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Abstract - Although most large superconducting magnets have been designed using the concept of cryostability, there is increased need for large magnets which operate at current densities above the cryostable limit (greater than 10^8 Am^{-2}). Large high current density superconducting magnets are chosen for the following reasons: reduced mass, reduced coil thickness or size, and reduced cost. The design of large high current density, adiabatically stable, superconducting magnets requires a very different set of design rules than either large cryostable superconducting magnets or small self-protected high current density magnets.

The problems associated with large high current density superconducting magnets fall into three categories; (a) quench protection, (b) stress and training, and (c) cryogenic design. The three categories must be considered simultaneously. The paper discusses quench protection and it implication for magnets of large stored energies (this includes strings of smaller magnets). Training and its relationship to quench protection and magnetic strain are discussed. Examples of magnets, built at the Lawrence Berkeley Laboratory and elsewhere using the design guidelines given in this report, are presented.

INTRODUCTION

Most of the work on large superconducting magnets has been based on the concept of cryostability. Virtually all superconducting magnets with stored energies above 3MJ use cryostabilized conductors. The concept of cryostability implies that there is sufficient helium in direct contact with the superconductor to insure good heat transfer in order to keep instabilities in the superconductor from driving the magnet normal [1].

Because large intrinsically stable superconducting magnets have been considered risky until recently, many magnet builders would not consider this approach when building large magnets. The use of high current density superconductors (current densities well above the cryostability limit of 10^8 Am^{-2}) offers a number of advantages in large superconducting magnets including: reduced magnet cold mass and size; increased access to the device requiring the magnetic field; more efficient helium cooling with enhanced cryogenic safety; and reduced construction cost.

The use of high current density conductors (with matrix current densities above 1.5×10^8 Am^{-2}) requires careful attention to problems in (a) quench protection, (b) magnetic strain and training, and (c) cooling system design. The design of a large adiabatically stable magnet is quite different from the design of either a large cryostable magnet or small high current density magnets. Quench protection becomes very important when one builds large high density superconducting magnets, one also must look at magnetic stress and strain. The problem of training is closely related to magnetic strain. Fortunately, the high current density superconducting magnet can use cryogenic systems which are easier to build and operate than most cryogenically stable magnet cryogenic systems.

This paper describes the implication of helium cooling on quench protection in large magnets. The role of magnet stored energy and conductor current density on quench protection and magnetic strain is also discussed. From an understanding of quench protection in high current density magnets, a rather radical magnet design concept emerges. The design rules given in this paper are controversial.. These rules however, are internally consistant and are the basis upon which a number of large high current density magnets have been built.

QUENCH PROTECTION

All large superconducting magnets require quench protection systems. A number of the remarks made in this section apply to large cryostable magnets as well as to large high current density magnets. There are important differences between quench protection of cryostable magnets and adiabatically stable magnets.

The design goal of cryostable magnets is to prevent quench when there is a heat-producing disturbance in the superconductor. Cryostability implies a negative normal zone propagation velocity. The design goal for adiabatically stable magnets, which operate at high current densities, is quite the opposite: the normal zone propagation velocity should be maximized in all directions.

For quench protection it is important to keep helium out of direct contact with the superconductor. Helium has a high specific heat. It will reduce the velocity of normal region propagation. Turn-to-turn propagation is affected more than quench propagation along the conductor. Helium in direct contact with the superconductor can contribute to voltage breakdown; helium within a coil does not contribute to the strength of the coil. The coil elastic modulus goes down. This appears to be highly controversial. Helium in direct contact with the superconductor is the very essence of the design of cryostable and near-cryostable magnets and is the favored method for preventing training in dipole and quadrupole magnets. The more the magnet stored energy and current density increase, the more important it becomes to remove helium from the windings.

The problem of quench protection falls into two categories: (a) hot-spot burnout occurs when the region of superconductor, which went normal early, goes to temperatures which can damage the coil and its insulation; and (b) high voltage breakdown and arcing will occur when one region of the coil is normal while the rest of the coil is superconducting (inadequate insulation is also implied). Hot-spot burnout and voltage breakdown often go hand-in-hand. It is sometimes difficult to determine which occurred first when one examines the carcass of a burned out superconducting coil.

In general, the higher the stored energy of the magnet, the lower the current density in the superconductor matrix. The superconductor matrix current

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density is directly related to the magnet stored energy because of conditions imposed on the system due to the quench protection system. Figure 1 is a plot showing the matrix current density J as a function of the magnet stored energy E in a number of superconducting magnets. Almost without exception, the points in Fig. 1 lie below and to the left of a line which is the product $EJ^2 = 10^{23}$ JA^2m^{-4} (mks units) [2]. Notable exceptions to the rule are the LBL thin solenoids.

