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Can High Current Density HTS Magnets be Quench Protected Using Methods Used to Protect High Current Density LTS Magnets?

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Abstract—In the 1970s the Lawrence Berkeley Laboratory (LBL) was testing high current density magnets where the EJ^2 limit was up to two orders of magnitude higher than the quench protection methods of the period would permit at the time. LBL was designing a high current density (J) thin solenoid with a large volume and stored energy (E). The accepted EJ^2 limit at the time was $\sim 10^{23} \text{ J A}^2 \text{ m}^{-4}$. In order to exceed the EJ^2 limit by two orders of magnitude, one had to greatly increase the quench protection voltages (V) and magnet current (I). In 1977, LBL tested four quench protection methods on a 2-meter diameter high current density solenoid with a stored energy of 2 MJ. Three of these quench protection methods worked well, but the fourth didn't appear to work. These methods will be discussed as to whether they can be applied to HTS or MgB_2 high current density magnets.

I. INTRODUCTION

The discovery HTS in 1986 [1] was widely heralded. Projects were either canceled or nearly cancelled because it was thought that HTS devices would soon replace LTS devices. In 1988, this author wrote a white paper to NASA concerning the use of HTS magnets for use in space [2]. One of the conclusions of this paper was that HTS magnets would have serious quench protection issues.

HTS magnets don't quench for some of the reasons that LTS magnets quench. Most LTS magnets quench due to filament flux jumps or sudden conductor motion [3], [4], [5]. Quenches in LTS magnet have occurred because of local heating due to mistakes in the cryogenic system or gross magnet movement due to stick-slip cold mass support system issues [6]. An important factor is the low resistivity normal metal in the conductor [5], [7]. LTS magnet quenches are rare when the conductor minimum propagation zone length is long [8], [9]. Conductors with critical temperatures $>20 \text{ K}$ are less prone to quenching because of the high conductor specific heat. Tape conductors can have large magnetization currents generated by changing magnetic fields perpendicular to the conductor flat face, so this requires that there be copper in the conductor. While spontaneous quenches

are less likely, magnets will quench if any part of the magnet is above the conductor T_c . An HTS magnet must be quench protected like LTS magnets.

The two major HTS magnet quench protection problems are; the low quench propagation velocities in all directions, and a reduced value of the integral of $J(t)^2 dt$ in the conductor between the magnet operating temperature T_o and a hot-spot temperature T_{HS} where J is the conductor current density.

Conventional wisdom says that one must do the following in order to safely quench an HTS magnet [10], [11]: 1) One must have more low resistivity normal metal in conductor to reduce J and extend the safe decay time; 2) one must detect the quench quickly and put a resistance across the coil to reduce current rapidly; and 3) one must sub-divide the coil to reduce the voltages to ground and between layers. Adding normal metal to an HTS conductor is problematic and the added metal makes the quench harder to detect. Some experiments at LBL between 1975 and 1978 have shown that there are other ways safely quench protecting high current density LTS coils that operate at low currents with a high stored magnetic energy. The question is, will any of these methods will work with HTS magnets operating at temperature $>20 \text{ K}$?

II. QUEST FOR THINNESS IN HIGH ENERGY PHYSICS SUPERCONDUCTING DETECTOR MAGNETS

In 1975, the Alvarez Group (named after Luis W. Alvarez, Nobel Prize in Physics 1968), of the LBL Physics Division launched the MINIMAG project, which was to include a thin 1-m diameter superconducting solenoid that was 1.8 m long, for a detector proposed for SPEAR-II at the Stanford Linear Accelerator Center (SLAC) at Stanford University [12], [13].

At the time, the concept of a thin Large superconducting magnet didn't seem possible. Superconducting magnets were cryogenically stable [14] with coils that were mostly copper in large stainless cryostats filled with liquid helium. What was meant by thin was being less than 1 radiation length thick for the coil, the cryostat and the helium. A radiation length of material is the thickness of material needed to reduce the energy of an electron by a factor of $1/e$ (~ 0.368) [15]. The mechanism for the energy loss is the effect on the electron entering the atom by the electrons going around the atom (bremsstrahlung radiation) and the size of the atom. So, the radiation length is a function of Z the atomic number and A the atomic weight. One radiation length of material is given in units of kg m^{-2} . To get the physical length of one radiation length of material one divides the radiation length by material density. Values for radiation lengths can be found in [16, Appendix, Table I]. The radiation lengths for the materials

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found in superconducting magnets [17]: copper 14.5 mm, Nb-Ti ~ 20 mm, 304 Stainless Steel 17.4 mm, plastic ~ 189 mm, and aluminum 88.9 mm. It is clear that the use of copper should be minimized and the best material to use in the cryostat is aluminum.

