(Multi) Normal Zone Propagation Velocity in high current density high field magnets

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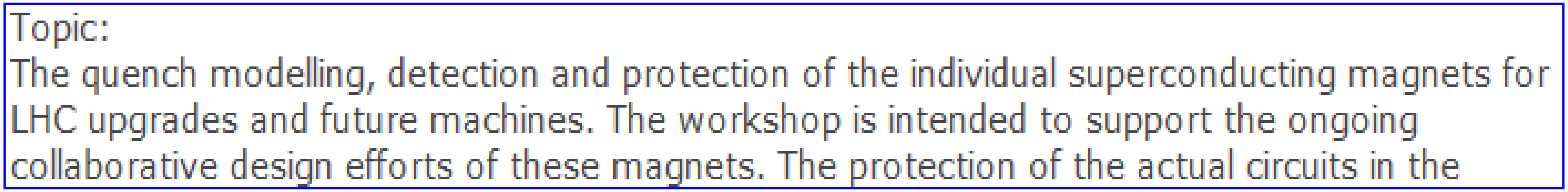
Scope



Topic:
The quench modelling, detection and protection of the individual superconducting magnets for LHC upgrades and future machines. The workshop is intended to support the ongoing collaborative design efforts of these magnets. The protection of the actual circuits in the

This implies in practice:

For Nb_3Sn, BSCCO-2212 and YBCO coils at 1.9 and 4.2 K:

- impregnated windings
- nearly adiabatic case for 1-100 ms time frame

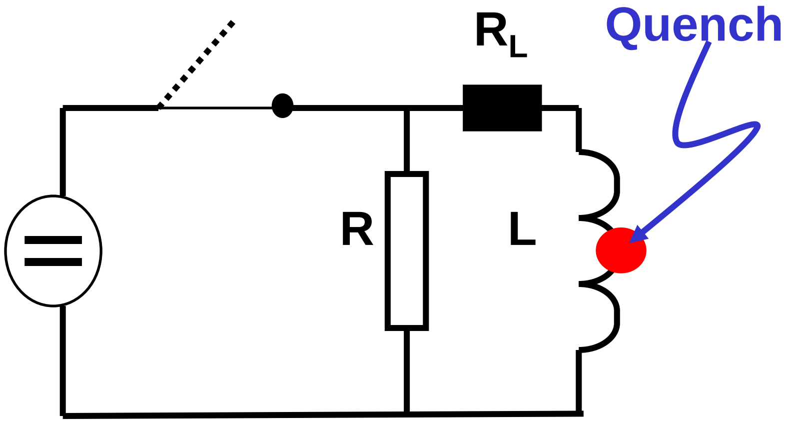
In fact, normal zone propagation in superconductors under adiabatic conditions is a simple case, well understood and documented.

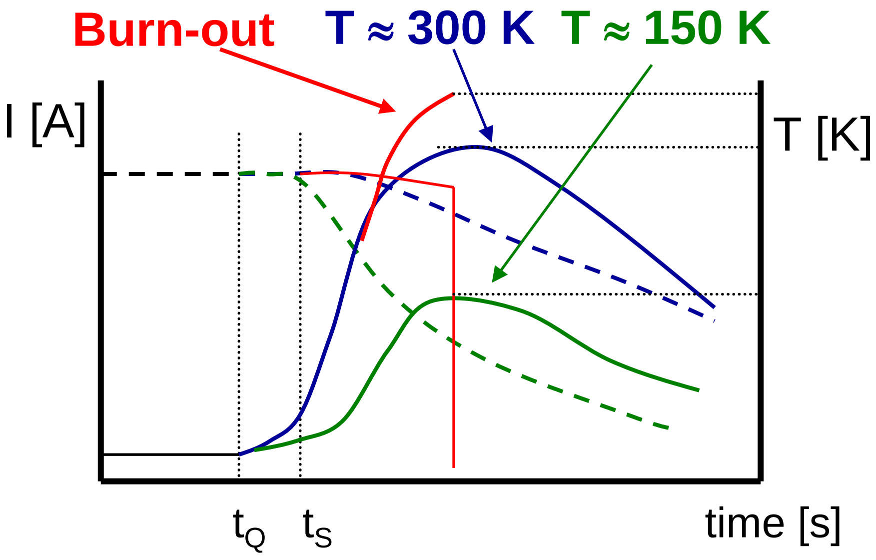
The challenge is more in the propagation through the coil windings in 3d and ways to accelerate this.

Preface

Quench protection, what for?

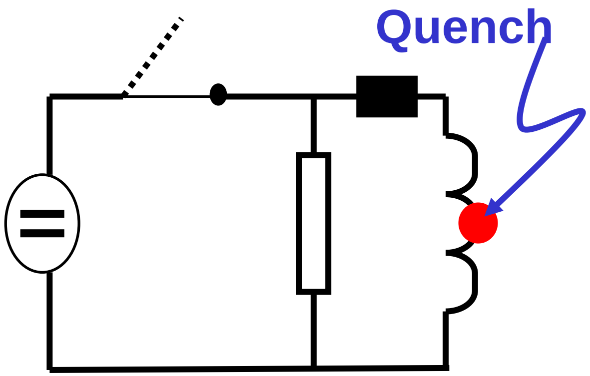
- Superconducting coil running at 4 K, what can go wrong ?
- Assume coil in circuit with power supply, switch and resistor as usual
- Quench, spontaneous transition to normal state in a hot spot larger than the MPZ
- ρJ^2 heating > temperature will go up
- Need a resistor, internally or externally or both, to bring the current down
- When not done, or too late the temperature will raise too high and the coil will die
- How to control this process
- What can be done…

