IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

SUPERCONDUCTING MAGNET SYSTEM FOR THE AGS HIGH ENERGY UNSEPARATED BEAM*

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Summary

A beam line to the Multi-Particle Spectrometer capable of handling 30 GeV/c secondary beams will consist of four large identical superconducting dipoles and a number of room temperature quadrupoles. The total bending angle is 20°, 5° per magnet, and the room temperature aperture required in the dipoles is 20 cm. The four dipoles will be of the cos θ type and will have an overall length of 2.5 m and nominal maximum field of 4.0 T at 2800 A. The conductor will be a thin, wide metal-impregnated braid. The circular aperture is surrounded by coils which are a six-block approximation to a single-layer cos θ current sheet, and a coaxial cylinder of laminated iron at helium temperature. Each magnet will weigh about 10 tons. The design of the dewar including its heat load is discussed. The system is planned to be operational in Fall 1975.

I. Introduction

The High Energy Unseparated Beam (HEUB) will provide secondary particles having momenta up to 30 GeV/c. The required total bend is 20°, to be divided among 4 superconducting dipoles and, as originally envisaged, with 4 high-gradient superconducting quadrupoles for focusing. After design of the magnets was almost completed, it was found that the total cost precluded construction of the quadrupoles, and they were replaced by existing normal quadrupoles.

The magnet has a warm bore, and current windings internal to a close-fitting circular iron shield at liquid helium temperature. The windings are grouped in 6 equal width segments per quadrant, as shown in Fig. 1, each of almost uniform but different current density. The magnet parameters are given in Table I.

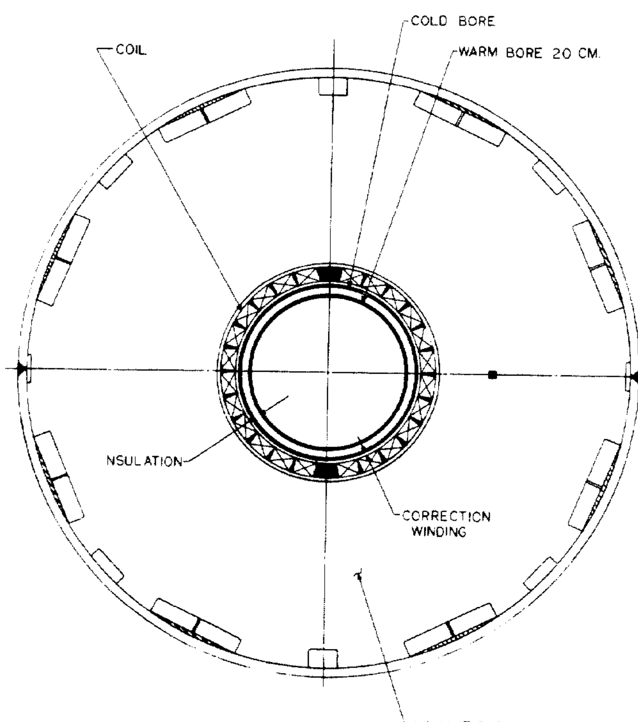

Fig. 1. Magnet cross section.

TABLE I. Magnet Parameters

Warm bore diameter	20.3 cm
Insulation thickness	0.95 cm
ID of winding	24.8 cm
Winding thickness (conductor width)	2.03 cm
ID of iron	29.8 cm
Iron thickness, including slots	25.7 cm
Magnetically effective iron thickness	23.2 cm
Length of magnetic iron	2.49 m
Magnetic length	2.17 m
Stored energy at 4 T	800 kJ
Inductance	0.20 H
Mass of magnetic iron	9230 kg

II. Magnet Mechanical Design

The HEUB dipoles are laminated structures built in two halves with the split on the median plane. The two halves are keyed and are held together by 1.3 x 5.1 cm stainless steel girth bands on 25-cm centers. The girth bands are also fabricated in two halves and are welded closed at final assembly after insertion of the coil assembly.

