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ESCAR, TESTS OF SUPERCONDUCTING BENDING MAGNETS AT THE ACCELERATOR SITE*

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Introduction

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

The project was funded and design work began in July 1974. During the next two years it became increasingly apparent that the funding rate was directly limiting the rate of completion of ESCAR and that an intermediate goal, a test of the unconventional aspects of the project, was desirable. To that end, twelve dipole bending magnets, one-half of those required for the total ring, were installed at the site along with the 1500 watt helium refrigerator, cryogenic distribution system, electrical power supplies, vacuum systems, and necessary instrumentation. 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.

ESCAR,[1,2] and the dipole magnets[3,4] have been described previously. The results of the systems tests have also been reported.[4,5,6] The tests involving the dipole magnets are described below.

Magnets

Magnet Characteristics. Of the three types of magnets planned for ESCAR, (multipole trim coils, quadrupole focusing magnets and dipole bending magnets), the dipoles were seen to involve the greatest effort. The requirements were for 4.6 T central field, 0.95 meter integrated-field length in an overall length of 1.2 meters, capable of being pulsed at 0.1 Hz. The field was to be of storage-ring qualtiy, i.e., no field multipoles greater than 10^{-3} of the dipole field in twenty-four dipoles, with a series-current field inequality of less than 0.1%. These requirements were all near the state-of-the-art, but were considered attainable. Figure 1 is a production dipole cross-section. The details of construction of these magnets are the subject of other reports.[3,4,6]

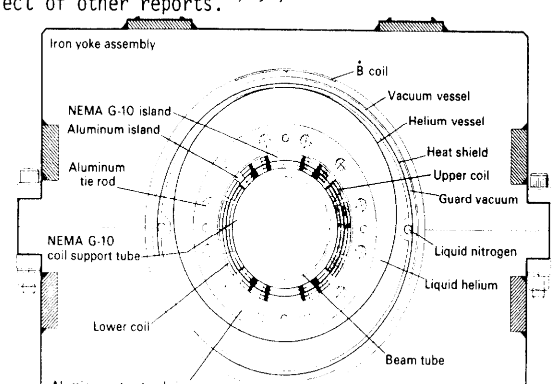

Fig. 1. Dipole Cross-Section

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Magnet Production. Twelve dipole magnets of suitable quality were produced from August 1976 to June 1977. Each of these had been operated to determine magnetic field quality and cryogenic soundness. The dipole field was aligned to a vertical reference to within 0.1 milliradian, and the coil had been centered within the iron shield. Each magnet was trained to between 3.5 and 4.3 T; the remainder of the training would take place as part of the operations at the accelerator site.

Site Installation. 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.

The design is based upon a two-phase helium flow in which all the magnet cryostats are connected in series at their upper 2-1/2 inch connecting passages, the string of magnets serving as the ring transfer line. A second smaller tube on the horizontal midplane 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. The vacuum vessel in this region is split on the horizontal centerline, and is 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 lead feedthroughs, and provides a connection to the vacuum pumps. The assembly of magnets is seen in Fig. 2.


Fig. 2. Quadrant Assembly.

Tests

Test Objectives. The planned test sequence was to conduct cryogenic experiments on one quadrant, then on both together, followed by electrical tests in the same sequence. Test objectives were:

a. To test the two-phase helium distribution concept, which involved gravity separation of liquid in magnet cryostats with weir-controlled levels.

b. To observe the 1500-watt refrigerator under variable loads and transient (magnet quench) conditions.

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c. Measure the cryogenic heat loads of the various components.

d. To observe the thermal insulting and beam tube vacuum systems at room temperature and with cryopumping taking place on helium-cooled surfaces.

e. To test magnet power, quench protection and energy extraction concepts on multiple-magnet assemblies.

f. To train magnets in place in groups to test for quench contagion and to see if such training is effective and feasible.

g. To evaluate the instrumentation, the controls, and the quality of diagnostic information.

Test Narrative.

