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Use of inductive heating for superconducting magnet protection*

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***Abstract*—**
The sensitivity of superconducting magnets to AC losses is well known. If superconducting magnets are this sensitive to AC fields, why not use AC fields for magnet protection, and in particular, for internal energy dump when a quench has been detected? The answer is the large reactive power needed to provide the rate of change of the fields required to quench of a large fraction of the magnet. In this paper we describe a novel approach where quench protection secondary windings external to the magnet are used to minimize the power to initiate the energy dump. The main requirement of these secondary windings is that the mutual inductance between the primary winding and the protection secondary windings has to be small, ideally zero. One means to provide for zero mutual inductance between the protection secondary winding and the primary winding is by designing a protection secondary winding that produces AC fields that everywhere in the volume are normal to the fields produced by the primary winding. Alternatively, appropriate windings can be made so that the coupling in one region is the opposite to that of another region, with zero total mutual inductance. The latter approach results in low voltages at the leads, but could result in high voltages within the coil. We describe several circuit topologies applicable to solenoidal and toroidal windings that satisfy these requirements. Calculations of the heating due to AC fields are presented, including eddy current heating in cable-in-copper-channel conductors. If the quench inducing coil is optimally designed and powered, the hysteresis of the superconductor dominates the heating. Thus, as a portion of the superconducting magnet quenches, the heating power shifts to those zones that are not yet in the current-sharing regime. This approach is an alternative to the use of resistive heating elements, which need to be placed on, or embedded in, the winding pack.

***Index Terms*—Quench; protection; AC losses**

I. INTRODUCTION

Protection of superconducting coils has been an issue since superconducting strands have been made. The problem occurs due to the presence of normal conducting zones in the superconducting magnet (quench) which may result in thermal runaway [1,2]. In the case of devices with large stored energy, the problem is compounded by the need to remove the large stored energy before the normal conducting zone temperature exceeds a safe level. The problem is local as usually only a small region of the superconducting cable is affected.

There are many forms of magnet protection, from providing sufficient stability to prevent the generation of normal conducting zones, to providing passive or active means to reduce the heating source, by decreasing the current in the superconductor. In the case of magnets or cables with large stored energies, the energy can be discharged by external means (applying an external voltage across the leads of the device to remove the current and thus the source of heating), or it can be achieved by releasing the stored magnetic energy by having a large normal conducting zone, distributing the energy in a large volume and thus preventing high local temperatures in the superconductor. For high performance magnets it is difficult to remove the energy from the magnet fast enough, due to the high voltages that would be required. In some applications it is attractive to protect the magnet by dissipating the magnetic energy in a substantial fraction of the volume of the magnet winding.

The conventional method for internal energy dissipation requires the presence of heaters within the superconducting magnet. This method disturbs the winding process and can result in coil winding issues during winding or operation. The heating energy per unit volume required for achieving the superconducting-to-normal conducting transition in the conductor depends on the nature of the magnet. Systems in good direct contact with liquid He require high energy inputs, on the order of 1 J/cm^3. However, dry magnets that are cooled in the absence of liquid cryogens by direct thermal conduction to a cold anchor (for example, a cryocooler) require much less heating energy per unit volume, usually less than 100 mJ/cm^3 [2].

This paper describes a novel approach for quench initiation.. In section II, a novel method of quench generation within a large section of the winding is described, based upon the use of AC heating of the winding induced by external coils. Section III describes the use of eddy currents to generate the heating. Section IV describes the potential of hysteresis losses to generate the heating. In section V alternative arrangements of AC coils for different applications are described. Finally, section VI provides the conclusions.

II. INDUCTIVE QUENCH.

It is well known that the SC conductor windings can be heated by the use of AC losses (losses due the presence of an AC magnetic field) [3]. Several AC loss mechanisms are known to occur in superconducting windings, including eddy current losses, hysteresis losses, and coupling losses. Eddy current losses are caused by magnetic field diffusion through the normal conducting material (non-superconducting fraction). Hysteresis losses are due to magnetization effects in the superconducting material, as the AC field penetrates the surface of the superconductor. Coupling losses are due to losses through the superconductor/normal conducting material interface due to flux linkage through twisted superconductors.

