

Quench Detection and Protection of an HTS Coil

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Abstract. A pulsed, modular HTS magnet for energy storage applications was constructed and tested. Charge and discharge pulses were accomplished in about 1 second. A recuperative cryogenic cooling system supplies 42 to 80 Kelvin helium gas to the magnet. A practical solution to overvoltage and overcurrent protection has been implemented digitally using LabVIEW. Voltages as little as 46 μ V greater than the expected value trigger the protection system, which stops the pulse profile and begins an immediate current ramp down to zero over 1 second. The protection system has displayed its effectiveness in HTS transition detection and damage prevention. Experimentation has demonstrated that current pulses on the order of seconds with amplitudes of up to 110 Amps can be achieved for extended periods. Higher currents produce joint heating in excess of the available cooling from the existing cryogenic system.

1. Background and Motivation

HTS magnets are a candidate technology to store and release energy on the order of megajoules in time frames of about 1 second [1]. The superconductor requires a cryogenic system to maintain an operating temperature below the superconducting transition temperature. It is not possible to construct a superconducting magnet without joints, which introduce regions of ohmic heating. The cryogenic system must remove the generated heat at a sufficient rate to prevent normal zone propagation and ultimately melting of the superconductor. With adequate cooling, current sharing results in a relatively gradual transition to the fully normal conducting state. It is possible to detect the voltage increase across the magnet as the superconductor begins to current share with the copper stabilizer. Immediately ramping the magnet current down upon detecting current sharing can then prevent damage to the superconductor. A protection system like this is critical to superconducting magnet energy storage device development, because it allows us to test coil modules of increasing size, current, and stored energy safely.



2. SMES Project Overview

An HTS magnet comprised of modular double-pancake coils was designed, built and tested [1]. Initial tests were performed on short HTS samples, followed by miniature coils, and finally large coil modules. The ultimate goal was to build a 3 MJ, 1 MW unit, with a 1 second charge time, and 5 second discharge time. The scale of the final design is illustrated in figure 1.

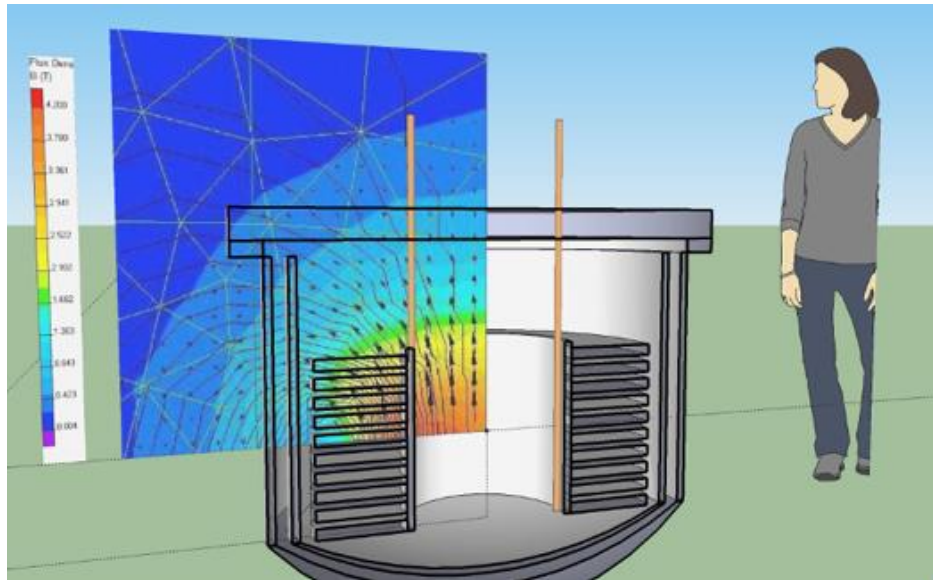


Figure 1. Full sized 3 MJ pulsed HTS coil.

The specifications of some project milestones are detailed in table 1. At present, coil modules up to 25 kJ, 25 kW have been built, and testing has been performed on a 7 kJ module.

Table 1. Summary of coil module parameters.

