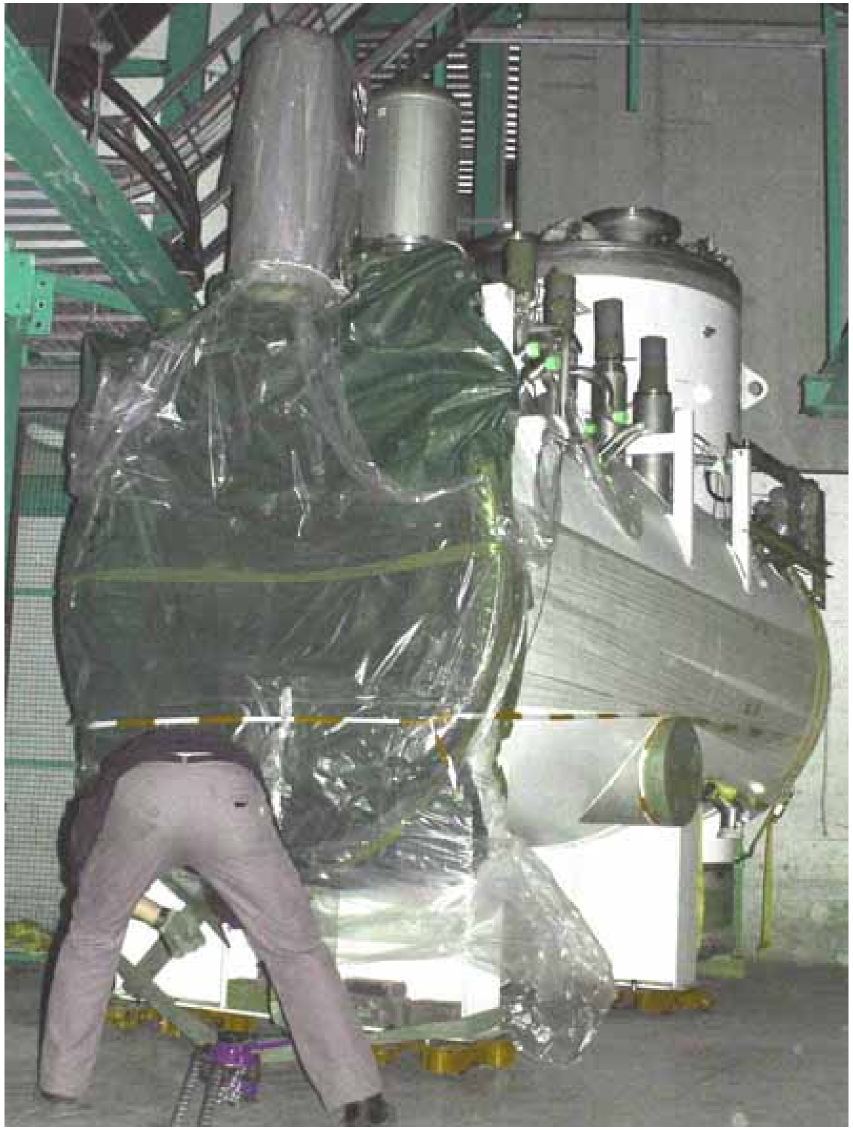
Lecture 4: AC Losses in Magnets - and Training

Plan

- summation of ac loss in superconductor
- ac loss and refrigeration load
- temperature rise and temperature margin
- cooling - conduction and heat transfer
- measurement of ac loss

- training - what is it
- energy releases in the magnet winding
- conductor design for stability



Summary of losses

1) Persistent currents in filaments

power W.m[-3]

$$P_f = \lambda_c \lambda_w \lambda_f M_f \dot{B} = \lambda_c \lambda_w \lambda_f \frac{2}{3\pi} J_c(B)\, d_f \dot{B}$$

loss per per ramp J.m-3

$$E_f = \lambda_c \lambda_w \lambda_f \frac{2}{3\pi} d_f J_o B_o \ln\left\{\frac{B_2 + B_o}{B_1 + B_o}\right\}$$

2) Coupling currents between filaments in the wire

power W.m[-3]

$$P_c = \lambda_c \lambda_w \lambda_{fb} M_c \dot{B} = \frac{2}{\mu_o} \lambda_c \lambda_w \lambda_{fb} \dot{B}^2 \tau(B)$$

$$\tau = \frac{\mu_o}{2\rho_t(B)} \left(\frac{p_w}{2\pi}\right)^2$$

3) Coupling currents between wires in the cable

transverse field crossover resistance power W.m[-3]

$$P_{tc} = \lambda_c \frac{1}{120} \frac{\dot{B}_t^2}{R_c} p \frac{c}{b} N(N-1)$$

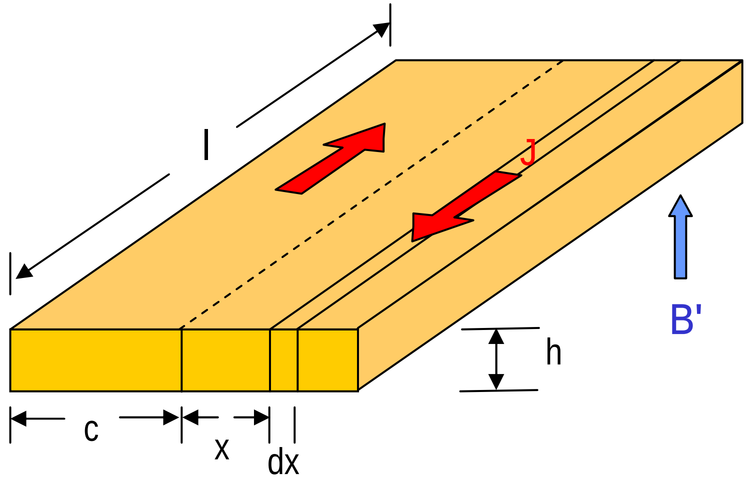
transverse field adjacent resistance power W.m[-3]

$$P_{ta} = \lambda_c \frac{1}{6} \frac{\dot{B}_t^2}{R_a} p \frac{c}{b}$$

parallel field adjacent resistance power W.m[-3]

$$P_{pa} = \lambda_c \frac{1}{8} \frac{\dot{B}_p^2}{R_a} p \frac{b}{c}$$

Other losses: eddy currents



field perpendicular to strip width ***2c***

current density at x $$J(x) = \frac{\dot{B}x}{\rho}$$

local power/unit volume $$p_v(x) = J^2\rho = \frac{\dot{B}^2 x^2}{\rho}$$

total power/volume of strip $$P_v = \frac{1}{c\,h\,l}\int_0^c p_v(x)\,h\,l\,dx = \frac{\dot{B}^2}{c\rho}\int_0^c x^2 dx$$

$$P_v = \frac{\dot{B}^2}{\rho}\frac{c^2}{3}$$

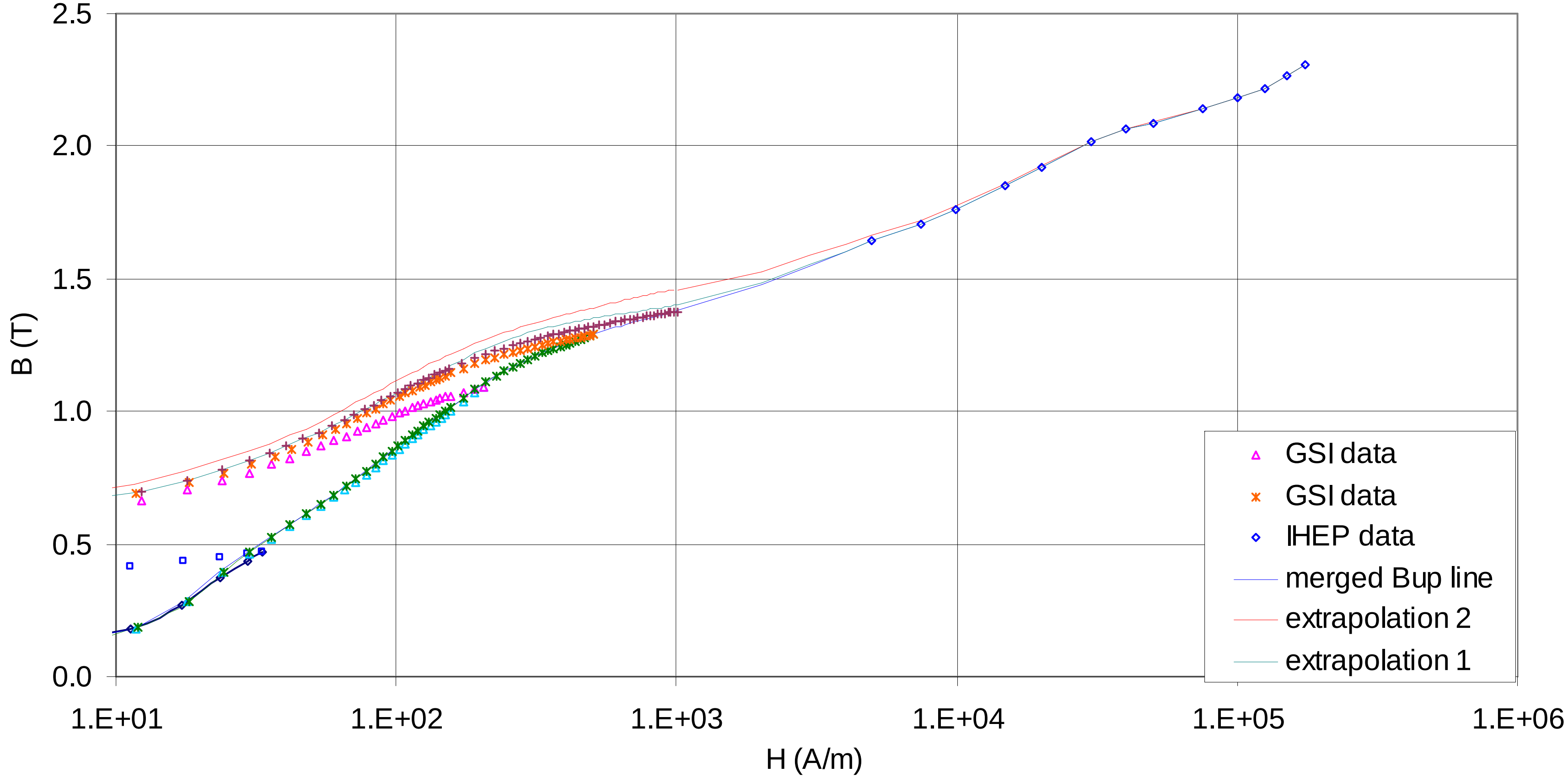
recap coupling between twisted filaments

$$P_c = \frac{2}{\mu_o}\lambda_c\lambda_w\lambda_{fb}\dot{B}^2\tau(B) = \lambda_c\lambda_w\lambda_{fb}\frac{\dot{B}^2}{\rho_t(B)}\left(\frac{p_w}{2\pi}\right)^2$$

so eddy loss is similar to coupling loss when strip width ~ ½ twist pitch

Other losses: iron hysteresis

loss per unit volume per cycle $E = \int \mu_o H dM = \int \mu_o M dH$ = area of hysteresis loop



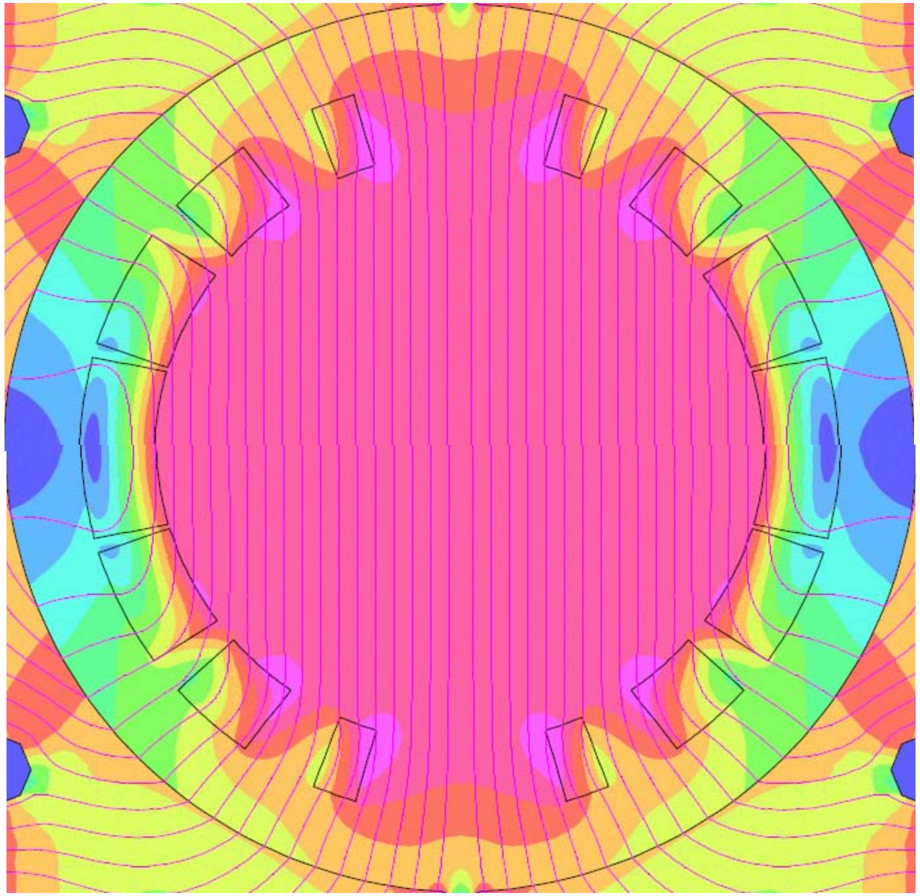
hysteresis data from GSI and high field (up only) data from IHEP - we need more data!

