USE OF SUPERCONDUCTORS IN HIGH ENERGY PHYSICS*

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INTRODUCTION

A recent visitor to Brookhaven, after listening to a lecture on our progress in superconductivity, looked at the experimental floor of the AGS and said "If superconducting beam transport is so wonderful why do I still see all of these iron and copper magnets along your high energy beams?" He was told to look again in a few years.

It seems certain that dc superconducting magnets will find many applications in nuclear and high energy physics, in beam transport components, in bubble chamber magnets and in specialized magnets where high fields are required or where fields must be maintained throughout large volumes. This can include cyclotron magnets.

But for accelerators whose magnets are operated under ac or pulsed conditions the story is quite different. Most of the design problems associated with synchrotron magnets have been solved in principle. But the problem remains of reducing the high losses that are met when fields in superconducting magnets must change rapidly with time. Probably this problem will have been solved by the end of next year. The information to be presented this week will, we expect, throw much light on the question.

Although this week's topic is ac effects, I shall speak briefly, for the sake of completeness, about rf cavity applications and dc applications, then turn to possible applications in systems where the field in a magnet must change with time.

RF APPLICATIONS

Rf applications were covered during the first week of the Summer Study. Most of the work in this field is in the 1000 to 3000 MHz range. The largest group working on rf applications is at Stanford where studies are in progress both in Stanford's Physics Department and at the two-mile linac (SLAC). This work is aimed at an electron linear accelerator with a 100% duty cycle. At Brookhaven we are working toward a 3000 MHz particle separator. At Karlsruhe a large group is experimenting with cavities for both linear accelerators and beam separators.

All of these applications call for high electric fields but do not involve very high magnetic fields (less than 1000 gauss). Lead plated on copper has been rather thoroughly investigated but the present trend is toward niobium cavities either machined or electroformed. To keep losses within tolerable limits it is not possible to operate at the boiling point of liquid helium — the temperature must be reduced to below 2°K into the range where helium becomes a superfluid. Although this calls for more than twice as much power input to the refrigerator, helium at these temperatures is a beautiful coolant. Experience gained at radio frequencies may very well lead magnet designers to call for superfluid helium cooling.

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*Work performed under the auspices of the U.S. Atomic Energy Commission.

Some rf work is in progress at lower frequencies for use in circuits requiring high frequency stability. Q's of over 10^{10} have been obtained and higher values are expected. This makes possible oscillators with stability approaching that of the NBS time standards.

MAGNETS FOR BUBBLE CHAMBERS, SPARK CHAMBERS AND LARGE SPECTROMETERS

The first superconducting magnet for a bubble chamber was built at Argonne. It has an inner diameter of 10 in. and runs at 42 kG. So far this is the only superconducting magnet that has been used with a bubble chamber as part of an experimental program. But a number of much more ambitious magnets are under construction or design. The 30-kG magnet for Brookhaven's 7-ft chamber and the 20-kG magnet for Argonne's 12-ft chamber will both be running by the end of this year. The Brookhaven magnet has already been cooled down and excited to half field.

At the Lawrence Radiation Laboratory, spectrometer magnets 7 ft in diameter are under design. At CERN model studies are under way for a 3.5-m bubble chamber magnet to run at 35 kG. The most ambitious such project probably is at the Rutherford Laboratory where a magnet for a 1.5-m bubble chamber is to be run at fields over 70 kG. The stresses to be experienced are to be restrained by an interwinding of stainless-steel strip 3 mm thick.

In all of these magnets high current density is not important because of their large size. All will be wound with fully stabilized NbTi superconductor. The magnets listed are typical — I have listed only a few of the large magnets under design or construction for use with bubble chambers, spark chambers or other large detecting devices.

BEAM TRANSPORT MAGNETS

At the AGS our annual power bill is about $1 million. More than two-thirds of this pays for operation of the dipole and quadrupole magnets that guide and focus secondary particle beams for the various experiments on our experimental floor. We have over 200 of these magnets; their total weight is over 3000 tons. About 180 power supplies provide power for these magnets; they range in size from a few to 600 kW. Total experimental power available is 37 000 kVA; to dissipate this power we need 3500 gal/min of cooling water.

Most of these magnets could be replaced by superconducting units. A 300-kW magnet would be replaced by a dipole dissipating perhaps 20 W. The refrigerator for this unit would require about 15-kW input. Thus the power consumption would be cut by a factor of twenty.

The cost of the present magnets is of the order of $20 thousand apiece. From present experience we estimate that the superconducting replacement would cost no more than this; eventually it should be cheaper.

