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

ESCAR SUPERCONDUCTING MAGNET SYSTEM*

W.S. Gilbert, R.B. Meuser, W.L. Pope, M.A. Green

Lawrence Berkeley Laboratory
University of California
Berkeley, California

Introduction

The ESCAR (Experimental Superconducting Accelerator Ring) project has been described previously.[1,2] Twenty-four superconducting dipoles each about 1 meter long, provide the guide field for this proton accelerator-storage ring. Injection of 50 MeV protons corresponds to a 3 kG central dipole field, and a peak proton energy of 4.2 GeV corresponds to a 46 kG central field. Thirty-two quadrupoles provide focusing.

The 56 superconducting magnets are contained in 40 cryostats that are cryogenically connected in a novel series "weir" arrangement. A single 1500-watt refrigeration plant is required.

Superconductor and Testing

The dipole magnets use a rectangular cable similar to that developed at RHEL, 5mm x 1mm, with a current carrying capability of greater that 2500A at 50 kG. The NbTi filaments are about 6 microns in diameter, and the cable has both low hysteresis loss in the superconductor and low coupling through the matrix under pulse operation.

Sample quantities of full-current cable (120 meter length), with 17 strands of 0.5 mm composite wire, have been delivered by Supercon, Inc. together with greater quantities of special lower-current versions of the same size cable (1200 meters) for use in mechanical test windings.[3] Enough full-current cable for one dipole (1200 meters) is scheduled for delivery by April 1975. Winding will start on receipt of the superconductor.**

MCA is also scheduled to deliver enough 17 strand cable for one dipole in April 1975.[4] Tests of the uncabled conductor indicate more than adequate current-carrying performance in the assembled cable.

Airco, Inc. has delivered a 13-strand version of cable (>1000 meters) using old low-current conductor that was on hand at Berkeley. This cable has been used for mechanical winding experiments and appears in Figure 1.[5]

The conductor for the quadrupole magnets is a single rectangular wire 0.14 mm x 0.07 mm, with NbTi filaments 15 microns in diameter. This 3000-filament conductor has been supplied by Supercon, Inc., and a solenoid magnet wound with this material has been tested. Short-sample performance was reached on the first quench, and no observable rate dependence or training was detected on subsequent transitions.

Dipole Magnet Coil Design

The coil design approximates a cosine distribution of current about a cylinder with four constant-current sectors per quarter circle. The four radial layers are wound as two double layers. The superconducting cable is wrapped with an open spiral of epoxy-impregnated fiberglass tape, which is cured after each double layer is wound. Figure 1 shows a winding of a quarter of a dipole with shortened straight sections and with the insulating spaces removed. This winding contains the Airco 13-wire cable mentioned above. There are four self supporting units that are assembled into a complete dipole: the upper half of the inner two layers, the lower half of the inner two layers, and the top and bottom halves of the outer two layers.

A new end configuration is clearly discernable in Figure 1. Compared with the usual half-round ends used in many saddle-shaped coils, these ends are more compact, result in end spacers of almost constant width, and give lower magnetic field aberrations. A small-radius bend at the end of the straight section is joined to the much larger radius of the given end turn at such a location as to make the winding both reasonable to build and achieve all the good things mentioned above. Our use of flexible cable and curing the epoxy spiral wrap after winding allows us to make this type of winding conveniently. Compactness of the end results in the physical length of the magnet's exceeding the effective or magnetic length by only 0.7 coil radius per end. For a half-round end of roughly comparable field quality this excess length is about 1.2 coil radius per end. This compactness in magnet ends is particularly important for ESCAR in that each dipole accounts for 15° of the bend. The resulting sagitta transforms end length into lost aperture. Table I lists the multipole components calculated in the straight section and the corresponding integrals through the ends and the straight section.[6] As can be seen, in the integral sense, the ends add negligible field distortion. Random current block placement errors of 0.2 mm add field distortions of $\Delta B/B = 1 \times 10^{-3}$ at the 6.2 cm radius used in Table I.

TABLE I

Field Multipole Components-ESCAR Dipole

Normalized to the dipole field, calculated at a radius of 6.2 cm (≈3/4 inner coil radius).

	n	2-dim. region straight section	Full-length Integrals: ends + straight section
Dipole	1	1.00000	1.00000
Sextupole	3	.0	.0
Decapole	5	.0	.0
etc.	7	.0	.0
	9	.00003	-.00009
	11	.00007	-.00006
	13	.00013	.00007
	15	-.00005	-.00015
	17	-.00092	-.00083
	19	.00006	.00005
Sum (3-19 inc.), abs. values		.00126	.00125

* Work supported by the U.S. Energy Research and Development Agency.

