STRUCTURAL SUPPORT SYSTEM FOR A SUPERCONDUCTING MAGNET COIL*

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Introduction

Today's synchrotrons, used for the study of the physics of the sub-nuclear particles of matter, are large and expensive. The largest, at the Fermi National Accelerator Laboratory near Chicago, was built in the early seventies at a cost of $250 million and is 4 miles in circumference. Future accelerators, if built along the same lines, will be staggering in cost, size, and in their demand for electric power and cooling water if they are to provide a significant advance in particle energy over the Fermilab machine.

The electromagnets that confine the high-energy particle beam and bend it into a circular path account for a large fraction of the cost and the electric power and cooling requirements of large synchrotrons. Superconducting magnets, highly developed within the last decade, can develop magnetic fields twice as strong as those that can be economically produced by conventional copper-and-iron magnets. The electric power consumption of superconducting magnets and their associated helium refrigeration system is only a few percent of that of an equivalent system of conventional magnets.

The purpose of the ESCAR (Experimental Superconducting Accelerator Ring) project (Figure 1), now under way at the Lawrence Berkeley Laboratory, is to gather data and experience in the design and operation of a relatively small synchrotron employing superconducting magnets. Such data are essential to ensure that the design of future large accelerators may proceed in a knowledgeable and responsible manner.

* Work done with support from the U.S. Energy Research and Development Administration.

Presented at the Spring 1977 Meeting of the Western Regional Strain Gage Committee of the Society for Experimental Stress Analysis. San Jose, California, March 4, 1977.

One of the many engineering problems associated with a superconducting magnet is the design of the coil suspension system. The coil, maintained at the temperature of liquid helium, must be held rigidly by a structure that does not conduct too much heat into the liquid helium system. The suspension system used on the ESCAR magnets is the main topic of this paper.

Coil Support System Requirements

The support system must be strong and stiff enough to avoid structural failure or excessive deflection. Loads on the system include those due to acts of God, such as earthquakes and gravity, and acts of the Devil, such as transportation-induced forces, forces transmitted from other components, unbalanced vacuum and pressure loads, and the pulsating magnetic attraction of the liquid-helium-cooled coil to its surrounding room-temperature iron shield.

The magnetic force is zero if the effective center of the coil coincides with the center of the iron yoke. (Centering is a four-dimensional problem.) But if the coil is off-center, a force is developed which tends to push it farther from the center. The coil-iron system, then, has a negative "spring constant". The support system must have a positive spring constant that is numerically at least equal to the magnetic spring constant in order for the system to be elastically stable. But in order to avoid excessive amplification of the eccentricity when the magnet is turned on, the support system must have a spring constant that is several times the magnetic spring constant. Eccentricity of the coil results in distortion of the magnetic field, which must be uniform to about one part in 500. And since a magnet must be turned on and off about 10 million times during its lifetime, eccentricity could cause fatigue failure of the support system.

Either the manufacturing tolerances must be such that the eccentricity is tolerable, or the support system must be adjustable. Strain-gages incorporated in the support system, which show how the forces change when the magnet is turned on, can aid the adjustment process.

The support system must accommodate the large thermal contraction of the helium system that occurs upon cooldown; about 0.15 in. for the 4-foot-long ESCAR magnets. And, in addition to not conducting excessive heat, the system must be inexpensive.

ESCAR Magnet Support System

Many weird and wonderful suspension systems have been employed in cryogenic systems over the past 30 years. These have consisted of systems of wire-rope cables, ball bearing units with ceramic or saphire balls, and stacks of crinkled washers, to name a few. Generally, the systems used in cryogenic liquid storage and transportation systems lack the necessary rigidity for our application. More rigid systems consisting of metallic "bicycle spokes" have been used successfully, but such systems are often large and complex. Merely substituting FRP (fiber-reinforced plastic) is a step in the right direction on all counts, but the cryogenic properties of such materials are not well known, and one can be trapped easily into an unsuccessful or costly design.

We have tried various "spoke" systems over the past decade, consisting of metallic and FRP spokes, in various numbers and arrangements, in both tension and compression.

The ESCAR system employs seven compression members. The minimum number of tension or compression members required to constrain a body rigidly is six. But an overconstrained system of at least seven members is necessary if the system must withstand forces applied in any direction without changing the sign of the load on any member. (If you don't believe it, get out your wire cutters and try it on your kid's bike.)

Both the thermal conduction and the stiffness are proportional to the area-to-length ratio, so a compromise must be made. The overall size depends on the forces and the allowable stresses.

A material having high ratios of elastic modulus and of strength to thermal conductivity must be employed. Metals are poor in this regard. The best materials are those employing boron fibers in an epoxy matrix. But they are expensive, and their properties are not well know. Commercially available fiberglass-reinforced epoxy -- NEMA G-10 grade -- is employed in our application because its performance is adequate, and its overall cost is low.

