Lecture 4: Quenching and Cryogenics

Plan

- the quench process
- decay times and temperature rise
- propagation of the resistive zone
- computing resistance growth and decay times
- quench protection schemes

- cryogenic fluids
- refrigeration
- cryostat design
  - conduction, convection & radiation

Magnetic stored energy

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

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

the magnet weighs 26 tonnes

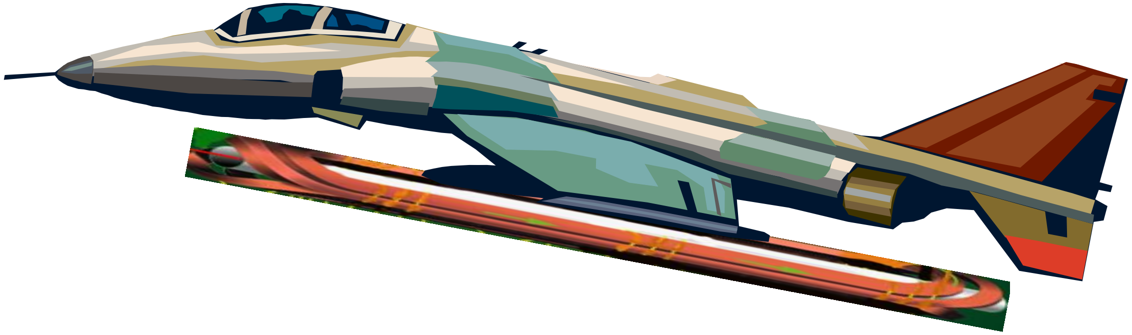
so the magnetic stored energy is equivalent to the kinetic energy of:-

26 tonnes travelling at 88km/hr

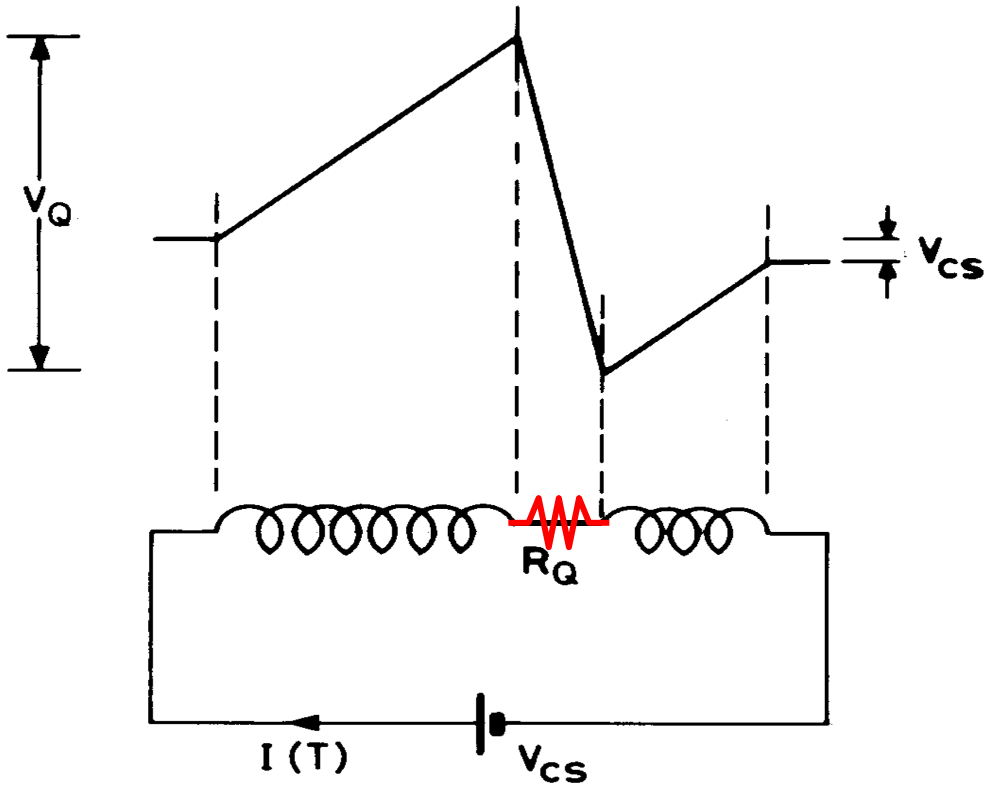
coils weigh 830 kg

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
- maximum temperature may be calculated from the current decay time via the U(θ) function (adiabatic approximation)
- internal voltages much greater than terminal voltage (= V_{cs} current supply)

The temperature rise function $U(\theta)$

- Adiabatic approximation

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

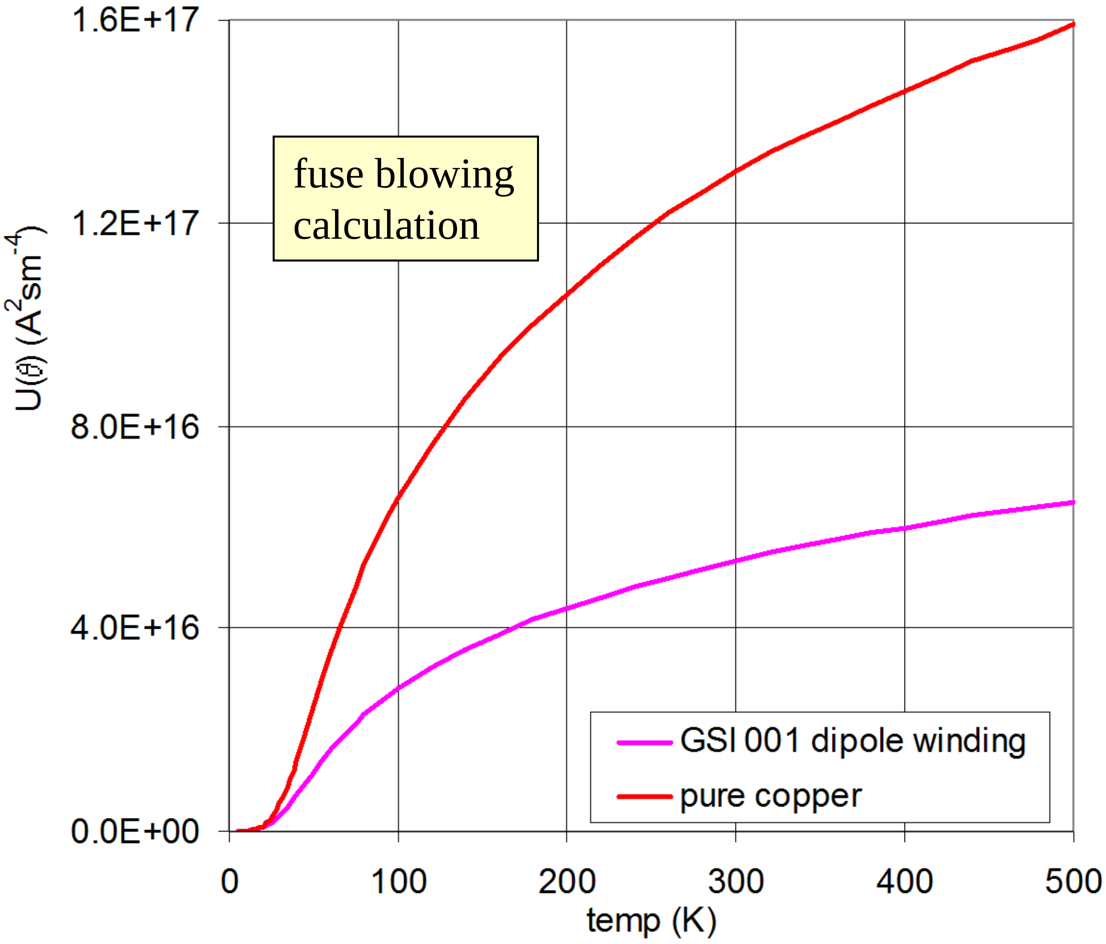
$J(T)$ = overall current density,
T = time,
$\rho(\theta)$ = overall resistivity,
γ = density
θ = temperature,
$C(\theta)$ = specific heat,
T_Q = quench decay time.

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

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

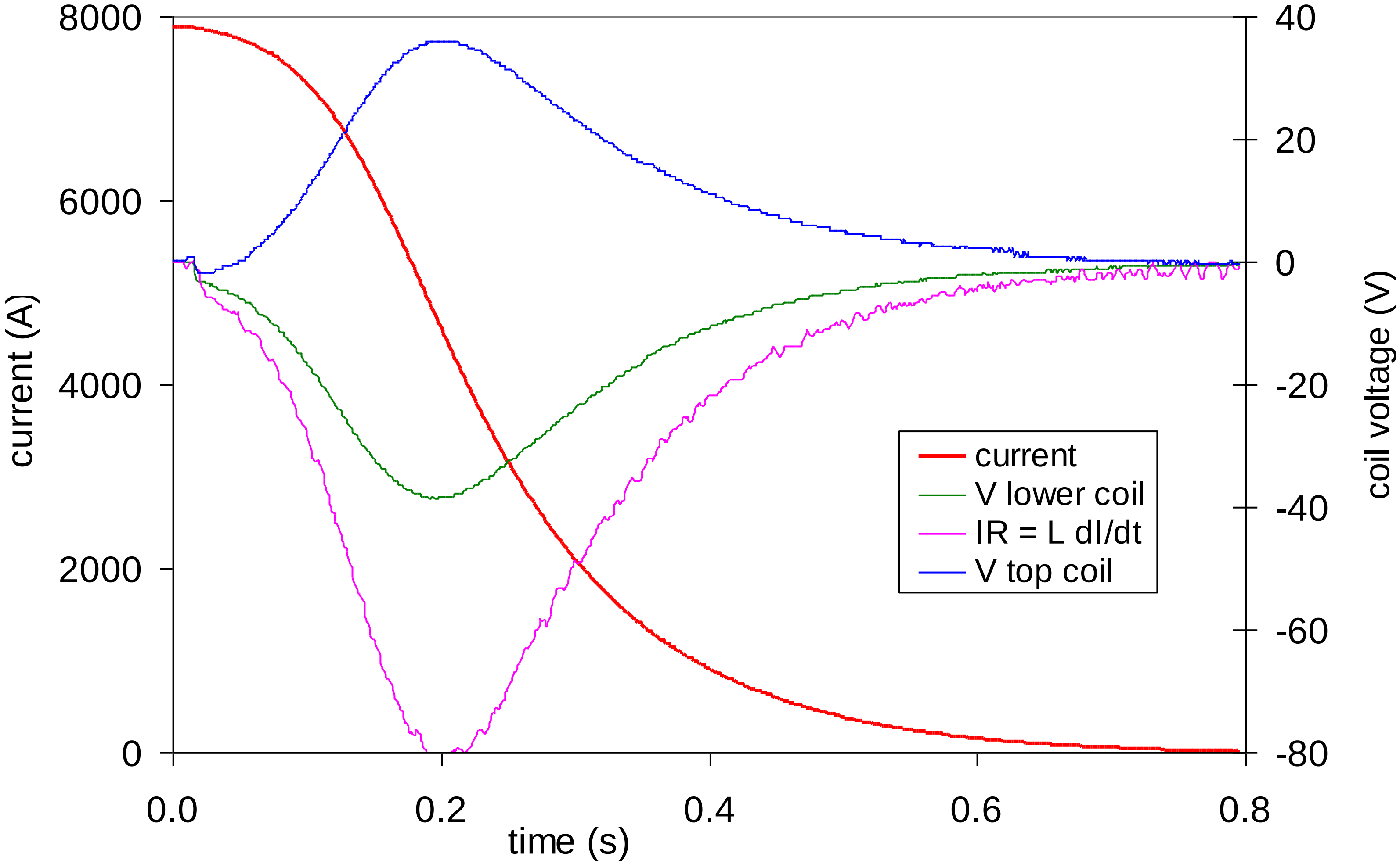
- GSI 001 dipole winding is 50% copper, 22% NbTi, 16% Kapton and 3% stainless steel