III. ALUMINUM MATRIX SUPERCONDUCTOR

One of the consideration was to find a company that could make a fine filament conductor with an aluminum stabilizer in place of copper. In November of 1975, we met with Doug Koop, Clay Weatstone and others from the Aluminum Company of America (ALCOA) to discuss a new three component superconductor they had developed with a 5056-aluminum matrix, with tubes made from Nb-Ti filled with an ultra-pure aluminum stabilizer with an RRR = 5000 after an anneal at 400 C. The material was available 18 cells, 54 cells and 160 cells extruded and drawn in 5056 Al, which has a resistivity a little lower than 6161-T4 aluminum. ALCOA claimed that this material would have many advantages.

A problem with this material was the smallest possible filament size was $>125 \mu\text{m}$, which leads to less stability and more sensitivity to conductor motion, and a shorter minimum propagation zone length due to high matrix resistivity. We tested a short length of the material. The Nb-Ti current density was 1700 A mm^{-2} at 4.2 K and 5 T, but we felt that the cell size was too large. We were looking for filament sizes of $<25 \mu\text{m}$. We did a crude measurement of quench propagation velocity and found that quenches propagated ~ 3 times faster because of the lower matrix specific heat at 4.2 K. We knew at the time that the quench propagation velocities in Nb₃Sn were a factor of ~ 3 lower than Nb-Ti at 5 T, because of the higher specific heat of the conductor near T_c. We didn't write about this material because of confidentiality agreements, but we did write an internal engineering note about the conductor [18].

A few years later, the Al matrix conductor problem was solved in France by soldering a copper matrix conductor into high RRR Al [19], and by co-extrusion of copper matrix conductor in high RRR Al [20], [21]. We didn't know that a high RRR ultra-pure aluminum conductor matrix speeds up the quench, along the wire, because the low matrix resistivity slows the spread of the current into the matrix causing a higher effective matrix current density near the superconductor [22]. LBL wound an insulated copper matrix superconductor on an annealed 1100-O mandrel with an RRR ~ 25 so the coil current would be transferred to the mandrel inductively during a quench to reduce the hot-spot integral of $j^2 dt$.

IV. DISCOVERY OF QUENCH-BACK

We built two coils 1002.5 mm in diameter and 461 mm long. The coils were wound on mandrel fabricated from annealed 1100-O aluminum that was 6.35 mm thick. A two-layer coil was wound over 1 mm of insulation to ground. The A coil had a conductor with a copper to superconductor ratio of 1.8. The B coil copper to superconductor ratio was 1.0. The filament diameter in both conductors was $\sim 13 \mu\text{m}$. The coil was potted with epoxy. There was also 1 mm of ground insulation on the outside of the coil. A 9.53 mm diameter 5083 Aluminum tube was wound on the outside of the coil to carry two-phase helium from a helium refrigerator operating at 4.5 K. The two-phase

Fig. 1. The Current Shift from the 1 m Coil to the Mandrel at 700 A. Note: the flux generated by the coil current plus the flux generated by mandrel current is equal to the total magnet flux. The coil is fully normal at the end of the rapid drop of the coil flux at time ~ 0.15 s [25].

helium tube eliminated the liquid helium vessel and reduced the magnet radiation thickness considerably [23].

We discharged 1 mF capacitor at 450 V into 10 mm diameter coil installed in the mandrel to quench part of the magnet. There were several similar coils 250 mm apart that picked up a signal from the quench going by, so we could get a good measurement of the quench velocity along the wire. The transverse quench velocity was measured by measuring the coil resistance growth early in the quench. We compared the calculated and measured quench velocities along the wire as a function of current density in the wire [24].

When testing the magnet, we started by quenching the magnet at low currents. The data was taken on an oscilloscope that could calculate the integral $i^2 dt$. This calculation would permit us to determine the maximum current that we could safely put into the coil for the next quench [25]. The highest overall conductor current density reached was $\sim 1200 \text{ A mm}^{-2}$.

The discovery of quench-back was a surprise. We expected the current to be inductively transferred to the low resistivity mandrel as the quench propagated in the coil, but we didn't think about the heating of the mandrel causing quenching the whole coil [24], [25]. Fig. 1 shows the magnetic flux due to the coil current and the magnet flux of the magnet measured for the magnet as a whole during a quench. The difference between the two is due to the current flowing in the mandrel. At the point where the mandrel current starts to increase rapidly is when the whole coil goes normal because of the heating from the mandrel (quench-back). This happens because the thermal diffusivity of the coil insulation is large, because the insulation volume specific heat is small at 4.5 K.

