Protection of superconducting magnet circuits

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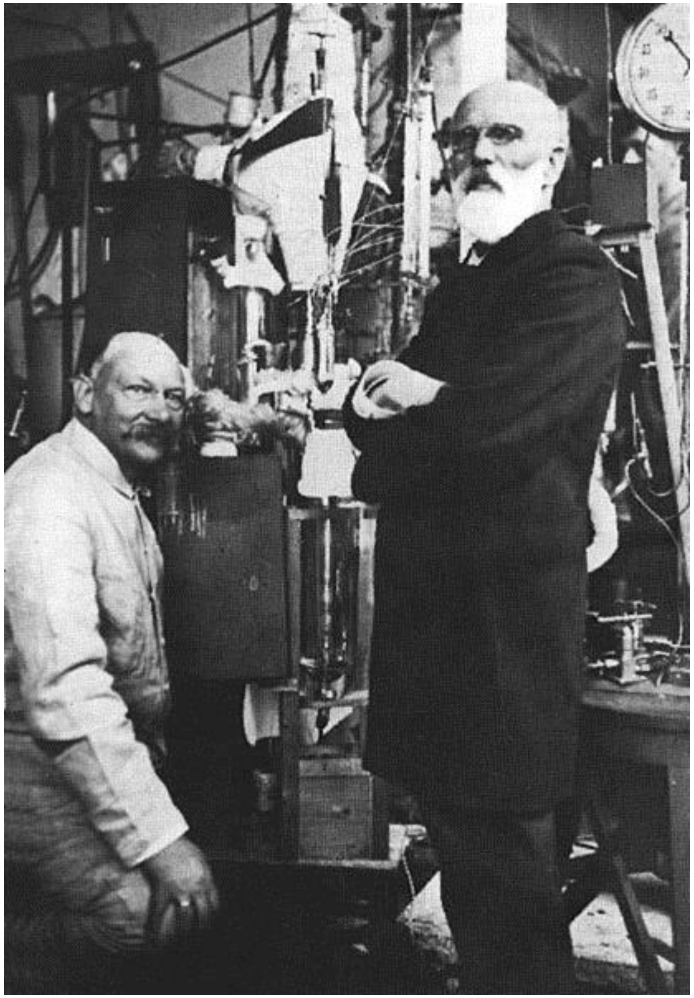
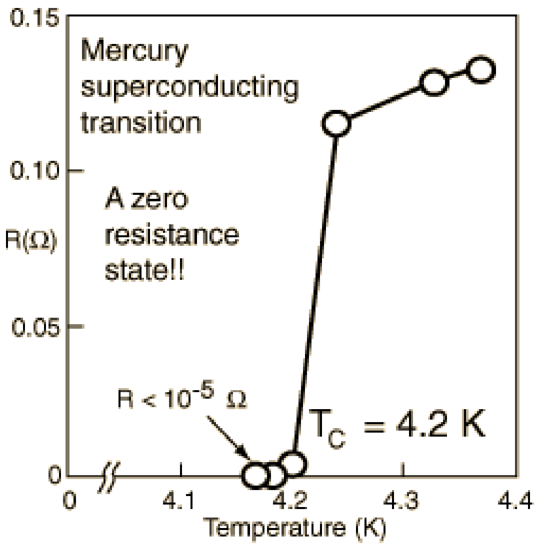
Outline

1. From superconductor basics to superconducting accelerator magnets
2. Causes and mechanisms of quenching
3. Quench memory and training
4. Detection and localization of quenches
5. Passive quench protection: how to dump magnet energy
6. Active protection: quench heaters and new methods of protection (CLIQ)
7. Protection of a string of magnets. Hardware examples.
8. References and literature

Discovery of superconductivity





H. K. Onnes, Commun. Phys. Lab.12, 120, (1911)

A first superconducting magnet

Lead wire wound coil

Leiden, 1912

Using sections of wire soldered together to form a total length of 1.75 meters, a coil consisting of some 300 windings, each with a cross-section of 1/70 mm^2, and insulated from one another with silk, was wound around a glass core.

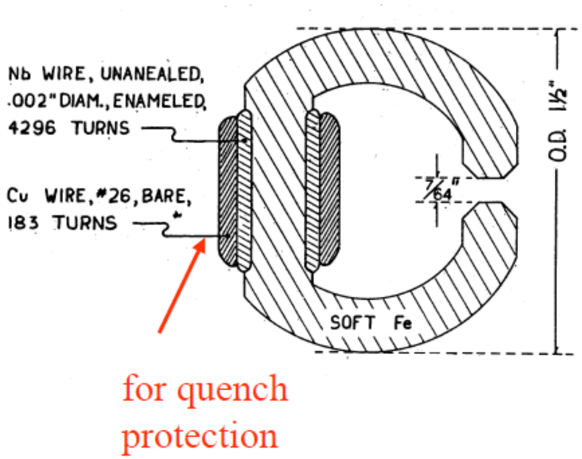
Whereas in a straight tin wire the threshold current was 8 A, in the case of the coil, it was just 1 A. Unfortunately, the disastrous effect of a magnetic field on superconductivity was rapidly revealed. Superconductivity disappeared when field reached 60 mT.

H. Kamerlingh Onnes, *KNAWProceedings* **16** II, (1914), 987. *Comm.* **139f**.

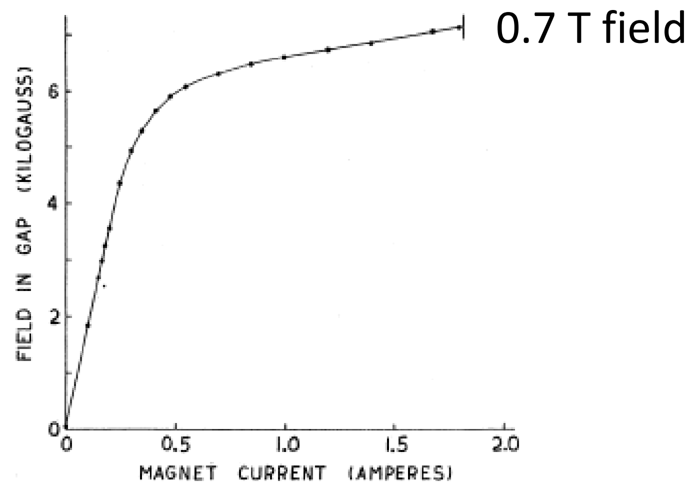
Reason: Pb is a "type-I superconductor", where magnetic destroys superconductivity at once at B_c=803 G.

Note: this magnet has reached 74% of its "operational margin" !

First type-II superconductor magnet

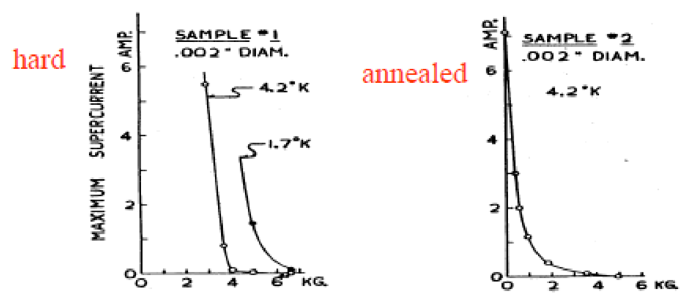


George Yntema, Univ. of Illinois, 1954



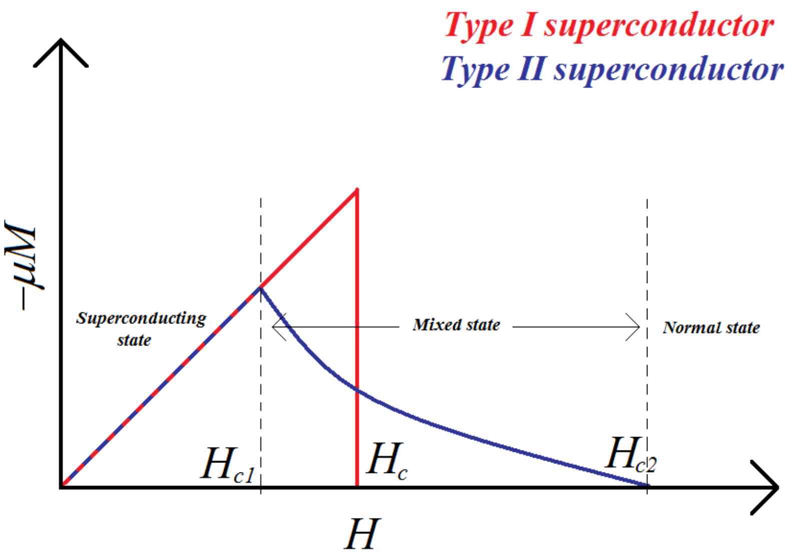
- The first successful type-II superconductor magnet was wound with Nb wire

It was also noted that "cold worked" Nb wire yielded better results than the annealed one…



But why some superconductors work for magnets and some do not? And what it has to do with the conductor fabrication technique?

Basics of superconductors

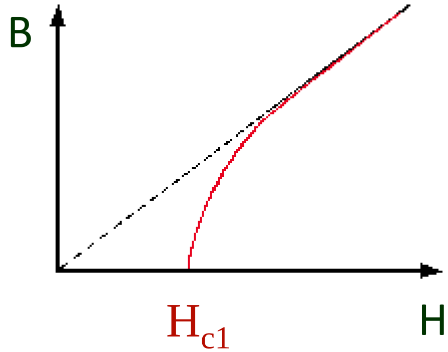


Type- I: Field penetrates the superconductor at H_c destroying bulk superconductivity at once

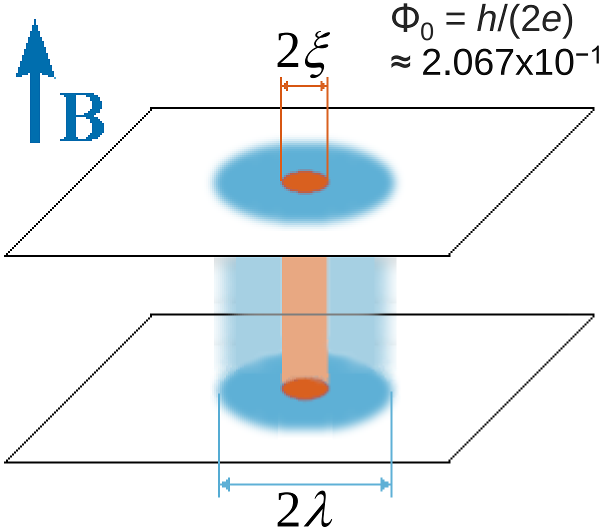
Type-II: Field penetrates the superconductor at H_{c1} in the form of quantized flux lines (vortices); vortex density increases with the applied field, and superconductivity is finally destroyed at H_{c2} (when normal vortex "cores" start to intersect)

Superconductor	T_c, K	H_c (or H_{c2}), T
Pb	7.19	0.08
In	3.14	0.03
Sn	3.72	0.03
Nb	9.26	0.82
NbTi	10	15
Nb_3Sn	18.3	30
MgB_2	39	74
YBCO	92	~100
$Bi_2Sr_2Cu_2O_{8+\delta}$	85	~120

Flux lines (vortices) in type-II superconductors

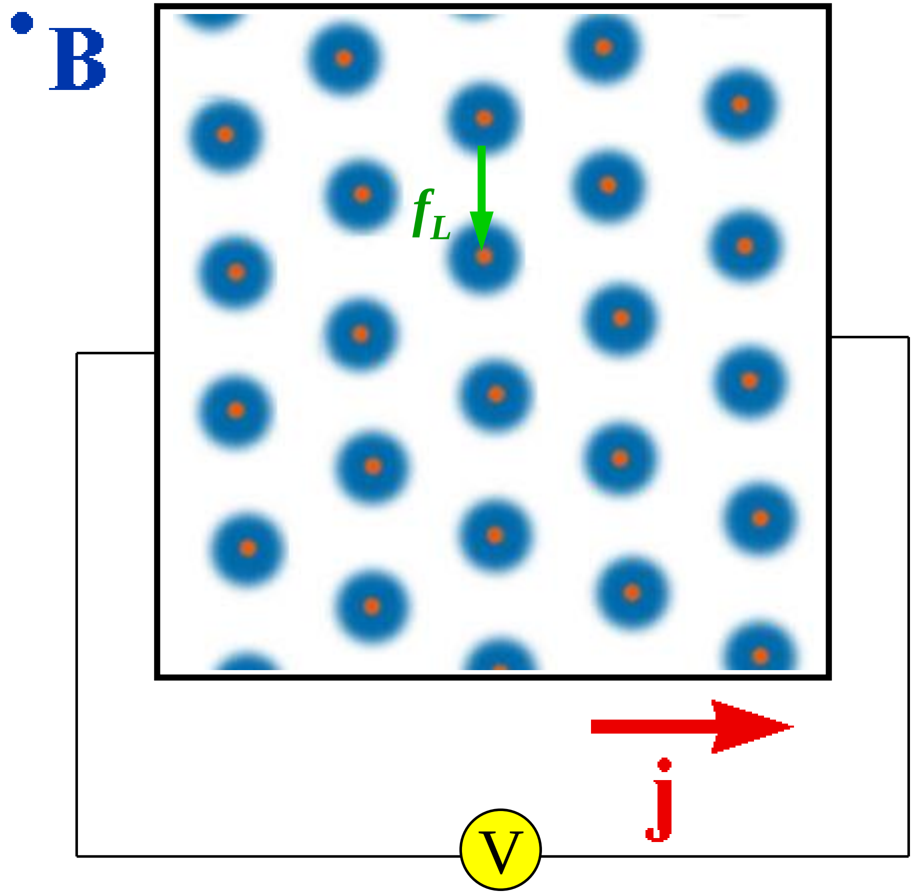


$\Phi_0 = h/(2e)$
$\approx 2.067\times10^{-15}$ Wb



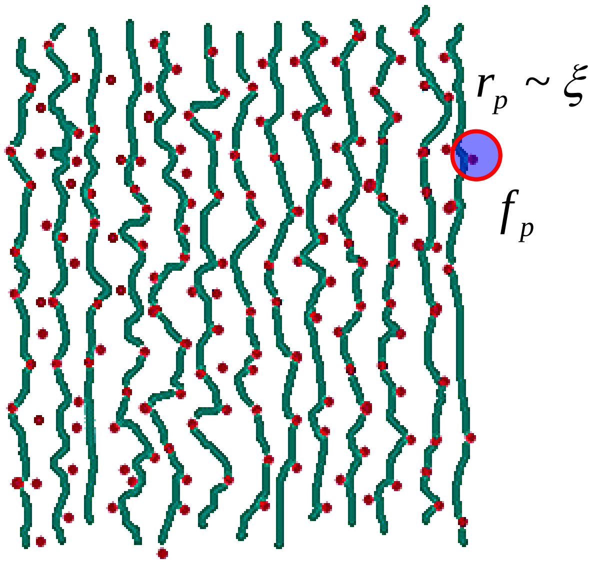
$$H_{c1} = \frac{\Phi_0}{4\pi\lambda^2}\ln\frac{\lambda}{\xi}$$

<u>*Abrikosov, 1957*</u>

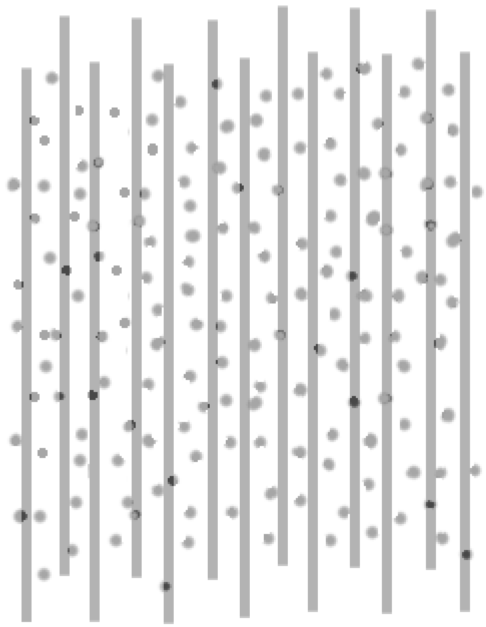


Flux lines and flux pinning

strong pinning

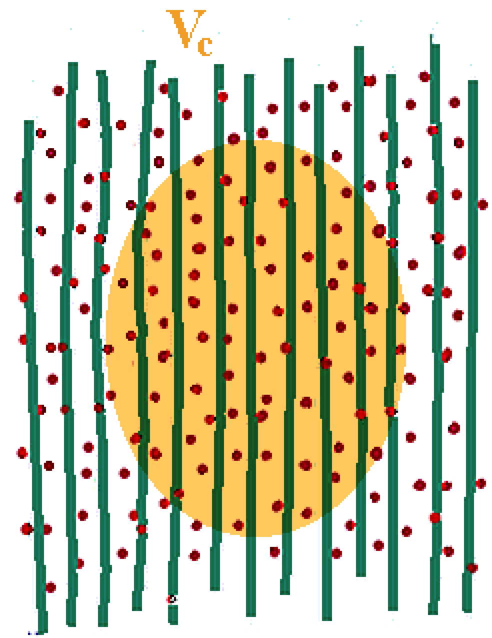


$$F_p = n_p f_p$$



?

