SUMMARY OF FIFTH WEEK OF 1968 SUMMER STUDY

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The fifth week of the 1968 Summer Study was devoted to superconducting magnets. The program for the first day was composed of papers concerned with general aspects of magnet design such as force calculations and questions of stability. Bubble chamber magnets were the subject for the second day and reports were presented on all the large magnet systems being constructed or designed for this purpose. The third day was devoted to beam handling magnets with progress reports from the major laboratories designing or building such devices. Thermonuclear applications for superconducting magnets occupied a large part of the discussion on the fourth day along with the most interesting ideas of P.F. Smith on the ac losses and stability of twisted multicore conductors. The fifth day included discussions of the use of superconducting magnets at the 200 GeV accelerator as well as a description of the CERN supercritical helium cooled magnet.

STRESSES

The first paper of the session was by P.G. Marston of Magnetic Engineering Associates and was concerned with the stresses produced in superconducting magnets by thermal, mechanical and magnetic forces. Marston did not cite specific magnets as examples but confined himself to general aspects of magnet design, pointing out sources of stress which are often overlooked such as the interaction between the magnet and induced current in nearby conducting materials during rapid field changes. He emphasized that caution must be used in employing general solutions to specific problems since such solutions can often give misleading results. The use of iron was discussed since it can result in a considerable reduction in the stress and lead to a useful reduction in ampere-turns even at relatively high fields.

The second paper by W.F. Westendorp of the General Electric Company was also about stress calculation. He described a method of calculating the axial and tangential stresses in cylindrical coils with and without reinforcing bands. The results were applied to coils wound from ribbon conductors. Computer calculations were used to prepare monographs which allow the easy determination of the maximum stress and field in simple solenoids if the bore and current density are specified.

HYBRID MAGNETS

The term "hybrid magnet" has been coined to describe magnets only part of which are superconducting. The design aspects of such magnets were outlined by D.B. Montgomery of the National Magnet Laboratory at MIT. Such a magnet can be an economical approach to high fields for laboratories which have on hand large dc generators or helium refrigerators. For fields above about 175 kG hybrid systems must be used since there are no superconductors currently available which will sustain useful current density above this field. Montgomery emphasized this by pointing out that a 120 kG superconducting magnet costs twice as much as a 100 kG magnet and the cost rises even more steeply at higher fields. The choice between water-cooled and cryogenic inner coils depends on what is available at a particular laboratory, and since the Magnet Laboratory is well supplied with dc power Montgomery confined himself to the use of water-cooled inner solenoids. He calculates that if a background field of 100 kG is available from the superconducting section it should be possible to reach 200 kG in a 1.5 in. bore with 2 MW of power while 300 kG would require 10 MW. In conclusion he described a hybrid magnet now being built at MIT where the outer section of an existing 225 kG water-cooled magnet will be replaced by a 60 kG superconducting coil reducing the total power required from 10 to 5 MW.

STABILITY

A review of the steady-state stability of composite superconductors was presented by Z.J.J. Stekly of Avco Everett Laboratories. He derived a set of normalized equations which take into account the cooling of the substrate, the thermal contact resistance between the substrate and superconductor, and the temperature rise in the superconductor itself. These parameters were shown to influence the shape of the voltage current curve at the onset of resistance. Stekly pointed out that for a superconductor strand size smaller than a certain value, the temperature rise in the superconductor is very small and its temperature is essentially the same as that of the substrate. Since it is necessary to have a temperature rise in the superconductor to cause instabilities or "flux jumps," material made from such fine strands should be inherently stable. The question of the inherent stability of finely divided superconductors was the subject of considerable discussion later in the week.

BUBBLE CHAMBER MAGNETS

The second day of the magnet week was devoted to bubble chamber magnets and the first magnet to be described was the one for the 12 ft diameter ANL chamber which was described by J.R. Purcell. This magnet uses a massive iron yoke and has an inner bore of almost 16 ft. Purcell related some of the problems that occurred during construction and pointed out how all very large magnets tend to become somewhat dated even before they are completed due to rapid progress in superconducting technology. The magnet is designed to use fully stabilized conductor and operate at low current density (1000 A/cm^2) with modest heat flux requirements (0.1 W/cm^2) which require only edge cooling of the strip conductor. Some of the details of this and the other bubble chamber magnets are summarized in Table I. The magnet is scheduled for initial cooldown in October 1968.

