THE FUTURE OF SUPERCONDUCTING MAGNETS*

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Some advantages and limitations to the use of superconducting coils in preference to conventional copper coils are mentioned. The current commercial availability of superconducting material is outlined and recent trends in conductor development are discussed. Some of the best recent magnets are mentioned and performance figures given. Definite plans for several larger coils which can be expected to operate within the next four or five years are described and some speculations on the most likely areas of application are made. Possible applications of superconductors to Accelerators and Accelerator Experimental Area use are also indicated. A brief assessment of some future trends is made and some possibilities for future studies are indicated.

I. Introduction

The objects of this paper are to state the main reasons for using superconducting magnets, to outline the most advanced developments to date, to speculate upon the most probable areas of application in the next ten years, and then to outline possible future developments in the light of the foregoing comments. Finally, since this is an accelerator conference, the further object is to comment on the possible applications to accelerator design and to accelerator experimental area use and also to suggest some problem areas worthy of further study. There will be no attempt in the time available to consider the uses of superconducting coils in machines and electronic devices.

II. The Desirability of Using Superconducting Coils

At conventional field intensities of the order of 20 kG or less, we can expect savings of the order of 20 to 50 in operating cost as compared with conventional magnets.[1, 2] This is due to the difference between operating a conventional power supply and water cooling system for a large magnet and operating a refrigerator which is required to maintain the low temperature environment. The savings are even more attractive in the case of bubble chambers, particularly hydrogen chambers, where the low temperature environment is already required and it is only necessary to refrigerate from hydrogen to helium for the magnet.

At high fields of the order of 80 kG and above, there is a considerable saving in capital cost as well as in operating cost.[3]

Where larger magnets have to be used with varying fields, some of the advantage of the superconducting coil is already lost since large power supplies are now necessary to inject and remove the field energy.

It is possible to operate copper coils at high current densities with elaborate cooling systems and expensive high power electrical supplies. Current densities of the same order can usually be obtained with superconducting coils with considerably less sophistication in design and little auxiliary equipment. There remains the possibility of operating the superconducting magnet without a power supply, and this is a particular interest in space and balloon-borne experiments where the conventional magnet with its power supply would be out of the question. Ion engines and minaturized MHD systems can also be made using superconducting magnets as permanent magnets.

Three important characteristics of a superconducting coil should be borne in mind in considering possible applications. First, the central magnetic field does not increase linearly with increasing current, but often has sudden large changes in dB/dt superimposed upon it.[4, 5, 6] Usually of the order of tens of gauss in smaller coils, with durations of the order of fractions of seconds to tens of seconds, the jumps do not occur at regular increments of current and their frequency of occurrence is usually greatest at some field well below the maximum value. The changes are due to redistributions of flux in the conductors as the flux penetrates them and to corresponding changes in the diamagnetic current pattern. The magnitude of the changes will depend upon the geometry of the coil, the size of the superconductors and the nature and volume of superconducting material involved. In well shunted coils, the windings may act as a shield, and flux movements can be large and uncontrolled.

Secondly, a residual field remains in the coil when the current is reduced to zero, the axial field distribution usually having peaks at the coil ends. These residuals can be of the order of a few kilogauss and cannot be reduced to zero

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by reversing the current.[6a]

The final factor involves coils operated in the persistent current mode. The flux distribution in these coils is very sensitive to changes in fields, currents, and to movements of ferromagnetic material in their vicinity. The flux system has zero viscosity and readjusts to keep the total energy constant. Chalmers[7] has also emphasized that a superconducting ring maintains a constant magnetic flux through it when changes are made in the permeability of the medium in which the coil is situated. A current carrying coil with a battery does not act in this way except for the initial inductive disturbances.

III. Current Developments

1. Materials

The range of materials currently available includes niobium zirconium, niobium titanium, and niobium tin which are available from a number of manufacturers in several countries for immediate use.[1, 2] Tertiary systems of niobium-zirconium-titanium are being used in Russia and Japan. Thin superconducting films with thickness of a few hundred Angstroms are also available in small quantities. Multiwire,[8] in which large numbers of superconductors with very small cross-sections are embedded in a normal matrix such as copper, has also been made in experimental quantities. A plasma spraying process for Nb_3Sn is now also available and offers both the possibility of reduced price and ease of fabrication of complex shapes.

Information on the maximum current density available at a given field with each material is readily available in the extensive literature on the subject.

