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Quench Protection Solutions for Magnets Fabricated with HTS Conductors

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Introduction

- **The Problem:** This paper discusses the elephant in the room that is rarely discussed by the HTS magnet community. This is quench protection of HTS magnets. This is not much of a problem when the magnet stored energies are low.

- **Quench Propagation Velocities**: The rate of quench propagation in HTS magnets is much lower in all directions than for Nb-Ti magnets.

- **Conductor Burn-out and Hot-spot Temperature:** With most HTS conductors the integral of current density squared with time is smaller than for Nb-Ti magnets. This compounds the quench protection problem.

- **Quench Protection methods:** Passive quench protection is difficult, but there are a number of active quench protection methods that will work.

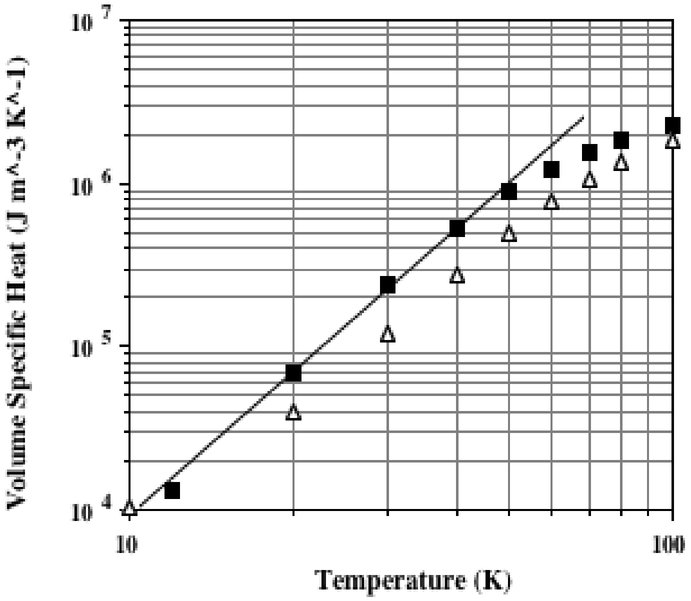
Quench Propagation Velocities

- An equation for adiabatic quench velocity along the wire is as follows:

