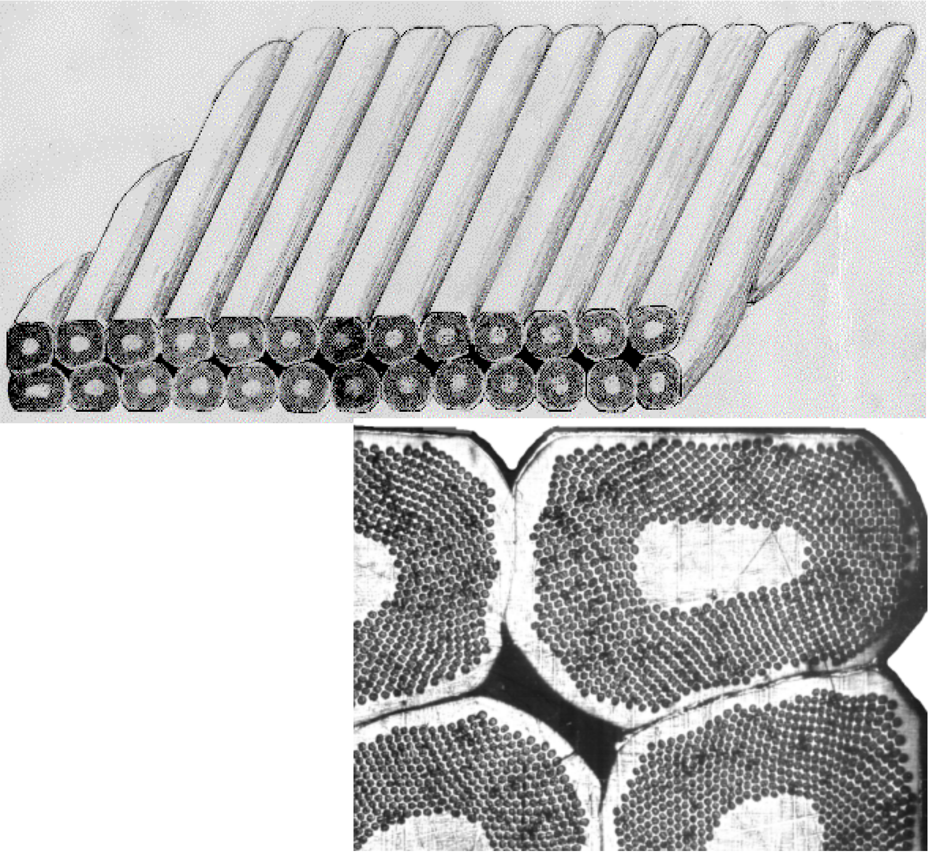
Lecture 3: Cables and Materials Manufacture



Rutherford cable

used in all superconducting accelerators to date

Cables

- why cables?
- coupling magnetization in cables
  - anisotropy
- resistance between strands
- measurement
- effect on field error in magnets
- BICCs and snap back
- manufacture of wire and cable

Why cables?

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

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

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

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

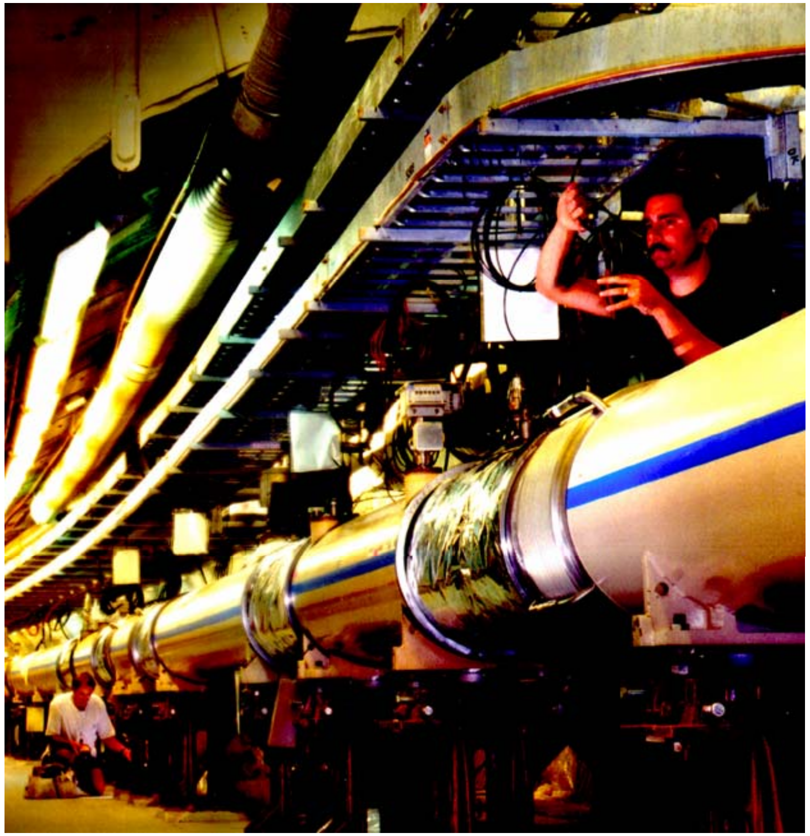
wire I = **167A**, charge voltage per km = **6400V**

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!

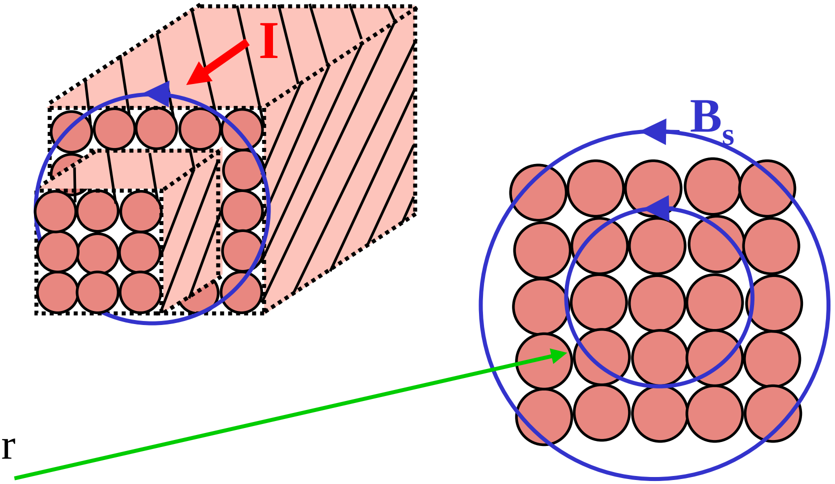


the RHIC tunnel

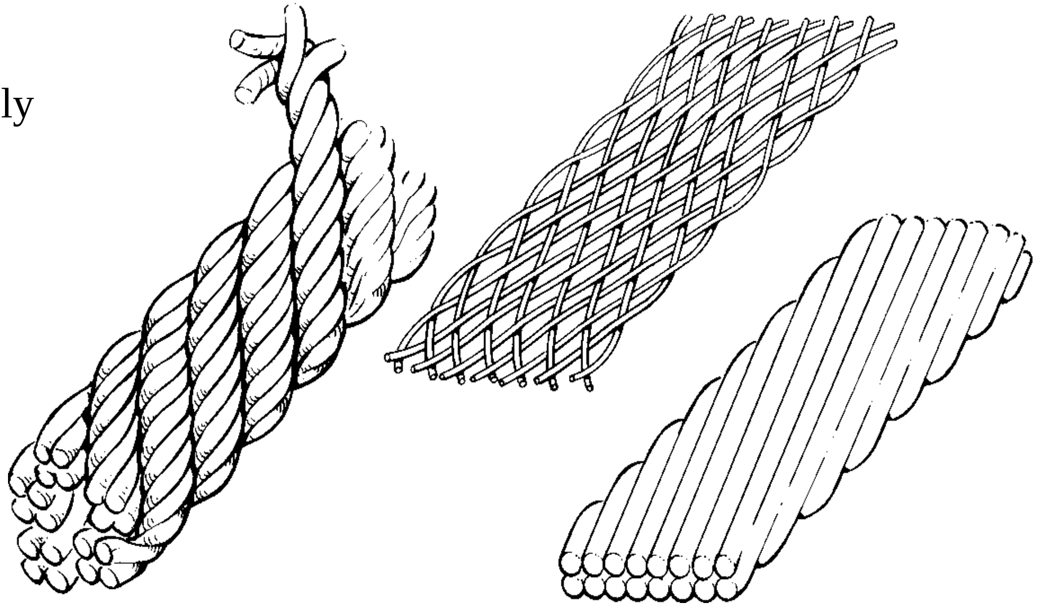
- a single 5μm filament of NbTi in 6T carries 50mA
- a composite wire of fine filaments typically has 5,000 to 10,000 filaments, so it carries 250A to 500A
- for 5 to 10kA, we need 20 to 40 wires in parallel - a cable

