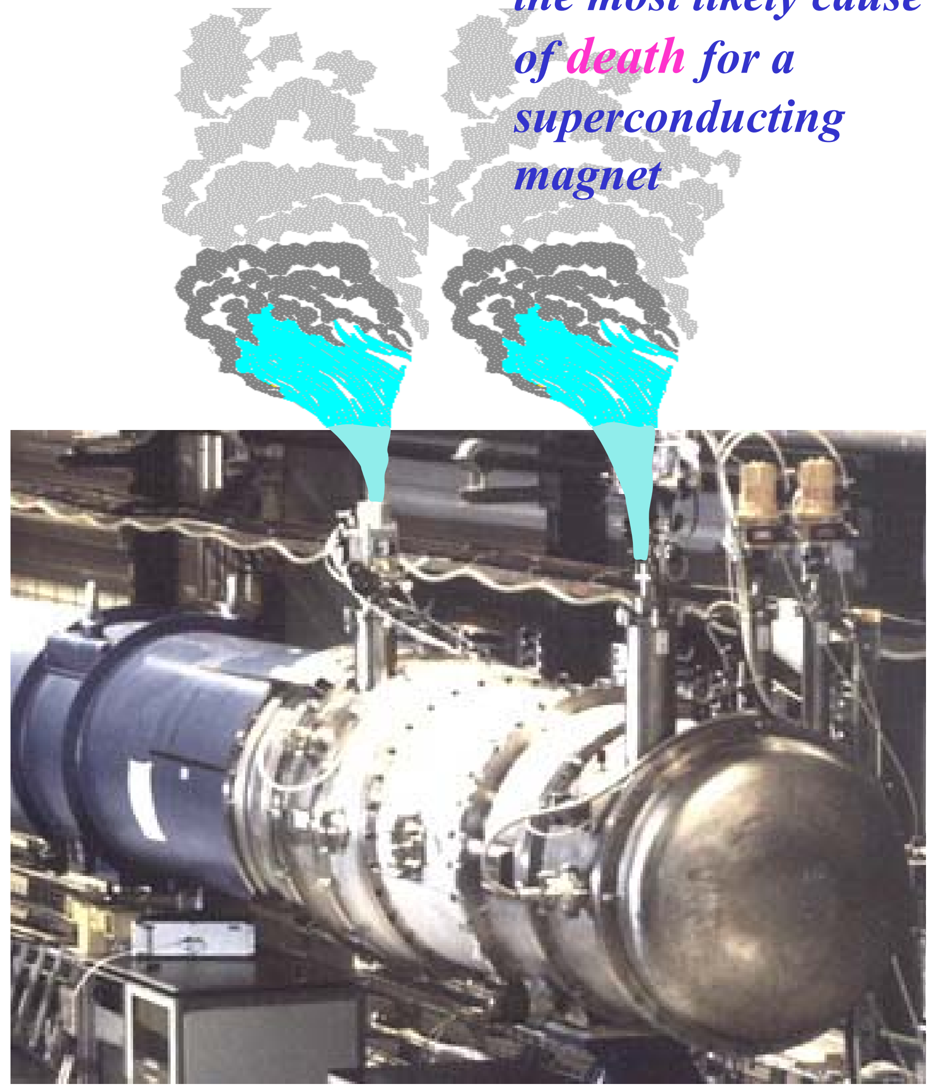
Lecture 4: Quenching

the most likely cause of death for a superconducting magnet



Plan

- the quench process
- decay times and temperature rise
- propagation of the resistive zone
- resistance growth and decay times
  - analytic model
  - computational
- quench protection schemes
- case study: LHC protection

Magnetic stored energy

Magnetic energy density $E = \dfrac{B^2}{2\mu_o}$ 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) $\boldsymbol{E = ½ LI^2}$ $\boldsymbol{L} = 0.12$H $\boldsymbol{I} = 11.5$kA E = 7.8 x 10^6 Joules

the magnet weighs 26 tonnes

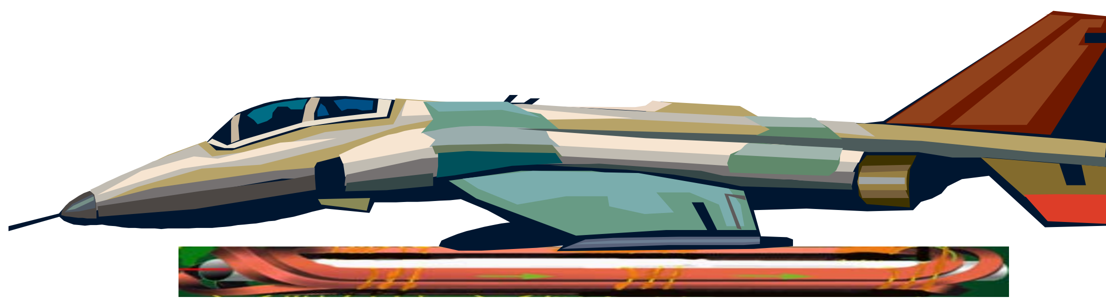
so the magnetic stored energy is equivalent to the kinetic energy of:-

26 tonnes travelling at 88km/hr

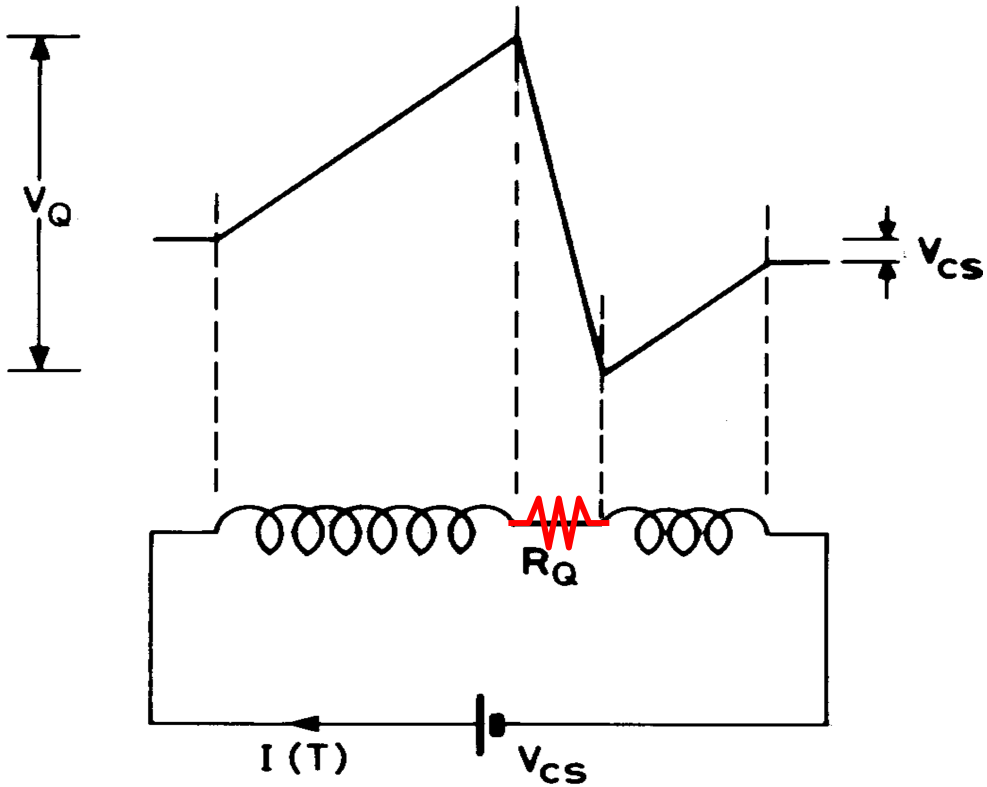
coils weigh 830 kg

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

The temperature rise function U(θ)

or the 'fuse blowing' calculation
(adiabatic approximation)

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

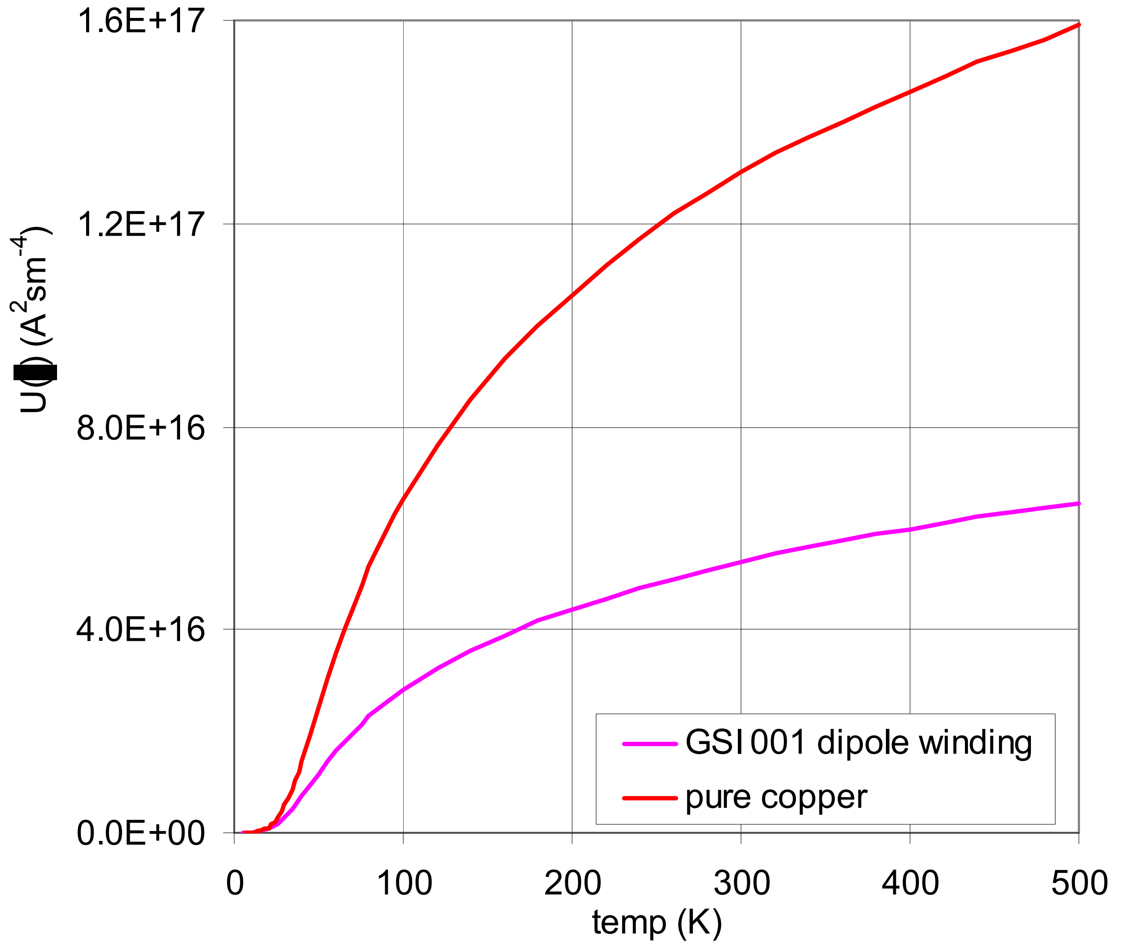
J(T) = overall current density,
T = time,
ρ(θ) = overall resistivity,
γ = density, *θ* = temperature,
C(θ) = specific heat,
T_Q = quench decay time.