weak pinning

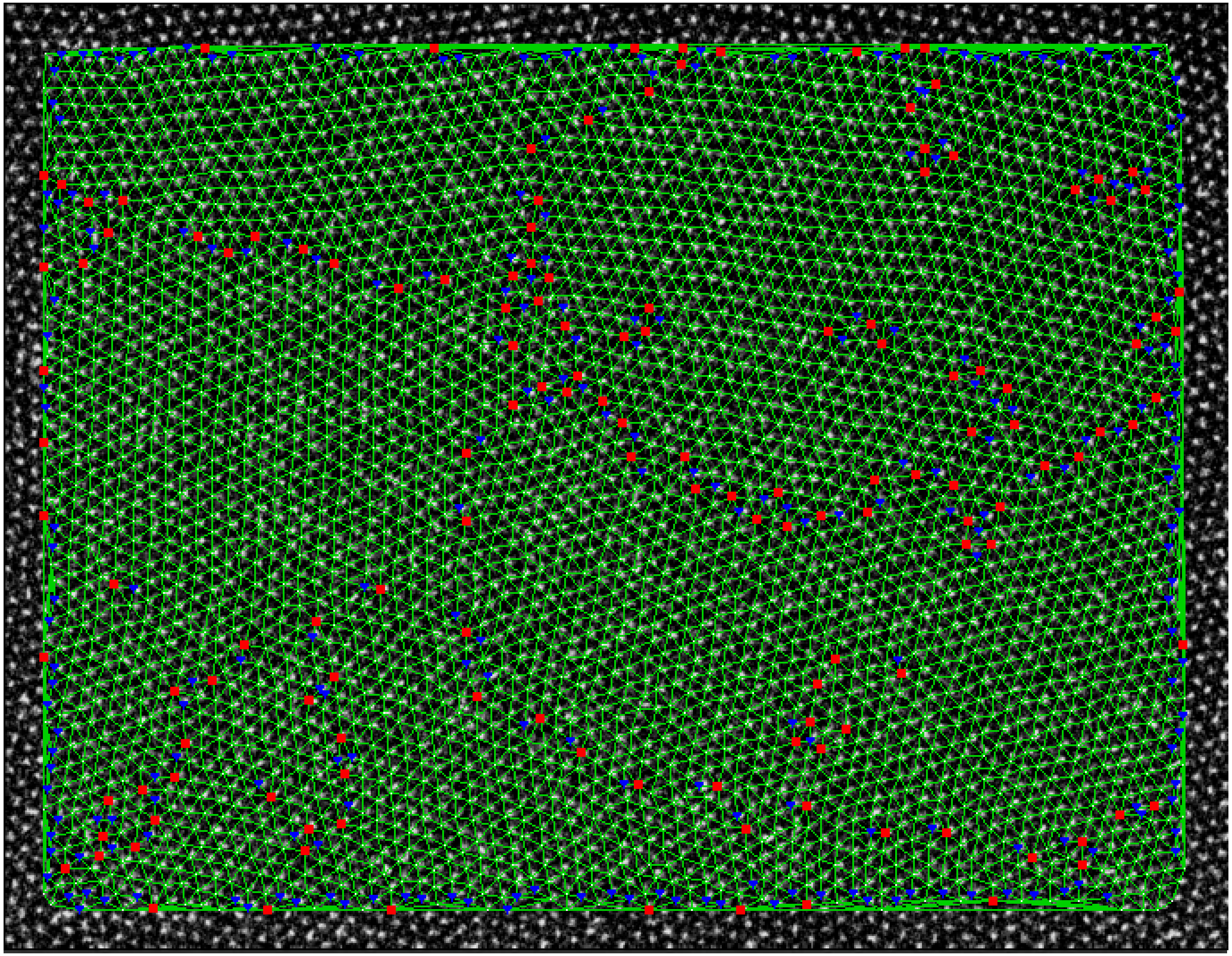


$$F_p = \left[\frac{1}{2} n_p f_p^2 \Big/ V_c \right]^{1/2}$$

$$V_c \sim c_{66}^2 c_{44}$$

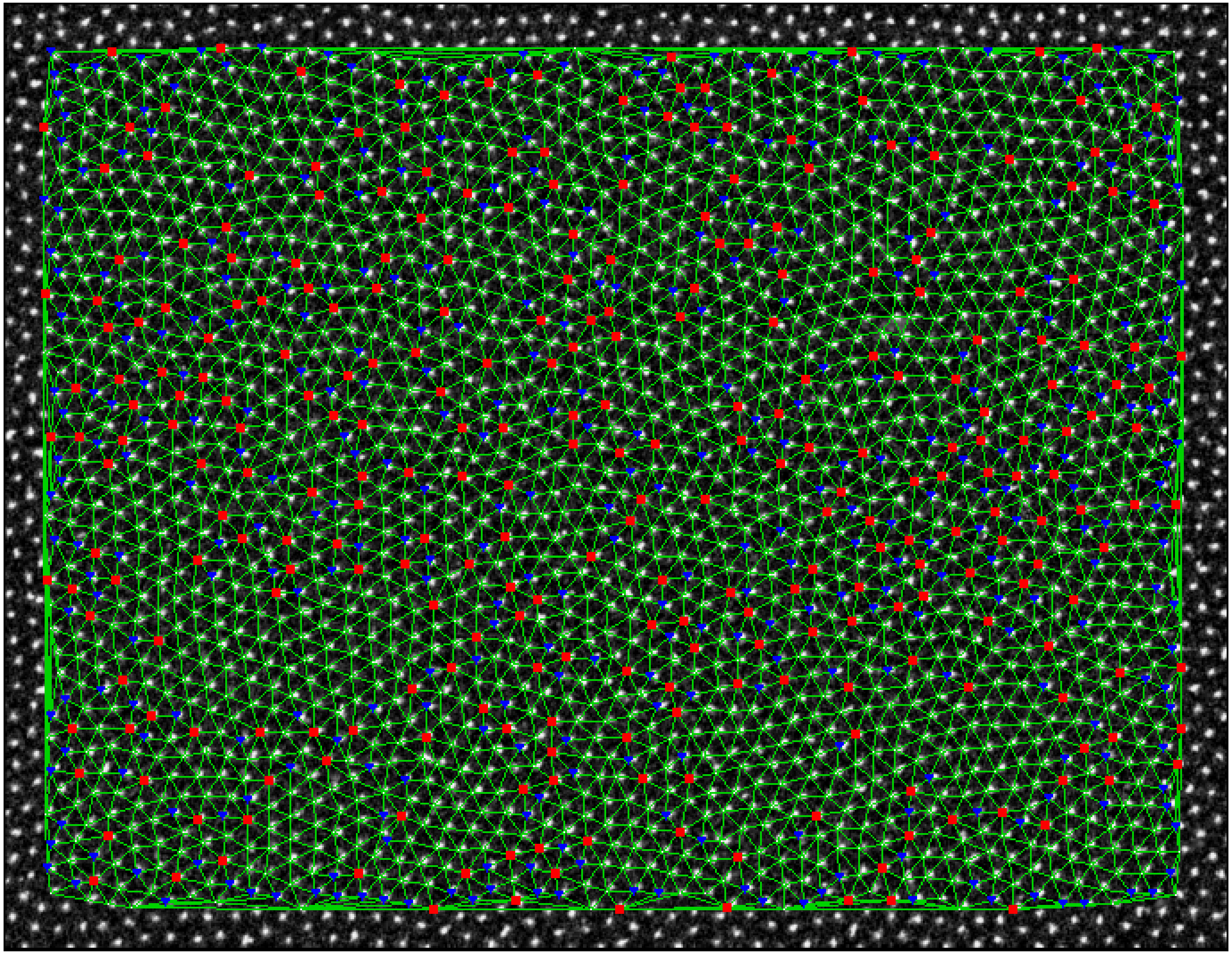
Larkin and Ovchinnikov,1979.

Weak pinning



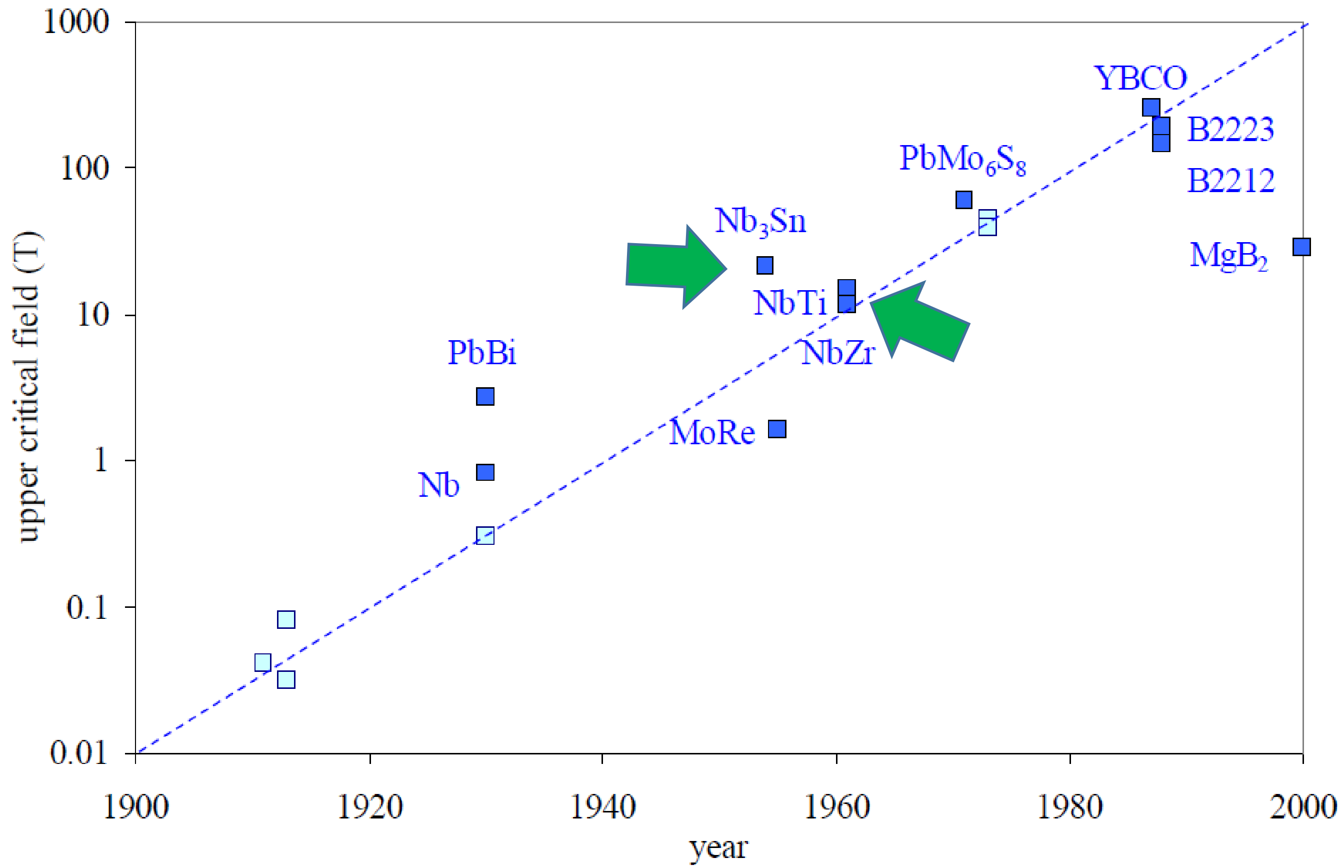
Vortex lattice in $NbSe_2$ (5 mT). When interaction between vortices is stronger than pinning interactions, long-range order exists in the lattice

Strong pinning



When pinning disorder "wins" over inter-vortex interaction (1 mT), lattice order is destroyed.

Superconductor discovery

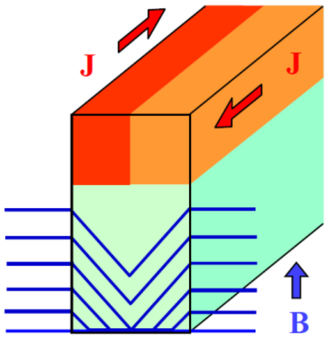


M.N. Wilson, "100 Years of Superconductivity , 50 Years of Superconducting Magnets", CERN Symposium, Dec 2011

It is a **combination** of high H_{c2} AND strong pinning (high J_c) that is essential for practical superconductors used in magnet applications.

Flux jumps and magnetization

- When pinning is strong, a significant amount of flux is trapped in superconductor (= magnetization)
- When current exceeds critical, instead of a gradual de-pinning of vortices, an "avalanche-like" instability occurs, called **"flux jump"**



Critical state:
$J_Y = -dB/dx$

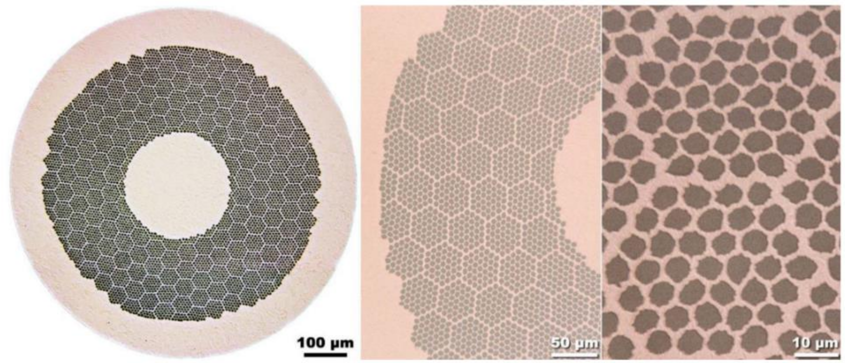
The mechanism of "flux jumping":

A small "bundle" of flux initially moves -> temperature rises->critical current density (pinning strength) is reduced -> more flux moves -> temperature rises further ->> a flux "avalance" forms, seen as a spike in voltage across the conductor…

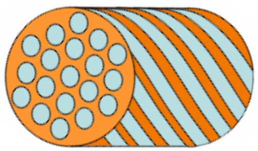
"Cure" for flux jumping: weaken the link in the feedback loop. This is primarily done by reducing diameter of a superconductig wire. Use many fine filaments instead of a large diameter wire. For NbTi the stable diameter is ~ 50 μm.

Conductor architecture

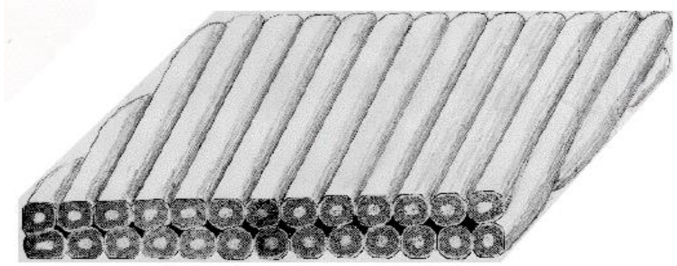
Stabilization: solid superconductor wire is replaced with an array of thin superconducting filaments embedded in copper matrix. Should a filament lose superconductivity, current will be redirected into the surrounding copper stabilizer



Twisting filaments along the strand length allows to reduce their stray magnetization

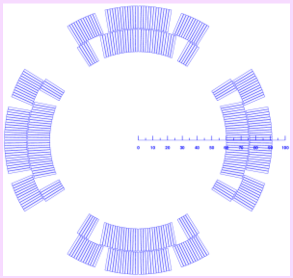
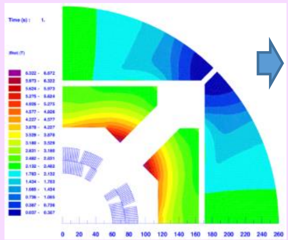


Transposition: superconducting strands forming a cable allow for a uniform current sharing, re-distribution in case of quenching, as well as additional magnetization reduction

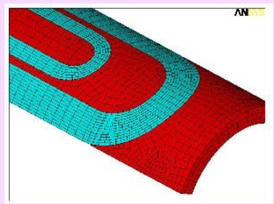
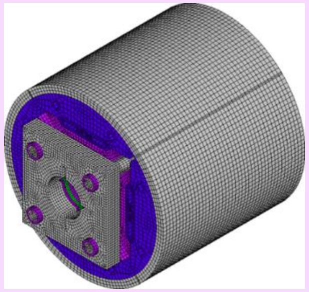


“**Nb-Ti - from beginnings to perfection**”, *Peter J. Lee NHMFL, Florida State University* and *Bruce Strauss U.S. Department of Energy, in “100 Years of Superconductivity*" “, CRC Press 2011

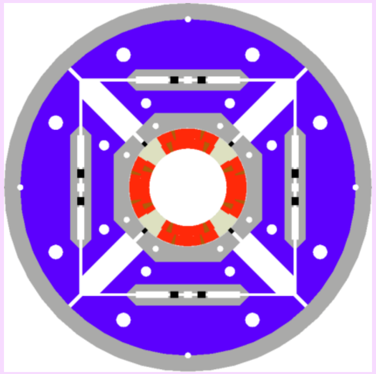
Superconducting accelerator magnets: design and construction steps

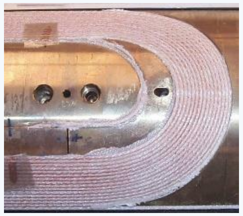
magnetic design and analysis

mechanical analysis



electromagnetic and mechanical model

winding

reaction (Nb_3Sn)

epoxy impregnation

QA

assembly, Pre-loading, QA

- Cryogenics
- Powering
- **Quench protection**
- Quench diagnostics

TEST
(field performance, field quality quench training stability, quench current memory, etc..)

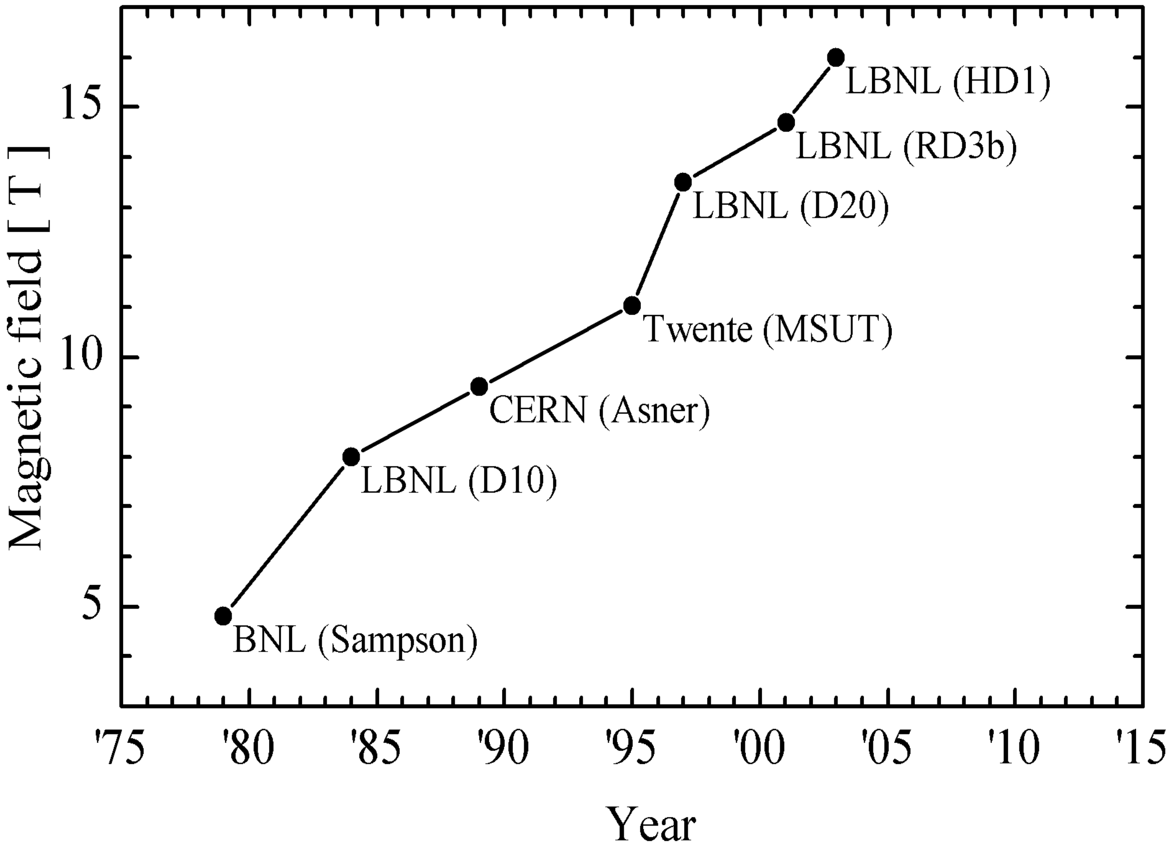
- Data analysis
- Quench locations
- Disassembly / cutting and post-test investigations