	7 kJ	25 kJ	500 kJ
Status	Tested	Built	Designed
Inner Radius (m)	0.15	0.15	0.15
Outer Radius (m)	0.25	0.25	0.3
Height (m)	0.048	0.096	0.288
# Turns	338	738	3600
Magnetic Field	0.6 T @ 270 A 1.1 T @ 500 A	2.0 T @ 500A	5.1 T @ 500 A
Stored Energy	2 kJ @ 270 A 7 kJ @ 500 A	25 kJ @ 500 A	490 kJ @ 500 A

The most recent tests were performed on one of the four coils which comprise the 7 kJ module. For this 15 mH coil, current was limited by ohmic heating, resulting in a maximum of 108 J of stored energy at 120 Amps. Well-made HTS face-to-face soldered lap joints can have resistances as low as tens of nano-ohms [2]. The most recent testing suggested undesirably large joint resistances totaling 0.6 mΩ.

The magnet was constructed from SCS4050 SuperPower 2G HTS tape [3]. Figure 2 details the material and thickness of each layer. The substrate material is Hastelloy C-276. The tape width was 4 mm and the overall thickness was 95 μm. The copper-to-superconductor ratio was 40:1. The minimum critical current at 77 K was 100 Amps. The superconductor was co-wound with a 5.2 mil thick stainless steel strap for mechanical support.



Figure 2. Materials and layer thicknesses of SuperPower SCS4050 HTS tape (not to scale) [3].

The superconducting magnet was actively protected using the “detect-and-dump” method [4]. Notably, no switch was employed to remove the power supply from the circuit. Instead, faults trigger a linear down-ramp of current from the power supply to limit the induced voltage. The dump resistor was arranged in parallel with the magnet. It consisted of three 1-Ohm, 100 Watt resistors in parallel, for a total resistance of 0.33 Ohms. In conjunction with the coil inductance of 0.15 mH, the RL circuit had a time constant of about 45 ms. An HP 6681A DC power supply capable of outputting up to 8 Volts and 580 Amps was used. Figure 3 shows a simple circuit diagram of the arrangement.

