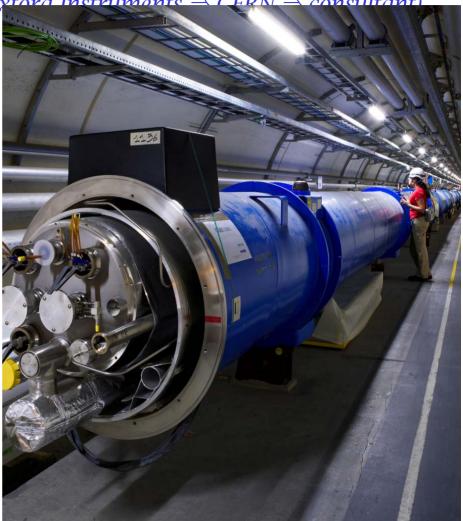
Superconducting magnets for Accelerators

Martin N Wilson (*Rutherford Lab* \Rightarrow *Oxford Instruments* \rightarrow *CERN* \rightarrow *consultant*) **Outline**

- why bother with superconductivity?
- properties of superconductors: critical field, temperature & current density
- magnetic fields and how to create them
- load lines, training and how to cure it
- screening currents and the critical state model
- magnetization and field errors
- fine filaments and cables
- quenching and protection
- hardware
- where to get more info



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Superconducting magnets for Accelerators *Who needs superconductivity anyway?*

Abolish Ohm's Law!

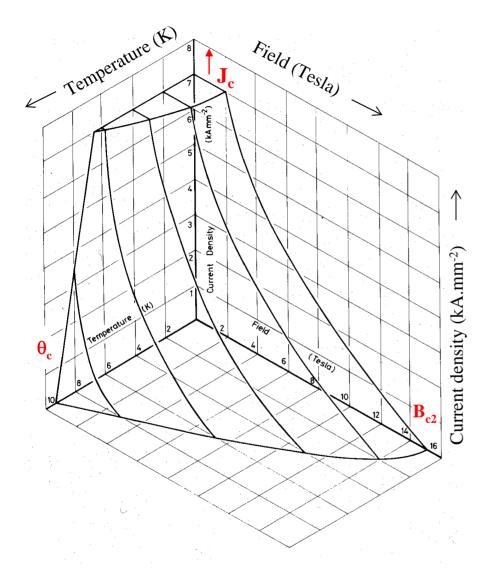
- no power consumption (although do need refrigeration power)
- high current density \Rightarrow compact windings, high gradients
- ampere turns are cheap, so we don't need iron (although often use it for shielding)

Consequences

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

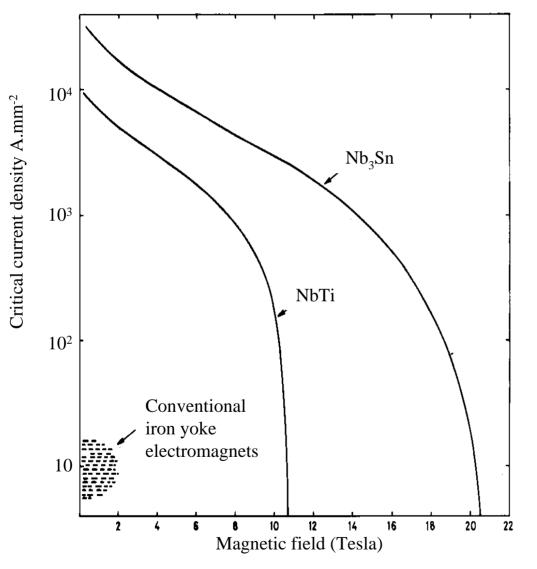


The critical surface of niobium titanium



- 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 J_c(B,θ) 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 Nb₃Sn 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

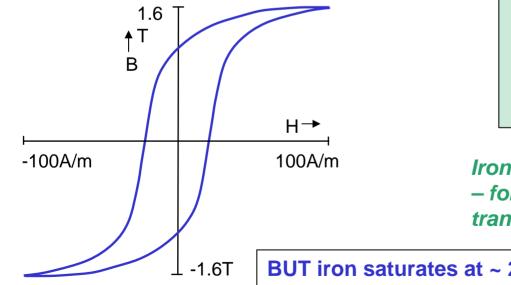
Filamentary composite wires

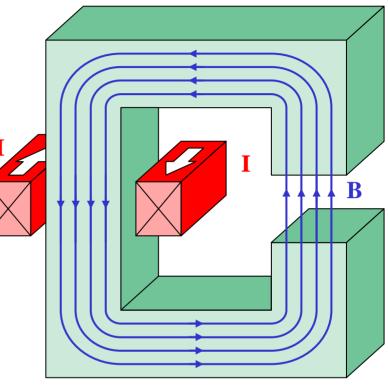


- for reasons that will be described later, superconducting materials are always used in combination with a good normal conductor such as copper
- to ensure intimate mixing between the two, the superconductor is made in the form of fine filaments embedded in a matrix of copper
- typical dimensions are:
- wire diameter = 0.3 1.0mm
- filament diameter = $5 50 \mu m$
- for electromagnetic reasons, the composite wires are twisted so that the filaments look like a rope

Fields and ways to create them: conventional

- iron yoke reduces magnetic reluctance
 - \Rightarrow reduces ampere turns required
 - \Rightarrow reduces power consumption
- iron guides and shapes the field