TABLE I

Bubble Chamber Magnets

Bubble Chamber	Bore (ft)	Central Field (kG)	Conductor	Iron	Stored Energy (MJ)	Status
ANL 12 ft	15.7	18	Nb48%Ti, 6 conductors in copper 2 in. x 0.10 in.	Yes	80	First test scheduled for Oct. 1968
BNL 7 ft	8	30	Nb48%Ti, 6 conductors in copper 2 in. x 0.08 in.	No	72	Tested in gas, Spring 1968
RHEL	5	70	NbTi in copper 5 cm x 5 cm	Shielding only	340	Design stage
CERN	15.5	35	NbTi in copper or aluminum	Shielding only	750	Design stage

The Brookhaven 7 ft diameter magnet was described by A.G. Prodell. This magnet uses a conductor similar to the Argonne coil but operates at higher current density and has partial face cooling of the conductor due to a novel spacer strip which is wound into the coils. A movie was shown of the coils being wound and assembled. The magnet is designed to produce approximately 30 kG in the chamber volume and does not use iron. A partial test of the magnet was made in the Spring of 1968 but due to refrigeration problems the Dewar could not be filled with liquid helium. It was possible, however, to power the magnet to half field in cold gas. Further tests are scheduled when the complete chamber has been assembled.

A design study for a high field chamber magnet was presented by D.B. Thomas of the Rutherford High Energy Laboratory. The design field of 70 kG poses considerably more difficult stress problems than the lower field magnets. Stainless-steel strip wound in parallel with the conductor is expected to give the required strength while "buttons" welded to the strip would provide face cooling of the conductor in a manner similar to the Brookhaven magnet. An iron shield is planned to reduce the stray field and it is incorporated in the support structure. Thomas also described a facility for testing conductor samples and a method of making joints in the conductor using shaped explosive charges. A small coil is being constructed using the conductor intended for the chamber magnet and this coil which produces 50 kG itself is expected to produce 80 kG when used as an insert in the CERN magnet "Braracourcix."

The CERN design study for a very large bore 35 kG chamber magnet was described by F. Wittgenstein. This magnet also used an iron flux shield. A scale model (1:20) of the magnet called "Braracourcix" has been built to study the fringe field. It consists of two coils of 40 cm bore set up to form a split pair. The upper coil is aluminum-stabilized while the lower half has the more conventional copper stabilizing material.

The final paper of the day was given by P.F. Smith of the Rutherford Laboratory and was concerned with possible instabilities in the wide composite conductors being used in the large bubble chamber magnets. Smith pointed out that while a conductor may be designed to carry the full transport current at field without undue temperature rise this may not be true during a flux jump since the magnetization current density is much higher than the transport current density. This effect is most pronounced for wide conductors and for conductors stabilized with low enthalpy materials such as aluminum. While he did not think that any of the coils previously described would be seriously affected, Smith cautioned that the stakes were very high and some experiments were in order.

BEAM HANDLING MAGNETS

The session on beam handling magnets began with an analytical paper by R.A. Beth of Brookhaven. Using a very elegant method of representing magnetic fields by complex quantities he derived ideal solutions for the current density distribution required around the periphery of an elliptical aperture to produce a magnetic field with the desired multipolarity in that aperture. Step function approximations to the ideal distributions were analyzed and coefficients calculated for distributions of up to four separate current density steps. Beth suggested that mechanical inaccuracies and the necessity of placing integral numbers of turns in each step would tend to outweigh the imperfections of the approximation even for three or four steps.

G. Parzen of Brookhaven presented calculations on superconducting dipoles formed from arrays of flat coils with currents chosen to produce a 50 kG central field. He indicated that good field regions could be made with two-plane rectangular arrays and even with single plane coils, although the latter case would lead to a field at the conductor which was 60% higher than the central field.

The first actual beam handling magnet to be described was the CERN quadrupole. The analytical design of this device was presented by A. Asner of CERN while the test procedures and results were given by D.N. Cornish of the Culham Laboratory. The magnet has an effective length of 70 cm and an inner radius of 65 cm of which 5 cm will be at room temperature. The conductor used is rectangular in cross section and has been designed to run at the minimum propagating current at an over-all current density of 15 000 A/cm^2. A small test coil made from this conductor and designed to produce the same field/ampere as the quadrupole has been operated successfully.

A superconducting bending magnet was described by J.D. Lawson of the Rutherford Laboratory. In cross section the windings of this magnet are in the form of two intersecting ellipses which form a circular aperture of 22 cm diameter. The effective length of the magnet is 140 cm and it is constructed from 0.15 in. round multicore conductor. The use of detachable current leads is planned and a flux pump will be used to maintain the field at a constant value.

