THE CLEOII DETECTOR MAGNET: DESIGN,TESTS, AND PERFORMANCE*

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Introduction

For the last five years, the CLEO collaboration, which operates a large general-purpose particle detector at Cornell University's CESR e^+e^- storage ring, has been designing, procuring, and commissioning parts for a wholly new detector to replace the venerable CLEO I, active from 1979 through 1987[1]. The new detector[2], dubbed CLEO II, stresses very good energy resolution for photons and π^0's as well as for charged particles. For good charged particle momentum resolution, a high magnetic field strength is desirable; for reasons of cost and saturation in the steel yoke, the design field was set at 1.5 T. The spatial and energy resolution for neutrals is to be attained with a highly segmented (approx. 8000 crystals) 30 ton array of CsI(Tl). So that the capabilities of the calorimeter not be compromised by extraneous material, the entire assembly should be contained within the coil ID; a superconducting solenoid with 3m ID, and 1.5 T field meets these needs.

The design of the new magnet is intended to keep the good features of the smaller CLEO I solenoid, such as low cryogenic load; while eliminating some of its weaknesses such as its poor insulating vacuum, sensitivity to refrigerator performance and susceptibility to utility failures . We considered and rejected a persistent current mode in view of the frequent need to de-energize the magnet for maintenance, accelerator studies. The requirements were then increased stability, low cryogenic heat load, passive cooling, and passive protection.

Oxford Instruments Ltd of Oxford in Great Britain and GA Technologies of San Diego, California each performed design studies for us in late 1984. GA Technologies explored a modern pool-boiling design; Oxford Instruments used a thermosyphon approach. Both designs met our criteria. A large number of potential builders were sent copies of both design reports and asked to submit their own proposals two months later. Six responded, including Oxford Instruments and GA Technologies. Oxford Instruments was selected on the basis of cost (5 bids were under $2 million) and design features. After final negotiations, the award was made in June, 1985. Construction was completed in June, 1987. The coil was tested successfully at 40% of full current at Oxford, without its steel yoke. The coil arrived at Cornell in October, 1987 reaching full current in December of that year. It was then moved to its final location and began routine operation in August,1989.

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I. DESIGN FEATURES

A. The Coil

The design of the coil was driven by the primary goals: low cryogenic heat load, passive cooling, stability, and self-protection. The operating current of 3300 amperes was a compromise between the need for low heat generation in the current leads for a large conductor for ease in construction and for protection. The choice of a 5 mm x 16 mm aluminum conductor increased the point source energy necessary to cause a quench from < 10 millijoules in the CLEO I coil to 6 joules in the final CLEO II design. The high purity aluminum (RRR=1000) was coextruded by Vacuumschmelze with Cu–NbTi flat cable (helical wind) of nine or eleven strands. (Fig. 1) The current density was 4% higher near the ends of the coil for better magnetic field uniformity. Self protection was built in by installing a thin shorted turn of high-purity aluminum next to the superconductor. To help support the magnetic hoop forces with the aluminum bobbin, Oxford chose to wind the coil on the inside of the bobbin. The all aluminum construction greatly minimized thermal stresses.

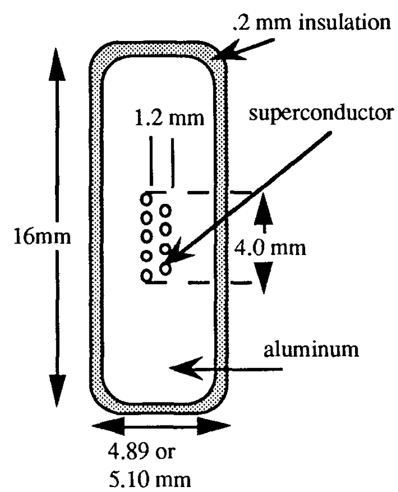

Figure 1. cross sectional view (schematic) of coil conductor

The winding was done by feeding the conductor, in compression, on the inside of the coil bobbin, slowly rotating on a turntable about the vertical axis, synchronized to the conductor

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feed. Several stations along the conductor path outside the bobbin prepared the conductor (shot blasting, degreasing, drying, burr detection, and taping); the last station was a platform inside the coil form that used a caterpillar feed and runway to push the conductor onto the previous turn. The platform rose and fell on jack screws as the two layers were put on. Using an inductive technique, Oxford monitored the coil for turn-to-turn faults with resistances a high as 10 ohms. The eight lengths of conductor were joined by welding. An 8m length on each of the conductors was first thinned to 3.3 mm. These were then laid over each other and welded with high purity aluminum filler rod along both edges. Oxford estimates the resistance of each joint to be less than 2×10^{-10} ohms.

