Title
FINAL REPORT ON THE EXPERIMENTAL SUPER, CONDUCTING SYNCHROTRON (ESCAR)

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FINAL REPORT

ON THE

EXPERIMENTAL SUPERCONDUCTING SYNCHROTRON (ESCAR)

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Final Report on the Experimental Superconducting Synchrotron (ESCAR)

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*See page 30.

Final Report on the Experimental Superconducting Synchrotron (ESCAR)

A. PROLOGUE AND OVERVIEW

ESCAR was conceived as a project in accelerator technology development which would provide data and experience to insure that planning for larger superconducting synchrotrons and storage rings would proceed in a knowledgeable and responsible manner. It consisted of the fabrication and operation of a relatively small proton synchrotron and storage ring with superconducting magnet elements for all of the main ring.

When completed, ESCAR (Experimental Superconducting Accelerator Ring) was to be an interesting and useful accelerator and storage ring in its own right, with considerable flexibility for a range of accelerator experiments and experiments with high-current stored proton beams.

Funding for the project started in July 1974 following preliminary studies(1) at Lawrence Berkeley Laboratory to establish the practical minimum in accelerator size and cost for a machine from which lessons useful to the accelerator community could be learned. Prior to that, the need for comprehensive systems development beyond the design of individual test superconducting magnets had been recognized by the 1971 HEPAP Subpanel on Advanced Accelerator Concepts and Technology.* That Subpanel recommended the support of a working pilot project to precede the utilization of the new superconducting technology in large scale accelerator construction.

To provide technical review and liaison with other interested institutions, the ESCAR Advisory Committee was appointed by W.A. Wallenmeyer of the DoE Division of High Energy Physics (then AEC). This group, chaired by Dr. George Wheeler, had Nationwide representation and met periodically at LBL throughout the project.*

The major design decisions were made by early 1975; work on a model dipole magnet and on refrigeration procurement was then in progress. The following general parameters were established; detailed parameters are given in the more

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* The HEPAP subpanel on Advanced Accelerator Concepts (1971) set up the following criteria for small-scale projects. The project should:

a) make use of new ideas on technology in a practical way;
b) be built at an existing laboratory;
c) be useful and exploitable for research;
d) cost on the order of 1 M $/year.

The HEPAP subpanel further outlined the advantages of such a plan:

1) It would bring about the solution of many unsolved and unforseen engineering problems.

2) It would provide experience for more intelligent selection of new technology items.

3) It would bridge the gap between the present and the next generation of accelerators.

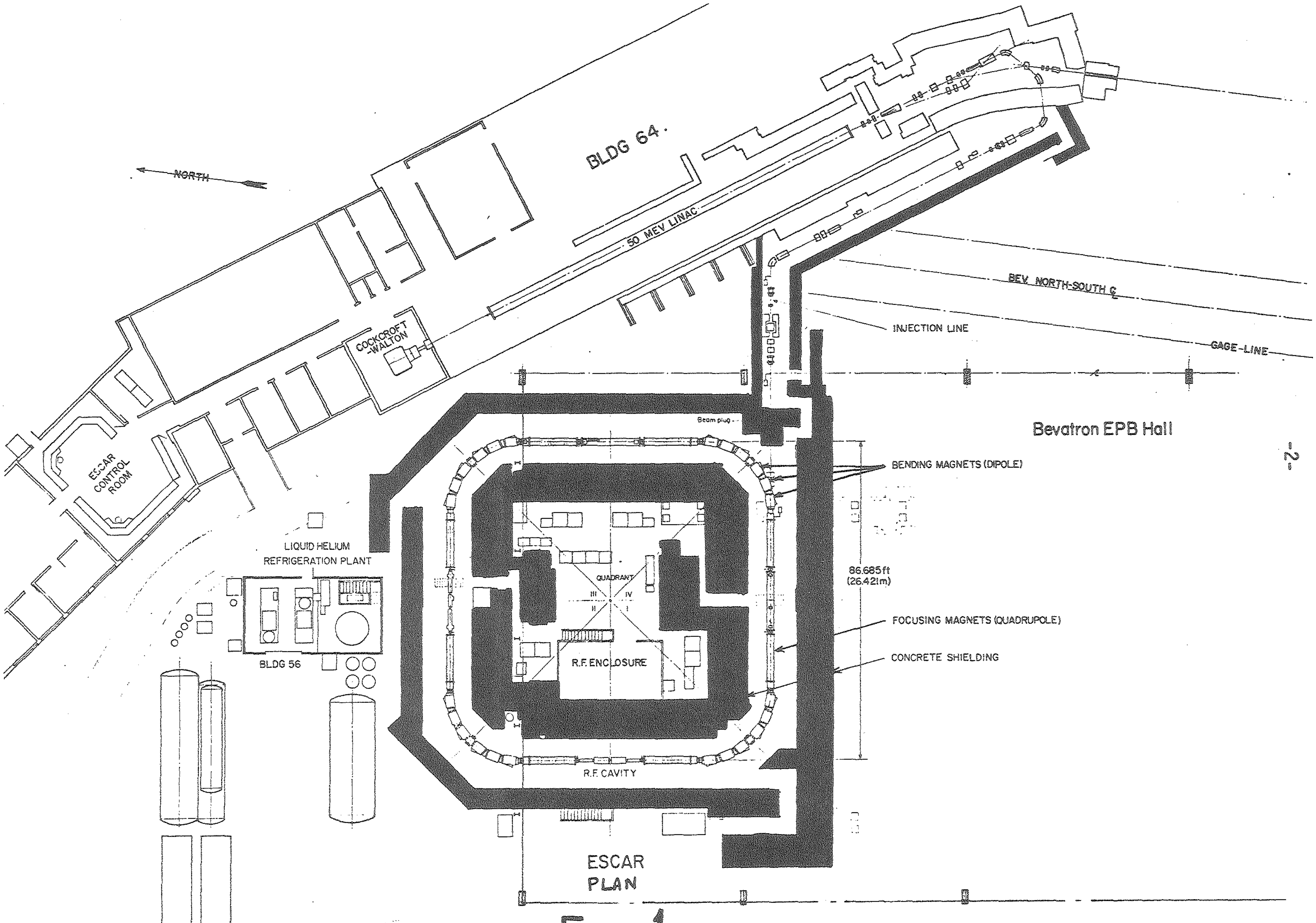

NORTH
BLDG 64.
50 MEV LINAC
COCKCROFT -WALTON
ESCAR CONTROL ROOM
BEV NORTH-SOUTH ℄
INJECTION LINE
GAGE-LINE
Beam plug
Bevatron EPB Hall
BENDING MAGNETS (DIPOLE)
LIQUID HELIUM REFRIGERATION PLANT
QUADRANT
III
IV
II
I
86.685 ft (26.421m)
FOCUSING MAGNETS (QUADRUPOLE)
BLDG 56
R.F. ENCLOSURE
CONCRETE SHIELDING
R.F. CAVITY
ESCAR PLAN

FIG. 1

specialized sections of this report. Figure 1 is a plan view of the total facility.

TABLE I

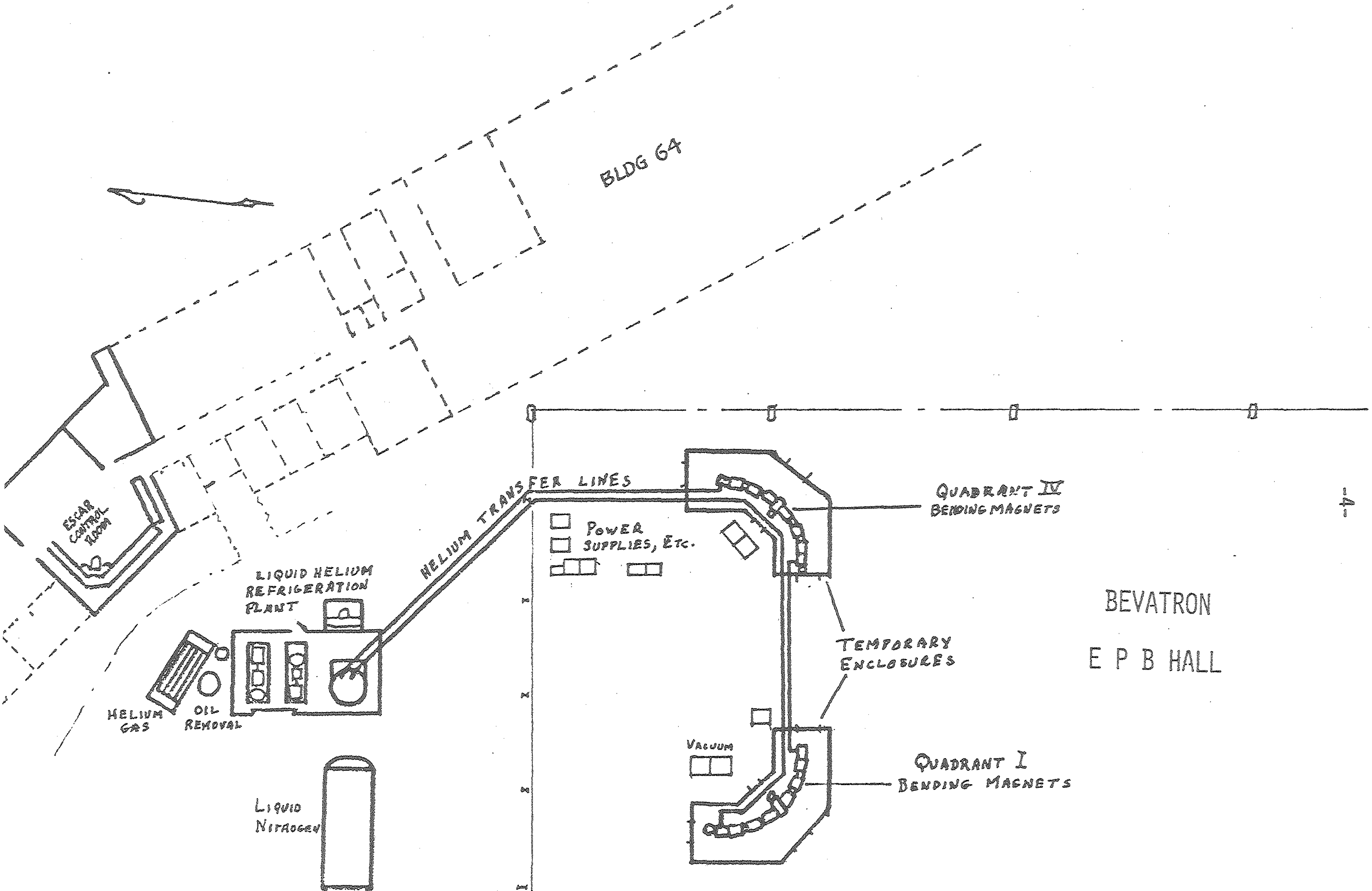
Maximum energy	4.2 GeV
Intensity	4 x 10^{12} protons/pulse
Pulse rate	6/minute or 0.1 hertz
Pressure	10^{-11} torr
Injection energy	50 MeV
Bending magnet field	4.6 T
Focus magnet gradient	20 T/m

The maximum energy was chosen to permit a realistic test of high-field magnets at reasonable cost. The intensity was a compromise recognizing the characteristics of the available injector linac, the desire to avoid excessive main-ring magnet apertures and the desire to investigate high-current beam effects. The pulse rate limit was imposed by reasonable power supply and refrigerator capabilities; the magnets were designed for an even greater rate. D.C. operation was also to be provided, and the low pressure expected in the beam tube with its cryogenic pumping would permit beam storage times of several hours.

The magnet modeling was completed in early 1976 and tooling had been prepared to permit then the start of production magnet winding. The production and testing of magnets, preparations for their installation at the final site, and cryogenic system fabrication then dominated the activities for the next 18 months. During this time, it was increasingly apparent that funding rate was directly limiting the rate of completion of ESCAR and an intermediate goal was desirable. Assembly of the ring that would permit an early test operation and evaluation of most of the new-technology systems was accordingly scheduled for the fall of 1977. Twelve dipoles, one half of those in the total ring, were installed at the site along with cryogenic distribution, refrigerator, electrical power supplies, and controls. The refrigerator had arrived in June 1977 and had been operated successfully. This truncated system was put through an extended series of tests which were completed in June 1978 at which time the ESCAR project was terminated. Our decision not to complete the ESCAR facility recognized the facts that funding to support an adequately brisk program had not and would not become available, that large scale systems work, although late, was now also in progress in other major superconducting accelerator projects, and that substantial evaluations and experience had been gained by the end of the systems tests. Figure 2 is a plan view of the elements involved in the 1977-1978 series of tests.

B. PROJECT DESCRIPTION

The following sub-sections of this report review the design planned for the complete accelerator in each category, define the portion that was actually built and tested, and give an evaluation of the experience. More detailed information, including an analysis of design constraints and choices, is available from LBL as informal internal notes and reports for accelerator



ESCAR, 1977 - 78 TEST ARRANGEMENT

FIG. 2

designers and others who may benefit from this material in their attack on similar problems. These reports are summarized and partially listed in Section D of this report.

I. Lattice and Beam Parameters

The guide field magnets are arranged in 4 symmetric quadrants connected by 4 straight sections. Each half-quadrant consists of 4 quadrupole and 3 dipole superconducting magnets, for a total of 24 dipoles and 32 quadrupoles. The cryogenic-temperature bore tubes of these magnets are the principal vacuum pumps for the ring, and a pressure of 10^{-11} Torr was expected. The dipole windings are connected in series and initially powered by four power supplies. Quadrupoles initially are to be connected in two groups, on two power supplies. Helium refrigeration capacity limits ring magnets to 6 pulses per minute for cyclic acceleration. D.C. operation as a storage ring is possible. Superconducting trim windings are provided for beam manipulation, diagnostics and resonance control. Beam diagnostic devices compatible with the high vacuum and cryogenic environment are provided. Beam tunes and transition energy may be varied over rather wide ranges by manipulation of quadrupole strengths. Transition energy was normally above the maximum machine energy to remove transition-crossing complications to beam experiments. It could be adjusted to be imaginary or within the machine's acceleration cycle if desired.

Injection is from an existing 50-MeV linear proton accelerator which is part of the Bevatron system. Beam transport is by an array of conventional bending and focusing magnets to a point under the south ESCAR straight section. An electrostatic wire septum and four "bump" magnets will stack successive turns of beam in the vertical plane. The R.F. acceleration voltage is programmed to capture 90% of the injected beam. Beam is decelerated and dumped at the end of each acceleration cycle. No beam is extracted from the machine. Figure 3 shows the effective magnet lengths along the beam orbit. Lattice parameters are listed in Table II.

TABLE II

Accelerated Beam		
No. of Particles	N_o	$4x10^{12}$ protons per cycle
Max. Momentum	P	5.0 GeV/c
Max. Energy	T	4.15 GeV
Pulse rate		6 per minute
*Initial horizontal tune	ν_y	3.3
*Initial vertical tune	ν_y	2.3
*Initial transition gamma	γ_T	2.8i(imaginary)
*Max. Beta functions	β_x	9.34m (in Q4)
	β_y	19.40m (in Q3)
*Dispersion in st. sect.	η_x	4.49m

*These are from one calculated example using two quadrupole circuits for initial running.