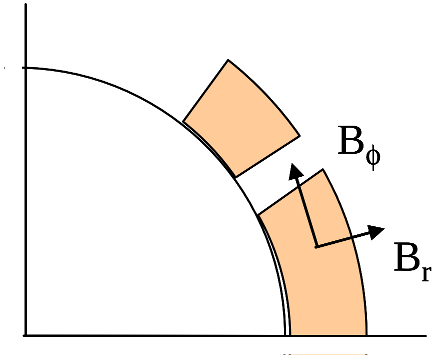
Losses in magnets: 1 refrigeration load

Must integrate the loss expressions over the magnet volume, taking account of the variation in magnitude and direction of B and B`

a) use a computer code, eg ROXIE, Opera etc
 - you will have to ask someone else

b) use a spreadsheet
 - my quick and dirty method

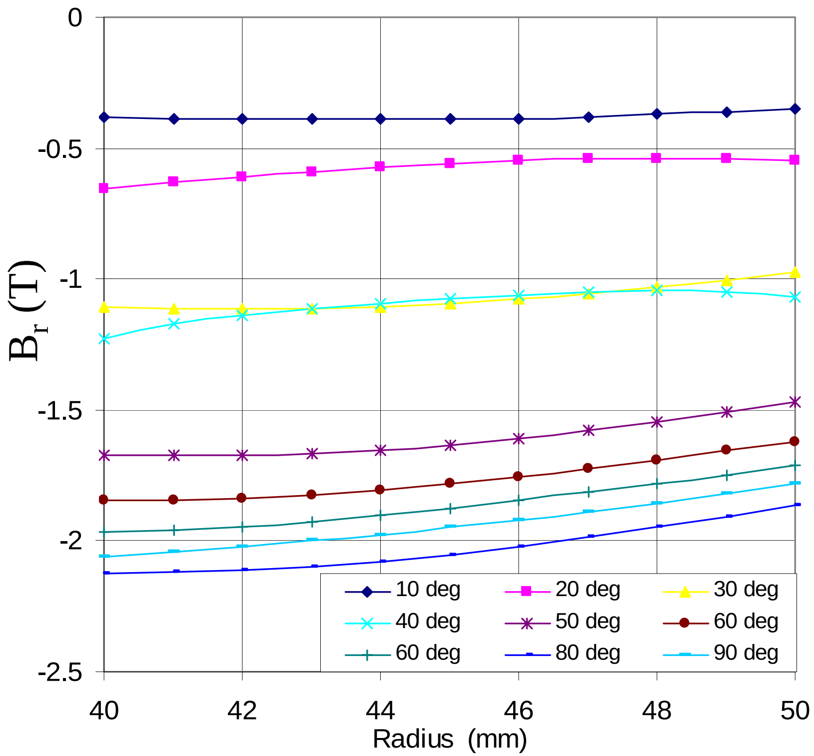


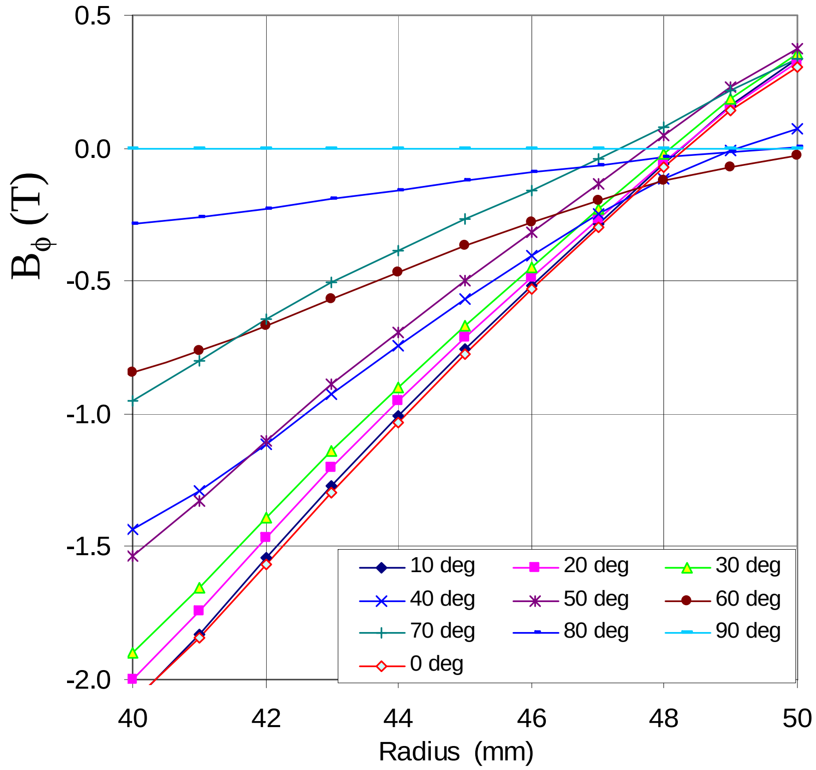


Field in a dipole

radial field (parallel to cable) ~ constant across cable

azimuthal field (transverse to cable) ~ linear gradient across cable





Losses in magnets: 1 refrigeration load

Appendix 14-4(4): Hysteresis and coupling losses in dipole 001 — 4.0T 4T/s — with Kim Anderson Jc transport current correction and magnetoresistance in ρ_{et}

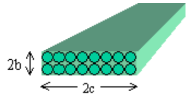
no proximity loss

filament coupling term includes magnetoresistance

cable half width a	c	4.87E-03	m
cable half thickness b	b	5.83E-04	m
cable twist pitch	p	7.40E-02	m
crossover resistance	Rc	6.00E-02	ohm
adjacent resistance	Ra	7.40E-05	ohm
number of strands	N	3.00E+01	
permeability fs	μo	1.26E-06	henry/m
cable filling factor	λc	0.826	
wire filling factor	λω	0.872	
matrix ratio	mat	2.250	
filament filling factor	λf	0.308	
wire trans res'y intercept	C_{pet}	1.69E-10	ohm.m
wire trans res'y gradient	m_{pet}	1.23E-10	ohm.m/T
wire twist pitch	p_w	4.00E-03	m
filament diameter	d_f	6.00E-06	m
Mod'd Kim Anderson	J_o	3.85E+10	A/m^2
Mod'd Kim Anderson	B_o	0.1300	Tesla
Mod'd Kim Anderson	A_0	4.35E+09	A/m^2
Mod'd Kim Anderson	A_1	-5.9E+08	A/m^2/T
Kim Anderson	J_{so}	3.00E+10	A/m^2
Kim Anderson	B_{so}	0.45	Tesla
max magnet current	Iext	6800	Amp
max aperture field	Bext	4.000	Tesla
computed aperture field	Bcomp	2.1215	Tesla
min magnet current	Iinj	1	Amp
min aperture field	Binj	0.00	Tesla
ramp ratio Bi / Be	f_r	0.00	
ramp time	Tr	1.000	sec
ramp rate	B\`	4.00	T/s
cook factor trans Rc	ftc	1.00	
cook factor trans Ra	fta	2.00	
cook factor par'l Ra	fpa	1.00	
cook factor hysteresis	fh	1.00	

crossover transverse power

$$P_{tc} = f_{tc} \cdot \frac{\lambda_c}{120} \cdot \frac{{B'_t}^2}{R_c} \cdot p \cdot N \cdot (N-1) \cdot \frac{c}{b}$$



adjacent transverse power

$$P_{ta} = f_{ta} \cdot \frac{\lambda_c}{6} \cdot \frac{{B'_t}^2}{R_a} \cdot p \cdot \frac{c}{b} \cdot \left(1 + \frac{1}{15} \cdot \frac{{G'_t}^2 \cdot c^2}{\ldots}\right)$$

note: in a gradient field G

$$P_{ta} = \lambda_c \frac{1}{6} \frac{\dot{B}_t^2}{R_a} p \frac{c}{b} \left\{ 1 + \frac{1}{15} \frac{G^2 c^2}{B_t^2} \right\}$$

adjacent parallel power

$$P_{pa} = f_{pa} \cdot \frac{\lambda_c}{8} \cdot \frac{{B'_p}^2}{R_a} \cdot p \cdot \frac{b}{c}$$

filament coupling power

$$P_{fm} = \lambda_c \cdot \lambda_w \cdot \frac{(B_{me} - B_{mi})}{T_r^2} \cdot \left(\frac{p_w \ldots}{2 \cdot \ldots}\right)$$

hysteresis power

$$P_{2h} := f_h \cdot \frac{\lambda_c \cdot \lambda_w \cdot \lambda_f}{T_r} \cdot \frac{2}{3} \cdot \frac{d_f}{\pi} \cdot \left[J_o \cdot B_o \cdot \ln\left(\frac{B_e + B_o}{B_i + B_o}\right) + A_0 \cdot (B_e - B_i) + \frac{A_1}{2.} \cdot \left(B_e^2 - B_i^2\right) \right]$$

proximity power

$$P_{2ph} := \frac{\lambda_c \cdot \lambda_w \cdot \lambda_f \cdot M_o}{\mu_o \cdot T_r \cdot k} \cdot \left(e^{-k \cdot B_i} - e^{-k \cdot B_e}\right)$$

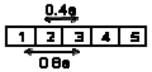
$$J_c(B) = \frac{J_o \cdot B_o}{B + B_o} + A_0 + A_1 \cdot B$$

transport current correction

$$\Delta P_{ch} = \frac{1}{9 \cdot \pi} \cdot \frac{d_f}{T_r} \cdot I_e^2 \cdot B_e \cdot \frac{(3 \cdot B_e + 4 \cdot B_{so})}{\left[J_{so} \cdot B_{so} \cdot \lambda_c \cdot \lambda_w \cdot \lambda_f (4 \cdot c \cdot b)^2\right]}$$

$$J_c(B) = \frac{J_{so} \cdot B_{so}}{B + B_{so}}$$

calc hyst & prox'y loss at 5 points in cable



Block limits for integration

block	min ϕ	max ϕ
1	0.00	15.67
2	17.08	36.24
3	41.28	55.22
4	66.21	73.17

length of magnet = 1.17 metre

turn area per degree = 7.89E-06 m^2

cycle time = sec

ramping/average factor

	ramping power Watts	mean power Watts	loss/ cycle Joules	fraction of total %
transv'se crossover	0.21		0.4	0.5%
transv'se adjacent	9.25		18.5	23.5%
parallel adjacent	0.13		0.3	0.3%
filament coupling	13.52		27.0	34.3%
hysteresis	14.73		29.5	37.4%
delta hysteresis	1.56		3.1	4.0%
total hysteresis	16.29		32.6	41.3%
total magnet	39.41		78.8	100.0%

