SUPERCONDUCTING MAGNETS AND CRYOGENICS

by

John R. Purcell

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Summary

Several significant superconducting beam line magnet systems are being constructed in the U.S. These will demonstrate the practicability of superconductors in beam lines. It is now time to consider some of the more subtle engineering problems associated with these magnets in order to assure a "next generation" of highly usable magnets. This paper presents some engineering approaches to better magnets for the future.

At present in the U.S., work on several significant superconducting beam line magnet systems is in progress. At Brookhaven National Laboratory they are constructing a secondary beam line to give a 20° bend at 30 GeV/c to go into operation during the fall of 1975. At Argonne we are going to use the SSR (Superconducting Stretcher Ring) prototype magnets to give a 33° bend at 12 GeV/c in the beam to the Argonne Effective Mass Spectrometer. This line will be in operation in late 1975. ESCAR (Experimental Superconducting Accelerator Ring) is proceeding and construction should start soon. Fermi National Accelerator Laboratory not only is planning the Energy Doubler but numerous external beam lines as well. It seems that at long last the time has come to use superconductors "en masse" to control high energy particle beams.

A puzzling thing is why beam line magnets took so long in "coming of age" (approximately ten years) when other superconducting magnets have been in use for many years. Part of the answer is, of course, that beam line magnets with precision field requirements and small size are harder to build than large experimental area magnets and funds for this type of development have been short. I don't believe that this is the complete answer and that understanding the errors of the past may help the future in utilization of superconductivity.

Designers of conventional room-temperature magnets know that the important parameters for the magnets are initial cost, power consumption, a field distribution which will do the job, and reliability. A corresponding measure of a superconducting magnet is initial cost, heat leak, a field distribution which will do the job, and reliability. It is worth noting that a figure of merit for superconducting magnets is not current density or percent of short sample. They are important only in their effect on the main parameters, principally initial cost and reliability. Part of the problems in magnet development can be directly traced to the failure to use correctly in the cryogenic design of magnets and cryogenics.

In the cryogenic design of magnets there are two distinct types. One type, such as accelerators, generates heat at 4°K due to pulsing, is steady state and generates no appreciable heat at 4°K. Beam line magnets (with negligible heat), bubble chamber magnets, and e.m. magnets are examples of the latter type. The design of these two types is completely different. For magnets whose main source of heat is from ambient temperatures, the most effective and economical method of keeping them cool is by cold boil-off of the liquid helium. This is such a well-accepted principle that it is sometimes ignored. The fact that the same principles apply to the outside of the cryostat is sometimes ignored is that the same principles apply to the outside of the cryostat and support system. First the cryostat is insulated and insulated again. For example, if this turns out to be too expensive, using liquid nitrogen. This frees more of the cryostat and through the leads, the additional heat approaches zero. A 1-W dewar with a liquid nitrogen shield would have a heat leak to the liquid nitrogen shielding; will withstand transporting by truck; and is good for a static vacuum system. This is in sharp contrast to the present huge gap between commercial laboratory magnet cryostats.

In practice, it is sometimes more practical to use cold boil-off gas. This frees more of the lead space for the leads. A good lead intro 1,000 A into the liquid when it is get cold boil-off gas. If not intercept gas is available, it is often within the cryostat and through the leads, the additional heat approaches zero. A 1-W dewar with intercept gas is not a 2-W system, but is less than 1-W, as long as all the boil-off gas is used for the leads. A good lead intro 1,000 A into the liquid when it is get cold boil-off gas. If not intercept gas is available, it is often within the cryostat and through the leads, the additional heat approaches zero. A 1-W dewar with intercept gas is not a 2-W system, but is less than 1-W, as long as all the boil-off gas is used for the leads.

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In practice, it is sometimes more convenient to
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presents some engineering approaches to better magnets for the future.

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In the cryogenic design of magnets distinct types. One type, such as accelerator magnets, generates heat at 4°K due to pulsing. It is steady state and generates no appreciable 4°K. Beam line magnets (with negligible heating), bubble chamber magnets, and experimental magnets are examples of the latter type. The cryogenic design of these two types is complex. For magnets whose main source of heat is from ambient temperatures, the most effective of keeping them cool is by cold boiloff, the liquid helium. This is such a well-recognized fact for current leads that it is common practice to cool them with cold boiloff gas, but what is ignored is that the same principles apply in magnets coming in from the outside; i.e., it should be kept with cold boiloff gas.