Similar situations exist at all of the high energy physics installations. At the 200-GeV machine in Weston the total number of magnets will eventually be considerably larger than the figures I have mentioned. I am confident that they will be largely superconducting from the beginning of operation.

DESIGN OF DIPOLES AND QUADRUPOLES

Superconducting dipoles and quadruopoles will bear little physical resemblance to their room temperature counterparts. The possibility of an economical increase in current density of two or three orders of magnitude has shaken magnet designers and has resulted in considerable debate as to how best to use it.

First let me be clear that the problem to which I address myself is that of dipoles and quadrupoles with small aperture, although their length normal to the field may be great. If the aperture is large, for example in the dipole magnet for a 7-ft bubble chamber, high current density is no longer so essential and cost and power consumption are the considerations that lead to the choice of a superconducting magnet. But if the aperture dimensions are a foot or less, novel designs are called for.

If infinite current density were available, a dipole or a quadrupole with a circular aperture could provide the desired fields if the current density around the coil varied as cos θ for a dipole or cos 2θ for a quadrupole (see Fig. 1). For finite current density and uniform coil thickness, the cos $n\theta$ distribution still gives ideal field patterns inside the aperture.

If, however, inadequate current density is available, the coil will become very thick — when the coil thickness begins to be of the order of the aperture dimensions one finds oneself in the absurd position of adding large quantities of current so far from the aperture that they are making virtually no contributions to the useful field.

Of course accurate establishment of a cosine distribution presents major design problems. Fortunately this is not necessary. Beth,[1] at Brookhaven, has shown that an approximation in the form of three or so blocks of constant current density can, if properly arranged, eliminate higher harmonics of the field pattern to such a high order that further compensation is unnecessary.

Other approaches than that of the coil of uniform thickness have been proposed by Beth at Brookhaven, by Septier at Orsay, and elsewhere. I shall say no more about them because they will be discussed in more detail next week.

Peak field strengths to be used in dipoles and quadrupoles will probably be of the order of 60 kG, at least in the initial stages of development. With the geometries that I am describing forces at fields over 60 kG are becoming unreasonable and are rising with the square of the field.

In the geometry that I have described, the peak field in the useful aperture is the highest field anywhere. Nowhere in the system of conductors is the field any higher.

Peak current densities for 60-kG peak generated by a coil 1.5 cm thick are about 60 000 A/cm^2.

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Stray fields outside of air core dipoles or quadrupoles can be quite troublesome in many applications. There are two ways for eliminating them. The first is to build another dipole or quadrupole coil of larger radius coaxial with the first. This can reduce the net external field identically to zero with an attendant sacrifice of a

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1. R.A. Beth, Brookhaven National Laboratory, Accelerator Dept. Report AADD-135 (1967).

fraction of the field in the useful aperture. The second method is to surround the coil with a cylinder of iron. This will result in an increase in the useful field. If, for example, the radius of the iron cylinder is large enough that the maximum flux density at the iron surface is 20 kG, the addition of iron will add 10 kG to the dipole field and somewhat less to the quadrupole field. The inner radius of the iron cylinder will be of the order of twice the coil radius. Whether or not it is appropriate to include the iron in the cooled volume we have not yet decided.

STORED ENERGIES

For dc dipoles and quadrupoles usable for beam transport, stored energies are relatively unimportant. If these components are to be pulsed for use in an accelerator, however, stored energies become quite important.

For a dipole or quadrupole having a coil thickness that is negligible compared with the aperture dimensions, it can be shown that the energy stored in the useful aperture and the energy stored in external fields are approximately equal so that, so far as stored energy is concerned, the unit may be said to be 50% efficient. This is better than many iron cored magnets; for example, in the magnets used in the AGS less than one-third of the total stored energy resides inside of the vacuum chamber. But if the coil thickness becomes appreciable the comparison rapidly becomes less favorable. For example, in a dipole whose aperture has a radius of 5 cm and whose coil is 1.5 cm thick, there is almost 50% as much energy stored in the coil as is stored in the useful aperture and the over-all efficiency has dropped from 50% to about 40%.

Again this points up the importance of high current density. If we think of 60-kG fields, the stored energy argument also forces us into the range of 60 000 A/cm^2.

PULSING OF SUPERCONDUCTING MAGNETS

Measurements and interpretation of losses in superconductors when the current is changed have already been the subject of much discussion during this Summer Study and are the main topic for this week. I shall not anticipate the coming presentations except to say that losses are too high by a factor between three and ten, if we think of pulsing at the rates now used in the AGS where the field is raised from zero to full field in about one second.

