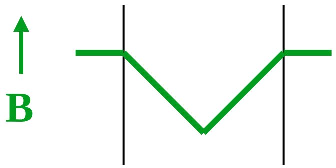
Problem for accelerators because it spoils the precise field shape

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

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

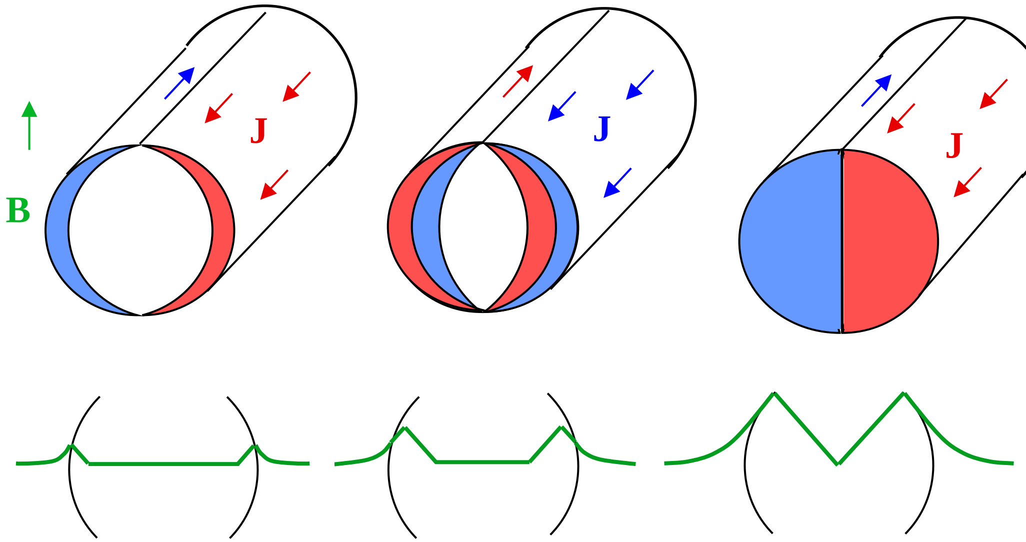
NB units of H

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

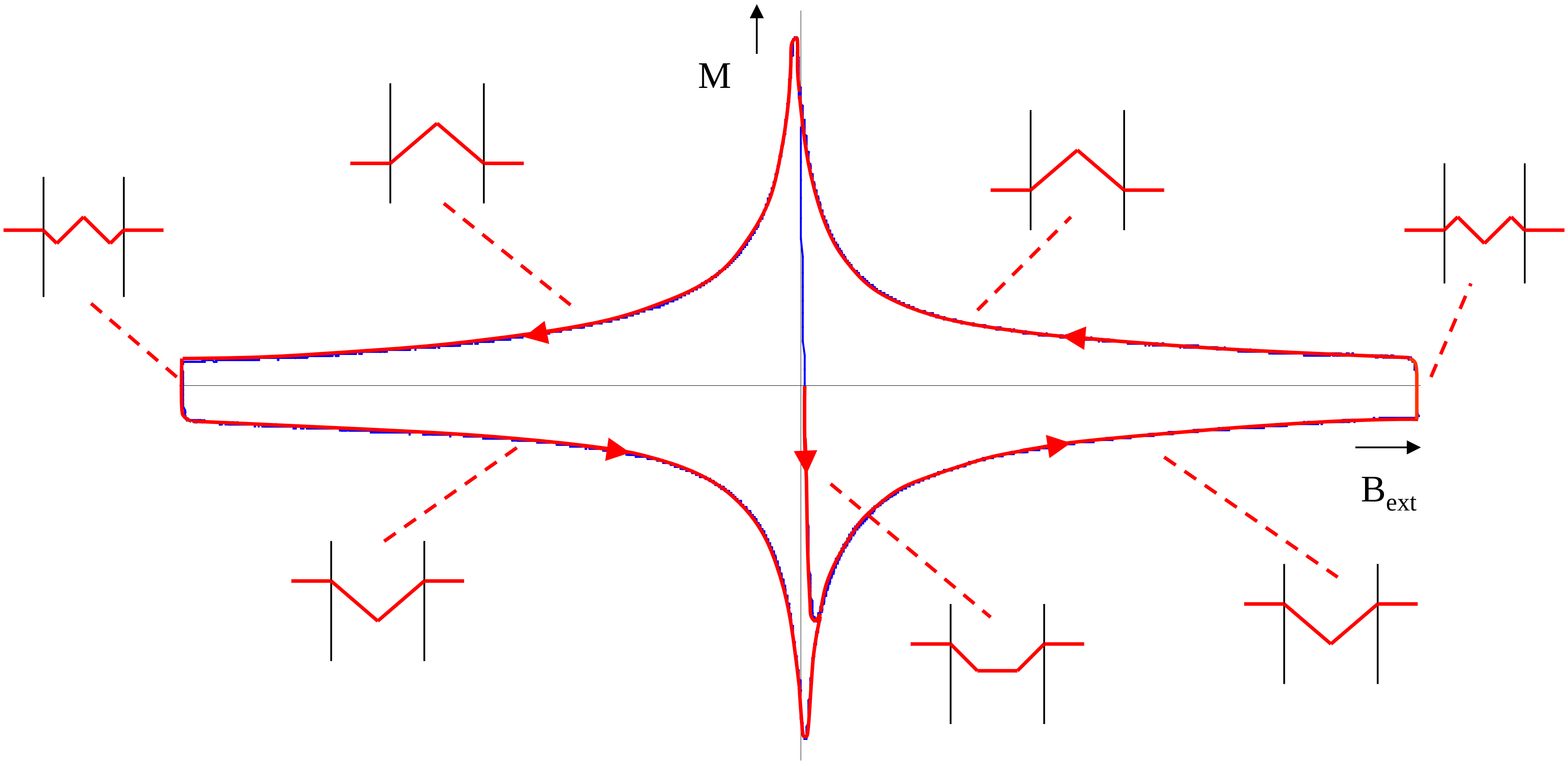
$$M = \frac{4}{3\pi} J_c\, a = \frac{2}{3\pi} J_c\, d_f$$

