A DC SUPERCONDUCTING BEAM SPLITTING MAGNET SYSTEM*

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Abstract

A dc superconducting beam splitting magnet was fabricated and tested at BNL. This component will be used to deflect high intensity protons onto two target stations during the same AGS pulse. This paper describes in detail the magnet system, the cryostat and the refrigerator. Initial fabrication difficulties are presented, and test results are included.

I. Introduction

The high energy accelerators today, because of their increased energy and high intensity, require that the proton be extracted into external areas for targeting. A beam of 10^{13} protons per pulse will be available in the near future at the AGS. The most efficient way of utilizing this high intensity beam will be by sharing on multiple target stations on the same machine pulse.

A device used to achieve this goal is the beam splitter system designed at BNL[1] which consists of several splitter magnet units separated by beam drift space. The separation of the two target stations and the available space in the direction of beam line require that the last unit of the splitter system should be capable of producing a total bend angle of $\pm$ 19 mrad at a beam energy of 30 GeV and the septum thickness of this unit is limited to .350 in. because of the weak kick capability of the prior units in the system.[1]

II. Splitter Magnet Design

General Design Considerations

Beam optics dictate that the aperture height of this magnet be 1 in. We selected the length of the magnet as 48 in. This length was considered to be reasonably short enough for us to produce such a magnet for the first time without too much difficulty and the magnetic field required to produce the desired kick was a reasonable 15.5 kG. The septum thickness of .350 in. consists of two widths of conductor plus the vacuum chamber walls plus insulation. This limits the conductor width to within .120 in. the overall current density is 41 kA/cm^2, with an anticipated conductor packing factor of 90%, the current density of the conductor would have to be 45 kA/cm^2 minimum.

The current carrying leads represent a large heat leak into the 4.2° K helium bath. The magnitude of the heat leak is greatly dependent on the amount of current it carries. Therefore, it is imperative for a magnet designer to lower the current requirement as much as practical. In order other words, the number of conductor turns should be kept as high as possible; this will increase the aspect ratio (ratio of the width to thickness) of the conductor in our case, beyond the practical limit of NbTi type material.

Therefore, Nb_3Sn solid ribbon with its combination of high current density, small cross-sectional area, and 18°K critical temperature was chosen as the conductor for this magnet. It is partially stabilized with copper strips on both sides of the superconductor. The physical dimensions of the ribbon composite are .007 in. thick x .118 in. wide. The manufacturers measured current carrying capacity was 450 A at 20 kG. Nb_3Sn is a ceramic-like intermetallic compound on the surface of a thin strip of Nb having a total thickness of .001 in. such that even with copper cladding the ribbon composite is very difficult to work with due to the brittleness of the superconducting compound. However, the large aspect ratio and high current carrying capacity enables us to obtain a thin splitter septum and to minimize the heat leak into the dewar.

Magnet Design

The splitter magnet shown in Fig. 1, consists of two apertures side by side. Since the magnetic pressure at each aperture is equal in magnitude and opposite in sense, the septum will not be subjected to a net force. Therefore, it is not necessary to constrain the septum laterally. The coil is a conventional saddle type. The flux lines are perpendicular to the face of the conductor within the pole face. Since the conductor cannot be bent edgewise due to its brittleness, the saddle portion of the coil consists of two equal and opposite smooth twists, the turns stacked on a 30° inclined surface with compound curves. This surface enables us to produce a coil saddle end without any mechanical kink. A pair of cast aluminum end blocks are used as part of the winding fixture and these blocks are incorporated in the actual magnet and serve as a support for the coil ends. The upper and lower blocks are rigidly mounted on a strongback on each end of the magnet, the upper blocks rest on the top of the vacuum chambers, the lower blocks are kept in proper position by the strongback. See Fig. 2. The azimuthal magnetic forces which act upon the upper and lower coil ends, are equal in magnitude and opposite in sense. Therefore, the strongback is in perfect equilibrium position at all times. There is no mechanical tie between

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the strongback and core. The difference in cooling rate between coil package and core is quite large. The conductor would have been overstrained if a mechanical tie existed between the coil and the core.