The choice between compression and tension members was made in favor of compression members because a cost analysis showed a savings of about $20,000, for the 24 magnets, over a previously built tension-rod system.

Figure 2 shows one of the 24 beam-bending magnets and its coil-support system. The coil and its system of aluminum rings, which resist the 300 000 lb electromagnetic bursting force, is contained within a pressure vessel through which liquid helium is pumped. The liquid helium vessel is surrounded by a liquid-nitrogen-cooled thermal shield that is surrounded by multi-layer, aluminized-mylar insulation and that, in turn, by the vacuum vessel, which is supported by the laminated-iron magnetic shield.

Over its 4-ft. length the magnet shrinks about 0.15 in. in going from room temperature to liquid helium temperature. The forces in the struts must not change greatly during cool-down, and the center of the magnet should not move appreciably. Constancy of position is assured by the symmetrical arrangement of struts, and constancy of force results from the angles of the struts. (See Fig. 3). If the axis of the strut is at right angles to the path of motion of its end, only a small higher-order change of length occurs. The strut itself shortens, however, so the strut angle must be a few degrees steeper.

A home-made strain-gage load cell is incorporated into each suspension unit (Figures 4 and 5). The outer end of the load cell is threaded to provide for adjustment. The inner end is milled to a square cross section. The gages (Micro-Measurements 062 UW) of a two-active-arm full bridge are cemented to the faces. The center of the load-cell body is drilled out to increase the sensitivity. The leads are terminated in a Bendix connector (7543 ÷ MS3112E-8-4S). A Budd P350 manually balanced strain indicator and a Budd SB1 switch and balance unit are used. Sensitivity of the cell is about 5 micro-strain per lb. The total load supported by the seven-strut system is 800 lb. Strut forces range from 400 to 700 lb. (Breaking strength at room temperature is 3000 lb.) Overall repeatability seems to be well within about 5 micro-strain or 1 lb. A piston having an O-ring seal is interposed between the load cell and the support strut, permitting replacement of a faulty cell while the system is under vacuum.

The strut is simply a piece of stock NEMA G-10 rod having its ends machined to a hemispherical shape. The ends rest in hemispherical depressions in the piston and the liquid-helium vessel. A copper sleeve, cemented to the strut near its warm end and attached to the liquid-nitrogen shield, reduces the heat conducted to the helium system.

Operating Experience

In addition to providing an aid to adjusting the centering of the coil, the load cells have proved useful for adjusting the strut pre-loads and for showing changes in load upon cooldown and due to creep. And on one occasion, analysis of the load-cell forces showed the presence of an accidental 1000 lb. force caused by an improperly designed magnetic-field-measuring probe.

So far, one magnet has been assembled and operated, and 12 are in various stages of assembly. The load-cell measurements have shown that the strut forces do not in fact change severely during cool-down; we got the angle about right. Trial-and-error adjustment of the coil centering by measuring strut loads with and without magnetic field, works reasonably well, although there are a few anomalies. For example, the struts were adjusted, finally, so that the compressive force in all of the struts decreased by roughly 10 lb. when the magnetic field was applied. This cannot be explained by any manipulation of the equilibrium, force-deflection, and compatibility equations, and the possibility of magnetic-field effects on the strain gages is easily ruled out.

We are still on the toe of the learning curve with respect to understanding what the load cells are trying to tell us. Whether we will need to install load cells on all future magnets remains to be determined. Meanwhile, having them is a great comfort.

Acknowledgements

Previous support systems designed by Robert Kilpatrick, William Chamberlain, and William Pope provided valuable experience which aided the ESCAR design. Detail Design of the present system was done by Richard Schafer. Klaus Halbach suggested using strain gages to aid in centering the coil. Winston Canady selected the gages, assembled and calibrated the load cells, and showed us how to use them. Jack Gunn served as consultant.