where a, d_f = filament radius, diameter

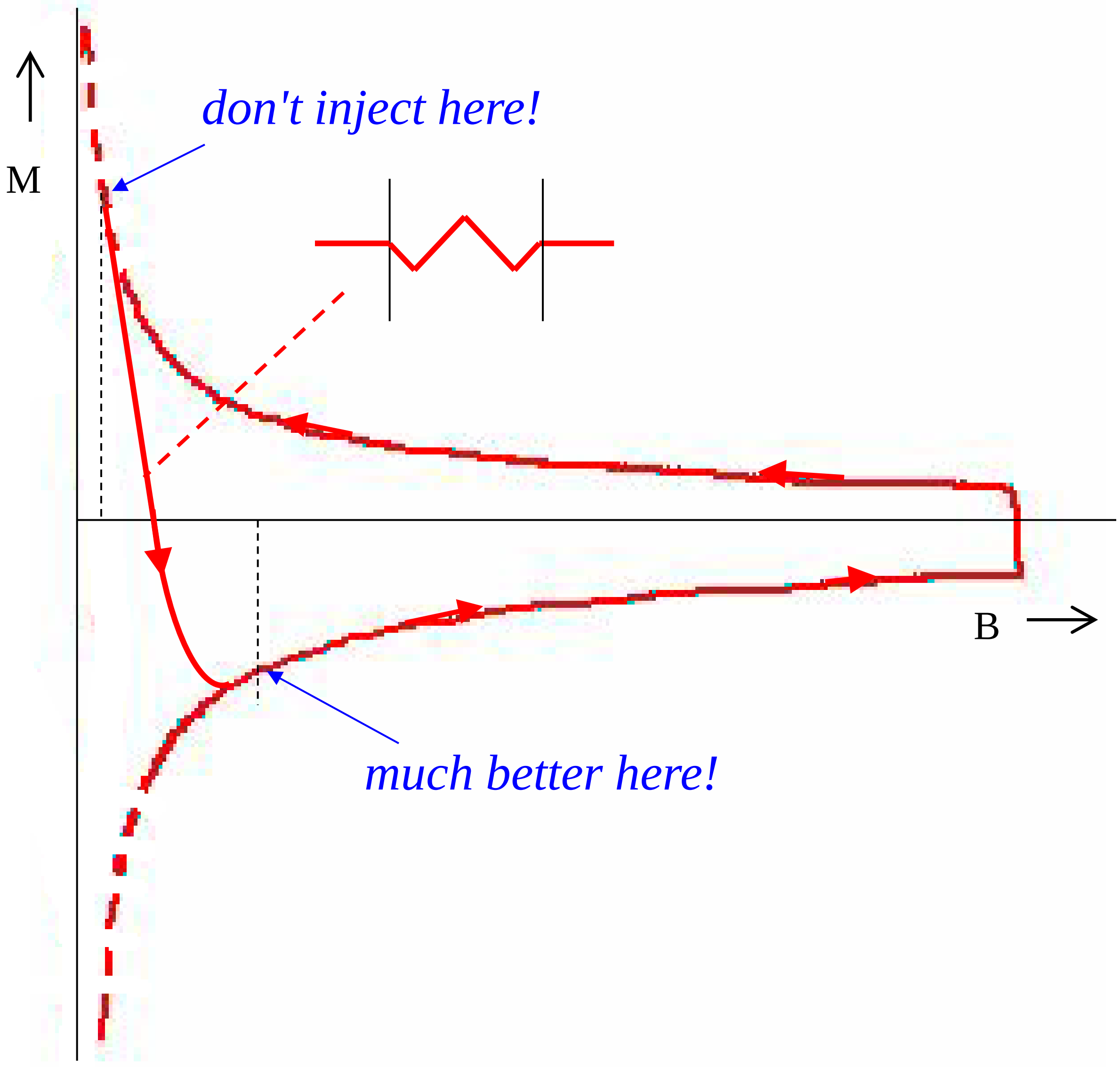
Note: M is here defined per unit volume of NbTi filament