$$V_L \approx 0.6\, J\left[{}^{LT_S}\!/_{C_S(h_S - h_o)}\right]^{0.5},$$

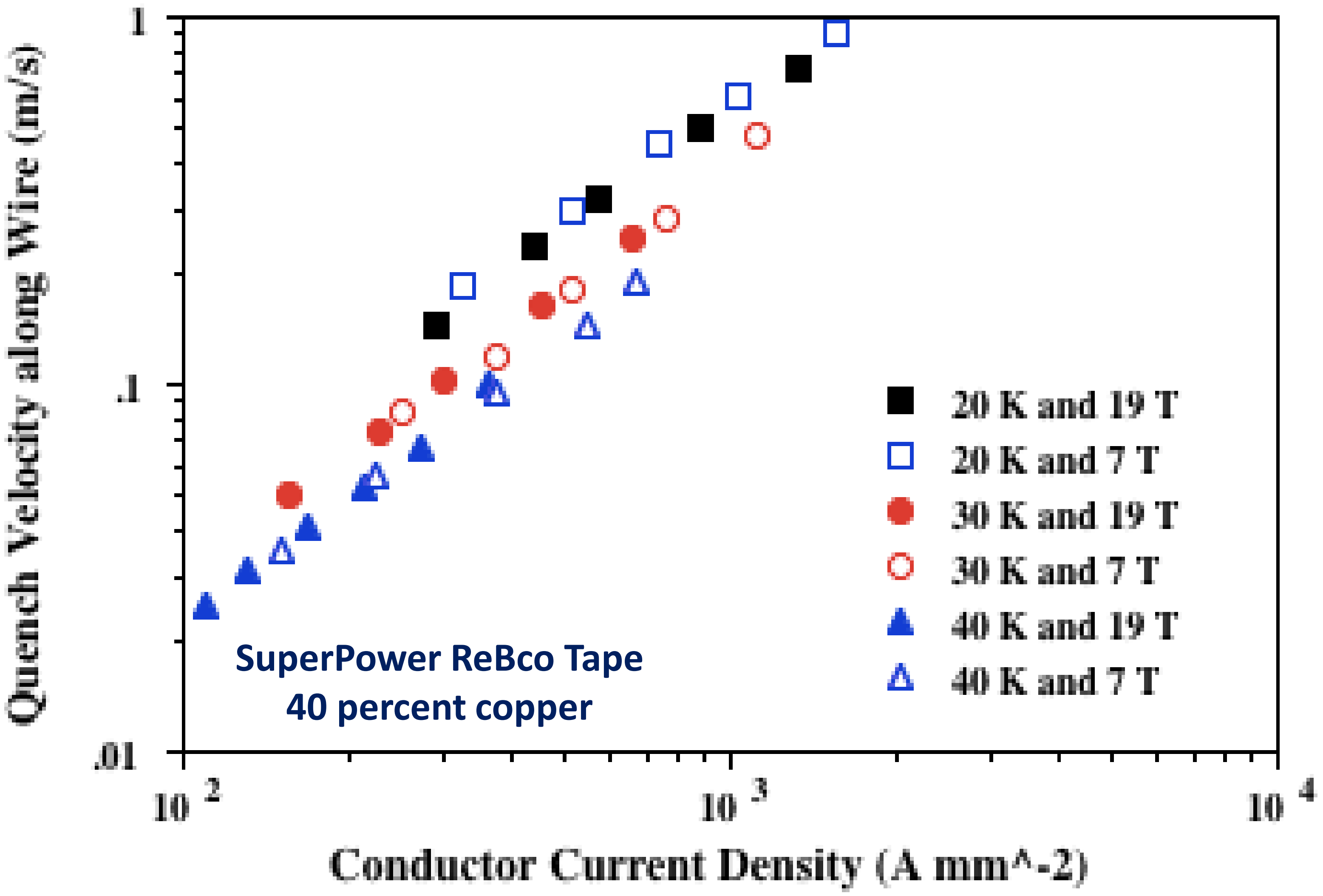
where V_L is the quench velocity along the wire, J is the conductor current density L is the Lorenz number T_S is a pseudo-critical temperature, C_S is the volume specific heat at T_S, and $(h_s\text{-}h_o)$ is the volume enthalpy change between T_S and T_o. For LTS conductors $T_S = T_C$ and for HTS conductors $T_S = (T_C + T_{CS})/2$, where T_{CS} is the engineering conductor T_C where the resistance is almost zero. Note, $h_S = C_S T_S$ and $h_o = C_o To$. V_L is independent of metal RRR and the copper to non-copper ratio r.

- In the temperature range where HTS conductors operate the change in C_S goes as T_S to the third power.



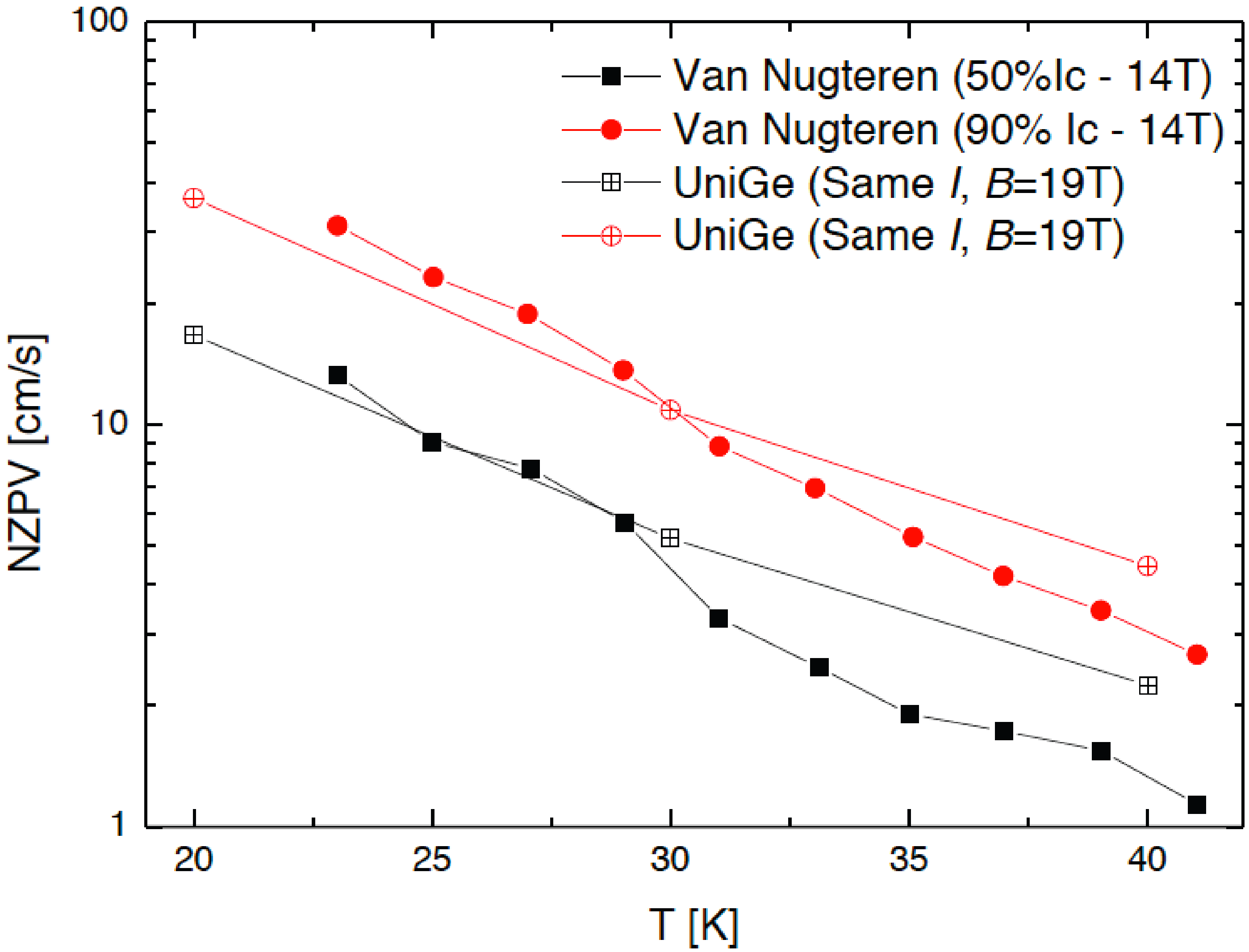
C(T) as a function of T for copper (closed square) and Haselloy (open triangle) at T = 10 to 100 K