The limit of $EJ^2 = 10^{23}$ JA^2m^{-4} is imposed by the burnout limits of the superconductor and the voltage and current limit which are set for various quench protection schemes [3].

$$EJ^2 = V_M I_0 \; F^*(T_M) \; \frac{r+1}{r} \tag{1}$$

where I_0 is the design current in the coil, V_M is the maximum allowable voltage in the coil during a quench, r is the normal metal to superconductor ratio in the matrix, and $F^*(T_M)$ is a function which relates the hot spot temperature T_M to other parameters. $F^*(T_M)$ is defined as follows:

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

where C(T) is the specific heat per unit volume as a function of temperature T; $\rho(T)$ is the electrical resistivity as a function of T; t is time; r and T_M have been previously defined. Using (2), hot-spot temperature can be related directly to the decay of the current in the normal region. Figure 2 shows the relationship of F*(T) and T for various resistance ratio grades of aluminum and copper. From Fig. 2, we can see that F*(T) for safe quenching is about 10^{17} A^2Am^{-4} S for copper based superconductors and $4 \times 10^{16} A^2Am^{-4}$ S for aluminum based superconductors. For typical cryostable magnets, the product of $V_M I_0$ is typically 10^6W.

The EJ^2 limit can be raised above $10^{23} JA^2m^{-4}$ in adiabatically stable coils. One method is to insulate the magnet so that the magnet voltages can be increased. Potting the coil in glass epoxy and increasing the coil current can increase the EJ^2 limit by a factor of three to five. Also important for quench protection is insulation of all circuits of the coil well.

Increasing coil insulation and current places a larger resistor across the magnet leads. Unfortunately, this does not improve the ability of the coil to protect itself without external quench protection.

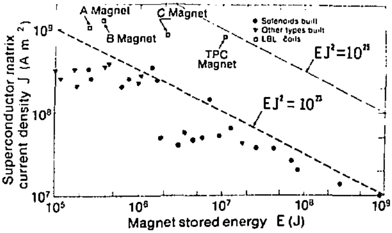


Fig. 1. Superconductor matrix current density versus magnet stored energy for a number of superconducting magnets. CBB 790-15604

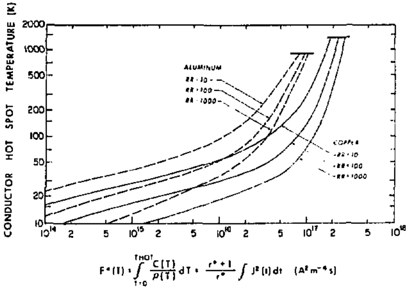


Fig. 2. Superconductor hot spot temperature versus F*(T) for copper and aluminum matrix superconductors. XBL 774-8481

Fail-safe quench protection requires maximum quench propagation rates within the magnet. In large coils, this becomes increasingly difficult. (i.e., long solenoids are difficult to self protect because the turn-to-turn quench velocity is much slower than normal region propagation velocity along the wire. One can increase the turn-to-turn quench velocity by proper selection of a superconductor but there appears to be a limit. The maximum turn-to-turn quench velocity is about 15 percent of the propagation velocity along the wire.)

A second method of quench protection, which is used in conjunction with improved insulation, is the use of a shorted secondary circuit closely coupled to the primary circuit (the superconducting coil) [4]. The L over R time constant of the secondary circuit should be longer than the L over R time constant of the superconducting coil when it is fully normal. The closer the coupling between the primary and secondary circuits, the better the secondary circuit performs.[4]

A well-coupled long time-constant secondary circuit will affect the quench process in the following ways:

a. During a quench, the current in the coil is shifted to the secondary circuits, reducing the integral of J^2 with time [5].

b. The secondary circuit will absorb a substantial part of the magnet stored energy. For example, if one coil in a series multicoil magnet system quenches, the secondaries in all of the coils will absorb the stored energy.

c. Transient voltages are reduced.

d. The shorted secondary causes the magnet to become normal faster than it would through normal zone propagation. This process is called "quench-back [6]." If one coil in a multicoil magnet system quenches, quench-back would cause the other coils to quench.

e. The use of shorted secondary circuits enhances the performance of some unconventional quench protection systems, such as the varistor resistor and the so-called current pulse discharge system [7].

