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SAFE AND FAST QUENCH RECOVERY OF LARGE SUPERCONDUCTING SOLENOIDS COOLED BY FORCED TWO-PHASE HELIUM FLOW

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ABSTRACT

The cryogenic characteristics in energy extraction of the four fifteen-meter-diameter superconducting solenoids of the g-2 magnet are reported in this paper. The energy extraction tests at full-current and half-current of its operating value were deliberately carried out for the quench analyses and evaluation of the cryogenic system. The temperature profiles of each coil mandrel and pressure profiles in its helium cooling tube during the energy extraction are discussed. The low peak temperature and pressure as well as the short recovery time indicated the desirable characteristics of the cryogenic system.

INTRODUCTION

The g-2 muon storage ring started its commission at BNL in April 1997. The successful experience in the operation of the large superconducting magnet has highly approved the cryogenic designs in many aspects. The g-2 magnet design was reported in 1994[1]. The cryogenic system design was reported in 1994[2] and 1996[4,6]. The early system tests were reported in 1996[3,5,8]. The design parameters for the g-2 power supply and quench protection system was evaluated by M. Green in 1993[7].

The g-2 magnet ring consists of four superconducting solenoids of 15 meters in diameter. The total cold mass at 4.5 K is 6.2 tons which is indirectly cooled by forced two-phase helium flow in tubes of 200 meters in length. The magnet is operated at 5200 A and the central field is 1.45 T. Total stored energy is 6.1 MJ. The refrigerator plant is capable of delivering 625 W at 4.5 K.

This paper discusses the cryogenic characteristics of its safe and fast recovery after the system quenches. The energy extraction tests at full-current (5175 A) and half-current (2450 A) were deliberately carried out for the quench analyses. The temperature and pressure profiles in the coil mandrels and cooling tubes during the energy extraction were measured. The maximum temperature of 38 K and the maximum pressure of 0.68 MPa were observed when the magnet quenched at the full current. The four large solenoids were re-cooled down to the superconducting temperature within 30 minutes after the full-current quench.

THREE SOLENOIDS AND COOLING SYSTEM

A cross section of the g-2 muon storage ring is shown in Figure 1. The four coil assemblies were built into three cryostats. The two OUTER solenoids supported by one mandrel share one common cryostat. The cold mass of the superconductor and aluminum mandrel in OUTER cryostat is 4010 kg. The thermal heat load in the OUTER cryostat is 60 W. The two cooling tubes of 16.2 mm in hydraulic diameter and the total length of 96 meter are arranged in a parallel flow path in opposite direction in OUTER mandrel. The inlet and outlet of helium to cooling tubes are located at the same interconnect position. The two INNER solenoids are built in separate cryostats. The cold mass of superconductor and aluminum mandrel in each INNER cryostat is 1040 kg. The thermal heat load in the cryostat is 61 W. One cooling tube of 16.2 mm in hydraulic diameter is attached to the coil mandrel in each inner cryostat. The total length of cooling tube in each INNER cryostat is 42 meters. The inlet and outlet of helium to the cooling tube are located at the same interconnect position.

There are three major parallel flow circuits in the cryogenic system which is shown in Figure 2, the main solenoid cooling circuit, the gas cooled leads circuit, and the cooling circuit for the Inflector solenoid and its leads. The two-phase helium flow in low gas quality is delivered from the sub-cooler so-called control dewar.

The three cryostats are linked together through a cryogenic interconnect chamber. In order to reduce the number of the cryogenic control valves and then the heat load, the main solenoid cooling circuit was designed so that the three cryostats can be cooled individually, any two of the three or three together. When the three rings are cooled together, they can be cooled either in series or in parallel flow schemes. The cooling circuit for the liquid nitrogen shield was also constructed the same pattern as the liquid helium flow circuit. These flow patterns of the three cryostats are shown in Figure 3.