Approximate upper critical fields and temperatures for the three most popular materials are: NbZr$\sim$60-70 kG, $T_c \sim 10^oK$; NbTi$\sim$ 120 kG, $T_c \sim 9^oK$; $Nb_3Sn \sim 250$ kG, $T_c \sim 18^oK$. Typical current densities are: NbZr$\sim 4 \times 10^5$ A/cm^2 at 20 kG; NbTi$\sim 10^5$ A/cm^2 at 40 kG and 4×10^4 A/cm^2 at 80 kG; $Nb_3Sn \sim 10^6$ A/cm^2 at 20 kG and $\sim 10^5$ A/cm^2 at 100 kG.[1, 2]

2. Conductors[1, 2, 9, 10]

The current densities obtainable in bulk materials are reduced in present conductors because of the use of coatings of normal conductors with good conductivity and of insulating coatings. Conductor characteristics vary with the nature and distribution of the defect structures in the superconductor. Short sample current carrying capacity is enhanced as the conductor dimensions are reduced. Conductors with higher critical temperatures and most favorable surface to volume ratios have decided advantages since the cooling medium is most often liquid helium at 4.2^oK and the changes in a superconductor as the flux moves will have less effect as the thermal environment is improved.

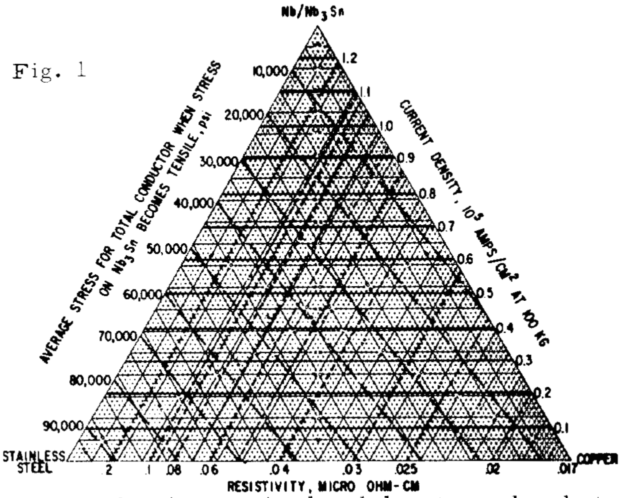
At the present time, in larger size coils, the stable conductor which can sustain a reasonable degree of over-current without propagation of the normal region after a portion of the superconductor has been driven into the normal state is the most attractive, and considerable study is being devoted to the development of improved types of stable conductor. Thus, the new large bubble chamber magnets which are under planning or construction will utilize stabilized conductors.[11]

In the case of the Argonne 12' bubble chamber magnet, the amount of copper in the conductor is being chosen not only for reasons of stability, but also so that the copper will support the stress anticipated in the conductor at full field. A further trend exemplified by the choice of the Argonne conductor is the requirement for a ductile superconductor which will itself continue to operate satisfactorily up to a given degree of strain. This favors niobium titanium. The magnet, with its central magnetic field of 20 kG and its 16 ft. inner diameter, represents perhaps the limit for conductors which contain no additional reinforcing. Consequently, for larger diameter coils at this field or for higher field coils at this diameter, it is imperative that superconductors containing shunting and reinforcing materials should be considered if a self-supporting winding is required. Alternatively, support structures must be developed to hold the conductors.

Reinforcing techniques have already been developed for Nb_3Sn conductors since the material is very brittle and can only be operated in compression. The superconductor in the RCA ribbon is compressed in manufacture by differential contraction of the Nb_3Sn layer and Hastalloy substrate on cooldown after the vapor deposition process. GE[12] has developed a range of composite conductors containing Nb_3Sn diffusion layers on a niobium substrate to give the current desired, copper cladding to any thickness to give the resistance/unit length specified, and stainless steel cladding to give the strength required. The combination of copper and stainless steel with the superconductor in the center puts the superconductor under high compression after cooling from the soldering temperature. Thus, when the conductor is strained, the superconductor is only operated to the limit of zero compression and never into the positive stress region. Naturally, similar considerations can also apply to conductors of niobium zirconium and niobium titanium.

M. Benz has developed a design chart for GE conductors (Fig. 1) which is used in the following way: The magnet designer decides upon the resistance per unit length of his conductor, the

Fig. 1



current density required and the stress level at which the conductor will operate. In the figure, the vertical lines from each angle to opposite sides of the triangle represent the scale for one each of these quantities. Thus, the vertical line from one apex to the opposite side represents a scale of from 100% Nb_3Sn to no Nb_3Sn. Similarly, another apex represents 100% stainless steel and the third 100% copper. Thus, the designer's statement of resistance per unit length, operating stress level, and current density enable the conductor manufacturer to decide from the chart whether or not he can furnish a conductor for these specifications. In most cases, a triangular area inside the main triangle will give feasible conductor configurations.

The other trend in these larger magnets is the use of strip type configurations. These, of course, are necessary when Nb_3Sn is used since it is usually fabricated in strips of width up to 1/2 in.[13] Cables and very thin strips have the advantage of reusability. Thicker strip type conductors are more difficult to use more than once, particularly on medium sized coils, whereas cables can be used many times. The strips have the advantage of a greater load-bearing area and a more determinate heat transfer surface, making design somewhat easier. In the composite stable conductors, the maximum safe operating current is determined by equating the heat dissipated in the copper for a given conductor current to the maximum safe heat transfer characteristic from the conductor to the helium. A conservative figure of 0.1 watts/cm^2 is usually taken.[4, 14] This leads to a temperature rise in the conductor itself of the order of about 0.1^{o}K for a well-cooled conductor. The foregoing discussion tacitly assumes a perfect electrical bond between the superconductor and the copper. Some manufacturers are claiming that they have developed metallurgical bonds for several of the newer conductors.

