Lecture 4: Quenching and Protection

Plan

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

Magnetic stored energy

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

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

the magnet weighs 26 tonnes

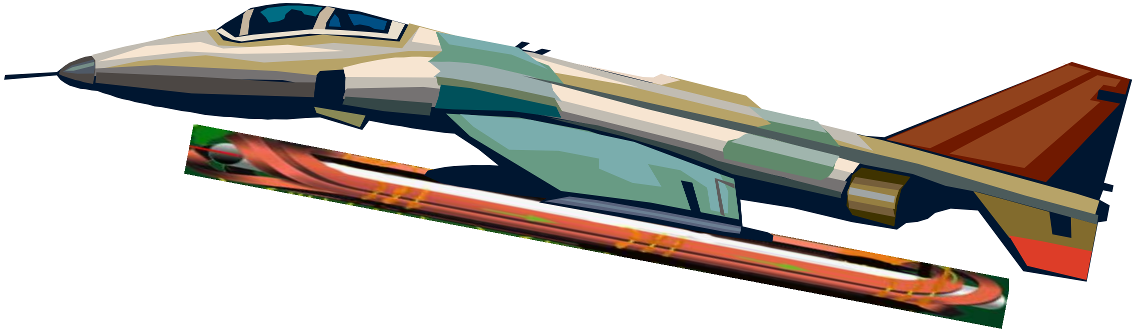
so the magnetic stored energy is equivalent to the kinetic energy of:-

26 tonnes travelling at 88km/hr

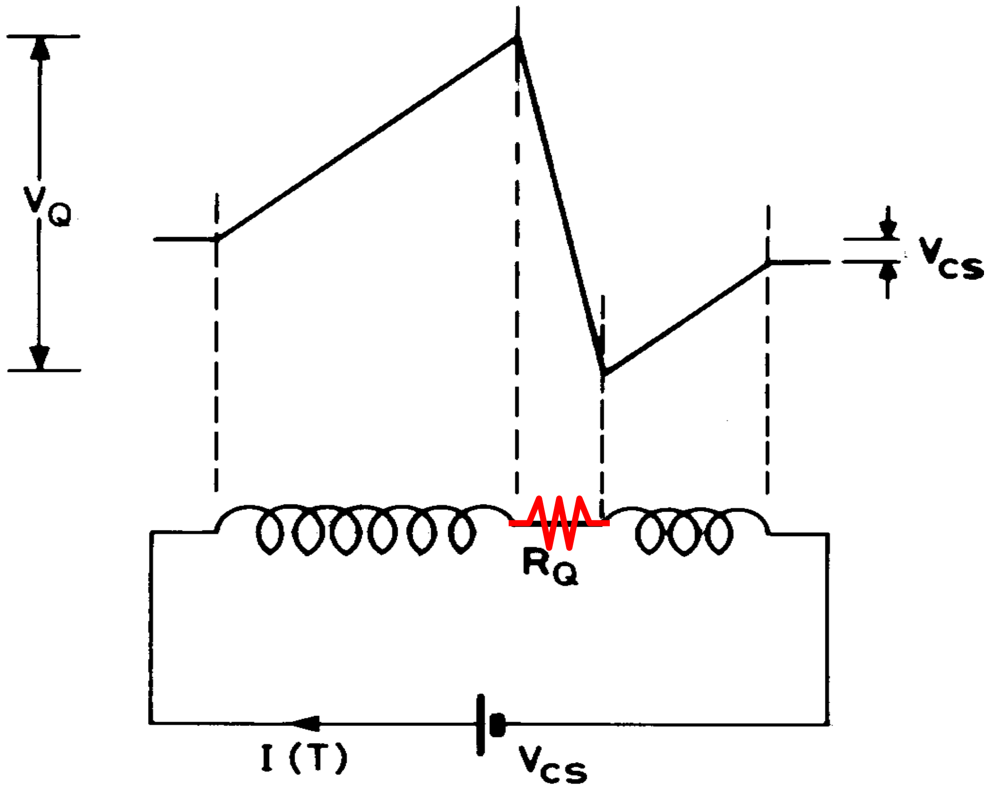
coils weigh 830 kg

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 $U(\theta)$

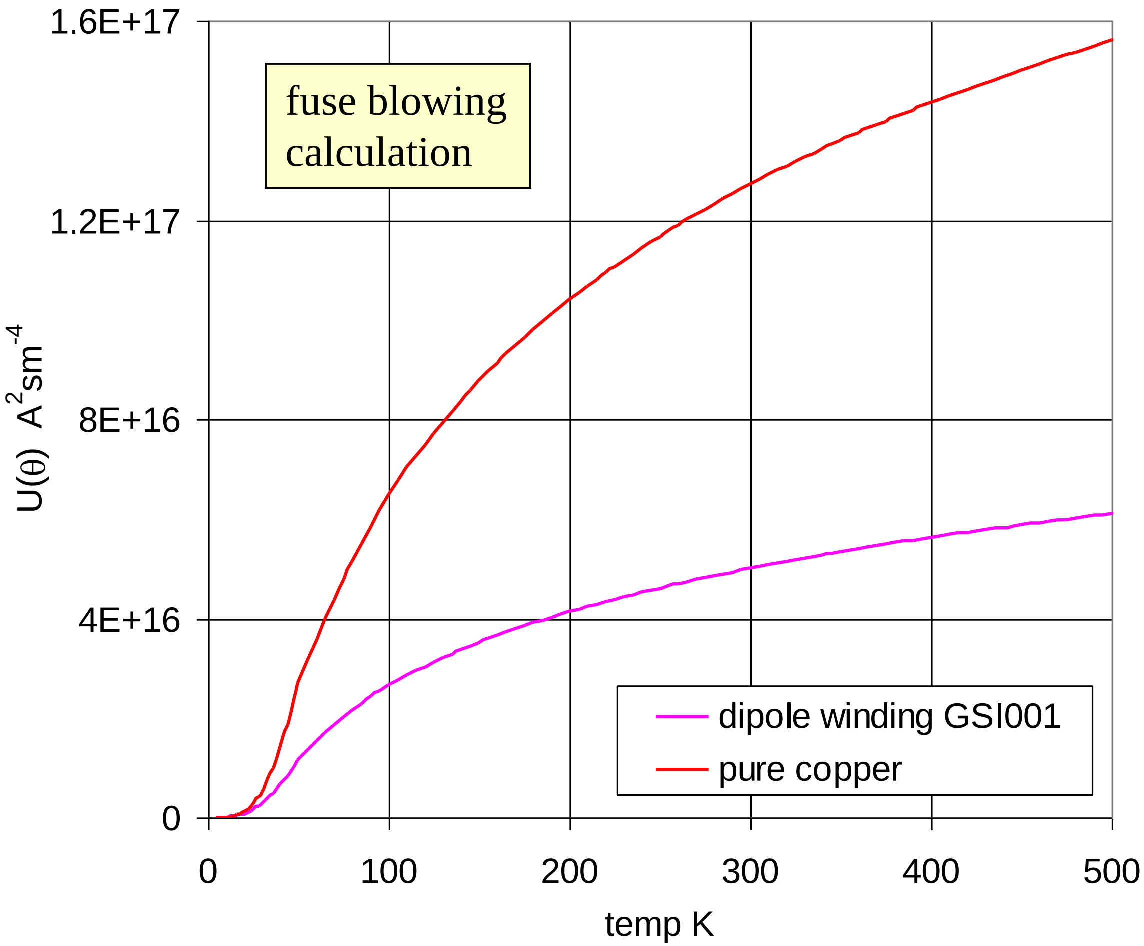
- Adiabatic approximation

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

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

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

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

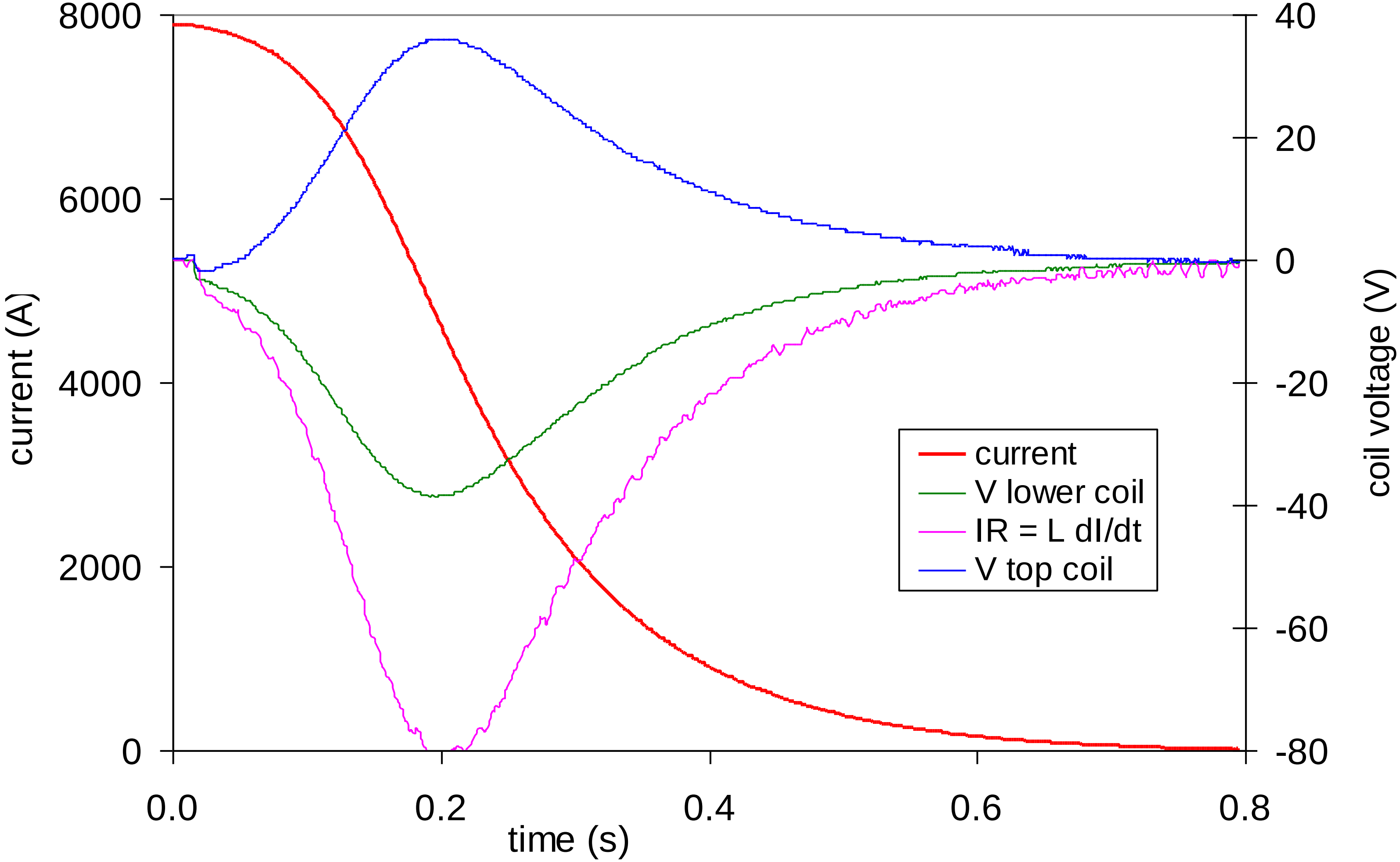


- GSI 001 dipole winding is 50% copper, 22% NbTi, 16% Kapton and 3% stainless steel

