Unit 12
Protection of Superconducting Accelerator Magnets – Episode I

Paolo Ferracin and Ezio Todesco
European Organization for Nuclear Research (CERN)

Soren Prestemon  (With many thanks to Helene Felice)
Lawrence Berkeley National Laboratory (LBNL)
Scope of the Lesson

- What is quench protection?
- What are the critical parameters?
- How does the quench propagate?

Protection Methods

- Electrical integrity
- Detection
Why do we need to protect the magnets?

- A superconducting accelerator magnet has a large magnetic stored energy: \( \frac{1}{2} LI^2 \).
- A quench produces a resistive zone,
- Current is flowing through the magnet.

The challenge of the protection is to provide a safe conversion of the magnetic energy to heat in order to minimize:
- Peak temperature ("hot spot") and temperature gradients in the magnet,
- Peak voltages.

The final goal being to avoid any magnet degradation:
- High temperature => damage to the insulation or stabilizer,
- Large temperature gradient => damage to the conductor due to differential thermal expansion of materials.
The faster this chain happens the safer is the magnet
Current decay/Hot spot correlation: the MIITs

Basic energy conservation

- Energy deposited by Joule heating inducing an increase in temperature based on the specific heat of the materials

\[ \gamma C_p(T) dT = \rho J(t)^2 dt \]

- With the assumptions that:
  - Joule heating only produced by stabilizer (Cu)
  - Heat capacity of conductor and insulation
  - Adiabatic condition: no longitudinal heat transfer

\[ A_{tot} \sum_k \gamma_k v_k C_{p,k}(T) dT = \frac{\rho_{Cu}(T,B)}{A_{Cu}} I(t)^2 dt \]

\[ 10^6 MIITs = \int_0^\infty I(t)^2 dt = A_{tot} A_{Cu} \int_{T_0}^{T_{max}} \frac{\sum_k \gamma_k v_k C_{p,k}}{\rho_{Cu}(T,B)} dT \]

By evaluating the MIITs from the current decay, we obtain an estimate of the hot spot temperature \( T_{max} \).
What are the critical parameters?

Typical scenario

- The current in the magnet is $I_0$, a quench occurs
- **Normal zone propagation** and voltage build-up
- **Detection** system based on some voltage threshold
- Magnet current starts to decay with a time constant $\tau = L/R$ where
  - $L$ is the total inductance of the system
  - $R$ is the total resistance in the system: normal zone + external
Once the normal zone has started to grow, it will continue to expand under the combined actions of Joule heating and heat conduction. The rate of this propagation is called quench propagation velocity.

Using some approximation, it can be derived from the heat equation

\[
\gamma C_p \frac{\partial T}{\partial t} = \nabla \cdot (k(T)\nabla T) + Q
\]

- In case of an adiabatic coil (heat transfer only by conduction – impregnated coils)
- assuming a constant propagation velocity
- assuming a 1D propagation
- assuming constant material properties wrt temperature

The quench propagation velocity \( v_{\text{long}} \) can be estimated by:

\[
v_{\text{long}} \approx v_{\text{dia}} \approx \frac{J_e}{\gamma C_{p,av}} \left( \frac{\rho Cu k_{av}}{\Delta T} \right)^{1/2}
\]

- where \( C_{p,av} \) and \( k_{av} \) include only copper
- where \( \Delta T = T_s - T_0 \) with \( T_s \) average temperature between critical temperature and current sharing temperature
Transverse propagation

The heat is also propagating from turn-to-turn: it is the **transverse propagation**

But is it a much slower propagation, about 10 to 100 times slower

Since the time scales are very different, including the transverse propagation does not affect the longitudinal propagation velocity estimate

The same formula as for longitudinal propagation can be used to estimate the transverse propagation velocity.

- Insulation plays a key role so the $C_{p,av}$ needs to include the insulation $C_p$
- The thermal conductivity also needs to be changed

\[
v_{\text{trans}} \approx v_{\text{long}} \left( \frac{k_{\text{trans}}}{k_{\text{long}}} \right)^{1/2} \frac{C_{p,av}}{C_{p,all}}
\]

5 ms

*Courtesy of Juan Lizarazo, LBNL*
Quench propagation

Caspi et al, TAS 2003
Ferracin et al, TAS 2004
Voltagess during a quench

In absence of external resistance in the circuit,

- the voltage comes first from the power supply (Vcs).
- After the detection of the quench the power supply is turned off and the current starts to decay.
- Some internal voltages due to the magnet inductance develop in the magnet

\[ V_Q(t) = R_Q(t)I(t) - M \frac{dI(t)}{dt} \]

Mutual inductance between the normal zone and the rest of the coil

\[ L \frac{dI(t)}{dt} - R_Q(t)I(t) = 0 \]
Self-inductance of the system

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

As the normal zone propagates, the I(t) decays and M increases. The internal voltage will rise to a peak and decreases.