load line fitting

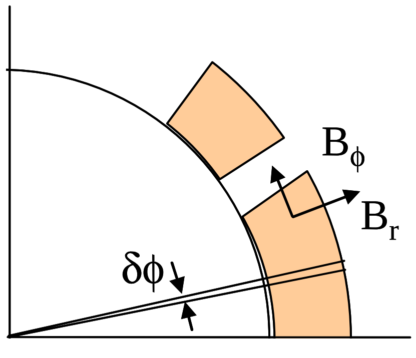
$$B(I) = C_L I + D_L I^n$$

C_L = 9.02E-04

D_L = -5.38E-05

n = 1.2000

summate the 5 loss terms around the coil section in segments of size δϕ

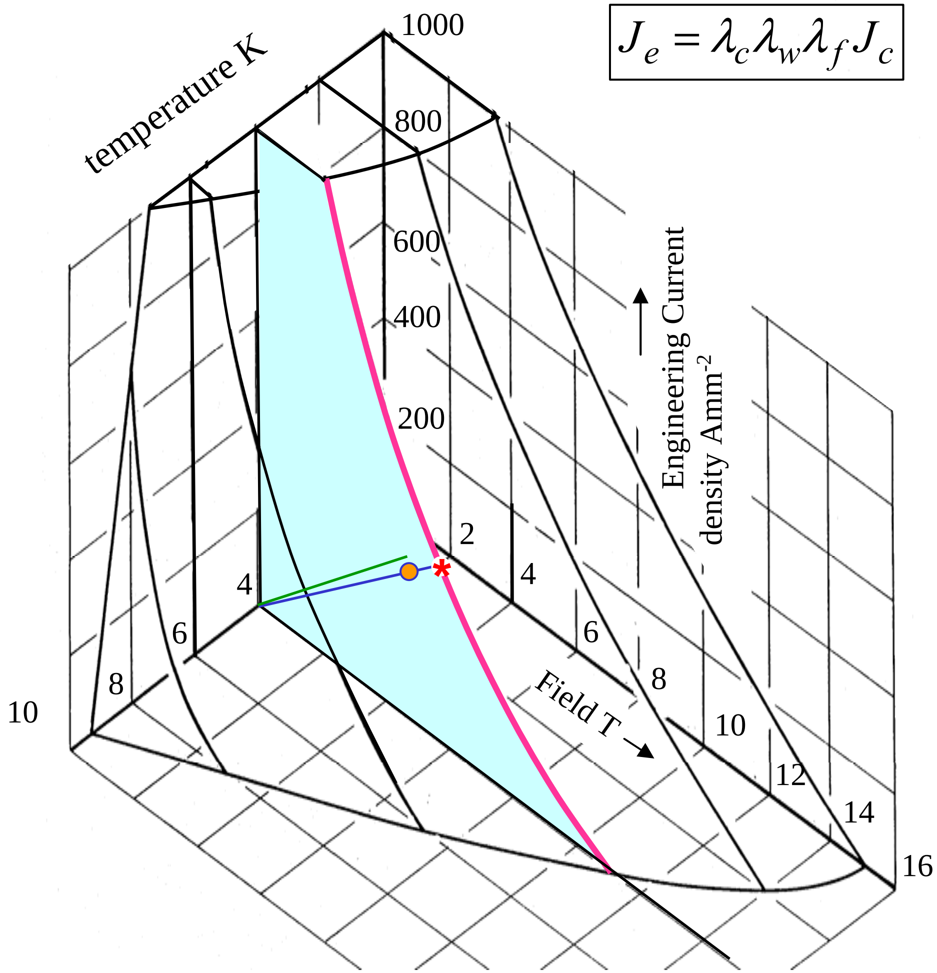


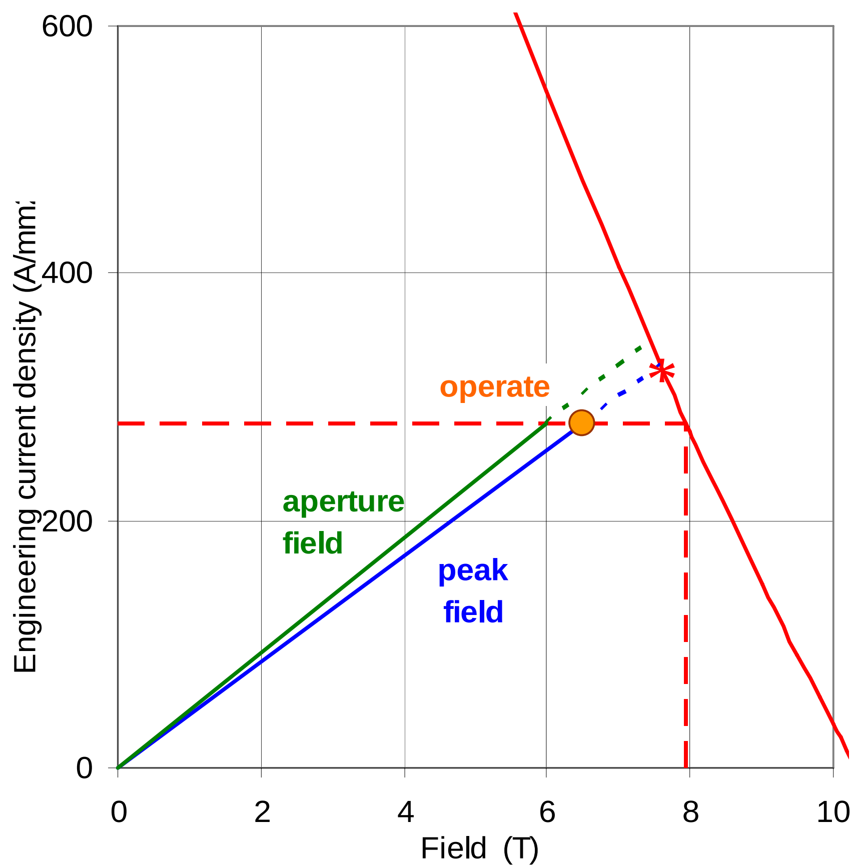
dc fields as computed at centre of cable					actual ramp rates and field					components of loss per unit volume of winding						sum of loss/m³	loss/m/ segm't
angle	B trans	G trans	B parl	Bmod	B\` trans	G\` trans	B\` parl	B\`mod	Bmod	Ptc	Pta	Pp	Pf	Ph	ΔPh	Ps	Pd
0	-0.822	244.3	0.000	0.822	1.550	460.6	0.000	1.550	1.550	148.0	6287.8	0.00	2777.5	4990.0	381.9	14585	0.1151
1	-0.822	246.6	-0.004	0.822	1.549	465.0	0.008	1.549	1.549	147.9	6299.3	0.00	2776.0	5008.1	384.5	14616	0.1153
2	-0.822	247.9	-0.047	0.823	1.549	467.4	0.088	1.552	1.551	147.9	6305.2	0.10	2782.7	5035.0	386.7	14658	0.1156

Critical line and magnet load lines

engineering current density

$$J_e = \lambda_c \lambda_w \lambda_f J_c$$

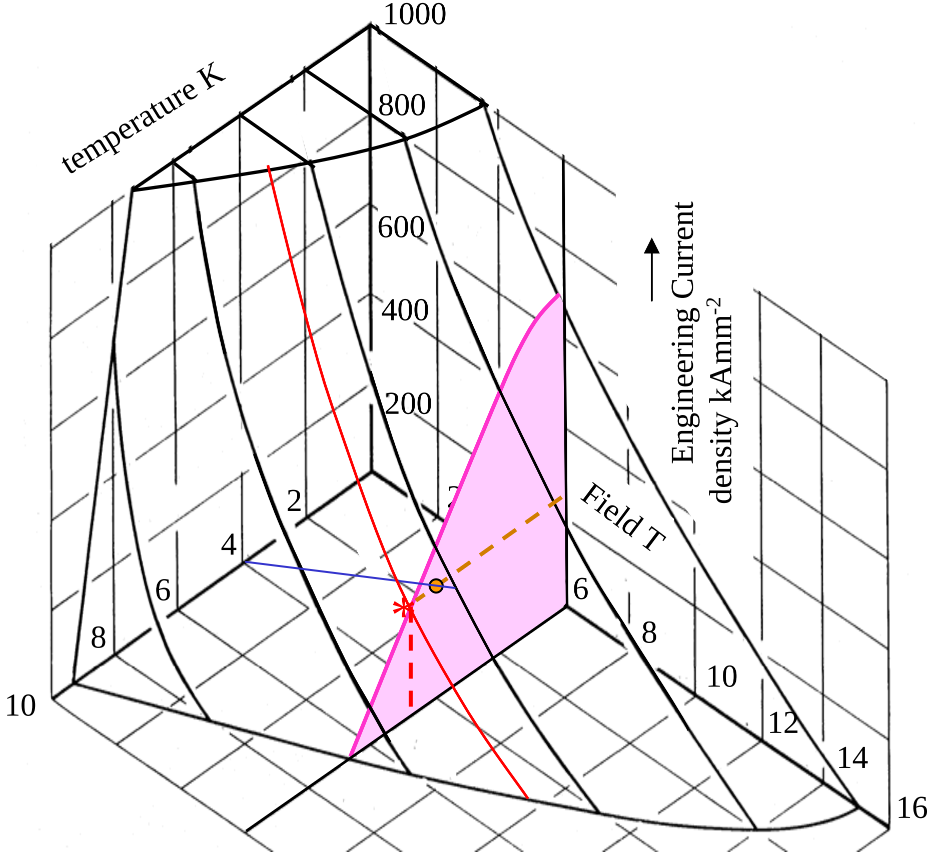


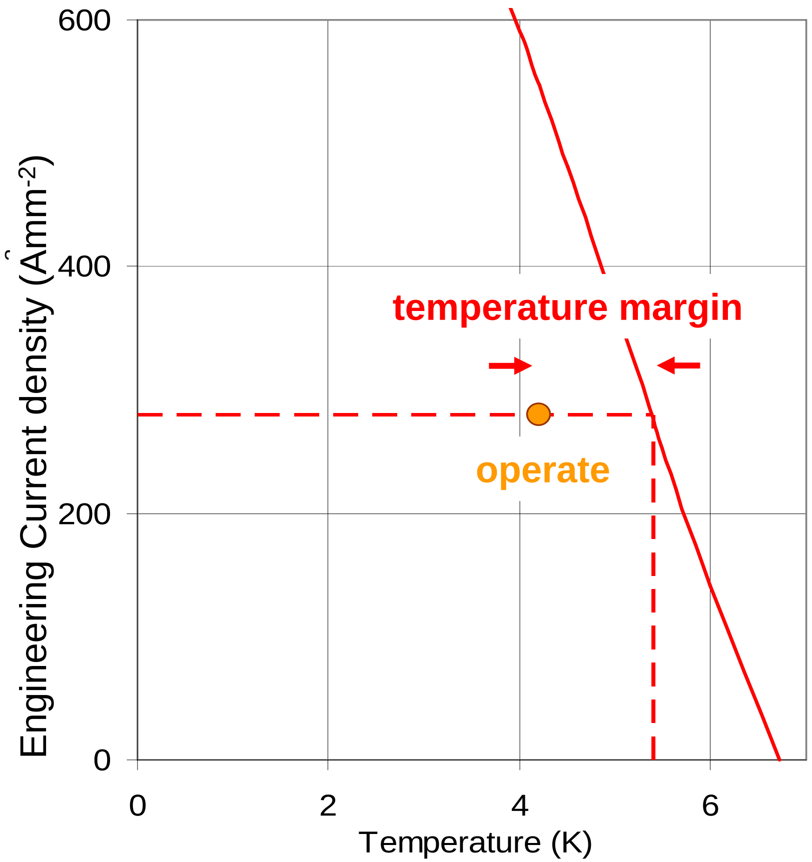


we expect the magnet to go resistive ***'quench'*** where the peak field load line crosses the critical current line *
usually back off from this extreme point and operate at ●

Temperature margin

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





in superconducting magnets temperature rise may be caused by

- ac losses
- sudden internal energy release
- poor joints
- beam heating

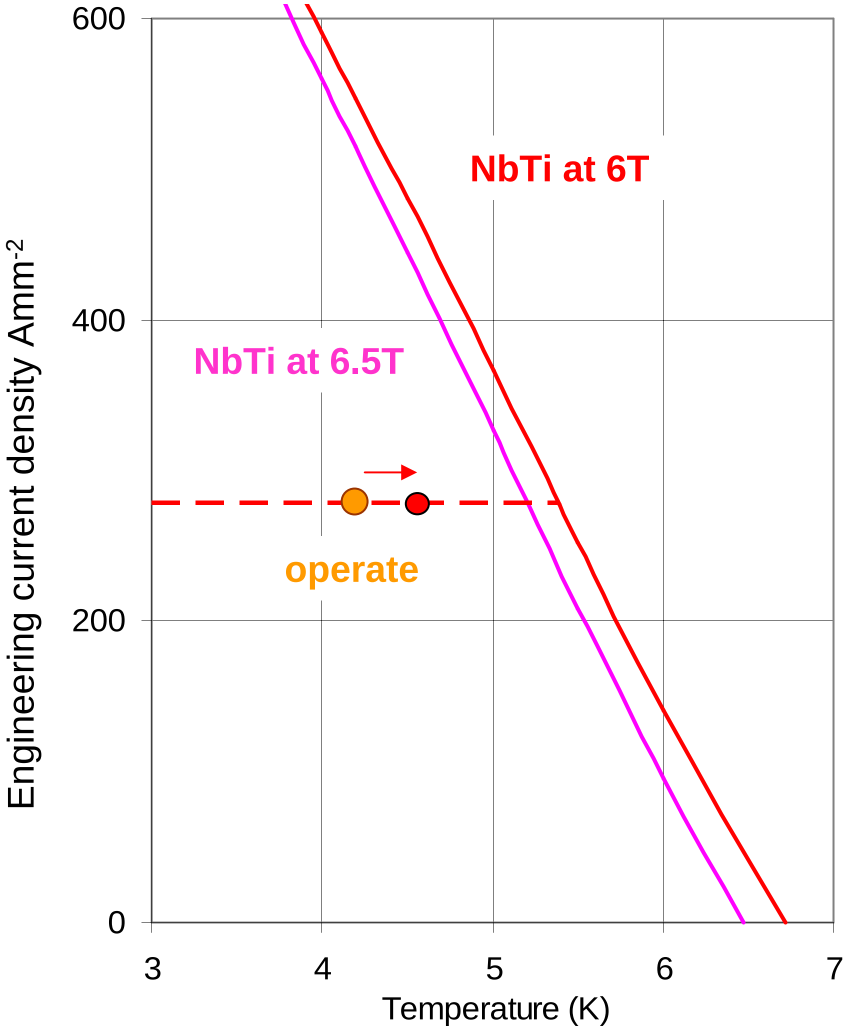
Temperature margin and ac loss

- for reliable magnet operation, we like to keep a temperature margin as a safety factor against unexpected temperature rises
  - mechanical movement
  - poor joints
  - beam heating
  - cryogenic fluctuations

- ac losses erode the temperature margin and must be factored into the magnet design
  - a 'safety factor' against an effect which is certain to happen is not a safety factor at all!

