Title
DESIGN, CONSTRUCTION, AND OPERATION OF 12 ESCAR BENDING MAGNETS

Author
Lambertson, G.

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DISCLAIMER

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I. INTRODUCTION

The goal of the ESCAR (Experimental Superconducting Accelerator Ring) Project was to build rapidly and operate a small, state-of-the-art, rapid-pulsing proton synchrotron using superconducting magnets. The magnetic field quality and beam tube vacuum were to be sufficiently good to permit operation as a storage ring for high current beams. The interacting systems aspects involved in a complete cryogenic accelerator were felt to be as challenging and important as the development of reproducible high-performance superconducting magnets.

Design work started in 1974, and twelve bending magnets, half of those required for the final accelerator, were installed at the accelerator site in November, 1977. The installed magnets were operated in a series of systems tests between November, 1977 and June, 1978. These tests concluded the project, which has been restrained by a very limited funding rate.

For related illustrations and information on cryogenic aspects of the tests, see Paper CA-3 of this conference. The magnets, and ESCAR, have been described in previous reports: 1,2,3,4,5,6,7, and a comprehensive report is in preparation.[8]

II. DESIGN

Design criteria

Cost and time restrictions dictated a small accelerator with too low an energy for high-energy particle physics experiments. However, novel lattice and tune arrangements were included in the design to allow maximum flexibility for proposed accelerator physics experiments.

The design momentum of 5 GeV/c requires a maximum field of 4.6T in each of the 24 1-meter-long bending magnets. Thirty-two focusing magnets in 8 groups of 4 require a maximum gradient of 20T/m. The storage ring capability dictates a dipole field uniformity of better than one part per thousand to a radius of 5 cm within the 7-cm-radius, cryogenic-temperature, high-vacuum bore tube. The minimum magnet rise time of 5 seconds corresponds to an accelerator cycle rate of 6 pulses per minute.

Design details of dipole bending magnets

The superconductor selected for these magnets is a 17-strand Rutherford-type cable of 6:1 aspect ratio. Each 0.020" diameter strands 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 is wrapped 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.

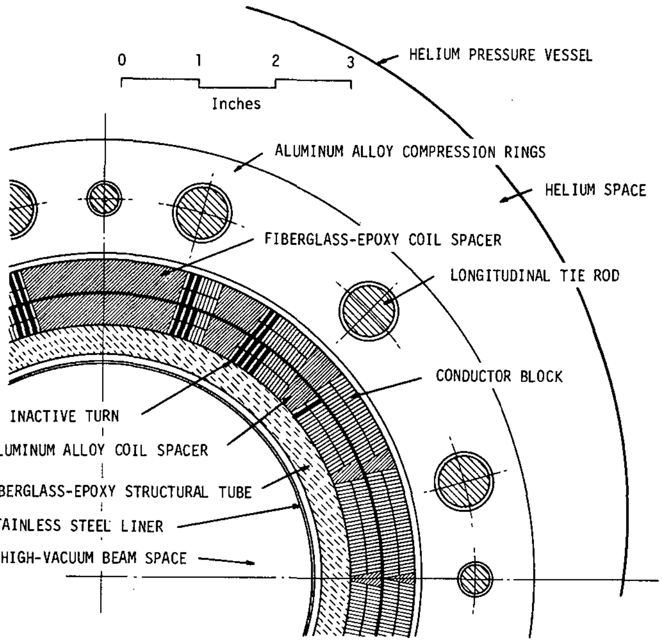

Fig.1. Magnet Transverse Cross-Section

Figure 1 shows a central cross-section of the magnet, in which the azimuthal distribution of conductors can be seen. The coil ends are quite compact to satisfy simultaneously the alloted mechanical length constraint and the magnetic length requirement. The compact end geometry results in a magnetic-field maximum at the conductor in the ends.

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 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 windings are 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.

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**University of California, Lawrence Berkeley Laboratory, Berkeley, California 94720

III. TESTS

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 struts.

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, determine 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.