Design improvements

Record high-field accelerator dipoles

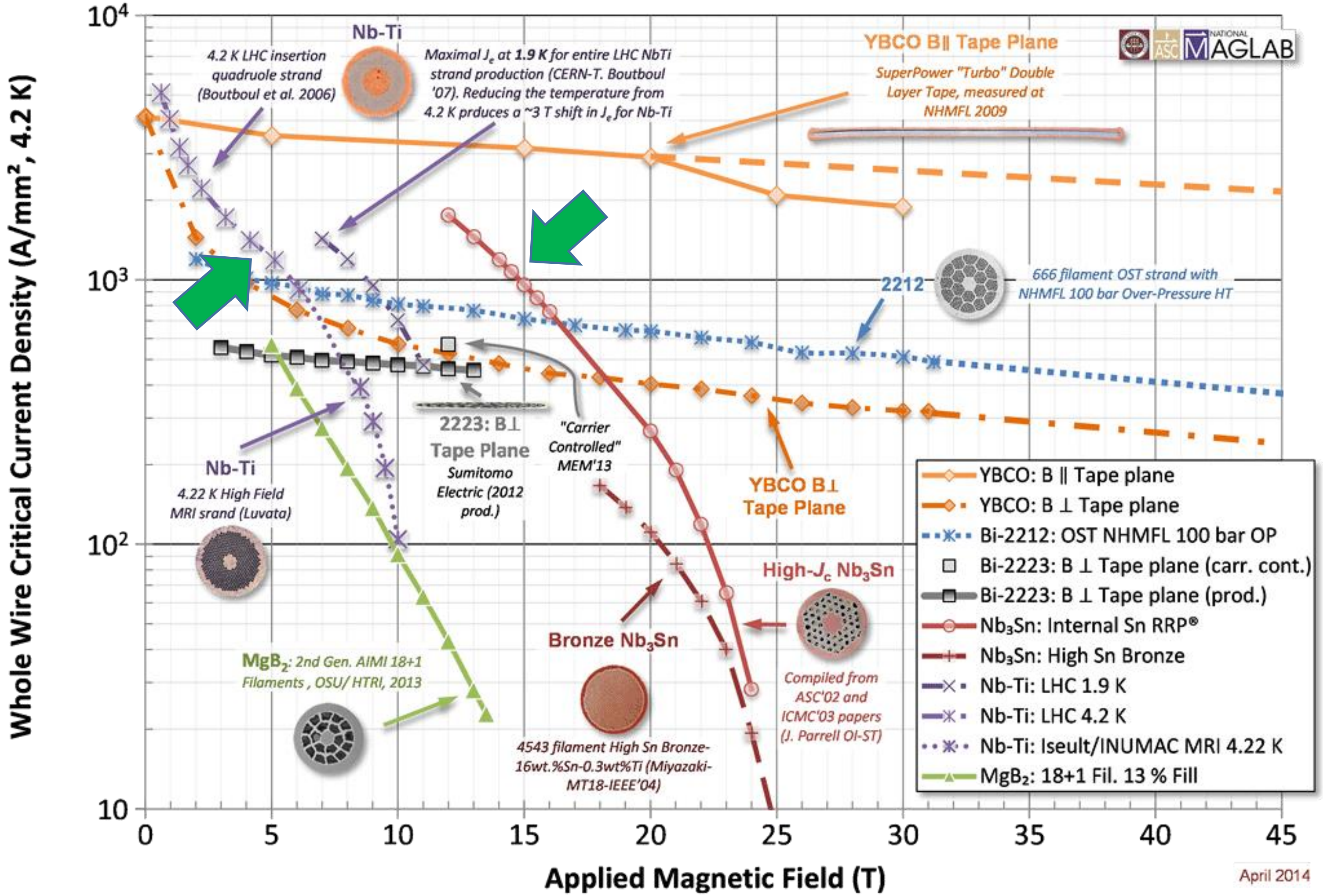
RD3

HD1



New approaches, new designs and new materials are explored to keep this trend…

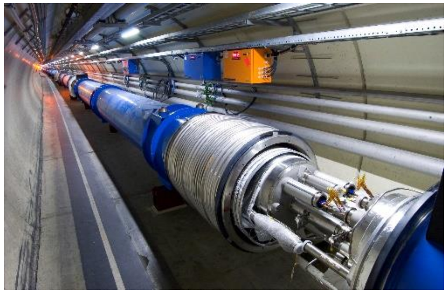
Superconductors for high-field applications



P. Lee, NHMFL

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

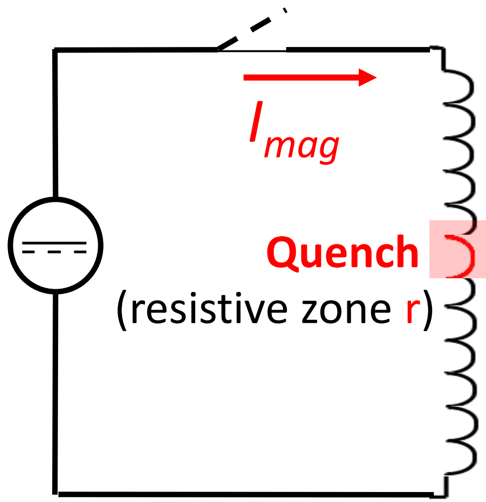
- ➢ 0.7 MJ of energy is sufficient to heat up from 4 K and melt ~1 kg of copper!
- ➢ Equivalent He gas release is 254 L / kJ => 177.8 m^3 of gas!

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**.

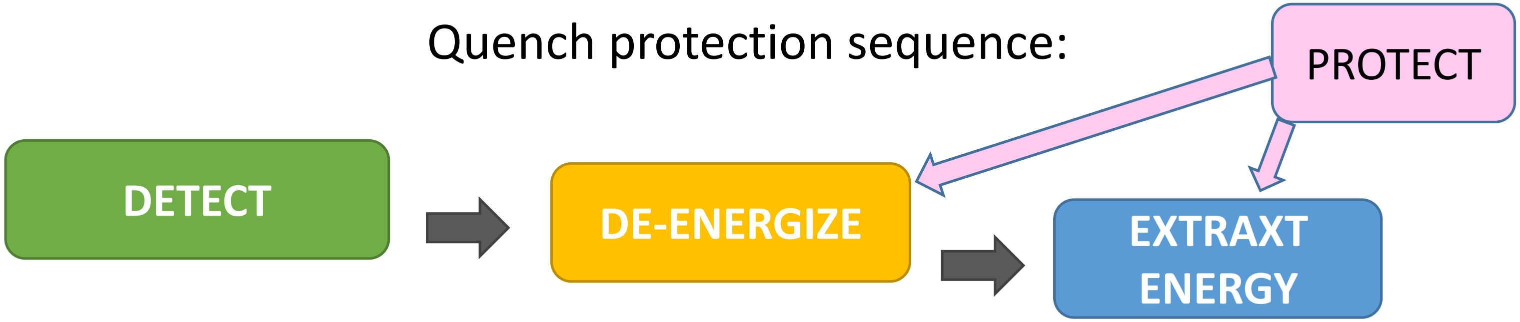


$$P = I_{mag}^2 r$$

$$E = \frac{LI^2}{2}$$

- 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.

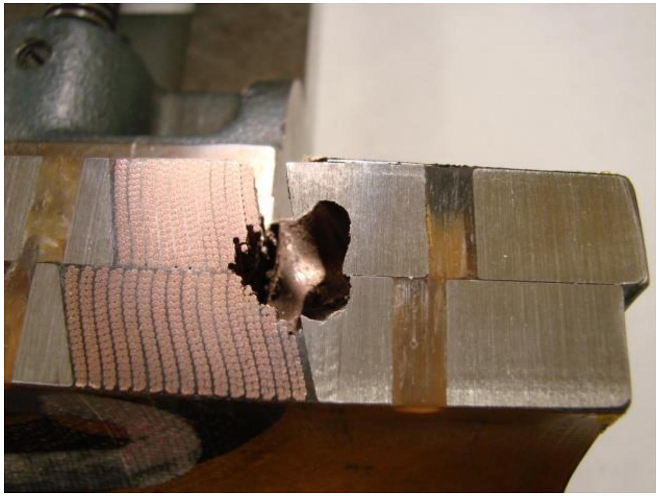
Quench protection sequence:



Quench in small-scale accelerator magnet

(movie)

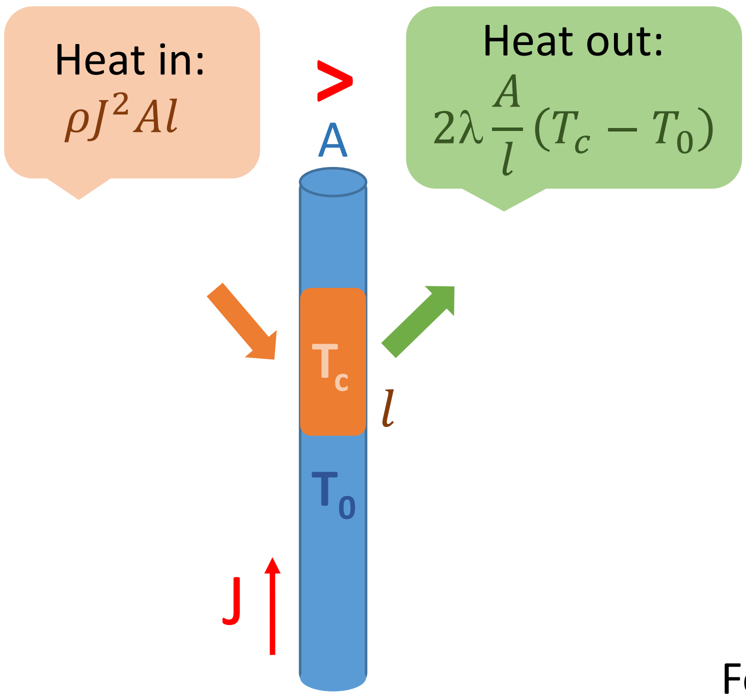
Quench in the CCT3 dipole (~ 80 kJ of stored energy)



Quench-related damage in the coil of HQ01 quadrupole

Onset of a quench: minimum propagating zone

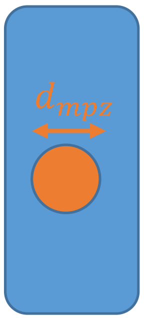
It only takes a small volume fraction of a current-carrying superconductor to be heated above its transition temperature to start a quench.



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

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

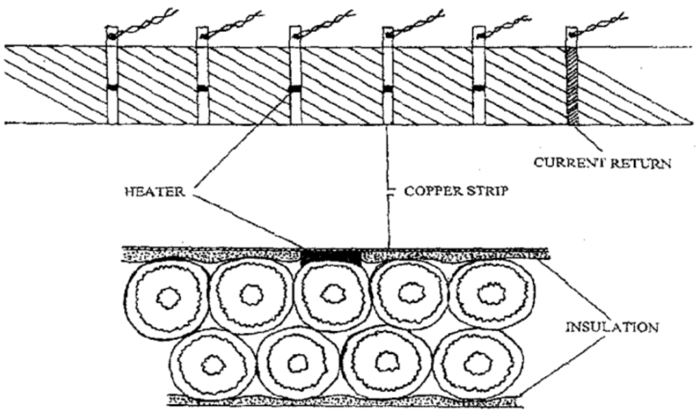


Fig 2. Schematic of the heater location on a strand in the cable.

A.K. Ghosh et al., 1997

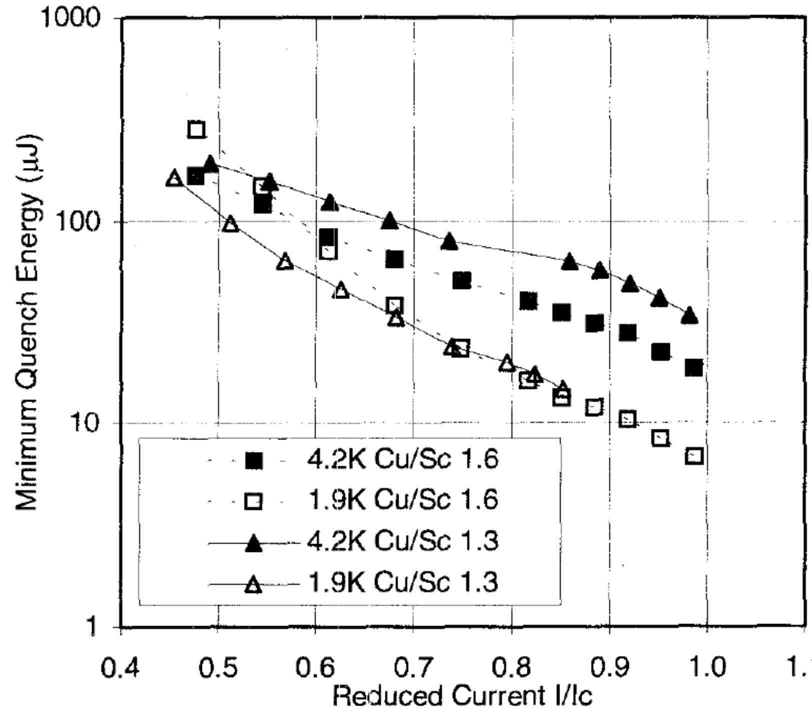
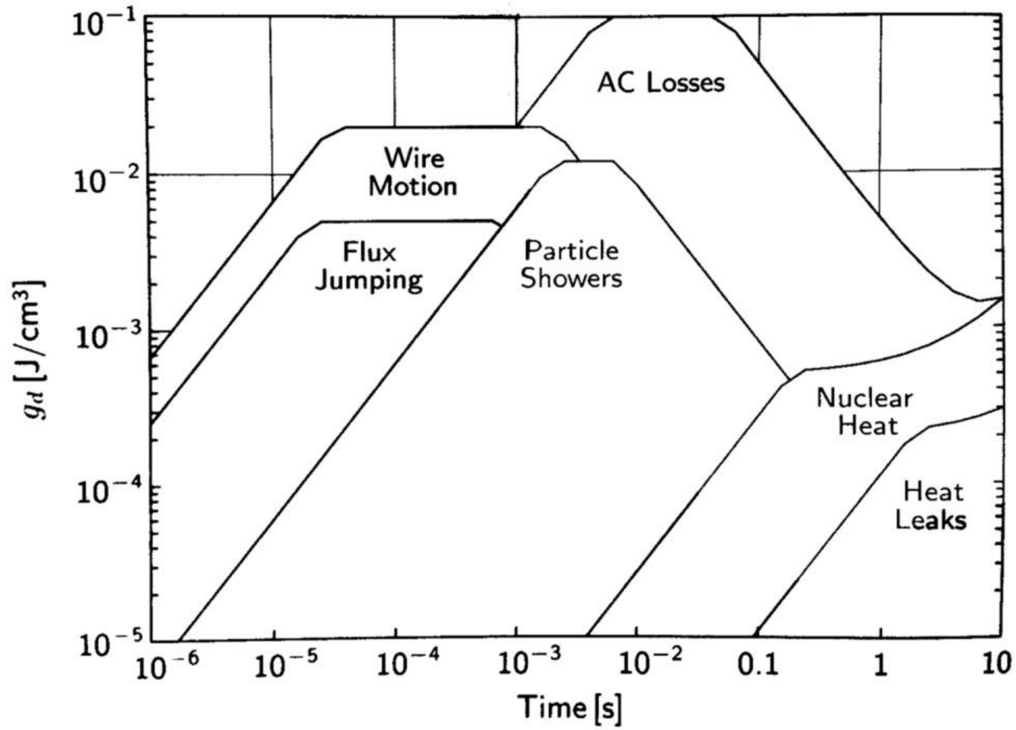


Fig. 3. MQE for two LHC type strands with different Cu/Sc ratio.

- 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?

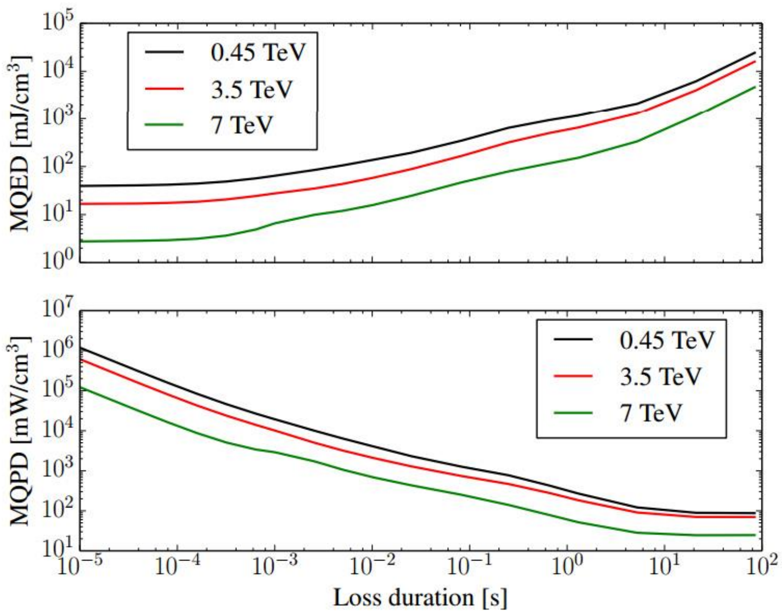
- Intrinsic
  - Conductor instability with respect to flux jumps
  - Conductor damage / broken strands
  - AC losses
- Mechanical
  - Motion of the conductor
  - Cracking and delamination of impregnation epoxy
- Thermal
  - Excess heating in splices or current leads
  - External heat leaks
  - Nuclear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

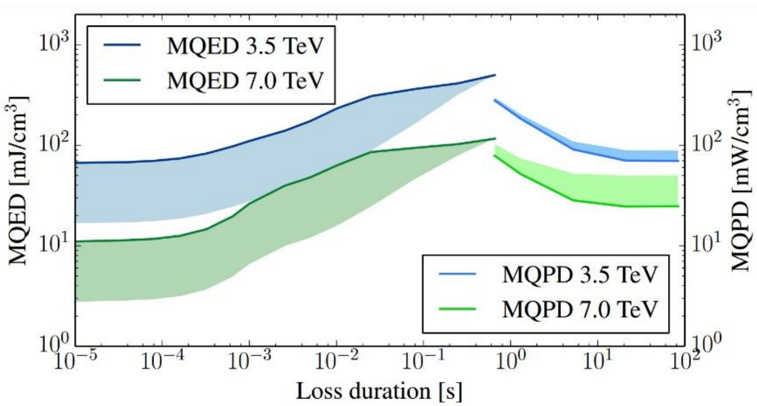


Disturbance spectra of accelerator magnets
(Y. Iwasa, "Case Studies in Superconducting magnets", Springer 2009)