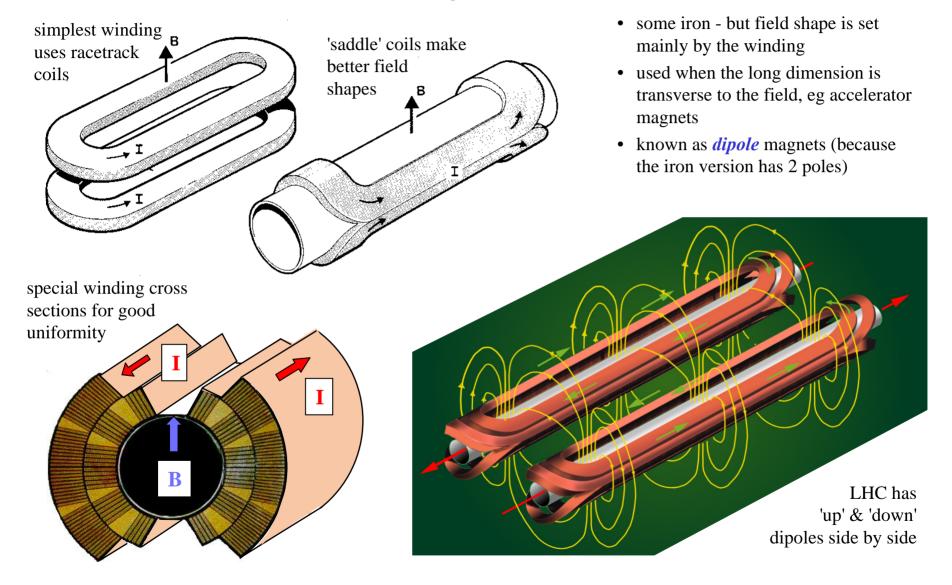


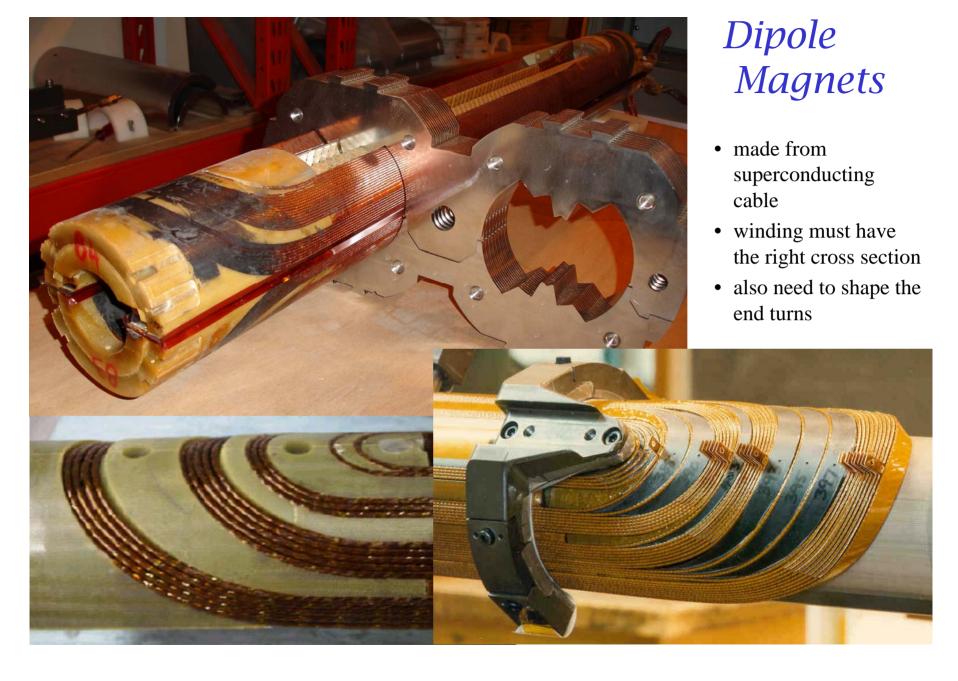


Iron electromagnet - for accelerator, HEP experiment transformer, motor, generator, etc

BUT iron saturates at ~ 2T

Fields and ways to create them: superconducting dipoles

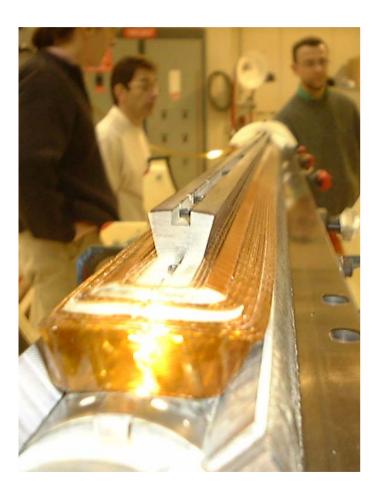


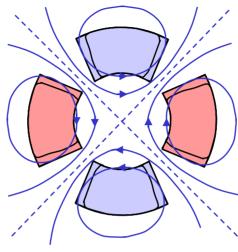


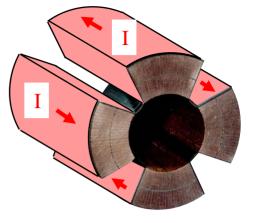
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Fields and ways to create them: superconducting quadrupoles

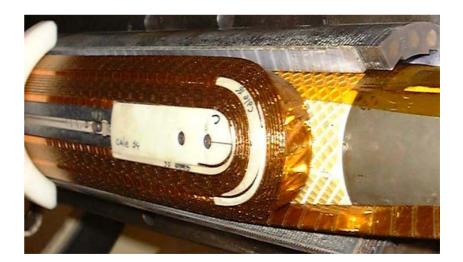
- gradient fields produce focussing
- quadrupole windings







 $B_x = ky$ $B_y = kx$

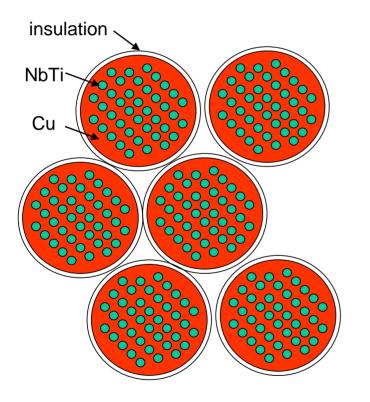


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Engineering current density

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 in the wire
$$\lambda_{metal} = \frac{1}{(1+mat)}$$

where *mat* = matrix : superconductor ratio

typically:

for NbTi mat = 1.5 to 3.0 ie $\lambda_{metal} = 0.4$ to 0.25

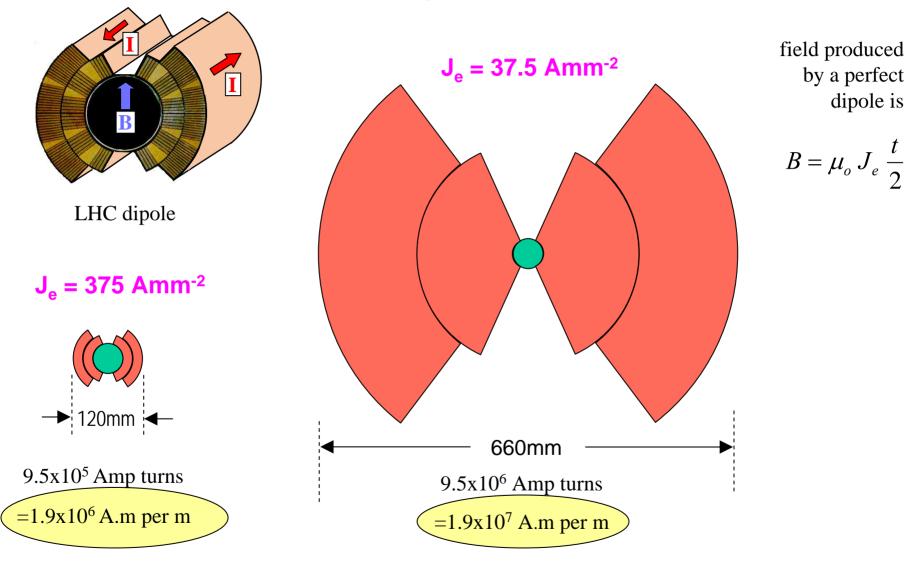
for Nb₃Sn *mat* ~ 3.0 ie $\lambda_{\text{metal}} \sim 0.25$

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

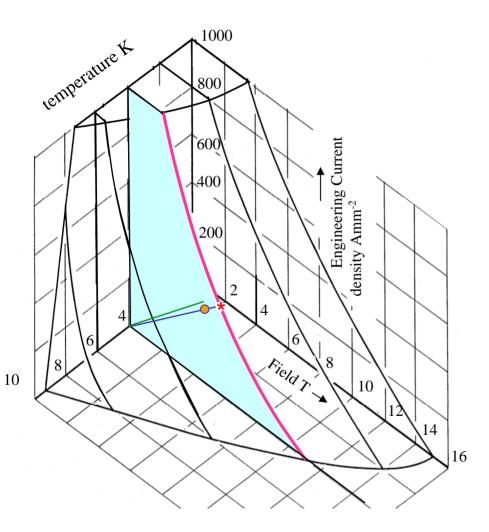
 $\lambda_{winding}$ takes account of space occupied by insulation, cooling channels, mechanical reinforcement etc and is typically 0.7 to 0.8

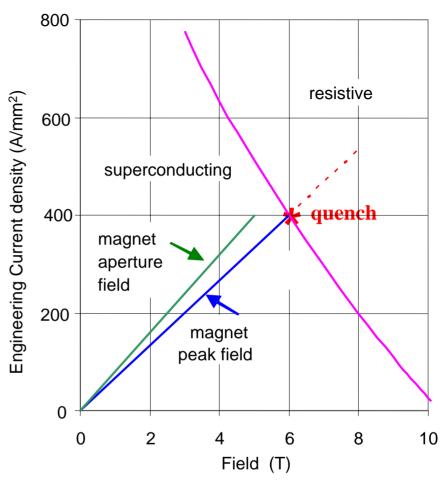
So typically J_{eng} is only 15% to 30% of $J_{supercon}$