- NB always use **overall** current density



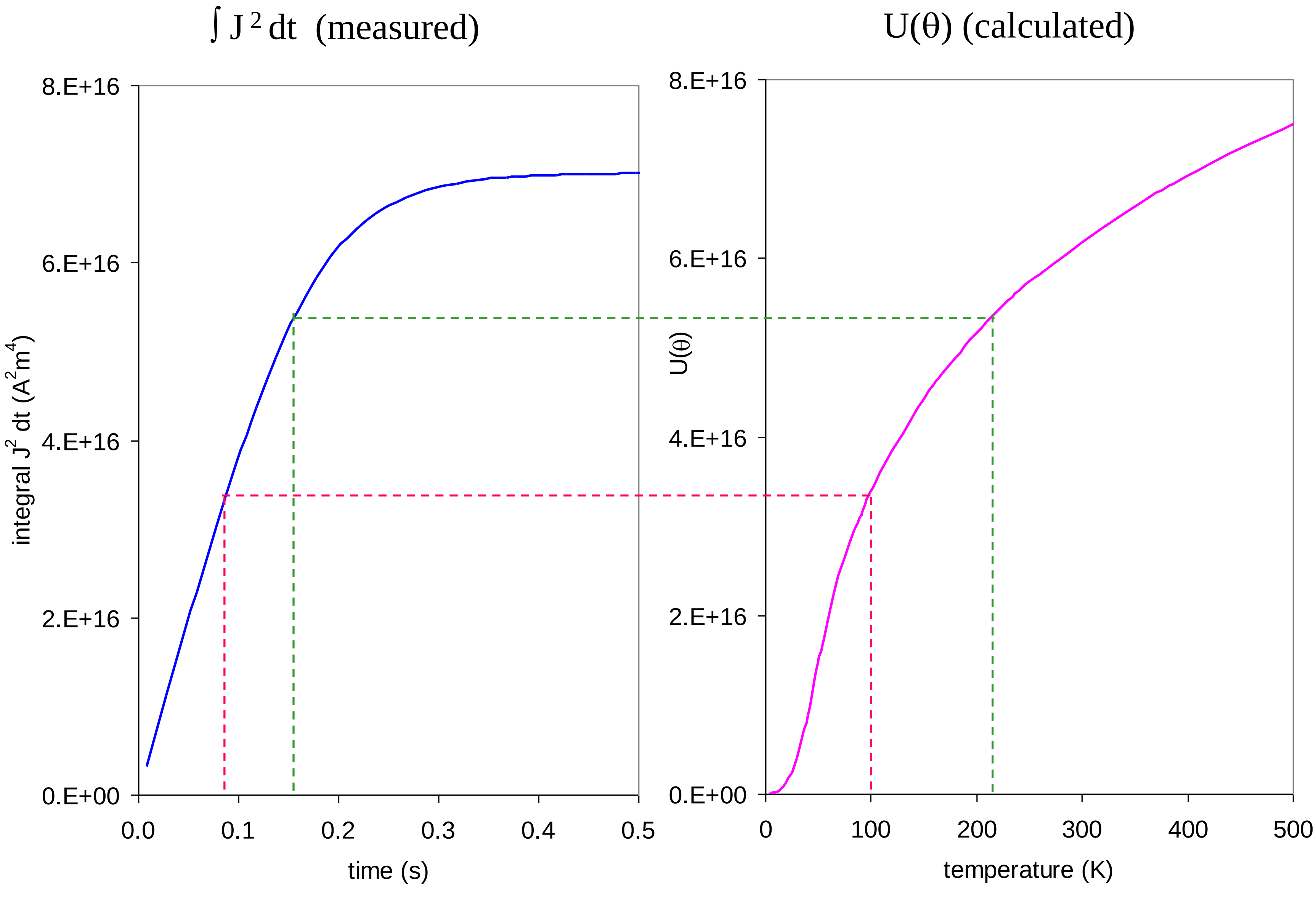
household fuse blows at 15A,
area = 0.15mm^2 J = 100Amm^{-2}
NbTi in 5T J_c = 2500Amm^{-2}

Measured current decay after a quench

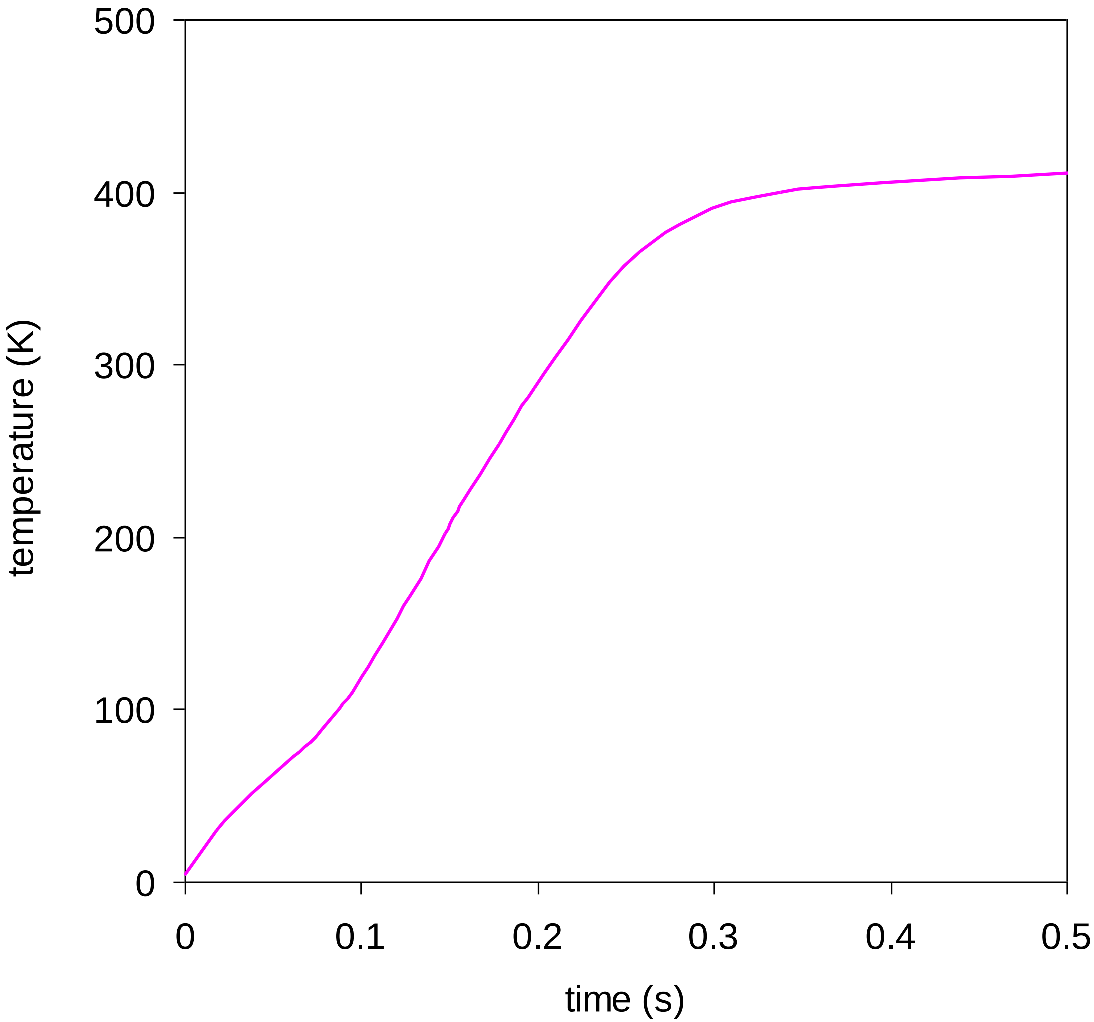


Dipole GSI001 measured at Brookhaven National Laboratory

Calculating temperature rise from the current decay curve

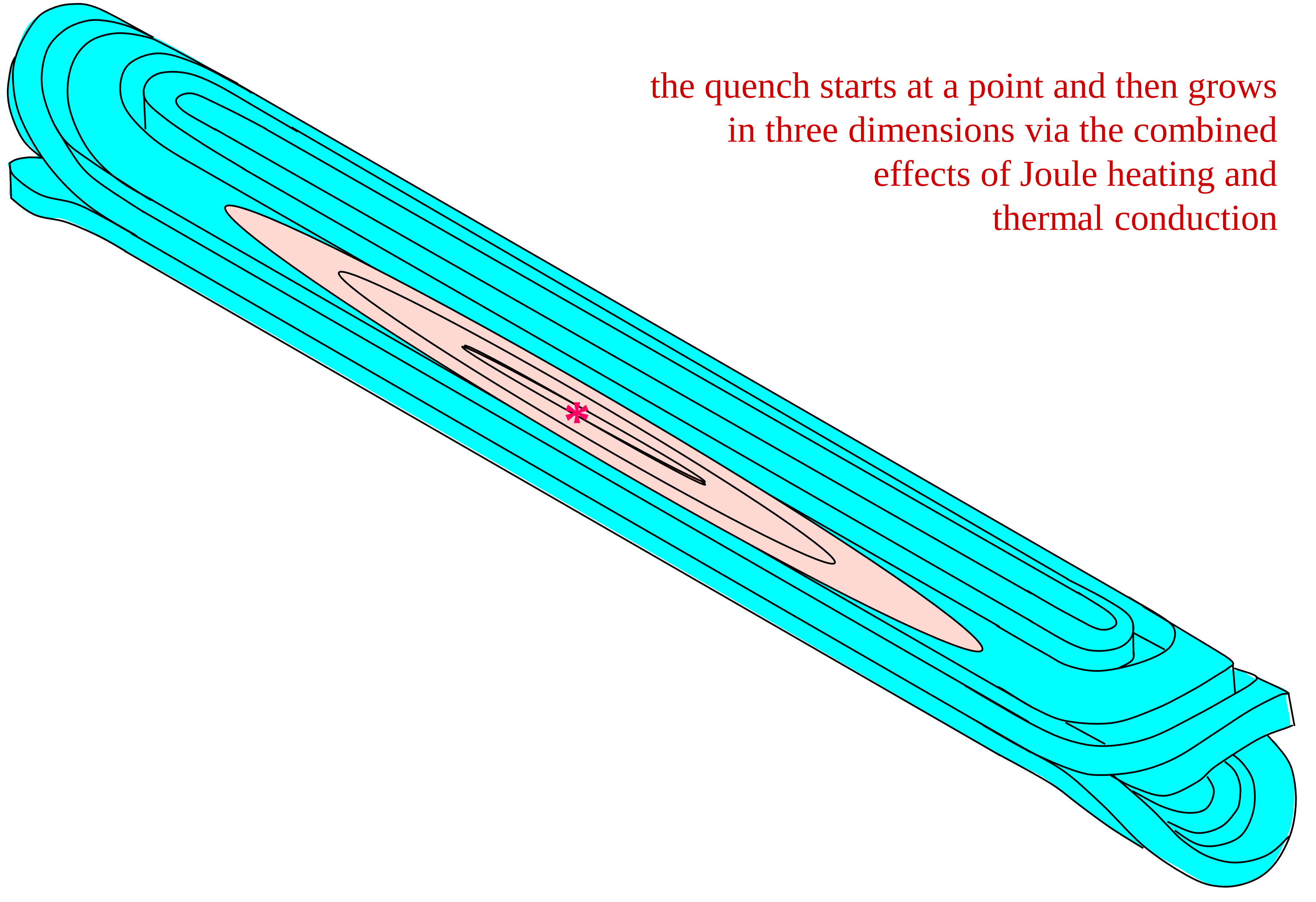


Calculated temperature



- calculate the U(θ) function from known materials properties
- measure the current decay profile
- calculate the maximum temperature rise at the point where quench starts
- we now know if the temperature rise is acceptable
  - but only after it has happened!
- need to calculate current decay curve before quenching

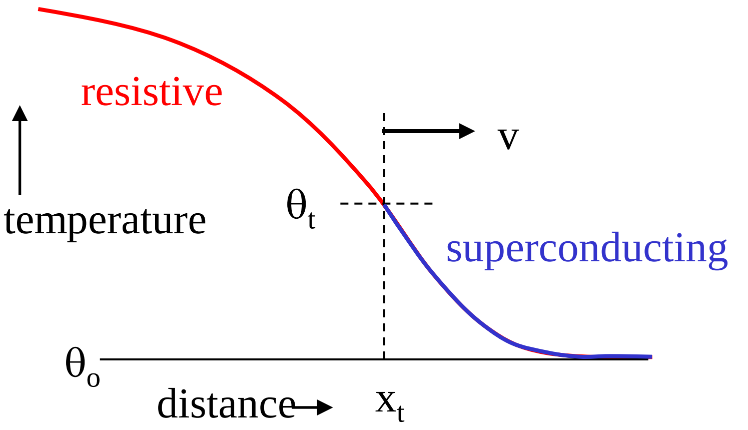
Growth of the resistive zone



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 1

- resistive zone starts at a point and spreads outwards
- the force driving it forward is the heat generation in the resistive zone, together with heat conduction along the wire
- write the heat conduction equations with resistive power generation $J^2\rho$ per unit volume in left hand region and $\rho = 0$ in right hand region.



$$\frac{\partial}{\partial x}\left(k A \frac{\partial \theta}{\partial x}\right) - \gamma C A \frac{\partial \theta}{\partial t} - hP(\theta - \theta_0) + J^2 \rho A = 0$$

where: k = thermal conductivity, A = area occupied by a single turn, γ = density, C = specific heat, h = heat transfer coefficient, P = cooled perimeter, ρ = resistivity, θ_o = base temperature

Note: all parameters are averaged over A the cross section occupied by one turn

assume x_t moves to the right at velocity v and take a new coordinate $\varepsilon = x - x_t = x - vt$

$$\frac{d^2\theta}{d\varepsilon^2} + \frac{v\gamma C}{k}\frac{d\theta}{d\varepsilon} - \frac{hP}{kA}(\theta - \theta_0) + \frac{J^2\rho}{k} = 0$$