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

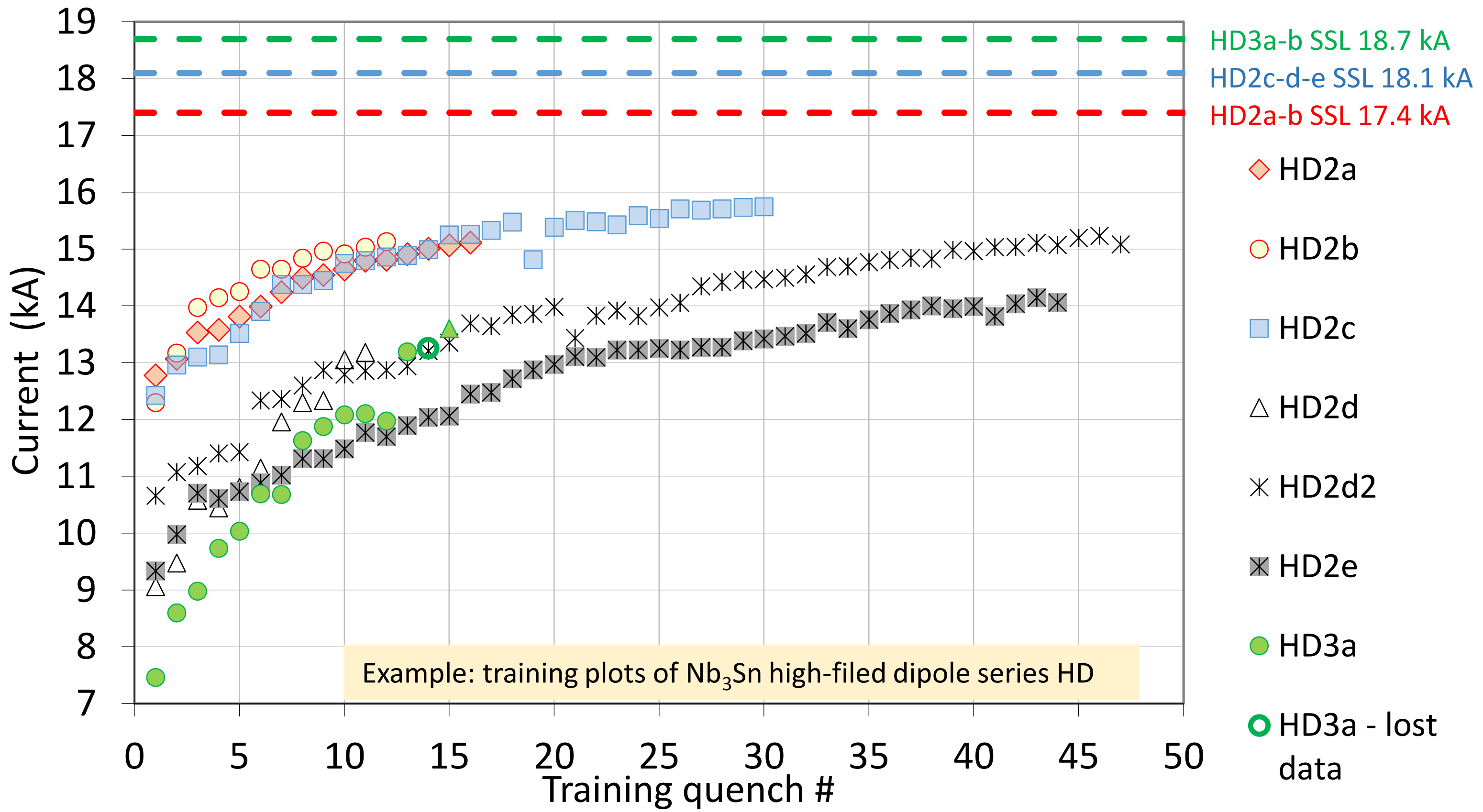




"Testing beam-induced quench levels of LHC superconducting magnets", B. Auchmann *et al.* Phys. Rev. ST Accel. Beams **18**, 061002 (2015)

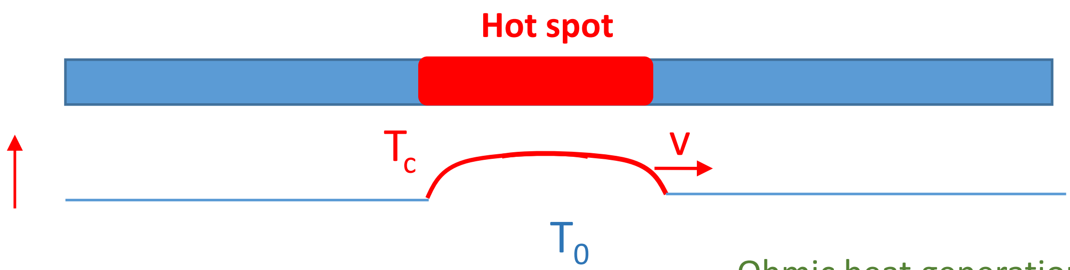
- Short-duration ($t < 50$ µs): The local quench level is determined predominantly by the volumetric heat capacity of a dry cable. The quench level in this regime is quantified by the Minimum Quench Energy Density (MQED).
- Intermediate-duration (50 µs - 5 s): The liquid helium in the cable interstices 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).

Magnet training



- Quench current gradually increases with every quench until "plateau" is reached
- "Memory" of a previous quench current (= **local** strain state)!
- Training is usually explained as gradual "compaction" of the winding under Lorentz forces, accompanied by a series of slip-stick or cracking/delamination events (causing a quench).
- Training is costly! Eliminating magnet training is a challenging and important problem.

Quench propagation: 1D model



Heat balance:

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

Heat capacity → C; Heat conductivity → λ; Ohmic heat generation → $g(J,T)$

Substituting: $\xi = z - vt$

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

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

General solution for the equation:

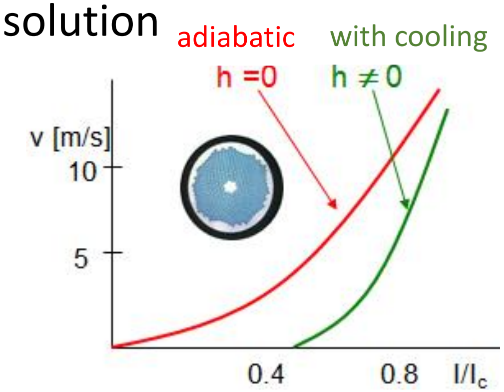
$$T(\xi) = \begin{cases}T_c - (T_c - T_w)\exp(\alpha\xi)\ , \xi < 0\\ T_0 - (T_w - T_0)\exp(-b\xi)\ , \xi > 0\end{cases}$$

- a travelling wave solution

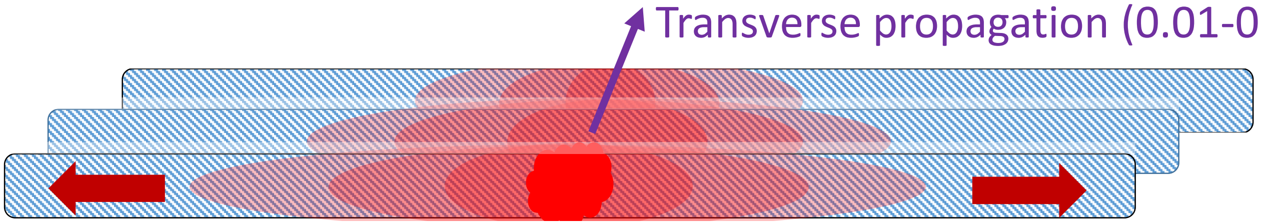
Then, substituting into the heat equation: $v_0 = \frac{J}{C}\sqrt{\frac{\rho\lambda}{T_c - T_0}}$

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

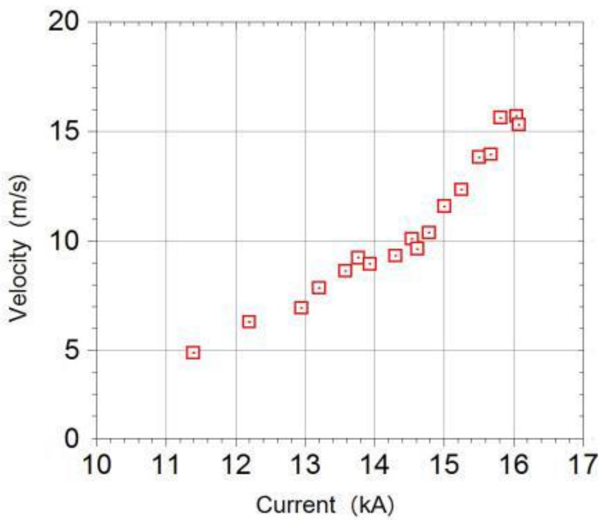


Quench propagation in 3D



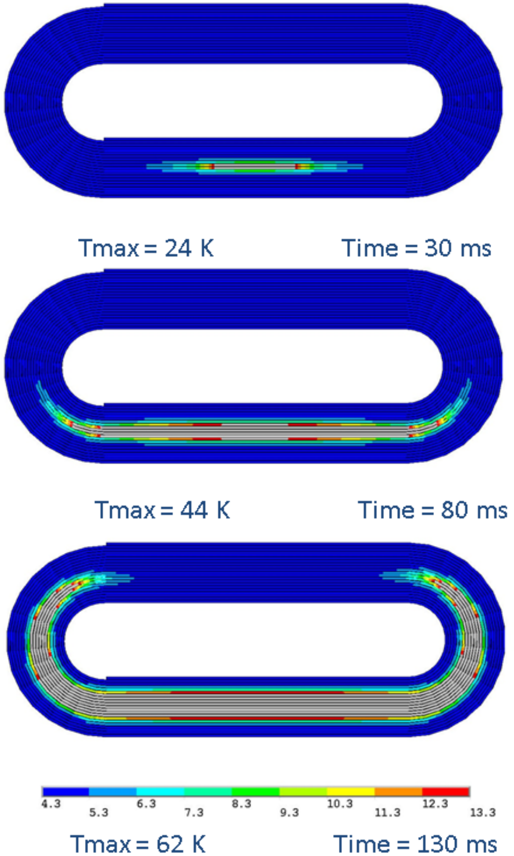
Resistance increase in the coil caused by the expansion of the normal zone AND continuing temperature increase within the normal zone

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



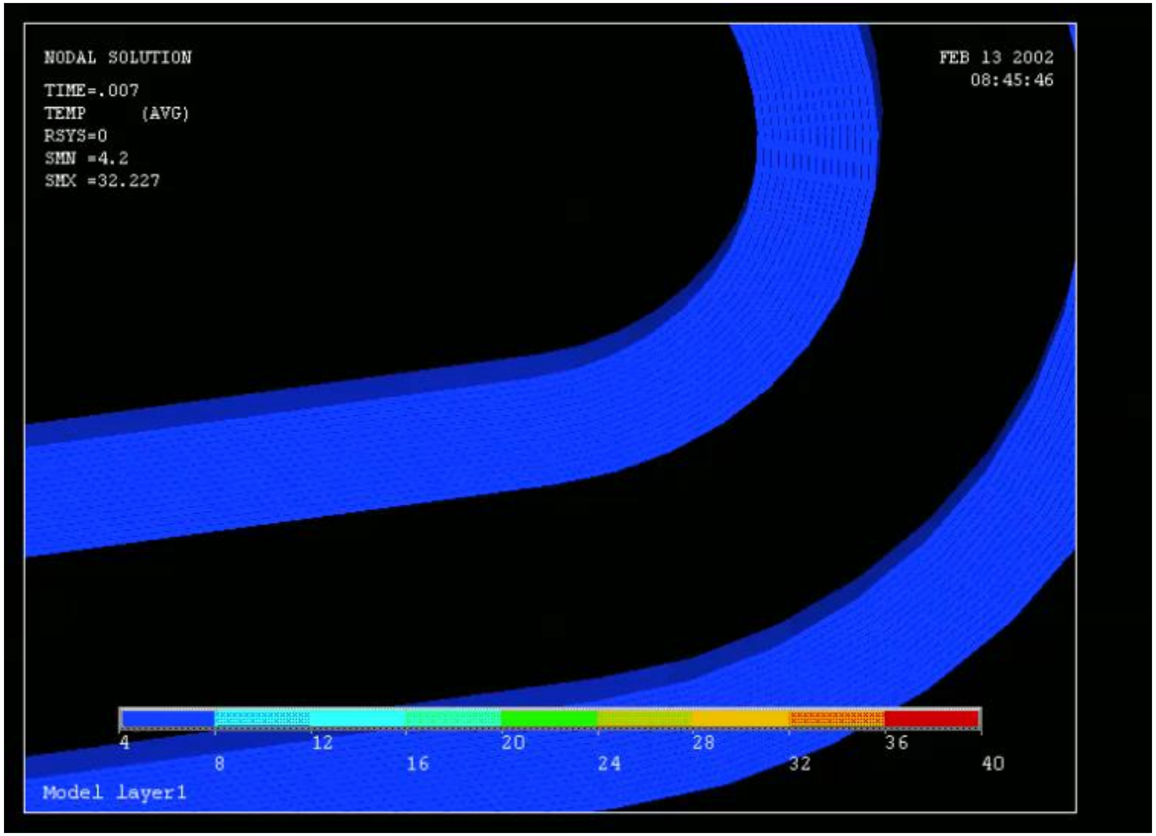
Quench propagation velocity measurements in HD3 high-field dipole (I_{ss}=18.7 kA)

Quench simulations: FEA



P. Ferracin, 2009

ANSYS – thermal electrical model

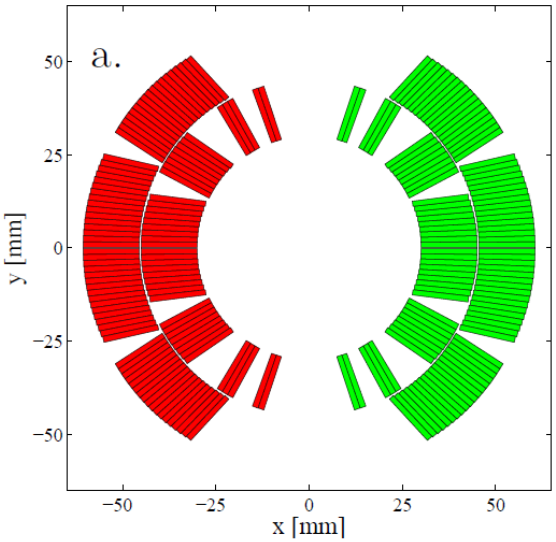


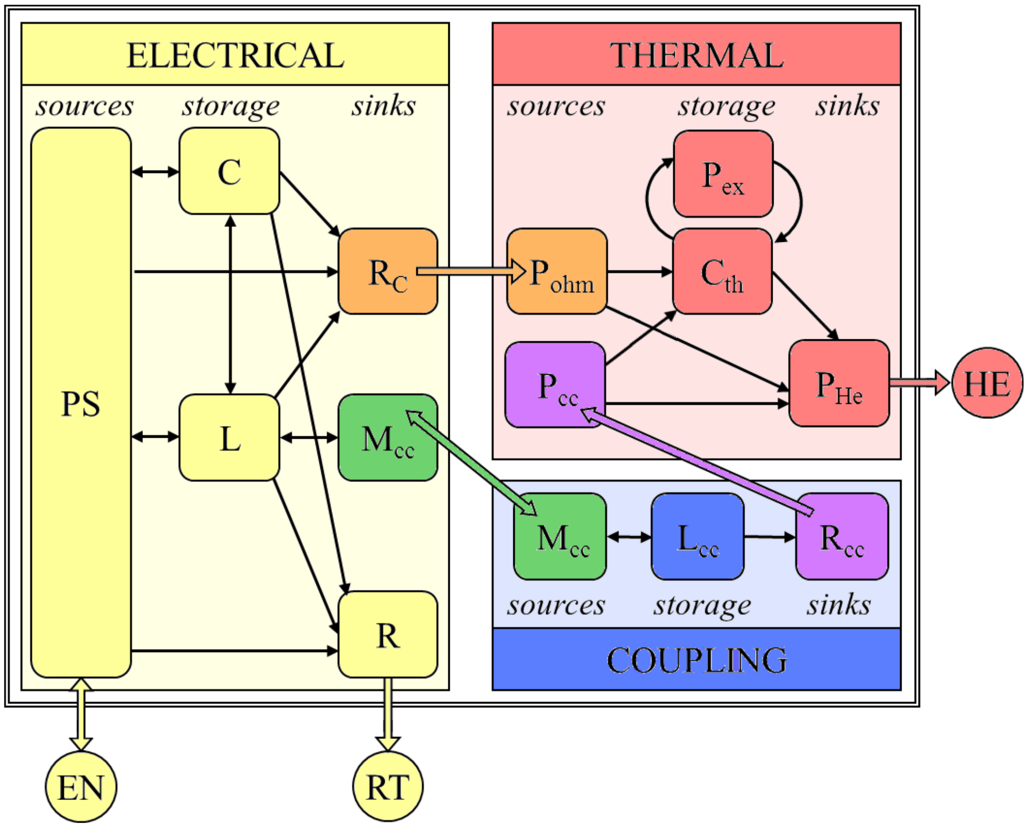
Courtesy: S.Caspi

(movie)

Lumped element and “circuit” models

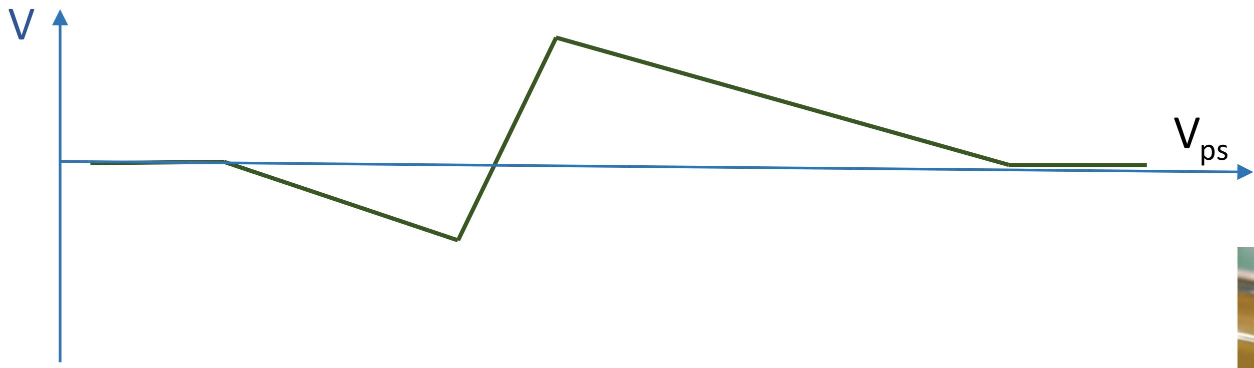
LEDET method (Lumped Element Dynamic Electro-Thermal)



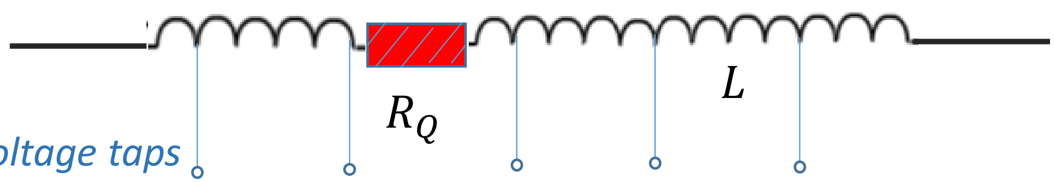


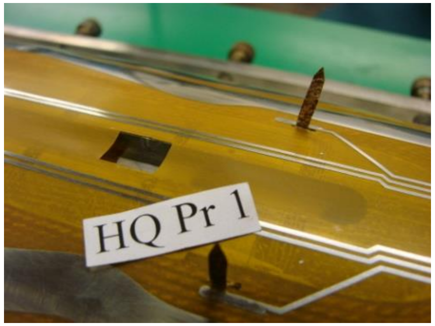
M. Maciejewski & E. Ravaioli, 2015

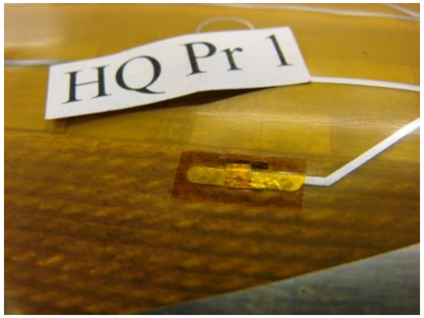
Voltage distribution in a quenching magnet



