# Basics of Superconducting Magnets

The most basic of superconducting magnets is a simple solenoid in which a wire form of superconducting material is wound around a coil form. Various configurations of split pair and multi-axis designs are possible through the use of multiple solenoids in series or operated independently to affect the magnetic forces on a given sample region. Careful design is used to find a fine balance between wire composition, diameter and distribution along the axis of the coil form. As part of the design process many variables are considered both with respect to the general field profile but also the manner in which the magnet will be used. Proper design assures a robust winding while avoiding excessive cooling losses due to excessive charging current or inadequate homogeneity.

Superconducting magnets must operate below both the critical temperature and the critical field of the material from which they are constructed. Table 1 illustrates the critical temperatures and fields of the most common superconductive materials used to fabricate magnets. Figure 1 shows how the capabilities of NbTi vary as a function of both temperature and field. For a superconducting magnet manufactured using NbTi, operation in the superconducting state is only possible below the surface indicated in this 3-dimensional graph.

| Material | Tc (K) | Hc (kG) |
|---|---|---|
| NbTi | 9.8 | 120 @ 4.2 K |
| | | 148 @ 1.2 K |
| Nb3Sn | 18.05 | 221 @ 4.2 K |

**Table 1: Properties of Common Superconductors Used in Magnets**

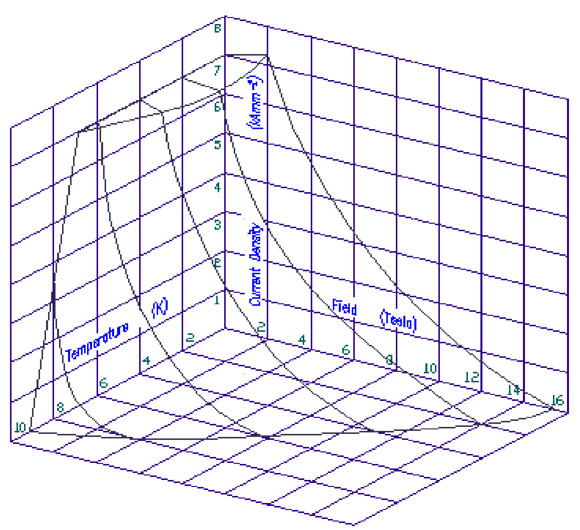


**Figure 1: NbTi Superconducting Properties**

As long as a superconducting magnet operates beneath the surface shown in Figure 1, the superconducting state is maintained and the magnet operates properly. If, however, one tries to operate the magnet above this surface, a "quench" will occur. For instance, if one is operating a magnet at the constant temperature of 4.2 Kelvin, the surface in Figure 1 reduces to a single 2-dimensional curve of current density vs. field. If one changes the "Current Density" scale to simply "Current" by considering a particular wire size and type, the curve in Figure 11 can be represented by something similar to that shown in Figure 2. A curve such as Figure 2 is frequently referred to as a "Short-Sample I-H Curve" since it represents the behavior of a short piece of a particular wire.

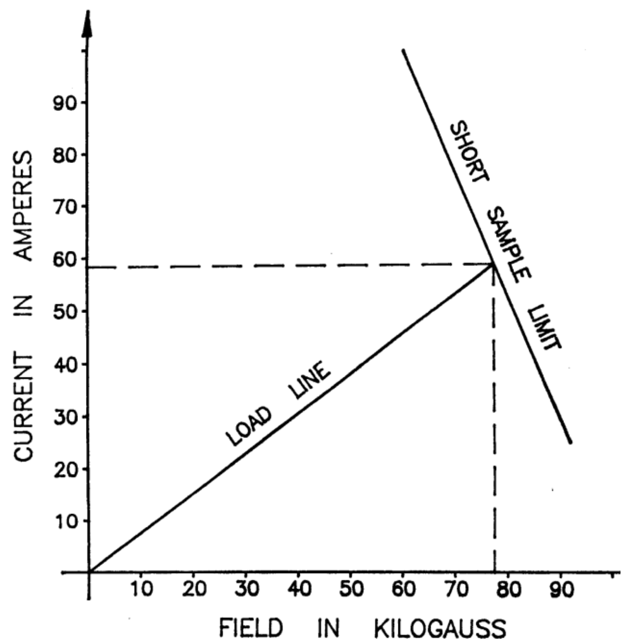


**Figure 2: Short Sample Characteristics**

If one has a superconducting magnet operating from a single power supply with all windings in series, then superposition implies that the operating point of the magnet can be represented by a "Load Line" showing the current in the magnet vs. the peak magnetic field on the windings. Such a load line is shown in Figure 2. One can see that as long as the magnet is operated below 58.5 amperes (which corresponds to a peak field of 7.61 tesla in the windings), superconductivity is maintained. If one attempts to drive the magnet past the short sample limit of the wire; however, the point where the peak field exists will undergo a transition back to the normal (resistive) state. This resistive region will quickly heat up due to the high current through it and the resistive region (called a "normal zone") will propagate until a) all of the energy stored in the magnet is dissipated or b) the entire magnet becomes resistive or c) sufficient cooling is provided to stop the propagation. Usually either (a) or (b) occurs resulting in a complete quench of the magnet.