- NB always use **overall** current density

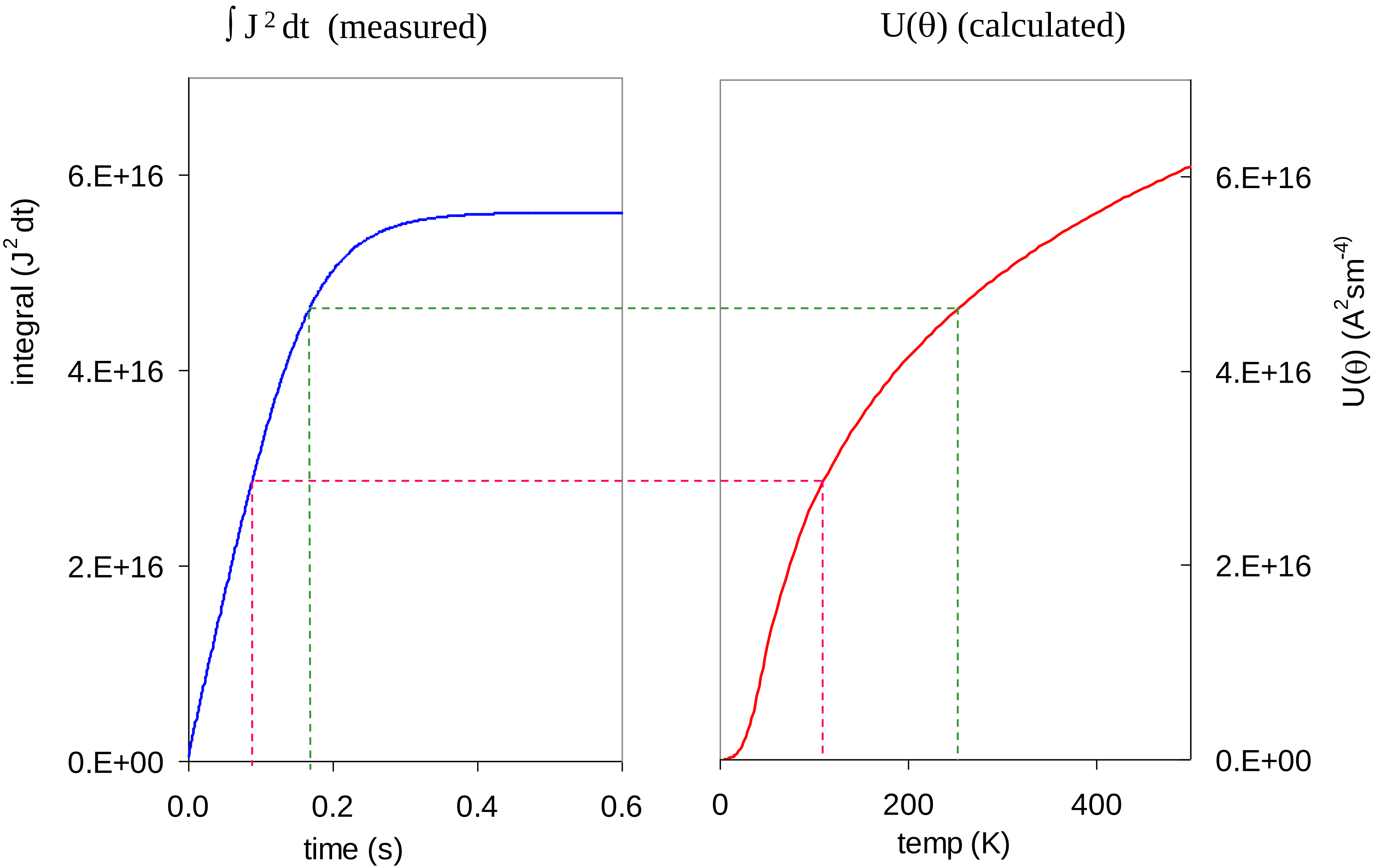
household fuse blows at 15A,
area = 0.15mm^2 J = 100Amm^{-2}
NbTi in 5T J_c = 2500Amm^{-2}