Results of tests of individual magnets

The magnetic field uniformities shown by all magnets was within the specified range, showing that all bundles of conductors were held within 0.1 mm of design positions. (Fig.1) Magnets were delivered from the shop with less than 0.3 mm eccentricity with respect to the iron yoke; this was detected and eleminated using the strain-gauge-instrumented support studs.

During early optimization of energy extractions, a pre-production magnet and the first production magnet were damaged due to overheating of part of the coil structure. Prompt quench detection, with dissipation of more than 60% of the stored energy in an external resistor, was used subsequently, with 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.2) During training the sextupole magnetic field component changed, indicating coil movement. (Fig.3) 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 midplane to bias the initial sextupole component opposite to the change in it caused by coil movement.

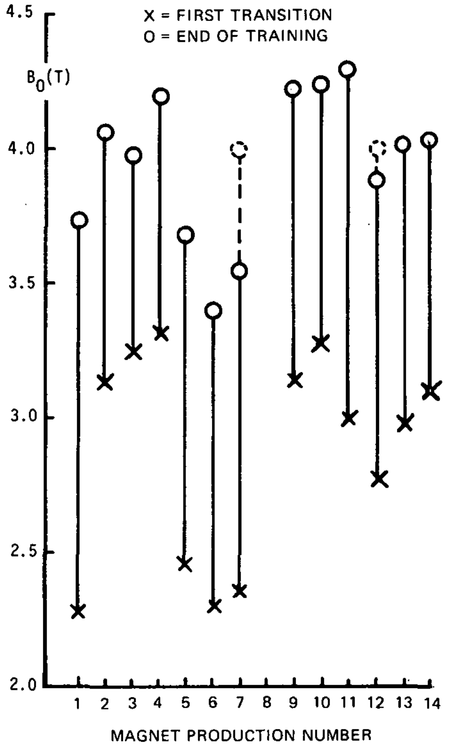

Fig.2. Training of Production Magnets

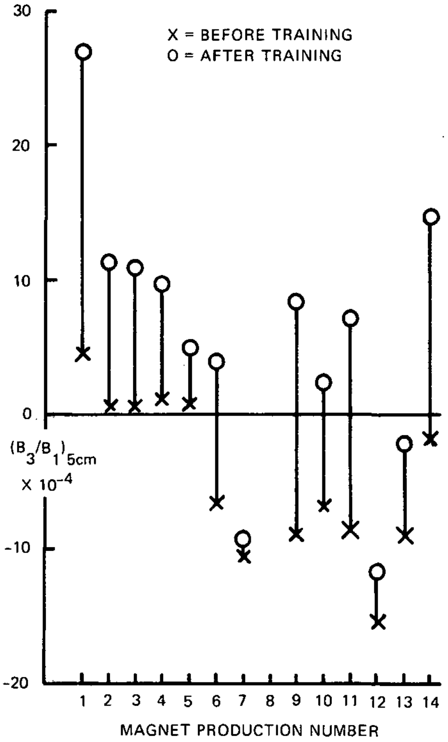

Fig.3. Change in Sextupole Component During Training of Production Magnets

Tests of magnets in quadrant assemblies

The twelve completed dipoles were aligned on support girders and joined to form two ESCAR ring quadrants 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. Three current leads were provided, 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 paper CA-3 at this conference.[7]

One-quadrant cryogenic tests. When cryogenic preparations were completed, we cooled down this quadrant and filled the magnets with liquid helium. These tests were extremely successful although there was a helium-to-insulating-vacuum leak. Special leak detection procedures had to be developed to find this leak in a helium-saturated system.

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 Ref.7.

First quadrant electrical tests. In testing the energy extraction circuit on the six series-connected dipoles, electrical breakdown to ground occured at several of the voltage monitor wires. 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 past 1200 amperes 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 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 completely and to continue tests only with the second quadrant.

Second quadrant 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 (in helium), and we reduced the voltage generated by the energy extraction to 700 V. 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 tests of single magnets, extraction voltages of 500 V were developed. 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 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 dumped 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 4 shows the full training history of magnet No.4 in the second quadrant, (production number 12).