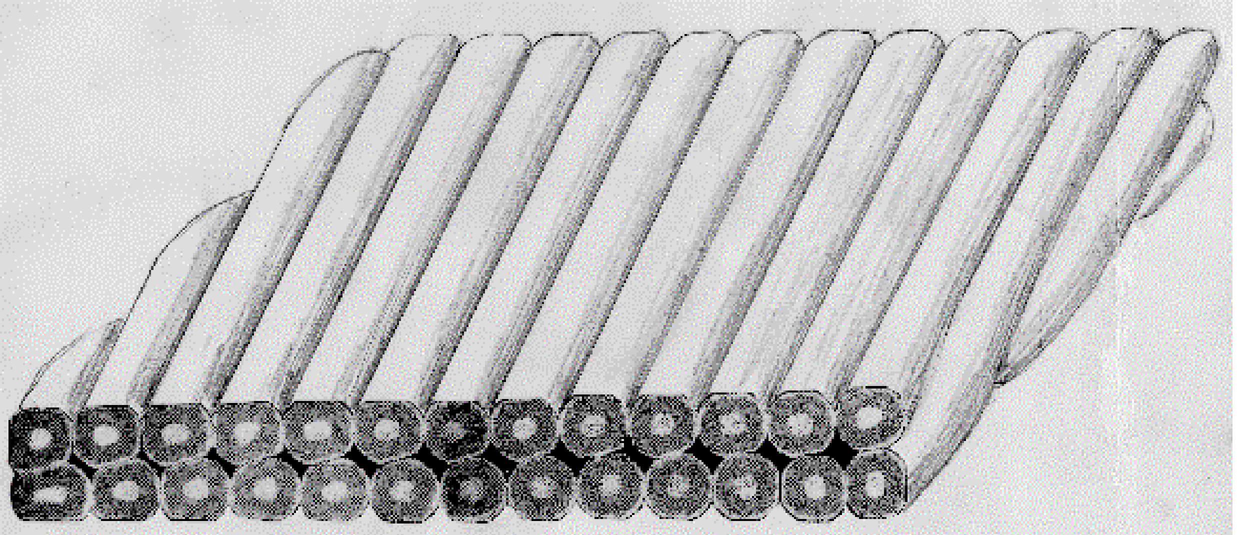
Types of cable

- cables carry a large current and this generates a **self field**
- in this cable the self field generates a flux between the inner and outer wires ⇒
- wire are twisted to avoid flux linkage between the filaments, for the same reasons we should avoid flux linkage between wires in a cable
- but twisting this cable doesn't help because the inner wires are always inside and the outers outside



- thus it is necessary for the wires to be fully **transposed**, ie every wire must change places with every other wire along the length of the cable so that, averaged over the length, no flux is enclosed
- three types of fully transposed cable have been tried in accelerators
  - rope
  - braid
  - Rutherford

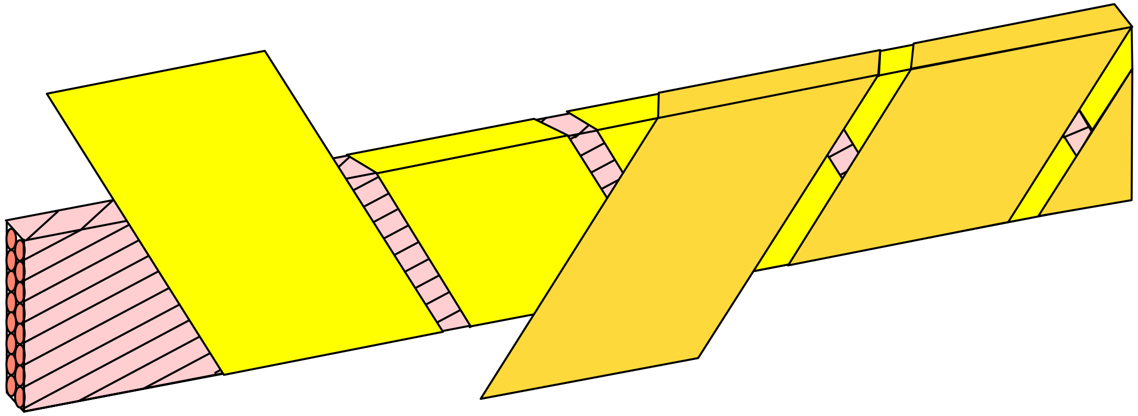




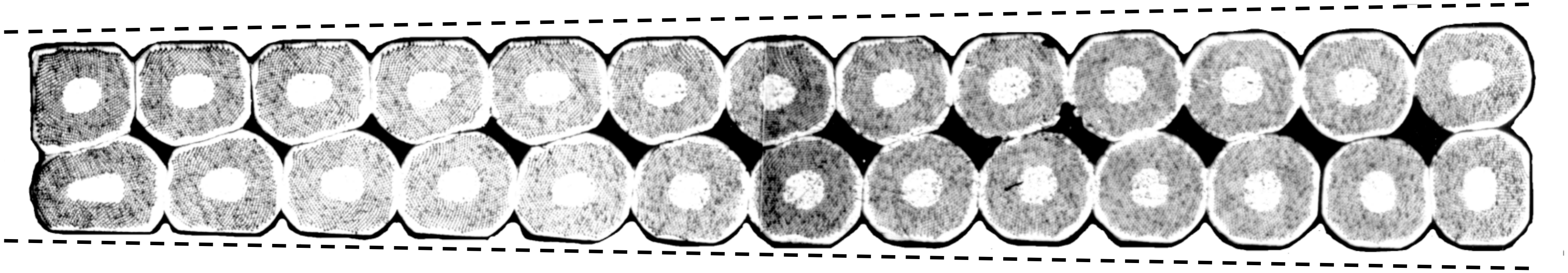
Rutherford cable

- the cable is insulated by wrapping 2 or 3 layers of Kapton; gaps may be left to allow penetration of liquid helium; the outer layer is treated with an adhesive layer for bonding to adjacent turns.

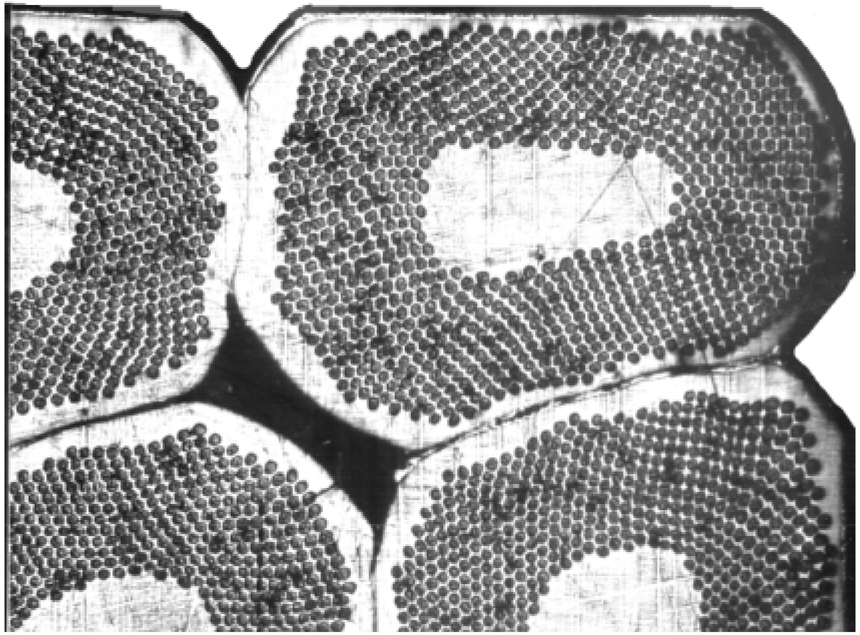
- Note: the adhesive faces outwards, don't bond it to the cable (avoid energy release by bond failure, which could quench the magnet)



Rutherford cable

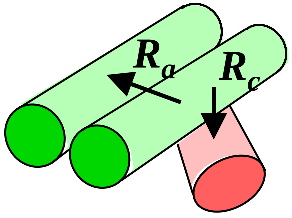


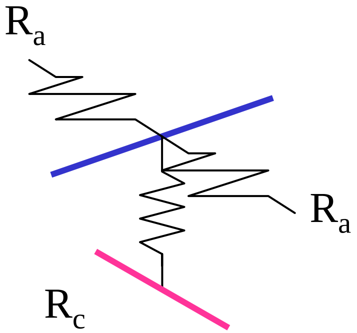
- The main reason why Rutherford cable succeeded where others failed was that it could be compacted to a high density (88 - 94%) without damaging the wires. Furthermore it can be rolled to a good dimensional accuracy (~ 10mm).
- Note the 'keystone angle', which enables the cables to be stacked closely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

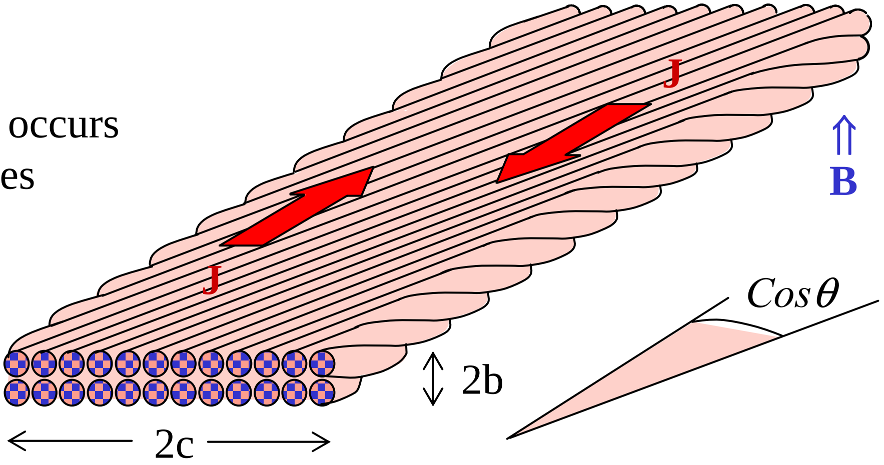


Coupling in Rutherford cables: resistances

Just like the filaments in the wires, coupling also occurs between the wires in a cable. The geometry makes things more complicated, but the processes are the same.







