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CARE AND TRAINING OF SUPERCONDUCTING MAGNETS

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Training

Superconducting magnets are notorious for the wide gap between the performance that is predicted on paper and that which is achieved for produced magnets. In the early years before multifilament conductors became available, many of the difficulties were associated with flux instabilities. However, the availability of this type of conductor solved this problem, and yet W. P. Smith[1] at RHEL still reported training and degradation in magnets built with such superconductor.

Fig. 1 shows some examples of magnets that train. The term training refers to the increase of peak current observed in a magnet when it undergoes a series of tests where the current is ramped up until the magnet quenches. The curves shown in Fig. 1 are for a number of different situations. There is a training curve for a 1 ft. long, 3 in. bore magnet from the early FNAL test program. Also shown is a training curve for a 21 ft. long dipole suitable for the Energy Saver.

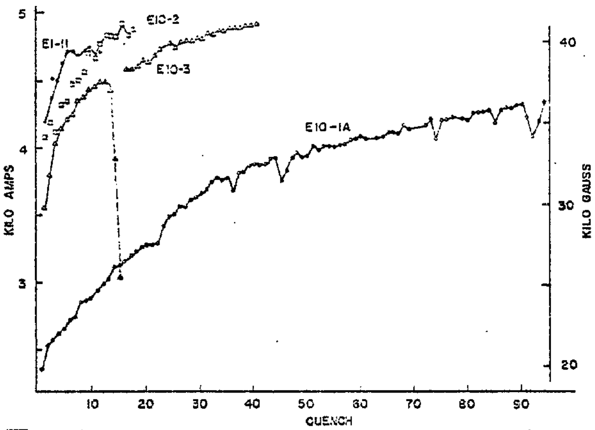


Fig. 1

Training occurs under widely different circumstances. Solenoids in general show a rather small amount of training, whereas, race-track type coils have given a great deal of difficulty in this respect. It should be noted that the training phenomena is most serious in magnet coils where a high current density must be achieved, such as coils for high energy particle accelerators or coils in rotating machinery. In these cases, the conductor cannot be cryogenically stabilized and if a portion of it goes normal, it necessitates shutting off the current through the conductor. While training can be tolerated in some cases as research type magnets, there are other cases where it is completely intolerable. Particle accelerators that are being constructed presently at Fermilab and Brookhaven require over 1,000 superconducting magnets, and each magnet may have of the order of 1 MJ stored in it. It is obviously impossible to construct a machine of magnets that take more than a few quenches to train; or just as importantly, from magnets that do not remember their training after they have been warmed to room temperature. One can easily think of other examples such as coils in rotating machinery or any coil where the energy stored is very large. It is interesting to note that it has been possible to construct field coils for a generator that do not exhibit training. It is also equally true that there are abundant examples where training problems have jeopardized the ultimate success of the program.

In order to proceed further, it is necessary to examine exactly how a superconducting magnet is designed. Fig. 2 shows in a simplified form the data

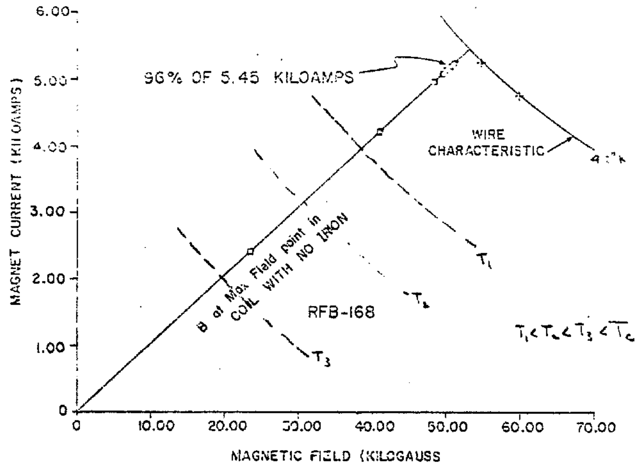


Fig. 2

necessary to predict the performance of a coil. The load line is the relationship between the highest field point in the magnet winding and the current through the winding, and can generally be satisfactorily calculated with programs on computers or measured by means of model tests. If the iron in the return yoke is not saturated, this line in general will be linear. The hyperbolic type curves shown are the characteristic curves of the superconductor. Any attempt to operate the conductor above the curve at a fixed temperature will result in the conductor going normal. Hence, Point A shown on the 4° K curve, which is the intersection of the superconductor characteristic and the magnet load line, represents what is called the short sample limit of the magnet. Notice that this prediction requires knowledge of three things:

1. The temperature,
2. The exact "high field point" load line,
3. And the characteristic of the superconductor at that point.

The first two variables can generally be satisfactorily obtained with fair accuracy. However, the characteristic of the superconductor at the high field point in general is not known but must be inferred from measurements done on samples of the conductor taken from the coil of cable from which the magnet is wound. The uniformity of the cable used in the Fermilab magnets is discussed in Ref. 2.

If a magnet trains asymptotically to a value that is less than the predicted short sample limit, it is referred to as degraded performance. Fig. 3 shows a histogram of the peak current reached in a series of magnets constructed at Fermilab in terms of the percent of the predicted short sample limit. It is clear that there is a tail on the low current side of the peak. This spread around the peak is consistent with the accuracy of the many measurements that are involved in obtaining the data for a histogram of this type. It is not known what causes the low current tail, but there are many sources that are possible to explain this effect. Ref. 3 addresses the question of the

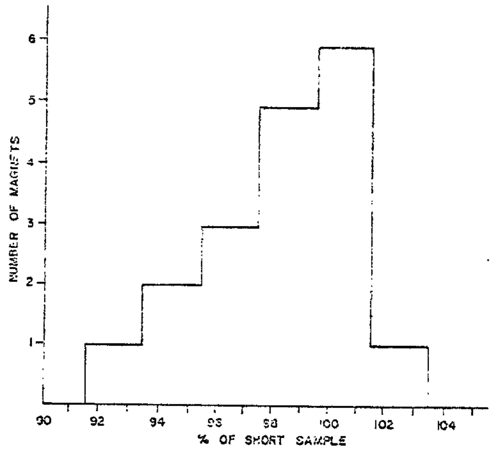


Fig. 3

performance in terms of the short sample properties in much more detail.