Inductive heating has been used in several instances in order to start quench in CICC cables [4].

The problem with heating the coil using AC losses by a small rippling oscillation of the main magnetic field is that the reactive power required to change the field is very high. The ratio of the energy in the AC magnetic field to that in the main magnetic field is of order B_{AC}/B_{DC}, (where B_{AC} and B_{DC} are the magnetic fields in the AC and DC fields, respectively), resulting in very high powers being required in the externally driven AC magnetic field.

The power requirement in the AC heating coils is minimized when the mutual inductance between the AC heating coil and the main SC coil is 0. In this case, it can be easily shown that the ratio of energies is ~ $(B_{AC}/B_{DC})^2$. There are a number of ways of implementing this method [5]. In this paper we describe calculations for inductive quench for a split solenoid magnet (for a compact SC cyclotron).

One question that needs to be addressed is whether the magnetic fields penetrate the winding. Whether the field penetrates or not depends on the nature of the field, the arrangement of the winding with respect to the magnetic fields, and the presence of conducting materials on the surface of the coils. The case of a split solenoidal superconducting winding surrounded by a toroidal winding in which current flows in the poloidal direction is shown in Figure 1. Varying current in the toroidal coil generates a toroidal magnetic field and a poloidally directed electric field, which the conductor cannot shield (the current is prevented from flowing in the poloidal direction because of the turn-to-turn insulation).

We have further investigated the penetration of the field into the winding in the case of presence of a metallic surface covering the winding, modeled using ANSYS [6]. The results are presented in Figure 2. In the figure in the left, the winding is surrounded by a continuous copper shell, which prevents the magnetic field from penetrating into the winding. Placing a toroidal gap anywhere in this shell allows the fields for penetrate. In the case of Figure 2 b, the electric break is at the top of the coil, preventing poloidal currents from flowing and shielding the induced magnetic field.

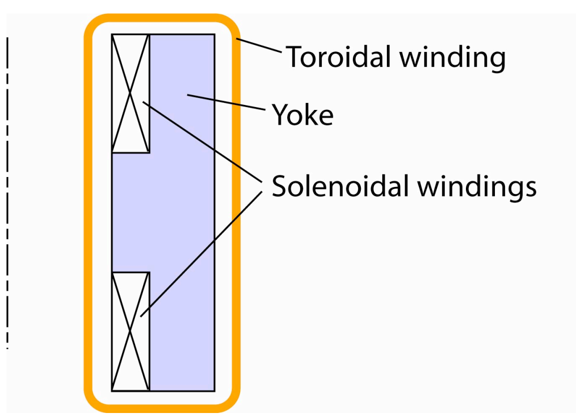

Fig. 1. Solenoidal split pair surrounded by a toroidal winding

The situation in the yoke is different. Figure 3 shows the magnetic field in the yoke (not displayed in Figures 2(a) and (b). The magnetic field does not penetrate deep into the resistive yoke. The magnetic field energy of the AC coil is concentrated in the region of the superconducting coil, minimizing the required reactive power. It should be pointed out that the iron is saturated by the strong DC field, resulting in low hysteresis losses in the iron.

