Quench Protection for Superconducting Insertion Magnets

Michael A. Green
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

MAGreen@lbl.gov

Abstract. Quench protection for Nb-Ni insertion magnets (wigglers and undulators) has not been a problem. The reasons are; the quench is relatively easy to detect, the stored energy is low, the quench propagates rapidly, quench heaters work because the coil thermal diffusivity at 4.5 K is high, and quench protection resistors will work. Superconducting insertion magnets require very high current densities in the magnet coil in order to be competitive with permanent magnet insertion magnets. The need for high coil current densities makes superconductors like Nb$_3$Sn and ReBCO HTS tapes attractive. The higher temperature superconductors have much lower quench propagation velocities, and the high-current-density versions of these materials often have much less copper in them than Nb-Ti. Since the quench temperature for these superconductors is two to ten times higher than Nb-Ti, the coil thermal diffusivity is much lower. This paper presents a number of quench protection options for insertion magnets made from materials other than Nb-Ti.

1. Introduction

The discovery of superconductivity in 1911 was one of the great discoveries in physics [1]. However, the engineering reality of superconductivity didn’t match the hope of early researchers in the field. As a result, superconductors that could be used to produce magnetic inductions above 8 T until 1961 [2]. The second wave of enthusiasm for superconductivity began to dim in the mid 1960’s because the conductors of that period were unstable when wound into magnet that could be used for something in physics. The first breakthrough was cryogenic stability of superconductors in magnet in 1965 [3]. This led to the construction of large bubble chambers in the 1970’s [4]. What the physics community really wanted was superconducting magnets that operate at current densities that are two orders of magnitude higher than conventional magnets. By the early 1970’s the process of stabilizing high current density superconductors such as Nb-Ti and niobium tin and protecting those during a quench was understood [5], [6].

During the 1960s and 1970s, the theory of quench propagation along a conductor and the quench protection for low temperature superconducting magnets was developed. Both were discussed in a paper by Cherry and Gittleman in 1960 [7], which led to the adiabatic theory of quench protection. The first FORTRAN computer program used for quench protection was being used at Brookhaven National Laboratory, the Rutherford Appleton Laboratory and some other places since the early 1970s. Large cryogenically bubble chamber magnets didn’t quench, because the heat was carried to the helium bath. The program, which assumed no heat transfer out of the coil, was good enough to use for magnet design. If one had measured quench propagation velocities as a function of current density in the conductor J at various magnetic inductions B in the Nb-Ti wire at 4.5 K, one could create a model for the quench velocities along the wire and perpendicular to the direction of current flow [8].
The quest for thin detector magnets (from a radiation thickness standpoint [9]) led to the use of high current density coils with a shorted secondary. Maddock and James pointed out that it was desirable to put the stabilizer in the conductor rather than inductively couple the secondary to the coil primary [10]. If one wants the coil to have a low radiation thickness the secondary should be made with a material such as high RRR aluminum with the high current density copper matrix Nb-Ti coil being quenched through the process of quench-back [11] [12] from the secondary. This technique has been applied to detector magnets since the early 1980s [4].

The thin detector coil program led to a better understanding of quench back from a well coupled mandrel [13] and it led to the use of a varistor (a resistor with a constant resistance as a function current, like back-to-back diodes) that caused 97 percent of the current in a coil to be rapidly transferred to a closely coupled residual resistivity ratio (RRR) = 20 aluminum mandrel, which combined with quench back led to spectacular reductions of a quench hot-spot temperature in the high current density conductor [14]. Quench-back was a factor, but not the dominant factor. We also tested quenching a two-layer coil by putting a pulse of current into a center-tap between the two layers. This method led to faster quenching than by quench-back alone [14].

2. Superconducting Wiggler and Undulator Magnets

Most of the wiggler and undulator magnets used on light sources are made with room temperature alternating polarity blocks of strongly magnetized permanent magnet materials such as samarium-cobalt and neodymium-iron. With these magnets the field where the electron beam is located is adjusted by changing the magnet gap. Superconducting versions of these magnets have been built and tested for about twenty years. The potential advantage of using superconducting wiggler and undulators is increasing the magnitude to the peak undulator or wiggler field on the beam axis. The continued use of permanent magnet undulators suggests that the problems with superconducting undulators make them less attractive. LBL has worked on such magnets since at least 2001 [15]. The primary reason for doing this has been that the ALS beam energy is 1.9 GeV. The beam energy and bending magnetic inductions are major factors in determining the energy that one can get in the light beam produced.