V. THREE QUENCH PROTECTIONS METHODS TRIED ON A TWO-METER IN DIAMETER COIL

Fabrication of the 2-meter diameter C test magnet was driven by the desire to have a larger time projection chamber (TPC) detector that would have a diameter of 2 m and a length of over 3 meters. The average coil diameter was 2004.3 mm; the two-layer coil length was 697 mm. The coil consisted of 860

Fig. 2. The 2-m diameter LBL C test solenoid in Early 1977 [26].

turns of Formvar insulated 1.5 mm round wire Nb-Ti with a copper to superconductor ratio of 1.8, with 2000 filaments $\sim 19.6 \mu\text{m}$ in diameter with a twist pitch of 20 mm. The coil was wound on an annealed 1100-0 RRR = 25 aluminum mandrel 9.53 mm thick with 1 mm of fiberglass epoxy insulation between the coil and the mandrel [26]. The two-layer coil had a center tap that was connected to room temperature by a 304-stainless steel pulsed lead. The coil current leads were gas cooled leads capable of carrying the maximum design current of $>1500 \text{ A}$. The maximum conductor current density is $\sim 800 \text{ A mm}^{-2}$. The mandrel was well coupled to the coil inductively. Quenches were initiated the same way as in the 1-meter diameter test coils. There were two layers of 6061-T6 wire 3 mm in diameter between the two-layer superconducting coil, with twelve bifilar (non-inductive) longitudinal quench propagators mounted 30 degrees apart, and the cooling tubes to ensure that superconducting coil doesn't lift off the mandrel when fully charged. There is 1 mm of ground insulation between support windings and the coil and the quench propagators.

The cooling tubes were 12.7 mm OD tubes extruded from 5056-Al. The spaces between the tubes were filled with Dacron to prevent cracking of the epoxy. These tubes carried two-phase helium provided by a helium refrigeration system that fed the helium into the tube at or near the saturated liquid line. The coil, the support wires and the cooling tubes were vacuum impregnated with epoxy. Fig. 2 shows the finished coil before it was put into the cryostat vacuum vessel.

The following active quench protection schemes were tried on the solenoid above: 1) We installed twelve bifilar longitudinal propagators 30 degrees apart on the outside of the coil that were in series with the coil. This was designed to be a passive quench protection system to make the magnet coil quench faster. 2) The second quench protection system was varistor put across the coil. This system was designed reduce the coil current rapidly to about 5 percent of the coil starting current. The magnet current

is supposed to stay low. 3) The third quench protection system was to discharge a 4.5 mF capacitor charged to 1000 V into the center tap of the coil.

A. Longitudinal Quench Propagators

This method didn't appear to work at currents $<1000 \text{ A}$. There was 0.5 mm of insulation between the propagator and the coil. In order for the propagators to work the normal region heated region has to be more than a minimum propagation zone log. The propagators as installed might heat up 4 mm of the magnet coil. In order for the coil to be stable, the minimum propagation zone in the conductor must be longer than that. Resistance heaters 20 to 30 mm wide might have been more effective. The propagators we used appeared not to be effective at the magnet currents tested. In 2014, a magnet at Michigan State University had an 80 mm wide resistor on the outside of the coil to heat the coil. This resistor was effective in reducing the integral of $j^2 dt$ in the coil, because the amount of superconductor turned normal was much longer than a minimum propagation zone [9], [27].

B. Quench Protection With a Varistor Across the Coil

The addition of a shorted secondary circuit changes coil quench protection. Any resistance in the coil circuit causes a portion of the ampere-turns in the coil to shift to the secondary circuit [28]. The speed of the shift is dependent on one minus the coupling coefficient ε for the two circuits where,

$$\varepsilon \approx \left[1 - \frac{M_{1-2}^2}{L_1 L_2} \right], \quad (1)$$

with L_1 the coil self-inductance, L_2 the secondary circuit self-inductance, and M_{1-2} the mutual-inductance between the coil and the shorted secondary circuit. For constant resistances the coil decay time constant $\tau_1 = L_1/R_1$ and $\tau_2 = L_2/R_2$. The longer decay time constant for the system τ_L is about $(\tau_1 + \tau_2)$. The shorter time constant is approximately as follows;

$$\tau_S \approx \frac{\varepsilon \tau_2 \tau_1}{\tau_1 + \tau_2}. \quad (2)$$

In real magnets neither resistance is constant with time. For a normal resistor, the current drops to about $\tau_1/(\tau_1 + \tau_2)$ as a function of time.