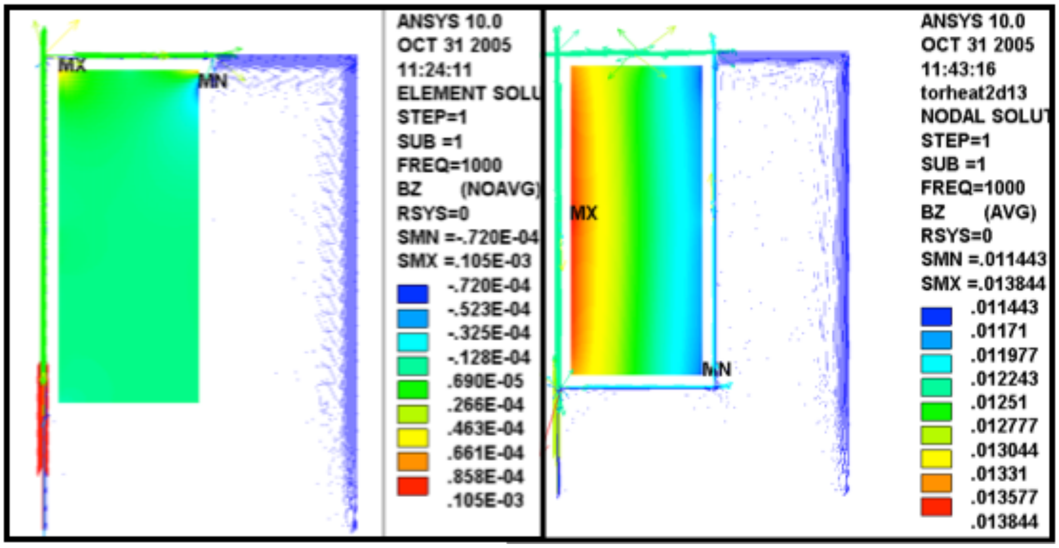

Fig. 2. Field strength (T) on the winding for the case of continuous shell (a) and discontinuous shell (b). Location of electrical break in copper shell surrounding the magnet also is shown.

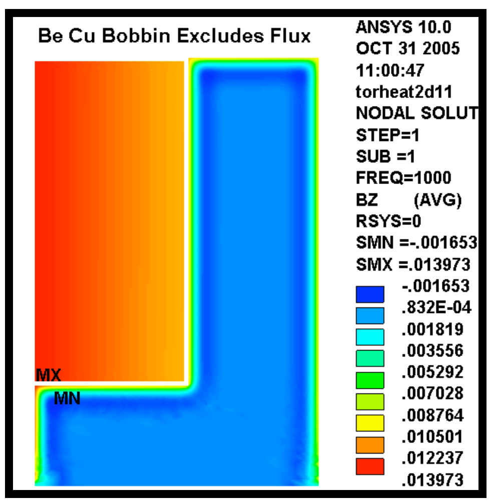

Fig. 3. Field strength (T) on the yoke for the case of discontinuous copper shell.

Even if the toroidal coil is not wound uniformly around the solenoid there are still magnetic fields induced in the bulk of the solenoid, although some of the non-toroidal magnetic fields could be shielded. Other geometries are possible that can accomplish local heating of the SC winding, but where there is partial shielding of the magnetic field by the winding itself. The saddle coils in Figure 4 also has 0 mutual inductance with the solenoidal coils.

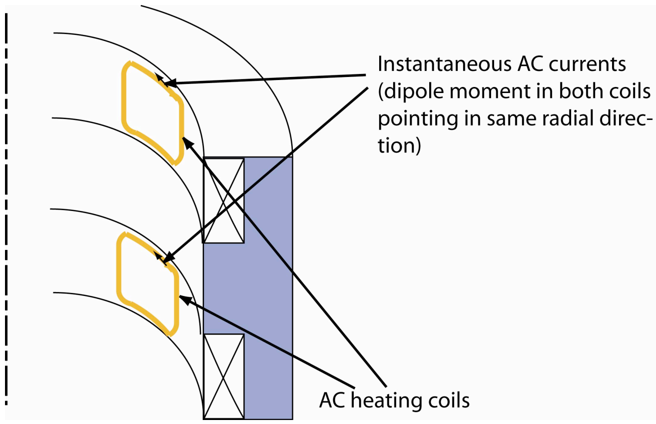

Fig. 4. Alternative AC inductive coil arrangements (M= 0).

III. Eddy current losses

A simple model has been put together to determine the AC losses in the superconductor cable, due to the presence of an oscillating AC field (in the toroidal direction, parallel to the winding). A 2-D model of the conductor is shown in Fig. 5.