Quench propagation velocity 2

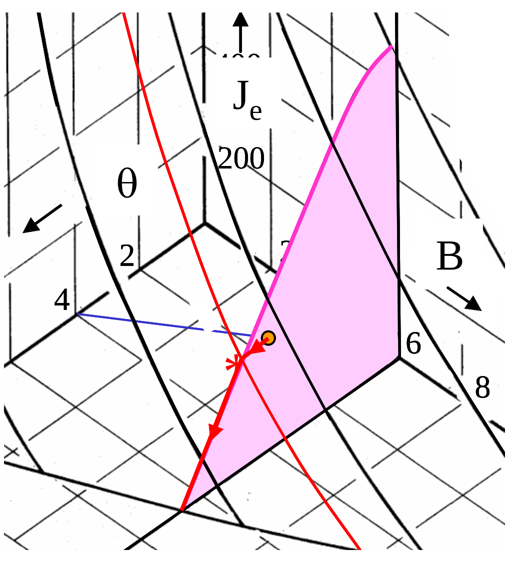
when $h = 0$, the solution for θ which gives a continuous join between left and right sides at θ_t gives the ***adiabatic propagation velocity***

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

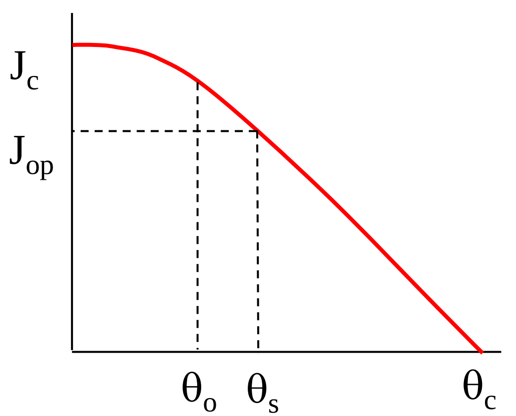
recap Wiedemann Franz Law $\rho(\theta).k(\theta) = L_o\theta$

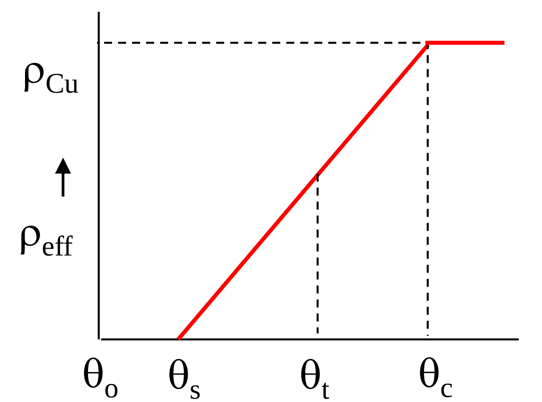
what to say about θ_t ?

- in a single superconductor it is just θ_c
- but in a practical filamentary composite wire the current transfers progressively to the copper



- current sharing temperature $\theta_s = \theta_o + margin$
- zero current in copper below θ_s all current in copper above θ_c
- take a mean transition temperature $\theta_t = (\theta_s + \theta_c)/2$





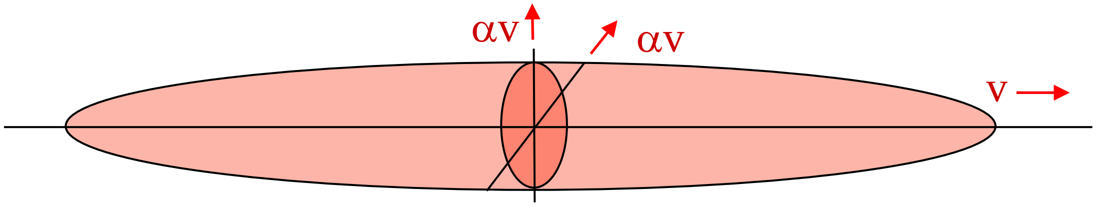
Quench propagation velocity 3

the resistive zone also propagates sideways through the inter-turn insulation (much more slowly) calculation is similar and the velocity ratio α is:

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

Typical values $v_{ad} = 5 - 20\ ms^{-1}$ $\alpha = 0.01 - 0.03$

so the resistive zone advances in the form of an ellipsoid, with its long dimension along the wire



Some corrections for a better approximation

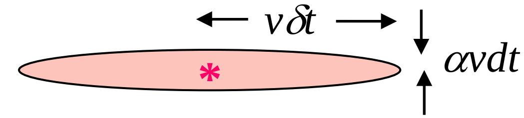
- because C varies so strongly with temperature, it is better to calculate an averaged C from the enthalpy change

$$C_{av}(\theta_g, \theta_c) = \frac{H(\theta_c) - H(\theta_g)}{(\theta_c - \theta_g)}$$

- heat diffuses slowly into the insulation, so its heat capacity should be excluded from the averaged heat capacity when calculating longitudinal velocity - but not transverse velocity
- if the winding is porous to liquid helium (usual in accelerator magnets) need to include a time dependent heat transfer term
- can approximate all the above, but for a really good answer must solve (numerically) the three dimensional heat diffusion equation or, even better, measure it!

Resistance growth and current decay - numerical

start resistive zone 1



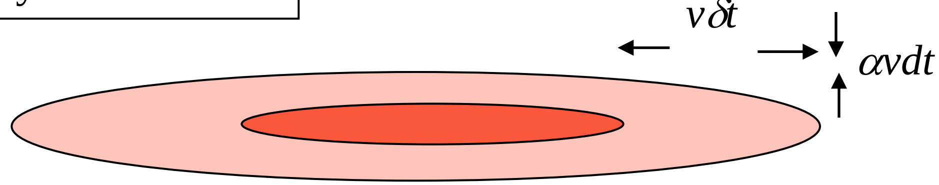
in time δt zone 1 grows $v.dt$ longitudinally and $\alpha.v.dt$ transversely

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



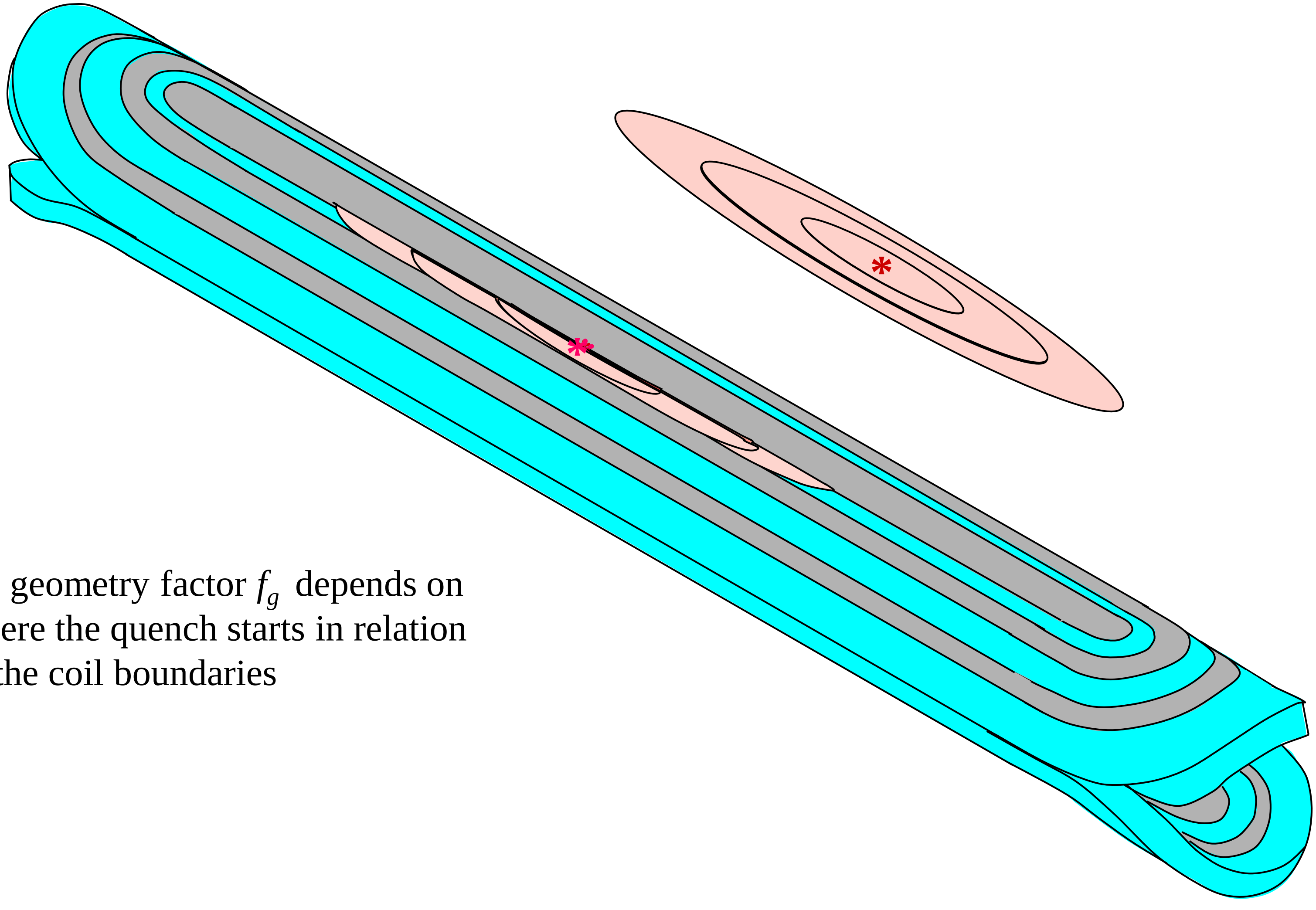
temperature of each zone grows by $\delta\theta_1 = J^2\rho(\theta_1)\delta t / \gamma C(\theta_1)$ $\delta\theta_2 = J^2\rho(\theta_2)\delta t / \gamma C(\theta_2)$ $\delta\theta_n = J^2\rho(\theta_1)\delta t / \gamma C(\theta_n)$

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 $\delta I = (I\,R/L)\delta t$

