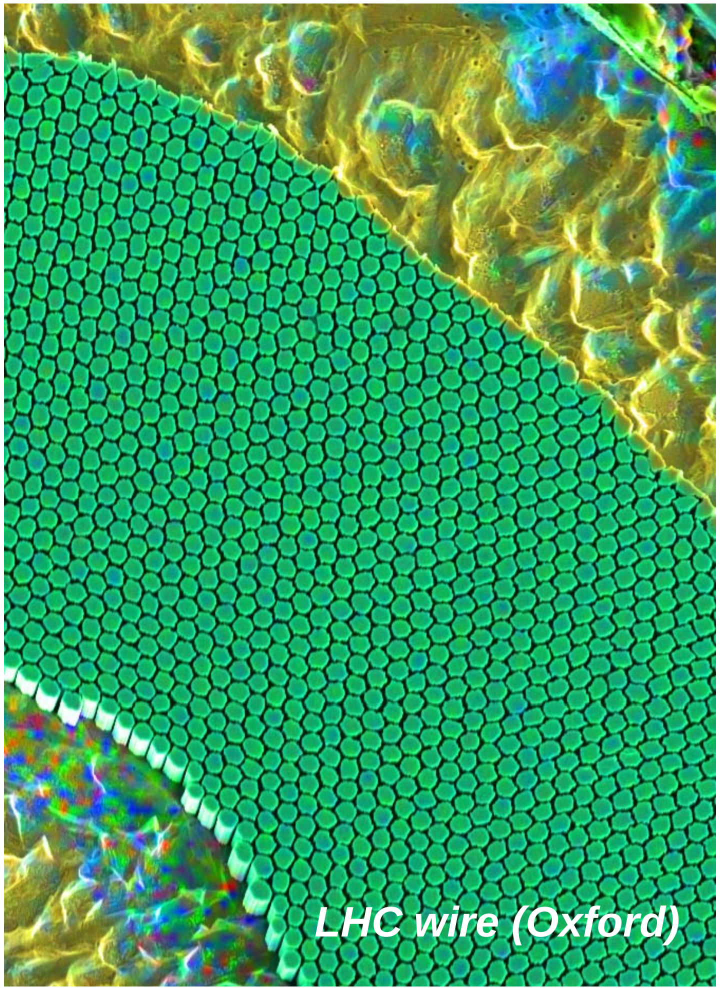
Advances in low loss NbTi Strand and Cable

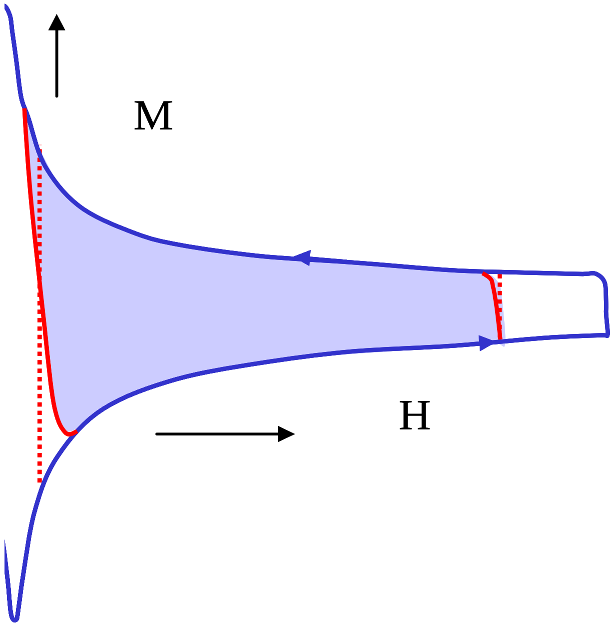
Martin Wilson

Plan

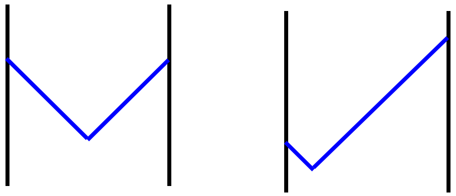
- Recapitulate general loss mechanisms
- Hysteresis loss - fine filaments proximity coupling etc
- Coupling loss within wires - transverse resistivity, barriers, stability
- Coupling loss between cables - interface resistance, stability, cores



AC loss general



- work done to change the field energy $\delta E = H\delta B$
- around a closed loop, energy dissipated in a magnetic material $$E = \oint \mu_o H dM = \oint \mu_o M dH$$
- away from end points, loss power $P = M\dot{B}$
- superconductor magnetization comes from
  - supercurrents ⇒ hysteresis
  - combined supercurrents and resistive currents ⇒ coupling
  - classical eddy currents
- with a transport current flowing, the power supply also does work, increasing the loss by a factor $$1 + \left({}^{I_t}\!/_{I_c} \right)^2$$



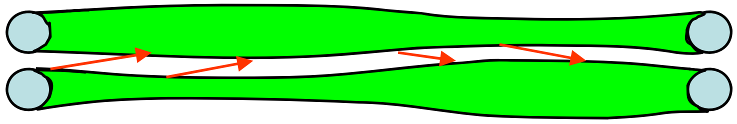
Hysteresis

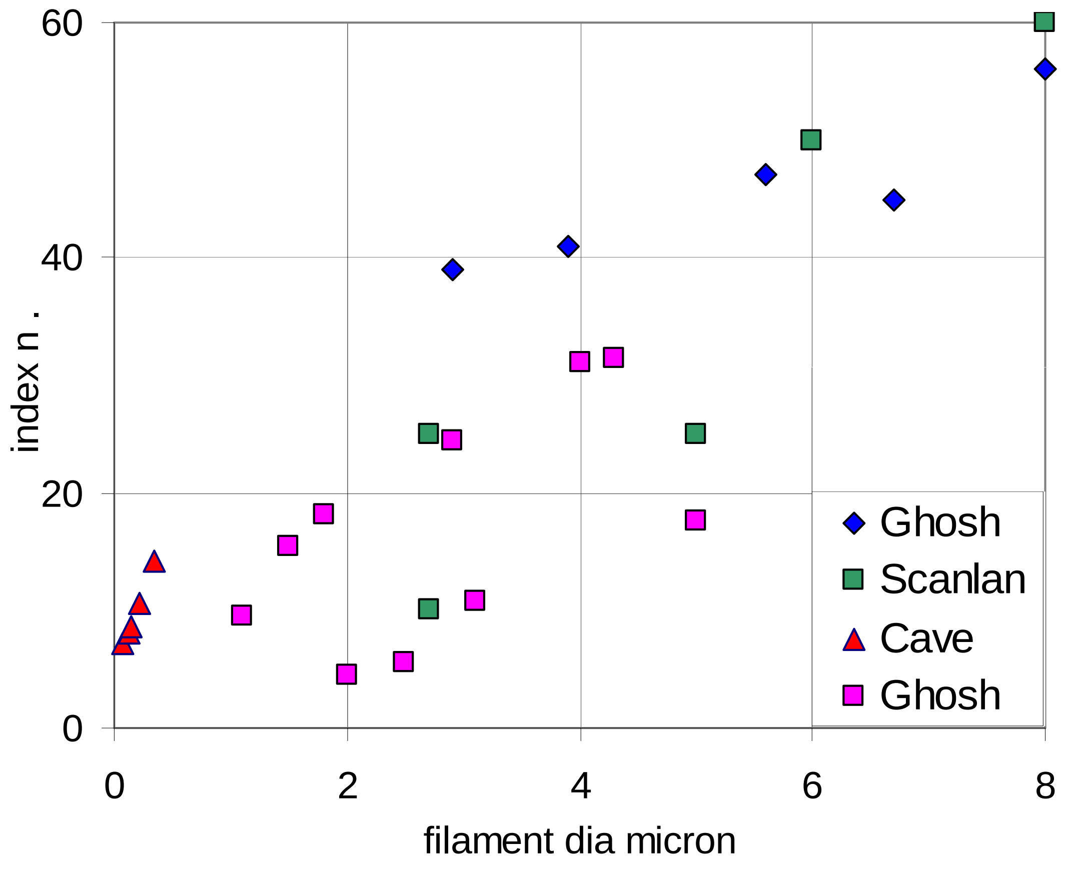
- for round filaments $$M = \frac{2}{3\pi} J_c \, d_f \qquad P = \dot{B} \frac{2}{3\pi} J_c \, d_f$$

⇒ *fine filaments*

Making fine filaments: resistive transition

- resistive transition $$\rho(J) = \rho_o \left\{ \frac{J}{J_o} \right\}^n$$
- depends on processing - 'sausaging'
- n always gets worse with finer filaments, so useful J gets less
- but intrinsic J_c does not get worse



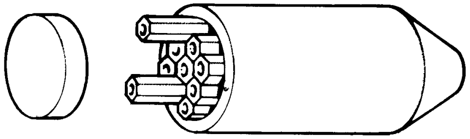


Intermetallics

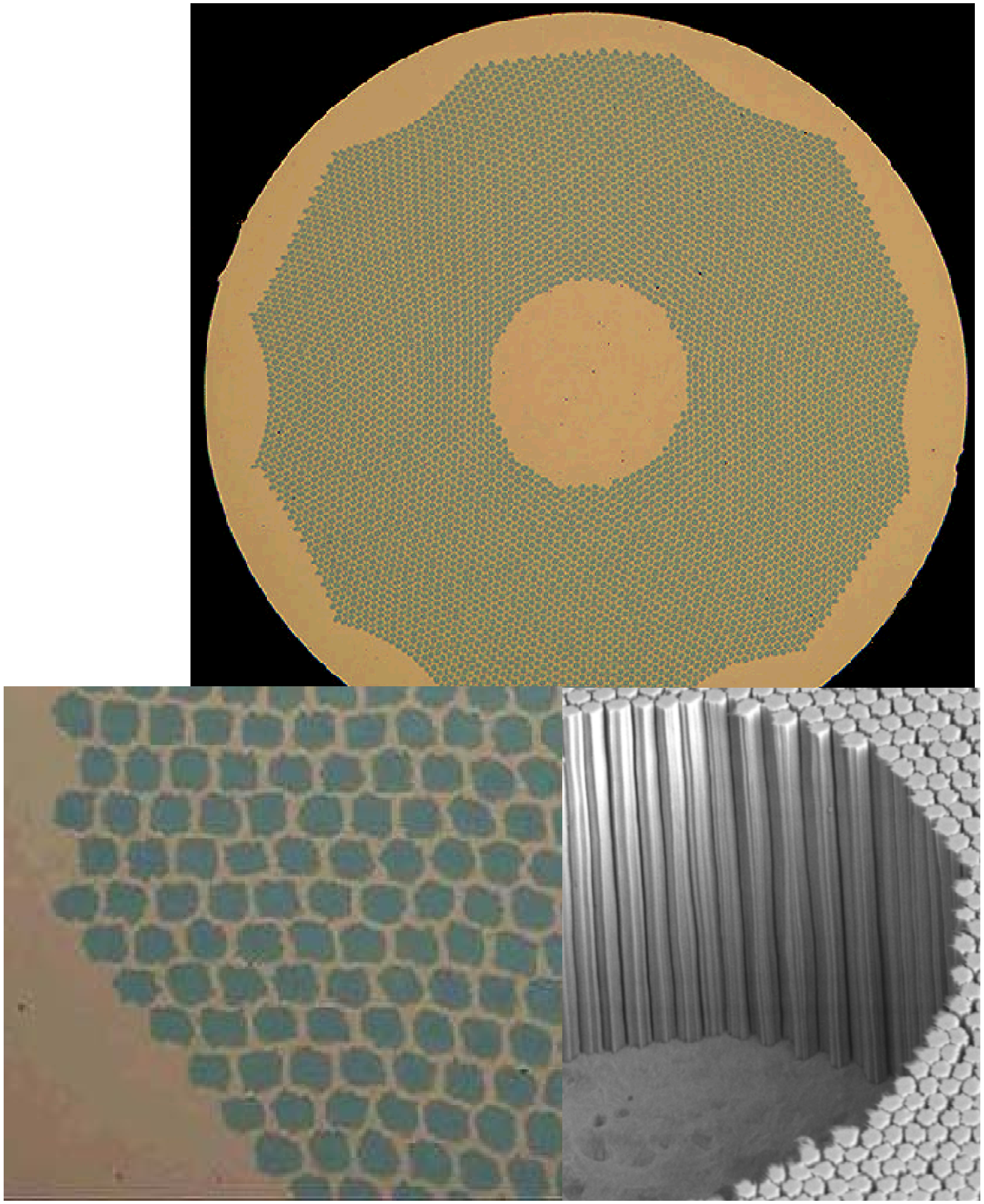
- CuTi intermetallic particles formed during extrusion pre-heat
- they don't draw down with the filaments ⇒ breakage
- must surround filament with diffusion barrier - usually Nb

