The Effect of Shorted Secondary Circuit Material on Quench Protection of an HTS Tape Solenoid discharged across a Varistor

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Abstract. Studies suggest that an insulated ReBCO tape solenoid coil that is well-coupled inductively to shorted secondary can effectively be quench protected by discharging the coil across a constant voltage resistor. The discharge voltage across the constant voltage resistor is much lower than it would be for a constant resistance resistor that is used to achieve the same final quench temperature with or without a shorted secondary. How this quench protection works, depends on the constant voltage resistor characteristics, the properties of the shorted secondary circuit material and the amount of the material in the circuit. A previous paper suggests that the RRR shorted secondary circuit material is not important, which means that aluminum can be used in the secondary circuit and structural aluminum can support both the coil and the secondary circuit when that aluminum is on the outside of a solenoidal coil.

1. Introduction
The discovery of type I low temperature superconductivity (LTS) by H. Kamerlingh Onnes [1] was an exciting event in physics but it wouldn’t lead to anything practical for over forty years. Type II superconductivity was probably observed in the late 1930s in material such as niobium when drawn into wire. This was of little interest until 1961 when it was demonstrated that niobium tin was superconducting in magnetic fields up to 8.8 T [2]. The superconductivity in alloys Nb-Ti and Nb-Zr was demonstrated shortly after the discovery of niobium tin. The discovery of cryogenic stability in 1965 [3] and intrinsic and dynamic stability [4] in the late 1960s led to the use of type II superconductor in high energy physics magnets [5], NMR magnet and later MRI magnets. Before LTS magnets could be built in any quantity, the production of LTS conductors (mainly Nb-Ti) had to be on an industrial scale. With the industrialization of superconductor production, helium refrigerators had to be produced on an industrial scale [6]. The discovery of high temperature superconductivity HTS in 1986 [7] was a physic event well covered by the press until the discovery of cold fusion.

HTS conductors have a number of nagging problems when compared to Nb-Ti, which was used in the Argonne 12-foot bubble chamber magnet a little over ten years after Nb-Ti was identified as a viable superconductor [8]. The problems include the following: 1) The superconductor is not ductile or strong. 2) The critical current of the conductor is strain sensitive like Nb3Sn and other A-15 LTS conductors [9]. 3) BSSCO conductors must be reacted in an oxygen atmosphere after winding. This means that pure copper can’t be part of the conductor. BSSCO can be cabled before reacting. ReBCO tapes are not reacted before winding. Adding copper to a ReBCO conductor can be a problem.
Reacting after winding adds to magnet fabrication cost of a magnet using this conductor. 4) The specific heat of the materials that make up all superconductor increases as the conductor temperature to the n power, where n is ~3. This leads to low quench propagation velocities along the conductor and perpendicular to the conductor. This also leads to coils that have a low thermal diffusivity. The time constant for getting heat into the coil or out of the coil can be large. 5) In tape conductors there is an anisotropy in the conductor engineering critical current $I_c$ and engineering critical induction $B_c$. The engineering values of $I_c$ and $B_c$ are defined by a threshold voltage when the current is flowing. Most HTS conductors are resistive making it difficult for them to operate in the persistent mode with very long decay time constants characteristically found in MRI magnets. 6) HTS conductors have short coherence lengths so conductor defects produce resistive behavior and persistent joints are difficult to produce with this conductor. 7) Finally, HTS conductors are expensive. The use of these materials is based on the total economics behind their use. Refrigeration and good quality cryostats are still required for HTS conductors as they are for LTS conductors running in the temperature range from 1.8 to 4.5 K. HTS conductors haven’t taken off in the power industry for the same reasons that LTS conductors didn’t take off in the early 1980s. In the power industry, it is about economics and reliability. Superconductors are used when they are the only viable or economic solution to a problem.

2. Quench Protection of LTS and HTS Magnets

There are some things that are true about the quench process. If a magnet can become fully normal in a time that is less than the decay time constant of a resistor that puts a voltage of 1000 V across the magnet leads, it is likely that no active quench protection system is needed. Passive quench protection is always better than active quench protection, because no quench detection system or system that protects the coil is needed. Unfortunately, almost none of these truths apply to HTS magnets. Quench propagation velocities along the conductor are about two orders of magnitude lower than for Nb-Ti conductor at 4.5 K at the same current density [10], [11]. Nb-Ti conductor also has more copper in it. Quench propagation perpendicular the direction of current flow is always slower for both types superconductors.