A widely spread normal zone will mitigate the peak voltage
Importance of the resistance growth
From the MIITs analysis point of view

\[
10^6 \text{MIITs} = \int_0^\infty I(t)^2 dt = A_{\text{tot}} A_{\text{Cu}} \int_{T_0}^{T_{\text{max}}} \frac{\sum_k \gamma_k \nu_k C_{p,k}}{\rho_{\text{Cu}}(T,B)} dT
\]

Assuming all energy deposited in the coil

- **Fast normal zone growth**
  \[\tau = \frac{L}{R}\] gets smaller
  - Reduced Local Joule heating in dV
  - Stored energy better distributed in the coil volume
  - Low hot spot temperature

- **Slow normal zone growth**
  - Long time constant \(\tau = \frac{L}{R}\)
  - Increased Local Joule heating in dV
  - Increased hot spot temperature
How much resistance do we need?

The normal zone has to grow fast to minimize the peak temperature and the peak voltage.

In rare cases the normal zone propagation is fast enough to provide enough resistance => the magnet is then self-protected.

By assuming that the resistance is constant over time, we can obtain a estimate of what is the required resistance.

$$10^6 MII Ts = \int_0^\infty I(t)^2 dt = \int_0^{t_{det}} I_0^2 dt + \int_0^\infty \left( I_0 e^{-\frac{R(t)}{L} t} \right)^2 dt$$

$$R = \frac{1}{2} \left[ \frac{L I^2}{10^6 MII Ts - I_0^2 t_{det}} \right]$$
In reality, the normal zone resistance is function of time, temperature and magnetic field through the magneto-resistance.

The stabilizer plays a major role in the normal zone resistance:

- If the stabilizer resistance is large, the current decays faster.

Opposite requirements for protection and stability:

- Protection would tend to request low RRR to hasten the current decay.
- Dynamic stability asks for a high RRR.
- In high operating field magnets, the magneto-resistance will lower the RRR.
  - High impact for high RRR.
How can we enhance the resistance?

Protection Methods

In most accelerator magnets, the “natural” resistance growth is insufficient to provide a good protection => Need to enhance the resistance

**Method 1:**
- Add an external resistor

**Method 2:**
- Apply additional heat to the coils to force them to become more resistive
  - Protection heaters mounted on the coils
  - Optimized to minimize thermal diffusion time

**Method 3:**
- Use of couple secondary circuits
  - Can be external or internal to the coil
  - Energy dissipation in the secondary circuit through the voltage generated by the mutual inductance between the coil and the secondary
  - Can lead to quenchback in cases where secondary becomes a heat source

**Method 4:**
- Coil subdivision
Method 1: Extraction - active protection

The system total resistance can be simply increased by the addition of an external resistor $R_{\text{ext}}$ also called extraction or dump resistor.

$R_{\text{ext}}$ is connected to the magnet after detection => active switching

Advantage: heat dissipated in $R_{\text{ext}}$ does not affect the cryogenics

Ideally we want $R_{\text{ext}} > R_n$ to force a fast current decay

but voltage develops across $R_{\text{ext}}$ and across the magnet $V_{\text{dump}} = R_{\text{ext}} I_0$

Typical $V_{\text{dump}}$ is below 1 kV

If $V_{\text{dump}}$ is too large:
- Difficulty to switch
- The magnet electrical integrity can be compromised

$R_{\text{ext}}$ is usually small with respect to $R_n$ because most of the magnets operate at high current.
Example: LBNL extraction rack schematics
Extraction resistor at LBNL

- “homemade”
- 1/8” diameter steel wire (~ 5 mm)
- Range of 30 to 120 mΩ
- G10 spacer to prevent motion and contact due to magnetic forces
- Note that the value of the dump resistor increases during extraction due to elevation of the steel wire temperature
Dump resistor at FNAL

- Made of 304 stainless steel
- Range of 10 to 120 mΩ
- Design choices are detailed in:

_Fermi National Accelerator Laboratory_

Design Note of a 10,000 Amp 2 MJoules Dump Resistor for the Magnet Test Facility

A. T. Visser
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

March 1990

*Courtesy of Guram Chlachidze, FNAL*
Method 2: Protection heaters – active protection