Making fine filaments: Single stacking

- single stacking makes the best wire
- when packing the extrusion cannister, rods buckle below ~ 1.5mm diameter
  ⇒ filament crossover ⇒ breakage
- for a 250mm diameter extrusion cannister, this limits the number of filaments to ~15,000



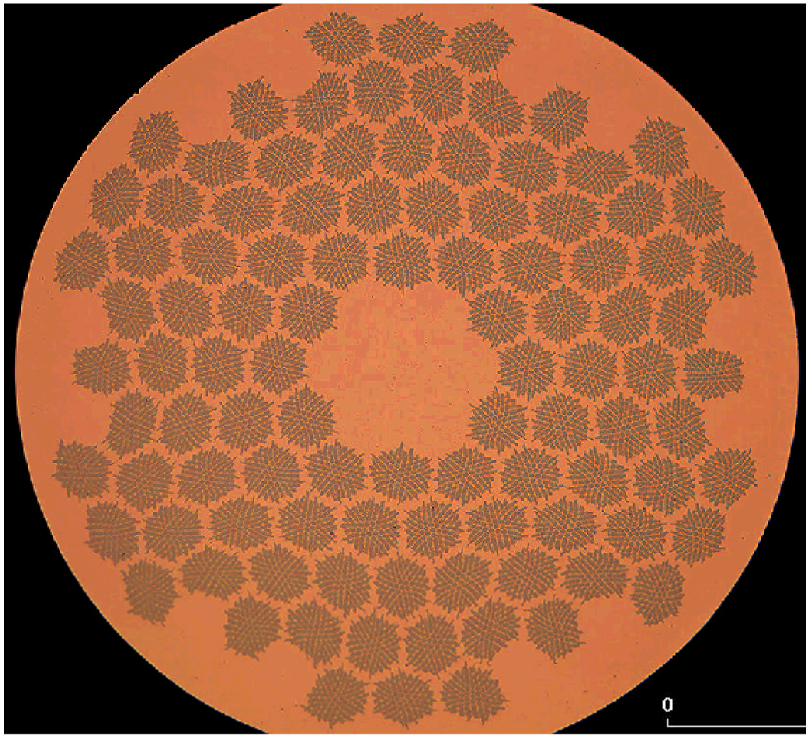
- for a 0.85mm diameter wire, 15,000 filaments
  ⇒ diameter ~ 4.5μm

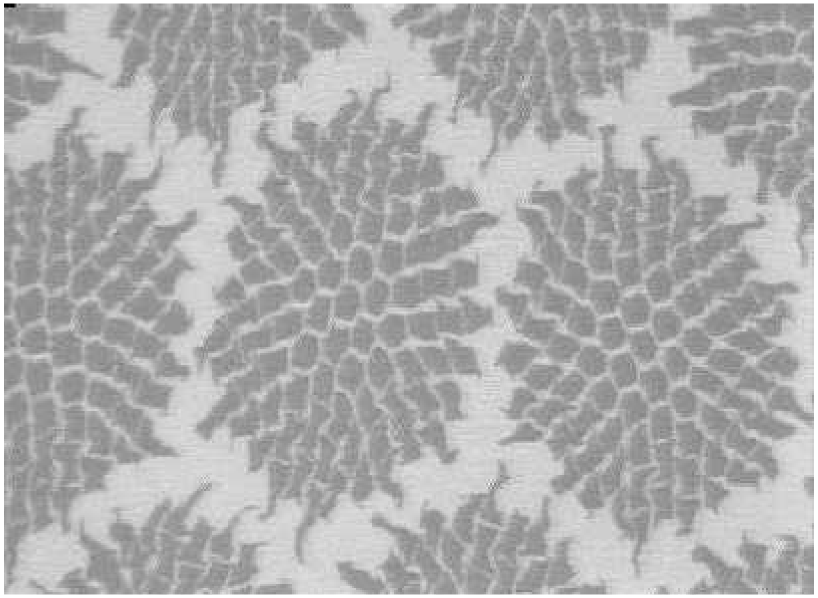


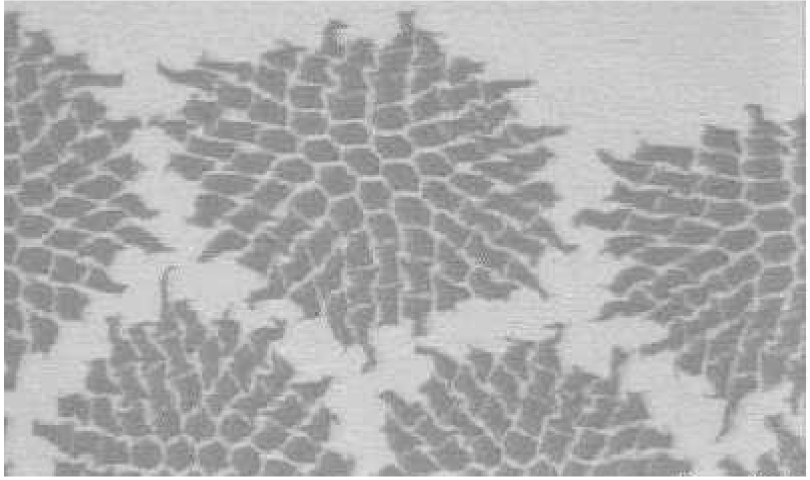
wire 3N7 by European Advanced Superconductors

Making fine filaments: Double stacking

- double stacking is easier and allows a large number of filaments
- but the filaments are more distorted





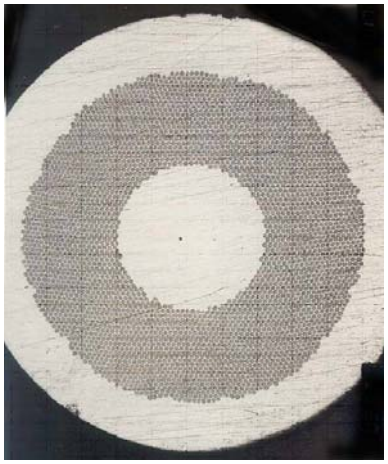


wire 2A212 by European Advanced Superconductors

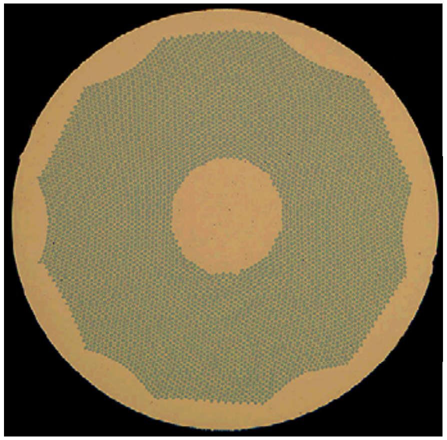
Fine filaments: distortion

- measure magnetization extrapolated to zero B` and J_c via transport current (measure at high field to minimize self field)
- calculate ratio

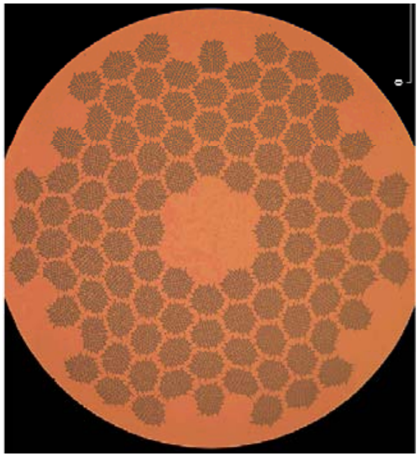
$$r = {}^{J_{cmag}}\!/\!_{J_{ct}}$$



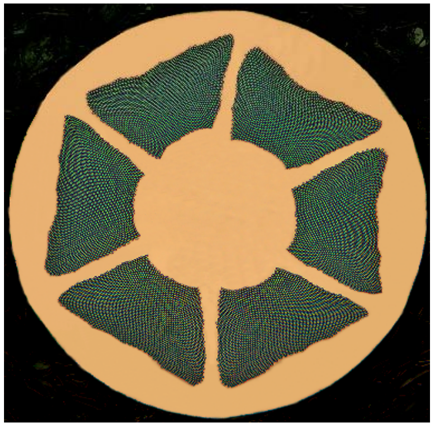
Oxford RHIC: r = 0.92



EAS 3N7: r = 0.94

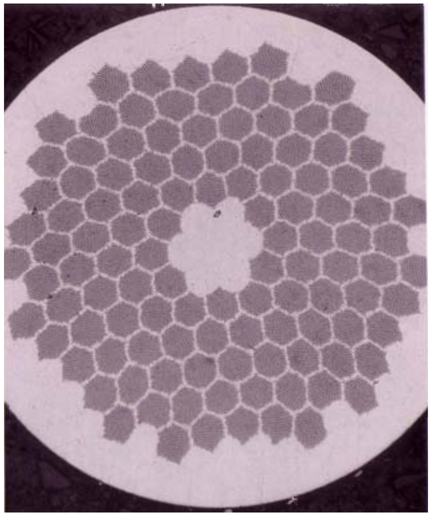


EAS 2A212:
r = 1.40



EAS K2001T4:
r = 1.15

EAS G2001T6:
r = 1.10

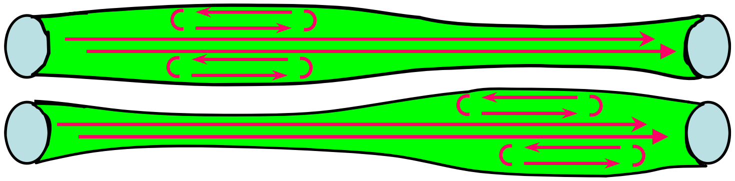


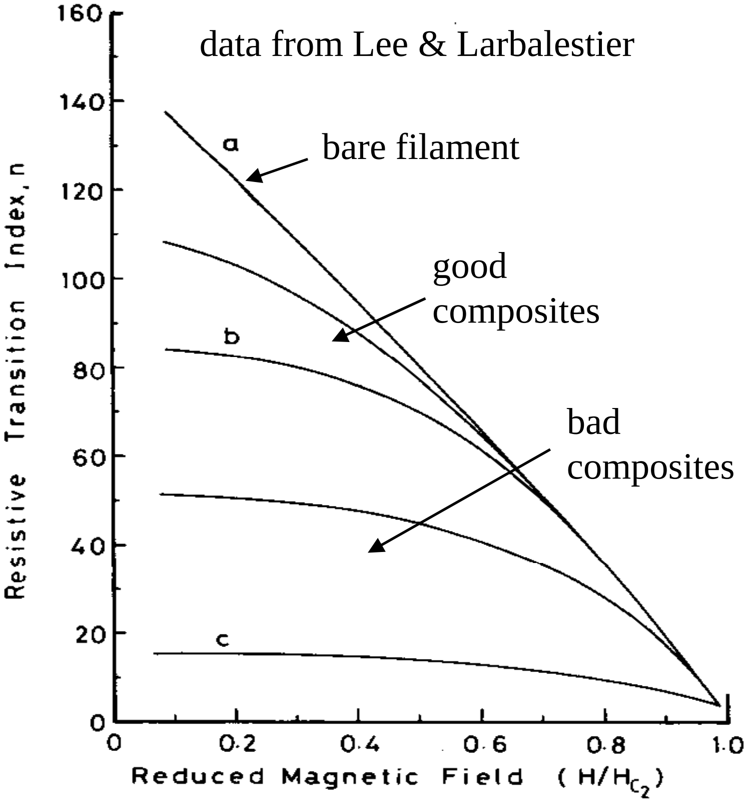
IGC SSC B944-2 (CuMn around filaments) r = 1.23

wire 2A212 by European Advanced Superconductors

Fine filament distortion: why is r <1?