Importance of engineering current density: dipoles



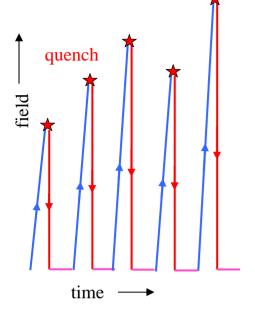
Critical line and magnet load lines



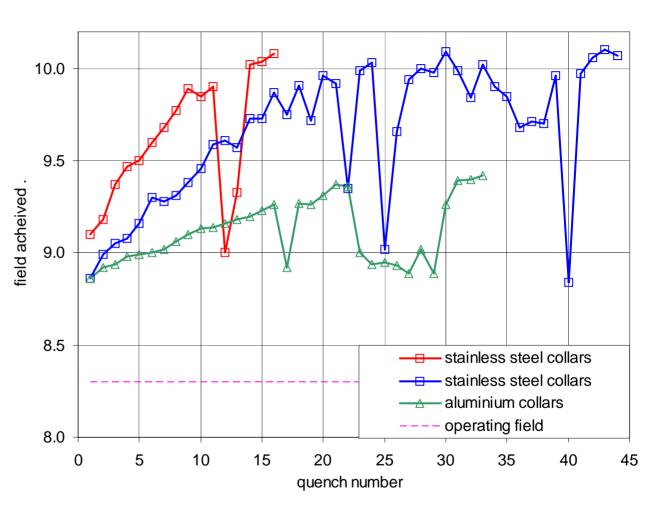


we expect the magnet to go resistive 'quench' where the peak field load line crosses the critical current line *

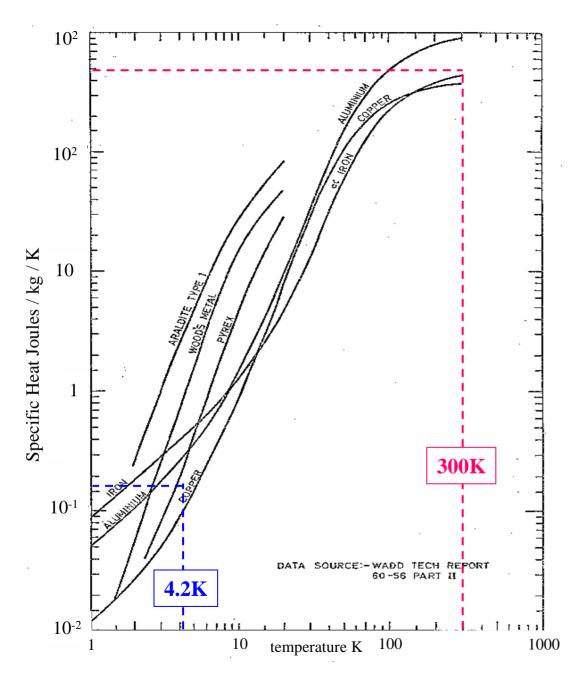
'Training' of magnets



- when the current (and field) of a magnet is ramped up for the first time, it usually 'quenches' (goes resistive) at less than the expected current
- at the next try it does better
- known as *training*



Training of LHC short prototype dipoles (from A. Siemko)



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

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Causes of training: (2) 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

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

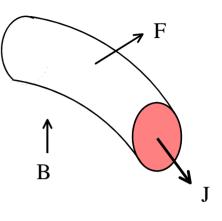
frictional heating per unit volume

 $Q = B.J.\delta z$

typical numbers for NbTi:

B = 5T $J_{eng} = 5 \times 10^8 \text{ A.m}^{-2}$ so if $\delta = 10 \,\mu\text{m}$ then Q = 2.5 x 10^4 J.m^{-3} Starting from 4.2K $\theta_{final} = 7.5\text{K}$

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





Causes of training: (3) 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. $brittleness + tension \Rightarrow cracking \Rightarrow energy release$

Calculate the stain energy induced in resin by differential thermal contraction

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

typically: $\epsilon = (11.5 - 3) \times 10^{-3}$ $Y = 7 \times 10^{9} \text{ Pa}$ $\nu = \frac{1}{3}$

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

triaxial strain



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

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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

most accelerator magnets are insulated using a Kapton film with a thin adhesive coating

2) Make the conductor able to withstand disturbances without quenching

temperature K • increase the 800 800 temperature Eng Current density (Amm⁻²) **Engineering Current** margin NbTi at 6T 600 600 400 lensity kAmm 200400 operate Field T 🔆 guench • increase the 200 minimum quench 10 margin 0 energy 2 0 6 Temperature (K)

Minimum quench energy MQE

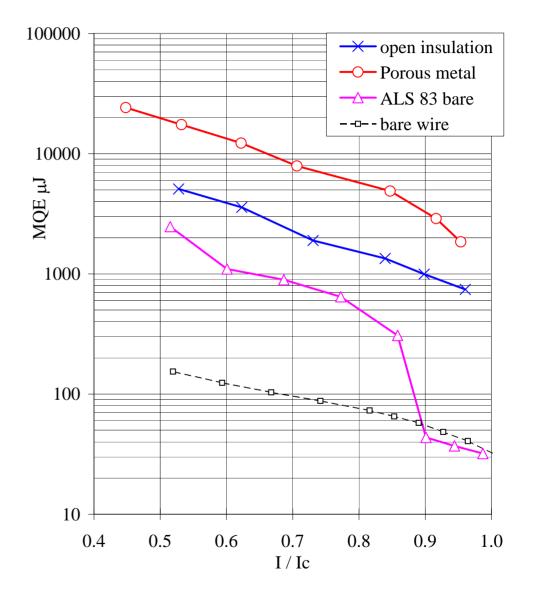
- MQE is the smallest energy input which quenches the conductor.
- measure it by injecting short (100µs) heat pulses at a point on the conductor.

large MQE

⇒ more stable conductor ⇒ less training

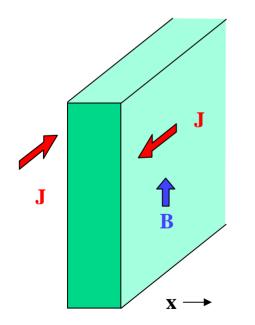
for a large MQE we need:

- large temperature margin
- large thermal conductivity need copper
- small resistivity need copper
- large specific heat difficult
- good cooling winding porous to liquid helium coolant



Persistent screening currents

- 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



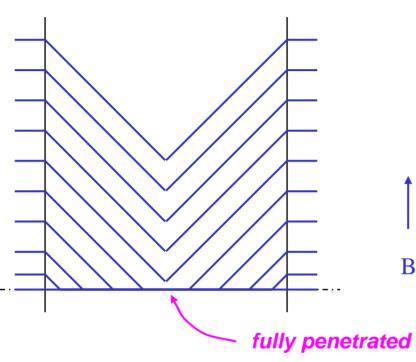
- usual model is a superconducting slab in a changing magnetic field B_v
- assume it's infinitely long in the *z* and *y* directions simplifies to a 1 dim problem
- *dB/dt* induces an electric field E which causes screening currents to flow at critical current density *J_c*
- known as the *critical state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

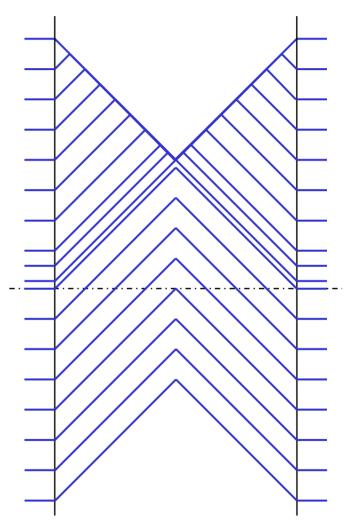
The flux penetration process

plot field profile across the slab



field increasing from zero

everywhere current density is $\pm J_c$ or zero (Bean model)



field decreasing through zero

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Magnetization of the Superconductor

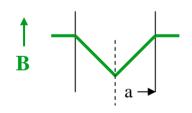
When viewed from outside the sample, the persistent currents produce a magnetic moment.