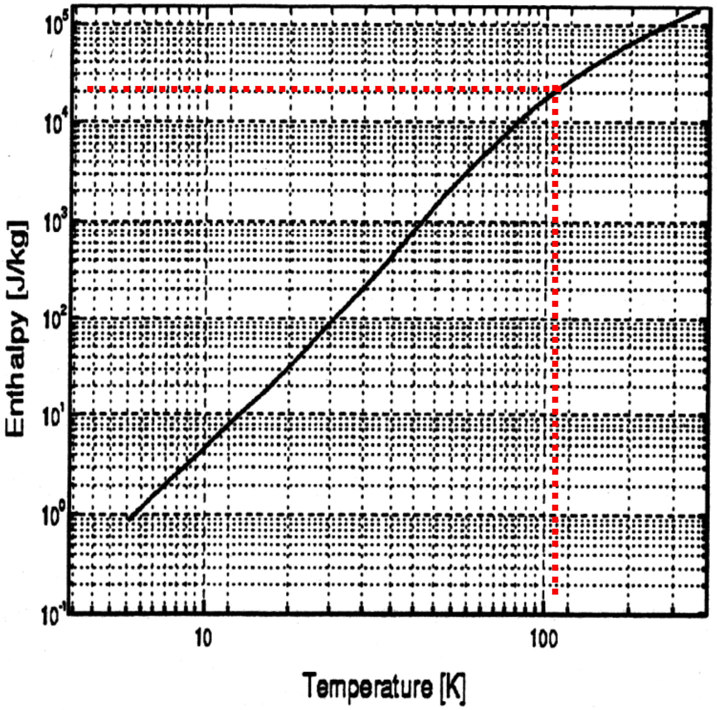




Stored energy to dump

- The energy stored in a magnet is $W_L = \frac{1}{2} L I^2$ [J] $= \frac{1}{2} \int BH\, dV$, the energy density being ½ BH or $B^2/2\mu_o$
- This energy could be absorbed by the magnet cold mass m assuming a safe peak temperature T_m
- $W_L/m = \int_4^{Tm} C_p(T)\, dT = H(T_m) - H(T_o=4.2) \approx H(T_m)$ since $C_p(4.2)$ is negligible
- Assuming 150 K, we can absorb about 20 kJ/kg cold mass provided uniformly distributed
- Usual values for W_L/m are in the range < 20 kJ/kg, so apparently no problem
- But the heat distribution must be controlling the normal zone spatial distribution and speed





Adiabatic heating of the conductor – Load Integral

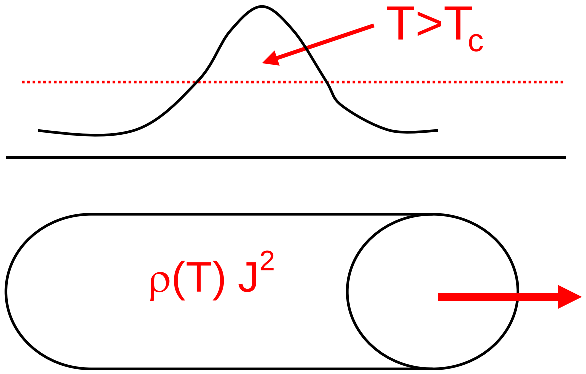
Temperature of the conductor

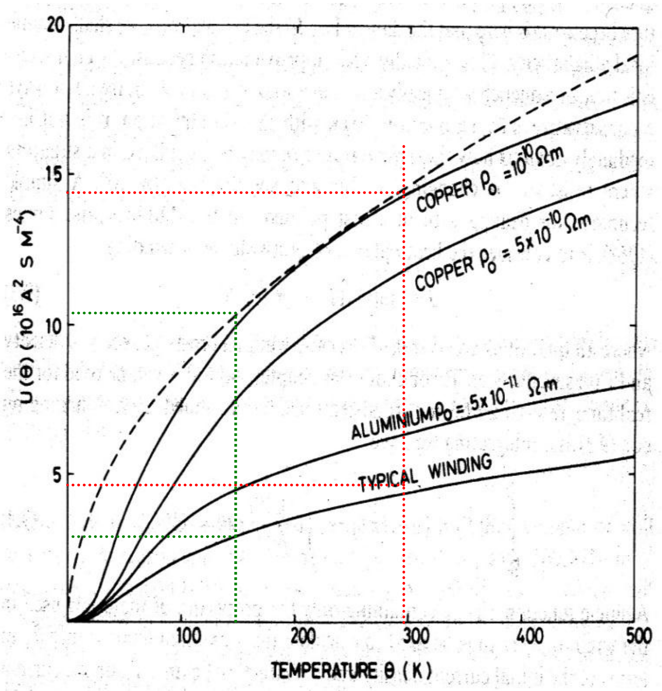
- Heating in the normal zone ρJ^2 is taken up by the conductor enthalpy, adiabatic case

$$\rho(T)\, J^2(t)\, dt = c(T)\, dT$$

$$\mathbf{{}_0\int^t J^2(t)\, dt = {}_4\int^T c(T)/\rho(T)\, dT = constant = F(T_m)}$$

- **F** is the load integral, also used to assess transient thermal loads in for example semiconductors
- **F** is a constant and can be calculated for any superconductor/matrix combination, wires, strands in cables
- **$F(T_m)$** values are in the range 2-10x10^{16} for 150K and 5-15x10^{16} for 300K peak temperature depending on the conductor composition