- transport current determined by narrowest paths
- magnetization current fills up the rest
- so $r = {}^{J_{cmag}}\!/\!_{J_{ct}}$ should be > 1
- but J_{ct} is measured with a certain electric field - usually $10^{-14}\ \Omega$m
- J_{cmag} is measured with zero electric field
- even bare filaments have an 'n' value
- estimate the decay of magnetization currents
- for n = 100 and a 6 µm filament, after 100 sec, J_{cmag} will have decayed to 88% of its $10^{-14}\ \Omega$m value





data from Lee & Larbalestier

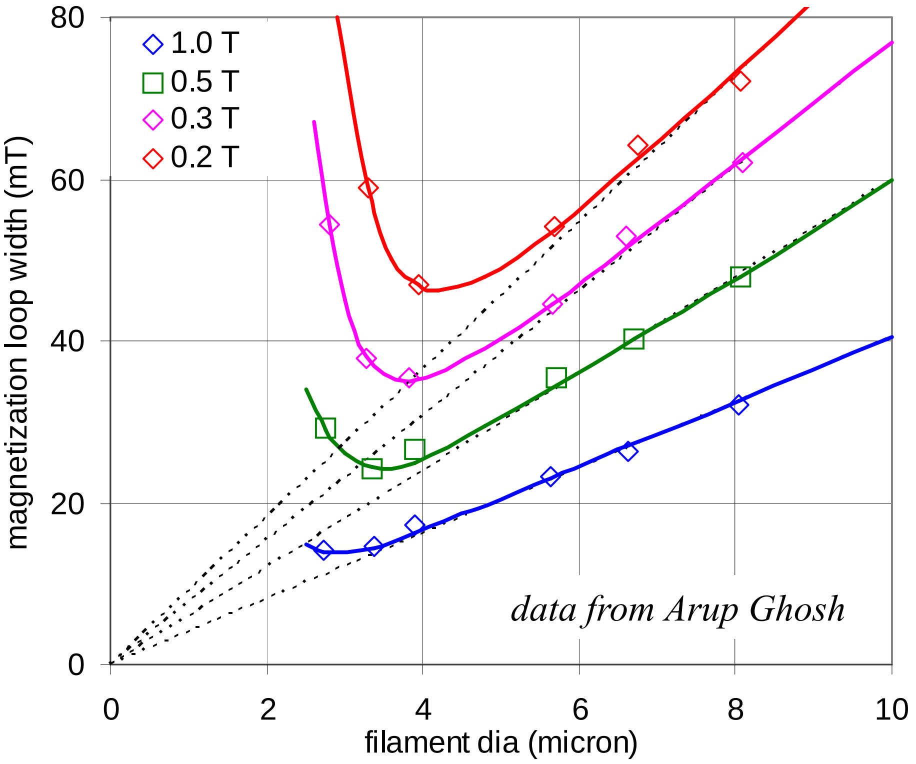
bare filament

good composites

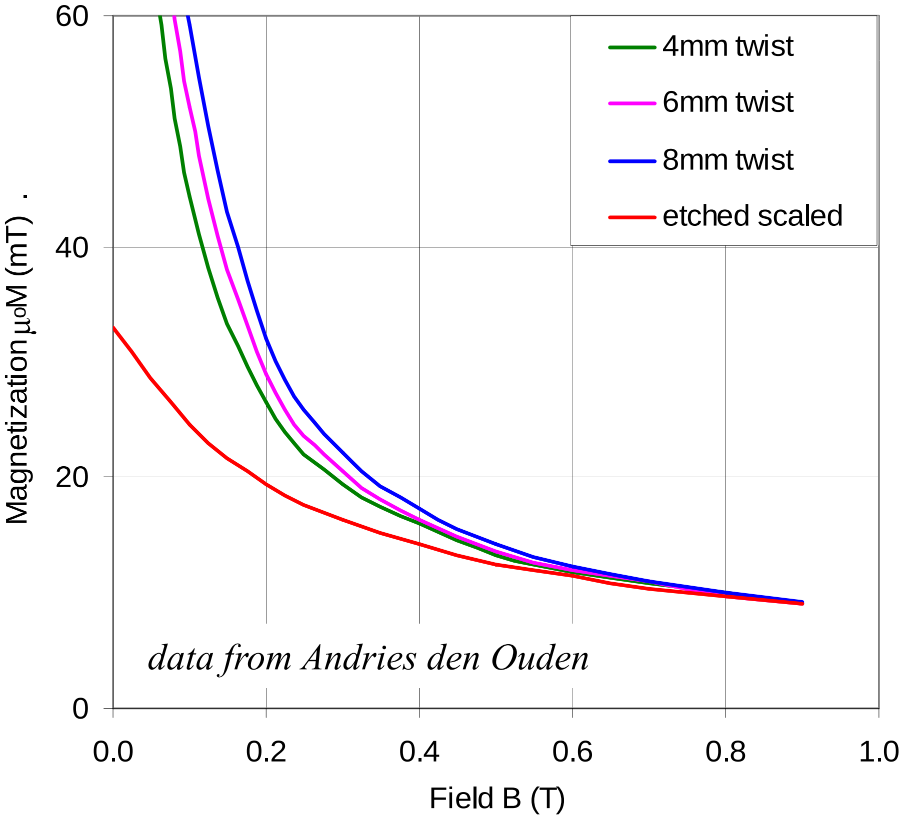
bad composites

Fine filaments: proximity coupling

- magnetization reduces with filament diameter down to a point - then it increases
- effect is strongest at low field



data from Arup Ghosh

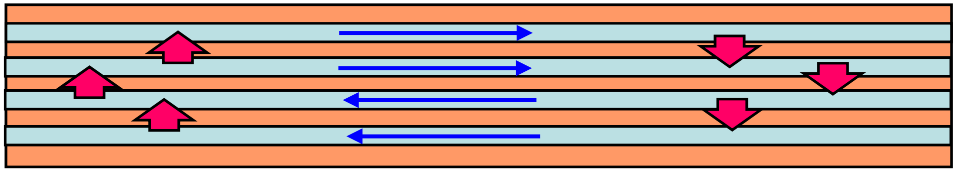


data from Andries den Ouden

- expected linear decrease is restored when filaments are etched
- enhancement of magnetization is ~ (twist pitch) $^{-1}$

Fine filaments: proximity coupling

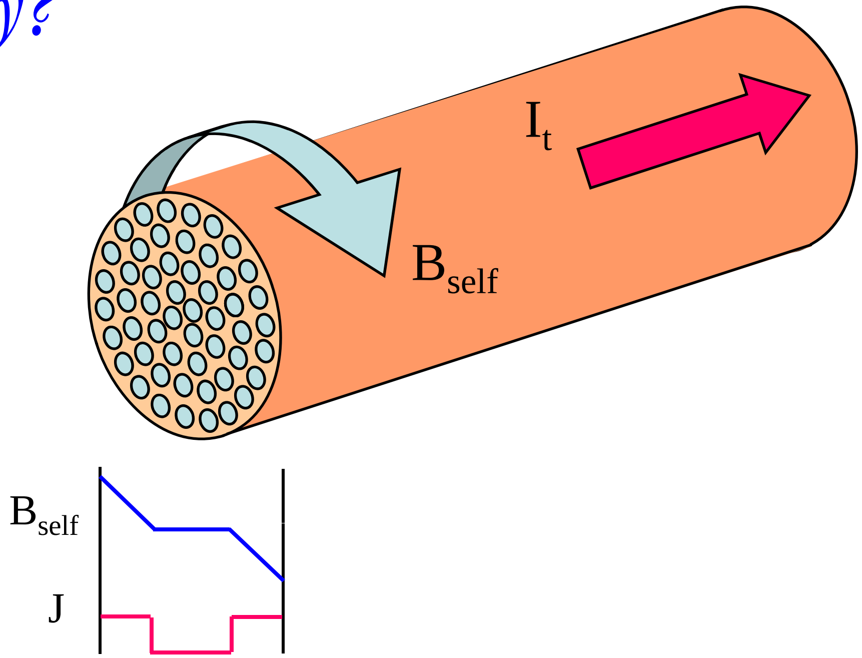
- experimental data on etching suggests that the effect is caused by supercurrents crossing the matrix



- linear dependence on twist pitch suggests these currents have a J_c
- Ghosh finds that transverse current density is given by $J_\perp = J_o e^{-ks}$ where s is the separation between the filaments and k depends on field and temperature
- for minimum sausaging and optimum wire yield, must have $s/d \sim 0.15$, where s is space between filaments and d is filament diameter - so 3µm filaments ⇒ 0.45µm separation
- Collings finds that transverse currents are suppressed by ferromagnetic additions to the matrix metal - 0.5% Mn in copper works well
- adding Si to copper also suppresses proximity currents and also reduces CuTi formation during extrusion
- Sumption found that a wire made by (low temperature) hydrostatic extrusion without Nb diffusion barriers had no proximity coupling down to 2µm filament diameter - perhaps the Nb barriers help to launch Cooper pairs across the copper

Fine filaments: how many?

- self field, due to transport current penetrates from the outside of the wire
- J_c in outer filaments nothing inside
- twisting makes no difference
- penetration produces self field losss (per ramp)



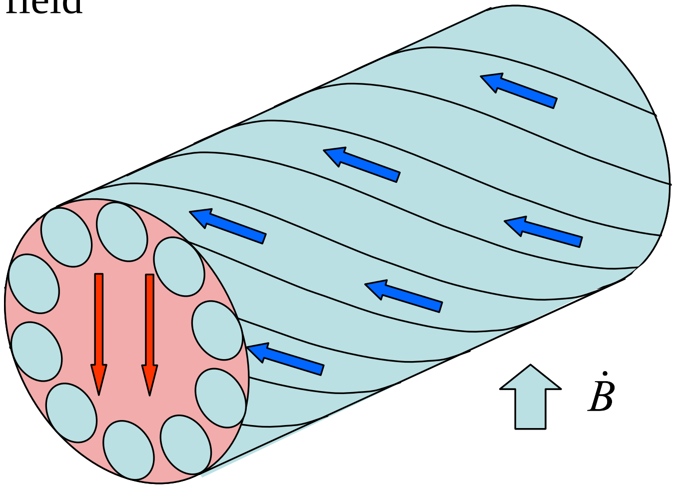
$$Q_s = \frac{B_s^2}{2\mu_o}\left\{\frac{4}{i} - 1 + 4\frac{(2-i)}{i^2}\ln\left(\frac{2-i}{2}\right)\right\}$$

where i - I_t / I_c

- when the self field loss becomes comparable with the hysteresis loss within the filaments, there is little to be gained from further subdivision
- for example, a 0.8mm diameter wire with 10^5 filaments of 2µm diameter will have Q_s / Q_h ~ 50% when ramped from 1T to 6T with i = 0.7

Eddy current coupling between filaments in wires

- currents flow along filament and across matrix parallel to field



- induced magnetization $$M = \frac{2}{\mu_o}\dot{B}\,\tau$$
- current decay time $$\tau = \frac{\mu_o}{2\rho_{et}}\left(\frac{p}{2\pi}\right)^2$$
- loss power $$P = \frac{\dot{B}_i^2}{\mu_o}2\tau = \frac{\dot{B}_i^2}{\rho_{et}}\left(\frac{p}{2\pi}\right)^2$$

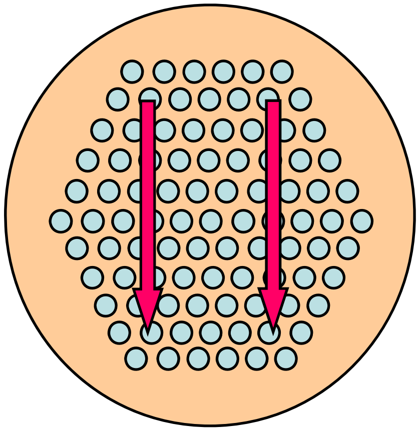
where p = twist pitch and ρ_{et} *is the effective transverse resistivity across the matrix*

- general formulation in terms of multiple time constants*

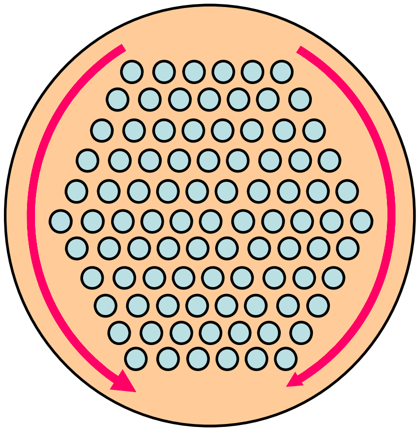
$$P = \frac{2\dot{B}_i^2}{\mu_o}\sum_n \tau_1 + \tau_2 + \tau_3 \ldots\ldots.$$

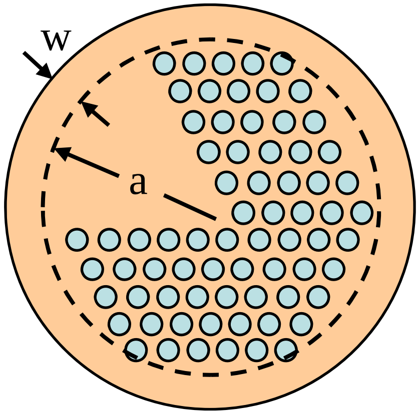
**Duchateau, Turck and Ciazynski: Handbook on Applied Superconductivity B4.3*