An interesting question to ask is the following: Did the magnet quench start at the predicted high field point? There has been experimental work both at Brookhaven and LBL that narrowed down the quench region to the nearest current block in a race-track winding. In one case at Fermilab, a 1 ft. model magnet was instrumented with enough voltage probes so that the quench wave could be observed as it propagated away from the high field point and by means of interpolation it was possible to ascertain the point that the quench stated to an accuracy of several millimeters. The majority of the quenches started at the predicted point. However, it was also observed that some of the quenches started elsewhere in the coil.

In the above discussion, we have tried to indicate that it is possible to construct a superconducting magnet coil whose performance is governed by the short sample limit. We now address the question of how many quenches does it take to "train a magnet." Solenoids in general show very little or no training. On the other hand, race-track type coils can exhibit a tremendous variability in this parameter. As mentioned above, it has been possible to fabricate field coils in a "race-track" configuration for a generator that shows no training. Some magnets that have been constructed at Fermilab have also exhibited essentially no training. Fig. 4 shows a histogram of the number

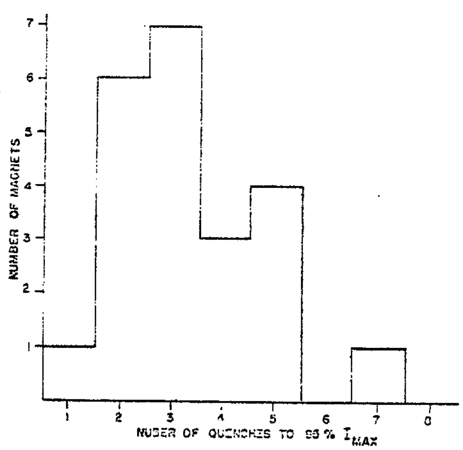


Fig. 4

of quenches necessary to train an Energy Doubler magnet to 95 percent of the short sample limit. It has not been possible to eliminate the training completely, but the number of cycles necessary are small enough so that it can be trained before it is placed in the machine, and indications are that the magnet remembers its training. The above discussion indicates the range of variability observed in the training of superconducting magnets. We now proceed to the theory of this process.

Theories of Training

In order to discuss the theory of training, it is necessary to address the questions, "what causes the conductor to become normal before it reaches the short sample limit, and why does the current increase with the quench number"? The theory proposes that the conductor is locally heated by bursts of energy released during excitation of the magnet. There are three sources for this energy. A first source is non-elastic deformation of the conductor material itself. We will come back to this question later. The second is the cracking or failure of the cable support matrix, and the third considers that small frictional motion of the wire due to Lorentz forces can supply the energy. The amount of energy necessary can be estimated as follows.

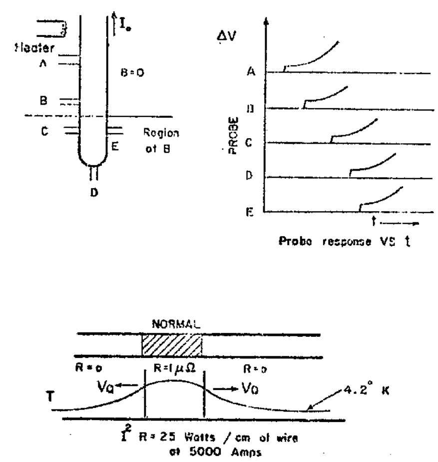


Fig. 5

Fig. 5 shows the situation in a piece of conductor when a short section of it has gone normal. In this section, the current is flowing in the copper matrix and generates heat which is removed by the liquid helium in contact with the cable. If the region that is normal is very short, the cooling can be sufficient to extract the heat produced by the I^2r losses, and the region will collapse and become superconducting again. The numbers shown on the figure are for the Fermilab cable with 5,000 amps through it. If the cable is normal at this current, 25 watts per centimeter of length are generated. This is almost 2 orders of magnitude greater than the ability of the helium to cool the cable. The study of these normal regions has been carried out in great detail. The most complete published work is that of S. L. Wipf at Los Alamos. The zone is governed by the heat equation. At any given current in the magnet, there is a critical length such that if the normal zone is longer than this length, the region will propagate along the cable, and if it is shorter than this length, the cable will recover to the superconducting state. This has been given the name by Wipf of Minimum Propagating Zone (MPZ). In order to obtain an estimate of the amount of energy necessary to start a quench, we calculate the amount of energy that instantaneously must be deposited in the cable in order to set up a region equal in length to the minimum propagating zone. Fig. 6 shows this energy in a typical conductor.

Suppose now that by some means, a delta function of energy in position and time is deposited in the conductor. The thermal relaxation times are exceedingly short, and if the energy is greater than the energy content of the minimum propagating zone, it will trigger a quench. If it is less than this value, the magnet will remain in its superconducting state.

Fig. 7 attempts to display the energy balance within a magnet structure. Again for purposes of illustration we have used a Fermilab Energy Saver type dipole. The horizontal scale represents temperature,

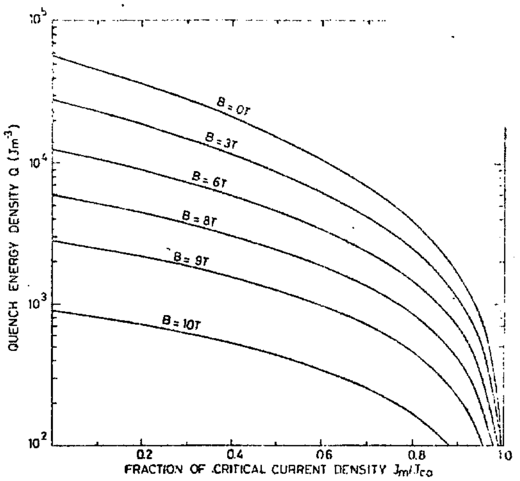


Fig. 6 (Ref. 5)