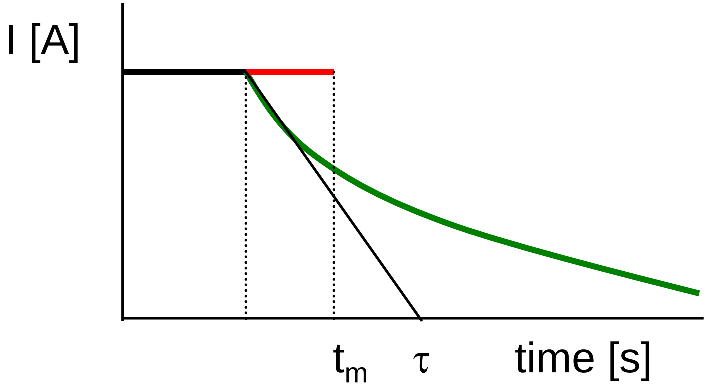




Adiabatic hot spot temperature

$$_{o}\int^{t} J^{2}(t)\,dt = {}_{4}\int^{T} c(T) / \rho(T)\,dT = \text{constant} = F(T_{m})$$

- Simple solutions exist for constant or exponential decaying currents



Constant current

$$J^{2}\,t_{m} = F(T_{m}) \rightarrow t_{m} < F/J^{2}$$

Exponential decay

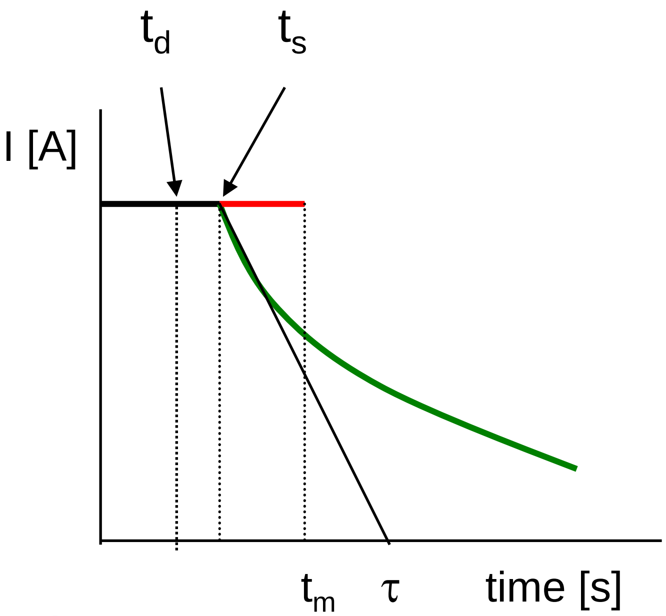
$$J^{2}\,\tau/2 = F(T_{m}) \rightarrow \tau < 2F/J^{2}$$

Examples

- NbTi/Cu and CuNi matrix conductors with J = 500 A/mm^2
- $F(300) \propto 1/\rho$
- F(300) for Cu is 1.4 10^{17} and ~1.4 10^{16} for CuNi (or pure NbTi)
- Maximum τ in NbTi/Cu before reaching 300 K is 1 second
- Maximum τ in NbTi or NbTi/CuNi is ~ few ms, so very little time to react and the conductor will burn out when used at high current density !

Controlling dumping time constant

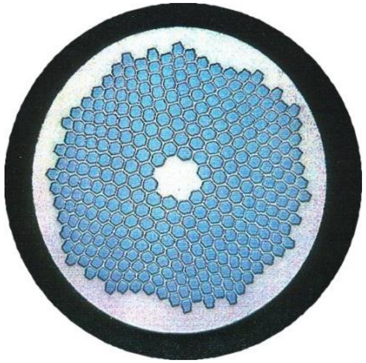
Challenge



- We need time to properly respond to a quench
- Time t_d required for detection, to verify and then to take action at time t_s
- The time t_d desired is 1-2 s when possible (essentially for filtering noise)
- Decay time τ must be far more than t_d, $\tau >> t_d$

Solution in low-current density (detector) magnets

- $\tau < 2F/J^2$ given F, we can only reduce J in the conductor matrix/stabilizer, add Cu or Al !
- then t_d (~1 second) << τ (minutes)
- In the seconds-minutes range also heat conduction will play a role, which greatly helps
- When possible (depends on how critical a high J is for getting your field) this strategy should be followed



Controlling dumping time constant

Solution in high-J magnets

(high-field NbTi or Nb_3Sn dipoles, quadrupoles)

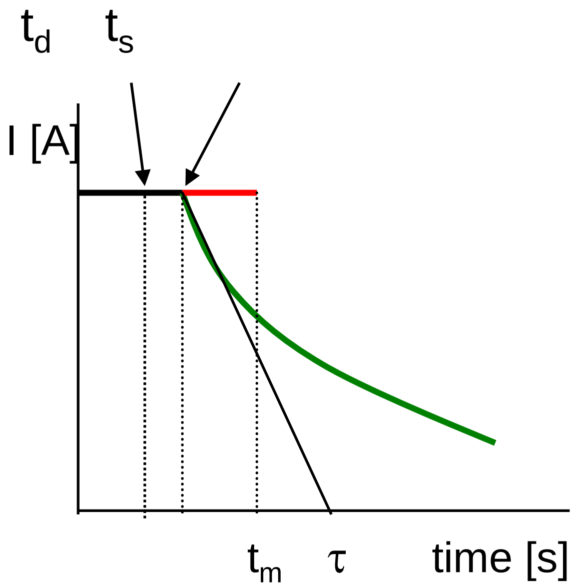
- $\tau < 2F/J^2$ given F, we can reduce J in the conductor matrix/stabilizer as far as possible, however, restrained by the high field requirement and cost
- t_d (5-10 ms) < τ (10-100 ms)