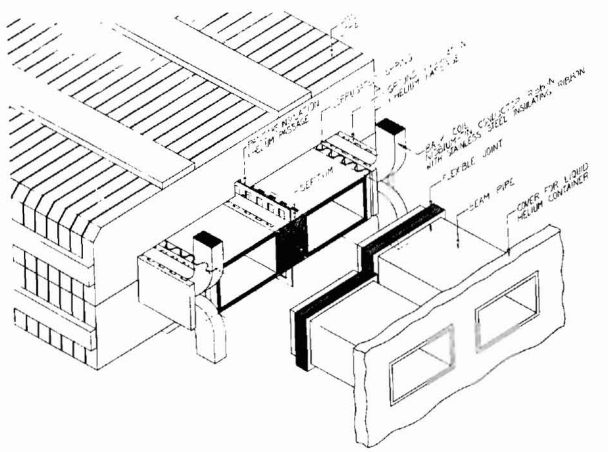

Fig. 1. Splitter magnet

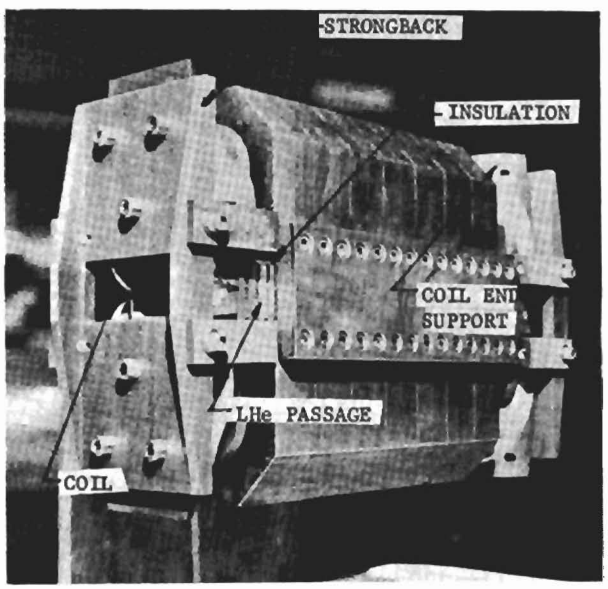

Fig. 2. 8 in. long model

A hard anodized aluminum strip of .016 in. thick is placed vertically between the pancakes as the insulation medium. There are a series of vertical slots machined on the strip, which occupy approximately 50% of the area, so that the coolant is directly in contact with the edges of the conductors, and these slots also serve as the escape passage for the helium. There are similar strips placed between the coils and the vacuum chambers, and between the coils and the steel. The insulation between turns is obtained by using a layer of very thin stainless steel ribbon (.0005 in. thick x .118 in. wide) which enables us to obtain a packing factor of 93%.

There are two sets of beryllium copper springs placed between the vacuum chamber and the back coil insulation strip, these springs exert a total force of 286 lb on the whole length of the coil. These springs keep the assembly tight at 4.5°K. The maximum possible tension on the conductor due to this force is approximately 0.5 lb, which is 25% of the allowable tension for the particular conductor we chose for this magnet.

The side wall of the vacuum chamber contributes to a part of the septum thickness. In order to achieve the required thickness of septum, we chose a cold bore approach. On the end of the vacuum chamber there are rectangular bellows which serve three purposes:

1) To compensate for the differential contraction rate between the vacuum chamber and the helium vessel.
2) To facilitate the assembly of the coils. (The chambers can then be pushed apart.)
3) To provide lateral motion under the spring load, which in turn keeps the septum tight at low temperature.

The steel used for this magnet is SAE 1006. The permeability of this steel at 15.5 kG induced field is 1200[2] at 4.2°K. The core is made up of 0.5 in. thick steel plates welded together with a separation of .010 in. between each plate. This not only speeds up the cool down time but also provides an escape passage for the helium.