In the absence of coupling losses, the losses from the eddy current heating can be calculated using conventional EM models. A model using COMSOL has been built [7]. The model assumes that the strands are made of pure copper (no superconductor), the same as the trench. Solder fills the empty space in the conductor. In order to incorporate surface resistivity, a thin layer has been placed around the strands and surrounding the inner surface of the trench. The dimensions of the elements in the conductor are shown in Fig. 5. The resistivities are: Cu, 1.4 10^9/Ωm; Solder, 0.25 10^9/Ωm; surface resistivity: 10^{-12} Ω/m^2.

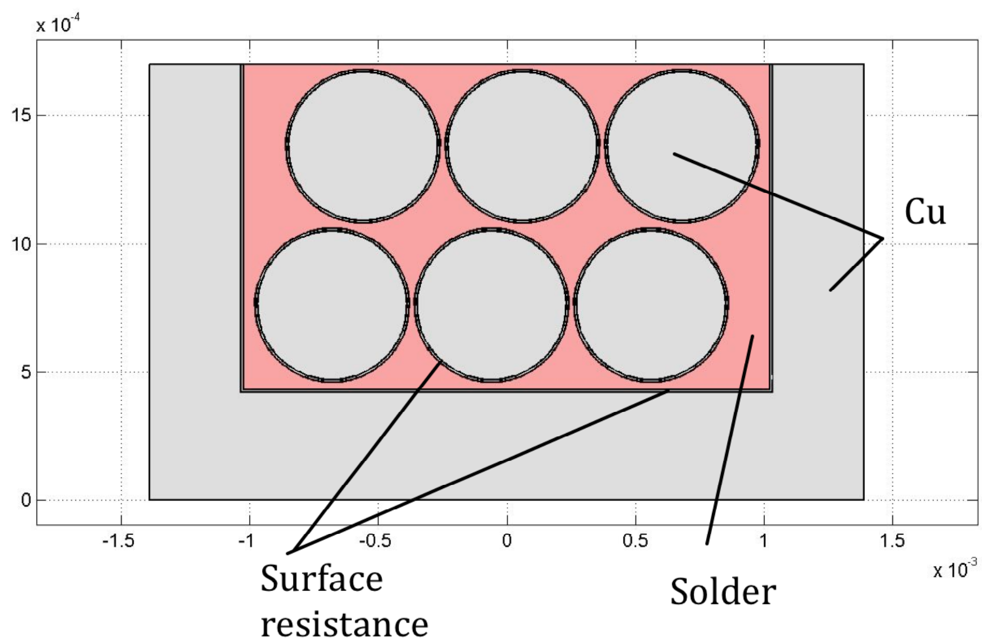

Fig. 5. Geometry of the conductor.

The magnetic field strength for different frequencies is shown in Fig. 6 and 7, for a peak external AC field of 0.013 T. Although the figures look similar, the minimum fields are very different, as shown in the color bar to the right of the pictures. At 200 Hz, the magnetic field permeates most of the conductor, while at 2 kHz, the field is shielded from the lower row of strands, but penetrates the upper row.