- so to get a true temperature margin, we need to calculate the worst temperature rise caused by ac loss and take that to be the operating temperature

- the **peak field point** is usually most sensitive to temperature; usually this point has the highest ac loss

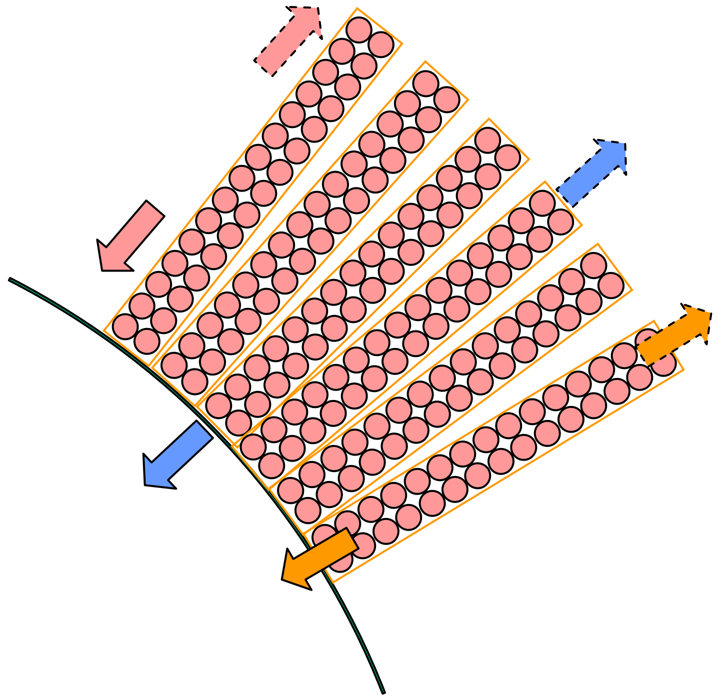


Factors in the temperature rise

conduction through the cable

conduction through the insulation

heat transfer to the helium



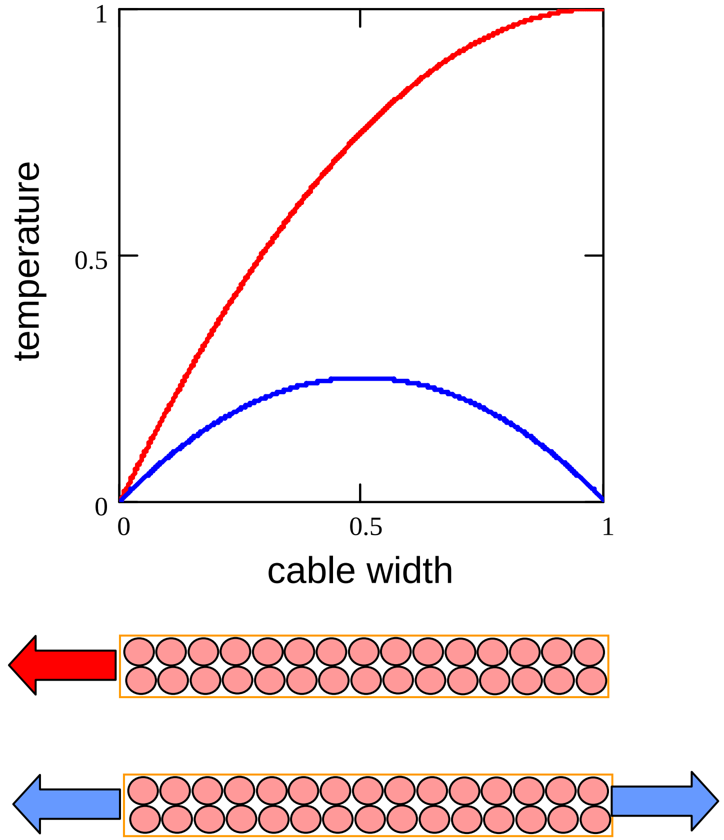
- usually there is no helium cooling on the broad faces of the cable
- cooling is much more efficient with helium in contact with inner and outer edge of cable

Conduction through the cable

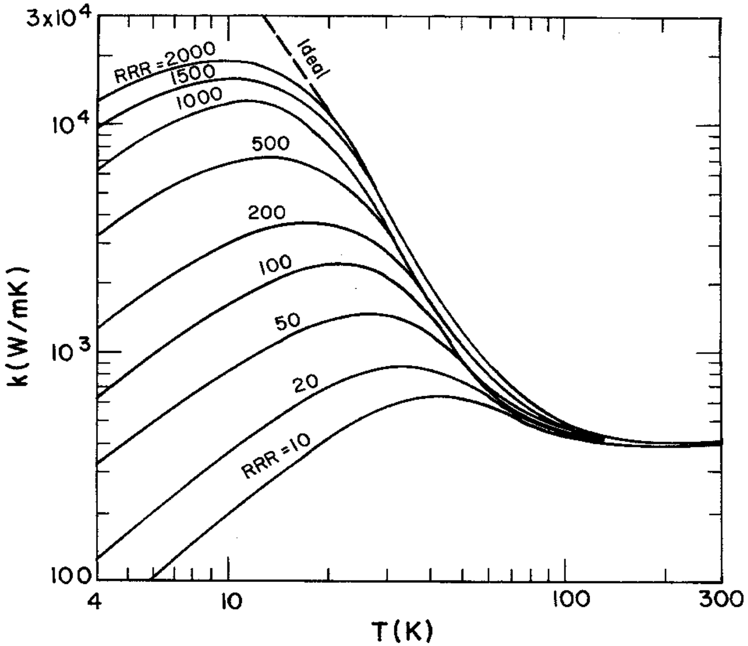
heat generation per unit volume P_v effective transverse thermal conductivity k_{eff} temperature rise

$$\Delta\theta = \frac{P_v}{k_{eff}}\frac{a^2}{2}(2\varepsilon - \varepsilon^2)$$

where a = half (full) width of cable and $\varepsilon = x/a$

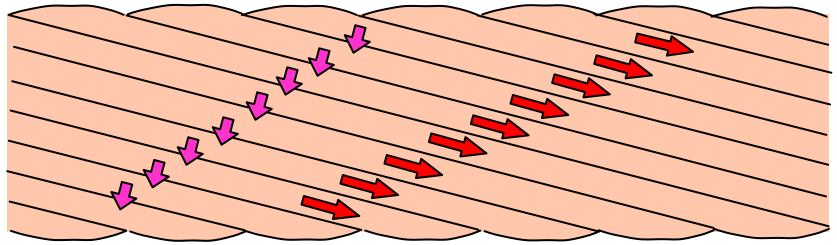


Note: k varies with temperature, but OK to assume constant for small temperature rises



Conductivity through the cable

- the best way is to measure it!
- if this is not possible (time!) then it can be estimated from a summation of two components in parallel:-



conduction along the wires

neglect NbTi, take filling factor of copper in cable and geometry factor to take account of slant angle of wires;

$$k_{effa} = k_{Cu} \frac{N}{p} \frac{c}{b} \pi d_w^2 \frac{mat}{1+mat} \frac{1}{\sqrt{p^2 + 16\, c^2}}$$

2c = cable width
2b = cable thickness
p = cable twist pitch

copper thermal conductivity k_{Cu} depends on purity and hardness; measure electrical resistivity and check via the Wiedemann Franz Law

$$k(\theta)\rho(\theta) = L_o\theta$$

L_o = Lorentz number
$= 2.45 \times 10^{-8}\ W\Omega K^{-2}$

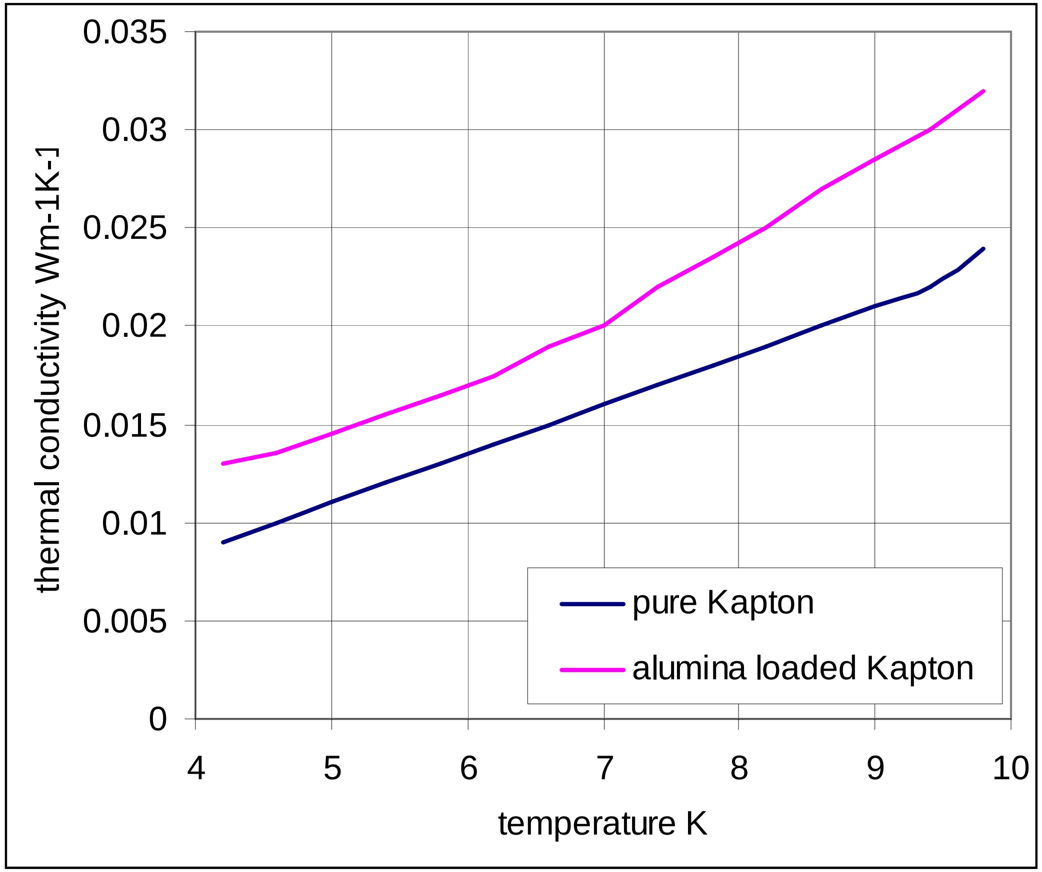
conduction between wires

can estimate from measured electrical R_a and the Wiedemann Franz Law (perhaps!)

$$k_{effb} = L_o\theta \frac{1}{R_a} \frac{2N}{p^2} \sqrt{p^2 + 16c^2}$$

Conduction through insulation

- thermal conductivity of insulating materials is very low at 4K
- it depends on temperature