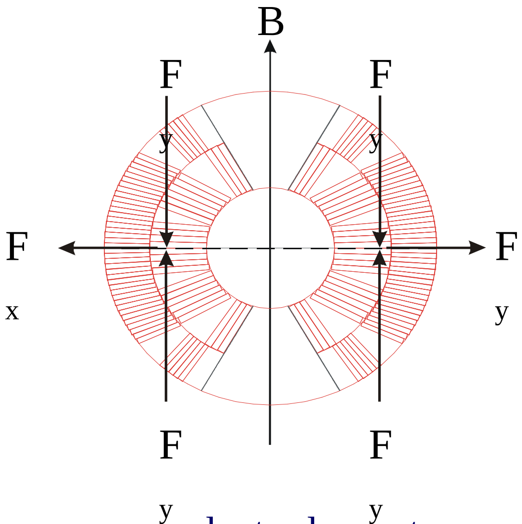
- Close to the limit, heat conduction cannot be fully exploited

- 5-10 ms detection time is very demanding for the detectors, filtering is hard, risk of spurious quenches

- A real problem for 11-16 T magnets, especially when built in 10-15 m length (not yet done so far !)

- Urgent need for a long study model to exercise quench protection in long high-field magnets



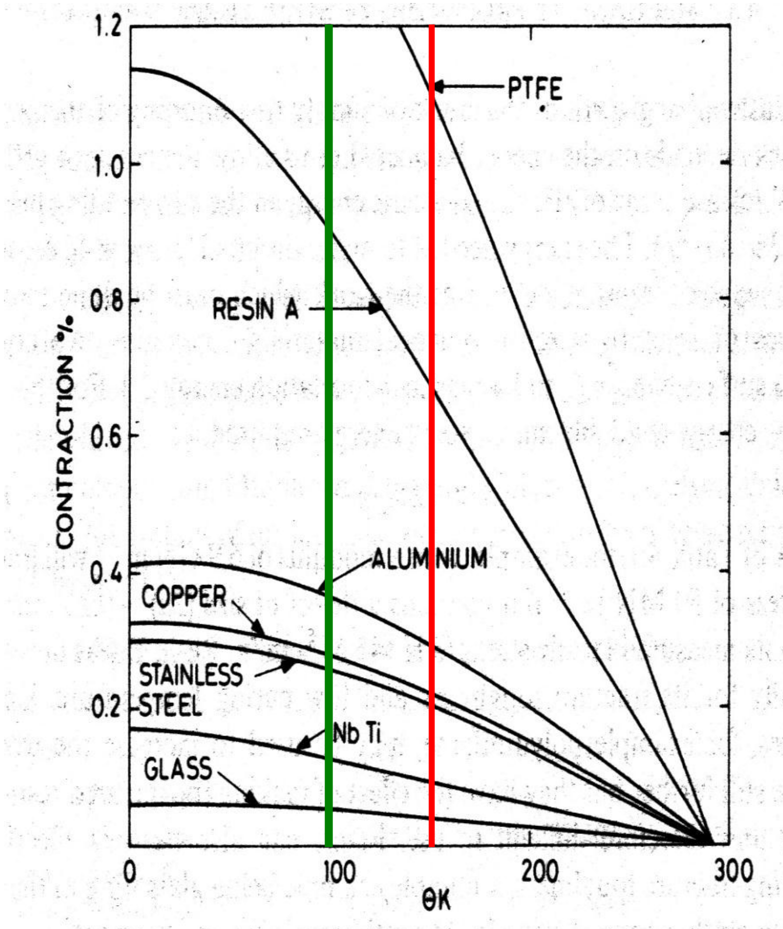


conductor lay-out

Safe hot spot temperature

Criterion for limiting hot spot temperature

- Beyond 900 K Al structures start to collapse
- Beyond 650 K we start to lose pinning, so J_c
- Also 300 K is far too high, as this implies severe thermal shock due to differential thermal contraction of the various materials in windings and interfaces to structures
- This may cause resin cracking, de-bonding, and thus training and degradation with time
- A safe hot spot temperature still is 100-150 K
- Usually 100 K is taken nominally and a peak of 200-300 K tolerable for exceptional cases when protection systems fail



300 K may be acceptable for a single R&D magnet, but is not an acceptable design value for series production of long magnets with accelerator quality meant to be installed in a system!

Normal zone propagation in wires in 1d

Expanding normal zone in a wire

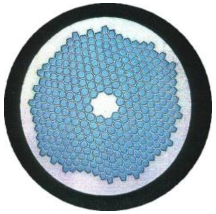
- Assume a normal zone in a wire, consider the 1-D heat balance equation in z:

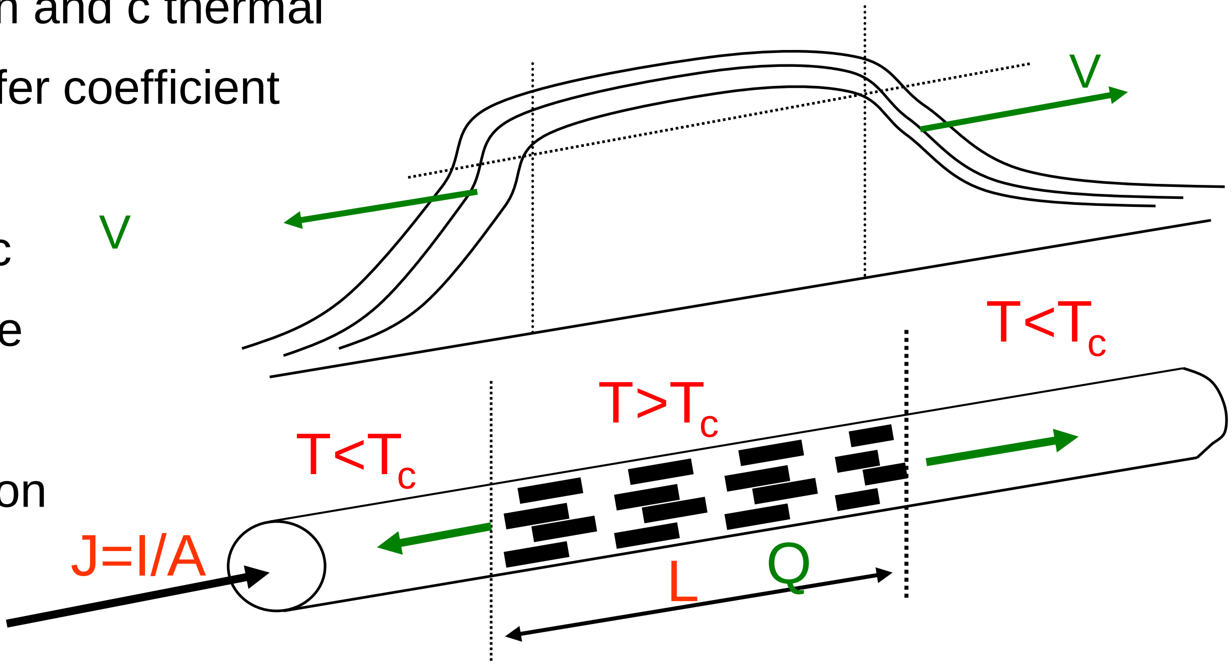
  $P.A + \partial/\partial z\, [\lambda(T)\, \partial T/\partial z]\, A = c(T)\, \partial T/\partial t\, A + h.p.(T_c - T_o)$

  where P(T) is the heat production in the zone

  $P(T) = \rho\, \eta^2 J^2\, (T - T_{cs}) / (1-\eta)(T_c - T_{cs})\ [W/m^3]$

  A area, p perimeter, λ, h and c thermal conductivity, heat transfer coefficient and specific heat
- For simplicity P, λ and c are taken at the average temperature $(T_{cs}+T_c)/2$
- A traveling wave solution can be found with constant velocity v





Normal zone propagation in 1d

An analytical solution is found in terms of a travelling wave with constant velocity v

Adiabatic conditions (h=0)

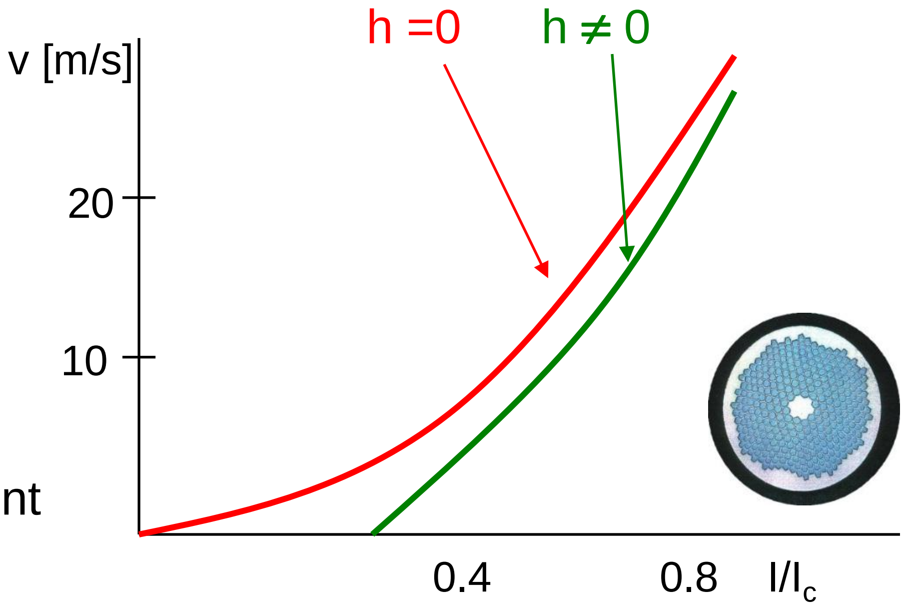
$v_z = J/c \{ \rho.\lambda / (T_{cs}/2 + T_c/2 - T_o)\}^{1/2}$ [m/s], so v $\propto$ J and 1/c as expected

- This velocity is valid in normal size conductors in fully impregnated coil windings where the heat transfer is negligible.
- Normal velocities in LTS are in the range 5-30 m/s

With cooling (h≠0, >>100)

$v_z = v_z(h=0)$ x correction factor

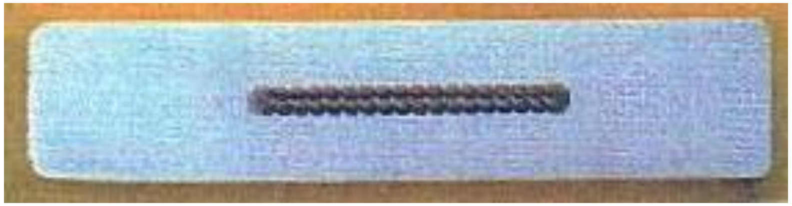
- Not further detailed here, #NA
- There are many cases that h≠0
- Cable-in-Conduit Conductors
- Helium in Rutherford-cables
- Large size Al stabilized conductors
- Causes velocity reduction at low current
- Usually marginal influence for high I/I_c