Magnetization of NbTi

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



Synchrotron injection



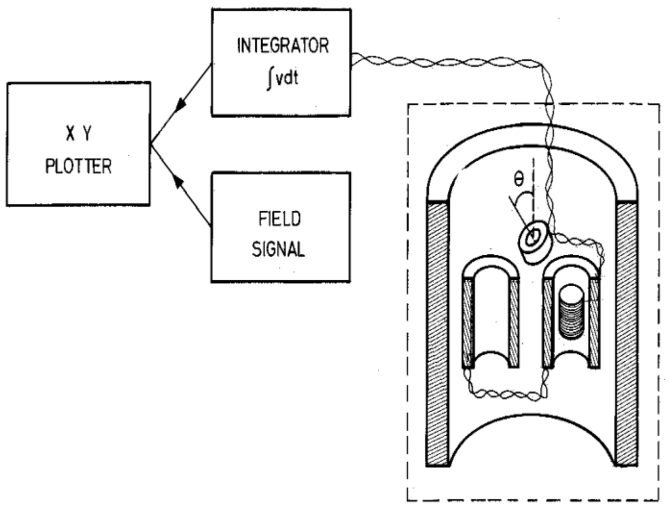
synchrotron injects at low field, ramps to high field and then back down again

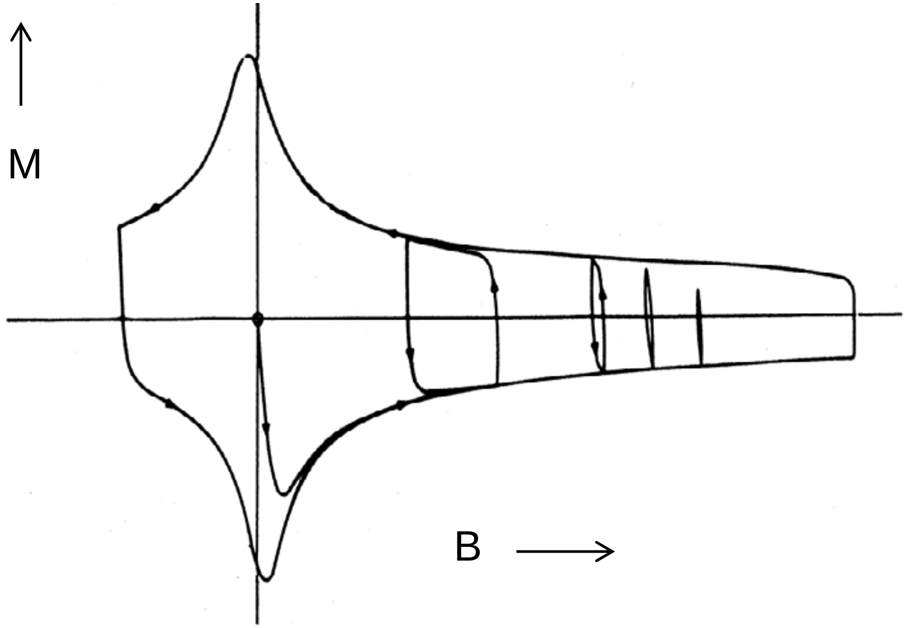
note how quickly the magnetization changes when we start the ramp up

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

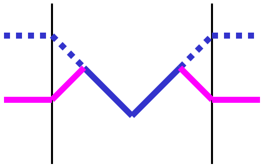
Measurement of magnetization

In field, the superconductor behaves just like a magnetic material. We can plot the magnetization curve using a magnetometer. It shows hysteresis - just like iron only in this case the magnetization is both diamagnetic and paramagnetic.





Note the minor loops, where field and therefore screening currents are reversing



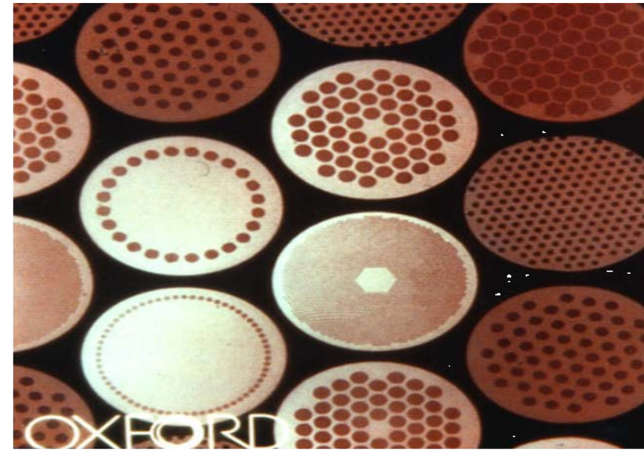
The magnetometer, comprising 2 balanced search coils, is placed within the bore of a superconducting solenoid. These coils are connected in series opposition and the angle of small balancing coil is adjusted such that, with nothing in the coils, there is no signal at the integrator. With a superconducting sample in one coil, the integrator measures magnetization when the solenoid field is swept up and down