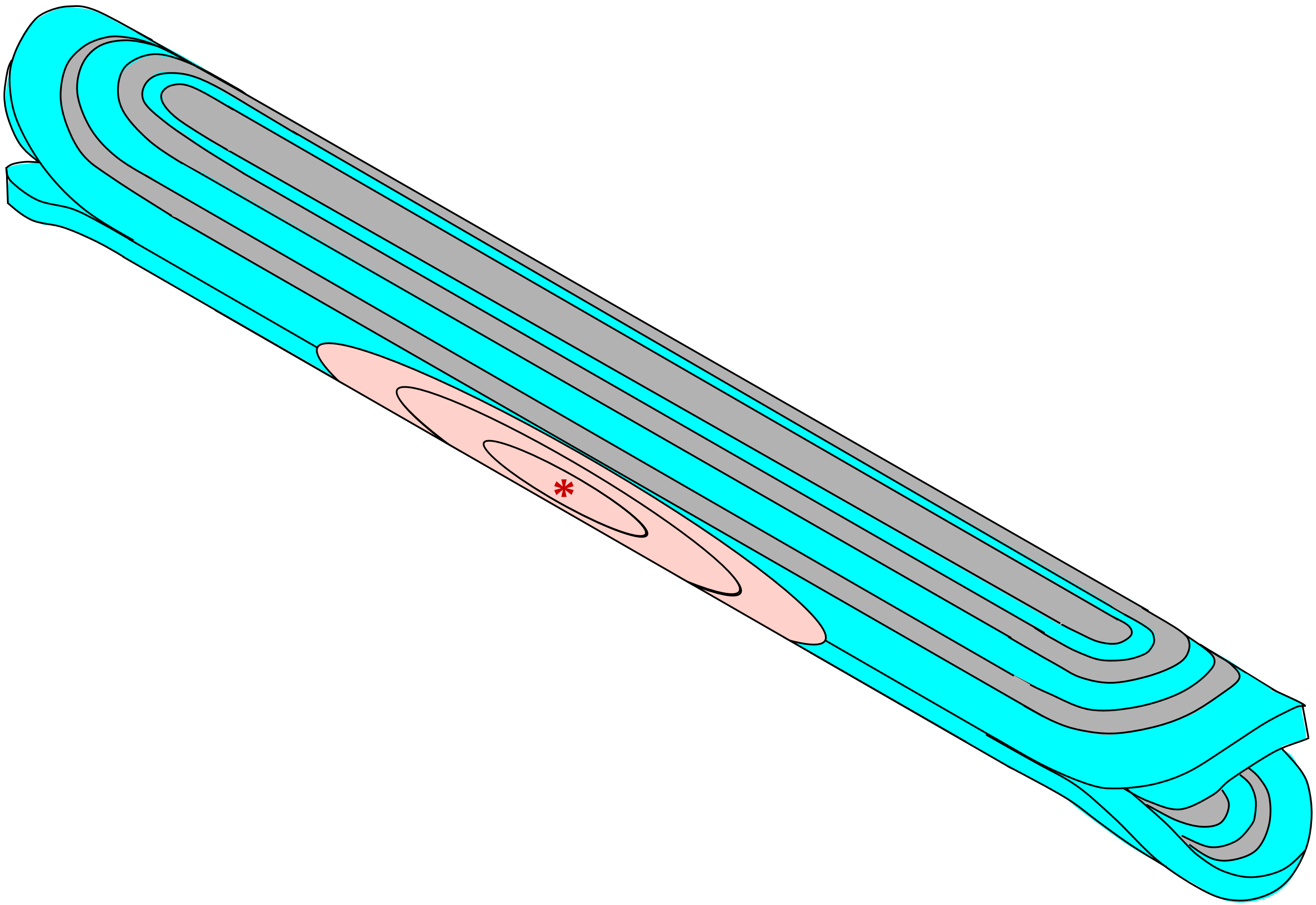
when $I \Rightarrow 0$ stop

Quench starts in the pole region

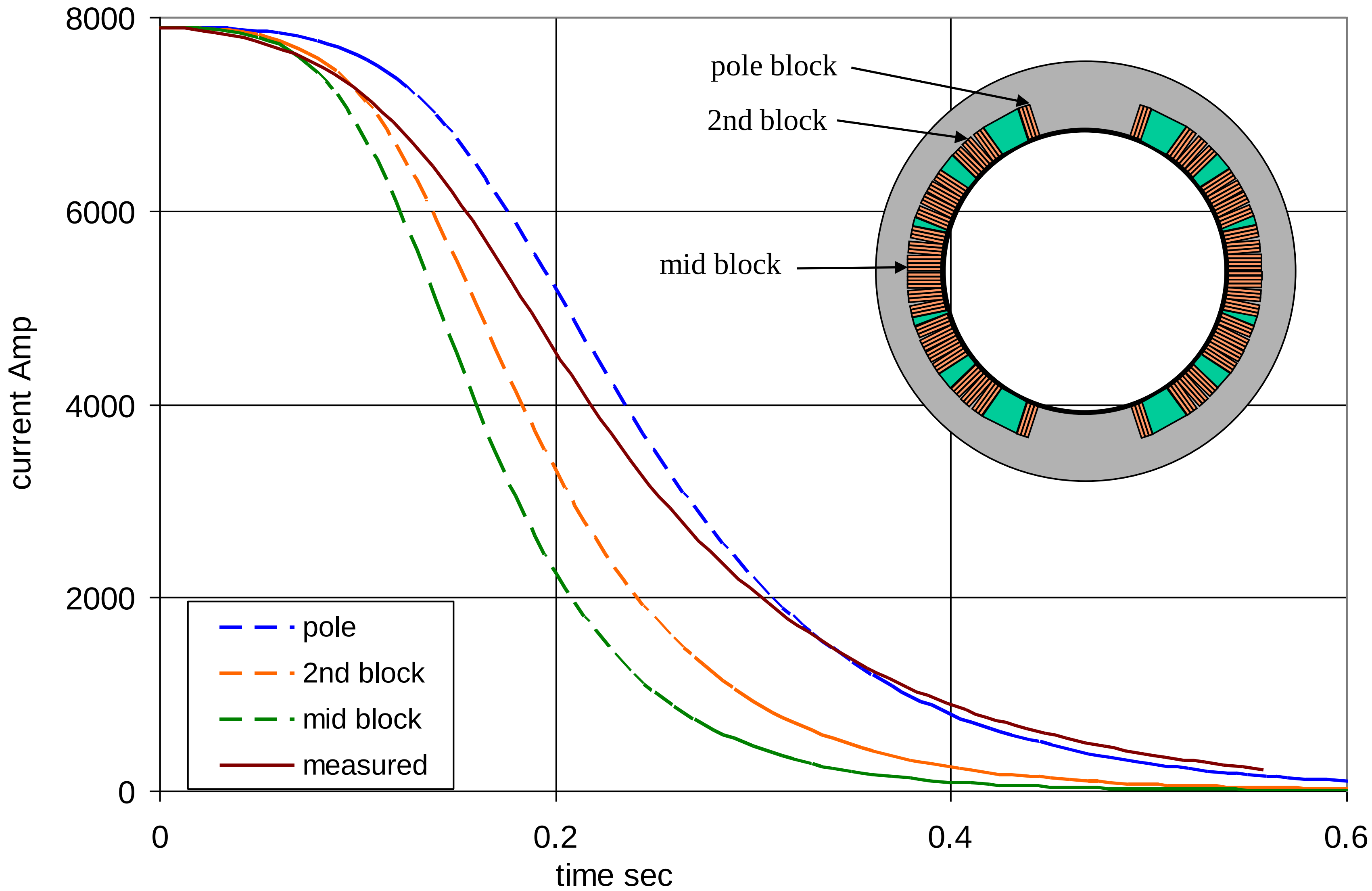


the geometry factor f_g depends on where the quench starts in relation to the coil boundaries

Quench starts in the mid plane

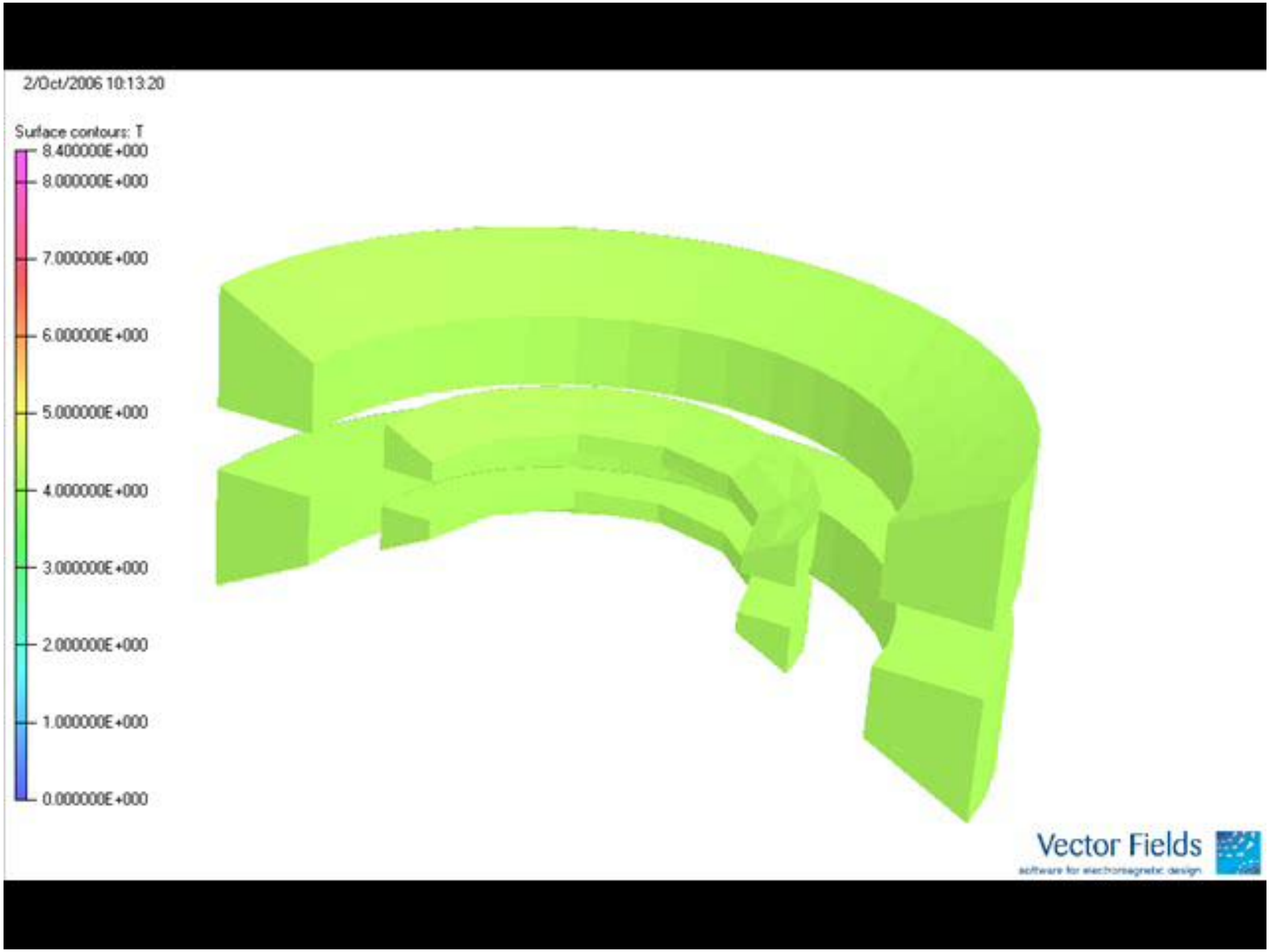


Computer simulation of quench (dipole GSI001)

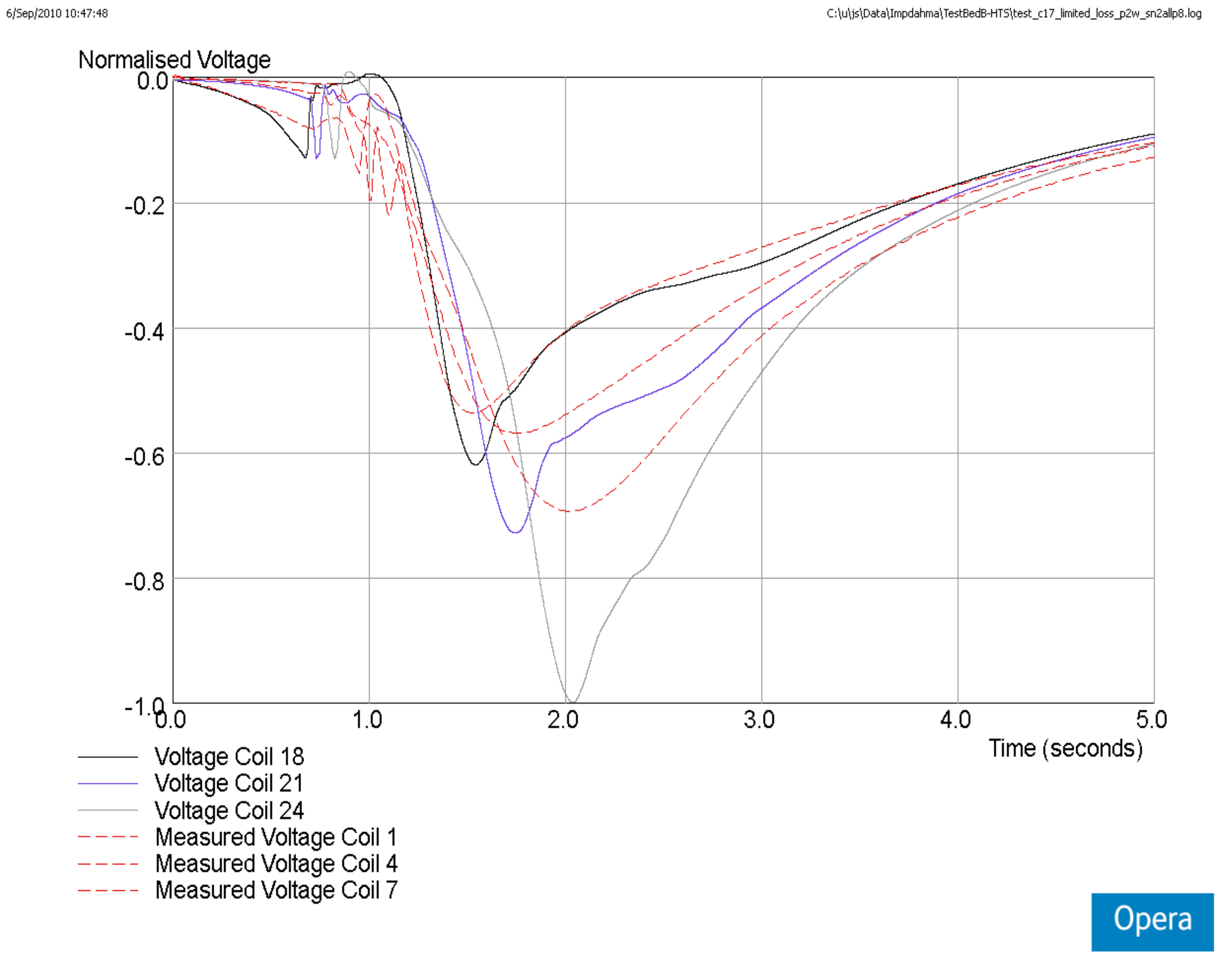


OPERA: a more accurate approach

solve the non-linear heat diffusion & power dissipation equations for the whole magnet



Compare with measurement



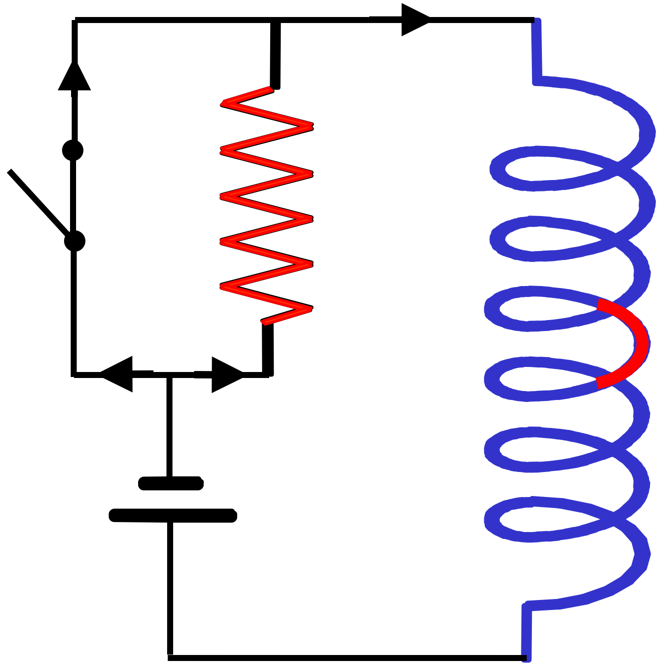
can include

- ac losses
- flux flow resistance
- cooling
- contact between coil sections

but it does need a lot of computing

Coupled transient thermal and electromagnetic finite element simulation of Quench in superconducting magnets C Aird et al Proc ICAP 2006 available at www.jacow.org