Coupling is via resistive contacts between the wires, we distinguish two different types of contact: ***crossover*** and ***adjacent***

For network modelling *(see Arjan Verweij)* we use resistances per contact ***R$_c$*** and ***R$_a$***

For the continuum model we use resistances per unit area of contact ***r$_c$*** and ***r$_a$*** To relate the two, note that, over a twist pitch ***p***, each strand makes (2N-2) crossover and 2N adjacent contacts

crossover area

$$A_c = \frac{2cp}{N(N-1)}$$

$$\boxed{R_c = \frac{r_c}{A_c} = r_c \frac{N(N-1)}{2pc}}$$

adjacent area per crossover

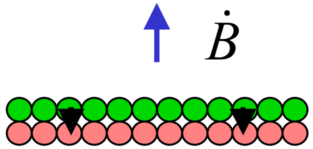
$$A_a = \frac{pb}{2N\,Cos\theta}$$

$$\boxed{R_a = \frac{r_a}{A_a} = r_a \frac{2N\,Cos\theta}{pb}}$$

Note: $\boldsymbol{r_c}$ and $\boldsymbol{r_a}$ depend only on surface properties, $\boldsymbol{R_c}$ and $\boldsymbol{R_a}$ also depend on geometry.

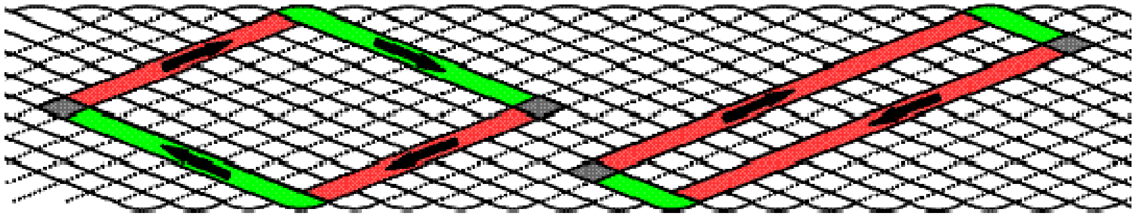
Perpendicular field: coupling via crossover resistance 1

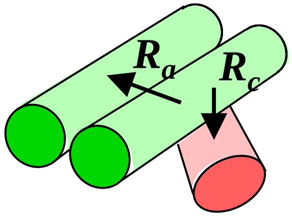
- Field transverse
  coupling via crossover resistance R_c



crossover resistance $\boldsymbol{R_c}$

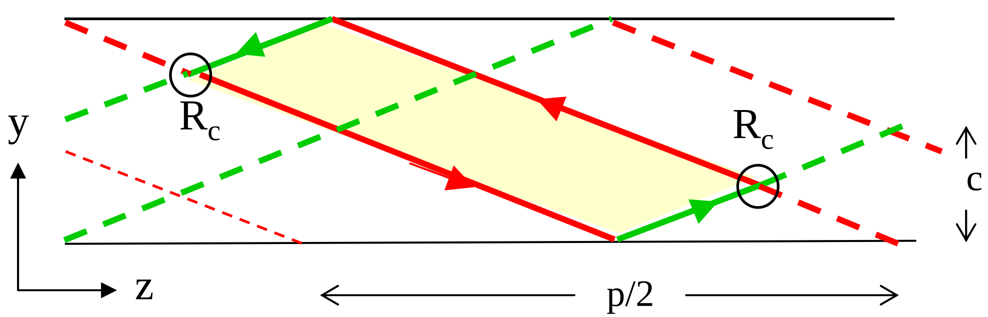
adjacent resistance $\boldsymbol{R_a}$

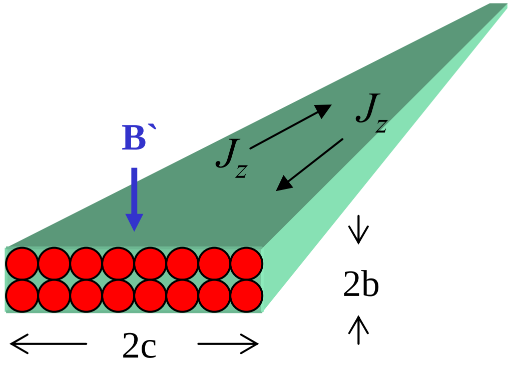




- changing perpendicular fields induce diamond shaped current loops
- current flows along the **top surface** then downwards through a crossover (grey) along the **bottom surface** and then over the edge and up to the **top surface**
- a whole range of different loops are possible, but they are all symmetrical about the cable centre line
- all shapes of loop are induced simultaneously by a changing field
- they must be summed together to calculate the magnetization
- for exact calculations, a network model should be used
- here we use an approximate continuum model, which gives similar answers

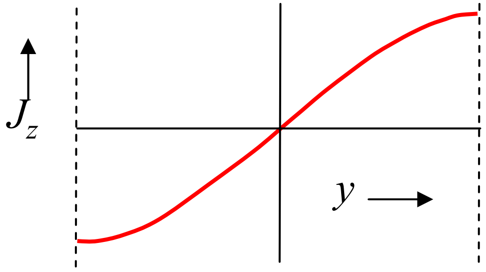
Perpendicular field: coupling via crossover resistance 2





- calculate voltage induced around the loop shaded yellow $V_{loop} = 2R_a I_{loop}$

- sum over all possible loops and resolve $\boldsymbol{I_{loop}}$ along direction parallel to cable



- current density in z direction

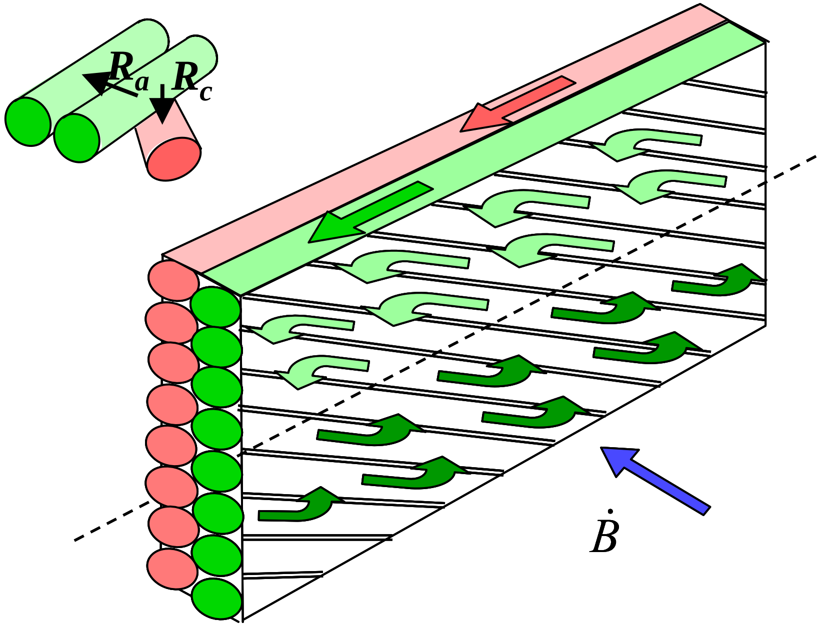
$$J_z(y) = \frac{\dot{B}_t p^2}{48\, r_c b c^2}\left(-y^3 + 3y^2 c - 2c^3\right)$$

- integrate current × area to get magnetization

$$\boxed{M_{tc} = \frac{1}{60}\frac{\dot{B}_t}{r_c} p^2 \frac{c^2}{b}}$$

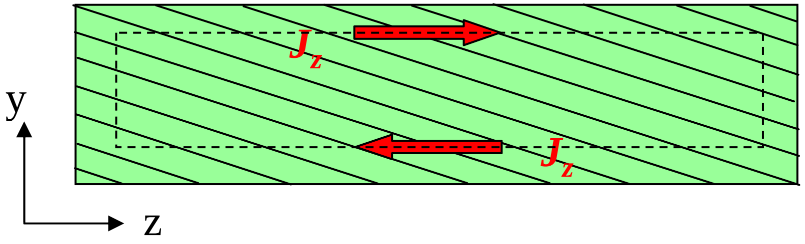
$$\boxed{M_{tc} = \frac{1}{120}\frac{\dot{B}_t}{R_c} p \frac{c}{b} N(N-1)}$$