The individual magnet halves are fabricated by stacking and compressing the laminations in a suitable fixture and then welding longitudinal tie-rods to heavy end plates before releasing the pressure on the laminations. The tie-rods and girth bands are shown in Fig.1; the smaller slots in the iron are for current and instrumentation leads, helium flow, and azimuthal positioning. The tie-rods and heavy end plates are type 304 stainless steel. The use of stainless steel serves two purposes. First, it assures the integrity of the magnet structure at cryogenic temperatures. Secondly, it makes it possible to closely match the axial contraction of the magnet steel to that of the superconducting coil. The clamping pressure is set at 3 N/mm^2 and the ratio of lamination area to that of the tie-rod cross section is 12:1. Under these design conditions the effective modulus of the laminations in the axial direction is approximately 5200 N/mm^2 and the contraction down to 4.2 °K of the assembled magnet is 92% of unrestrained type 304 stainless steel.[1] The integrated contraction coefficient for the magnet core between 300 °K and 4.5 °K is, therefore 2.7 x 10^{-3} and the measured coefficient for the superconducting coil is 2.8 x 10^{-3}. The maximum stress in the tie-rods is 90 N/mm^2 and occurs at 4.5 °K.

The coil assembly is a combination of superconducting braid, type 310 stainless steel braid and special plastic wedges. Mechanical stability is essential to conductor stability and is obtained by designing for a small interference fit (0.15 mm) between the coils and the iron at the operating temperature of 4.5 °K. This requires 0.4 mm interference at 300 °K. To accomplish the assembly, the coil structure is cooled to 80 °K giving about 0.1 mm clearance in the iron bore at 300 °K. The girth bands are welded closed under these conditions. Upon reaching a uniform temperature of 300 °K throughout the iron and coil structure, the girth bands are stressed at approximately 130 N/mm^2, still well below their elastic limit. Cooling to 4.5 °K adds very little to the stress in the girth bands in spite of the smaller contraction of the iron because the design median plane gap at room temperature closes up due to the differential shrinkage between the iron and stainless steel on the one hand, and the coil structure on the other hand. The additional stress due to magnetic forces is relatively small compared to contraction stresses. At 4 T, the maximum stress in the laminations is 18 N/mm^2 due to the magnetic forces, which are predominantly in the horizontal direction and cannot be taken up by hoop stress

*Work performed under the auspices of the U.S. Energy Research & Development Administration.

in the girth bands.

III. Conductor

The conductor consists of a flat braid of 95 wires, each 0.305 mm in diameter, with 1.2 twists/cm and with a 10 μm layer of Cu-10 wt% Ni on the outside to reduce eddy currents. Each wire contains 517 9-μm NbTi filaments embedded in OFHC copper, with a nominal Cu/Sc ratio of 1.25:1. The braid will be partially impregnated with a soft alloy, In- 7 wt% Pb, chosen for its heat capacity which improves conductor stability. The lead is included to increase the resistivity, but cannot exceed about 7% without the alloy becoming superconducting at 4.5 °K. The high heat capacity of the chosen alloy increases the internal voltage during quench from 4 T, which is computed to have a peak value of 213 V to ground with the terminals shorted by a diode.

The metallic braid impregnant causes considerable "coupling" owing to reduced resistance between touching wires. The effect of this coupling is to introduce a charge-rate dependent magnetization superimposed on the dc magnetization of the superconductor.[2] This could cause objectionable field distortion, but use of the copper-nickel jacket has decreased the time constant of the magnetization to less than one minute, so that it is not expected to be a problem.

The specifications call for the wire to carry 55 A at 4.2 °K and 4.0 T and to have a tensile strength of 44 N (22 N after kinking). The completed braid will be 20.3 mm by 0.688 mm including a 0.076 mm wrapping of resin-impregnated glass tape.

The braid current required for 4 T is 2850 A or 30 A/wire, which is 6.9% higher than would be required if there were no iron saturation.

IV. Field Quality, Conductor Placement and Correction Windings

The two-dimensional designs of both dipole and quadrupole were carried out by Dahl and Taylor and are reported by them in detail.[3,4] The fundamental objective in the designs is to achieve the desired field quality with the least complicated magnet structure, subject to the various constraints of finite conductor size, electrical insulation requirements and ease of winding.

The required field quality is $\Delta B/B \leq 1 \times 10^{-3}$ within a diameter of 15 cm. The quality increases with the number of current blocks used to approximate the ideal current distribution. The six-block per quadrant design gives a larger diameter with good field than needed, 22 cm if there is no conductor placement error.

