Superconducting magnets for Accelerators

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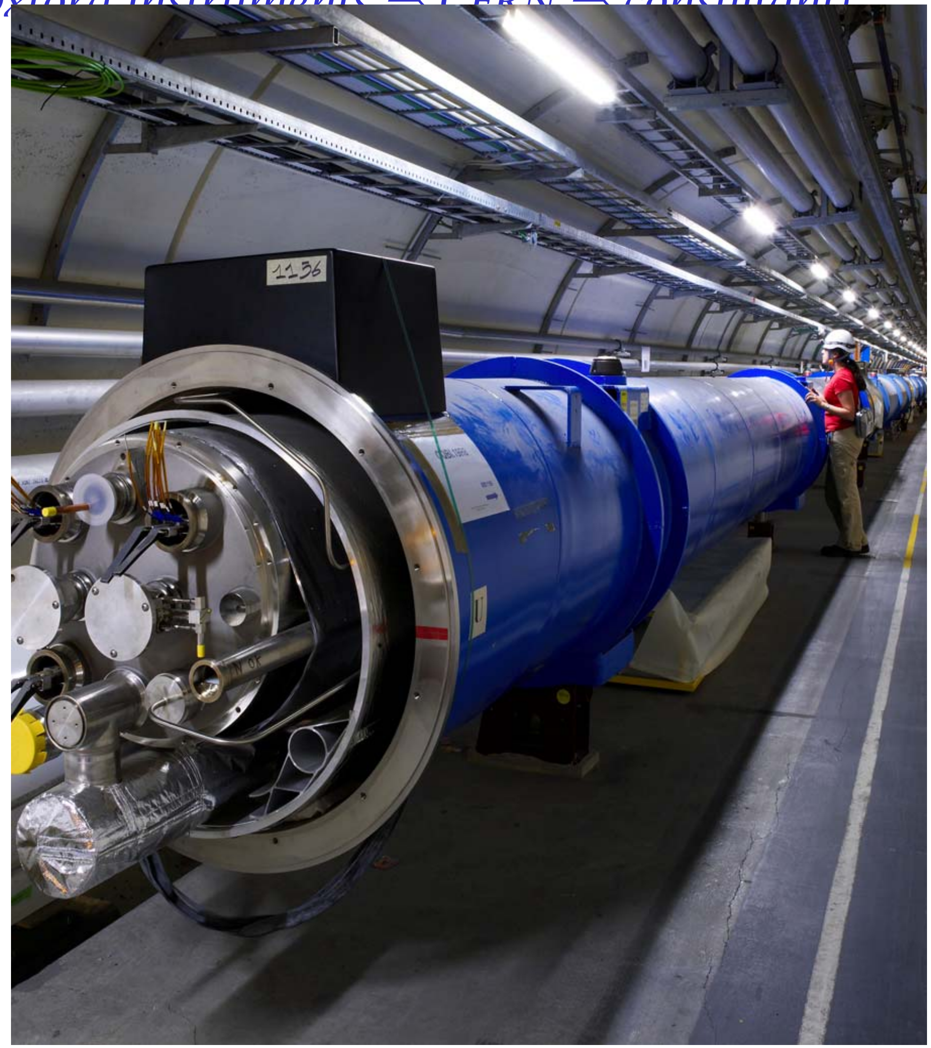
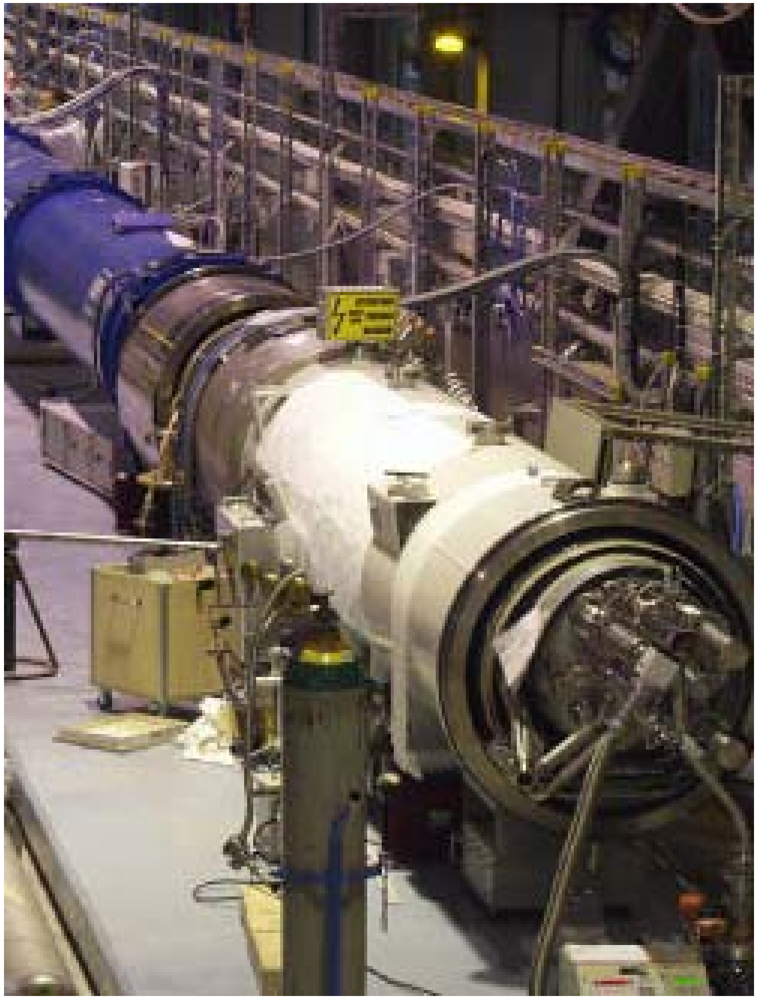
Outline

- 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
- fine filaments, composite wires & cables
- magnetization, field errors & ac losses
- quenching and protection
- hardware
- where to get more info



Who needs superconductivity anyway?



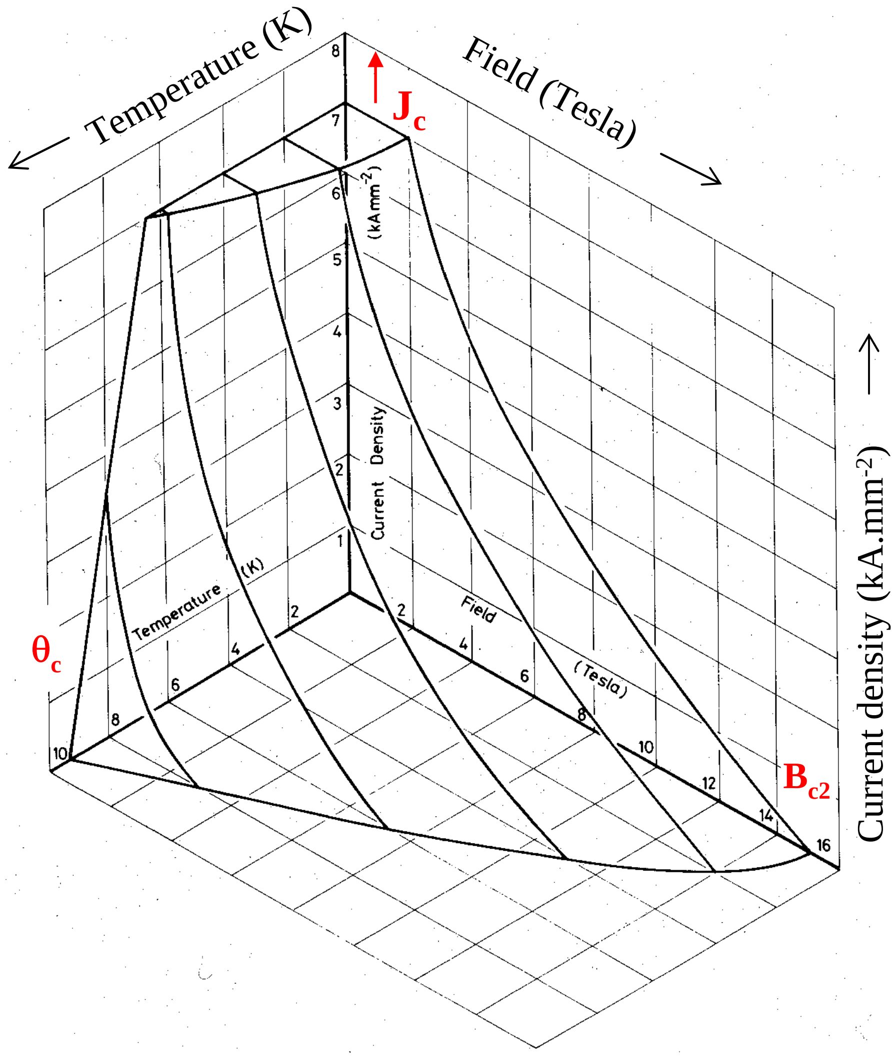
Abolish Ohm's Law!

- 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

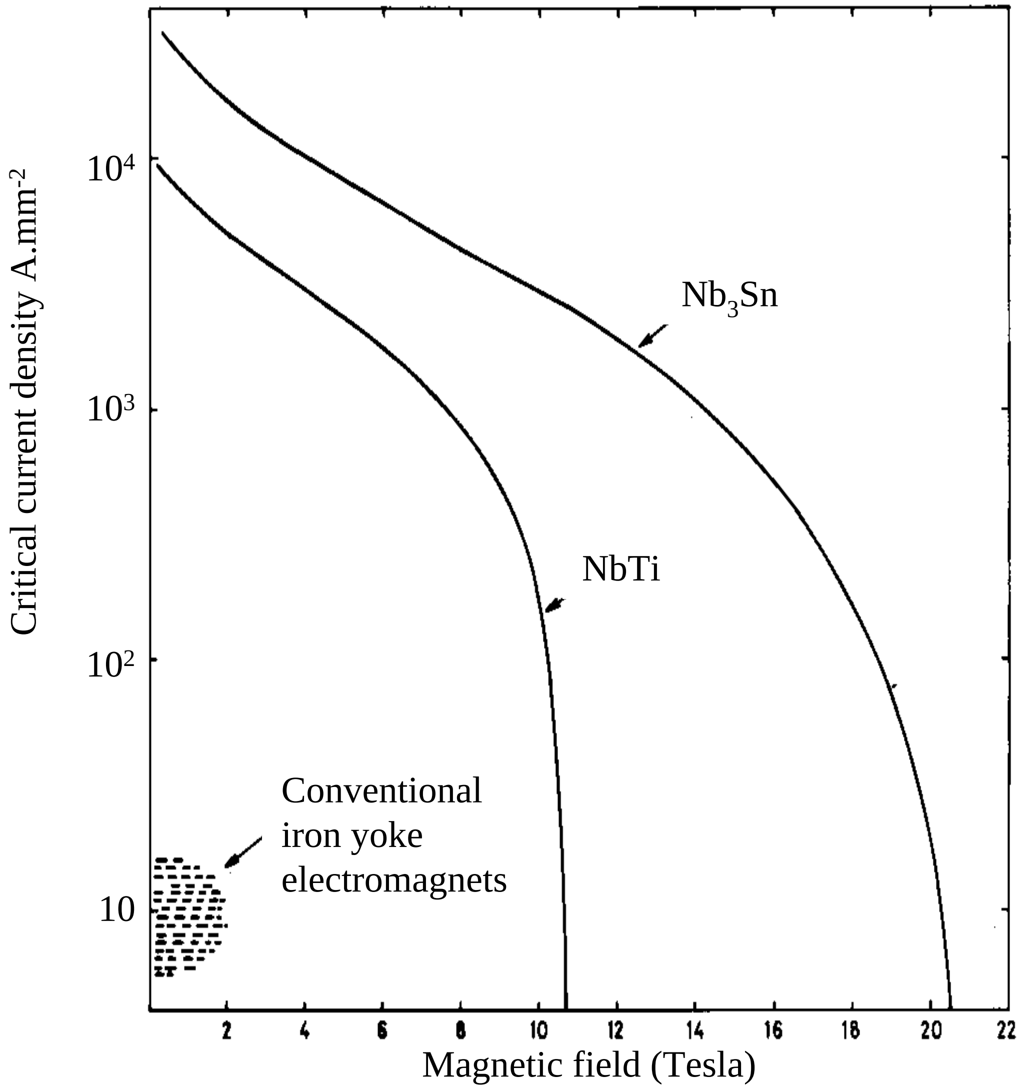
- lower power bills
- higher magnetic fields mean reduced bend radius
  ⇒ smaller rings
  ⇒ reduced capital cost
  ⇒ new technical possibilities
  (eg muon collider)
- higher quadrupole gradients
  ⇒ higher luminosity

The critical surface of niobium titanium



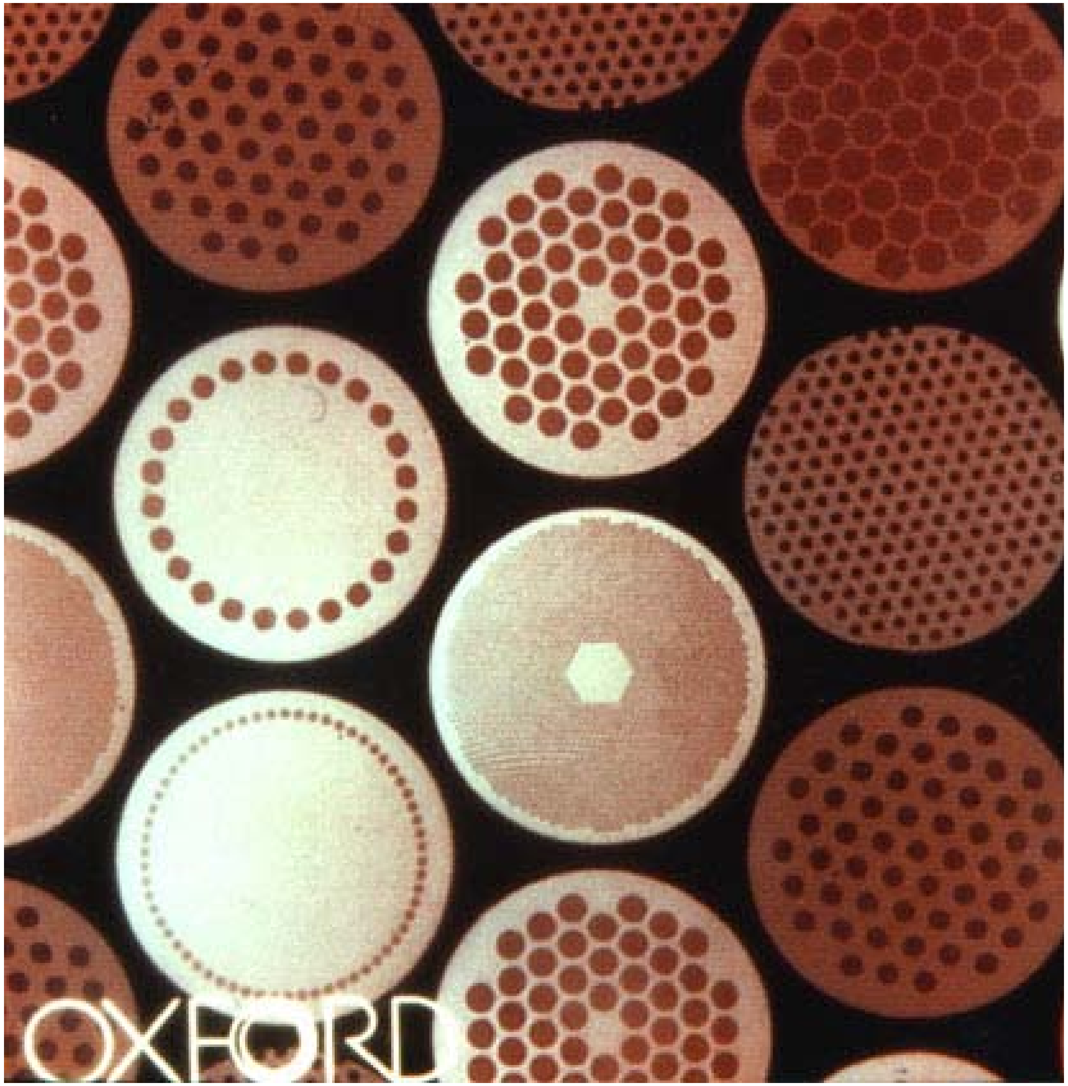
- Niobium titanium **NbTi** is the standard 'work horse' of the superconducting magnet business
- it is a ductile alloy
- picture shows the **critical surface**, which is the boundary between superconductivity and normal resistivity in 3 dimensional space
- superconductivity prevails everywhere below 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

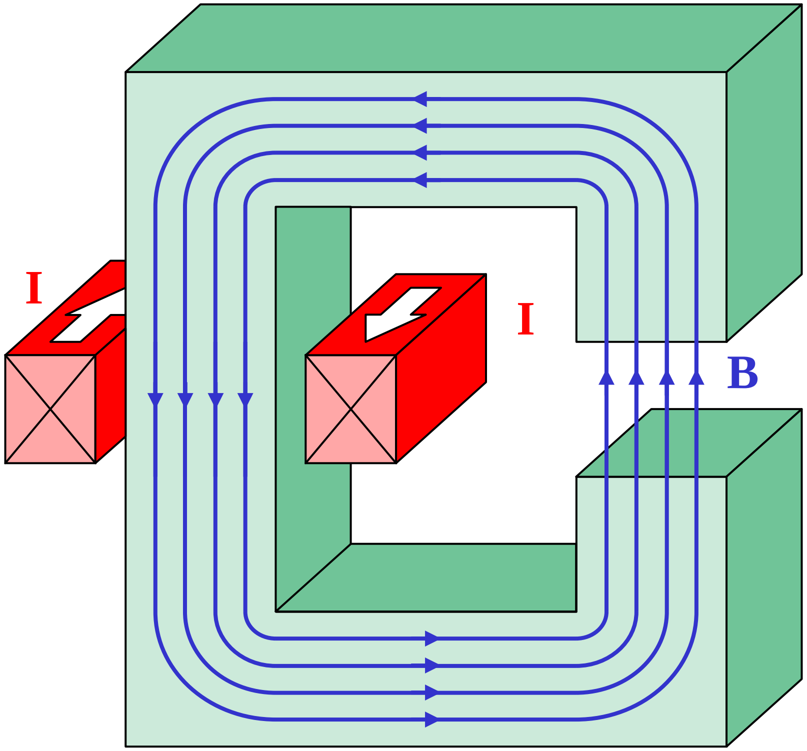
Filamentary composite wires



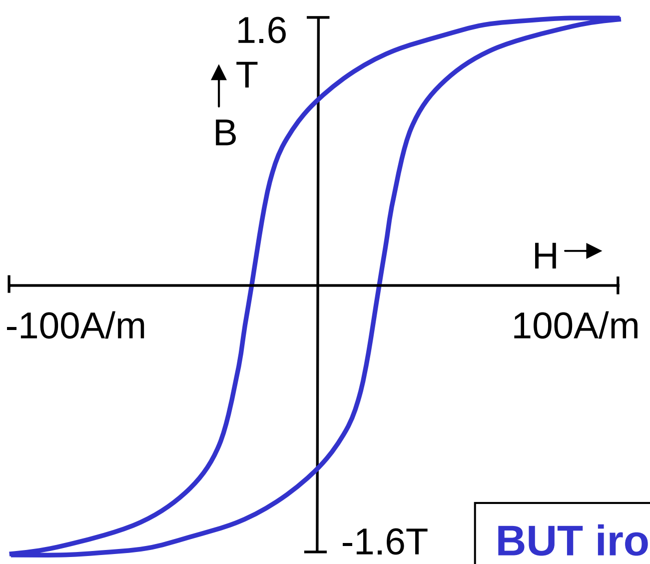
- for reasons that will be described later, superconducting materials are always used in combination with a good normal conductor such as copper
- to ensure intimate mixing between the two, the superconductor is made in the form of fine filaments embedded in a matrix of copper
- typical dimensions are:
- wire diameter = 0.3 - 1.0mm
- filament diameter = 5 - 50μm
- 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
  - ⇒ reduces ampere turns required
  - ⇒ reduces power consumption
- iron guides and shapes the field