An 8 in. long "C" magnet model shown in Fig. 2 was fabricated to verify the feasibility of winding such a coil configuration with Nb_3Sn ribbon and also to prove the soundness of the mechanical design. The choice of the steel length was determined by the existing helium dewar available to us at that time. The winding tension on the .007 in. conductor was controlled by a simple frictional brake built into the supply spool. The stainless steel insulating tape was .0002 in. thick. The braking torque on the conductor supply spool was kept constant, the tension on the conductor was 3 lb maximum, however, the tension for the .0002 in. thick stainless steel tape was near zero. The complete coil was wound by manipulating the winding fixture by hand. The model was tested in both a vertical and a horizontal position involving a total of twelve runs. The model was thermally cycled four times during the test runs. A peak current of 500 A was achieved easily with a conventional dc power supply. A charging voltage of 10 mV was sufficient to reach the peak current within 15 min. The overall current density reached approximately 90 kA/cm^2, and the measured field in the gap was approximately 28 kG. Therefore, the short model seemed to prove that the current density chosen for the actual splitter was adequate and reasonably conservative.

The effect of the number of turns on the leakage field was studied,[3] since only a small fraction of the septum carries current. It showed that the fifty or more turns of ribbon would produce a leakage field past the septum which is essentially the same as that produced by a solid conductor septum. The leakage field for this short model was computed to be 77 G at 16 kG. A measurement was made at a point .1 in. from the septum face and it was found that the leakage field was 50 G at 16 kG. This is in reasonable agreement with computed results.

A more elaborate winding fixture, shown in Fig. 3, with an automatic tension control system was fabricated for the full scale coils. Few modifications were made to assure a better result; however, the maximum allowable tension on the conductor was lowered from 3 lb to 2 lb and the stainless steel ribbon thickness was increased from .0002 in. to .0005 in. to eliminate any possible breakage during winding. All the superconducting material was tested cold on a solenoid form before use.

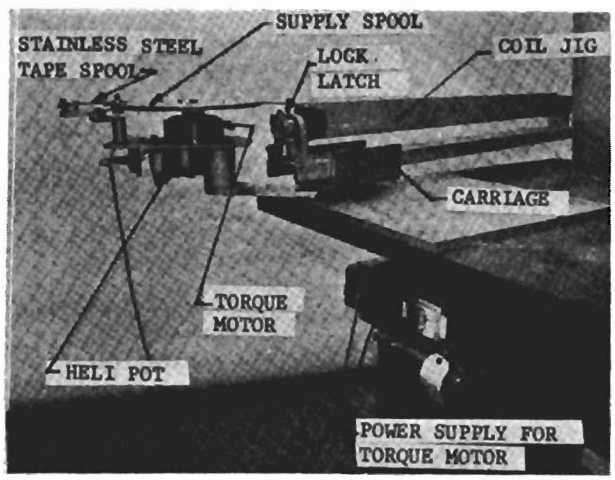

Fig. 3. Coil winding fixture.

The magnet was first tested in a 2 ft by 10 ft vertical dewar during the early part of May, 1972. It was operated under a closed loop system with a CTI Model 1400 refrigerator/liquefier. See Fig. 4. It was run for three days with power supplied either through a flux pump[4] or from an external power supply or a combination of both. See Fig. 5. The magnet coil showed an excessive resistance of $2.0 \times 10^{-4}\ \Omega$ at a current of 166 A. The maximum current obtained, without overloading the power supply and cryogenic system, was 177 A, equivalent to a field of 11.8 kG, (a field of 15.5 kG is required). The flux pump alone was able to raise the current to 155 A.

To understand and eliminate the resistance problem, the magnet was disassembled and a close inspection was made of the coils and the connections. The following findings are believed to be the cause for the excessive resistance:

Fig. 4. Refrigerator/liquefier

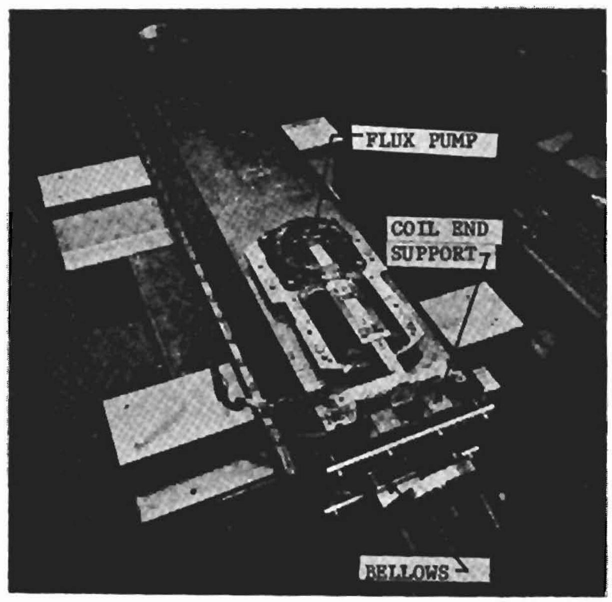

Fig. 5. Bottom view of magnet.

a) The ductility of the ribbon was less than that of the ribbon used for the short model magnet such that the full scale coils suffered unexpected fracturing.
b) A certain amount of stretching of the superconductor was found, especially in the initial turns where the sharpest radie occur.
c) Kinks were found in some of the conductors.

New superconducting material was wound onto a 3.5 in. diameter by 4 in. long solenoid form and tested for current and voltage drop before using. Approximately 1 mV maximum voltage drop at 400 A minimum current was allowed for each ribbon length of about 660 ft. This could not be achieved with enough ribbon to make all four coils and it was finally discovered that 400 A through this coil length a 3.5 in. bore form is sufficient to stretch and create resistance in the inner turns of the test coil unless it is very tightly and uniformly wound. The test method must therefore be revised before the next magnet is built.

Other mechanical and electrical tests were made on the ribbon and its joints which may be summarized as follows:

a) 3 lb straight tension caused no measurable electrical damage.
b) Bending over a 1.5 in. diameter with no tension caused no electrical damage.
c) 1 lb tension over 1.5 in. diameter caused electrical damage.
d) Bending over 0.75 in. diameter with no tension caused electrical damage.
e) Pb-Sn eutectic solder joints show 100 times lower resistance at $4.2^{o}K$ at 10 kG level than a pure indium joint as used in the model.

In view of the results of these tests, the coil jig was inspected and modified and new coils were wound with increased care. All joints were made with Pb-Sn solder. Each coil was tested individually for current limit (480 to 530 A) and voltage drop across each of 3 to 10 sections formed by inserting emf taps in the coil. The voltage drop totals were all less than 1 mV at 400 A which was our estimated tolerance. In every case, some resistance was found across the first few turns and probably resulted from the initial winding radius being too small (about 0.375 in.) at the 4 right angle bends on each turn.

The magnet was reassembled and set up for retest in the vertical dewar on July 14, 1972. The flux pump was turned on and in less than a minute it stopped working due to shorts in the leads. Enough control of the pump still existed, however, to open the magnetic switches so that an external dc current could be applied to the magnet. By this system, the magnet was then energized and held at various field levels up to 21 kG over a 5 day period. The total voltage drop of all coils and joints at 21 kG or 319 A was 1.37 mV for a total resistance of $4.4 \times 10^{-6}\ \Omega$. Fifty-two percent of this resistance was in the inner 12 turns of coil #2 and 39% in the inner 18 turns of coil #3. Since this was above the intended field of operation and still below the measured power output curve of the flux pump, the magnet coils were then considered acceptable.

III. Magnetic Measurements

The method used to measure this magnet is straightforward and economical. There are 18 search coils per gap. Each search coil consists of 500 turns of wires. Nine of the coils are mounted at each end of a 12 in. long phenolic block, the height and width of this block are slightly smaller than those of the inside dimensions of the vacuum chamber and are held against the septum face by a leaf spring squeezed between the block and the side wall of the vacuum chamber. The field was mapped across the width of the gap at three different places, namely, .100 in. from the septum face, at the center of the aperture and at .250 in. from the back coil. The field was also mapped across the height of the gap at three different places, namely, the median plane, the upper pole face, and the lower pole face. The measurements were done at both 10 kG and 16 kG. The data were obtained by sliding the search coil block azimuthally in and out of the magnet aperture. See Fig. 6. A total of 72 runs were made. The current to the magnet was continuously adjusted to maintain a constant field. The field uniformity in both gaps was found to be within 0.5%.[5] The accuracy of the measurement is believed to be within a few tenths of a percent.