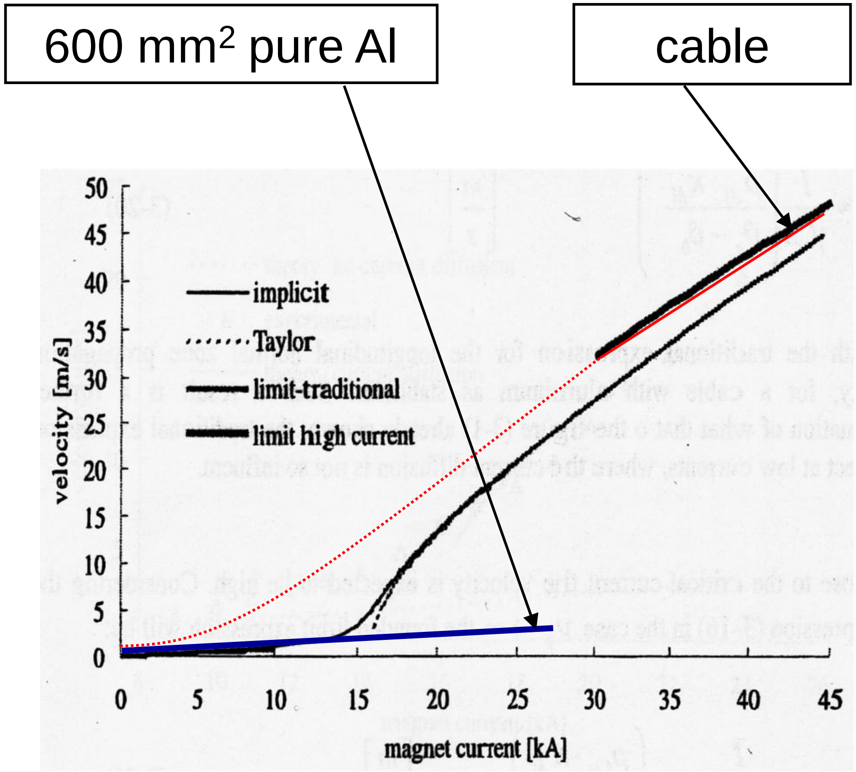
Non-standard case: example ATLAS conductor

2d heat and current diffusion into the Al stabilizer

- Large size requires to include heat and current diffusion !
- Example ATLAS Barrel Toroid conductor:
- 40 strands Rutherford cable (60 mm^2) inside Al stabilizer of 57x12 mm^2
- I_c = 65 kA at 5 T
- What is J=I/A in this case?
- At low current: dominated by Al
- At high current: dominated by cable (almost adiabatic)
- Good example of non-uniform conditions requiring a dedicated analysis in more dimensions
- Be careful with using too simple formulae



ATLAS BT conductor 57mm x 12mm

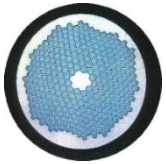


600 mm^2 pure Al

cable

Normal zone propagation in coil windings

Propagation along the impregnated conductor (Rutherford cable)

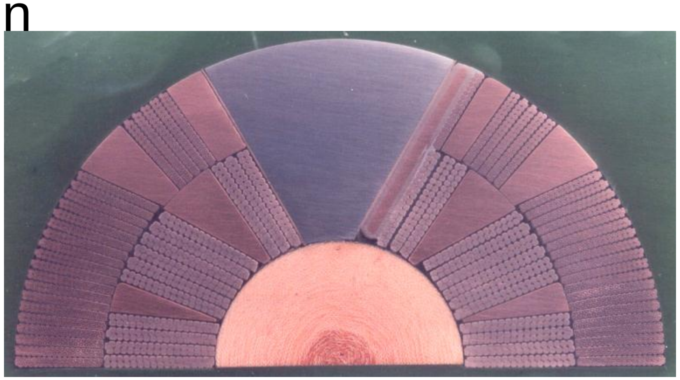


- As before $v_{//} = J / c \, [\rho \, \lambda / (T_{cs}/2 + T_c/2 - T_o)]^{1/2}$

Transverse direction in windings: cable-to-cable

- Heating through many layers of insulation dominating the velocity in transverse direction

  $v_\perp = v_{//} \, [\lambda_\perp / \lambda_{//}]^{1/2} \approx v_{//} / 70$ to $v_{//} / 20$



- Normal values are in the range:

  $V_{//} =$ 5-30 m/s and $V_\perp =$ 10-100 mm/s

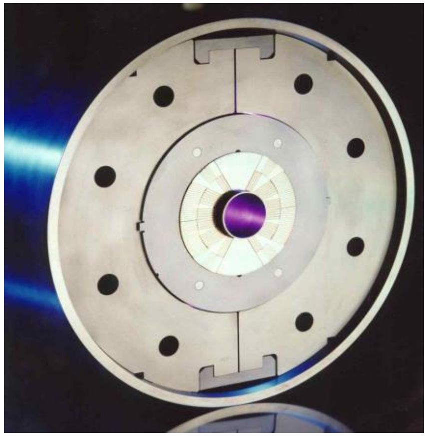
Resistance increase in the coil

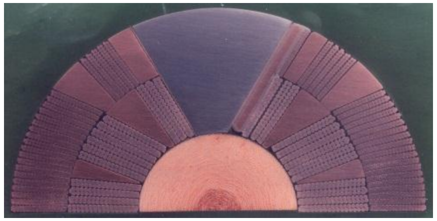
- Due to $v_{//}$ and $v_\perp$ and by $\rho(T)$ since the temperature will rapidly increase
- The resistance is found by integration over the affected volume in 3 dimensions.
- Many numerical codes exist to perform this integration.