Perpendicular field: coupling via adjacent resistance



- consider the current paths shown to find an effective resistivity along the cable

$$\rho_{ez} = \frac{N}{p} r_a \, Sin\theta$$



- equate the the rate of change of flux linked to the resistive voltage and thus find a longitudinal current density

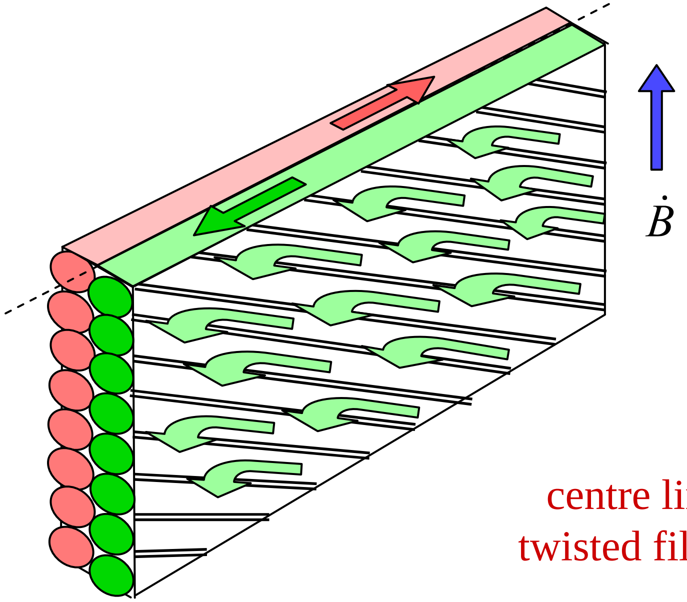
$$J_z(y) = \frac{\dot{B}_t \, p \, y}{N \, r_a \, Sin\theta}$$

- integrate current × area to get magnetization

$$\boxed{M_{ta} = \frac{1}{12} \frac{\dot{B}_t}{r_a} \frac{p^2}{N} \frac{c}{cos\theta}}$$

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

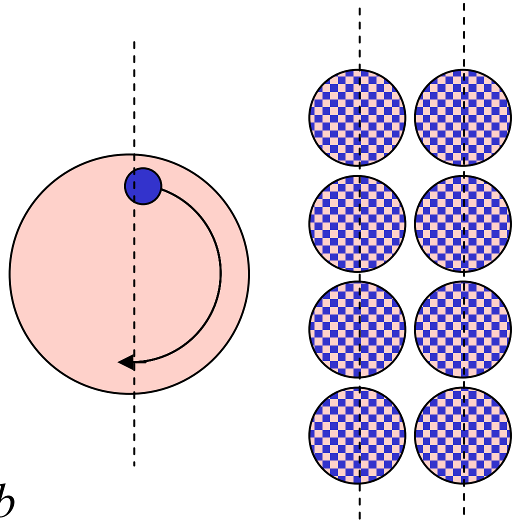
Parallel field: coupling via adjacent resistance



- consider the current paths shown to find an effective resistivity along the cable

$$\rho_{ez} = \frac{N}{p} r_a \, Sin\theta$$

(take flux linkages to centre line of wires because all twisted filaments rotate about it)



- equate the the rate of change of flux linked to the resistive voltage and thus find a longitudinal current density

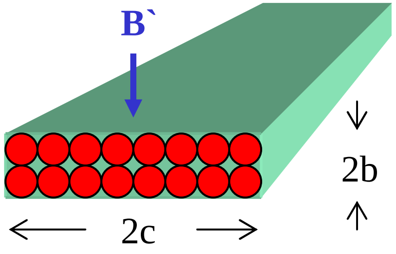
$$J_z = \frac{\dot{B}_p \, p \, b}{2 N \, r_a \, Sin\,\theta}$$

- integrate current × area to get magnetization

$$\boxed{M_{pa} = \frac{1}{16} \frac{\dot{B}_p}{r_a} \frac{p^2}{N} \frac{b^2}{c \, cos\theta}}$$

$$\boxed{M_{pa} = \frac{1}{8} \frac{\dot{B}_p}{R_a} p \frac{b}{c}}$$

Summary of coupling magnetization in cables



- Field transverse
  coupling via crossover resistance R_c

$$\boxed{M_{tc} = \frac{1}{60}\frac{\dot{B}_t}{r_c}p^2\frac{c^2}{b}}$$

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

where M = magnetization per unit volume of cable, p twist pitch, N = number of strands

- Field transverse
  coupling via adjacent resistance R_a

  where θ = slope angle of wires $Cos\theta \sim 1$

$$\boxed{M_{ta} = \frac{1}{12}\frac{\dot{B}_t}{r_a}\frac{p^2}{N}\frac{c}{\cos\theta}}$$

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

- Field parallel
  coupling via adjacent resistance R_a

$$\boxed{M_{pa} = \frac{1}{16}\frac{\dot{B}_p}{r_a}\frac{p^2}{N}\frac{b^2}{c\cos\theta}}$$

$$\boxed{M_{pa} = \frac{1}{8}\frac{\dot{B}_p}{R_a}p\frac{b}{c}}$$

(usually negligible)

- Field transverse
  ratio crossover/adjacent

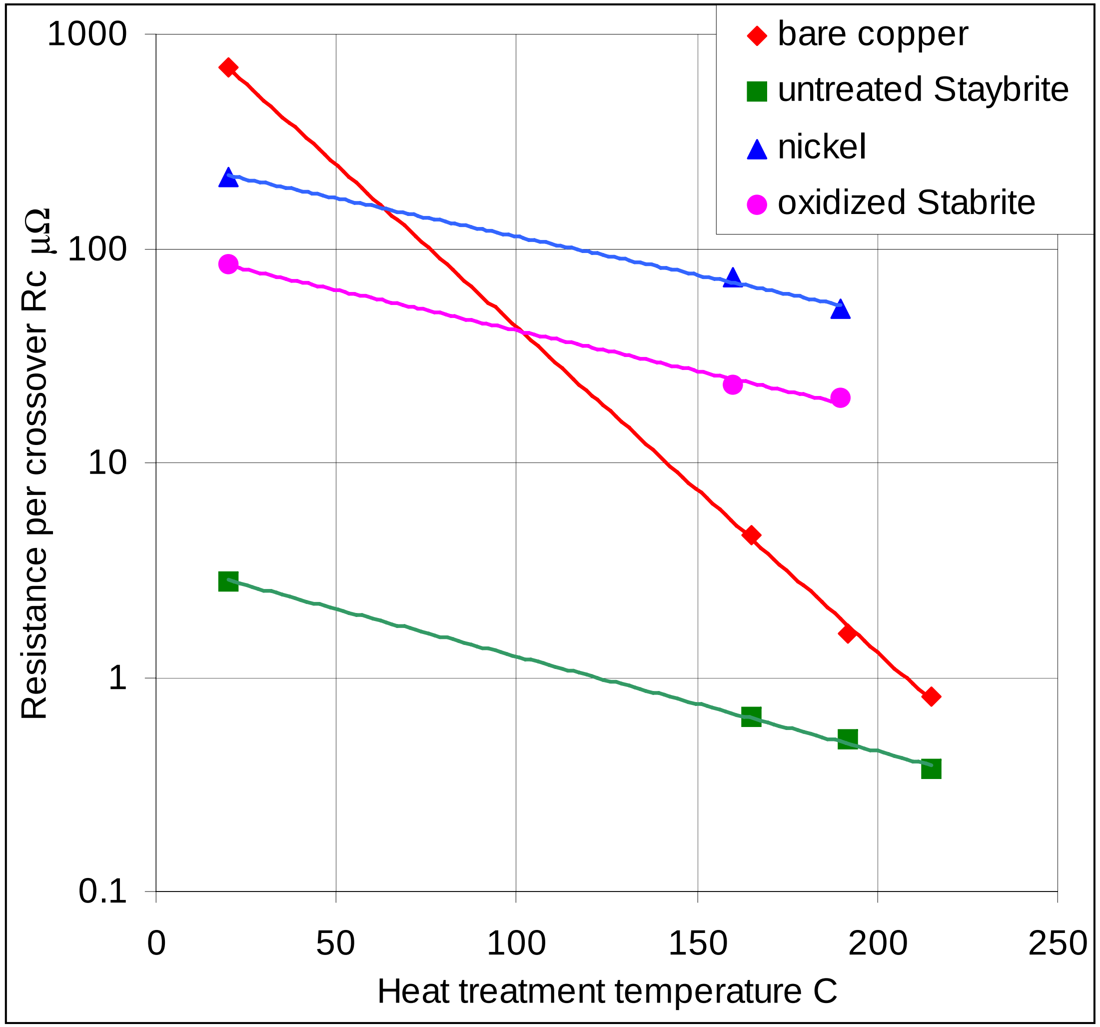
$$\frac{M_{tc}}{M_{ta}} = \frac{R_a}{R_c}\frac{N(N-1)}{20} \approx 45\frac{R_a}{R_c}$$

So without increasing loss too much can make R_a 50 times less than R_c - anisotropy