IV. Dewar Design

The shell of the helium container is made of .093 in. thick austenitic stainless steel. A reversed "T" bar is welded to the top of the shell and serves as a magnet support and an assembly fixture. The magnet assembly is fixed to the "T" bar at one end and free at other end. This allows the magnet to slide freely along the longitudinal axis during the cool-down period. The helium container with the magnet attached are hung at two points located outside of the shell by a pair of bicycle chains. See Fig. 7. The chain arrangement greatly reduces the thermal loss due to its numerous contact surfaces. A welded thin wall bellows is used to separate the thermal insulation vacuum space from the beam vacuum enclosure. This avoids contamination of the insulation space due to the accidental dumping of the beam vacuum enclosure. There are also quick acting gate valves on each end to isolate the cold beam vacuum chamber of the magnet from the room temperature beam pipe. This should prevent a prolonged period of exposure of the cold surface to the atmospheric surrounding in the event of a vacuum fault of the system on either side of the splitter. Multilayer superinsulation is used for reducing the radian thermal loss. (Double faced aluminized mylar plus a layer of polyester separator is the insulation scheme adapted.) The superinsulation density is 44 double layers per inch. A total of 77 double layers are used for an insulation thickness of 1 3/4 in. The estimated ideal apparent thermal conductivity is approximately 1.5×10^{-5} Btu/hr ft^{o}R.[6] One service stack is located at each end of the dewar. This allows the penetration of the helium supply and return lines plus an emergency vent tube at one end of the dewar. The flux pump leads, contingency current leads, liquid level, thermal couple leads, voltage tabs and another emergency vent are located at the other end of the dewar. The vacuum tank is made of .375 thick aluminum alloy. The indium alloy will be used as cold joint seals, however, the metal "G" type seal is used for the room temperature joints. A set of radial adjustments are located at each end of the helium container which will enable us to make adjustments after the magnet assembly is cooled down to 4.5°K, if necessary.

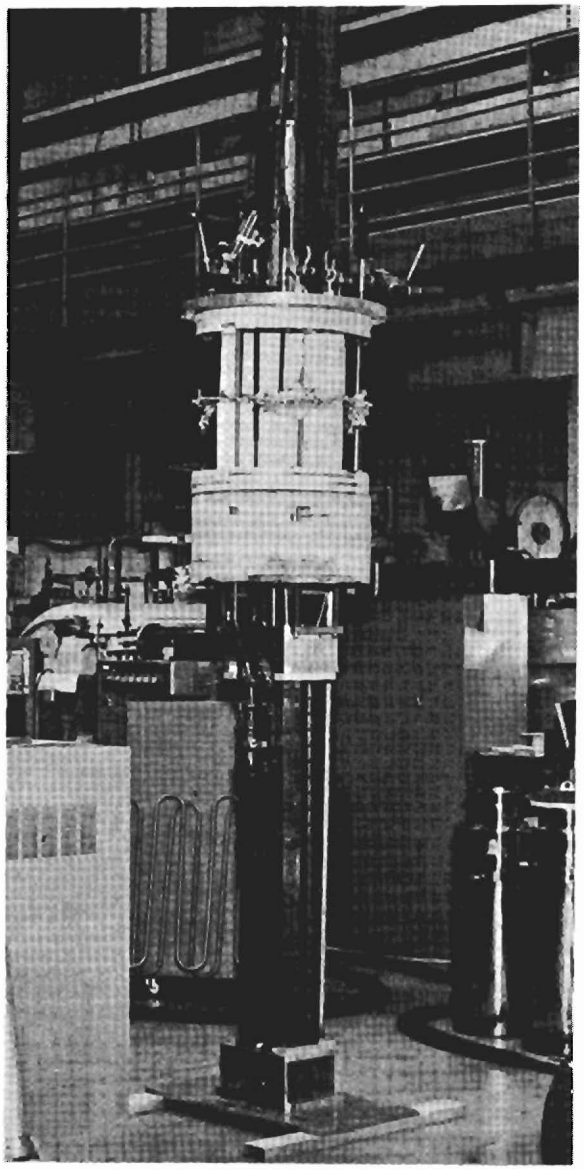

Fig. 6. Magnet ready for magnetic measurement.