Injection			
	Linac Energy	E_L	50 MeV
	Linac Current	I_L	75 mA protons
	Linac Emittance	ε_L	2 cm-mrad
	Linac momentum spread	$\Delta p/p$	+.002
Accelerator			
	Bend per dipole	θ_B	15°
	Dipole effective length	S_B	.95 m
	Bend radius in dipole	R_B	3.63 m
	Dipole field	B_o	4.6 tesla
	Quadrupoles, design max. gradient	B'	20 tesla/meter (all)
	Quadrupoles, initial gradients (two circuits, $\gamma_T = 2.82$ i)		
		$Q_1 = Q_4 = 15.35$ T/m	
		$Q_2 = Q_3 = -12.68$ T/m	
	Ring center orbit length	C	96 m
	Average bend radius	C /2π	15.28 m
	Aperture R. F. Section		12.7 cm diameter
	Aperture, remainder (with small exceptions)		14.0 cm diameter
	Ring beam tube vacuum		10^{-11} torr
	Injection line vacuum		10^{-6} torr
	Beam tube temperature, straight sections		Various; cold where possible
	Beam tube temperature, remainder	4.4°K (L He)	

II. Superconducting Magnets, Cryostats

Introduction

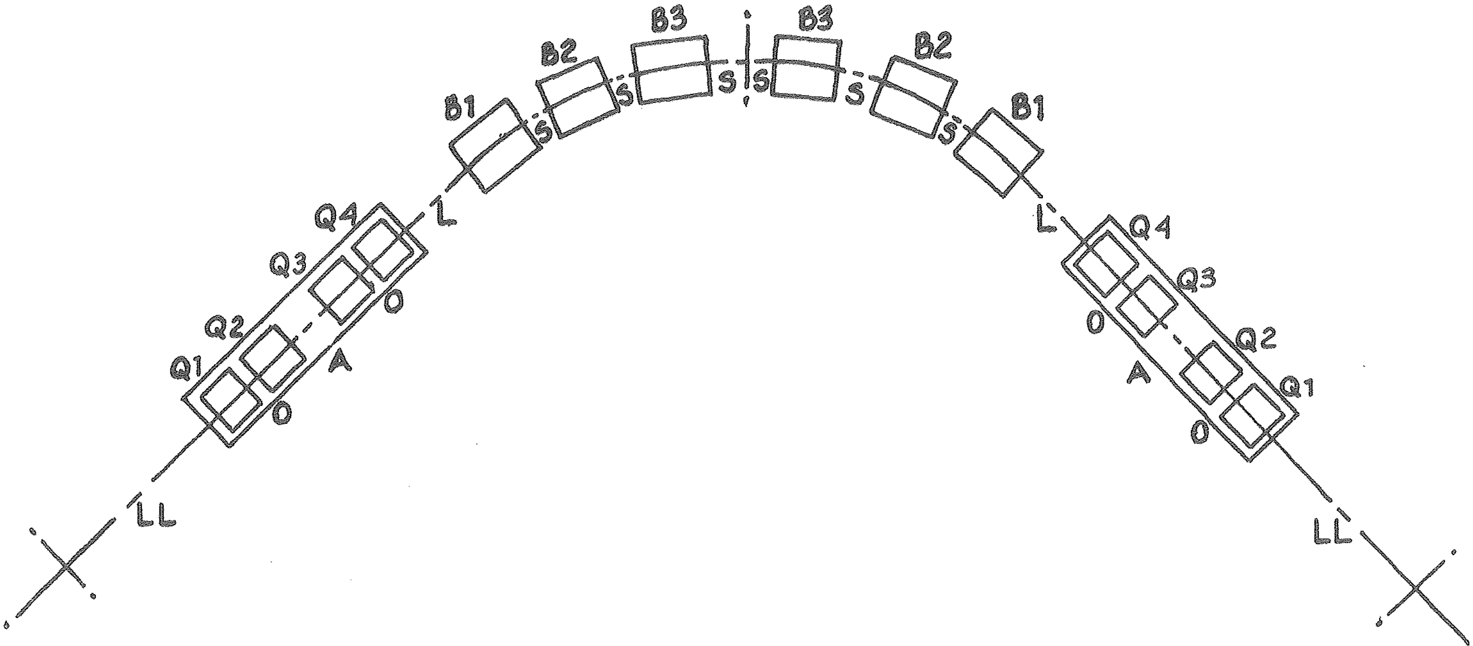
Three types of superconducting magnets are required for the ESCAR accelerator ring. They are:

1. 100 trim coils for various beam experiments and adjustment of tune and working lines
2. 32 quadrupoles, for beam focusing.
3. 24 dipoles, for beam bending

The development of the dipole magnets was recognized as the most difficult task and we concentrated our efforts in this area. 12 dipoles, were produced and tested during the course of the project. One full size model quadrupole was built and successfully tested at the end of the project. The trim coils were designed but none were built as their production was to coincide with that of the quadrupoles.

1. Trim Coils

The 100 trim coils mentioned above were designed to be wound from single insulated round multifilament NbTi conductor of less than 50-ampere capacity. These coils were then to be buried in the fiberglass epoxy bore tubes and, where required, nested together. Under each of half the quadrupole coils (16) are trim windings for regular sextupole, skew sextupole, regular octupole, and skew octupole. Between the quadrupoles, at the midpoints of the quadrupole groups are skew quadrupoles and horizontal and vertical dipoles. At the centers of the 4 quadrants between bending magnets are a regular sextupole and horizontal and vertical dipoles. The peak strengths of all the trim windings are of the order of a few hundred gauss-meters.



Radius (Circ./2 π)	R	15.29	m	
Magnetic Radius	ρ	3.6287	m	
Cell Length	Lc	24.0	m	
Quadrupole Effective Length	ℓ_Q	0.6	m	
Dipole Effective Length	ℓ_B	0.95	m	

Drift Lengths (Effective):

LL	3.00 m
O	0.20 m
A	0.70 m
L	1.36 m
S	0.43 m

FIGURE 3

2. Quadrupoles

The development of the quadrupoles was assumed to be, and actually was, much easier than that of the dipoles. The final design has a current of 300 amperes producing the required maximum gradient of 20 tesla per meter. The associated maximum field in the coil is only 2 tesla and the Lorentz forces and pulsed superconducting losses are small, as compared with those in the dipoles.

An "overlapping ellipse" configuration, with 6 layers wound from a simple solid round conductor was used. The insulation on the wire consists of a layer of formvar with an overcoated bondable coating (Polybondex). Each layer was wound individually, then bonded with heat, forming a rigid structure with the conductors accurately placed. The design calls for the thin iron return yoke to be placed in contact with the coil and with the helium, a "cold iron" design (see Fig 4). The design current is only 60% of the short sample current of the superconductor selected for model tests.

In order to test rapidly the structure, cryogenic behavior, and superconducting stability of the quadrupole coil, we tested the model quadrupole, without the iron return yoke, in a vertical cryostat (pool boiling). External structural constraint was supplied by a banding of berylium copper wire, wound at maximum tension. Without the iron return, the coil current needed to meet design gradient increased from 300 amperes to 525 amperes. The first quench on run-up occurred at 600 amperes, or 95% of the short sample limit on the no-iron load line. Ramp-rate sensitivity was not determined

The test operators found the experiment somewhat uneventful, or even boring, but the magnet designers and builders didn't share their feelings. We judged the quadrupole development program as successful even though the end of the ESCAR program prevented the testing of the final quadrupole in its cold iron return yoke and horizontal cryostat.

3. Dipoles

a. Design Details of Dipole Bending Magnets

The superconductor selected for these magnets is a 17-strand Rutherford-type cable of 6:1 aspect ratio (Fig. 5). Each 0.020" diameter strand contains 2100 NbTi filaments, 6 microns in diameter in a copper matrix, with a thin coating of silver-tin solder on each strand. The combination yields high current capacity, low pulsed-current hysteresis losses, and low coupling between strands. The cable, compacted and sized, is insulated with overlapped Mylar tape and a partially open barber-pole wrapping of B-stage epoxy-impregnated fiberglass tape. The coil, when wound and baked, is thus insulated, permeable to liquid helium, and moderately rigid.

Figure 6 shows a central cross-section of the magnet, in which the azimuthal distribution of conductors can be seen. The coil ends (not shown) are quite compact to satisfy simultaneously the alloted mechanical length constraint and the magnetic length requirement. The compact end geometry causes the region of maximum magnetic-field to appear at the conductor in the ends.

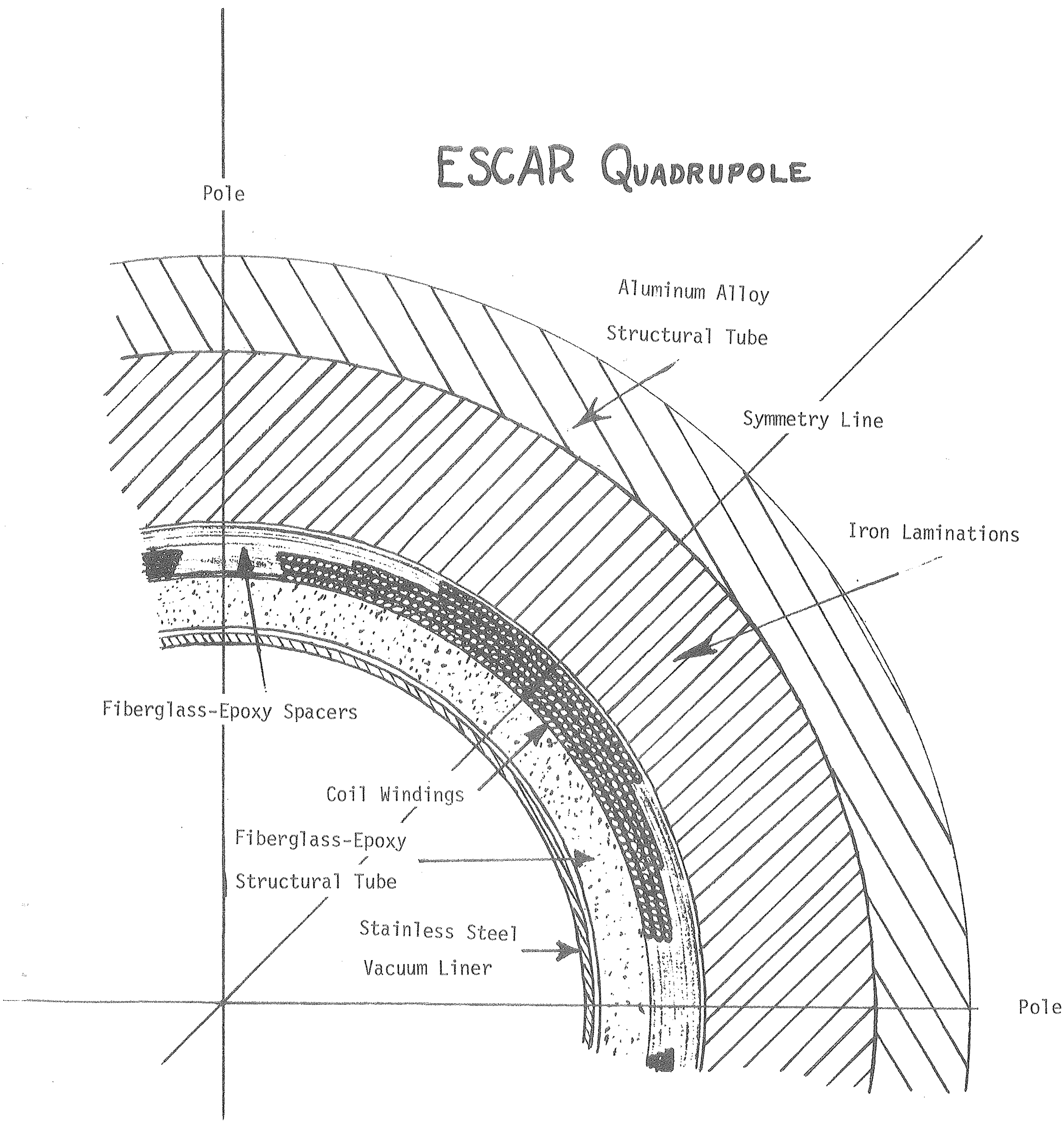
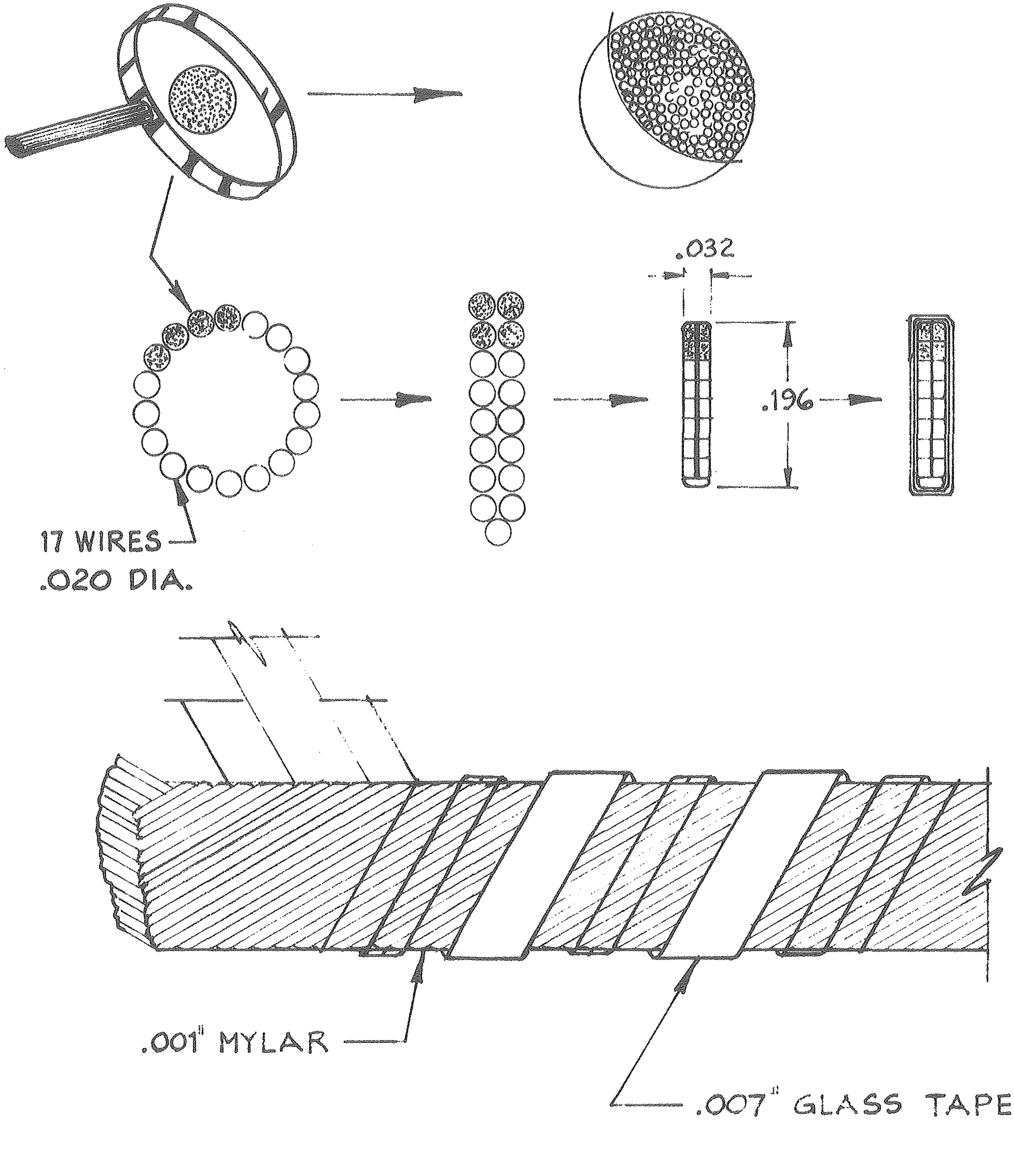
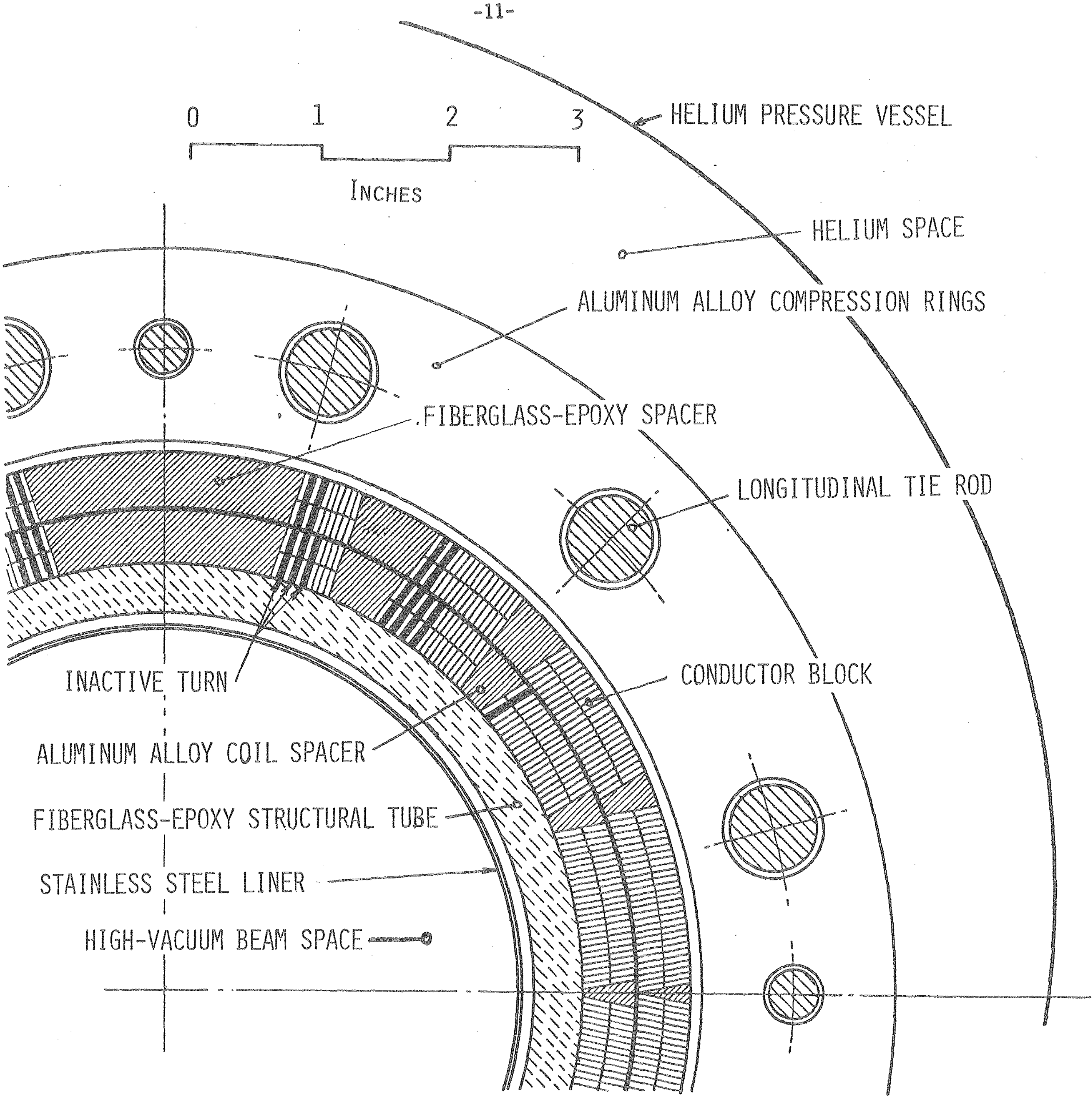