NbZr and NbTi conductors have been used most because they were the first to be commercially available and have so far been cheaper and simpler to use. Nb_3Sn is the best available high field material and thanks to techniques of magnet construction pioneered by Brookhaven National Laboratory, RCA and GE, is available in a range of conductor sizes and currents to suit most magnet designs. Choice of conductor type is now dictated largely by price and attainable average current density in the windings. Cabled and strip type conductors of NbZr and NbTi are now available capable of carrying currents of several thousand amperes at 60 to 80 kG. RCA has made copper clad ribbons of width 1/2 in. and thickness 0.015 in. which carry 1200 A at 100 kG in coils. GE can supply a ribbon of width 1/2 in. and average thickness of 0.0055 in. in which the product of field, H, and current, I, is given by $HI = 3 \times 10^7$ up to at least 100 kG.

3. Present Magnets

The Argonne 45 kG, 11 in. i.d. superconducting helium bubble chamber magnet,[15] which consists of the two outer radial sections of the 67 kG coil, is still the only superconducting magnet of any size (25 in. o.d., 12 in. long, stored energy~500,000j) to have been operated in a complex engineering installation.[16] This has generated a great degree of confidence in such magnets.

One large 37 kG, 12 in. bore, 3.7 Megajoule transverse field coil with a uniform transverse field region of the order of 5 ft. long has also been successfully operated.[17]

In Livermore, a minimum "B" baseball magnet of 10 in. diameter also has been successfully installed for use in a plasma-physics experiment.[18, 19] Superconducting baseballs of one meter i.d. are under consideration.[20]

In recent months, RCA has successfully operated a 140 kG, 2 in. i.d. magnet and have operated their 6 in. core coil for NASA-Lewis[21] which, it is hoped, will attain 140 kG central field, at 103 kG in a preliminary test. Like the 10 in. bubble chamber magnet system, this magnet is also unstable and has been safely discharged at 103 kG. The 2 Megajoules of stored energy is absorbed by copper secondaries distributed throughout the coil to ensure a reasonably uniform temperature distribution on discharge. These unstable systems can be operated indefinitely at almost any field below the quenching field without discharging the coil and are systems in which the highest average current densities can be expected.

Model quadrupole systems have been tested in Brookhaven National Laboratory, but improved versions have yet to be tested in a complete cryogenic system in an accelerator beam.[22, 23] Nevertheless, they demonstrate the feasibility of making quadrupole type fields in bores up to 4 in. with Nb_3Sn strips. Other quadrupole models are under study in Europe.[24, 25]

An electron microscope lens using superconducting windings has been operated at resolutions of the order of 10-20 Å and has demonstrated the value of the greater stability of such a lens when operated in the persistent current mode as opposed to a lens with conventional copper windings.[26,27]

A polarized target will be used in a π-p scattering experiment at CERN this year.[28] The required magnetic field is 25 kG with a 10^{-4} homogeneity over a 5 cm sphere. The magnet consists of a Helmholtz pair of coils, each coil with a tapered cross-section so that the access in the direction of the field is of 90^o aperture at room temperature. The complete magnet has been tested in an experimental cryostat at full current and corrections are being made in order to balance the two coils to get the anticipated field uniformity. The two cryogenic systems will be operated using closed cycle refrigeration with an ADL-Collins liquifier.

A small superconducting bending magnet with iron was used recently in a successful experiment on corpuscular ionography with the CERN Synchrocyclotron where it produced a transverse field of more than 45 kG in a room temperature gap of rectangular section 0.8 in. x 1.6 in. x 2 in.[29]

A variety of recent magnets incorporating newer conductors have been recently developed and operated in Argonne.[30] These include a heavy section NbTi coil which has so far been operated at a stable average winding current density of almost 10,000 A/cm^2 at 60 kG with a 4 in. i.d. Various high current conductors for field ranges from 20 to 80 kG, both stable and unstable, have also been developed and evaluated, and aluminum shunted, stainless steel reinforced cables have also been operated in coils. A 9.4 in. i.d., 29 kG, tape wound coil with an average winding current density of 14,000 A/cm^2 has also been constructed and tested.