Magnet-Cryostat System Design

In late 1974 both warm-iron and cold-iron dipoles were analyzed. The design problems associated with field aberrations caused by iron saturation in the close fitting cold-iron alternative were judged to require additional computational effort on a scale incompatible with our schedule, and so in late December the decision was made to proceed with the warm-iron alternate. The warm iron is far enough from the coils so the iron doesn't saturate. Structural support for the coil is provided by an aluminum alloy ring structure which is shrunk onto the coil. The magnet-cryostat assembly within the cold helium region is shown in Fig. 2.

Cryogenic Design -- "Weir Cryostats" and Helium Pressure Drop

The cryogenic simplicity of passing the helium coolant through all the magnets in series is economically attractive, but requires the sizing of flow passages through the various series elements compatible with the allowable total pressure drop.[7] Figure 3 shows the helium pressure around the ring under minimum static and maximum pulsing heat loads. Under the higher load the pressure drop around the ring is 1.5 psi, which is within the design specifications for the refrigeration plant. Most of this pressure drop occurs in the straight section transfer lines (corrugated commercial tubing was assumed). However, even the slight pressure drop of 0.002 psi between the two ends of a magnet cryostat results in a helium liquid level difference of 1 cm. This slope is indicated in the sketch shown at the top of Figure 3.

Cryogenic Design -- Helium Distribution

The helium distribution system, shown in Figure 4, is divided into two circuits. The primary helium circuit, which contains the four quadrants of dipoles and quadrupoles, is a simple series circuit which carries up to 100 gs^{-1} of two phase helium at 4.5° K. This primary circuit has by-pass circuits around each of the magnet quadrants. These by-pass circuits are used when one or more magnet quadrants are warmed up while the others remain cold. The Joule-Thompson valve for the magnet circuit is located near the first magnet quadrant cooled by the stream. The pressure drop in the magnet circuit must be low in order to have a nearly constant temperature in the magnets. (See Fig. 3) the maximum temperature in the magnets will be 4.6° K.

The second helium circuit supplies five sets of cryogenic vacuum panels with liquid helium. The cryopanels are on a separate circuit because: the circuit mass flow rate is 20 gs^{-1}; the panels must be warmed up for cleaning every few months; and the pressure drop in the cryopanel circuit is not as critical as it is in the magnets. Both helium circuits are supplied by the refrigerator control box. The refrigerator, which is not shown in Fig. 4. is within 15 m of the control box.

References

1. R. Avery, et.al., Experimental Superconducting Accelerator Ring (ESCAR), Proceedings of the IXth International Conf. on High Energy Accelerators, SLAC, Stanford, Calif, May 2-7, 1974, also LBL-2603.

2. T. Elioff, W. Gilbert, G. Lambertson, and R.B. Meuser, ESCAR-First Superconducting Synchrotron Storage Ring, presented at the Applied Superconducting Conf., Chicago, Ill., Sept. 30-Oct. 2, 1974, also LBL-3078.

3. Supercon, Inc., 9 Erie Drive, Natick, Mass. 01760.

4. MCA-Magnetic Corp. of America, 179 Bear Hill Rd., Waltham, Mass. 02154.

5. Airco, Inc. - Central Research Lab., Murray Hill, New Providence, New Jersey 07974.

6. J.B. Rechen, ESCAR Dipole Magnet Coil Design Parameters, Magnet "D-3", ESCAR Note #13, February 27, 1975.

7. W.L. Pope, Dipole Cryostat 2ϕ Helium Flow Passage Sizing, ESCAR Note #14, February 13, 1975.

8. R.A. Byrnes, M.A. Green, The ESCAR Helium Refrigeration System, written in the Proceedings of the 1975 Particle Accelerator Conference.

** Note added in Proof

A small solenoid has been wound with the full-current Supercon cable. 96% of short sample performance (10^{-12} ohm cm resistivity) was achieved on the first transition -- approximately 2100 amperes at 60 kG. The second transition was 98% of short sample.