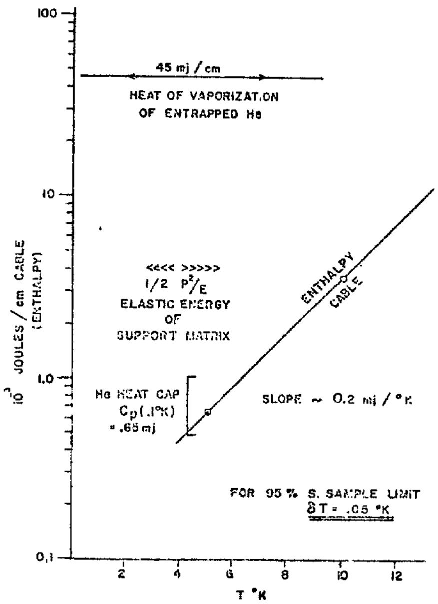


Fig. 7

and the vertical scale represents energy per unit length of the cable. The curve labeled cable enthalpy represents the total heat content of the 23 conductor cable as a function of temperature. It is seen at 5° K the energy content of the cable is less than a millijoule per centimeter of length. The slope of this curve at the operating temperature of 4.2° K is about .2 mJ per degree K. The critical temperature for NbTi is about 10° K. Hence, it would take about 10 mJ of energy per centimeter of cable in order to raise the temperature to the point where it would no longer be superconducting. However, when the cable is in a magnetic field and carrying a current, a much smaller change in temperature will drive the cable normal. For instance if the cable is at 90 percent of the short sample limit, a change 0.1° K will change the cable from superconducting to normal. In addition to the enthalpy of the cable, there are two other potential heat sinks available. The first is the specific heat of the matrix and any liquid helium contained around the wire. The Fermilab cable has a certain amount of open space available for helium which amounts to about 10 percent of the cross section of the wire. Hence, an arrow is indicated on the curve showing the heat capacity of the captured liquid helium for 0.1° K change in ambient temperature assuming no boiling. It is equal to .65 mJ per centimeter of length of wire. However, the ultimate heat capacity of this captured helium would be represented by the heat of vaporization, and that is shown by an arrow near the top of the graph, and it is 45 mJ per centimeter of length. It is thus clear that the helium represents a major heat sink within the structure of the wire.

To give some idea of the sources of energy available for initiating a quench, an arrow indicates the elastic stored in the matrix. This is calculated from $1/2\ p^2/E$, where p is the pressure within the matrix, and E is the Youngs modulus. For the Fermilab magnet, Youngs modulus is about 10^6, and p is several thousand pounds per inch. It is clear that the energy stored elastically is much larger than the energy needed to drive the wire normal when it is carrying a current close to the short sample limit. However, it is surprising to see that this energy is not enormously large compared to the energy required to initiate a quench, nor is it enormous compared to the heat sink available in the helium.

At this point, it should be evident that the situation is extremely complicated. There are two sources of energy available in the magnet to drive the wire normal. The first would involve yielding of the support matrix. The level of energy available for this is represented by $1/2\ p^2/E$. Only a small fraction of this energy would be available if the support yields. On the other hand, it is also possible that frictional forces due to the motion of the superconductor against the supporting structure could also generate heat and drive the conductor normal. A simple calculation would indicate that one of the conductors moving frictionally a distance less than .001 cm would generate enough energy to drive the cable normal. It is thus obvious that there are adequate sources of energy to cause a magnet to quench before the short sample limit. In fact it is utterly amazing that magnets are able to operate within 95 percent of the short sample limit.

The Experimental Survey: Confusion Reigns

It is now possible to understand why the experimental situation is so confused. There are a large number of variables available to the magnet builder. He can change the conductor, the support matrix, the shape, the cooling, and the clamping depending on the requirements for the magnet. It would be nice to be able to draw from the literature some general principles that would lead to successful magnet construction. However, this report is little changed from those that have been given over the previous five years. The main challenge of superconducting coil fabrication is to remove the "black magic" and find reproducible principles for coil fabrication. As experience is teaching us, there is still much work to be done. At present each large project invents its own techniques, but these are not readily transferable to other applications. The "freshman physics" is not yet well understood. This will be illustrated in some of the following examples.

Consider now the variables that can be found in various coils reported in the literature.

1. Cooling. The coolant may be subcooled liquid helium, He-II, or subcooled supercritical helium. The coolant can be in contact with the superconductor or isolated from it by the insulation.

2. The support structure. In order to keep the conductors from moving under the Lorentz forces, it is necessary that the mechanical clamping force be greater than the magnetic force when the magnet is cold. This latter condition causes real trouble because of differential shrinking with temperature of the different materials in the magnet.

   Three methods are being used at present to clamp the coil:

   A. The coil is assembled at room temperature under sufficiently high preload so that the mechanical forces remain greater than the magnetic forces even when the coil is cold. (For externally confined coils, the coil tends to shrink away from the support.) The greater the differential shrinking between the components, the greater the preload necessary at room temperature. In order for this approach to be successful, the magnet constructor must control the elastic properties of the insulation support matrix very carefully. In any given case, a solution does not have to exist. The forces may be so large that they crush the support matrix at room temperature.

   B. One can make use of the differential shrinkage in order to clamp the coil. Aluminum in general shrinks more than the coil composite, so if the coil is externally supported and clamped at room temperature, the forces will increase as it is cooled.

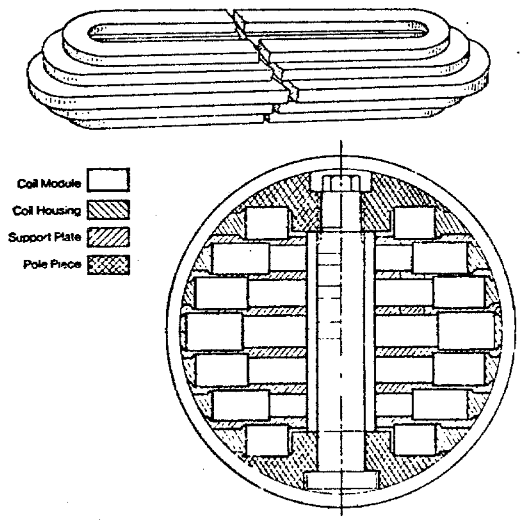
   C. The last method of clamping the coil involves impregnating it thoroughly with glass-filled epoxy. For this method to be successful, the coil must be vacuum impregnated, and all of the voids must be carefully removed. The glass filling considerably strengthens the epoxy and prevents cracking when thermal and magnetic stresses are applied. A careful stress analysis of the coil must be carried out to ensure that the stress levels do not exceed the strength of the epoxy.