Controlling R_a and R_c: coatings

- surface coatings on the wires are used to adjust the contact resistances $\boldsymbol{R_c}$ and $\boldsymbol{R_a}$
- the values obtained are very sensitive to pressure and heat treatments used in coil manufacture (to cure the adhesive between turns)
- with a bare copper surface, the contact resistance is high, but heat treatment under pressure causes the oxide to dissolve into the copper and produces pure copper contact points
- metallic coatings have more stable oxide layers

data from David Richter CERN

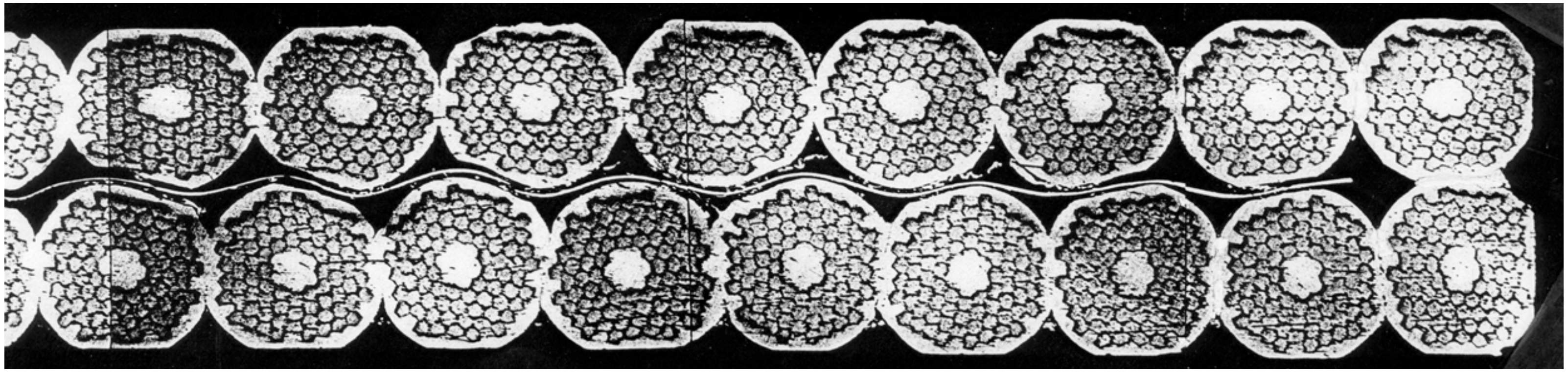


Controlling R_a and R_c: cores

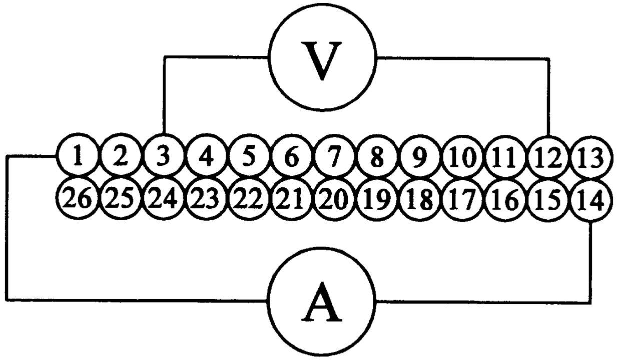
recap the anisotropy of magnetization
(and therefore losses)

$$\frac{M_{tc}}{M_{ta}} = \frac{R_a}{R_c}\frac{N(N-1)}{20} \approx 45\frac{R_a}{R_c}$$

- some of us have the idea that and high resistance between strands is not a good thing - it is more difficult for the current to share in the event that one strand has too much current or suffers a temperature spike - so high $\boldsymbol{R_c}$ and $\boldsymbol{R_a} \Rightarrow$ instability (contentious).
- because of the anisotropy, we can keep the losses low by increasing $\boldsymbol{R_c}$ only, while keeping $\boldsymbol{R_a}$ low
- a resistive (eg stainless steel) core foil gives high $\boldsymbol{R_c}$ and $\boldsymbol{R_a}$
- it is not affected much by heat treatment but reduces the filling factor slightly

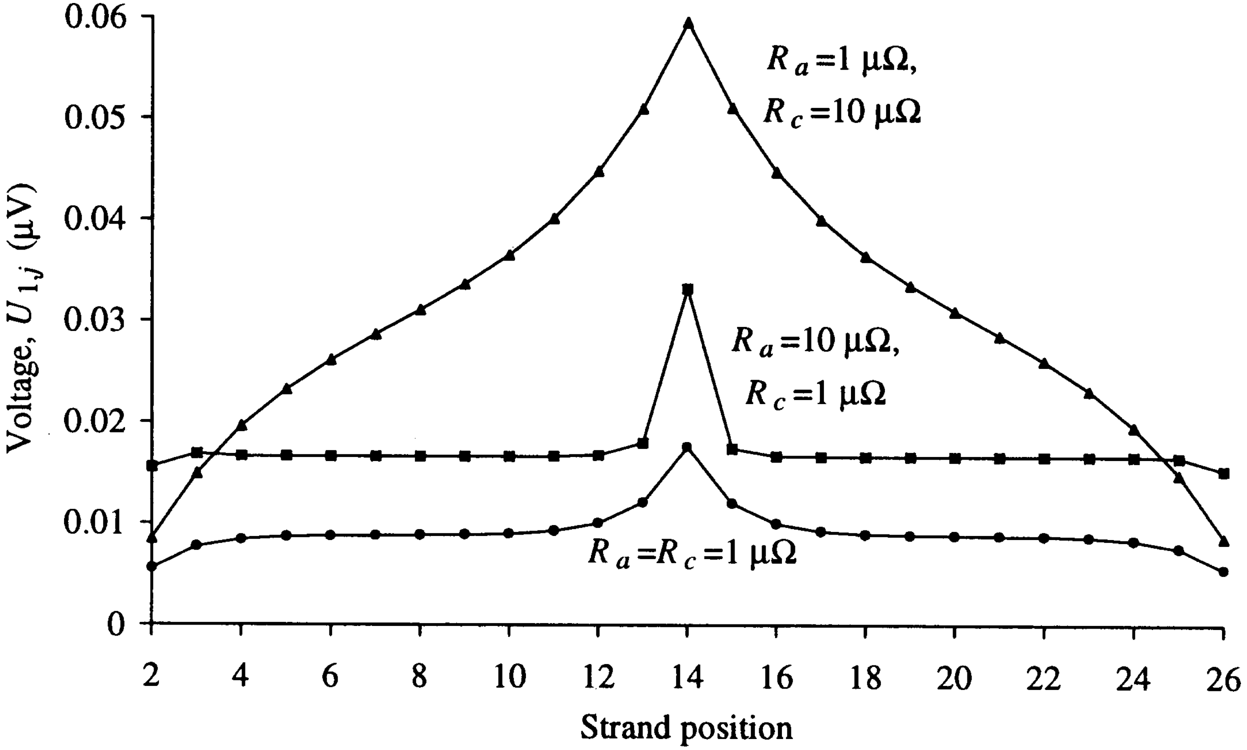


Measurement of r_c and r_a



- the best way is to measure magnetization directly, but this is expensive for a large cable
- a cheaper quicker alternative is to inject current between opposite sides of a cable sample and measure the voltage distribution between all the wires

- shape of the plots depends on the ratio R_a / R_c
- for details see *'Electrodynamics of superconducting cables in accelerator magnets', AP Verweij Thesis University Twente 1995*



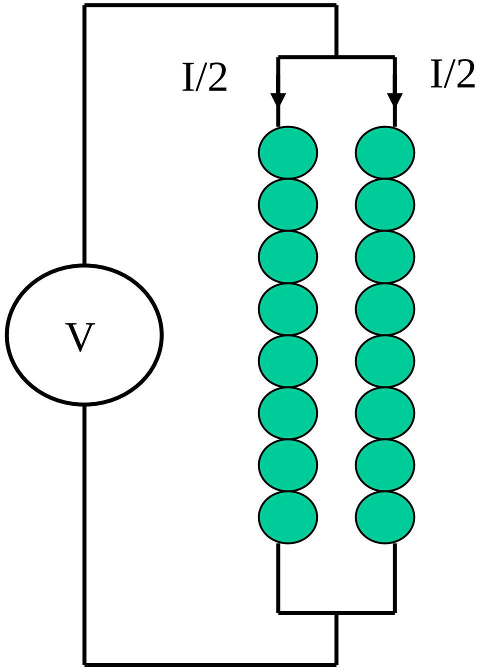
Measurement when $r_a << r_c$

Cored cables when $R_a << R_c$ are a rather simple case.
The current divides in two and each branch flows between *N/2* wires, where *N* is number of wires in cable