V. Refrigerator/Liquefier

The refrigerator/liquefier will be located outside the beam cave, which is convenient for routine maintenance and daily inspections. The transfer line required a 20 ft each way with a 6 ft long flexible portion which will allow a lateral adjustment of the magnet assembly. This feature is required for beam sharing. The rigid portion of the line is buried underneath the concrete shield, however, there is a bayonet connection located at each side of the shield which will enable us to retract the whole line without great difficulty in the event of trouble. The remotely controlled J-T valve is located at the dewar.

The heat load of the dewar system is estimated at 15 W for the flux pump mode and the loss in the transfer line is estimated at 13 W. A total refrigeration capacity of 43 W is needed if a safety factor of 2 is applied to the dewar loss estimate. Should the flux pump develop trouble, external current leads will be used which will add an additional 3 W to the requirements.

The helium refrigerator/liquefier chosen for this project is a Cryogenic Technology, Inc. Model 1400 with dual compressors and a LN_2 pre-cooling provision. This machine is rated at 70 W at 4.5°K or 24 liter/hr with LN_2 pre-cooling, 52 W at 4.5°K or 11 liter/hr without LN_2 pre-cooling. We have chosen this high capacity machine for the following reasons:

a) A decreased cooldown time will shorten the downtime of the beam line.
b) During steady state conditions the system could operate without LN_2 pre-cooling.
c) The added compressor will provide a back-up during routine maintenance and repair.
d) The additional cost for the second compressor was reasonable.

Figure 8 shows the basic cryogenic system schematic. The pre-cooling gas is distributed along the whole length of the magnet by a sprinkler pipe. See Fig. 9. This will not only minimize the cooldown time, but also reduces the thermal stress due to uneven cooldown. There are two features which are somewhat different than in the standard machine. First, manual valves have been installed in the cold box to allow proper utilization of available refrigeration in the low pressure return gas stream. The heat exchangers can be completely bypassed or gas can return to the discharge side of either the first or second expansion engine, and finally the return gas can pass through the J-T heat exchanger. Second, two separate vacuum-jacketed super-insulated transfer lines are used instead of the standard coaxial type of line.

Both machine and transfer lines have been tested in the cryogenic facility at the AGS. The machine performs satisfactorily, the loss for the transfer line is approximately 10 W. The machine was operated in conjunction with magnet testing for 800 hours. The machine, when properly operated, can run unattended for long periods and deliver constant refrigeration.

VI. Present Status and Future Plans

The magnet is presently being assembled into its own dewar. The completed assembly will be tested in a simulated field condition for an extensive period of time. It will also be cycled thermally many times during the testing period. This should reveal the effect of the thermal cycling on the magnet assembly. The reliability of the indium sealed joints can also be studied. A sudden dumping of beam pipe vacuum will also take place to study the effect of such a shock upon the system performance.

VII. Acknowledgement

The authors wish to express their gratitude to Dr. A. van Steenbergen of the AGS Division for his continuous support for this project. Our special thanks to Mr. K. Robins who has operated the equipment for tests while R. Britton was absent. Without his ingenious improvisations, the second test would have been delayed due to the burnout of the flux pump wires. We also would like to express our appreciation to the following persons: Mr. F. Abbatiello for his work in flux pump and coil winding; Mr. J. Allinger for his work in the cryogenic support system for the full length magnet cold tests and the magnetic measurement device; Messrs. S. Hsieh and J. Weisenbloom for their work in magnetic measurement; and Mr. R. Rohrbach for his work in cryogenic systems.