Measured Quench Propagation Velocities in ReBCO Tape



M. Bonura and C. Senatore, University of Geneva, slides presented at EUCAS-2015, Lyon France, 11 Sept. (2015).

The Effect of I/I_c on Quench Velocities in ReBCO Tape



SuperPower A Furukawa Company

SCS4050

4.0 mm wide
0.1 mm thick
40 percent Cu

M. Bonura and C. Senatore, University of Geneva, slides presented at EUCAS-2015, Lyon France, 11 Sept. (2015).

Transverse Quench Velocities and a Summary

- In a layer wound ReBCO solenoid, the transverse quench velocities V_R and V_Z are:

$$V_R = VL(kR/kL)^{0.5} \text{ and}$$

$$V_Z = V_L(k_Z/k_L)^{0.5},$$

where V_L is the quench velocity along the wire, V_R is the quench velocity in R direction, V_Z is the quench velocity in Z direction, k_L is the effective thermal conductivity along the wire, k_R is the effective thermal conductivity in the R direction and k_Z is the effective thermal conductivity in Z direction. V_R is controlled by the Hastelloy thermal conductivity and V_Z is controlled by the copper thermal conductivity.

- Quench velocities are a function of field orientation because T_c is a function of field orientation. This makes quench velocity calculation in a coil more complicated. The longitudinal and transverse quench velocities are shown below for Nb-Ti and ReBCO at 200 A mm^{-2} and 800 A mm^{-2}.

V_L for Nb-Ti @ 200 A mm^{-2} = about 3 m s^{-1}
V_L for Nb-Ti @ 800 A mm^{-2} = about 30 m s^{-1}
V_{TRANS} /V_L for Nb-Ti = 0.01 to 0.05

In a RRR = 1000 aluminum matrix Nb-Ti V_L is faster

V_L for ReBCO @ 200 A mm^{-2} = about 0.04 m s^{-1}
V_L for ReBCO @ 800 A mm^{-2} = about 0.25 m s^{-1}
V_{TRANS} /V_L for ReBCO = 0.05 to 0.35