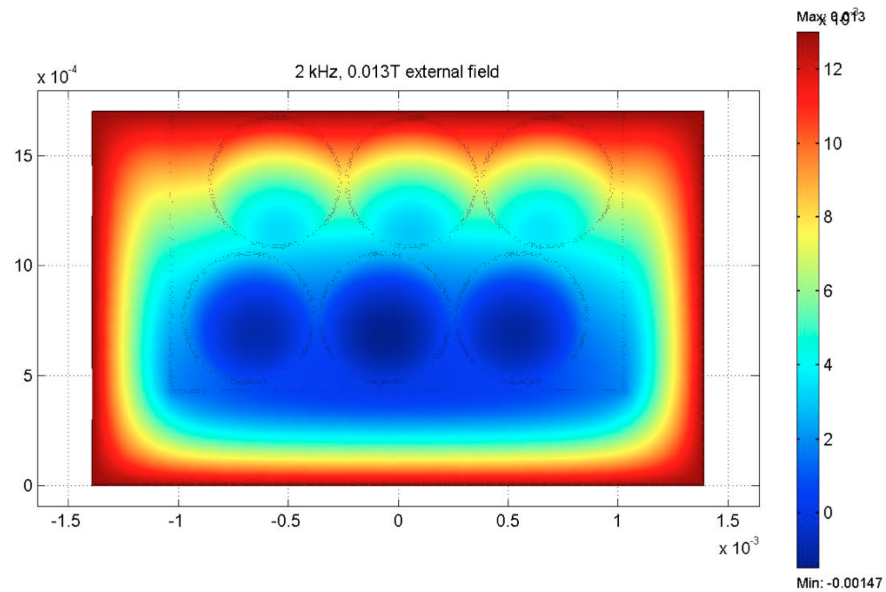

Fig. 6. AC magnetic field across the conductor, at 2 kHz. Magnetic field strength spread: Max: 0.013 T; Min: -000147 T

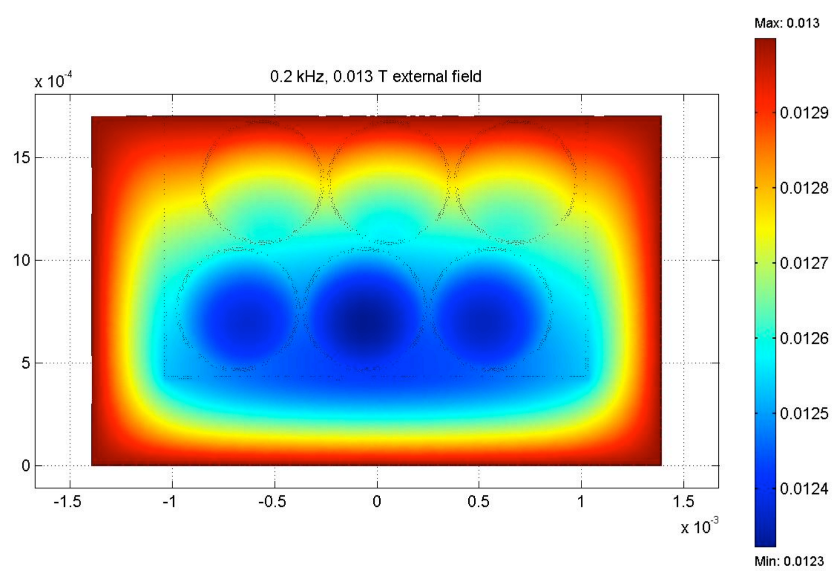

Fig. 7. Same as Figure 6, for 200 Hz; magnetic field strength spread: Min: 0.0123 T; Max: 0.013 T.

The model has been used to determine the eddy current heating for the case of 2 kHz. The dissipated power due to the AC fields has been calculated to be 0.25 W/cm^3, or about 2 times larger than assumed in Table 1.

The effect of increased resistivity of the solder and surface resistivity have been investigated. The resistivity of the solder and the surface resistivity have substantial implications for the field penetration (and thus the heating rate). It is possible to adjust these numbers to obtain additional flexibility in the design of the toroidal quenching system.

IV. Hysteresis losses.

The hysteresis losses, per half-cycle, are calculated using the bean model. There is no transport current in the poloidal direction. The applied field is parallel to the direction of the conductor.

The transport current is in the same direction as the AC field, while the induced currents are perpendicular to the axis of the conductor.

The losses, per cycle of the AC field, are about 27 J/m^3, or 27 μJ/cm^3. Assuming that the AC is at about 2 kHz, then the losses, in 100 ms, are 5 mJ/cm^3. This value in itself will not quench the superconductor, as the enthalpy change is on the order of 10 mJ/cm^3 at the highest fields, but it contributes significantly to the energy for quench.

If the effective SC diameter is 60 microns, the hysteresis losses are then 20 J/m^3, while if it is 70 microns the losses are 18 J/m^3. It is interesting to note that, opposite to the perpendicular hysteresis losses, for parallel hysteresis the losses decrease with increasing superconductor effective diameter. This effect can be understood noting that, for a constant amount of superconductor, subdividing the filaments results in increased superconductor surface per unit length that contributes to hysteresis dissipation, and thus in increased average power dissipation.