For a simple uniform field bending magnet used as a light source, the critical photon energy $\epsilon$ given in keV at the peak beam flux is as follows;

$$\epsilon = 0.665 E^2 B,$$  \hspace{1cm} (1)

where $E$ is the electron beam energy given in GeV and $B$ is the bending magnet induction given in T. From (1) it is clear that one wants a high energy photon beam and one wants a high value of $B$. A higher $B$ can be produced by a superconducting magnet provided the coil current density is high.

The beam from a bending magnet is anything but coherent and the beam is not very bright. Hence insertion devices have alternating magnet field with a period of $\lambda$. A wiggler has a long period such that the angle that the beam is bent at a much greater than the scatter angle of the beam. The scatter angle is the rest mass of the electron divided by the beam energy. An insertion device is an undulator when the beam bend is the scattering angle or less. One uses a $K$ factor to determine whether the magnet behaves like a wiggler or bending magnet or if it behaves like an undulator, which produces a coherent light beam like a laser. The value of $K$ can be calculated using the following expression;

$$K = 93 A B_0 \lambda_o,$$  \hspace{1cm} (2)

where $B_0$ is the highest magnitude of the magnetic induction given in T and $\lambda_o$ is the period of the insertion magnet cell given in meters. When $K \gg 1$, the magnet is a wiggler which produces an incoherent beam because the beam comes from different parts of the electron trajectory through the magnet. For $K$ from $<1$ to 2, the light beam has coherence and it behaves like a laser, which is why undulators are so important in storage ring or a free electron laser (FEL) [16], [17].
The electron that is being bent by the insertion device is in a vacuum tube with a very high vacuum (about 1 nPa). This true for a permanent magnet insertion device or a superconducting insertion device. The electron beam in a storage ring or an FEL can have currents in the range of 100 mA to over 1 A. The beam flowing through the beam tube has discrete pulses that cause heating in the beam tube. The inner surface of the beam tube must be made from a low resistivity metal to minimize the beam heating. The beam tube for a permanent magnet insertion device is often air cooled and at worst it is water cooled. When the insertion device is superconducting, the beam heating must be taken up at some temperature that is close to 20 K. At 20 K a high RRR aluminum can have a very low resistivity and the bore tube can be designed to resist the vacuum forces when the cryostat vacuum is at 100 kPa or a little more [17].

A superconducting undulator is more complicated than a permanent magnet undulator because of the complexity of the cryogenic system needed to cool, the magnet, the beam tube, the shield and the leads that power the magnet system. With the right combination of neodymium and iron, there are permanent undulator magnets that have a 25 percent higher peak field on the beam line at 80 K than at room temperature [18]. Some would argue that this increase in the magnetic field on the beam axis may not be worth the problems caused by having a cryogenic system. A pure superconducting insertion magnet with return iron and without iron poles is illustrated in Figures 1 and 2. The peak induction point in either direction is between the plus and minus currents. The peak field points are in the middle of the space between the two coil packages. Most of the stored magnetic energy is in the gap between the two coil packages. In most cases the coils are wound in slots in the iron. In this case, the iron between the coils carries the flux to the peak field points along the magnet. The peak field in the coil is proportional to the coil current density regardless of the magnet gap except at the lowest currents [19]. The magnet gap affects the peak field on the beam axis. A small gap has a higher field.

Figure 1. A pure superconducting undulator with an iron return from one pole to the other.
Figure 2. Two pieces of iron with superconducting coils wound around them. Each coil structure is connected to the other using a non-magnetic stainless-steel frame. The iron is liquid helium cooled.

Figure 3. A Section of an LBL Nb₃Sn test coil for a small-gap FEL undulator.

Much of the first work on undulators used low copper (about 40 percent Cu) Nb-Ti with small enough filaments to avoid flux jumps. The Jc of a modern Nb-Ti is from 3000 to 3500 A per square mm at 5 T and 4.2 K. Modern niobium tin conductors can achieve a current density of 3000 A per square mm at 12 T and 4.2K. This means that niobium tin can reach current densities in the non-copper parts of the conductor of more than 6500 A per square mm at 5 T and 4.2 K. In undulator experiments in 2001, LBL didn’t reach anywhere near that level of current density [15]. It was
thought that the culprit was large filament sizes and flux jumps at low fields [20]. By 2017, LBL was producing niobium tin undulators that were better than Nb-Ti. See Figure 3 on the previous page.