When one uses an ordinary resistor across the coil, the voltage across the resistor is linear with current and τ_1 is nearly constant at the quench start. With a varistor, the effective resistance increases as the current goes down, so τ_1 and τ_s become much smaller. The result is a more rapid decrease in the coil current. The combination of low ε and the varistor caused reduction τ_1 reduces the coil current much more than would be achieved using an ordinary resistor with the same starting resistance as the varistor. The varistor protected coil can have a much lower integral of $j^2 dt$ than the coil protected by an ordinary resistor. How well the varistor performs depends on varistor material [29]. The varistor voltage $V(t)$ is a function of the current $I(t)$ in the varistor and the varistor starting voltage V_0 and starting current I_0 as given below;

$$V(t) = V_0 \left[\frac{I(t)}{I_0} \right]^b, \quad (3)$$

where b is a constant that applied over a wide range of currents. If $b = 0$ the varistor is a constant voltage device. If $b = 1$ the

Fig. 3. The voltage V vs current for the LBL test coil varistor [28].

Fig. 4. The current flowing in the magnet coil versus time after a quench for the three quench protections methods. Starting current = 500 A. The effect of quench-back is clearly seen in the no quench protection case. The varistor appears to reduce the current over 20-fold. The center tap quench protection system seems to turn a lot of the coil normal in less than 1 second. [30], [31].

varistor is an ordinary resistor. At very high or very low currents through the varistor, $b = 1$ [29].

Varistors come in two general types, metal oxide varistors (MOV), which are predominantly zinc oxide with b between 0.01 and 0.06 and silicon carbide varistors, which at the time were called thyrite varistors with b between 0.2 and 0.3. The varistor used came out of one of the LBL electronic shops and wasn't specified in the papers of the time. Fig. 3 shows voltage across the varistor as a function of current plotted on a log-log plot. The slope of the varistor voltage plot shows $b = \sim 0.24$. The 1977 varistor was made silicon carbide, the only type of varistor commonly available at that time [29].

We got very good quench protection results using the varistor in 1977. Fig. 4 shows the coil current versus time for the three types of quench protection at 500 A.

The three methods were 1) no protection (only bore tube quench back), 2) protection by putting a 2000 V across the coil with a varistor, and 3) putting a pulse of current into the coil center tap at 1000 V (next section.) [30], [31]. Fig. 5 shows the resulting hot spot temperatures for three different methods of protection as a function of current in the coil.

C. Center-Tap Current Pulse Quench Protection

The energy stored in a capacitor was discharged into the center-tap of a two-layer coil in ~ 2 ms. The current in one layer

Fig. 5. The Hot-spot Temperature after a Quench with Three Types of External Quench Protection on the 2-meter diameter coil. The no quench protection case is just quench-back from the 1100-O aluminum bore tube [31].

Fig. 6. This figure shows the layer resistance as a function of time. The outer layer started at 500 A and went up to ~ 1100 A. The inner layer current went down to ~ 100 A and then it became superconducting, until the heat from the outer coil drove the inner coil normal again [31].

goes up and the current in the other layer goes down so the net current didn't change. The effect on the resistance of each coil layer is illustrated in Fig. 6. A portion of both layers went normal because of AC losses within the layers.

The center-tap quench protection system clearly worked on the LBL 2-meter diameter solenoid all the way to the design current for the magnet. The case shown in Fig. 7 was the best case for this quench protection method. When the voltage in the capacitor was reversed, the inner layer current went up and the outer layer current went down. The magnitude of the voltage was the same for both cases. When the current went up in the inner layer instead of the outer layer, the hot-spot temperature during the quench went up. No explanation for this was given in [31]. The inner layer is closer to the RRR = 25 mandrel, so it is likely that some of the energy went into the mandrel instead of the layer superconductor. The same quench protection experiment

was tried by putting a current pulse from the capacitor into the magnet gas-cooled lead that connected to the outer layer of the coil. In order to get good quench protection performance, the capacitor voltages had to be increased from 1000 V to 2000 V, which meant the energy stored in the capacitor was increased by a factor of four [31].

D. Quench Protection Summary

Quench-back from the RRR = 25 aluminum mandrel clearly worked in all magnets at all currents. The longitudinal quench propagator didn't appear to work at low currents. We don't know if it worked at high currents. The last quench of the C coil was done at 1450 A with no quench protection except quench back. T_{HS} was <300 K. The varistor across the coil was clearly the most effective quench protection method tried. The only potential problem with this method was voltage breakdown when the cryostat vacuum was poor [32]¹. Any leads in the coil vacuum space must be properly insulated to avoid breakdown. The center-tap quench protection method appeared to work well but having a reliable capacitor bank that stayed charged over the life of the magnet was an issue, when it was implemented on the 10 MJ PEP-4 solenoid [33].