B. The Thermosyphon System

One key design goal was to have the coil ride out utility or refrigerator failures. This problem might be solved by use of a bath-cooled coil. A new solution uses gravity to pump helium around the magnet— a thermosyphon. An insulated pipe delivers cold helium liquid to a manifold at the bottom of the coil from a 700 liter dewar above the magnet. A set of rib-like risers carries the helium up around the outside of the coil where it absorbs heat from the coil bobbin and decreases in density. All the risers are then connected together at the top and return to the dewar through a single pipe. The difference in density between the up and down legs provides adequate circulation to handle cryogenic and ramping heat loads. An additional feature is that a heat concentration provides additional drive to the nearby risers, increasing the local cooling. Ordinary forced cooling would encounter increased impedance, reducing the available cooling. The details of the thermal coupling are important to both the operations of the coil and the coil-protection scheme. The risers are stainless steel tubes embedded in indium-packed channels cut in the coil bobbin. The thermal impedance of this interface turned out to be higher than anticipated, limiting the cooling power of the thermosyphon to about 200 watts. This limits our ramp rate to 3-4 volts or about one and one half hours to reach full current. Temperatures of 5-6.5 K were common on the bobbin during ramping. The drying out of the thermosyphon at high heat loads allows the shorted secondary to induce quenchback in the coil should a quench start. A set of valves allow us to use a forced flow through the cooling pipes during cooldown. The small inventory of helium in the pipes eliminates the "bomb" character of large bath cooled magnets, while the 700 liter dewar provides approximately one day of operation even with disabled refrigeration.

C. Radiation Screen

The radiation shield is constructed as inner and outer cylinders from aluminum honeycomb panels. A typical panel is about 3.6 m x 1.2 m x 15 mm with an embedded pipe bonded to one side; the honeycomb and one side were perforated to allow pumping. The outside is covered with about 100 layers of aluminized mylar to reduce the liquid nitrogen requirements. The coil side was polished or lined with a high emissivity material to reduce the radiant heat load on the coil. Oxford supplied a controller for ramping the shield from room temperature to 80 K and the reverse. It simplified cooldown, but turned out to be very sensitive to the liquid nitrogen quality. We are considering ways to avoid these problems during routine operation. The heat load to the radiation shield is a little less than 50 watts.

D. Power Leads

The current leads were designed by Oxford to have minimal heat conduction at the operating current and extended survival time with loss of gas cooling. The extra thermal mass was obtained from the long 1 m length and by adding material in the form of fins. The detailed design was fine tuned for the measured residual resistivity ratio of the copper used by a program that analyzed both the steady-state and transient behavior. Before installation the leads were tested to 110% of the operating current and at operating current for 20 minutes with no gas cooling. The performance indicated that the magnet could ramp down over a 2 hour period without quenching and with no part of the lead exceeding room temperature.

The control , monitoring and alarm functions supplied by Oxford make operation nearly automatic. The flow is controlled by the temperature of a point 20% from the warm end. This allows for automatic adjustment of the flow to match the current in the lead and the return pressure of the refrigerators. A minimum flow valve parallels the servo valve to soften the possible failure condition of a closed servo. The controller has two different set-points: one optimized for refrigerator operation; the other, "over-cooled", for dewar operation. A second set of controllers powers heaters on the warm end of the leads to prevent condensation. Alarms are generated when the temperature control point exceeds a setpoint or when the flowmeters registers no flow. The "no-flow condition" generates alarms during the normal fluctuations of no current or ramping operation. We plan to add a time interval requirement.

E. Coil Supports

The stainless steel cryostat, which supports the entire 30 ton weight of the CsI calorimeter is fixed to the massive steel return yoke. The coil must be movable within the cryostat to accommodate thermal contraction, and positioned so as to minimize the magnetic decentering forces. There are four axial supports all at one end, and sixteen radial supports . They are made from 318 ELI titanium tube and are adjusted through their coupling to bellows sealed ports in the cryostat wall and end flanges. The axial supports act both in tension or compression, while the pairwise arranged radial supports are purely in tension. acting almost tangential to the coil. Strain gauges on all supports monitor the magnetic loads.

F. Refrigeration System

The magnet is cooled by either of two Koch Processes Model 1430 Liquifiers. The system is constructed to have nearly complete redundancy for the active components -- the refrigerators and their compressors. In addition to the 700 liter dewar above the coil, there is a 1000 liter dewar that can be filled by either refrigerator or from a vendor's dewar. These various sources are connected together with appropriate valving in a large cryogenic switch box(called Son-Of-Box) and to the coaxial transfer line going to the 700 liter dewar above the coil. The low-loss coaxial line also transports cold gas return and liquid nitrogen for the radiation shield. This line, a 15 meter semi-flexible design, was constructed by Kabelmetal of Hanover, Germany and permitted operation in two different locations without rebuilding. A new liquid nitrogen distribution system (200 feet) constructed by MVE Cryogenics was a major improvement, necessary for operation of our radiation shield.