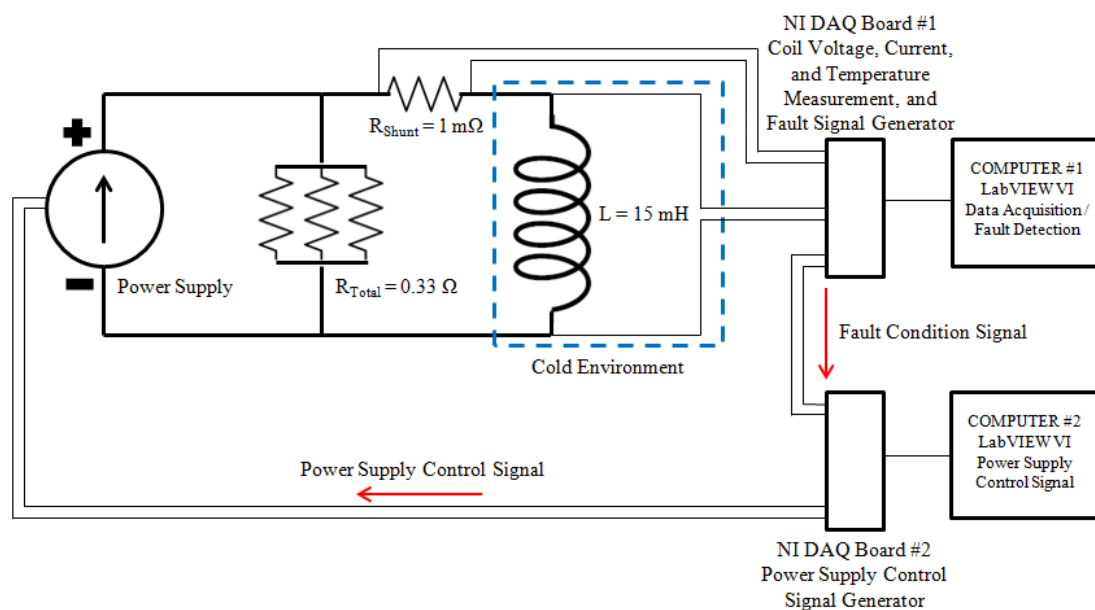
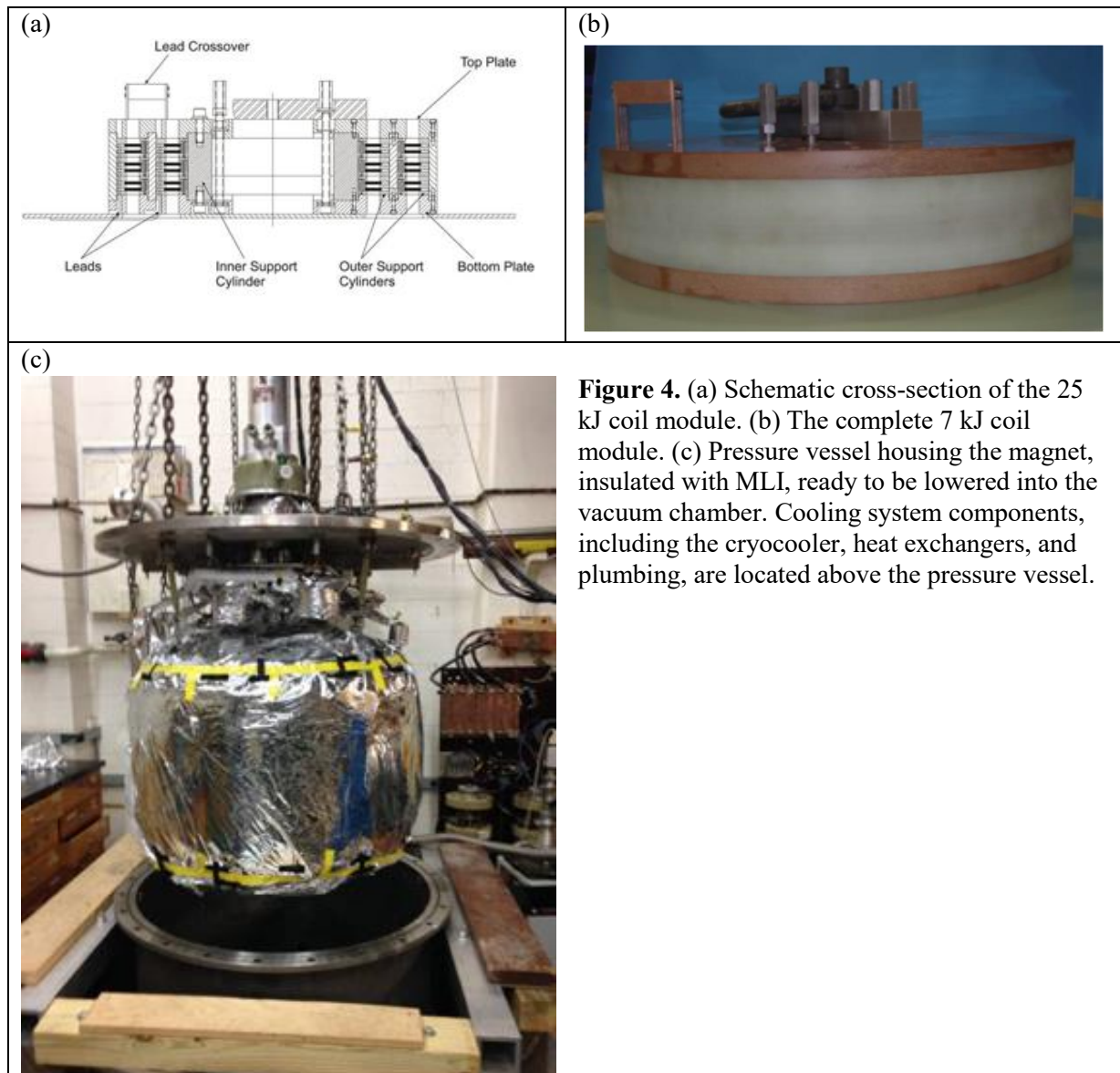


Figure 3. Circuit diagram, including the power supply, dump resistors, shunt resistor, superconducting magnet, coil voltage measurement, coil current measurement, and power supply control.

Magnet cooling was achieved using helium gas cooled by a Cryomech AL200 GM cryocooler. Utilizing a recuperator, the system supplied helium gas to the magnet at temperatures between 42 and 80 Kelvin, depending on the mass flow rate. Most testing was performed at 42 K inlet gas temperature, corresponding to a mass flow rate of 0.6 grams per second. Heat loads on the pressure vessel housing the magnet resulted in a temperature difference between the inlet and outlet gas. Typical outlet temperatures were about 72 K. A thermometer mounted on the magnet indicated the magnet temperature was somewhere in between, typically about 53 K. Figure 4 displays a coil cross-section, the 7 kJ coil package, and the fully assembled system.