Measured current decay after a quench

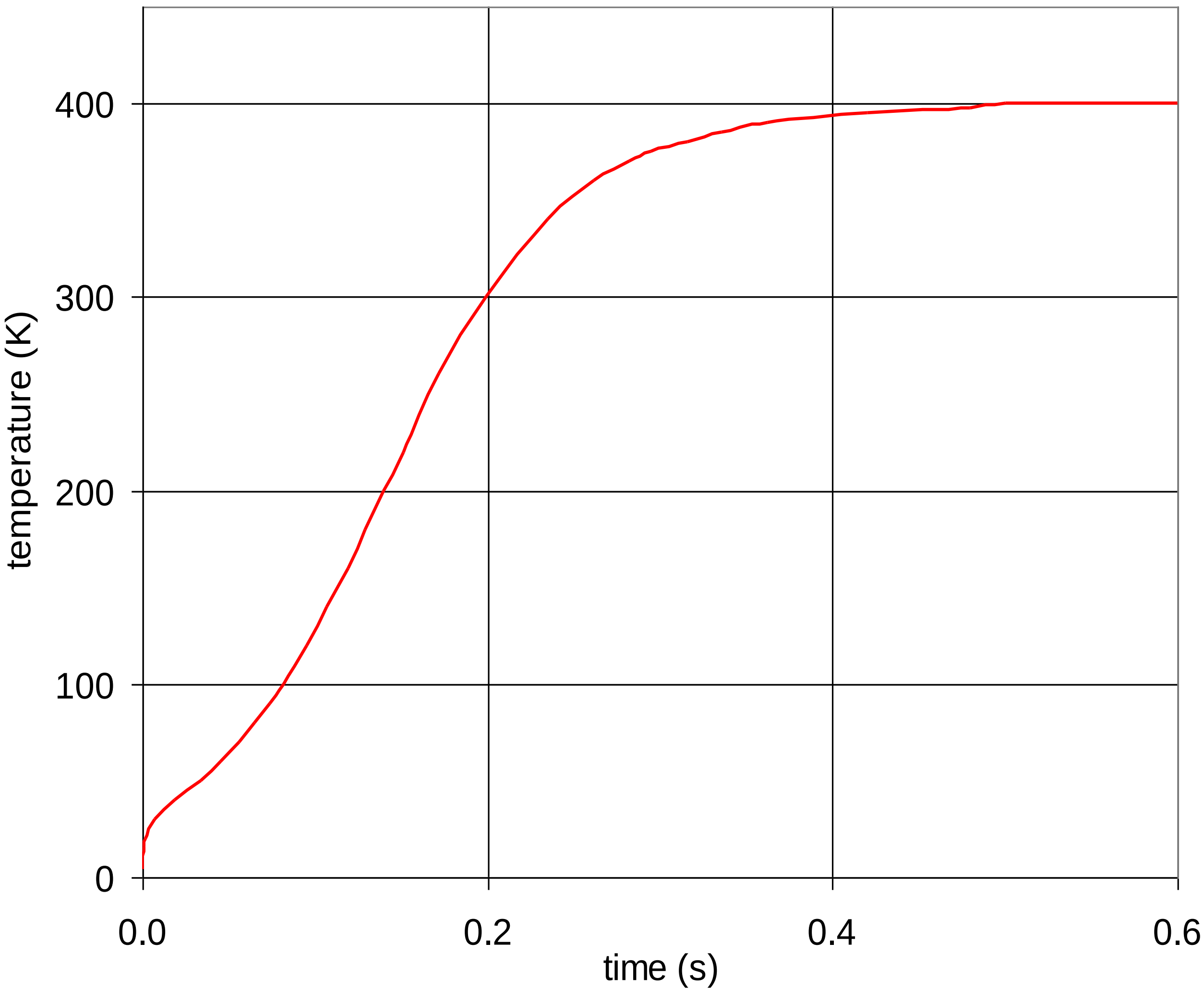


Dipole GSI001 measured at Brookhaven National Laboratory

Calculating temperature rise from the current decay curve

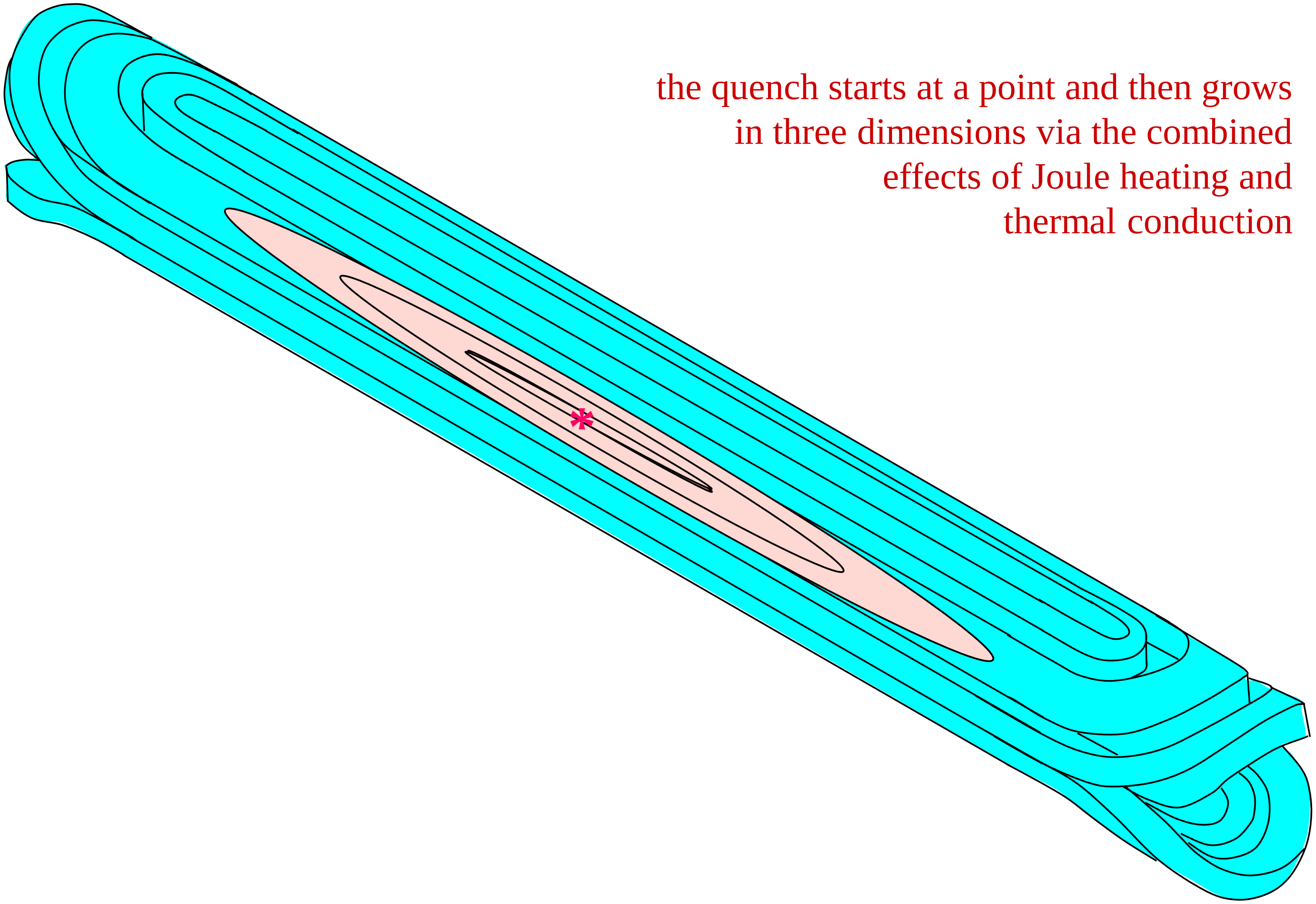


Calculated temperature



- 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

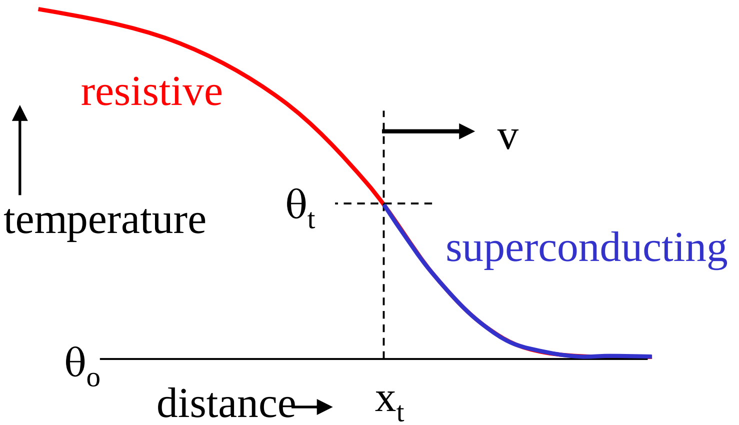
Growth of the resistive zone



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
- driving it forward is heat generation in the resistive zone and heat conduction along the wire
- heat conduction equation with resistive power generation $J^2\rho$ per unit volume.



$J^2\rho$ at left side

$\rho = 0$ at right

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

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

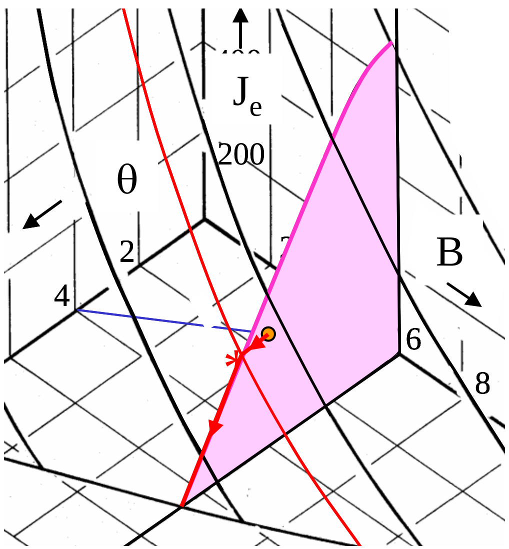
when $h = 0$, the solution for θ which gives a continuous join between left and right sides at θ_t gives the ***adiabatic propagation velocity***

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

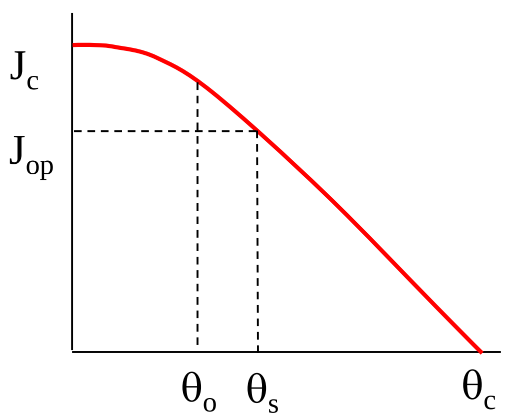
recap Wiedemann Franz Law $\rho(\theta).k(\theta) = L_o\theta$

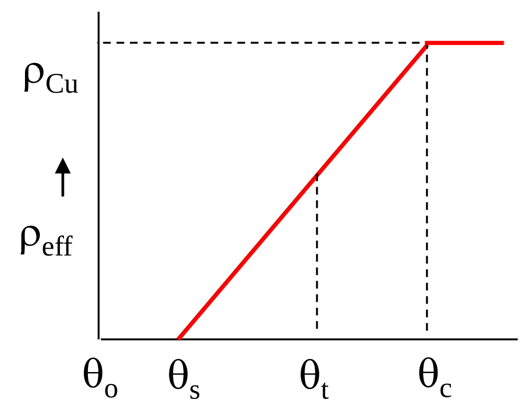
what to say about θ_t ?

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





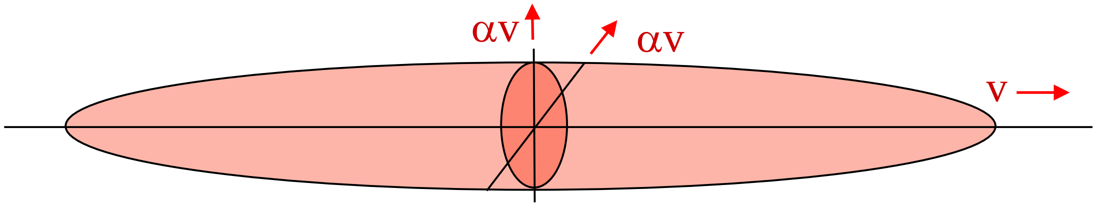
Quench propagation velocity 3

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

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

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

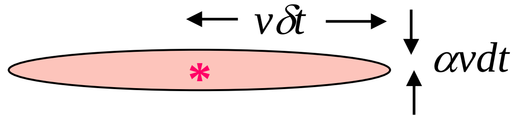
- because C varies so strongly with temperature, it is better to calculate an averaged C by numerical integration

$$C_{av}(\theta_g,\theta_c) = \frac{\int_{\theta_g}^{\theta_c} C(\theta(\theta)}{(\theta_c - \theta_g)}$$

- 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



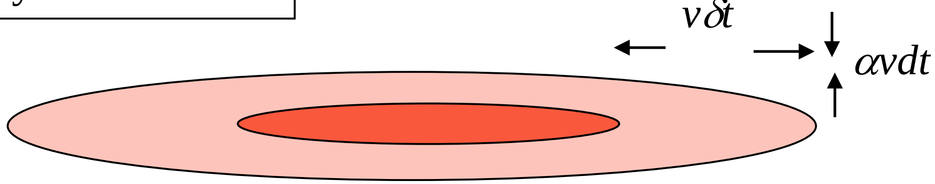
in time δt zone 1 grows $v.dt$ longitudinally and $\alpha.v.dt$ transversely

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 $\delta\theta_1 = J^2\rho(\theta_1)\delta t\,/\gamma C(\theta_1)$ $\delta\theta_2 = J^2\rho(\theta_2)\delta t\,/\gamma C(\theta_2)$ $\delta\theta_n = J^2\rho(\theta_1)\delta t\,/\gamma C(\theta_n)$

