Protection of superconducting magnet circuits

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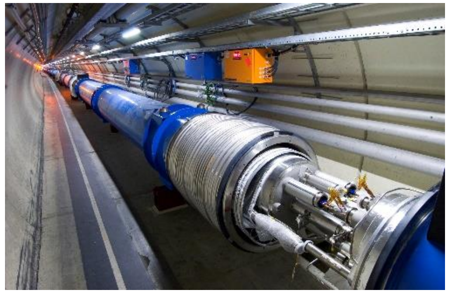
Stored energy of a superconducting magnet

Magnet is an inductor, hence: $E = \frac{LI^2}{2} = \frac{\mu_0}{2}\int B^2 dV$



- The 14-m long LHC dipole has a stored energy of **7 MJ** at the design filed of 8.4 T

- Smaller scale (~1 m long) prototype accelerator dipoles and quadrupoles at their operational current are typically in 0.5-0.7 MJ range

This is a lot of energy!

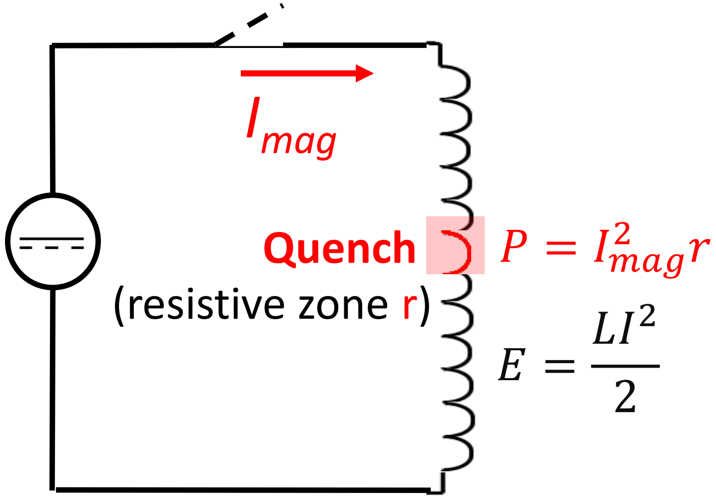
- ➢ 0.7 MJ is energy of a car (2000 kg) moving at 60 mph
- ➢ 0.7 MJ of energy is sufficient to heat up from 4 K and melt ~1 kg of copper!
- ➢ Equivalent He gas release is 254 L / kJ => 177.8 m^3 of gas!

If the gas cannon be released quickly…. ->

What is a quench?

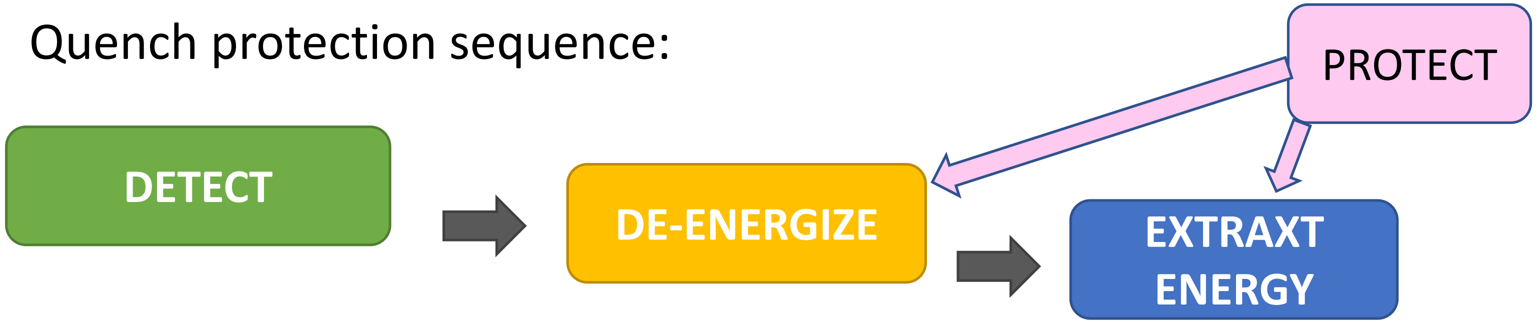
A formation of an unrecoverable normal zone within a superconductor

Quenching will convert energy supplied by the current source **AND** magnet stored energy into **heat**.



- When quench occurs, energy release is **localized** in the normal zone of the conductor!
- If that zone is small in volume, Quench may lead to unrepairable magnet damage of the magnet windings or other electrical infrastructure (splices, current leads, etc…).
- **Quench protection** is an array of techniques used to prevent such damage from occurring.

Quench protection sequence:



DETECT

DE-ENERGIZE

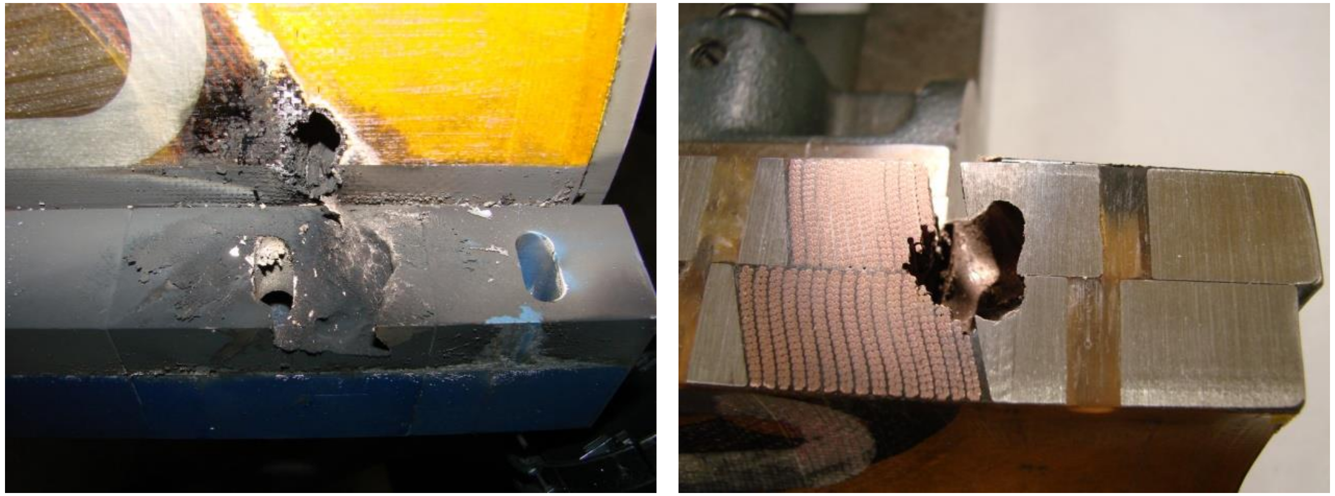
PROTECT

EXTRAXT ENERGY

Quench in small-scale accelerator magnet

(movie)

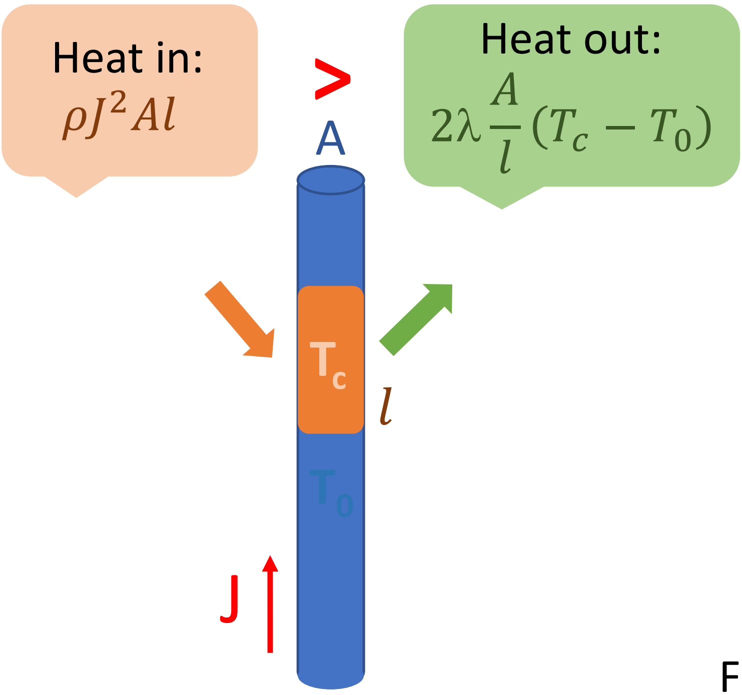
Quench in the CCT3 dipole (~ 80 kJ of stored energy)



Quench-related damage in the coil of HQ01 quadrupole

Onset of a quench: minimum propagating zone

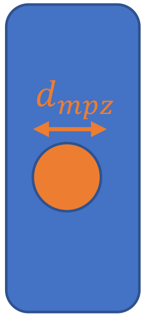
It only takes a small volume fraction of a current-carrying superconductor to be heated above its transition temperature to start a quench.



$$l_{mpz} = \sqrt{\frac{2\lambda(T_c - T_0)}{\rho J^2}}$$

3D case:

$$d_{mpz} = \pi\sqrt{\frac{2\lambda(T_c - T_0)}{\rho J^2}}$$



ρ – resistivity in normal state
λ – heat conductivity

For a pure NbTi wire (no stabilizer): l_{mpz} ~1 μm

For a multi-filamentary NbTi strand: l_{mpz} ~1 mm

Given that specific heat of metals at low temperatures is ~1000 times less than at room temperature, this l_{mpz} yields a very small amount of heat needed to start a quench…

Minimum quench energy

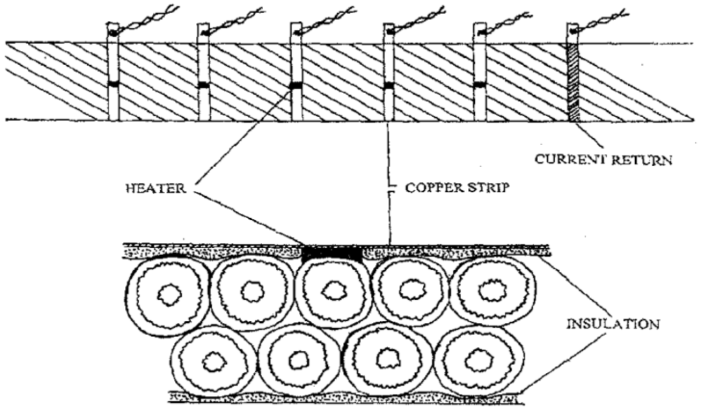


Fig 2. Schematic of the heater location on a strand in the cable.

A.K. Ghosh et al., 1997

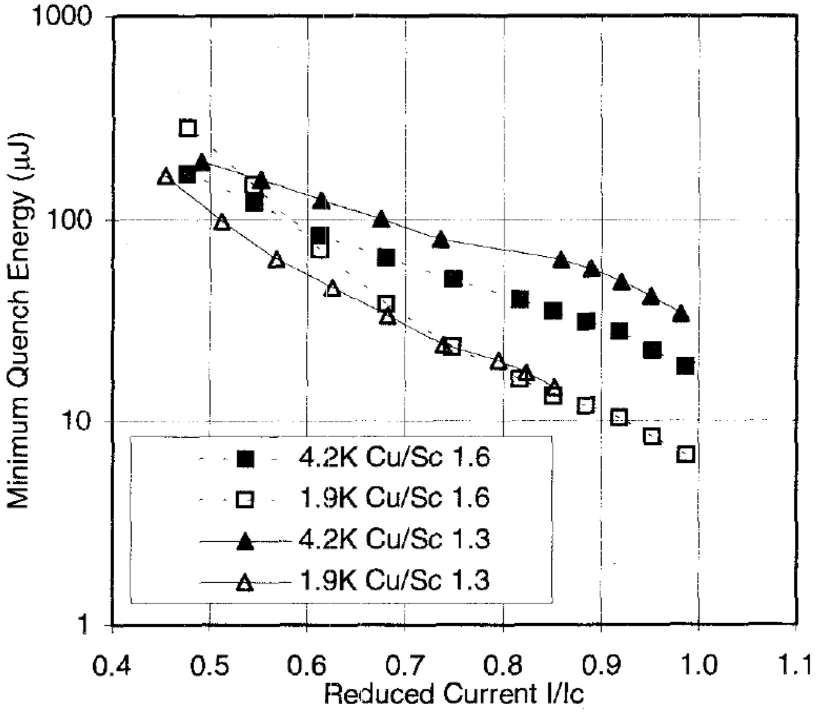
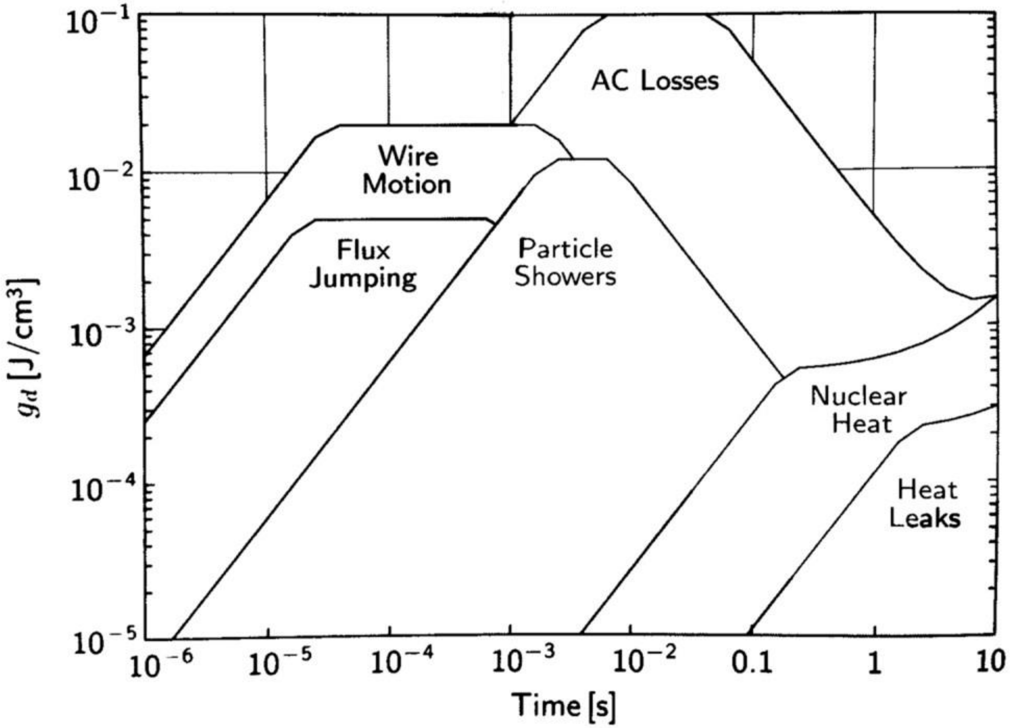


Fig. 3. MQE for two LHC type strands with different Cu/Sc ratio.

- 10 μJ is the kinetic energy of a staple dropped from a 3 cm height….
- …and is **~10^{11} -10^{12} times less** than a stored energy of a typical accelerator magnet!

What can start a quench?