Methods of quench protection: 1) external dump resistor



- detect the quench electronically
- open an external circuit breaker
- force the current to decay with a time constant

$$I = I_o e^{-\frac{t}{\tau}} \qquad \text{where} \qquad \tau = \frac{L}{R_p}$$

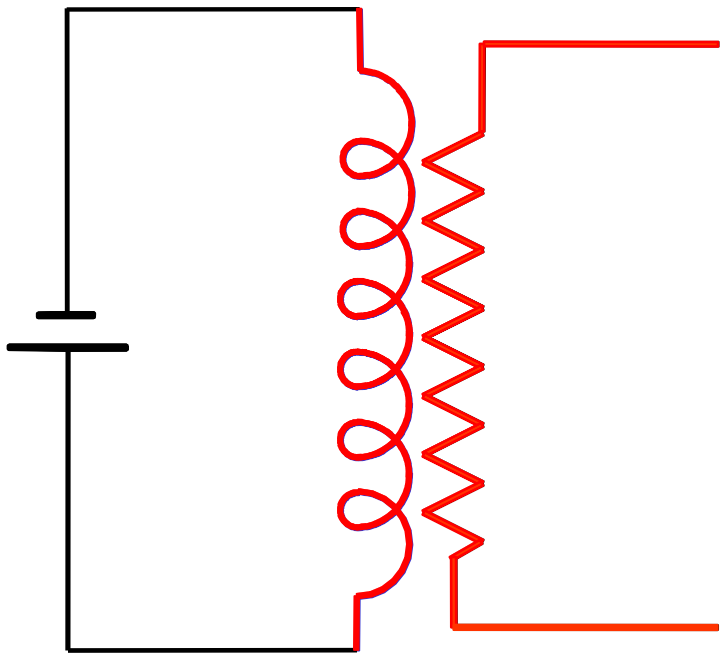
- calculate θ_{max} from

$$\int J^2 dt = J_o^2 \frac{\tau}{2} = U(\theta_m)$$

$$T_Q = \frac{\tau}{2}$$

Note: circuit breaker must be able to open at full current against a voltage $V = I.R_p$ (expensive)

Methods of quench protection: 2) quench back heater



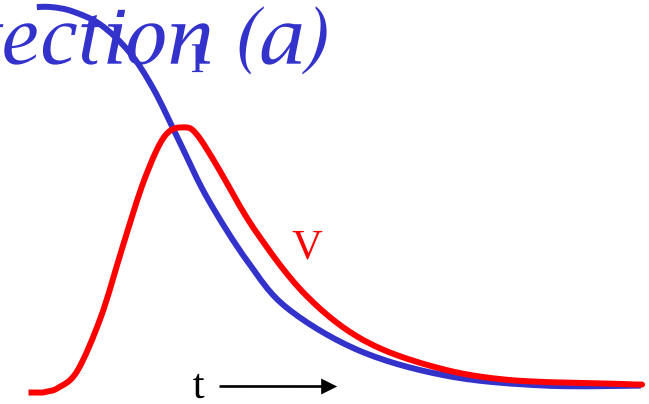
- detect the quench electronically
- power a heater in good thermal contact with the winding
- this quenches other regions of the magnet, effectively forcing the normal zone to grow more rapidly
  $\Rightarrow$ higher resistance
  $\Rightarrow$ shorter decay time
  $\Rightarrow$ lower temperature rise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

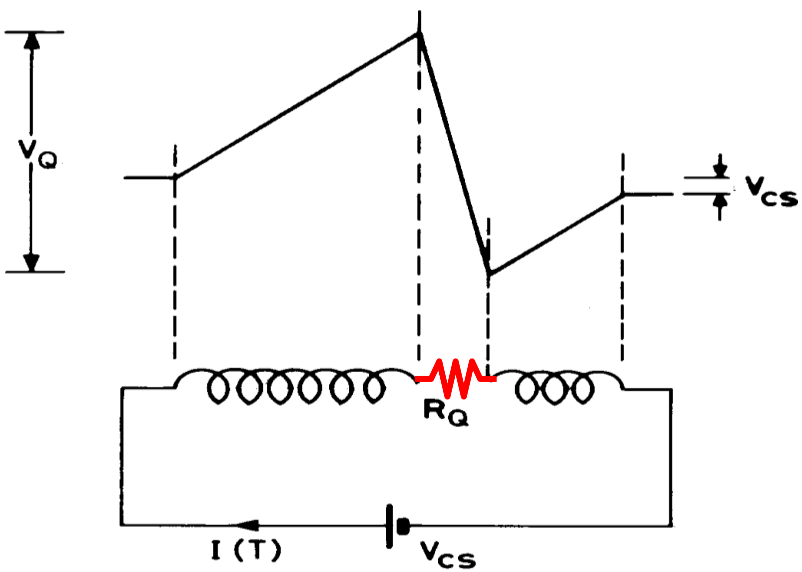
Note: usually pulse the heater by a capacitor, the high voltages involved raise a conflict between:-

- ***good themal contact***
- ***good electrical insulation***

method most commonly used in accelerator magnets ✓

Methods of quench protection: 3) quench detection (a)



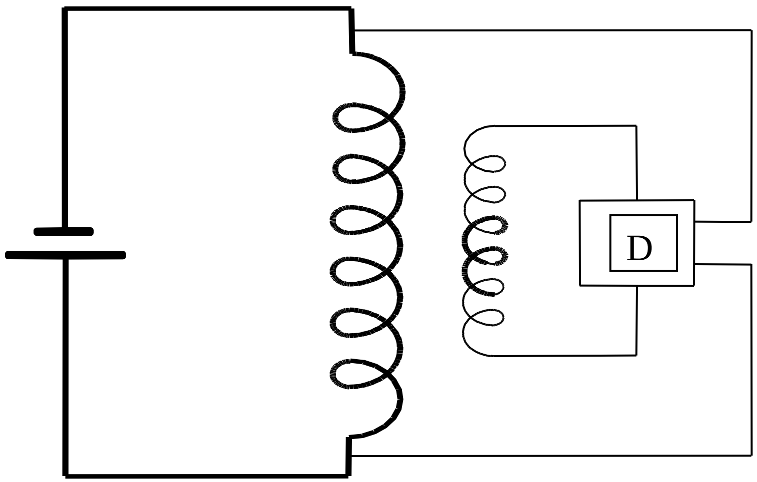


internal voltage after quench $V = IR_Q = -L\frac{dI}{dt} + V_{cs}$

- not much happens in the early stages - small $dI/dt \Rightarrow$ small V
- but important to act soon if we are to reduce T_Q significantly
- so must detect small voltage
- superconducting magnets have large inductance $\Rightarrow$ large voltages during charging
- detector must reject $V = L\,dI/dt$ and pick up $V = IR$
- detector must also withstand high voltage - **as must the insulation**

Methods of quench protection: 3) quench detection (b)

i) Mutual inductance



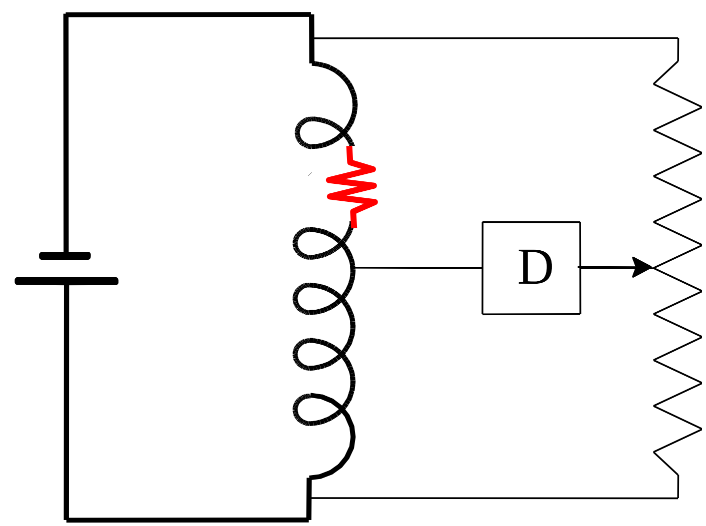
detector subtracts voltages to give

$$V = L\frac{di}{dt} + IR_Q - M\frac{di}{dt}$$

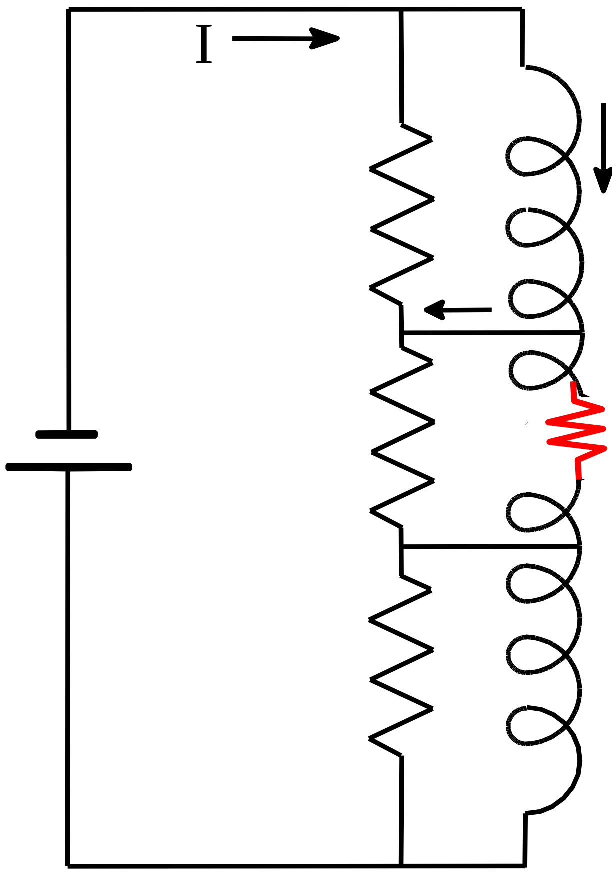
- adjust detector to effectively make $L = M$
- M can be a toroid linking the current supply bus, but must be linear - no iron!

ii) Balanced potentiometer

- adjust for balance when not quenched
- unbalance of resistive zone seen as voltage across detector D
- if you worry about symmetrical quenches connect a second detector at a different point

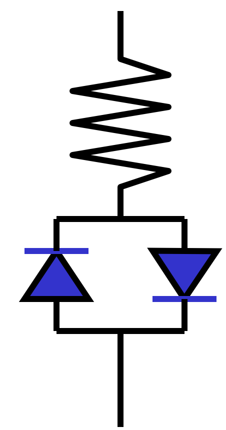


Methods of quench protection:
4) Subdivision



- resistor chain across magnet - cold in cryostat
- current from rest of magnet can by-pass the resistive section
- effective inductance of the quenched section is reduced
  - $\Rightarrow$ reduced decay time
  - $\Rightarrow$ reduced temperature rise
- current in rest of magnet increased by mutual inductance effects
  - $\Rightarrow$ quench initiation in other regions

- often use cold diodes to avoid shunting magnet when charging it
- diodes only conduct (forwards) when voltage rises to quench levels
- connect diodes 'back to back' so they can conduct (above threshold) in either direction



Quenching: concluding remarks

- magnets store large amounts of energy - during a quench this energy gets dumped in the winding
  ⇒ intense heating (J ~ fuse blowing) ⇒ possible death of magnet

- temperature rise and internal voltage can be calculated from the current decay time

- computer modelling of the quench process gives an estimate of decay time
  – but must decide where the quench starts

- if temperature rise is too much, must use a protection scheme

- active quench protection schemes use quench heaters or an external circuit breaker
  - need a quench detection circuit which rejects $L\,dI/dt$ and is **100%** reliable

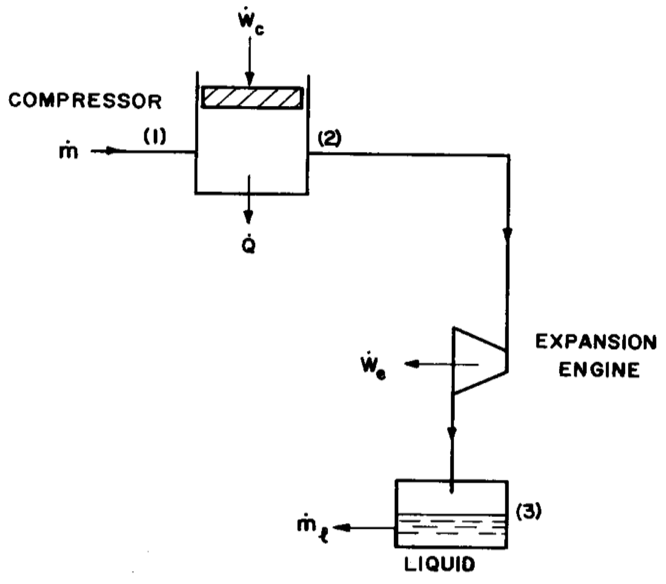
- passive quench protection schemes are less effective because V grows so slowly at first
  - but are 100% reliable

always do quench calculations before testing magnet ✓

Cryogenics: the working fluids

	boiling temperature K	critical temperature K	melting temperature K	latent heat of boiling J kg^{-1}	specific heat at const pressure J kg^{-1}K^{-1}	density kg m^{-3}
Helium	4.22	5.2		2.08×10^4	5.30×10^3	125
Hydrogen	20.3	32.9	13.8	4.45×10^5	$9.67E\times10^3$	71
Neon	27.1	44.5	24.6	8.58×10^4	1.86×10^3	1207
		the gap				
Nitrogen	77.4	126.2	63.2	1.99×10^5	2.04×10^3	806
Argon	87.3	150.7	83.8	1.61×10^5	1.12×10^3	1395
Oxygen	90.2	154.6	54.4	2.13×10^5	1.70×10^3	1141