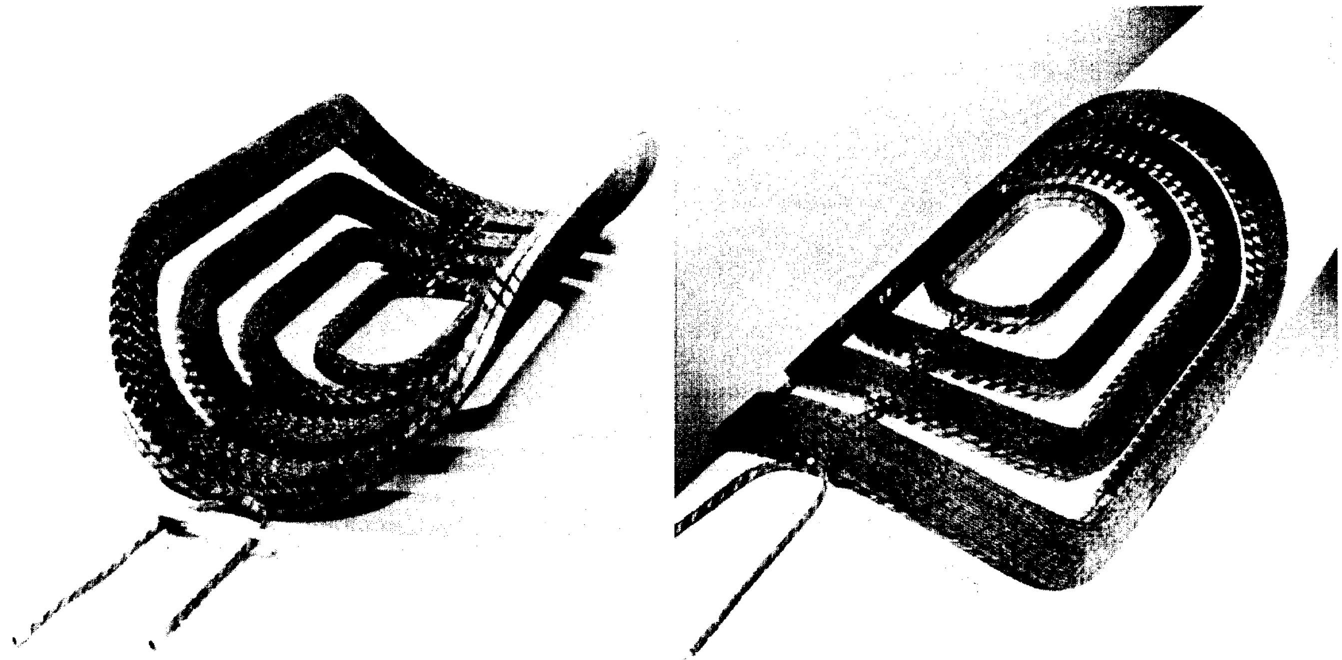

Figure 1 - ESCAR Dipole End Winding Model

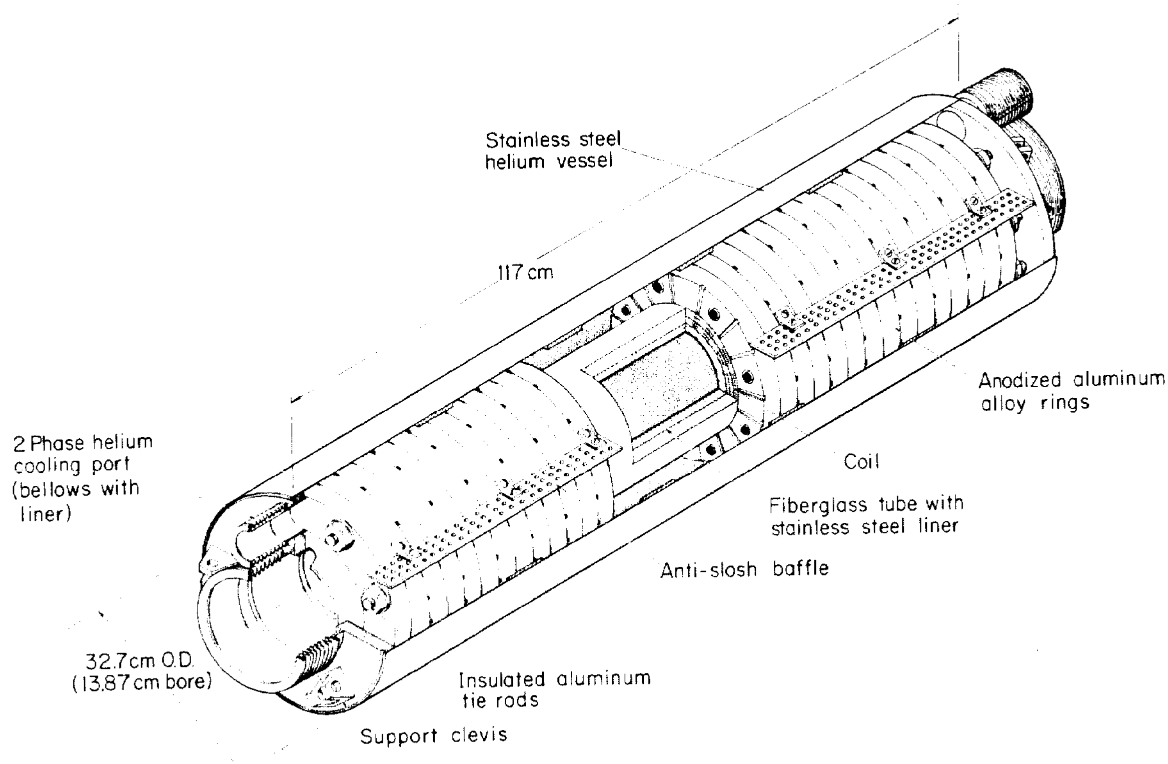

Figure 2 - Dipole-Cryostat Cold Assembly