ESCAR QUADRUPOLE
Pole
Aluminum Alloy
Structural Tube
Symmetry Line
Iron Laminations
Fiberglass-Epoxy Spacers
Coil Windings
Fiberglass-Epoxy
Structural Tube
Stainless Steel
Vacuum Liner
Pole

FIG. 4



R.H.E.L. "Rutherford" Cable,
as used on ESCAR
Fig. 5



DIPOLE, CENTRAL CROSS-SECTION

FIGURE 6

All active coil turns are connected in series, with soldered splices between coil windings made at the ends, where the field is low. The beginning and the end of the whole coil winding emerge at opposite ends, with a straight-through conductor for return current on the midplane, thus making the coil connections accessible from both ends for magnet interchangeability.

The cylindrical coil assembly is supported on a stainless-steel-lined epoxy-fiberglass bore tube. Radial and longitudinal restraint of the coil is provided by a system of external aluminum-alloy rings and longitudinal tie rods. The surrounding helium vessel is eccentric to the coil assembly to provide maximum flow area at the top with minimum liquid volume. A multilayer-insulated liquid-nitrogen-cooled shield surrounds the helium vessel and is, in turn, surrounded by the vacuum vessel. The helium vessel is rigidly supported from the vacuum vessel end flanges by a system of seven short, epoxy-fiberglass compression struts incorporating strain-gauge load sensors. The cryostat is rigidly attached to the iron return yoke, which supports and locates the entire assembly.

The coil winding, magnet and cryostat assembly, testing, and most of the parts fabrication were done by LBL personnel.

b. Test Procedures for Individual Dipole Magnets

The tests of each production magnet, mounted in its horizontal cryostat and iron yoke, included measurements of the following:

At room temperature:
- Magnetic field quality
- Response to pulse voltage up to 300 V

During Cooldown:
- Coil resistance.
- Magnetic field quality.
- Cryogenic behavior, especially the helium vessel support sruts.

In the superconducting state:
- Training and quench behavior.
- Effect of current ramp-rate and pulse frequency on heat generation,
- Quench current, and recovery time.
- Dipole field direction and alignment to external fiducials to 0.3 mrad.
- Centering of the coil within the iron yoke, using the strut load cells.
- Magnetic field quality at various current levels both before the first quench and at intervals during training. Combinations of coils on a rotating long coil assembly, in the cold bore, measure dipole field integrals and orientation and all harmonics to the fourteenth, both through the central region and through the ends of the magnet, to an accuracy of 1 part in 10^5 of the dipole field.

c. Tests of Individual Magnets

The magnetic field uniformities shown by all magnets were within the specified range of $B/B \leq 10^{-3}$, showing that all bundles of conductors were held within 0.1 mm of design positions. Magnets were delivered from the shop with less than 0.3 mm eccentricity with respect to the iron yoke; this was detected and eliminated using the strain-gauge-instrumented support studs during powering of the magnet..

During development of the energy extraction procedure, a pre-production magnet and the first production magnet were damaged due to overheating of part of the coil structure. Subsequently the provision of prompt quench detection, and dissipation of more than 60% of the stored energy in an external resistor resulted in no further damage during individual magnet testing.

The magnets quenched initially at about 80% of short-sample current and trained, at various rates, up to about 95%. (Fig. 7) During training the sextupole magnetic field component changed, indicating coil movement. (Fig. 8)

A few magnets were warmed, and then retested at liquid-helium temperature; they varied in the amount of training retained. These results are consistent with a combination of too low a coil compressive modulus with insufficient pre-loading by the structural rings.

After coil movement was inferred from the tests of the first few magnets, shims were inserted on the horizontal mid-plane to bias the initial sextupole component opposite to the change in it caused by coil movement. This was not entirely satisfactory.

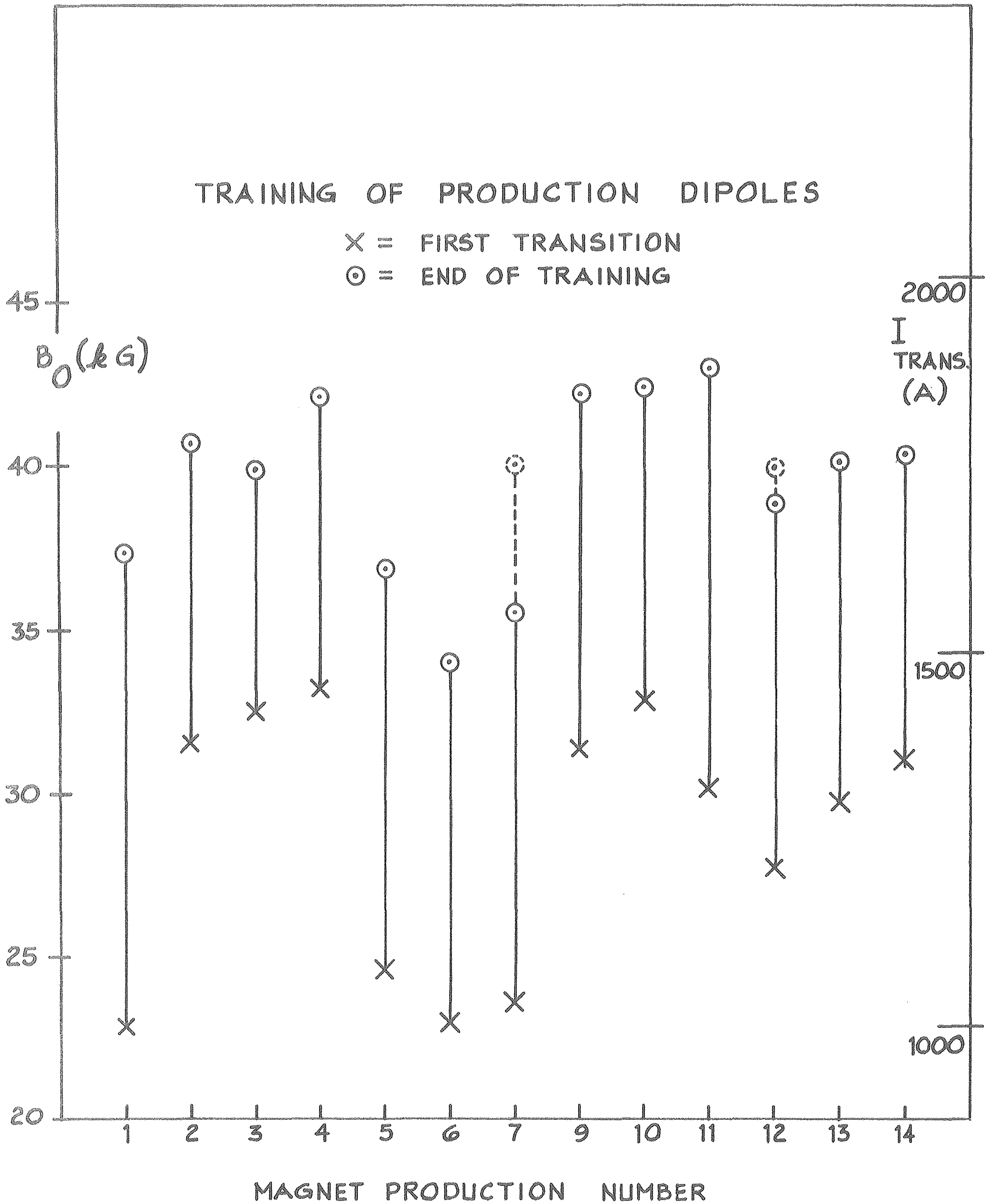
d. Tests of Magnets in Quadrant Assemblies

The twelve completed dipoles were aligned on support girders and joined to form ESCAR ring quadrants IV and I at the site. All magnets formed one series cryogenic helium circuit. Electrically, each group of six dipoles was connected in series, on one power supply with three current leads, the center-tap connection permitting energy extraction from whichever three-magnet group contained the normal-going magnet.

In addition to normal control and monitoring provisions, instrumentation peculiar to this superconducting system was provided, including:

Magnet voltage taps to monitor temperature during cool-down and warm-up.
Liquid helium level gauges in magnets.
B-dot coils for quench detection.
Helium gas flow meters for vapor-cooled current leads.
Helium system pressure gauges.
Insulating vacuum instrumentation and interlocks.
Bore-tube ultra-high vacuum instrumentation.

The planned test sequence was to conduct cryogenic experiments on one quadrant, then on both together, followed by electrical tests in the same sequence. Cryogenic tests are briefly noted below. They are more fully reported in the section on refrigeration and cryogenic distribution.