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

$$= U(\theta_m)$$

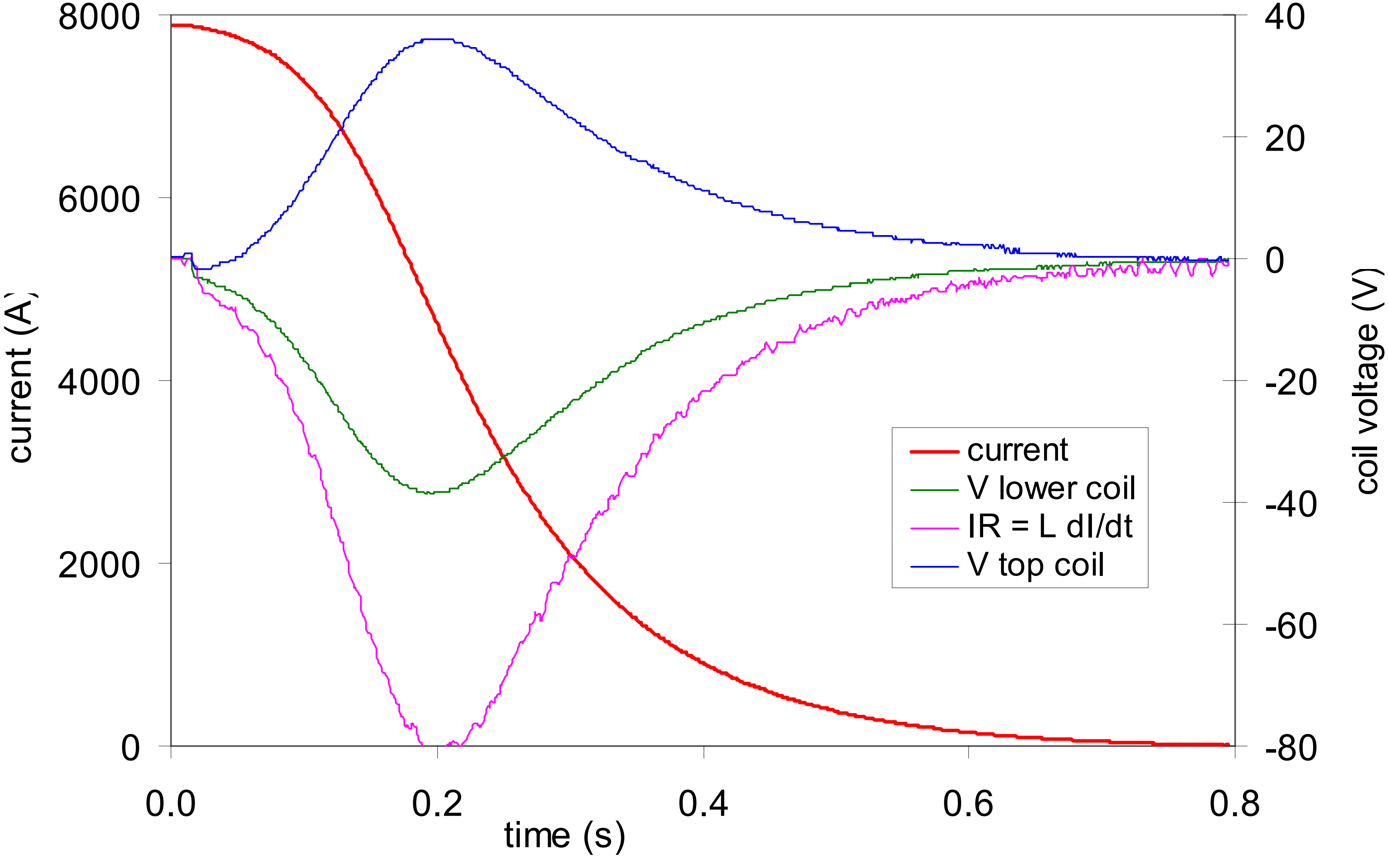
$$J_o^2 T_Q = U(\theta_m)$$

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



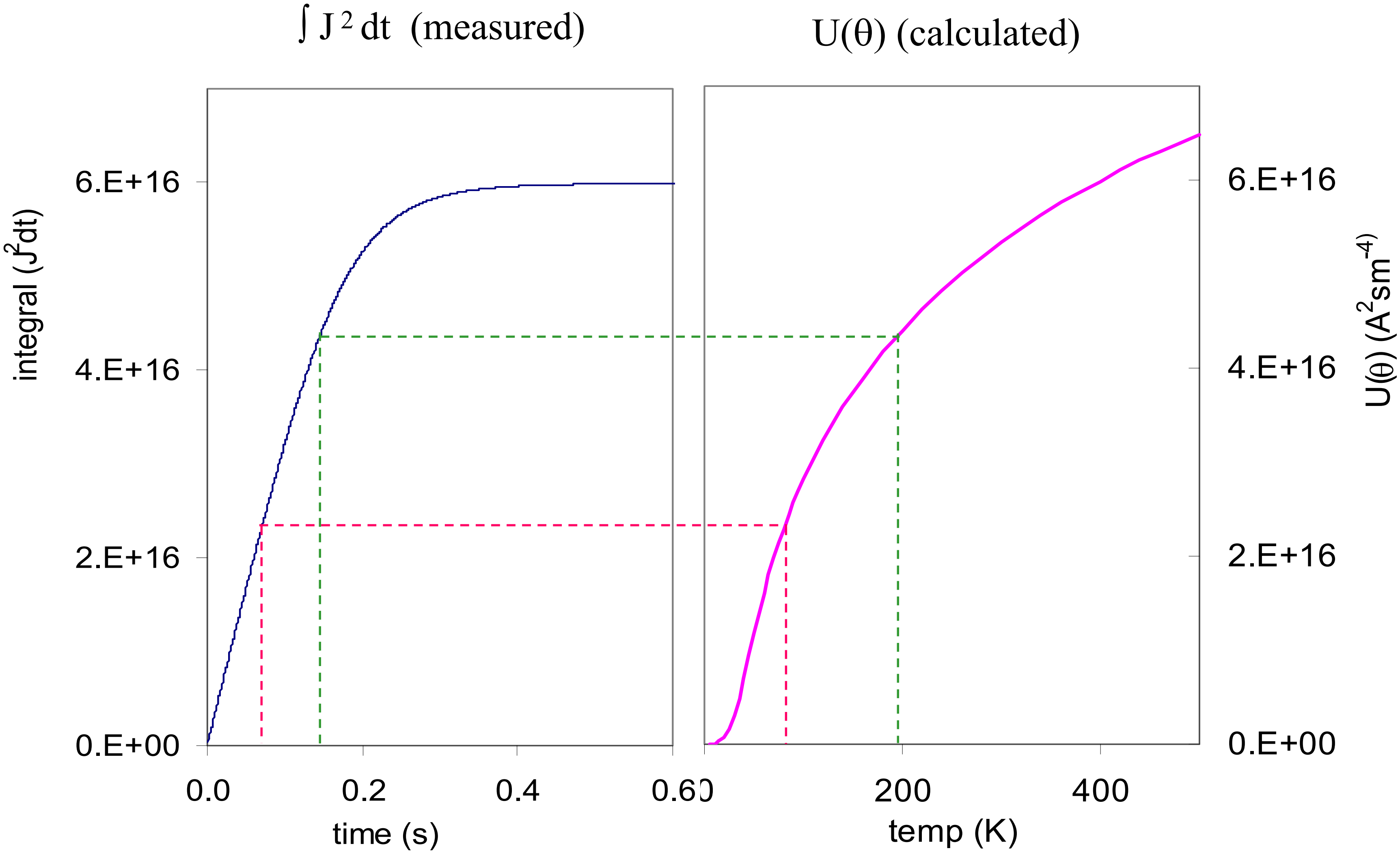
- NB always use **overall** current density