There are forms of HTS conductors [21] that can be used for undulators. LBL and others have been looking at using second generation ReBCO tapes for undulators or FELs operating at 4.5 K [22], [23]. By 2016, it was clear that ReBCO tapes coils can operate at a current density that is potentially higher than niobium tin coils. ReBCO tapes can be wound without reaction after winding. Like niobium tin, these tapes are sensitive to strain, but in a magnet such as an undulator magnet one should be able to control the strain. At a temperature of 4.5 K, one should be able to achieve coil current densities in excess of 3000 A per square mm in an insulated magnet with a peak induction in the conductor at 5 T. the insulation on the conductor should be less than 10 microns thick and the Hastalloy layer should be reduced to 25 or 30 microns. This author believes that there should be at least 10 microns of copper in the conductor for stability.

As with other HTS conductors, the quench propagation velocities are low, especially in the parts of the coil that is away from the magnet gap. The local critical temperature $T_c$ and the engineering critical temperature $T_e$ can be quite high, almost an order of magnitude higher than Nb-Ti. In the regions of the coil away from the gap the quench propagation velocities will be quite low. I would expect these velocities to be similar to the measured quench propagation velocities measured at the University of Geneva [24] shown in Figure 4. Most of the ReBCO coil conductor will be in a low field region of the magnet. The critical current in the conductor is anisotropic. In the region of the magnet gap the magnetic field will be perpendicular to the coil. In other regions of the coil the perpendicular component of the field will be lower. In the regions of the coil away from the gap the energy needed to quench the conductor will be high. Because the thermal diffusivity of the coil is low at higher temperatures, the time constant to get the heat into the coil winding will be long. If the coil $T_c$ is 25 K, one has a time constant of 2 to 2.5 s to get the heat into the coil [25]. At 3000 A per square mm, one can’t expect to prevent the coil from burning up at the hot-spot by using a quench heater.

Figure 4. Quench propagation velocities for SuperPower tape that is 44 percent copper and silver as a function of the current density in the conductor. Most of the rest of the conductor is Hastalloy C-276.

3. Superconducting Wiggler and Undulator Magnet Quench 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 [8];

$$E_0 I_0^2 = \frac{r}{2} \int F^*(T_{HS}) V_0 I_0,$$  (3)
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 magnet current at the start of the quench $\Gamma$ 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;

$$F^*(T_{HS}) = \frac{1}{f}F(T_{HS}) = \frac{1}{f} \int_{0}^{T_{HS}} \left[ \frac{C(T)}{\rho(T)} \right]_{LRNM} dT = \frac{1}{f} \int_{0}^{\infty} J_0 J(t)^2 dt,$$

(3a)

where $C(T)$ is the low resistivity normal metal (LRNM) volume specific heat as a function of temperature $T$, $\rho(T)$ is the LRNM 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 $t = 0$ (quench start). In most cases, the LRNM is copper. The non-copper metals force the current into the LRNM increasing its $J$.

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 $J_0$ squared to the integral of $J$ squared $dt$ 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).

$$V_0 = \frac{I_0 L_1}{\Gamma F(T_{HS})} \frac{1}{f} \int_{0}^{\infty} J_0^2 dt.$$

(4)

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. (3) 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. Another thing that one can do is split the magnet $E$ into separate quench protection circuits. Reducing the current density in the conductor is not an option. A second reason for not adding a low-resistivity metal to an HTS conductor is the difficulty detecting the quench [26].

Figure 5 shows the value $F$ for $\text{RRR} = 100$ copper and Hastalloy and other high resistivity metals such as normal superconductors [26]. $F$ is found in equations (3), (3a) and (4). The $F$ of normal non-copper elements in most conductors are similar to Hastalloy, because $C$ and $\rho$ have similar values. The hot spot temperature of the conductor can be calculated by multiplying the copper $F$ by $1/f$ to get $F^*$ and using that value in Figure 5 to estimate the hot spot temperature $T_{HS}$ during the quench.