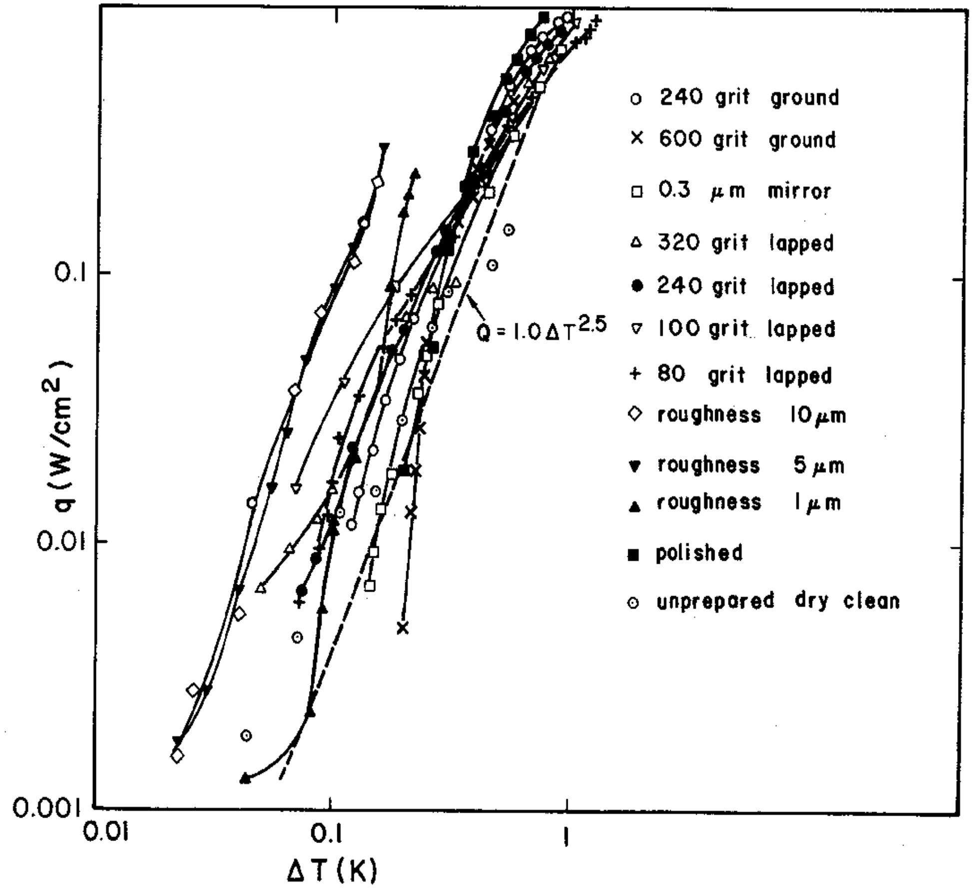
Some insulators at 4.2K

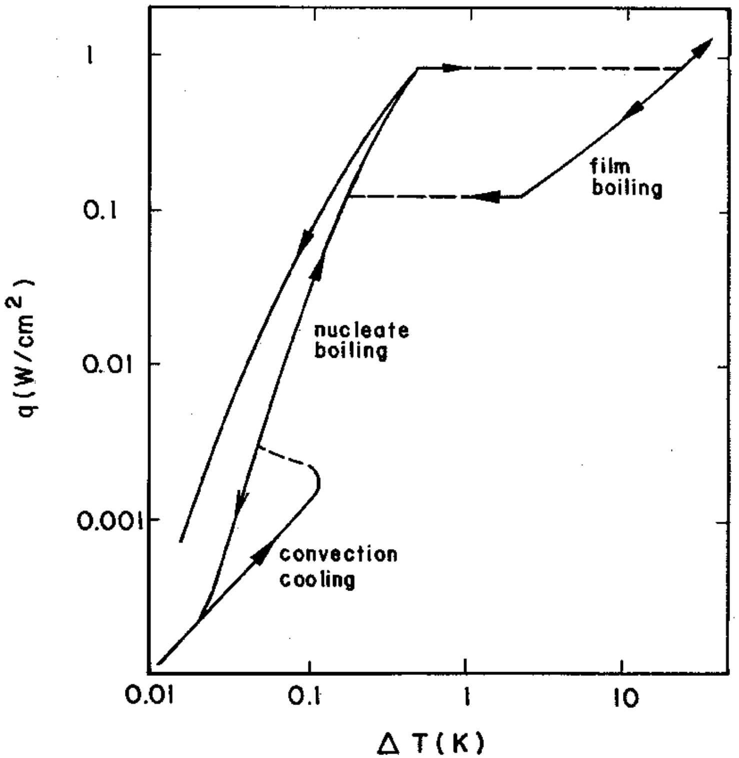
material	k $Wm^{-1}K^{-1}$
glass	0.1
epoxy resin	0.06
polystyrene	0.03
teflon	0.05
nylon	0.01
alumina loaded epoxy resin	0.1

Thermal conductivity of two types of Kapton
Rule DL et al NIST 91

Heat transfer to boiling liquid helium

- heat transfer to boiling liquid helium is hysteretic -
- if you exceed the peak nucleate boiling flux the temperature rises above critical for the superconductor

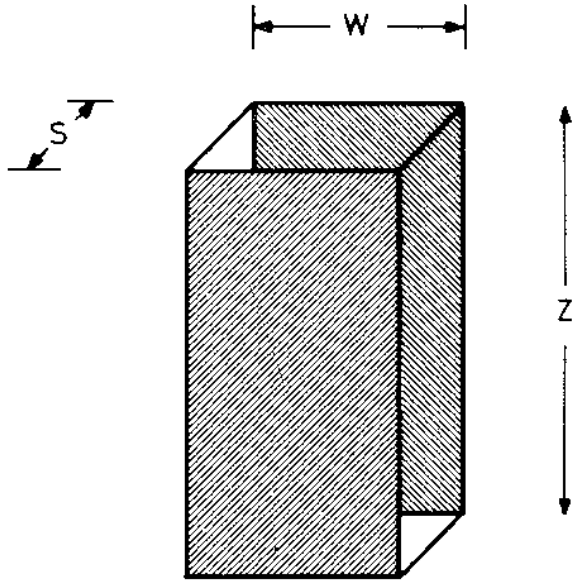




- so for ac loss must keep below peak nucleate boiling flux
- temperature rise depends on surface finish

Boiling in narrow channels

when the helium is confined to a narrow channel the peak nucleate boiling flux is reduced; Sydoriak presents the following correlation



$$\phi_{pnbf} = \frac{1.8\, s}{z^{1/2}\left(s + 0.11 + 0.037n\right)}$$

where ϕ_{pnbf} = peak nucleate boiling flux (W/cm^2 of channel wall)

s = separation between channel walls (cm)

z = channel height (cm)

n = number of walls heated

Cooling by forced flow supercritical helium

heat transfer to forced flow supercritical helium can be approximated by the Dittus Boelter correlation, provided the flow is turbulent, ie Re > 10^5

$$Nu = 0.259 \, \mathrm{Re}^{0.8} \, \mathrm{Pr}^{0.4} \left(\frac{\theta_w}{\theta_b} \right)^{-0.716}$$

where Nu = Nusselt number
Re = Reynolds number
Pr = Prandtl number
θ_w = wall temperature
θ_b = bath temperature

the heat transfer coefficient h ($Wm^{-2}K^{-1}$)

$$h = Nu \frac{k}{D_h}$$

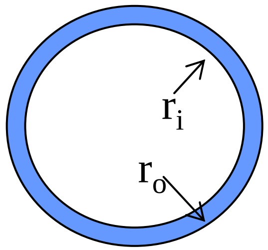
where k = gas thermal conductivity
D_h = hydraulic diameter of channel

$$\mathrm{Re} = \frac{M}{A_h} \frac{D_h}{\mu}$$

$$\mathrm{Pr} = \frac{\mu \, Cp}{k}$$

where M = mass flow rate
μ = viscosity
Cp = specific heat at constant pressure

for a channel of annular cross section



$$D_h = \frac{4 A_h}{2\pi (r_o + r_i)}$$

see Arp V Adv. Cryo. Engineering Volume 17 pp342

Pressure drop in forced flow supercritical helium

provided the flow is turbulent, ie Re > 10^5, the pressure drop along a channel carrying forced flow supercritical helium is

$$P = \frac{2f}{D_h\,\rho}\left(\frac{M}{A_h}\right)^2$$

where

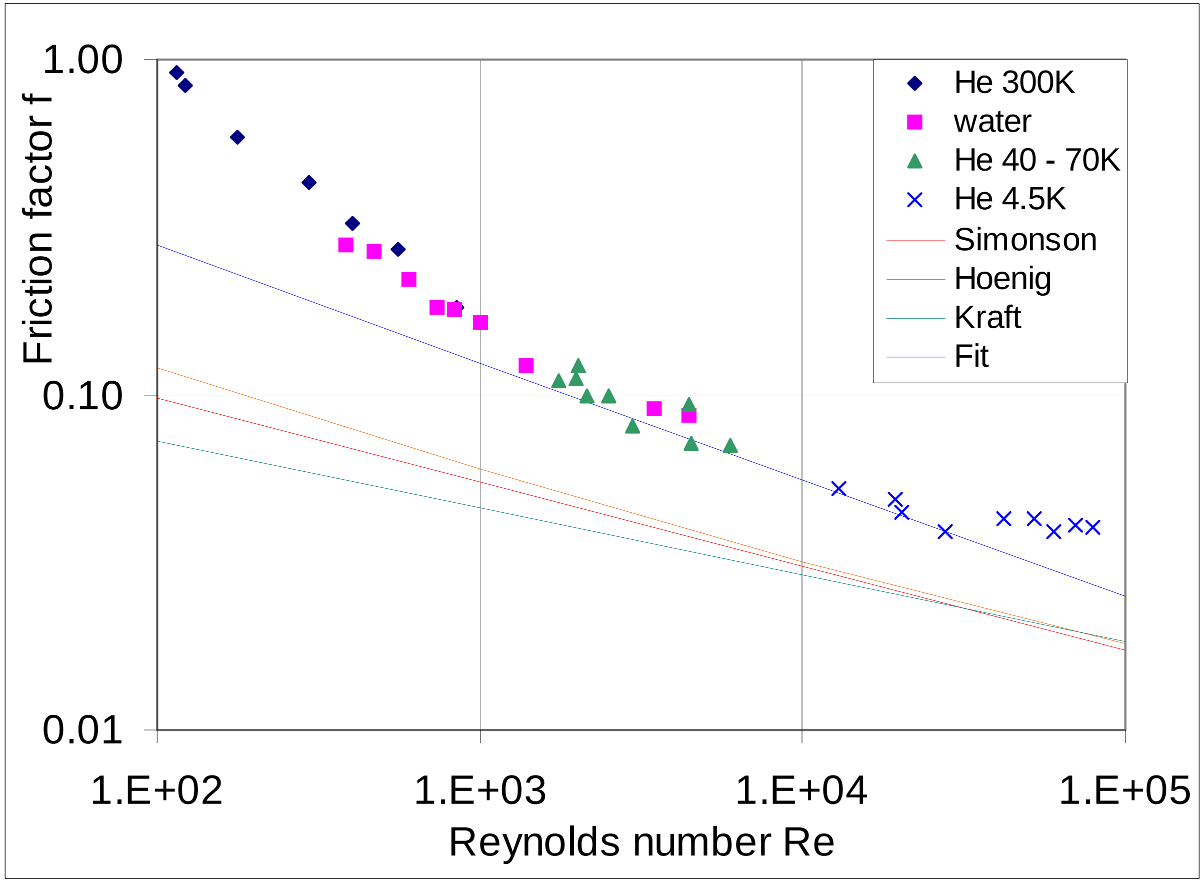
f = friction factor

D_h = hydraulic diameter of channel

M = mass flow rate

ρ = gas density

A_h = cross sectional area of channel



measurements of friction factor in the Euratom large Tokamak conductor

Heat transfer to superfluid helium

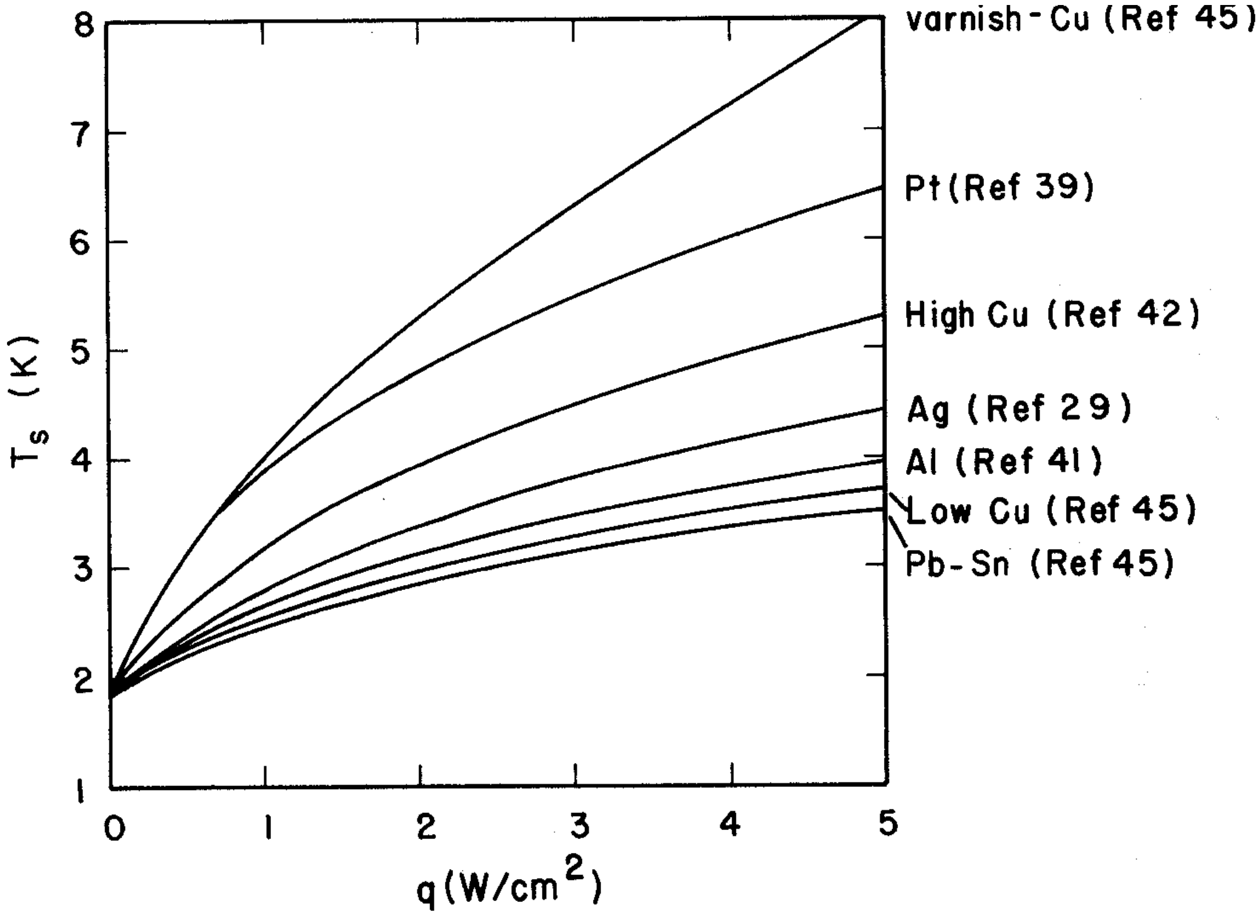
the temperature drop between a heat generating surface and superfluid helium 2 is caused by phonon mismatch, known as Kapitza resistance

it may be represented by

$$Q' = \alpha \left(\theta_w^n - \theta_b^n \right)$$

where
Q' = heat flux per unit area

α & n are experimentally determined



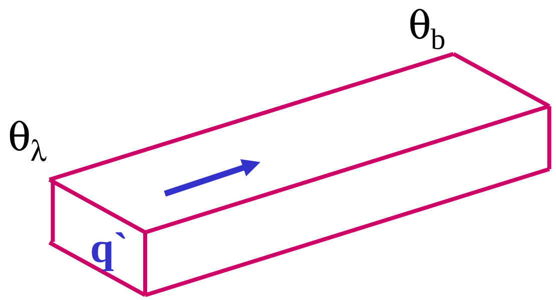
Heat transfer to superfluid helium

Kapitza coefficients depend on the surface $Q' = \alpha\left(\theta_w^n - \theta_b^n\right)$