3. Detection/Protection Scheme

3.1. Current Agreement

A practical engineering solution for both overcurrent and overvoltage conditions was developed based on insights from previous LTS work [5], using LabVIEW [6]. The current ramp profile, used for diagnostic measurements [7], was controlled using a signal generated in LabVIEW. With the appropriate multiplicative factor, the control signal was converted into an expected power supply output current value. The LabVIEW program also measured the current flowing through the magnet using a 1 m Ω current shunt. Each loop iteration checked that the measured current agreed with the expected current to within a threshold. If the measured current deviated from the expected current by more than the defined threshold, LabVIEW sent a control signal which linearly reduced the current to zero over 1 second. An immediate drop to zero current would result in a large inductive voltage which risks damaging the magnet.

This ramp down began one loop iteration after the fault was detected. LabVIEW was configured to take 300 samples at 15,000 samples per second, resulting in roughly 20 milliseconds between loops. A 16 bit National Instruments DAQ and a voltage range of ± 1.5 volts resulted in voltage sensitivity of $46 \mu\text{V}$. Consequently, voltages as little as $46 \mu\text{V}$ in excess of defined thresholds triggered the protection system. Non-ideal power supply control required the current agreement threshold to be set relatively large. Lag time between the control signal and power supply output, as well as current overshoot upon ramp completion, resulted in discrepancies between expected and measured current which became larger with increasing maximum current. We used a 5 Amp threshold with 20 Amps maximum current, up to a 25 Amp threshold with 110 Amps maximum current.

3.2. Voltage Agreement

A similar method was used for voltage agreement. Based on the magnet design and voltage measurements during ramp, an estimate for the coil inductance was known. Inductive voltages produced with safe, low current linear ramps confirmed an inductance of about 15 mH. Likewise, the voltage produced by small amounts of constant current indicated joint resistances totaling $0.6 \text{ m}\Omega$. These two values were used to produce a first approximation for the expected value of the coil voltage for the ramping and constant current sections of the trapezoidal-shaped ramp, respectively. In LabVIEW, the measured coil voltage was compared to either the expected inductive voltage during ramping, or the expected resistive voltage while the current was held constant. A slight threshold was added to the expected values, and any voltage in excess of the threshold set point triggered LabVIEW to begin a ramp down to zero current over 1 second. Figure 5 shows two pulses at 110 Amps maximum current, with a 2 second ramp up, 2 second ramp down, 2 second hold time at max current, and 4 second dwell between pulses. The figure includes the current and voltage measurements, as well as the trip voltage threshold.

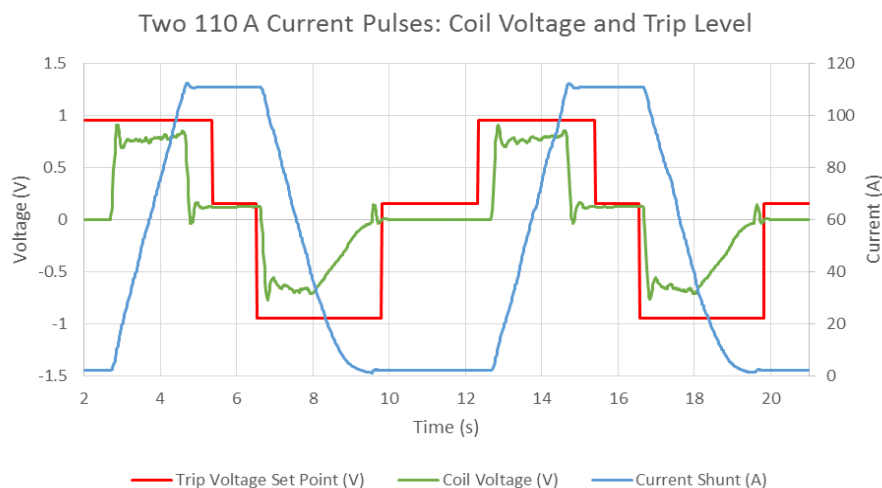


Figure 5. A pair of current pulses up to 110 Amps maximum current. The voltage threshold is set based on whether an inductive voltage in addition to a resistive voltage is expected for a given section of the ramp.

3.3. Non-Ideal Behaviour

In practice, both the timing and values of the expected voltage required fine-tuning to prevent unnecessary faults. At the ends of each ramp, the power supply overshoot the target current. This produced slightly larger than expected inductive voltages, which we accounted for in the threshold set point. In addition, it produced inductive voltages due to oscillations while the power supply attempted to bring the current under control, during a time frame in which there ideally would be no inductive voltage.

As a consequence, we were forced to delay the transition from checking against inductive voltage to resistive voltage by several tenths of a second. This effect was compounded with temporal lag between the control signal and the power supply output. The end result required conservative manipulation of the set points as we tested different current values, and often resulted in unnecessary fault events. However, the technique proved effective at protecting the magnet from damage due to overcurrent and overvoltage events.