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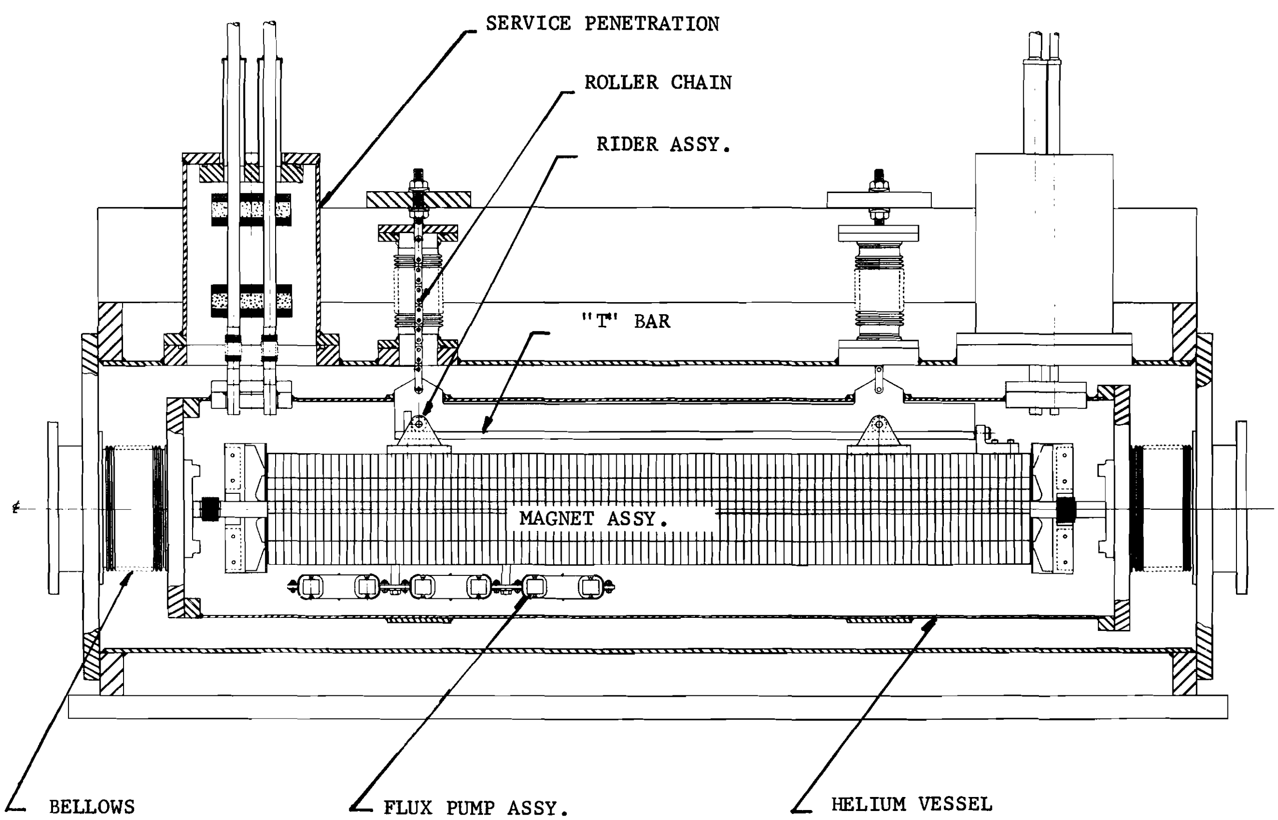

