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# SUPERCONDUCTIVITY FOR HIGH ENERGY PHYSICS AT LRL-BERKELEY†

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The LRL-Berkeley superconducting program related to high energy physics is described in functional terms. DC magnets for use in accelerator experimental areas are discussed as are pulsed magnets as would be appropriate to a proton synchrotron. Fundamental studies and areas of cryogenic engineering and system investigations are outlined.

## 1. INTRODUCTION

Superconducting magnet systems have been under study at LRL-Berkeley since 1965, first in the 200 GeV Accelerator Study Group, and later in the Advanced Accelerator Study Group. We here refer to magnets specifically for use with high energy accelerators and associated physics experimental areas. Other groups at LRL have built and used superconducting magnets for other uses: chemistry, inorganic materials, solid state physics, cosmic ray studies.

In the course of the 200 GeV study, we investigated the relative costs and advantages of utilizing superconducting transport elements which, technologically, seemed to be just coming of age. The initial studies showed that the superconducting magnets might be competitive in costs with the conventional copper and iron magnets in the experimental area, but the uncertainties were larger than the indicated cost difference between the two approaches. A joint LRL-NAL superconducting program, conducted at LRL, was funded in FY 1968–1969 with its major goal of reducing the uncertainties involved in using superconducting transport elements in the 200 GeV experimental areas. During FY 1970 our major emphasis shifted to Bevatron area magnets which generally are of larger aperture and are shorter than those needed for the 200 GeV accelerator.

Cryogenic engineering, cryogenic system studies and operational tests comprise an important portion of our overall program. Fundamental studies of superconducting material include measurements on magnetization, flux jump stability, pulsed losses, and magnetic fields. The study and development of pulsed magnets, such as would be used in a synchrotron, are included in our overall program.

## 2. DC TRANSPORT MAGNETS

### 2.1. *3-foot long solenoid*

In order to get operating experience in using a superconducting magnet in a physics experiment an end corrected solenoid was operated at the 184-in. cyclotron. Neutrons were analyzed through the interaction of their magnetic moments with the solenoid's axial magnetic field. The warm bore is $4\frac{1}{4}$ in. diameter, the overall length $3\frac{1}{2}$ ft, and the axial magnetic field some 60 kG. The magnet was kept superconducting for the entire run of $5\frac{1}{2}$ months in late 1968.(1,2) The magnet contains 130 lb of superconducting wire and is shown in Fig. 1. The cryostat appears in Fig. 2.

### 2.2. 4-*in.* i.d. *dipole*

A bending magnet with a 4-in. i.d. and a field of approximately 30 kG is appropriate to the 200 GeV physics experimental area. Figure 3 displays a most successful magnet in this range. Flat pancakes were wound with rectangular, twisted, multicore conductor 0.050 in. × 0.125 in. These pancakes were then bent to shape and assembled into the final configuration. With 4 layer thickness winding, material short sample behavior was achieved with and without an outside concentric iron return yoke. The central field without iron is some 27 kG; with iron 35 kG. The overall magnet length is $1\frac{1}{2}$ ft. Details of these magnet tests are given in UCRL-18885.(3)

### 2.3. 6.5 *in.* i.d. *dipole*

A larger bending magnet was constructed through a winding in place technique. The i.d. is

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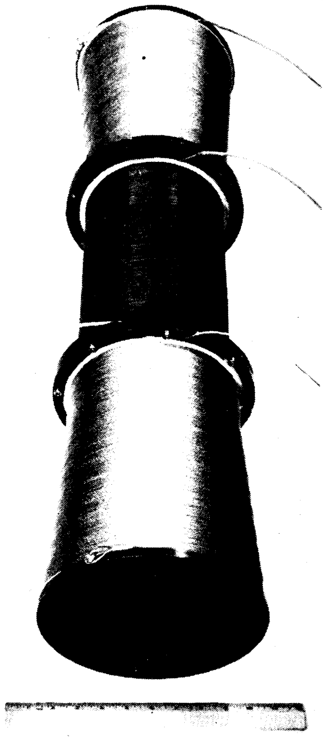

FIG. 1. 3-ft long solenoid.