Integral of $C(T)/\rho(T)$ dT and Integral of $J(t)^2$ dt

There is a function F that is a function of the volume specific heat C and the material resistivity ρ;

$$F(T) = \int_0^T \frac{C(T)}{\rho(T} dT\,.$$

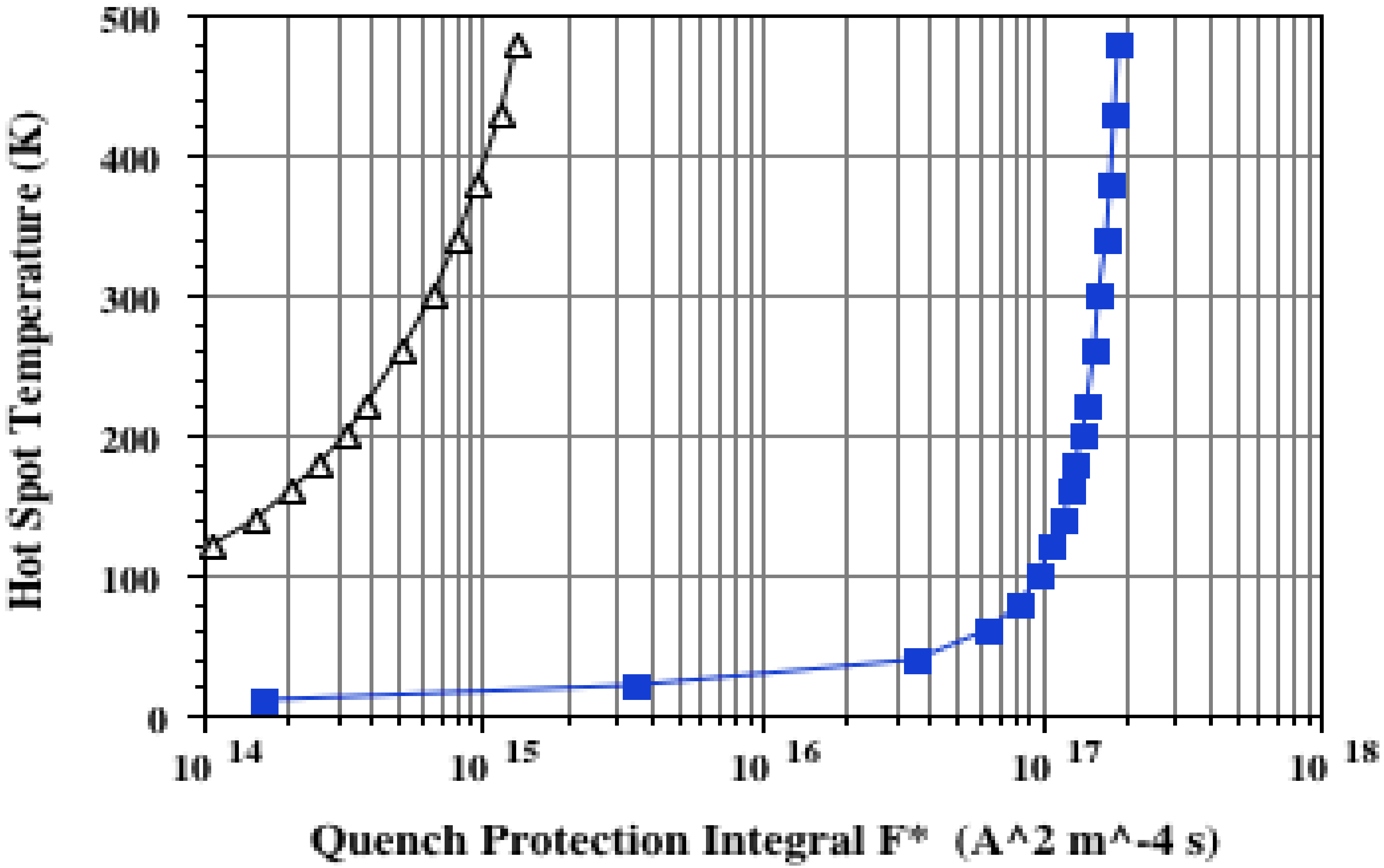
when the thermal diffusivity is low at a temperature T > 25 K the following function of F applies;

$$\frac{\delta F}{\delta t} \approx J^2,$$

where J is the current density in the conductor as a function of time t. One combine the two equations to get the following form that applies to a conductor with low ρ copper where the copper to non copper ratio is r;

$$F^*(T) = \int_0^T \frac{C(T)}{\rho(T)} dT = \frac{r+1}{r} \int_0^t J(t)^2\, dt$$

The F* Function for Hastelloy (triangle) and Copper (square)



Is copper needed an HTS conductor?