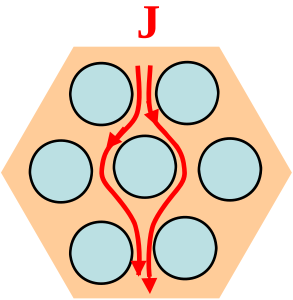
Effective transverse resistivity



Two main
types of
current path

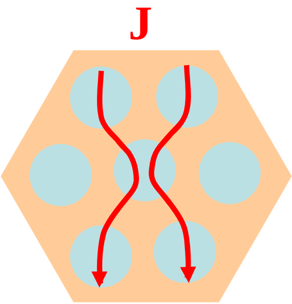






poor contact

$$\rho_{tp} = \rho_m \frac{1+\lambda}{1-\lambda}$$



good contact

$$\rho_{tg} = \rho_m \frac{1-\lambda}{1+\lambda}$$

eddy currents

$$\frac{1}{\rho_{et}} \approx \frac{1}{\rho_t} + \frac{w}{a\rho_m} + \frac{aw}{\rho_m}\left(\frac{2\pi}{p}\right)^2$$

- add reciprocal resistances
- or add time constants
  (Duchateau et al treatment is more exact)

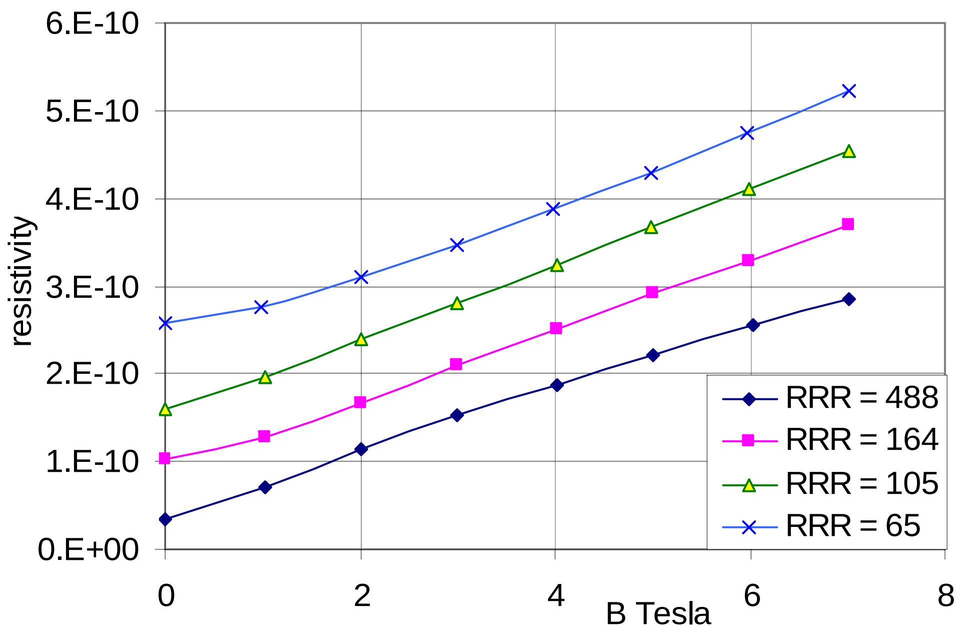
Matrix resistance

1) Magnetoresistance

- lots of good data from Fickett
- all for perpendicular B
- but it's all we have - fitted by

$$\rho(B) = (1+r)\,\rho_{B=0}$$

$$\beta = \log\left\{\frac{15.5\times 10^{-9}\,B}{\rho_{B=0}}\right\}$$



$$\log(r) = -2.66 + 0.317\,\beta + 0.623\,\beta^2 - 0.184\,\beta^3 + 0.0183\,\beta^4$$

2) Size effect

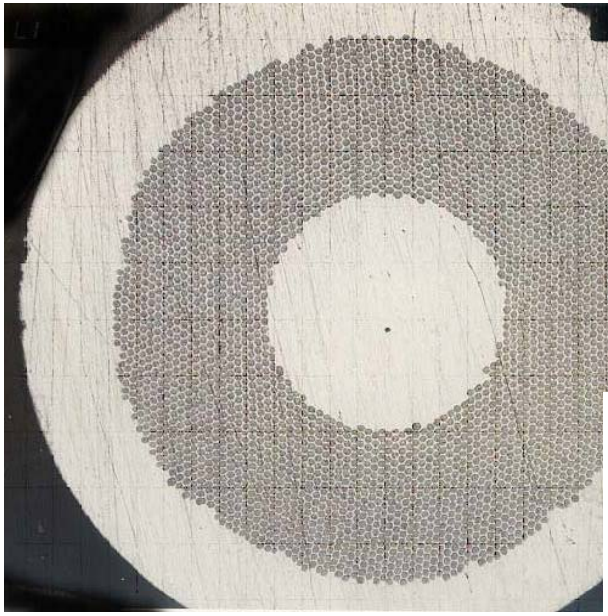
- separation of filaments is comparable with electron mean free path ⇒ increase in resistivity to ρ_s

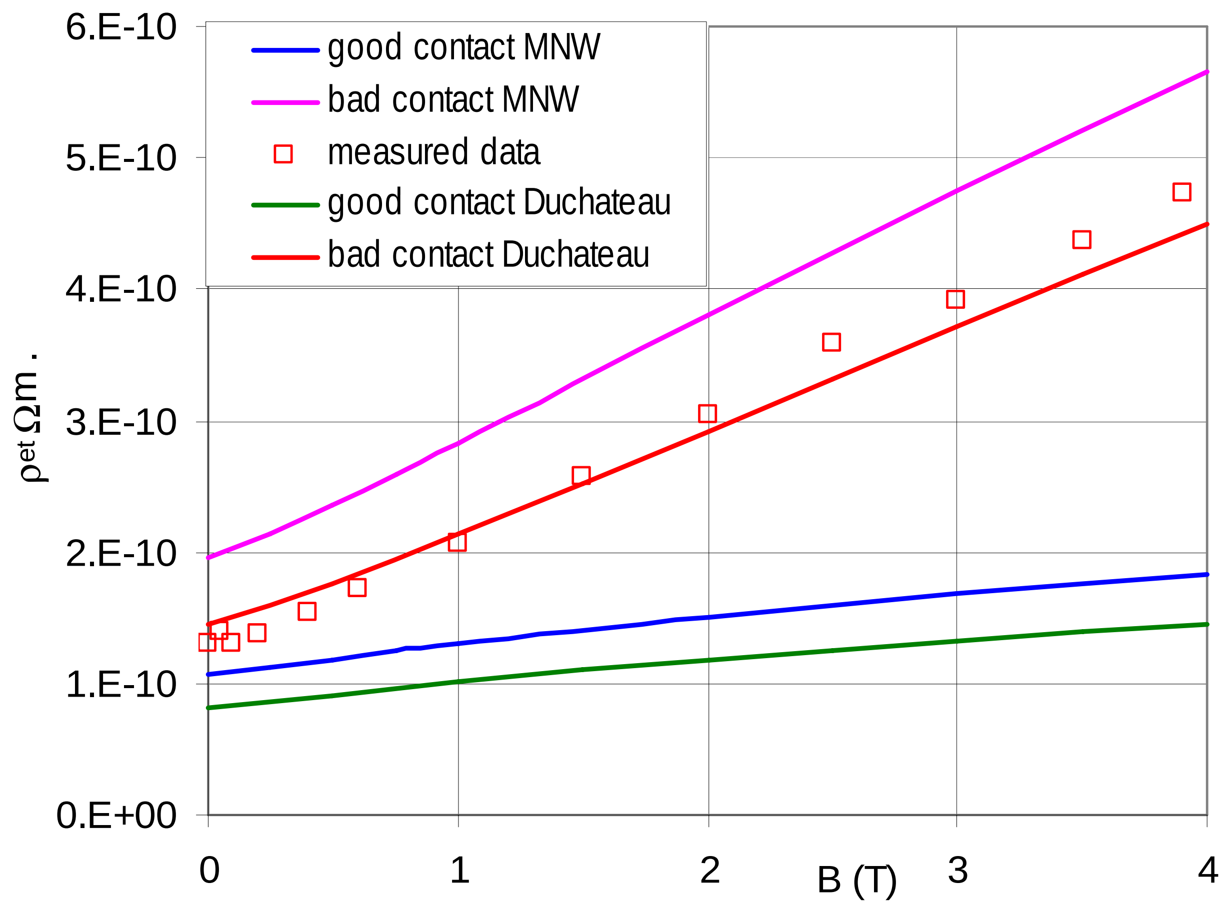
$$\rho_s = \rho_o(1 + l/s)$$

where l *is the electro mean free path; for copper* $\rho_o l = 6.45\times 10^{-16}\,\Omega m^2$

- example: for RRR= 150 and an inter-filament spacing of 1µm, the resistivity of copper between filaments is increased by a factor 6.7

Calculated and measured ρ_{et}

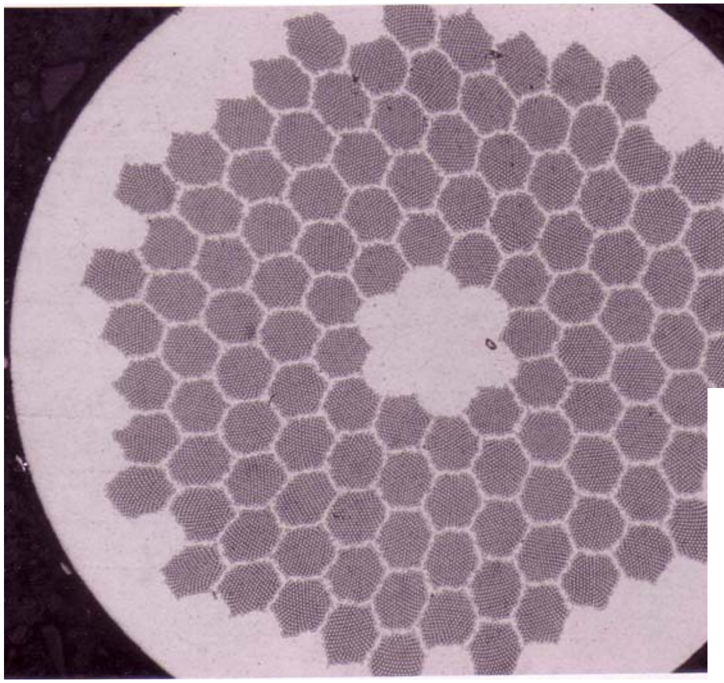


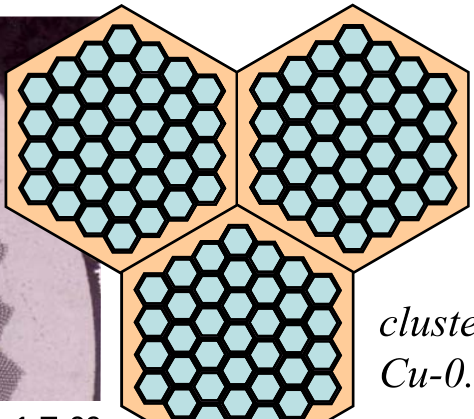


- RHIC wire with 6μm filaments and 13mm twist pitch
- theory of Duchateau fits better because it includes the central island
- good or poor contact?

  - measure it!