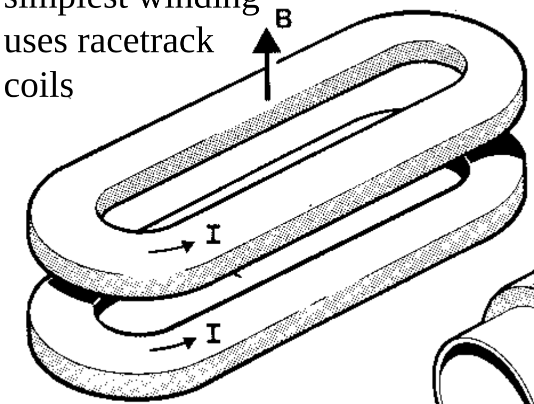
Iron electromagnet
– for accelerator, HEP experiment
transformer, motor, generator, etc



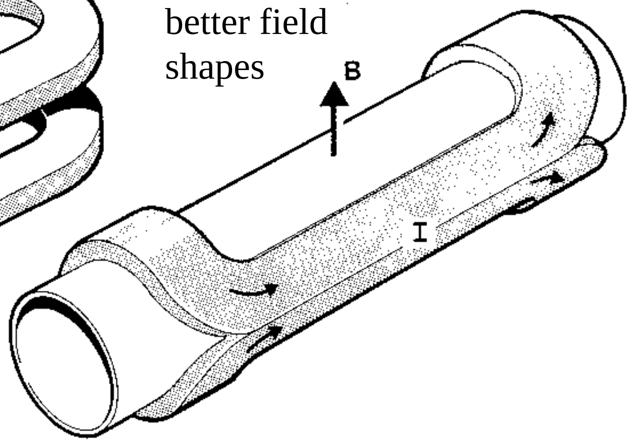
BUT iron saturates at ~ 2T

Fields and ways to create them: superconducting dipoles

simplest winding uses racetrack coils

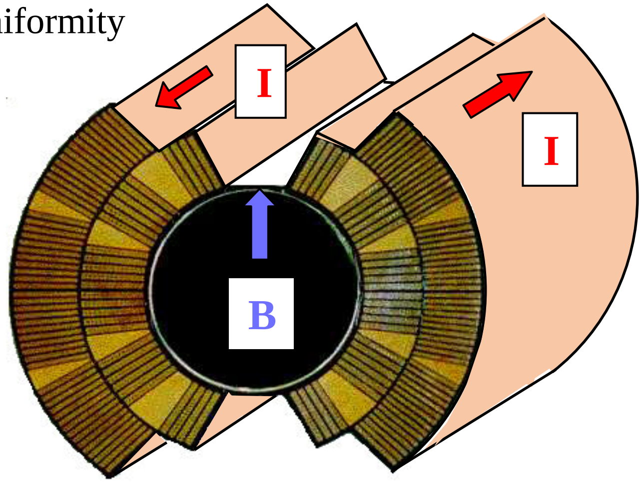


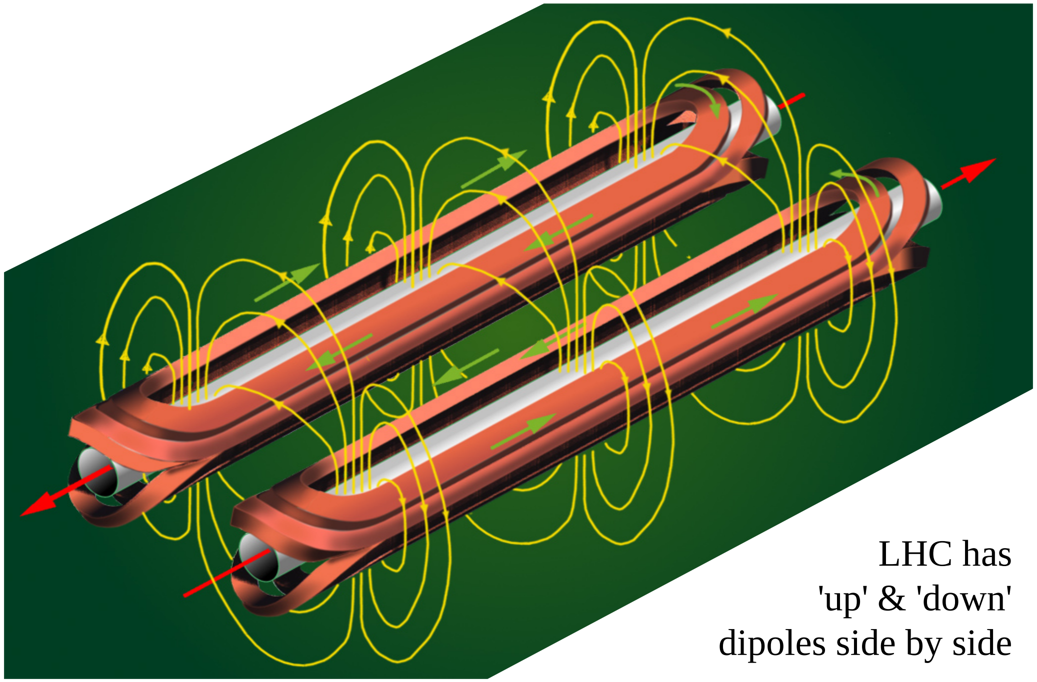
'saddle' coils make better field shapes



- 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





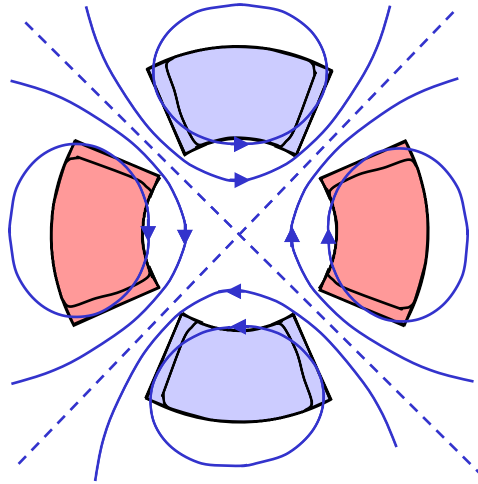
LHC has 'up' & 'down' dipoles side by side

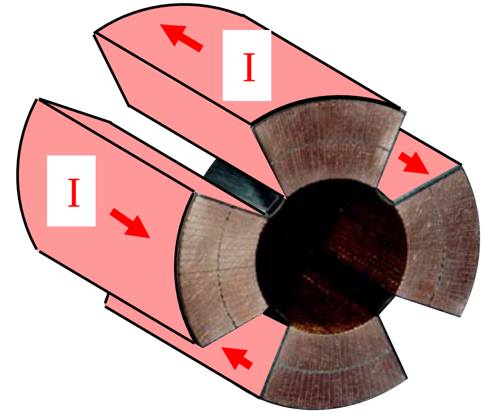
Dipole Magnets

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

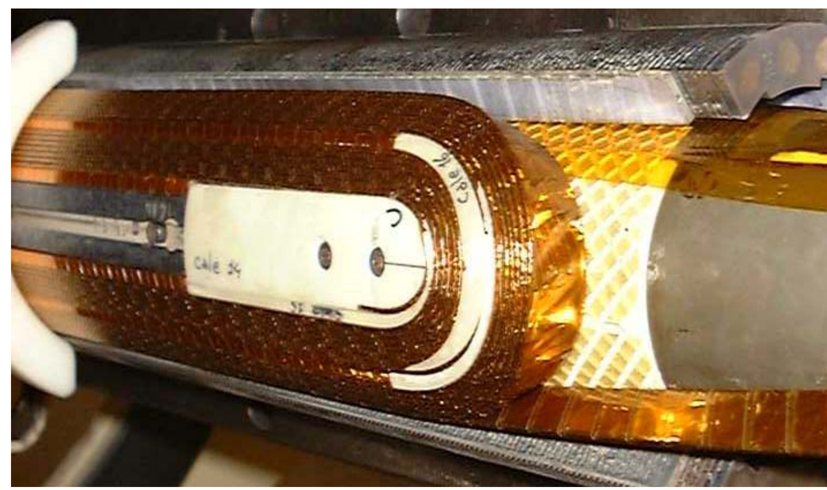
Fields and ways to create them: superconducting quadrupoles

- gradient fields produce focussing
- quadrupole windings

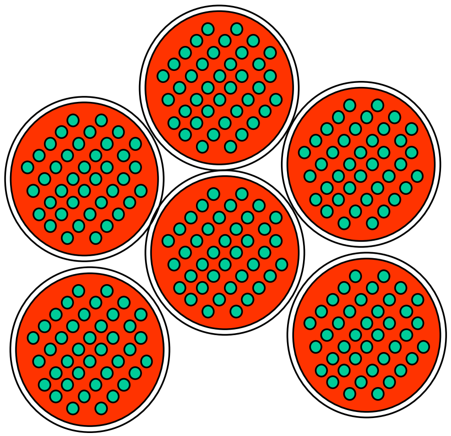




$B_x = ky$ $\qquad$ $B_y = kx$



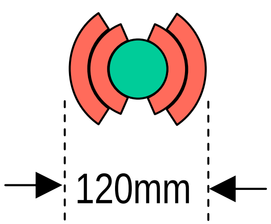
Engineering current density



engineering current density $J_{eng} = J_{sup} \times$ dilution

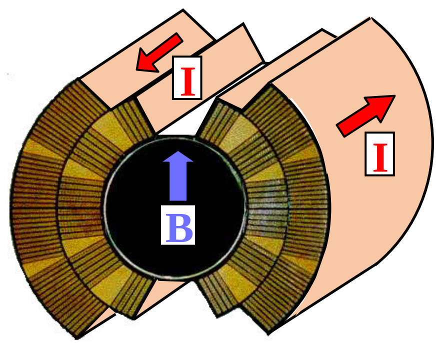
dilution (by copper, insulation, structure) ~ 33%