R.B. Britton outlined the Brookhaven program on beam handling magnets. To date two quadrupoles have been built and a dipole is under construction. The design of these magnets uses the stepped current density approach outlined earlier by Beth. The magnets are made from ½ in. wide Nb_3Sn tape wound with stainless-steel ribbon. The stainless tape serves as an insulation and also to effect the changes in current density. These coils are designed to operate at a very high current density (50 000 A/cm^2) and are consequently very compact.

A quadrupole doublet of 20 cm i.d. and 30 cm effective length was described by J.D. Rogers of LASL. The quadrupole field is produced by changing the radial thickness of winding in one quadrupole while the other uses aluminum spacers to vary the effective current density.

PULSED MAGNETS

The author described some recent experiments on pulsed superconducting magnets made from Nb_3Sn ribbons. The results indicate that reliable magnets capable of being pulsed to 50 kG in one second can be constructed and made to operate at very high current densities. The losses incurred during pulsed operation are too large to permit the use of such magnets in synchrotrons at least with presently available conductors but it is expected that more suitable materials will be available in the near future.

INTRINSICALLY STABLE CONDUCTORS

One of the highlights of the week was a paper by P.F. Smith of the Rutherford Laboratory outlining his work on filamentary superconductors. Smith began his discussion by pointing out that very fine wires should be subject to very small temperature rises during a flux jump and should thus be inherently stable when smaller than a certain diameter. He then extended this to include fine strands of superconductor in a conducting matrix and showed that a conductor formed in this way would act the same as a solid superconductor if its length exceeded a certain value which is always short relative to the lengths used in magnets. He then suggested that by twisting the wire with a pitch shorter than this characteristic length this coupling between the filaments could be removed with a corresponding increase in stability and reduction in ac losses. Smith then described an extensive experimental program designed to test his conclusions. He indicated that preliminary results were in good qualitative agreement with the theory.

THERMONUCLEAR DEVICES

A survey of the uses of superconducting magnets in controlled thermonuclear experiments was presented by C.E. Taylor of the Lawrence Radiation Laboratory. In almost all experiments of this type magnetic fields are used to confine the charged particles of a plasma. In general such plasma containment devices can be divided into two classifications, "open ended" and "closed ended" machines. The fields required do not usually exceed 60 kG and are thus within the range of present NbTi technology. While superconducting magnets are used in most applications because they are more economical than conventional devices there are some applications where the unique properties of superconductors make them indispensable. An example of this is the floating ring type of experiment in which a ring containing persistent supercurrents is levitated in a magnetic field forming part of the plasma containment vessel. Taylor listed the principal CTR experiments now being planned which utilize superconducting magnets.

The next speaker, W.F. Gauster of the Oak Ridge National Laboratory, described in more detail the superconducting magnet system designed for the IMP project which was mentioned by Taylor. This system consists of two mirror coils and a quadrupole whose fields combine to produce a configuration which has a central field of 20 kG and which increases to at least 26 kG in any direction from the center. The peak field in the system is 75 kG. Gauster pointed out the difficulties in calculating the forces in such a nonaxisymmetrical system. The experimental program associated with the design and construction of these magnets was described by D.L. Coffey. To test the conductors a series of solenoids were constructed with their windings in series opposition to approximate the forces and gradients experienced in large systems. To date the mirror coils have been built and tested and will be installed in the Fall of 1968. The complete system is expected to be operating by 1969.

SUPERCONDUCTING MAGNETS AT THE 200 GeV ACCELERATOR

R. Meuser of LRL discussed the possible uses of superconducting beam handling magnets at the new 200-400 GeV accelerator being constructed at Weston, Illinois. His survey indicated that about 250 magnets would be required, with 77% of them being quadrupoles and the rest bending magnets. It was estimated that approximately half of these magnets would require radiation shielding and about 40% would be used in beams which would become shorter due to the higher fields and gradients available. Meuser pointed out that current density becomes increasingly important for magnets of small aperture and higher multipolarity and suggested that due to the uncertainties in costs both Nb_3Sn and NbTi based design should be investigated. He finished by describing the test program at LRL, which includes operating a long solenoid with a closed loop refrigerator.

FORCED HELIUM COOLING

A magnet constructed from hollow superconductor was described by M. Morpurgo of CERN. The conductor was formed by embedding superconductors of 0.01 in. diameter in an aluminum pipe. The magnet was then cooled by forcing helium through the hollow conductor. The solenoid appeared to operate in a completely stable fashion and could be operated slightly into the resistive region without quenching.