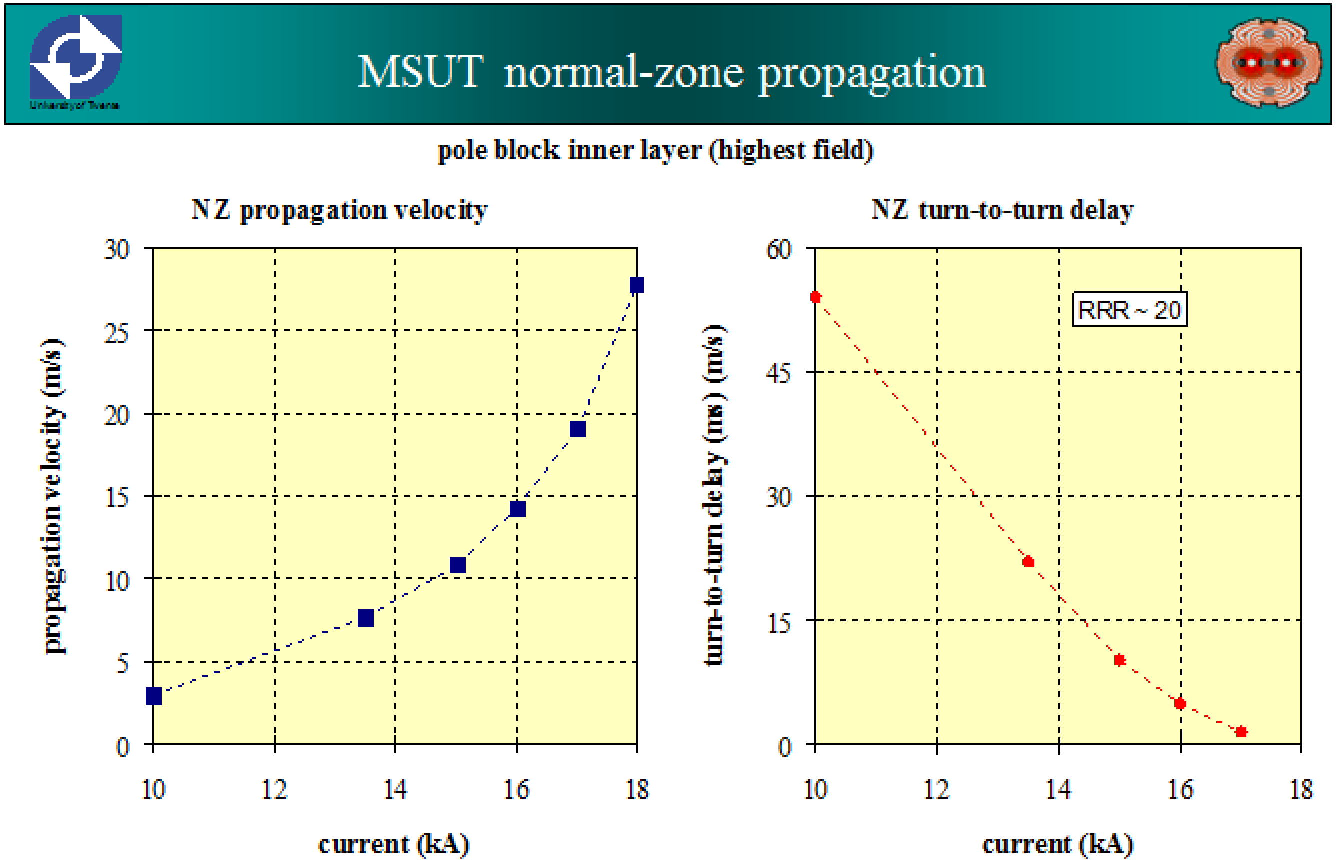
Example: propagation in 11T-MSUT Dipole Magnet (1995)

Features: 11.3 T/18.6 kA at 4.4 K, 50 mm bore, 1 m long, 130 MPa, 192 filaments, 33 PIT strands R-cable, fully impregnated.

NZ propagation velocities were measured and are according adiabatic case: ~ 30 m/s in strands and ~ 1 ms turn-to-turn.







MSUT normal-zone propagation

pole block inner layer (highest field)

Acceleration of propagation

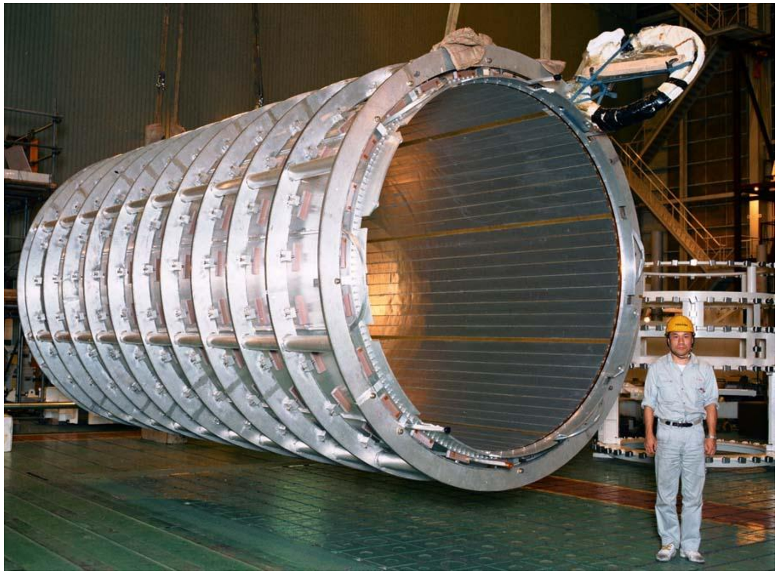
Three methods

- Quench propagation can be accelerated by introducing additional normal zones:
  - switching on additional heaters
  - making thermal short cuts, or
  - instantly force a global transition by overcurrent or induced AC current loss