3. Insulation. A number of types of insulation are being used at present. One involves using an open-weave epoxy filled glass tape wrapped around the conductor (BNL). In another (FNAL) case, the conductor is insulated first by wrapping a mylar film around it and then spiral wrapping the composite with the epoxy filled tape. In still other cases the formvar or some other plastic film type insulation may be applied directly to the superconducting composite. For epoxy impregnated coils, epoxy may also serve the insulation purpose. Insulation has two important effects. First, it can thermally isolate the superconductor from the coolant, but it also is the nearest source of strain energy that the superconducting wire sees, and thus its effect can be very complex.

4. Conductor. The conductor used can be either a simple multifilament single strand composite, or it can have the much more complicated structure of a woven braid or a multistrand cable. In the latter two cases, the strands of the braid of the cable may be additionally fixed with solder filling or left free to move. For braid or cable, one may have an additional source of heat available at a very vulnerable point in the system due to frictional motion of the adjacent strands over each other.

It is now appropriate to examine a number of different experimental programs and see if the results can be understood on the basis of the preceeding considerations.

Example 1. Generator Field Coil, Ref. 6. General Electric has an active program to study superconducting field windings for a generator. During the course of this program, perhaps 10 race-track type windings have been built. These coils are approximately 1-1/2 m long by 1/4 m wide and have a cross section that is of the order of 3 cm by 6 cm. The conductor is approximately .05 in. x .1 in. monolith, with formvar insulation and a ratio of 1.6 to 1 for copper to NbTi. See Fig. 8. These coils store an energy of the order 1/2 MJ and have a short sample limit of about 7 Tesla. Not only are the anticipated forces large, but there is also the



Field Winding Support Structure

Fig. 8, Ref. 6

possibility of mechanical shock and vibration. Thus, this application represents a real challenge to the support sturcture. It must absolutely restrain all motion of the conductor. Hence, if one can successfully build this type of winding, one would expect a minimum of training. The results from this program show a series of coils that reach the short sample limit on the first quench. In order to achieve this behavior, the following construction techniques are used:

1. The coils are wound with a great deal of care. The epoxy bonds to the formvar and when the impregnation is done, all voids are carefully filled.

2. Surfaces within the structure that must move tangential to each other are supported by a material with a low shear modulus and a high compressive modulus, thus avoiding any type of stick slip motion.

3. The whole coil assembly has a tapered interface with respect to the torque tube which is shrunk on at room temperature.

4. The moduli of thermal expansion are such that the coil is still preloaded when it is cold. It is interesting to note that only the outer conductors of the winding blocks are in contact with liquid helium. This coil represents an encouraging sign that if one pays enough attention to the support of the individual conductors, the training indeed can be eliminated.

Example 2. Accelerator Type Magnets. BNL, FNAL, and LBL all have active programs to study saddle type coils for accelerator applications. These coils are several meters long, and 7-1/2 cm to 12 cm i.d. They typically store of the order of 1 MJ and operate at fields of the order of 4 Tesla. This type of magnet must be ramped. The Tevatron goes 4 Tesla in 20 seconds; Isabelle 5 Tesla in a few minutes. In order to control eddy current losses, it is necessary to use either a Rutherford type cable (Tevatron) or a braid (Isabelle). The cable has poor structural stability and hence must be embedded in a support matrix. In the past this has been formed by a spiral wrap of B stage glass tape around the conductor. This leaves a porous structure in which helium can circulate and remove the heat generated by ramping. Other solutions to supporting the conductor are being investigated at LBL and Saclay which involve leaving out the B stage glass tape and using plastic film.

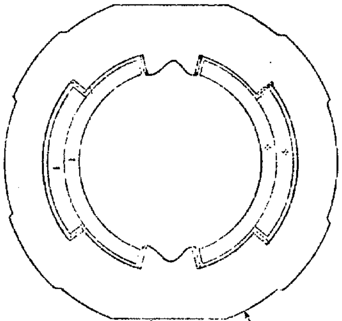
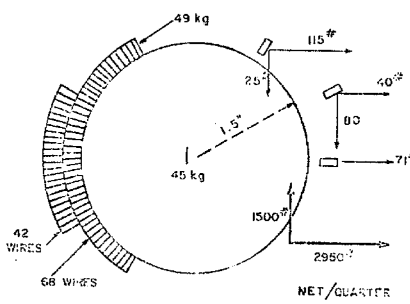


Fig. 9



FORCES AND FIELDS IN A SERIES E MAGNET

Axial Force = $\frac{\partial}{\partial z}\left(\frac{1}{2} L I^2\right)$

= 16000 #

Fig. 10

Fig. 9 shows a cross section of the FNAL magnet, and Fig. 10 shows the forces on the conductors that must be supported. This particular coil is forced under high pressure into a stainless collar at room temperature. The coefficients of thermal contraction are such that the mechanical forces are greater than the magnetic forces when it is cold. Fig. 4 shows a histogram of the number of quenches to short sample limit for these magnets, and Fig. 3 shows the percentage of short sample current achieved. In this magnet, there is no question that the conductors move. The radius changes about 2-1/2 mils during excitation, and there is azimuthal compression of the winding. In fact if the mechanical forces of compression are not greater than the magnetic forces, the last turn next to the key can actually move away from the key during excitation. The change in radius is proportional to I^2 and hence elastic. It shows very little hysteresis. However, the azimuthal motion has given more trouble. Early in the program, magnets were built such that the elastic forces when cold were less than the magnetic forces, and the conductor at the key moved. Fig. 11 shows data from 81 magnets whose training took from one quench to over 25. Some magnets in this series had preload small enough so that there was motion of the wire at the collar. Two or three mils of azimuthal motion can be expected on the basis of the elastic properties of the insulation alone. The vertical axis shows the average motion of the cable exhibited by all of those magnets that took a given number of quenches to train. The error bars are just a square root of the number of magnets at each point. It is seen that this motion does not couple into the training until it is large enough so that the conductor is completely unclamped. Why it takes some magnets one quench and others 10 quenches to train when the conductor remains clamped is a mystery.