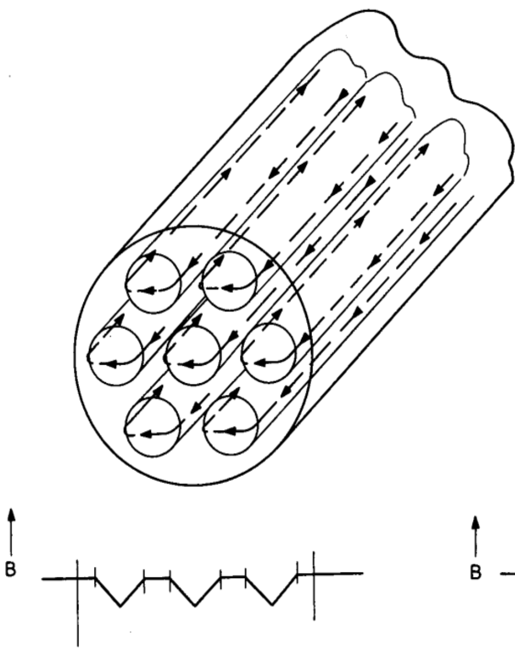
Fine filaments

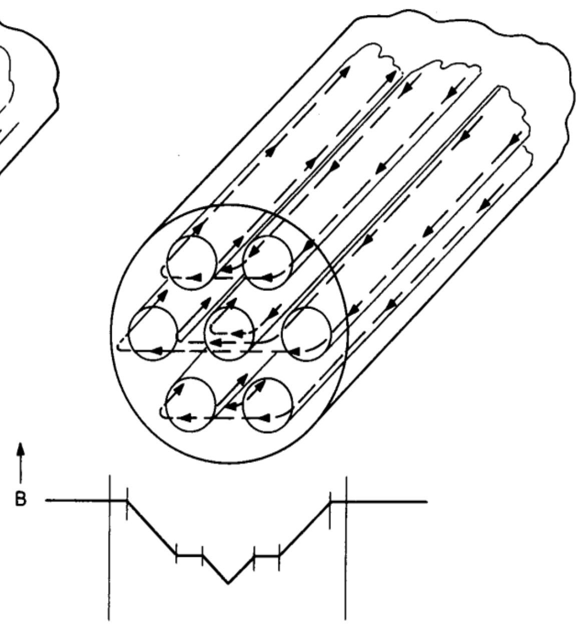
recap

$$M = \frac{2}{3\pi} J_c \, d_f$$

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



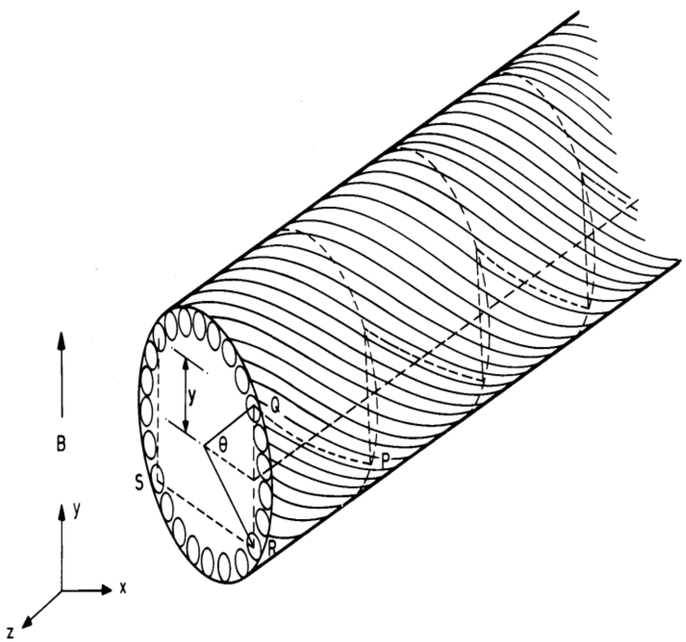




Unfortunately, in changing fields, the filament are coupled together; screening currents go up the LHS filaments and return down the RHS filaments, crossing the copper at each end.
In time these currents decay, but for wires ~ 100m long, the decay time is years!
So the advantages of subdivision are lost