Coils which use long time constant shorted secondary circuits will dump most of their energy into the secondary circuit when the magnet quenches. This energy ends up being removed by the helium refrigeration. A shorted secondary circuit is not an effective way to quench protect a cryogenically stable magnet [8]. The "quench back" phenomenon is a key element of the shorted secondary circuit when it is used in adiabatically stable magnets. Quench back permits one to protect large high current density magnets when EJ^2 is above 10^{24} JA^2m^{-4}.

Quench-back is caused by heating the superconductor until it turns normal. Two methods of quench back come into play depending on the rate of magnetic field change in the superconductor [6,9]:

a. Quench-back is caused by heating of the secondary circuit as current is shifted to it from the primary circuit. This method, called "thermal quench-back," is controlled in part by the thermal properties of the electrical insulation between the primary and the secondary circuits. Thermal quench-back dominates at low currents in a large magnet.

b. Quench back can also be caused by A.C. loss heating in the superconductor due to magnetic field changes in the superconductor. This method, called "magnetic quench-back," does <u>not</u> require good thermal contact between the primary and secondary circuits. The superconductor must be tailored to make magnetic quench back easier. This is done by lengthening the superconductor twist pitch so that coupled A.C. loss is increased [10]. (This is not appropriate if short charge times are required.) In general, magnetic quench-back occurs only at high currents in a large magnet.

Fast quench-back is essential for fail safe quench protection in large high current density magnets. When the current density of the primary coil superconductor (matrix plus superconductor current density) exceeds 5×10^8 Am^{-2}, a number of short-time constants come into play. The two dominant short-time constants are the short-time constant related to coupling between the primary and secondary circuits and the short-time constant related to the skin depth of the secondary circuit. For fast quench-back, it is desirable to have a thin, well-coupled secondary circuit or circuits which have very low resistivity.

The need for fast quench-back in large magnets has resulted in the evolution of the dual secondary circuit concept. The first secondary circuit is a heavy, relatively high resistivity circuit which becomes the depository for much of the magnets stored energy. The second circuit is a very low resistivity, thin, close coupled circuit which has the function of speeding up quench-back. Current is shifted to the low resistivity circuit (the thin circuit) first. Once the coil goes normal through quench back, the thin secondary circuit heats up until the current is shifted into the heavy higher resistivity circuit. The dual secondary concept was tested in the TPC magnet [11].

Using a well coupled secondary circuit or circuits, one can design magnets which operate at EJ^2 limit substantually above 5×10^{23} JA m^{-4}. As a general rule, for magnets with closely coupled secondary circuits,

$$\epsilon EJ^2 < 10^{23}\ JA^2m^{-4} \tag{3a}$$

where ϵ is one minus the coupling coefficient between the primary and secondary circuits. For a simple system with two coupled circuits,

$$\epsilon = \left[1 - \frac{M^2}{L_1L_2}\right] \tag{3b}$$

where L_1 is the inductance of the primary circuit, L_2 is the inductance of the secondary circuit, and M is the mutual inductance between the two circuits.

The shorted secondary circuit concept is not appropriate for large magnets which must be charged quickly. Charge time can be reduced by limiting the current flow in one or more of the secondary circuits during charging using a diode circuit across the secondary circuit which is wound in the form of an insulated circuit. The turns in the insulated secondary circuit must be insulated from one another, and there must be <u>good</u> ground plane insulation between the insulated secondary circuit and all other circuits, primary or secondary [12]. Experimental work at LBL suggests that the EJ^2 limit can be extended to 10^{25} JA^2m^{-4} with well coupled, shorted secondary circuits.

MAGNETIC STRAIN AND TRAINING

Magnetic strain and training go together. Recent studies of training in solenoids show that magnet training is strain dependent [13,14]. Stress and strain in large superconducting magnets are related directly to the current density in the conductor, average coil radius of curvature, and central magnetic induction. In large, high current density magnets, the magnetic forces must be carried by both the superconductor and support elements. The stress problem is often reduced to one of controlling the magnetic strain.

The superconducting coil structure should be designed considering strain <u>not</u> stress. The following rules are suggested for high current density coils:

a. The average strain should be less than 0.15 percent. If the average strain is kept below this value, training is usually minimized.

b. The coil and its support structure should have as high an elastic modulus as possible in all directions.

c. In solenoid-type coils, the superconductor itself should carry much of the magnetic force.

d. Stress and strain concentratins should be carefully monitored, and local strains should be kept below 0.25 to 0.3 percent.