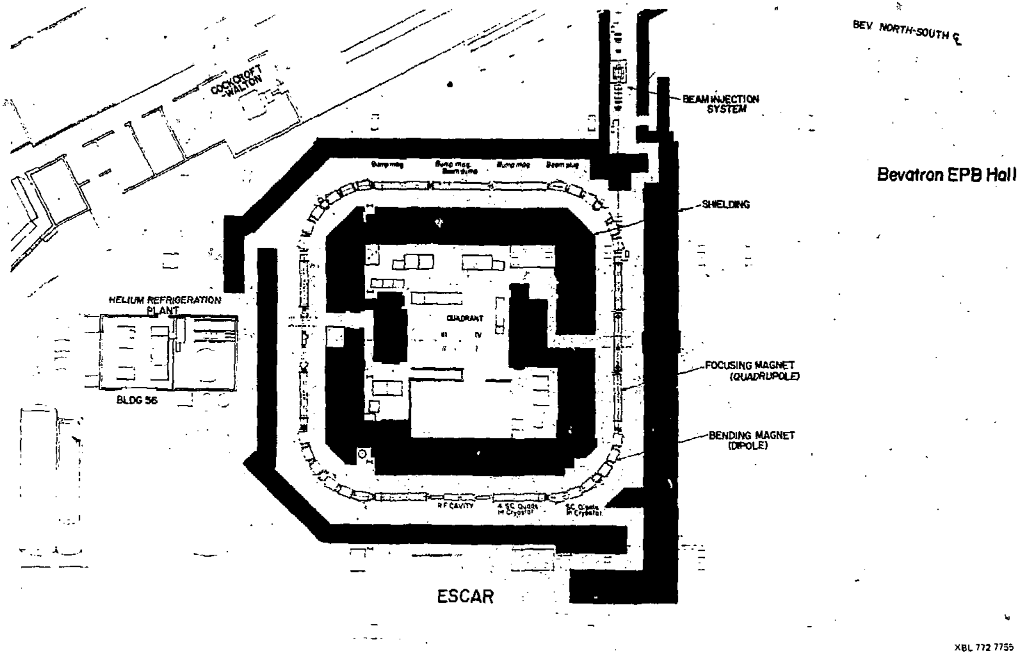

Figure 1. Plan view of ESCAR.

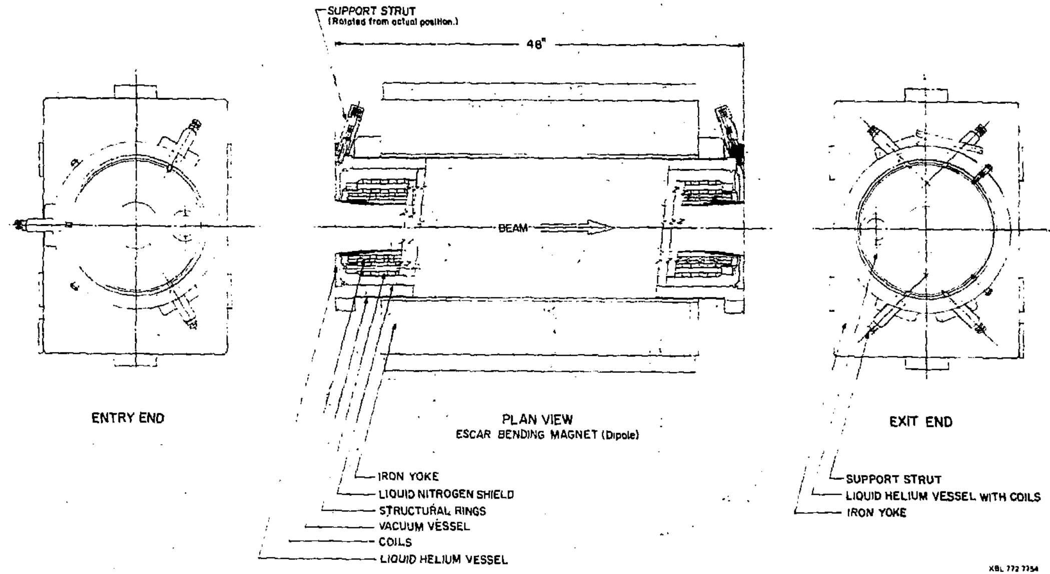

Figure 2. Escar bending magnet.

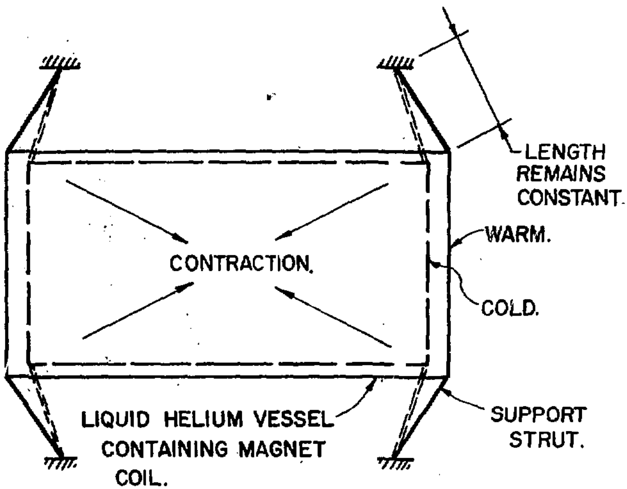

Figure 3. Action of support struts upon vessel cool-down.