Heaters

- Extra heaters are positioned in the windings, multiple normal zones are created

Thermal shorts (ATLAS Solenoid)



- Pure Al strips are glued on the windings in the bore in axial direction
- Quench propagates from one end to the other end through only 2 insulation layers, rather than through hundreds
- Another advantage: the method is passive, not requiring detection
- Method too slow for HF coils

Acceleration by multiple normal zones

To stay well below 300K, need to make the coils normal within 10 ms, (depending on details of conductor, coil diameters, materials etc.), also assuming some 10 ms detection and heater firing time.

How to bring a 15 m long D or Q magnet to normal state within 10 ms?

We need for propagation a uniform solution and protection per meter of coil.

Cable-to-cable propagation is marginal, only the next cable reachable within few ms.

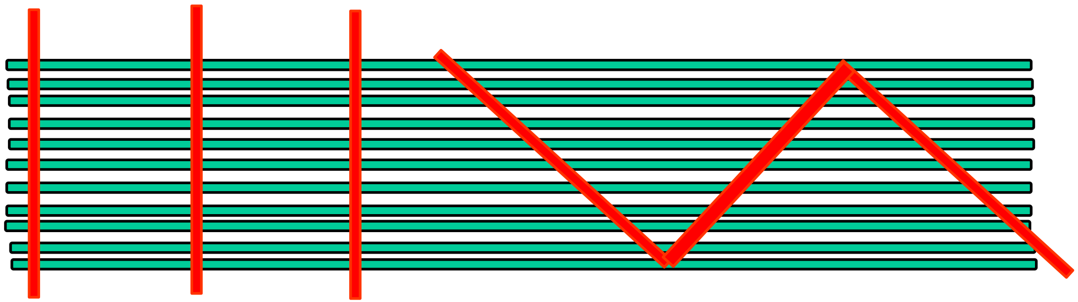
Layer-to-layer is too slow, so we need transverse line heaters on both layers (or a redundant and heavy heating system in-between the two layers).

⇒ Heating system with spot-like “heating stations” is not good enough for the 5-10 ms range and T_max < 150K.

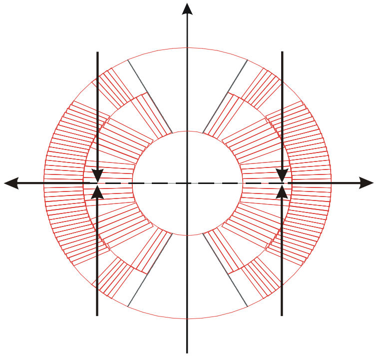
⇒ Likely need heating of all, usually both layers and instantly heat a short section in nearly all cables.

Worst case: rely on longitudinal propagation only => Initiate multiple normal zones in all cables periodically.

Heaters and power for long magnets



Heater layouts introducing hot spots in all cables



Example:

Switch 15 m magnet to normal state in 10 ms with 15 m/s nz velocity

15 m with15 m/s => 1 s, need 50 hot line heaters in 15 m, 3 per meter.

Heating power:

1 ring type heater element sized ~ 20 cm x 0.5 cm,

when using 25 W/cm^2 one needs 250 W/heater, 750 W/m for 1 layer

with heaters in 2 layers, 1.5 kW/m, ~ 25 kW per single bore magnet of 15 m!

with 2 fold redundancy and 2 apertures: ~ 100 kW per magnet

Perhaps at 50-70% less when relying on a cable turn-to-turn propagation

Doable but not that nice!

Ideas of instantly heating of all cables

1. Use pulsed over-current , go beyond Ic

- Not practical as we need some +3-5kA single pulse from capacitor bank and even higher below nominal current.

2. Heat from AC loss induced by dB/dt, generated by surface coils

- Works in principle, was used in magnetic switches, but activation coil with supply or capacitor drive must be rather powerful, meaning thick, no 100 % surface coverage, not practical.
- Advantage though is galvanic isolation present.

3. Heat from AC loss by induced current oscillation

- Variant of 1, but now many periods, higher frequency, based on AC loss rather than over-current, relatively low current needed. Used in the past for sc gate / switch opening.

A hybrid system of the Induced Current Oscillation system and the all cables touching periodic heaters system may be the best as it provides redundancy which is needed anyway.

Conclusion

- Quench protection requirements of magnets must be respected from the beginning, otherwise magnets will degrade or die…….
- For low voltage, diode-shorted magnets the protection is based on normal zone propagation velocity. In compact high field accelerator magnets we find 10-30 m/s, by far not enough to warrant hot spot temperatures below 150 K, which should still be the driving criterion.
- Essentially for driving a coil normal in 10-20 ms range, following a quench, all turns in the coil must be heated at intervals of some 10 cm and in all layers; or even better, instantly go normal across the entire coil.
- Much faster and more robust heating systems must be developed.
- The induced ac-current method deserves a serious development but requires a second redundant system.
- Quench propagation studies on realistic long magnets are urgently required to assess the various options and test new ideas.
- “Keep it simple, robust and redundant”, is the way to success.