By using the preceding design rules, one should be able to obtain the following conditions in high current density solenoids or toroids:

$$E_LJ^2 \quad 2 \times 10^{24}\ JA^2m^{-5} \tag{4a}$$

for continuous coils, and

$$E_LJ^2 \quad 10^{24}\ JA^2m^{-5} \tag{4b}$$

for luminous coils with enhanced field regions. E_L is defined as the stored energy per unit length along the coil axis and J is the superconductor matrix current density. The above values are rough. A detailed stress analysis is required, particularly in larger lumped coil systems.

Training is related to strain in coils. Historically, it has, been less of a problem in solenoidal coils than it has in dipole and quadrupoles. The methods for eliminating training are controversial. Training is believed to be caused by mechanical breakage within a coil which causes the superconductor to move in the magnetic field. The heat generated by this motion causes the coil to go normal.

Three general approaches have been tried to eliminate training (there are other approaches but their success has been limited to very small magnets). These approaches are:

a. Impregnate the winding with liquid helium that will absorb the energy created by conductor motion, thus preventing coil quench.

b. Cool the magnet to 1.8 or 2.0 K, and energize the magnet to the design current.

c. Stiffen the magnet coil to minimize average strain and local strains.

The impregnation of magnet winding with helium is the favored method for eliminating training in dipoles and quadrupoles [15] (Dipoles and quadrupoles built at CERN are notable exceptions [16]. Helium must be kept <u>out</u> of the windings to provide a viable quench protection of large high current density magnets. To obtain a stiff coil structure with minimum magnetic strain, the helium must be kept <u>out</u> of the coil structure. It must therefore be concluded that impregnation with helium in the winding is not a viable method of preventing training in large high current density coils.

Cooling the magnet coil to 1.8 or 2.0 K may or may not be a viable method of preventing or reducing coil training in magnets which do not have helium in direct contact with the superconductor. Recent studies in the USSR suggest that improved training performance in magnets cooled to 1.8 to 2.0 K is due primarily to reduced temperature [17]. Other researchers maintain that the improved heat transfer to a 1.8 K bath of superfluid helium is the dominant factor [18].

Once one accepts that a large high current density coil must be well insulated, an understanding of the basic cause of the training problem is needed. It is becoming increasingly apparent the training is related to strain. The author of this paper advocates epoxy impregnation to minimize sudden conductor motion. The author feels that the type of epoxy used to impregnate the coil is less important than the technique used to apply the epoxy [19]. However, there are other views on this matter [20,21].

After selecting epoxy impregnation, the modulus of the coil must be increased to reduce strain concentrations in the coil. Prestrain and restrain all or parts of the coil, and chose the magnet operating point to provide ample margin. The author recommends the following:

a. Remove helium from the coil.

b. Use a monolythic conductor with a high modulus in all directions. Cable and braid should be avoided because the coil modulus will be lower and strain concentrations will occur adjacent to the superconductor.

c. Densely pack the coil structure and impregnate with a hard epoxy.

d. Fill all voids in the coil with epoxy. Vacuum impregnation is the best method.

e. Fill unfilled epoxy regions with glass or dacron. This prevents cracks formation and arrests the development of cracks already formed [22].

f. Avoid sharp corners because there will be strain concentrations at such corners.

g. Avoid joints where the epoxy will be put in tension.

h. Prestrain the superconductor 0.2 to 0.3 percent before or during winding.

i. Prestrain the whole coil at room temperature if possible [13]. The prestrain must be in the same direction as magnetic strain (this may not be possible in some types of magnets).

j. Set the design current below 80 percent of critical current along the load line.

Some of the steps recommended in the previous paragraph are considered controversial. The LBL experimental solenoids use most of these steps. Training was observed in one of the solenoids when an epoxy joint failed [4] and the solenoid trained to critical current in five quenches. No training has been observed in thin solenoids since the first one was built, although it is possible that the LBL thin solenoids are not large enough to see the effects of training. The LBL solenoids operate close to the $E_L J^2$ limits set by (4), and they do operate at EJ^2 limits substantially above 10^{23} JA^2m^{-4}.

CROYGENIC SYSTEM DESIGN

The major problem shared by all large superconducting magnetics is the cryogenic system. The conventional method used to cool most large magnets is helium bath cooling. The larger the magnet system, the more cumbersome bath-cooling becomes. Many large systems have each coil in a separate cryostat. This takes space, and the problem of cryogenic distribution becomes apparent. For example, large systems use thousands of liters of liquid helium which must be stored. A long time is needed to cool down a large bath-cooled system. Because the heat of vaporization and density of helium is small, a large quantity of gas is formed when the liquid helium is boiled in a quench or some other accident results in large heat flow into the helium bath. Cryogenic safety and pressure relief systems become an important factor in the design of a bath-cooled device.