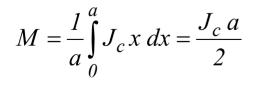
Problem for accelerators because it spoils the precise field shape

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

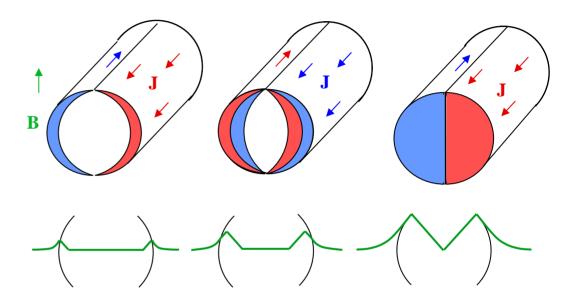
$$M = \sum_{V} \frac{I.A}{V} \qquad \text{NB units of } H$$

for a fully penetrated slab





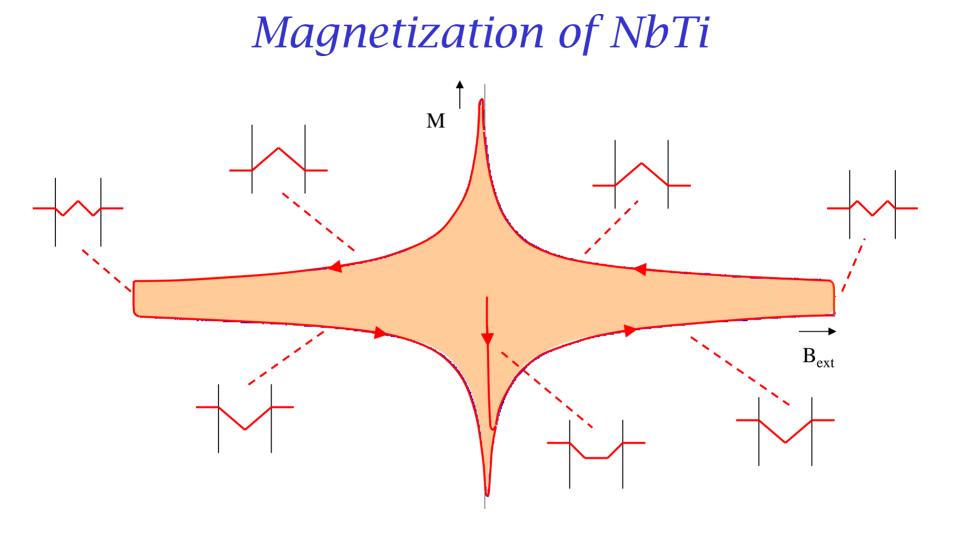
for **cylindrical** filaments the inner current boundary is roughly elliptical (controversial)



when fully penetrated, the magnetization is

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

where d_f = filament diameter Note: M is here defined per unit volume of NbTi filament

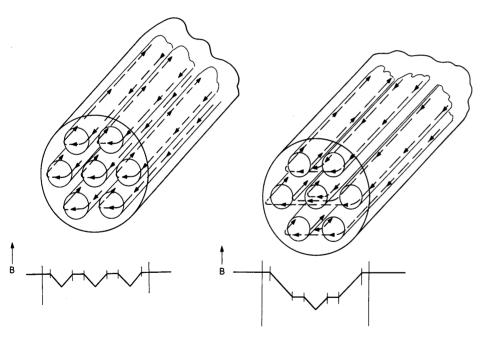


Note the area enclosed by the magnetization loop, also called the hysteresis loop, is the work done on the superconductor by the magnetic field.

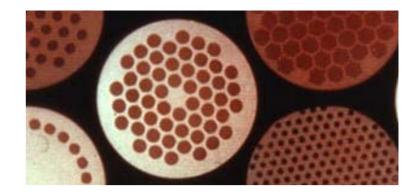
It appears as an ac loss (heat dissipation) and gives us an (unwelcome) extra refrigeration load

recap
$$M = \frac{filaments}{3\pi} J_c d_f$$

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



but in changing fields, the filaments are magnetically coupled; screening currents go up the left filaments and return down the right



Fortunately the coupling currents may be reduced by twisting the wire



coupling currents behave like eddy currents and produce an additional magnetization

$$M_e = \frac{dB}{dt} \frac{l}{\rho_t} \left[\frac{p_w}{2\pi} \right]^2$$

where ρ_t = resistivity across the copper and p_w = wire twist pitch

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Rate dependent magnetization

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

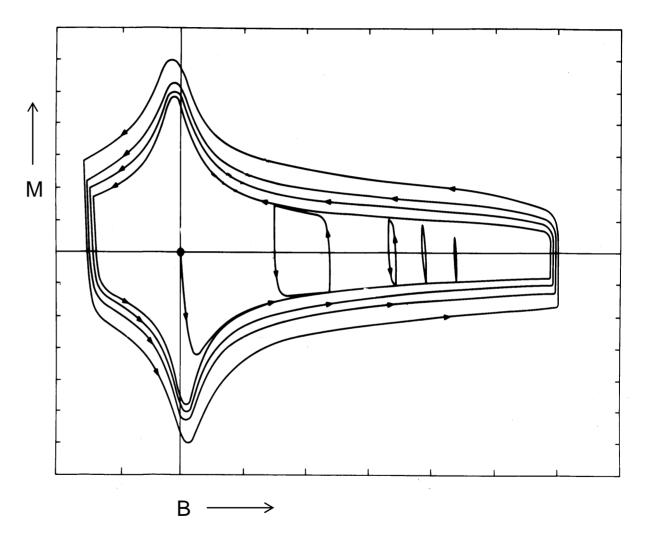
$$M_f = \frac{2}{3\pi} J_c d_f$$

and eddy current coupling between the filaments

 $M_e = \frac{dB}{dt} \frac{1}{\rho_t} \left[\frac{p_w}{2\pi} \right]^2$

M_f depends on *B M_e* depends on dB/dt

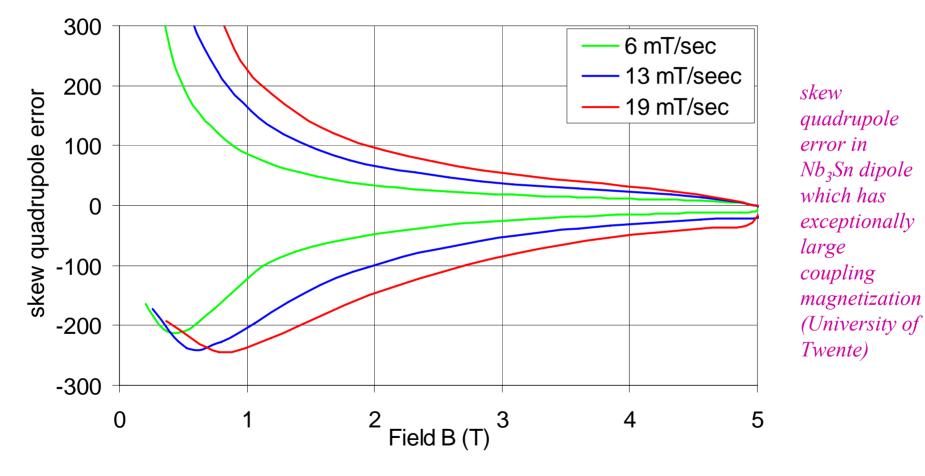
Note M_f defined per unit volume of NbTi filament and M_e per unit volume of wire