Metal	Surface condition	T_s at 1 W/cm^2	α (W/cm$^2 \cdot$ K)	n
Cu	As received	3.1	0.0486	2.8
	Brushed and baked	2.85	to	
	Annealed	2.95	0.02	3.8
	Polished	2.67	0.0455	3.45
	Oxidized in air for 1 month	2.68	0.046	3.46
	oxidized in air at 200° C for 40 min	2.46	0.052	3.7
	50–50 PbSn solder coated	2.43	0.076	3.4
	Varnish coated	4.0	0.0735	2.05
Pt	Machined	3.9	0.019	3.0
Ag	Polished	2.8	0.06	3.0
Al	Polished	2.66	0.049	3.4

from 'Helium Cryogenics' by SW Van Sciver

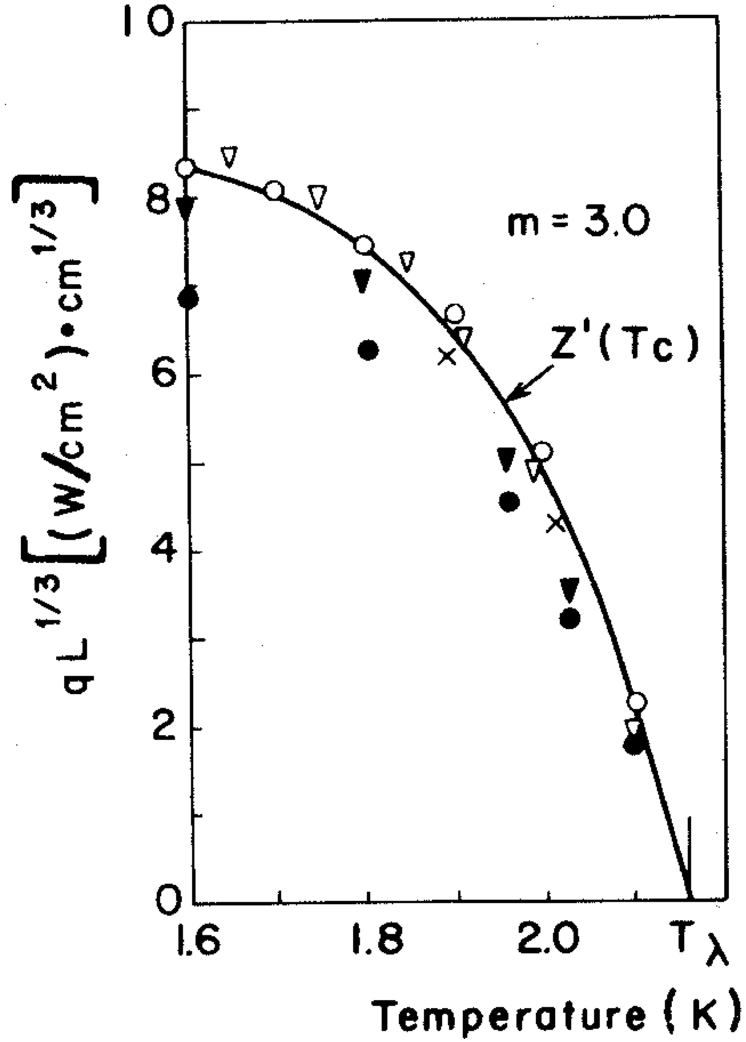
Critical superfluid heat flux in channels



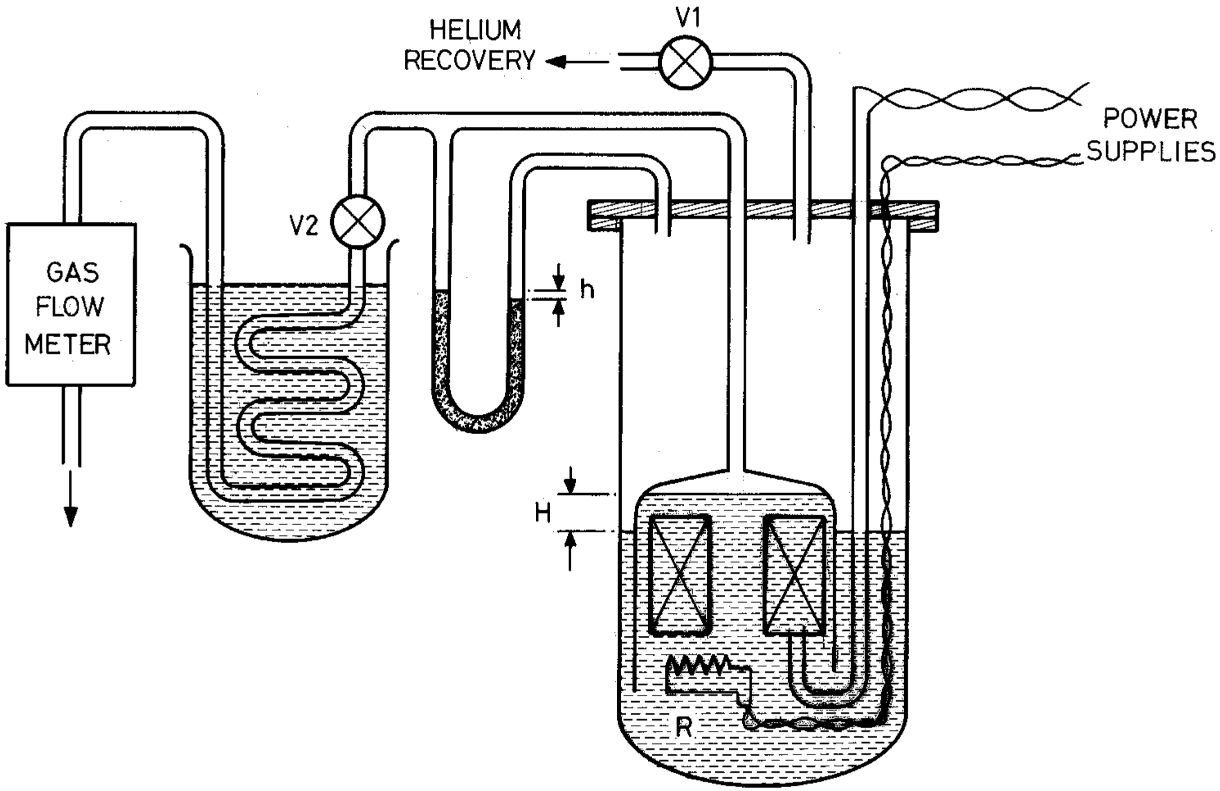
- consider a cooling channel connecting the hot surface to the bath
- critical heat flux in this channel is reaches when the temperature at the hot end reaches the lamda point
- the condition for lamda point is

$$q'^{*} L^{(1/m)} = Z(\theta_b) = \left\{ \int_{\theta_b}^{\theta_\lambda} \frac{d\theta}{f(\theta)} \right\}$$

- this gives the heat carrying capacity of the channel



Measurement of ac loss



Calorimetric

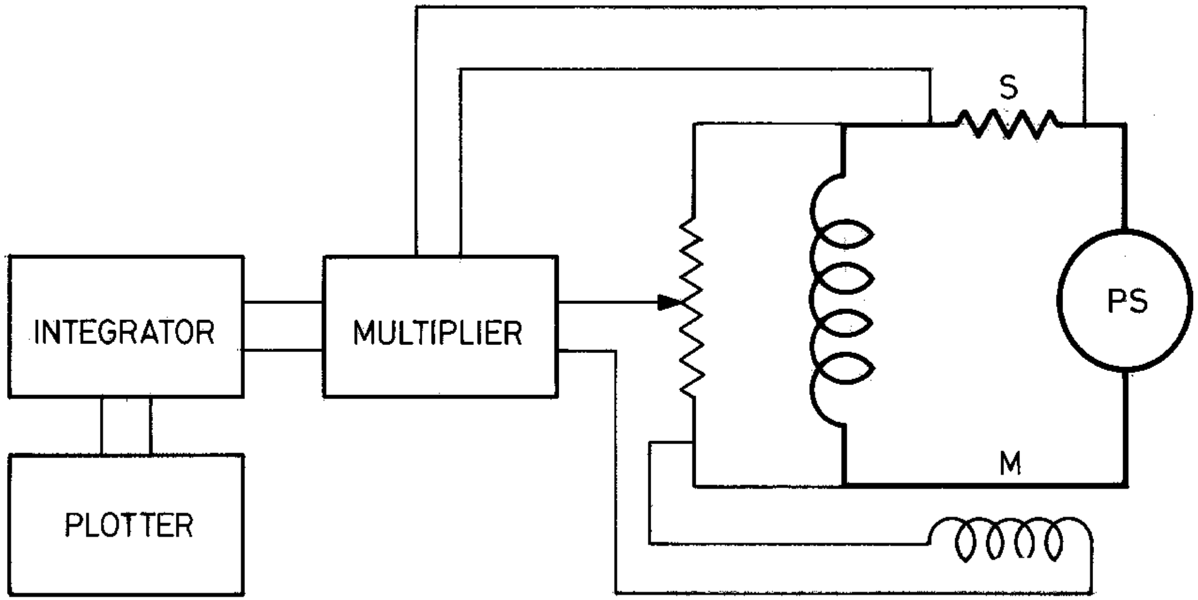
- the most direct measurement
- measure the volume of helium gas boiled off and multiply by the latent heat

- **for good accuracy don't forget to:**
  - *wait for steady state conditions*
  - *calibrate with the resistor*
  - *warm the gas to a defined temperature before measuring its volume*
  - *measure the gas pressure (latent heat depends on pressure)*
  - *equalise pressure between the 'bell' and rest of cryostat (gas might bubble out under)*

Measurement of ac loss

Electrical

- measure the net work done by the power supply and integrate over a cycle
- subtracting a term $M\,dI/dt$ can improve accuracy by reducing the ± range of integration - but M must be linear - no iron!