J_e = 375 Amm^{-2}



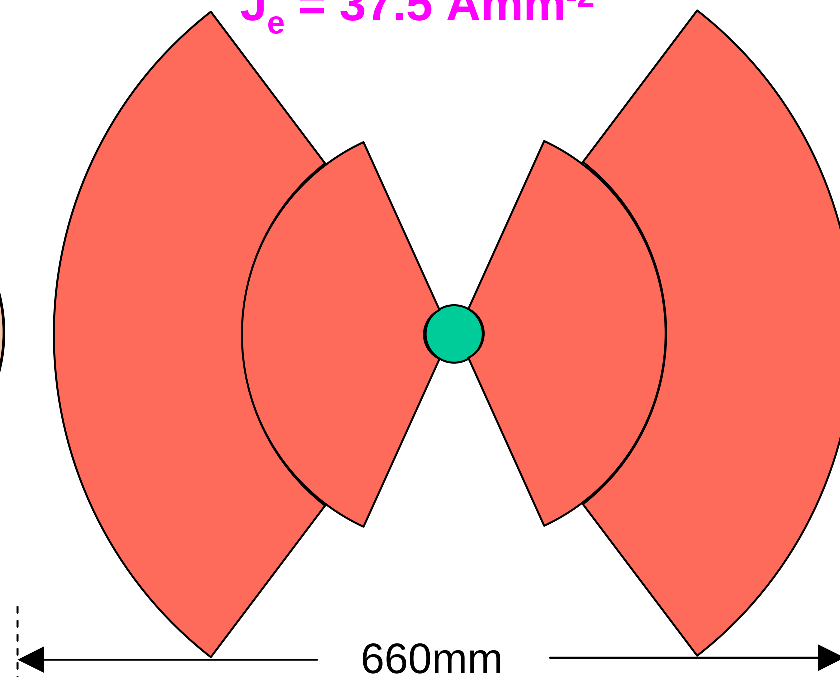
9.5x10^5 Amp turns

=1.9x10^6 A.m per m



LHC dipole

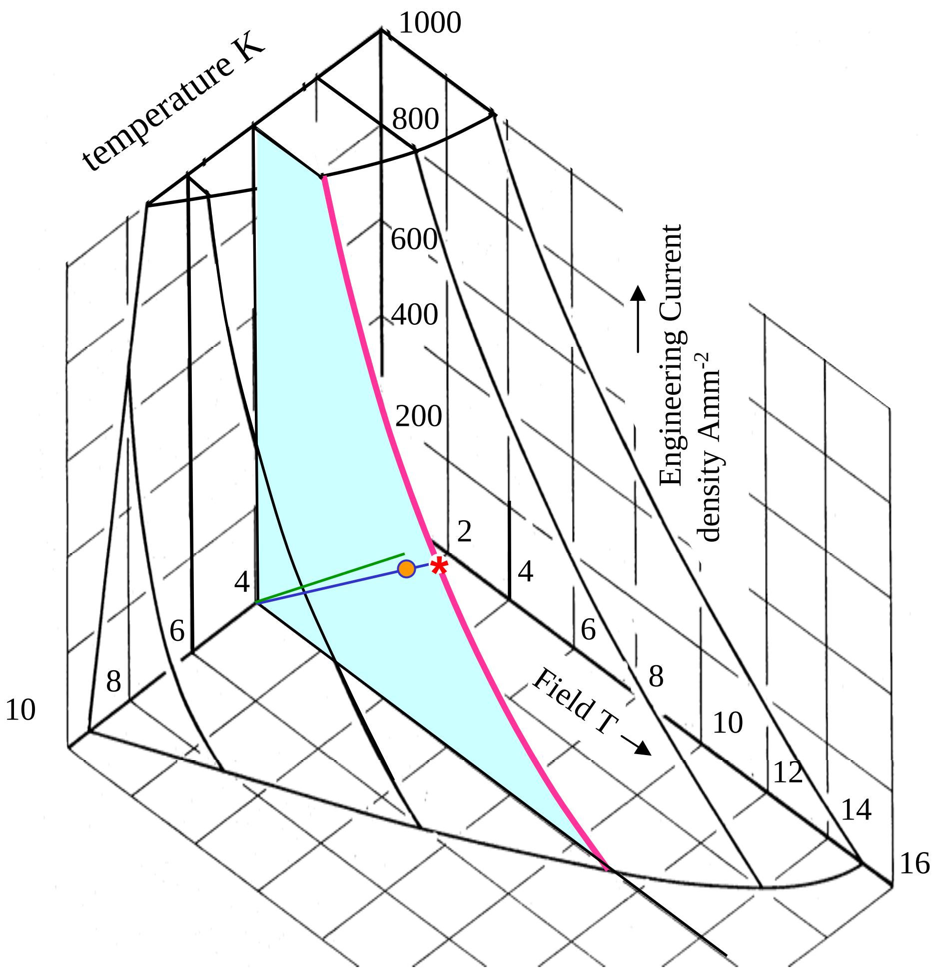
J_e = 37.5 Amm^{-2}

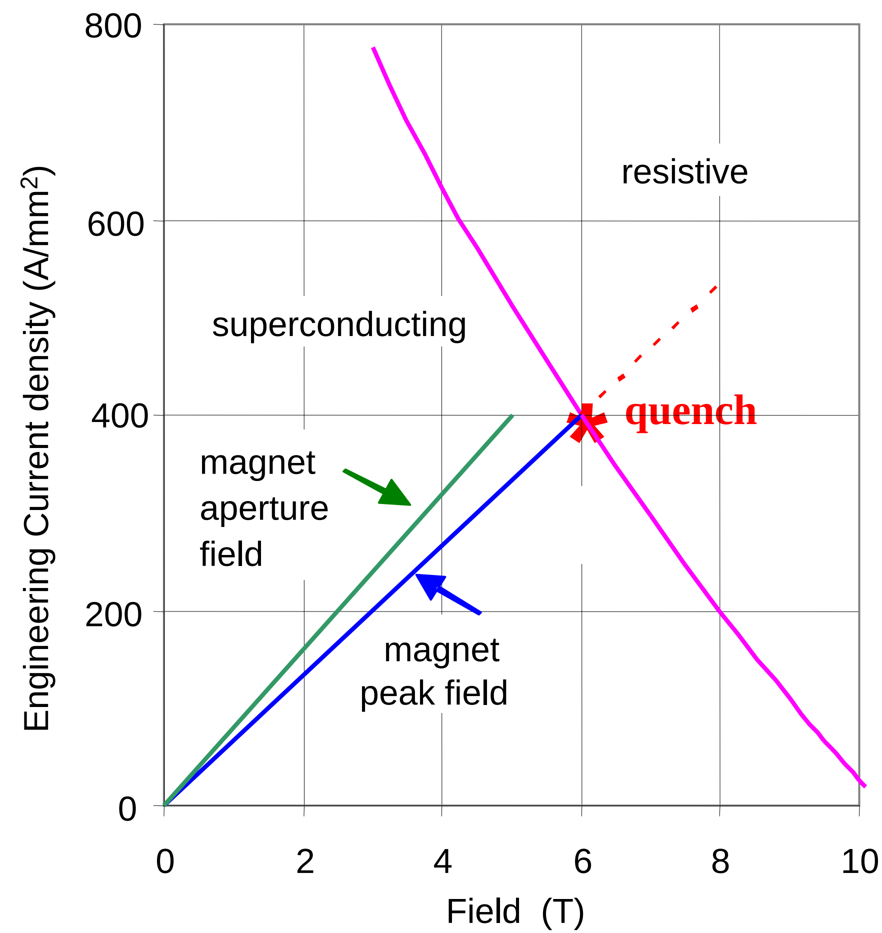


9.5x10^6 Amp turns

=1.9x10^7 A.m per m

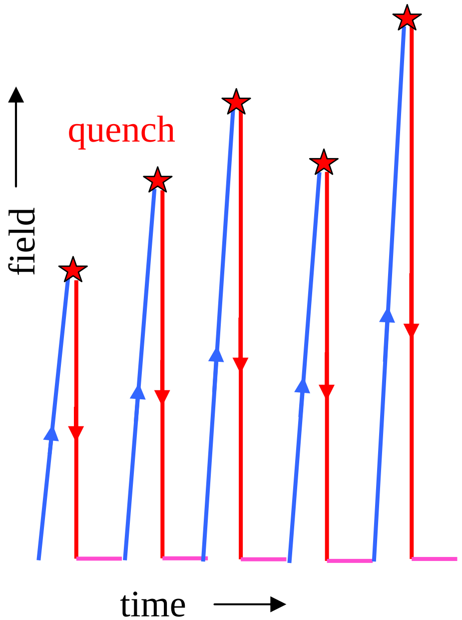
Critical line and magnet load lines

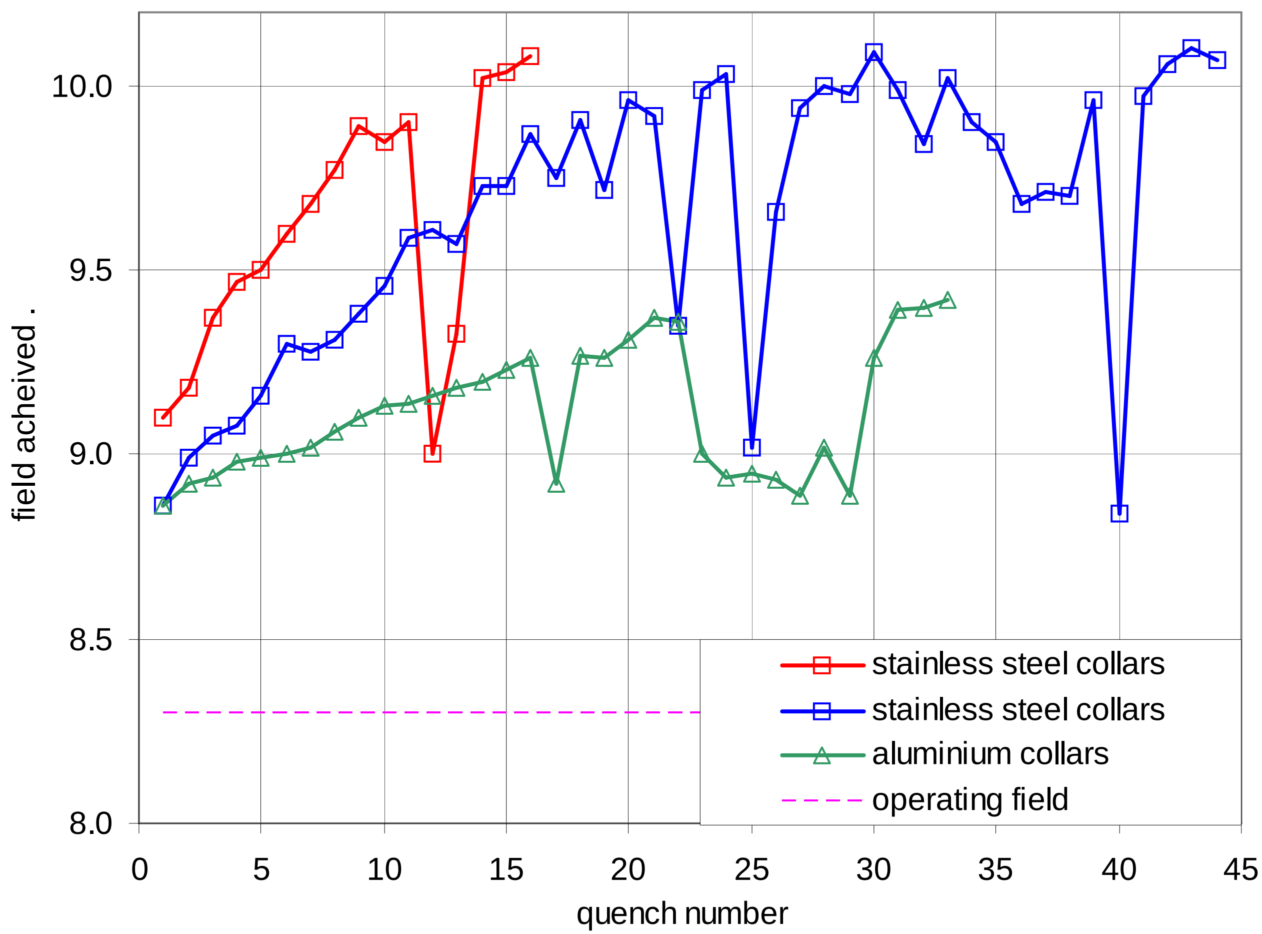




we expect the magnet to go resistive ***'quench'*** where the peak field load line crosses the critical current line *

'Training' of magnets

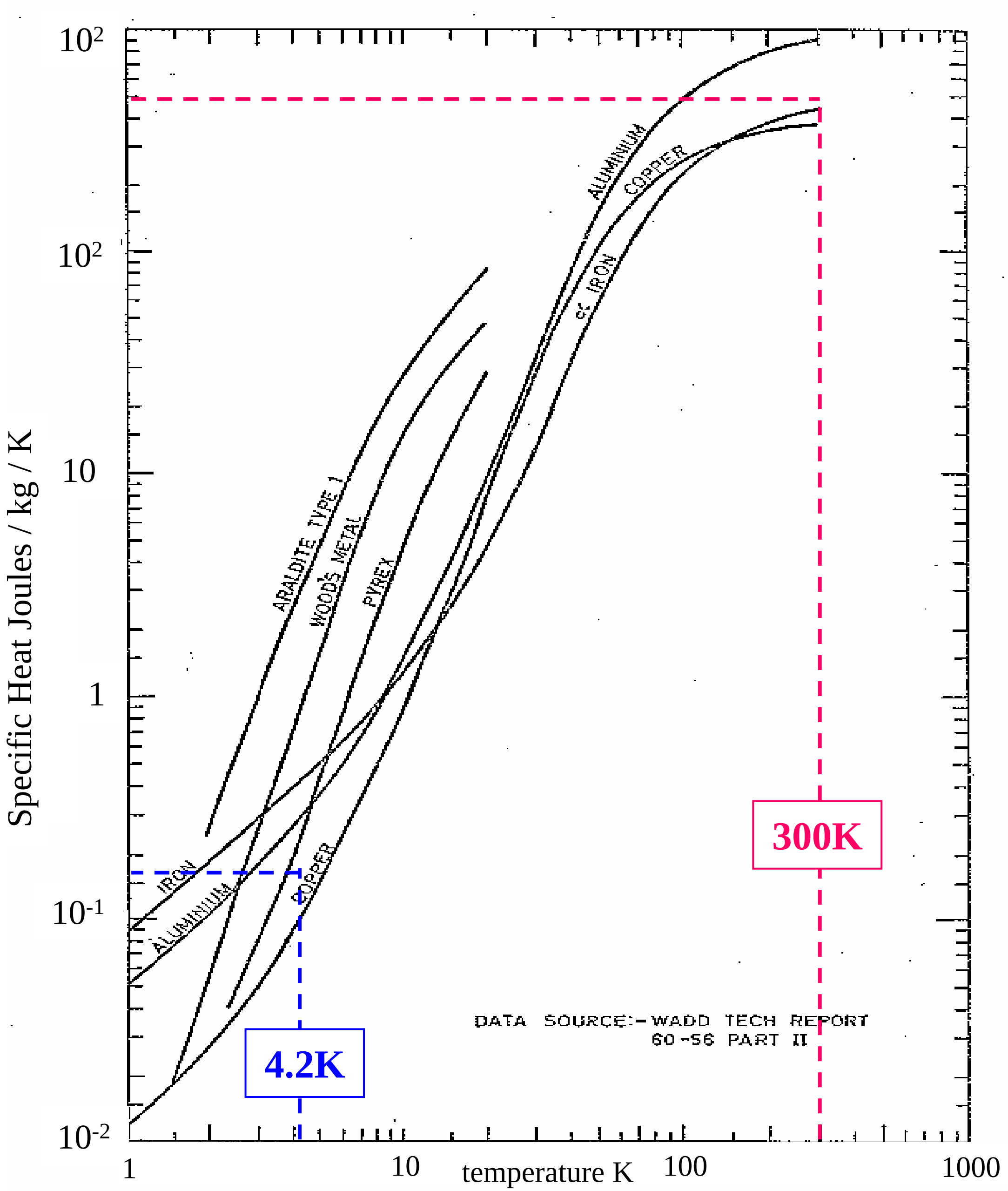




- when the current (and field) of a magnet is ramped up for the first time, it usually 'quenches' (goes resistive) at less than the expected current
- at the next try it does better
- known as ***training***

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

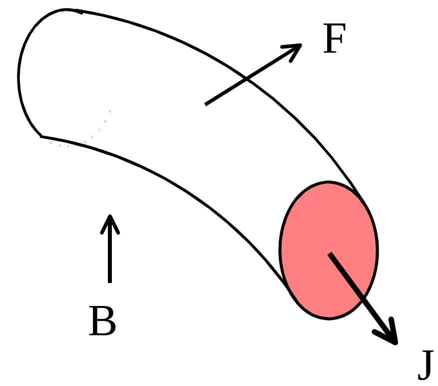
Causes of training: (1) low specific heat



- 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

Causes of training: (2) conductor motion

- Big electromagnetic forces in magnets
- Bursting force in LHC dipoles = 320 tonne/m
- Conductors are pushed by the electromagnetic forces.
- Frictional heating if they move



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

so if $\delta = 10$ μm

then Q = 2.5×10^4 J.m^{-3}

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

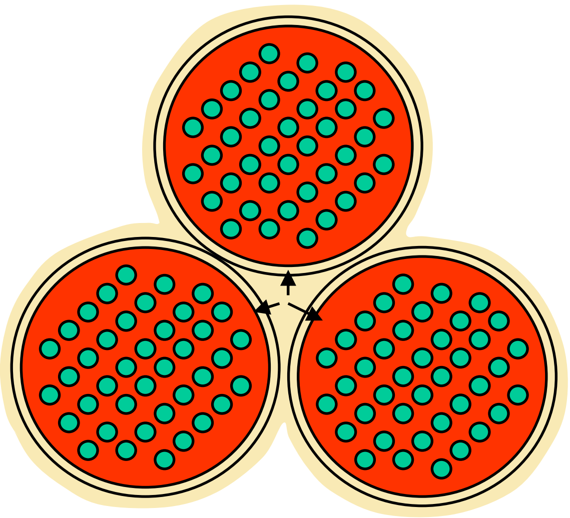
*can **you** engineer a winding to better than*

10 μm?

Causes of training: (3) resin cracking

- try to stop wire movement by impregnating the winding with epoxy resin
- the resin contracts much more than the metal - so it goes into tension
- it also 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

thermal contraction of Cu ~ 3×10^{-3} (room to 4K)

thermal contraction of resin ~ 11×10^{-3}

so $\varepsilon = (11 - 3) \times 10^{-3}$

typically $Y = 7 \times 10^{9}$ Pa   n = 1/3

strain energy $$Q_1 = \frac{\sigma^2}{2Y} = \frac{Y\varepsilon^2}{2}$$ $Q_1 = 2.5 \times 10^5$ J.m^{-3} *(uniaxial strain)*

if released adiabatically, raises temperature to $\theta_{final} = 16\text{K}$

How to reduce training?

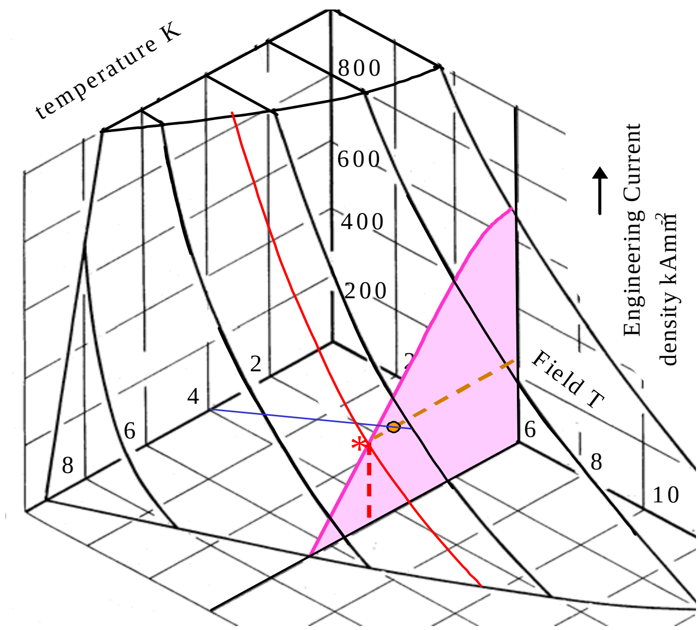
1) Reduce the disturbances occurring in the magnet winding

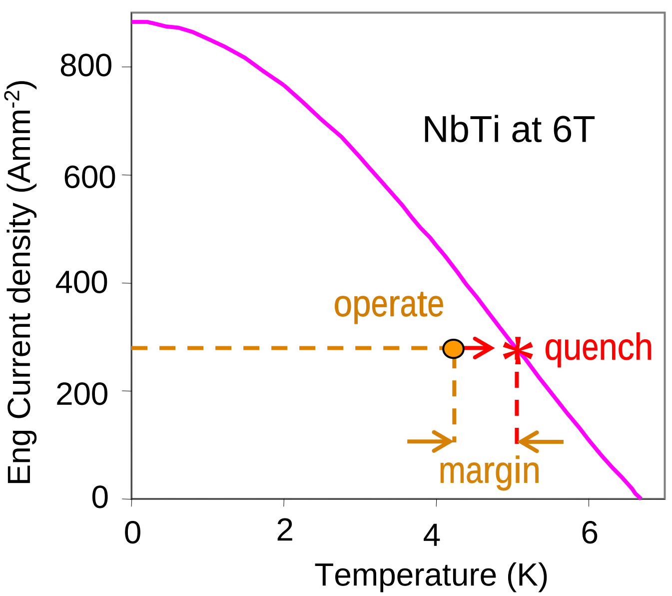
- make the winding fit together exactly to reduce movement of conductors under field forces
- pre-compress the winding to reduce movement under field forces
- if using resin, minimize the volume and choose a crack resistant type
- match thermal contractions, eg fill epoxy with mineral or glass fibre

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

2) Make the conductor able to withstand disturbances without quenching

- increase the ***temperature margin***
- increase the ***minimum quench energy***





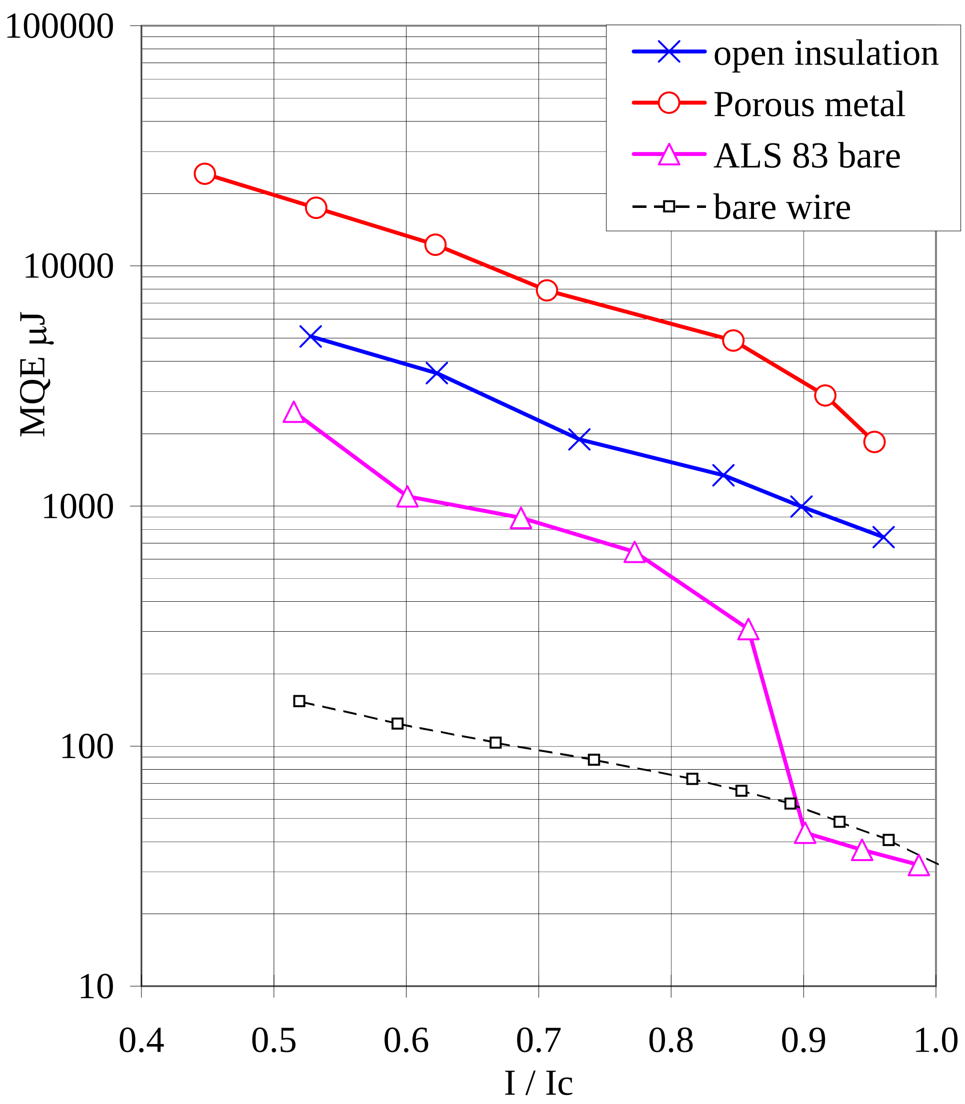
Minimum quench energy MQE

- 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
$\Rightarrow$ more stable conductor
$\Rightarrow$ less training

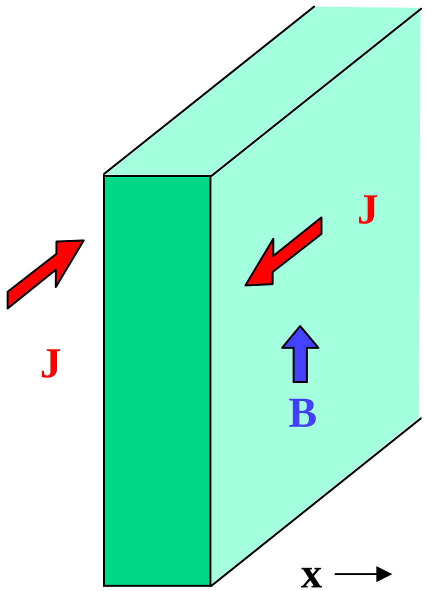
for a large MQE we need:

- 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



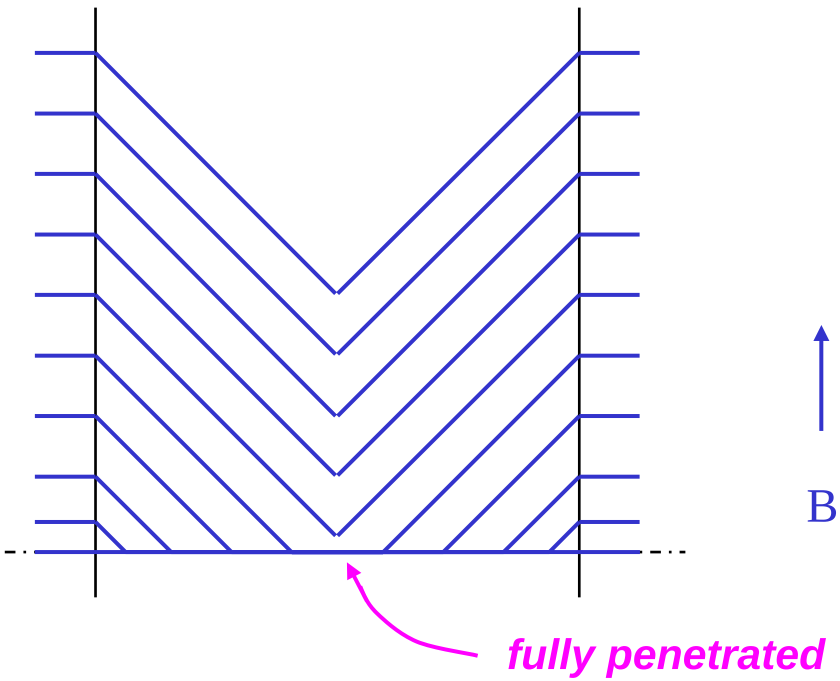
- usual model is a superconducting slab in a changing magnetic field B_y
- assume it's infinitely long in the z and y directions - simplifies to a 1 dim problem
- ***dB/dt*** induces an electric field E which causes screening currents to flow at critical current density J_c
- known as the ***critical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