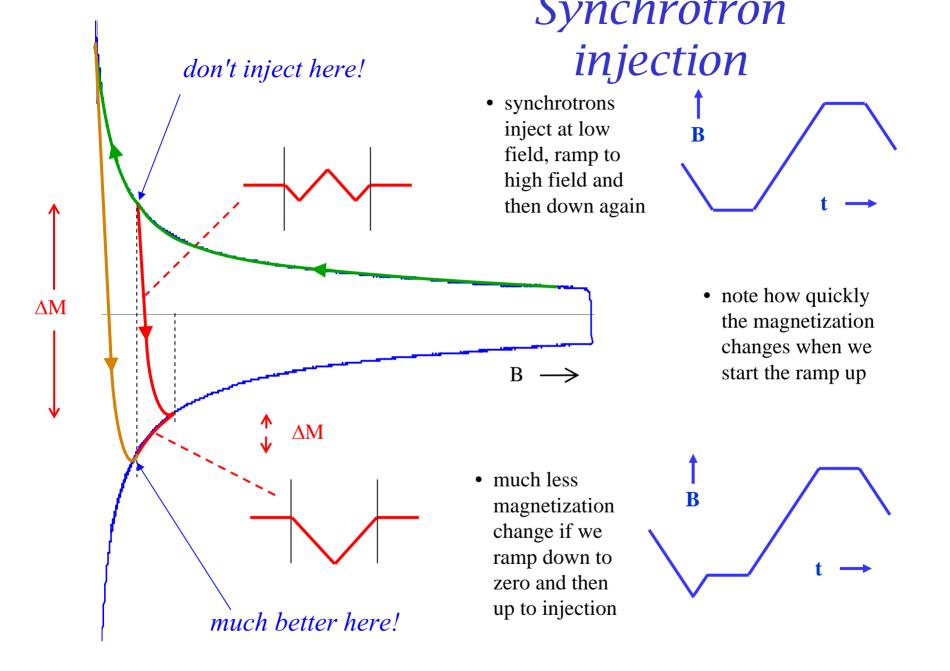
Magnetization and field errors

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



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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

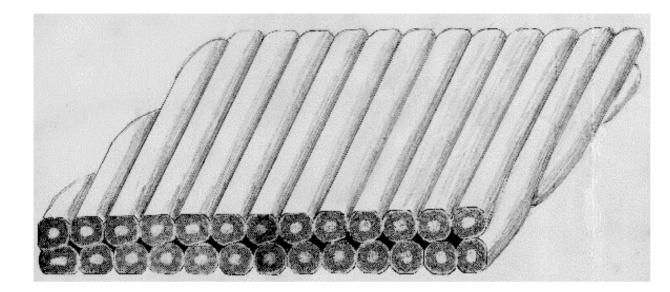
$$E = \frac{1}{2}LI^2 \qquad \qquad V = \frac{LI}{t} = \frac{2E}{It}$$

- **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 = 74kJ/m, t = 4s, 30 strand cable cable I = 6.8kA, charge voltage per km = 5.4kV wire I = 227A, charge voltage per km = 163kV
- so we need high currents!

the RHIC tunnel

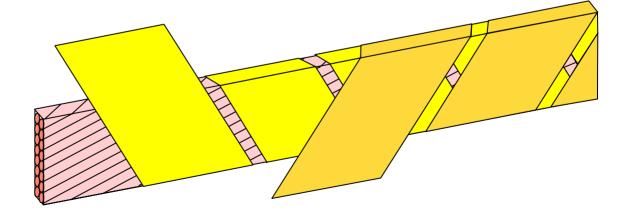
- a single $5\mu m$ filament of NbTi in 6T carries 50mA
- a composite wire of fine filaments typically has 5,000 to 10,000 filaments, so it carries 250A to 500A
- for 5 to 10kA, we need 20 to 40 wires in parallel a cable

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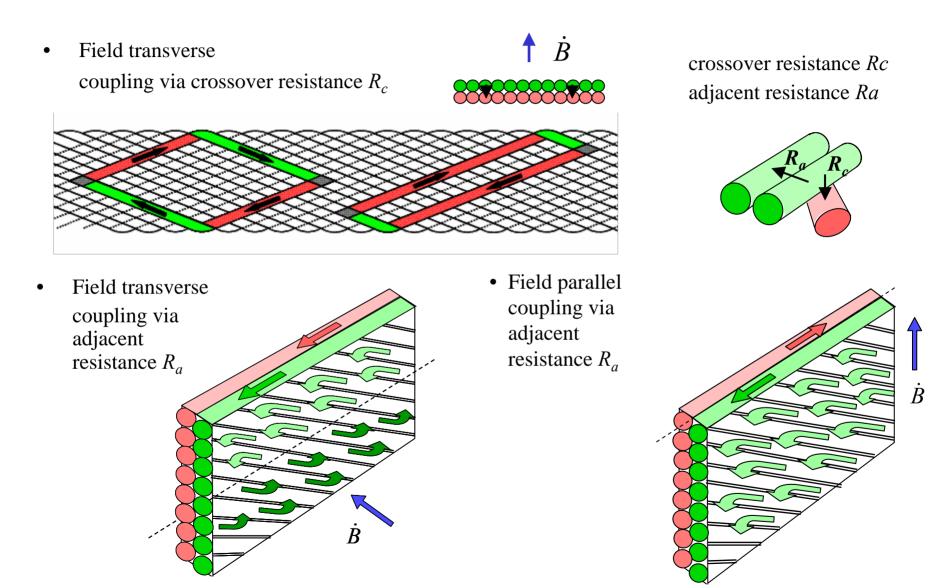


Rutherford cable

- the cable is insulated by wrapping 2 or 3 layers of Kapton; gaps may be left to allow penetration of liquid helium; the outer layer is treated with an adhesive layer for bonding to adjacent turns.
- Note: the adhesive faces outwards, don't bond it to the cable (avoid energy release by bond failure, which could quench the magnet)



Coupling in Rutherford cables



Magnetic stored energy

Magnetic energy density

 $E = \frac{B^2}{2\mu_o}$ at 5T $E = 10^7$ Joule.m⁻³ at 10T $E = 4 \times 10^7$ Joule.m⁻³

LHC dipole magnet (twin apertures) $E = \frac{1}{2}LI^2$ L = 0.12H I = 11.5kA $E = 7.8 \times 10^6$ Joules

the magnet weighs 26 tonnes

so the magnetic stored energy is equivalent to the kinetic energy of:-

26 tonnes travelling at 88km/hr



coils weigh 830 kg equivalent to the kinetic energy of:-

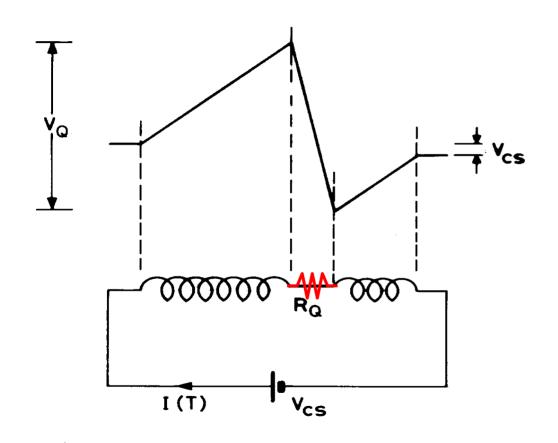
830kg travelling at 495km/hr



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The quench process



- resistive region starts somewhere in the winding at a point
 this is the problem!
- it grows by thermal conduction
- stored energy ¹/₂LI² of the magnet is dissipated as heat
- greatest integrated heat dissipation is at point where the quench starts
- internal voltages much greater than terminal voltage (= V_{cs} current supply)
- maximum temperature may be calculated from the current decay time via the U(θ) function (adiabatic approximation)