TRAINING OF PRODUCTION DIPOLES
X = FIRST TRANSITION
⊙ = END OF TRAINING
45
40
35
30
25
20
B0 (kG)
2000
1500
1000
I TRANS. (A)
1
2
3
4
5
6
7
9
10
11
12
13
14
MAGNET PRODUCTION NUMBER

FIGURE 7

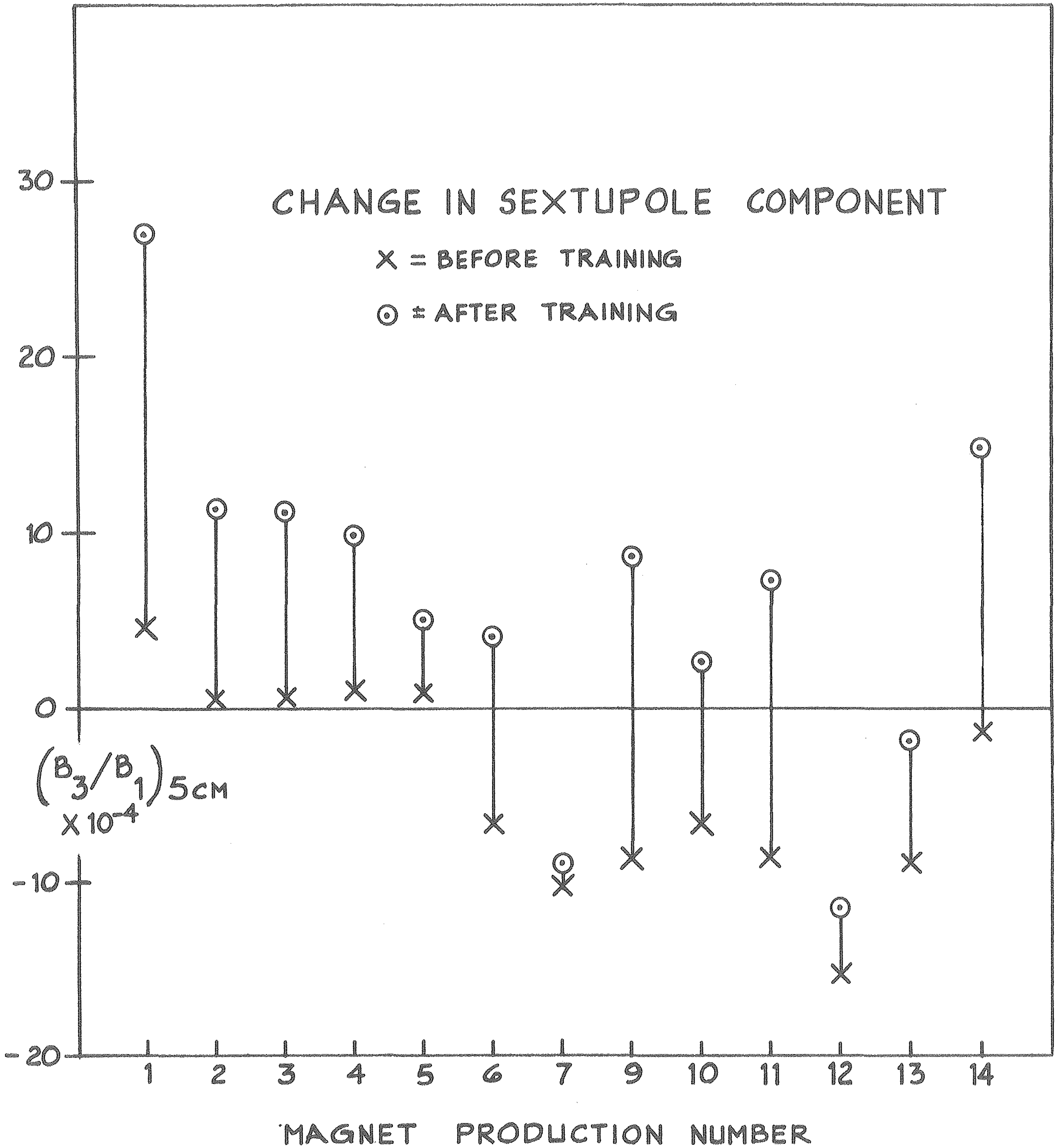

CHANGE IN SEXTUPOLE COMPONENT
X = BEFORE TRAINING
⊙ = AFTER TRAINING
30
20
10
0
-10
-20
(B3/B1) 5 CM
X 10-4
1
2
3
4
5
6
7
9
10
11
12
13
14
MAGNET PRODUCTION NUMBER

FIGURE 8

One-quadrant cryogenic tests. When cryogenic preparations were completed, we cooled down Quadrant IV and filled the magnets with liquid helium. These tests were extremely successful although there was a severe helium-to-insulating-vacuum leak. Special techniques were developed to find this leak in the extended, limited-access, helium-saturated system. Successive upstream injections of a probe gas into a carrier gas drifting slowly through the insulating space were observed on a residual-gas analyzer on the helium system. Analysis of responses indicated the region containing leak, which was then pin-pointed by detailed probing after the indicated vacuum-and-thermal-shield section was opened.

Two-quadrant cryogenic tests. Twelve magnets, in two quadrants of six magnets each, were cooled and filled with liquid helium. Numerous cryogenic flow experiments were carried out as outlined in Refrigeration and Cryogenics, Subsection III of this report.

Quadrant IV electrical tests. In testing the energy extraction circuit on the six series-connected dipoles, electrical breakdown to ground occurred at several of the non-superconducting voltage monitor wire feed-throughs, causing damage to the power supply control circuitry as well as to monitoring circuits. After all the known damage was repaired, tests resumed. On the first current excitation, the power supply was programmed to ramp to 100 amperes. Due to a faulty circuit element, the current rose uncontrollably and could not be turned off from the control panel. Current leads on one or more magnets burned through, and the current was thus eventually interrupted. The resulting electrical arcs burned holes in the helium system, dumping the liquid helium into the insulating vacuum space and to the atmosphere through a spring-loaded safety cover plate. There was sufficient damage, electrical and mechanical, to cause us to disconnect this six-magnet group and to continue tests only with the second quadrant.

Quadrant I electrical tests. Guided by experience from the first quadrant test, we improved the voltage holdoff capability of the second 6-magnet string to withstand 2 kV to ground, and we reduced the voltage generated by the energy extraction to 700 V. These voltage tests were conducted with all internal connections at their operating temperatures and in helium, as the dielectric strength of helium is considerably less than air or most other gases. The power supply responded properly in all second-quadrant tests. Three magnets, in series, were powered as a group and the energy extracted from all three as a group. During the earlier tests of single magnets, extraction voltages of 500 V were applied. The corresponding voltage for the three-magnet string would be 1500 V, so our breakdown limit of 700 V resulted in a smaller fraction of the total magnet energy being deposited in the dump resistor, and the magnet current decayed more slowly. As much as 275 kilojoules was deposited in the normal-going magnet, which is higher than the energy stored in any one magnet.

The training process with this arrangement was slow, probably due to the excessive energy being dissipated in one magnet on each quench. One magnet eventually developed a resistive character during this training although it had undergone more than 100 quenches during its previous individual training. This experience stresses the importance of having the initial testing and training cover the highest voltage and energy deposition to be expected under installed operating conditions.

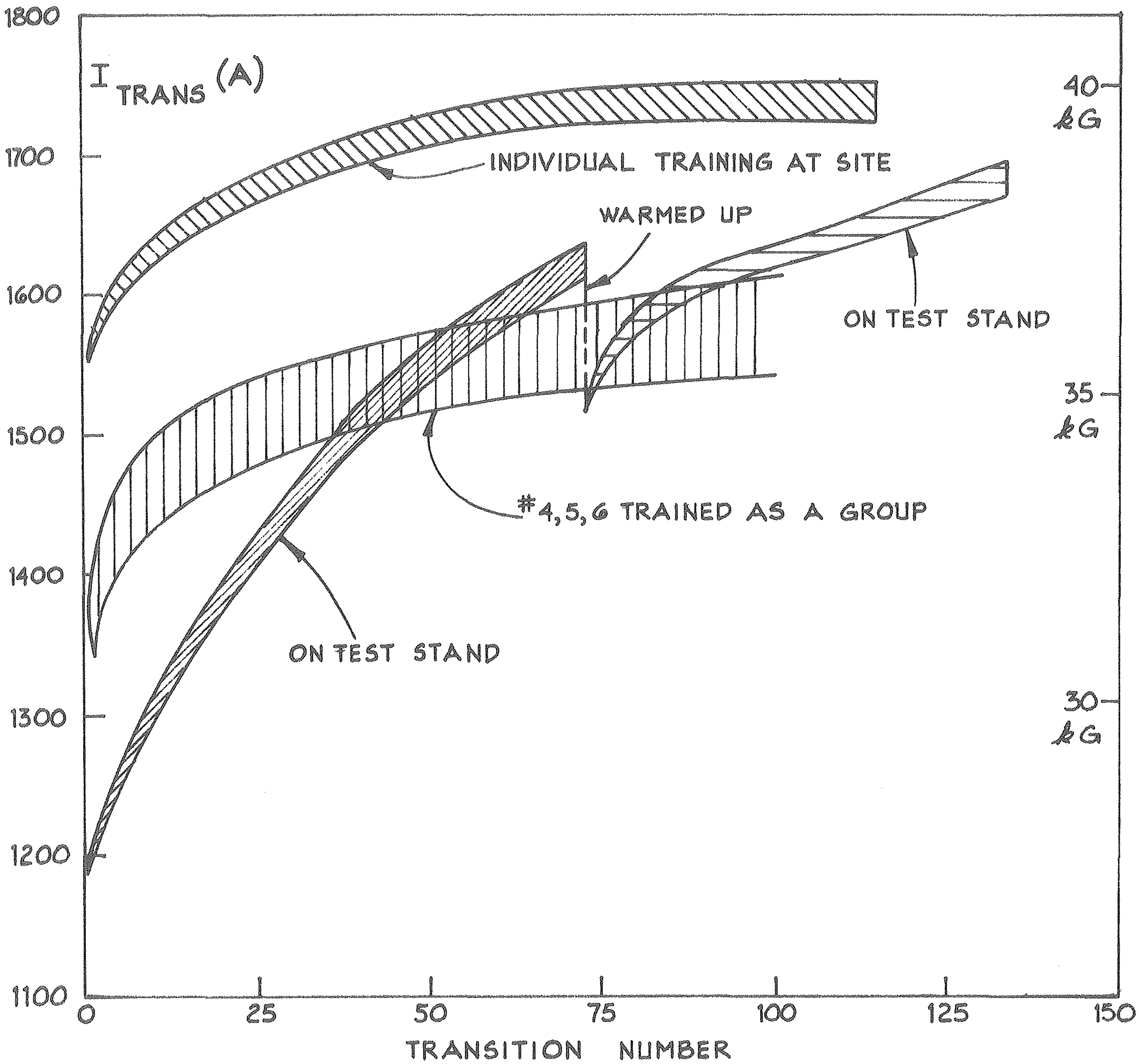
Figure 9 shows the full training history of magnet No. 4 in the second quadrant, (production number 12). Initial individual training, the training of Nos. 4, 5, and 6 as a group, and later individual training of No. 4 as installed are shown. Since individual magnets were not monitored in group training, the transitioning magnet is not identified directly during this sequence. Magnet No. 4 reached 4.0 Tesla when trained as installed but separately powered. The quadrant cooling system with high mass flow was quite a different cryogenic environment from the quiet pool-boiling system used in the individual magnet test, but no evidence of altered magnet performance appeared.

Thermal sensitivity trends are shown in Figure. 10. For the single-pulse data a single linearly-rising current ramp was applied to the magnet until it quenched. After cooling periods of at least three minutes this was repeated, but on successively faster-rising ramps, tracing out the curves shown. To evaluate the rapidity of heat removal, the continuous-pulsing data were taken. A long string of triangular pulses of constant duration but slowly increasing current-swing from 100A to maximum is imposed until the magnet quenches. The cycle time is then changed and the process repeated to obtain a range of data. The magnet having epoxy in the coil cable evidently has poorer heat-transfer than the one without epoxy leading to a greater sensitivity to current rate-of-rise.

TABLE III

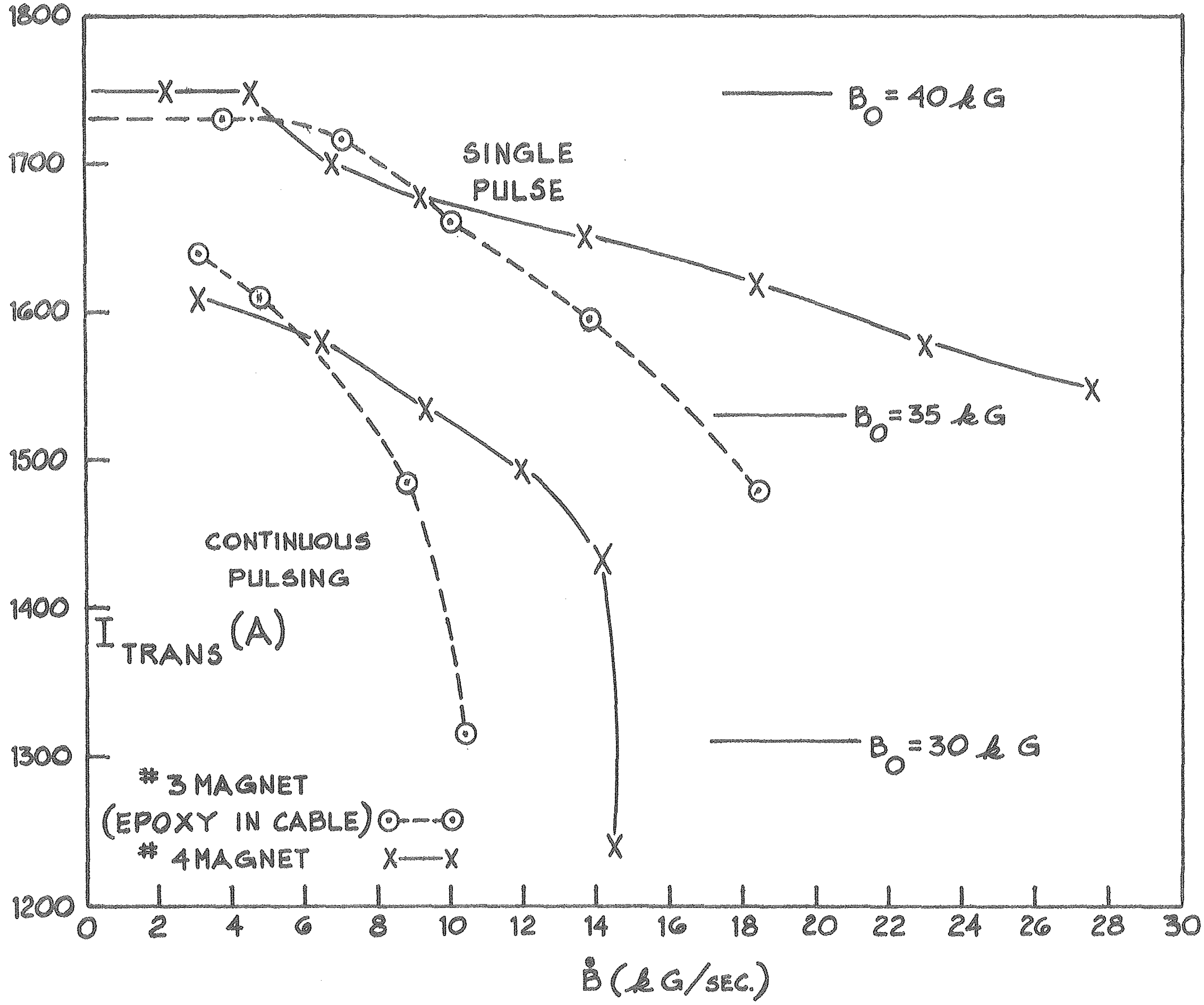
ESCAR Dipole Magnets -- Goals and Results

ITEM	DESIGN	ACHIEVED
Central Dipole Field B_o	4.6T @ 0.1 Hz	4.0 to 4.3T, Single Pulse 3.6T @ 0.1 Hz Continuous
Magnetic Field Harmonic Error	$(C_n/C_1)^5$cm $\leq 1 \times 10^{-3}$	C_3 and $C_5 \approx 10^{-3}\ C_1$
Cryogenic Heat Load	50W/6 Magnets with 2 Current Leads	(90 $\pm$ 15) W/6 Magnet Group With 3 Current Leads
Production Yield or Reliability	> 90% Hoped For	12 Production Dipoles Operated Out of 13 Wound
Production Rate	$\geq$ 1 Magnet/Month	10 Magnets/5 Months
Cool Down and Helium Fill	2 - 3 Days, Entire Ring	0.35 Days, 12 Dipoles
Warm Up	2 - 8 Days, Entire Ring	0.25 Days, 6 Dipoles
Alignment - Dipole Angle	Vertical $\pm$ 0.5 m-rad	Vertical $\pm$ 0.3 m-rad
Quench Detection, Energy Extraction	Protect Magnets	Of 15 Dipoles Individually Tested Over A 2-Year Period, 2 Magnets Overheated and were Damaged



TRAINING HISTORY OF MAGNET
#4, 2ND QUADRANT (PRODUCTION #12)

FIGURE 9



RATE SENSITIVITY
TWO MAGNETS

FIGURE 10

Summary of Experience with Magnets

The production of twelve magnets in sequence resulted in substantially identical units with low product failure rate. The helium-permeable coil structure, well ventilated for high pulse rate, also has low rigidity and consequently required training. Absence of massive cold iron was in this experiment a worthwhile convenience. When the magnets were series connected and operated in an accelerator-type circuit, voltage breakdown limitations reduced the effectiveness of the energy-removal system and caused some damages. A subsystem test for future accelerator applications is recommended. However, there was no effect from the altered cryogenic environment, no quench-contagion between magnets, and the general lack of exotic problems stands as an encouragement to the accelerator builder. Table III summarizes much of our experience.