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

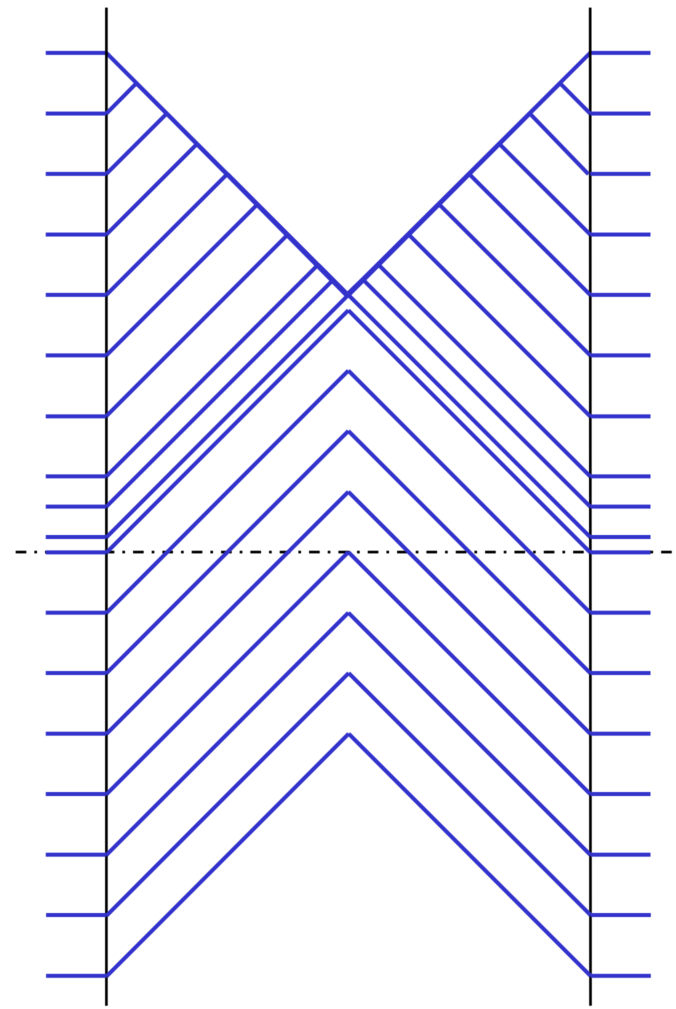
- so uniform J_c means a constant field gradient inside the superconductor

The flux penetration process

plot field profile across the slab



field increasing from zero



field decreasing through zero

everywhere current density is ± J_c or zero

(Bean model)

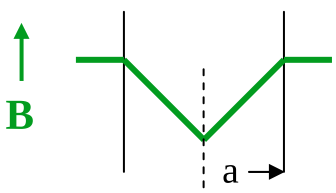
Magnetization of the Superconductor

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

define a magnetization (magnetic moment per unit volume)

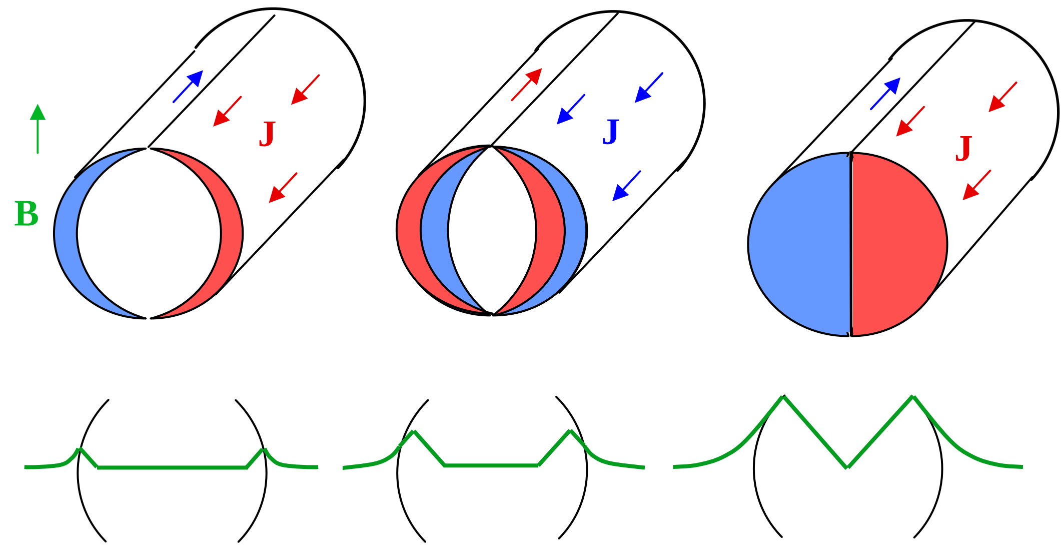
$$M = \sum_V \frac{I.A}{V} \qquad \textit{NB units of H}$$

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)

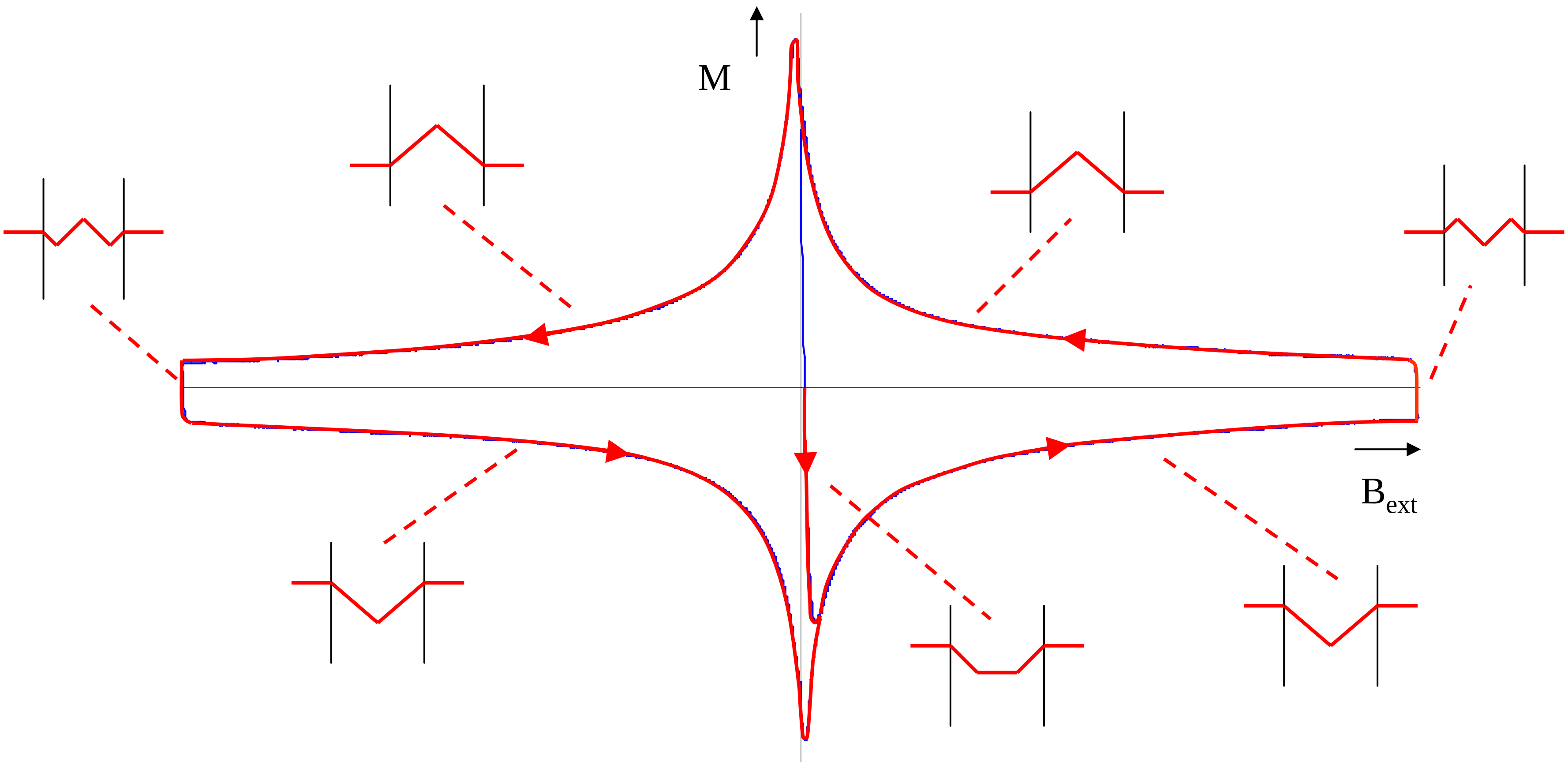


when fully penetrated, the magnetization is

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

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

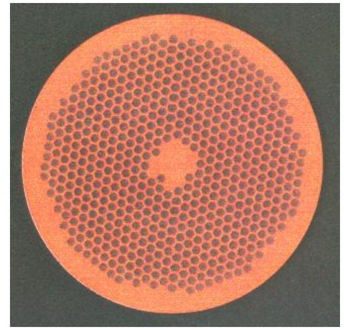
Magnetization of NbTi

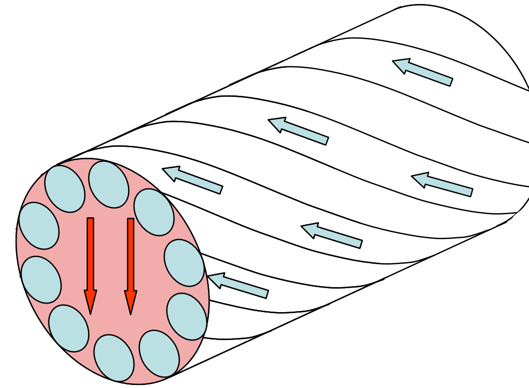


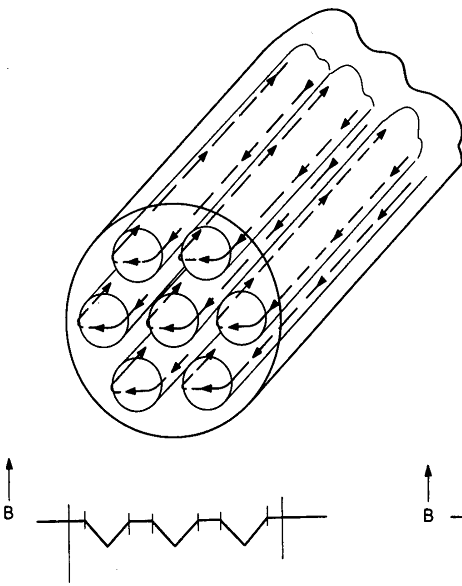
Coupling between filaments

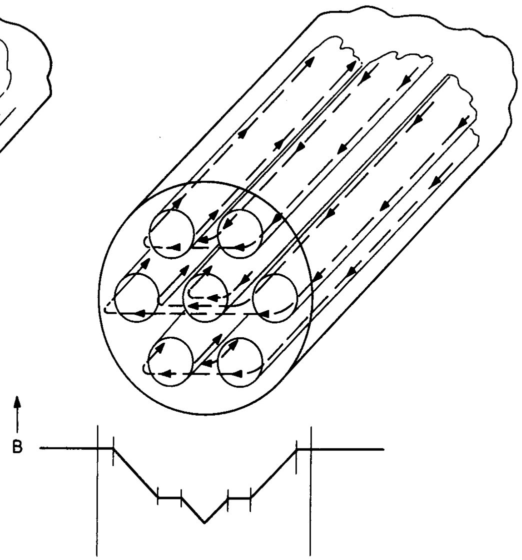
recap $M = \frac{4}{3\pi} J_c\, a$

- reduce M by making fine filaments
- for ease of handling, 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

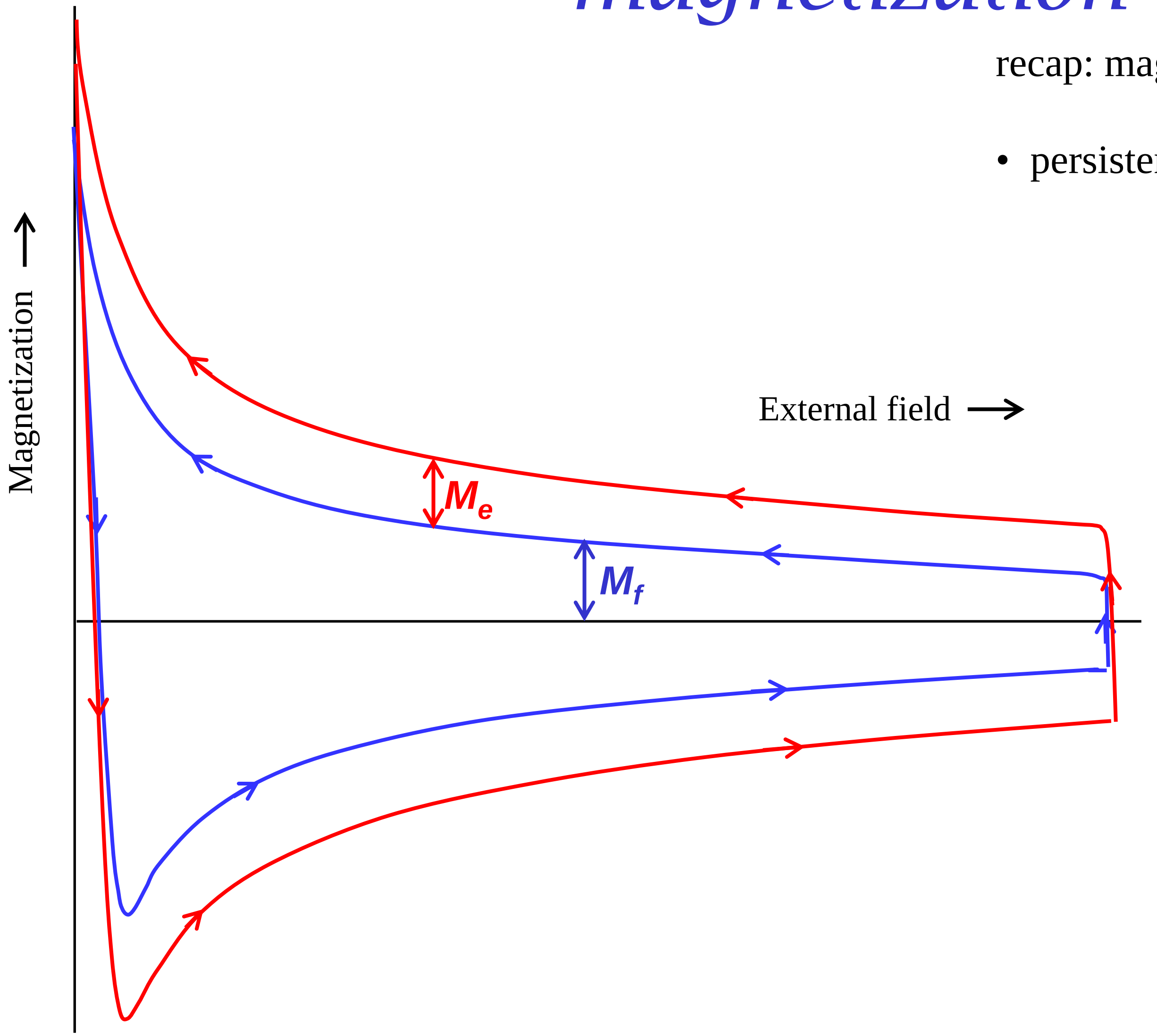
- fortunately the coupling currents may be reduced by twisting the wire

- coupling currents behave like eddy currents and produce an additional magnetization

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

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

Coupling ⇒ rate dependent magnetization



recap: magnetization has two components:

- persistent current in the filaments

$$M_f = \frac{2}{3\pi} J_c(B)\, d_f$$

M_f depends on B

- 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_e depends on dB/dt

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

Why cables?

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

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

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

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

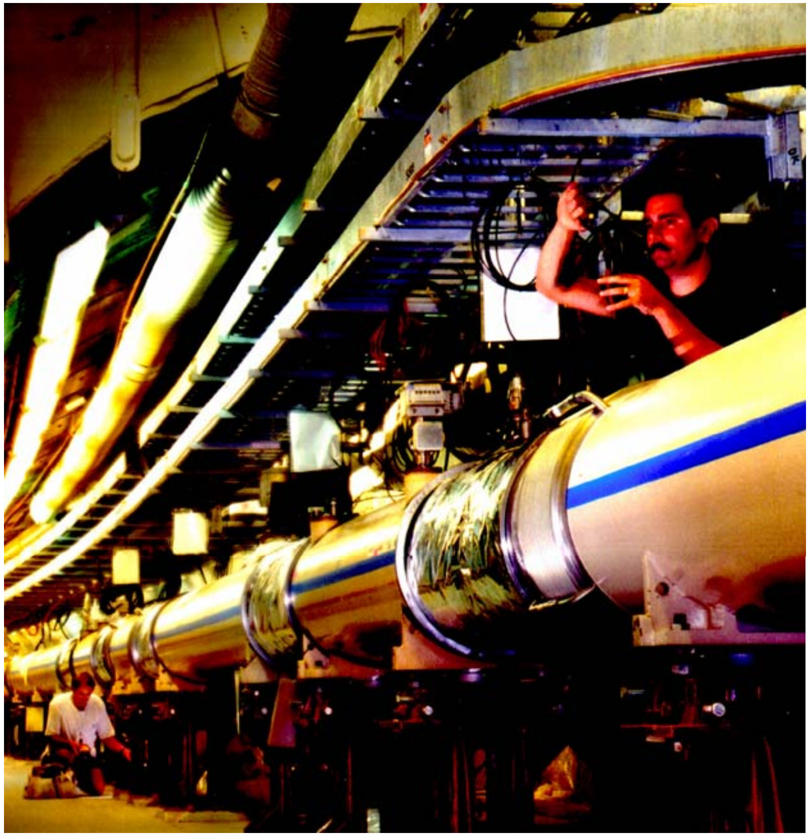
wire I = **167A**, charge voltage per km = **6400V**

FAIR at GSI E = 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**

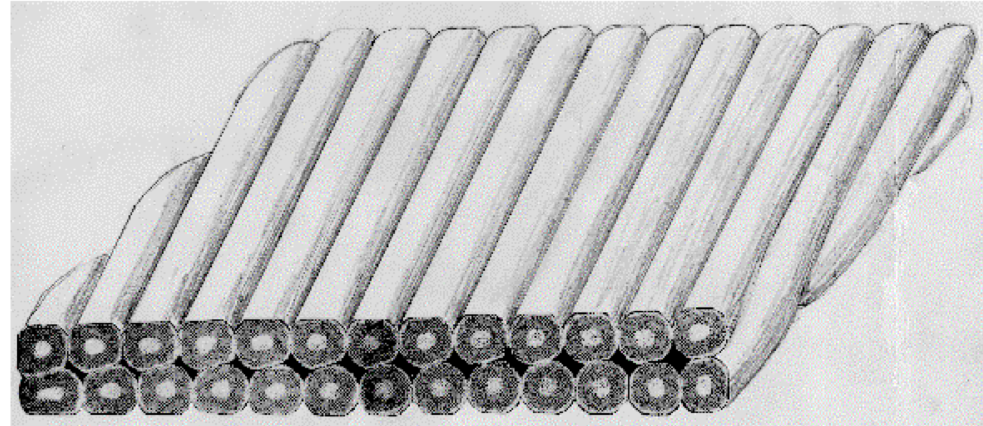
- so we need high currents!