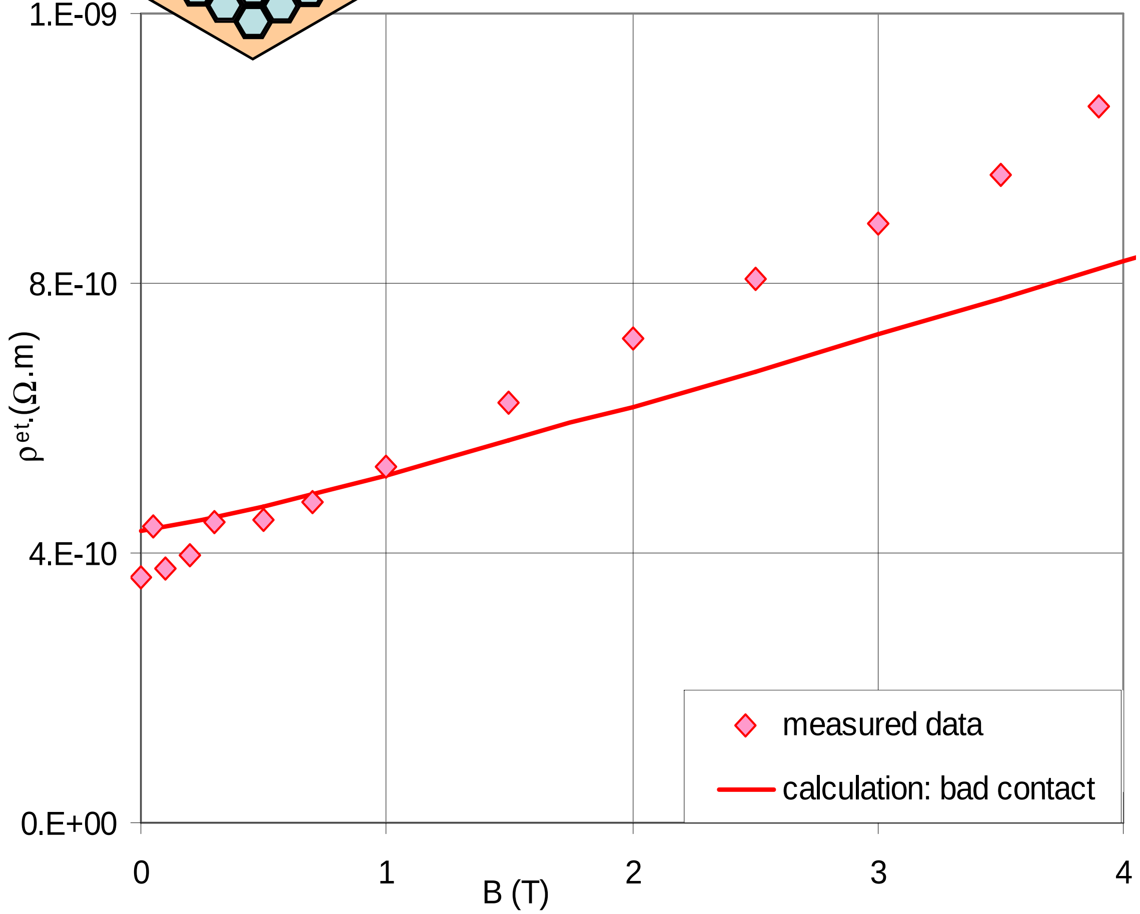
Another example





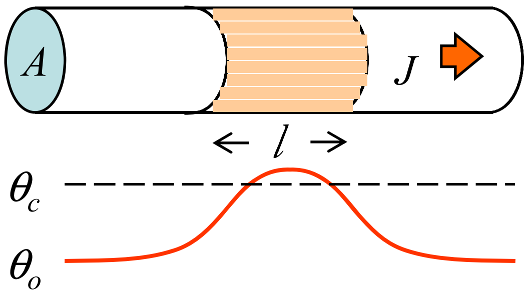
clusters of filaments surrounded by Cu-0.6wt%Mn, all in a sea of copper

- IGC B944-02-20: wire diameter 0.65mm, filament diameter 2.6μm
- model as 'macro-filaments, bad contact applies because there is no superconducting path across macro filaments
- ρ_{ef} increased by only a factor ~ 3, although $\rho_{CuMn} = 250\times10^{-10}$ Ωm ~ 60× the local copper



Constraints on increasing ρ_{et}

Crude model for MQE



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

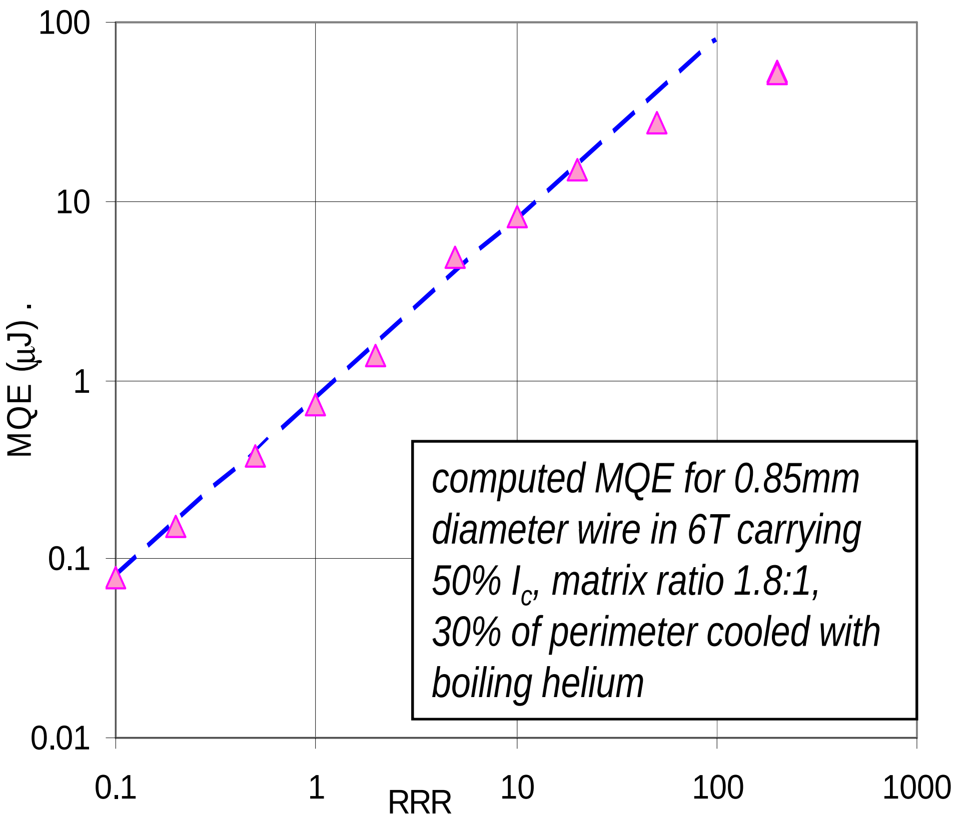
(all parameters averaged over the cross section)

$$l = \left\{\frac{2k(\theta_c-\theta_o)}{J^2\rho}\right\}^{\frac{1}{2}} \cong \frac{\left[L_o\left(\theta_c^2-\theta_o^2\right)\right]^{\frac{1}{2}}}{J_c\rho}$$

(using Wiedemann Franz Law L_o = Lorentz number)

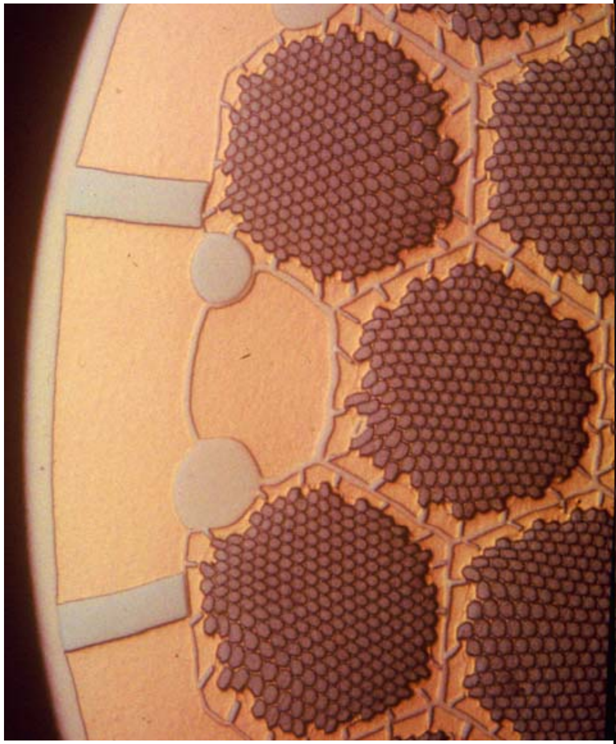
Conclude: need matrix with a resistivity which is low in longitudinal and high in transverse directions - anisotropic material

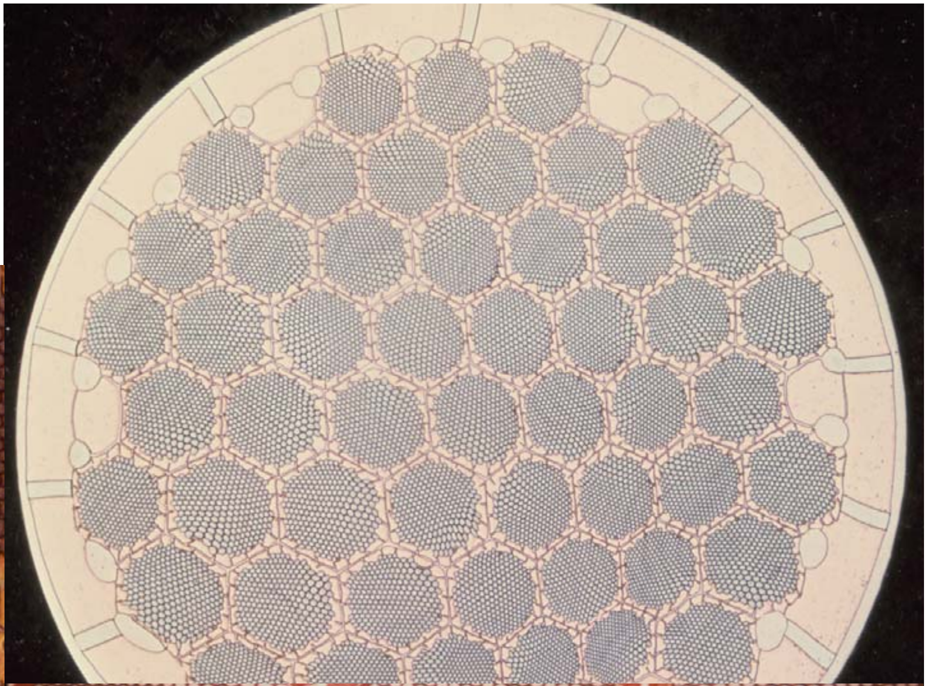
- use resistive alloy in the matrix
- but conflict with stability (early experiments on training)
- take minimum quench energy MQE as a criterion of stability

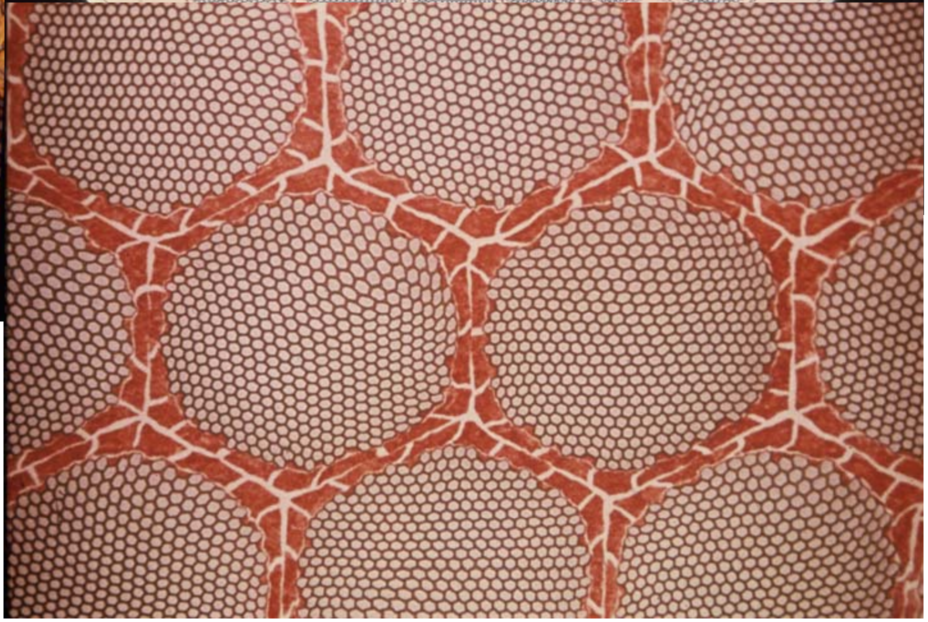


computed MQE for 0.85mm diameter wire in 6T carrying 50% I_c, matrix ratio 1.8:1, 30% of perimeter cooled with boiling helium