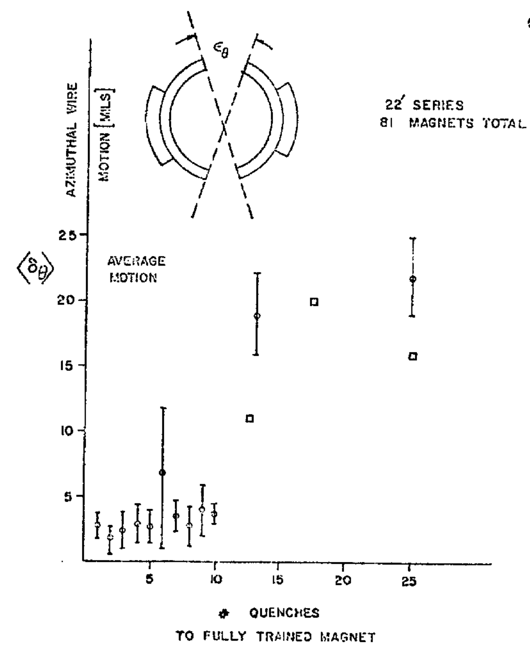


Fig. 11

There is another puzzle associated with these magnets. Fig. 1 shows the training curve of a 1 ft. long model as well as one for a 10 ft. long magnet. Both were tested in the vertical dewar and both magnets have the same cross section and were built with substantially the same wire. In this case the high field point is located at the place where the turn next to the key reverses its direction at the end of the coil. The field at this point is about 20 percent higher than it is on the axis of the magnet. This is true for both the 1 ft. magnet and the 10 ft. magnet, so if this is the only region of the magnet that needs training, it may not be surprising that the training curves look similar. However, the training curve for a 21 ft. magnet in its completed cryostat and yoke looks the same.

In this case, the high field point moves away from the very end and is located at any place along the wire next to the key. The field is about 10 percent higher than it is on the axis. (The length of the iron yoke was carefully adjusted to make this true.) There is now 21 ft. of active length of the magnet that can get involved in the training. Early in the development of these magnets, there was a concern that the number of quenches to train a magnet of this type might be proportional to its length. That is clearly not true. A quench apparently relieves strain along the whole length of the magnet.

There is another curiosity in the FNAL experimental series. Early in the program a great deal of trouble was caused by turn-to-turn shorts. The B stage glass tape could easily be shorted through by a small chip. In an attempt to solve this, several 1 ft. model magnets were constructed from cable that had been coated with several mils of epoxy paint. This was over-wrapped with B stage glass tape in the normal manner. Fig. 12 shows the training curve of El-3. Others in this series displayed similar curves, and these were perhaps the worst magnets ever made at FNAL. This lead to an early conclusion that due to the thermal stresses that can set up, epoxy was bad if it was in intimate contact with the wire. Consequently, a second solution was adopted which consisted of over-wrapping the Rutherford type cable with 1 mil mylar tape. The B stage glass tape is now wrapped on top of this. Thus, there is no epoxy in contact with the conductor, and there is excellent turn-to-turn insulation. The mylar tape is still porous enough so that helium can enter into the spaces around the strands. The heat transport through the overall system is clearly decreased. However, it should be noted that there is perhaps another effect that the mylar wrapping can exert; namely, it insulates the strands themselves from heat generated by friction in the coil structure, and hence it may actually have a beneficial effect upon the training properties of the coil.

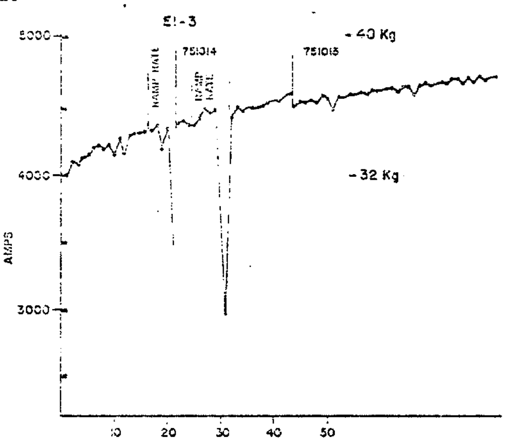


Fig. 12

If a magnet trains badly, it is difficult to isolate and diagnose the cause. At Fermilab, we have used two methods to detect motion of the cable. One is by coupling directly to the winding via a rotary transformer. This method is sensitive to less than 1 mil of motion in the windings but must be corrected for any elastic deformation under the Lorentz forces. We have also verified the conductor motion by observing the behavior of the low order multipole coefficients. In the Fermilab magnets, the key angles effect particularly the quadrupole, sextupole, octapole and decapole moments. It is possible to deduce the motion of the conductors given the variation with current of these lower four moments.

BNL has used a different scheme.[7] Since the critical current is a nearly linear function of temperature, they have plotted the quench current versus temperature for one of their magnets. The quench point is a linear function of temperature until the forces on a current block becomes big enough so that the Lorentz forces exceed the preload. At this point, the quench current does not increase as the temperature is reduced. Frictional motion of the winding is thus indicated. Other techniques involve the use of voltage taps across the coil to find out which parts are going normal and sensitive thermometers embedded in the coil to find out where the quench is starting.

Example 3. Solenoids. Traditionally the easiest coils to build have been solenoids. Symmetry handles the forces well, and many such coils have been built that exhibit little or no training. However, as one goes to higher fields, the forces can become strong enough to cause the layers in the winding to delaminate with which then results in training. Ref. 6 from the GE field coil program has some examples of solenoids that were built which did not train. A second sample is provided by a solenoid built at the National Magnet Laboratory at MIT, Ref. 8. The structure of this coil has received a comprehensive analysis, both statically and dynamically, and many measurements have been made on the completed coil. Fig. 13b shows a typical cross section of the winding; the individual conductors have been modeled as shown in Fig. 13a. The model makes an attempt to include the superconductor, the copper, the formvar insulation, and the epoxy filling. This magnet

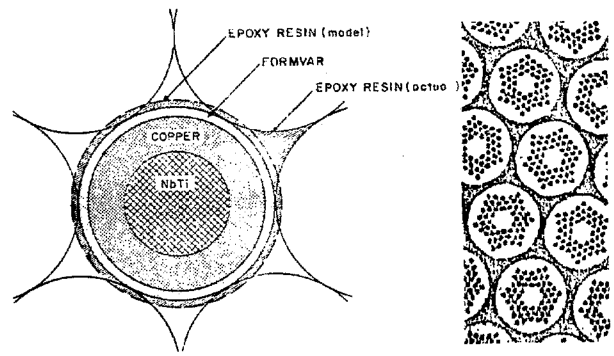


Fig. 13a Fig. 13b

trained in about five quenches. During training, the coil was well instrumented with strain gauges, and those measurements have confirmed the predictions of the stress analysis. The authors interpret this as strong evidence that the observed training was associated with stress induced cracking before the coil became separated from the coil form. This separation was predicted for the calculations. After it was complete, the coil reached its short sample limit of 95 amps.