III. Refrigeration and Cryogenic Distribution

1. Introduction

Central to the use of superconducting magnets in accelerators is the transport of the helium coolant around the machine to the magnets. ESCAR, because of its rapidly pulsed magnets has the largest heat load per meter of any of the proposed superconducting accelerators, over 20 watts per meter at 4.5° K. Pool boiling, replenished by a two-phase helium stream, was the coolant system chosen. This design incorporates a two-phase helium flow in which all the magnet cryostats are connected in series at their upper passages, the string serving as the ring transfer line. This is shown schematically in Figure 11a.

2. System Assembled for Tests

For these operations, six dipole magnets were assembled in each of two adjacent quadrants. Within a quadrant all of the magnet cryostats are series-connected (for refrigerant flow), and for these tests the two quadrants were series-connected.

A flow schematic for the two-quadrant subsystem is shown in Fig. 11b. The mixture of gaseous and liquid helium is circulated from the refrigeration plant to the quadrants and back. Room-temperature helium gas that has given up its refrigeration to the current leads is returned to compressor suction. Details of component sections are given below.

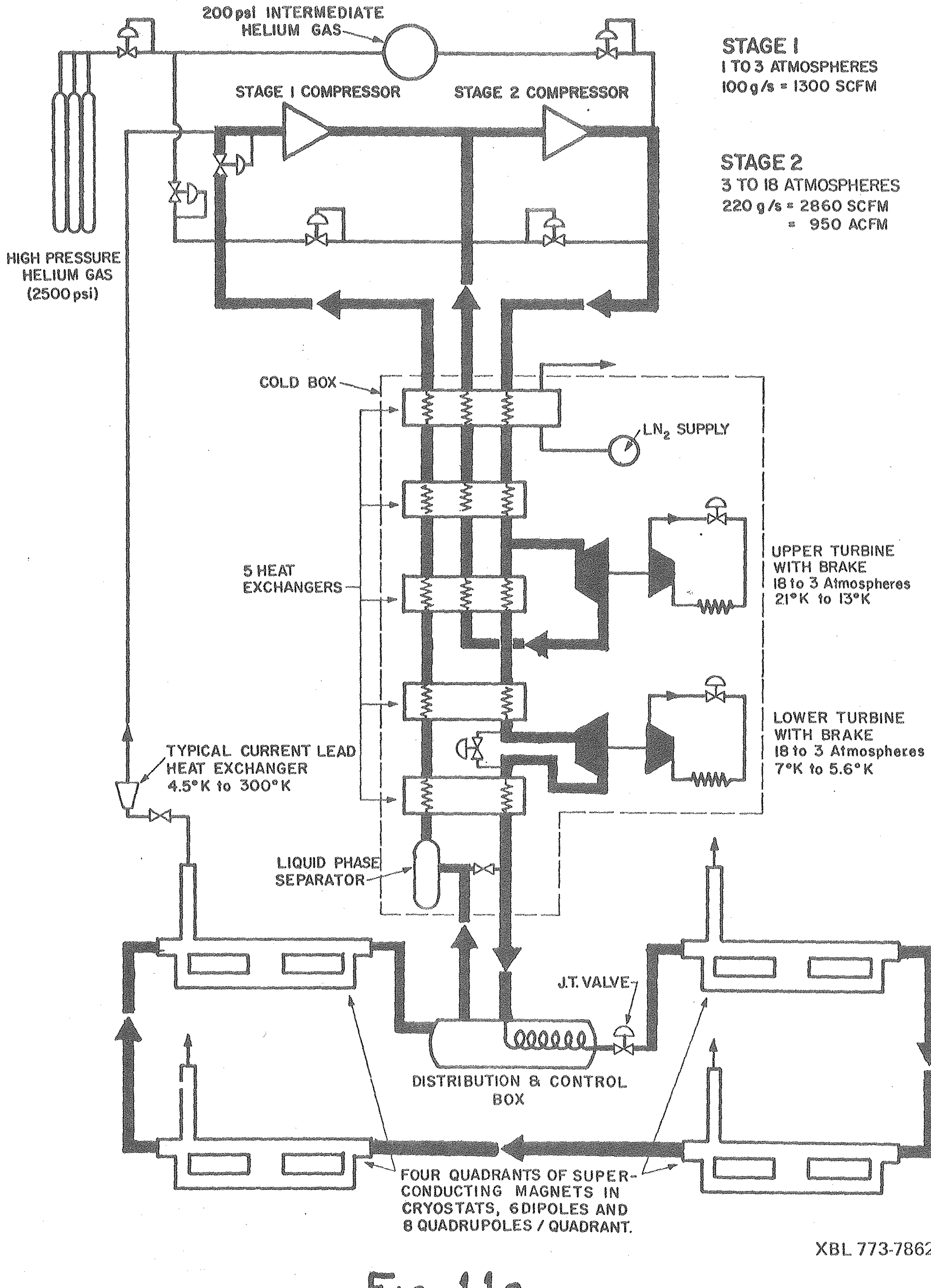
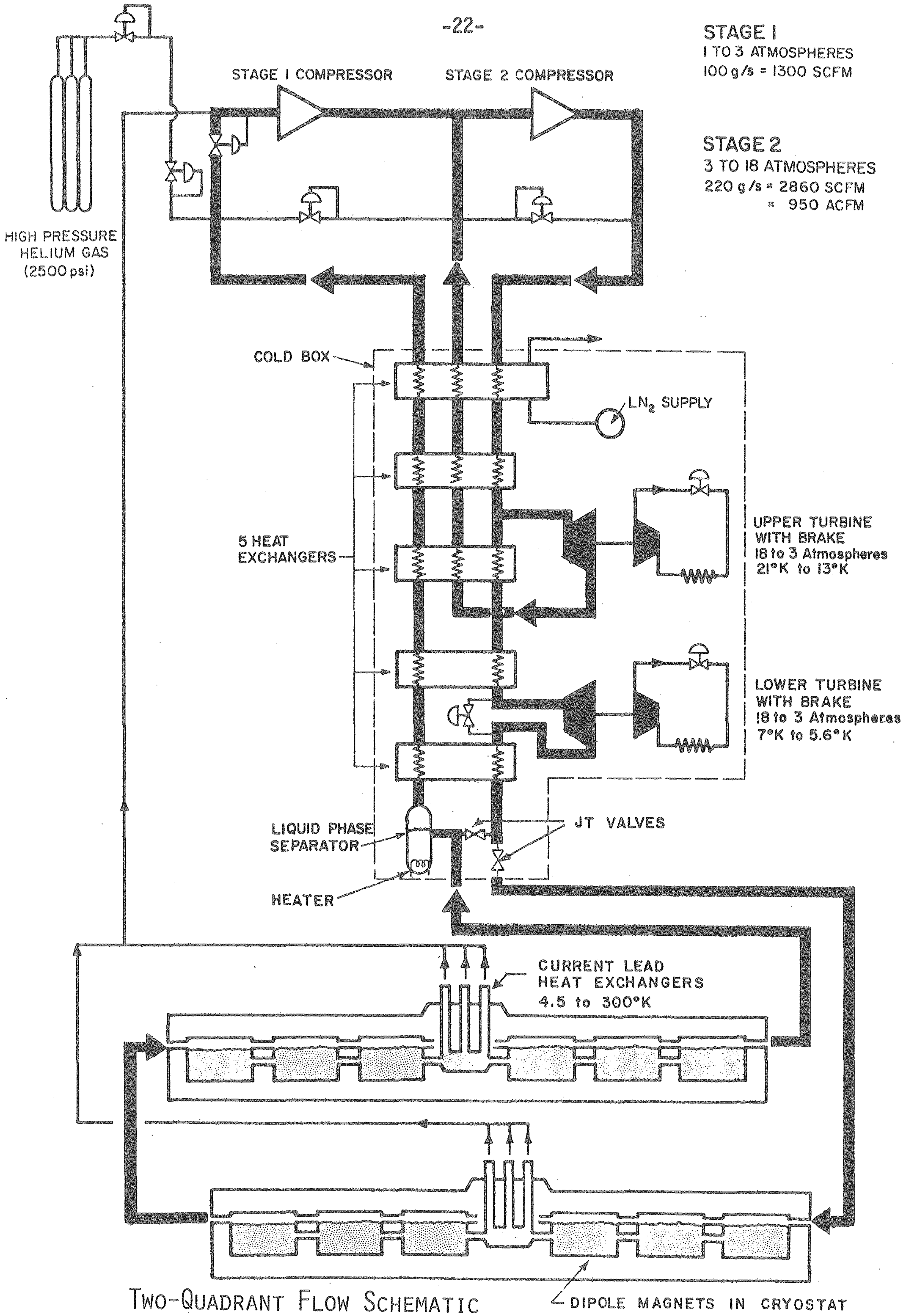

200 psi INTERMEDIATE
HELIUM GAS
STAGE 1
1 TO 3 ATMOSPHERES
100 g/s = 1300 SCFM
STAGE 1 COMPRESSOR
STAGE 2 COMPRESSOR
STAGE 2
3 TO 18 ATMOSPHERES
220 g/s = 2860 SCFM
= 950 ACFM
HIGH PRESSURE
HELIUM GAS
(2500 psi)
COLD BOX
LN2 SUPPLY
5 HEAT
EXCHANGERS
UPPER TURBINE
WITH BRAKE
18 to 3 Atmospheres
21°K to 13°K
LOWER TURBINE
WITH BRAKE
18 to 3 Atmospheres
7°K to 5.6°K
TYPICAL CURRENT LEAD
HEAT EXCHANGER
4.5°K to 300°K
LIQUID PHASE
SEPARATOR
J.T. VALVE
DISTRIBUTION & CONTROL
BOX
FOUR QUADRANTS OF SUPER-
CONDUCTING MAGNETS IN
CRYOSTATS, 6 DIPOLES AND
8 QUADRUPOLES / QUADRANT.
XBL 773-7862

Fig. 11a



Two-Quadrant Flow Schematic

Fig. 11b

XBL 783-7862

Refrigerator Plant

The helium refrigerator consists of three major components: The cold box, the compressors, and the controls. Capacity of the plant was based on cooling requirements of a complete accelerator ring of 56 magnets plus cryopanels. A meeting at LBL in May 1974 of prospective users and suppliers had established as a desirable module a refrigerator of about 1500 watts at 4.2° K. Fermilab and LBL initiated the purchase of one such complete plant for FNAL and a cold box only for LBL. LBL would purchase screw compressors independently, undertake their evaluation and investigate their oil-removal requirements also.

The system specifications included:

1. Performance
   a. 1450 W at 4.5 K plus 3 g/s liquefaction rate. (LBL Specification).
   b. 360 ℓ/hr as a liquefier.
   c. 950 W plus 1.7 g/s at 4.5 K plus 1250 W at 21 K. (Fermilab).

2. All expansion and compression to be done with rotary equipment.

3. Complete control by a single operator from a remote location.

4. Minimum operating costs for electrical power, LN feed, maintenance, and manpower.

The cold box is a Helix Corp. CTi-Sulzer 1500 W unit which includes six Trane brazed-aluminum heat exchangers and two Sulzer gas-bearing expander turbines. All valve control and bayonet penetrations to the 8 ft diameter by 15 ft high vacuum insulated box are located in the top plate. Delivery to LBL was made in June 1977, and acceptance tests were completed October 1977 and produced outputs of up to 1900 W. Operations proceeded through the winter and spring of 1977-78.

The Sullair Corp. oil-injected screw compressors were purchased directly by LBL. Subsequent development of oil removal equipment and determination of its performance was also to be done by LBL. Efficiencies are about as predicted, 75 to 85% volumetric and 65 to 75% isentropic. Total installed power is 230 HP (first stage) and 920 HP (second stage) for a total of 1150 HP (with an added potential of about 90 HP using interstage cooling). Displacement is 1710 CFM at 3550 RPM for both machines. Operation of the first stage is 1 to 3 atm compression at 113 g/s and second stage is 3 to 18 atm at 250 g/s with helium gas.

Compressor control is all local and manual. Cold box controls are converted to electrical signals at the coldbox and brought out through an umbilical cable to the control room. Main control is by a Texas Instruments "5 TI" micro-processor-based controller. It is well known that solid-state devices may fail in unsafe modes, but this was not completely taken into account in this design, causing more reliance on skilled operators than originally desired. Revisions are in process to correct these problems. Because of the unreliability of the controller, it was found prudent to have two operators in attendance at all times during refrigerator operation.