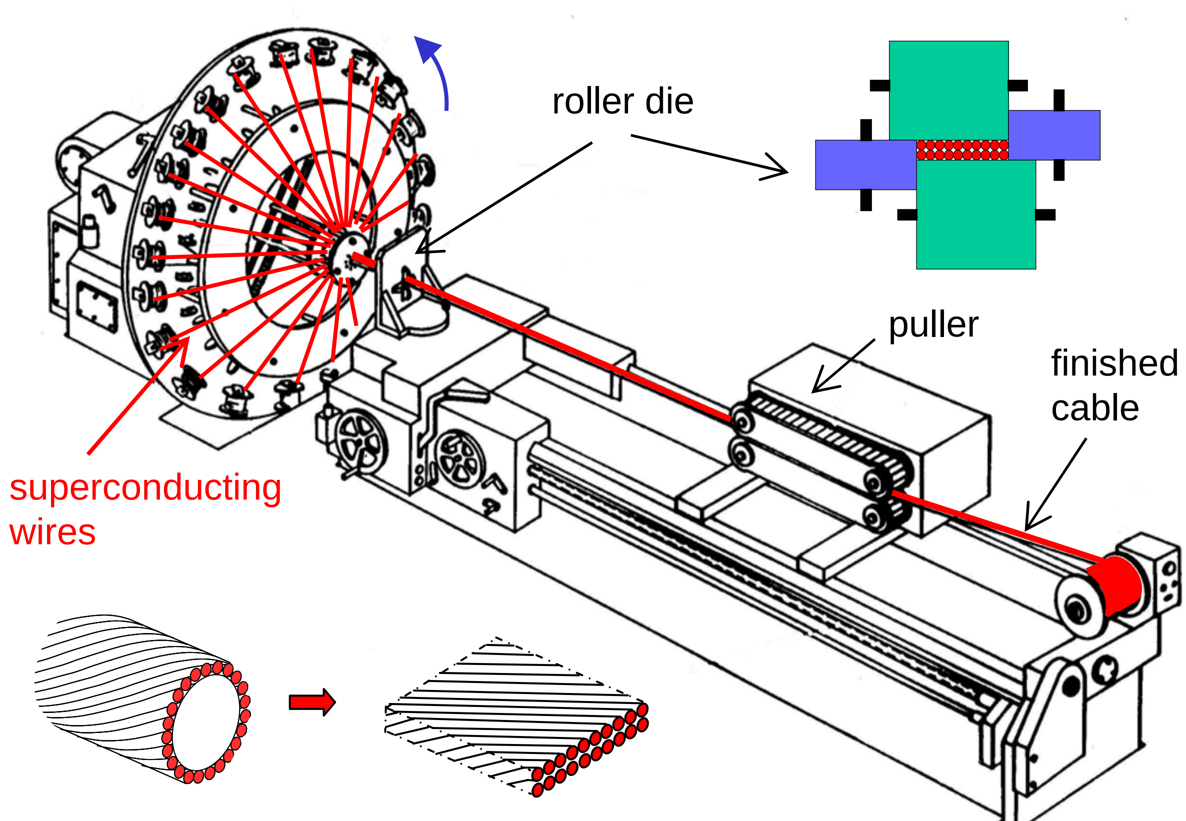
the RHIC tunnel

- a single 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

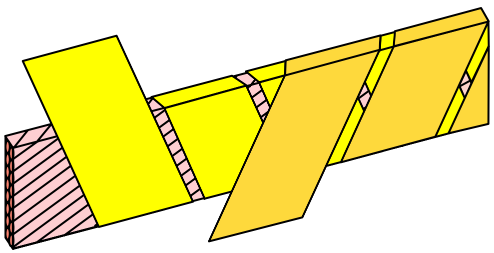
Rutherford cable



- fully transposed - every strand changes places with every other



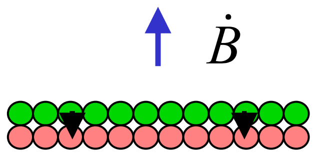
- cable insulated by wrapping 2 or 3 layers of Kapton



- gaps may be left to allow penetration of liquid helium
- outer layer is treated with an adhesive layer for bonding to adjacent turns.

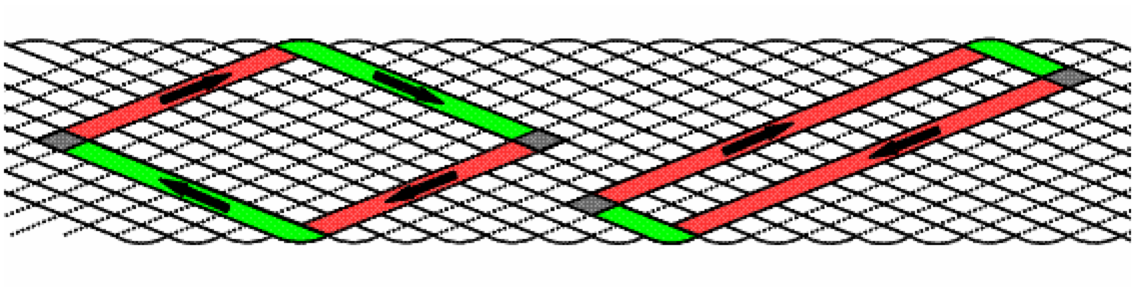
Coupling in Rutherford cables

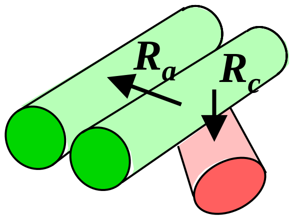
- Field transverse
  coupling via crossover resistance R_c



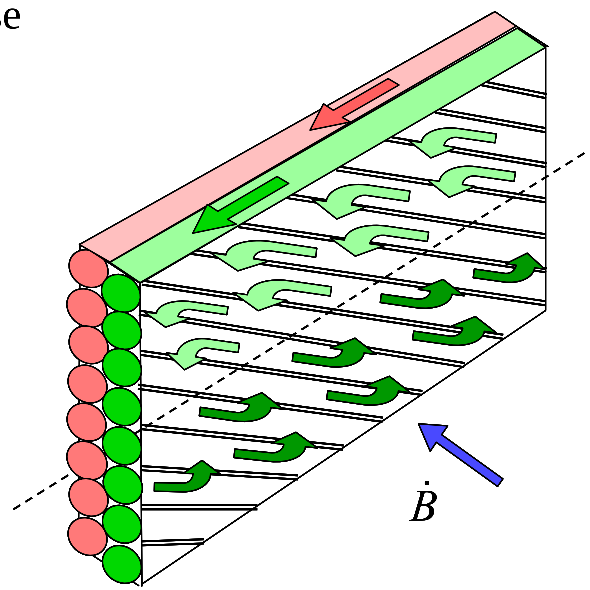
crossover resistance $\boldsymbol{R_c}$

adjacent resistance $\boldsymbol{R_a}$





- Field transverse
  coupling via adjacent resistance R_a

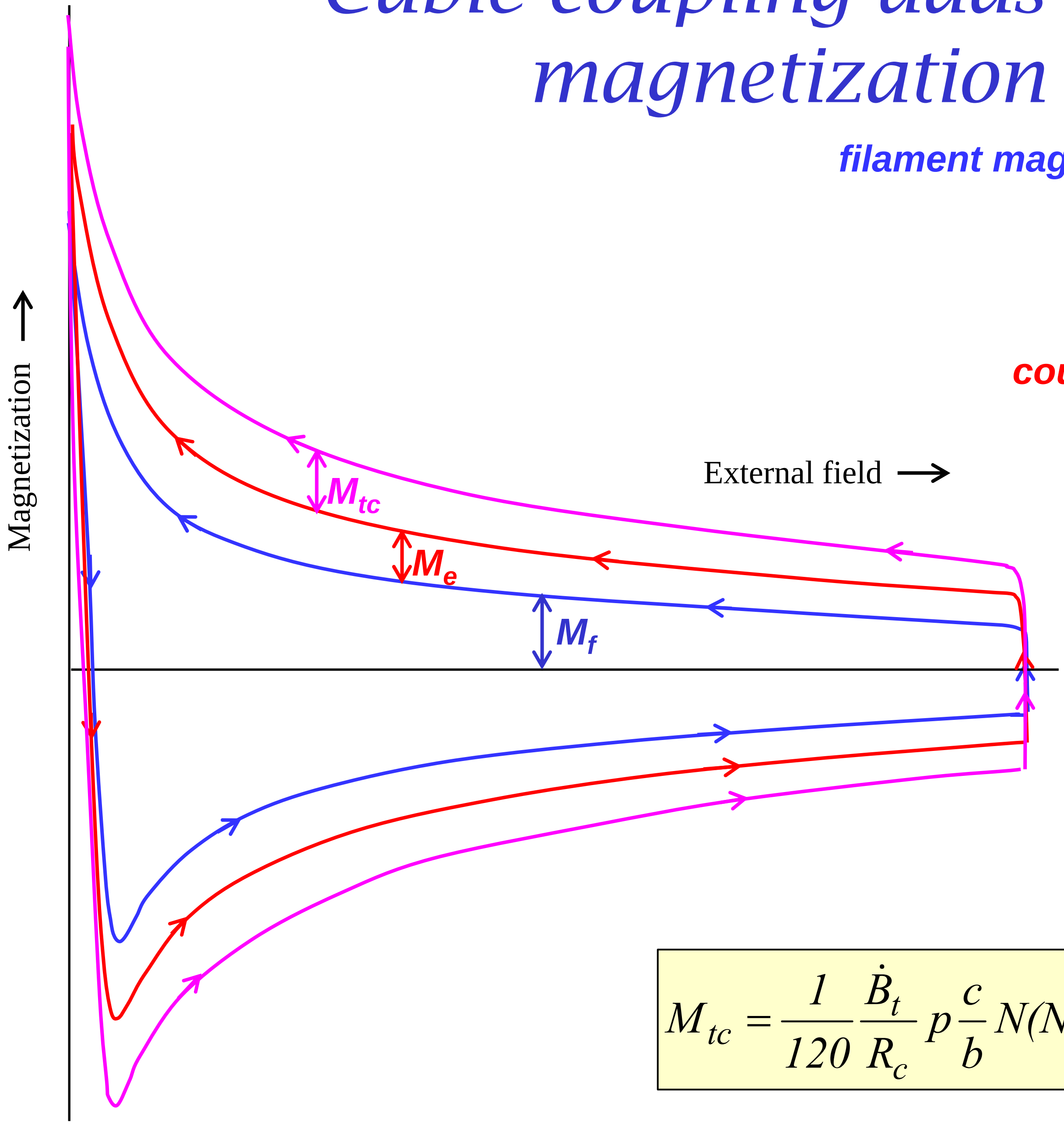


$$M_{tc} = \frac{1}{120}\frac{\dot{B}_t}{R_c}\,p\,\frac{c}{b}\,N(N-1)$$

$$M_{ta} = \frac{1}{6}\frac{\dot{B}_t}{R_a}\,p\,\frac{c}{b}$$

(Field parallel gives much smaller coupling via adjacent resistance $\boldsymbol{R_a}$)

Cable coupling adds more magnetization



filament magnetization M_f depends on B

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

coupling between filaments M_e depends on dB/dt

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

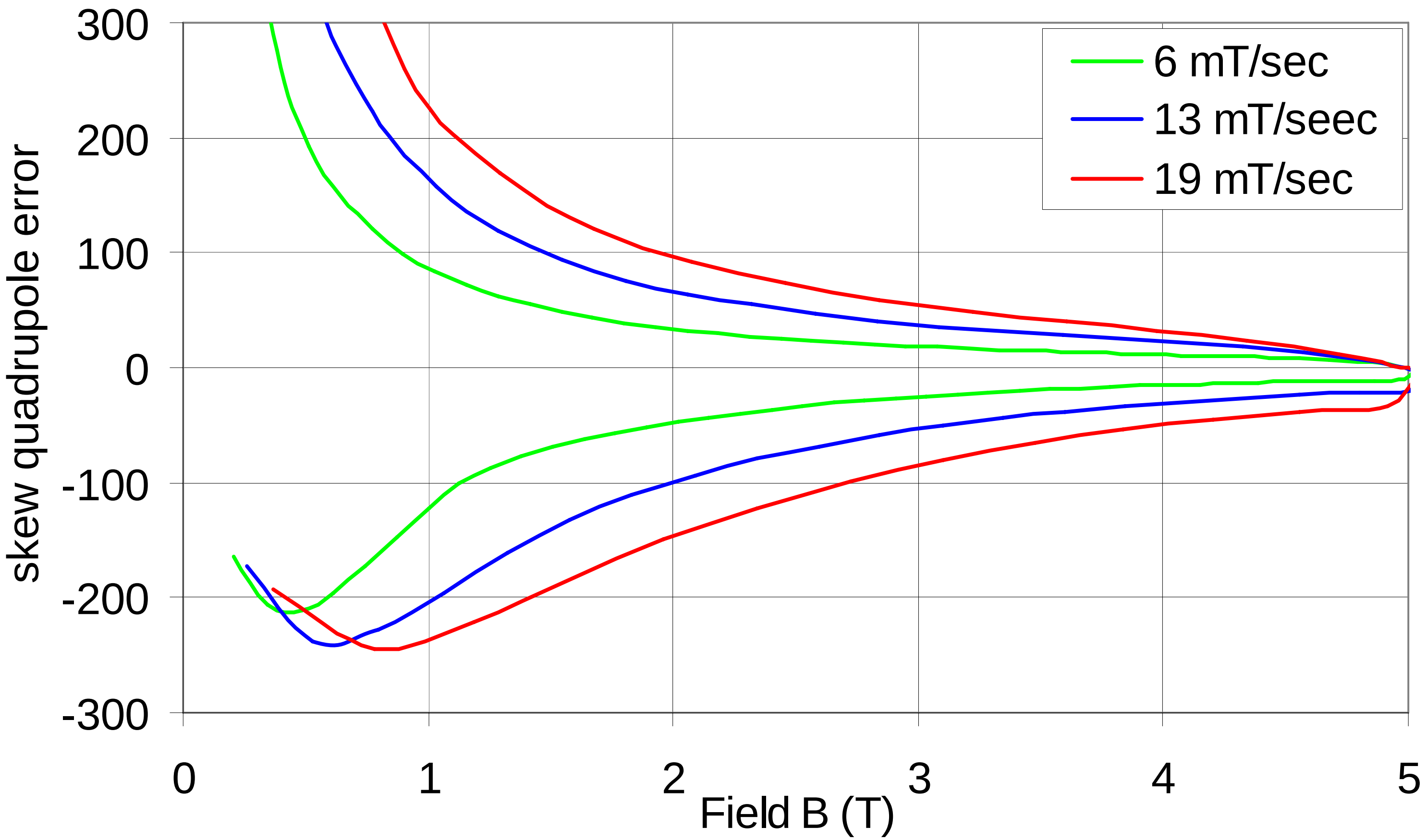
coupling between wires in cable depends on dB/dt

$$M_{tc} = \frac{1}{120} \frac{\dot{B}_t}{R_c} p \frac{c}{b} N(N-1)$$

$$M_{ta} = \frac{1}{6} \frac{\dot{B}_t}{R_a} p \frac{c}{b}$$

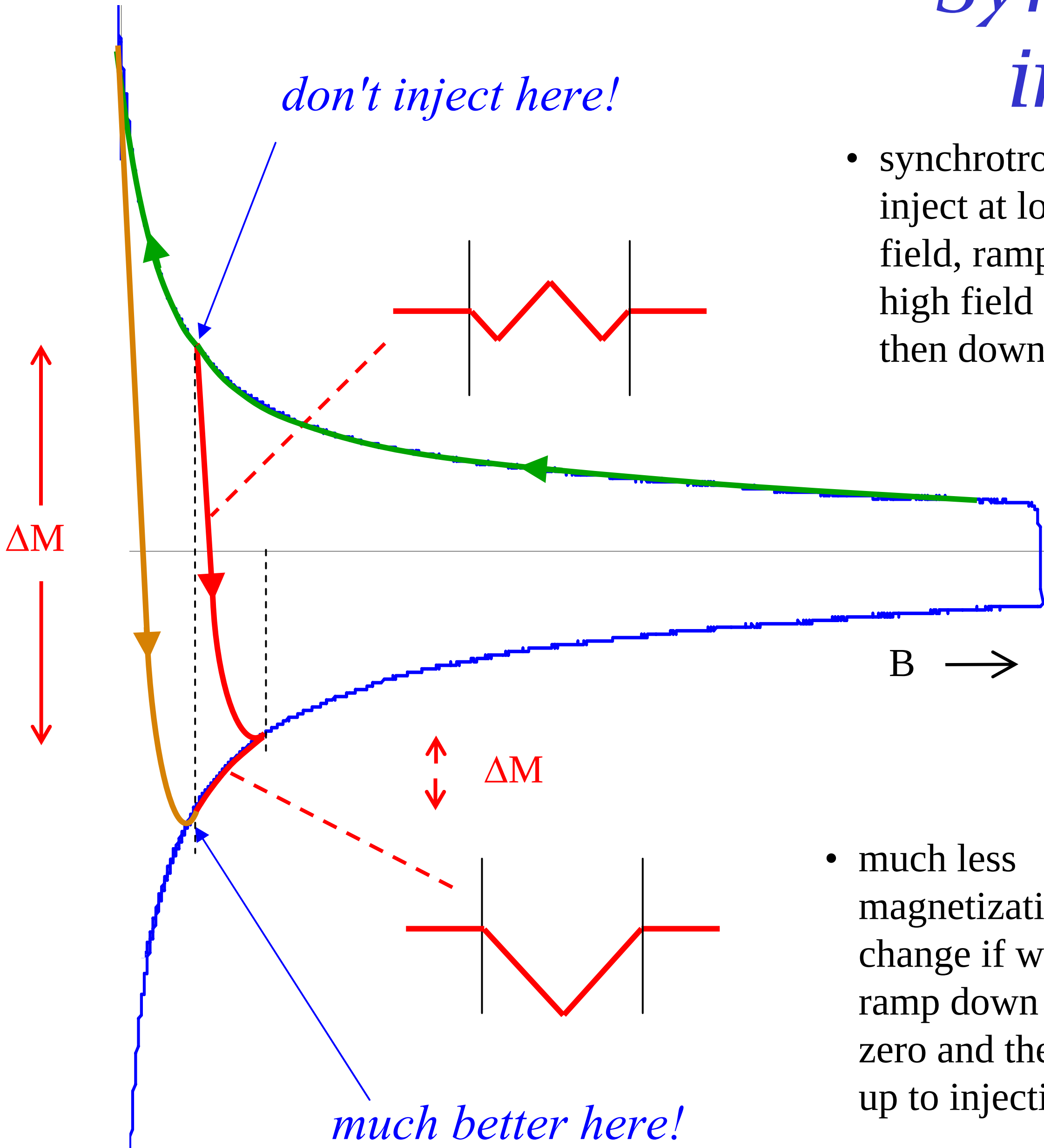
Magnetization and field errors

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

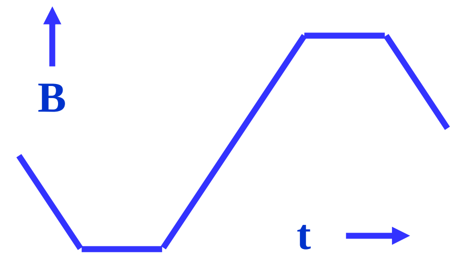


skew quadrupole error in Nb_3Sn dipole which has exceptionally large coupling magnetization (University of Twente)