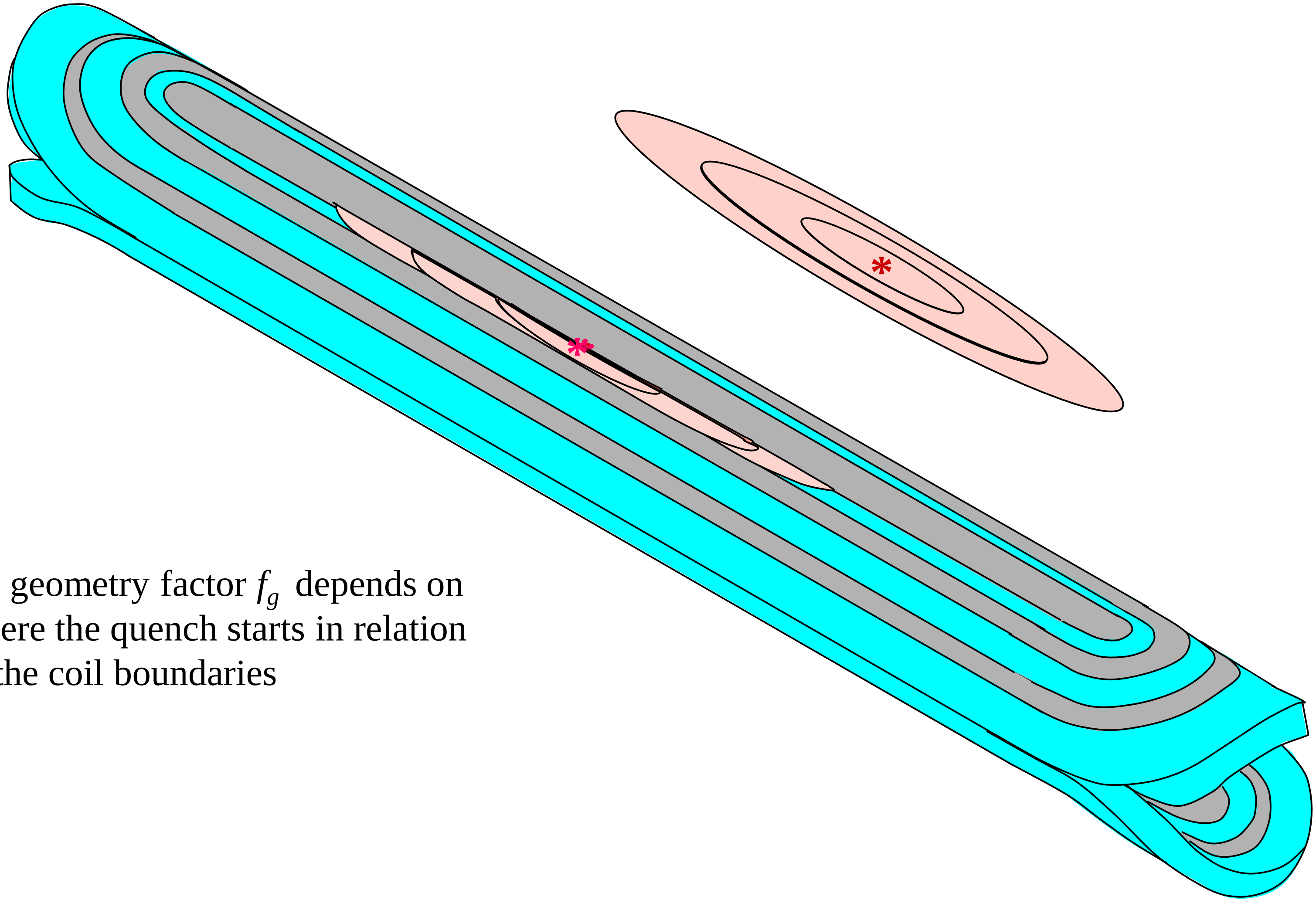
resistivity of each zone is $\rho(\theta_1)$ $\rho(\theta_2)$ $\rho(\theta_n)$ resistance $r_1 = \rho(\theta_1) * f_{g1}$ (geom factor) $r_2 = \rho(\theta_2) * f_{g2}$ $r_n = \rho(\theta_n) * f_{gn}$

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

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

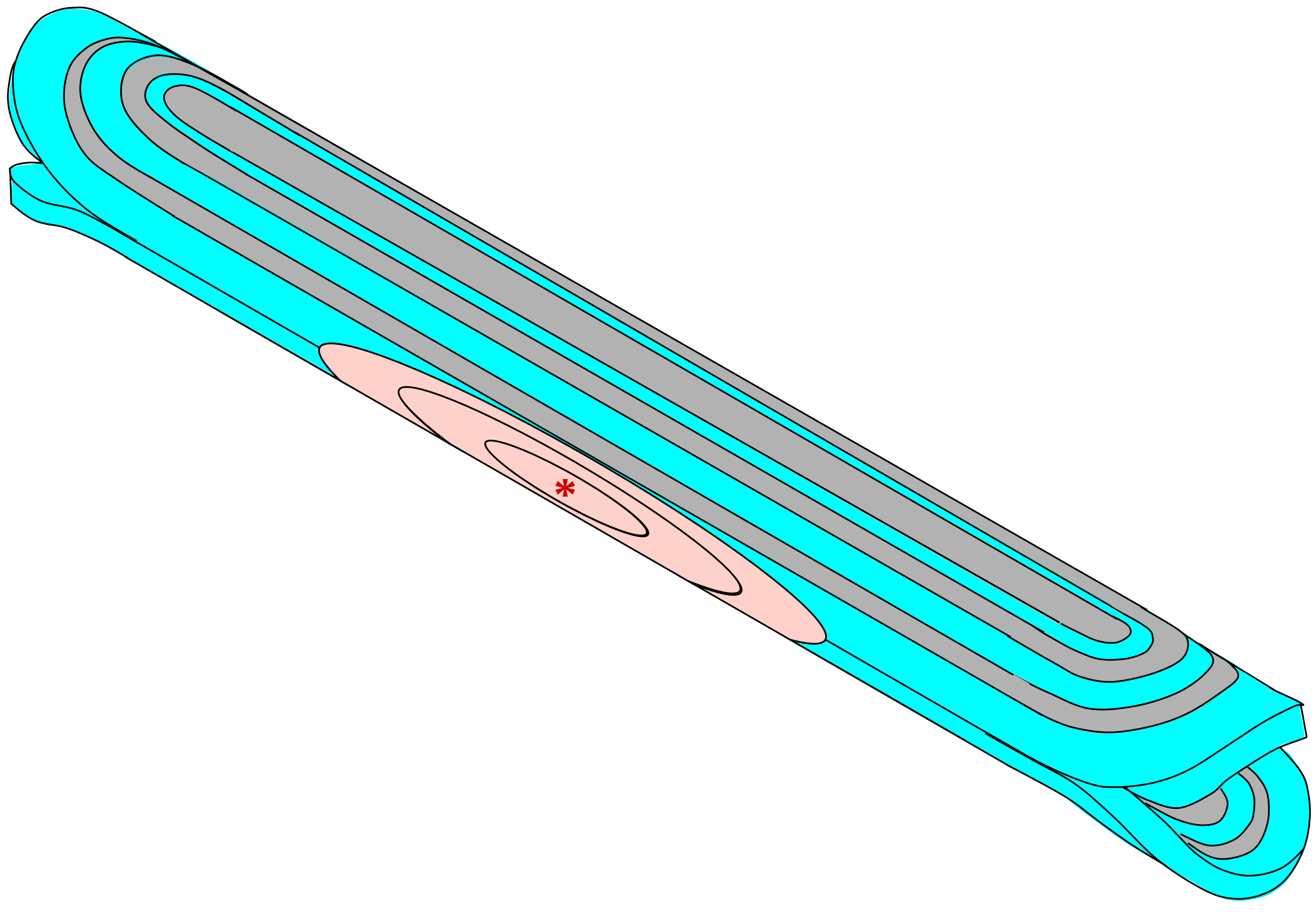
when $I \Rightarrow 0$ stop

Quench starts in the pole region

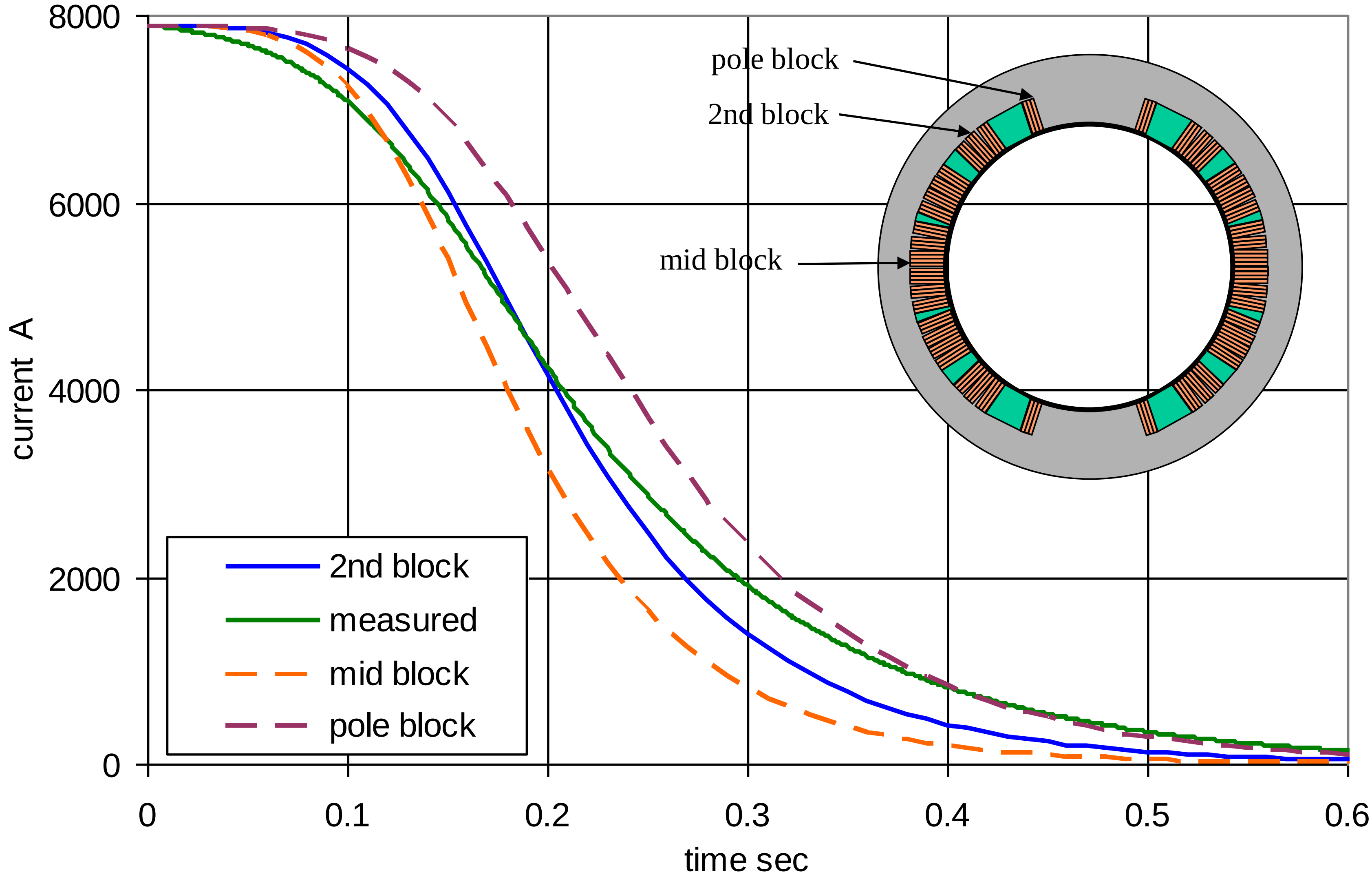


the geometry factor f_g depends on where the quench starts in relation to the coil boundaries