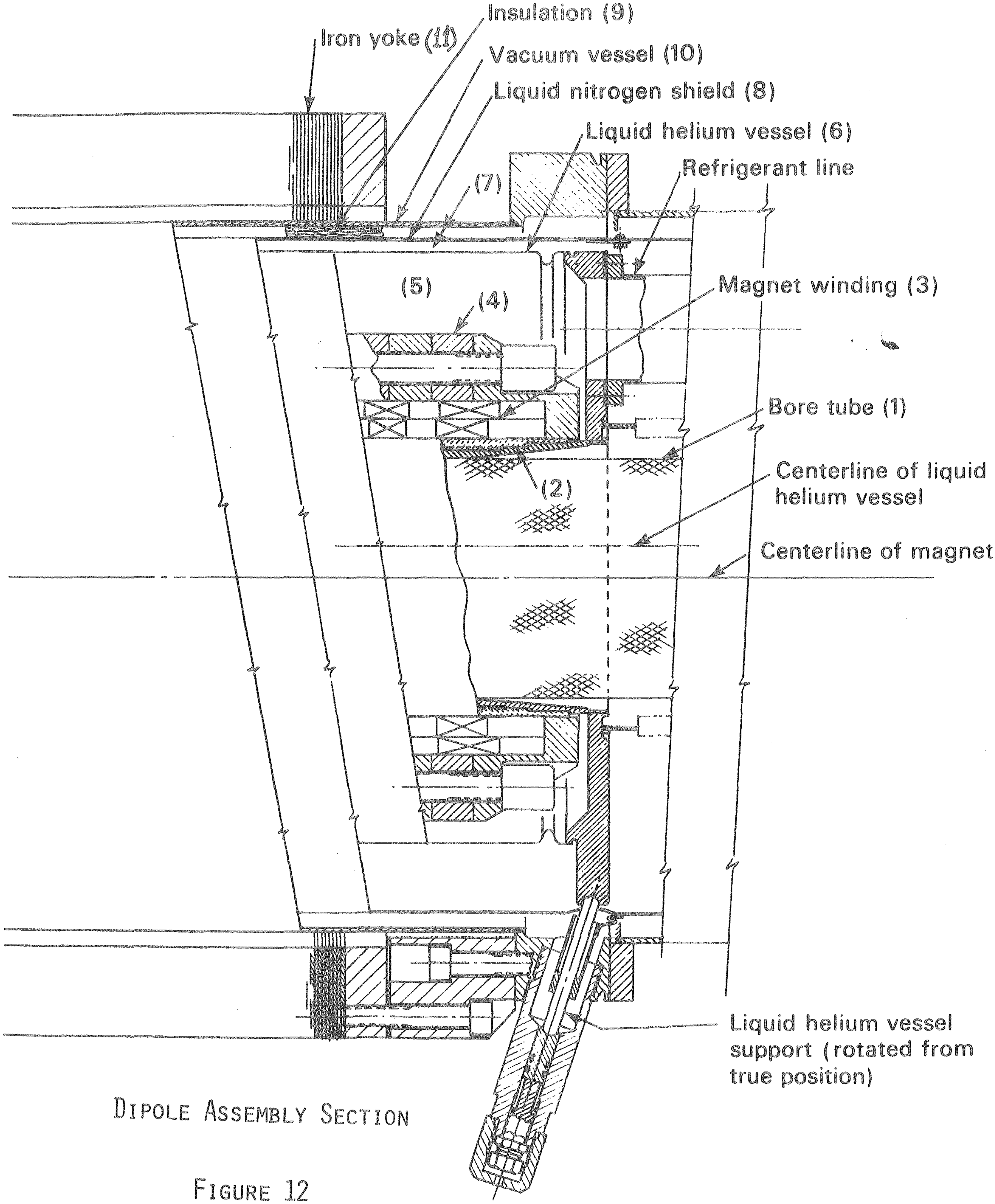
Magnet Cryostats

The magnets are cooled by pool boiling in series-connected cryostats. The cryostats are filled by a gravitational separation of liquid from the coolant stream. The axis of the cryostat is displaced vertically from that of the magnet so as to minimize the liquid volume and maximize the flow cross-section above the magnet. The large flow cross-section results in a reduced velocity, which enhances the liquid-vapor separation. Liquid level is controlled by the vertical location of the transfer line. When the liquid level reaches the level of the transfer line, which is slightly above the top of the magnet, no further collection of liquid can occur. One end of the horizontal magnet cryostat is shown in Fig. 12. Except for the circumferential location of the supports, the two ends are mirror images. Going from inside to outside, we encounter in order: (1) a stainless steel barrier separating the ultra-high vacuum from liquid helium; (2) an epoxy-fiberglass tube; (3) the coil; (4) the aluminum structural-ring system, which resists the tendency of the coil to go out-of-round under the influence of the Lorentz body forces; (5) the main helium reservoir; (6) the stainless steel outer wall of the helium vessel: (7) the insulating vacuum; (8) the liquid-nitrogen-cooled radiation shield; (9) multi-layer insulation, limiting heat radiation to the nitrogen shield; (10) the stainless steel wall of the vacuum vessel, and, finally, (11) the laminated iron yoke.

The coil weight and magnetic forces due to its possible eccentricity with respect to the iron are transmitted first to the fiberglass tube, then to the end extensions of the stainless steel bore tube, and finally to the end plate of the helium vessel.

The helium vesssel is supported from the vacuum vessel by a system of seven epoxy-fiberglass (NEMA G-10) compression struts. The room-temperature ends of the struts seat into adjusting screws that also serve as strain-gage load cells. At assembly, the struts are adjusted, using the strain indication, to achieve the desired pre-load. When the magnet is first turned on, the struts are readjusted so that the change in force due to the application of magnetic field is reduced to a low level, ensuring centering of the coil within the iron to better than 1 mm.

The helium vessels are joined near the top by a 2-1/2 inch diameter tube that carries the two-phase helium. A second smaller tube on the horizontal midplane contains all the electrical wiring and connects each adjacent helium vessel to a junction box where all of the electrical connections are made. The flanged connections between the tubes and the vessels, and the cover plate for the junction box, are secured with screws and sealed with epoxy-versamid adhesive. The nitrogen-cooled shield and the multilayer insulation are carried through the intermagnet region where the vacuum vessel is split on the horizontal centerline, screwed and glued together and to the adjacent magnet vacuum vessels. At the midpoint of a six-magnet quadrant, a much larger vacuum tank contains the high-current and instrumentation electrical feed-throughs, and provides a connection to the vacuum pumps. The assembly of magnets is seen in Fig. 13.



DIPOLE ASSEMBLY SECTION

FIGURE 12

XBL 789-1795

Helium Transfer Lines

The same line size is used for both the cold helium supply and the cold return. The helium conduit is a 2 inch OD x 0.035 inch wall, type 304 stainless steel tube that is insulated with 40 layers of aluminized (one side), perforated and crinkled mylar, centered within a 3.5 in. OD (3 in., schedule 5) aluminum vacuum jacket. The inner tube is supported within the vacuum jacket by 1/4-inch diameter fiberglass pins, 120 degrees apart, which extend radially from a fiberglass collar on the inner tube, through the insulation, and bear on the inside of the vacuum jacket. The transfer line was prefabricated in 20-foot lengths, which were later joined in the field. Each 20-foot module had the pin supports located near each end and at the center. The prefabricated elements were joined in the field by welding the inner line, wrapping the weld area with aluminized mylar (which is interleaved with the adjacent laminates), and coupling the vacuum-jacket segments with a larger-diameter collar that seals to the outer surface of each with an O-ring. Differential expansion between the inner and outer lines is accommodated by thin-walled bellows on the inner line. Bends are made in the inner line with a bend radius equal to the tube diameter, whereas on the outer line a mitered flange joint is used (Fig. 14). Approximately 400 ft. of transfer line was installed: 200 ft. supply and 200 ft cold return. The vacuum space is compartmented by a barrier in the jacket at approximately the midpoint of both the supply and the return. Ports for pump-down and pressure relief were provided at several locations along each of the isolated vacuum jacket segments.

Prior to fabrication of the transfer line, heat rate measurements were made with two liquid-helium-filled transfer-line test models. These were of full diameter but of reduced length; one 10 ft. long, the other, 20 ft. The 10-foot model was tested both with and without inner line supports which allowed an assessment of the support contribution to the total heat input. A heat leak of 0.1 W was observed for a single three-pin support and 0.2 W/m for the unsupported line. The inner line in the longer test model was supported at three points along the 20-ft. horizontal section and at one location on the approximately one-foot vertical section. This second test model corresponded in length and support spacings to the prefabricated modules envisioned for the prototype ESCAR line and also incorporated an insulated elbow so that its performance should be representative of the final configuration. The measured heat rate to this line was approximately 0.25 W/m.

High-Current Gas-Cooled Magnet Leads

The helium gas used to minimize the heat leak represented by the magnet current leads is evaporated from liquid at 4.2° K, cools the leads and is returned to the refrigerator at room ambient temperature to be re-compressed and re-cooled. The flow from all the leads was budgeted at 3.0 grams per second, which represents about one-quarter of the refrigeration load. Most commercially available leads require too high a gas flow for their stability, so a design was developed at LBL for ESCAR which met its requirements and can be scaled to different stable maximum currents. Six such leads were used in ESCAR tests, performing predictably and satisfactorily. A pair of these leads has recently been run, with enhanced cooling-gas flow, at 3000 Amperes. Details are presented in Ref 2.

Transfer Line and Joint

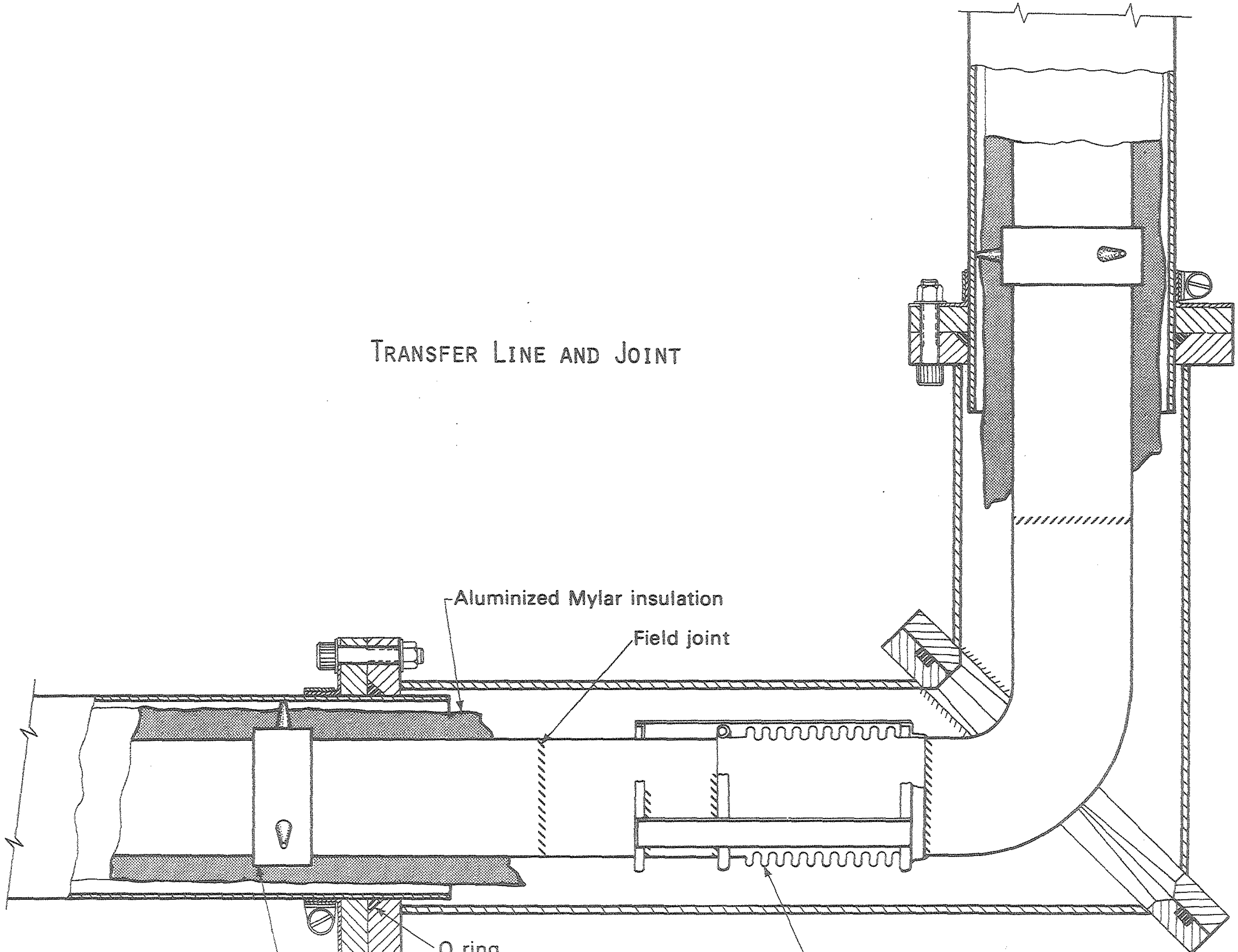


Figure 14

XBL 788-1462

Pressure Relief

Helium Space. The pressure relief system has been sized to accomodate a quench of a string of six dipole magnets with total absorption of the stored energy in the helium coolant and a simultaneous loss of the vacuum insulation surrounding the magnet cryostats. Under these conditions, energy is transferred to the helium both from the magnets and from the containing vessels. Consideration of the maximum possible heat-transfer rates from these surfaces leads to a vent rate requirement to avoid over-pressurization. For the ESCAR design a vent area of 19 cm^2 at each dipole quadrant was computed as necessary to maintain the pressure below 4 atm. absolute. A large cryogenic relief valve, which is set to open at 44 psig, and which has approximately one half of the above area, is provided at each quadrant. Additionally, a 20 cm^2 burst disk (minimum rupture = 50 psi) is also provided at each quadrant.

Transfer Line Vacuum Space. Combination pump-out and pressure-relief valves are provided at each end and the center of each isolated transfer line vacuum jacket segment. The relief capacity of these valves is not large, and further, they may be susceptible to plugging with fragments of the aluminized Mylar insulation. Therefore, additional 1-inch relief valves were provided. The insulation adjacent to each was restrained with bridal-veil netting in an attempt to preclude plugging of the valve in the event of a catastrophic rupture of the inner line. Additional pressure relief is provided by the slip joint construction of the vacuum jacket. A large positive pressure that was not otherwise relieved would simply result in a separation of the vacuum jacket segments.

Cryostat Vacuum Space. Positive pressures in the cryostat insulating space are relieved by a 2000-cm^2 spring-loaded access cover.

3. System Operation

The operation of the refrigerator with the 12-magnet heat load went smoothly. There are many benefits in having a large capacity available for rapid cooldown, as well as for overcoming excessive heat loads in the research equipment due to vacuum and thermal leaks. Time schedules and manpower loads are improved also.

Refrigerator performance during acceptance tests demonstrated capacity of about 1900 W and during magnet filling, liquefaction rates of up to 400 ℓ/hr were obtained. The rapid-cooldown heat exchanger makes it possible to cool the cold box in a few hours.

Most of our operations after cooldown and filling were run at reduced compressor capacity, with about a 500 kW power input. The screw compressor is very flexible in operation and can be run over a wide range of capacity. The turbine system, however, is designed to run very near its' maximum load; therefore, most of our operations were conducted with 600 to 900 W on the internal heater. At times only the upper turbine was used.

The operations were conducted for continuous periods of as long as two weeks for one or two shifts per day. The system was shut down at midnight, and restarted at 7:00 a.m. This mode of operation demonstrates a remarkable flexibility for a helium refrigerator plant, as usually all trapped impurities migrate to the cold end in a few hours of outage and plug the system, requiring complete warm-up and purge. This was not evident during these runs, probably due to the increased concern with oil and contaminant removal on this machine.