In the foregoing an attempt has been made to indicate that superconducting magnets have been built that do not train or at least show a minimum amount of training. It is now useful to look at a series of experiments that were designed to explore why training takes place. These experiments are aimed at understanding the role that the matrix or the conductor may play.

Experiments Related to Training

A series of experiments at NBS, Ref. 9 is concentrating on effects due to the role that the support matrix. If cracking of the matrix is responsible for releasing heat, then it should be possible by applying mechanical strain to a coil to cause it to quench at a point below its short sample limit. Fig. 14 shows the experimental setup used to apply such a mechanical strain to a small coil that is 18 cm in i.d. Different techniques were used for fabricating these composite rings. The split conical washers can apply a tensile force to the sample which is embedded in an external magnetic field. By controlling the external field and the current through the sample, the fraction of the short sample current carried by the coil can be controlled. Force is applied to the coil until it quenches and the strain at the quench point measured. Fig. 14 shows the apparatus used for these experiments. It is seen that a phenomena very much like training is exhibited each time the strain that the

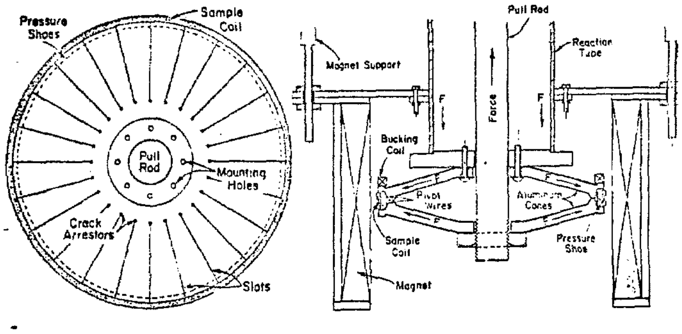


Fig. 14

coil is able to sustain is larger. Furthermore, as the current carried approaches the critical current, this strain necessary to quench becomes less. Fig. 15 shows some of the information that has already been obtained. Two coils, one with the fiberglass and one without fiberglass to strengthen the epoxy are compared. It is found that the coil with fiberglass is much more resistant to quenching than the one without. A second phenomena similar to real magnets is also observed. If the coil is first strained up to a certain level and then the strain reduced, the first quench is observed to take place at a strain greater than was first applied.

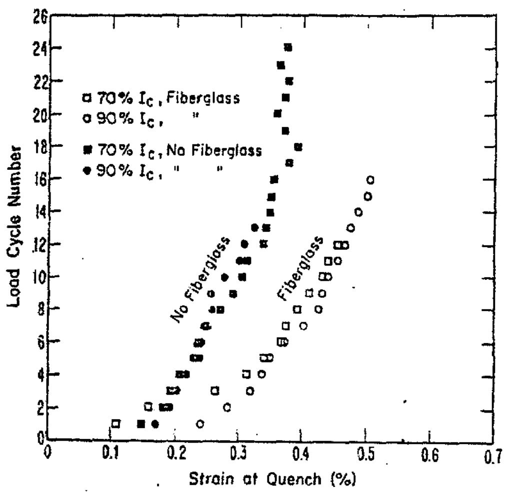
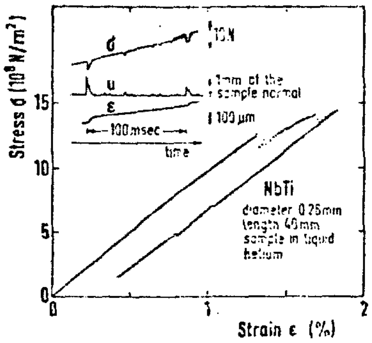


Fig. 15

There are two remarks to be made on this experiment. One is that the applied forces are different than in a real coil. In this case, the forces are being applied to the matrix, and the matrix is pushing on the wire. A real solenoid has the situation just reversed. A second very important point is that the strains being explored are in the range of a 0.1% to 1% or more. In the previous magnets discussed, the strain is much lower than this. For instance, the axial strain on the FNAL magnets is less than .03%. The NMR magnet studied at the National Magnet Lab has a strain of the order of a few tenths of a percent, and

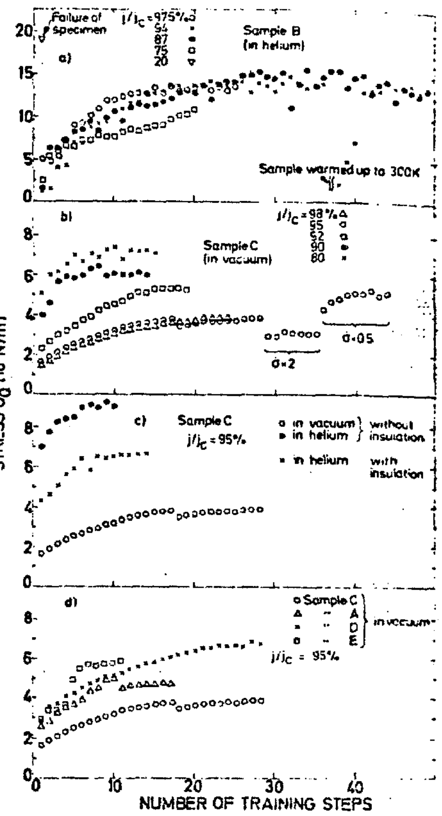


Serrated stress-strain curve of an NbTi wire. The stress rate is 1.5×10^3 N/m^2 sec. In the region where serrations occur, the time from point to point is 1 msec. The inset shows stress, strain, and voltage drop on the specimen in the serrated region. The voltage is converted into the length of the specimen becoming normal.