The average current density in a coil $j\lambda$ is the product of the current density, j, in the conductor and the ratio, λ, of cross-sectional area of conductor to cross-sectional area of coil. In smaller unstable coils of the order of 1/2 in. bore, values of $j\lambda \geqslant 5 \times 10^4$ A/cm^2 have been attained at up to 40 kG. Slightly larger 1 in. bore coils at 100 kG have been operated with $j\lambda \approx 2 \times 10^4$ A/cm^2. Larger magnets of the order of 14 in. winding i.d. have been operated at $j\lambda \approx 10^4$ in the unstable mode. Small insert magnets with short lengths of stable conductor (≈300 ft.) have been operated in the stable mode at $j\lambda \approx 10^4$ A/cm^2. Single pancakes of Nb_3Sn up to 8 x 10^4 A/cm^2 at 60 kG have been made. Stable coils of the order of 12 in. i.d. have been operated at $j\lambda \approx 5 \times 10^3$ A/cm^2, while the mammoth 16 ft. i.d. Argonne bubble chamber coil is designed to operate at $j\lambda \approx 10^3$ A/cm^2. These represent both the present day limitations which can be met and boundaries to be crossed in the future.

IV. Magnets for the Immediate Future

Very large magnets have been proposed in at least three Bubble Chamber installations partly because of present emphasis on neutrino physics. Superconducting coils will be used in the first of these which is now under construction at Argonne National Laboratory by a group under the direction of E. G. Pewitt.[11] This has a magnet of i.d. 16 ft. and will be used with iron to produce a 20 kG central field. Conventional windings could be used and the choice here was dictated on the basis of an annual saving of $350,000 to $400,000 in operating power cost. The specifications of the magnet are tabulated below and a system layout is shown in Fig. 2.

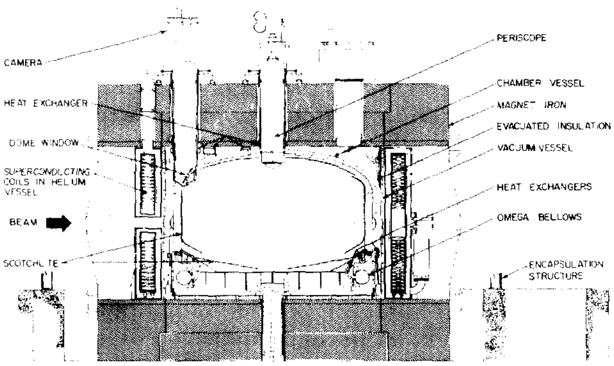
Superconducting Magnet Characteristics
Argonne National Laboratory 12 ft. Hydrogen Bubble Chamber

Field:	20 kG
Ampere turns:	5 x 10^6
Current	2,000 Amps.
Conductor dimensions:	5 cm x 0.254 cm
Inductance at windings:	40 Henrys
Number of pancakes:	30
Energy stored in field:	80 x 10^6 Joules
Wt. of copper in windings:	45,000 kG
Wt. of superconductor:	300 to 450 kG
Hoop stress on winding:	420 kG/cm^2
Coil axial compressive force:	6.8 x 10^5 kG
Wt. of iron:	1.45 x 10^6 kG
Inside diameter of coil:	478 cm
Length of coil:	304 cm
Power supply voltage:	10 Volts
Charging time:	2.25 Hrs.
Heat transfer rate required for 100% stability:	100 mw/cm^2
Resistivity of stabilizing copper at 20 kG field:	1.7 x 10^{-8}Ω/cm

Table I

A new integral conductor, 2000 A, 20 kG, composite of multiple NbTi strands drawn down with copper to produce a metallurgical bond between superconductor and copper is being supplied by Supercon Division of National Research Corporation to meet ANL conductor design specifications. Scheduled for completion in 1969, a further period of at least one year for evaluation and testing will be required before the chamber is on full time operation.

The other two large chambers have been designed by Brookhaven[31] and CERN.[32] The



12-FT HYDROGEN BUBBLE CHAMBER

Fig. 2: 12 ft. Hydrogen Bubble Chamber under construction at Argonne National Laboratory.

BNL split coil system will attempt to utilize more of the potential of the superconductor by operating at 30 kG and having no iron return path. The stray magnetic field from such a system introduces some novel problems. Brookhaven is constructing a half-scale model of its proposed hydrogen chamber.

The CERN group is considering a similar system with 35 kG central field located in an iron house to produce magnetic shielding for the auxiliary experiment. M. Derrick,[33] in a bubble chamber review paper, has commented that the three chambers are novel in inverse proportion to the expected completion date.

High-field chambers are more in favor at SLAC and the Rutherford Laboratory and 1.5 meter diameter 70 kG systems are planned.

A novel high-energy physics experiment scheduled to begin this year is the Alvarez balloon-borne experiment which combines the present day sophistication of high energy physics instrumentation with the older cosmic ray techniques in an attempt to obtain information in the range of 300 GeV and beyond.[34] The detectors will be located in a 15 kG transverse magnetic field of length 2 meters and bore 1 meter. The magnet design is due to C. E. Taylor of Livermore.