Measured current decay after a quench

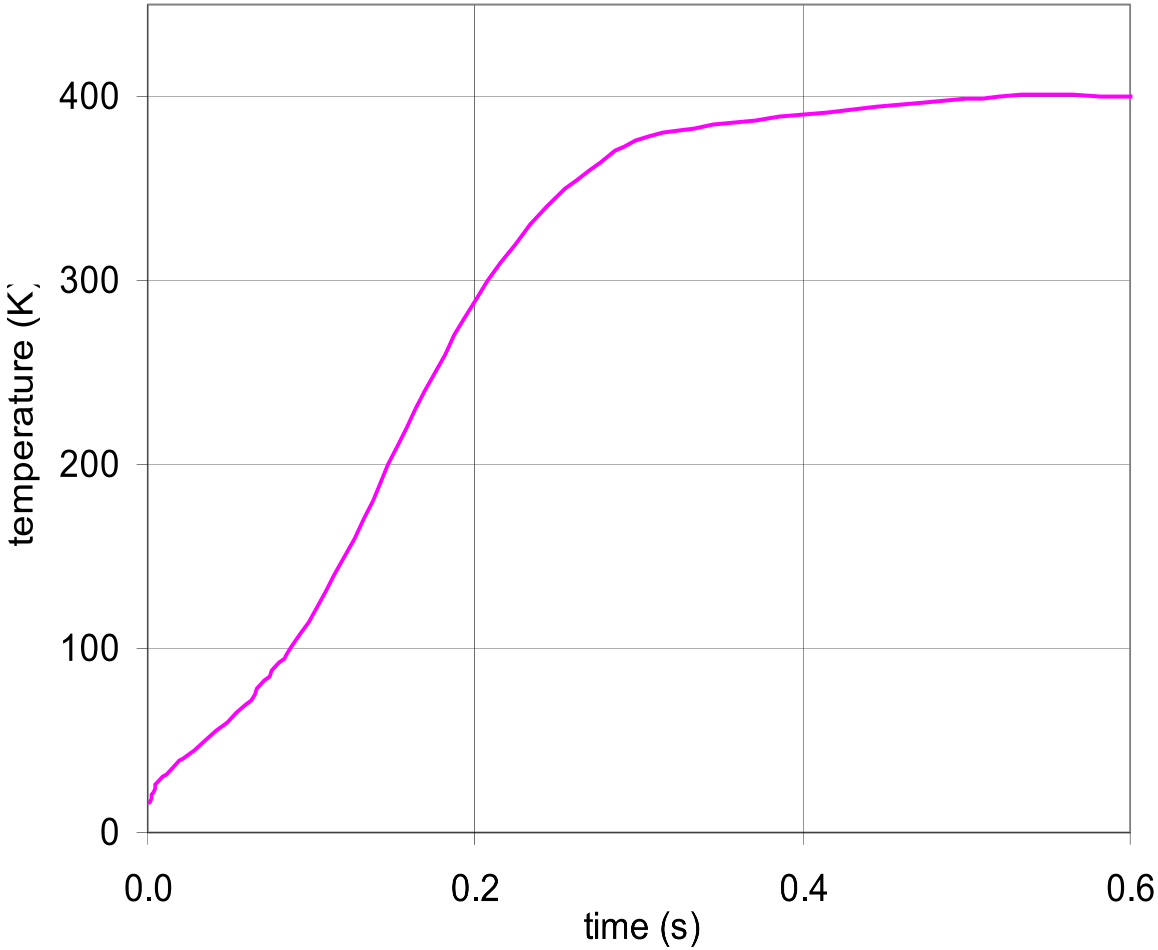


Dipole GSI001 measured at Brookhaven National Laboratory

Calculating the temperature rise from the current decay curve

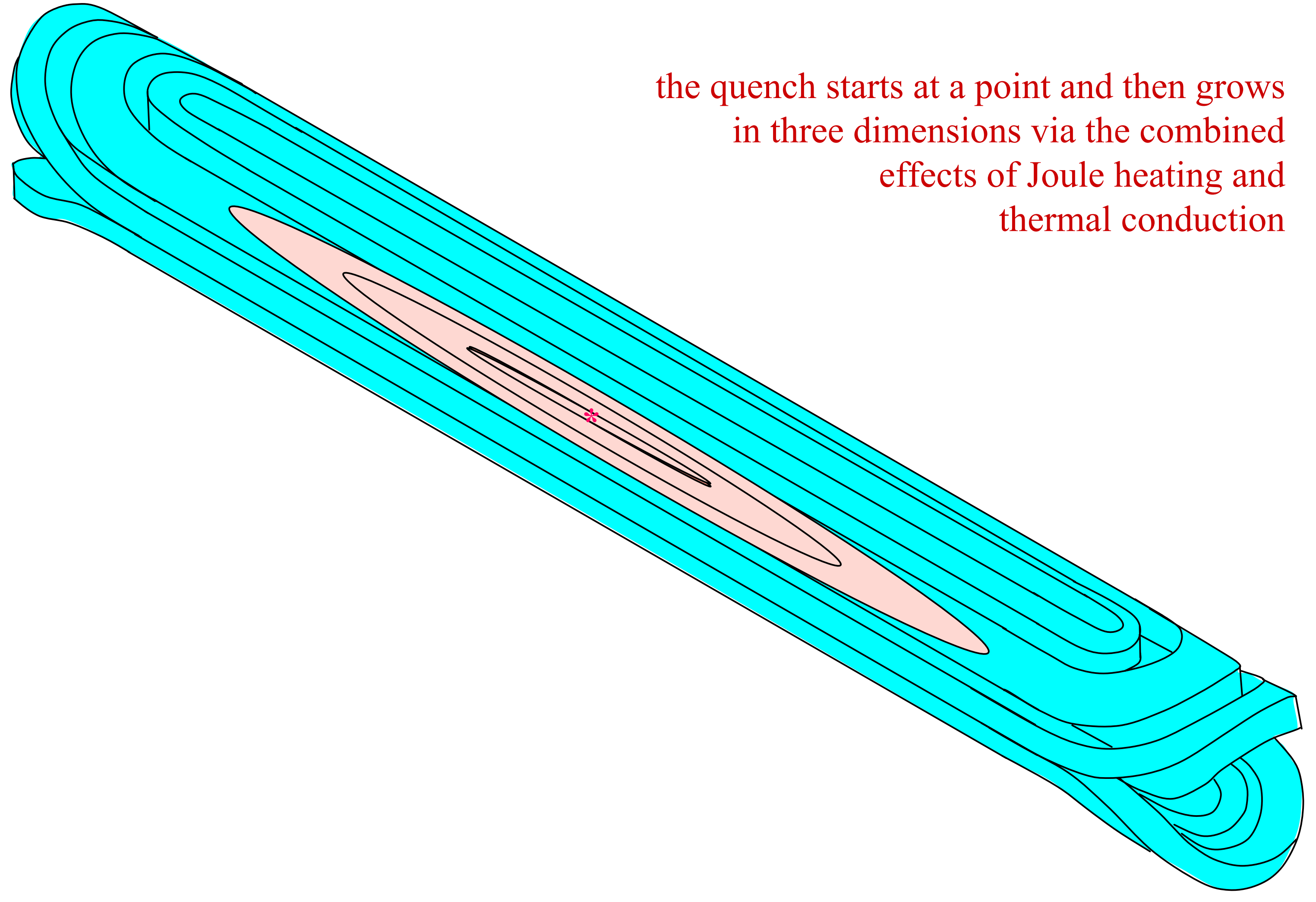


Calculated temperature



- 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

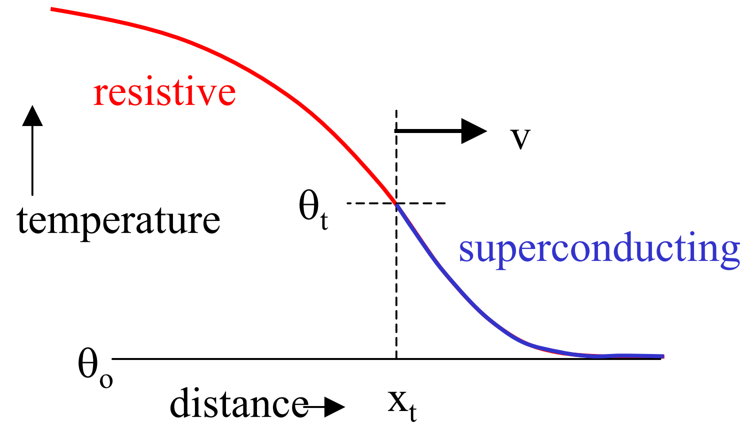
Growth of the resistive zone



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

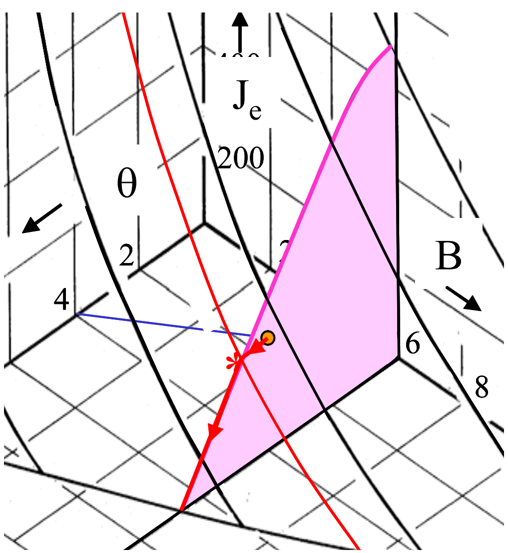
when $h = 0$, the solution for θ which gives a continuous join between left and right sides at θ_t gives the ***adiabatic propagation velocity***

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

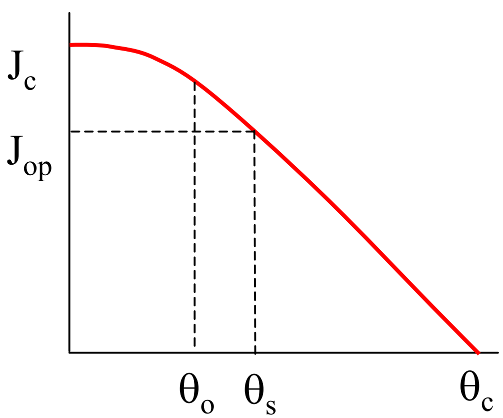
recap Wiedemann Franz Law $\rho(\theta).k(\theta) = L_o\theta$

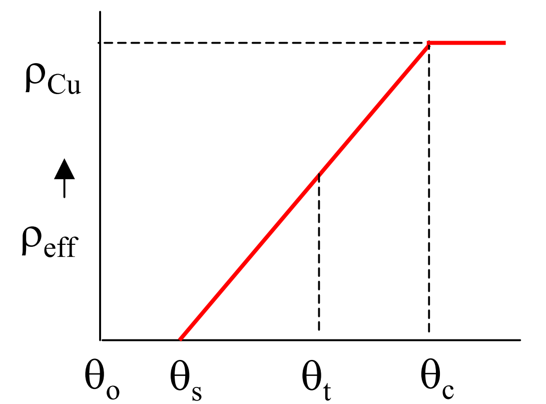
what to say about θ_t ?