3.4. Demonstration of Effectiveness

Previous experiments without an overvoltage protection system in place relied on entering the current sharing state and then manually shutting off the power supply in the event of quenching. Figure 6 displays a quench event at 110 Amps without the protection system in place.

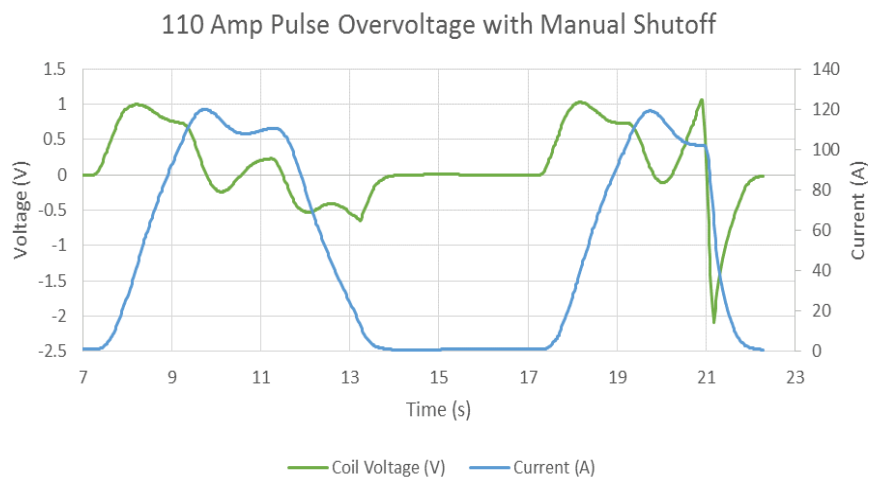


Figure 6. A pair of current pulses up to 110 Amps maximum current. With no overvoltage protection system, the power supply was shut off manually at about $t = 21$ seconds when a noticeable voltage rise appeared across the coil, indicating current sharing.

Poor power supply control resulted in inductive voltage oscillations throughout the entire ramp profile. The first pulse was successful, but the second pulse exhibited a sharp rise in voltage as the critical surface was exceeded. At about 1 volt the power supply was shut off manually.

By comparison, figure 7 shows a quench event at 110 Amps with the protection system in place.

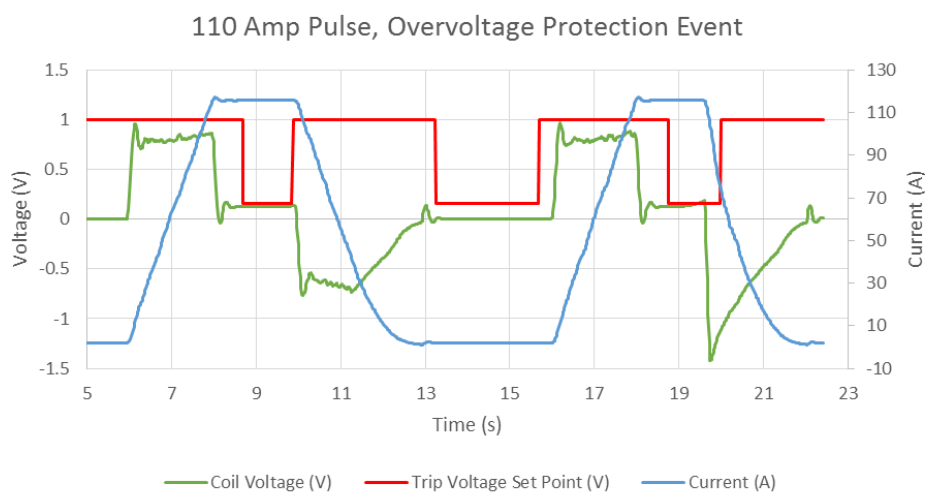


Figure 7. A pair of current pulses up to 110 Amps maximum current, with the second pulse exhibiting an overvoltage event just before $t = 20$ seconds, promptly followed by a down ramp to protect the coil.

Power supply control was superior for this experiment. During the flat portion of the second ramp, voltage excursion from the expected value began, and was quickly detected. The trip voltage set point was 160 mV. Due to lag time between when the power supply received a signal and output accordingly, 198 ms elapsed between fault detection and the beginning of the down ramp despite the LabVIEW program sending the ramp down signal after one 20 ms loop iteration. Consequently the voltage exceeded the trip voltage by 26 mV, compared to the theoretical minimum excess detection voltage of 46 μ V. This voltage exceeded the typical resistive voltage due to joints at 110 Amps by about 58 mV, compared to about 1 V without the protection system. A power supply with a faster response time could approach the theoretical limits of detection and response time set by the LabVIEW program.