Quench starts in the mid plane

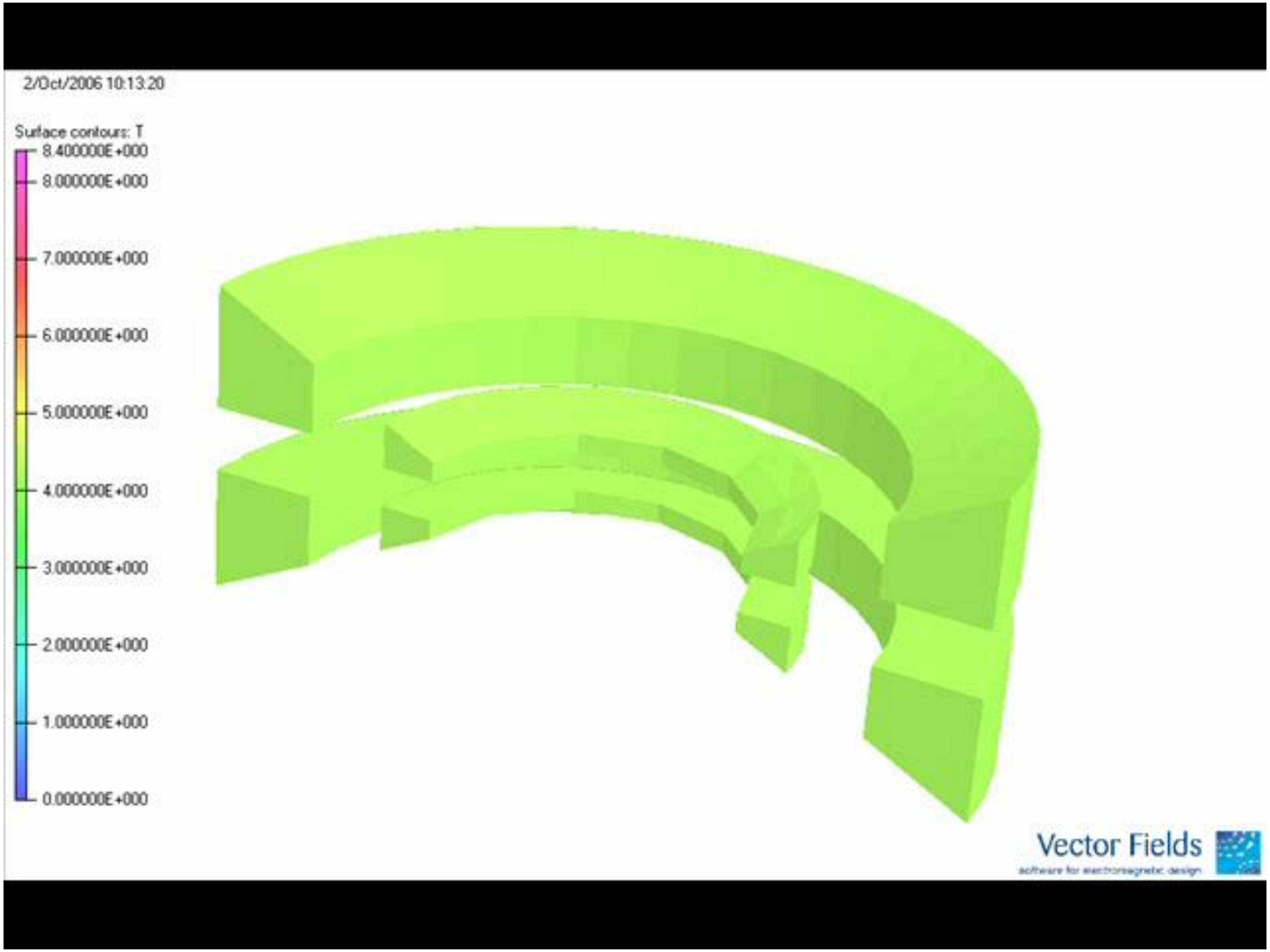


Computer simulation of quench (dipole GSI001)

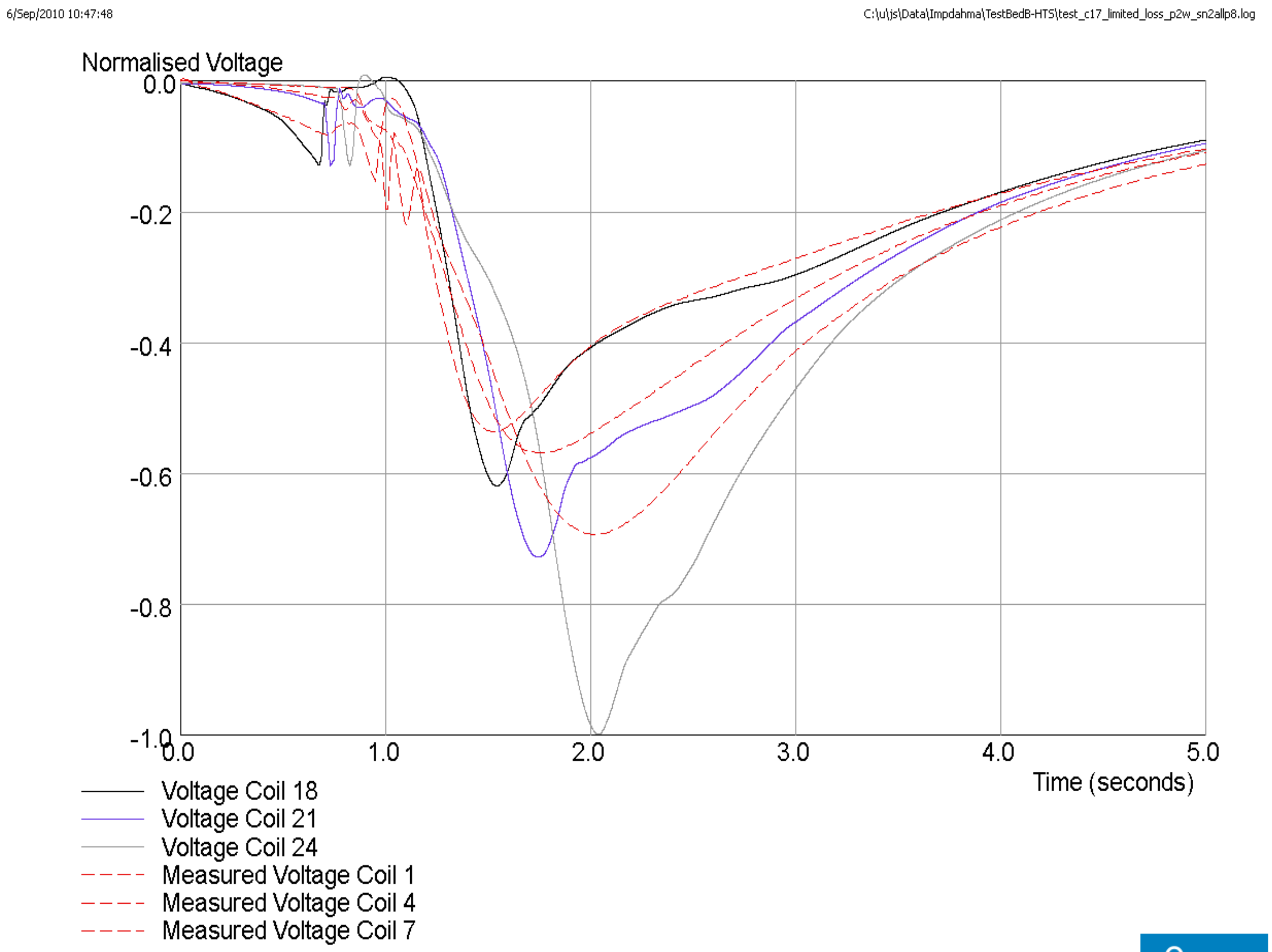


OPERA: a more accurate approach

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

Opera

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

Mini Tutorial: U(θ) function

It is often useful to talk about a magnet quench decay time, defined by:

$$\int_{\theta_o}^{\theta_m} J^2 dt = J_o^2 T_d$$

i) For the example of magnet GSI001, given above, $T_d = 0.167$ sec
Use the $U(\theta_m)$ plot below to calculate the maximum temperature.

ii) This was a short prototype magnet. Supposing we make a full length magnet and compute $T_d = 0.23$ sec. - should we be worried?