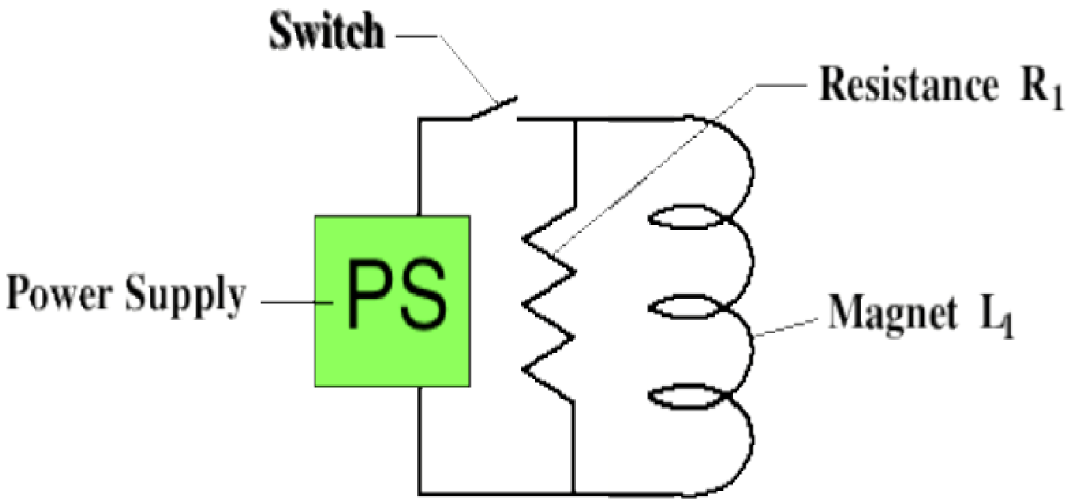
- Copper is needed in a ReBCO tape conductor to stabilize the conductor against flux jumps and increase the MPZ length to increase the conductor minimum quench energy.

- Copper is also needed to increase the F* of the conductor. Copper increases the quench protection capability of the conductor and it lowers the hot-spot temperature in the magnet to prevent burnout.

- Too much copper in the conductor makes quenches more difficult to detect. There is a trade-off between quench detection and ability to increase F* to improve quench protection.

Quench Protection with a Resistor and the EJ^2 Limit

- Putting a resistor across a magnet causes and exponential decay in J with an L/R time constant of the magnet circuit. One can calculate then calculate the F* for a given L/R time constant in the magnet using the circuit below;



Quench Protection by discharging through a resistor

- The F* for an exponential decay a magnet with a self inductance L$_1$ through a resistor R$_1$ can be given as follows;

$$F^{*} = \frac{L_1}{2R_1}\frac{r+1}{r}J_0^{\;2},$$

where J$_0$ is the current density at the start of the current decay through the resistor R1. With some manipulation one can up with the following form;

$$E_0 J_0^2 = F^{*}(T_{HS}) V_0 I_0$$

where T$_{HS}$ is the hot spot temperature and V$_0$ and I$_0$ are the starting voltage and current at t = 0.