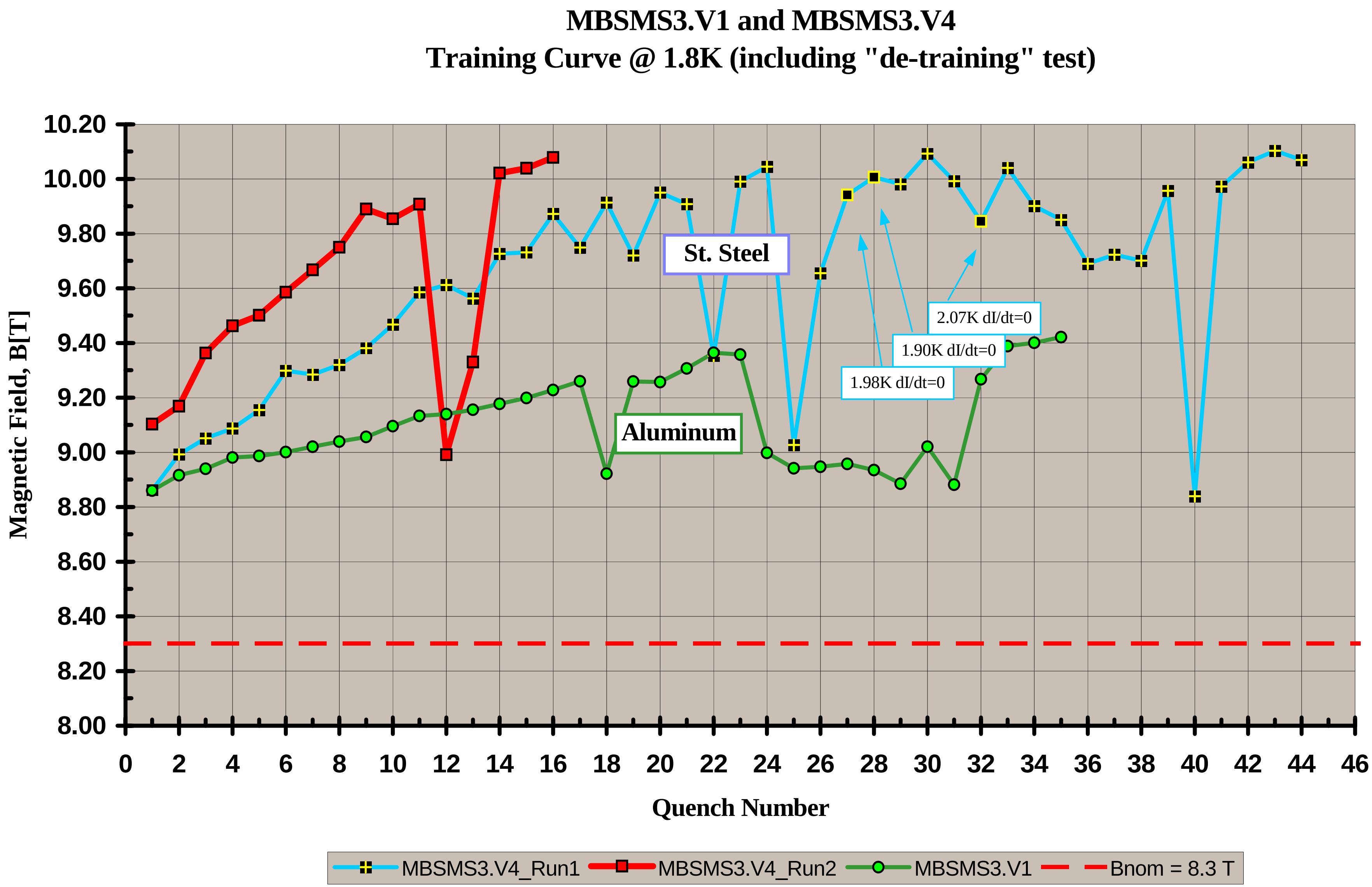
Advantages

- fast response
- no special cryogenics needed - OK with refrigerator

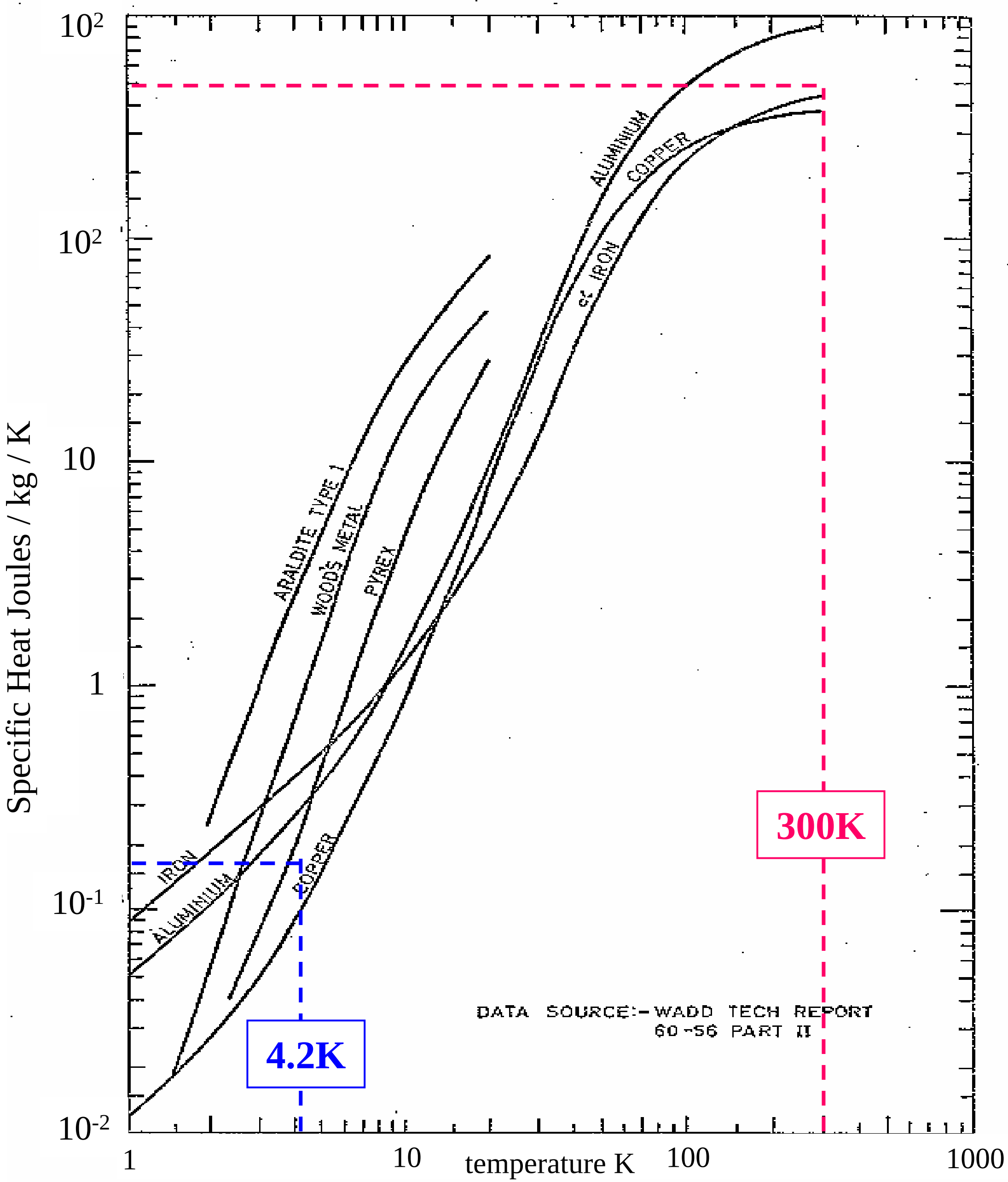
Disadvantages

- must go round a full cycle
- problems with thermoelectric emfs
- pickup

Training of an early LHC dipole magnet



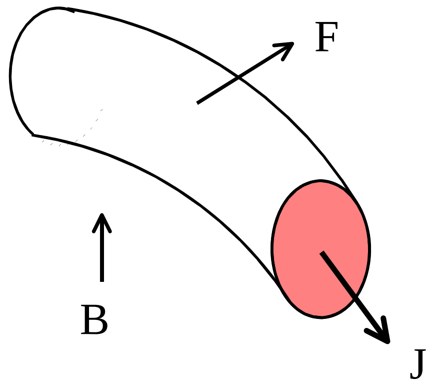
Causes of training: (1) low specific heat



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

Causes of training: (2) high forces

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

so if $\delta = 10$ µm

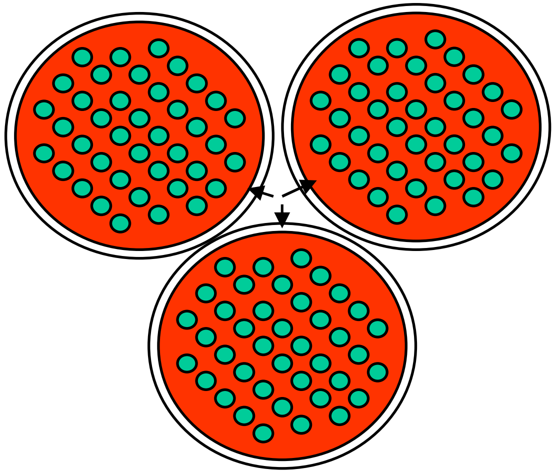
then Q = 2.5×10^4 J.m^{-3}

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

can **you** engineer a winding to better than **10 µm?**

Causes of training: (3) differential thermal contraction

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



Calculate the stain energy induced in resin by differential thermal contraction

let: σ = tensile stress Y = Young's modulus

ε = differential strain ν = Poisson's ratio

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

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

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

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

Interesting fact: magnets impregnated with paraffin wax show almost no training although the wax is full of cracks after cooldown.

Presumably the wax breaks at low σ before it has had chance to store up any strain energy

How to reduce training?

1) Reduce the disturbances occurring in the magnet winding

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

2) Make the conductor able to withstand disturbances without quenching

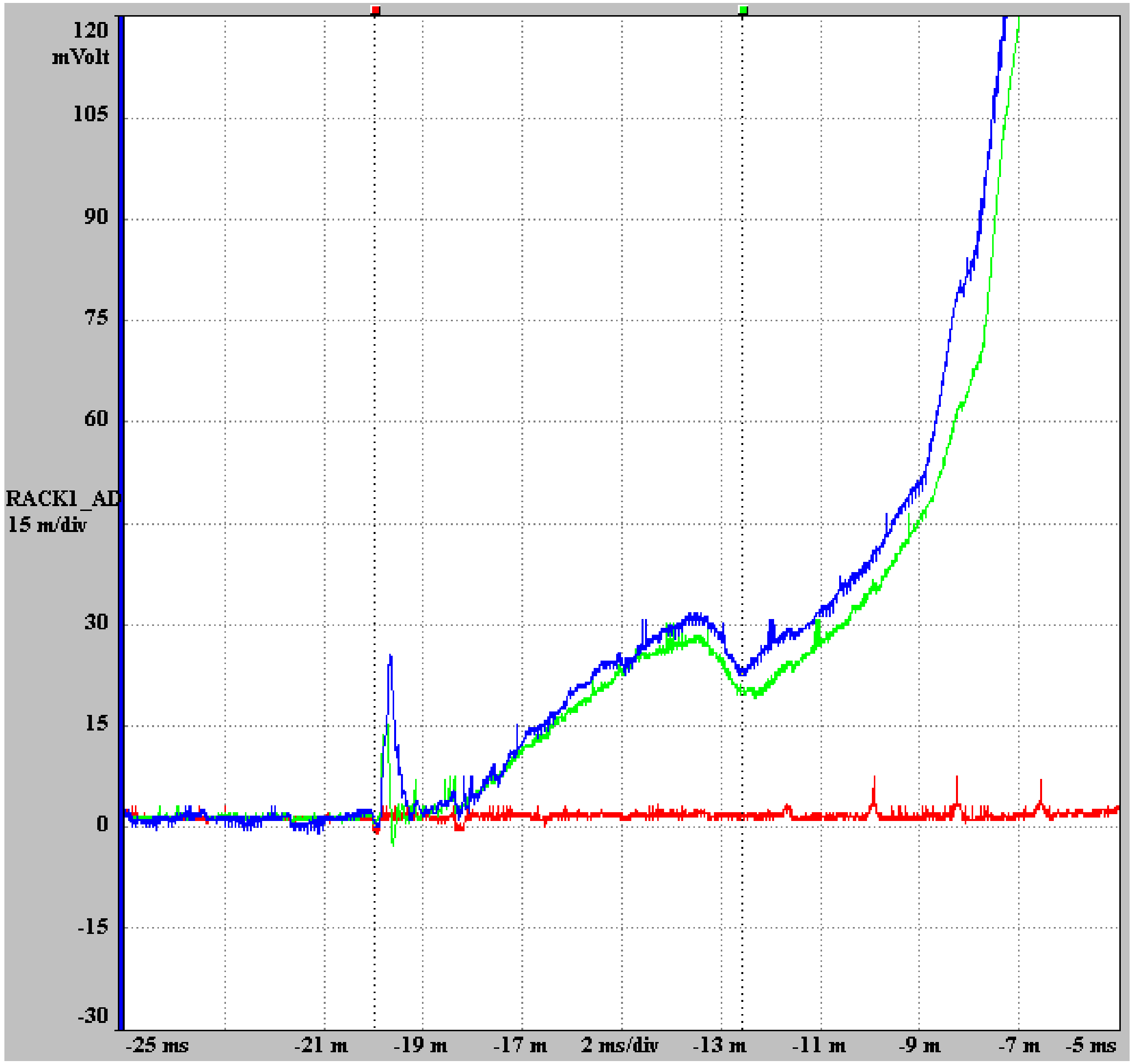
- increase the temperature margin
  - operate at lower current
  - higher critical temperature - HTS?
- increase the cooling
- increase the specific heat

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

Minimum Quench Energy MQE

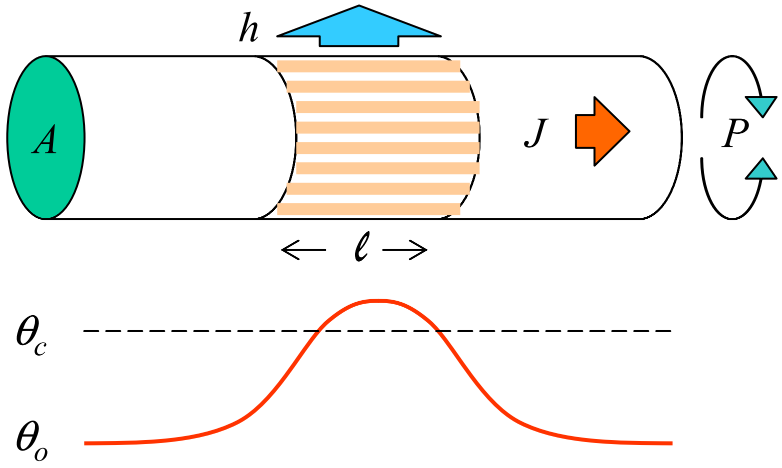
= energy input at a point which is just enough to trigger a quench

Quench initiation by a disturbance



- CERN picture of the internal voltage in an LHC dipole just before a quench
- note the initiating spike - conductor motion?
- after the spike, conductor goes resistive, then it almost recovers
- but then goes on to a full quench
- can we design conductors to encourage that recovery and avoid the quench?