A number of superconducting coils are also proposed for some fusion experiments. These include improved and larger baseball type minimum "B" systems for Livermore, a superconducting DCX3 device for the Thermonuclear Division in Oak Ridge, and a system for the NASA Lewis Research Center with 150 kG, 6 in. i.d. mirrors and a central 72 kG, 20 in. i.d. section. Higher field center coils are also under construction for this device. MHD studies continue and one or two large magnets are being proposed and developed in conjunction with these. Scaled up somewhat in size from the AVCO model, with complete system design as opposed to a magnet feasibility study, they will utilize magnetic fields of the order of 60 kG.

V. Supermagnet Applications

My conclusion is that the area of greatest potential application at the moment is high energy physics with its associated accelerator facilities. This includes new bubble chamber coils, beam transport elements, and possibly spark chamber coils. The possibilities for accelerators should be assessed separately. The magnets have application for some industrial consumers and familiarity with the coils and the associated cryogenic techniques on the part of a larger number of people will no doubt lead to many novel applications which have not yet been foreseen.

The main possibilities for large scale applications would appear to be MHD and fusion generators. However, the success of the reactor program and the potentialities of the breeder reactor would tend to indicate that even if the researches in fusion and MHD were successful, they might never become economically competitive with other sources of power. This would mean that they would be used, if they ever become available at all, only in specialized and limited applications.

The fusion research studies involving steady fields are committed to the use of superconducting magnets. This again is a limited and small scale use. Magnets are required in various fields of physics such as solid state, and consequently, many superconducting magnets will continue to be required by university and industrial laboratories.

Superconductors will also be used in limited quantity in electron microscopy and in medical and biological research.

VI. Possible Applications to Accelerator Experimental Area Use

1. Bubble and Spark Chamber Coils

Bubble chamber applications have been discussed. Spark chamber systems are also feasible and the greater potential and saving here may be in the development of higher field coils than are currently being used with subsequent reductions in size of the auxiliary equipment. The argument for the use of superconducting coils with the large spark chambers is similar to that for bubble chambers with the exception that a cryogenic system has to be supplied whereas the liquid hydrogen chambers already have such a system down to about 20°K. The economic argument is not so favorable now as in the bubble chamber case.

2. Bending Magnets

Bending magnets can either be of the split coil type, which is effectively how they are used in bubble chambers, or they can consist of saddle shaped type coils (Fig. 3). The use of iron at conventional fields results in magnets with well defined edges whose optical properties are well known. Coils without iron pose fringing field problems which must be solved if the high field properties of the superconductor are to be utilized. Light superconducting or ferromagnetic screens may now be desirable to reduce the stray field effects on adjacent components. Where this high field potential can be applied, great savings in weight and space can be made and there is the potential of some saving in equipment cost.

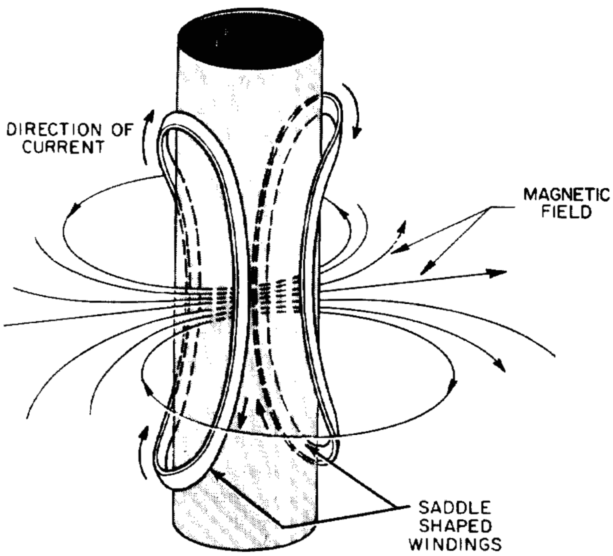


Fig. 3: Principle of Transverse Field System with Saddle Shaped Windings.

3. Quadrupole Beam Transport Systems

Quadrupole magnets are essential components in beam transport systems for large accelerators. No experience has yet been gained with superconducting quadrupoles in such systems. The difficulties of maintaining beam lines in operation with conventional magnet systems are well known and any significant increase in reliability would be welcomed. Most operating accelerators are already fairly well equipped with beam transport magnets. New systems will be installed only where a definite technical or economic improvement can be expected. The new 200 GeV accelerator and experimental area together with the proposed higher energy facility (800-1000 GeV) consequently become the logical areas to explore, particularly because of the stiffer beams which have to be handled.

Superconducting quadrupoles offer the possibility of shorter focal lengths and therefore shorter beam lines because of the potential increase in field gradient which is possible. They offer the possibility of reduced size and weight for a given focal length and of improved stability. Finally, they offer potential savings in operating cost and possibly in capital cost. On this point, it should be noted that this savings in operating cost is only significant in comparing superconducting and conventional systems for larger systems. Thus, in the Argonne 12 ft. Hydrogen Bubble Chamber, the superconducting coil displaces a conventional coil with an 11 Megawatt power supply and a yearly power cost of about \$400,000/yr. Obviously, even at 1 Megawatt, the situation is not so attractive and the potential saving of \$40,000/yr. is perhaps barely realizable in practice. This type of argument lets us define the borderline region between superconducting and conventional coil systems on the basis of savings in operating cost.