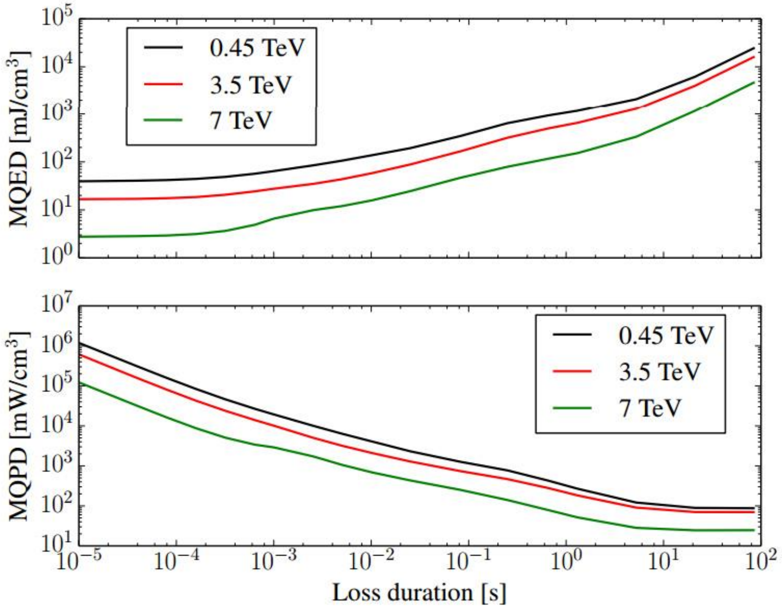
- Intrinsic
  - Conductor instability with respect to flux jumps
  - Conductor damage / broken strands
  - AC losses
- Mechanical
  - Motion of the conductor
  - Cracking and delamination of impregnation epoxy
- Thermal
  - Excess heating in splices or current leads
  - External heat leaks
  - Nuclear and beam radiation

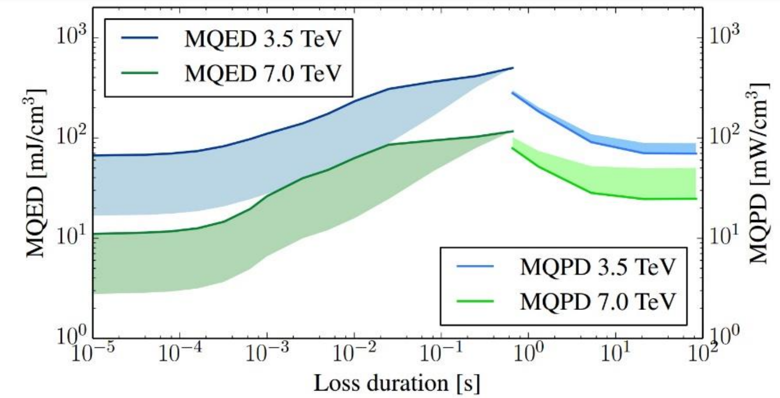


Disturbance spectra of accelerator magnets
(Y. Iwasa, “Case Studies in Superconducting magnets”, Springer 2009)

Quenching is therefore considered a natural part of the magnet operation, and magnet systems should be designed to handle it safely.

Note on beam losses and quenching





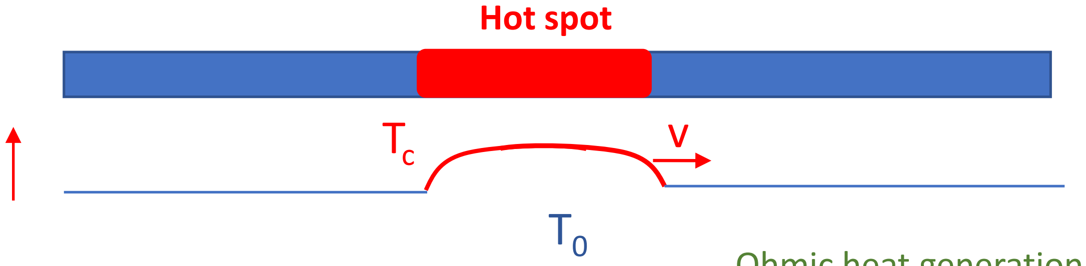
"Testing beam-induced quench levels of LHC superconducting magnets",
B. Auchmann *et al.* Phys. Rev. ST Accel. Beams **18**, 061002 (2015)

- Short-duration ($t < 50$ μs): The local quench level is determined predominantly by the volumetric heat capacity of a dry cable. The quench level in this regime is quantified by the Minimum Quench Energy Density (MQED).

- Intermediate-duration (50 μs - 5 s): The liquid helium in the cable interstices and, to a lesser extent, around the insulated conductor plays a crucial role.

- Steady-state ($t > 5$ s): The heat is constantly removed with a rate that is mainly determined by the heat transfer to the helium bath through the cable insulation. The quench level, is expressed as a Minimum Quench Power Density (MQPD).

Quench propagation: 1D model



Heat balance:

Heat capacity

Ohmic heat generation

$$C\frac{dT}{dt} = \lambda\frac{d^2T}{dz^2} + \mathrm{g}(J,T)\,,$$

Heat conductivity

Substituting: $\xi = z - vt$

$$\lambda\frac{d^2T}{d\xi^2} + Cv\frac{dT}{d\xi} + \mathrm{g}(\xi) = 0\,, \qquad \mathrm{g}(\xi) = \begin{cases}\rho J^2\,, \xi < 0\\ 0 \quad\;\,, \xi < 0\end{cases}$$

$$T_w = T(\xi = 0) = 0.5(T_c + T_0)$$

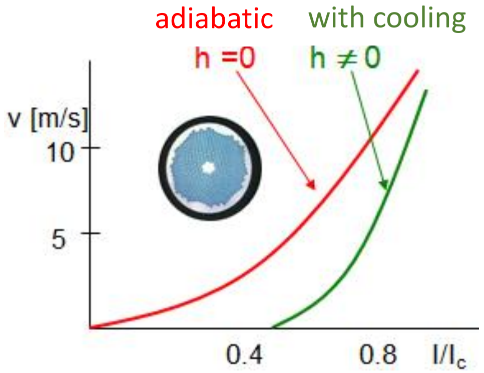
General solution for the equation:

$$\mathrm{T}(\xi) = \begin{cases} T_c - (T_c - T_w)\exp(\alpha\xi)\,, \xi < 0\\ T_0 - (T_w - T_0)\exp(-b\xi)\,, \xi > 0\end{cases}$$

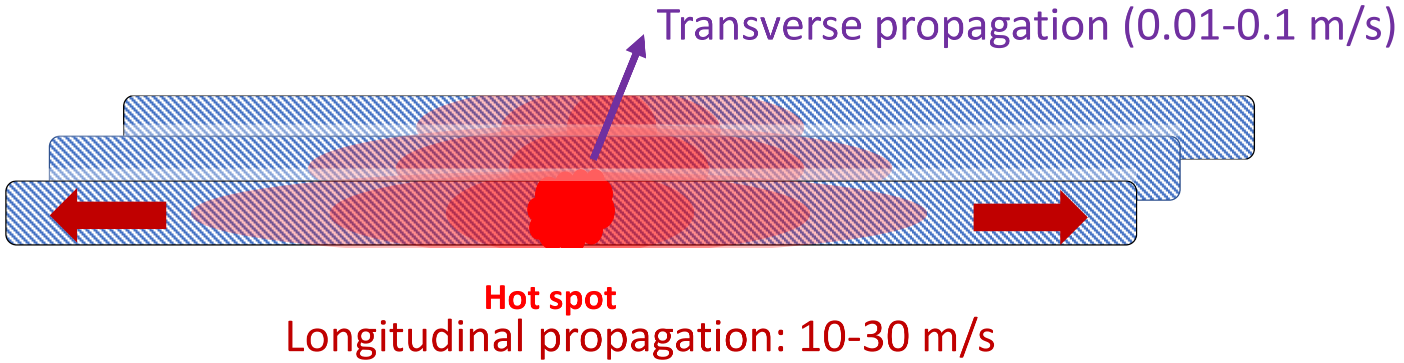
- a travelling wave solution

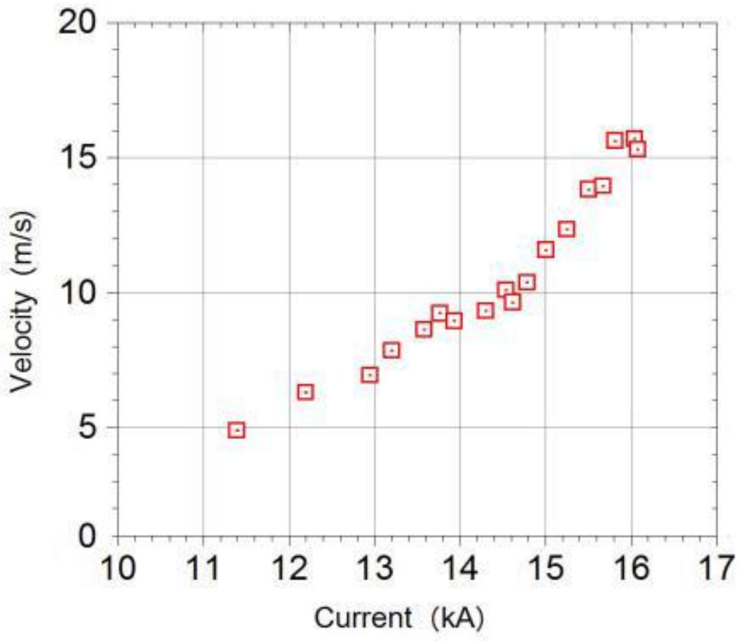
Then, substituting into the heat equation: $v_0 = \frac{J}{C}\sqrt{\frac{\rho\lambda}{T_c - T_0}}$

Assuming $C\sim T^3$: $v = v_0\sqrt{\frac{4T_0^5(T_c - T_0)}{T_c^2(T_c^4 - T_0^4)}}$ Dresner, 1994



Quench propagation in 3D



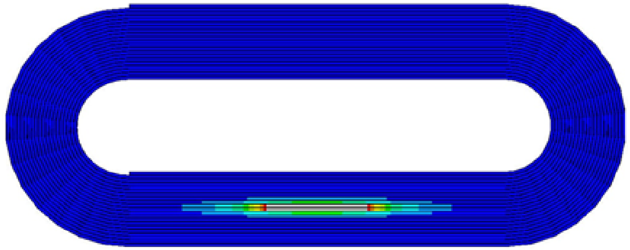


Quench propagation velocity measurements in HD3 high-field dipole (I_{ss}=18.7 kA)

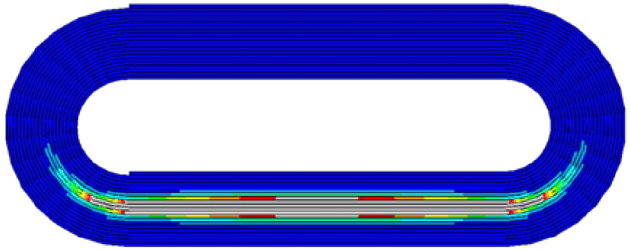
Resistance increase in the coil caused by the expansion of the normal zone AND continuing temperature increase within the normal zone

The total coil resistance can be found by integrating $\rho(T,B)$ over the normal volume