The temperature rise function $U(\theta)$

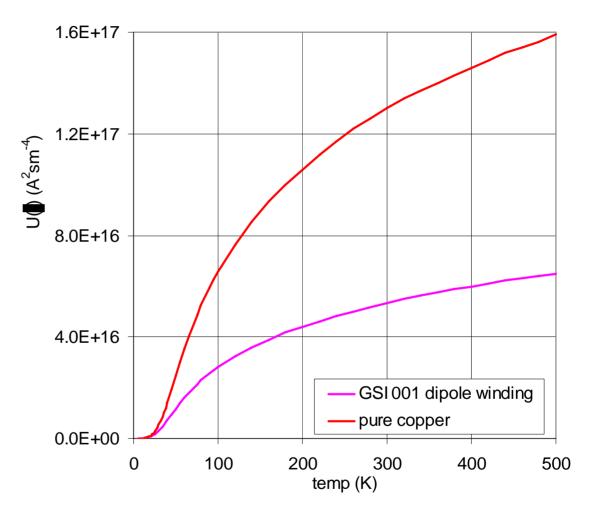
or the 'fuse blowing' calculation (adiabatic approximation)

$$J^{2}(T)\rho(\theta)dT = \gamma C(\theta)d\theta$$

J(T) = overall current density, T = time, $\rho(\theta) = \text{overall resistivity,}$ $\gamma = \text{density,} \quad \theta = \text{temperature,}$ $C(\theta) = \text{specific heat,}$ $T_Q = \text{quench decay time.}$

$$\int_{0}^{\infty} J^{2}(T) dT = \int_{0}^{\theta m} \frac{\gamma C(\theta)}{\rho(\theta)} d\theta$$
$$= U(\theta_{m})$$
$$J_{0}^{2} T_{0} = U(\theta_{m})$$

GSI 001 dipole winding is 50% copper, 22% NbTi, 16% Kapton and 3% stainless steel

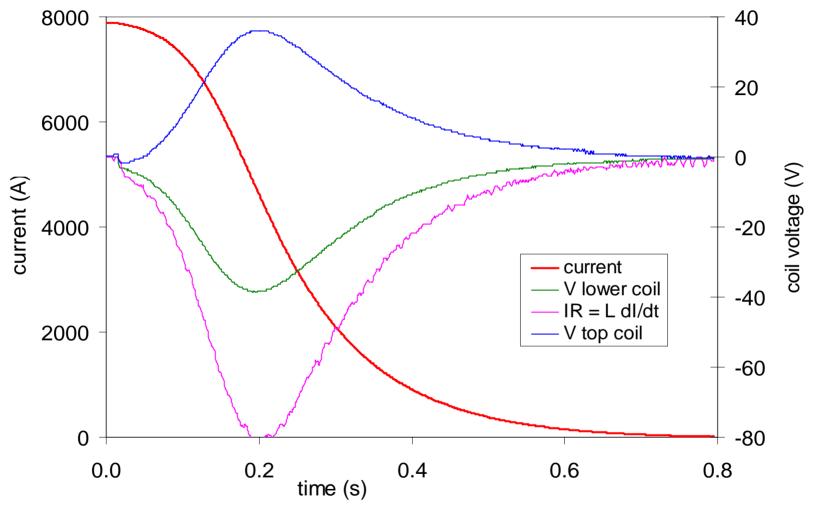


• NB always use **overall** current density

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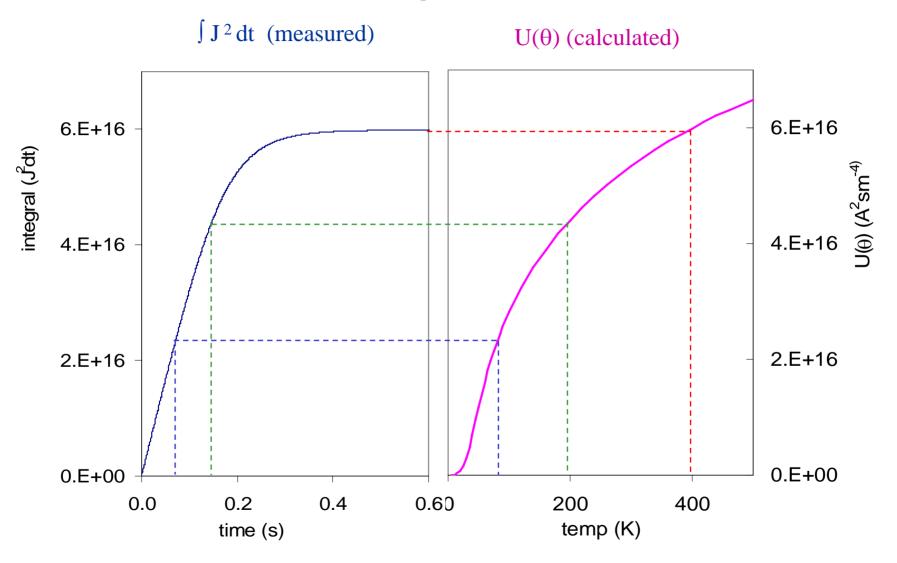
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Measured current decay after a quench



Dipole GSI001 measured at Brookhaven National Laboratory

Calculating the temperature rise from the current decay curve



Growth of the resistive zone

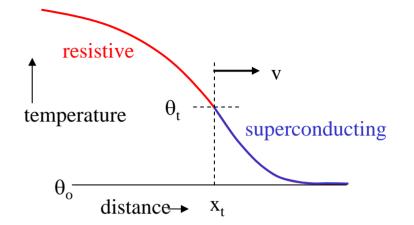
the quench starts at a point and then grows in three dimensions via the combined effects of Joule heating and thermal conduction

Quench propagation velocity

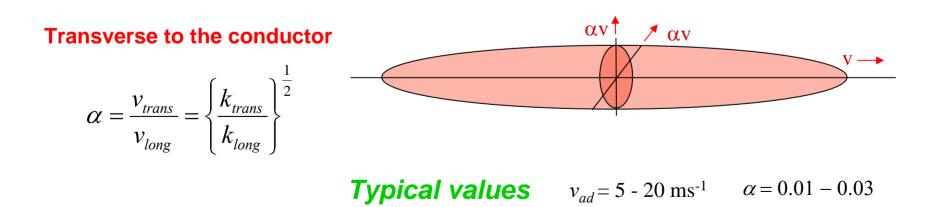
- resistive zone starts at a point and spreads along the conductor and transverse to it
- the force driving it forward is the heat generation in the resistive zone, together with heat conduction along the wire