Fig. 16, Ref. 10

the generator field coil windings have a strain of the order of 0.1%. Thus, actual magnets are operated at strains much below the area that is being explored here. However, it may also be true that there are places in real magnets where the strain is concentrated and hence is much larger than the average values.

A major study by Pasztor and Schmidt, Ref. 10 has indicated that the conductor itself may yield inelastically and that this effect may play some role in the training of magnets. Fig. 16 from that paper shows the serrated yielding of a NbTi sample. The theory is that as the sample yields, it heats which softens it



Short-sample training without external field. (a) Bare single-core conductor in liquid helium. (b) Composite conductor placed in vacuum. (c) Influence of cooling conditions on the training of a composite conductor; wire placed in vacuum and in liquid helium with and without lacquer insulation, respectively. (d) Comparison of different composite conductors (see Table I). Sample E was loaded with 5.5×10^3 N/m^2 without a transport current after the fourth training step. The stress rate is 7.4×10^3 N/m^2 sec in (a) and 3×10^3 N/m^2 sec in (b)–(d).

Fig. 17, Ref. 10

and lets it expand locally until it work-hardens. Simple calculations show that the local ΔT could be as high as 60° K due to the very low heat capacity of the material.

In their experiment, the conductor was studied under externally applied stress and, as in the preceeding experiment, the wire was immersed in an externally applied field, and the current through it could be varied. Thus, the fraction j/j_c could be varied at will. The sample of wire could also be studied either in vacuum or immersed in liquid helium. Fig. 17 shows the results of a number of experiments done during this study. Sample A was a single core conductor .4 mm in diameter with a copper to superconducting ratio of 1.3 to 1. Sample B had the copper jacket etched off and hence was a NbTi conductor whose radius was .26 mm. Sample C was a multifilament conductor .4 mm in diameter with 60 filaments. The copper to superconducting ratio was 1.4 to 1. In the figure, the stress is shown on the vertical axis and as in the case of the previous experiment, we see a phenomena displayed that is very reminiscent of training a magnet. The peak strains here would correspond to almost a percent. Example C in this figure shows the important role that cooling can play. The top curve was a conductor cooled by liquid helium, and the bottom curve is for the same conductor in vacuum.

The stress strain curve of a sample of conductor was measured, and this curve showed hysteresis. The area contained inside of the loop is a measure of the amount of energy available for directly heating the conductor. Measurement of the actual heating from the inelastic behavior of the wire was made. We cannot go into all of the details of this paper here, but this study does show that applying stress to a conductor can cause it to quench and also training is observed, i.e. greater stress can be applied in subsequent cycles.

The work above stimulated investigation of whether or not winding a coil with prestressed wire would decrease the winding. Ref. 11 refers to these experiments. We show here only the result of one such experiment, that of Schmidt and Turck. Fig. 18 gives the results of the training of a square shaped solenoid wound with either prestressed or non-prestressed wire. The top two curves refer to an epoxy impregnated magnet, and the lower curve refers to a magnet wound without epoxy. The prestraining resulted in a permanent strain of about 1/4 of a percent. It is seen that prestraining the wire reduced the training observed in the coil. The wire used in this particular case had a copper to superconductor ratio of 1.9 to 1 and 450 filaments of superconductor. There is not universal agreement that prestraining the wire results in fewer quenches to train. See Ref. 11.

Ref. 12 refers to some papers presented at this conference that relate directly to either the source of the energy for causing a quench or the energy required to initiate the quench.

A number of experiments have observed acoustic emission taking place during the training of a magnet. In addition, the previous paper by Pasztor and Schmidt monitored the acoustic emission from the serrated yielding of a single conductor. Fig. 19 shows the noise events observed during training of a 1 ft. magnet at Fermilab.

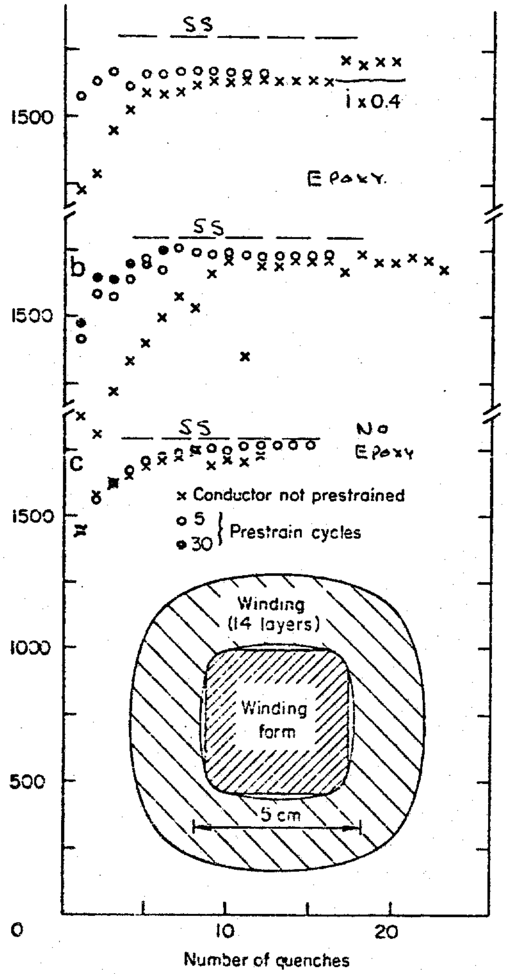


Fig. 18

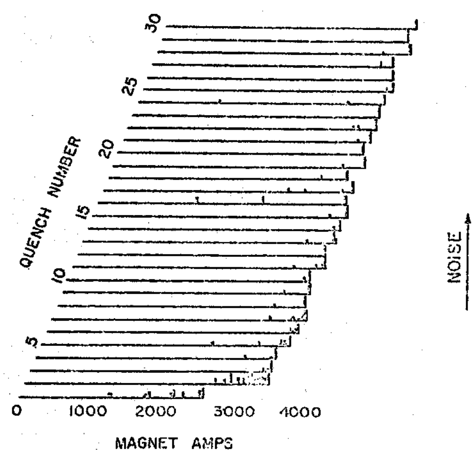
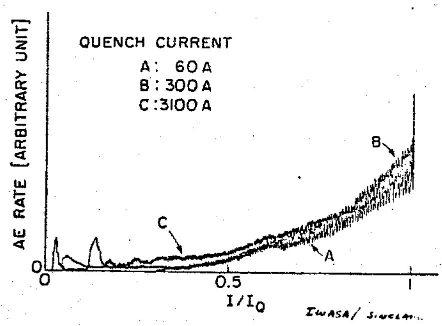


Fig. 19



Acoustic emission rate versus reduced current traces for three magnets. Trace A, solenoid; Trace B, split-pair; Trace C, dipole.