Another active protection scheme consists in adding heaters to the coil

Advantages:
- Design flexibility
- Optimized placement on the coil to maximize efficiency
- Fast response time

Disadvantages:
- Powering of the heaters put an additional electrical strain on the system
- Balance needs to be found between optimized thermal diffusion time and dielectric strength
- Attention must be paid to the electrical integrity of the “coil + protection heater” system
Protection Heater design

Protection heaters (PH) are usually made of thin stainless steel strips as thin as 25 microns

\[ R_{PH} = \frac{\rho_{ss} L_{PH}}{A_{PH}} \]

The heaters should provide

- The coverage of several turns
- The coverage of a full cable twist pitch

The design should minimize the thermal diffusion time (factor limiting the heater efficiency)

The heaters are powered by the discharge of a capacitor

- The \( R_{PH}C \) constant determines the time constant of the discharge \( \tau_{PH} \)
- The voltage across the capacitor determines the voltage across the heaters \( V_{PH} \)
- \( R_{PH} \), \( V_{PH} \) and \( \tau_{PH} \) define the energy deposited in the heater
The efficiency of the heaters depend on the heat diffusion time from the protection heater to the conductor.

- For a given operating current, the diffusion time is primary dictated by the amount of insulation between heaters and coil.
  - The more insulation between the PH and the coil, the slower will be the diffusion.
  - Trade-off between efficiency and electrical integrity.

- Cooling condition might also affect the heater efficiency.
- The temperature margin in the magnet.

![Graph showing delay to quench onset vs. peak power for different magnet currents.]

*Courtesy of Tiina Salmi, LBNL*
Method 3: Coupled secondary circuit – Passive protection

A secondary circuit is coupled to the magnet via the mutual inductance $M$.

Magnetic flux is shared between the magnet winding and the secondary. A voltage is generated in the secondary, allowing for energy dissipation.

$\frac{dI_p(t)}{dt} + R_Q(t)I_p(t) + M \frac{dI_s(t)}{dt} = 0$

$\frac{dI_s(t)}{dt} + R_s(t)I_s(t) + M \frac{dI_p(t)}{dt} = 0$

Protection method used in magnets producing long-term steady-state fields such as detectors.

Note: the coupling produces heat in the secondary during ramping.
Impact of the secondary circuit on the time constant

\[ L_p (1 - k^2) \frac{dI_p(t)}{dt} + R_Q(t)I_p(t) - I_s(t) \frac{MR_s(t)}{L_s} = 0 \]

Coupling coefficient \( k = \frac{M}{\sqrt{L_p L_s}} \)

- If the current in the secondary is small, the system behaves as if the inductance of the magnet was smaller:
  \[ L_{eff} = L_p (1 - \frac{M^2}{L_p L_s}) \]
  - Which leads to a smaller time constant \( \Rightarrow \) faster current decay
  \[ \tau_{eff} = \frac{L_{eff}}{L_p} \tau_p \]
Quench-back: when the secondary becomes a heat source

Due to eddy currents, the secondary circuit becomes a heat source.

If the secondary is in thermal contact with the coil winding, the heat generated by the secondary can be used to quench the main coil faster. This is called **quench-back**.

We also refer to **quench-back** when any other mechanisms relying on dI/dt contribute to quenching the coil.

- Such as AC losses

Some examples in the second protection session.
What are the basic requirements for quench-back to occur?

- The secondary must heat above the current sharing temperature of the coil (+margin for thermal diffusion)

- The secondary must be in good thermal contact with the magnet

- The thermal rise time for the secondary must be significantly shorter than the magnets characteristic time constant
  - this is the time constant associated with combined normal zone growth, external resistor, and the inductive contribution from the secondary
Method 4: Coil subdivision

- The coil is subdivided in several sections
- When one section quenches, the current of the other section is shunted through a resistance
- If the resistance are in thermal contact with the coil sections, they can be used as passive heaters as they heat up
  - Similar to quench-back

- The technique can be expanded to a large number of subdivisions

- Diodes can be integrated to the circuit
  - Diodes are nonlinear circuit elements that carry current only when subjected to voltages greater than a threshold voltage
Importance of the electrical integrity

Quench and protection are source of voltages in the magnet. Several possible failure points:
- Coil to ground (or to structure): ground insulation
- Internal failure: layer to layer, turn-to-turn
- Coil to Protection heaters