3.5. Protection Technique Validity with Increasing Stored Energy

An MIITS calculation gives an estimate of the temperature rise during a quench found by equating the integral of the heat capacity over temperature with the integral of current squared over the time of the quench, as in equation (1) [8], [9].

$$\int_0^t I^2 dt = A^2 \int_{T_0}^T \frac{C(T)}{\rho(T, B)} dT \quad (1)$$

Figure 8 displays the results of the MIITS calculation, and the resulting quench temperature relative to the maximum allowable temperature before damage to the HTS occurs.

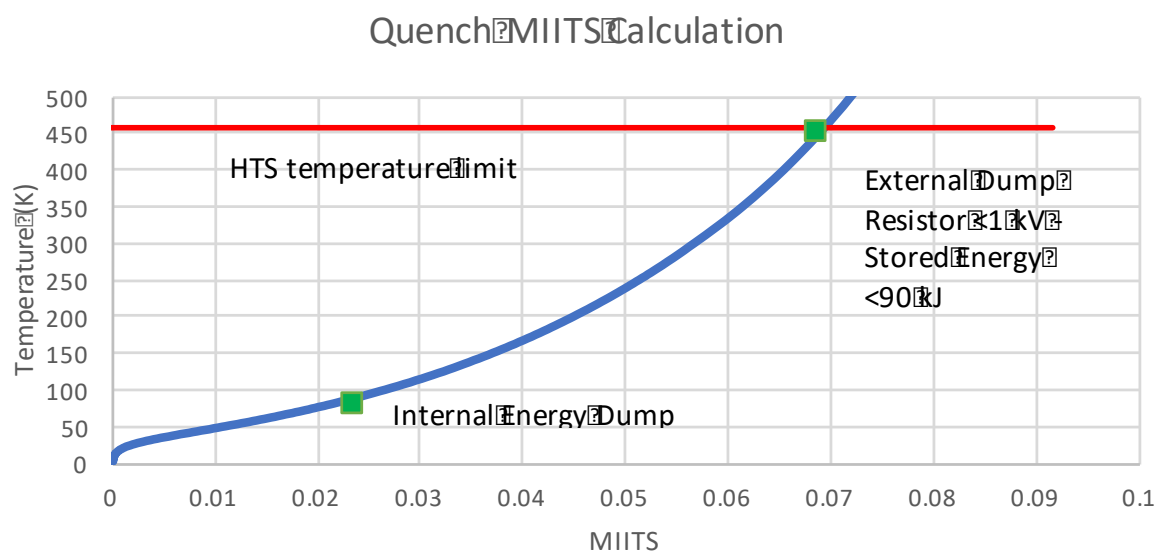


Figure 8. Quench temperature as a function of the time integral of the current squared.

If the stored energy is deposited over the conductor and the co-wound stainless steel strap, the temperature rise during a quench is small, with final temperatures of about 100 K. Uniform distribution of stored energy would require a quench heater. Rather than employing a quench heater, an external resistor was used to dump the stored energy. Allowing the dump voltage to rise to the system limit of 1 kV by varying the dump resistance, and thus changing the dump time constant, restricts the quench temperature below the HTS temperature limit of 185 °C if the stored energy is below about 90 kJ. Above 90 kJ, changes in the quench protection system, such as active switches, quench heaters, or conductor modifications will be required.

4. Conclusions

This paper details progress made toward a 3 MJ, 1 MW helium gas cooled HTS magnet with charge and discharge times on the order of a second. Testing has been performed on part of a 7 kJ module, which was limited to 108 J of stored energy at 120 Amps due to joint resistances on the order of 0.6 m Ω , orders of magnitude larger than desired. At high current, heating in excess of available convective cooling power caused the HTS to current share with the copper stabilizer. The resulting voltage increase was detected using LabVIEW. If it exceeded a defined threshold above the expected value, LabVIEW ramped the current down to zero over 1 second to prevent damage to the magnet. This protection circuit is crucial to safely test more coil modules with increasing current and stored energy as we improve the joint resistances and cooling system. However, MIITS calculations suggest the present protection system will only be adequate up to stored energies of about 90 kJ. Beyond this, modifications to the protection circuit will be required.

References

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