Twisting

coupling may be reduced by twisting the wire



B`

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

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

just like eddy currents

where ρ_t is the transverse resistivity across the composite wire

$$\rho_t = \rho.\frac{1+\lambda_f}{1-\lambda_f}$$

where ρ is resistivity of the copper matrix and λ_f = filling factor of superconducting filaments in the wire section

extra magnetization due to coupling

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

where M_w is defined per unit volume of wire

Rate dependent magnetization

recap: magnetization has two components: persistent current in the filaments

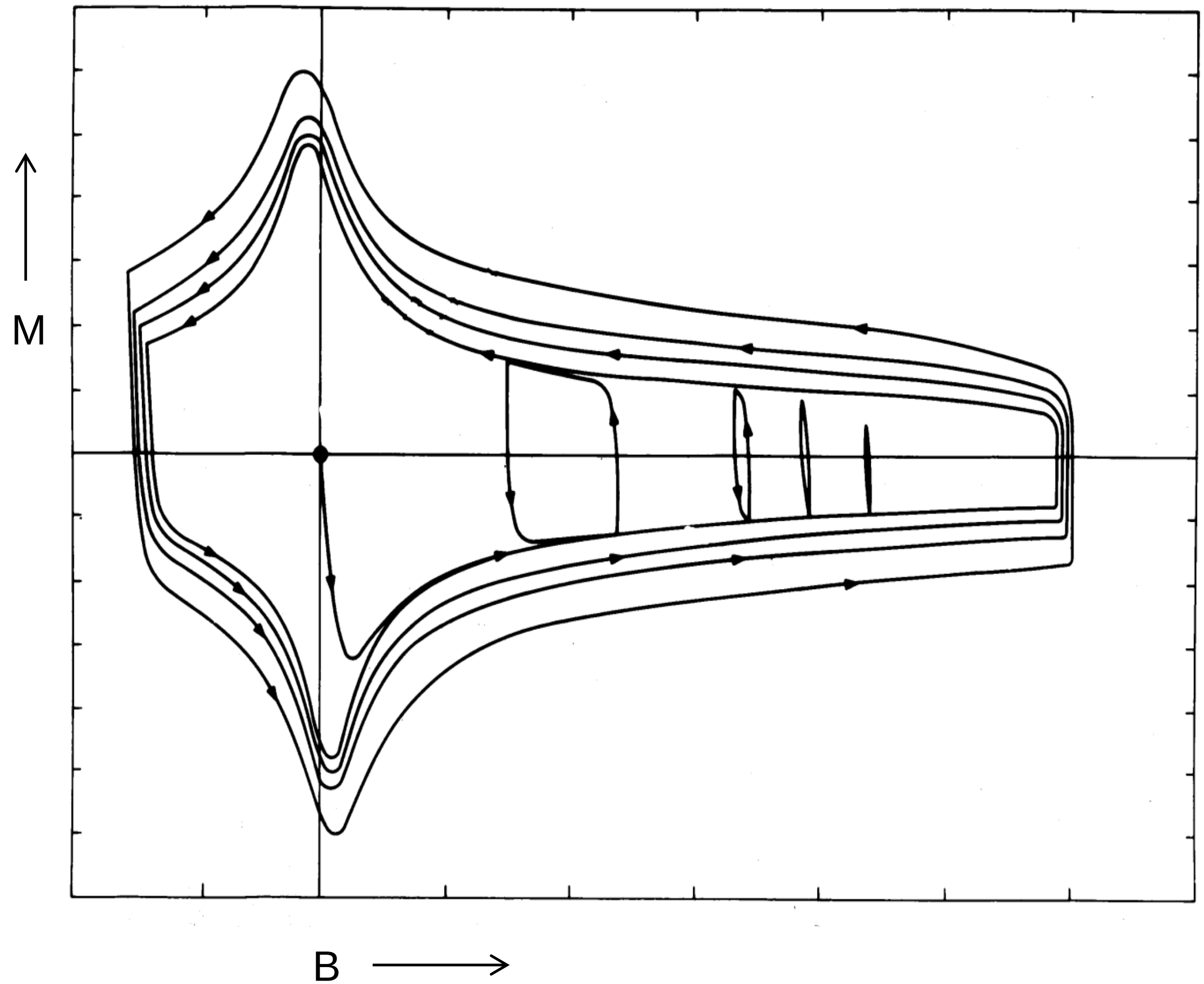
$$M_f = \frac{2}{3\pi}\lambda_f\, J_c\, d_f$$

and coupling between the filaments

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

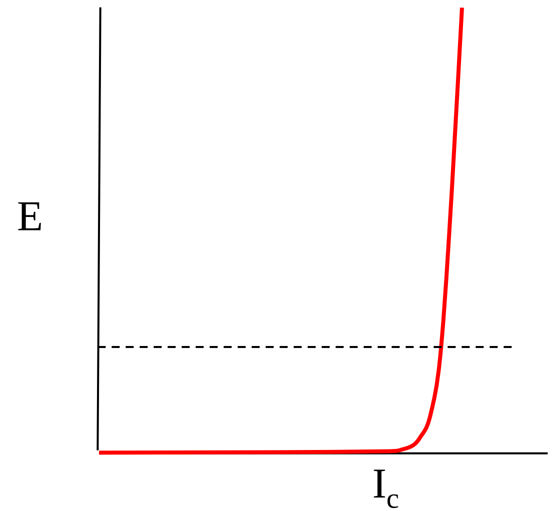
first component depends on B the second on B`