VI. WILL ANY OF THESE QUENCH PROTECTION METHODS WORK WITH HTS MAGNETS?

Quench protection of any superconducting magnet is largely a study of time constants. The quench protection equation below illustrates this;

$$E_0 J_0^2 = \frac{\Gamma}{2} f F(T_{HS}) V_0 I_0, \quad (4)$$

where E_0 is coil stored energy at $t = 0$ and J_0 is the conductor current density at $t = 0$. V_0 is the voltage across the coil section at $t = 0$, and I_0 is the magnet current at $t = 0$. Γ is between 2 and 3 depending on the resistor type. $F(T_{HS})$ is the integral of $j^2 dt$ from $t = 0$ to infinity, and f is the fraction of low resistivity normal metal in the conductor. For magnets built before 1975, $E_0 J_0^2$ was $\sim 10^{23}$ J A² m⁻⁴ and $F(300$ K) is $\sim 1.5 \times 10^{17}$ A² m⁻⁴ s⁻¹ for RRR = 100 copper. For $E_0 = 2$ MJ, $J_0 = 10^9$ A m⁻², $I_0 = 1$ kA, $V_0 = 1$ kV, and $f = 0.5$, the quench time must ~ 250 ms, for an ordinary resistor with no shorted secondary and 375 ms, if the resistor is a perfect varistor with no shorted secondary.

For quench-back to work effectively one must get the heat from the secondary across the ground insulation into the coil in a time of the order 100 ms, which is easily done at 4 K. The thermal penetration depth λ as a function of time t is given as follows;

$$\lambda(t) = (\alpha t)^{0.5} [34], \quad (5)$$

where $\alpha(T) = k(T)/C(T)$, where α is the thermal diffusivity as a function temperature T , $k(T)$ is the heat transfer coefficient as a function of T and $C(T)$ is the volume specific heat as a function of T . The value of $k(T)$ can increase a factor of two or three between 4 K and 100 K, but $C(T)$ can change over four orders of magnitude. If the ground insulation thickness is more than 0.5 mm and the magnet temperature T is >25 K, quench back is unlikely to occur in any magnet.

For the same reason that quench back is less likely to be effective for magnet operating at 25 K or above, longitudinal

quench propagators and heaters to quench the coil won't be very effective. Quench propagation in a coil is much slower at temperatures above 25 K [35]. Much more energy is also required in order to initiate a coil quench.

Any kind of resistor across the coil with a closely coupled secondary will cause the magnet current to shift to the secondary rapidly. However, the coil current I will end up at $I = \tau_1/\tau_L I_0$. With a varistor, the coil current can be quickly reduced to a few percent of the starting current I_0 . The lower the value of ε , the faster the coil current goes down [36]. The value of b has a strong effect on the volume of conductor in the secondary circuit, the amount of copper in the HTS conductor, and the material in the secondary needed to control the current bounce back towards the end of the quench protection process [37]. Having an ε as large as 0.50 can have a significant effect on the quench protection of some types of superconducting magnets, such as undulator magnets [38].

The center-tap quench protection system that was successful at Berkeley in the 1970's could work on thin HTS magnets but orders of magnitude more energy must go into the coil via the center-tap. The use of super capacitors [39] could potentially provide the needed energy and allow for quench protection at reasonable voltages. This author intends to look more at super capacitor characteristics as part of investigating the use of this quench protection method for HTS magnets in future. It is too early to rule out this method of quench protection.

VII. CONCLUSION

The normal zone propagation rate in HTS magnets is much lower than for LTS magnets. Typical HTS tape conductors have a low copper content, which makes quench protection more difficult. Active quench protection methods can work provided run-away quench detection is reliable and fast enough so that integral of $J^2 dt$ is small during the quench detection phase compared to the integral of $J^2 dt$ for a hot spot temperature of 300 K. Experiments at LBL suggest that reducing the quench detection voltages 1 mV is possible [40].

The key to active quench protection of HTS coils is transferring the current from the coil to a shorted secondary circuit rapidly. The secondary circuit is most efficient if the HTS magnet closely coupled inductively to the secondary and a varistor is used to force as much of current from the coil to the secondary as possible. The RRR in the shorted secondary doesn't appear to be very important [37]. It is unlikely that heat from the secondary can heat an HTS coil fast enough to have any meaningful effect on the quench process. Reliable high voltage insulation is a key element in any of these methods of quench protection. This is especially true when the insulation is within the magnet vacuum space.

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¹This effect is known as "Townsend's breakdown condition" or "Paschen's law."

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