Minimum propagating zone MPZ



- think of a conductor where a short section has been heated, so that it is resistive
- if heat is conducted out of the resistive zone faster than it is generated, the zone will shrink - vice versa it will grow.
- the boundary between these two conditions is called the minimum propagating zone *MPZ*
- for best stability make MPZ as large as possible

the balance point may be found by equating heat generation to heat removed.
Very approximately, we have:

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

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

where: k = thermal conductivity ρ = resistivity A = cross sectional area of conductor

h = heat transfer coefficient to coolant – if there is any in contact

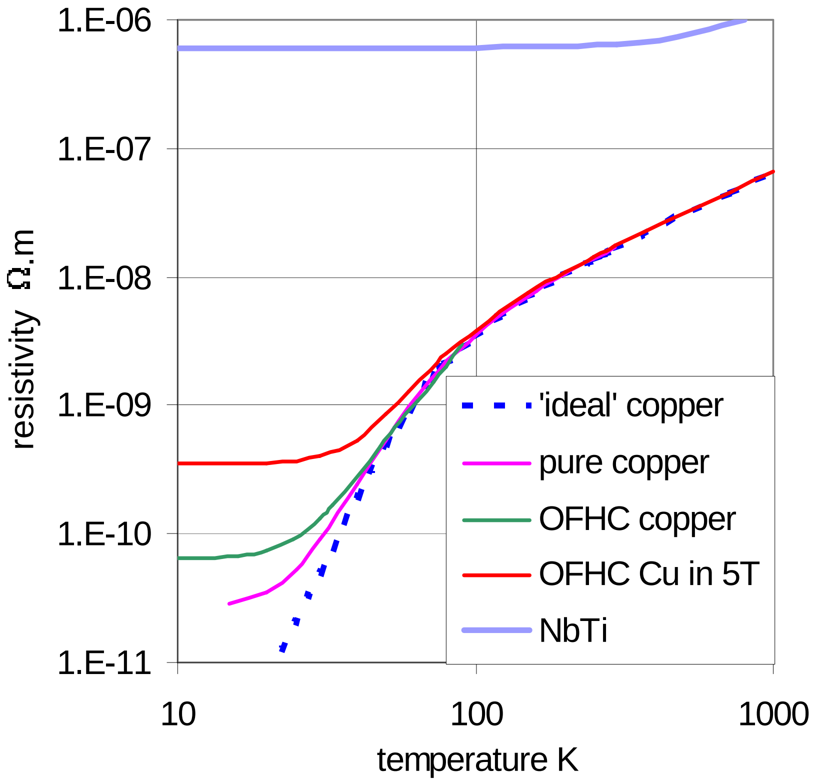
P = cooled perimeter of conductor

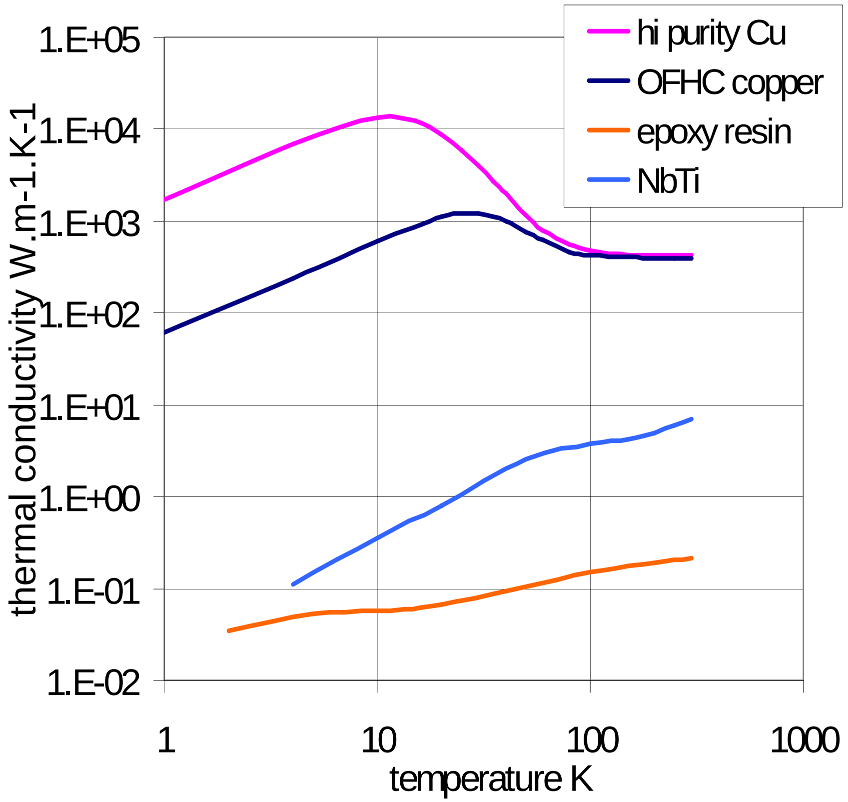
Energy to set up MPZ is called the Minimum Quench Energy *MQE*

How to make a large MPZ and MQE

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

- make thermal conductivity k large
- make resistivity ρ small
- make heat transfer ***hP/A*** large (but $\Rightarrow$ low J_{eng})



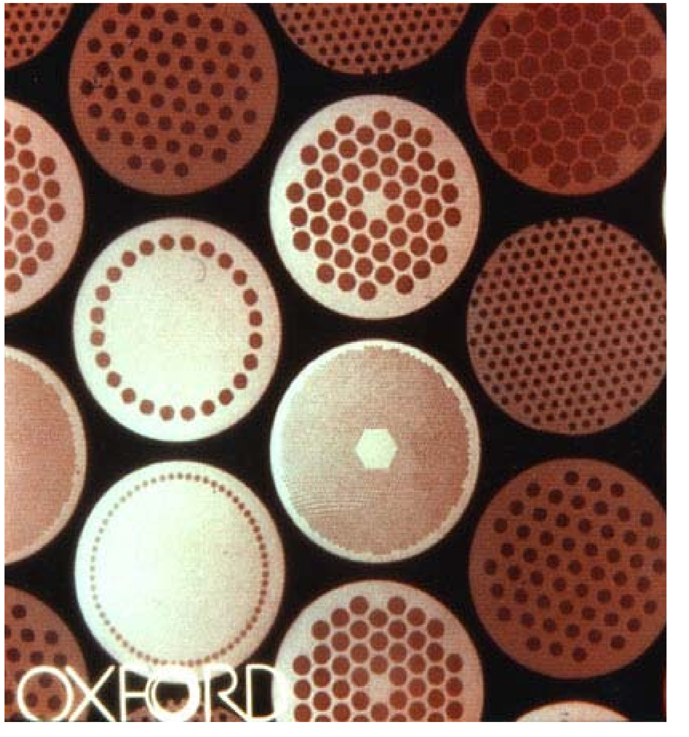


Large MPZ ⇒ large MQE ⇒ less training

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

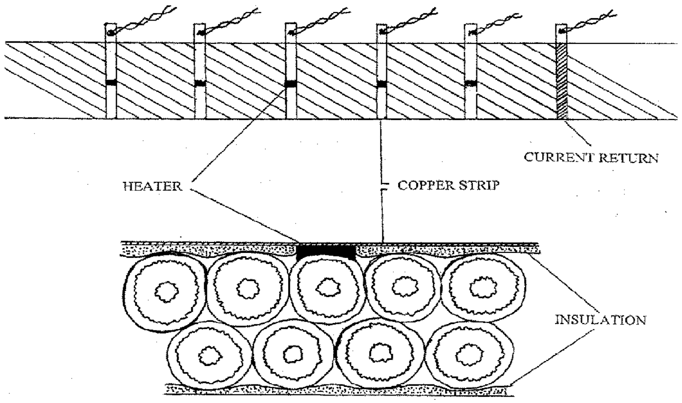
- make thermal conductivity k large
- make resistivity ρ small
- make heat transfer term *hP/A* large

- NbTi has high ρ and low k
- copper has low ρ and high k
- mix copper and NbTi in a filamentary composite wire
- make NbTi in fine filaments for intimate mixing
- maximum diameter of filaments ~ 50μm
- make the windings porous to liquid helium
  - superfluid is best
- fine filaments also eliminate flux jumping
  (see later slides)

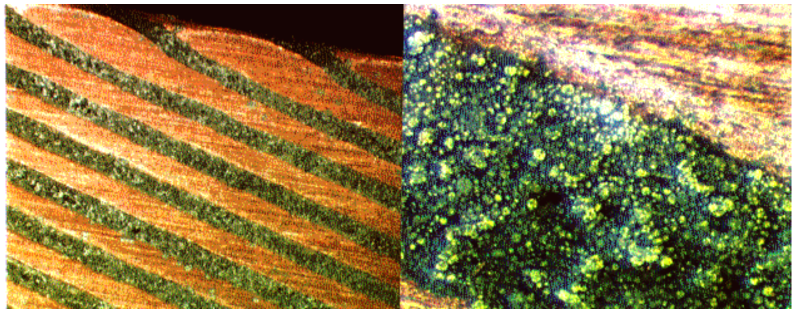


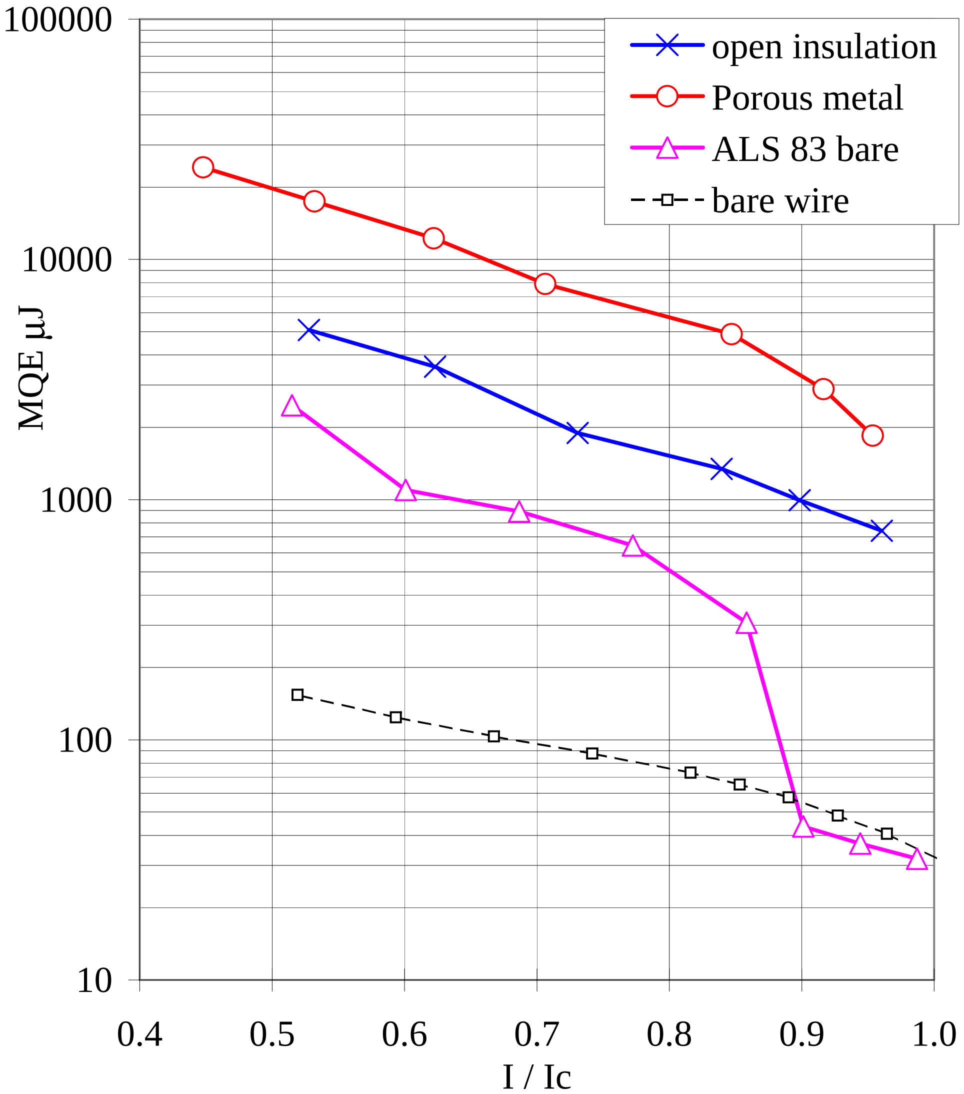
Measurement of MQE

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



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





AC loss and Training: concluding remarks

- ac losses may be calculated from the sum of 5 terms; 2 in the wires and 3 in the cable
  - in most practical situations, these terms are independent
- refrigeration load is calculated by summing over the winding volume
- peak temperature rise may be found by calculating conduction through the cable + insulation and heat transfer to the helium coolant
- different heat transfer mechanisms apply for boiling liquid helium, supercritical helium and superfluid helium
- the peak temperature rise reduces the temperature margin (safety factor) of the magnet
- ac loss may be measured calorimetrically or electrically
- training is thought to be caused by the transient release of mechanical energy within the magnet
  (before fine filaments it was also caused by flux jumping)
- training may be reduced (not yet cured) by
  a) reducing the energy release
  b) making conductors which can absorb a certain energy without quenching