A forced cooling system will provide all the cooling that is needed because high current density coils do not require helium in the winding. The forced-cooled system avoids nearly all of the major problems encountered in a large bath-cooled system. The advantages of forced cooling are:

a. Cooldown is well controlled because the helium flows in a well defined path.

b. The mass of a forced-cooled system is less than a bath cryostat system.

c. Forced cooling can be carried in tubes which are part of the cast coil structure.

d. The amount of helium in direct contact with the magnet coil is minimized, quenches are well controlled, and cryogenic safety is enhanced.

Many of the tubular cooling systems which have built use supercritical helium with helium pressures above 2.25×10^5 Pa. Two-phase cooling offers three advantages over single-phase cooling:

a. Two-phase cooling implies boiling in the pipe. Lower operating temperatures occur in a two-phase system. The system exit temperature is lower than the entrance temperature.

b. The helium mass flow in the circuit for a given amount of refrigeration is lower for a two-phase system than for a single-phase system. The pressure drop is often lower.

c. Boiling two-phase helium can absorb large local heat fluxes without changing the temperature of the stream.

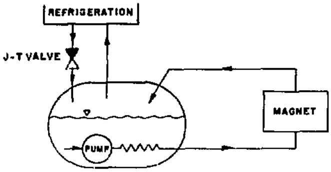
The major objection to two-phase cooling has been the problem of flow oscillations. The choice of mass flow per unit area, tube length, and flow circuit configuration can eliminate flow instabilities [22].

Both single-phase and two-phase forced cooling systems have been used to cool high current density, epoxy impregnated magnets for a number of years [23,24]. The results of our studies support the use of two-phase forced cooling. The key to two-phase flow is the elimination of parallel paths and minimization of circuit pressure drop by reducing the inlet quality to the flow circuit. Two kinds of systems can be used to circulate low quality helium (quality is defined in the same sense as it is for steam) through the magnetic cooling tube. They are: 1) a liquid pump used as a circulator, or (2) the refrigerator compressors used as a circulator. Both systems, which are shown in Fig. 3, use a heat exchanger in a helium bath to insure that the helium will enter the cooling system at or near the saturated liquid line. Because the pot of liquid can be used to control the cooling system, LBL calls this liquid dewar the "control dewar."

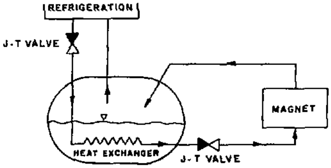
The use of a control dewar with its heat exchanger eliminates the need for large quantities of liquid helium at or near the magnet coils. LBL has demonstrated that gas-cooled electrical leads can be run directly off the forced flow circuit without detriment to either the refrigeration system or the leads themselves. LBL experients have been operated with the control dewar as far away as 20 m from the magnet itself. Refrigeration can be delivered at temperatures between 4.5 and 4.8 K (when the refrigeration pressure or suction pressure is above 1 atm and the control dewar temperature is about 4.4 K) provided the mass flow in the flow circuit is high enough (about 1 gs^{-1} for each 16 W required), and the heat exchanger in the control dewar is covered with liquid helium. The TPC magnet was successfully tested using either a helium pump or a refrigerator to deliver two phase helium to the magnet cooling circuits [24].

CONCLUDING COMMENTS

Large high current density magnets can be built using adiabatically stable superconductors. These magnets can operate well above the $EJ^2 \approx 10^{23}$ JA^2m^{-4} line provided care is taken in designing quench protection for the coils. Although the author does not advocate replacing large cryogenically stable coils with adiabatically stable coils, it is possible to build high current density magnets for use in a number of areas of scientific research.



a) LIQUID HELIUM CIRCULATION WITH PUMP



b) LIQUID HELIUM CIRCULATION WITH REFRIG. COMPRESSOR

Fig. 3. The two basic two-phase flow systems with the control dewar. XBL 773-7856A

The use of large, high current density magnets has been studied in a number of areas. At least one experiment using a large, high current density magnet has been proposed for the United States Space Shuttle program [25]. The use of large, high current density coils has been advocated for at least one area of fusion research [26].

The gains which have been made in the development of high current density coils make them worthy of consideration in a variety of applications. Increased accessability to the space within the coil, the reduction of magnet size and mass, and a potential reduction of cost of these devices will make high current density superconducting magnets attractive in the years to come.

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