6.5 in. and the length is approximately 3 ft. Rectangular multicore conductor 0.052 in. × 0.127 in., with Formvar insulation, was used. Eight layer thicknesses were used and the design central field was 35 kG. The conductor was untwisted causing instabilities that resulted in degraded magnet performance—the final central field was close to 20 kG.

2.4. *Bevatron area dipole*

We are now fabricating a bending magnet for Bevatron area use, using twisted, rectangular, multicore conductor. A clear warm bore of 8 in. diameter and a central field of 40 kG requires 10 layers of rectangular conductor ($\frac{1}{8}$ in. high) to be used. The winding length is 40 in., and the cryostat length is 53 in. Approximately 400 lb of conductor are needed for this magnet.

2.5. *Bevatron area quadrupole doublet*

A quadrupole doublet to match the above dipole is also being fabricated. The clear warm bore is 8 in. diameter and the design field gradient is 6 kG inch$^{-1}$. Each of the quadrupoles is 29 in. long and the doublet fits into a cryostat 67 in. long.

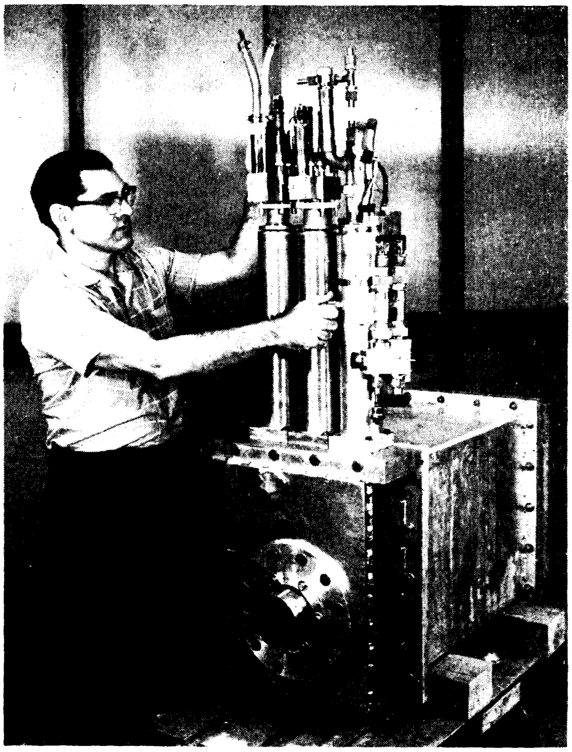

FIG. 2. Warm bore cryostat containing solenoid.

2.6. *Large volume magnets*

Large volume magnets, based on Helmholtz coils, for bubble chambers, spark chambers, and target spectrometers have been investigated. A set of target spectrometer types called backstop magnets have gone through the conceptual design stage. One particular design has been carried farther; the design field is approximately 60 kG and the total bending strength is 1.0–1.5 MG-inch. Final design and fabrication will follow the dipole and quadrupole doublet fabrications discussed above.

## 3. FUNDAMENTAL STUDIES

3.1. *Magnetization tests*

Fundamental information on superconductor behavior can be obtained from magnetization tests on small samples. One can obtain the dependence of the hysteresis loss on the type of superconductor, the filament size, twist rate. Flux

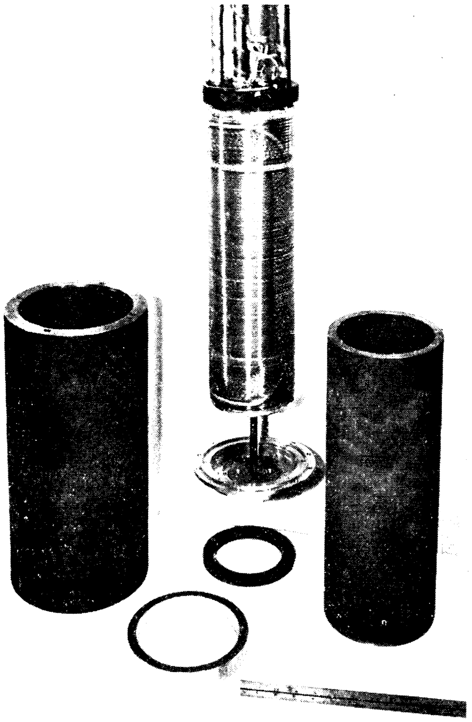

FIG. 3. Dipole transport magnet.

