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The HERA proton storage ring will contain 422 superconducting dipole magnets and 224 superconducting quadrupole magnets. Each of these superconducting magnets will be connected at the Magnet Measurement Facility and individually tested before being installed in the 6-km ring tunnel. This paper discusses the cryogenic experience at the Measurement Facility during the various phases of the magnet tests. The computer-automated cool-down procedure used for thermal cycling of the magnets is described. The behavior of the cryogenic system for dipole and quadrupole magnets during quench and quench recovery is discussed. The results of cryogenic tests performed on the first superconducting magnets for HERA are summarized.

INTRODUCTION

The HERA Magnet Measurement Facility at DESY in Hamburg is located in the Magnet Test Hall, which has 1800 m² of floor area and adjoining five-story office space. This building is adjacent to the Cryo-Hall which houses the three, identical HERA helium refrigerators, helium storage capacity and cryogenic purifiers. Any of the three refrigerators can be used to supply the Measurement Facility. Each has a capacity of 6.5 kW of refrigeration at 4.2 K or 1200 L/hr of liquid helium without consumption of liquid nitrogen.

The connection from the Cryo-Hall to the Measurement Facility is a fourfold helium transfer line which is 85 m in length. A large helium subcooler, elevated 3.5 m above the magnet test stands, is located on the balcony of the Magnet Test hall. The subcooler maintains the helium supply temperature for the test stands at 4.3 K and the 200-L liquid volume of the subcooler buffers the refrigerator from transients in the Measuring Facility. Individual sections of vacuum-insulated transfer line, each approximately 10 m long, are used for the supply and return of helium to the eight test stands. The operation of this system depends on the vertical transfer of single-phase and two-phase helium.

Presently, four of the eight test stands are set up for the 9-m HERA dipole magnets and the remaining four are for 4-m quadrupoles. Fig. 1 is a flow diagram for one of the magnet test stands. The instrumentation is represented by P for a pressure sensor, T for a temperature sensor (dual diodes) and F for a flow meter. Check valves (omitted in the figure) are included in the system wherever a warm line connects to a 4-K circuit. The cryogenic system of the Magnet Measurement Facility is discussed in greater detail in previous publications.^{2,3}

PROCESS-CONTROL COMPUTER

A process-control computer system is installed to automate the operation of the Measurement Facility.⁴ This is capable of both continuous control and batch processing needed to make operation of the Measurement Facility completely automatic as well as supplying requested information and allowing manual intervention by the

operator if desired. The computer system contains multiple, distributed, state-of-the-art computers connected by a redundant communication link (Fig. 2). One of these computers in the Magnet Test hall is responsible for data acquisition from all instruments on the eight test stands. The data from the temperature sensors is pre-processed by a dedicated front-end computer which contains the calibration curves for the temperature diodes. A separate display computer supports the operator's consoles, color graphics, an alarm printer, display monitors and data storage for historical trending.

Programming of the computer system uses a highly flexible language for the applications software. This is important because accumulated experience during operation of the Measurement Facility can be immediately coded into the programs. The complete software package is built from modules which perform each of the cryogenic functions during the series of operating phases for a magnet installed on a test stand. This begins with cool-down and ends with warm-up of the magnet being tested. The process-control computer is capable of running the software modules in parallel for simultaneous operation of all eight test stands.

Additional programs running at a higher priority level check the safety interlocks, distribute the supply of helium and limit the overall refrigeration demand of the Measurement Facility. When operation requires simultaneous warm-up and cool-down of several test stands in parallel, information supplied by the computer to the operator is especially important for tuning the helium distribution so that the available refrigeration is optimally used.

CRYOGENIC TESTS OF HERA MAGNETS

The first quadrupole from the German manufacturer reached 6700 A (33 percent above design) for its first quench at a temperature of 4.7 K. Afterwards the magnet current was ramped upward 120 times until the magnet quenched. The quadrupole showed no signs of training. The magnet was ramped to 6000 A an additional 2000 times. The magnet underwent temperature cycles from room temperature to operating conditions at 4 K and back to room temperature 30 times. These tests on the magnet simulate the expected life cycle during 10 years of accelerator operation. An autopsy of the magnet revealed no signs of internal damage due to these tests.

The first 9-m dipole magnet from the Italian production reached a quench current of 6400 A at 4.7 (27 percent above design) without training. This magnet underwent the same series of life cycle tests as the previously tested quadrupole. An autopsy of this magnet will take place before the start of dipole production.

During these expected-life tests of the magnets, the cryogenic system performed without problems. Recovery from a quench takes less than 10 minutes even though the temperature of a dipole magnet is temporarily elevated to approximately 25 K. The quench does not affect operation of the other test stands. The cryogenic system responds to the quench by automatically venting the single-phase pressure pulse to a buffer tank through pilot-operated relief valves. The single-phase supply to the magnet is closed off for approximately 1 minute as long as the magnet pressure is above the normal operating value.

Heat load measurements were made on the first magnets at both the 4 K and 60 K temperatures. These measurements require that the magnet be operated with extremely low helium flow and that the cryogenic conditions remain constant until thermal equilibrium is achieved. At least 8 hours is required for such a measurement of a magnet. Although the results were successful, the digitizing accuracy of the readout electronics for the temperature sensors is being improved in order to achieve an overall measuring accuracy of better than ± 1 W.

MAGNET SCHEDULE

The delivery schedule for all superconducting magnets of the HERA proton ring is shown in Fig. 3. To date, the schedule shows delivery for 14 dipoles and 9 quadrupoles. Equal numbers of dipoles come from Germany and Italy. The first 9 quadrupoles include all of the pre-series needed to check the manufacturing process before the start of the full-scale production run for quadrupole magnets. These come from the German and the French manufacturers. Up until now the delivery of magnets has been less than one magnet per week on average. Six test stands have been available since the beginning of 1988 so that new arriving magnets have remained on the test stands long enough to develop magnet measuring techniques, to debug cryogenic control programs and to train the operators of the system.

However, Fig. 3 shows that the delivery of magnets will steadily increase until a peak rate of approximately 14 magnets per week is reached sometime in the final quarter of 1988. This delivery rate will continue for the first half of 1989. The capacity of the cryogenic system is perfectly adequate to cope with the maximum expected delivery rate of magnets. This capability is shown in Fig. 4. On this projected schedule, 60 percent of the time is allocated to measurements of magnetic properties. The installation/cool-down accounts for 20 percent and warm-up/replacement for the other 20 percent of the time which the magnet occupies the test stand. However, the measurement of magnets at a rate equaling the delivery clearly will require around-the-clock operation of the Magnet Measuring Facility.

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Fig. 1 Process and instrumentation digram for one test stand.

Fig. 2 EMCON D/3 process-control system.

Fig. 3 Delivery schedule for HERA superconducting magnets.

Fig. 4 A projected testing schedule