FORCED FLOW COOLING OF ISABELLE DIPOLE MAGNETS*

J.A. Bamberger, J. Aggas, D.P. Brown, D.A. Kassner, J.R. Sondericker,
and T.A. Strobridge†

ABSTRACT

The superconducting magnets for ISABELLE will use a forced flow supercritical helium cooling system. In order to evaluate this cooling scheme two individual dipole magnets were first tested in conventional dewars using pool boiling helium. These magnets were then modified for forced flow cooling and retested with the identical magnet coils. The first evaluation test used a 1 m long ISA model dipole magnet whose pool boiling performance had been established. The same magnet was then retested with forced flow cooling, energizing it at various operating temperatures until quench occurred. The magnet's performance with forced flow cooling was consistent with data from the previous pool boiling tests. The next step in the program was a full-scale ISABELLE dipole ring magnet, 4.25 m long, whose performance was first evaluated with pool boiling. For the forced flow test the magnet was shrunk-fit into an unsplit laminated core encased in a stainless steel cylinder. The high pressure gas is cooled below 4 K by a helium bath which is pumped below atmospheric pressure with an ejector nozzle. The performance of the full-scale dipole magnet in the new configuration with forced flow cooling, showed a 10% increase in the attainable maximum current as compared to the pool boiling data.

INTRODUCTION

Brookhaven's Intersecting Storage Ring Accelerator, ISABELLE, will use two concentric magnet rings in which protons are accelerated and then allowed to collide in experimental regions. The ring magnets used to bend and focus the beam will be superconducting with resultant cost and energy savings. The ISABELLE design and details of the proposed refrigeration system are documented elsewhere.^{1,2} Initial tests of an ISA 1 m model magnet and of a full-scale ISABELLE dipole magnet have been carried out over the past year to evaluate effectiveness of the forced flow cooling scheme and to gather operating experience with the combined magnet refrigeration system. The results of these tests are discussed here.

1 m LONG MODEL MAGNET ISA-IV

Pool Boiling Tests

The ISA-IV magnet, using NbTi superconductor, had been tested previously in a vertical test dewar with the entire 1 m long $\times$ 8 cm i.d. magnet and iron submerged in liquid helium. The construction of the magnet has been described in detail by Sampson.³ The test results for these magnets have been reported by McInturff.⁴ Figure 1 shows the configuration of the ISA dipole as constructed for these pool boiling tests.

In order to modify the ISA magnet for forced flow cooling, passages for the helium stream were provided by slotting the fiberglass bands surrounding the magnet core. The 28 slots, measuring 0.5 cm $\times$ 0.25 cm deep, were milled into the bands as shown in Fig. 2. The modified coil with iron laminations was then shrunk into a 36 cm o.d. $\times$ 1.8 cm thick stainless steel tube eliminating the need for a dewar. This modified magnet was tested once more in the vertical test dewar to compare performance with the previous pool boiling tests. The magnet performed as it had in previous pool boiling tests ruling out any possible degradation in performance that might have been ascribed to the slotted band construction.

Fig. 1 ISA model dipole magnet without the upper section of laminated core.

Fig. 2 ISA magnet coil with slotted passages in fiberglass bands for coolant gas flow.

Manuscript received August 16, 1976.

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

†Brookhaven National Laboratory, Upton, New York 11973.

*National Bureau of Standards, Cryogenics Division, Boulder, Colorado 80302.

Forced Flow Test

Flow Schematic and Description of Apparatus: A schematic diagram for the forced flow test is shown in Fig. 3. The 12.5 g/s JT flow exiting from the refrigerator is cooled to 4.6 K in a heat exchanger submerged in liquid helium; the helium stream, at a pressure of 13 atm, is then directed through the magnet entering at T-3 and exiting at T-4. The primary heat load of 6 W produces a temperature rise of 0.16 K for the helium

MASTER

CONTRACT NO. E(30-1)-16

stream through the magnet. Conduction heat flow from the 3600 A power leads causes an additional temperature rise of 0.1 K so that the gas temperature out of the magnet entering the heat shield is about 2 K higher than the incoming gas. The helium gas is warmed another 0.2 K by the heat load of 8 W in the radiation shield so that a typical temperature for the helium exiting the heat shield and entering the external JT valve is 5 K. The magnet assembly with the surrounding heat shield is installed in a vacuum tank, which also houses the helium subcooler.

ISA II MAGNET
FORCED FLOW COOLING SCHEMATIC

Fig. 3 Schematic flow diagram for forced flow cooling system of 1 meter magnet.