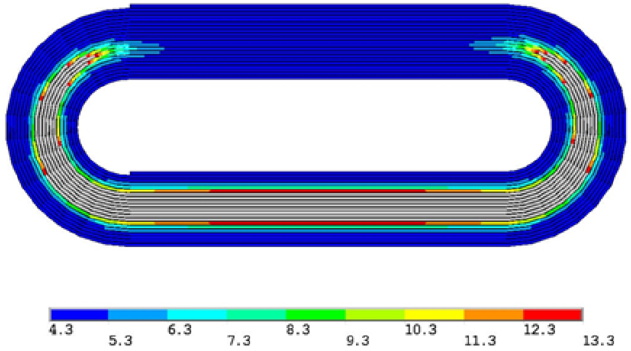
Quench simulations: FEA



Tmax = 24 K Time = 30 ms



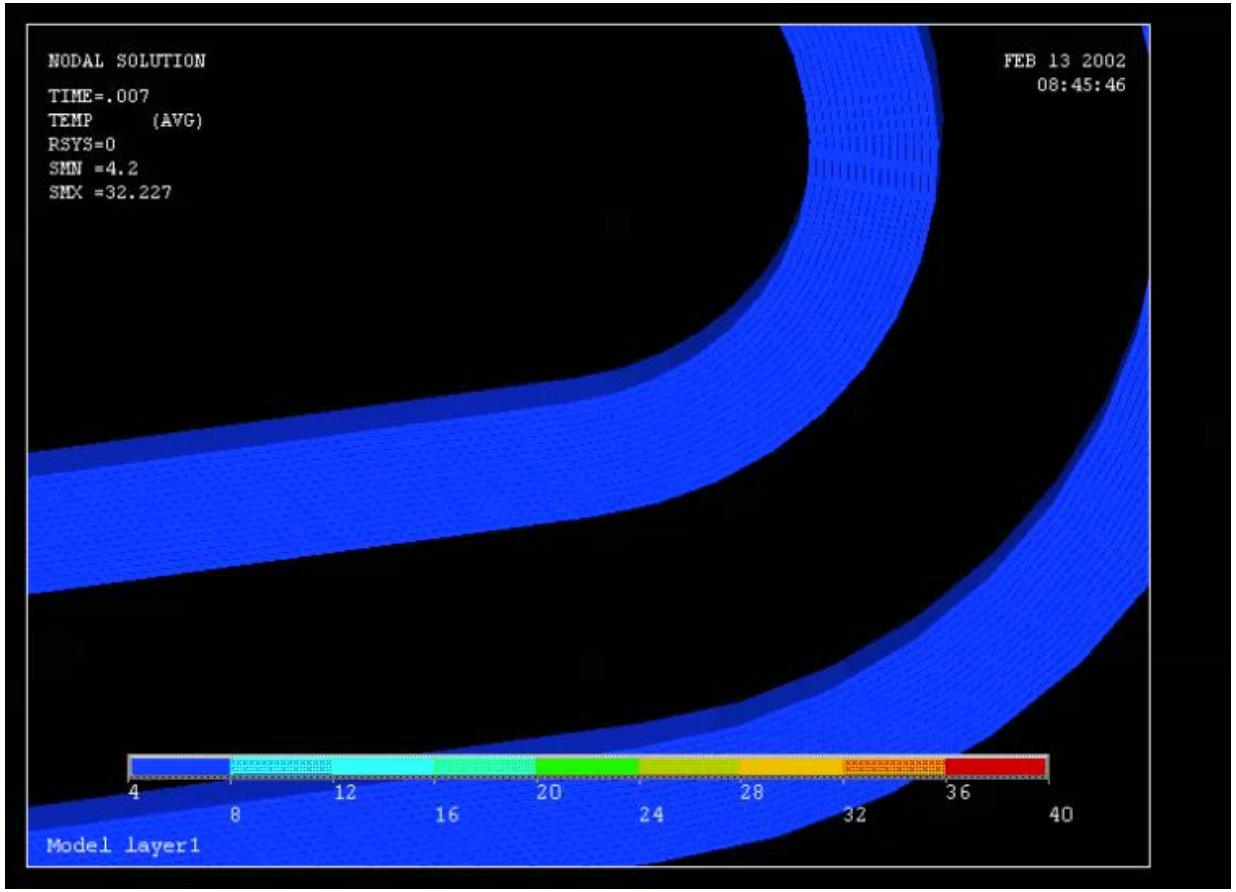
Tmax = 44 K Time = 80 ms



Tmax = 62 K Time = 130 ms

P. Ferracin, 2009

ANSYS – thermal electrical model

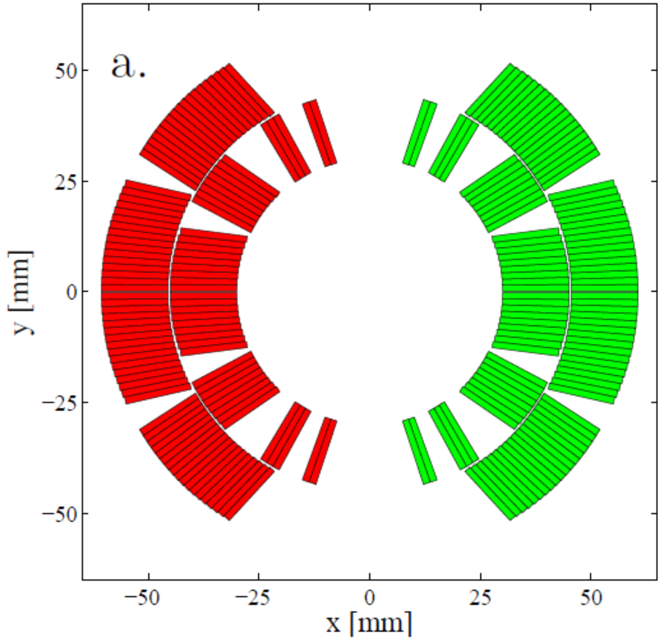


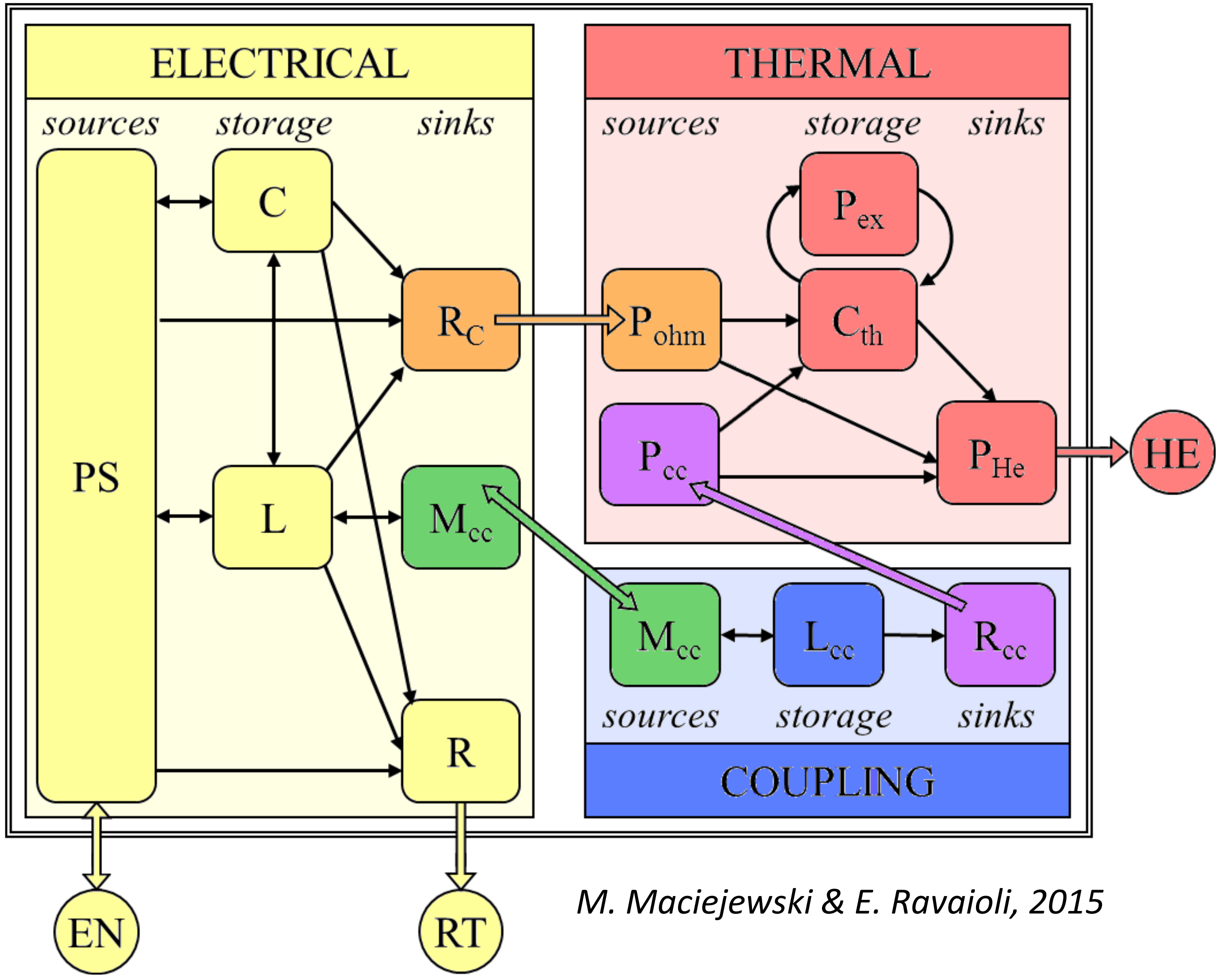
Courtesy: S.Caspi

(movie)

Lumped element and “circuit” models

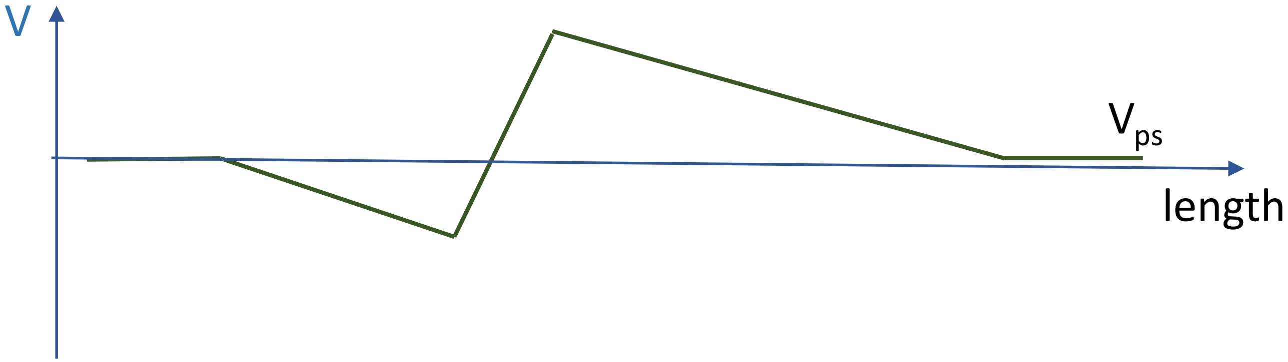
LEDET method (Lumped Element Dynamic Electro-Thermal)



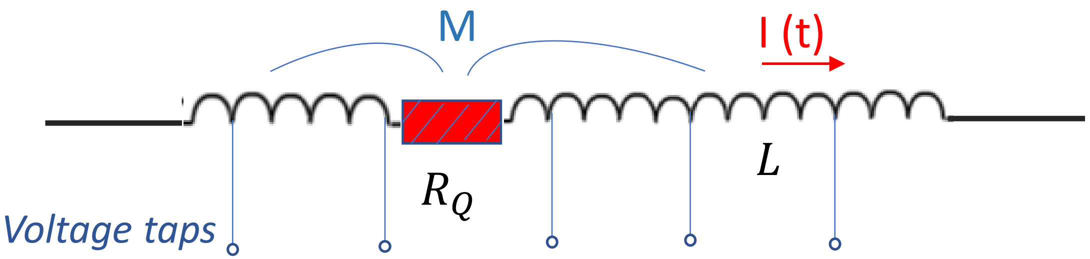


M. Maciejewski & E. Ravaioli, 2015

Voltage distribution in a quenching magnet



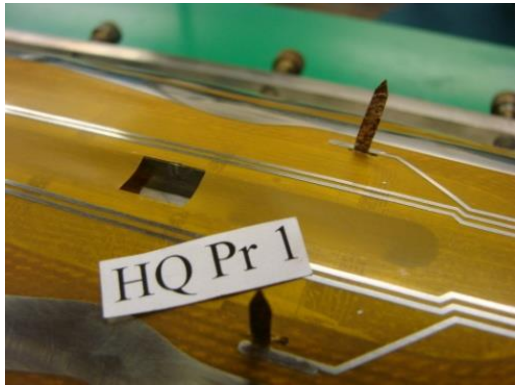
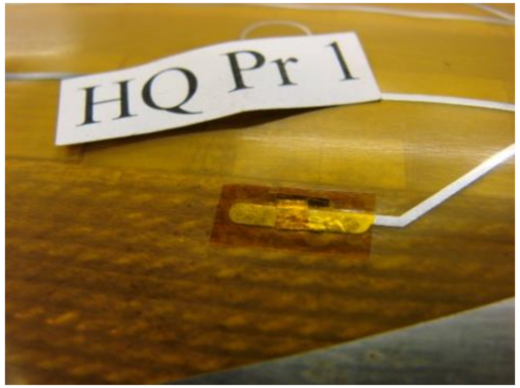
$$V_Q(t) = I(t)R_Q(t) - M\frac{dI(t)}{dt} \qquad L\frac{dI(t)}{dt} \cong \mathrm{I(t)}R_Q(t)$$



$$V_Q(t) = I(t)R_Q(t)(1 - \frac{M}{L})$$

$V_Q(0) = V_Q(\infty)$ =0 => peaks during the quench

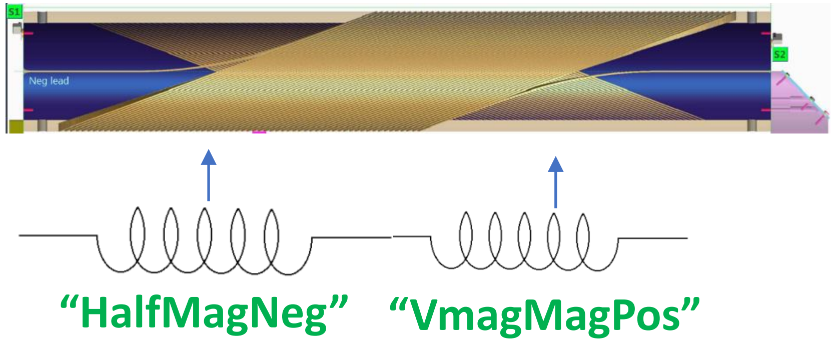
Internal magnet voltage during quench may reach several hundreds of volts!

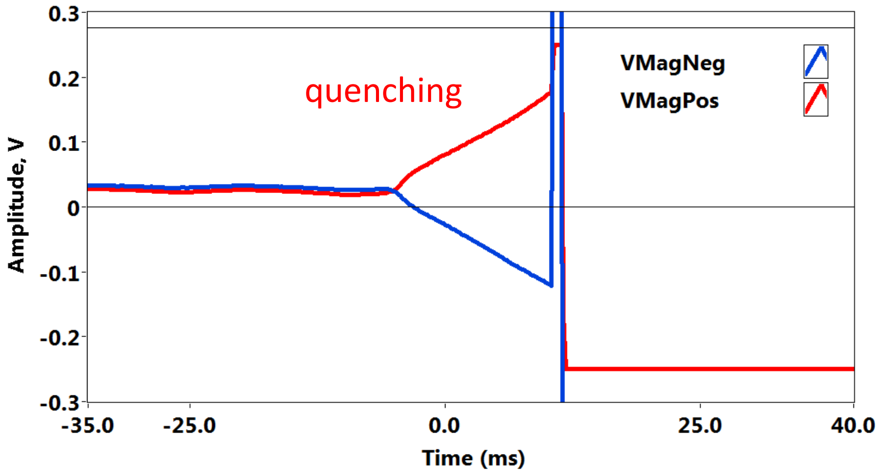



Voltage taps examples

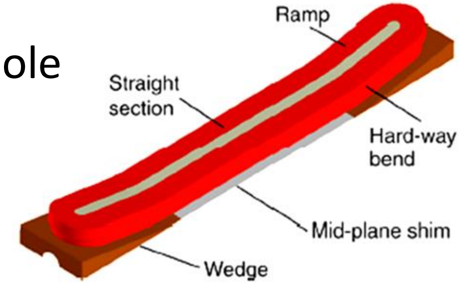
Detecting and localizing quenches

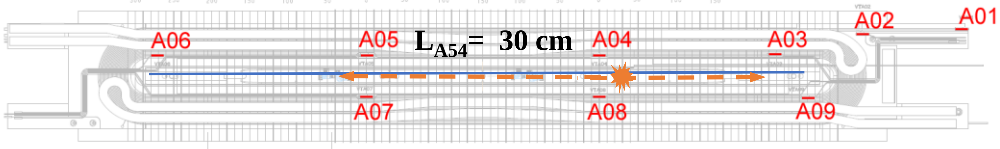
CCT3 Nb_3Sn dipole

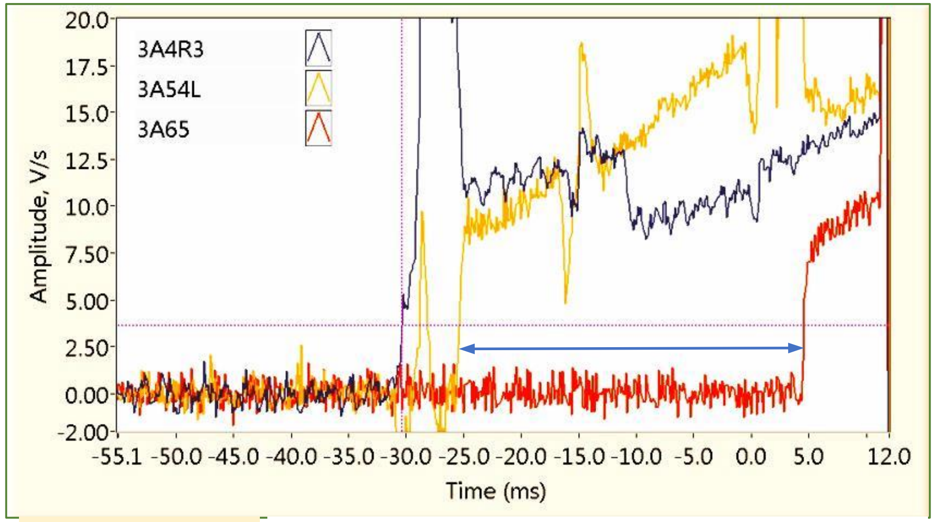




HD3 Nb_3Sn dipole







3A43: -30.4 ms
3A54: -25.3 ms
3A65: +4.5 ms

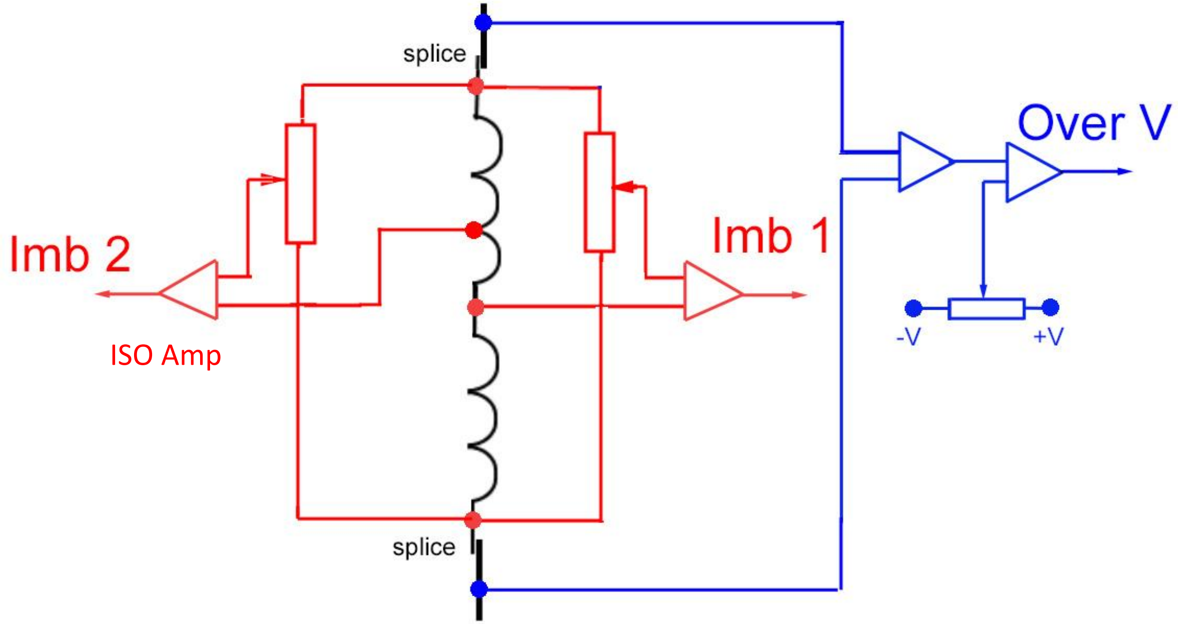
Quench is ~5 cm from the Vtap A4 in the A43 segment

dt = (25.3 + 4.5) = 29.8 ms => V = 10.1 m/s

Quench detection scheme

➢ Imbalance detector

- Imbalance bridge circuit detects resistive voltage in any branch of the coil winding, by comparing potential of a pre-selected voltage tap to that provided by a resistive divider.
- Several (at least 2) imbalance circuits are used in order to detect symmetric quenches