Before discussing a quench protection method that will work for HTS magnets, it is useful to mention quench protection methods that won’t work. In the opinion of this author, the following quench protection methods are unlikely to work because of the high specific heat in the conductor and the lower thermal diffusivity of the HTS coil. These include quench-back from a low resistivity mandrel [12] and heating from coil current flowing in a resistor mounted on or within the coil [13]. The higher the $T_c$ of the conductor the less likely any of the preceding methods will be effective for protection.

Two basic equations can be used to explain how magnet quench protection works when a magnet is discharge through an ordinary resistor or a constant voltage resistor. They are as follows [14];

$$E_0J_0^2 = \frac{f}{2} F^*(T_{HS}) V_0 I_0,$$

where $E_0$ stored energy at $t = 0$, $J_0$ is the conductor current density at $t = 0$, $V_0$ is the voltage across the coil section at $t = 0$, $I_0$ is the magic current at the start of the quench $T$ is between 2 and 3 depending on the resistor type and $f$ is the fraction of low resistivity normal metal in the conductor. The function $F^*$ applies to the low resistivity metal in the conductor, which takes the following form;

$$F^*(T_{HS}) = \frac{1}{f} F(T_{HS}) = \frac{1}{f} \int_{T_0}^{T_{HS}} \left[ C(T) \right]_{LRNM} dT = \frac{1}{f} \int_{0}^{\infty} f(t)^2 dt,$$

Where $C(T)$ is the low resistivity normal metal volume specific heat as a function of temperature $T$, $\rho(T)$ is the low resistivity normal metal resistivity as a function of $T$, and $j(t)$ is the current density in the conductor as a function of time from the initial time (quench start). Figure 1 shows the value F for copper and aluminum for various values of residual resistivity ratios (RRR) [15].
\[ F^*(T_{HS}) = \frac{1}{T} F(T_{HS}) = \frac{1}{T} \int_{T_0}^{T_{HS}} \left[ \frac{C(T)}{\rho(T)} \right]_{LNNM} dT = \frac{1}{T} \int_0^\infty J(t)^2 dt, \]

Figure 1. Hotspot temperature for copper and aluminum with RRR=10, RRR=100, and RRR=1000 as a function of \( F^* \) [15]. (Note: the scale for \( F^* \) in the figure is from \( 10^{14} \) to \( 10^{18} \) A per m squared.)

The second equation that is of importance is the equation for the peak discharge voltage across a resistor to discharge the coil section such that the maximum hot-spot temperature is <300 K. The equation assumes that the quench is detected at time zero. Any quench detection time \( t_d \) will add \( t_d \) times \( J_0^2 \) to the integral of \( J^2 dt \) during the discharge from zero to infinity, which means that the initial voltage \( V_0 \) across the coil must increase. The equation below shows the initial voltage \( V_0 \) for a perfect constant resistance (where the current decays exponentially) and a perfect constant voltage resistor (where the current decay linearly).

\[ V_0 = \frac{I_0 L_{1s}}{F(T_{HS})} \frac{1}{T} \int_0^\infty J(t)^2 dt. \] (2)

For a constant resistance resistor \( \Gamma = 2 \) (exponential current decay with a time constant \( \tau_1 = L_1/R_0 \)) and \( \Gamma = 3 \) for a constant voltage decay (linear current decay).