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







Voltage taps examples

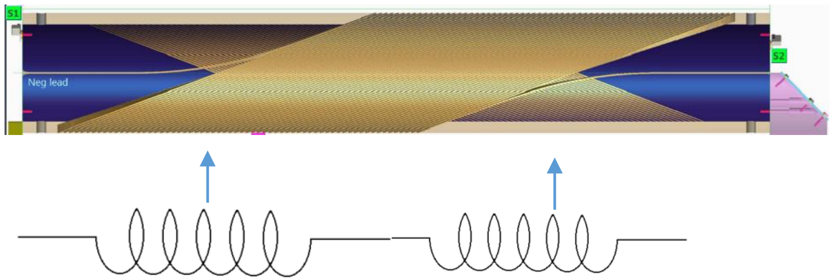
$$V_Q(t) = I(t)R_Q(t)(1 - \frac{M}{L})$$

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

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

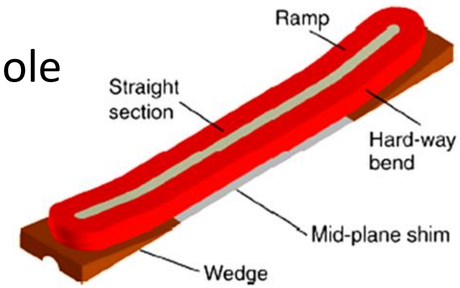
Detecting and localizing quenches

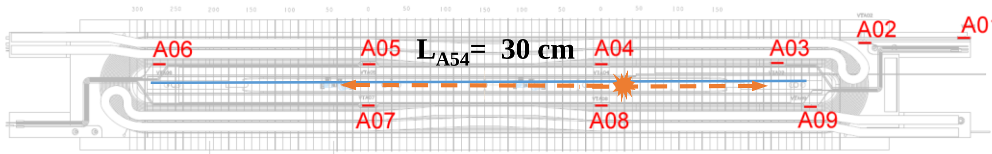
CCT3 Nb_3Sn dipole

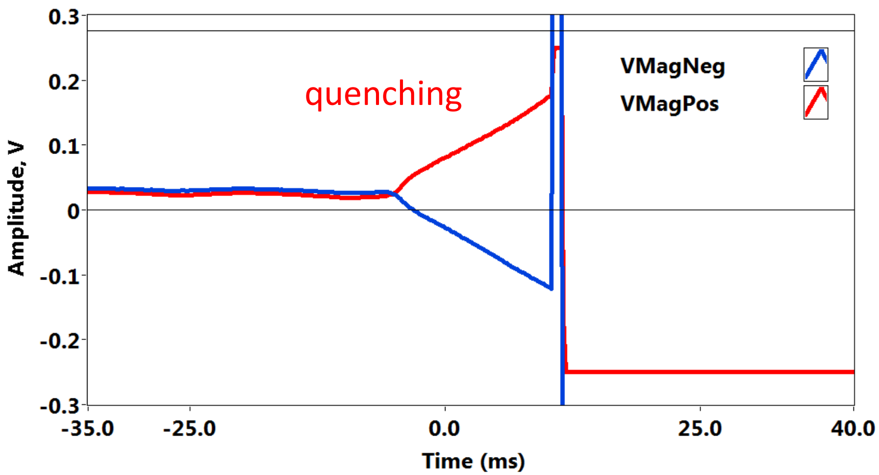


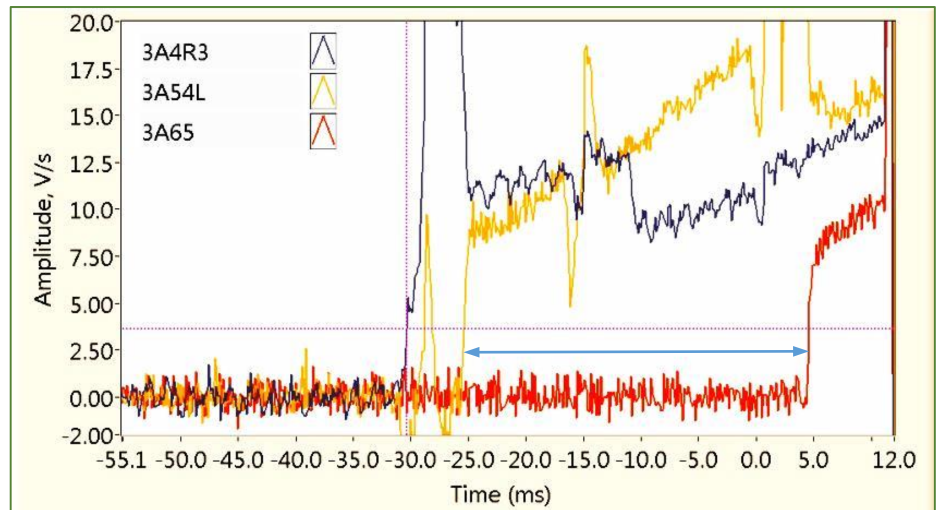
"HalfMagNeg" **"VmagMagPos"**

HD3 Nb_3Sn dipole









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

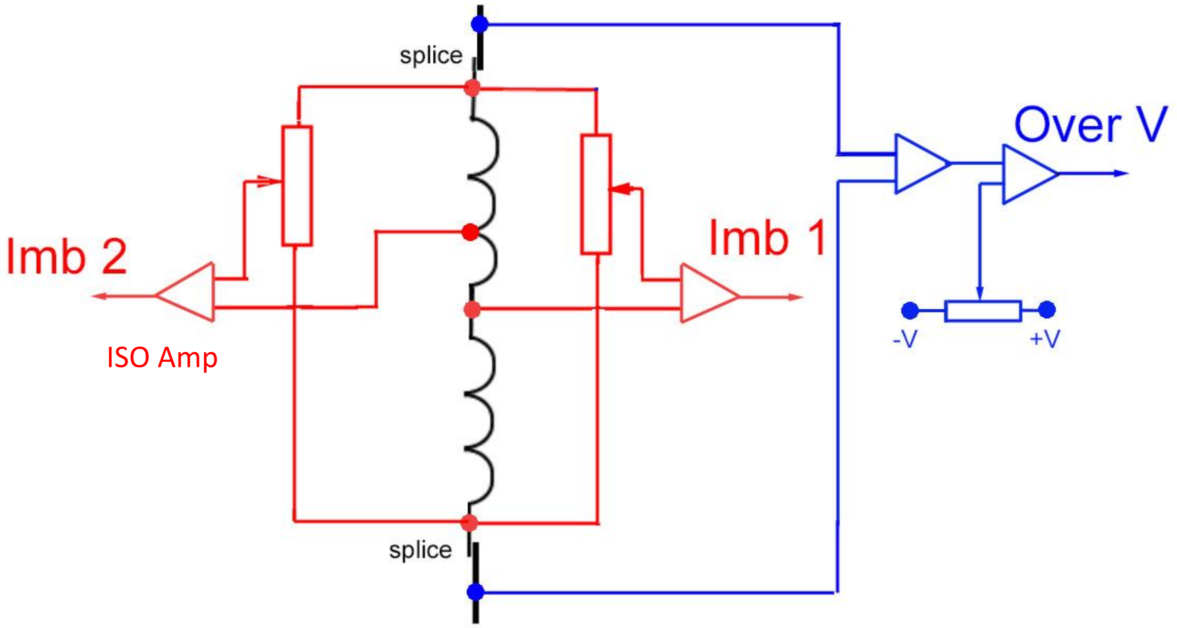
Quench is ~5 cm from the Vtap A4 in the A43 segment

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)

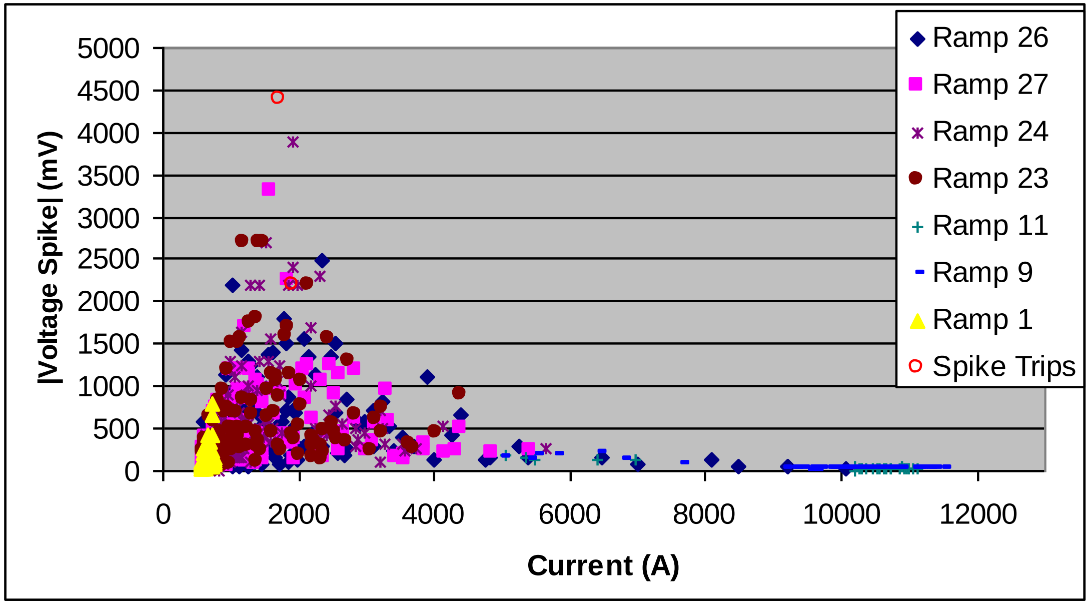
Quench is detected when either of the detector circuits outputs voltage above pre-set threshold. Typical Imb. threshold is ~100 mV for research magnets. A time interval over which voltage rises above the threshold is often called “detection time”. (t_d).

Detection threshold

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).

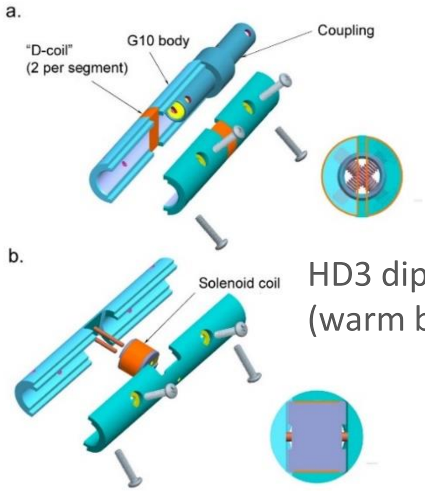
In Nb_3Sn magnets, it is challenging to pick a safe threshold because of flux jumps:

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

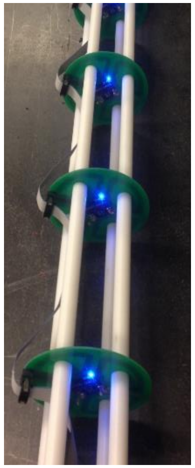


FNAL TD-07-015 TQS02a Voltage spike analysis – C. Donnelly et al.

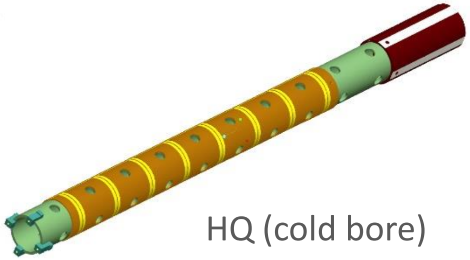
Inductive quench antennas



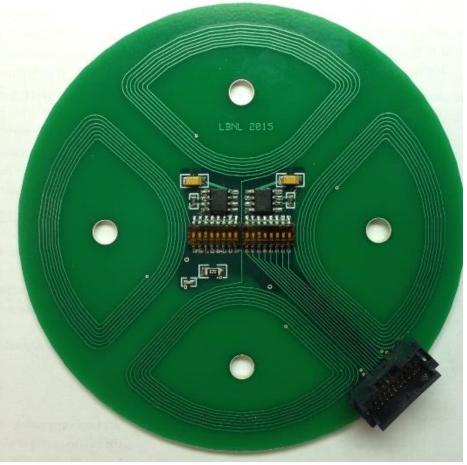
HD3 dipole (warm bore)



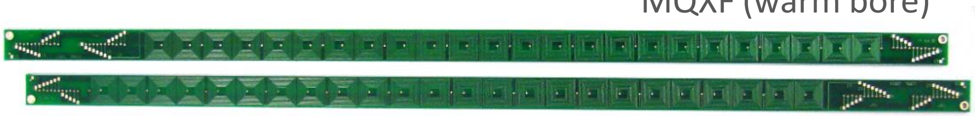
Inductive pickup coils detecting re-distribution of current in the quenching cable allowing to localize quenches and understand their origins.



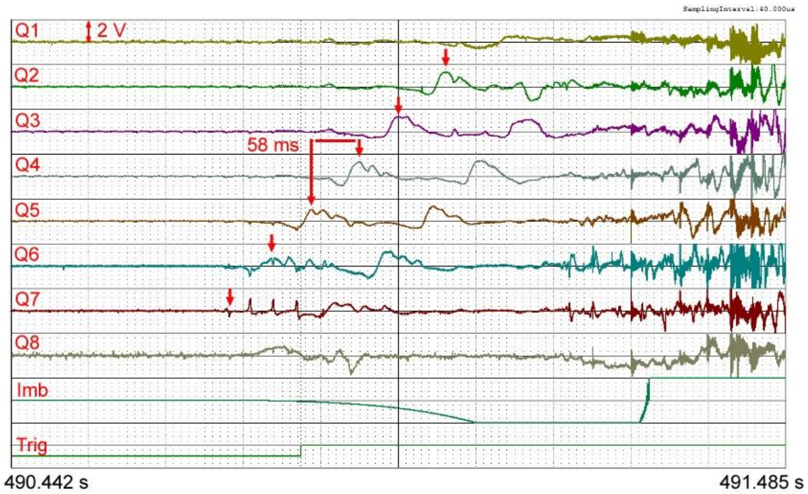
HQ (cold bore)



MQXF (warm bore)

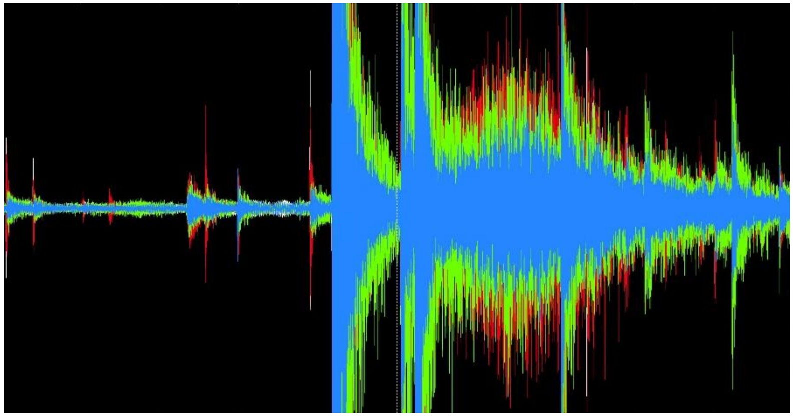


CCT2 linear arrays

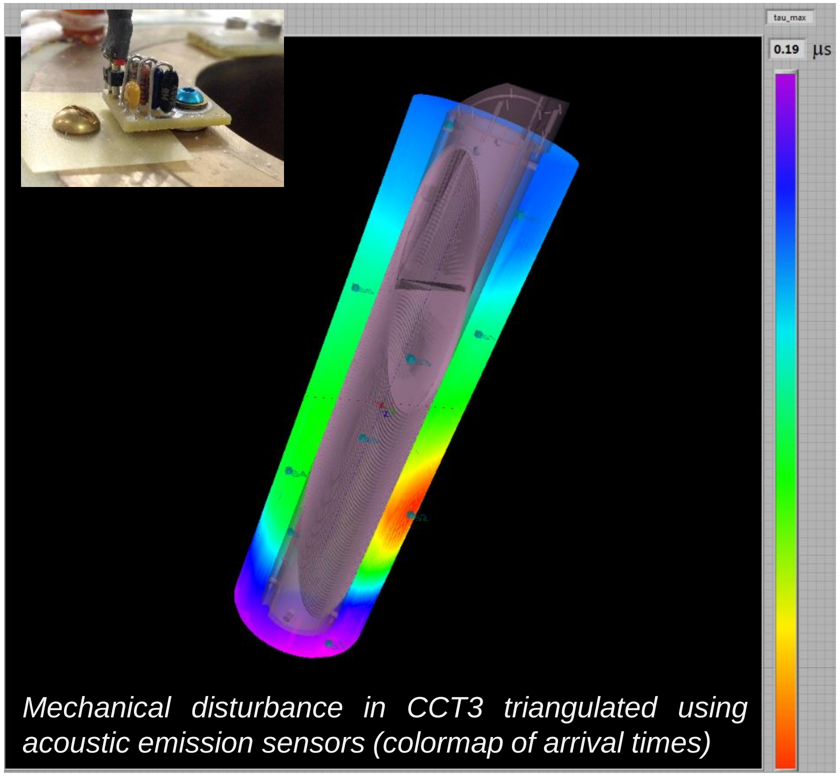


Development and propagation of a slow quench in HQ02b at 6 kA recorded by the quench antenna

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:

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

heat generation *windings enthalpy*

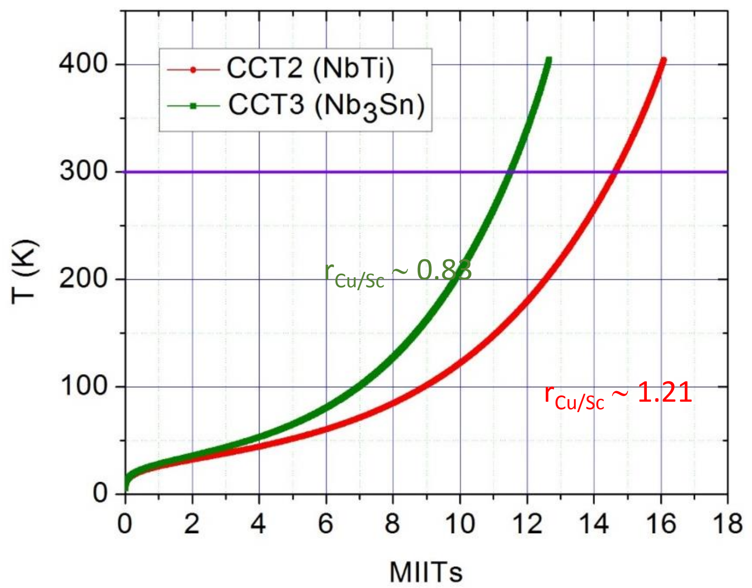
$$\int_{T_0}^{T_q} \frac{c(T)}{\rho(T)} \mathrm{dT} = \int_0^\infty J^2\, dt$$