One-quadrant cryogenic tests. When cryogenic preparations were completed, the Quadrant IV six-dipole group and the 1500-watt refrigerator were cooled down together. The magnet string was filled with liquid helium twice and both the fill and boil-off rates were inferred from liquid levels. A severe helium-to-insulating vacuum leak developed, terminating the run. This leak required special techniques and several weeks to locate in the 8-meter-long, limited-access, helium-saturated system. Successive upstream injections of a probe gas, (neon or argon) into a carrier gas (nitrogen) drifting slowly through the insulating space were observed on a residual-gas analyzer installed on the evacuated helium system. Analysis of responses indicated the region of the leak, which was then pin-pointed by detailed probing after the indicated vacuum-and-thermal shield section was opened.

Two-quadrant cryogenic tests. When all twelve magnets, in two groups of six each, were connected cryogenically, they were cooled and filled with liquid helium, attaining fill rates of over 400 liters per hour. Heaters in the transfer line ahead of the second quadrant were used to alter the two-phase helium quality so that the behavior of helium liquid levels in a downstream quadrant could be observed. The system remained stable and predictable while the major refrigeration heat load was transferred between the transfer line heaters and the refrigerator internal heater.

Quadrant IV electrical tests. During the cryogenics two-quadrant tests above, connection and checkout of the magnet power supply, quench detection and energy extraction system were also taking place. 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, upon detection of a transition, the energy extracted from all three as a group. The voltage limit of 700 V resulted in only 60% of the total magnet energy being deposited in the dump resistor, and the magnet current also decayed more slowly. As much as 275 kilojoules was deposited in the normal-going magnet, more 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.

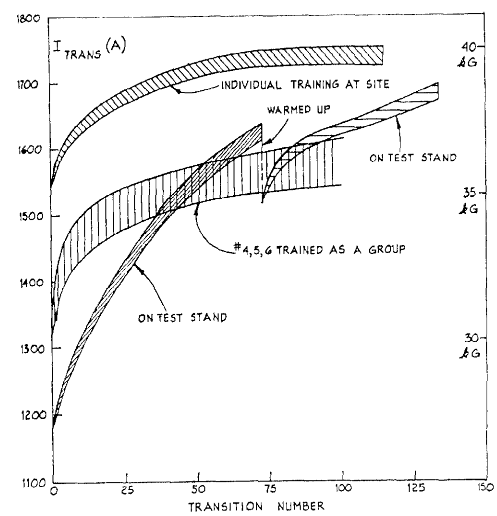

Fig. 3. Training History of One Magnet

Figure 3 shows the full training history of magnet No. 4 in Quadrant I, (production number 12). The trends of 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.

Vacuum observations. Concurrently with the tests above, the behavior of the various vacuum systems was observed, and, as necessary, leak-hunting procedures were developed. Leaks ranged from annoying to crippling. Several involved helium, which is not cryopumped to any great extent or pumped well by conventional pumps.

Generally, the insulating vacuum systems performed as expected. Initial pumping to the 10^{-5} torr range was sufficient to determine leak-tightness. When liquid helium was present, the pressures dropped to the 10^{-7} torr range, and pumps could be valved off.

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.

These 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. The pressures recorded by these gauges were typically in the 10^{-7} torr range when the system was warm, and below 10^{-9} torr when liquid helium was present in the magnets.

One of the more interesting vacuum experiments involved a nude ion gauge mounted on a bracket 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.

Conclusions

The ESCAR Project was an appropriate means to address the total systems problems involved in a realistic combination of superconductivity, cryogenics and existing accelerator science.

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. Reducing the task was the license to take greater risks because of the relatively small size and the experimental nature of the project. 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. 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 ESCAR experiment did not proceed sufficiently far to capitalize on the opportunity to evaluate its cold-wall vacuum system, but the straightforward achievement of low pressure without surface conditioning and the freedom from helium leaks in the bore-tube system were encouraging results. 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 depends on the details of a particular application.

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.

Acknowledgments

Many people have made significant contributions to ESCAR over the years of the projects' existence. Our thanks go to all, but to acknowledge such contributions by including all their names here, though justified, is not practical.

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