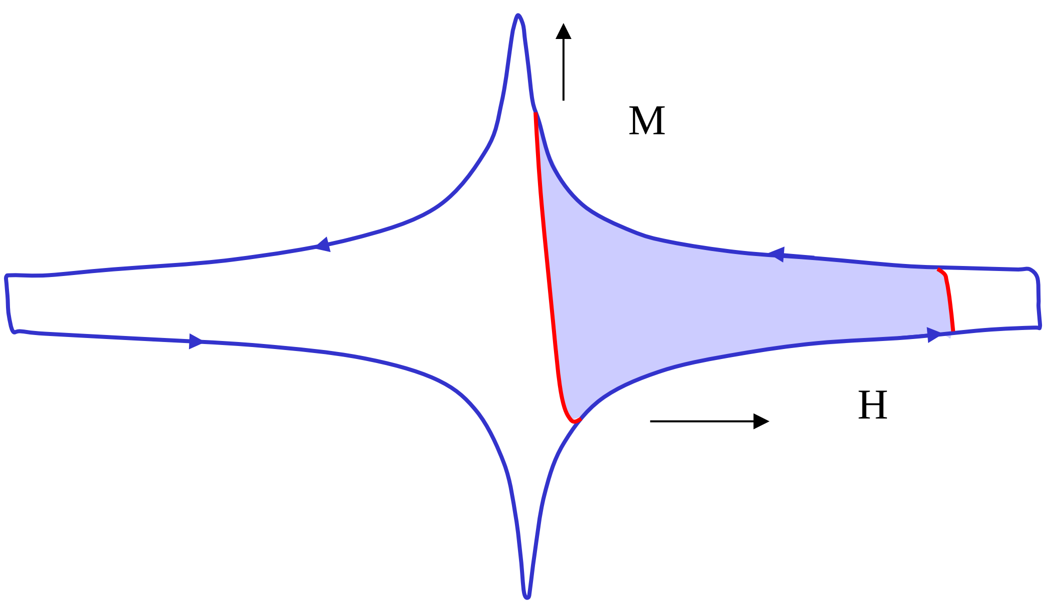
both defined per unit volume of wire



AC Losses

- When carrying dc currents below I_c superconductors have no loss but, in ac fields, all superconductors suffer losses.
- They come about because flux linkages in the changing field produce electric field in the superconductor which drives the current density above $I_{c.}$
- Coupling currents also cause losses by Ohmic heating in those places where they cross the copper matrix.
- In all cases, we can think of the ac losses in terms of the work done by the applied magnetic field

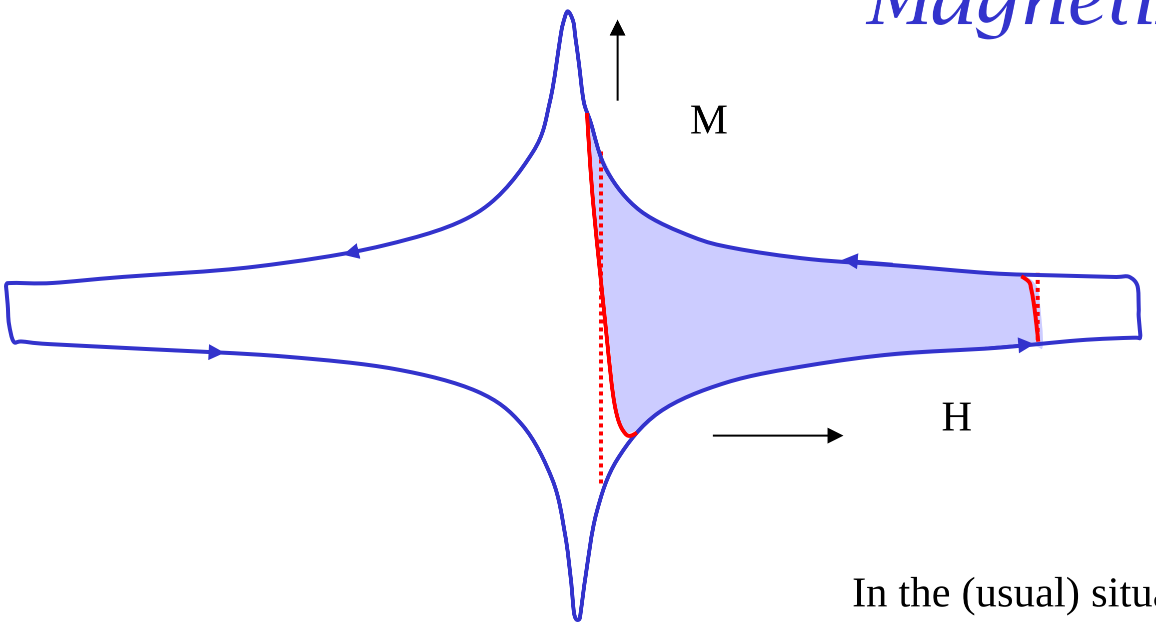




- The work done by magnetic field on a sample of magnetization *M* when field or magnetization changes