" $U(T)$

(M)IITs

"Millions of I*I*Time"

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



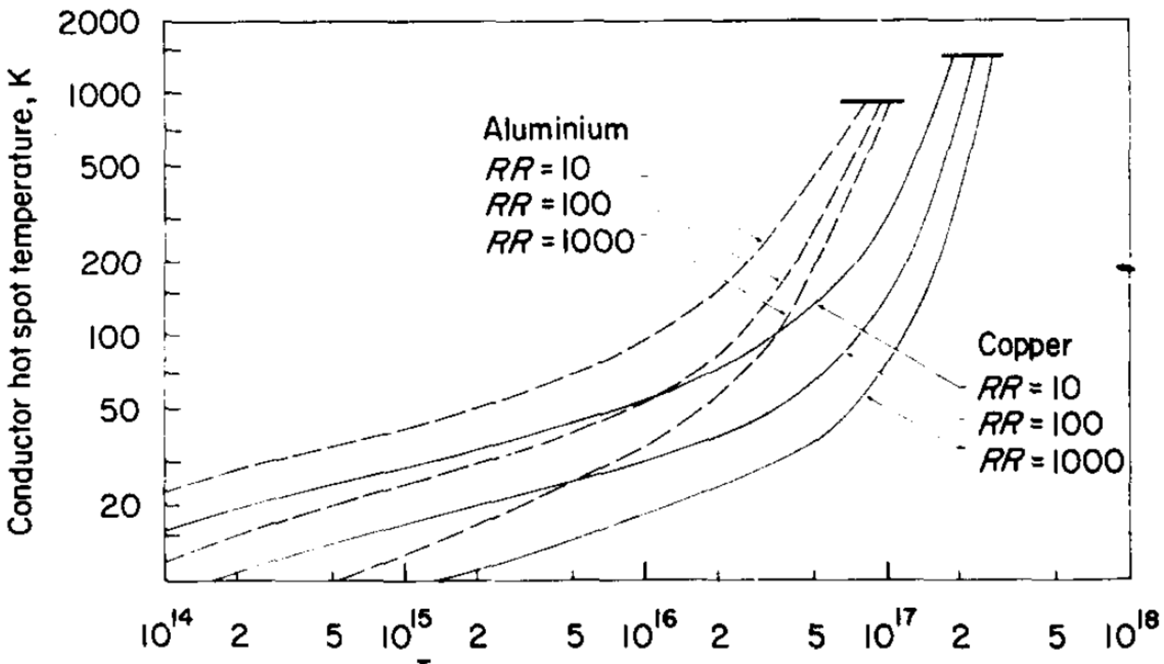
$$F(T_q) = \int_{T_0}^{T} \frac{c(T)}{\rho(T)} \mathrm{dT} = \frac{1+r}{r} \int_0^\infty J^2\, dt$$

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



$$F(T) = \int_{T=0}^{T_{hot}} \frac{C(T)}{\rho(T)}\, dT = \frac{r+1}{r} \int J^2(t)\, dt,\ A^2 m^{-4} s$$

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

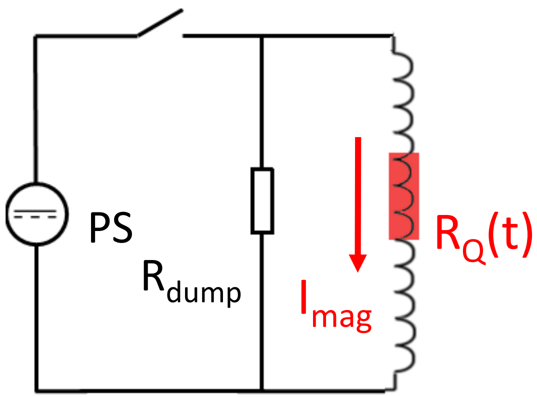
Cable RRR> 150-200 is typically required for high-field accelerator magnets

Protection using a dump resistor

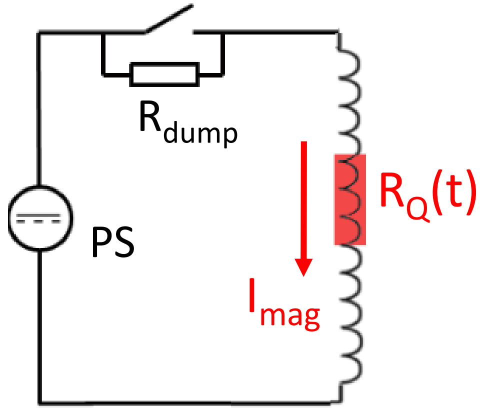
By adding external resistor to in series with the quenching magnet, part of its energy can be "extracted" outside of the cryostat

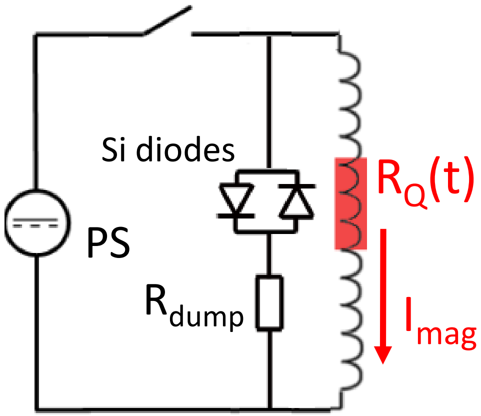
Efficiency of energy extraction depends upon $R_Q(t)/R_{dump}$. At best ~50-60% of magnet energy is typically extracted outside of the cryostat using this method.

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



"Standard" scheme





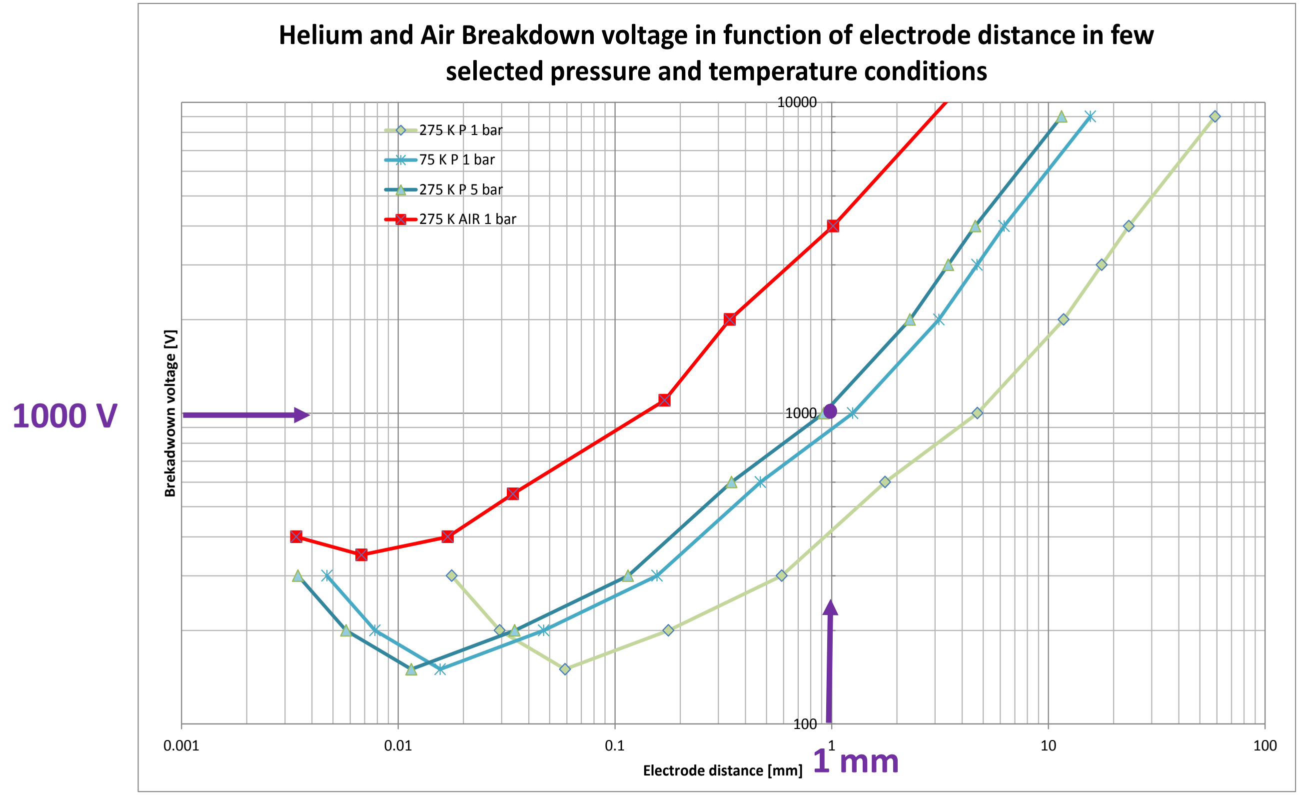
Modified schemes: ramping rate is not limited by the dump resistor

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

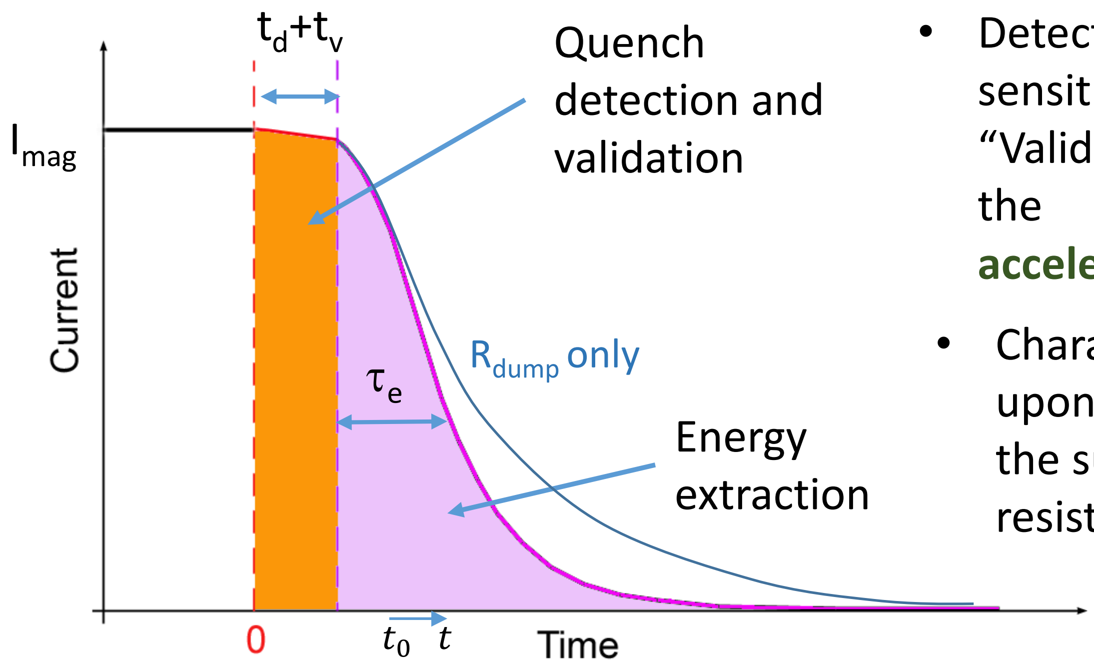
Typically voltages allowed in cryogenic He environment are < 1000 V (Paschen's law).



*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



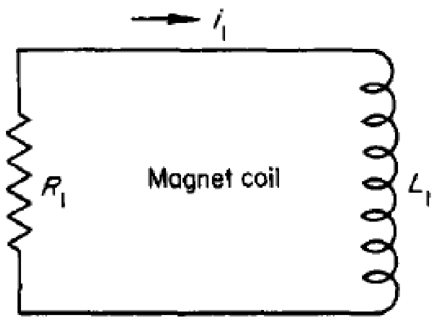
- Detection time t_d depends upon sensitivity and thresholds of QDS. "Validation time" t_v is typically defined by the hardware. **Typically, for LTS accelerator magnets (t_d+t_v) ~ 7-15 ms**
- Characteristic extraction time τ_e depends upon magnet (dynamic) inductance and the sum of magnet resistance and dump resistance:

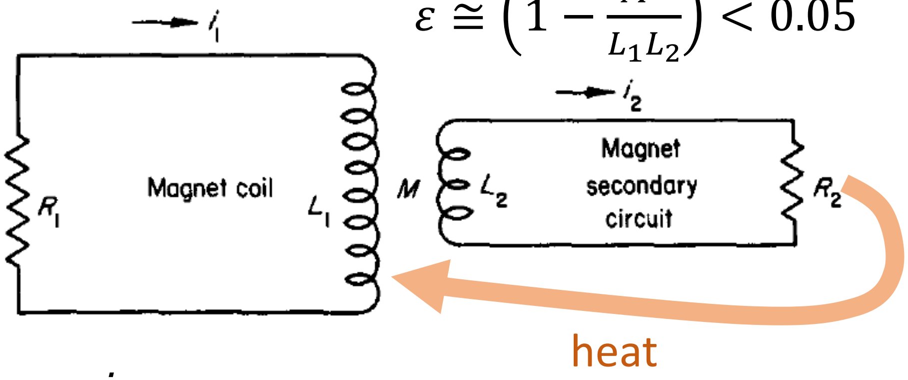
$$I(t) = I_0(t_0)\, e^{-t/\tau_e} = I_0 e^{\frac{-t(R_{mag}(t)+R_{dump})}{L(t)}}$$

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





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

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

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

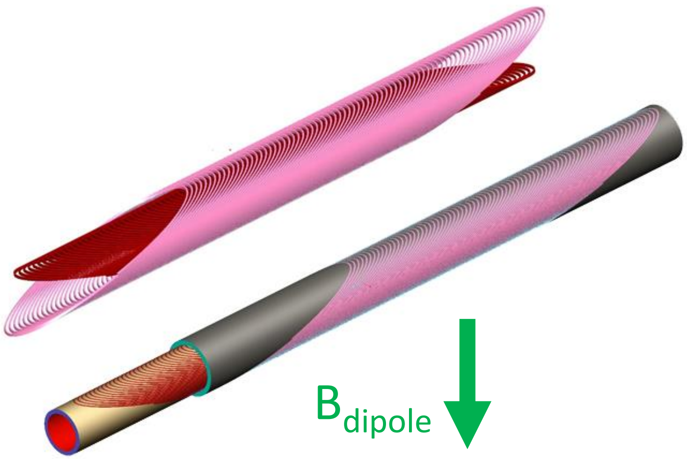
$$\tau_1 = {L_1}/{R_1} \quad \tau_2 = {L_2}/{R_2} \quad \tau_L \sim \tau_1 + \tau_2 \quad \tau_s \sim \frac{\varepsilon \tau_1 \tau_2}{\tau_1 + \tau_2}$$

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

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.

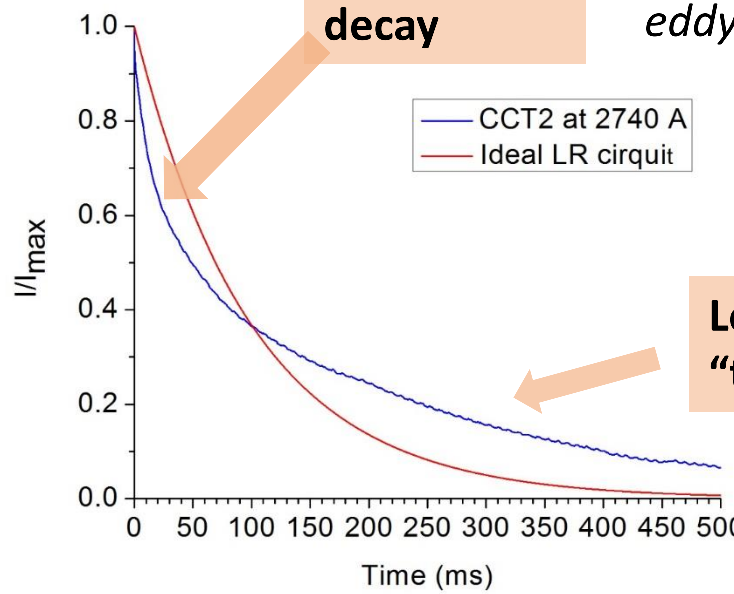
Example: current decay in Nb_3Sn canted cosine theta dipole



Al bronze mandrel

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

Energy is "pumped" into eddy currents

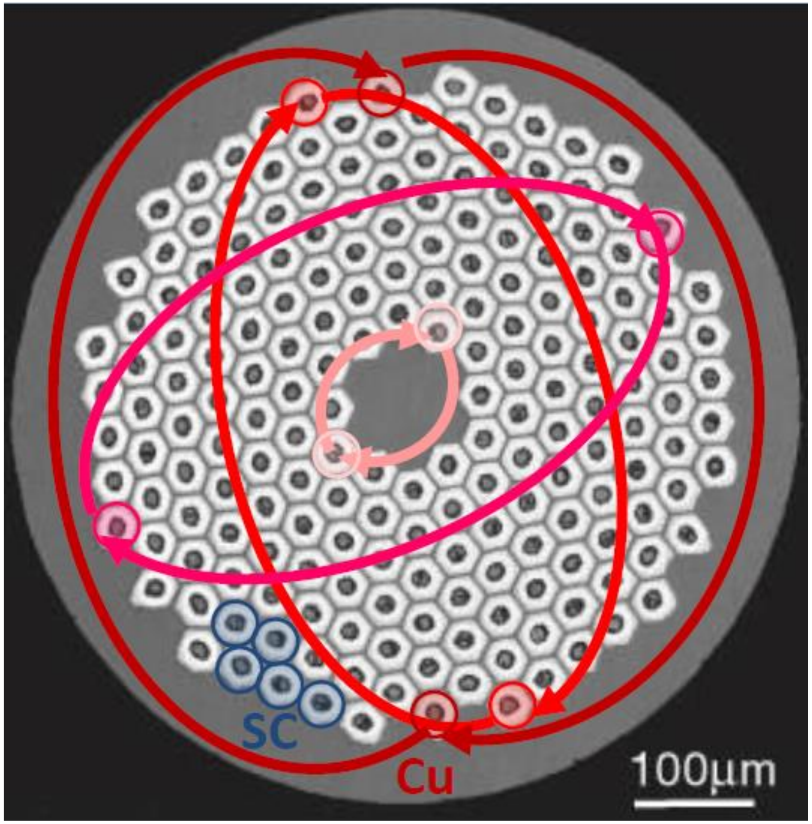


Long "tale"