The maximum acceptable harmonic coefficients in the expansion $B = B_0(1 + \Sigma b_i x^i)$ of the field on the median plane in the dipole are $b_i = 10^{-3} r^{-i}$ where r is the desired radius of good aperture in cm. Thus, in the dipole with r = 7.6 cm, $b_1 = 1.3 \times 10^{-4}\text{cm}^{-1}$, $b_2 = 1.7 \times 10^{-5}\text{cm}^{-2}$, $b_4 = 3.0 \times 10^{-7}\text{cm}^{-4}$, etc. The corresponding errors due to a 0.25-mm random error in block placement are[3] $b_1 = 1.1 \times 10^{-4}\text{cm}^{-1}$, $b_2 = 5.2 \times 10^{-6}\text{cm}^{-2}$, $b_4 = 5.2 \times 10^{-8}\text{cm}^{-4}$. A 0.25-mm centering error of the coils in the iron shield gives $b_1 = 1.0 \times 10^{-4}\text{cm}^{-1}$. These placement errors are about 5 times the random errors achieved[5] in the ISA dipoles, but there were also systematic coil placement errors in the ISA models. The causes of these systematic errors are known and are expected to be reduced in the present magnets.

The number of turns per block are, from the midplane 42, 41, 36, 29, 20 and 10. With ∞-μ iron, this conductor arrangement gives a field of 1.514 T/kA. The peak field in the two-dimensional winding is 1.614 T/kA. The positions of each turn and the wedge sizes are given by Taylor and Dahl.[3]

Two-dimensional computations with saturable iron were made using program GRACY.[6] In lieu of data on Vitrenamel, permeability data for 1.8% Si iron at LHe temperature were used.[7] The effects of the slotted iron exterior were computed and shown to give no different field shape than would iron with a smooth exterior and thickness to the bottom of the slots.

Table II gives the computed harmonic coefficients b_2 and b_4 to be expected from iron saturation at various central field levels.

TABLE II

Field, T	$b_2, 10^{-5}\text{cm}^{-2}$	$b_4, 10^{-7}\text{cm}^{-4}$
2.0	0.	0.
3.0	4.6	1.4
4.0	9.1	2.6
5.0	3.7	3.1

The sextupole term (b_2) in the dipole is 5 times greater than desired and must be corrected, but the decapole term is within tolerance. The sextupole correction winding is a two-block approximation to cos 3θ to avoid introducing an 18-pole term, and consists of 84, 0.3-mm wires connected in series and precisely placed in each block. A current of 36.2 A will give a $b_2 = 11.0 \times 10^{-5}\text{cm}^{-2}$ at 4 T. A b_4 winding is also installed, but is not expected to be used ordinarily. This is a 2-block approximation to a cos 5θ winding, having half the A-turns of the sextupole winding.

The superconductor magnetization is greatest at zero field. At 0.5 T or above, this contribution to field error is expected to be negligible. The dipole ends are uncorrected, but only the b_4 term is expected to be outside tolerance; it is additive to that produced by iron saturation and about the same magnitude.

V. Dewar

Figure 2 shows a section through the dewar axis. The single tubular, stainless steel supporting leg is the most unusual feature. The advantages of this method of support are twofold: the magnet and dewar can contract axially about the center; a two-point support would require motion at one or both supports. Secondly, all services except LN_2 are brought in through a single central port with a single seal and bellows between the inner and outer vessels.

Seam welds in the inner dewar are made from the inside; this puts the helium in contact with the weld bead rather than the residual crack on the back of the seam which is difficult to clean thoroughly; experience has shown that outgassing from residue left in the cracks is more harmful to the helium system than to the vacuum system.

The magnet is precooled with liquid nitrogen, which passes through a waffle-shaped jacket welded directly to the vacuum side of the inner vessel. This forms a manifold of which the inner vessel is one wall. Heat transfer from the magnet to the LN_2 is mainly by free helium convection.

Most of the vacuum seals are at room temperature, but the two thimble shaped caps forming the ends of the inner vessel (the waffle manifold is mounted on these caps) are bolted to the center section. The seal at these two points is at LHe temperature and is a hollow stainless steel "O" ring compressed in a groove between indium gaskets. The interior of the hollow ring can be pressurized to 70 atm from the outside, thus making it possible to stop a leak without disassembly should one occur at the seal.

The warm central bore tube has 1.4 cm of superinsulation and vacuum between it and the magnet coil support tube.

VI. Refrigeration

The HEUB refrigeration system was designed to provide sufficient capacity for cooldown and continuous operation of the dipole and quadrupole magnets, but will now provide for a general-purpose facility in addition to the dipoles. Figure 3 is a schematic flow diagram for the refrigeration system showing the major components.