From Eq. (1) it is clear that for a given magnet module stored energy \( E_0 \), one must increase the magnet initial current \( I_0 \), and or increase the initial discharge voltage \( V_0 \) for a given HTS conductor. The other action one can take is to reduce the initial current density \( J_0 \) in the HTS conductor by adding low resistivity normal metal such as copper or aluminum which also increases \( f \). Adding copper or aluminum to a BSSCO conductor can’t be done before reaction and it is difficult to do after reaction. With conductors made of ReBCO there may be ways of adding copper or aluminum, but conductor delamination may be an issue, or doing so may strain the conductor too much. One real downside of the added low-resistivity metal to an HTS conductor is the difficulty of detecting the quench [16]

3. HTS Magnet Protection with a coupled shorted-Secondary and a Constant-voltage Resistor
The concept of using a shorted secondary to help with quench protection was discussed by Maddock and James [17] in 1968. This paper discussed cryogenic stability and the possibility of having a shorted secondary circuit that could take up the energy from a non-cryogenically stable magnet coil into a shorted secondary that is inductively coupled to magnet coil. The author felt that it was better to
put the conductor in the shorted secondary coil into the primary rather than couple it to the secondary. The authors of this paper pointed out that a coupling coefficient between the primary and the secondary is always less than one.

In the mid 1970’s there was a strong desire to make a superconducting magnet thin so that muons and other particles could go through the magnet coil and its cryostat [5]. The cryogenically stable bubble chamber magnets had 10 to 20 times more copper than superconductor. The measure used to determine the transparency of the conductor and cryostat was the material radiation thickness [18]. The matrix materials were the dominant cause of coil radiation thickness. The two matrix materials were copper and aluminium. One radiation thickness of Cu is 14.3 mm and for Al it is 89 mm. The goal at the time was to build a magnet that was to be between 0.4 and 0.6 radiation lengths thick. At the time, there were attempts at fabricating a Nb-Ti conductor with the superconductor in an aluminium matrix [19]. Such a conductor was made, but the filaments of Nb-Ti were not uniform because the drawing parameters of Nb-Ti and Al are very different. Nb-Ti tubes filled with high RRR aluminium powder were drawn in a 5056 Al Matrix. A better option was Nb-Ti cables co-extruded in an aluminium matrix, but that didn’t happen until the early 1980s [20].

The desire to make a superconducting coil mostly out of aluminium led to the use of a shorted secondary (see Fig.2) and the concept of quench-back as a way to quench protect an LTS magnet passively [21]. Active quench protection was seriously explored, because the passive protection might not work with \( E_0 = 10 \text{ MJ} \). With a well coupled shorted secondary one could make the coil current drop very rapidly with a short exponential time constant. Depending on the electrical conductivity of the secondary, the current in the conductor could drop to 25 percent of the starting current. Thus, greatly speeding up the quench back process. The remaining current in the coil would decay away at a time constant that was the decay time constant of the secondary [15], [22]. These methods of quench protection were tested in early 1977 on a 2 MJ coil. An ordinary resistor can be used with an HTS coil, but the conductor still has to be at least 75 percent copper. Quench-back is unlikely to be of much benefit, because the thermal time constants to get the heat into the HTS coil are too long [23].

The use of a constant voltage resistor (Varistor) across the coil (see Fig. 3) permits one to reduce the copper content in the HTS conductor. Note: in Figure 3, the standard symbol for varistor is back to back diodes. This is how a varistor is supposed to behave. This is demonstrated in Ref [23] by using a copper secondary insulated winding and a varistor with a starting voltage across each coil of 2.0 kV with a stored energy of each coil ~1.8 MJ instead of resistor discharge voltage from 120 kV.
The stored energy per unit mass of the HTS coil, the insulation, and the shorted copper secondary winding is \(~6.5\) J per gram. The use of a varistor to rapidly shift the current from the primary to the secondary was first tried in 1977 at the Lawrence Berkeley Laboratory [15], [24] in an LTS superconducting magnet with a stored energy of 2 MJ and a peak coil current density of 820 A per square mm. The varistor drove the current down to 3 percent of the starting current in \(~130\) ms. At the end of the quench the calculated hot-spot temperature was 55 K. The actual hot spot temperature was lower, because the magnet insulation and the helium cooling tubes were not counted in the calculation. The secondary circuit was a 9.4 mm thick bore tube that was made of 1100-O aluminium with a measured RRR of \(~20\).