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

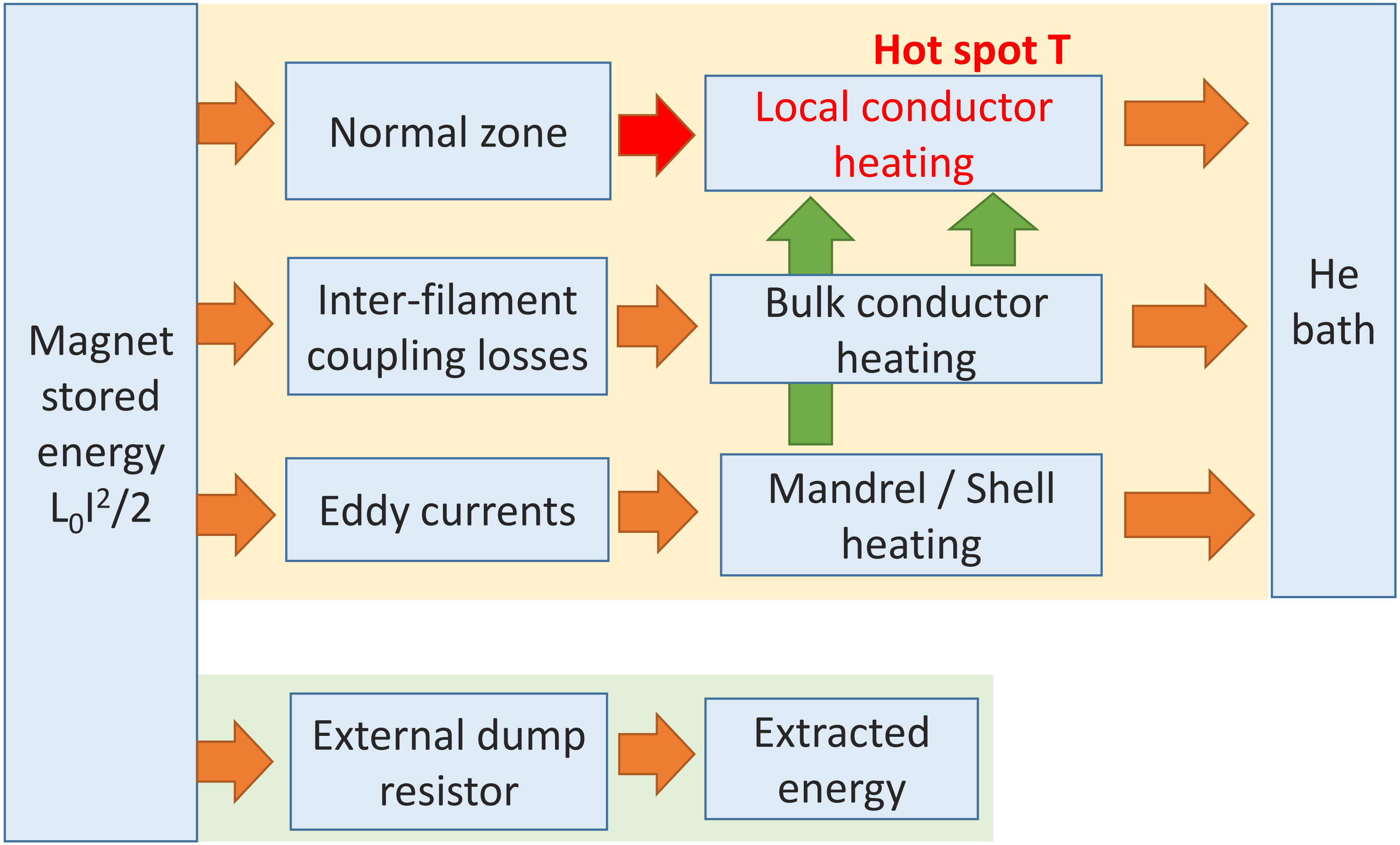


Inter-filament "coupling loss"

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

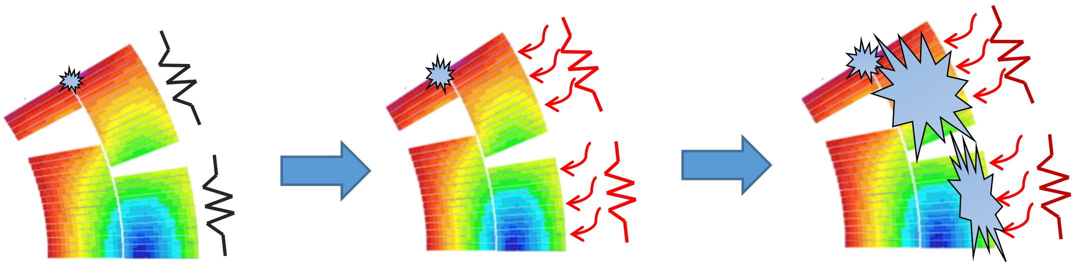
- When current in the magnet is varied, ac magnetic field induces currents in the (resistive!) copper matrix between the superconducting filaments.
- This currents heat up the conductor interior, thus depositing heat in the bulk rather than at the surface
- The "time constant" of the **inter-filament 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

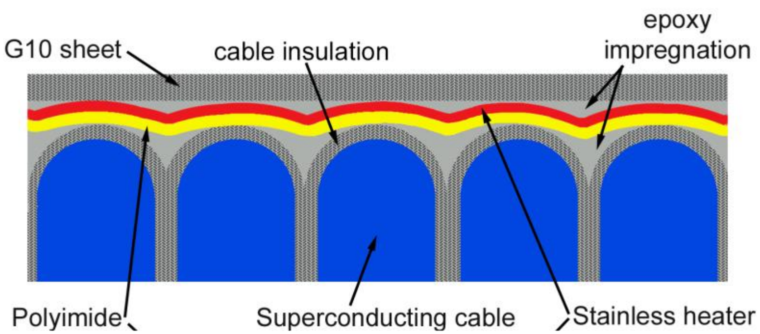


Protection heaters

"**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:

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

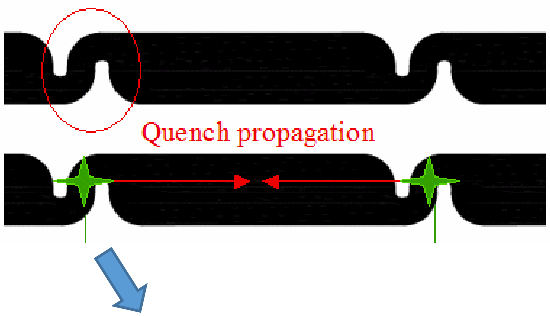
(50-150 W/cm^2 typical)

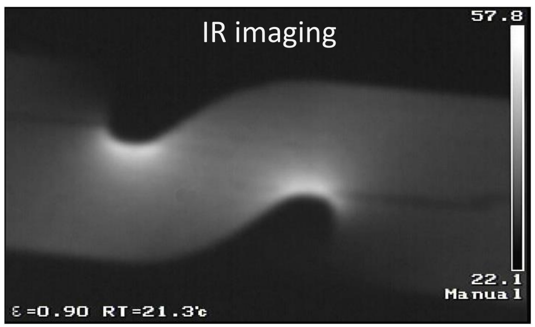
PH strip on top of the HQ-series coil

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.

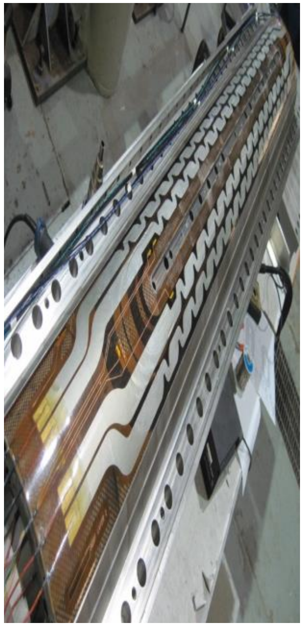
- Uniform heaters strips are not suitable for long magnets, as the voltage V_{PH} required to keep the same P_{PH} grows prohibitively large (~ L_{PH}).

Protection heaters with “heating stations





Heating stations

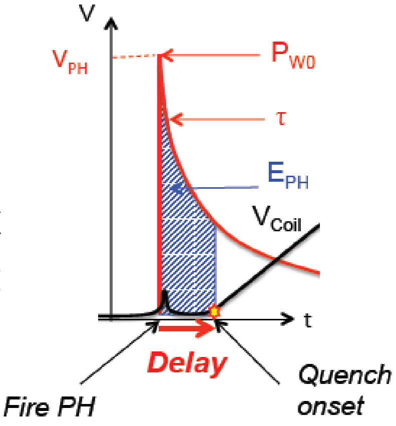


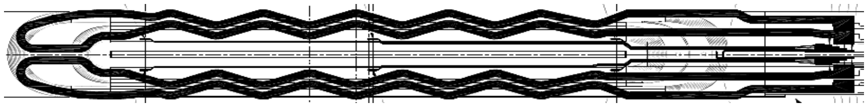
Selective copper plating

“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}.

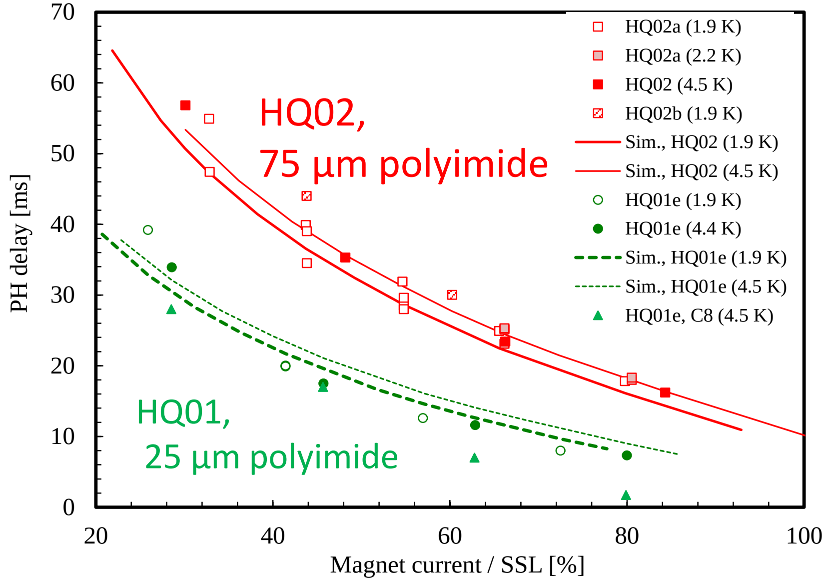
Protection heater delays

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 $T_{cs}(B)$) .



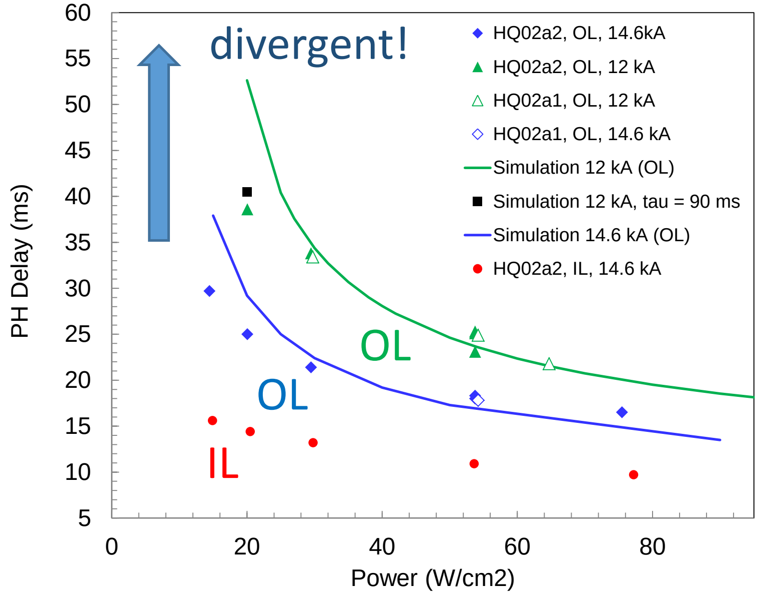


PH peak power = 50-55 W/cm², τ = 40-45 ms

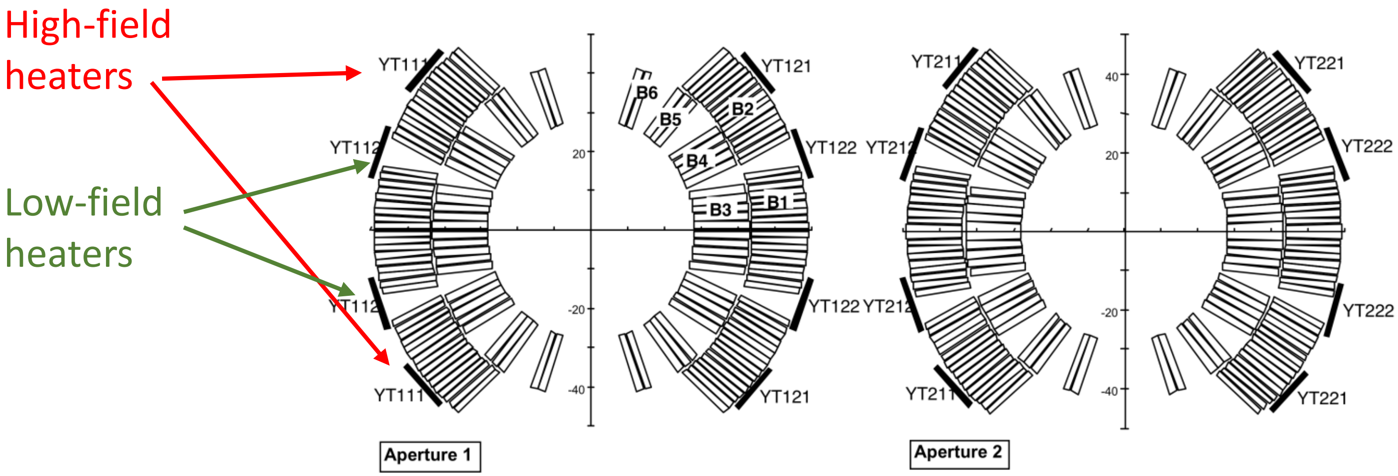


τ = 90 ms

T. Salmi, WAMSDO Workshop, CERN



Redundancy and optimization of PHs



- 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

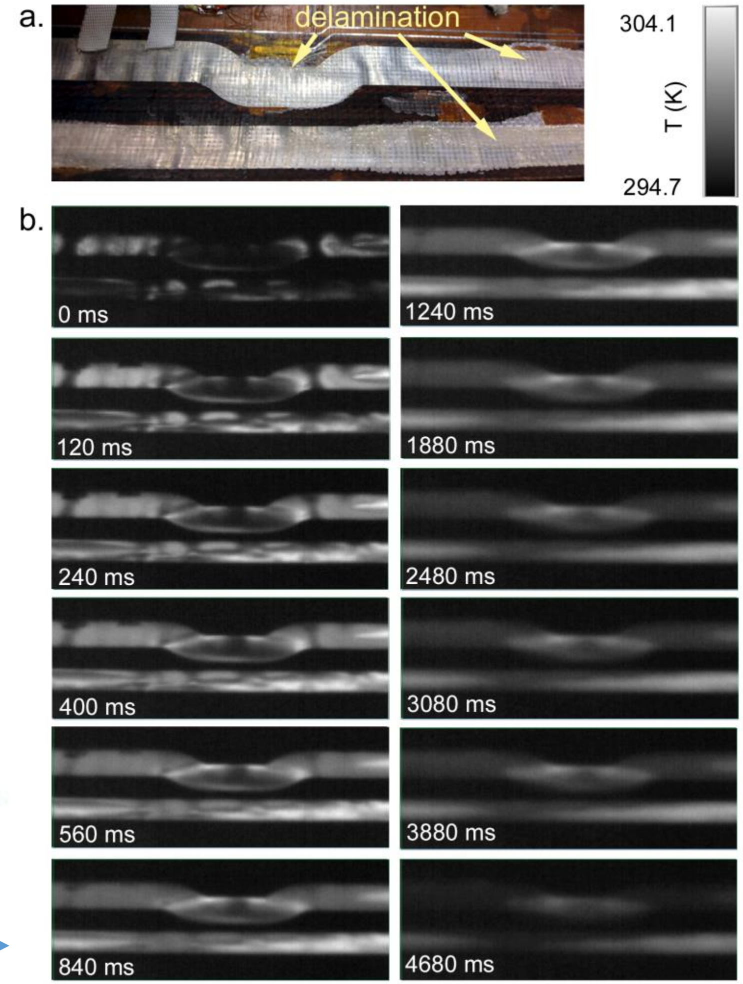
Some drawbacks of PHs

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…

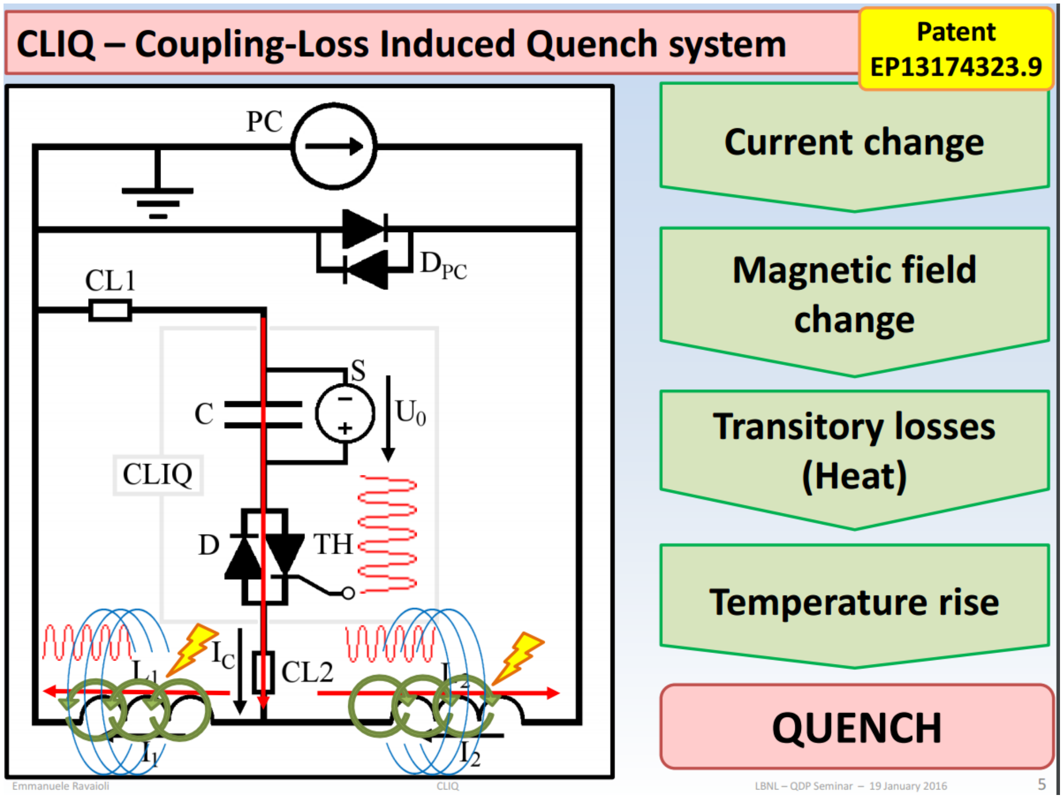
Using dB/dt for quench protection

- 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

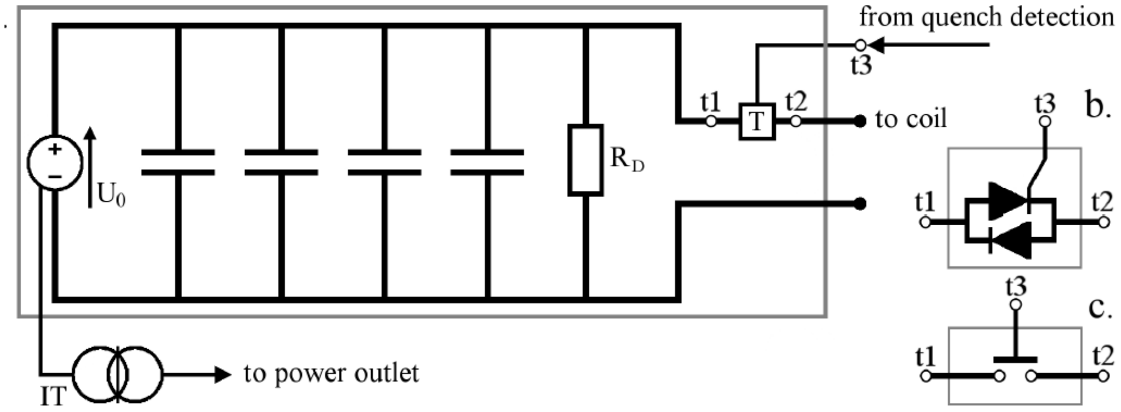
CLIQ (Coupling Losses Induced Quench)



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

- 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 unit schematics



E. Ravaioli, PhD Thesis, 2015

CLIQ unit including a bank of six electrolytic capacitors with a total capacitance of 28.2 mF rated for a charging voltage of 500 V.