The refrigerator was built by Cryogenic Technology, Inc. to BNL specifications and is equipped with four reciprocating expansion engines which are arranged so that they may be operated in pairs. Only one pair of

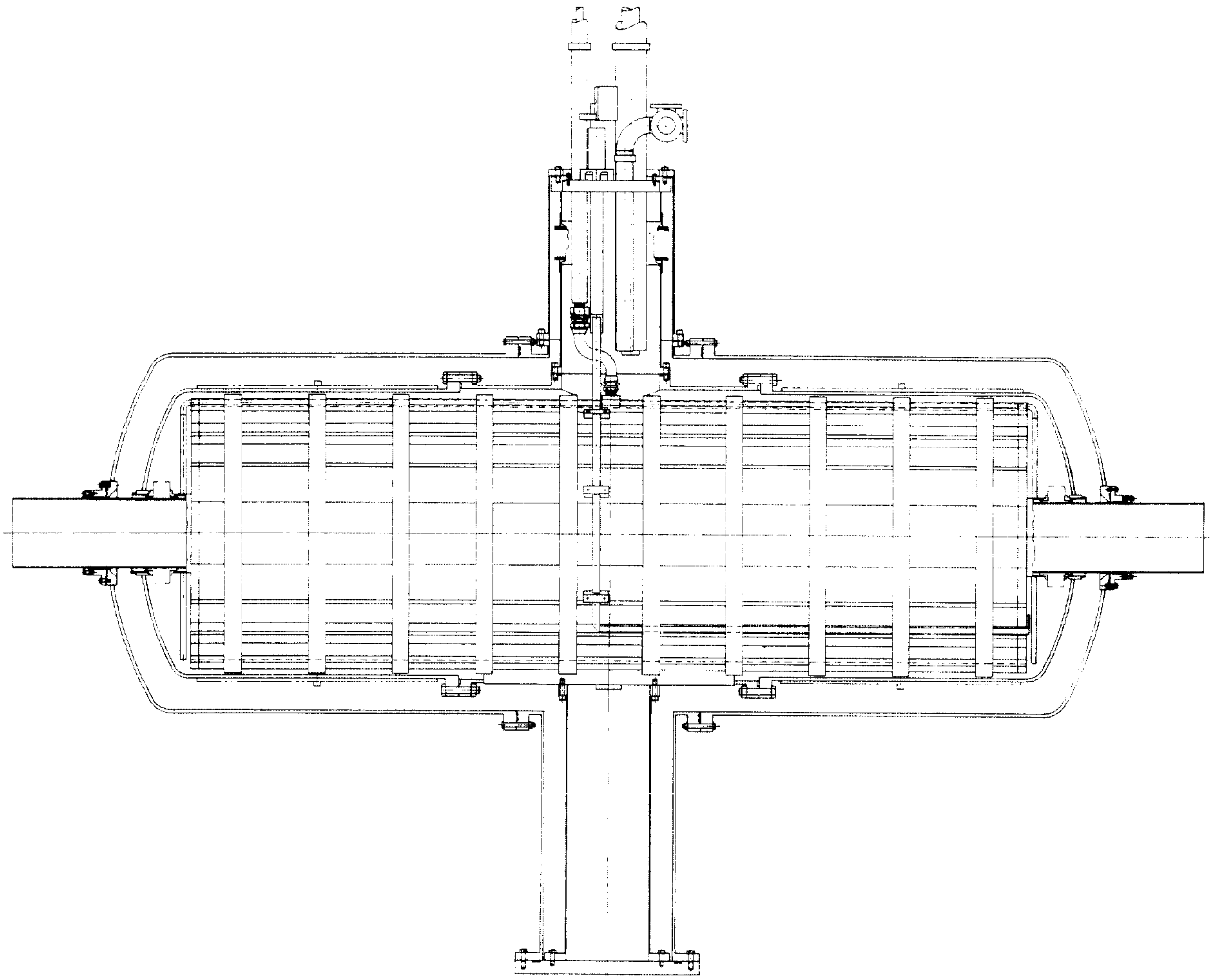

Fig. 2. Magnet cross section.