$$W = \int \mu_o H dM = \int \mu_o M dH$$

Magnetization and AC Losses



Around a loop the red 'crossover' sections are complicated, but usually approximate as straight vertical lines (dashed). So ac loss per cycle is

$$E = \oint \mu_o M dH \cong \oint M dB$$

In the (usual) situation where ***dH>>M,*** we may write the loss between two fields $\boldsymbol{B_1}$ and $\boldsymbol{B_2}$ as

$$E \cong \int_{B_1}^{B_2} M dB$$

so the loss power is

$$P = \frac{2}{3\pi} \dot{B}\, \lambda_f \; J_c \, d_f + \frac{2}{\mu_o} \dot{B}^2 \tau$$

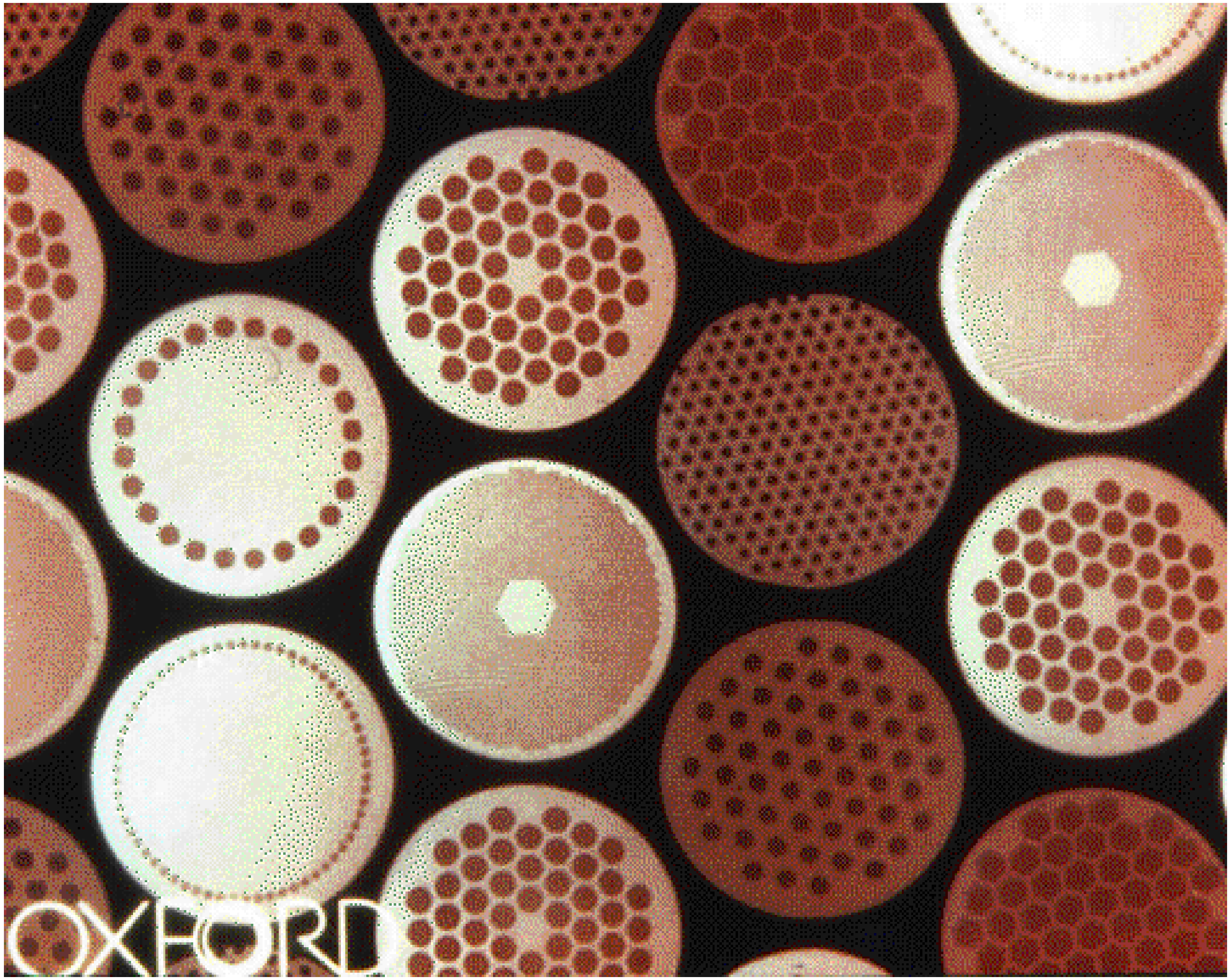
losses in Joules per m^3 and Watts per m^3 of superconductor

$$W = \int \mu_o H dM = \int \mu_o M dH$$

This is the work done on the sample
Strictly speaking, we can only say it is a heat dissipation if we integrate round a loop and come back to the same place
 - otherwise the energy just might be stored