Refrigeration

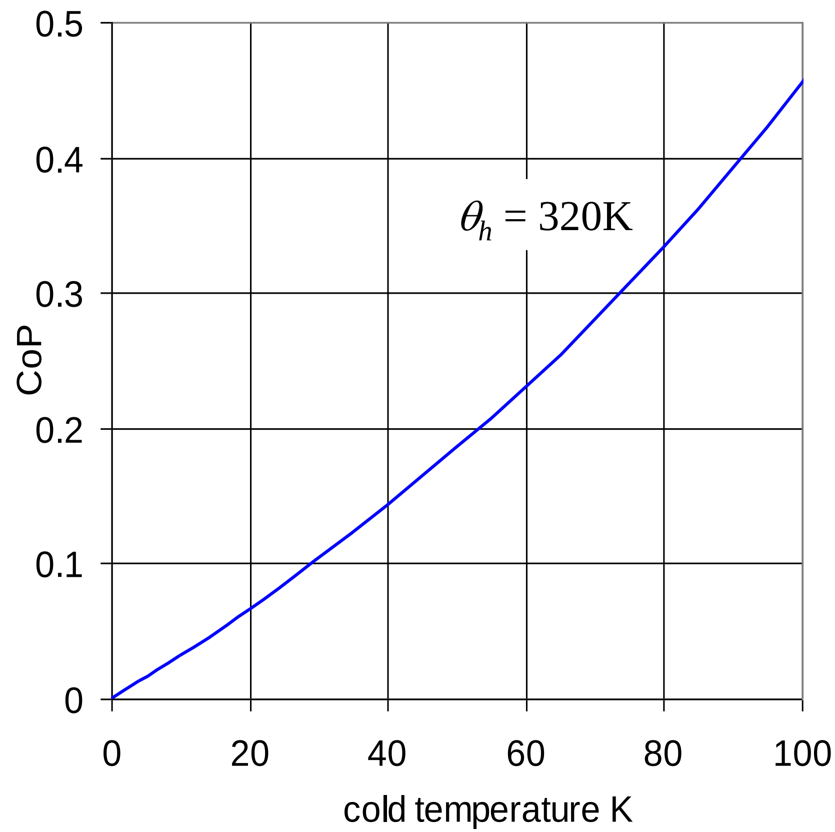


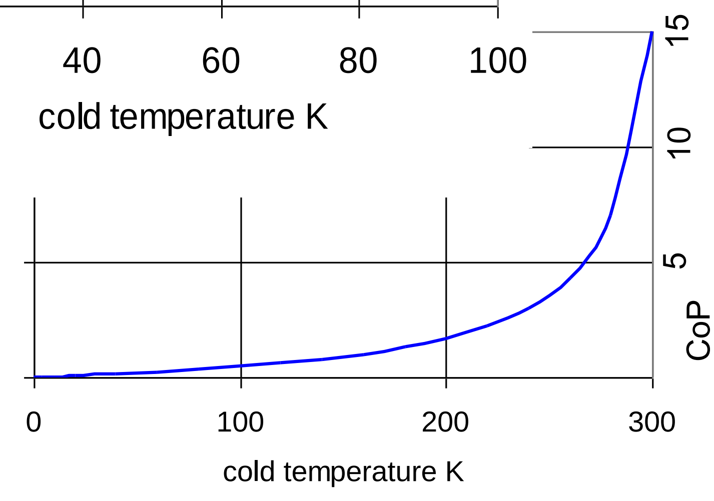
- the most basic refrigerator uses compressor power to extract heat from low temperature and reject a larger quantity of heat at room temperature
- Carnot says the **Coefficient of Performance CoP**

  = cooling power / input power

$$CoP = \frac{\theta_c}{\theta_h - \theta_c}$$

at 4.2K CoP = 1.3%





Collins helium liquefier

gas from compressor

↓

heat exchanger - cooled by upstreaming gas

heat exchanger - cooled by upstreaming gas | expansion turbine - cooled by doing work

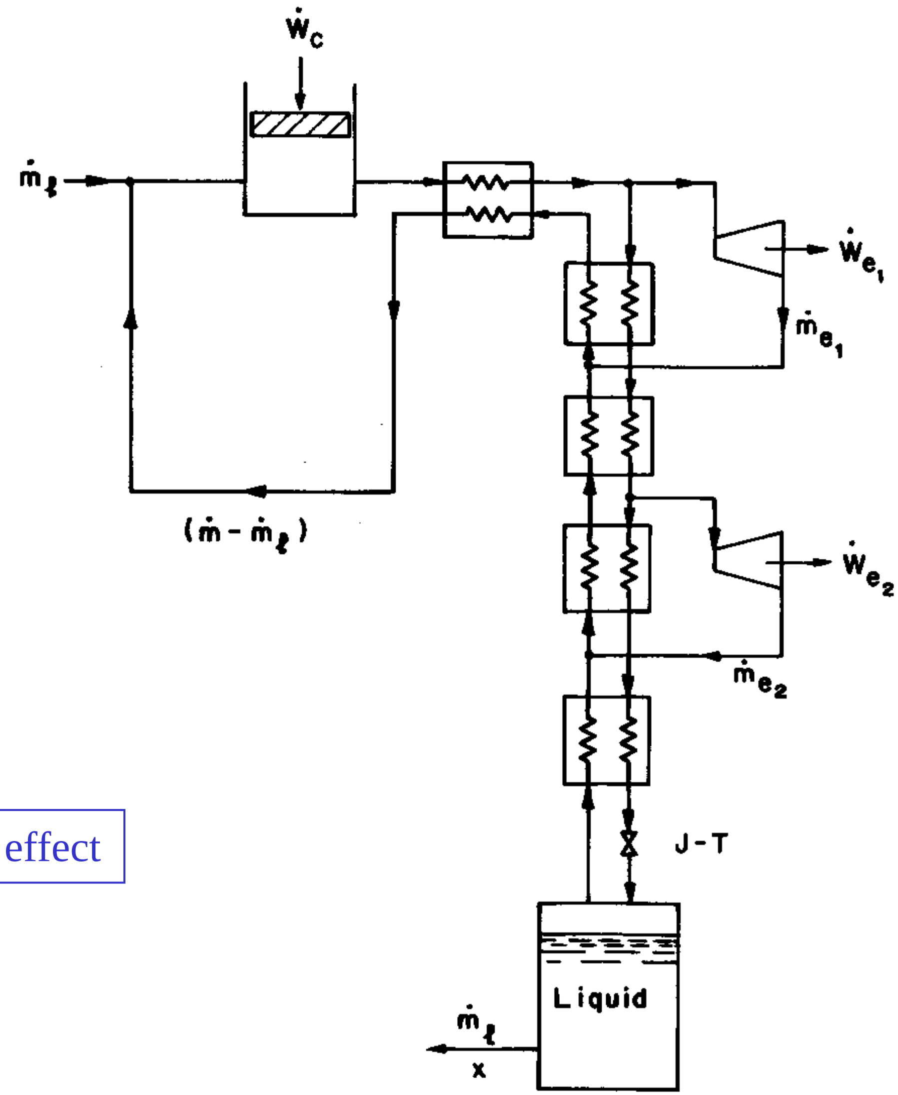
↓

repeat

↓

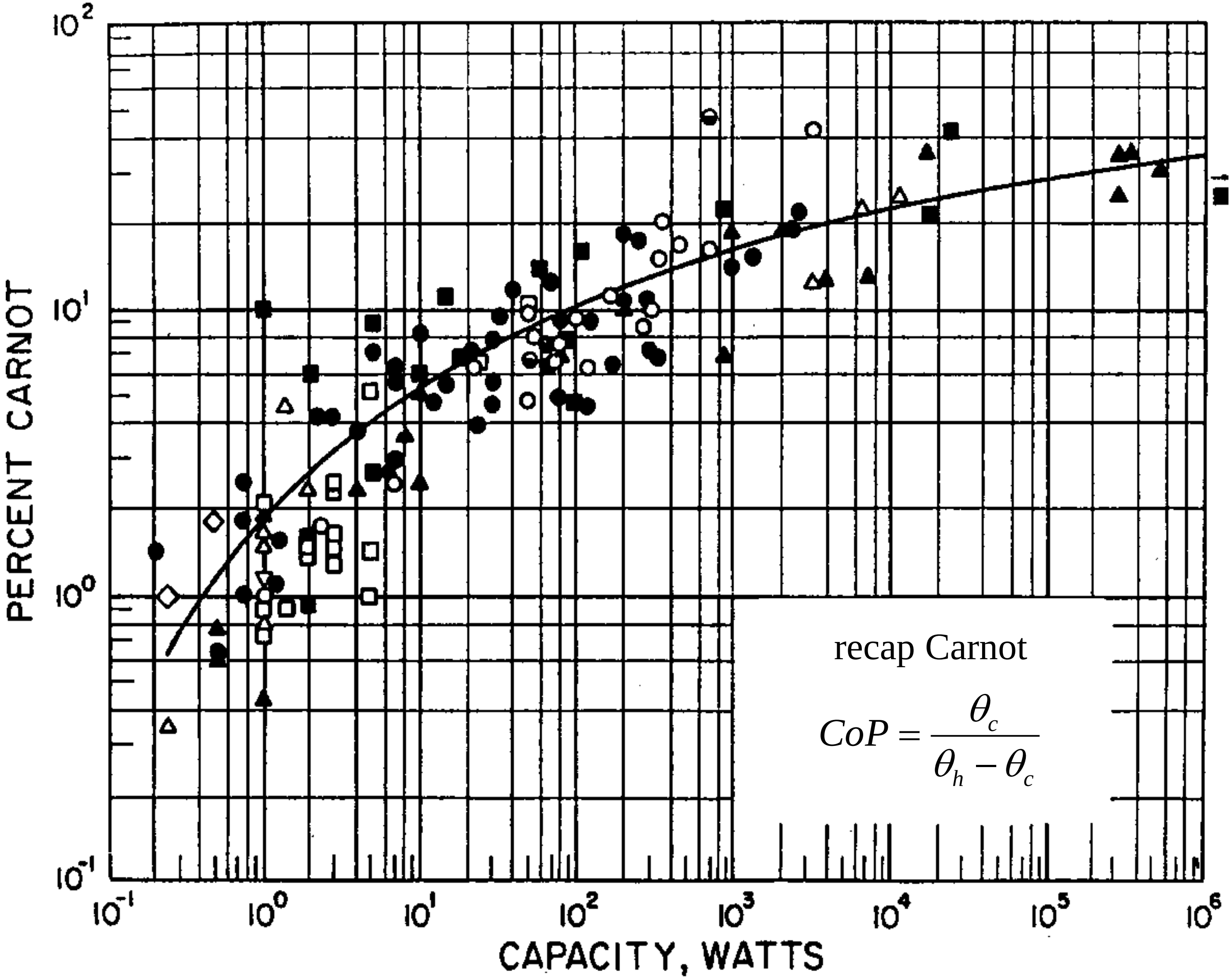
expansion valve - cooled by Joule Thompson effect