The implication of the EJ^2 Limit on Quench Protection

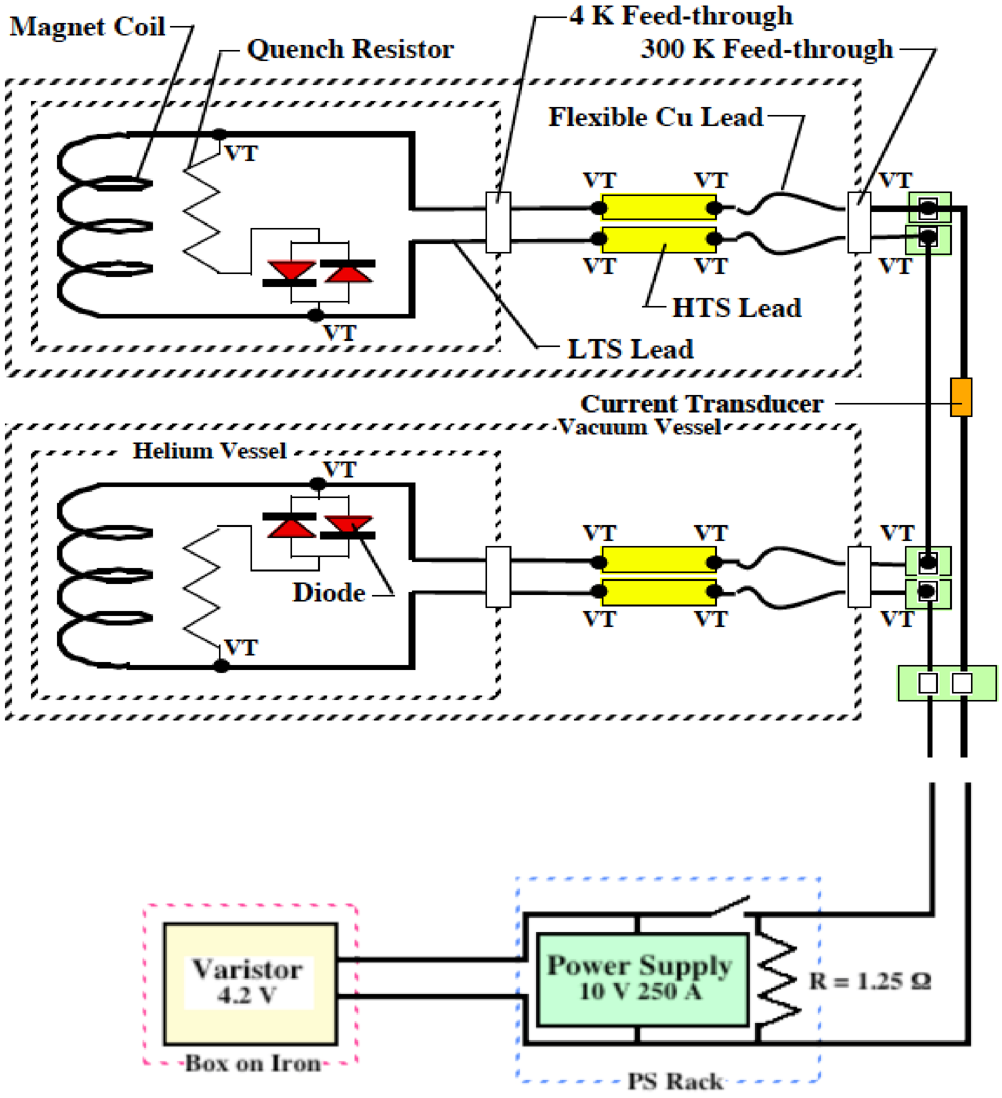
- For a given magnet stored energy E_0, in a magnet circuit, one must reduce the conductor current density J_0 so that the magnet can be protected. This applies to both LTS and HTS magnets.

- The EJ^2 equation explains why magnets with a large stored energy have large currents in the magnet circuits. If the magnet current is 1000 A and the discharge voltage is 1000 V, the value of $E_0J_0^2$ will be about 10^{23} J A^2 m^{-4}. The voltage limit V_0 is set by the voltage to ground limits and the layer-to- layer voltage limits. Many quench codes do not calculate the voltages very well so one must be conservative in setting the voltage limits. When doing quench calculation, the voltage counts as well as the hot spot temperature. To be conservative, the maximum hot spot temperature must be less than room temperature.

Steps one can take to quench protect HTS magnets

- **Increase the conductor Copper Content:** One should increase the copper in the conductor as much as possible without making quench detection impossible. An alternative is to use a shorted secondary circuit. This will be studied for a future paper.
- **Sub-divide the coils with diodes and resistors across the coils:** Sub-dividing the coil does two things. It reduces the voltages in the coils and T_{HS} and EJ^2 limits applied to the whole magnet can be applied to each sub-division. This has been done in LTS magnets with great success.
- **Use a non-inductive quench protection resistor to speed up a magnet quench:** This quench protection method has been used in a magnet at Michigan State. This can be applied with each sub-division. In HTS coils, the resistor would be buried within the coil.

The MSU method of Coil Subdivision and Coil Heating



- When the switch opens the magnet is discharged across 1.25 ohm resistor causing the cold diodes within the cryostats to fire. The two coils are separate circuits that are inductively coupled. Heat from the resistor causes a coil to become normal faster.

- If this method is used on HTS coils, the resistors should be buried in the middle ot the coil with full ground-plane insulation between the resistor and coils. This method can work with HTS coils that are cooled using coolers at 20 K to 40 K. There are other variations of the scheme, which can be looked at in a future paper.

Concluding Comments

- HTS conductors have quench velocities that are two orders of magnitude lower that Nb-Ti magnets with copper based superconductors
- The low copper content of ReBCO and other types of HTS conductors means that quench F* for safe quenching is lower. HTS magnets must be actively protected. Quench back as used by LBL in the 1970’s may not be and option. A future paper will look at quench back as an option.
- Three things one can do to protect an HTS magnet have been identified. They are; 1) add copper to to reduce the conductor J, 2) sub-divide the magnet to reduce voltages and reduce energy faster, and 3) bury the quench protection resistors within the coil to quench more of each coil.
- This author has several other schemes that may improve quench protection for HTS magnet. Expect more papers from this author.