let sample length = l_s measured voltage = V current = I

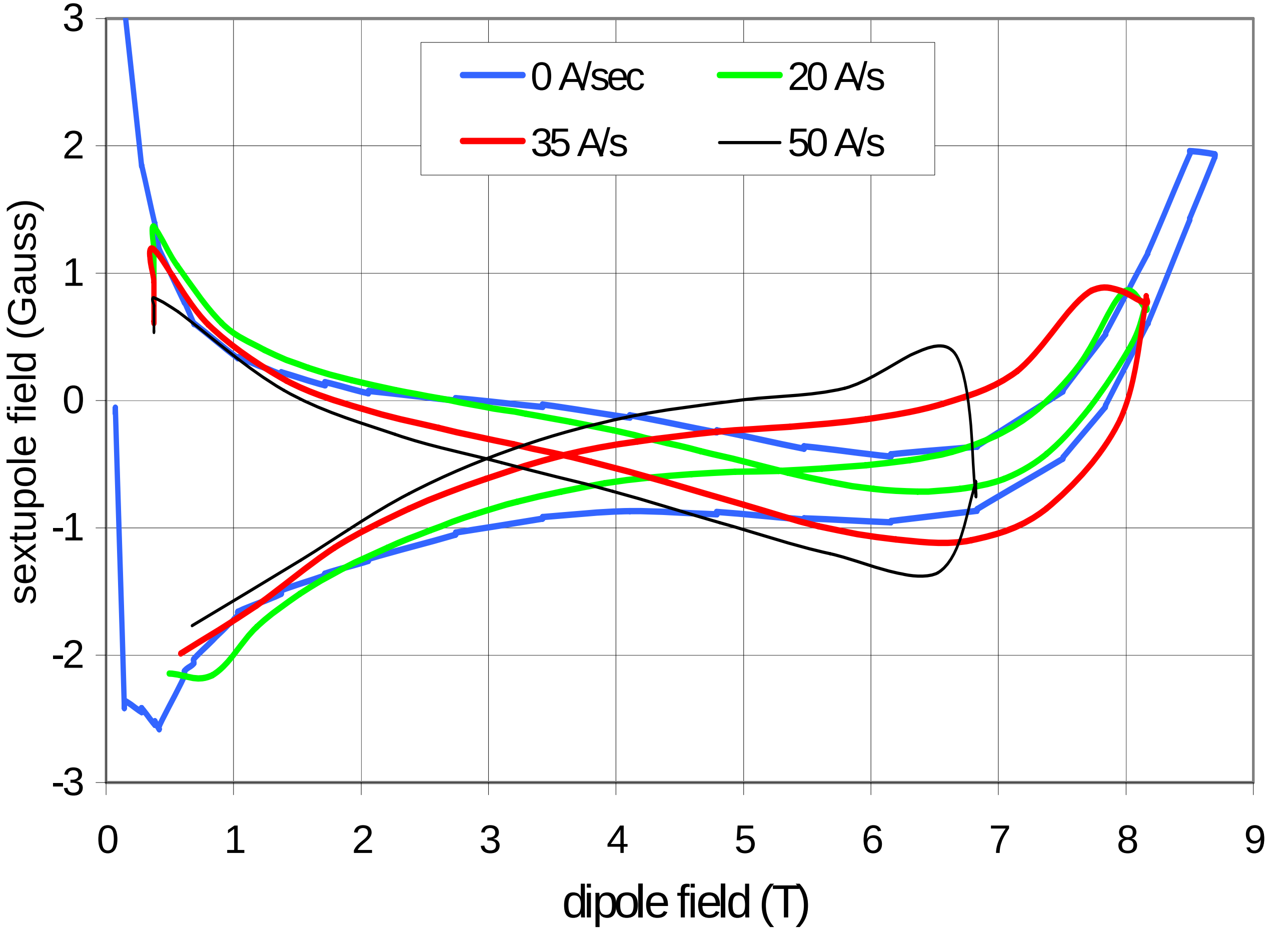
$$\frac{2V}{I} = \frac{N}{2}\frac{r_a}{b\,l_s}$$

$$\boxed{r_a = 4\frac{V}{I}\frac{b\,l_s}{N}}$$



Field errors caused by coupling

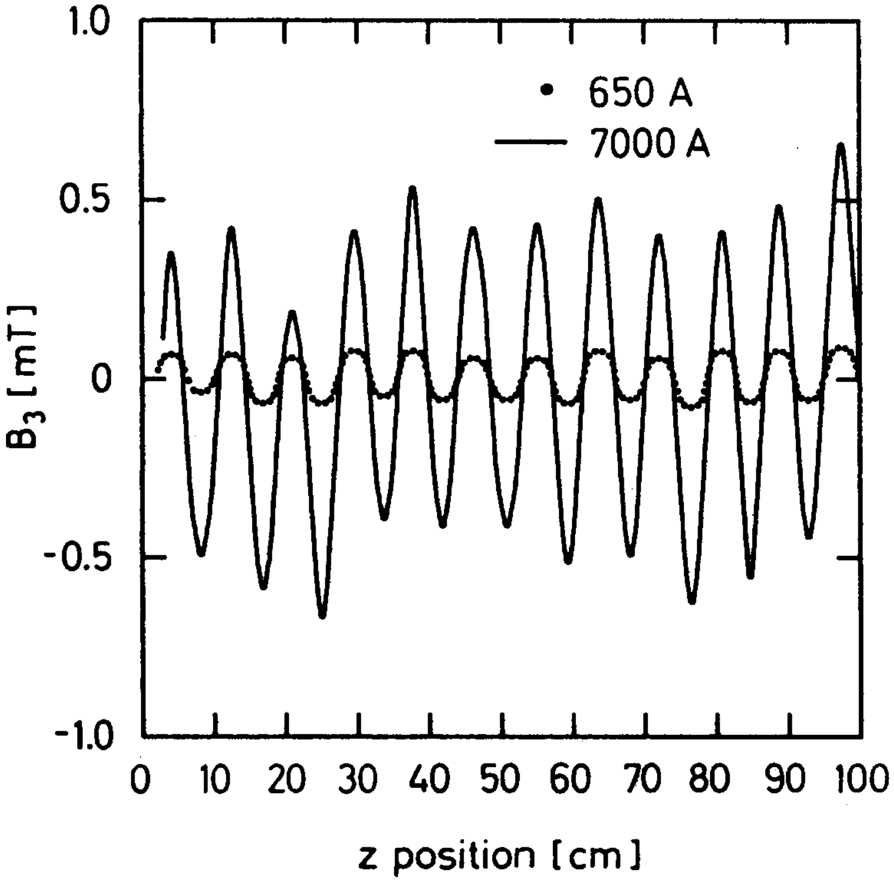
- plot of sextupole field error in an LHC dipole with field ramped at different rates
- error at low field due to filament magnetization
- error at high field due to
  a) iron saturation
  b) coupling between strands of the cable
- the curves turn 'inside out' because
  - greatest **filament** magnetization is in the **low** field region (high J_c)
  - greatest **coupling** is in the **high** field region (high dB/dt)



data from Luca Bottura CERN

Long range coupling: BICCs

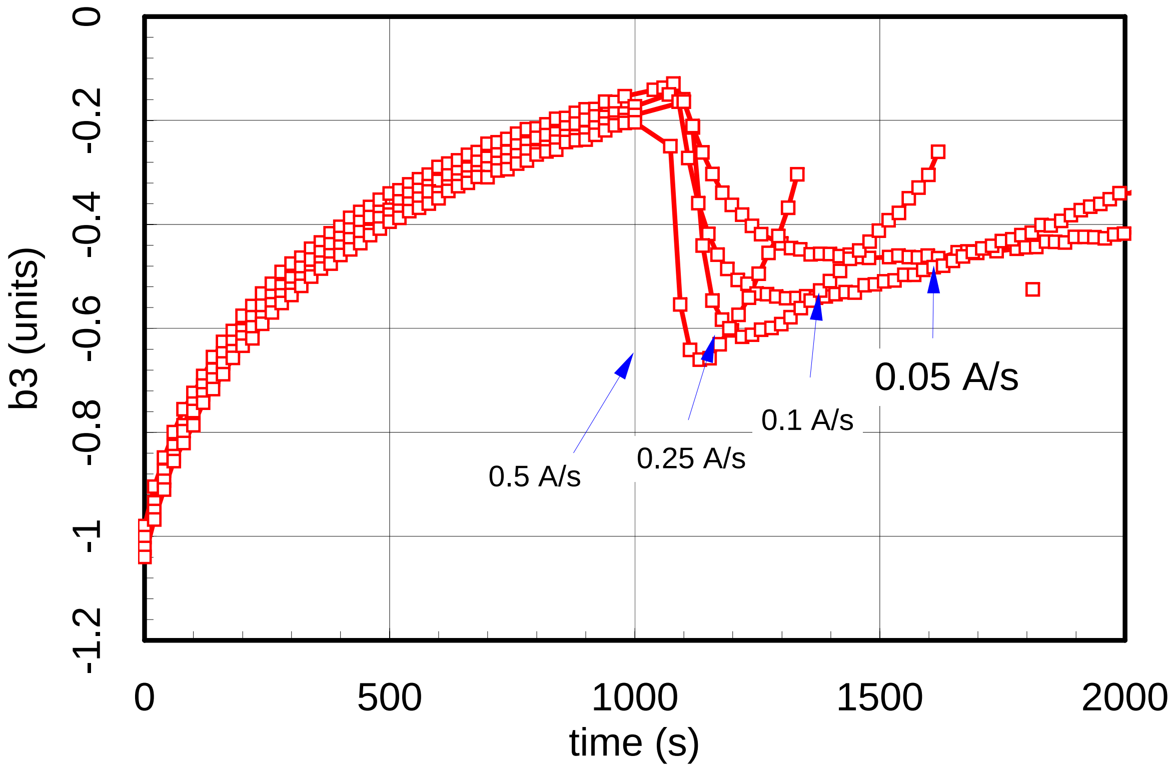
- measuring the field of an accelerator magnet along the beam direction, we find a ripple
- wavelength of this ripple exactly matches the twist pitch of the cable
- thought to be caused by non uniform current sharing in the cable
- Verweij has called them 'boundary induced coupling currents' **BICCs**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