gas (returns to compressor) | liquid



from Helium Cryogenics SW Van Sciver pub Plenum 1986

Practical refrigeration efficiencies

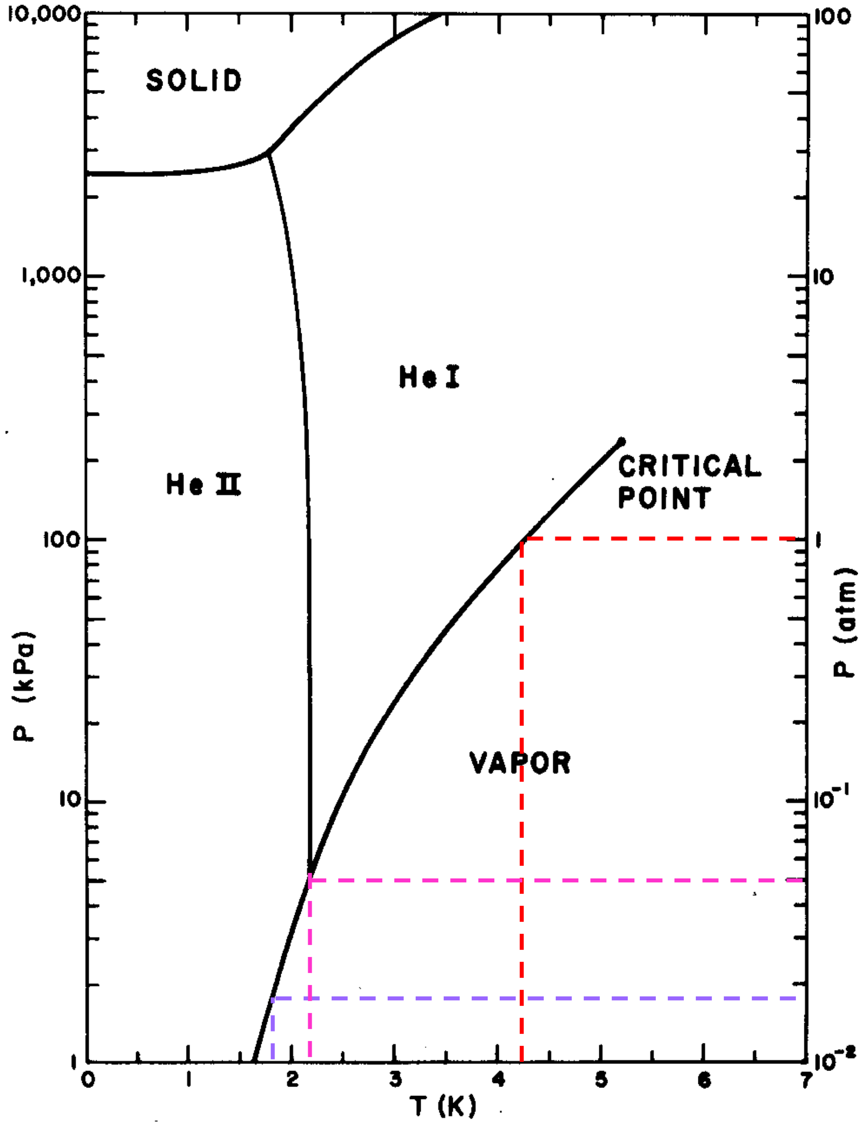


$$CoP = \frac{\theta_c}{\theta_h - \theta_c}$$

- practical efficiencies as a fraction of Carnot, plotted for operating refrigerators, as a function of cooling power.
- operating temperature does not make much difference
- but size matters!

TR Strowbridge: 'Cryogenic refrigerators, an updated survey' NBS TN655 (1974)

Properties of Helium



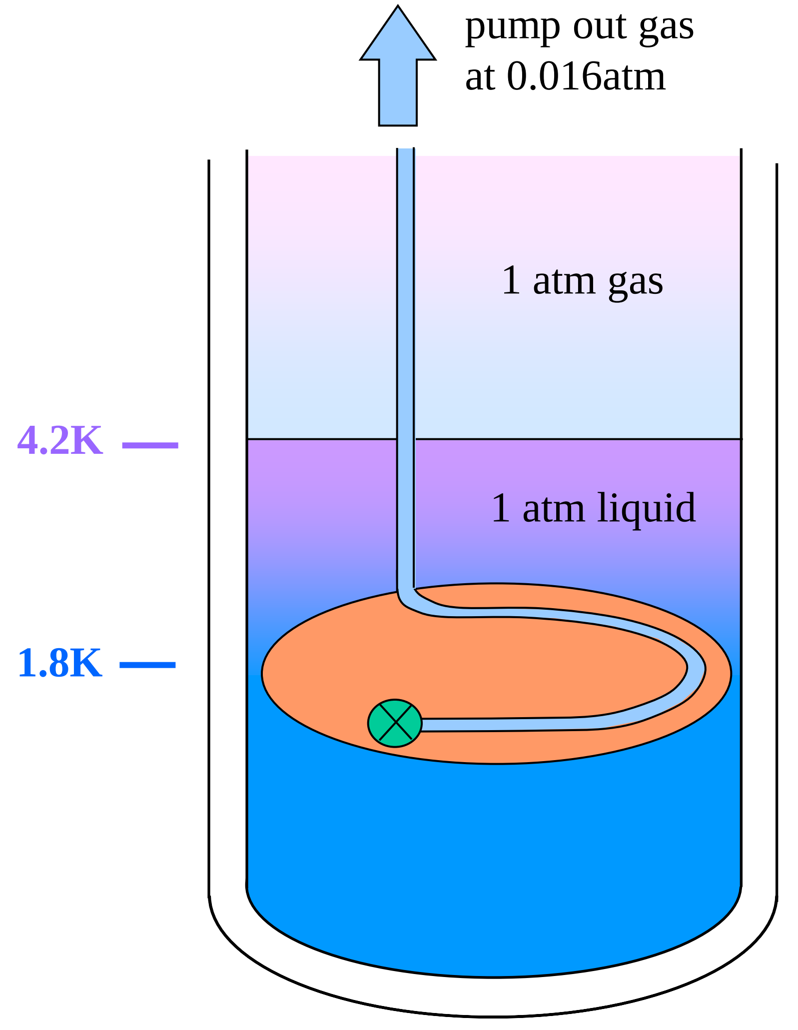
- helium has the lowest boiling point of all gases and is therefore used for cooling superconducting magnets
- below the **lamda point** a second liquid phase is formed, known as **Helium 2 or superfluid**
- it has zero viscosity and a very high thermal conductivity

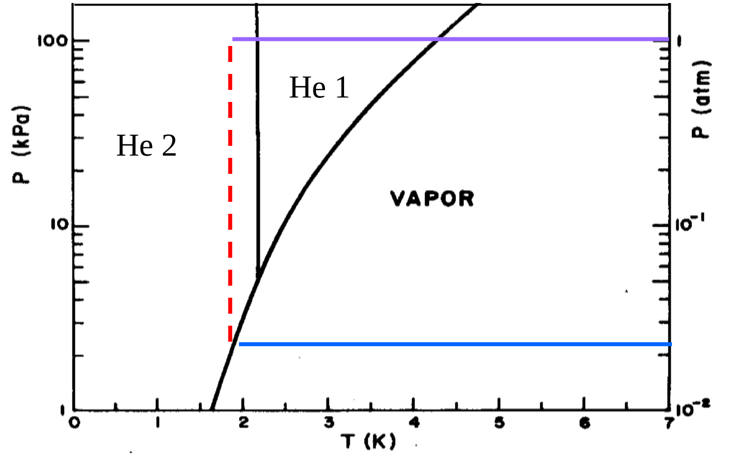
<u>Some numbers for helium</u>

boiling point at 1 atmos	4.22K
lamda point at 0.0497 atmos	2.17K
density of liquid at 4.22K	0.125 gm/cc
density of gas at 4.22K	0.0169gm/cc
density of gas at NTP	1.66×10^{-4}gm/cc
latent heat of vaporization	20.8J/gm
enthalpy change 4.2K⇒293K	1506J/gm
ratio Δenthalpy/latent heat	72

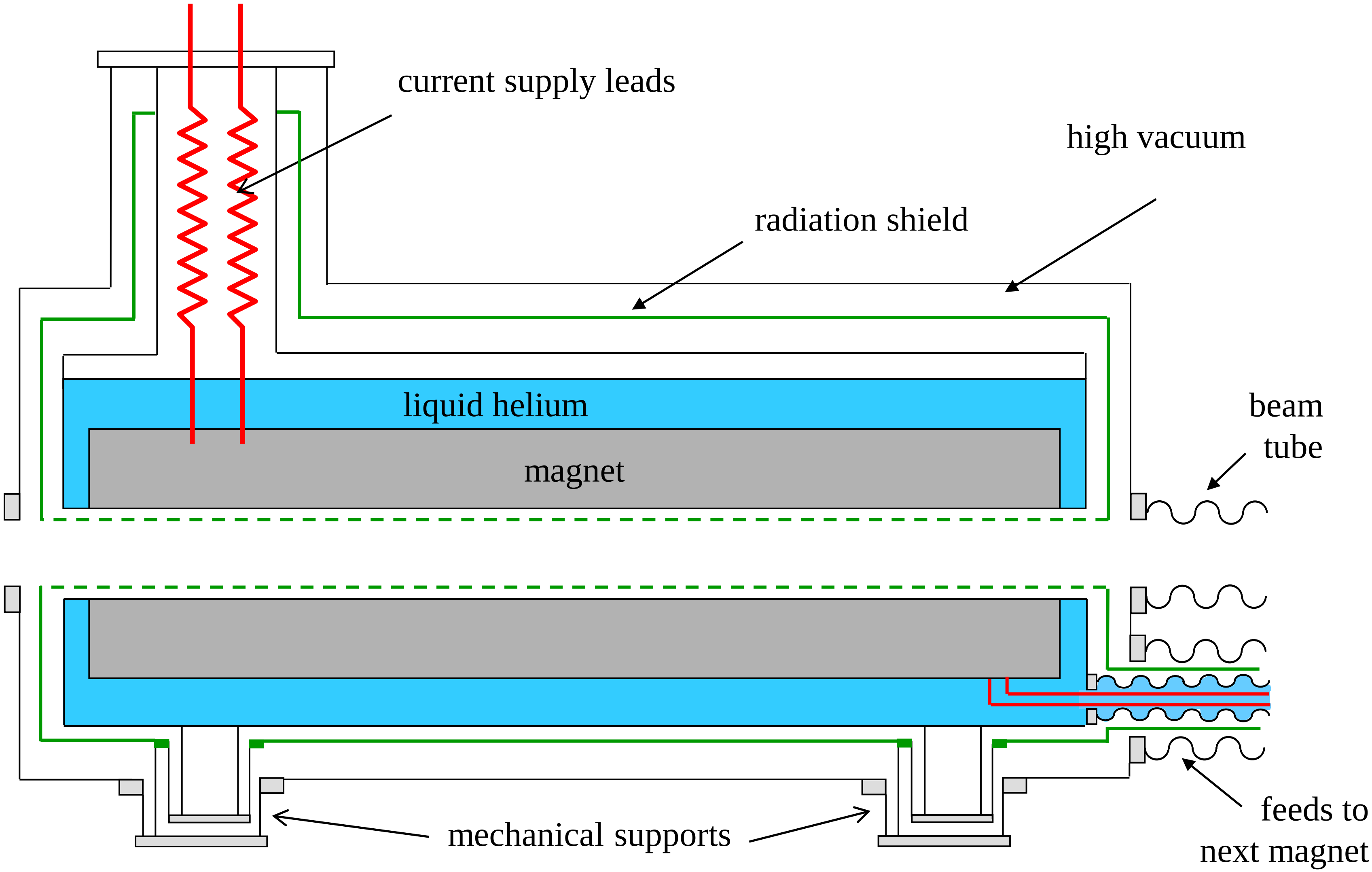
Subcooled Helium II

- HeII is an excellent coolant because of its high thermal conductivity and specific heat
- NbTi works much better at the lower temperature
- but for practical engineering, it is inconvenient operate at pressures below atmospheric
- the 'lamda plate' allows us to produce HeII in a system operating at atmospheric pressure
- used in LHC and commercial NMR magnets





Accelerator magnet cryostat essentials



Cryogenic heat leaks

1) Gas conduction

at low pressures (<10Pa or 10^{-4} torr), that is when the mean free path ~ 1m > distance between hot and cold surfaces

$$\frac{Q}{A} = \eta_g P_g \Delta\theta$$

where η_g depends on the accommodation coefficient; typical values for helium ⇒

$\theta_{cold} \sim \theta_{hot}$	η_g (W.m^{-2}.Pa.K)
4 ~ 20K	0.35
4 ~ 80K	0.21
4 ~ 300K	0.12
80 ~ 300K	0.04

not usually a significant problem, check that pressure is low enough and use a sorb

2) Solid conduction

$$\frac{Q}{A} = k(\theta)\frac{d\theta}{dx}$$

a more convenient form is

$$Q\frac{L}{A} = \int_{\theta_c}^{\theta_h} k(\theta)\, d\theta$$

look up tables of conductivity integrals

3) Radiation

heat flux $\frac{Q'}{A} = \varepsilon\sigma\theta^4$

transfer between two surfaces $\frac{Q'}{A} = \left\{\frac{\varepsilon_c\varepsilon_h}{\varepsilon_c + \varepsilon_h - \varepsilon_c\varepsilon_h}\right\}\sigma\,(\theta_h^4 - \theta_c^4)$