## *Stored Energy and Quench Protection*

The amount of energy stored in a magnet is a direct function of its geometry and operating conditions. The amount of energy is

$$W = \left(\frac{1}{2}\right) L I^2$$

where $L$ is the magnet's inductance in henries, $I$ is the operating current in amperes and $W$ is the energy in joules. Most small laboratory magnets have maximum stored energies on the order of a few thousand to a few hundred thousand joules (kilojoules). Larger magnets frequently are capable of storing several million joules (mega-joules).

Superconducting magnets must always be designed with the amount of stored energy capability in mind. This is because when a quench occurs, this energy is converted to heat (usually in the windings) over a period of about a few seconds at most. This rapid conversion can induce not only high temperatures in the windings (especially at the point in the windings where the quench initiates), but also high voltages if they are not properly controlled. External devices are frequently used to help distribute the heat generated in a quench over the entire magnet windings. The epoxy with which the windings are impregnated also helps speed the normal zone's propagation. A rapid normal zone propagation is usually the key to distributing the heat generated from becoming localized and damaging the superconductor. Without these devices, voltages of several thousand volts and temperature rises at the point where the quench initiates of 500 Kelvin or more are easily possible. This can damage both the superconducting filaments and the wire's insulation material.

## *Forces With-in Magnets*

When a superconducting magnet is charged there are many forces which begin acting upon it - both internal and external. The basic physics formula

$$\vec{F} = \vec{I} \times \vec{B}$$

applies where $F$ = force, $I$ = current, and $B$ = field. This is the familiar "right hand rule" where $F$, $I$, and $B$ are all vector quantities. Since there is usually considerable current in a superconducting magnet's windings and it is generating high magnetic fields, it follows that the forces within the windings can become extreme.

The forces on and in an axisymetric magnet system can usually be broken down into axial and radial components. Axial components consist of forces between coil sections such as the attraction between two coils in a split-pair helm-holtz design, or the repulsion between two coils forming a magnetic field gradient. Even simple solenoids with only one coil have axial forces trying to compress the windings, so long coils must take this into account.

Radial forces, sometimes called "hoop forces", are those forces which are trying to make the magnet expand in diameter. In magnets with small inner and outer diameters, hoop forces are usually not difficult to restrain since the windings themselves are put in tension by these forces and can easily support the stresses. Magnets with large bores, however, can have problems with radial forces and sometimes need additional force restraints other than the windings themselves.

## *Training*

As mentioned in Section 1.0, the way to quench a superconducting magnet is to try to drive it beyond its capabilities. One way to do this is by forcing it to try to operate beyond its short sample limit of field and/or current. This is a materials limitation. Another way to quench it is by heating the superconductor above its critical temperature.

The forces described in Section 1.2 try to force the wires within a superconducting magnet to move. This movement MUST be completely restrained because even the smallest wire movement will generate heat due to friction and can quench the magnet. To restrain wire movements most superconducting magnets are potted using epoxy, ceramic, or some other material. These materials are usually very proprietary to magnet manufacturers since they are crucial to the magnet's performance. The materials have special characteristics in terms of their thermal and mechanical specifications.

"Training" is a phenomenon that occasionally occurs during the first time or two a magnet is charged. Training is a premature quench (i.e. a quench before the short sample limit of the magnet is reached in terms of field and current) due to wire movement. Training in a well designed and constructed solenoid is extremely rare; however, in multiple coil systems where there is a wider variety of forces acting in many different directions, training is not so surprising. Usually, once a magnet has been trained to the short sample limit of the wire, training will no longer occur.

## *Persistent Mode*

Superconducting magnets have one particularly nice capability over resistive magnets - once a current has been placed in them, virtually no power is needed to maintain that current. The windings are a perfect conductor of electricity; therefore, the magnet dissipates no energy due to resistive heating. If one takes a superconducting magnet at full current and places a piece of superconducting wire across its input power terminals, the current in the magnet windings will begin to flow through this short and the power supply can be shut off.

This type of superconducting short is called a Persistent Switch. This is usually made by installing a superconducting wire that is very resistive when warm across the terminals of the magnet. A small heater is placed in close proximity to the wire. When the magnet is being charged, the persistent switch heater is turned on so the short across the magnet terminals is driven above its critical temperature and effectively becomes a resistor across the magnet terminals. When the appropriate operating current in the magnet is reached, the heater is shut off and the persistent switch is allowed to cool until it becomes superconducting. At this point the power source to the magnet is no longer needed.

Persistent mode operation has many advantages; the two most important being:

1) Turning off the power supply can reduce the heat load on the cryostat. Some systems are built such that the power leads to the magnet can even be disconnected and removed to further reduce the heat load on the helium.

2) The stability of the magnetic field is extremely good in persistent mode assuming the magnet was made with truly zero resistance wire splices. Very sensitive experiments frequently require this stability.

Omission of persistent switch in Cryogen-FREE magnet systems:
As detailed above, persistent switches must be heated to allow for changes to be made to the operational

status of the magnet. Due to the limited thermal budget available in Cryogen-FREE magnet systems, introduction of this heat is undesirable. Designed specifically for the operation of superconducting magnets, the Cryomagnetics line of power supplies offer exceptional stability eliminating the need for switches in most cases. This allows for the use of lower capacity cryocoolers.