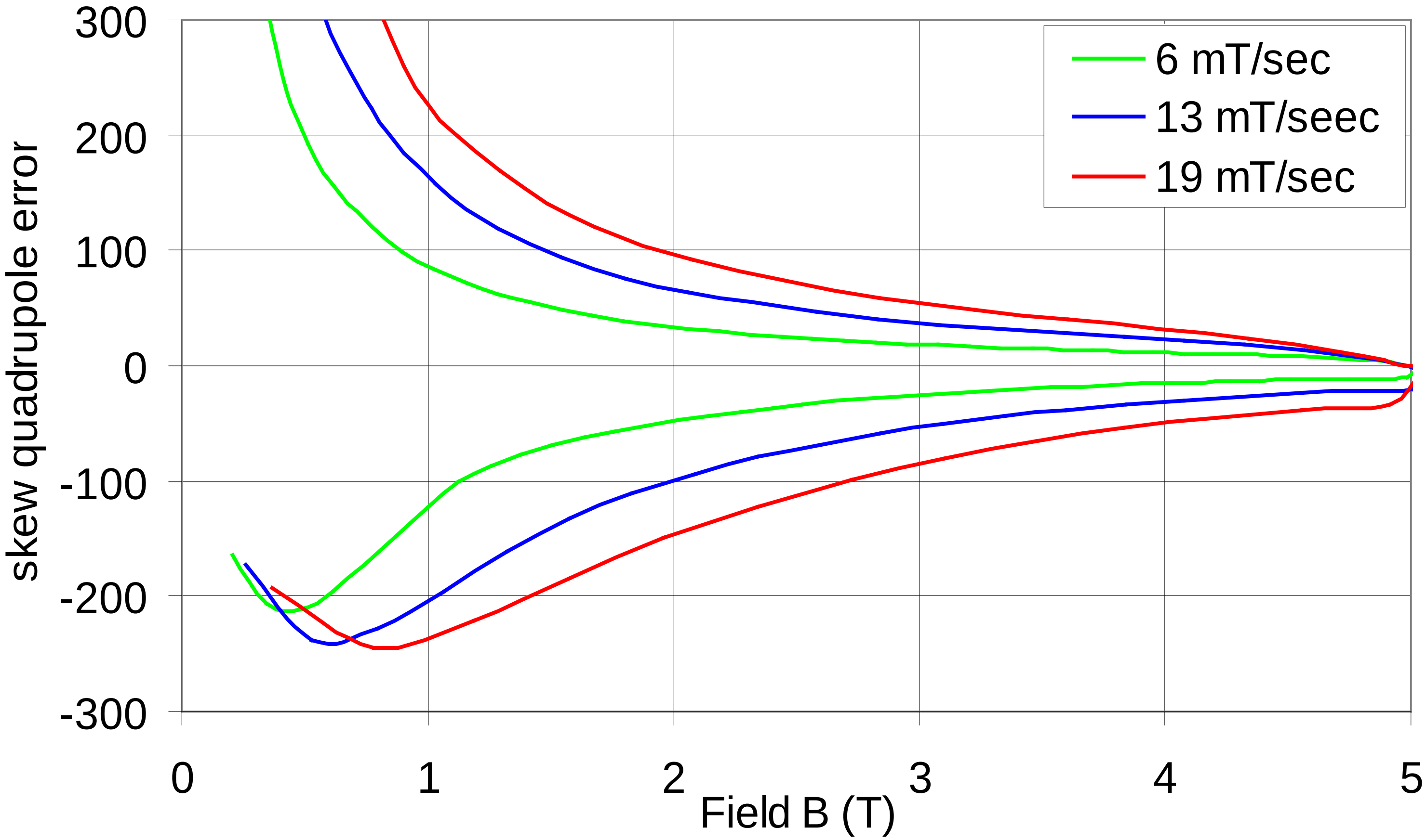
Fine filaments for low magnetization

- the finest filaments are made for accelerator magnets, mainly to keep the field errors at injection down to an acceptable level.
- in synchrotrons, particularly fast ramping, fine filaments are also needed to keep the ac losses down
- typical diameters are in the range 5 - 10μm. Even smaller diameters would give lower magnetization, but at the cost of lower Jc and more difficult production.



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)

Concluding remarks

a) training

- expected performance of magnet determined by intersection of load line and critical surface
- actual magnet performance is degraded and often shows ‘training’
  - caused by sudden releases of energy within the winding and low specific heat
- mechanical energy released by conductor motion or by cracking of resin
  - minimize mechanical energy release by careful design
- 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

b) fine filaments:

- magnetic fields induce persistent screening currents in superconductor
- flux jumping happens when screening currents go unstable $\Rightarrow$ quenches magnet
  - avoid by fine filaments - solved problem
- screening currents produce magnetization $\Rightarrow$ field errors and ac losses
  - reduce by fine filaments
- filaments are coupled in changing fields $\Rightarrow$ increased magnetization $\Rightarrow$ field errors and ac losses
  - reduce by twisting