Synchrotron injection

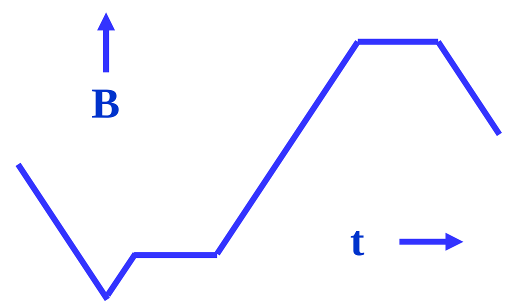


- synchrotrons inject at low field, ramp to high field and then down again

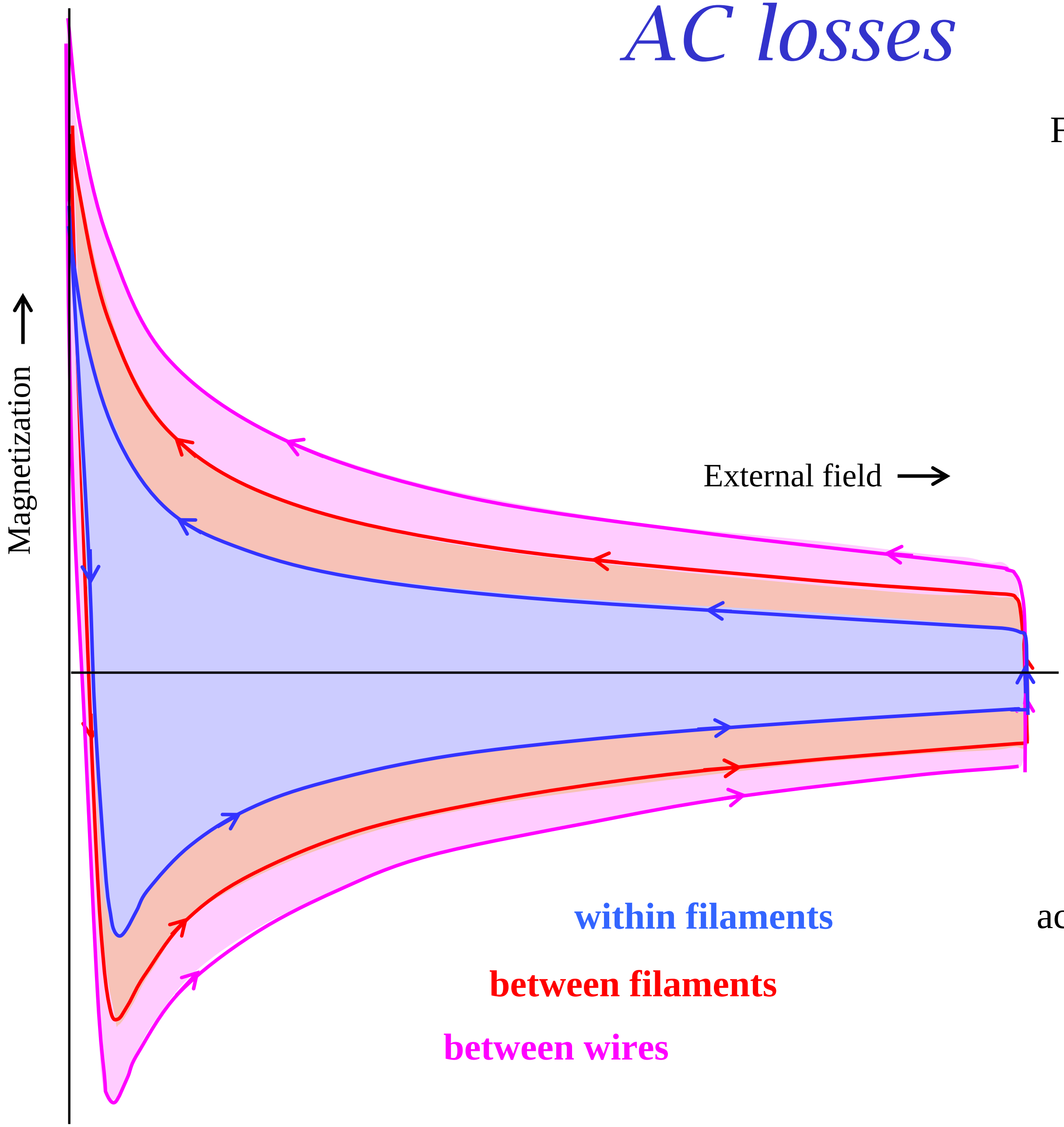


- note how quickly the magnetization changes when we start the ramp up

- much less magnetization change if we ramp down to zero and then up to injection



AC losses



For a magnet material, work done by magnetic field

$$dW = \mu_o H dM$$

around a closed loop

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

loop comes back to same place
- field energy is same
- so work done is ac loss in material

ac loss is area of hysteresis loop

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

Magnetic stored energy

Magnetic energy density $E = \frac{B^2}{2\mu_o}$ at 5T $\boldsymbol{E}$ = 10^7 Joule.m^{-3} at 10T $\boldsymbol{E}$ = 4×10^7 Joule.m^{-3}

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

the magnet weighs 26 tonnes

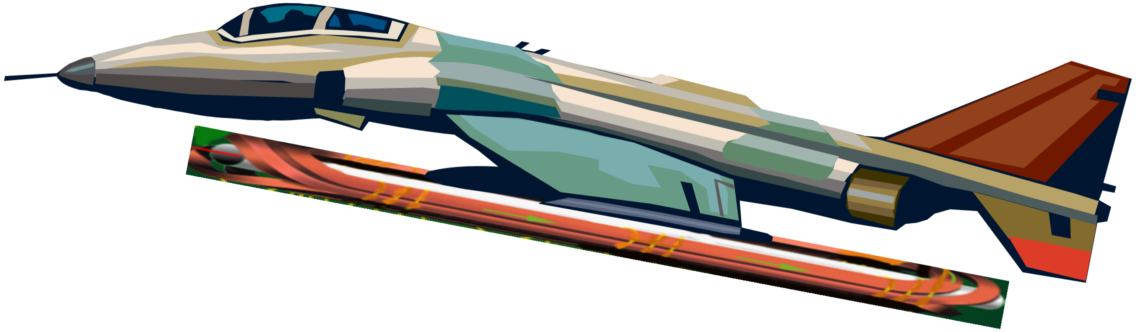
so the magnetic stored energy is equivalent to the kinetic energy of:-

26 tonnes travelling at 88km/hr

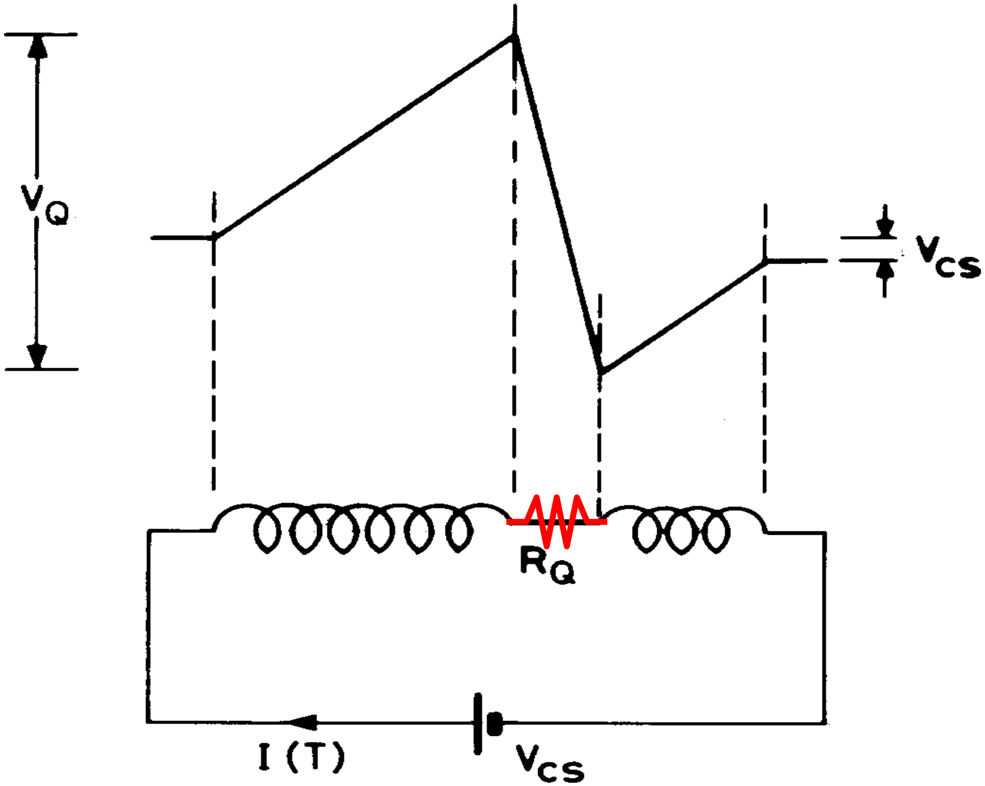
coils weigh 830 kg

equivalent to the kinetic energy of:-

830kg travelling at 495km/hr



The quench process



- resistive region starts somewhere in the winding at a **point**
  - this is the problem!
- it grows by thermal conduction
- stored energy $\frac{1}{2}LI^2$ 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(θ)

or the 'fuse blowing' calculation
(adiabatic approximation)

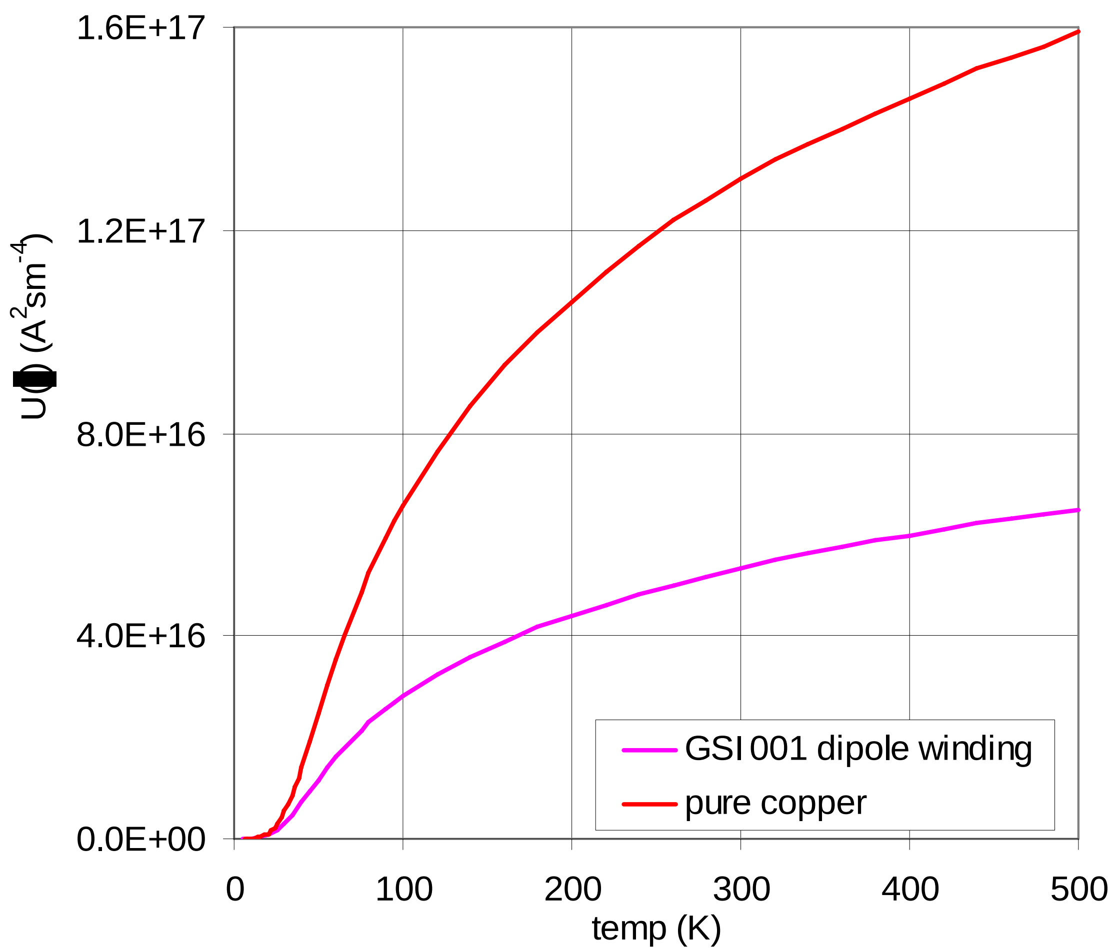
$$J^2(T)\rho(\theta)dT = \gamma C(\theta)d\theta$$

J(T) = overall current density,
T = time,
ρ(θ) = overall resistivity,
γ = density, *θ* = temperature,
C(θ) = specific heat,
T_Q = quench decay time.

$$\int_o^\infty J^2(T)\,dT = \int_{\theta o}^{\theta m} \frac{\gamma C(\theta)}{\rho(\theta)} d\theta$$

$$= U(\theta_m)$$

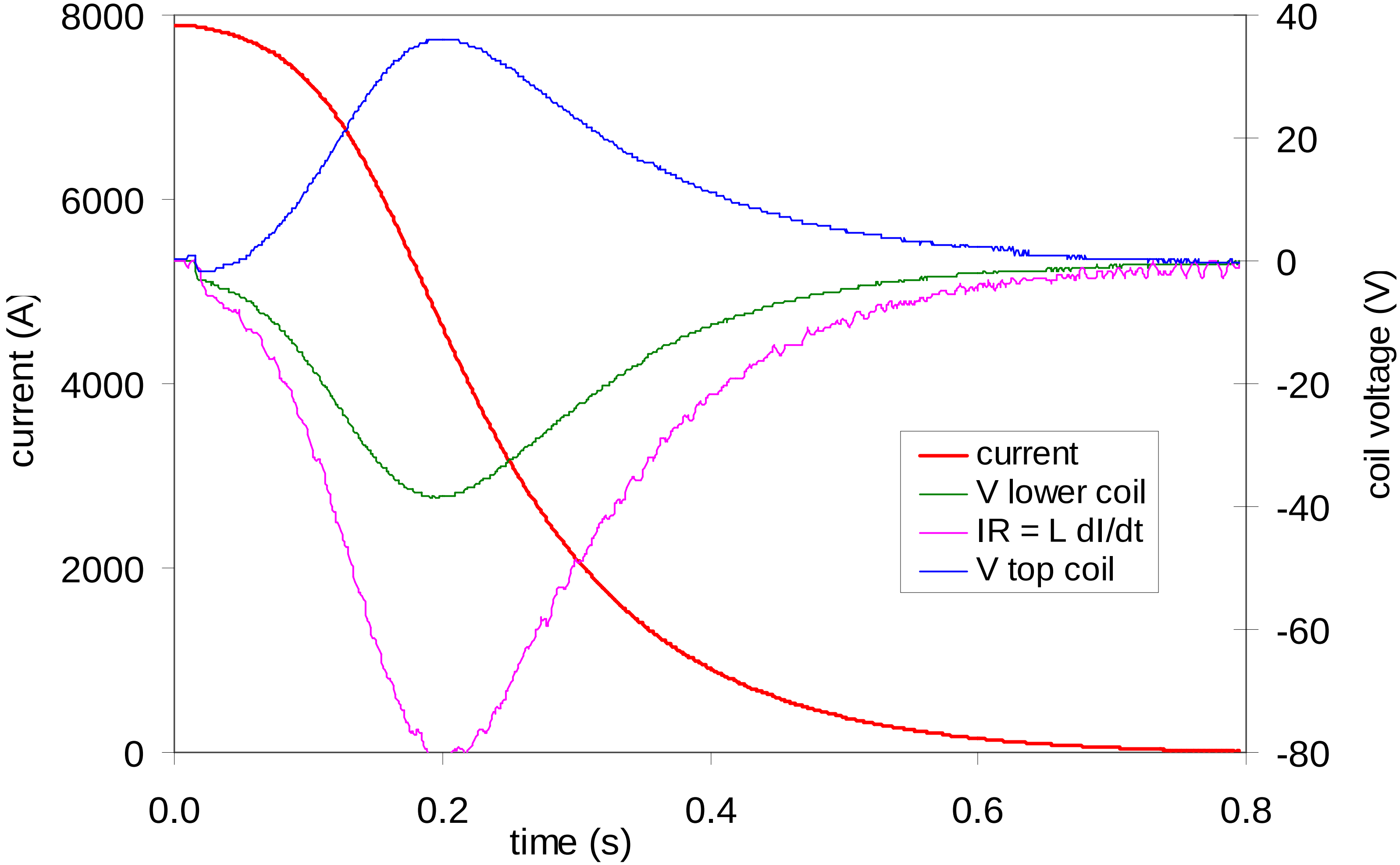
$$J_o^2 T_Q = U(\theta_m)$$



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

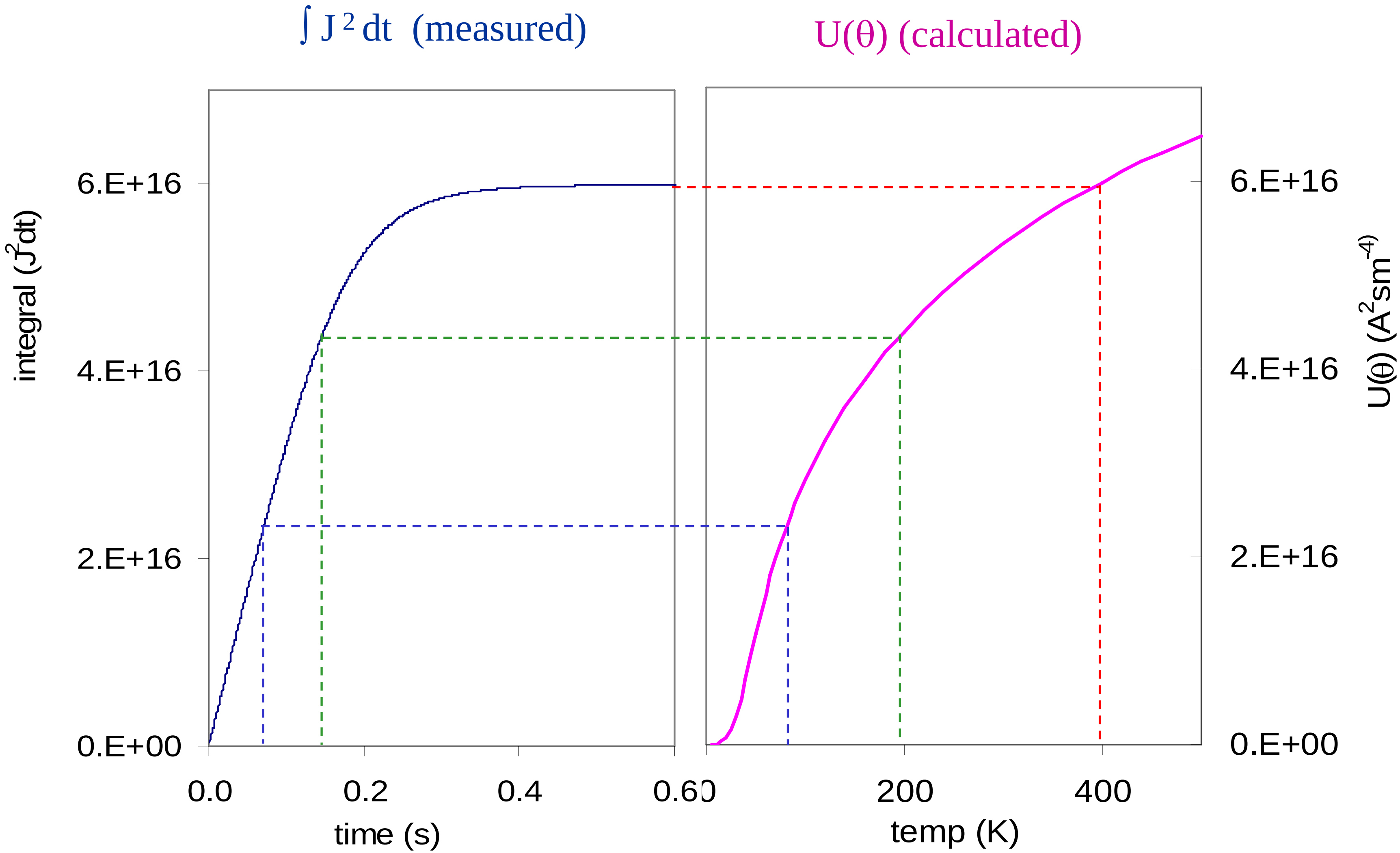
- NB always use **overall** current density