*Figure 5. Hotspot temperature for RRR=100 Cu and Hastalloy C-276 as function $F$.***
For a typical Nb-Ti short period undulator say $\lambda = 16$ mm, the value of overall coil current density $J_{\text{COIL}}$ would be from 1300 to 1700 A per square mm. To get the value of $J_0$ shown in equation (1), one should multiply $J_{\text{COIL}}$ by a factor of 1.15 to 1.25. The same multiplication factor can be used for niobium tin undulators. In this case $J_{\text{COIL}}$ is between 1600 and 2200 A per square mm. In the case of ReBCO coils one wants a value of $J_{\text{COIL}}$ to be between 2200 and 3000 A per square mm. For a ReBCO coil, one wants the multiplications factor to be as close to one as possible. The values given above are stretch, given what this author knows is available in ReBCO conductors today in 2019 with the field perpendicular to the conductor flat face [27].

For those who advocate a no-insulation approach to quench protection, the multiplication factor could be one. The non-insulation approach may prevent premature quenching, but once a coil does quench, the energy will, in this author’s opinion, end up in the region where the quench started (likely in the gap region where fields are the highest). This author could be wrong. He needs to be convinced that not having insulation in the coil is a viable way of quench protection for any ReBCO coil.

Table 1 compares the quench properties of a Nb-Ti undulator with $J_0 = 1800$ A per square mm, a niobium tin undulator with $J_0 = 2280$ A per square mm, and a ReBCO undulator with $J_0 = 3120$ A per square mm. The ReBCO case seems optimistic. The table shows the stored energy per meter scaled from the Nb-Ti case, which almost matches an undulator tested at SINAP in China in 2017 [28]. The quench voltage calculation is based on the conductor current density, which is a factor in determining the peak field in the conductor in the region of the gap between the two coils.

Table 1 The effect of coil current density, stored energy, and magnet current on the discharge voltage across the coil using an ordinary resistor to discharge the magnet during a quench.

| Parameter                        | Nb-Ti Coil | NbSn Coil | ReBCO Coil |
|----------------------------------|------------|-----------|------------|
| Coil Current Density (A mm^-2)    | 1500       | 1900      | 2600       |
| Conductor Current Density $J_0$ (A mm^-2) | 1800       | 2280      | 3120       |
| Stored Energy $E_0$ (kJ per m)    | ~50        | ~80       | ~150       |
| Low $\rho$ Normal Metal Fraction $f$ | 0.44       | 0.2       | 0.44       |
| Starting Current $I_0$ (A)       | 400        | 507       | 1200       |
| Self-inductance $L_1$ (H per m)  | 0.625      | 0.624     | 0.209      |
| Resistor Quench Voltage $V_0$ (kV per m) | 6.1        | 27.4      | 18.4       |

From Table 1 above, one can see that because of the high coil current densities the discharge voltages across a resistor are excessive (> 2 kV). This ignores the fact that the coils are wound on a soft iron core that is at the same temperature as the superconducting coil (~4.5 K). The electrical resistivity is in the range from 1 to 3 n$\Omega$ meters depending on iron purity and the degree of cold work in the iron [29]. Soft iron in a magnet has an RRR less than 100. The iron should be well coupled to the coil since the coil is wound around the iron. The iron close to the coils is well coupled, but the iron around the cooling holes is less well coupled to the coil.

A varistor in place of an ordinary resistor will cause the current in the coil to drop rapidly [13], [14], [30], [31]. The reduction of the conductor current density by a factor of ten will reduce the quench protection voltages shown in Table 1 to a number that is below 2 kV per meter for all of the cases. Since the mass of the iron (~76 kg) is much greater than the mass of coils, the final iron temperature will be between 45 and 65 K with most of the stored energy of the undulator ending up in the iron. The high current densities in the conductor means that quench detection must occur quickly.

4. Concluding Comments

In insertion magnets, the peak field in the coils is linear with coil current density. The peak field in the coil is almost independent of the magnet gap. When the gap is increased the peak field in the gap goes
down. One-meter long Nb-Ti undulators can be protected by a resistor that puts 2 kV across the coil when the coil current density is <1000 A per square mm. At this current density, a superconducting undulator is probably not competitive with a permanent magnet undulator.

Superconducting undulators have added complications. Refrigeration must be available at 4.5 K, ~20 K and ~50 K with the coils at the lowest temperature. Quench protection for magnets with high current density coils becomes more difficult. Ordinary resistors and heaters can’t be used for high current density HTS coils. A varistor with closely coupled secondary may be a viable alternative.

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