Need to provide a reliable insulation scheme
- Example of a TQ LHC Accelerator Research Program (LARP)

**Diagram Image**
- Bronze or titanium outer pole
- 5 mil dry S2 glass sheet
- 5 mil Kapton trace
- 5 mil G-10 shim
- 10 mil ceramic and binder sheet
- Bronze or titanium inner pole
- 5 mil Kapton trace
- 20 mils
- 10 mils
- 10 mils

*Courtesy of Rodger Bossert, FNAL*
Quality control is important to insure proper electrical integrity

**Hipot**

- Look for leakage current between coil and magnet components under high DC voltage
- Verify that the coil sustains the required voltage limits without breakout

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Coil to end-shoe
Non-linear current rise indicates **decrease of resistance** with the applied voltage. This is a “warning sign” sign of potential breakthrough failure.

Coil to structure
Failure occurred with no “pre-cursor”

Coil to protection heater
Steep current rise is another “precursor” of failure

*Courtesy of Maxim Marchevsky, LBNL*
The purpose is to test for shorts and insulation breakdown, turn-to-turn and coil-to-coil parts.

A steep voltage impulse is sent to the winding:
- Generated by the discharge of a capacitor
- This non-linear voltage creates a turn-to-turn voltage difference
- Damped oscillation of the voltage with frequency:

\[
 f = \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}
\]

Here \( L \) is the inductance of the coil and \( C \) is the net capacitance (including inter-turn and coil-to-coil parts capacitance).
Impulse test failure/breakout

A short through the **turn-to-turn** insulation will create a parallel path in the winding and reduce the effective inductance, thus **increasing** the oscillation frequency.

A short through the insulation between **winding and parts** (end parts, central pole, etc…) will increase the effective capacitance, thus **decreasing** the oscillation frequency.

A discharge (arching), either inside the winding (between the layers) or outside the winding (coil to parts), will cause a characteristic high frequency (> 1 MHz) noise to appear near the peaks of the oscillatory waveform.

**Courtesy of Maxim Marchevsky, LBNL**
Example of electrical failure

Layer-to-layer failure
Detection: a key parameter

Need to detect the quench as soon as possible to **avoid MIITs build-up**

- Choice of voltage thresholds to be compared with magnet signals
- Optimization of these thresholds

Principle: looking for **voltage imbalances** in the magnet

- Difference between 2 voltages which are supposed to be the same
  - Cancelation of the inductive component
  - Allowing detection of resistive voltage growth

The detection triggers the extraction and the firing of the protection heaters

- In case of failure, all the protection scheme is impaired
- **Redundancy** required to improve reliability
Voltage taps

Detection relies on instrumentation

- Voltage taps in the magnet

- Voltage taps installation on a Nb₃Sn magnet
Example of a quadrupole

Positive lead to Coil 9-outer layer
Bottom lead of dual NbTi lead is in direct contact with positive flag.

Negative lead to Coil 7-inner layer
Bottom lead of dual NbTi lead is in direct contact with negative flag.
Type of voltage imbalances

- Schematics representing all the voltage taps of the system
- Some vtaps are used to look at imbalances
- The rest of the vtaps aims at locating the quench origin

Example of LBNL:
- Imbalance 1: \( \frac{V_{mag}}{2} - V_{center} \)
- Imbalance 2: difference between half magnet voltages
  \[ (V_{coil\,9} + V_{coil\,8}) - (V_{coil\,5} + V_{coil\,7}) \]
- Over-Voltage: absolute value of \( V_{mag} \)
Detection: the choice of the threshold

In Nb$_3$Sn magnets, it is challenging to pick a safe threshold
- Because of flux jumps
- Requires to adapt threshold as the current is ramped up

The signals are then compared to threshold
- If threshold reached,
  - PS turned off
  - extraction
  - PH

Current decay

Courtesy of Xiaorong Wang, LBNL

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

The goal of quench protection is to convert - safely - magnetic energy into heat.

- Minimizing hot spot temperature and peak voltages

Protection strategies rely on various methods

- Active protection: relies on external resistance and/or protection heaters
- Passive protection: dissipation in a secondary circuit via magnetic coupling. It can include quench-back.

Electrical integrity must be guaranteed

- Importance of the QA methods: hipots and impulse tests

Quench detection also plays a key role in the protection scheme
In the Next Episode

- Some examples of magnet systems protection
- An example of protection heater design
- Presentation of some codes
References

G. Ambrosio et al, TQS01c test results summary, TD-07-007
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