Where sufficient room is already available in experimental areas, reductions in beam length or component size are unimportant unless a definite technical reason for this exists. The projected new facilities are so expensive that considerations of capital cost and operating cost become secondary to the need for higher reliability of operation. In view of the problems involved and the cost of these new facilities, there is a case for studying the potential gains to be anticipated from the use of superconducting coils but there is not too much time available if the types of service facilities in these areas, and the layout of the areas themselves has to be decided within about five years.

In the case of the 200 GeV machine, a preliminary study on refrigeration requirements for superconducting magnets in the experimental areas has been made and brings to focus some of the refrigeration problems involved.[35] The study, extremely valuable, appears to imply that the superconducting systems might be as large, and therefore have equivalent field gradients to conventional systems. It assumes typical quadrupole magnets to be 8 in. i.d. x 19 in. o.d. and typical bending magnets to be 8 in. i.d. x 30 in. o.d. with lengths of the order of 2 meters and stored energies of 2×10^6 Megajoules. It should now be followed by a study comparing the use of the best conventional systems with the most advanced superconducting systems that are considered feasible.

It has been estimated that 164 general purpose magnets will be required in the 200 GeV experimental areas, distributed in three halls, the largest of which is about 2000 ft. long and 400 ft. wide. It has also been assumed that 130 of these units may be in operation at any one time. Present day large superconducting magnets with resistive contacts and the potential for operating as cryogenic magnets have ohmic losses which have not been considered in the study. The variations in cost and power dissipation for the examples studied reveal that the cost of each extra watt (per magnet) of power dissipation for the total system is about $1.2 x 10^6/watt. At these costs, it is worthwhile spending some time developing superconducting coils in the 2 Megajoule range with minimal power dissipation and highest possible current density. There would be little comfort in operating these coils as cryogenic systems in the stable mode at these prices in view of the proven reliability of systems which in fact, do discharge if the critical current is exceeded.

The cheapest system considered in the report envisaged a central liquifier with Dewar distribution at $7.1 x 10^6 for a total 10 year operating plus capital cost. A system with individual magnet refrigeration was estimated at $13.5 x 10^6, with the refrigeration units priced at $31,000 each. This is, of course, an initial estimate and will provoke thought and discussion. It has already produced a swift reaction in one cryogenics company who feel that they could produce the estimated $13.5 x 10^6 system for $8.3 x 10^6 using higher capacity refrigeration units than those considered above,[36] priced at only $15,000 each with an additional $5,000 per unit to represent the price of a central compressor for each 20 refrigeration units. Perhaps this type of reduction is indicative of things to come.

P. F. Smith and G. P. Haskell have conducted a number of theoretical studies in recent years on the economics of superconductors in high energy physics equipment.[37] In their latest paper,[38] they have compared superconducting and conventional quadrupoles for complete focussing systems with particular reference to particle beams in the momentum range of from 1 to 1000 Gev/c. They conclude that order of magnitude reductions in the capital cost of focussing high energy beams, with substantial shorter image to object ratios may be feasible with superconducting coils at high magnetic fields. They ignore operating costs and assume that superconductors will at least be operated at 100 kG to realize the greatest saving. Generalizations of this type may be too sweeping, but these studies have the merit of giving others a base from which to develop further ideas and suggest to me, at least, that high field developments are essential.

4. Solenoids and Horns

Solenoids still have their attraction in some applications, one of which is for a beam guide such as a muon channel where the beam must not be allowed to drift in free space and where decay to the muon mode is taking place. Superconducting coils offer a clear advantage in such cases over conventional solenoids both in capital costs and operating costs at fields beyond 20 kG.

In a serious study as to whether or not to use superconducting coils in a polarized proton target, we decided in our case that a conventional magnet would be better. Our assessment was based on the fact that most of the meaningful physics to be studied involved forward scattering and the access angle in the forward direction with a conventional magnet was about twice that obtainable with a split coil system. The Saclay Group is using a split superconducting coil system with a polarized proton target, but this is now the only possibility since they wish to work at 90^o to the incident beam.

We have considered the possibility of using superconductors for pion focussing horns with field configurations similar to that of the type built by van der Meer, et al. The Argonne horn operates in the pulsed mode with current densities of the order of 3×10^5 A/cm^2 in the thin aluminum skin. Aluminum was chosen in preference to copper because the reduction in density was essential to obtaining a tolerable particle absorption. Consequently, superconductors are not applicable to horns of this type since there would be difficulty in supporting the superconductor to withstand the forces, current densities of this order may not be attainable, the higher density material would lead to increased particle absorption and consequently, to lowered efficiency, and finally the radiation heating effects might degrade the superconductor performance.