➢ Over-voltage detector

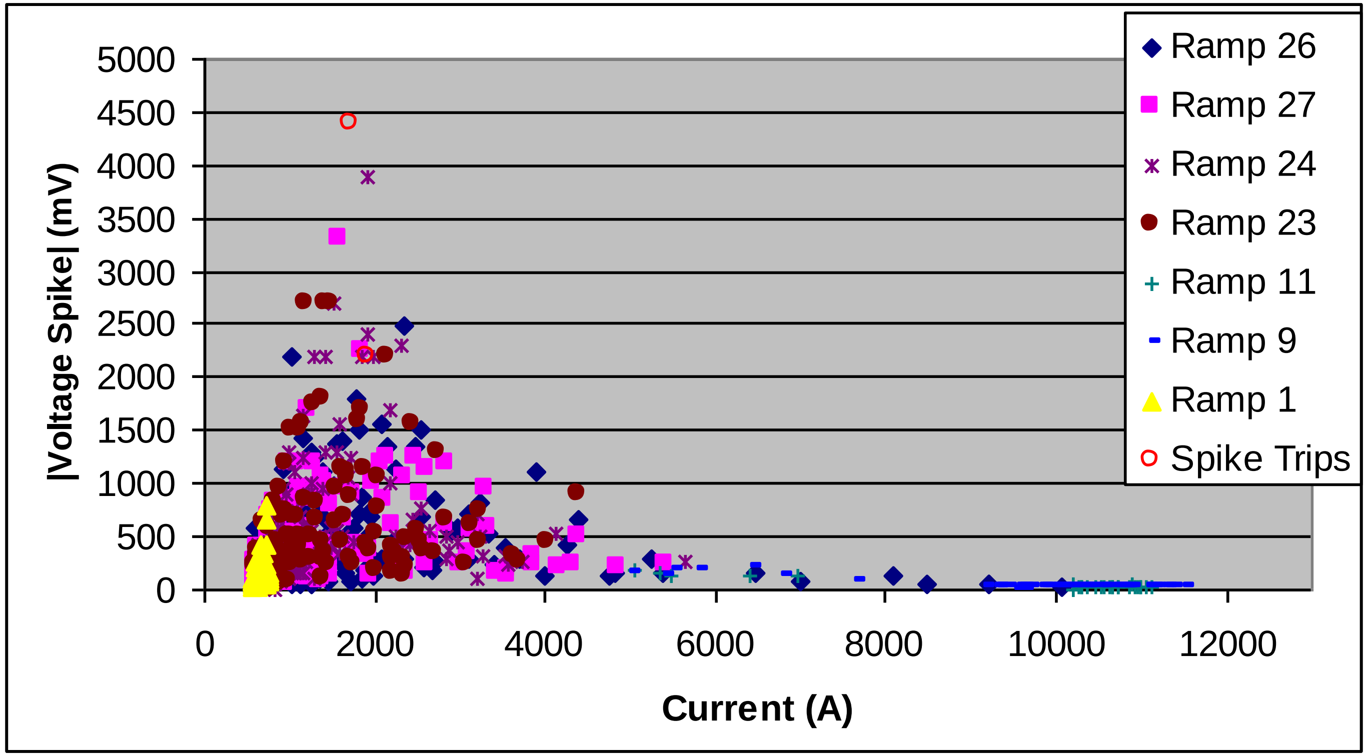
- Voltage across coil compensated for the inductive component. Often includes resistive junctions (splices)

Quench is detected when either of the detector circuits outputs voltage above pre-set threshold. Typical Imb. threshold is ~100 mV for research magnets. A time interval over which voltage rises above the threshold is often called "detection time" (t_d).

Detection threshold

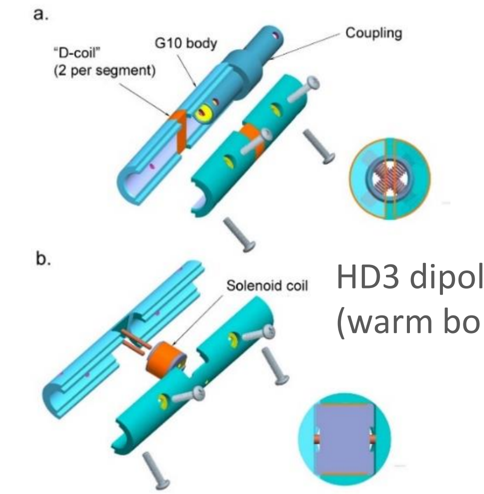
In Nb_3Sn magnets, it is challenging to pick a safe threshold because of flux jumps:

- Threshold may need to be adapted as current is ramped up.
- Low-pass filtering
- "Points above threshold" counter

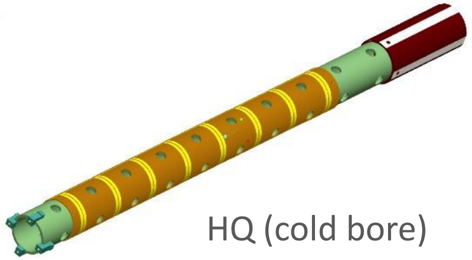


FNAL TD-07-015 TQS02a Voltage spike analysis – C. Donnelly et al.

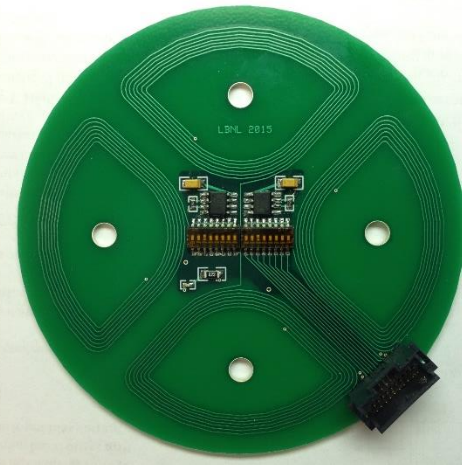
Inductive quench antennas



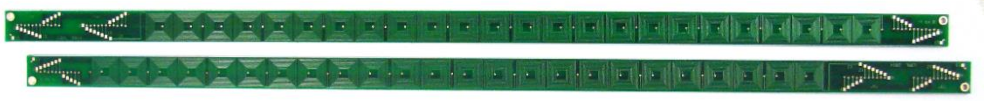
HD3 dipole
(warm bore)



HQ (cold bore)

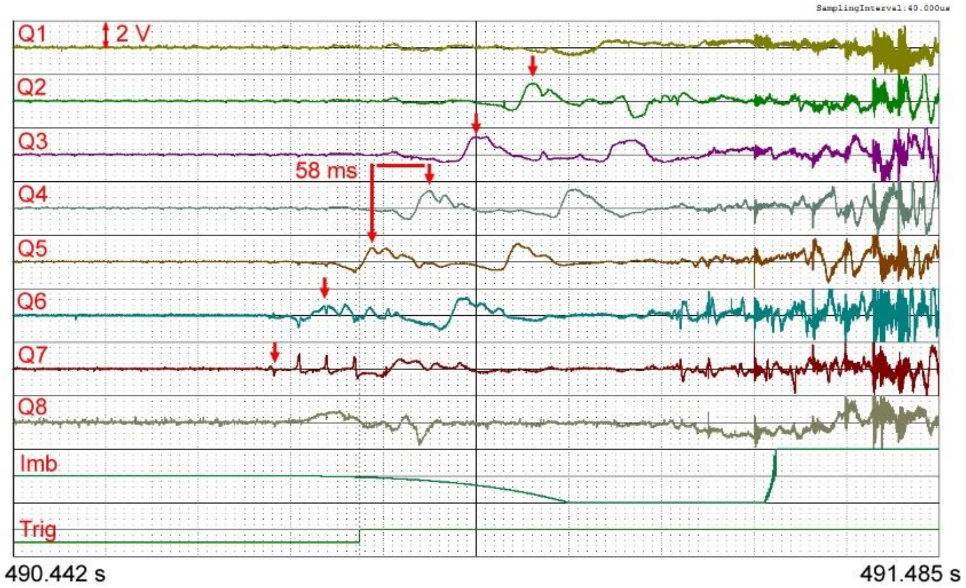


MQXF (warm bore)



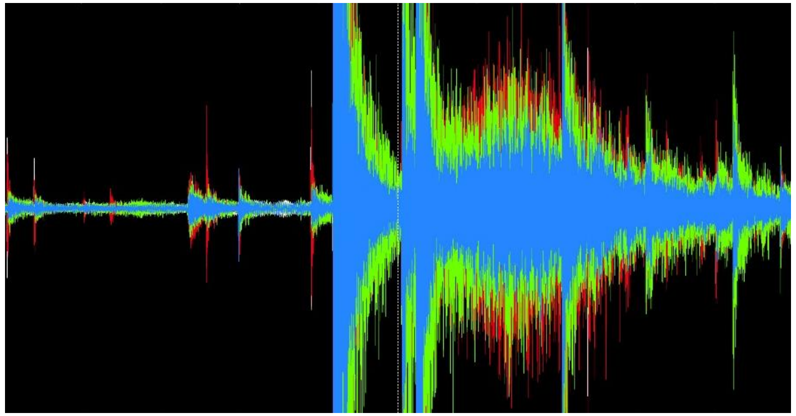
CCT2 linear arrays

Inductive pickup coils detecting re-distribution of current in the quenching cable allowing to localize quenches and understand their origins.

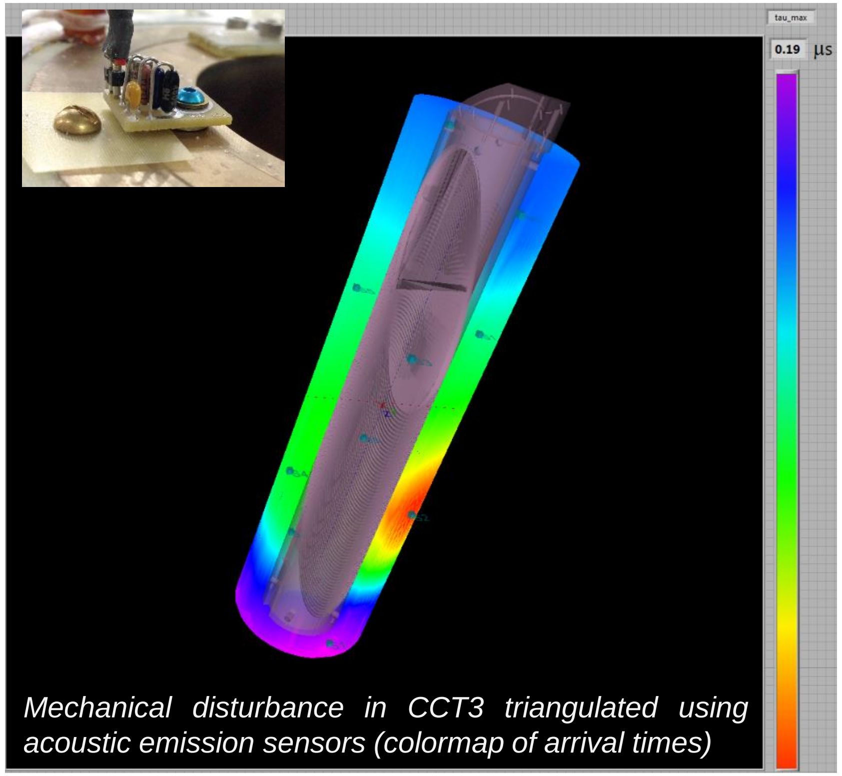


Development and propagation of a slow quench in HQ02b at 6 kA recorded by the quench antenna

Acoustic emission sensors



- Acoustic emission detection / triangulation system uses arrays of piezoelectric sensors to detect mechanical events / quench precursors in the magnet, and also to localize quenches using triangulation technique.



Mechanical disturbance in CCT3 triangulated using acoustic emission sensors (colormap of arrival times)

At present, non-voltage quench diagnostics are primarily used as secondary tools, in correlation with the voltage-based technique. This may change in the future with respect to HTS-based magnets, where slow quench propagation makes voltage-based detection difficult.

Temperature rise and hot spot temperature

Following Maddock and James (1968). Hot spot temperature can be estimated using a simple adiabatic approximation:

Heat balance of unit volume of winding:

Resistivity of the stabilizer Ω m

Volumetric specific heat (averaged) J/m^3 K

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

Current density, A/m^2

heat generation

windings enthalpy

$$\int_{T_0}^{T_q} \frac{c(T)}{\rho(T)} \mathrm{d}T = \int_0^\infty J^2\, dt = \frac{1}{A^2}\int_0^\infty I^2 dt$$

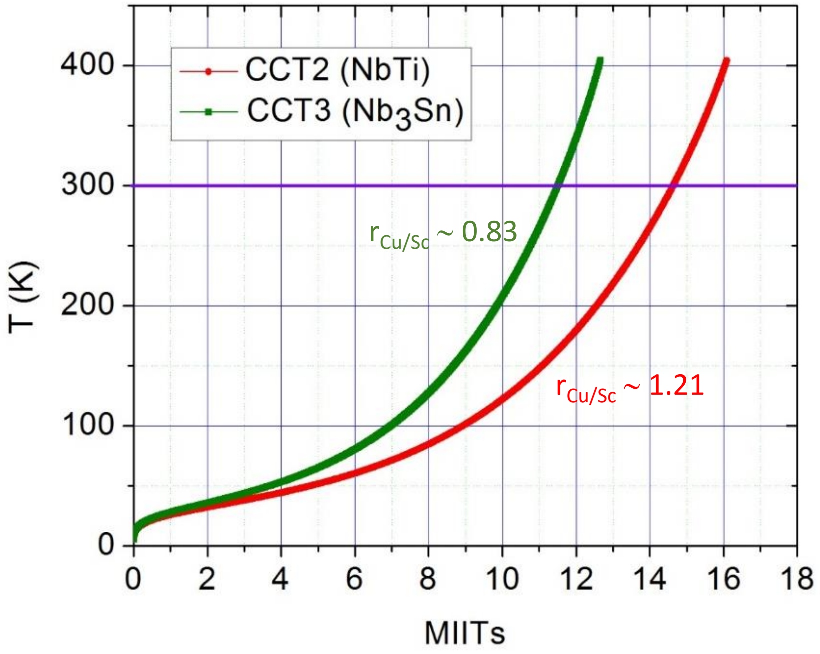
$$\underset{U(T)}{/\!/}$$

Cross-sectional area of the conductor

(M)IITs

“Millions of I*I*Time”

For the stabilized conductor with copper volume fraction *r* :



$$F(T_q) = \int_{T_0}^{T} \frac{C(T)}{\rho(T)} \mathrm{d}T = \frac{1+r}{r}\int_0^\infty J^2\, dt$$

Note that adiabatic T_q is not dependent on the size of the normal zone!