V. AC System implications.

Two models have been used to investigate the requirements and characteristics of the AC inductive quench system. The first one, described above, uses a computer code to model the current flow through the conductor and the heat generation, using the actual geometry of the conductor. The second one is simple, using analytical formulas for the skin depth and the power dissipation [8].

Two circuits have been analyzed. One with a large capacitor bank that has enough energy for fast quenching both split solenoids (in a few milliseconds), and the other one with a driven oscillator that quenches both spit coils in about 100 ms. The capacitance circuit has characteristic that couples the ringing frequency and the energy in the capacitor (eventually coupled to the heating in the iron yoke and in the toroidal and split solenoid coils).

The simple model [8] calculates the skin depth assuming 25 RRR copper (which includes magnetoresistivity). The effect of the solder and the solder resistance has not been included. In order to calculate the heating power, a simple formula is used that assumes that a fraction of the magnetic energy density in the conductor in the absence of the skin currents is dissipated in the conductor. It is determined, after a few hand calculations, that this fraction is about 0.15. The most difficult parameter to calculate, because of the multiple paths with different electrical conductivity, is the surface where the currents flow (the product of the length of the path of the skin current times the skin depth). The energy dissipated per cycle is then calculated, assuming an exponential shielding current distribution in the conductor (in those cases without full penetration). The magnetic energy in the superconductor in the absence of shielding currents is calculated, and then the ratio is determined. The assumption of 0.15 for this ratio is conservative.

TABLE I. Characteristics of Toroidal Field Quenching Magnet for Both Ringing Capacitor and Driven Systems.

		Capacitor	Driven
Frequency	Hz	200	2000
$B_{inductive}$	T	0.25	.013
Skin depth	m	$9.5\ 10^{-4}$	$3.02\ 10^{-4}$
Average heating power	W/cm^3	1.8	0.13
Time to 8 K	s	0.005	0.1
Heating energy to magnet	J/cm^3	0.01	0.01
Magnetic energy, iron self-shielded	J	405	3
Current in toroidal coil	A	1000	200
Turn density	turn/m	119	52
Conductor thickness	(m)	$9.5\ 10^{-5}$	$8.5\ 10^{-5}$
Reactive power, Iron self shield	W	$5.1\ 10^{5}$	$3.8\ 10^{4}$
Toroidal magnet inductance	H	$8.1\ 10^{-4}$	$1.5\ 10^{-4}$
Capacitance	F	$7.8\ 10^{-4}$	
Toroidal coil voltage	V	1020	380

The results from the calculations of the simple model are shown in TABLE I. Each circuit model has its own set of constrains, and neither has been optimized. Note that the ringing frequency of the capacitor is smaller than the one with the oscillator, in order to decrease the maximum voltage in the toroidal winding (but increasing the peak magnetic field, and the conductor current). However, because of the very short duration of the event, the current density in the toroidal winding can be made substantially higher (limited by heating in the toroidal coil). For the case of the capacitor-driven circuit, the losses are substantially higher, and a few periods are required before all the energy is absorbed in the coils.

There is little heating of the support ring (assumed to be steel), as the eddy currents flowing in this circuit shield the inside of the ring and the iron is saturated. This resistive power needs to be added to the in-phase power in the driven circuit, and to the capacitor bank in the case of the capacitor driven circuit.

VI. Conclusion

It is well known that AC fields can be used to generate quench. This paper describes a practical means of implementing the concept, using coils that require small reactive powers. Several implementations are described for solenoidal coils, with coils that have null mutual inductance to the solenoidal coil. The calculations illustrate the potential of inducting quench in a solenoidal magnet with a toroidal AC winding system for quench initiation. The results indicate that a simple toroidal winding, driven by either a capacitor or an oscillator at audible frequencies, can be used to quench the bulk of the winding pack in times of interest, on the basis of only eddy current losses. Hysteresis losses have also been calculated, and by themselves can provide about half of the energy required for quenching the superconductor in 100 ms.

We are in the process of calculating the effect effectiveness of this method for CICC [9]. Because the high resistivity of the sheath and the fact that, if magnetic, the sheath is saturated, the fields will penetrate the sheath for frequencies less than a few kHz.

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