### 4. Commercial Constant Voltage Resistors for Quench Protection

A constant voltage resistor (varistor) behaves like back-to-back diodes. To first order, varistor heating is the forward voltage \(V_0\) times the magnet current \(I\). For the magnet in [23], \(I_0 = ~307\) A, so at the start of the quench varistor heat production with a \(V_0 = 2\) kV is \(~614\) kW. At a time of \(t = 80\) ms, the heat deposit rate in the varistor is down to \(< 2\) kW. At the end of quench with a 10 s time constant, the total energy deposited in the varistor is \(~35\) kJ, which is a 1.9 percent of the 1.8 MJ removed from the magnet per coil. The remainder of the magnet energy per coil ends up in the shorted secondary circuit. A copper secondary circuit is adiabatically heated from 25 K up to about 104 K. The heat stored in the copper secondary circuit is \(~11\) J/g. Only a small portion of the copper energy is transferred to the coil. One should assume no energy reaches the magnet coil.

A perfect constant voltage varistor is not achievable. Varistors can be made from materials such as ZnO and semi-conductors such as silicon or silicon carbide [25]. The difference between a diode and a varistor is the fact that the varistor has the same forward voltage in both directions. Most of the varistors that one finds while looking online do not have the ability to absorb 50 kJ of energy without permanently damaging the varistor. The kind of varistor that is need is one that looks like the hockey puck diodes that are commonly part of rapid constant voltage discharge systems for magnets and the cold diodes that are commonly used as part of the quench protection system for high inductance magnets that can be charged slowly using a 10 V power supply [13].

Commercial varistors from Metrosil [26] are like stacks of hockey puck diodes that are commonly used for superconducting magnets at 300 K or temperatures down to 4 K. Figure 4 shows a Metrosil varistor designed to carry up to 16000 A with a voltage drop of \(~800\) V. Metrosil varistors can operate at \(T\) up to 155 C. The total heat capacity from 25 to 155 C of the 16.7 kg varistor is \(~1.6\) MJ, but the magnets protected have very low inductances. A similar device that can carry up to 4000 A at 2000 V, would have a varistor mass of \(~8.5\) kg. This type of varistor could safely handle up 1000 A at 2000 V with a temperature rise of \(<30\) C, when used with a shorted secondary. The problem with the varistor shown Fig 4 is that a reduction of the current by a factor 100 will reduce the voltage across coil by a factor of four. The voltage the varistor \(V = V_0 \cdot (1/I_0)\) to the \(\delta\) power where \(\delta\) is the forward voltage factor as function current. Metrosil varistors have a \(\delta\) = 0.2 to 0.3 like other diode devices. One must reduce the value of \(\delta\) as much as possible.

![Fig. 4. A Metrosil varistor pack that will carry 16 kA at 800 A. The pack is 500 mm long with 14 active discs that are about 160 mm in diameter [26].](image-url)
5. What are the Items that affect the Quench Protection of a ReBCO Coil with a Varistor?

The two obvious things are to increase the coil current so one doesn’t have to increase the coil discharge voltage and increase the copper content in the ReBCO conductor. Increasing the current alone, will allow for a conductor with lower copper content. From [26] we know that the voltage has a large effect on how rapidly the current goes down during the first part of the quench. The coupling factor $\varepsilon$ between the coil and the secondary circuit is a large factor early in the quench. The definition of the $\varepsilon$ factor is:

$$\varepsilon = 1 - \frac{(M_{1-2}/L_1)L_2}{\sqrt{L_1}L_2},$$

where $L_1$ is the self-inductance of the coil, $L_2$ is the self-inductance of the secondary circuits and $M_{1-2}$ is the mutual inductance between the two circuits. The secondary circuits must be physically close to the coil.

As the secondary circuits get thicker, $\varepsilon$ must increase. As the value of $\varepsilon$ gets higher, the value of $V_0$ must go up in order for the coil current to go down rapidly enough at the quench start. The value of $\delta$ doesn’t have a large effect early in the quench, but later in the quench process it becomes more important. The RRR of the shorted secondary doesn’t have much effect at the beginning of the quench, but it does have an effect on current returning to the coil later due to the voltage across the coil changing sign. Fig. 5 shows the assumed coil configuration with copper secondary circuits just inside of the coil and just outside of coil with 1 mm of ground insulation all around the coil package. Each coil is around an iron pole that is 1.0 meters in radius. The two poles are 180 mm apart, and the peak induction between the poles is $\sim 2$ T. The total stored magnetic is $\sim 3.6$ MJ. Most of the stored energy is between the iron magnet poles, so it is reasonable that the allotted stored energy per coil is $\sim 1.8$ MJ. Because this magnet is an iron dominated magnet, the coupling between the two coils and the two shorted secondary circuits should be very good. The coupling between the coil and their shorted secondary should also be good. Fig. 6 shows the current decay at two different voltages (1000 and 2000V) with two coppers (RRR of 30 and 100).