Usually, T_Q< 350 K is considered “safe” for epoxy-impregnated windings of experimental magnets. In accelerators T_Q < 150-200 K is usually sought. Higher temperatures may lead to epoxy breakdown leaving conductor unsupported under Lorentz forces, resulting in loss of magnet quench performance.

Effect of RRR on hot spot temperature

RRR= $\rho_{300\ K}/\rho_{4.2K}$

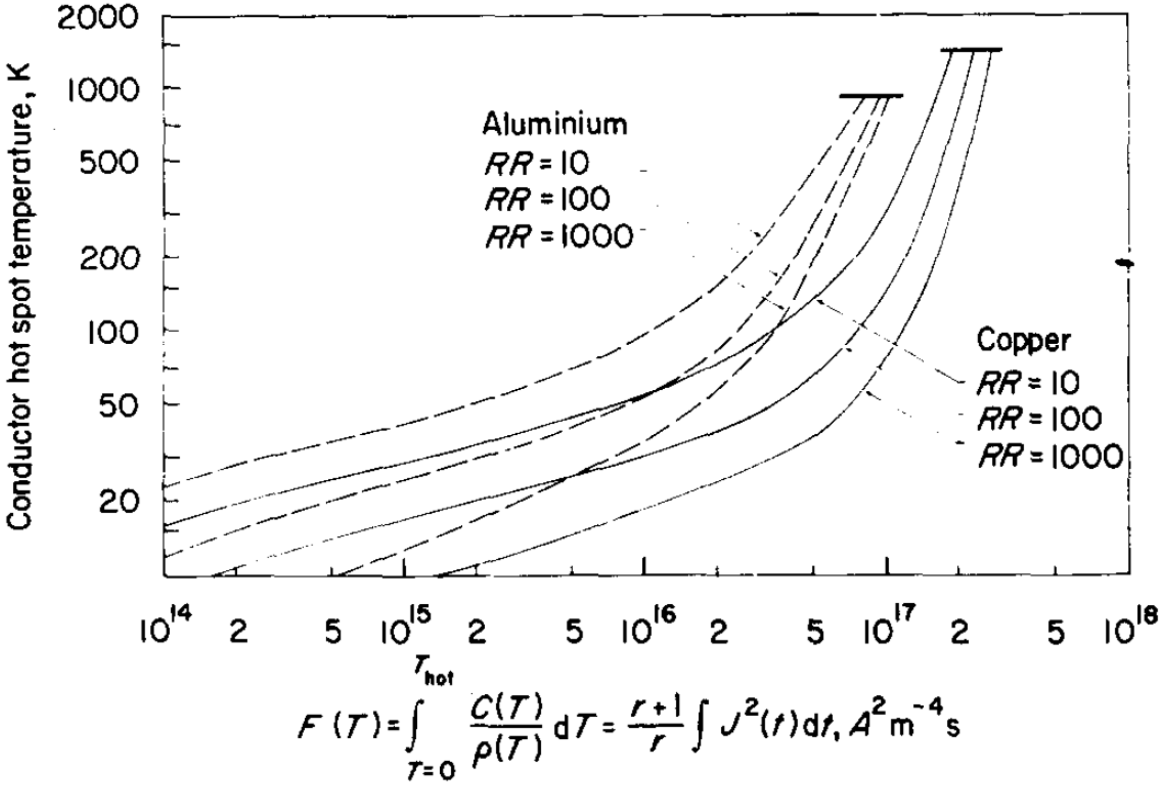


Fig. 1 Peak hot spot temperature T_M as a function of $F(T_M)$ for various coppers and aluminiums

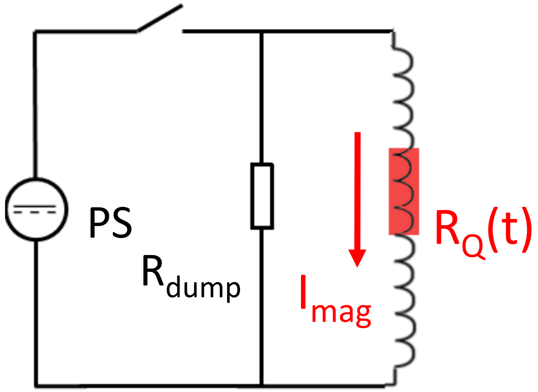
Cable RRR > 150-200 is typically required for high-field accelerator magnets

Protection using a dump resistor

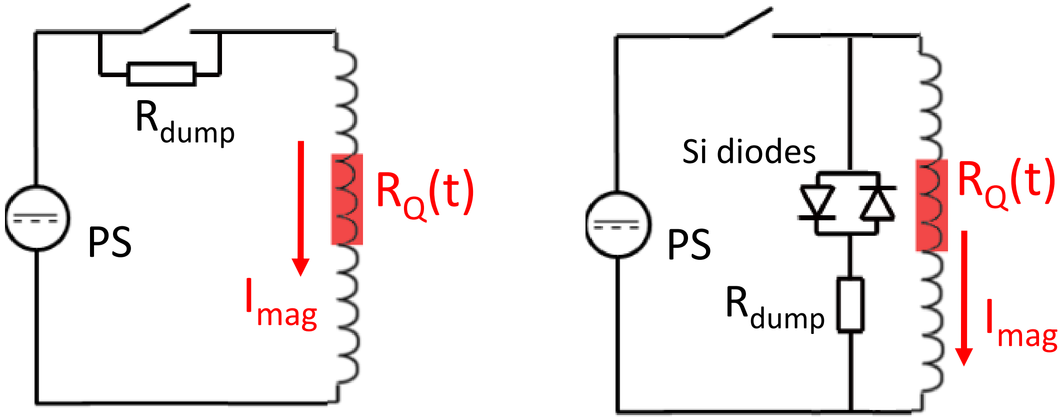
By adding external resistor to in series with the quenching magnet, part of its energy can be “extracted” outside of the cryostat

Efficiency of energy extraction depends upon $R_Q(t)/R_{dump}$. At best ~50-60% of magnet energy is typically extracted outside of the cryostat using this method.

$$L\frac{dI(t)}{dt} = \mathrm{I(t)}R_Q(t) + I(t)R_{dump}$$



“Standard” scheme



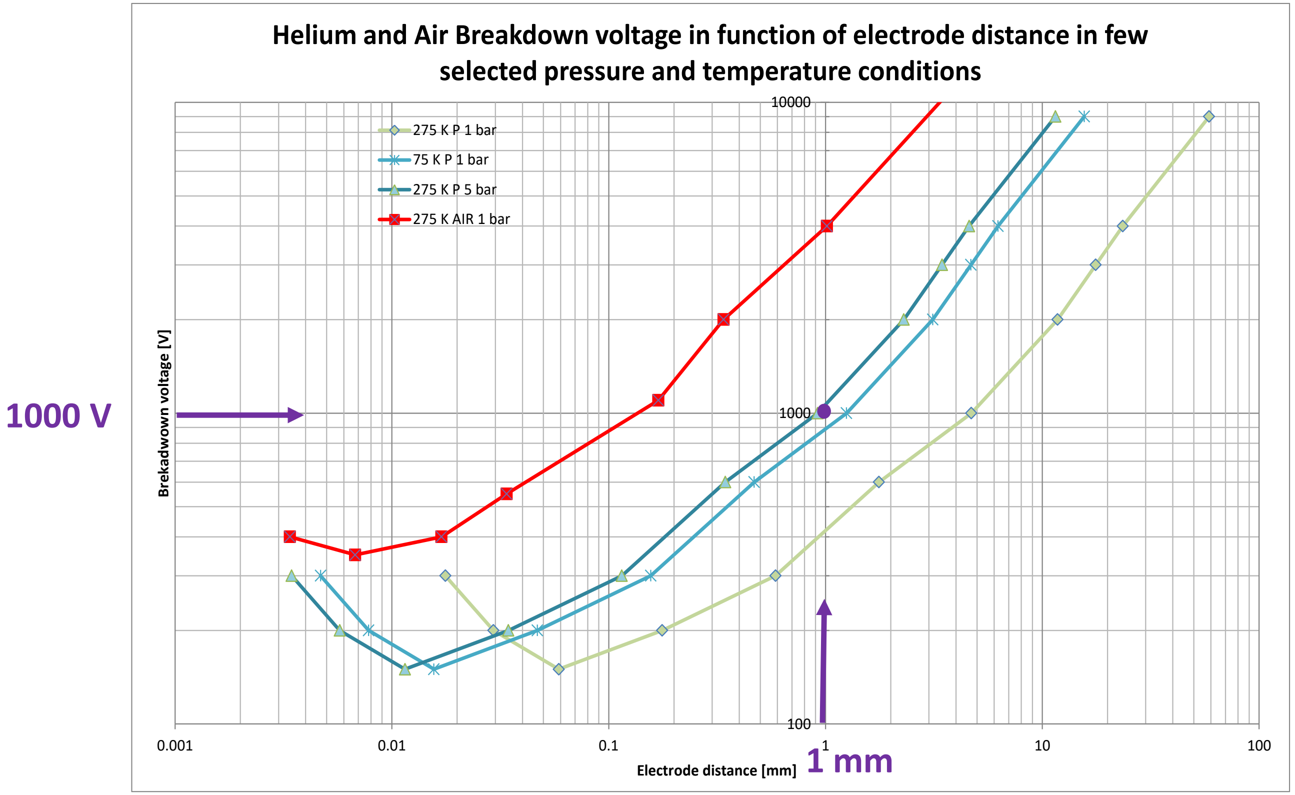
Modified schemes: ramping rate is not limited by the dump resistor

A drawback: **high voltage appears across magnet terminals**

Peak voltage: $V_{mag\,max} = I_{mag}\,R_{dump}$

High voltage as a cause of damage in quenching magnets

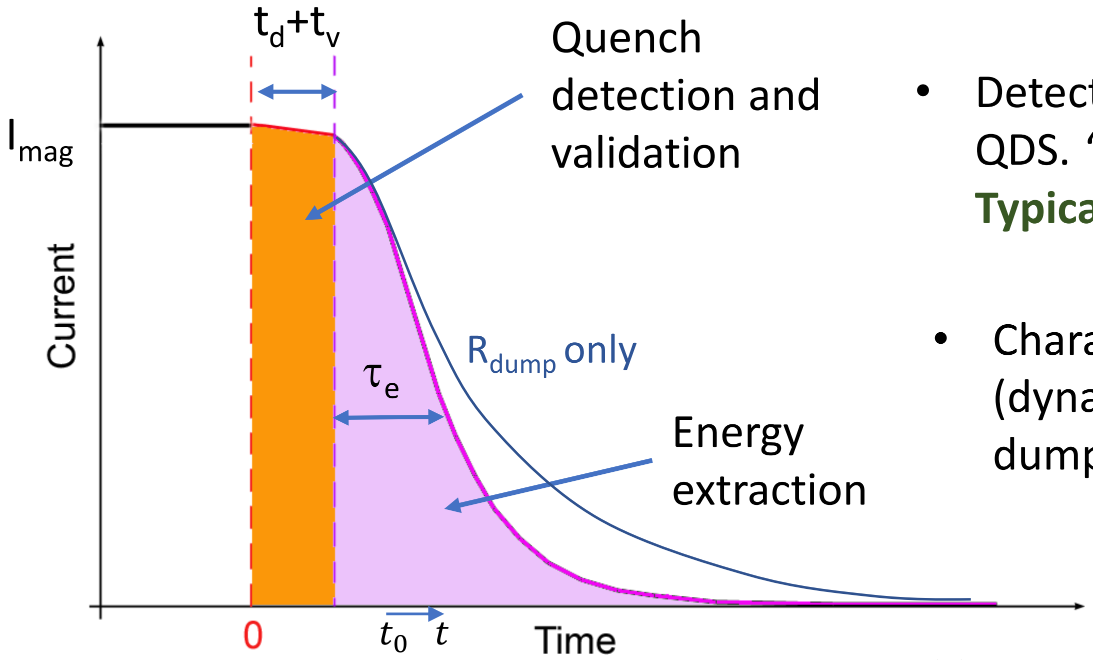
Typically voltages allowed in cryogenic He environment are < 1000 V (Paschen's law).



*From P. Fessia's report on LHC electrical guidelines

Arcing (gas discharge) may start uncontrolled energy release and eventually destroy the magnet. Therefore in practice R_{dump} is limited to under ~100 mΩ in order to keep the maximal allowable magnet voltage $V_{mag\,max} = (I_{mag}\, R_{dump})$ < 1000 V.

Quench protection timeline and objective



- Detection time t_d depends upon sensitivity and thresholds of QDS. "Validation time" t_v is typically defined by the hardware. **Typically, for LTS accelerator magnets (t_d+t_v)~7-15 ms**

- Characteristic extraction time τ_e depends upon magnet (dynamic) inductance and the sum of magnet resistance and dump resistance:

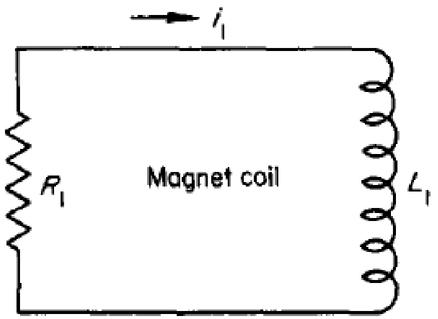
$$I(t) = I_0(t_0)\, e^{-t/\tau_e} = I_0 e^{\frac{-t(R_{mag}(t)+R_{dump})}{L(t)}}$$

As magnet inductance scales with magnet size, τ_e can be reduced by increasing R_{dump} and reducing L(t) (**passive** protection), or by increasing $R_{mag}(t)$ (**active** protection).

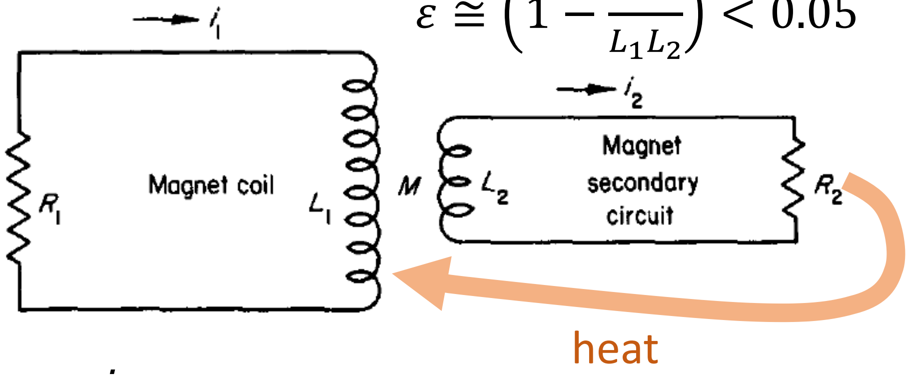
Typically, for LTS accelerator magnets τ_e~ 50-200 ms.

The goal of protection is to reduce τ_e as low as possible, thus keeping the MIITs (and so the cable temperature T_q) within acceptable limits.