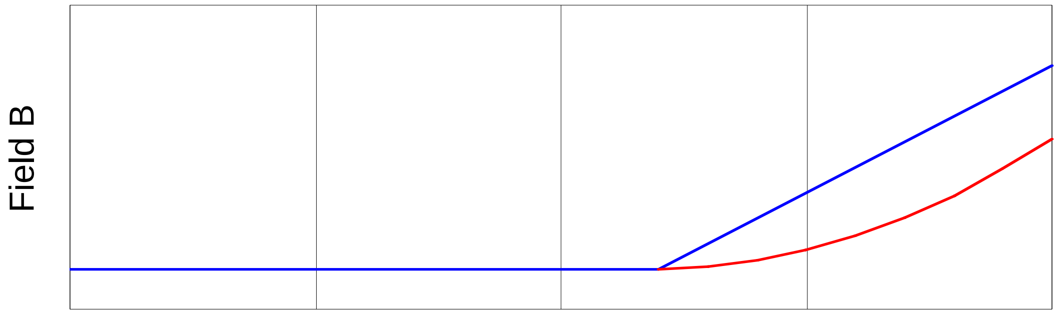


sextupole measured in SSC dipole at injection and full field

Snap back

- during the injection platform of an LHC dipole, the sextupole error term **integrated over the magnet length** decays with a time constant of ~ 1000sec.
- when the ramp is started, the error term 'snaps back' to its earlier value
- it is difficult to find a time constant of 1000 seconds in any of the usual coupling modes
- BICCs have such a time constant, but integrating the oscillating field over the magnet length gives zero!

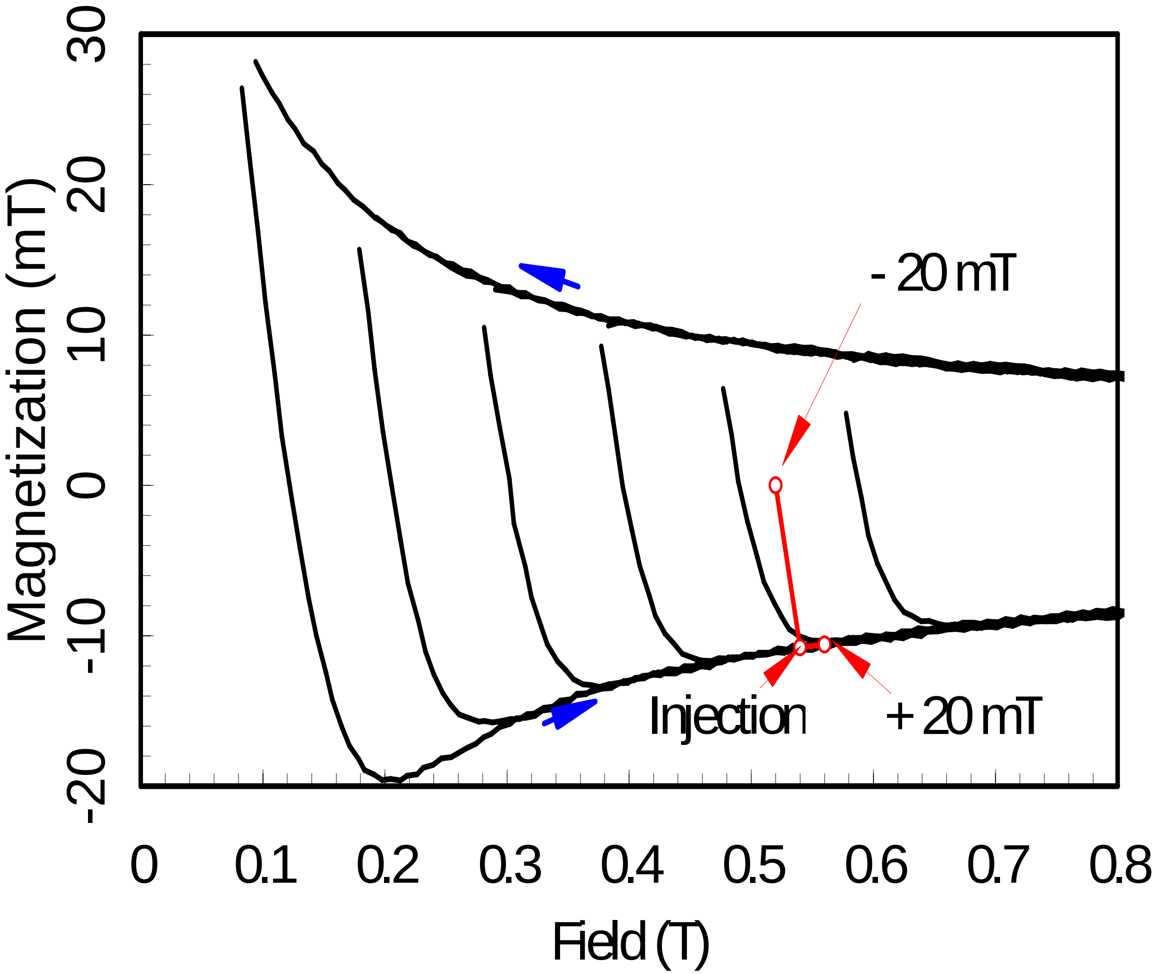


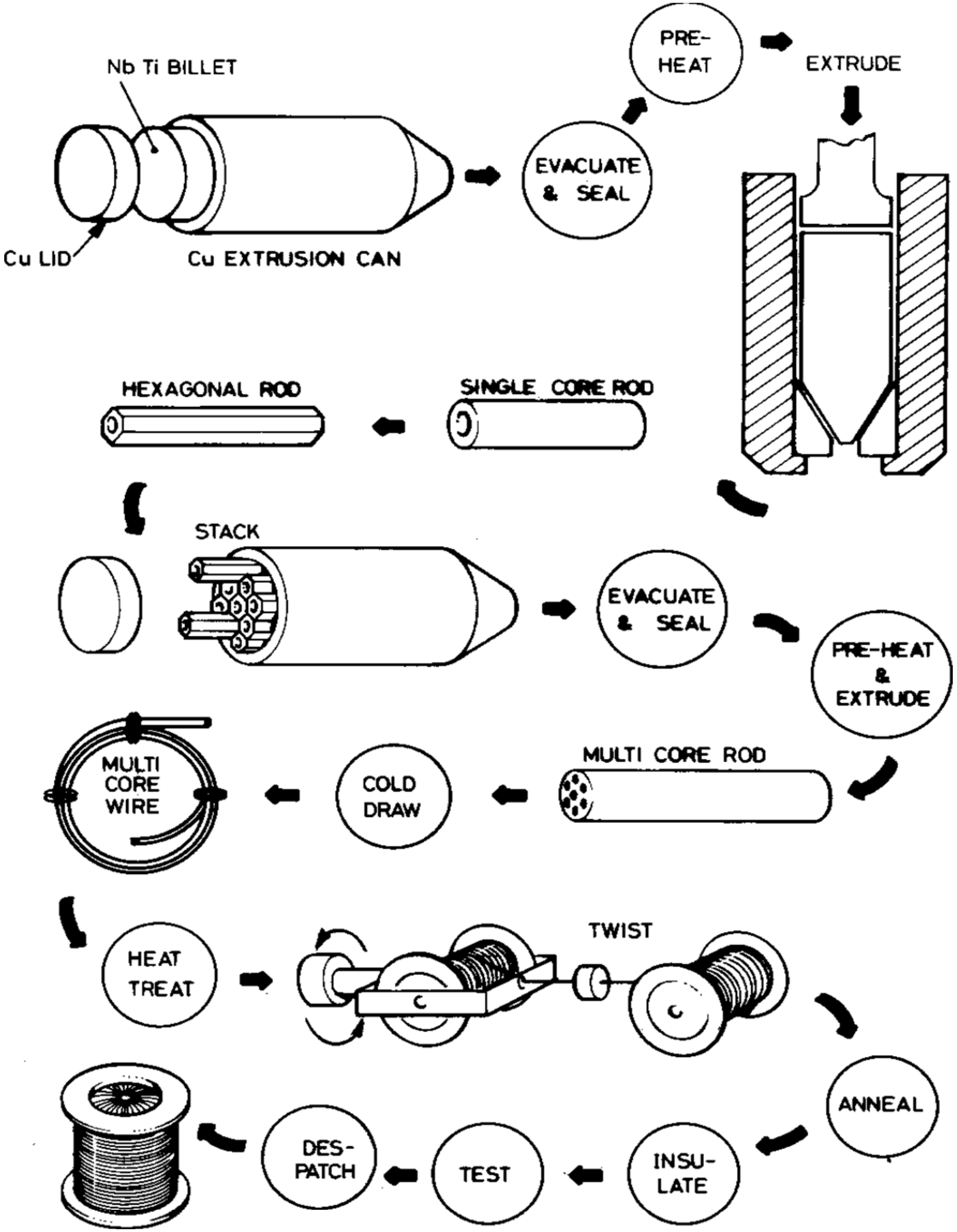


Snap back: an explanation

- BICCs produce a field component which alternates ± 20 mT along the magnet
- imagine the hysteresis curve of NbTi filaments subjected to this oscillation
- a 20 mT increase produces very little change in filament magnetization
- a 20 mT decrease produces a large change in filament magnetization
- thus the hysteresis curve acts as a 'rectifier' enabling the oscillating BICCs to produce a dc level