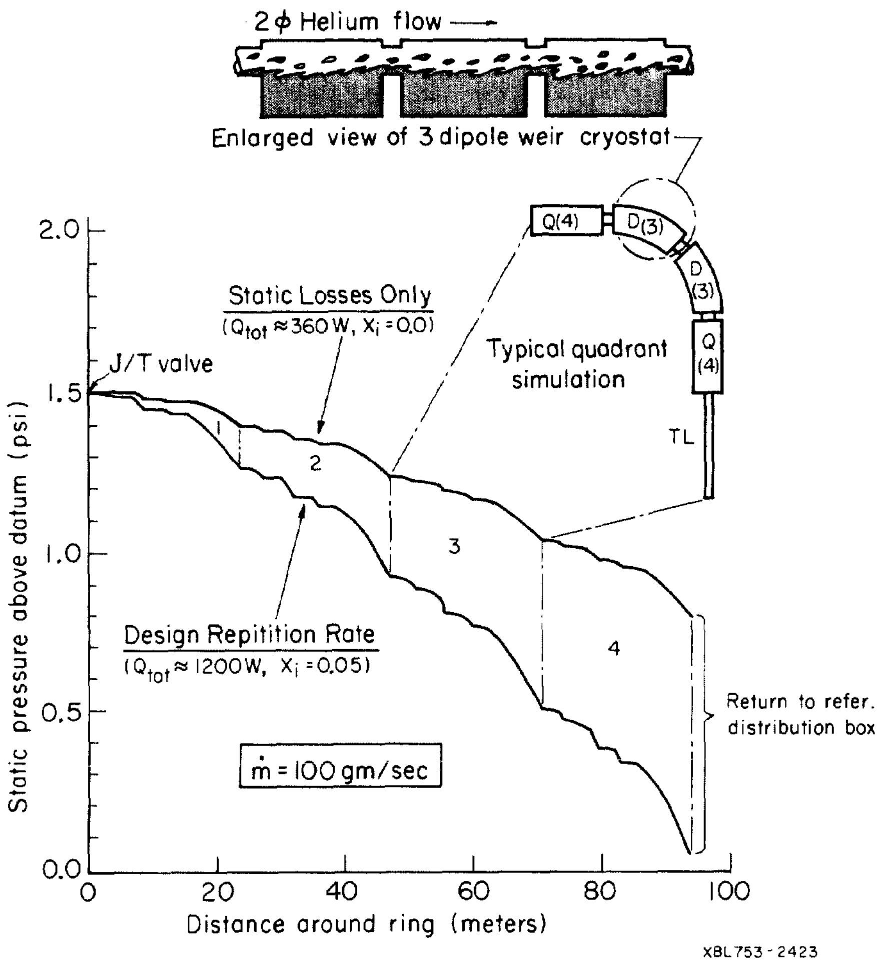

Figure 3 -
Pressure drop around ESCAR Ring

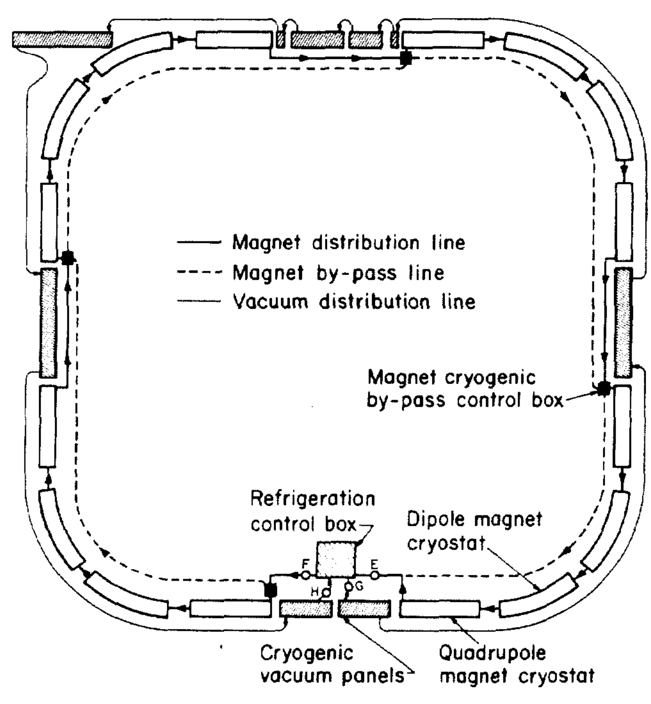

Figure 4 -
ESCAR helium distribution schematic