CLIQ performance scaling

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

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!

POWER is the key parameter

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

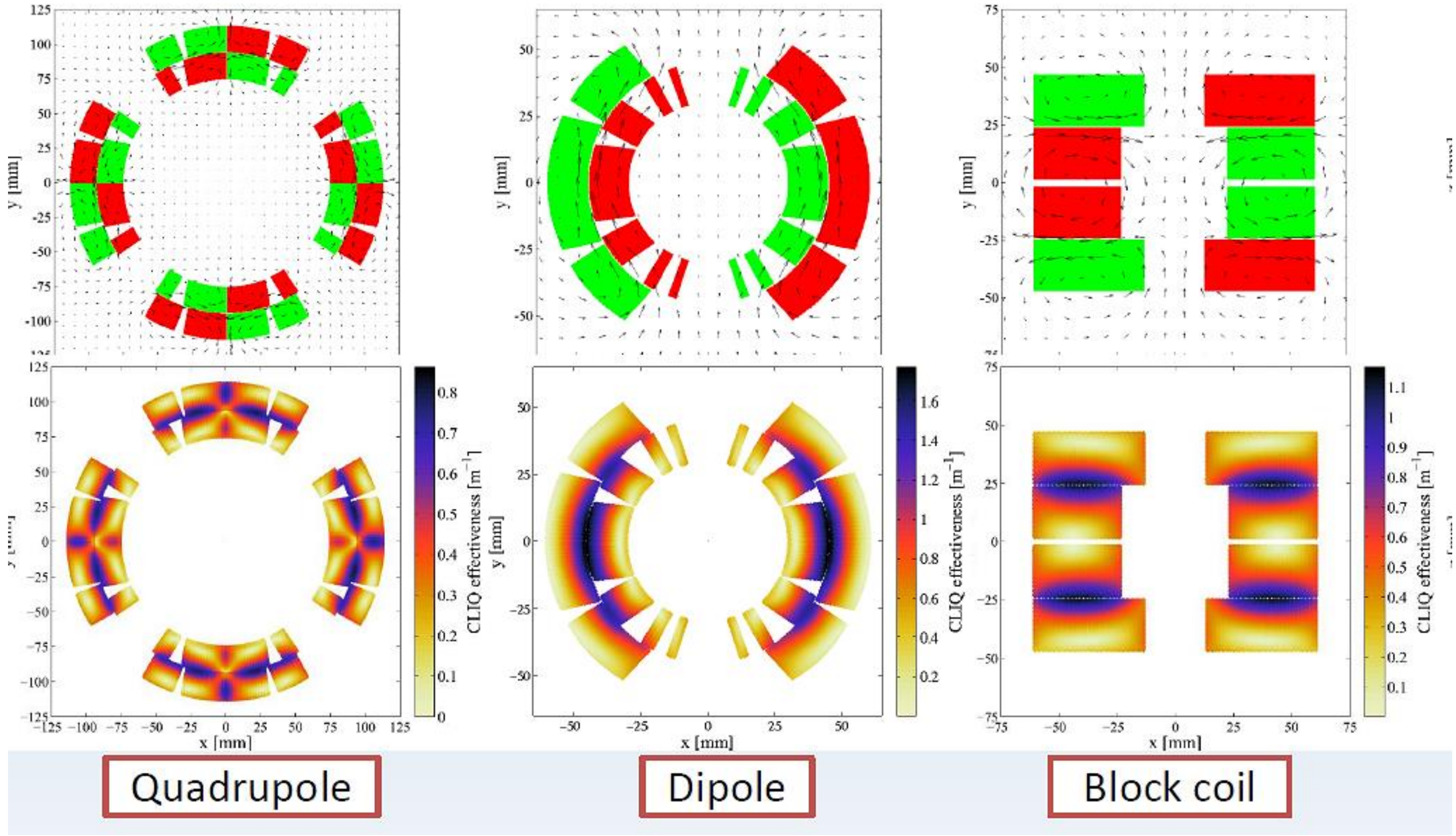
At low current

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

ENERGY is the key parameter

By choosing a proper combination of CLIQ system parameters (C, U), protection for both low and high filed regime can be realized.

CLIQ effectiveness optimization

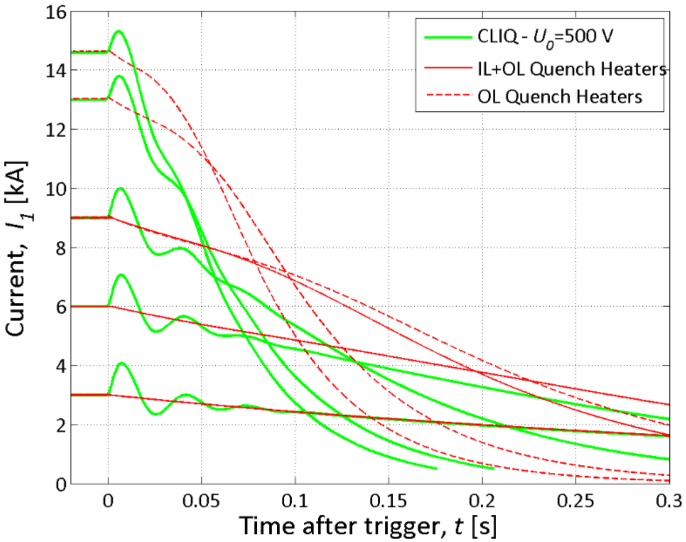


By sub-dividing coil electrically, and introducing opposite current changes in physically-adjacent sections, CLIQ effectiveness can be further improved

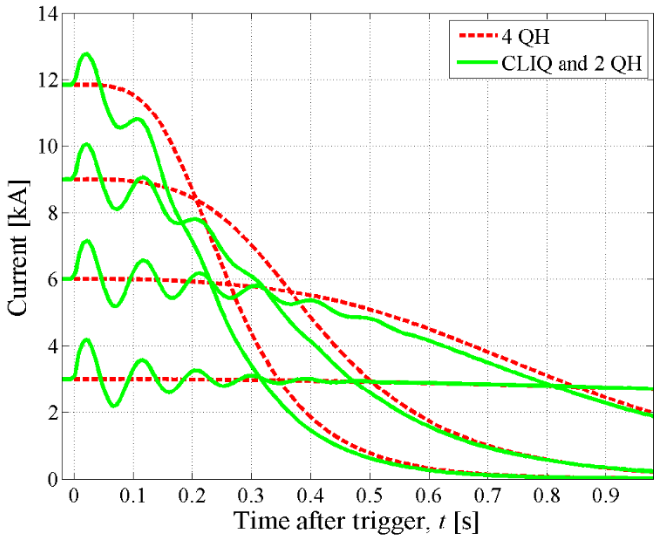
Con: requires additional "CLIQ leads".

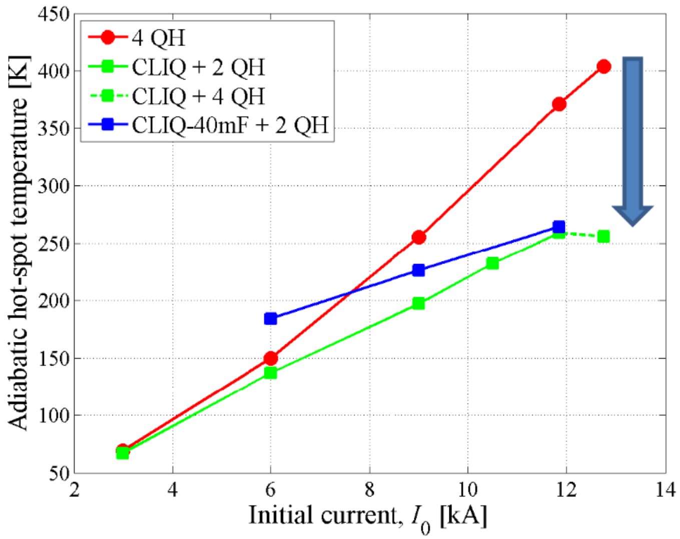
E. Ravaioli, PhD Thesis, 2015

Hybrid protection (PHs + CLIQ)



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

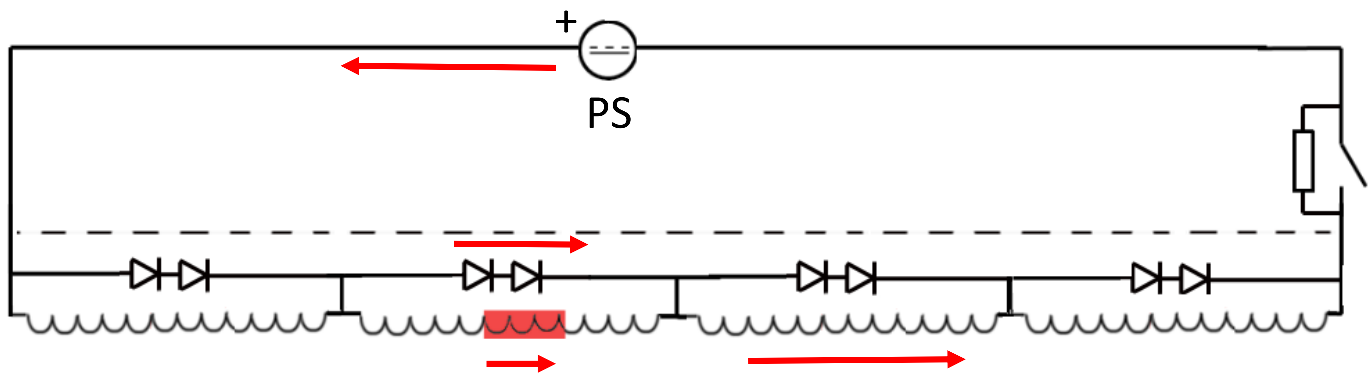




CLIQ test on a full-scale LHC dipole

E. Ravaioli

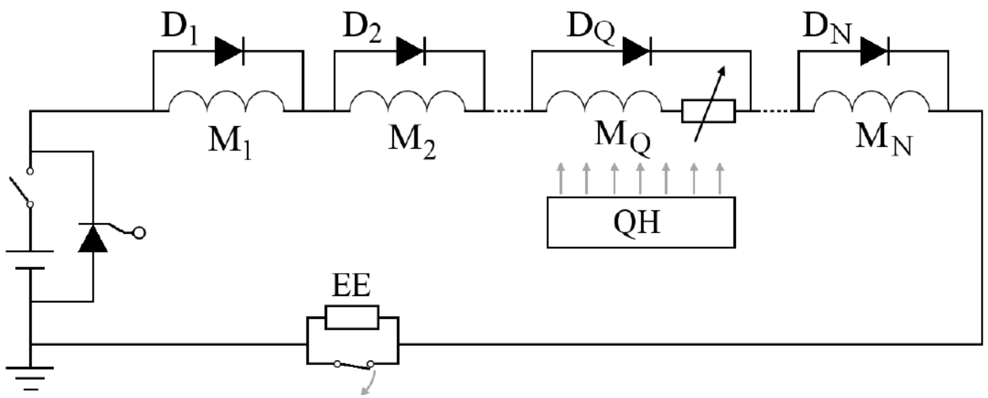
Protection of a chain of magnets



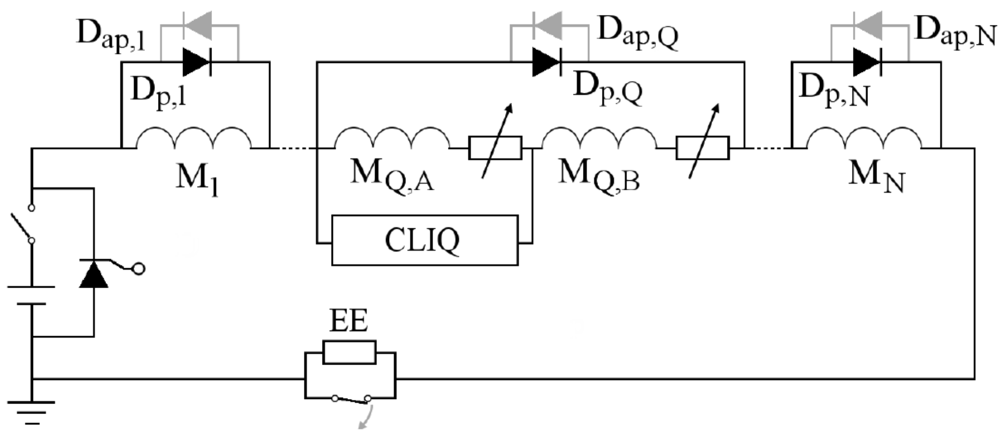
- Strings of silicon diodes are added in parallel to each magnet. Diodes start to conduct at ~2-5 V of bias at liquid helium temperature, and therefore are not carrying any current during ramping or normal magnet operation.
- As quench occurs, voltage across the magnet rises above, its diodes become 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.

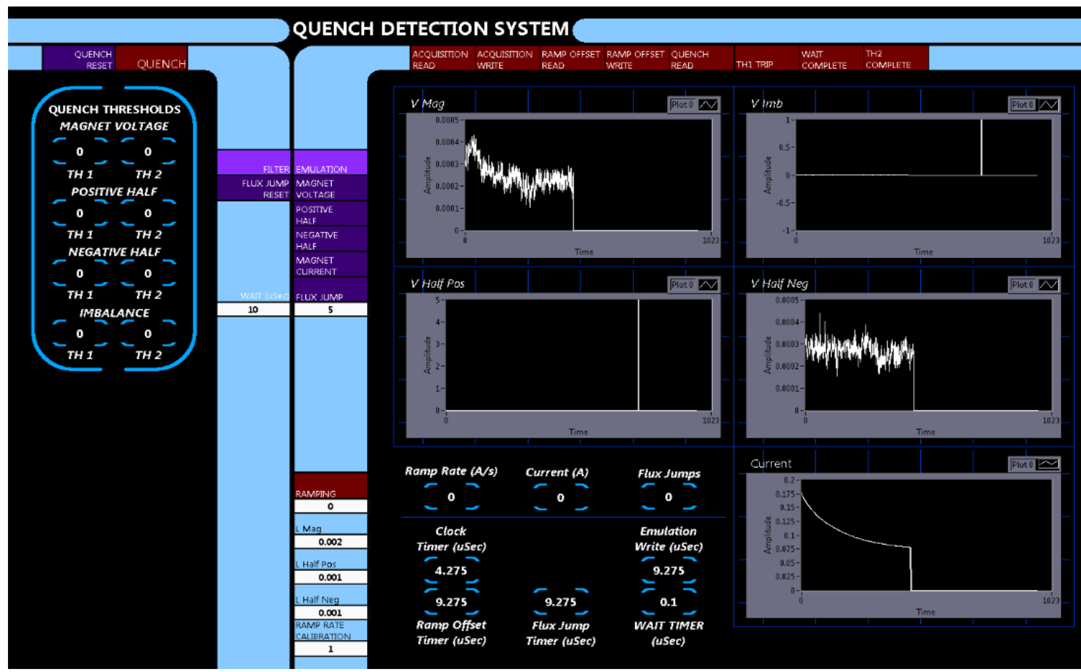


Schematic of a chain of NM superconducting magnets (M1-MN) protected by CLIQ, by-pass diodes in parallel (Dp;1-Dp;N) and antiparallel (Dap;1-Dap;N), and an energy-extraction system (EE). Only the CLIQ system connected to magnet MQ is shown.

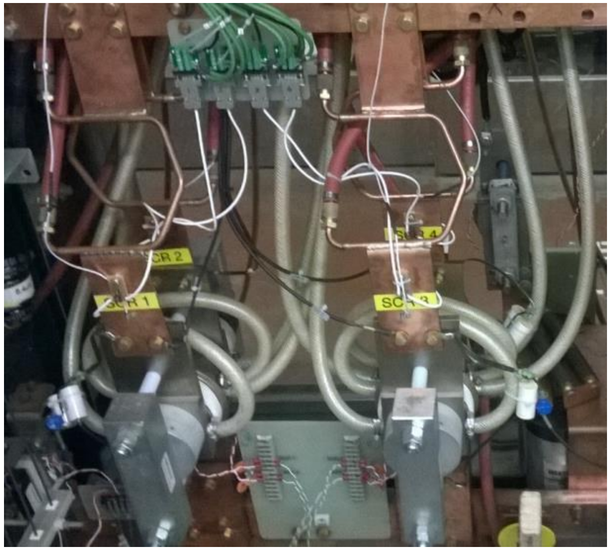
E. Ravaioli, PhD Thesis, 2015

FPGA-based quench detection system (LBL)

- 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 (LBL)



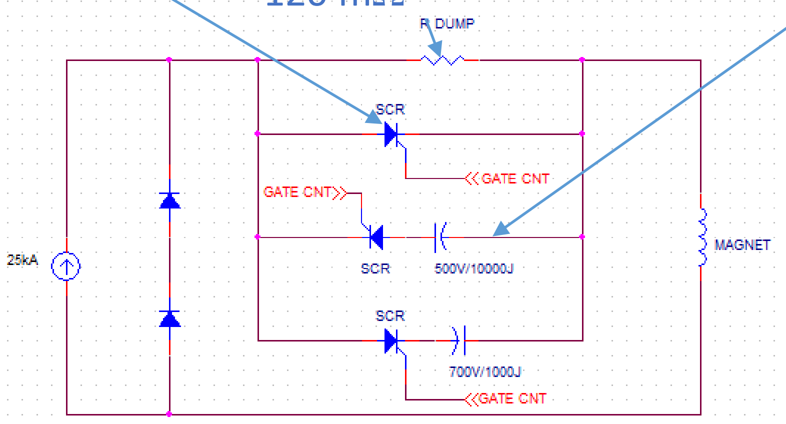
4xN5946FC220 SCRs

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

Dump Resistor

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

Capacitor Bank



- Extraction upgrade with IGBTs is planned in 2017

References for further reading

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