Possibly, if we build a 200-GeV accelerator with superconducting magnets and pulse it very slowly, taking ten to fifty seconds to reach full field, present materials are adequate. But we hope to cycle the machine as rapidly as Nature will allow.

Another complication in using pulsed magnets in an accelerator comes from the fact that the field is used during almost the whole cycle of increasing field. A high order of precision is required throughout the cycle and distortions or flux jump discontinuities will cause the beam to be lost. So, while we ask for high current densities and so cannot allow admission of a lot of normal stabilizing metal, at the same time we require a high order of stability. We hope that these requirements are not completely inconsistent.

SUPERCONDUCTING SYNCHROTRONS

For acceleration of protons to the range of hundreds or thousands of GeV the synchrotron is the only accelerator of demonstrated capability. It is a device, like the AGS, in which during acceleration the protons travel on a circular orbit in which they are maintained by a rising magnetic field. It consists essentially of an injector of as high energy as is economically feasible, a set of bending magnets which maintain the circular orbit, a set of focusing magnets which prevent large excursions from the orbit, and a set of rf accelerating cavities. There are many additional complications which are described in many books and reviews on the subject.

For over seven years the AGS has produced protons of the world's highest energy — 33 GeV. But last November the Russians brought into operation a machine for almost 90 GeV; this will be the world's largest for some time. The next step will be either the 200-400 GeV synchrotron at Weston, Illinois, or a 300-GeV synchrotron under design in Europe.

As a major application of superconducting magnets we are studying here a 2000-GeV synchrotron. The AGS would serve as its injector and its main magnet ring would be about two miles in diameter. Fortunately there is adequate space for this on the Brookhaven site.

The main ring would have about four and a half miles of its six mile circumference filled with magnets. About seven-eighths of this distance would be occupied by bending magnets — dipoles with 60-kG peak field. The other eighth would be quadrupoles for focusing. Rf accelerating stations would be distributed at intervals around the ring The stored energy in the magnet system would be about 700 MJ.

The accelerated beam would be extracted and fed through an array of superconducting beam transport dipoles and quadrupoles to a variety of happy experimenters from all over the world.

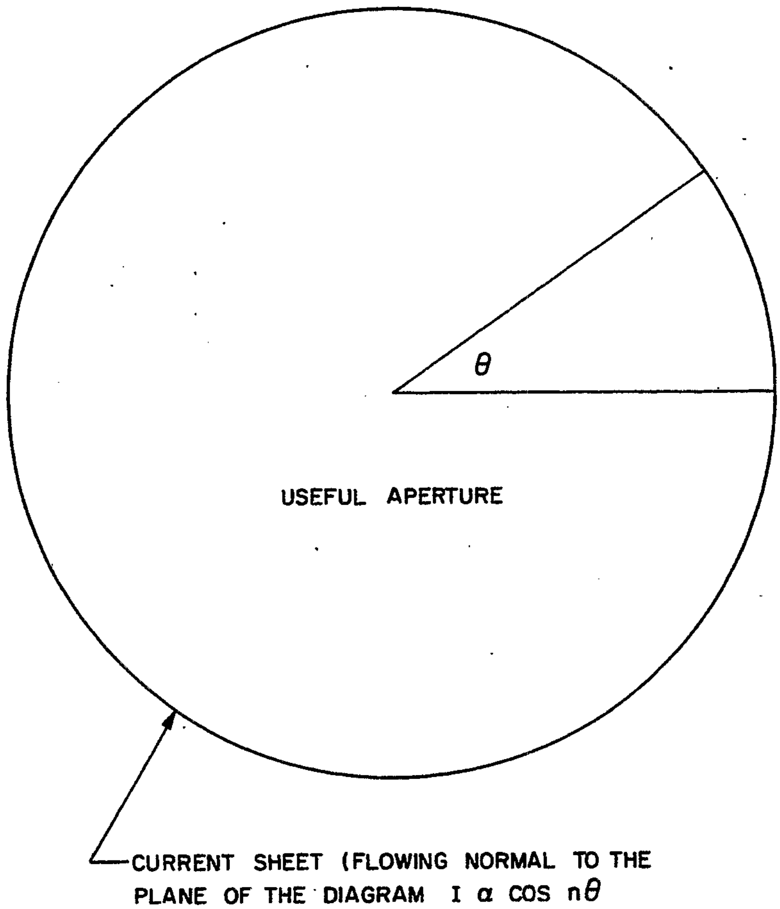

Fig. 1. Geometry for multipole magnet with circular aperture.