Anisotropic ρ: the physicist's idea

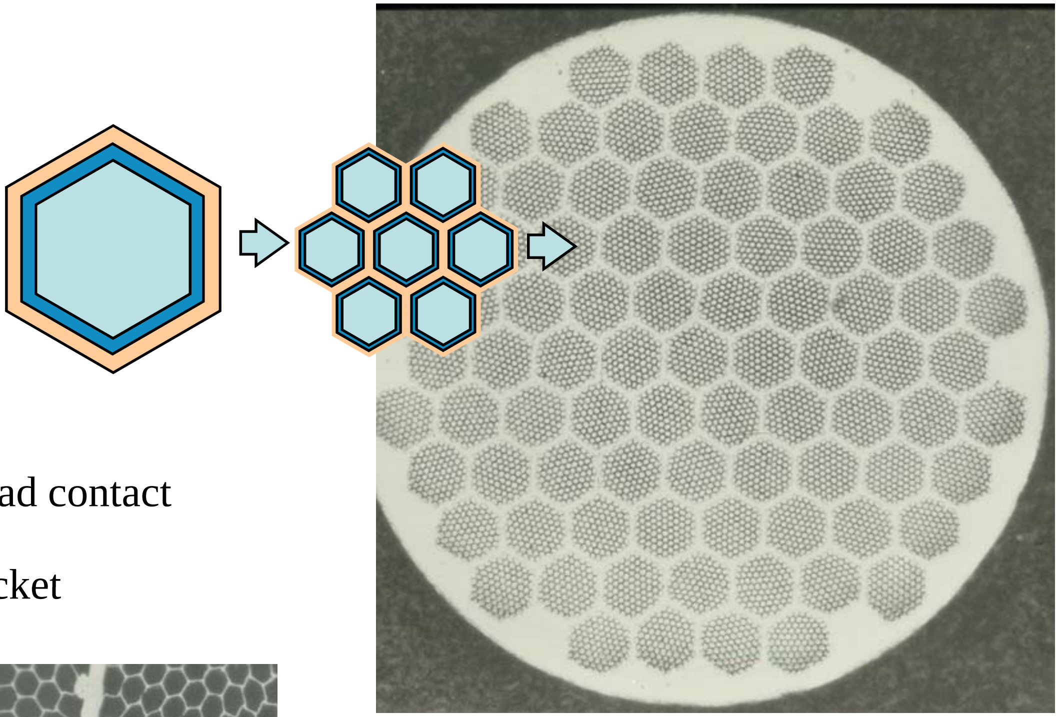




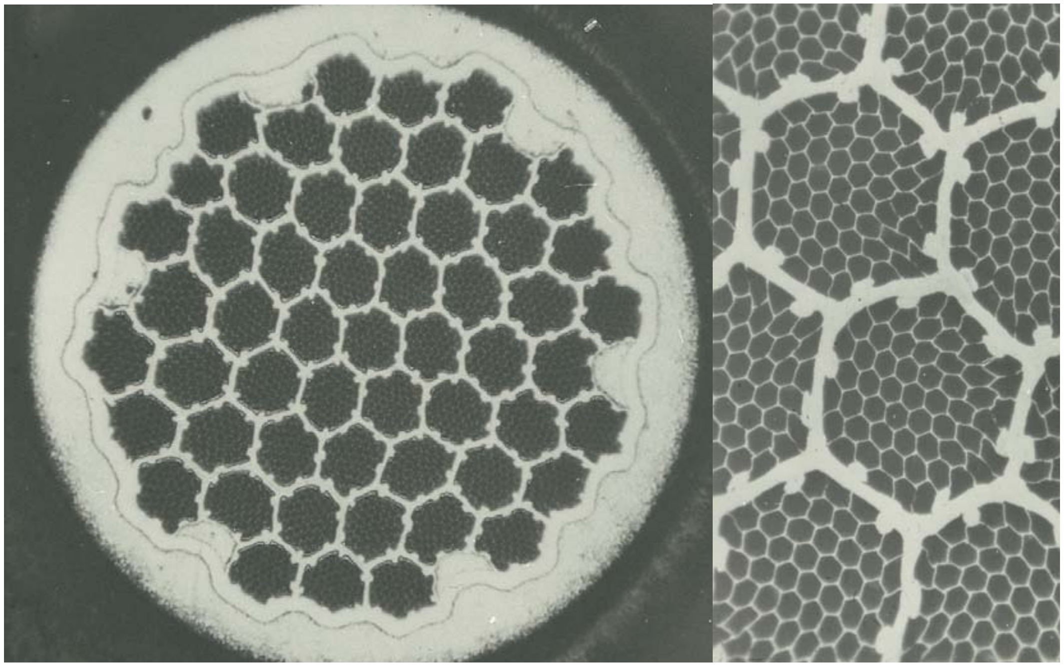


- good blocking of currents across filament clusters and around the jacket
- **problem:** they couldn't make it!

Anisotropic ρ: the wire maker's idea



- barrier round each filament,
  immerse in a sea of copper
- good mechanical properties for drawing
- **problem:** only change ρ_t from good to bad contact
- **problem:** conduction round the outer jacket

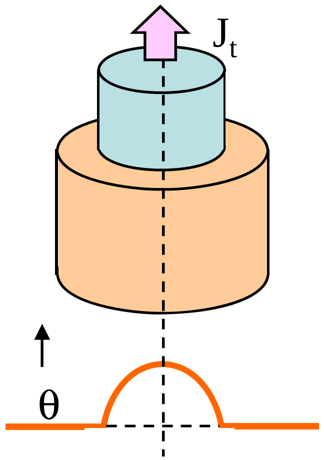


idea 2

- resistive material throughout the core
- thick barrier between core and jacket
- copper jacket
- low losses
- **problem:** stability - the copper is too far from the filaments

Stability: do filaments see the copper?

- MQE analysis assumes that the NbTi are intimately mixed - how intimate?
- over long lengths the electric field in NbTi and copper are the same
- what about the temperature?
  - uniform over Cu but not NbTi

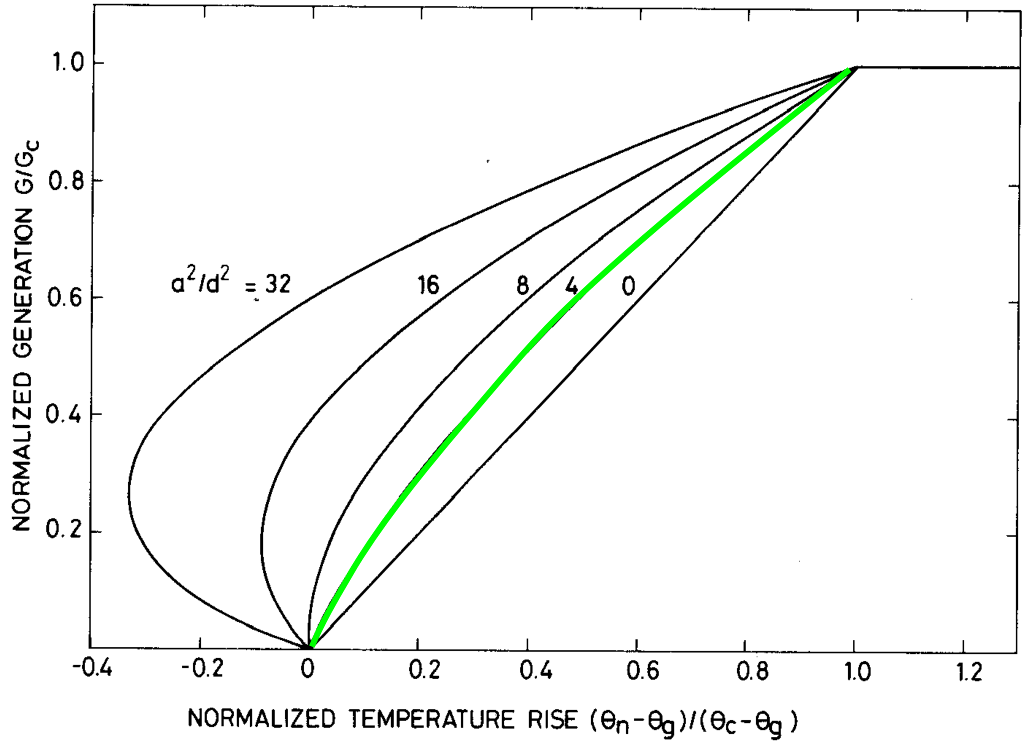


- define a characteristic distance

$$d^2 = \frac{k(\theta_c - \theta_s)(1-\lambda)}{\lambda J_t^2 \rho}$$

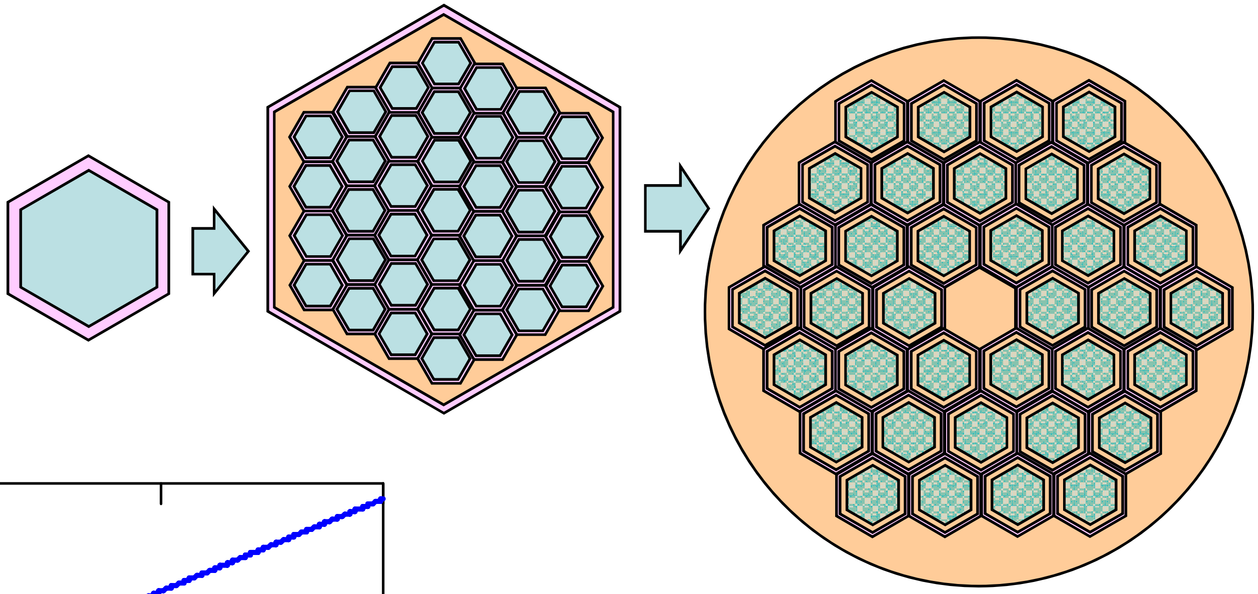
where k = thermal conductivity of NbTi, θ_s = current sharing temperature, J_t = transport current density in NbTi, λ = local filling factor, ρ = copper resistivity, a = filament radius

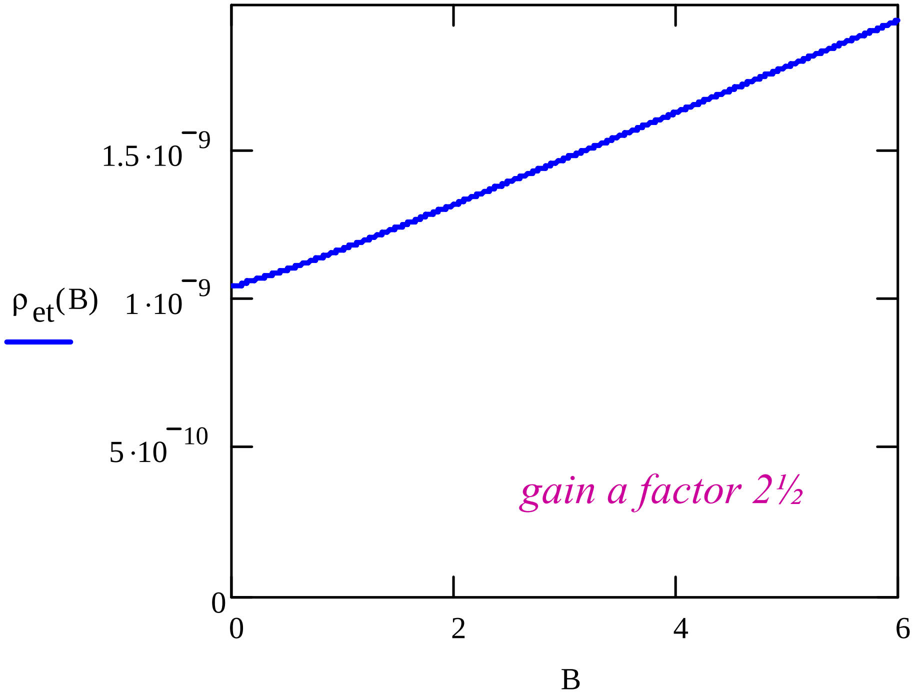
- solve for power generation as a function of copper temperature θ_n
- for acceptable behaviour choose $a^2/d^2 < 4$, ie $d_{fil} < 4d$
- for NbTi in Cu at 6T d ~ 10µm
- so require $d_{fil} < 40\mu m$
- a mixture of NbTi and CnMn typically has $k \sim 10 \times k_{NbTi}$
- so macro filament diameter can be ~ 120µm



Ideas for future wires (1)

- barriers more efficient in blocking crossing current
- still respect the dynamic stability condition
- CuMn next to filament to suppress proximity coupling