Using the combination of the four valves one can distribute the mass flow rates to each of the three rings and get desired cooling performance according to the cooling power requirement. It is important because the pressure drops in the OUTER and the INNER cooling tubes are different even though the parallel-cooling pattern is employed. Because each ring can be isolated from others, the way of cooling circuit designed had provided the great advantages in various tests during engineering runs. The pressure relief valves located at the inlet and outlet of the cooling flow are also

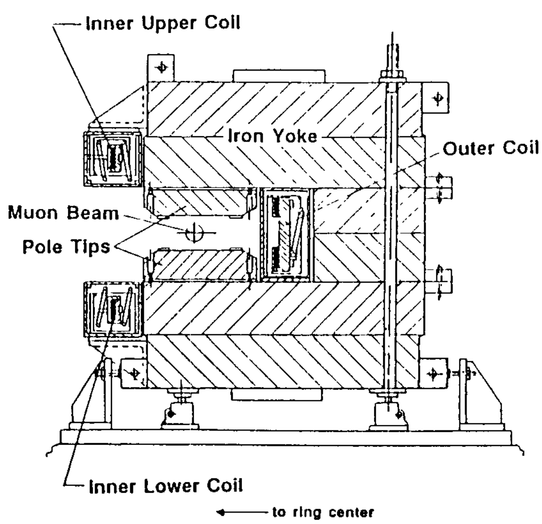

Figure 1. Cross section of the g-2 storage ring

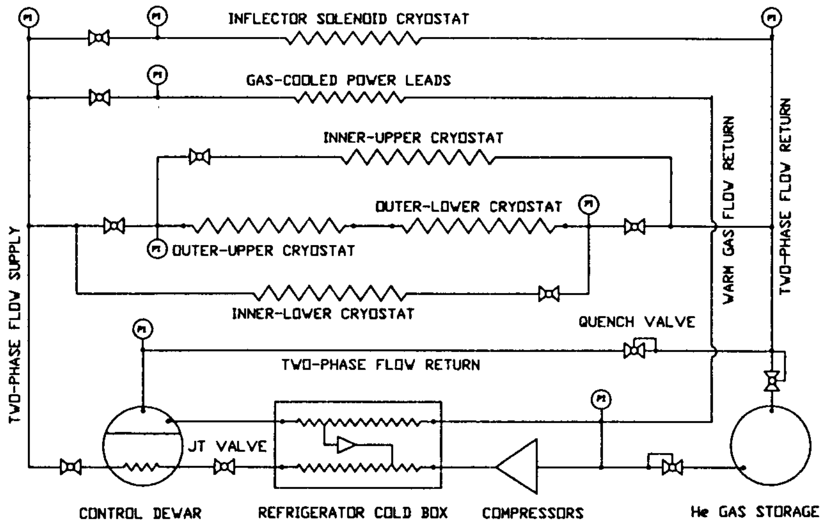

Figure 2. Simplified flow diagram of the g-2 cryogenic system

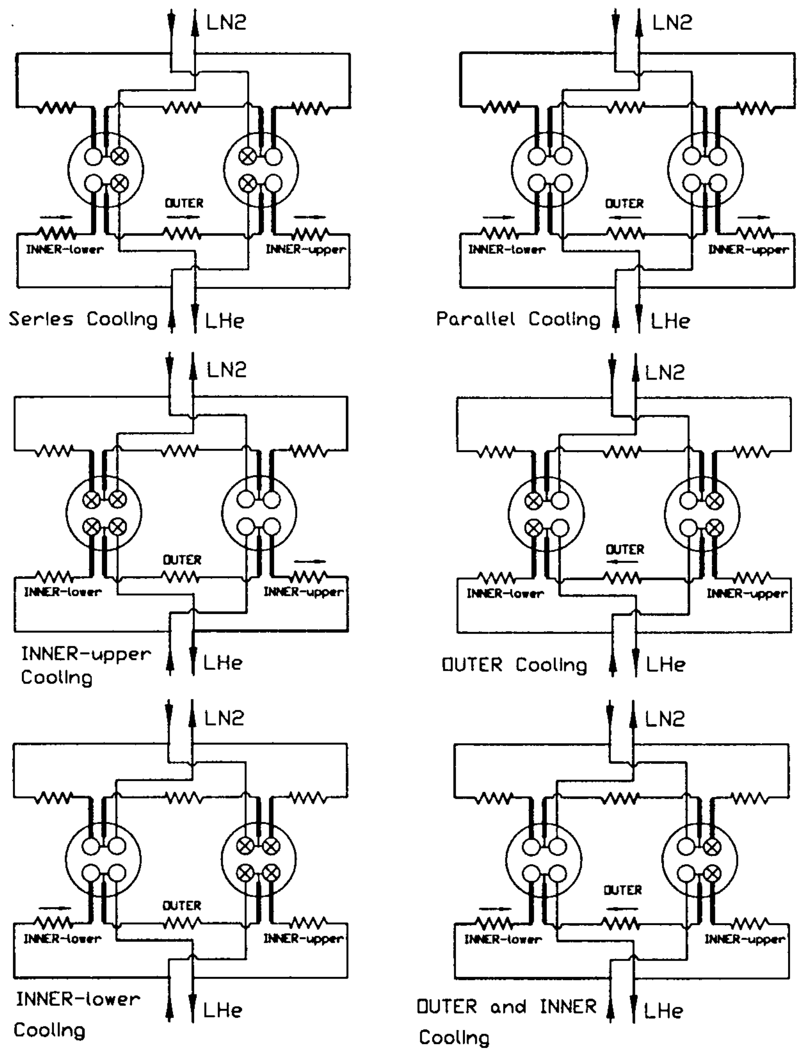

Figure 3. Interconnections of three cryostats for different cooling purposes

directly connected to the interconnect between the OUTER cryostat and each of the two INNER cryostats. This reduces the tube length between the relief valves so as to reduce the maximum pressure when the magnet quenches.

ENERGY EXTRACTION

To study the quench behaviors of the four solenoids and to test its cooling system, a series of energy extraction tests were carried out at low current, half-current and full-current comparatively with the magnet operating value. The magnet discharge was initiated by introducing a dump resistor in quench protection system or switching off the power supply of the magnet. Since the solenoids are all surrounded by the aluminum mandrels, when the dump resistor is put across the electrical power leads the eddy currents are induced in the aluminum mandrel. The heat generated by the eddy current in the mandrel drives the superconducting solenoid above the critical temperature, which causes them to become normal. This mechanism also applies to the situation when part of the superconducting solenoid quenches. The phenomenon is called the "quench-back". The quench-back is beneficial if a spontaneous quench has occurred, as the energy gets distributed uniformly across solenoid mandrel assembly. As a result, the hot spot temperature at the point where the magnet quenches occurred is reduced. The quench-back can also occur in between