Inductive protection



$$\varepsilon \cong \left(1 - \frac{M^2}{L_1 L_2}\right) < 0.05$$



$$i = i_0 e^{-t/\tau_1} \quad \tau_1 = {L_1}/{R_1}$$

$$i = \frac{i_0}{i_L - i_S}\left[(\tau_1 - \tau_s)e^{-t/\tau_L} + (\tau_L - \tau_1)e^{-t/\tau_s}\right]$$

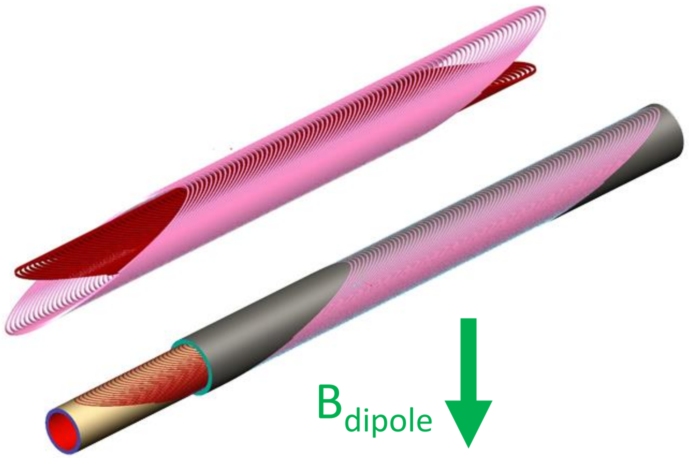
$$\tau_1 = {L_1}/{R_1} \quad \tau_2 = {L_2}/{R_2} \quad \tau_L \sim \tau_1 + \tau_2 \quad \tau_s \sim \frac{\varepsilon \tau_1 \tau_2}{\tau_1 + \tau_2}$$

$$F(T_M) \cong \frac{r+1}{r} j_0^2 \left(\frac{\tau_1}{2}\right) > F(T_M) \cong \frac{r+1}{r} j_0^2 \left[\frac{\tau_1^2}{2(\tau_1 + \tau_2)} + \frac{\tau_s}{2}\right]$$

M. A. Green, Cryogenics 24, p. 659 (1984)

- A secondary LR circuit inductively coupled to the magnet coil will reduce the quench integral, removing portion of the magnet energy and dissipating it in the secondary circuit
- Heat dissipated in the outer circuit can be also supplied back to the coil to quench its superconducting fraction. This is called “quench back”; it can employed for quench protection to reduce hot spot temperature and coil voltage during quench.

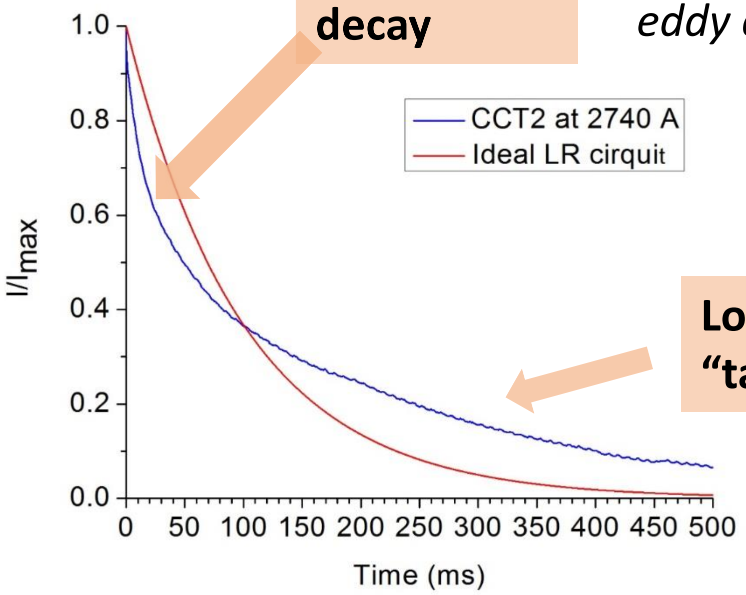
Example: current decay in Nb_3Sn canted cosine theta dipole



Al bronze mandrel

Faster than $e^{-\frac{R}{L}t}$ initial decay

Energy is “pumped” into eddy currents

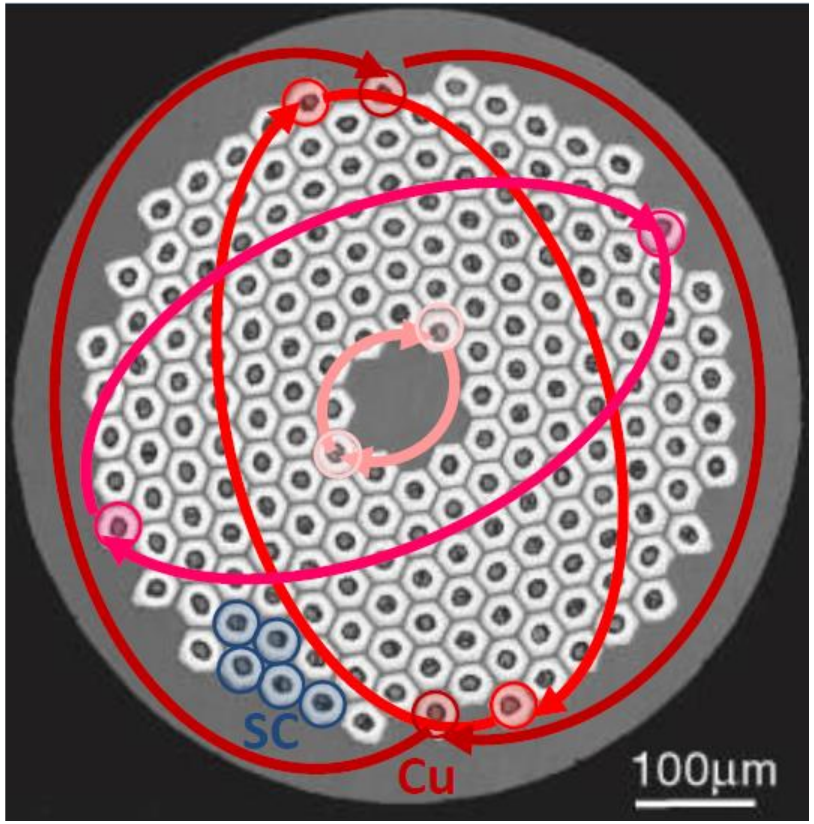


Long “tale”

Eddy currents take a long time to decay

Current decay (normalized) measured at 20 mΩ dump resistor.
Calculated magnet zero-frequency inductance is 2.0 mH.

Bulk heating of the conductor with ac losses

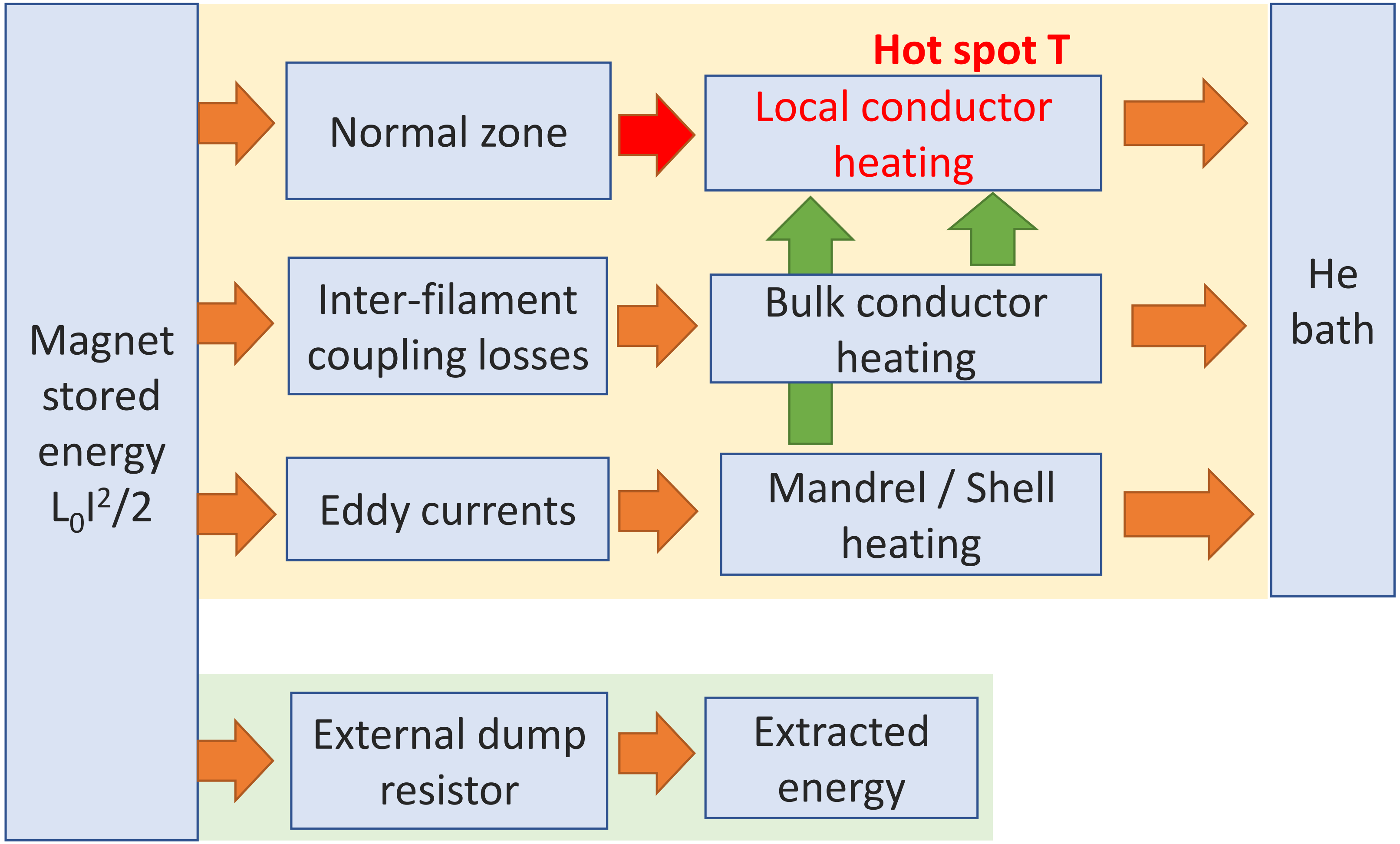


Inter-filament "coupling loss"

$$P_{if} = \left(\frac{l_f}{2\pi}\right)^2 \frac{1}{\rho_{eff}} \left(\frac{dB_t}{dt}\right)^2$$

- When current in the magnet is varied, ac magnetic field induces currents in the (resistive!) copper matrix between the superconducting filaments.
- This currents heat up the conductor interior, thus depositing heat in the bulk rather than at the surface
- The "time constant" of the **inter-filament currents** (determined by the stray inter-filament inductance and matrix resistivity, $\boldsymbol{\tau_{if} = \frac{\mu_0}{2}\left(\frac{l_f}{2\pi}\right)^2 \frac{1}{\rho_{eff}}}$, is typically 10-20 ms for LTS strands, which is ideal for quench protection purposes.
- Other types of ac loss are inter-strand (much larger time constant) and hysteretic loss (frequency-independent, but smaller magnitude). The latter may be useful for future HTS magnet protection.

Energy dissipation during passive protection



Magnet stored energy $L_0 I^2/2$

Normal zone

Hot spot T

Local conductor heating

Inter-filament coupling losses

Bulk conductor heating

Eddy currents

Mandrel / Shell heating

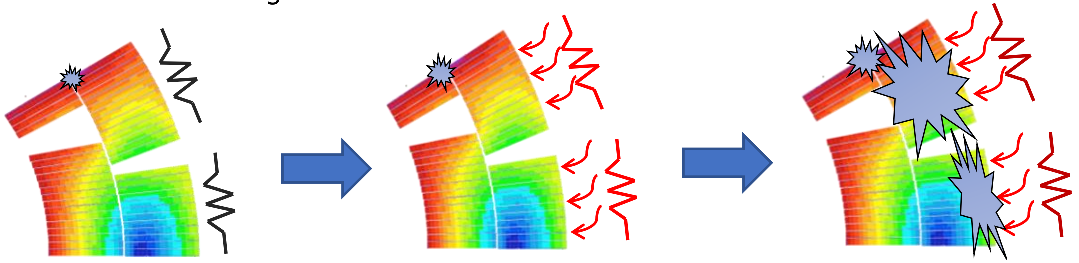
He bath

External dump resistor

Extracted energy

Protection heaters

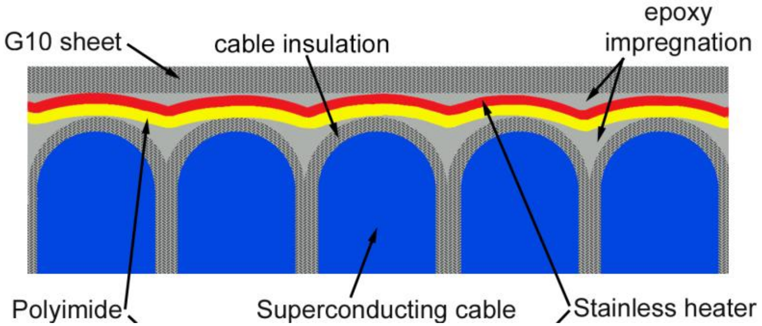
“**Protection heaters**” are thin foil strips placed (usually epoxy-impregnated) on top of the winding. Heaters are normally operated by discharging a switch (thyristor, IGBT)- controlled capacitor bank (often called “HFU” – heater firing unit). They are fired as soon as quench is detected to **spread normal zone across the magnet** (thus increasing R_{mag}).



Quench

PHs fired

Normal zone spreads



Power / surface:

$$P_{PH} = \frac{V_{PH}^{2}(t)}{r_{ss} \times L_{PH}^{2}} \left(W / cm^{2}\right)$$

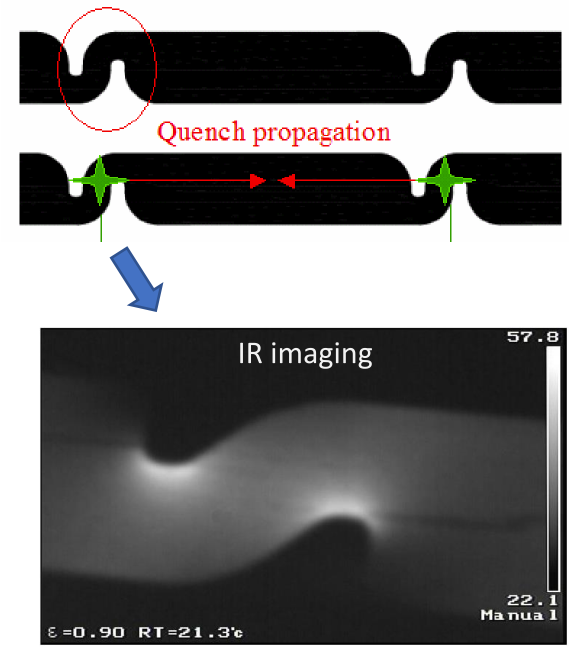
(50-150 W/cm^2 typical)

PH strip on top of the HQ-series coil

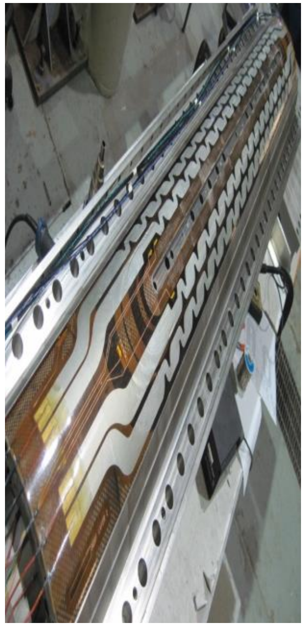
Uniform stainless strip covering the largest possible area of the coil winding is the simplest protection heater. It is usually fabricated on top of the 25-75 micron-thick polyimide (Kapton) layer.