G. Steel Yoke

The steel yoke was designed simultaneously with the coil and cryostat to optimize the interfaces between them. The availability of some steel from the dismantled Space Radiation Effects Laboratory Synchrocyclotron, stored at the Brookhaven National Laboratory, determined the yoke slab thickness as 36 cm. There are three layers of steel separated by gaps of 9 cm for muon detectors in an octagonal geometry. Only the inner two layers are used for the magnetic flux return. The pole pieces form nesting rings on each end to satisfy several functions. The outer collar with an octagonal outside and an inner radius (resembling a nut) supports the rest of the steel and the cryostat. Penetrations provide access to the adjustable radial and axial supports for the coil. The successively nesting pole rings allow the installation of the CLEO II detector elements and passage for their cables. The inner ring (2 m outer diameter) rests on rails to provide access to the ends of the central tracking chamber.

II. Tests and Operation

A. Acceptance Tests

A first set of tests was made, without the magnet steel, at 40% of the operating current at Oxford's construction facility. Vacuum integrity, cryogenic heat load, and magnetic excitation were measured. A series of tests of the thermosyphon were made by energizing built-in heaters at various levels. A quench was initiated by turning off the thermosyphon with the heaters on. The quench started at 9.1 K; the heater input was 45 kJ. The time evolution of the quench and the maximum temperature (32.7 K) matched Oxford's quench model prediction (34.5 K).

After a cooldown time of twelve days, using one refrigerator, the tests within the steel at Cornell started with two self-induced quenches at full current. Their origin is still not understood. The quenches took about one minute; the coil reached an average temperature of 65 K, in agreement with the Oxford predictions. After operating the coil at the full field of 1.5 T at 3300 amps, the temperature margin was tested with the heaters. The coil was warmed by 1.5 K (the expected margin was 2.2 K) ; the current margin was explored by running at 102% of the full current.

B. Field Homogeneity

The magnetic field was mapped with a 3-axis Hall probe referenced to a fixed NMR probe. Traverses in z (the axial direction) were made at fixed radius and azimuth. Eventually, we scanned at eight radii and sixteen azimuths. The data, averaged over azimuth , were fit to appropriate polynomials in r and z. Radial fields were deduced from the variation of B_Z. Fig. 2 shows typical results for B_Z. Field uniformity over the 2m long x 1 m radius drift chamber volume was better than 0.1%, and was limited by the (inferred) radial fields near the ends.

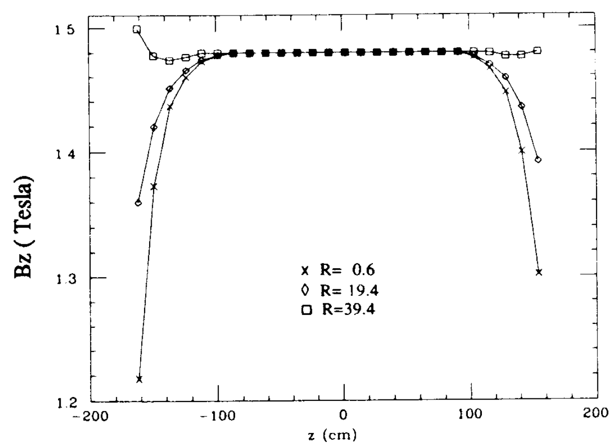

Figure 2. Behavior of the axial field for 3 radii (in cm.) The data is averaged over azimuth.

III. Operating Experience

At this writing the magnet has been operating at field without serious incident for ~six months. The cryostat vacuum has remained at 10^{-6} Torr with no external pumping and the effective refrigeration load has been comfortably within the capabilities of one Koch model 1430 (Oxford estimated 8.3 watts and 14 l/hr.) All the various styles of cryogenic operation have been attempted successfully. Operation is largely unattended except for routine refrigerator maintenance and for field ramp-up and ramp-down. We gratefully acknowledge the competence, diligence, and hard work of the Oxford team in providing us with a fine tool for high-energy physics.

TABLE I

VITAL STATISTICS OF THE CLEOII MAGNET

Manufacturer	Oxford Instruments, Ltd.
Magnetic Field	1.5 T, uniform to <0.1% over drift chamber volume
Diameter	2.9 m clear bore
Length	Coil: 3.5 m, cryostat 3.8m
Coil Electrical	3300 A, 4.6 H, 25 MJ
Weight	7000 kg cold mass, 20,000 kg cryostat, 800,000 kg steel
Stability, Protection	Intrinsically stable, quenchback from high purity Al secondary
Cooling	Indirect, thermosyphon

IV. REFERENCES

[1] D.Andrews et al. ,Nucl. Instrum. Methods A **211**,47 (1983)

[2] CLEO collaboration, Cornell report CLNS-85/634 (unpublished)