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SUPERCONDUCTING MAGNETS AND CRYOGENICS*

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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 approachs 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[1] 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[2] 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)[3] is proceeding and construction should start soon. Fermi National Accelerator Laboratory not only is planning the Energy Doubler[4] but numerous external beam lines[5] 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 feeling that current density in itself is important and should be as high as possible, in disregard of the fact that stability problems increase in proportion to the current density squared.

An example of not utilizing existing technology is in magnet cryostats. Commercially, a 500-ℓ liquid helium dewar can be purchased for about $6,000. It will have a heat leak to the liquid of 0.146 W with no liquid nitrogen shield; will withstand the shock of transporting by truck; and is good for years with a static vacuum system. This is in sharp contrast to most magnet cryostats that are more expensive by factors of 5 to 10, have higher heat leaks by orders of magnitude, and are fragile. The magnet cryostat must support more weight than a liquid helium dewar and may need to be adjustable for alignment purposes, but it still seems we could do a lot better with cryostats by more fully utilizing dewar technology. Perhaps as magnets become more predictable more effort will be put into the cryogenics of the system and close the present huge gap between commercial dewars and laboratory magnet cryostats.

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

In practice, it is sometimes more convenient to cool the radiation shield and support system with liquid nitrogen. This frees more of the boiloff gas to be used for the leads. A good lead introduces 1 W per 1,000 A into the liquid when it is generating its own intercept gas. If intercept gas is available from another source within the cryostat and this gas is passed through the leads, the additional heat from the leads approaches zero. A 1-W dewar with a 1,000-A lead is not a 2-W system, but is less than 1.2 W for the combination, as long as all the boiloff gas is taken through the leads.

These factors lead to a design procedure for steady state magnets that will optimize the heat leak of the system. First the cryostat is designed without current leads to give as low a heat leak as is economically feasible, using liquid nitrogen for shielding. For example, if this turns out to be 2 W, then the magnet should operate at 1,000 A with optimum leads. If the magnet is designed to operate at a lower current, then the heat leak will still be 2 W and nothing will be gained by the lower current. If the magnet is designed for a higher current, then the liquid helium boiloff rate will increase accordingly.

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

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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 that a liquefier is that a typical 100 ℓ/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 70 W for the 100 ℓ/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 100 ℓ 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[2] 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 ℓ/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 complete toroidal field will have a stored energy of 4,000 MJ. In addition to the toroidal field coils, the device will require superconducting ohmic heating coils, which are solenoidal windings with a stored energy of several hundred MJ. The coils must be pulsed from -80 kG to +80 kG in a time of about 1 second. To attempt to meet the needs of the MHD program or the fusion program with watercooled copper magnets would require a staggering amount of power and would certainly make these energy sources much less attractive.

Perhaps with these other users for superconducting magnets appearing, the development costs can be shared, rather than borne by high energy physics alone. The development of superconductivity for fusion 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 lead to a better understanding of magnets in general and provide design information useful for high energy physics magnets.

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