- 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 $\theta_t = (\theta_s + \theta_c)/2$





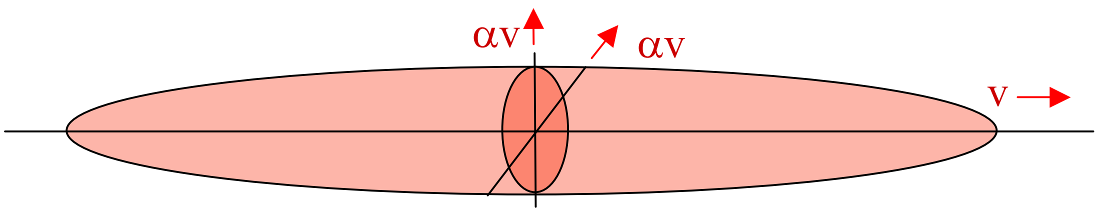
Quench propagation velocity 3

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

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 (approx) 1

This is an approximate analytic theory based on some simplifying assumptions:

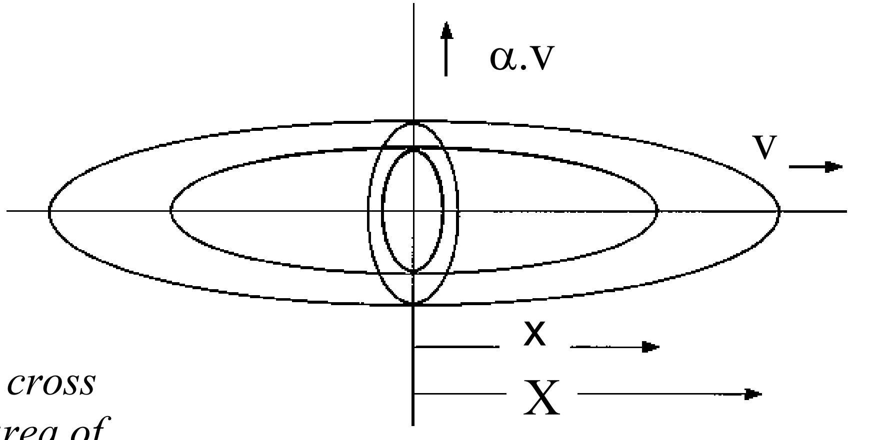
a) current remains constant at it starting value until all the inductive stored energy energy of the magnet has been dissipated, then it falls to zero

b) temperature rises given by a parabolic approximation to $U(\theta)$, define U_1 at θ_1

$$\int J^2 dt = J_o^2 T_d = U(\theta(\approx U_1 \left\{ \frac{\theta}{\theta_1} \right\}^{\frac{1}{2}}$$

c) resistivity increases linearly with temperature

after time T the resistive zone has grown to an ellipse of semi axis $x = vt$ and ellipticity α



resistance of the zone

$$R = \int_O^X \frac{4\pi x^2 \alpha^2 \rho(\theta)}{A^2} dx$$

where A = cross sectional area of a conductor

substitute

$$\rho(\theta) = \rho_1 \left(\frac{\theta}{\theta_1} \right) = \rho_1 \left(\frac{U}{U_1} \right)^2 = \rho_1 \frac{J_o^4 \tau^2}{U_1^2}$$

where τ is the local elapsed time since normality:

at the centre $\tau = T$, at the edge $\tau = 0$ and in between $\tau = T - x / v$

Resistance growth and current decay (approx) 2

$$R = \int_O^X \frac{4\pi x^2 \alpha^2 \rho(\theta)}{A^2} dx = \int_O^X \frac{4\pi x^2 \alpha^2}{A^2} \rho_1 \frac{J_o^2 \tau^2}{U_1^2} dx$$

recap τ is the elapsed local time since normality:

$$R = \int_0^{vT} \frac{4\pi x^2 \alpha^2 \rho_1 J_o^4 \left(T - x/v\right)^2}{A^2 U_1^2} dx = \frac{4\pi \rho_1 \alpha^2 J_o^4 v^3 T^5}{30 A^2 U_1^2}$$

where: v = longitudinal velocity, α = ratio longitudinal/transverse velocity, ρ_1 = resistivity at θ_1, $U_1 = U$ function at θ_1, J_o = current density at start

Next we estimate the characteristic time T_Q of current decay by setting energy dissipated in the normal region equal to the initial stored energy E (assuming $I = I_o$ is constant throughout)

$$\int_0^{T_Q} I^2 R(T) dT = E \qquad \int_0^{T_Q} J_o^2 A^2 \frac{4\pi \rho_1 \alpha^2 J_0^4 v^3 T^5}{30 A^2 U_1^2} dt = E$$

characteristic decay time T_Q of the quench

$$T_Q = \frac{1}{J_0} \left\{ \frac{45 U_1^2 E}{\pi \rho_1 \alpha^2 v^3} \right\}^{\frac{1}{6}}$$

Resistance growth and current decay (approx) 3

maximum temperature (at centre of normal zone) from

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

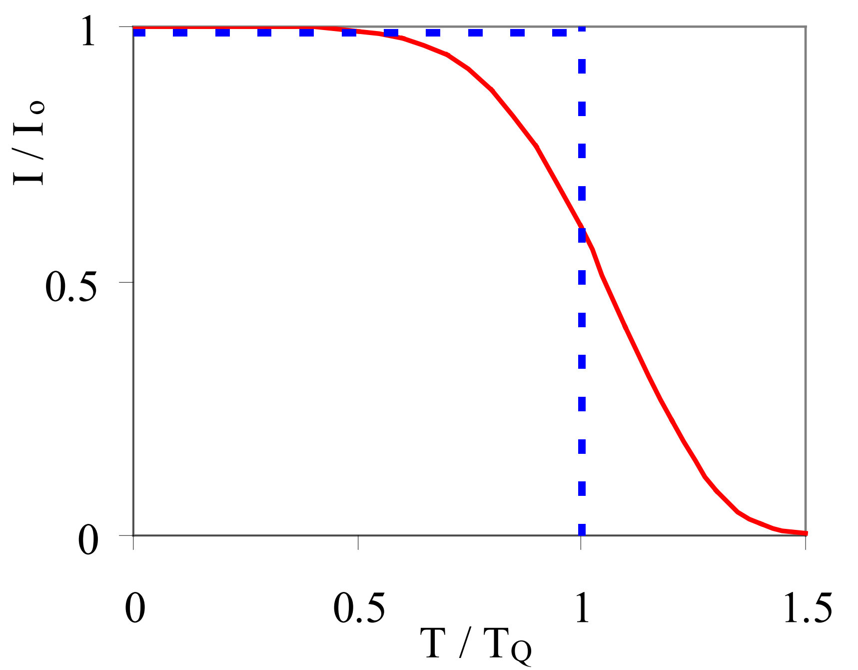
with the parabolic approximation

$$\theta_m = \frac{J_0^4 T_Q^2 \theta_1}{U_1^2}$$

substitute back to get the current decay curve

$$I(t) = I_o e^{T^6 / 2T_Q^6} = I_o e^{t^6 / 2}$$

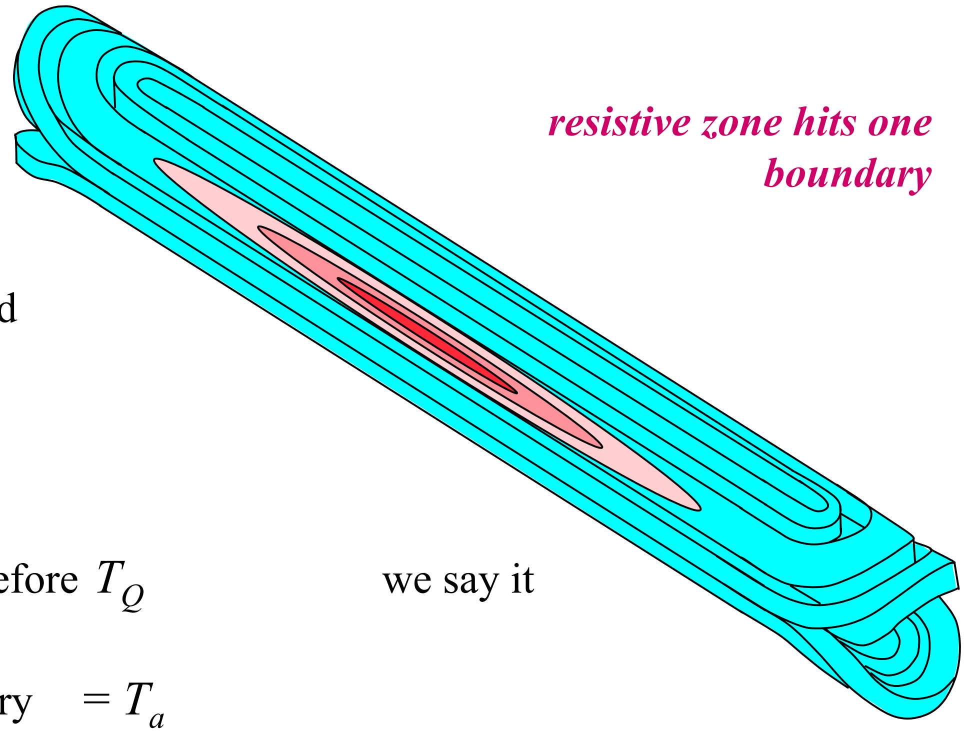
where $t = T/T_Q$



perhaps the original approximation (a) wasn't so bad after all!

Resistance growth and current decay (approx) 4

The simplified model assumes the resistive zone grows without limit. In practice however it will eventually hit a coil boundary. When this happens:



resistive zone hits one boundary

- expansion of the resistive zone is truncated
- rate of increase in resistance slows down
- decay time increases
- final temperature of hot spot increases