Stefan Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ Wm^{-2}K^{-4}

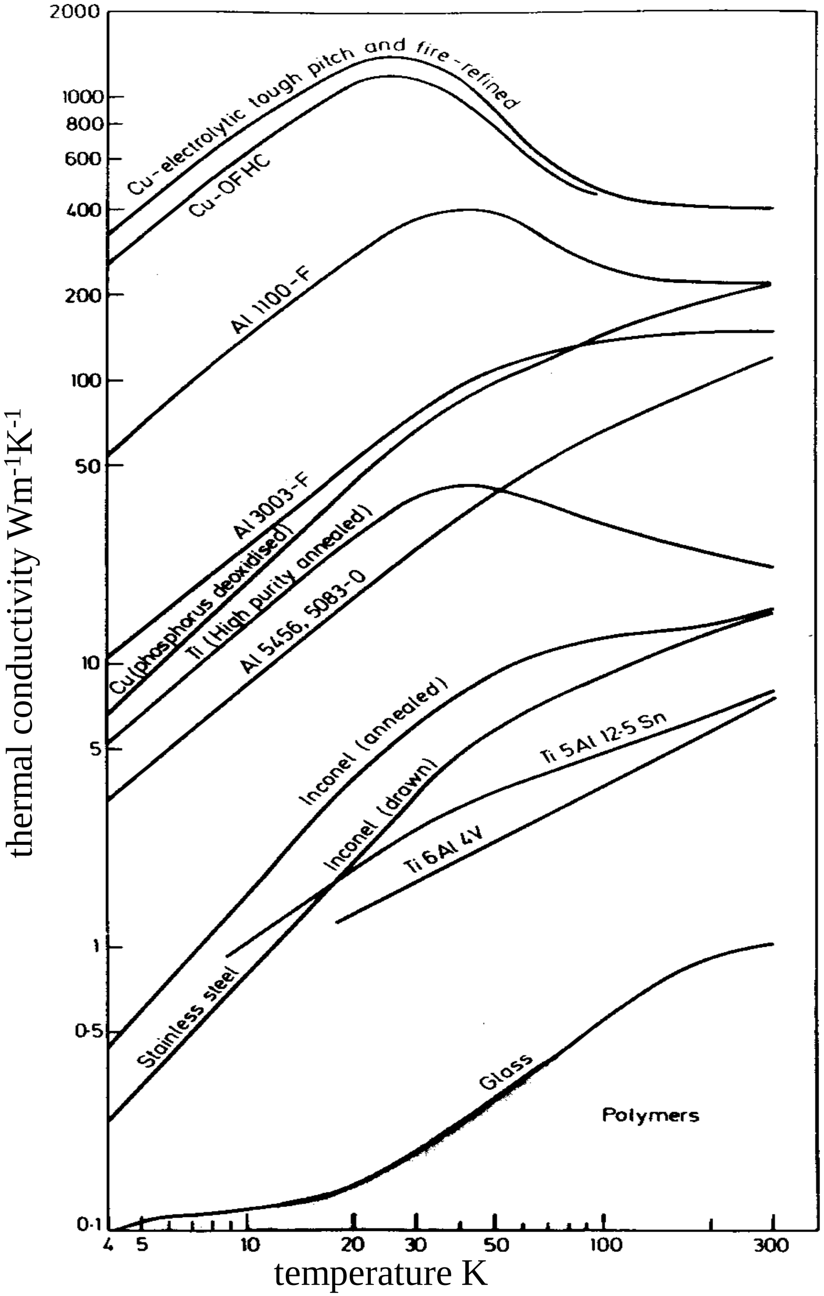
4) Current Leads

optimization problem; trade off Ohmic heating against conducted heat - lecture 5

5) Other sources

ac losses, resistive joints, particle heating etc

Thermal conductivity

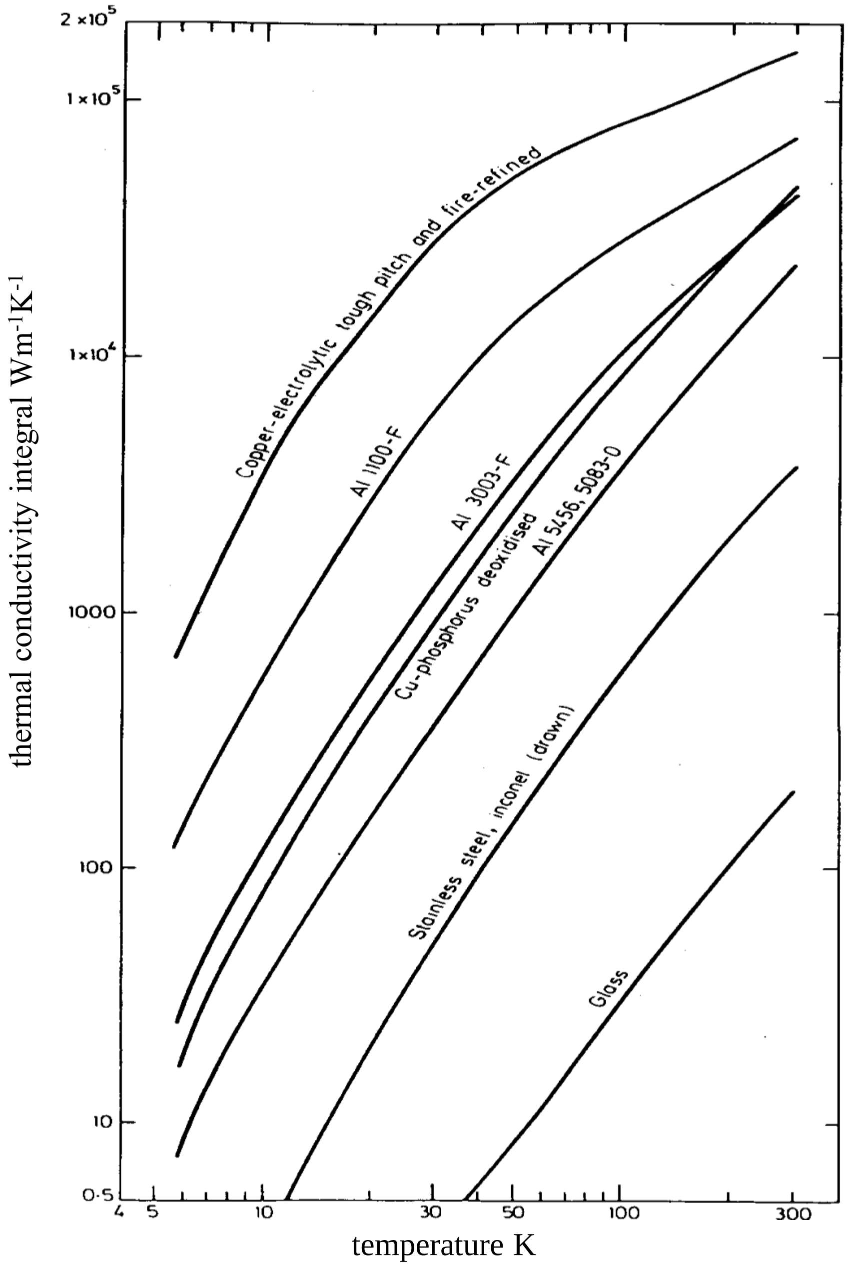


- pure metals have much higher k than alloys
- annealing increases k
- for pure metals can get a reasonable estimate from Weidemann Franz Law

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

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

Thermal conductivity integrals



recapitulate

$$Q' = \frac{A}{L}\int_{\theta_c}^{\theta_h} k(\theta)\, d\theta$$

where Q` is heat flow A is area of cross section and L is length

read the difference between θ_c and θ_h from the graph

selected values

temperature interval K	4 to 1	77 to 4	300 to 77
material			
copper	600	71540	91430
brass	5.1	1898	18063
stainless steel	0.6	329	2743
pyrex	0.18	18.3	182.9
nylon	0.018	12.4	69.1

Radiation and emissivities

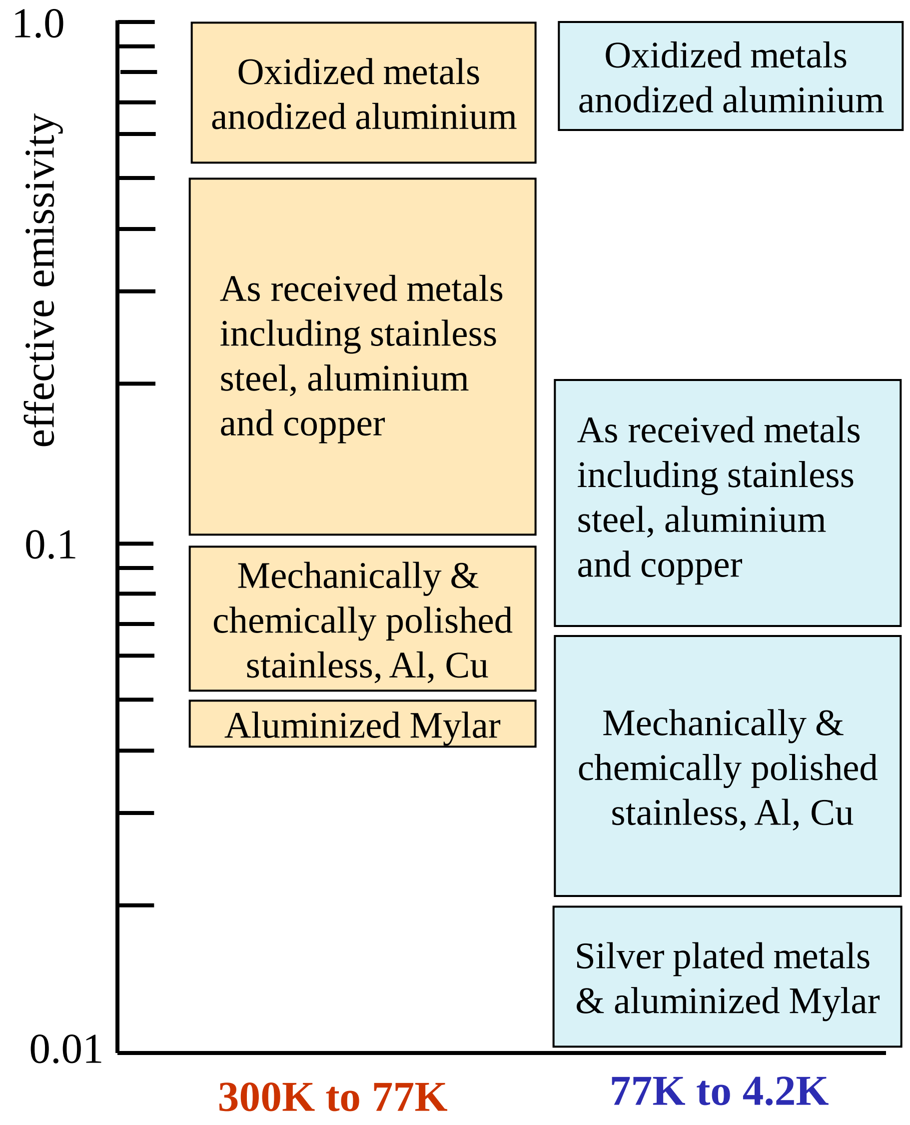
often work in terms of an effective emissivitiy between two temperatures ε_r

$$\frac{Q}{A} = \left\{ \frac{\varepsilon_c \varepsilon_h}{\varepsilon_c + \varepsilon_h - \varepsilon_c \varepsilon_h} \right\} \sigma \left(\theta_h^4 - \theta_c^4 \right)$$

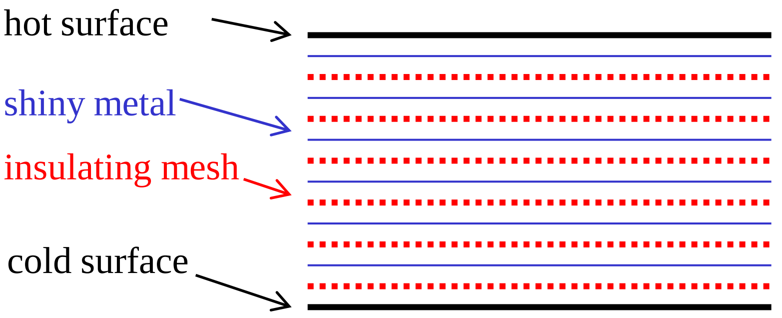
$$= \varepsilon_r \sigma \left(\theta_h^4 - \theta_c^4 \right)$$

Stefan Boltzmann constant

$\sigma = 5.67 \times 10^{-8}\ \mathrm{Wm^{-2}K^{-4}}$



Superinsulation



Because radiated power goes as θ^4 you can reduce it by subdividing the gap between hot and cold surface using alternating layers of shiny metal foil or aluminized Mylar and insulating mesh.

Note - the structure must be open for pumping.

- care needed in making corners of superinsulation
- aluminized Mylar is only useful above ~80K, low temperature radiation passes through the aluminium coating

The greatest radiation heat leak is from room temperature to the radiation shield. For this reason, superinsulation is most often used on the radiation shield

Some typical values of effective emissivity $\boldsymbol{\varepsilon_r}$ for superinsulation

$$\frac{Q}{A} = \varepsilon_r \sigma \left(\theta_h^4 - \theta_c^4\right)$$

1 layer of aluminized Mylar	0.028
5 layers of crinkled aluminized Mylar	0.017
10 layers of crinkled Mylar interleaved with glass fibre mesh	0.0072
5 layers of aluminium foil interleaved with glass fibre mesh	0.0094
10 layers of aluminium foil interleaved with glass fibre mesh	0.017
20 layers of NRC2	0.005
200 layers of NRC2	0.004
2 x 24 layer Jehier* blankets	0.002

* Jehier SA BP 29-49120 Chemille France

Cryogenics: concluding remarks

- producing and maintaining low temperatures depends on liquefied gases
  - helium for the lowest temperature

- refrigeration depends on alternately compressing and expanding the gas
  - heat exchange can extend the temperature reach

- lots of power needed to produce low temperature cooling ~ 1000× for liquid helium

- for an efficient cryostat must minimize heat inleak - conduction, convection and radiation