Measured current decay after a quench

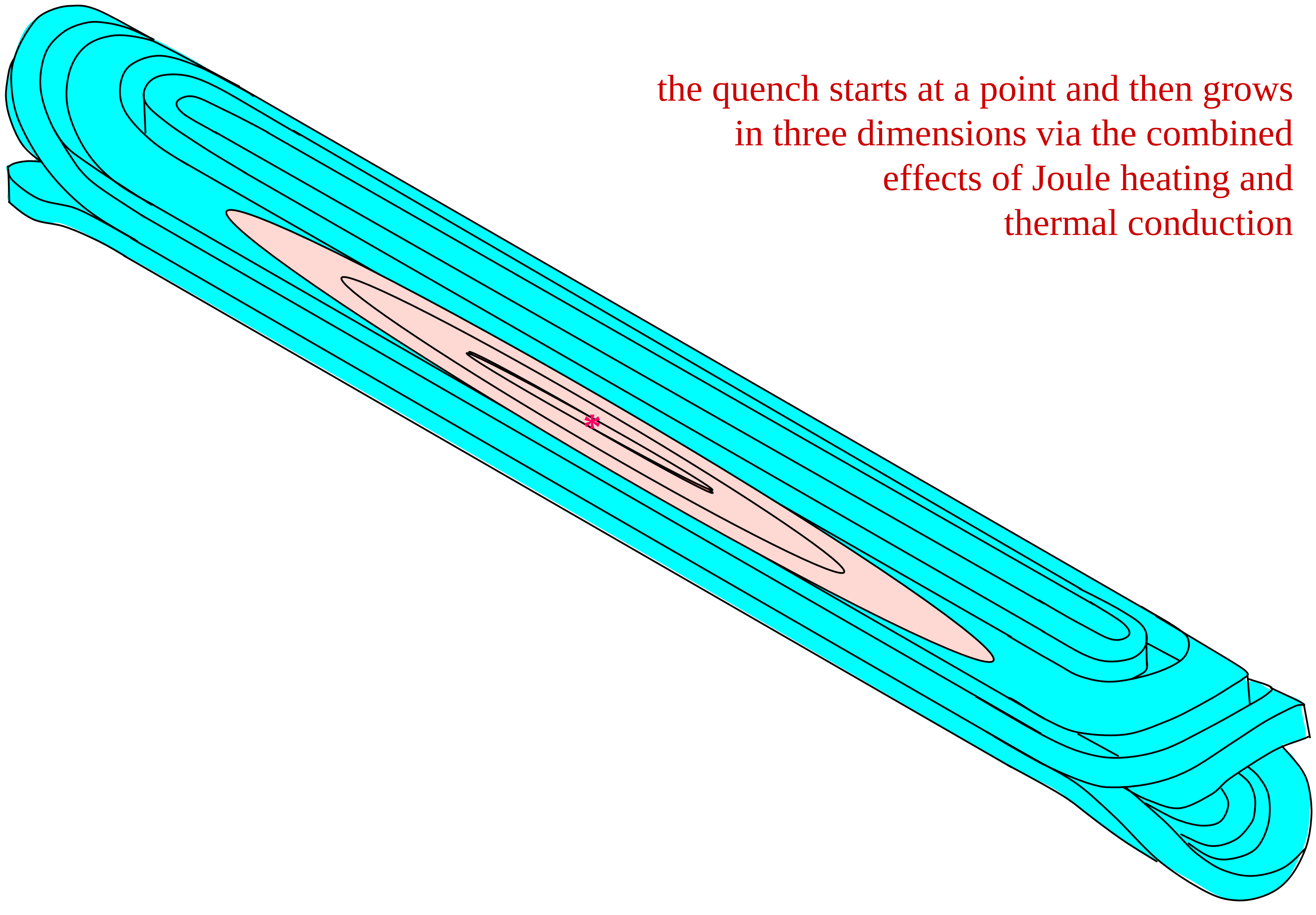


Dipole GSI001 measured at Brookhaven National Laboratory

Calculating the temperature rise from the current decay curve



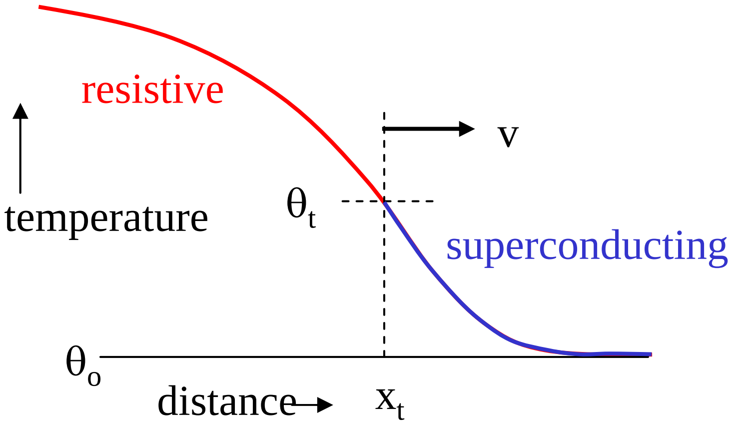
Growth of the resistive zone



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



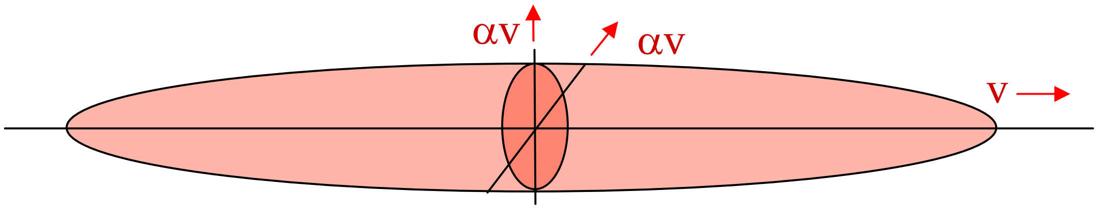
Along the conductor

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

where: J = engineering current density, γ = density, C = specific heat, ρ = resistivity, k = thermal conductivity, θ_t = transition temperature

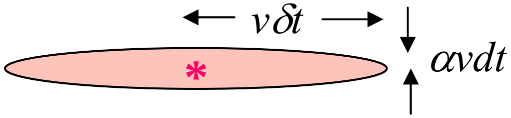
Transverse to the conductor

$$\alpha = \frac{v_{trans}}{v_{long}} = \left\{\frac{k_{trans}}{k_{long}}\right\}^{\frac{1}{2}}$$



Typical values v_{ad} = 5 - 20 ms^{-1} α = 0.01 – 0.03

Computation of resistance growth and current decay



start resistive zone 1

↓

in time δt zone 1 grows $v.dt$ longitudinally and $\alpha.v.dt$ transversely

↓

temperature of zone grows by $\delta\theta_1 = J^2 \rho(\theta_1)\delta\tau / \gamma C(\theta_1)$

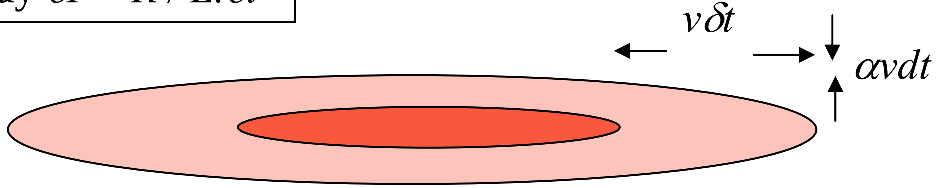
↓

resistivity of zone 1 is $\rho(\theta_1)$

↓

calculate resistance and hence current decay $\delta I = R / L.\delta t$

↓



in time δt add zone n:
$v.\delta t$ longitudinal and $\alpha.v.\delta t$ transverse

↓

temperature of each zone grows by $\delta\theta_1 = J^2\rho(\theta_1)\delta t/\gamma C(\theta_1)$ $\delta\theta_2 = J^2\rho(\theta_2)\delta t/\gamma C(\theta_2)$ $\delta\theta_n = J^2\rho(\theta_1)dt/\gamma C(\theta_n)$

↓

resistivity of each zone is $\rho(\theta_1)$ $\rho(\theta_2)$ $\rho(\theta_n)$ resistance $r_1 = \rho(\theta_1) * f_{g1}$ (geom factor) $r_2 = \rho(\theta_2) * f_{g2}$ $r_n = \rho(\theta_n) * f_{gn}$

↓

calculate total resistance $R = \sum r_1 + r_2 + r_{n..}$ and hence current decay $\delta I = (I R / L)\delta t$

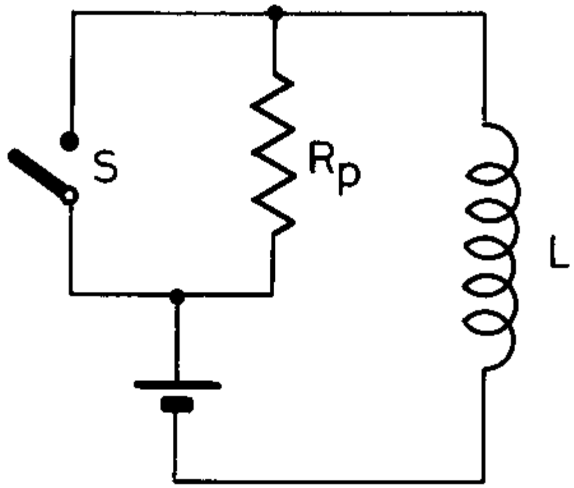
(loop back to "in time δt add zone n")

↓

when $I \Rightarrow 0$ stop

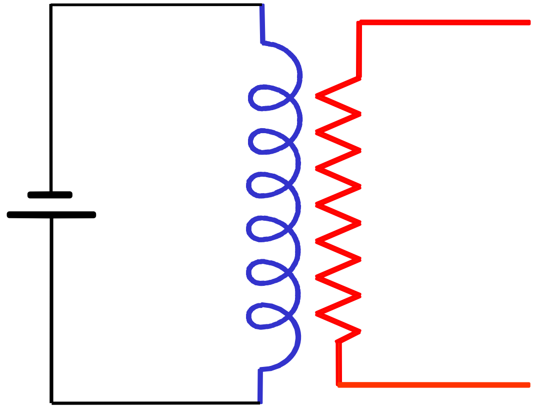
Methods of quench protection:

1) External dump resistor



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

2) Quench back heater



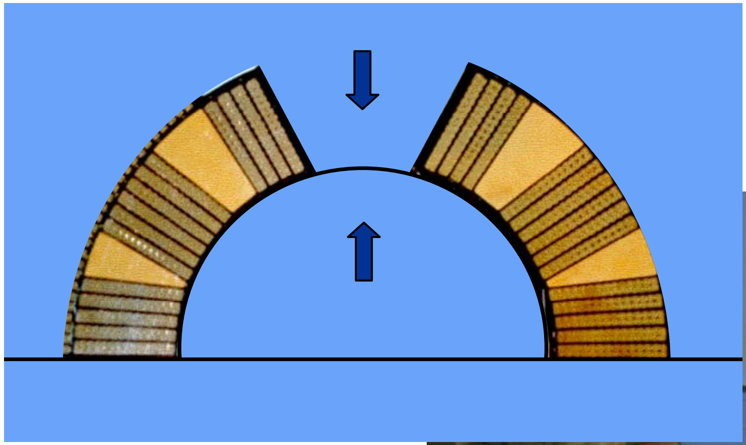
method most commonly used in accelerator magnets ✓

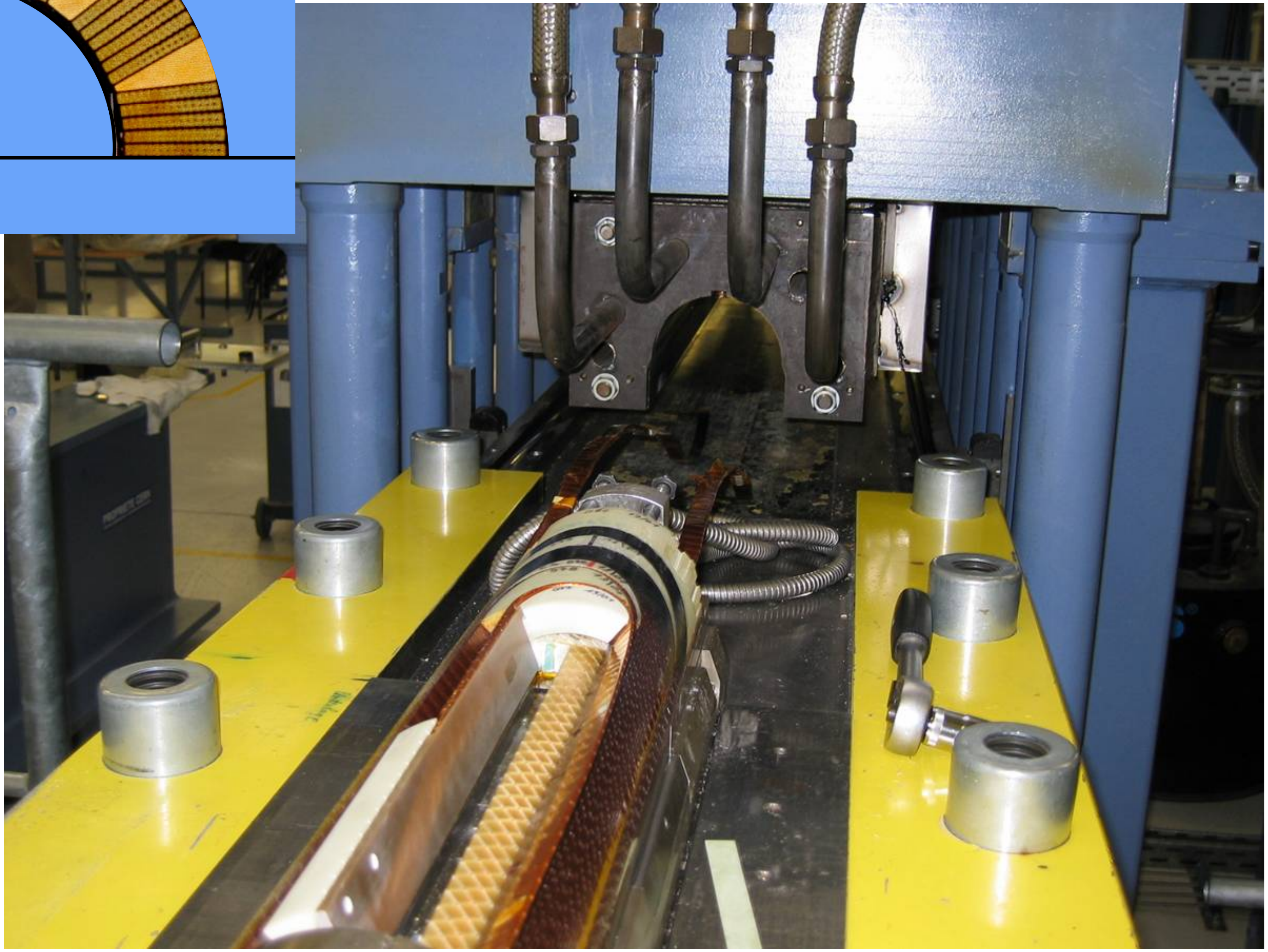
- detect the quench electronically
- power a heater in thermal contact with the winding
- this quenches other regions of the magnet, forcing the normal zone to grow more rapidly
  $\Rightarrow$ higher resistance
  $\Rightarrow$ shorter decay time
  $\Rightarrow$ lower temperature rise at the hot spot

Winding an LHC dipole

photo courtesy of Babcock Noell

Curing press





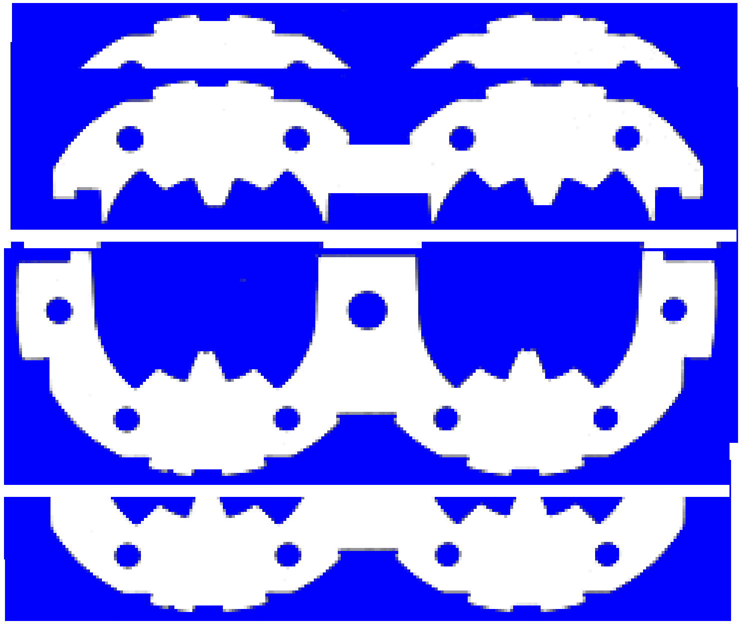
Collars

How to make an external structure that

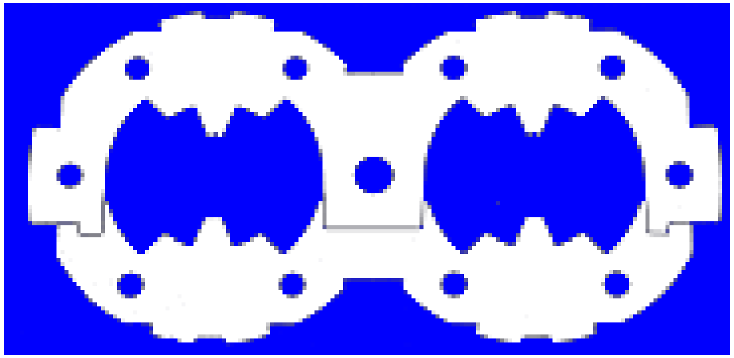
- fits tightly round the coil
- presses it into an accurate shape
- has low ac losses
- can be mass produced cheaply
- ???