- ➢ Uniform heaters strips are not suitable for long magnets, as the voltage V_{PH} required to keep the same P_{PH} grows prohibitively large (~ L_{PH}).

Protection heaters with “heating stations



Heating stations

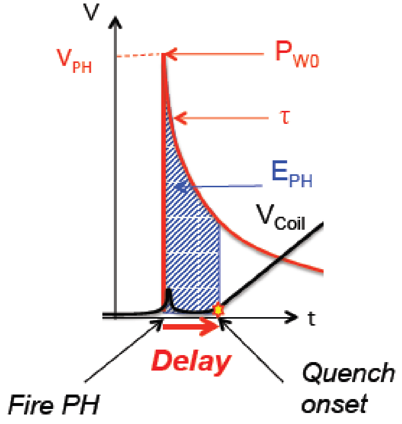


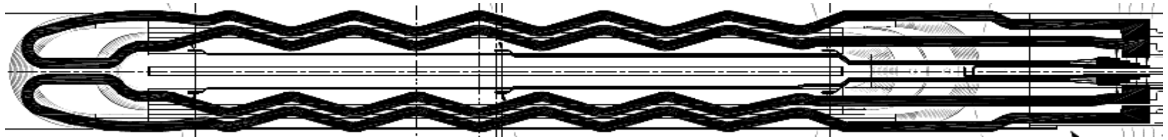
Selective copper plating

“Heating stations” are zones of higher resistance fabricated by means of narrowing a current path or by selective cooper-plating. Such heaters can be scaled up in length, and rely on forming periodic normal zones that subsequently expand as quench propagate. Relying on quench propagation, however, slows down growth of $R_{mag,}$ compared to uniform strip heaters of same P_{PH}.

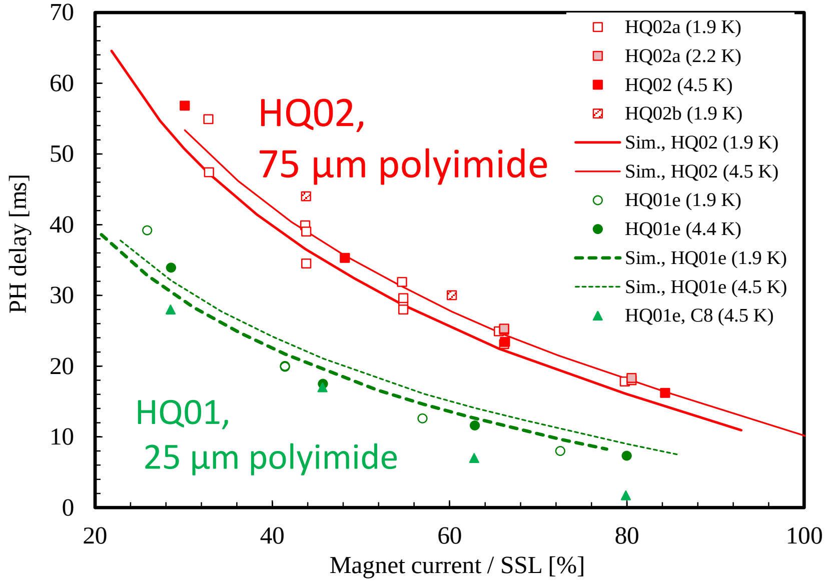
Protection heater delays

It takes time (typically a few milliseconds) for the heat generated by a protection heater to diffuse into the cable through the polyimide layer and cable insulation, and heat the cable strands above $T_{cs}(B)$. Heater delay is thus a function of heater power (limited by the max allowable temperature), net insulation thickness, and magnet current (which controls the $T_{cs}(B)$) .



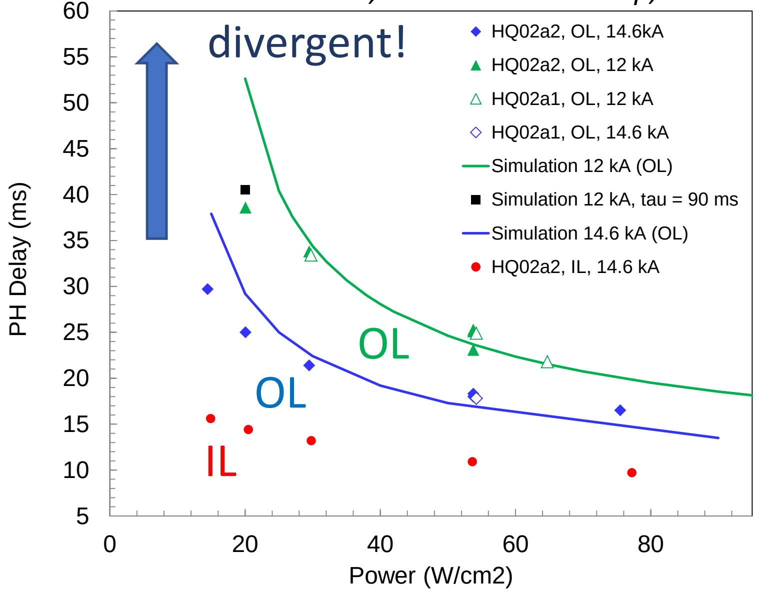


PH peak power = 50-55 W/cm², τ = 40-45 ms

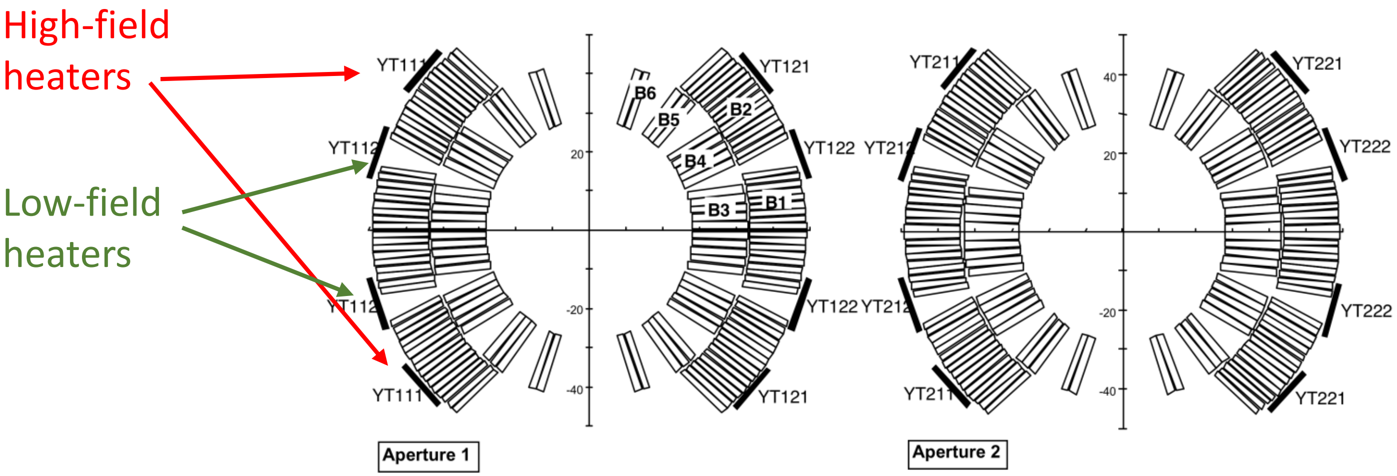


τ = 90 ms

T. Salmi, WAMSDO Workshop, CERN



Redundancy and optimization of PHs


High-field heaters

Low-field heaters

- Individual powering for redundancy, and power optimization for heater strips covering low and high-field zones.
- Optimization of a heater strip layout is required so that the heaters are effective at every current level of the magnet (low to high). A combination of various patterns can also be used
    - ➢ Short “heating stations” are less effective
    - ➢ Heated length equal to cable transposition length is desirable for low-current

Heater simulation and optimization software packages:

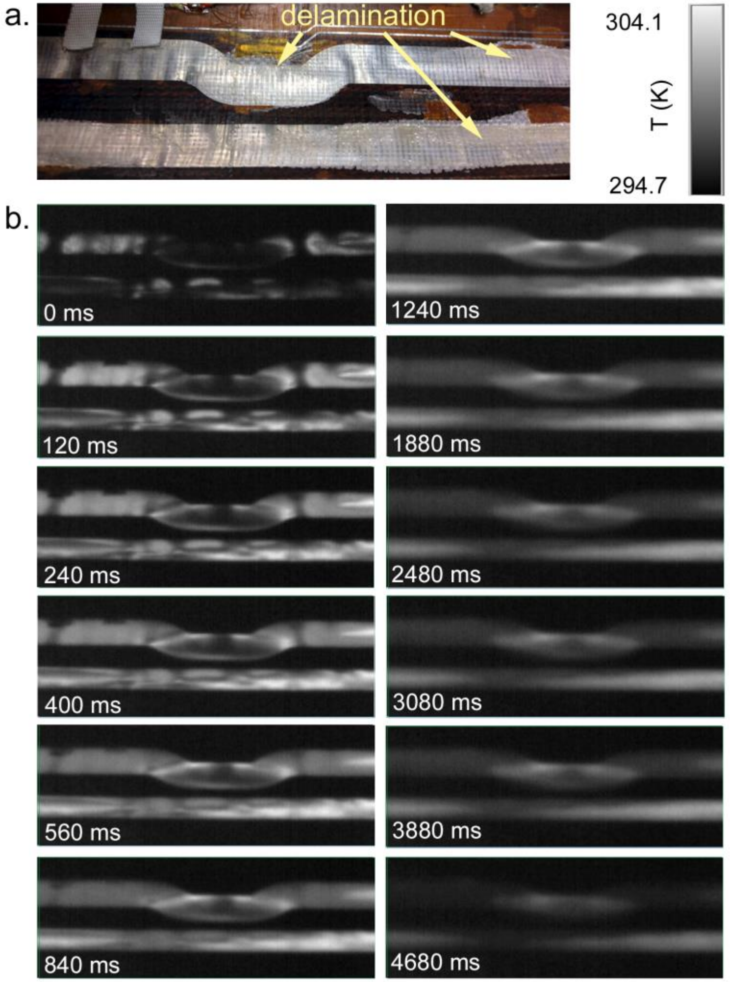
SPQR: DOI: 10.1016/s0011-2275(01)00008-x
QUABER: DOI: 10.1109/20.119887
CoHDA (Tampere University of Technology): DOI: 10.1109/TASC.2014.2311402

Some drawbacks of PHs

PHs while widely used have some drawbacks:

- Delamination (bubbles form), especially when heater is placed on unsupported (IL) surface of the coil
- Electrical breakdowns
- Poor performance at low magnet currents

Non detected failure of a QH. As seen after dismounting during inspection of the QH.



Thermal imaging of delaminated PH strips →

Protection heaters rely upon on thermal diffusion across insulation, and may be intrinsically too slow for protecting some types magnets…

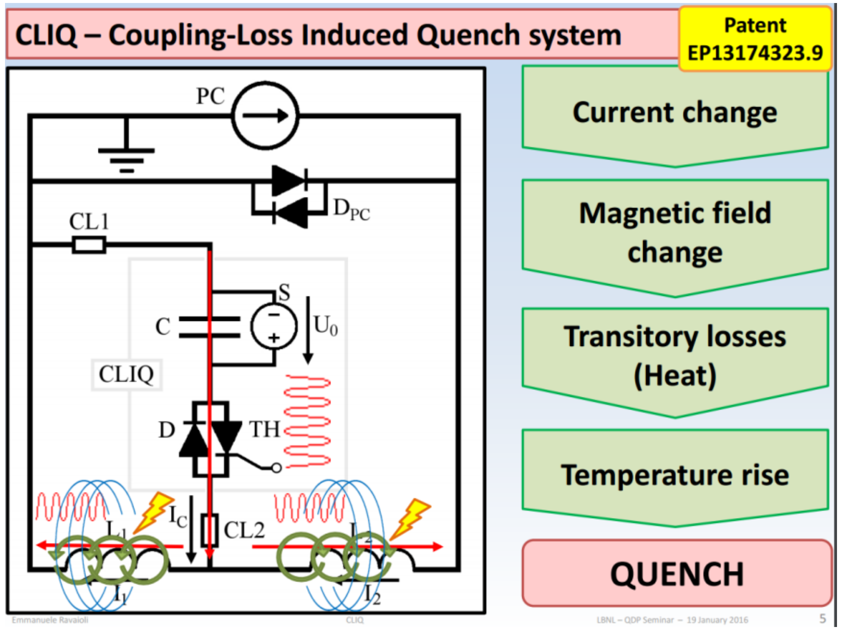
Using dB/dt for quench protection

- In fact, we always get some *dB/dt* when during energy extraction (whether due to R_{dump}, magnet resistance or both).
- If this field variation turns out to be sufficient for heating the conductor above T_{cs}, quench will spread in the magnet windings (thus accelerating current decay and increasing *dB/dt* even further…).
- This phenomenon is often observed in high-field accelerator magnets and in fact same "quench back" as we discussed earlier (except that we are dealing with inter-filament coupling currents rather than a secondary coil).

However, one can initiate ac loss in the magnet (and drive it into a quenched state) during energy extraction in a much more efficient way. It is done using a novel* technique called CLIQ.

***First ideas on inducing ac current in the magnet for quench protection were presented in: "QUENCH PROTECTION FOR A 2-MJ MAGNET", J.A. Taylor et. al., Applied Superconductivity, Pittsburg, PA, September 25-28, 1978**
http://escholarship.org/uc/item/41f3s8sz

CLIQ (Coupling Losses Induced Quench)



CLIQ – Coupling-Loss Induced Quench system

Patent EP13174323.9

Current change

Magnetic field change

Transitory losses (Heat)

Temperature rise

QUENCH

- CLIQ operates by discharging a capacitor bank directly into the windings upon detecting a quench.
- An LCR circuit formed in that way oscillates at its resonant frequency (typically 20-50 Hz), inducing inter-filament losses ac in a winding that are sufficient to quench its volume at once.
- Connecting capacitor bank to the central portion of the winding reduces effective inductance, making CLIQ more effective and adaptable to various magnet configurations

CLIQ effectiveness ψ is a function of:

- Coil geometry
- Position of CLIQ connections
- Conductor parameters
- Etc...