If the zone hits a boundary in one direction before T_Q we say it is **bounded in one dimension.** let:

time after quench when zone hits boundary $= T_a$

resulting decay time $= T_d$

normalized values $t_a = T_a / T_Q \quad t_d = T_d / T_Q \quad t = T/T_Q$

Approx theory (not proven) shows that, **provided** $T_a < T_Q$

$$t_d \approx \left\{ \frac{1}{3t_a} \right\}^{1/5}$$

$$I(t) = I_o e^{-\frac{3t_a t^5}{2}}$$

hence find T_d and θ_m

Resistance growth and current decay (approx) 5

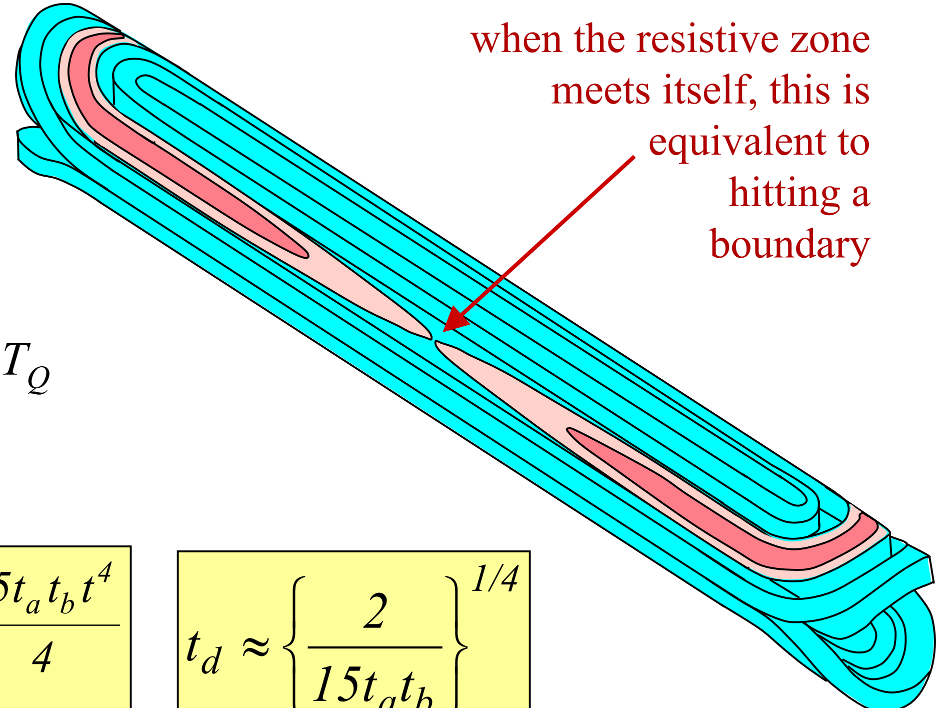
When the zone hits boundaries in two directions before T_Q we say it is **bounded in two dimensions**

time hits first boundary $= T_a$

second boundary $= T_b$

normalized values $t_a = T_a / T_Q \quad t_b = T_b / T_Q$

$t_d = T_d / T_Q \quad t = T / T_Q$



provided T_a and $T_b < T_Q$

$$I(t) = I_o e^{-\frac{15 t_a t_b t^4}{4}}$$

$$t_d \approx \left\{ \frac{2}{15 t_a t_b} \right\}^{1/4}$$

When the zone hits boundaries in three directions before T_Q we say it is **bounded in three dimensions**

time hits third boundary $= T_c$

normalized value $t_c = T_c / T_Q$

provided $T_a \quad T_b$ and $T_c < T_Q$

$$I(t) = I_o e^{-10 t_a t_b t_c t^3}$$

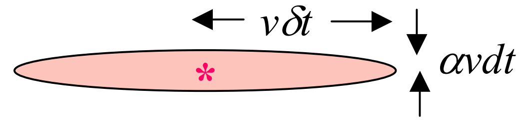
$$t_d \approx \left\{ \frac{1}{20 t_a t_b t_c} \right\}^{1/3}$$

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 $\delta\theta_1 = J^2\,\rho(\theta_1)\,\delta\tau\,/\,\gamma\, C(\theta_1)$

↓

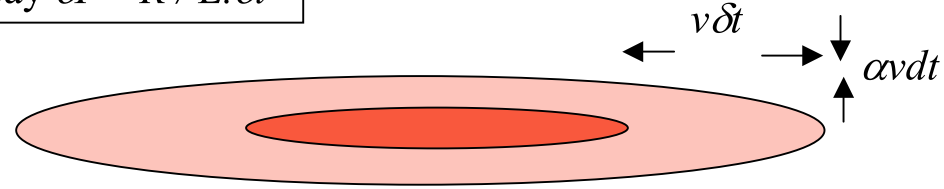
resistivity of zone 1 is $\rho(\theta_1)$

↓

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) $r_2 = \rho(\theta_2) * f_{g2}$ $r_n = \rho(\theta_n) * f_{gn}$