5. Accelerator Magnets

In its present state of development, the superconducting coil is best suited to dc applications and to slowly varying fields. Possibilities exist for using such coils in machines such as cyclotrons. I considered the possibility of using superconducting coils in a variable energy cyclotron study with an ANL group and in a sectored cyclotron with a Swiss group under Blaser, E.T.H. Zurich. In the first case, the conventional coil was expected to have a power supply of less than 1 Megawatt, so that the operating cost would be low ($40,000/yr.). A further requirement was the ability to adjust the field to within 10% of the maximum value in a few seconds which dictated the size of the power supply for the superconducting coil. Consequently, one could expect little potential saving in operating cost and perhaps even an increased capital cost because of the need for similar power supplies in the two cases with an additional refrigerator for the superconducting coil. A consideration in the second case was whether or not a significant saving in space could be made with superconducting coils around each sector. It was anticipated that the copper coils would be operated at $j\lambda$ = 4000 A/cm^2, which is near the operating point for large stable superconducting coils and it was decided that the cryogenic system would be complex and prohibitively expensive. Discussions on the possibility of using significantly higher magnetic fields in cyclotrons usually end with the conclusion that present machines are scarcely big enough for the external experimental area equipment to be assembled around them. Consequently, the conclusion seems to be that superconducting coils are not an attractive possibility for cyclotrons unless designers invent new types of machines which utilize the potential advantages of the superconductor.

Superconducting screens to provide field free injection regions, a possible means of varying energy in variable energy machines, or a possible beam ejection system are a possibility. F.F.A.G. machines are very complex and need iron. There would appear to be little to gain by adding the further complexity of superconductors and operating at the same field levels. The very large machines will almost certainly be pulsed unless some entirely new acceleration scheme containing a large number of dc guide magnet paths can be evolved. If one merely considers the AGS type machine design and replaces the existing guide field magnets with iron free superconducting coils at, say, 100 kG, the machine size can be reduced but the power supply will still be large to introduce the field energy. Storage schemes such as flywheels will still be used. Alternatively, completely different approaches to the design problem may be more profitable. One of the main advantages of the superconducting magnet is the small power supply which is required. This is lost in pulsed systems. Copper losses are high in existing machines and it might be that a 20 to 30% decrease in operating cost by the replacement of such coils with superconducting coils would be sufficient justification for the change.

Whether or not pulsed high field superconducting coils are feasible is an open question. In energy storage schemes, the field energy has to be produced quickly for some applications and some encouraging results have been obtained. The high field superconductors have non-reversible magnetization curves and exhibit high energy loss per cycle of magnetization. Such losses depend upon the degree of field penetration and in 0.010 in. diameter NbZr wires have been computed to be much higher than in copper at 60 c/s. The losses can be reduced by reducing the conductor dimensions.

Experiments on superconducting to normal transitions in Nb25%Zr and Nb_3Sn in fast pulsed magnetic fields (dH/dt from 10^9 to 10^{11} Oersteds/sec) have resulted in measured values of upper critical field, H_{c_2}, which are less than 25% of the static field values.[39] In our case, we are interested in slower rates of about 10^5 Oersteds/sec and it would be valuable to have precise measurements in this range. It was observed that the measured values of H_{c_2} under these pulsed conditions increase with decreasing sample size with rapid increases below 0.04 mm (0.0015 in.) diameter. Copper wires of similar size under similar conditions of test would be heated far above the zero field transition temperatures for the superconductors. Consequently, normally conducting coatings on the superconductor should be reduced or eliminated for such applications.

We have pulsed an 8 in. bore, 16 in. long, 6 kG magnet to full field in 0.1 sec. at an average rate of rise of current of 5000 A/sec^2. A small magnet of 1 in. bore has been pulsed to 50 kG in one second.[40] Similar preliminary tests have been carried out in Brookhaven National Laboratory.[41]

Smith, of the Rutherford Laboratory, has suggested that if NbZr conductors of thickness 0.0002 in. can be used, a satisfactory high field magnet for Nimrod could be designed. We have been able to have such material fabricated, but have not yet evaluated it. He speculates that this would enable the energy of Nimrod to be doubled in the next few years with minimum expense and no change of radius. No doubt these possibilities exist and should be studied. In this particular case, the attraction is that little else need be changed in the already existing accelerator complex which provides some reasonable justification for funding a study of the problem.

In considering the feasibility of pulsed superconducting accelerators, we have first to establish the desirability of funding such development studies as are necessary. Consequently, a serious initial study, based on the assumption that pulsed high field superconductors are available would indicate whether or not any significant advantages for the overall accelerator system might accrue from their application. A favorable conclusion would justify the funding of studies aimed at developing low loss, high field pulsed conductors, at least to the point where it could be clearly seen that they were either feasible or not.