jump behavior is also obtainable. Our older apparatus uses a pair of collinear pickup coils in a solenoid with an i.d. = $5\frac{1}{4}$ in. and a length of 10 in. The maximum sweep rate of 5 kG/sec between 0 and 40 kG is determined by our power supply. Our new facility uses coaxial pickup coils in a smaller solenoid which allows one to sweep the samples at rates as high as 50 kG/sec between 0 and 38 kG.

### 3.2. *Short sample testing and superconductor resistivity*

A variety of test magnets and measurement methods have been used in short sample testing. It has only recently become apparent that the results are variable depending on the test methods and acceptance criteria. The resistivity of a superconductor, near its current limit, ranges from $10^{-14}$ to $10^{-11}\ \Omega\cdot\text{cm}$ and some materials have even worse resistivities (as high as $10^{-9}\ \Omega\cdot\text{cm}$). The voltage sensitivity for these tests is better than 1 $\mu$V.(4)

### 3.3. *Magnet degradation*

Several solenoid magnets, all of the same size, have been wound with different conductors to search for correlations between magnet degradation and results of short sample and magnetization tests. Solenoids of different sizes wound with the same conductor have been built to investigate the dependence of magnet degradation on the magnet stored energy, helium ventilation, and method of construction.

### 3.4. *Losses in pulsed magnets*

We have been measuring losses in pulsed magnets for several years. An electrical multiplier method is primarily used although we have used a helium boil-off measurement method for cross checks.(5,6)

### 3.5. *Magnetic field measurements*

Considerable computation effort is involved in performing two-dimensional and three-dimensional calculations for solenoids, dipoles, and quadrupoles. The computations cover both air-core and iron-shielded magnets.

Measurements in liquid helium involve either: integrating the voltage on a pickup coil, which requires either movement of the coil or a change in the field; measuring a property that depends on the field, such as the resistance in a bismuth magnetoresistance probe. We are using all of these methods in our studies of superconducting magnets.

## 4. CRYOGENIC ENGINEERING AND SYSTEM STUDIES

### 4.1. *Cryostats*

Two horizontal warm bore cryostats have been fabricated. One was for the solenoid discussed in the dc transport magnet section; the cryostat length is $3\frac{1}{2}$ ft. A larger cryostat, $4\frac{1}{2}$ ft long, will contain the Bevatron dipole discussed in the same section. One cryostat, $5\frac{1}{2}$ ft long, to house the quadrupole doublet discussed has been designed and fabrication is about to begin. All cryostats tend to be expensive and new problems are anticipated for the nonmetallic cryostats that will be required for the low loss, pulsed magnets that are required for superconducting synchrotrons.

### 4.2. *Refrigerator-liquefier*

We have been operating a helium refrigerator-liquefier for over a year. The refrigeration capacity is 35 W at 4.2 °K and liquid can be produced at 9 liters/hour. The system runs unattended and has been running for over 70 per cent of the total possible time (24 hours a day basis). An impure helium recovery system is being added.

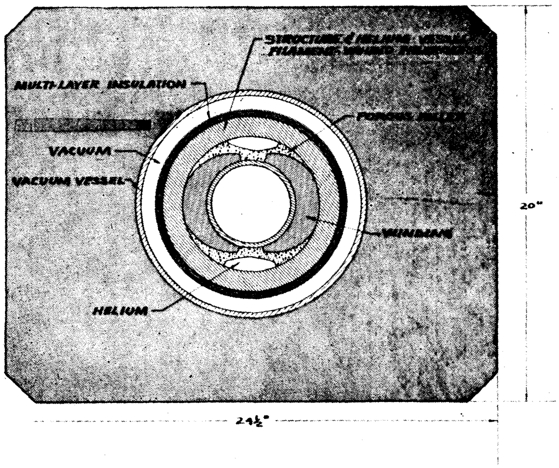

FIG. 4. Synchrotron magnet-cryostat.