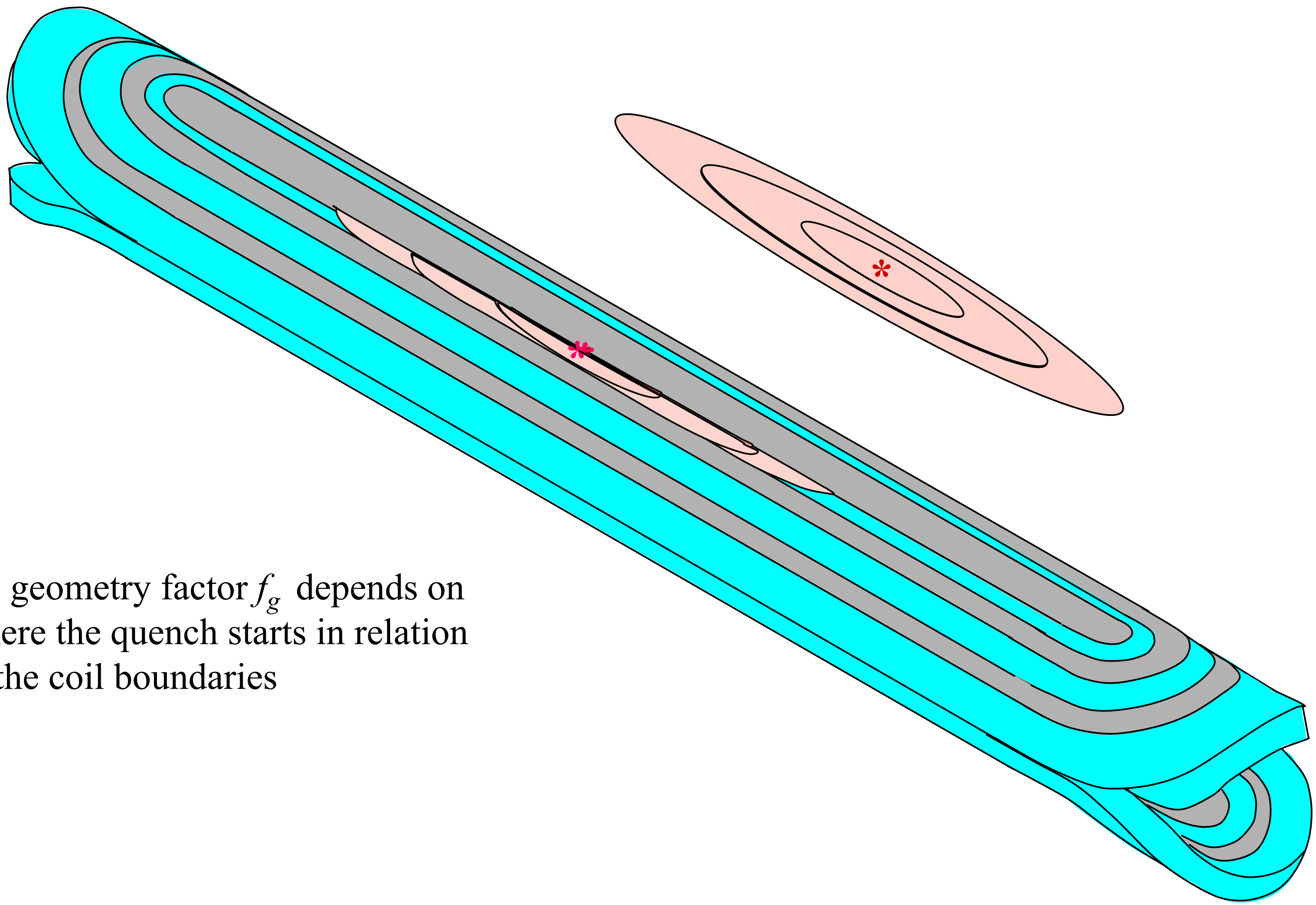
↓

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

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

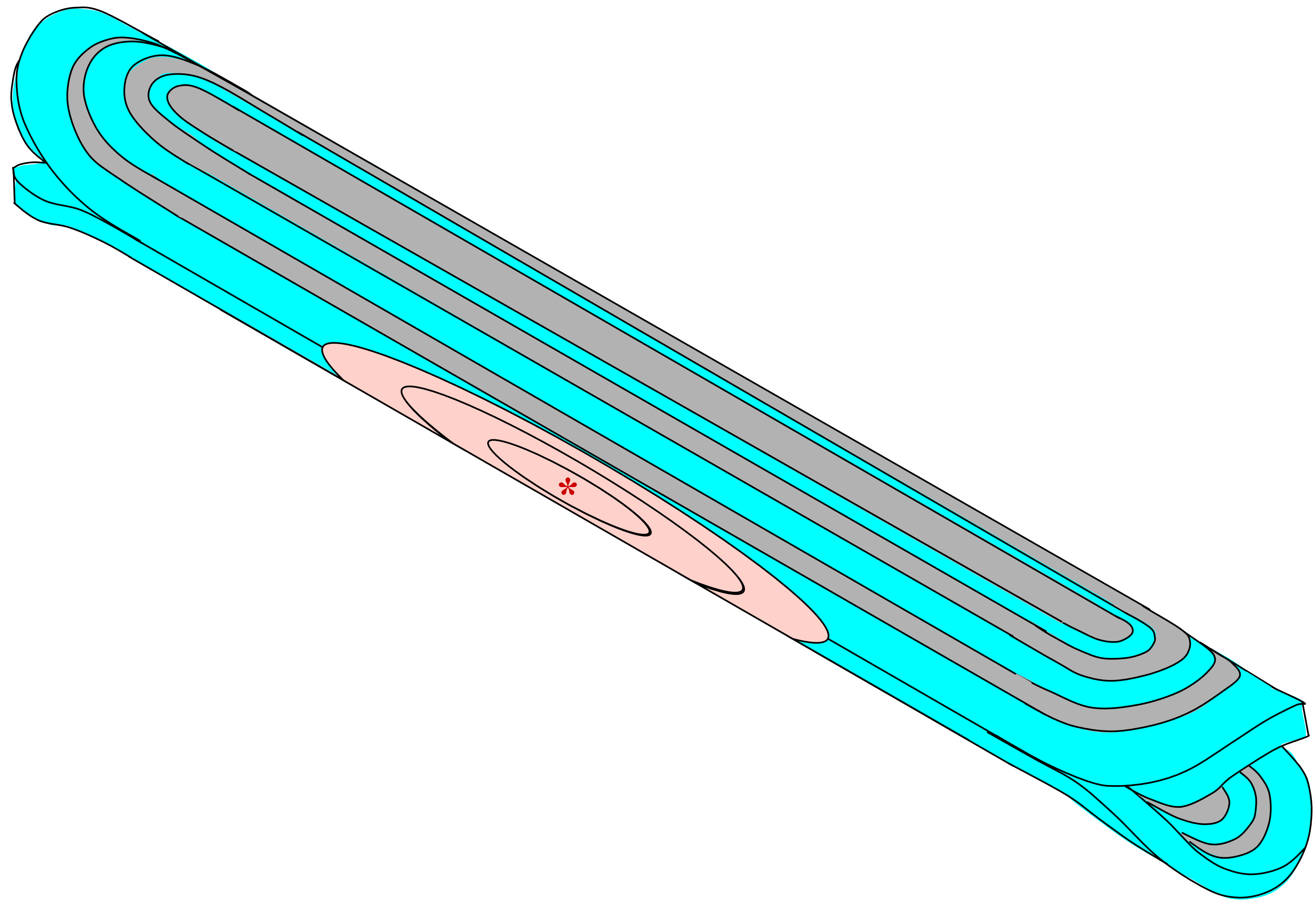
when $I \Rightarrow 0$ stop

Quench starts in the pole region

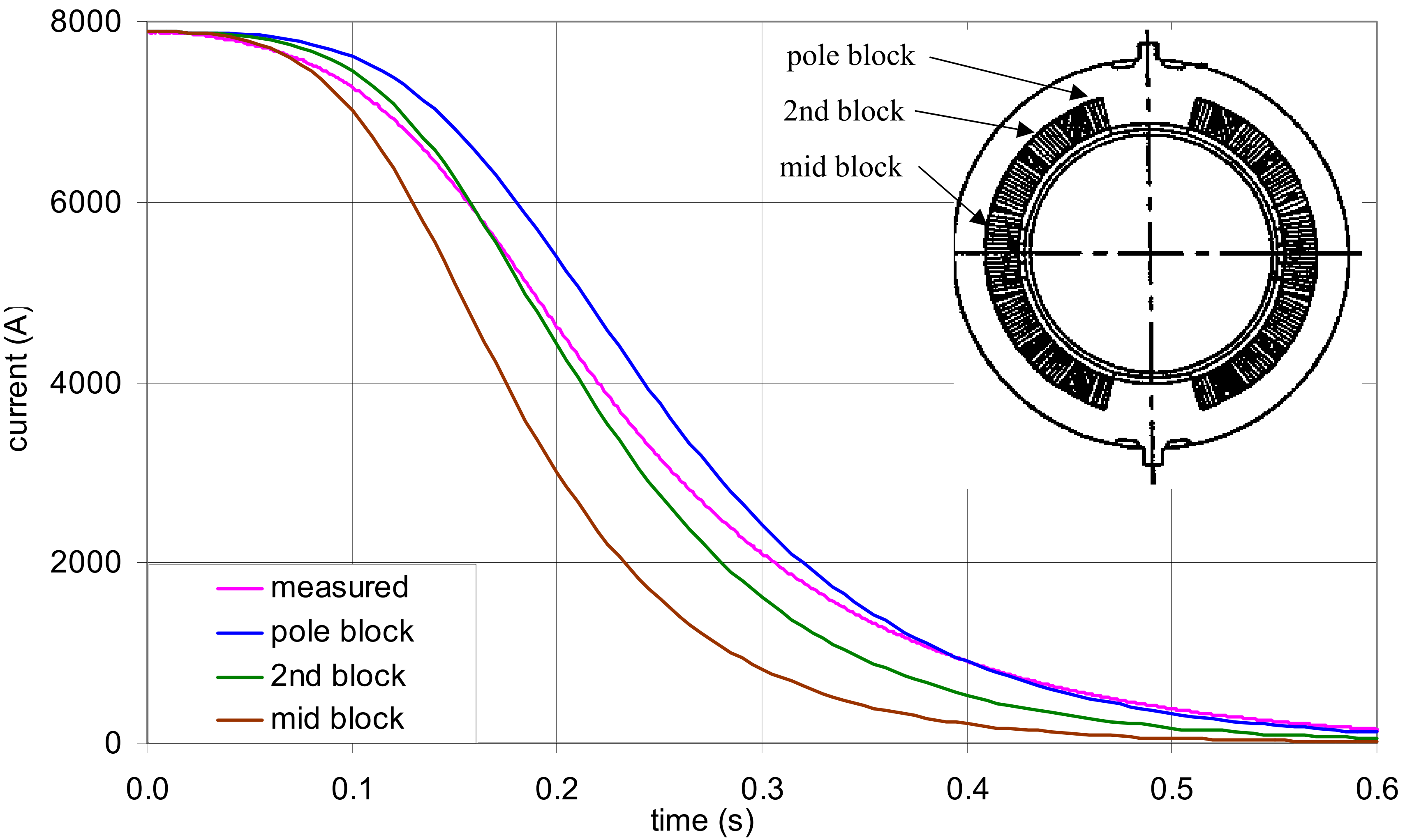


the geometry factor f_g depends on where the quench starts in relation to the coil boundaries

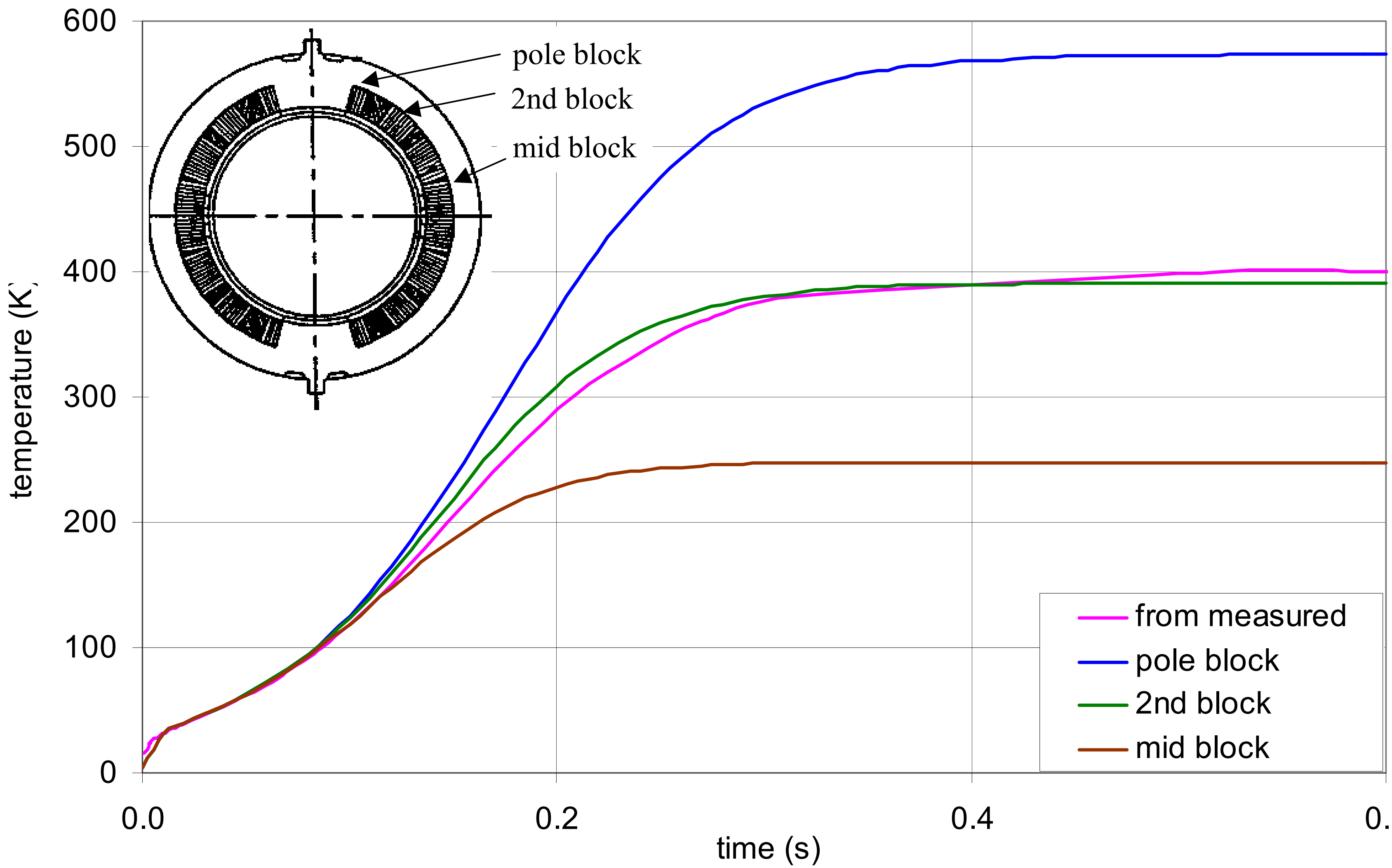
Quench starts in the mid plane



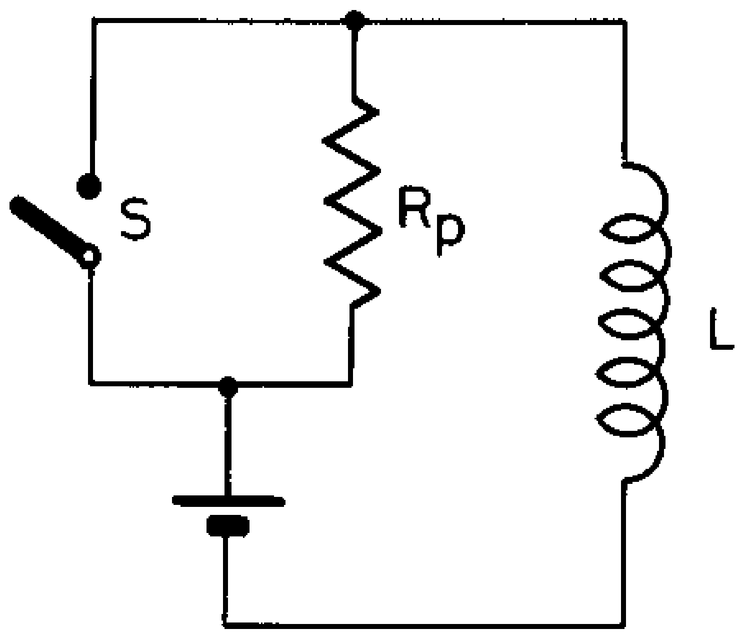
Computer simulation of quench (dipole GSI001)