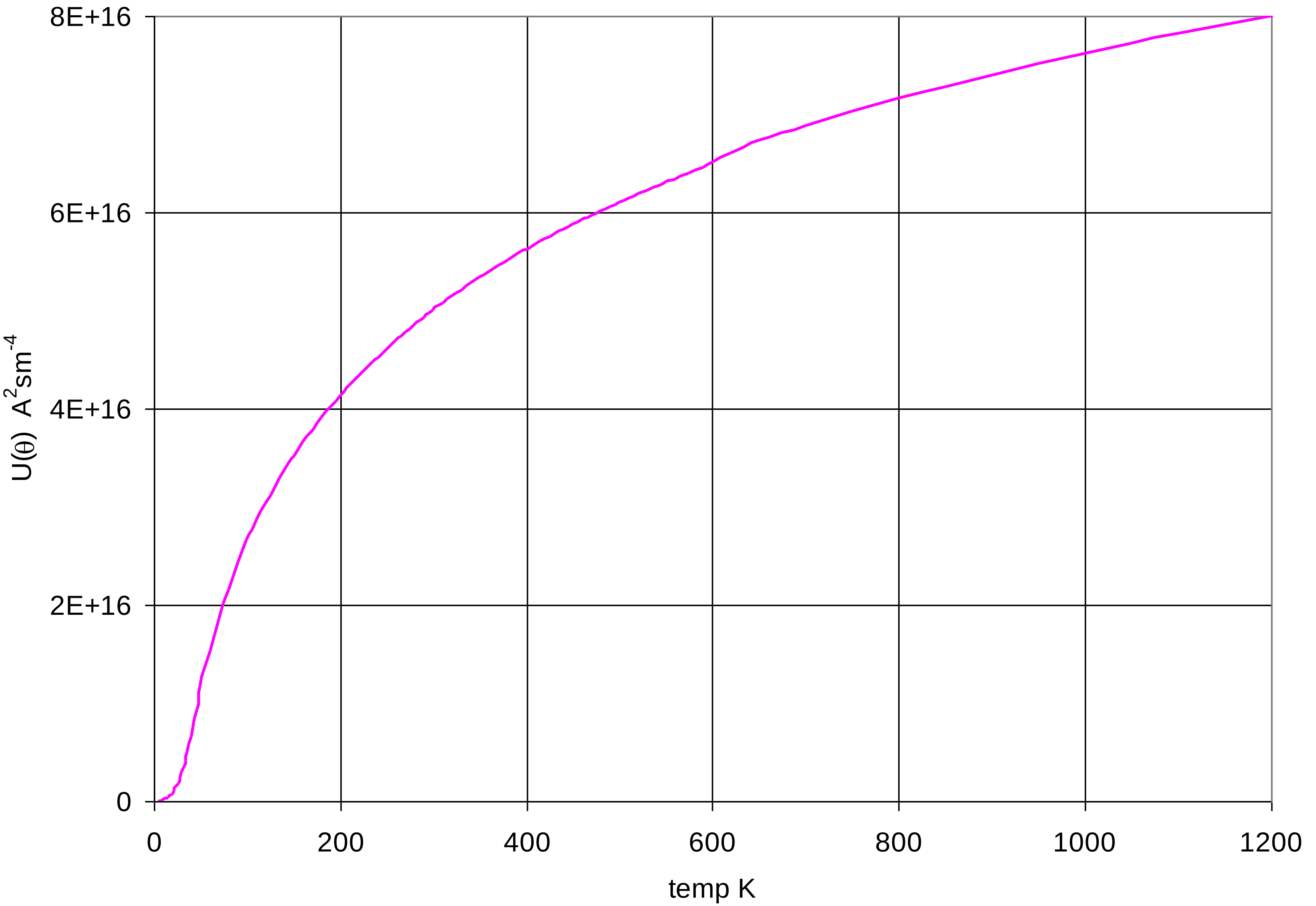
iii) If we install quench back heaters which reduce the decay time to 0.1 sec, what will the maximum temperature rise be?

Data

Magnet current $I_o = 7886$ Amps

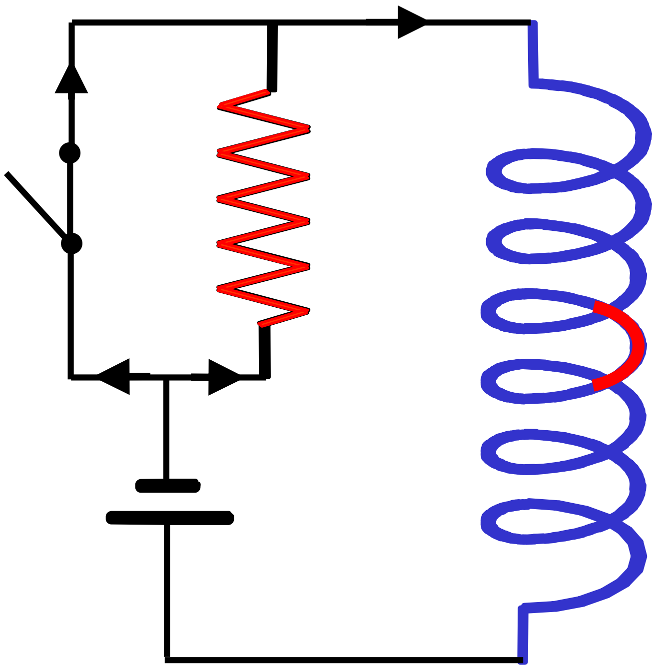
Unit cell area of one cable $A_u = 13.6$ mm^2

$U(\theta_m)$ function for dipole GSI001



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 τ

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

- calculate θ_{max} from

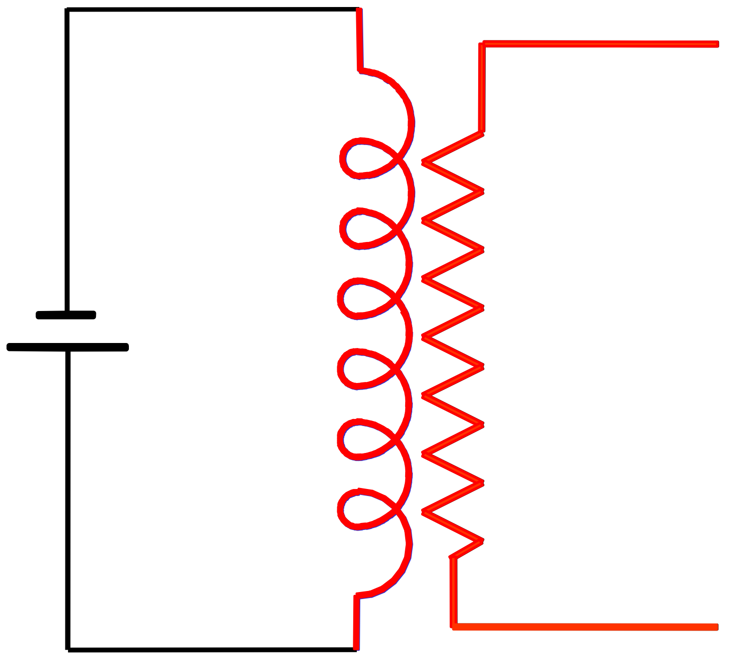
$$\int J^2 dt = J_o^2 \frac{\tau}{2} = U(\theta_m)$$

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

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
- quenches other regions of the magnet, forcing normal zone to grow more rapidly

$\Rightarrow$ higher resistance

$\Rightarrow$ shorter decay time

$\Rightarrow$ lower temperature rise at the hot spot

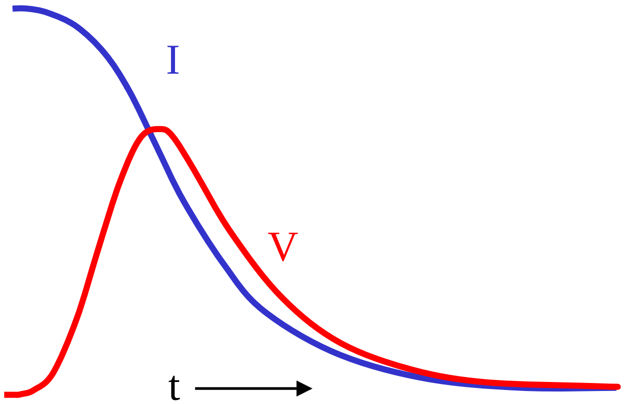
⇨ spreads inductive energy over most of winding

Note: usually pulse the heater by a capacitor, the high voltages involved raise a conflict between:-
- ***good themal contact***
- ***good electrical insulation***

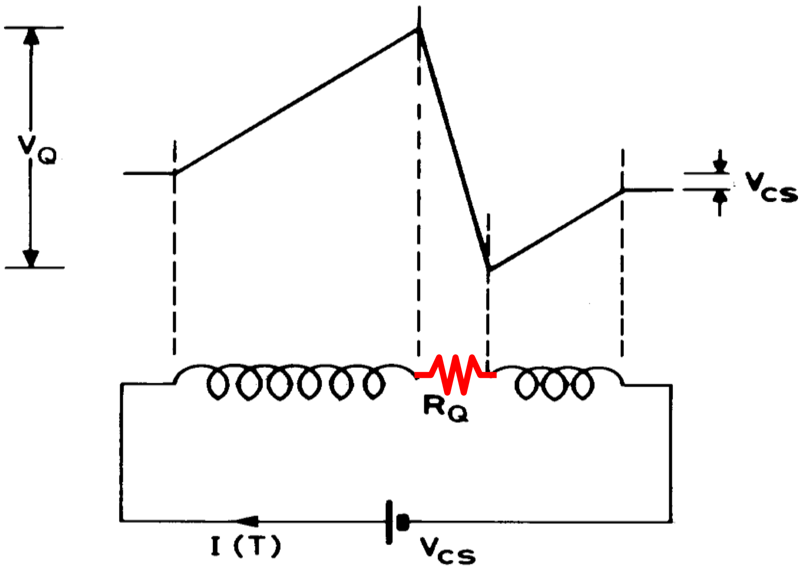
method most commonly used in accelerator magnets ✓

Methods of quench protection:

3) quench detection (a)



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

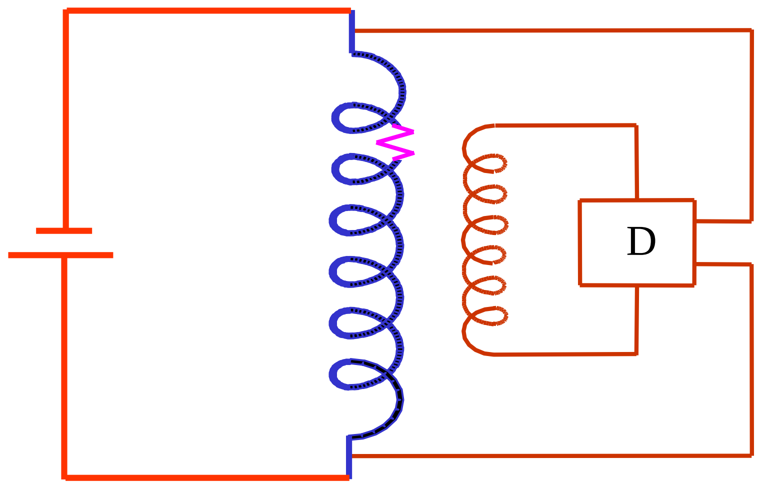


- not much happens in the early stages - small $dI/dt \Rightarrow$ small V
- but important to act soon if we are to reduce T_Q significantly
- so must detect small voltage
- superconducting magnets have large inductance $\Rightarrow$ large voltages during charging
- detector must reject $V = L\,dI/dt$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



