

Quench Protection

Comments on quench protection in response to Kirk's question. I may have missed some cases, and I may have got some of it wrong, but here is the story as I remember it.

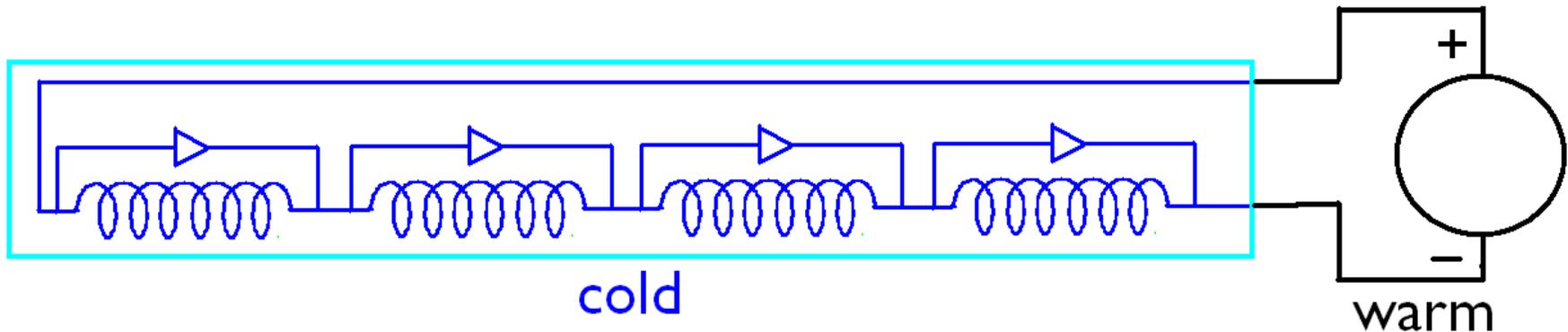
A quench can do damage if, after it starts, the current continues to flow for so long that that local region, now normal, heats up to a damaging temperature. The current will tend to fall because of the resistance developing in the normal region about the quench. But it may fall too slowly if:

- a) The quench propagates too slowly, or
- b) The magnet is one of several in series, so that if only one magnet quenches, the inductance of the others will generate a voltage to try and maintain the current, causing their energy, as well as the one that quenched, to be all dumped in the one.

I Consider 5 cases of quench protection, from none, to fully active.

1. A magnet needs no protection if, no matter where a quench starts, the quench propagates so fast that the total magnet resistance rises rapidly enough to lower the current before any part of the coil gets too hot. All the magnetic energy in the coil is dumped, as heat, in that coil, but the temperature rises at all locations in the coil are acceptable.

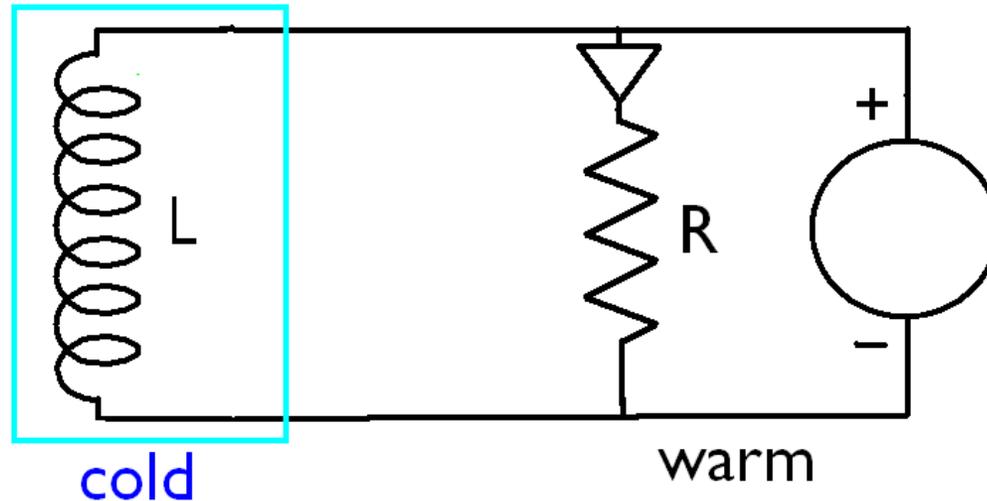
2. Even with rapid quench propagation there can be a problem if several coils are fed in series. Then when one coil quenches, and the other coils do not, the energy of all coils end up in the one that quenched. To protect from this, a cold diode can be connected across each magnet.