ESCAR Dipole Magnets -- Goals and Results

ITEM	DESIGN	ACHIEVED
CENTRAL DIPOLE FIELD B_0	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 ± 15/6 MAGNET GROUP WITH 3 CURRENT LEADS
PROUDCTION 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 DAY, 6 DIPOLES
DIPOLE COST (PRODUCTION)	MINIMUM	$39,000 EACH, TESTED BUT NOT INSTALLED
ALIGNMENT-DIPOLE ANGLE	VERTICAL ± 0.5 m-rad	VERTICAL ± 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

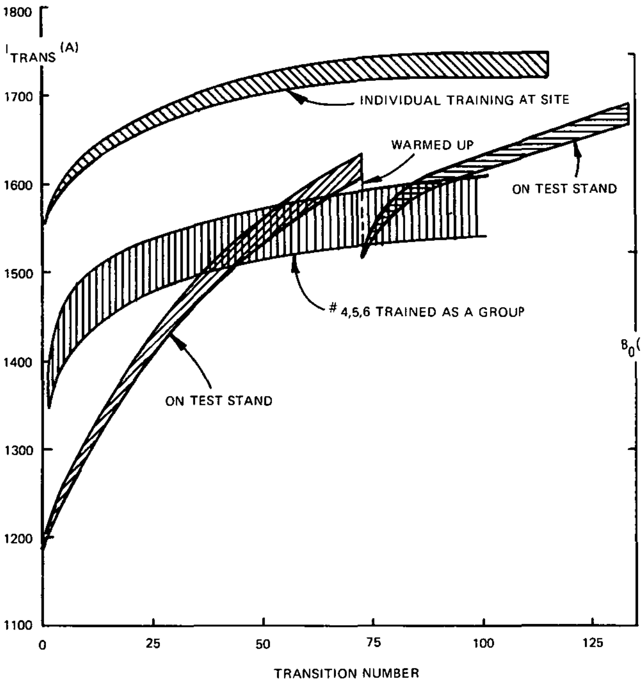

Fig.4. Training History of One Magnet

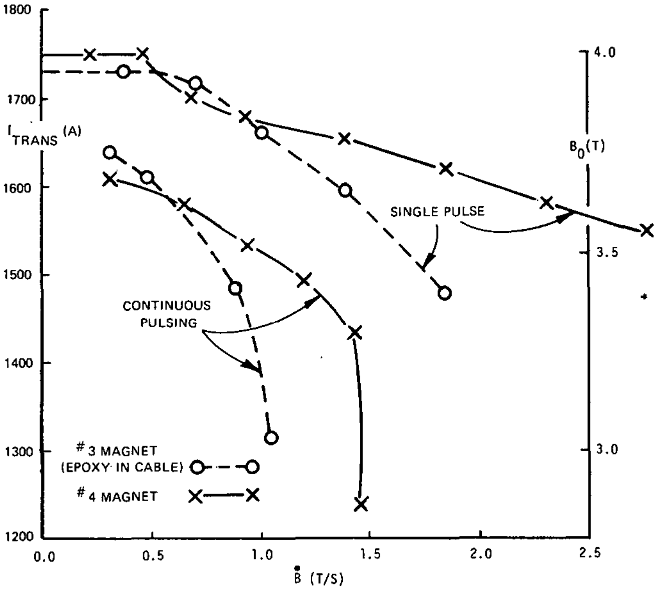

Fig.5. Ramp-Rate Sensitivity

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.

Another clue to the thermal behavior of these magnets is the ramp-rate sensitivity data of Fig.5. In the single-pulse curves, the magnet is allowed to cool for at least 3 minutes following a quench before a rising current ramp drives the magnet normal again. In the continuous-pulsing mode, we use a long string of triangular current pulses, between 100A and a maximum current,which is slowly increased until the magnet quenches. The magnet with epoxy in the cable apparently has poorer heat transfer properties, leading to a greater sensitivity to current rate-of-rise.

CONCLUSIONS

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.

ACKNOWLEDGEMENT

Significant contributions to this work were made by the personnel of the shops and other support groups. To acknowledge such contributions by including all their names here, though justifiable, is not practical.

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720