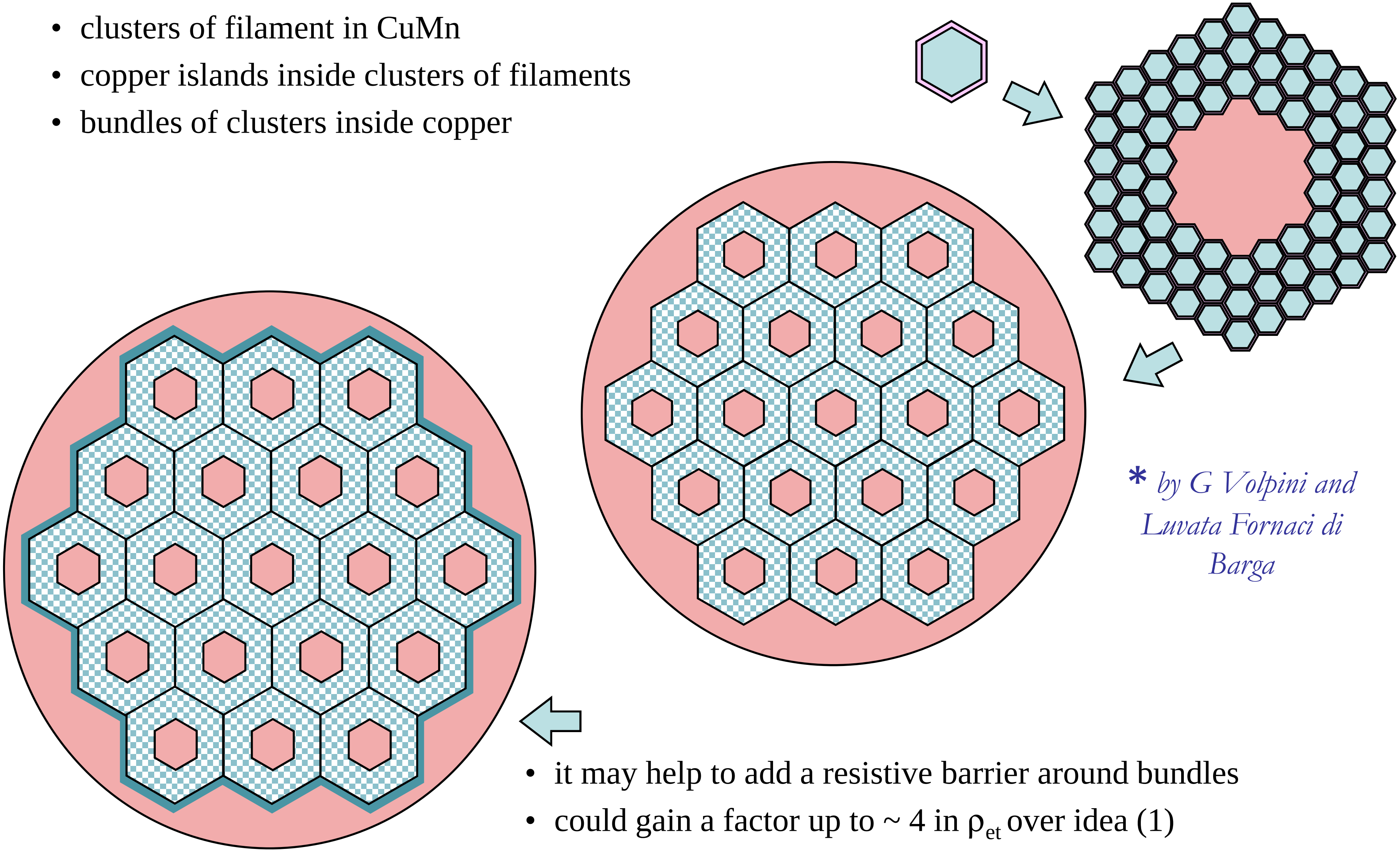


gain a factor 2½

resistivity across the core	$\rho_{ec}(0)$	$1.1\times10^{-8}\Omega$m
resistivity across the filamentary region	$\rho_{ef}(0)$	$2.6\times10^{-9}\Omega$m
around the outer barrier	$\rho_{eb}(0)$	$7.4\times10^{-8}\Omega$m
around the outer Cu jacket	$\rho_{eo}(0)$	$2.5\times10^{-9}\Omega$m
overall transverse resistivity for the wire	$\rho_{et}(0)$	$1.11\times10^{-9}\,\Omega$m

*Ideas for future wires (2) - a better idea**

- clusters of filament in CuMn
- copper islands inside clusters of filaments
- bundles of clusters inside copper

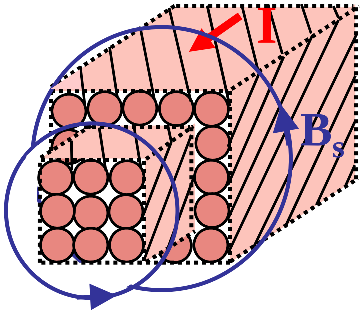


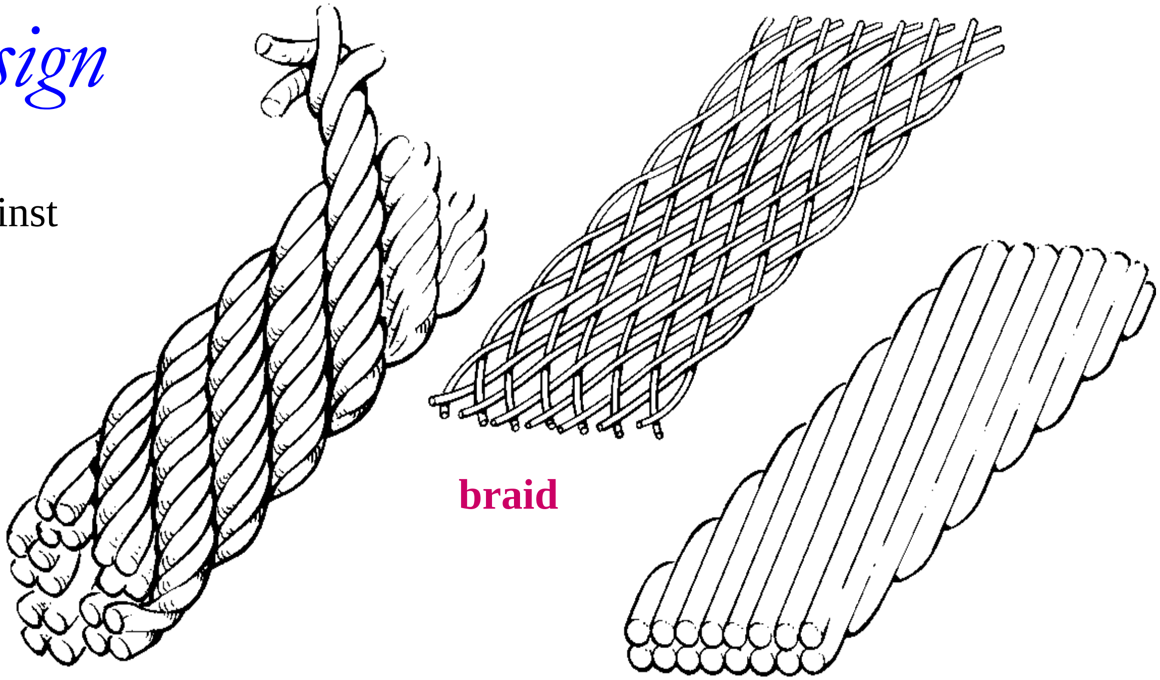
** by G Volpini and Luvata Fornaci di Barga*

- it may help to add a resistive barrier around bundles
- could gain a factor up to ~ 4 in ρ_{et} over idea (1)

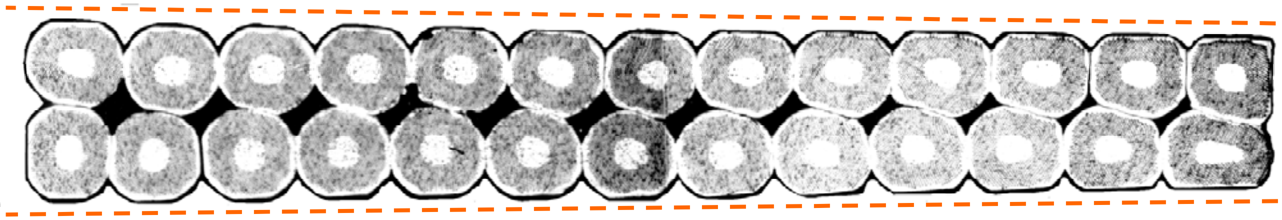
Cables: style of design

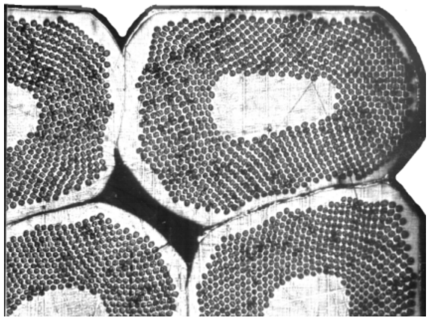
- wires must be fully transposed against self field





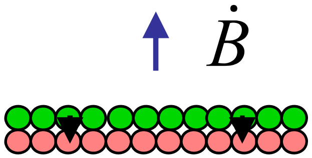
- rope: AC3
- braid: MOBY and early RHIC
- Rutherford: AC5 and Tevatron
- Rutherford probably won because it can be compacted to high density and tolerance





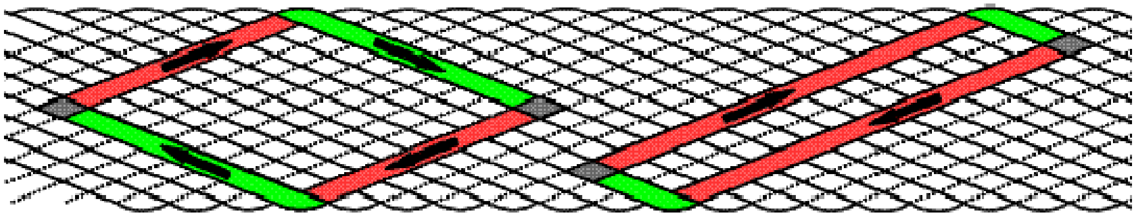
Cable coupling patterns

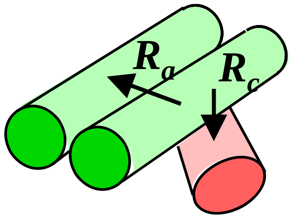
1) Field transverse: coupling via crossover resistance R_c



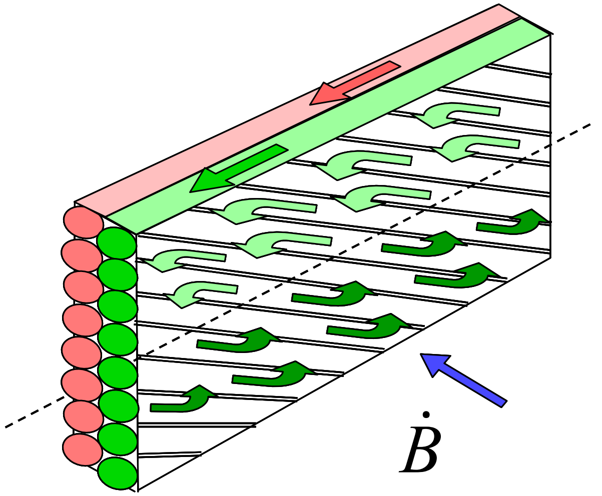
crossover resistance $\boldsymbol{R_c}$

adjacent resistance $\boldsymbol{R_a}$

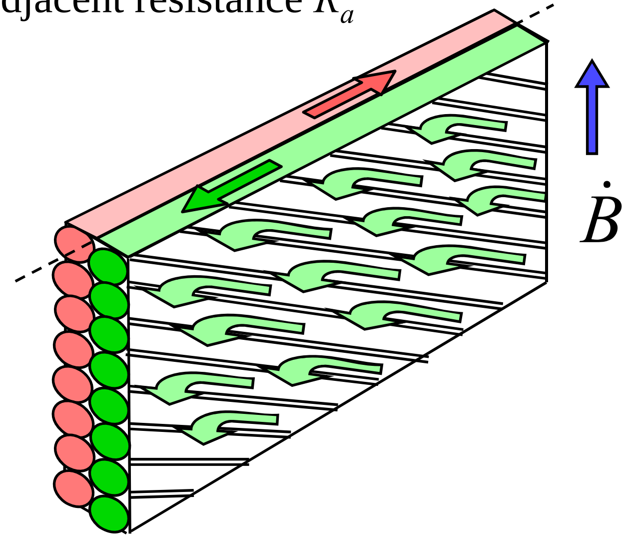




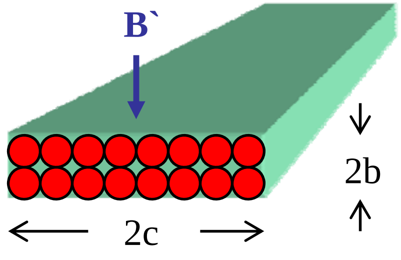
2) Field transverse: coupling via adjacent resistance R_a