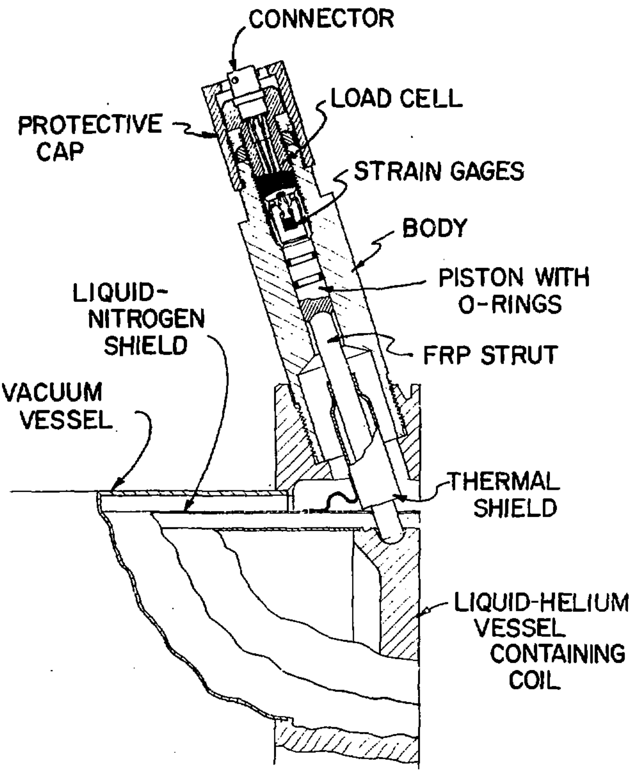

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Figure 4. Support unit cross section.

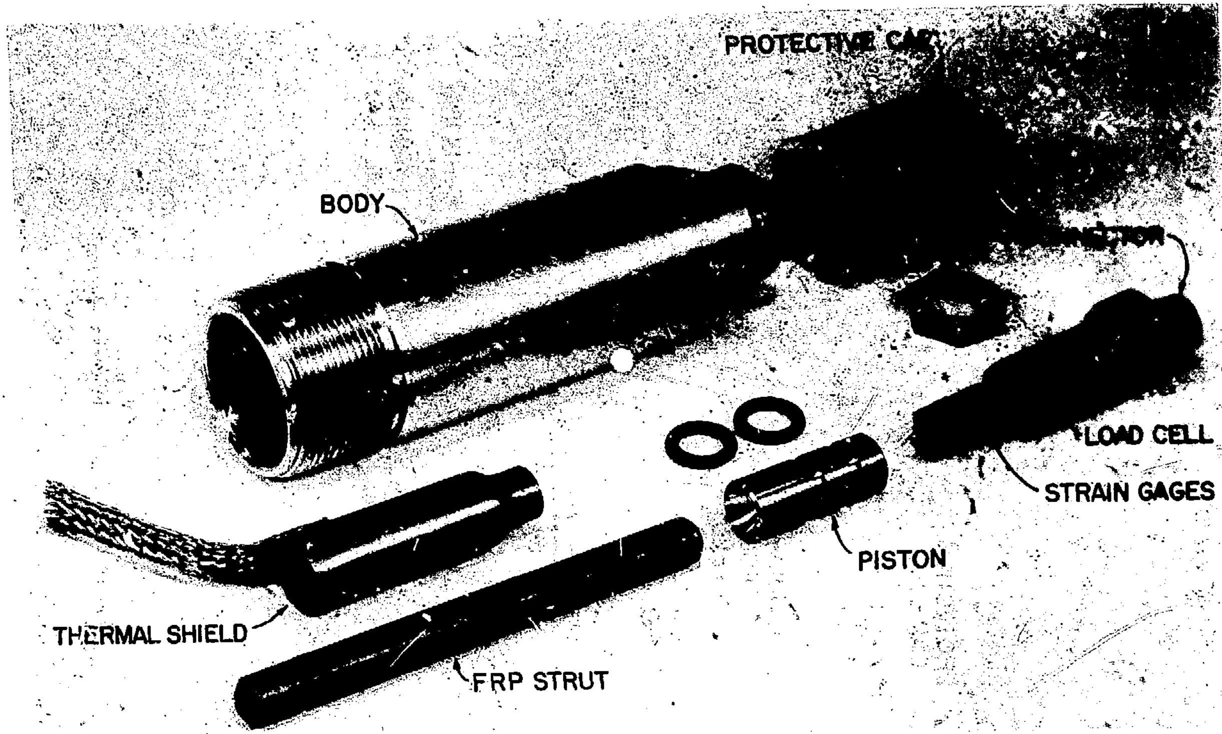

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Figure 5. Support unit parts.