At high current

- Low energy needed to start the quench
- High energy density, needs to be quick!

$$\frac{P_{IF}}{vol} \sim \psi^2 \frac{U_0^2}{l_m}$$

POWER is the key parameter

At low current

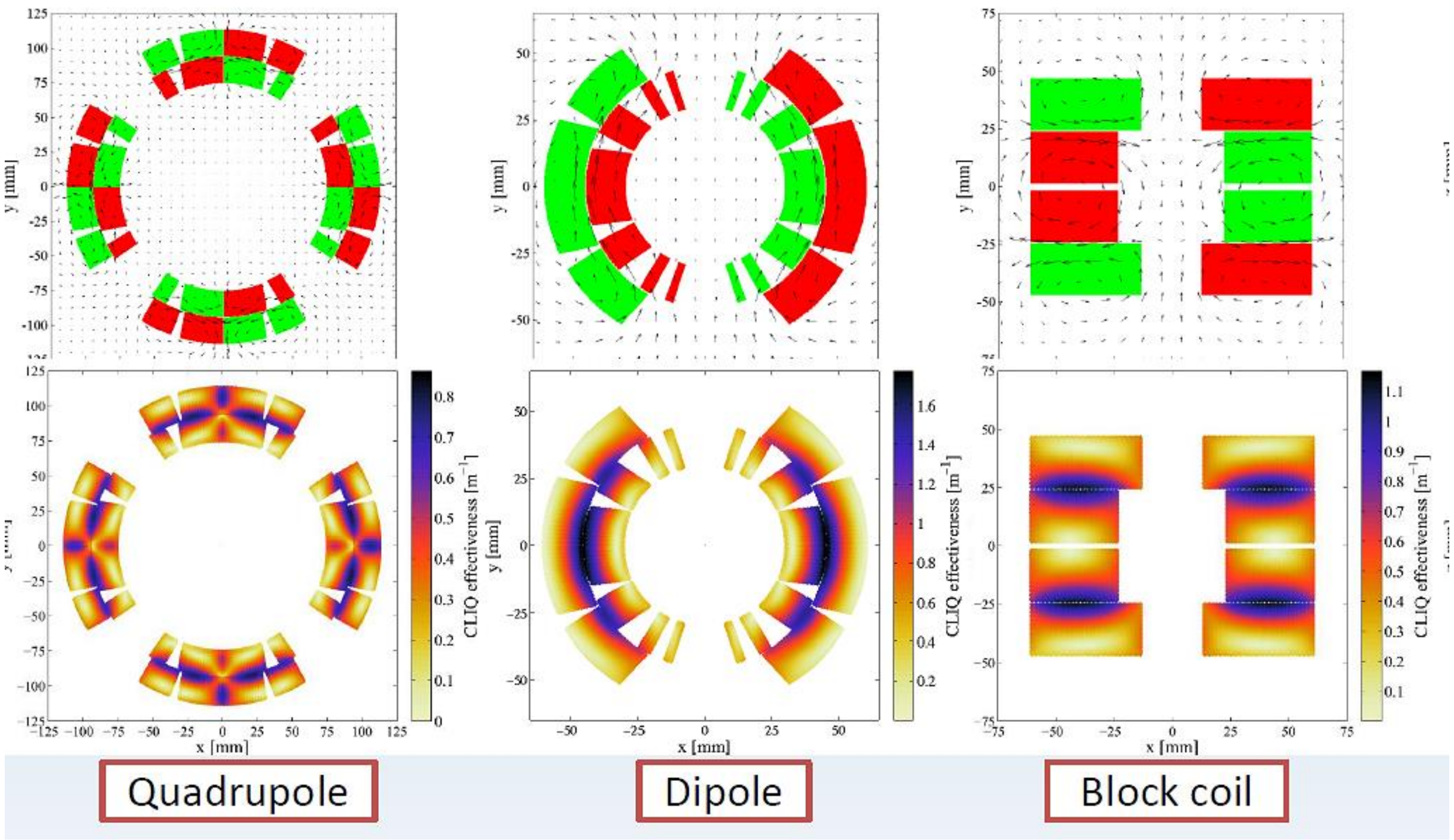
- High energy needed to start the quench
- Low energy density, velocity not critical

$$\frac{E_{CLIQ}}{vol} \sim \frac{CU_0^2}{l_m}$$

ENERGY is the key parameter

E. Ravaioli et al., Supercond. Sci. Technol. 27, No. 4, 044023, (2014).

CLIQ effectiveness optimization

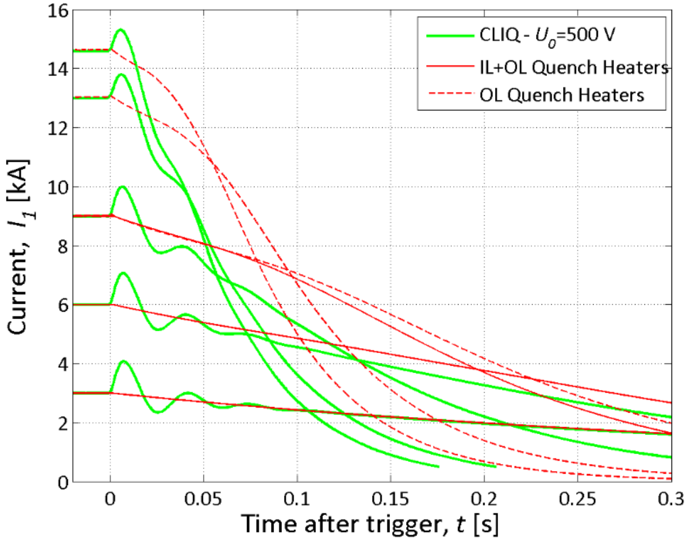


By sub-dividing coil electrically, and introducing opposite current changes in physically-adjacent sections, CLIQ effectiveness can be further improved

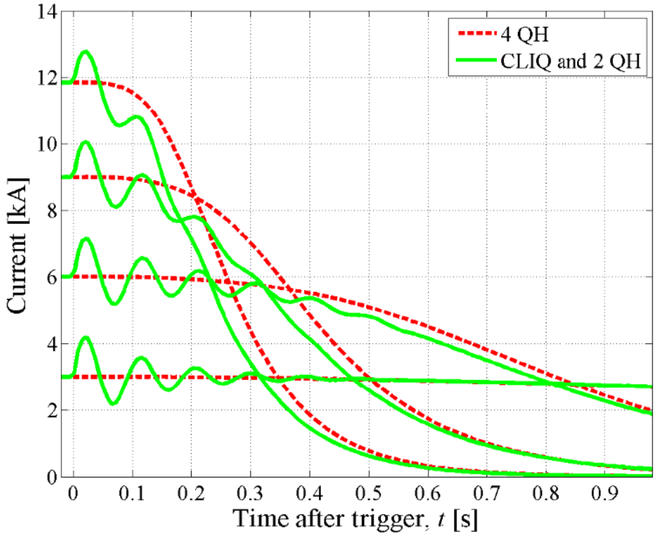
Con: requires additional "CLIQ leads".

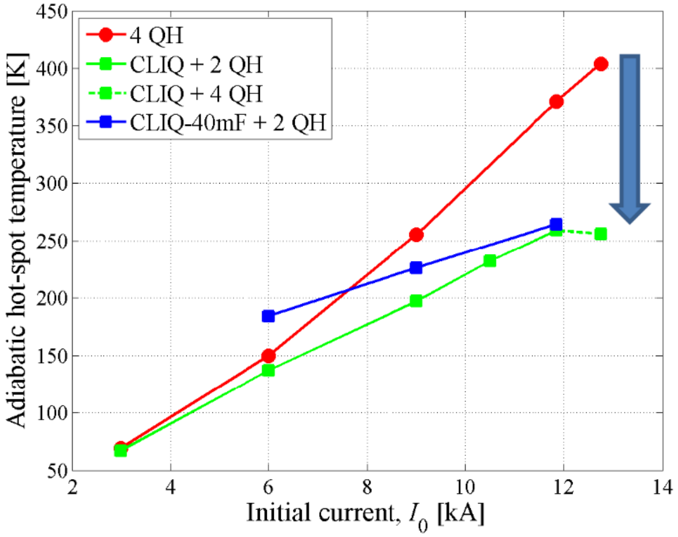
E. Ravaioli, PhD Thesis, 2015

Hybrid protection (PHs + CLIQ)



Example of CLIQ and heater studies on HQ02 high-field Nb_3Sn quadrupole. Clearly, using CLIQ the current decay is substantially shortened, yielding as much as 100 K difference in the hotspot temperature.

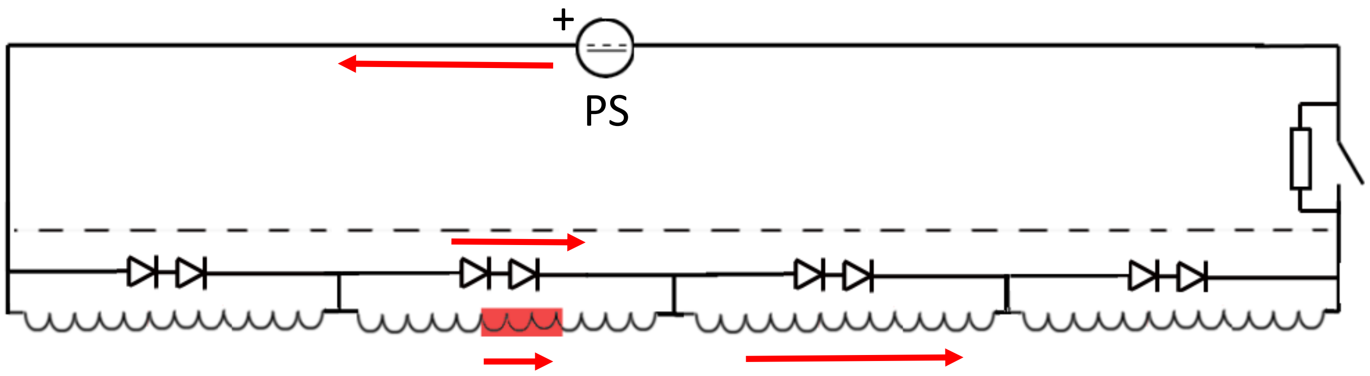




CLIQ test on a full-scale LHC dipole

E. Ravaioli

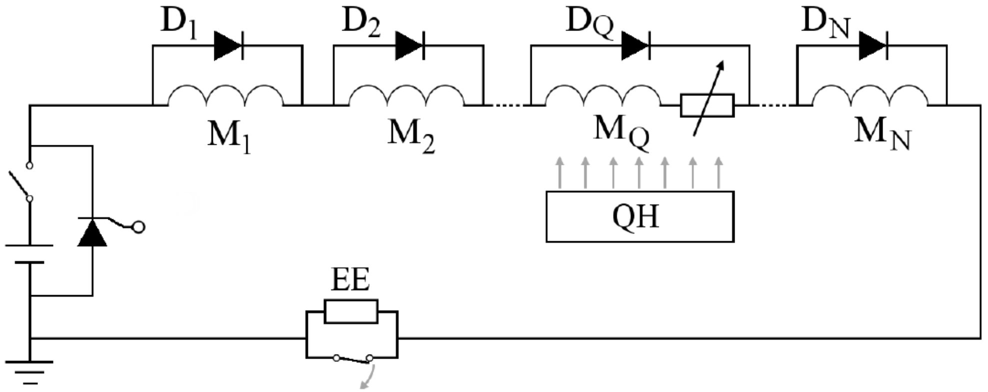
Protection of a chain of magnets



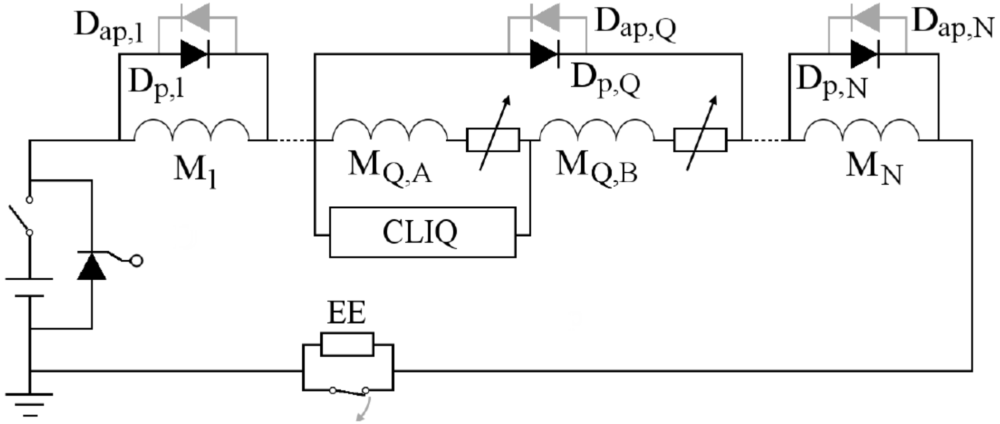
- Strings of silicon diodes are added in parallel to each magnet. Diodes start to conduct at ~2-5 V of bias at liquid helium temperature, and therefore are not carrying any current during ramping or normal magnet operation.
- As quench occurs, voltage across the magnet rises above that level, its diodes become conductive and so the chain current is bypassed through them
- This decouples the magnet energy and rundown time from the string energy and run-down time, reducing heat dissipation
- Same scheme can be used for protection of multi-coil magnets (quadrupoles, sextupoles). A complete accelerator can be also split in several chains, depending on its size.

A Powerex R7HC1216xx Diode rated at 1600 A

Chain of magnets with active protection



Electrical scheme of a chain of NM superconducting magnets (M1-MN) protected by active quench heaters (QH), by-pass diodes (D1-DN), and an energy-extraction system(EE). In this example, only the active protection system of magnet MQ is activated.



Schematic of a chain of NM superconducting magnets (M1-MN) protected by CLIQ, by-pass diodes in parallel (Dp;1-Dp;N) and antiparallel (Dap;1-Dap;N), and an energy-extraction system (EE). Only the CLIQ system connected to magnet MQ is shown.

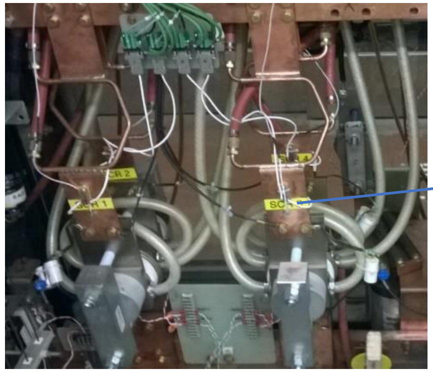
E. Ravaioli, PhD Thesis, 2015

Quench protection at LBNL test facility

- FPGA-based quench detection system
  - 2 μs response time (with internal 40MHz clock)
  - Programmable signal recognition capability
  - Flux jump identification and counting
  - Data 1 MSPS four channels data logging
  - Programmable digital delay line for extraction
  - Programmable heater firing sequencer
  - Inductive voltage automatic compensation

- Energy extraction system

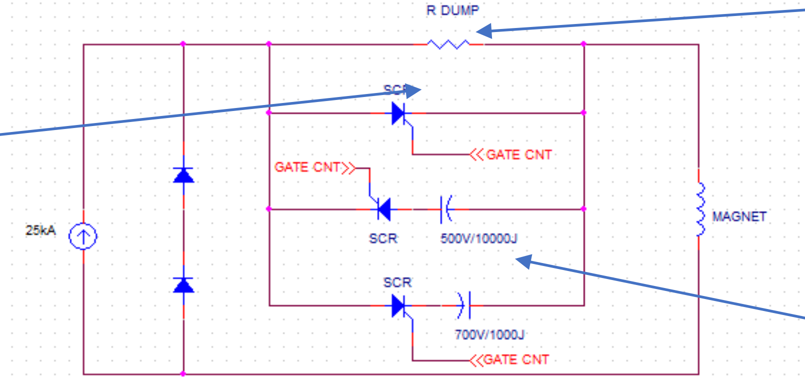
4xN5946FC220 SCRs



  - 6000A @ 55C each
  - Max voltage 1800V
  - Min extraction time 1 ms

Dump Resistor

- Adjustable: 20,24,30,40,60, or 120 mΩ



M. Turqueti

Capacitor Bank

References for further reading

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- **K.-H. Mess, P. Schmuser, S. Wolf, "Superconducting Accelerator Magnets", World Scientific, 1996**
- Y. Iwasa, "Case Studies in Superconducting Magnets", Springer 2009

- A. Devred. "Quench origins" https://lss.fnal.gov/archive/other/ssc/sscl-255.pdf
- A. Devred, General Formulas for the adiabatic propagation velocity of the normal zone, IEEE Trans on Magnetics, Vol. 25, No. 2, March 1989