- Answer make collars by precision stamping of stainless steel or aluminium alloy plate a few mm thick

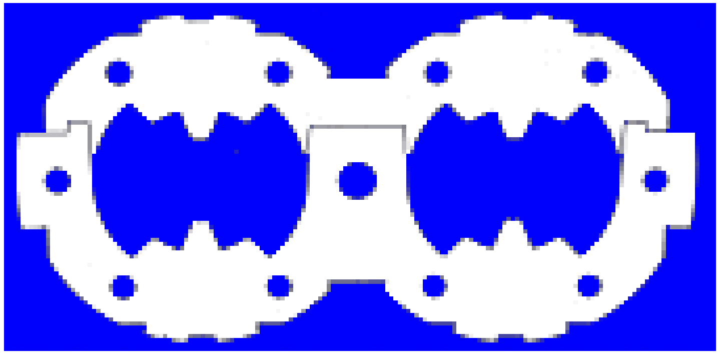
- inherited from conventional magnet laminations



press collars over coil from above and below

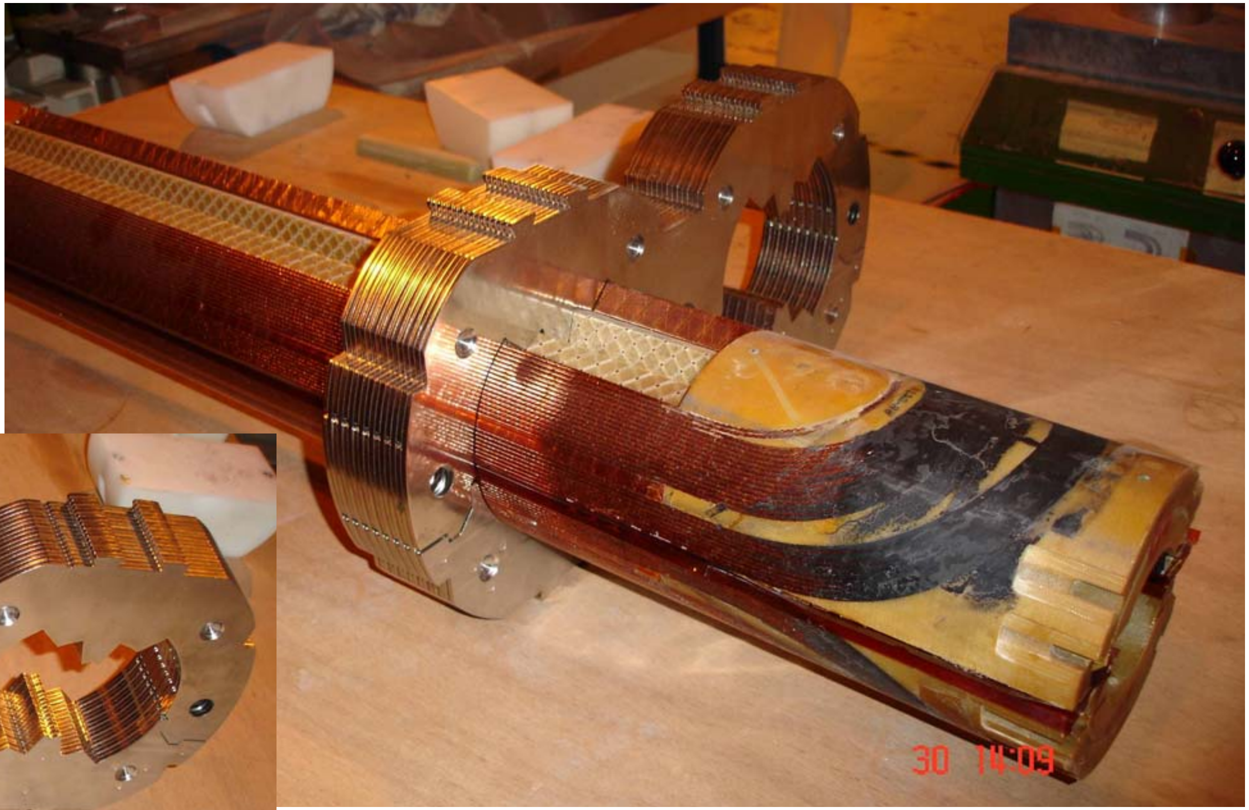


invert alternate pairs so that they interlock

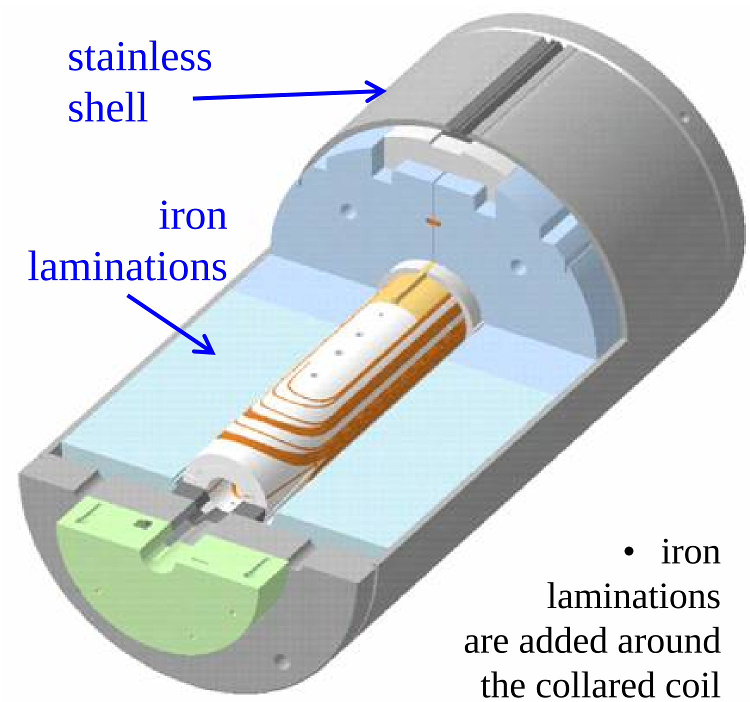


push steel rods through holes to lock in position

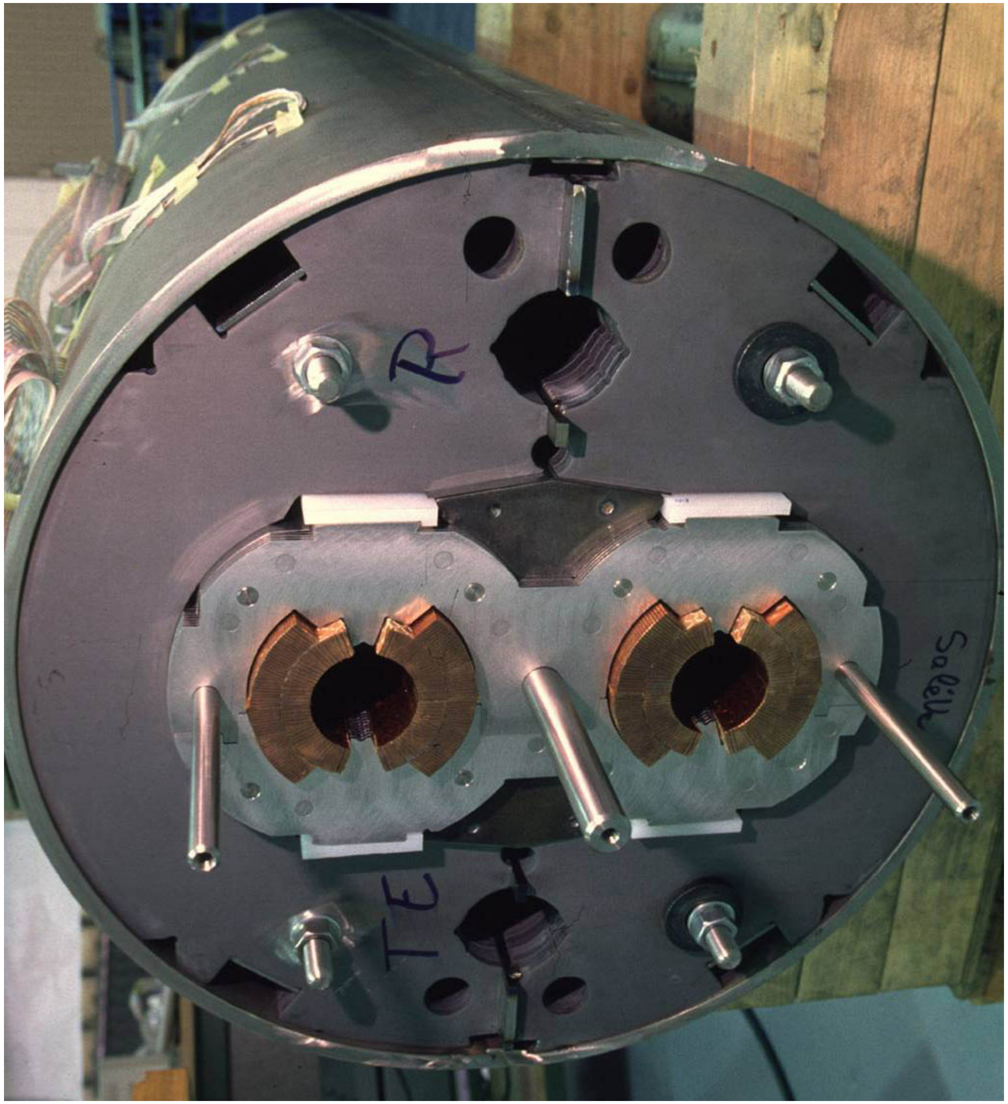
Collars and end plate (LHC dipole)



Adding the iron

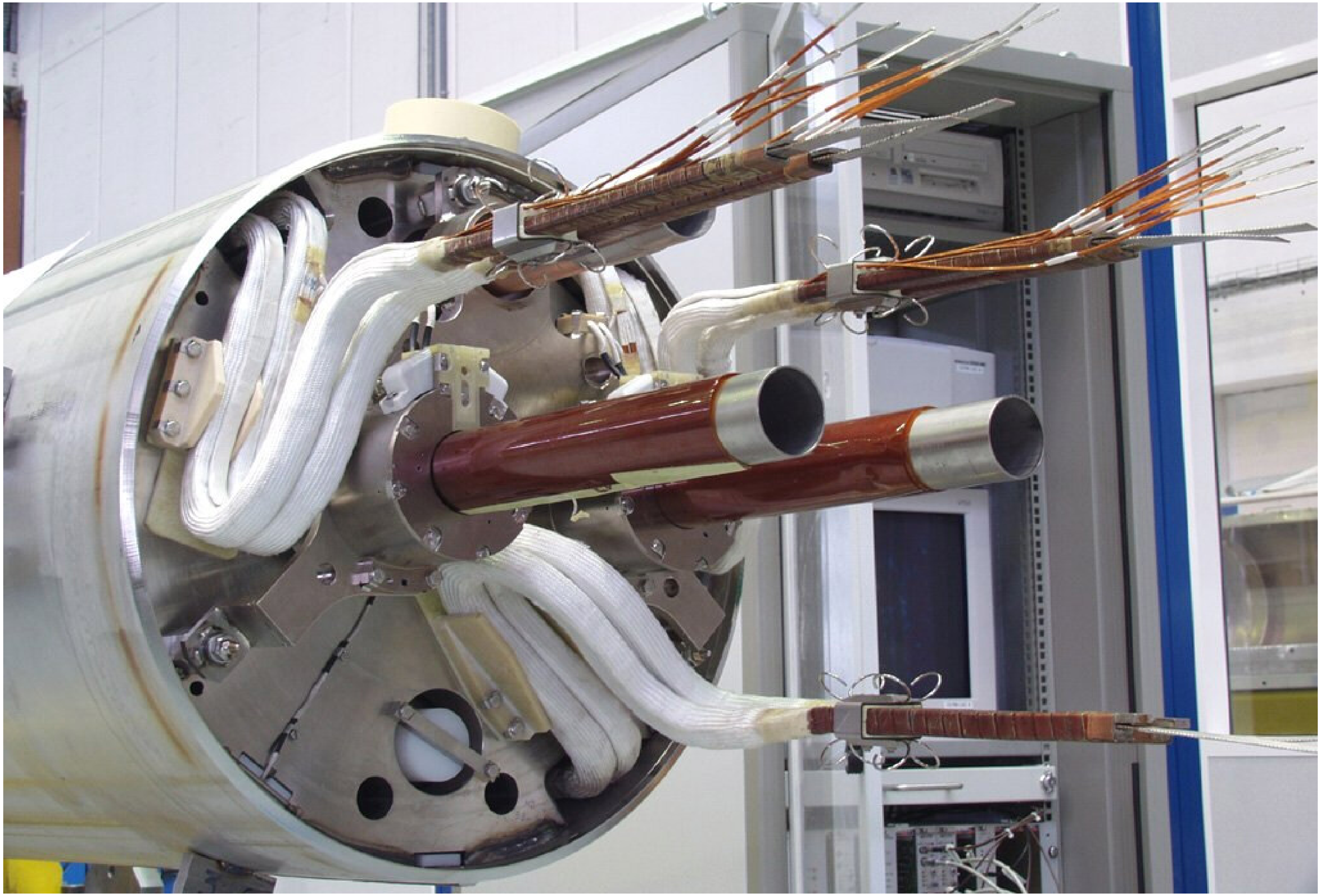


- iron laminations are added around the collared coil

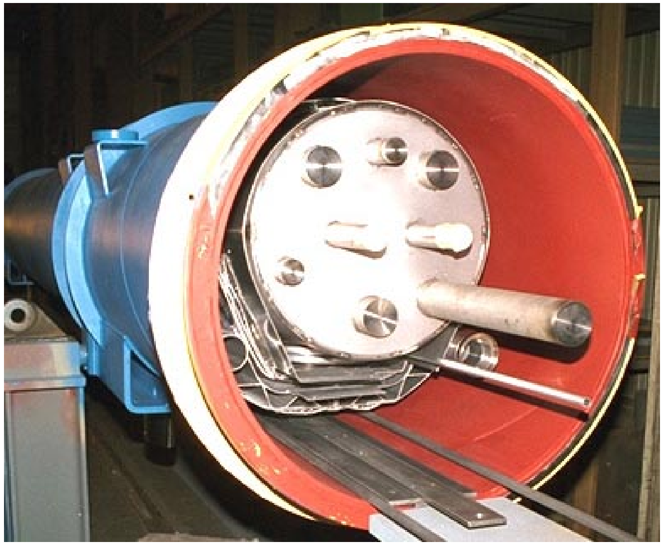


- they are forced into place, again using the collaring press
- remember however that pure iron becomes brittle at low temperature
- the tensile forces are therefore taken by a stainless steel shell which is welded around the iron, while still in the press
- this stainless shell can also serve as the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

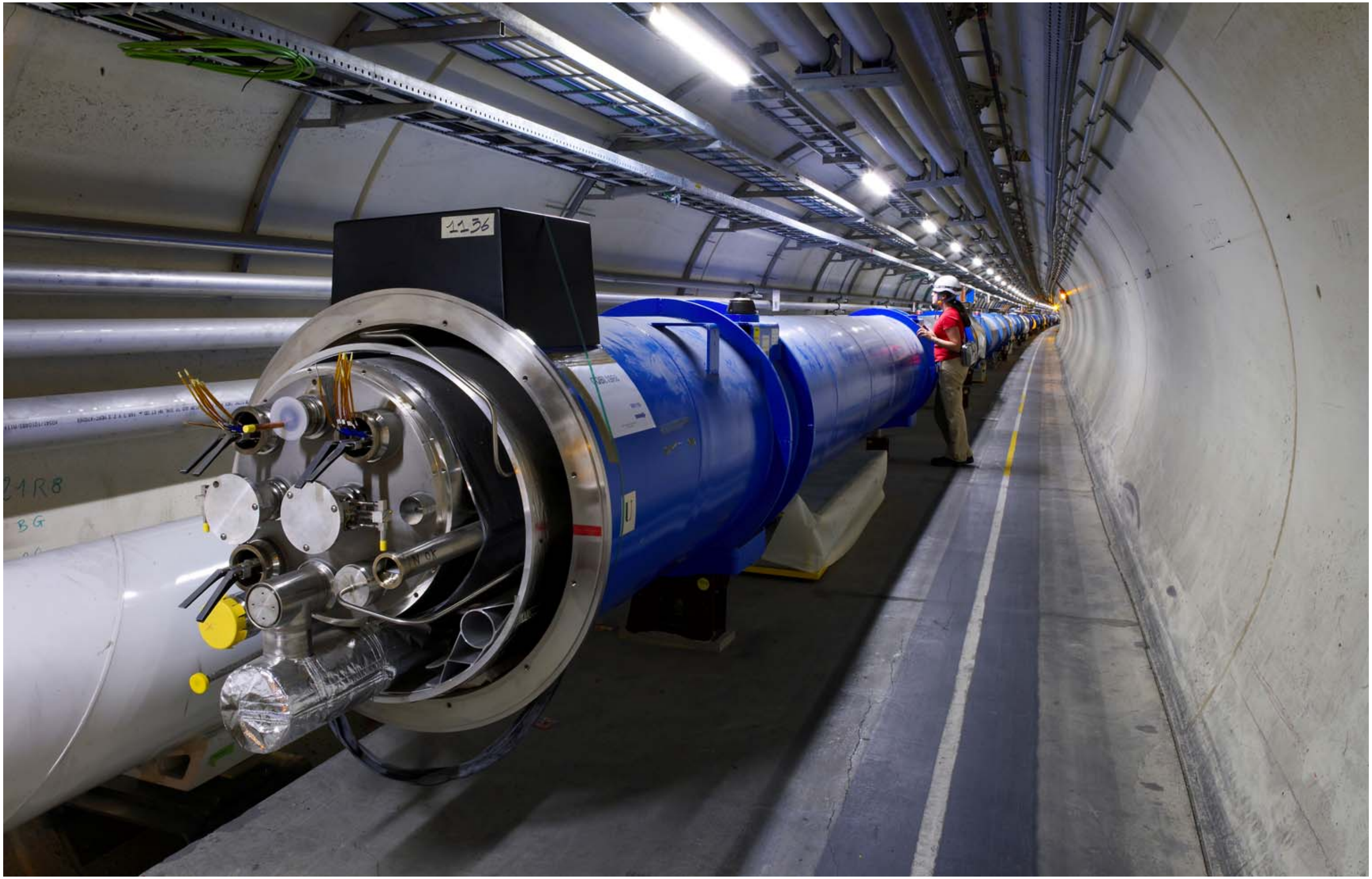
Dipole inside its stainless shell



Complete magnet in cryostat



Make a lot of Magnets and install in the tunnel



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
- magnets don't reach their expected current/field first time but show training
  - control training by reducing movement, attention to contraction and increasing MQE
- persistent screening currents produce magnetization of the superconductor which causes field errors and ac loss – need fine ~ 5μm filaments
- accelerators need high currents, so must use many wires in parallel – a cable
- coupling between filament in wire and between wires in cable increases magnetization
- magnets store large inductive energy which is released at quench as heating – must protect
- magnet manufacturing 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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- High Field Superconducting Magnets: FM Asner, pub Oxford University Press (1999) ISBN 0 19 851764 5
- Case Studies in Superconducting Magnets: Y Iwasa, pub Plenum Press, New York (1994), ISBN 0-306-44881-5.
- Superconducting Magnets: MN Wilson, pub Oxford University Press (1983) ISBN 0-019-854805-2
- Proc Applied Superconductivity Conference: pub as IEEE Trans Applied Superconductivity, Mar 93 to 99, and as IEEE Trans Magnetics Mar 75 to 91
- 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 mjball @ comcast.net

Superconducting Materials

- Superconductor Science and Technology, published monthly by Institute of Physics (UK).
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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 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

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