each solenoid as the case of the g-2 magnets. One quenched solenoid may drive the other solenoid packages to quench, which will also avoid the entire stored magnetic energy to dissipate in a single solenoid. In this paper, the temperature and pressure histories of solenoid mandrels and their cooling flows as the g-2 magnet quenches are presented and discussed.
Two groups of temperature and pressure profiles of solenoid mandrels in energy extractions are given in Figure 4 for half-current and full-current quench respectively. In each group there are four plots, three temperature plots for each of the three solenoids and one pressure plot for the cooling fluid. The four temperature profiles given in each temperature plot contains four measurements at evenly positioned points around each ring, which is also illustrated in Figure 5. The flow direction in the cooling tube of each solenoid mandrel is also shown in each figure. It must be indicated that the cooling flows in three cryostats were not isolated from each other during the tests. This allows the high pressure and high temperature gaseous in one quenched solenoid to quickly divert to others and dissipate the stored energy. The cryogenic characteristics of this process are discussed in the following sections.

HALF-CURRENT ENERGY EXTRACTION

The OUTER solenoid quenched 7.6 seconds after the magnet started to discharge. The temperature of the mandrel was 7.8 K (critical temperature) at this time. It took about 90 seconds to reach the average peak temperature of 20 K. The entire mandrel was cooled back to 5 K in 12 minutes. The helium flow direction in the cooling tube closed to these four temperature sensors was clockwise. The temperature sensor at 3 o'clock was the one at the upstream and close to the inlet of cooling flow. This portion of the mandrel started to drop the temperature at 30 seconds. The temperature profiles showed a clear gradient along the ring because of continuous cooling flow through the tube. The initial rate of temperature rise was 0.27 K/sec. The rate of re-cooling of the mandrel was 0.2 K/sec.
Neither of the INNER solenoids quenched at half-current energy extraction. The eddy current heating induced by quick discharging of the magnet reached its first peak in 2