VII. Some Thoughts for the Future

1. Materials

While Nb_3Sn, NbTi, and NbZr have been exploited to a considerable extent, intensive studies of other possibilities such as V_3Ga, V_3Si, Nb_3Al, the niobium nitrides, and the search for new materials with higher critical fields or temperatures will undoubtedly continue.

There remains considerable incentive to develop materials which are either inherently stable or at least more stable than those currently available at comparable current densities. Programs to develop techniques for controlling amplitude, distribution, and density of flux pinning sites are typical of those which should lead to improvements in this area.

2. Conductors

Composite conductors of enhanced current density and comparable stability to those now available can be developed by utilizing these more stable materials. Improvements in conductor resistivity, volume to surface ratio, and the interface bond resistance between superconductor and normal metal are also desirable for this reason. The use of Al with its saving in weight, in addition to its superior conductivity at higher magnetic fields, should also be encouraged. Improved techniques for bonding Al to various superconductors should be developed.

Higher field magnets of the order of 3 ft. i.d. and medium field magnets of the order of 10 to 20 ft. i.d. will necessitate the development of high strength composite conductors.

Ultra-high current conductors and very low current conductors will become available. Techniques for fabricating and using conductors of much smaller dimensions than those now available require development. As familiarity with operating techniques and improvements in detecting devices and safety devices is developed, the degree of overcurrent specified as a safety precaution in larger magnets will decrease and consequently, increases in operating current density will follow.

Operating experience with magnets of stored energy in the range of one to five Megajoules will undoubtedly lead to the adoption of safe, unstable designs operated within their stable limit so as to reduce coil volume and cooling area to a minimum while giving maximum current density.

Composite conductors which resemble normal large conductors, with a central space for the cooling fluid, have also been suggested because of the attraction of eliminating the need for helium tanks around the winding.[42]

3. Contacts

Contact resistances of the order of one μohm have been used in many coils. Ribbon type contacts of the order of 10^{-8} ohms are also easily attainable. Reductions in these values will occur as the desire to keep the total system dissipations as low as possible grows. Truly superconducting contacts of various types, which are easy to fabricate, should be developed. Operation of many magnets in the persistent mode will become more general as confidence in this type of operation is gained.

4. Cryogenics

The cryogenic system is a natural part of the superconducting magnet system. Cryogenic engineering technology is well established and the use of the best cryogenic techniques in present magnet systems has probably only been limited because of the novelty of the magnets themselves. Increasing familiarity with these techniques will develop as more people become involved in low temperature work and as management becomes ready to authorize reasonable expenditures for this type of effort.

The importance of good cooling in superconductor applications is now generally realized. Experimentation with various types of cooling system and heat transfer technique will lead to a wide range of acceptable cooling techniques. One simple expedient for obtaining higher currents in shunted superconductors during charge would be the use of a manually operated plunger to move the liquid helium through windings when normal regions tend to appear during charge. The use of self-contained liquid helium circulation systems may permit helium to flow through the windings at least during charge. Supercritical helium at high pressure is also being considered to increase acceptable heat transfer rates by orders of magnitude. Gas cooling has already been shown to be a possibility.

The pressure to develop large helium refrigeration systems below the λ point for superconducting linac development will lead to their more general availability and to their use in magnet operation. Improved performance in Nb_3Sn magnets below the λ point and in some NbZr magnets has already been reported. The elimination of resistive regions due to flux jumps in short samples operated below the λ point has also been observed; this confirms the thermal nature of the problem.[6]

5. Radiation

Little is known about the operation of different types of superconducting magnet in various types of radiation environment. More information is needed on the operating characteristics of the coils under irradiation and upon their anticipated lifetimes under integrated long-term exposure. The results will be colored by the specifics of design and the types of constructional materials used for insulation.

Radiation induced defects appear to enhance the short sample characteristics of some magnet superconductors. This enhancement continues with increasing defect density until a maximum short sample characteristic is reached when further increases in defect density reduce the short sample characteristic. Radiation induced defects seem to anneal out near room temperature. Radiation intensities necessary to induce defects usually cause sufficient nuclear heating within the superconductor to raise its temperature to or beyond the critical temperature. The problem of operation during irradiation, therefore, may reduce to that of limiting the superconductor exposure in the most favorable thermal environment to that which produces a minimal local temperature rise at any point in the winding.

6. Power Supplies

The problems of powering magnets up to 4000 A have been overcome, using cheap reliable supplies, with lead losses of the order of 1 watt/ 1000 A. Flux pumps are not yet generally available, but have reached a sufficient degree of development to sustain normally acceptable losses (of the order of 1 or 2 watts) in most coils. Higher loss rates are scarcely acceptable in any case. Unipolar generators are also available at current levels of 10,000 A and beyond at almost any specified power with zero ripple, and experimentation in this current range is therefore to be expected.

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