Now, when one coil quenches, a voltage develops that shorts the current through the diode. The magnet that quenches must absorb its own energy, but the other magnets can continue to carry current that, because it does not flow through the quenched coil, does not dump their energy in the quenched coil. In due course the power supply is turned off to bring down the other magnets in a safe way. This is done in RHIC and, I think, in the LHC.

The diodes are chosen so that the low voltages used in normal ramping are not enough to make the diode conduct. The voltages after a quench are much higher.

3. The next level of protection is to use a warm diode that shorts the coil as above, but has an external resistance in series with it.



Now, when there is a quench, the rising resistance of the coil generates enough voltage to allow the diode to conduct the current through the external resistor. The introduction of the resistance generates a voltage across the coil that brings the current down faster than in the cold diode case. Now some fraction of the stored energy is dissipated in the external resistor, thus reducing temperature rise in the coil.

The fact that the power supply is still connected has little effect because it will be a low voltage supply that will add little current to that flowing through the resistor.

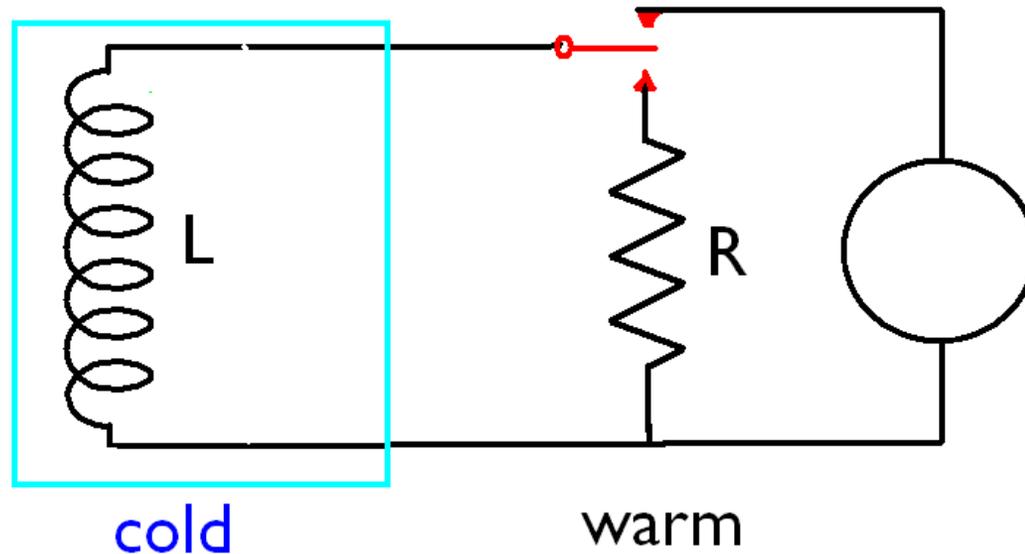
4. Simple active protection uses heaters that are fired to induce more general quenches after taps have detected a given, limited quench.

This can help two problems:

- With multiple magnets in series: if one quenches, all are actively quenched. Now all coils absorb their own energy, but do not absorb energy from other magnets. This avoids the need for cold diodes, and is used in the TeVatron
- Even with a single magnet there can be a problem if a quench occurs in a location that propagates too slowly. Then the current drops only slowly and too much of the total energy is dumped in the small region where the quench started. If such a quench is detected and a heater fired to cause a quench in a larger region, or one from which the propagation is more rapid, then the local heating is reduced.

This may not be easy in our case because a heater on the outside will be attempting to quench the conductor in a low field region from which a quench will propagate only slowly. Adding heaters to quench the inside, through the mandrel is problematic because both thermal expansion and the magnetic forces are such as to open a gap between mandrel and inside of the coil, thus reducing the needed thermal conduction.

5. True active protection does not use heaters. When a quench is detected an external switch disconnects the power supplies and connects all coils to external resistors. The resistors are chosen to be high enough to bring the currents down fast enough to avoid any excessive local heater at the quench, but they must be low enough to avoid too high voltages that could cause damaging electrical breakdown. This is the option that we are considering for 40 T solenoids, and may well be the only reasonable option for the spectrometer coils.



Numbers

For temp rise < 200 K, and RRR=50 (including magneto resistance)

$$\int j^2 dt < 10.6 \cdot 10^{16} \quad (Am^{-4}s)$$

j is the current density in the copper stabilizer

The required time constant is

$$\tau = \frac{2 \cdot 10.6 \cdot 10^{16}}{j_{Cu}^2}$$

The external shunt resistor needed

$$R = \frac{L}{\tau} \quad L = 2 U / I^2$$