4.3. *Cryogenic engineering and total system studies*

The role of superconducting magnets in accelerator experimental areas and superconducting synchrotrons is strongly influenced by the economics of the refrigeration system. Several studies have been made.$^{(7-9)}$

## 5. SUPERCONDUCTING SYNCHROTRON

A conceptual study on pulsed superconducting synchrotrons has been carried out under the general programs discussed above. The dipole magnet in its integral fiberglass structure-cryostat is shown in Fig. 4. The cold bore is 4 in. diameter and the field is 51 kG. The overall current density is 20 000 A/cm$^2$ at the maximum field of 56 kG which occurs in the end windings; this is a fairly conservative current density for this material. With multifilament NbTi superconductor with filament diameter of 0.3 mil (7 $\mu$) the stored energy is 0.30 MJ/m and the pulse loss is 250 J/m cycle. The reference magnet in a typical tunnel cross section is shown in Fig. 5.

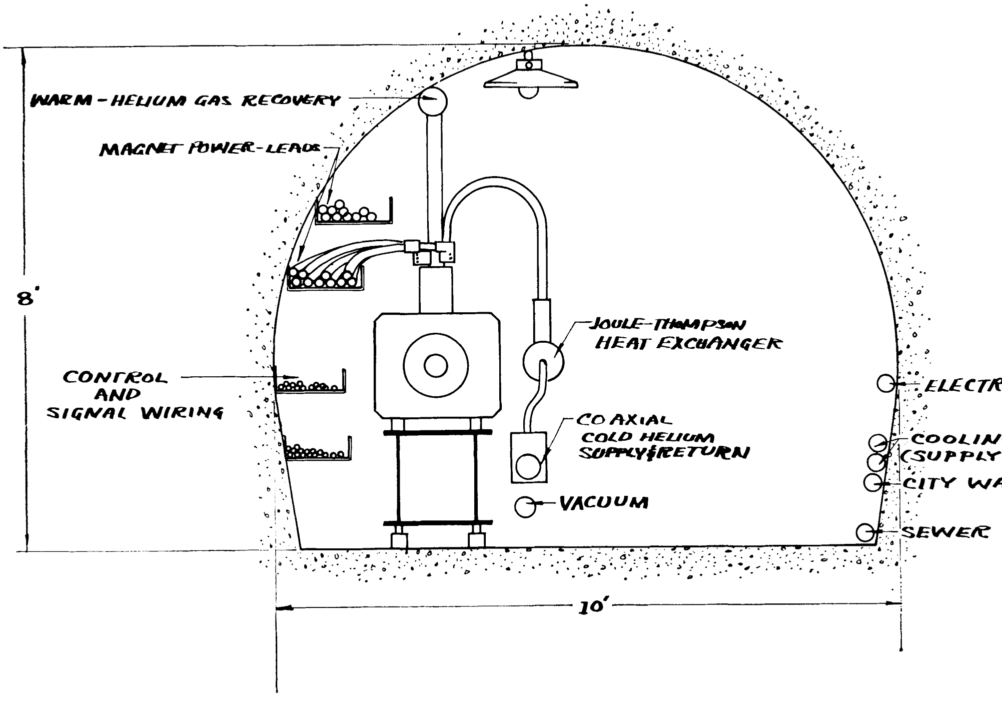

FIG. 5. Synchrotron tunnel cross section.

Magnets similar to the reference design are under development. Superconducting synchrotrons appear to offer economical and attractive solutions to the problems of building future accelerators once satisfactory pulsed magnets have been demonstrated.

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