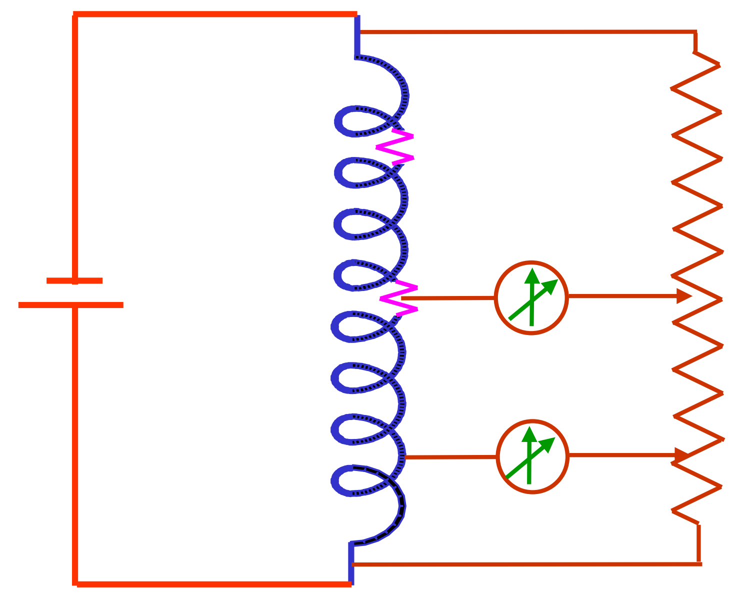
detector subtracts voltages to give

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

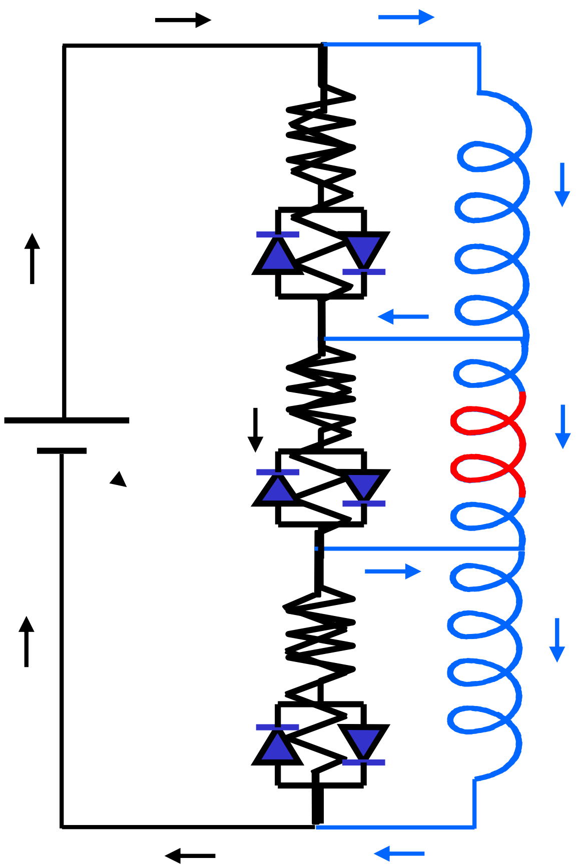
- adjust detector to effectively make $L = M$
- M can be a toroid linking the current supply bus, but must be linear - no iron!

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 2nd 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

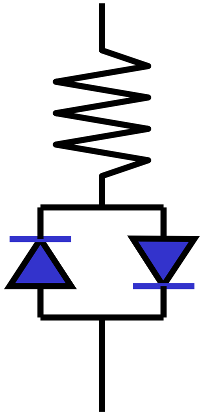
  ⇒ reduced decay time

  ⇒ reduced temperature rise

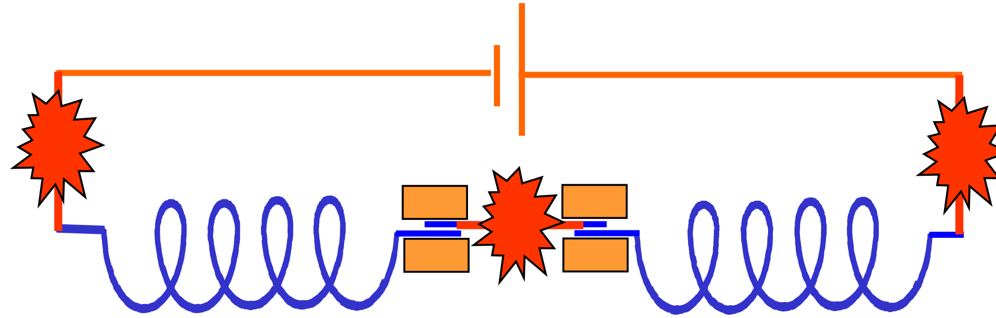
- current in rest of magnet increased by mutual inductance

  ⇒ quench initiation in other regions

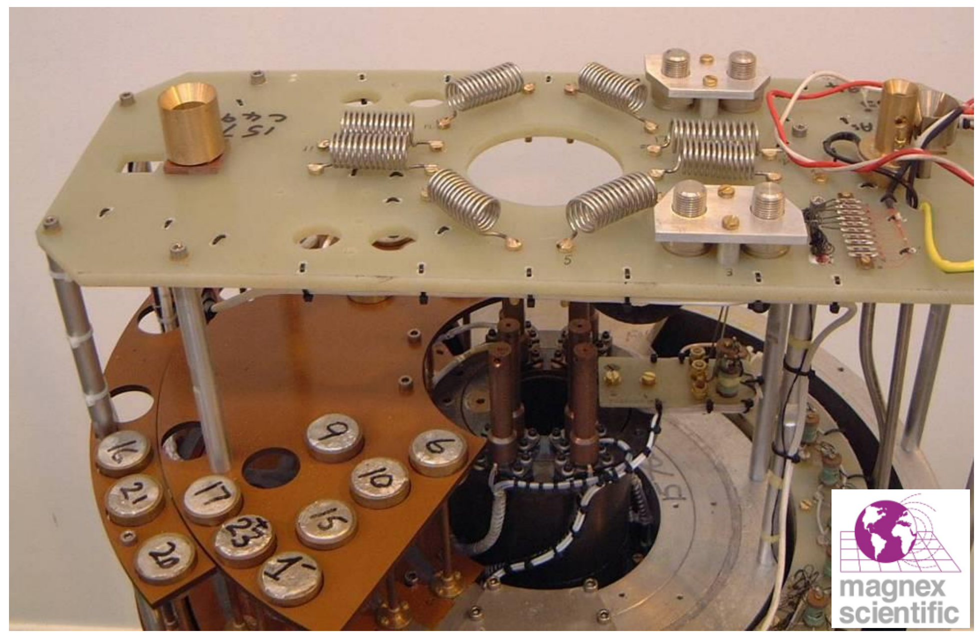
- often use cold diodes to avoid shunting magnet when charging it
- diodes only conduct (forwards) when voltage rises to quench levels
- connect diodes 'back to back' so they can conduct (above threshold) in either direction



Inter-connections can also quench



any part of the inductive circuit is at risk



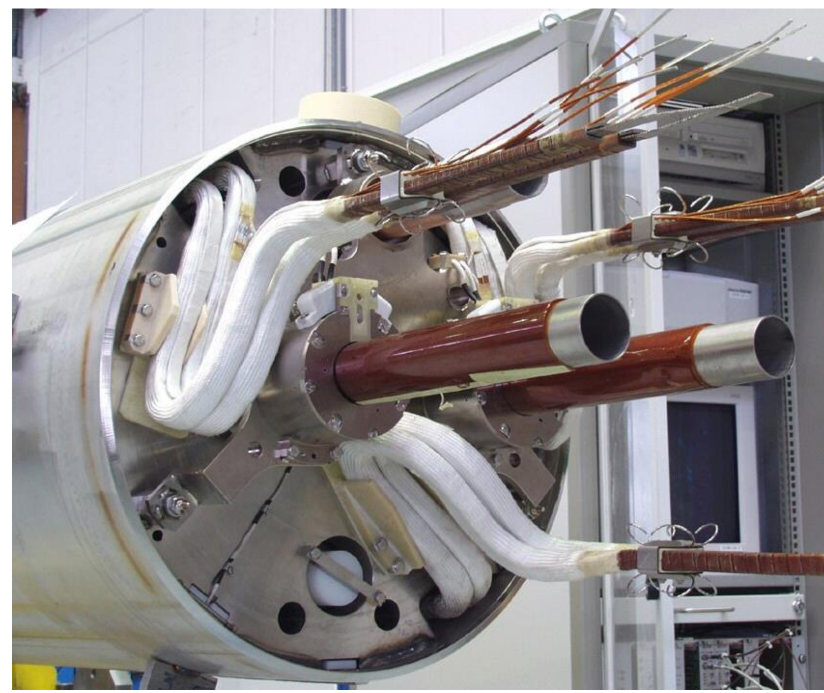
- coils are usually connected by superconducting links
- joints are often clamped between copper blocks
- link quenches but copper blocks stop the quench propagating
- inductive energy dumped in the link
- current leads can overheat

LHC dipole protection: practical implementation

It's difficult! - the main challenges are:

1) Series connection of many magnets

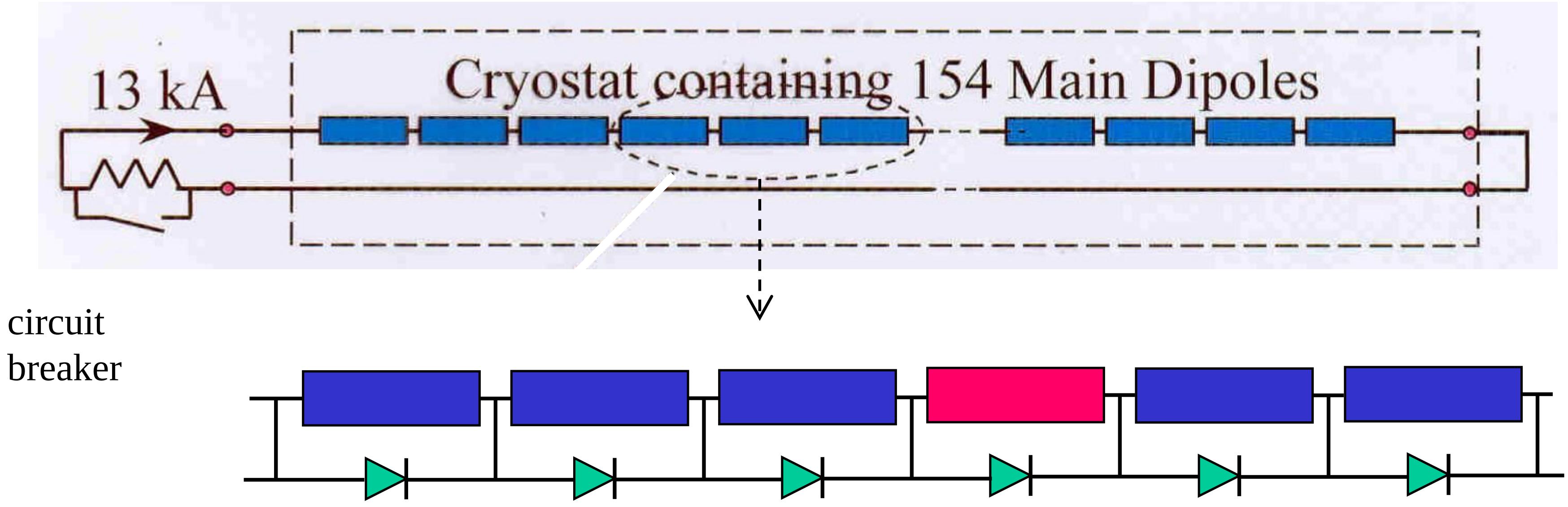
- In each octant, 154 dipoles are connected in series. If one magnet quenches, the combined energy of the others will be dumped in that magnet $\Rightarrow$ vaporization!
- **Solution 1**: cold diodes across the terminals of each magnet. Diodes normally block $\Rightarrow$ magnets track accurately. If a magnet quenches, it's diodes conduct $\Rightarrow$ octant current by-passes.
- **Solution 2:** open a circuit breaker onto a resistor (several tonnes) so that octant energy is dumped in ~ 100 secs.



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

- Individual magnets may burn out even when quenching alone.
- **Solution 3:** Quench heaters on top and bottom halves of every magnet.

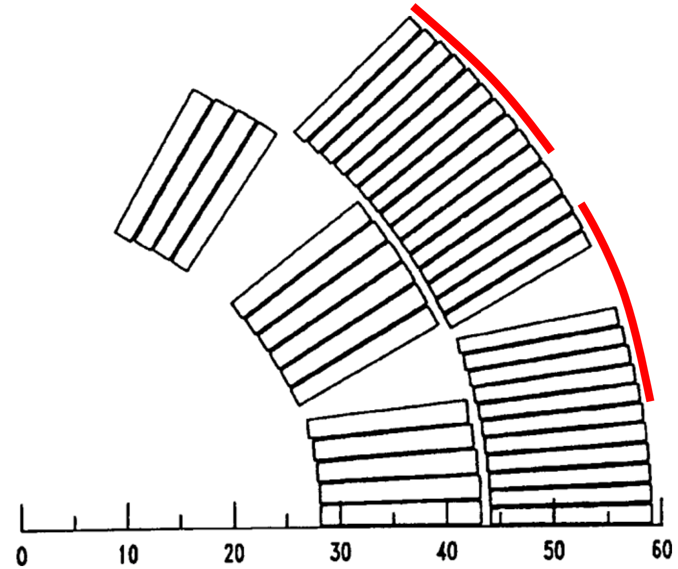
LHC power supply circuit for one octant

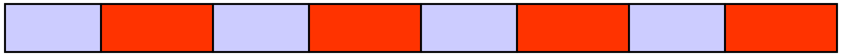


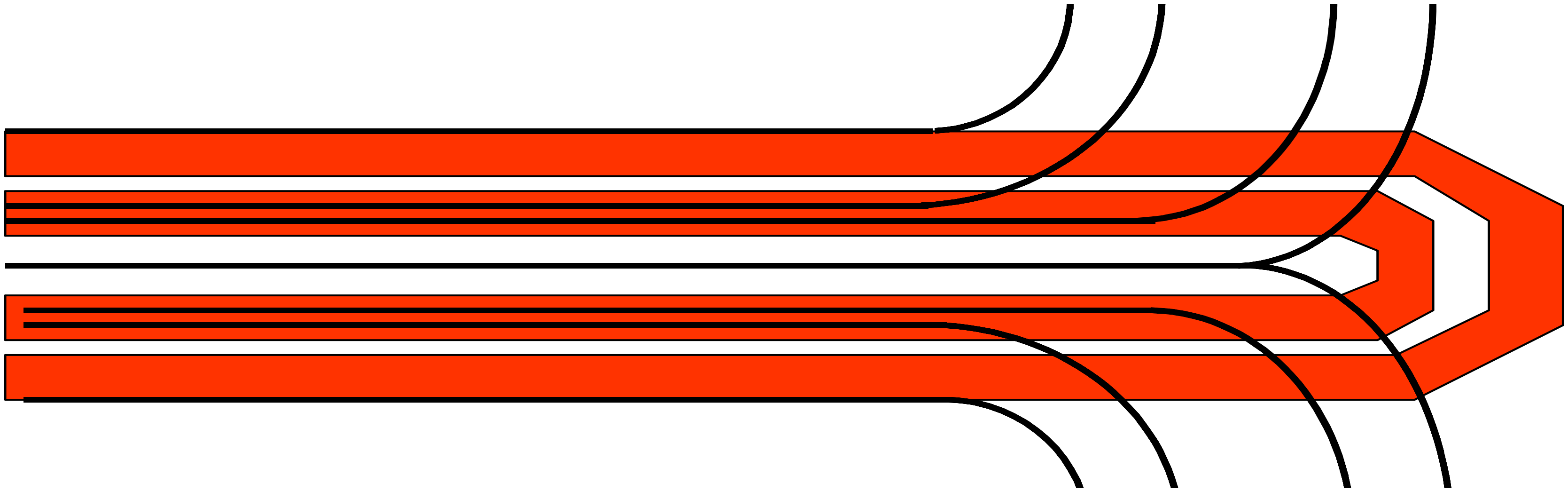
- in normal operation, diodes block ⇒ magnets track accurately
- if a magnet quenches, diodes allow the octant current to by-pass
- circuit breaker reduces to octant current to zero with a time constant of 100 sec
- initial voltage across breaker = 2000V
- stored energy of the octant = 1.33GJ

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

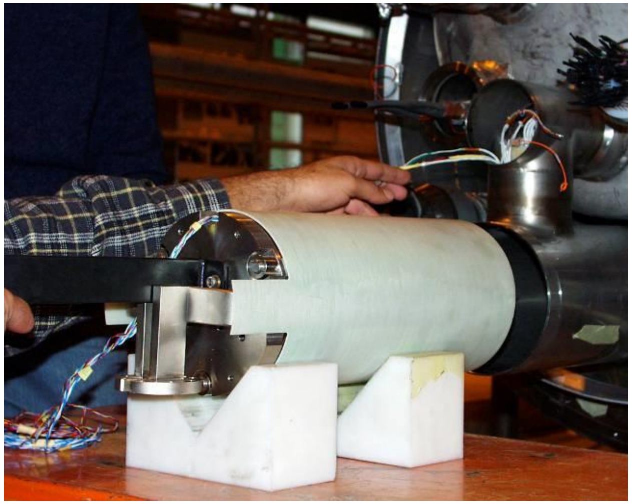




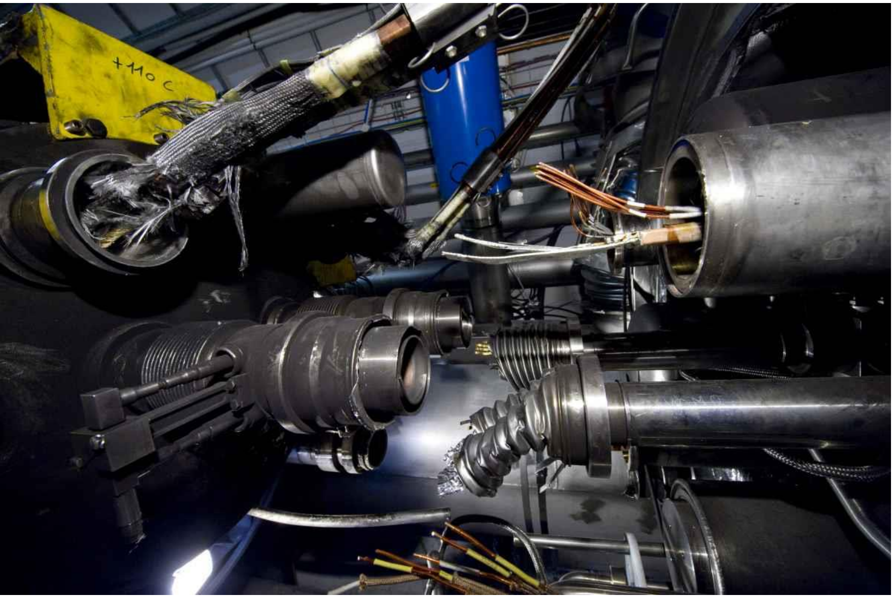


Diodes to by-pass the main ring current

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



Inter-connections can also quench!



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
- don't forget the inter-connections and current leads

always do quench calculations before testing magnet ✓

iter
china eu india japan korea russia usa

ITER
Cadarache
France

first plasma 2020?

B_{maxTF} = 11.8T

R_o = 6.2m

B_{maxCS} = 13T

E_{TF}= 41GJ

output power
500MW