Computer simulation of quench temperature rise



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

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

- calculate θ_{max} from

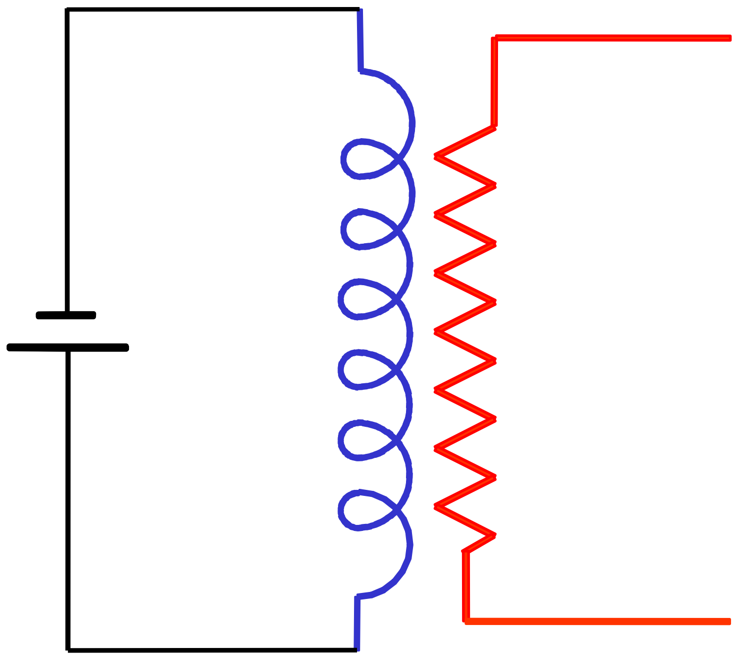
$$\int J^2 dt = J_o^2 \frac{\tau}{2} = U(\theta_m)$$

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

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

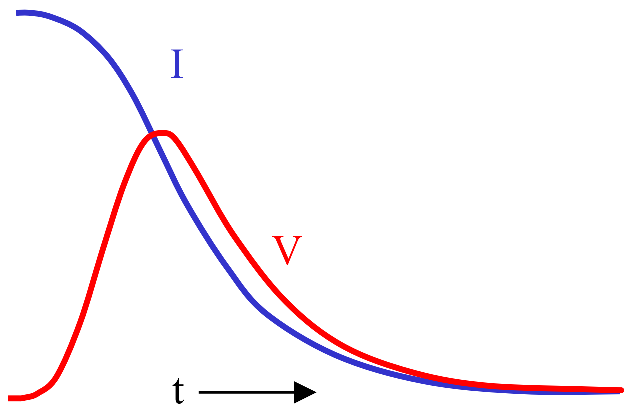
Note: usually pulse the heater by a capacitor, the high voltages involved raise a conflict between:-

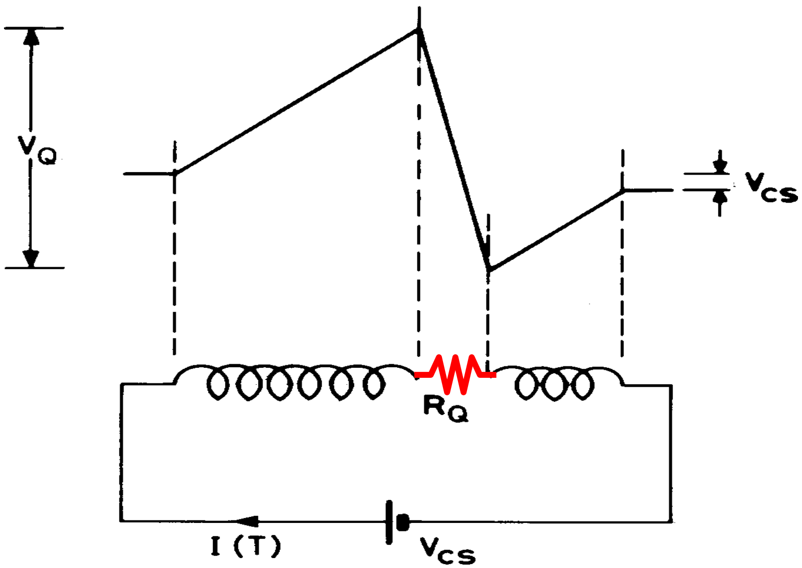
- ***good themal contact***
- ***good electrical insulation***

method most commonly used in accelerator magnets ✓

Methods of quench protection:

3) quench detection (a)





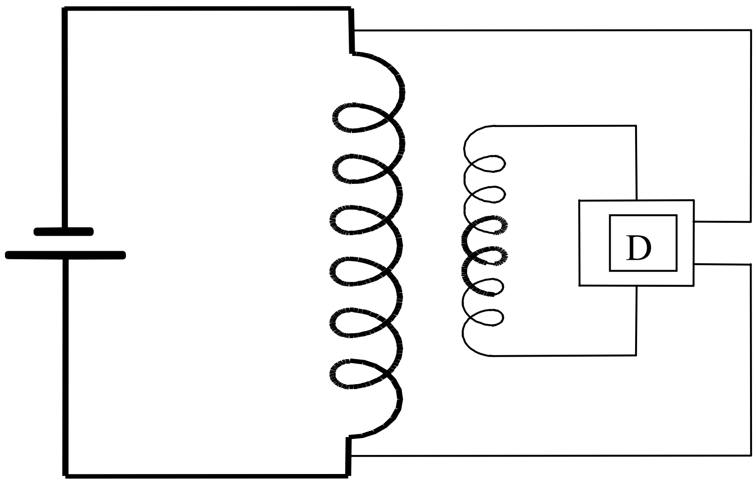
internal voltage after quench $V = IR_Q = -L\frac{dI}{dt} + V_{cs}$

- 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



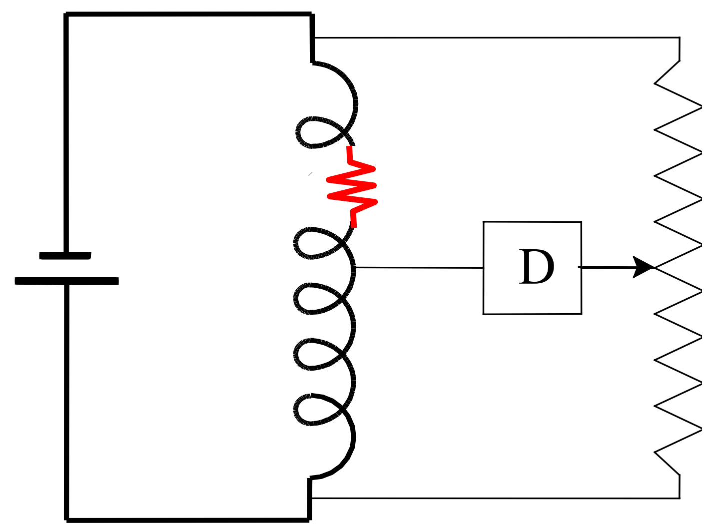
detector subtracts voltages to give

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

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

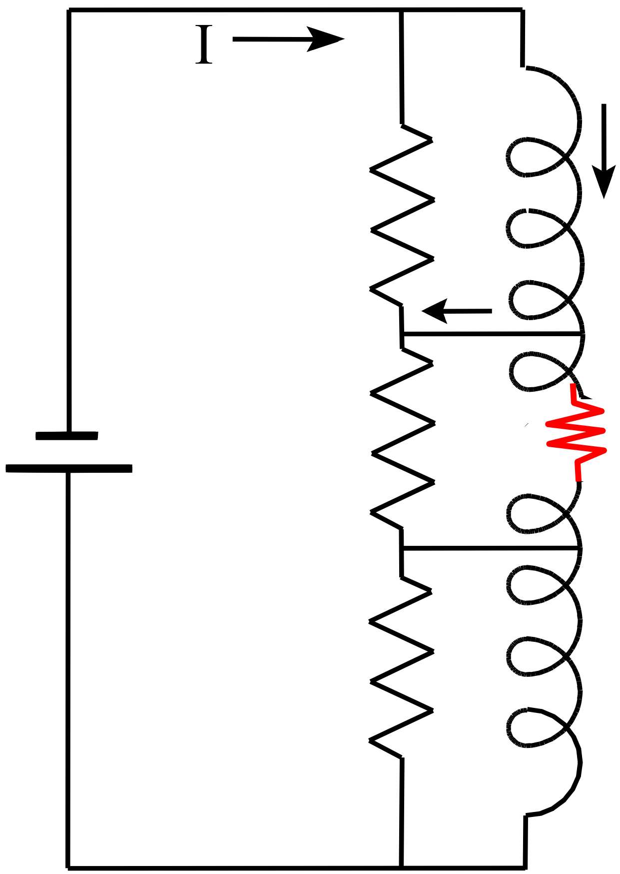
ii) Balanced potentiometer

- 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

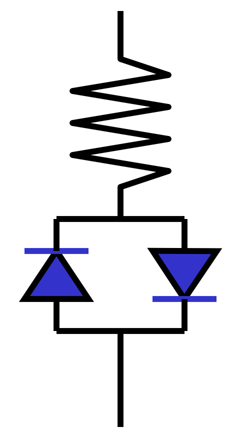


- resistor chain across magnet - cold in cryostat
- current from rest of magnet can by-pass the resistive section
- effective inductance of the quenched section is reduced

  ⇒ reduced decay time

  ⇒ reduced temperature rise
- current in rest of magnet increased by mutual inductance effects

  ⇒ 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

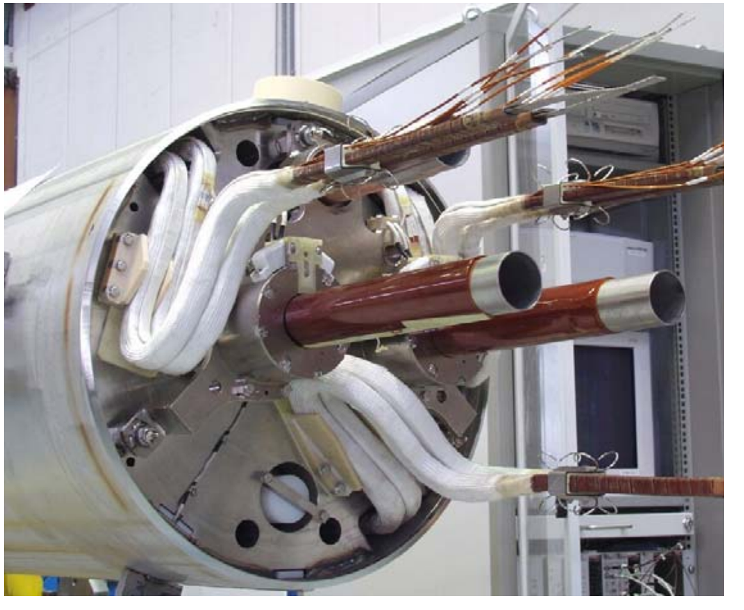


Case study: LHC dipole protection

It's difficult! - the main challenges are:

1) Series connection of many magnets

- In each octant, 154 dipoles are connected in series. If one magnet quenches, the combined inductance of the others will try to maintain the current. Result is that the stored energy of all 154 magnets will be fed into the magnet which has quenched ⇒ vaporization of that magnet!.
- **Solution 1**: put cold diodes across the terminals of each magnet. In normal operation, the diodes do not conduct - so that the magnets all track accurately. At quench, the diodes of the quenched magnet conduct so that the octant current by-passes that magnet.
- **Solution 2:** open a circuit breaker onto a dump resistor (several tonnes) so that the current in the octant is reduced to zero with a time constant ~ 100 secs.