Along the conductor

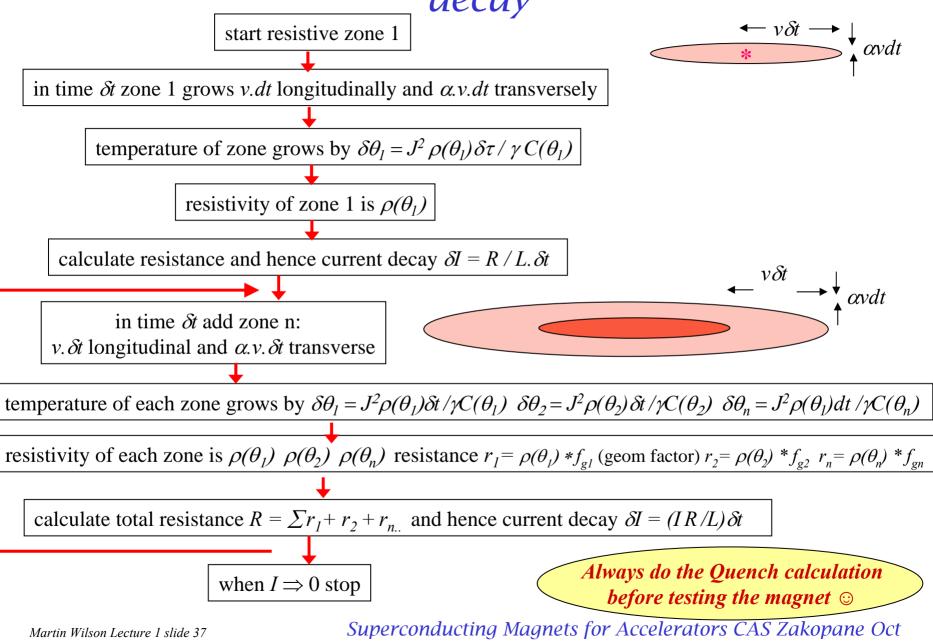
$$v_{long} = \frac{J}{\gamma C} \left\{ \frac{\rho k}{\theta_t - \theta_0} \right\}^{\frac{1}{2}}$$



where: J = engineering current density, $\gamma =$ density, C = specific heat, $\rho =$ resistivity, k = thermal conductivity, $\theta_t =$ transition temperature



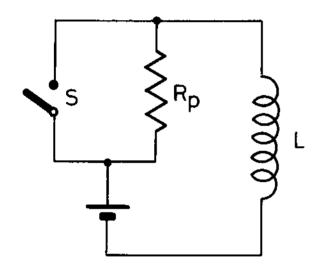
Computation of resistance growth and current decay



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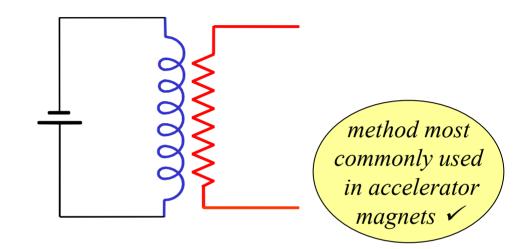
Methods of quench protection:

1) External dump resistor

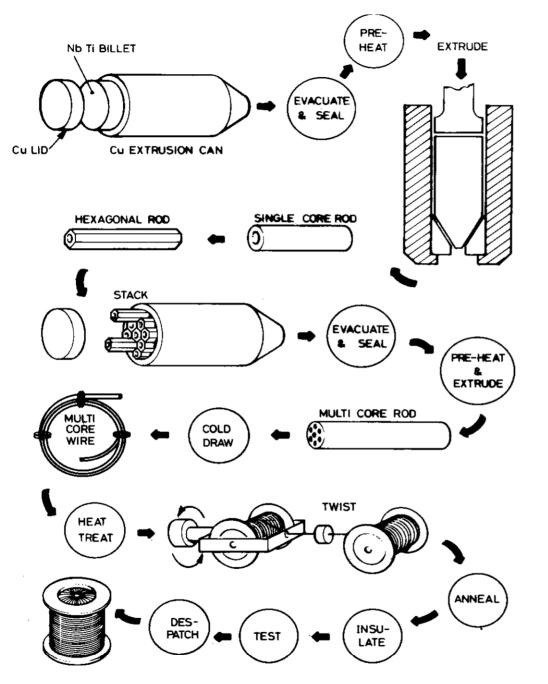


- detect the quench electronically
- open an external circuit breaker
- force the current to decay through the resistor





- detect the quench electronically
- power a heater in thermal contact with the winding
- this quenches other regions of the magnet, forcing the normal zone to grow more rapidly
 - \Rightarrow higher resistance
 - \Rightarrow shorter decay time
 - \Rightarrow lower temperature rise at the hot spot

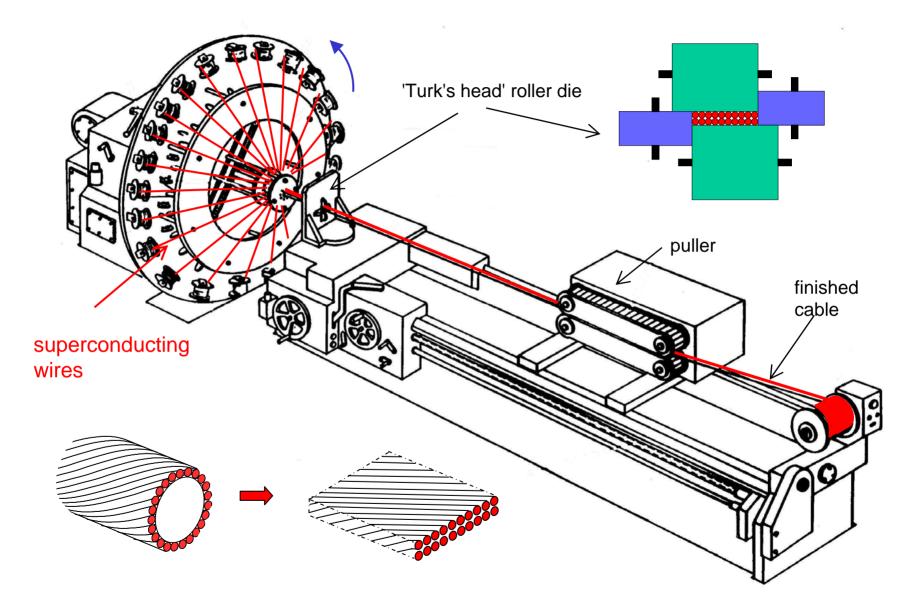


Manufacture of NbTi

- 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

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Cable manufacture



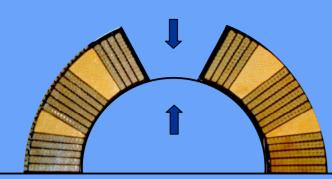
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Winding an LHC dipole



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adhesive under pressure



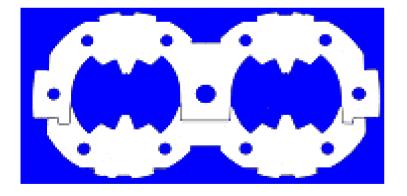


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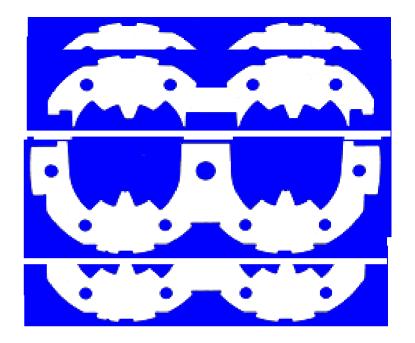
Collars

How to make an external structure that

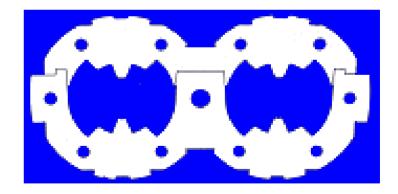
- fits tightly round the coil
- presses it into an accurate shape
- has low ac losses
- can be mass produced cheaply
- ???
- Answer make collars by precision stamping of stainless steel or aluminium alloy plate a few mm thick
- inherited from conventional magnet laminations



invert alternate pairs so that they interlock



press collars over coil from above and below



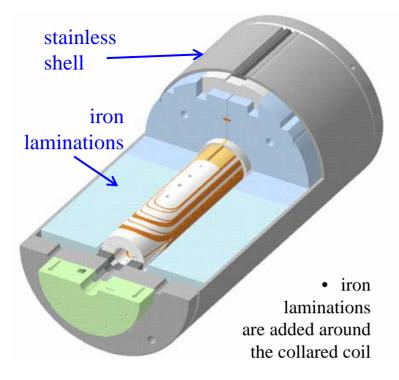
push steel rods through holes to lock in position