Fig. 5. A schematic of an HTS coil with two copper secondary circuits inside and outside the HTS Coil

Fig. 6. Current decay in the HTS coil with secondary windings as a function of voltage across the leads and copper RRR.

Fig. 7 shows the percentage of the starting current $I_0$ times number of coil turns and the secondary circuits as a function of time from the quench start at $t = 0.01$ s to $t = 100$ s in a log-log plot with a starting voltage 2000 V for RRR = 30 copper in the secondary with a $\delta = 0.05$ and $\varepsilon = 0.01$. In this case the bounce back of the primary current is less than 1 percent, which is more than acceptable for HTS conductors with $f > 0.25$. The total thickness for the HTS coil shown in Fig 5 is 10.6 mm with ground insulation. The conductor $f = 0.457$, $J = 799$ A per square mm. Each copper coil in Fig. 5 is 16.4 mm thick. The quench protection voltage without the secondary circuit would be $\sim 120$ kV.
6. Aluminum versus Copper Secondary Circuits

It is clear that the RRR of the secondary is not important during the first part of the quench protection process. In fact, one can go through the whole quench process without the voltage going negative, which causes the current to flow back into the coil from the shorted secondary [23]. A certain amount of bounce-back current is OK as long as the current density in the HTS conductor is low (say < 70 A per square mm) during the coil current bounce-back. Aluminum as a secondary material is great to use even though it electrical conductivity is 65 percent of that of copper. Aluminum is 3.3 times less dense than copper and the cost per kg is roughly one third of that of copper in July 2019. Annealed 1100-O aluminium has an RRR from 14 to 30. Aluminium 99.999 percent pure can have an RRR of well over 1000. Pure aluminum can be bonded to 6061-Al to make a secondary circuit that would be able to carry the magnetic forces that would occur when the magnet current shifts to the secondary circuits. If the secondary circuits were fabricated with the same mass of 1100-O aluminium as copper of RRR = 30, the resistance of the secondary would be two thirds of the copper secondary at the beginning of the quench and less than half the resistance in the middle of the quench when bounce-back occurs. The secondary temperature at the quench end would be lower. Aluminium is less sensitive to magneto-resistivity than copper at high fields [27]. The major down side of using aluminium secondary circuits is the increase in the value of ε.

7. Concluding Comments

The basic equation for quench protection (1) tells us that one improves quench protection by increasing the magnet starting current I₀ and starting quench voltage across the magnet V₀, and by reducing the HTS conductor current density J₀ by increasing the copper fraction f in the conductor. One of the difficulties of increasing the copper fraction in an HTS conductor is the fact that the quench is harder to detect. The time between a quench occurring and the detection of the quench so that action can be taken is critical for high current density HTS conductors even when using shorted secondary circuits as a means of quench protection.

Well-coupled shorted-secondary circuits made from RRR = 20 aluminum can be effective when the mass of the aluminium is the same as the copper circuit it replaces. The coil assembly shown in fig. 5 is a layer wound coil using 4 mm wide ReBCO tape. If one replaces the layer wound coil with a coil...
made from three double pancakes of 12 mm wide tape, the quench voltage can be reduced by a factor of three for a given value of e. The terminal voltage will have to be increased to make up for the increase in e due to a thicker secondary circuit. In a large HTS solenoid, using aluminium shorted secondary circuits may be the best way to quench protect such a magnet. Using a varistor to protect the magnet reduces the quench voltage, but the voltage persists for some time. One must avoid breakdown at high voltages when the conductor is in vacuum.

8. References
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