Prior to cooldown from ambient temperature, the complete helium circuit would initially be purged and dried with an ice filter to a dew point of -60° C or less. Cooldown rates were initially limited to 50 K/hr and the temperature difference between the coolant and upstream magnet was limited to 50° K. These limits were later relaxed with no apparent ill effects. The first cooldown of a single quadrant from ambient temperature was accomplished in 13.5 hours. This time was later reduced to 6.6 hours (from 275° K). 12 hours were required for the cooldown of two quadrants (2500 kg cold mass). Temperature differences between magnets tended to decrease as cooldown progressed and were virtually zero below 30 K. The magnets generally transitioned to the superconducting state (9.5 K) almost simultaneously. Once the cryostats were full, gas make-up was closed off and internal heater power was brought on (say 400 to 800 W) to keep the suction pressure at the desired value. Fill time for the 205-liter volume (one quadrant) was typically 30 to 40 minutes. On two occasions only one expander turbine was operating and the fill time was approximately doubled. The magnets filled in sequence beginning with the upstream magnet. In a given magnet, little liquid collection occurred until the adjacent upstream magnet had reached the connection level, approximately at the midplane, which demonstrated that the cryostats are effective liquid/vapor separators.

As part of these tests, the magnets were powered and caused to undergo normal transitions repeatedly, a process called "training". Power was applied to magnets either singly or in groups of three. Transitions caused the deposit of as much as 275 kilojoules of heat into the liquid helium surrounding one magnet, causing evolution of gas, pressure increase, and loss of liquid helium in the affected magnet's cryostat. On a typical transition, the pressure at the refrigerator suction increased about 2 psi and recovered in about one minute. The affected magnet lost about 5 ℓ of liquid and regained it in about two minutes. After a pause of 5 to 6 minutes the current was increased until the next transition occurred, usually at a greater current.

The largest pressure rise experienced in the helium system occurred when an external power supply malfunction caused arcing which punctured the helium pressure vessel, causing a large transfer of liquid into the insulating vacuum space. The pressure rise on the refrigerator return went to an estimated 30 psi, yet the turbines and compressors stayed on until manually shut-down.

The heat rate to one dipole quadrant (inferred from boil off measurements) was found to vary from about 105 W to 15 W as the liquid level fell from 94% to 26% in a time period of 75 minutes (current leads not cooled).

During normal operation the pressure drop between the centers of the two quadrants has been found to be between 2 to 4 inches of water. This low pressure drop, which is about as predicted, is necessary to maintain a low helium saturation temperature to maximize the superconductor's current capacity.

An electrically heated vaporizer was incorporated in the transfer line, ahead of the second dipole quadrant, to simulate the flow dynamics within magnets located at the downstream end of a series-connected string of magnets. Power input was sufficient that dry-out conditions in the coolant stream could be approached even with full refrigerator flow. No flow instabilities or liquid level oscillations occurred as a result of coolant quality changes. With large power inputs to the heater, a migration of liquid occurred from the upstream magnet cryostats so that the liquid level increased from magnet to magnet in the downstream direction. We believe that the migration was through the inter-magnet lead conduits which connect the magnet cryostats below the liquid level. Further, this effect appears to be in agreement with the pressure gradient that exists as a result of velocity head losses at the entrance to each magnet cryostat. Stable liquid-level depressions as large as 9 cm have been observed in the upstream magnet.

IV Vacuum Systems

Introduction

There are six (6) distinct vacuum systems within ESCAR:

1. 10^{-11} Torr cryopumped beam tube
2. 10^{-6} Torr injection beam line with curved transitions region into main ring beam region
3. Thermal insulation region in superconducting magnet cryostats
4. Thermal insulation region in helium refrigerator cold box
5. Thermal insulation region in helium transfer lines
6. Pumping and leak checking equipment to purge helium and other systems of impurities and establish their freedom from leaks.

1. 10^{-11} Torr Cryopumped Beam Tube

One of ESCAR's principal features and a major departure from conventional accelerator vacuum practice is the use of the beam bore tube as a distributed cryopump. The 14 cm. diameter stainless steel bore tube is bathed, on the outside, with the magnet's liquid helium at about 4.2° K. With proper rough pumping and operational procedures, ultimate pressures in the 10^{-12} Torr region are expected.

In the six-dipole quadrant test the bore tube bellows was welded together for a total length of 8 meters. The magnet bore tubes, while initially cleaned before assembly and carefully handled throughout, did not undergo any special cleaning, bombardment, baking or outgassing treatment. Each six-magnet string was provided with special end closures and was pumped by a liquid nitrogen trapped 4-inch diffusion pump. Nude Alpert-type ion gauges in room-temperature bore extensions were used to monitor pressures at each end of each magnet group, and also directly over the pump trap. A gold-seal high vacuum valve could isolate the pump from the bore tube. Two six-dipole groups were tested, but most of the data came from one of the groups. These data are presented in the detailed report, Ref. 3.

One of the more interesting vacuum experiments involved a nude ion gauge mounted, on a bracket, at the center of one of the dipole magnets, within the cryogenically cooled bore tube itself. Even though this gauge radiated 7 to 10 watts to the bore tube, the pressure indicated as low as 10^{-11} Torr, the lower limit for this gauge.

2. Beam Injection Line and Transition Section to Cold Region

The injection beam line was designed but not built. Six 500 ℓ/sec ion pumps were calculated to yield a 10^{-6} Torr pressure. A curved, liquid-helium cooled, transition tube through the last bend magnet with a length-to-diameter ratio of 40 and with no line-of-sight path was calculated to support the 5-decade difference in pressure between the two ends.

3. Thermal Insulation Volumes in Magnet Cryostats

Superficially the thermal insulation of the magnet cryostats is similar to that of the refrigerator cold box, which system was pumped below 10^{-5} torr, then cryopumped, and then sealed off. The magnet cryostats differ in that the vacuum system is far more mechanically complex in having many connections that are subject to leaks. It also contains a liquid-nitrogen-cooled shield between the helium volume and the room temperature vacuum tank. A 4-inch oil diffusion pump with a water cooled baffle and a pumping speed of some 700 liters per second pumped a six-dipole quadrant from the center point. Ion gauges were installed at both ends of the quadrant, as well as at the middle. The base pressure when warm was near 10^{-6} Torr, and below 10^{-7} Torr when cold. When the system was cold, we valved off the diffusion pump for short periods as an experiment but usually the diffusion pump was in the system.

Several types of leaks into the vacuum system occurred. The details of these and the leak detection systems developed to correct them, are covered in the detailed report, Ref. 3.

4. Helium Refrigerator Cold Box

The helium refrigerator cold box insulation vacuum space was pumped with an untrapped 6-inch diffusion pump, supplied by LBL, backed with a KC-15 mechanical pump. Thermocouple and ion gauge instrumentation were supplied as part of the cold box. The operational sequence was to pump to the 10^{-5} Torr range and then start refrigeration. As soon as cryopumping reduced the pressure further, the diffusion pump was valved off.

5. Helium Transfer Lines

The multi-layer insulation space for the transfer lines was pumped with liquid-nitrogen trapped mechanical pumps which were valved off when the lines were cold and carrying liquid helium. Vacuum barriers were provided at the refrigerator end, mid-way in the run of line and at the connections to the magnet cryostats.

6. Pumping and Leak Checking

All cryogenic gas handling systems must be purged of impurity gases before they are cooled and after they have been leak checked and pressure tested. We used a variety of well-trapped mechanical vacuum pumps for this purpose.

Leak checking of these systems was done with conventional helium mass spectrometer instruments where the residual helium background of the system permitted, while assembling the magnet strings and piping systems.

After the systems had been in operation it was found that the helium system, (which included the magnet coil assemblies in their cryostats), and to a lesser extent the magnet multi-layer-shield insulating vacuum space were saturated with helium and were slow to release it. For sensitive leak-checking under these conditions a residual gas analyzer (RGA) and a probe gas such as neon or argon were used.

V. ELECTRICAL

Virtually all ESCAR sub-systems had substantial electrical power, control and instrumentation requirements. Many of these, due to the nature of the project, had unconventional aspects which required special study and implementation as well. As a result, the electrical effort was large and at times governed the pace of the test phases of the project. These sub-systems are discussed below, with the exception of the Injection Line and Beam Dump (covered in Section VI.1.), Radio-Frequency Acceleration System (Section VI.2.), and Proton Beam Instrumentation, for which space was allocated in the ring, but no design was done.

1. Vacuum Systems. The several vacuum systems used for the limited-system tests were partially improvised and did not represent parts of the final accelerator system. Controls, interlocks, alarms and monitoring were local, monitored at intervals by the test crew.

2. Refrigerator Power and Control The installed power for the compressors on the 1500-watt capacity (tested to 1900 watts) helium plant is approximately one megawatt. This required an installation effort comparable to a major Bevatron physics experiment. The refrigerator cold box was monitored and controlled by a microprocessor-based solid state controller, programmable for automatic operation. Signals and controls were brought out of the top of the cold box to an interface and conditioning panel, then to the controller and to displays for the human operator. The system had not previously been thoroughly analyzed or tested, so there were numerous component failures, interface mis-matches and other electronic problems which consumed considerable electrical engineering talent and time to analyze and correct. Vigilant skilled operators were required for all but steady-state conditions.

3. Accelerator Interlocks and Alarms Interlocks in a superconducting accelerator not only serve the standard functions of personnel protection and protection of major equipment, but must act in such a way as to preserve certain conditions. The cryogenic temperatures required for operation are difficult to achieve, so they should be preserved during limited emergencies and repairs. The vacuum systems are essential to this, so should be maintained as well as possible during short-duration emergencies also. Care is also required in the start-up and shut-down sequences of all of the systems, so their needs and conflicts are part of the interlock task. Items such as quench protection and loss-of-power emergencies require rapid automatic operation, others require only operator action after suitable alarms. The one adverse incident, in which magnet current rose without control, was the result of combined operator and equipment error. This caused us to re-examine our controls and procedures and to add a manually-operated overriding turn-off for the power supply system. The controls served well throughout the remainder of the multiple-magnet tests.

4. Magnet Power and Control The power supply modules available to ESCAR were 500-kW and 250 kW units available from FNAL where they are used to power conventional magnets. For the design pulse rate of 0.1 Hz, eight 500 kW supplies would be required for the dipoles and four 250 kW supplies for the focusing quadrupoles, which would be connected in four circuits for full flexibility in control of beam focussing. Initial operation was to use four 500 kW and two 250 kW supplies, with a lower pulse rate capability, to speed up the project and lower its complexity.

Individual magnet testing involved one 500 kW supply and provided a test bed for studies of ripple filtering, quench protection and energy extraction. This type of supply, using twelve phased thyristors as basic rectifiers, develops several volts of 720 Hz ripple voltage under steady-current conditions with a superconducting magnet load. This ripple was not detrimental to magnet operation, but had to be reduced to no greater than 100 millivolts for reliable quench detection and analysis. Signal filters were needed wherever magnet voltages were analyzed or balanced.

During the tests involving six series dipole magnets, a breakdown from magnet diagnostic voltage taps to ground induced transients large enough to destroy five SCRs in the power supply, so a conventional Bevatron quadrupole was put in each lead of the power supply, with an electrolytic capacitor across the leads to protect the supply. This would not be required after the initial check-out phase was complete. One power supply was used for these tests, with standard current control and feedback. Reference levels, cyclic waveforms and limits were provided at the ESCAR control room console.

5. Monitoring and Data Acquisition On single magnet tests, as full an analysis of the magnet behavior as possible was sought, so all accessible parameters were measured. In the later tests of six and twelve dipole groups tests of these were not used in order to minimize the number of high-voltage wires traversing the magnet string in the liquid helium space and emerging to room-temperature connectors. Consequently, analysis of events such as quench, energy extraction, and individual magnet behavior was quite limited during multiple-magnet tests.

Magnet temperature was monitored during cool-down and warm-up by measuring the resistance of the magnet coils and calculating the temperature from known data. This was either chart-recorded to observe trends or calculated by a small on-line computer and printed at intervals. Between the onset of superconductivity and the appearance of liqid helium in the magnet vessels the temperature could be inferred from the entering and exiting gas temperatures.

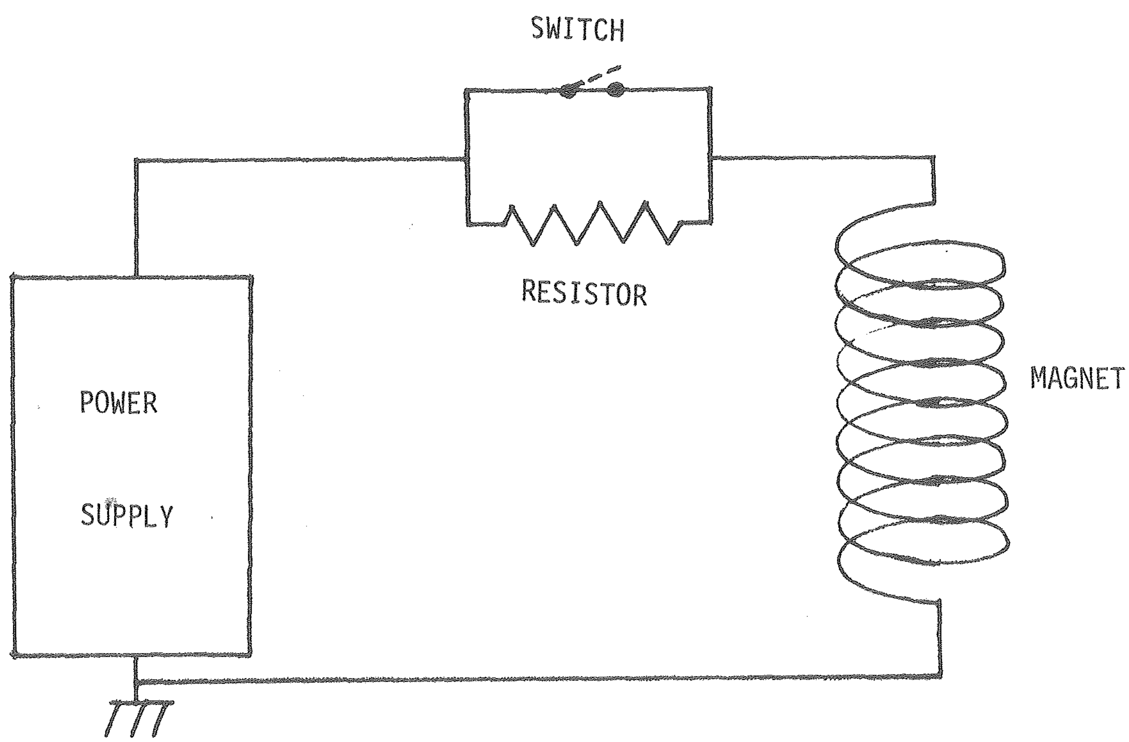
A superconducting liquid level gauge was installed in each magnet, with control console readout or recording. Only four of each group of six were connected through to the control console.

The principal signals monitored during electrical powering of a six-dipole magnet group were power supply voltage and current, magnet group voltage, quench detection trip signals and liquid helium levels. Voltage developed across the energy extraction resistor was used for analysis of a quench event. Most signals were chart-recorded; twelve channels were available for the purpose.

6. <u>Magnet Quench Protection</u> High current-density coil windings such as those used in ESCAR magnets require a means for detection of the onset of the normal resistive state of the superconductor and a means for rapid depletion of the stored energy of the magnet, preferably in some external element. If magnet current is allowed to persist or to decay due only to the increasing resistance of the magnet winding, the coil may overheat sufficiently to be damaged.