explanation by Rob Wolf of CERN





Manufacture of NbTi

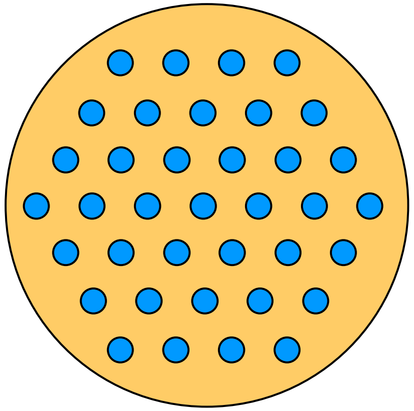
- vacuum melting of NbTi billets
- hot extrusion of the copper NbTi composite
- sequence of cold drawing and intermediate heat treatments to precipitate αTi phases as flux pinning centres
- for very fine filaments, must avoid the formation of brittle CuTi intermetallic compounds during heat treatment

  - usually done by enclosing the NbTi in a thin Nb shell
- twisting to avoid coupling - see lecture 2

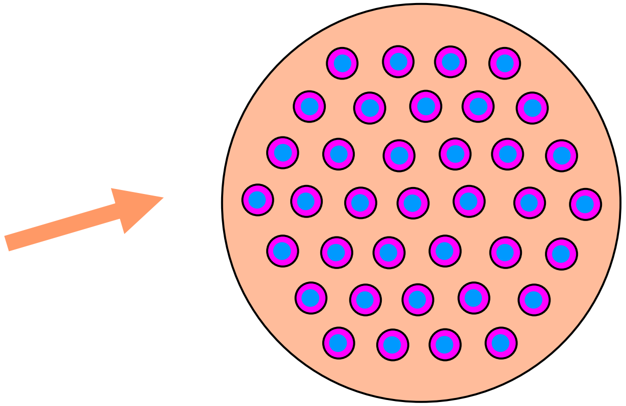
Manufacture of filamentary Nb_3Sn wire

Because Nb_3Sn is a brittle material, it cannot be drawn down in final form.

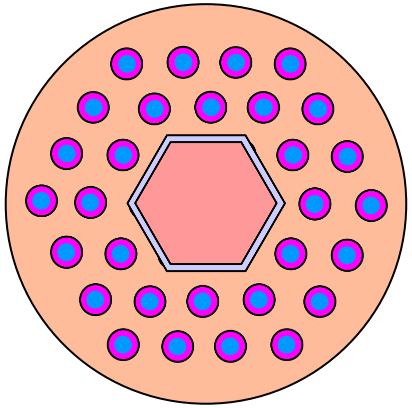
Instead we must draw down pure niobium in a matrix of bronze (copper tin)

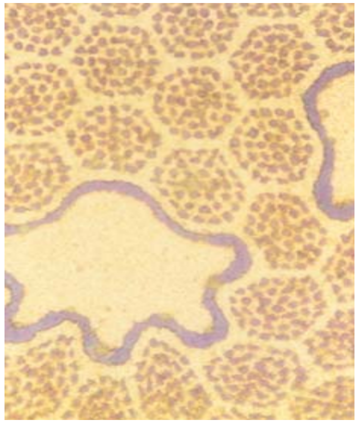


At final size the wire is heated (~700C for some days) tin diffuses through the Cu and reacts with the Nb to form Nb_3Sn

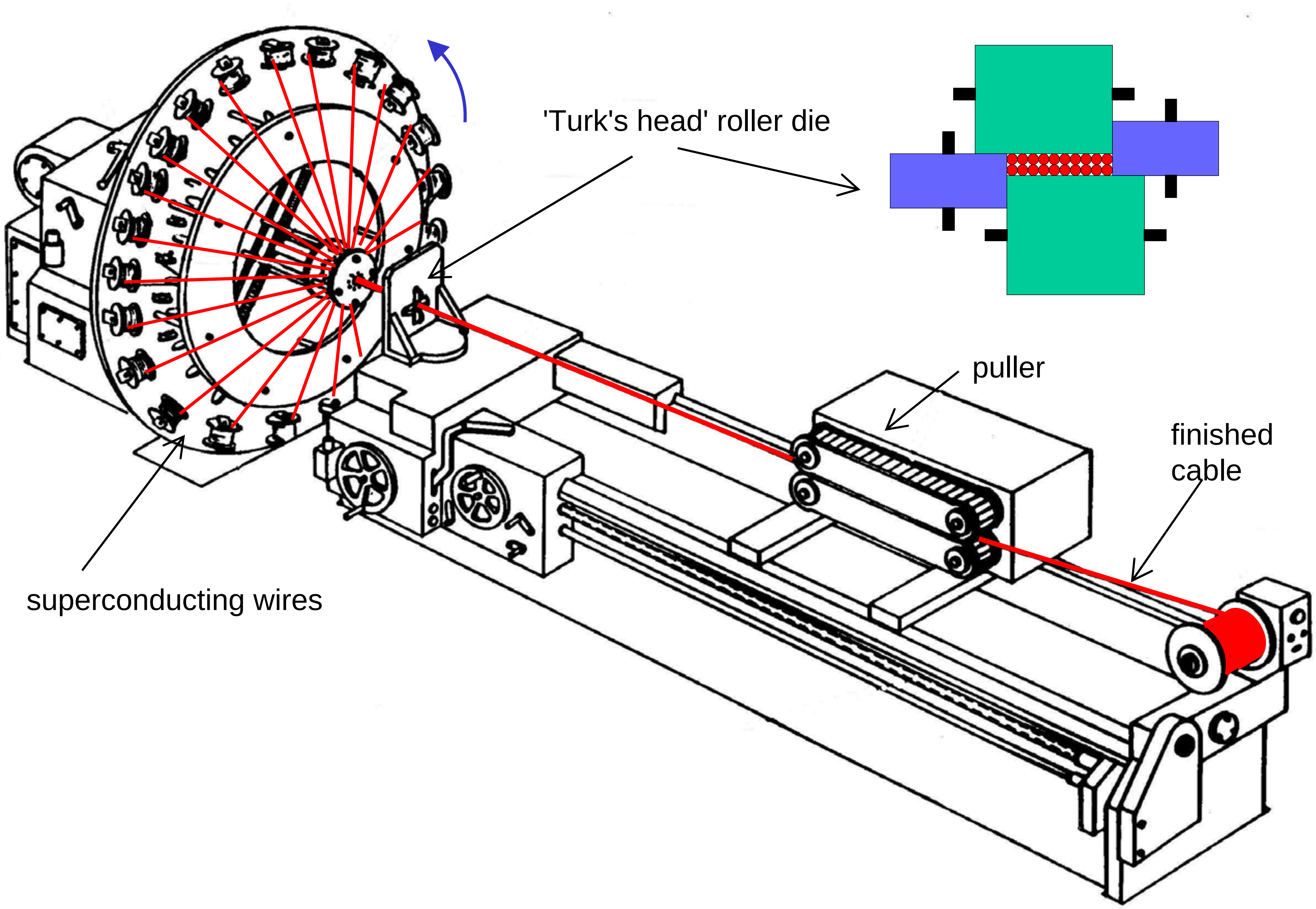


Unfortunately the remaining copper still contains some tin and has a high resistivity. We therefore include 'islands' of pure copper surrounded by a diffusion barrier





Cable manufacture



Cables: concluding remarks

- accelerator magnets need high current because they must be connected in series
- high currents need cables of 20 - 40 wires
- cables must be fully transposed to get uniform current sharing between the wires
- wires in the cables become coupled in changing fields and acquire additional magnetization
  - similar to the filaments in composite wires, but more complicated because of geometry
- we distinguish between coupling magnetization coming from crossover and adjacent resistance R_c and R_a and fields perpendicular or parallel to the broad face of the cable
- in all cases the increased magnetization $\Rightarrow$ loss
- need to control loss by surface treatment to increase R_c and R_a or core to increase R_c only
- measure R_c and R_a resistively
- cable magnetization also $\Rightarrow$ field error
- boundary induced coupling currents BICCs give some interesting 2nd order effects