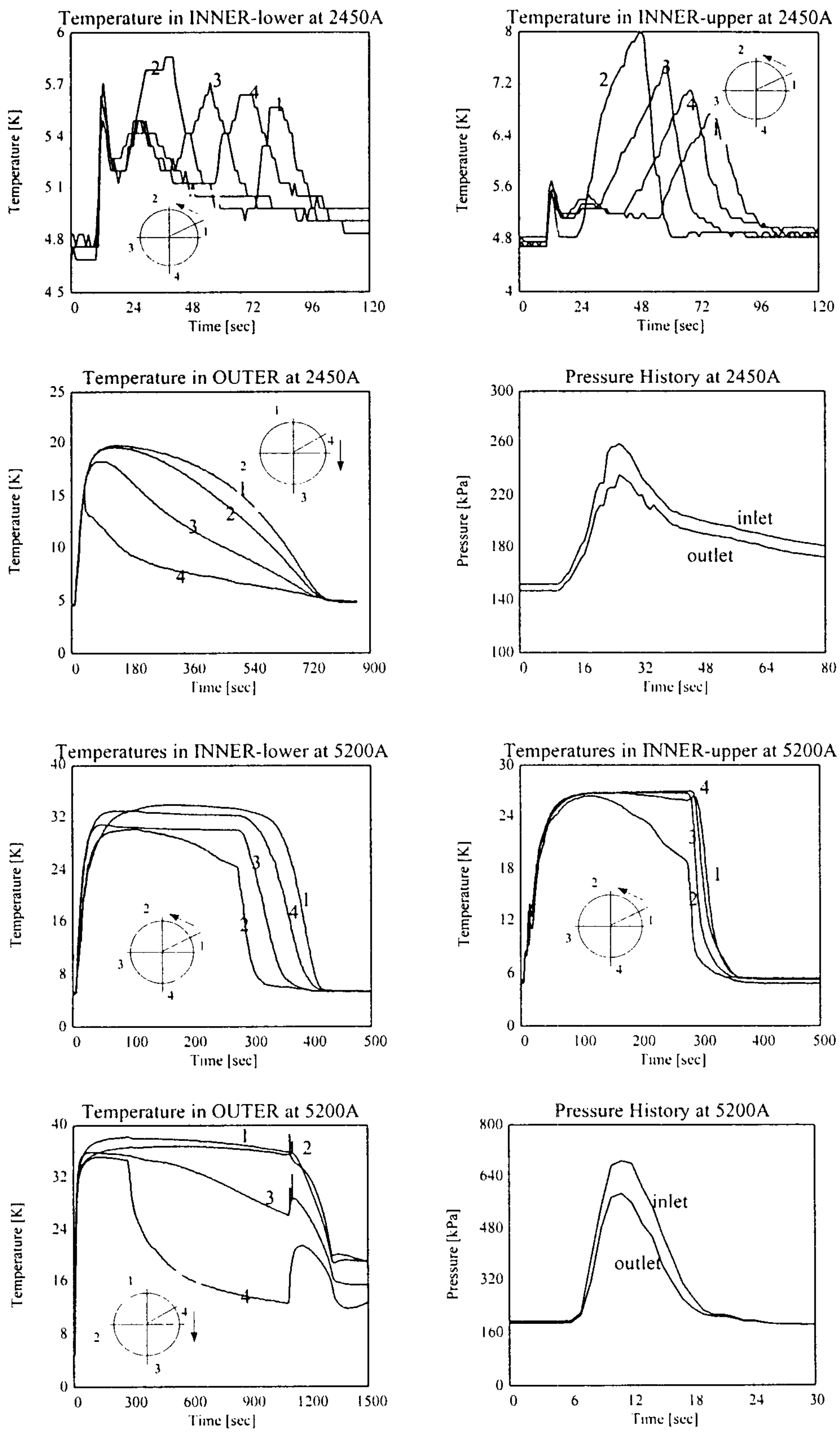

Figure 4. Temperature and pressure profiles during energy extraction

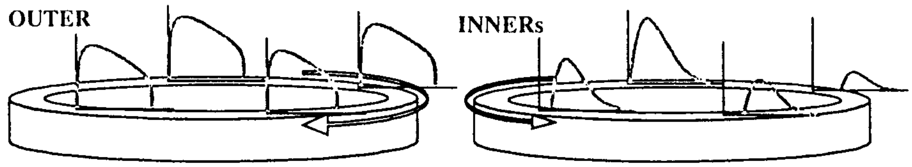

Figure 5. Schematic of temperature profiles along the solenoid mandrels

seconds and raises the temperatures about one degree. This early dissipation of heat continued in 7 seconds. The temperatures increase again when the OUTER solenoid was quenching. One can observe that the entire ring was not heated up uniformly along the INNER mandrel ring. Every portion of the ring experienced an "A" shape of temperature up-and-downs in about 40 seconds in sequence. There is also a decay pattern in the peak temperature along the ring in the flow direction of counter clockwise. The front wave of peak temperature travels at a velocity of 1.5 m/sec. It indicated that not only did cooling fluid continuously carry the heat in the INNER mandrels away, but also the heat was carried in by warm fluid in the quenched OUTER mandrel tube. This phenomenon suggested that not only did the quench-back distribute the stored energy from one solenoid to others, but also the back-flow diffused the energy through each other ring. Like the quench-back, the back-flow also help to reduce the peak temperature in the cooling tubes. The two INNER solenoids were cooled back to 5 K in 90 seconds.

FULL-CURRENT ENERGY EXTRACTION

For the 5200 A energy extraction, all four solenoids quenched and quench-back occurs in 2 seconds. About 60 percent of total stored energy were deposited into three solenoids and mandrels. The maximum temperature of the INNER-lower mandrel was 34 K and that of the INNER-upper was 27 K. The maximum temperature of the OUTER mandrel reached 38 K. The recovery time for the INNER-lower mandrel was 7 minutes and that for INNER-upper mandrel was 6 minutes. The recovery time for the OUTER mandrel was about 30 minutes. The temperature histories are also given in Figure 4.

The peak pressure in the cooling tube increased with mandrel temperature and the rate of thermal energy transfer to the helium in the cooling tube. The pressure relief valves are installed at the upstream and downstream of the each cryostat. Once the magnet quenches, the pressure in the flow circuit was regulated by these valves, which allows the warm gas to by-pass the control