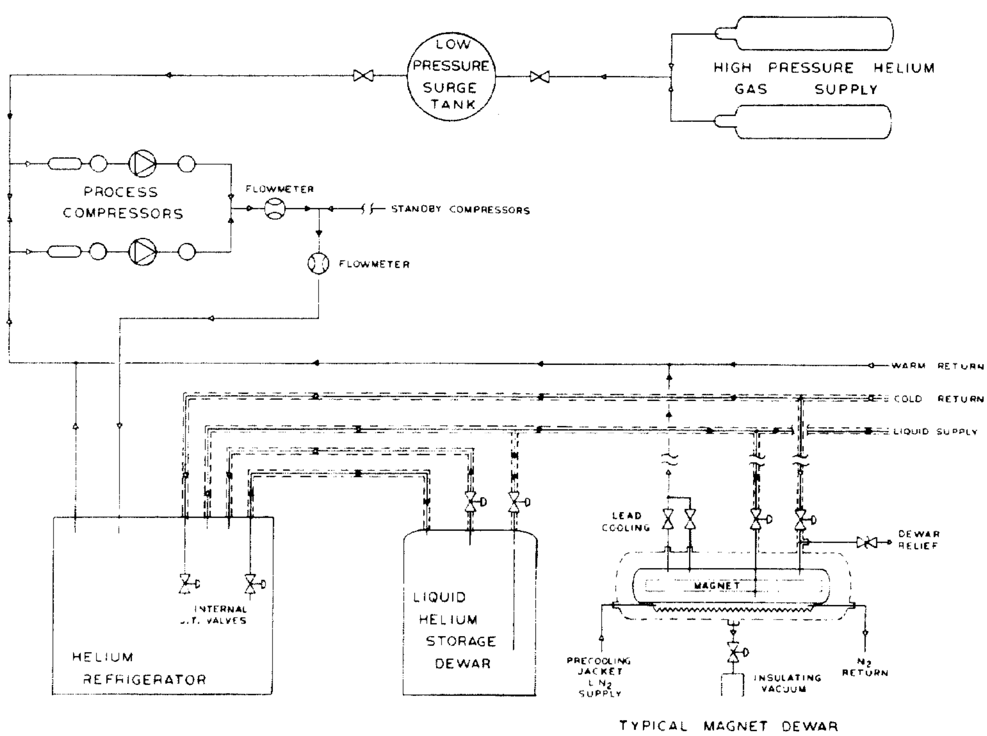

Fig. 3. Refrigerator flow diagram.

engines is normally operated to achieve the rated refrigeration capacity of 1130 watts at 4.4 °K while the other pair is on standby, providing redundancy and increased system reliability. Both pairs of engines may be operated in parallel during initial cooldown for added refrigeration capacity or to maximize the helium liquefaction rate during start-up of the system. Dual purifiers at the 80 °K level and at the 20 °K level are part of the refrigerator's cold box. These are arranged with valving and heaters so that one of each dual purifiers can be reactivated while the other is on-line.

Reciprocating, 3-stage Norwalk compressors supply a total of 152 g/s helium at 18 atm. The new compressors for this facility will be tied into a common process line with existing compressors which also serves the 7-ft Bubble Chamber. The compressor power for rated capacity is about 600 kW, but only as many compressors will be run as are needed for partial load operation.

It is estimated that each magnet will require approximately 4500 liters LN_2 for cooldown to 100 °K, estimated to take 18 hours. The nitrogen is then evacuated from the cooling jacket and the refrigerator used to cool the magnet to operating temperature. The helium returned by-passes fewer heat exchangers in the refrigerator as the magnet temperature drops.

Sufficient helium is initially to be liquefied into the 4000 liter helium storage vessel to fill the four magnet dewars, estimated to require a total volume of 720 liters. After the magnets have been cooled to operating temperature, liquid is transferred from the storage dewar to fill the magnet dewars. It is estimated that the entire cooldown and fill procedure will require four days.

During steady-state operation the final expander output is directed entirely to the storage dewar where liquefaction occurs. Liquid helium is transferred to the magnet dewars as required to maintain the helium level in each dewar. A portion of the cold gas evolved from the magnet dewars is used for cooling the power leads of the superconducting magnets.

The calculated refrigeration requirements are summarized in Table III. (Values of helium flow requirements for the gas-cooled power leads are based on manufacturer's performance specifications.)

TABLE III. Heat Load Summary

Radiation, Conduction, Penetrations (per magnet)	47.5 W
Current Leads (pair)	31.2* W/2800 A
Transfer Line, Valves, Connections, Storage Dewar	190 W
TOTAL, 4 magnets and system	505 W

*Includes decrease in refrigerator capacity due to lead gas returned warm.

Acknowledgments

The magnets are a cooperative effort of the Accelerator Department with active participants too numerous to list, but special thanks are due J.G. Cottingham, who performed the quench calculations, G. Danby, who detailed the performance requirements, and A. McInturff, mainly responsible for the braiding facility.

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