3) Field parallel: coupling via adjacent resistance R_a



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*
r_c *and* r_a *are resistance * unit area of contact,* R_c *and* R_a *are resistance per contact*

- 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)

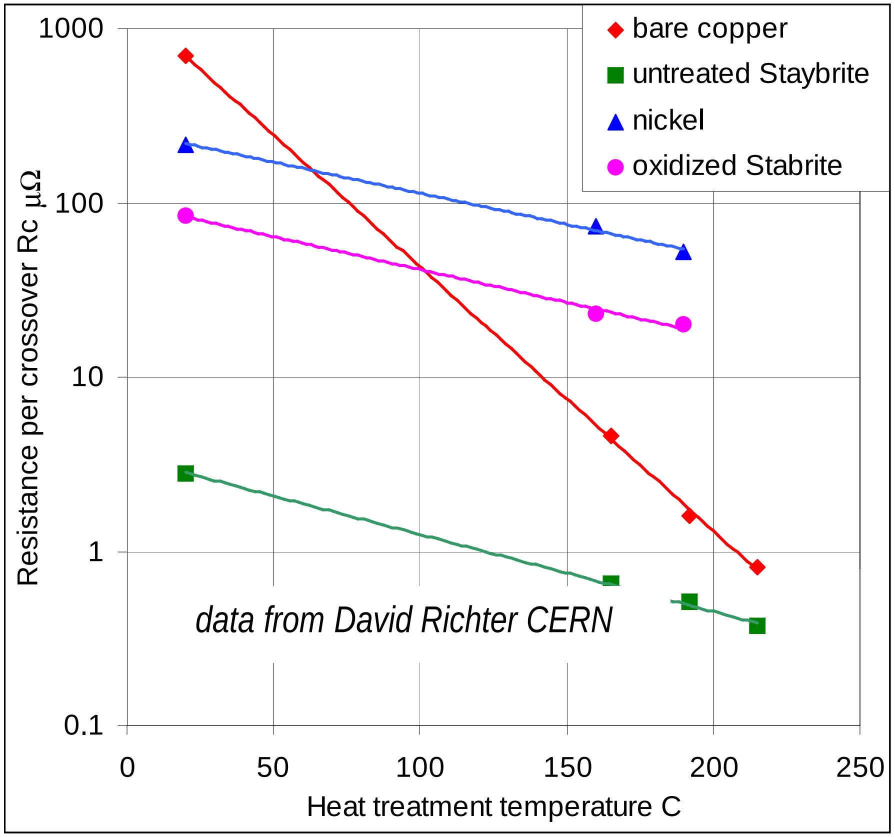
- Field transverse
  ratio crossover/adjacent

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

So without increasing loss too much can make $\boldsymbol{R_a}$ much less than $\boldsymbol{R_c}$ - anisotropy

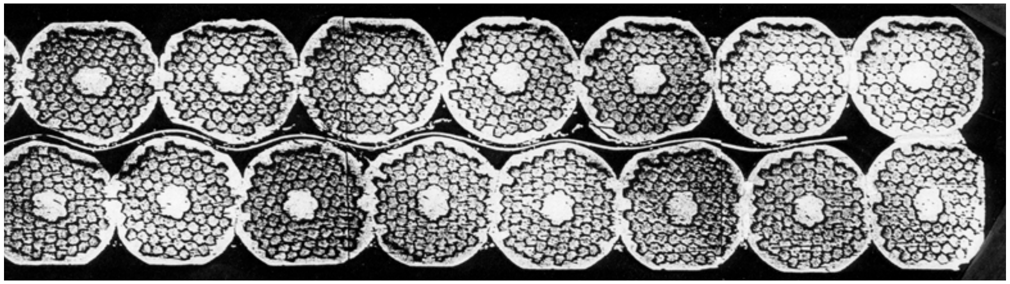
R_a and R_c

- we can increase (and reduce losses) R_a and R_c by surface coatings and creative chemistry
- but do we want them to be too large?
- worries about stability and current sharing
- memories of MOBY and Rutherford quadrupole, type A/B behaviour in SSC booster dipoles
- suggest we should make R_a and R_c as large as necessary to limit the loss - but no larger
- because the loss is anisotropic, it pays to make R_a and R_c anisotropic



data from David Richter CERN

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

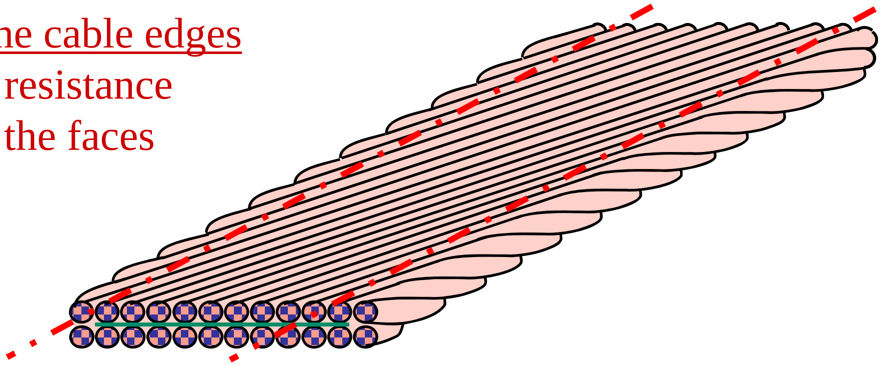


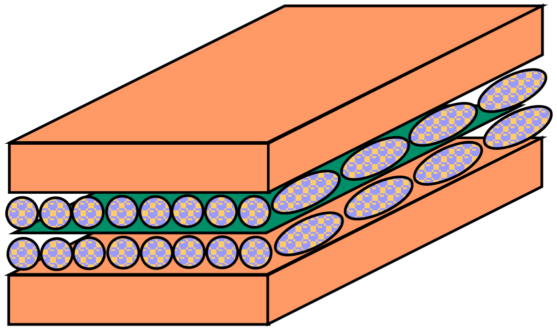
- cored cable, make $R_c \sim 40 \times R_a$
- lower losses with good stability

Measuring r_c when it's >> r_a

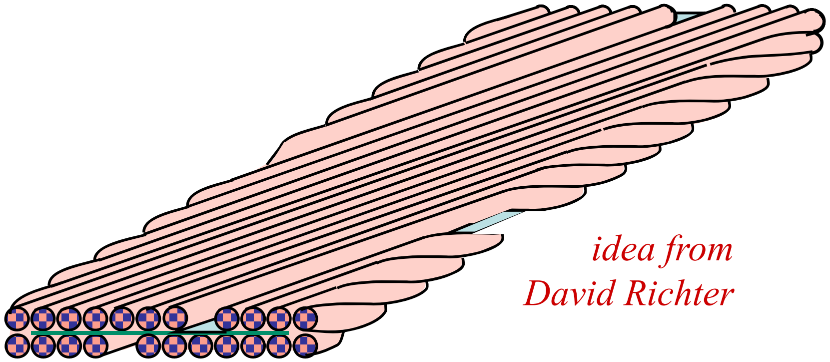
Usually, only a tiny fraction of current goes through the core, making it difficult to measure r_c in an intact cable. Two methods of forcing current through the core:

a) <u>cut off the cable edges</u>
measure resistance
between the faces





b) <u>remove two</u>
<u>wires</u> measure
resistance
between the
remaining 2
groups of wires



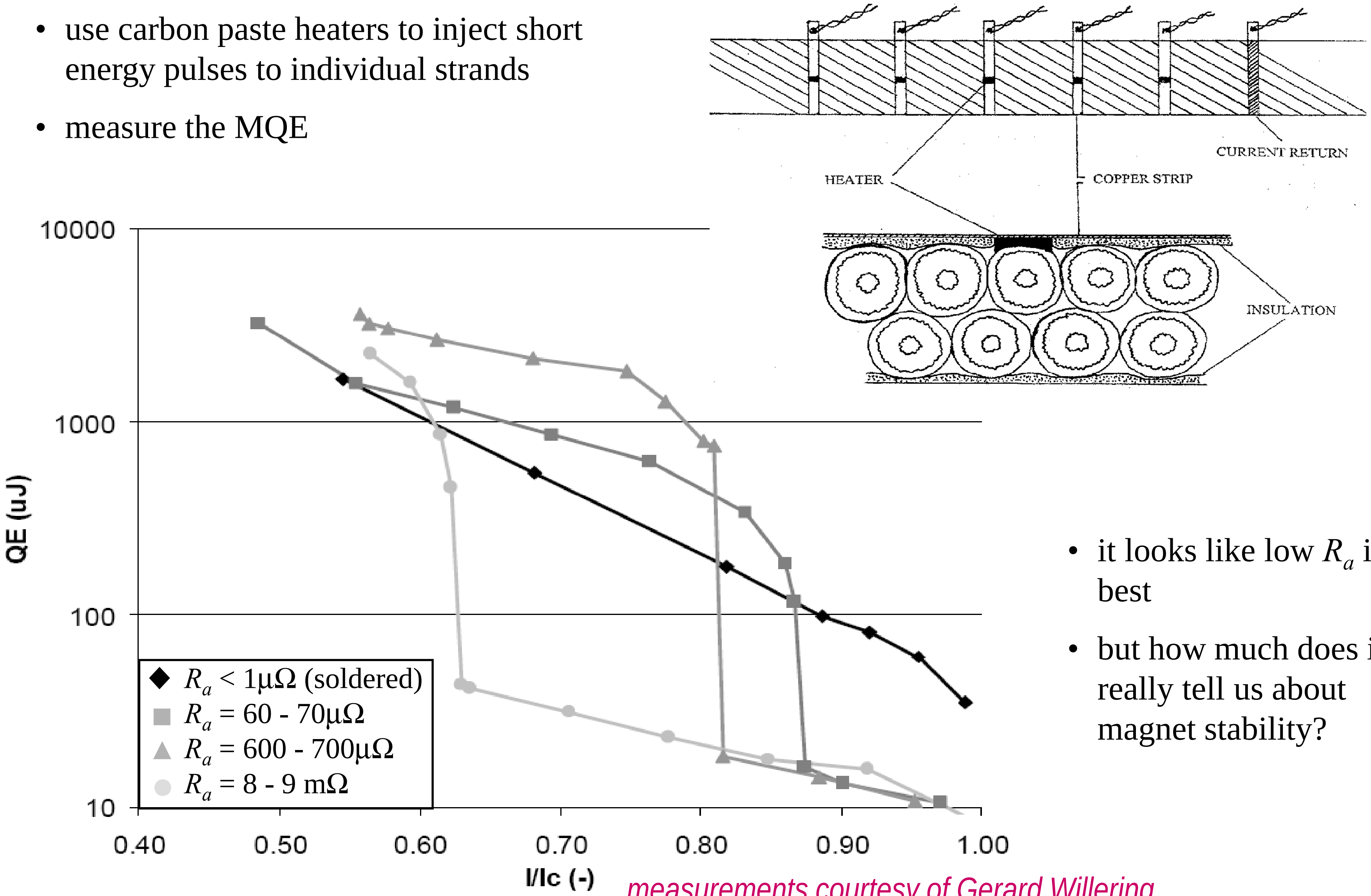
idea from
David Richter

Typical numbers

- for stainless core foil find R_c ~ 10mΩ
- for FAIR target R_a ~ 200μΩ

Measuring cable stability

- use carbon paste heaters to inject short energy pulses to individual strands
- measure the MQE



- it looks like low R_a is best
- but how much does it really tell us about magnet stability?

measurements courtesy of Gerard Willering

Low loss NbTi Strand & Cable: concluding remarks

✧ Hysteresis Loss

- usually dominant ⇒ many very fine filaments (but not too many or self field loss)
- filament distortion: - longitudinal ⇒ low n - transverse ⇒ enhanced magnetization
- intermetallics: - diffusion barriers or low temperature extrusion
- stacking: - single stack ⇒ best properties - double stack ⇒ more filaments
- proximity coupling: - ferromagnetic additions to copper CuMn - or no diffusion barrier

✧ Coupling between filaments

- anisotropic matrix resistance - high transverse ⇒ low loss, - low longitudinal ⇒ stability
- MQE gives estimate of stability - critical distance for intimate mixing of NbTi and Cu
- new ideas needed for higher transverse resistance without loosing stability

✧ Cables

- the high interface resistance needed to control losses high ramp rate may prejudice stability
  - surface coatings ⇒ $R_a > R_c$, - core ⇒ $R_a << R_c$ ⇒ low loss without losing stability

✧ NbTi

- now into middle age, NbTi still offers substantial advantages for pulsed use:
  - the finest filaments, low filament distortion,
  - precise fine structures of resistive alloy and copper in the matrix with no mixing
  - ductility