Collars and end plate (LHC dipole)



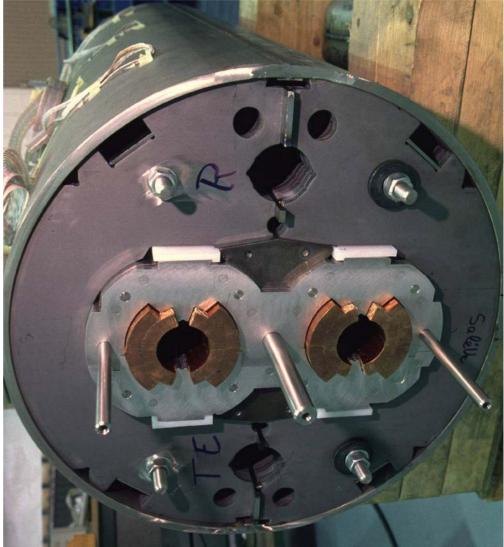


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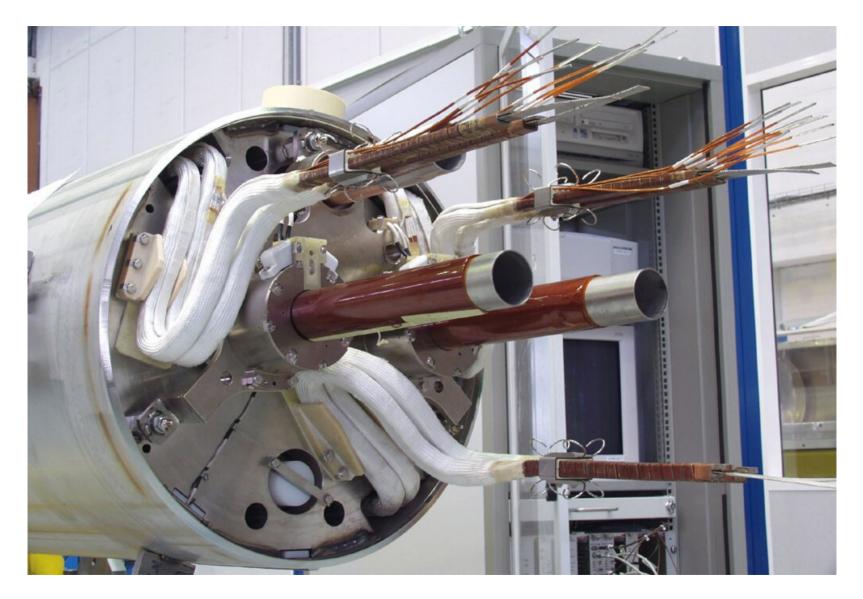


- they are forced into place, again using the collaring press
- remember however that pure iron becomes brittle at low temperature
- the tensile forces are therefore taken by a stainless steel shell which is welded around the iron, while still in the press
- this stainless shell can also serve as the helium vessel

Adding the iron

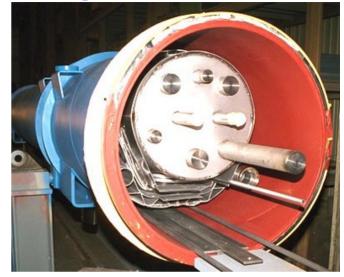


Dipole inside its stainless shell





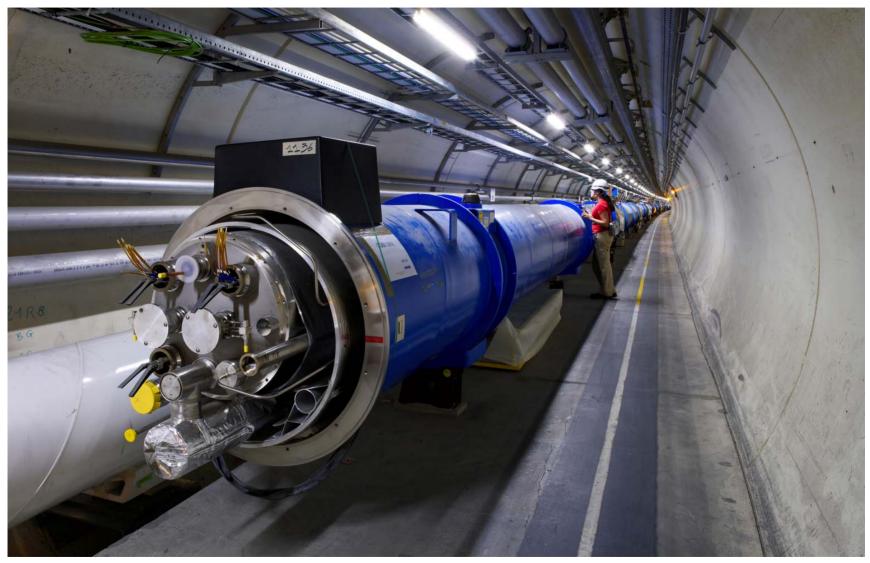
Complete magnet in cryostat





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Make a lot of Magnets and install in the tunnel



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Concluding remarks

- superconductivity offers higher magnetic fields and field gradients, with less energy dissipation
- NbTi is the most common superconducting material and has been used in all accelerators to date
- superconducting magnets do not use iron to shape the field, so must use special winding shapes
- engineering current density is a crucial factor in magnet design
- magnets don't reach their expected current/field first time but show training
- persistent screening currents produce magnetization of the superconductor which causes field errors and ac loss need fine ~ $5\mu m$ filaments
- accelerators need high currents, so must use many wires in parallel a cable
- magnets store large inductive energy which is released at quench as heating must protect
- manufacture of wires and cables is an industrial process
- for magnet manufacture, techniques have been developed to ensure accurate winding shape and minimize conductor movement

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Some useful references

Superconducting Magnets

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- Handbook of Applied Superconductivity ed B Seeber, pub UK Institute Physics 1998
- JUAS lectures on superconducting magnets (and all accelerator topics) http://juas.in2p3.fr
- 'Superconducting Accelerator Magnets' DVD available from <u>mjball @ comcast.net</u>

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- High Temperature Superconductors: Processing and Science, A Bourdillon and NX Tan Bourdillon, Academic Press, ISBN 0 12 117680 0

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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 data web sites

- 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 <u>www.cryogenics.nist.gov</u>
- Plots and automated data-look-up using the NIST equations are available on the web for a fee from <u>www.cpia.jhu.edu</u>
- Other fee web sites that use their own fitting equations for a number of cryogenic material properties include: <u>www.cryodata.com</u> (cryogenic properties of about 100 materials),

and <u>www.jahm.com</u> (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 <u>www.matweb.com</u> *thanks to Jack Ekin of NIST for this information*

Cryodata Software Products

GASPAK

properties of pure fluids from the triple point to high temperatures.

<u>HEPAK</u>

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. <u>METALPAK, CPPACK, EXPAK</u>

reference properties of metals and other solids, 1 - 300 K.

<u>CRYOCOMP</u>

properties and thermal design calculations for solid materials, 1 - 300 K. SUPERMAGNET

four unique engineering design codes for superconducting magnet systems.

<u>KRYOM</u>

numerical modelling calculations on radiation-shielded cryogenic enclosures.