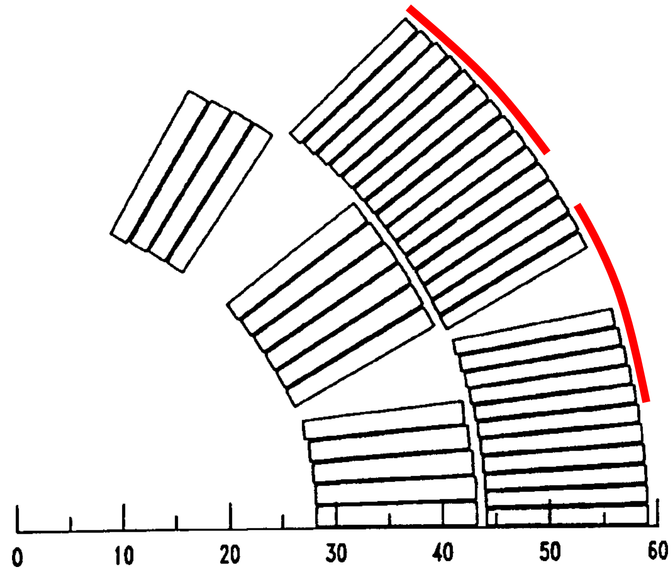


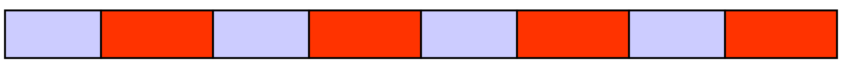
2) High current density, high stored energy and long length

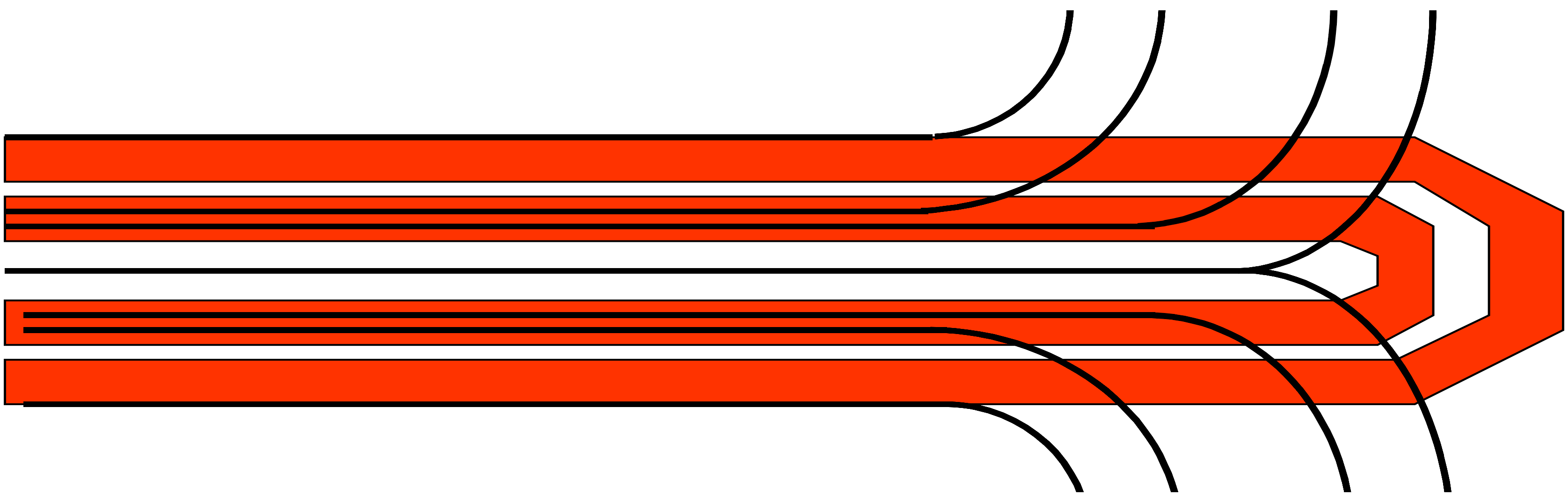
- As a result of these factors, the individual magnets are not self protecting. If they were to quench alone or with the by-pass diode, they would still burn out.
- **Solution 3:** Quench heaters on top and bottom halves of every magnet.

LHC quench-back heaters

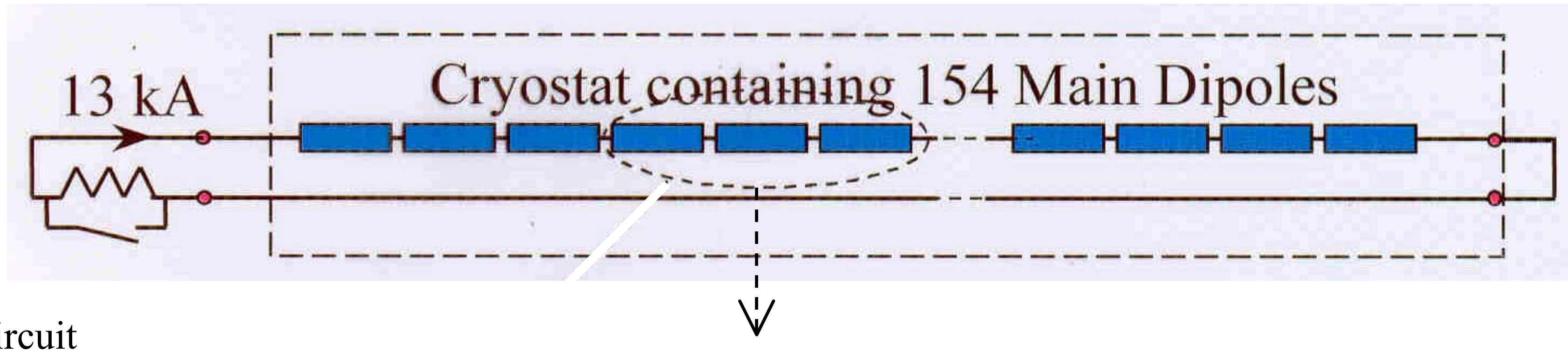
- stainless steel foil 15mm x 25 μm glued to outer surface of winding
- insulated by Kapton
- pulsed by capacitor 2 x 3.3 mF at 400 V = 500 J
- quench delay - at rated current = 30msec
  - at 60% of rated current = 50msec
- copper plated 'stripes' to reduce resistance



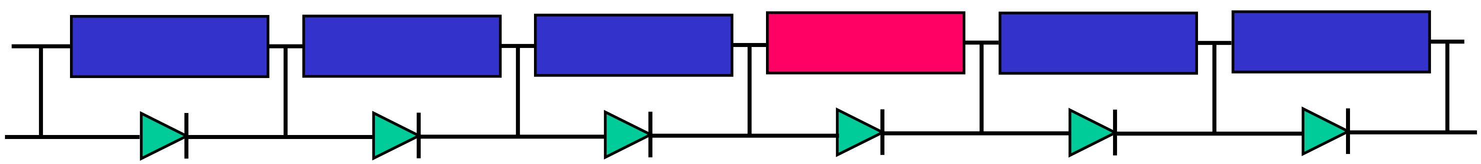




LHC power supply circuit for one octant



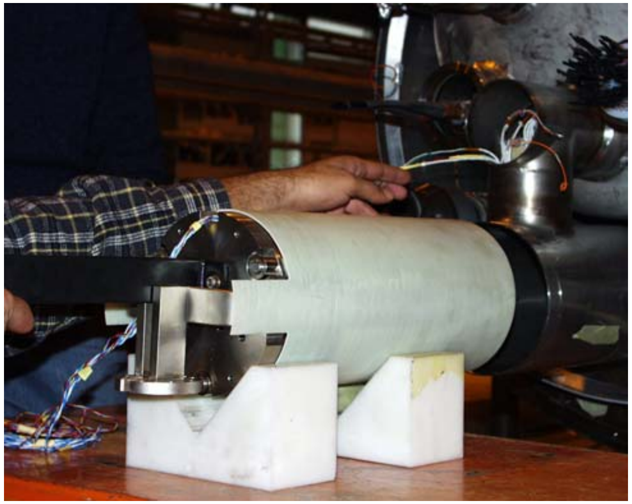
circuit
breaker



- diodes allow the octant current to by-pass the magnet which has quenched
- circuit breaker reduces to octant current to zero with a time constant of 100 sec
- initial voltage across breaker = 2000V
- stored energy of the octant = 1.33GJ

Diodes to by-pass the main ring current

Installing the cold diode package on the end of an LHC dipole



Quenching: concluding remarks

- magnets store large amounts of energy - during a quench this energy gets dumped in the winding
  ⇒ intense heating ($J \sim$ 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 must reject $L\,dI/dt$ and be **100%** reliable
- passive quench protection schemes are less effective because V grows so slowly at first
  - but are 100% reliable
- protection of accelerator magnets is made more difficult by series connection
  - all the other magnets feed their energy into the one that quenches
- for accelerator magnets use by-pass diodes and quench heaters
- remember the quench when designing the magnet insulation

always do the quench calculations before testing the magnet ✓