In the system evolved on ESCAR, a voltage proportional to the changing magnetic field is compared to the voltage developed across the magnet inductance during charging and discharging cycles. These signals can ordinarily be balanced by suitable proportioning and subtraction. If the magnet coil develops resistance, the signal shows an imbalance, and the energy extraction system is triggered. In practice, a detection level equivalent to a normal resistive character in one-thousandth of the coil of one magnet could be detected within 50 milliseconds of the quench onset. The electronic switching then occupied less than 1 millisecond.

Energy extraction can best be understood from a simplified schematic, Fig. 15.



For normal operation the switch is closed and power supply voltage is applied to the magnet. Power supply voltage is positive while the magnet current is increasing, zero at steady current and negative while current is decreasing. Upon detection of a quench the switch is opened, forcing the magnet current to flow through the resistor. This develops a negative voltage across it, which in turn drives the current down and extracts the energy stored in the magnet and dissipates it in the resistor. In our system, the power supply voltage is also inverted, increasing the energy extraction.

For most of our individual magnet tests the switch was a shunt trip-actuated mechanical circuit breaker with a current interruption time of 15 to 20 milliseconds. Later, and for all of our multiple magnet tests, an SCR-controlled extraction system interrupted current in less than 1 millisecond.

Our first resistors consisted of bifilar-wound coils using several hundred feet of heavy electrical cable. Later a water-cooled, stainless-steel tubing resistor was used.

One of the limits to the efficiency of extraction of energy from the magnet is imposed when the voltage across the resistor and power supply reaches the voltage breakdown limit of the magnet assembly. In single-magnet tests, a resistor of 0.25 ohms was used which, with the power supply inversion assisting, removed up to 80% of the magnet stored energy, imposing about 500 volts on the magnet circuitry in the process. In group testing, extraction is from whichever 3-magnet group contains a normal-going magnet, with a similar circuit. If it is desired to extract a similar proportion of the energy, a proportionate increase in the extraction resistor would impose 1500 volts on the system. This is close to the breakdown limit of magnet circuitry insulation, so the resistor was set to develop a maximum of 700 volts. Only 60% - 70% of the energy of three magnets was now extracted, with as much as 275 kilojoules dissipated in the quenched magnet. This is to be compared with approximately 70 kilojoules absorbed on single-magnet training quenches.

7. Magnet Voltage Testing

All magnet coils were tested for short-circuits and proper number of turns by measuring with a full bridge for resistance, inductance, and loss factor, Q. In addition an impulse testing method was used in which a short square wave of voltage was impressed upon the coil current leads, and the subsequent ringing waveform was displayed on a storage oscilloscope. Any voltage breakdown resulted in a damped wave, compared to the standard. Early testing was carried out to 300 volts, and later impulse testing was carried out to 1500 volts in room-temperature helium gas, which is a poor dielectric.

Special breakdown tests from lead to lead, and from magnet to ground used a "megger" in the 2000 volt to 3000 volt range, also in helium.

8. Magnetic Measurements

Extensive development of both mechanical and electrical components was required for the magnetic measurements program. Field multipoles within the bore tube regions were measurable to 1 part in 10^5 of the dipole component both for central straight sections and for length-integrated fields. The dipole vector was measured to an angular precision of $\pm$ 30 micro-radians. This angle was then set to the vertical by reference to a spirit level whose setting could then be reproduced in the field to $\pm$ 100 micro-radians. A more detailed discussion of these systems is given in Ref. 4.

VI. Conventional Facilities

The work described below is categorized as "conventional" in that the design is not peculiar to the superconducting accelerator.

1. Injection Beam Line, Beam Dump

The injection beam line from the 50 MeV proton linac to the ESCAR main ring was designed and many of the magnets were entirely or partially fabricated. Details can be found in Ref. 5. Five bending magnets were fabricated up to the final assembly stage. Eight steering magnets were completed and have been put to use in other Bevalac beam lines. Since the injection beam line is conventional, its completion was scheduled for the latter part of the project.

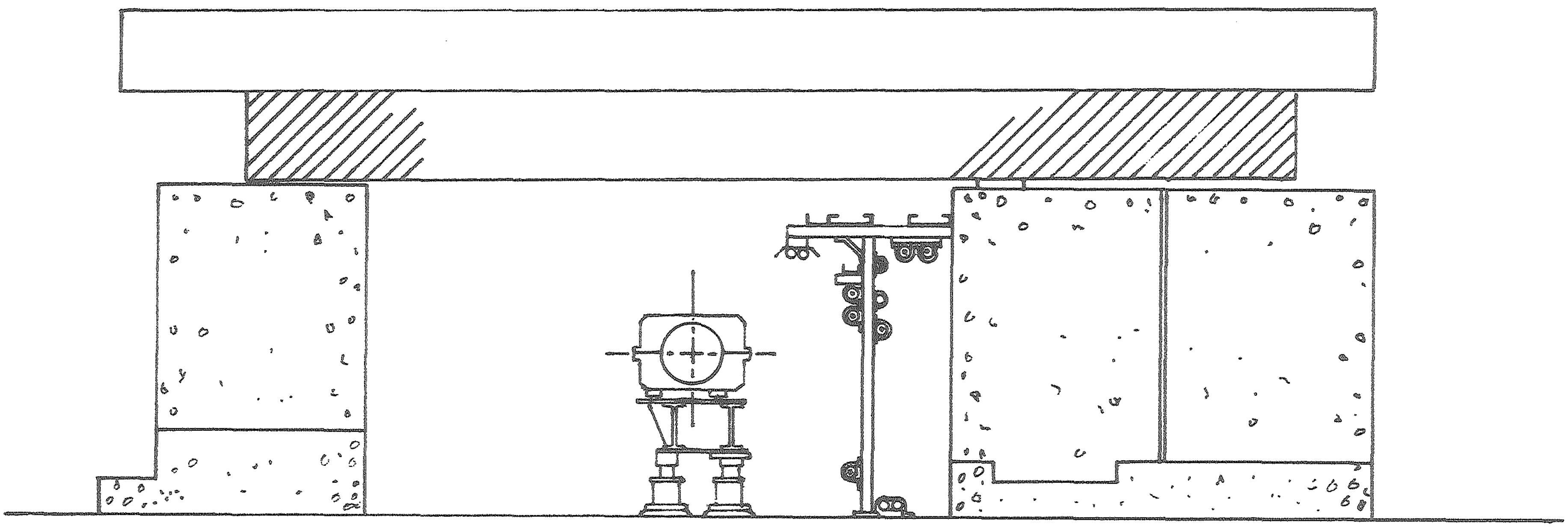
The need for, and a proposed design of, a main ring beam dump is also presented in Ref. 5.

2. Radio-Frequency Acceleration System

The RF requirements of ESCAR were analyized at an early date (Ref. 6) and some hardware was assembled, principally ten Collins 30-60 MHz R.F. power generators and three 1.5 to 4.5 MHz acceleration cavity structures that had been obtained from the Brookhaven AGS. ESCAR was to accept injected beam and accelerate it at the first harmonic of the circulation frequency, which varies from about 1 MHz at injection to 3 MHz at 4 GeV. Injection efficiency was studied and voltage profiles were prescribed for best capture efficiency in the presence of space charge. The cavities could easily be modified for the frequency range required, but would need alteration to accommodate cryo-pumping for high vacuum compatibility. The R.F. power generators would have to be extensively re-worked for these low frequencies, but were matched to the 11th-harmonic bunching frequency planned later. This high-harmonic bunching possibly could be done with beam-excited passive cavities or with the further-modified AGS cavities.

3. Shielding and Site Work, Ring Magnet Support and Alignment

The shielding design for ESCAR was based on a 4 x 10^{12} protons-per-pulse beam at 4.1 GeV, 6 pulse per minute, possible 24-hour per day operation. Beam was to be decelerated and dumped into a copper block in the East straight section after each pulse. To save substantial amounts of



SHIELD ENCLSOURE CROSS-SECTION

FIGURE 16

money and time, existing shielding components were to be used as available. 70% of those required were located, partially from discontinued beam caves at the 184" cyclotron at LBL and some from LLL. The remainder were to be purchased.

The floor of the Bevatron External Proton Beam (EPB) hall was adequate to support the ESCAR shielding, but since ESCAR extended outside of the EPB hall to the North, a heavy slab extension for this area was contracted for and poured in December, 1976. Provision was made to extend all utilities from the EPB hall under this new slab in conduits.

Details of piping, wiring, utilities routing and location, etc. were drawn up to fit the final shielding design. Figure 16 shows a typical cross-section of the accelerator tunnel.

Site layout monuments were placed and surveying completed for component placement in June 1977. Re-surveying after shielding was in place was to be done through floor-level channels under the shielding, through the block foundations.

The establishment of the horizontal survey control grid and the positioning of 12 of the ring bending magnets at the site were carried to completion, and are described in Ref. 5. The alignment system for the ring focusing magnets and other components of the accelerator, such as the injection line, would have been basically similar to that for the ring bending magnets.

Three bending magnets are supported from a common girder, which is in turn supported from the floor. Each magnet and each girder is supported from the usual array of three screw jacks having appropriate adjustable constraints. These three-magnet girder assemblies were also the module for transport from shops to site.

The relative horizontal positions of the three magnets on a girder are established using a special fixture incorporating dial indicator gages. Relative heights are established using ordinary precision optical leveling techniques.

A nine point horizontal control grid is established using only distance measurements. The horizontal position of each group of three bending magnets is adjusted using modified standard optical-tooling techniques. The height and pitch angle of each group is adjusted using optical leveling techniques. Roll angle of the group is adjusted using a preccision spirit level. Magnetic measurements are used to determine the direction of each magnet's magnetic field with respect to reference points on top of the yoke; roll is then adjusted at the site by a simple re-leveling procedure.

C. Epilogue and Conclusions

The project was an appropriate means to address the total systems problems and to force the development work to combine realistically the technologies of superconductivity, cryogenics, and existing accelerator science. It was advantageous to address these problems on a small scale accelerator, as, even today we are many years away from a full scale superconducting accelerator system. Progress in the required technologies has been slow and costly. The expectation that ESCAR would be completed quickly did not recognize that the design and development effort for a novel small accelerator is not markedly less than required for a full scale accelerator and that funding restrictions were very rigid. In comparison with other superconducting accelerator projects being pursued, the combined requirements of rapid pulsing, storage-ring magnet field quality, and compactness were quite demanding. In the direction of reducing the task was the license to take greater risks because of the relatively small size and the experimental nature of the project.

The production of conductor for ESCAR introduced to this country the manufacture of flat twisted (Rutherford) cable. That form is still the most suitable for pulsable magnets, but the highly ventilated coil structure as built had insufficient rigidity to prevent some motion and training. Corrections and design iterations, more usual in a full scale project, were not pursued because of the short schedule. Still, it was demonstrated that repeatability of conductor placement and uniformity between magnets was satisfactory in serial production with reasonable fabrication controls. Following damage of the first magnet in testing, all of the following production magnets were found to be acceptable.

A program of complete tests and measurements on each magnet prior to installation in the ring was essential to the interpretation of the systems test. An omission was our failure to anticipate the voltage stresses in the full system; even then, only electrical connections peculiar to the full quadrant structure, not the test setup, were vulnerable to breakdown. We would recommend for any proposed accelerator a comprehensive test of as much of the final system as practical. Measurements of individual magnets should include the direction of the magnetic field and its transfer to alignment marks in order to permit initial angular positioning; mechanical readjustment of this after complete assembly in place is made inconvenient by the usual cryogenic and vacuum connections (e.g. bellows) that mechanically couple adjacent magnets. Behavior of the magnets in the systems test was encouraging in that no quench contagion, or other exotic problems appeared.

A significant outcome of the two-quadrant tests was the successful performance of the cryogenic system. That performance included a demonstration that a simple two-phase circulation scheme was not only free of flow instabilities that some persons had considered likely, but that the heat removal was adequate to serve a synchrotron pulsing at 1 tesla/sec. The success does not remove the still-existing need to adapt and modify the commercial refrigerator for greater operational convenience. The refrigerator electrical controls, not fail safe as supplied to us, are still being made to conform to good engineering practice. Our experience indicates that today's cryogenics is ready for large scale application in accelerators. We also note that ESCAR and then other accelerator projects have provided considerable stimulus to the commercial market for large rotary compressors and gas-bearing turbines in helium service.

The ESCAR experiment did not proceed sufficiently far to capitalize on the opportunity to evaluate its cold-wall vacuum system. An evaluation at this time would be particularly worthwhile because of the considerable cost of the vacuum system in large storage rings. The straightforward achievement of low pressure without surface conditioning and the freedom from helium leaks were positive results. It will be possible for existing accelerators to make specific measurements of desorption or cryopumping, but the curtailed ESCAR program leaves unexplored many practical and unexpected aspects. A considerable effort remains before the accelerator designer will know if the seemingly attractive simplicity and economy of cold-wall vacuum is in fact really free of prohibitive faults. Techniques for locating leaks in the various insulating-vacuum and helium systems were devised as needed, but these were barely adequate and this aspect of a new accelerator should be given proper consideration to insure against excessive waste of operating time.

The electrical systems could be regarded as straightforward, and in most respects that has been the case, but the important area of magnet safety and quench protection introduced demands on the design of both magnets and cryogenic system. It should therefore be considered early in the component development stage. The best method for disposing of the stored magnetic energy is still without general agreement and may, in fact, depend on the details of a particular application. The magnet power supplies were not found to present unusual aspects. Instrumentation was more involved because it had to penetrate the cold and evacuated conditions in the cryostats. Certainly in the future, one would foresee the need and opportunity to develop new beam monitoring devices for the cryogenic conditions.

The attention toward systems aspects in ESCAR has been an opportunity to contribute to the necessary and inevitable progress toward large scale utilization of the new technologies. While there was not the opportunity to achieve all the project goals, successes during the development and tests completed did advance the art in

- utilization of cabled superconductor
- repeatability in coil production
- high field quality
- magnet testing and alignment techniques
- cryostat design
- screw compressors and modern refrigerators
- high-capacity cryo-distribution (two-phase)
- operation safety in vacuum and helium systems

We also were able to stimulate the serious consideration of cold-wall vacuum for accelerators. We advise that designers provide adequate excess capacity in parameters such as current density and refrigeration and incorporate the total system requirements early in the design process. With such precautions, the benefits of the technologies should be available along with reliable operation free of unexpected limitations.

D. ESCAR Reports and Publications

The written reports, notes, and publications covering the ESCAR project are principally in the form of informal internal laboratory reports in the following categories:

ESCAR Design Guide papers (EDG-00) (39 papers)
ESCAR Notes (ESCAR-00) (59 notes)
Mechanical Engineering Notes on ESCAR (MN-0000) (170 notes)
Electrical Engineering Notes on ESCAR (EET0000) (3 notes)
Lawrence Berkeley Laboratory Reports (LBL-0000)
Others, not uniformly categorized.

Formal reports which were presented at conferences and/or published are usually also in the form of LBL reports as well.

Engineering drawings are on file also.

All are available from LBL upon specific request.

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