Fig. 20, Ref. 13

Iwasa and Sinclair, Ref. 13 have made a very interesting observation. This is illustrated in Fig. 20. Three magnets: a solenoid, a split-pair, and a dipole are plotted. The horizontal scale is I/I_c, and the vertical scale is the acoustic emission rate in arbitrary units. The magnets have been normalized on both the horizontal and vertical axis. However, it is interesting to observe that the shape of these acoustic emission curves are rather similar. So far, acoustic emission has not been used as a monitor to protect superconducting magnets, and more work in this area may be very interesting, especially if it can be shown that the phenomena has a predictive capability of indicating the quench current of a magnet.

There is another area of study receiving much attention that is related to training. If heat could be removed from the conductor more rapidly, one might expect to affect the training. Superfluid helium is capable of doing this, and the effect on magnets has been studied at a number of different laboratories. We pick here an example from an LBL ESCAR dipole. Fig. 22 shows this data.[14] The dotted curves along the bottom of the figure shows the expected training of this magnet. The points indicate the actual quench level observed as the helium was cycled back and forth between He-I and He-II. The interesting point is made that only a few quenches at low temperature were required in order to train the magnet to its short sample limit at 4.2° K. The expected training if all done at 4.2° would have been much slower than that observed at the lower temperature.

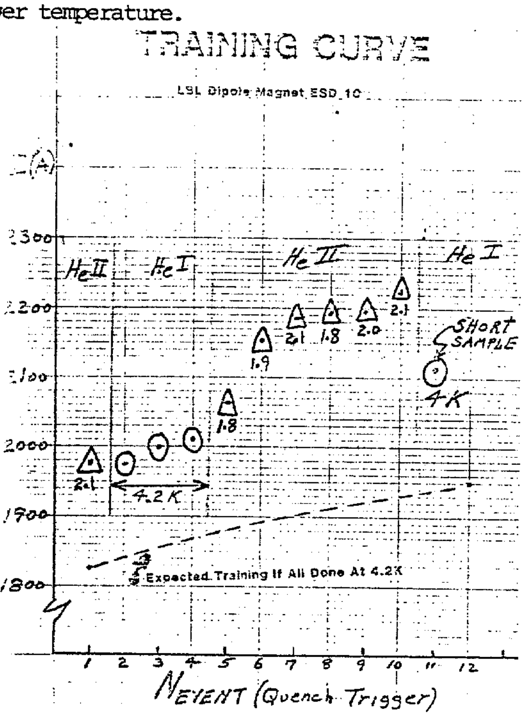


Fig. 21, Ref. 14

As a final example of problems caused by training, I would like to refer to the correction coil for the FNAL Energy Doubler. Originally, it was planned to place dipole trimming coils inside of the focussing quadrupoles. These trimming coils were to operate at only a few hundred amps and are used for removing errors from the closed orbit. Ref. 15 is the paper reported at this conference. Fig. 22 shows a curve indicating the training history of the dipole TSD-1 in the field of the quadrupole TQ-9. Originally, the trim coil was trained up to the point shown on the right hand load line. The current in the quadrupole was then reduced to zero, and the trim coil trained up the left hand load line. Finally, a field of 1.5 Tesla was then turned on in the quadrupole with the resultant training history shown along the middle load line. Additional experience with this type of phenomena was obtained in a correction coil package containing several different overwound multipoles, such as quadrupole, sextupole, and octapole. Since these coils had to be independently adjusted, it was impossible to predict what the new training history would be for a new field configuration. The coils which were fabricated from a bonded wire were apparently cracking apart under the Lorentz forces. In this particular case, training was completely unacceptable, and the problem was solved simply by going to a larger size wire which would then operate at a smaller fraction of the critical current in a given field.

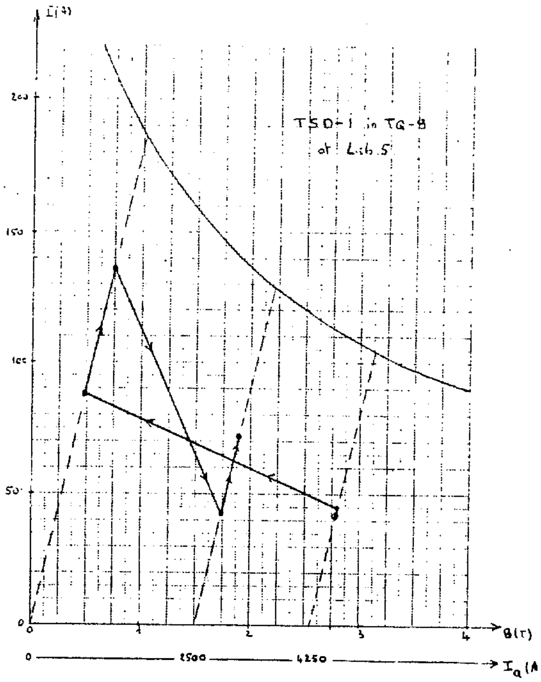


Fig. 22, Ref. 15

Summary

In summary, one can say that it is possible to control training. In order to do this, very careful attention must be given to the support of the conductor. However, much additional work in this field would be welcome. Work elucidating the disturbance spectrum of the support matrix and how to control it would be very useful. It is important to understand how to control friction and the heat it generates. Ways to control failure of the matrix at higher force level are going to have to be developed before magnets at higher field levels become practical. In addition, studies of He-II as a coolant need to be carried out, and finally, the role of acoustic emission relative to the training of magnets needs to be clarified.

I would like to thank my many colleagues that have contributed to the ideas that I have expressed in this talk.

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