dewar and to exhaust directly into the gas buffer tank. Because of using these control valves, the pressure in the control dewar as well as that in the mandrel cooling circuits is maintained at desired low level during the magnet quenches. Meanwhile, the sub-cooled helium in the control dewar can continue to flow into the cryostats as long as the quench pressure is relieved, which carried away thermal energy to reduce their maximum temperature.

The highest measured pressure in the cooling tube for a quench at full-current was 0.68 MPa. The pressure reached the maximum in 5 seconds and decayed back in another 10 seconds. Within this 15 seconds, about 4 kilograms of helium stored in the cooling tubes were expelled through the pressure control valves. Once the pressure dropped, the cooling fluid started to flow in and to carry the heat away from the warm mandrel and to drop the temperature of mandrels. The pressure transducers were located in the inlets and outlets of three cryostats. The points in the cooling circuit some distance from the pressure transducer may be at a pressure that was up to 40 percent higher than the pressure measured at the highest pressure transducer.

CONCLUSION

The cryogenic characteristics of the g-2 magnet quenches was investigated by discharging the magnet using the dump resistor and power supply switch. The phenomena of the quench-back by eddy current heating and the back-flow of warm gas from quenched solenoid have been observed. The low peak temperature and pressure in long cooling tube was obtained at low and high level current quenches. The operating temperature of superconducting solenoids was recovered within a half-hour. The cryogenic system may be ready for re-powering up of these large superconducting solenoids within an hour. The safe and fast quench recovery is obtained in operating the g-2 magnet. This was achieved not by using the large capacity of refrigeration but by the rational system design. There are some advantages shown in the cryogenic design of the g-2 superconducting magnet, which includes the uses of large buffer volume, sub-cooled control dewar, by-pass quench gas circuit, versatile interconnect of three cryostats, and the automatic cryogenic control.

ACKNOWLEDGMENT

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