In practice, it is sometimes more effective to cool the radiation shield and support system with liquid nitrogen. This frees more of the boiloff gas used for the leads. A good lead introduces 1,000 A into the liquid when it is generated; intercept gas. If intercept gas is available, other source within the cryostat and therefore through the leads, the additional heat free space approaches zero. A 1-W dewar with a 1,000 A lead is not a 2-W system, but is less than 1.3 combination, as long as all the boiloff gas is used for the leads.

These factors lead to a design process for steady state magnets that will optimize the system. First the cryostat is designed to operate at a current that gives as low a heat leak as economically feasible, using liquid nitrogen. For example, if this turns out to be 1,000 A with 1,000 A leads, the magnet should operate at 1,000 A with leads. If the magnet is designed for a higher current, then the heat leak will still be a current, but a lower current. If the magnet is designed for a higher current, then the boiloff rate will increase accordingly.

A system that operates by transferring liquid helium in batches to the magnet and return gas back to the liquefier has other advantages. The system is not dependent on a refrigerator running continuously. A reserve dewar can be kept to serve during the time the

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A system that operates by transferring the liquid
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tages. The system is not dependent on a helium re-
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down for repairs or maintenance. Only one cold line is required to each magnet and this line is only used during refilling, taking perhaps one hour per day, making the heat leak of the transfer lines much less important.

A fact that leads designers to use a refrigerator rather than a liquefier is that a typical 100 t/h machine can deliver 400 W at 4°K when in a refrigeration mode. When the 400 W is compared to the latent heat of 7°C W for the 100 t/h, it would seem wise to use the machine as a refrigerator. What is overlooked is that the sensible heat of gas amounts to ~50 W/h per liter in warming from 4°K to room temperature. This means that evaporating 100t of liquid helium per hour can intercept close to 5,000 W of heat from the room temperature environment.

A well-designed "warm gas return system" is not only more efficient, but is easier to operate and has greater reliability because the system is not tied to continuous operation of refrigeration machinery. The SSR magnet system was designed with these parameters in mind with the result that the helium boiloff rate for a 10-ft module containing three magnets is less than 1 t/h and time between refills is greater than 24 hours.

For magnets that are pulsed or which have a heavy radiation load and thus have a heat load at 4°K, a refrigerator should be used to remove the pulsing portion of the heat load. The heat leak portion of the heat load should be minimized by boiloff gas interception as with steady state magnets.

The high energy physics community has been the leader in the use of superconducting magnets with bubble chamber magnets such as the ANL 12-ft, the BNL 7-ft, the NAL 15-ft, and the CERN BEBC; various experimental area type magnets; and magnets for use with polarized proton targets. However, other needs are rapidly approaching. In the near future (approximately ten years) the magnetohydrodynamic (MHD) program will require magnets suitable for full scale power plants. These will be 60 kG dipoles with a 3 m x 3 m aperture, 15 to 20 m long. The next generation fusion device, called an experimental power reactor, is scheduled for completion in 1985. Each D-shaped toroidal field coil will be about 10 m tall and 7 m across. Twelve to twenty-four such coils mounted together to form a "doughnut" shape will comprise the complete toroidal field winding.

The peak field will be 75 to 80 kG and the toroidal field will have a stored energy of 650 MJ. In addition to the toroidal field coils, the require superconducting ohmic heating coils are solenoidal windings with a stored energy of several hundred MJ. The coils must be pulsed -80 kG to +80 kG in a time of about 1 sec to attempt to meet the needs of the MHD program with water-cooled copper. How can require a staggering amount of power and certainly make these energy sources much less efficient.

Perhaps with these other users for superconducting magnets appearing, the development plan can be shared, rather than borne by high energy alone. The development of superconducting MHD will not be aimed at high energy magnets, but the "spin off" benefits will profit us all. Oak Ridge National Laborator's multimillion dollar development program to be used in fusion machines. This program will lead to a better understanding of magnets and provide design information useful for physics magnets.

REFERENCES
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fusion program with watercooled copper magnets would
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and MHD will not be aimed at high energy physics type
magnets, but the "spin off" benefits will undoubtedly
profit us all. Oak Ridge National Laboratory has a
multimillion dollar development program for magnets
to be used in fusion machines. This program should
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