FIG. 7 SUPERCONDUCTING SPLITTER DEWAR

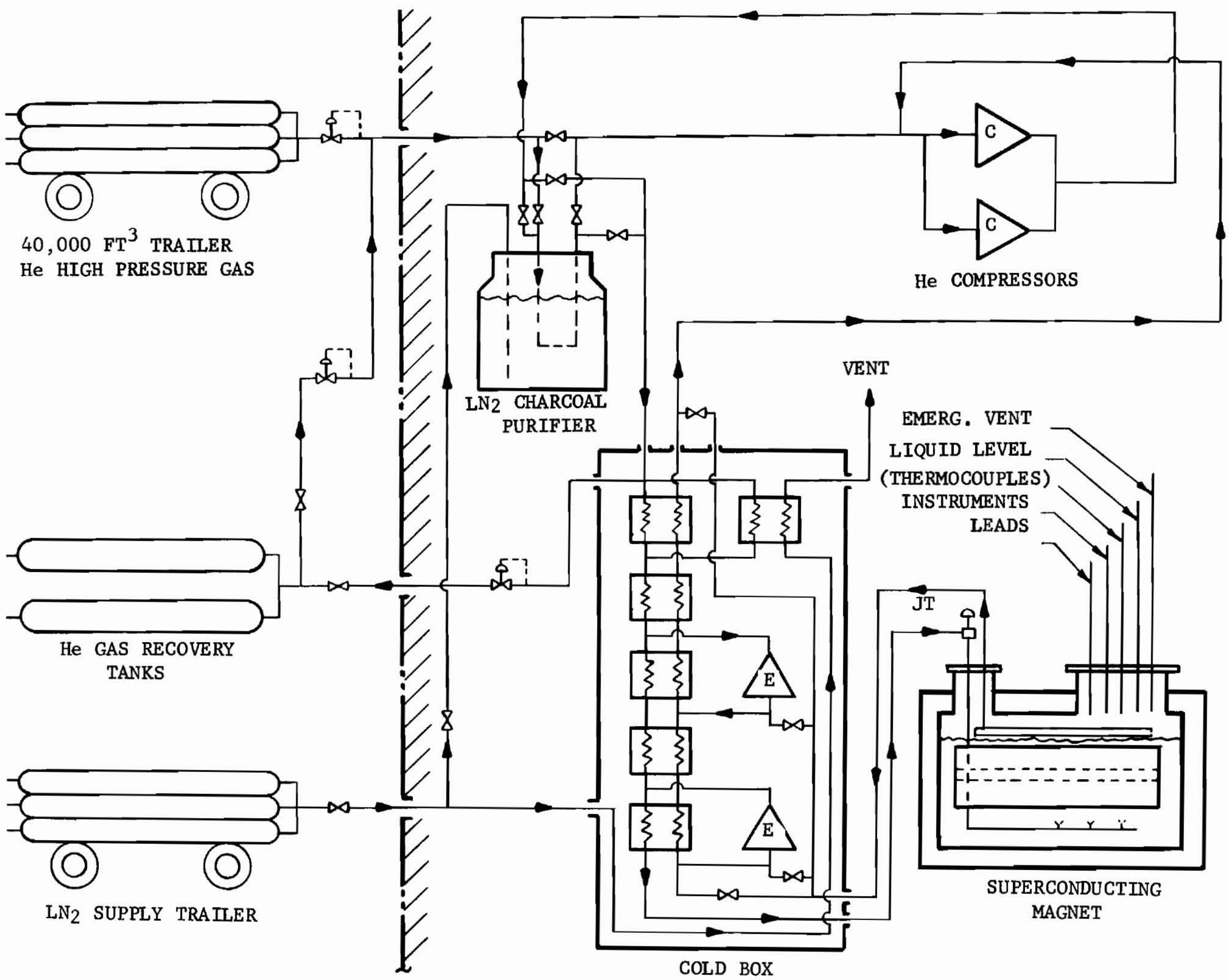

FIG. 8 CRYOGENIC SYSTEM SCHEMATIC

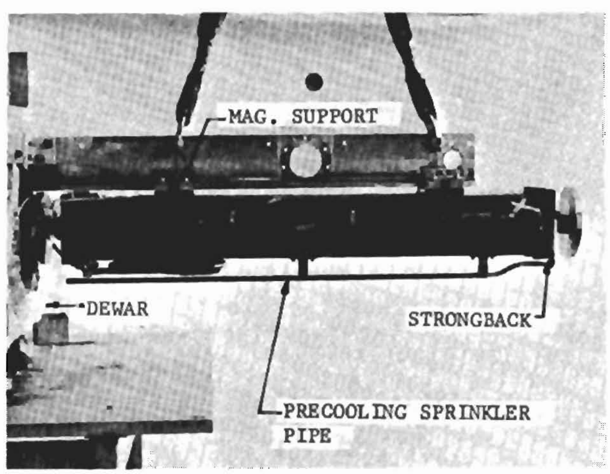

Fig. 9. Magnet being inserted into dewar