Test Results and Comparison with Pool Boiling Data: The transition temperature (zero current) was measured at ~9.8 K. The magnet temperature was increased from 4.8 K in discrete steps. At steady-state temperature conditions the magnet was energized and the current increased until quench occurred. The forced flow test data is plotted in Fig. 4 together with data from previous pool boiling tests and predicted short sample performance. The forced flow test data does not indicate any measurable deviation from the data obtained for pool boiling.

Fig. 4 ISA magnet performance data with pool boiling and forced flow cooling.

FULL-SCALE ISABELLE MAGNET - MARK II

Pool Boiling Tests

The 4.25 m long x 12 cm i.d. (8 cm i.d. warm bore) MK II magnet was first tested in a horizontal dewar, submerged in liquid helium operating with a closed system refrigeration system. Vertical passages are provided in the split iron laminations for circulation of helium coolant and for venting the coil. The results of extensive tests for the MK II magnet, using this pool boiling method have been reported earlier.

Forced Flow Test

Magnet Construction (Refer to Fig. 5): The identical coil was used for evaluating the magnet's performance under forced flow conditions. Eight spiral grooves measuring 1.74 cm wide x 0.305 cm deep are milled into the fiberglass-epoxy cylinder on the cold bore tube of the magnet to provide channels for the high pressure helium coolant at the i.d. of the coil. The main magnet coils are held on the bore tube with fiberglass bands, slotted with twenty-six 0.5 cm wide x 0.38 cm deep channels for the coolant flow on the o.d. of the magnet coil. The nonsplit iron laminations are "shrunk" into the 2.54 cm thick x 50.8 cm o.d. stainless steel tube which also serves as the helium vessel. The magnet coil is then precooled to liquid nitrogen temperature and shrunk-fit into the inner bore of the laminated iron structure, assuring an interference fit between the coil and the iron at operating temperatures.

Fig. 5 Cutaway view of Mark II magnet (end section) as constructed for forced flow cooling.

Magnet Assembly (Refer to Figure 6). The magnet is suspended from the vacuum vessel with chains, stabilized laterally with centering rods, to minimize heat flow to the magnet by conduction. Multilayer insulation and a double aluminum foil heat shield, cooled by the helium return gas stream, surround the magnet to intercept radiant heat flow.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Fig. 6 Isometric assembly of 4.25 m long ISABELLE magnet, vacuum tank, and supports.

Flow Schematic and Cryogenic System: Figure 7 shows the flow diagram of the cryogenic system used for forced flow cooling of the MK II magnet. A Claude cycle refrigerator, not included in the flow schematic, delivers the High Pressure Gas (HPG) at about 17 atm and 5 K to the precooler (T-1). The HPG is progressively cooled flowing through heat exchanger coils in the liquid helium precooler and subcooler vessels. The HPG from the subcooler (T-3) then enters the magnet where it first circulates through the magnet core (primary heat load), leaving the magnet core at T-9. Here a small portion of the total HPG stream is diverted through the gas cooled magnet power leads, then returning to warm compressor suction. The major portion of the HPG flow continues through a pipe inside the magnet's vacuum tank which is attached to the heat shield surrounding the magnet (secondary load). The HPG leaving the heat shield (T-4) then returns to the subcooler system, passing through the calorimeter Q_1 , then through a sintered metal filter. With valve "G" open, the HPG enters

the primary nozzle of the ejector whose low pressure section, T-8, is connected to the top of the sub-cooler tank. A JT valve, installed in parallel with the ejector, is isolated from the ejector system by valve "E". For mass flow requirements in excess of limits imposed by sonic velocity in the ejector nozzle, the JT valve is used in parallel with the ejector. A heater in the precooler tank prevents liquid floodback should too much liquid helium accumulate. The subcooler's level is automatically maintained by modulating valve "D" operating on sub-cooler level signal.

For the first magnet test runs a single ejector was used in parallel with the JT valve. Figure 8 shows the ejector's construction. The position of the primary ejector nozzle is adjustable by means of a gear drive to optimize its clearance in respect to the diffuser section. For later runs a second ejector was installed in parallel with the first one, achieving lower magnet temperatures. Both ejectors were designed and built at NBS, Cryogenics Division, Boulder, Colorado.

Fig. 8 Cutaway view of ejector nozzle.

Fig. 7 Schematic diagram for forced flow cooling system used with full scale ISABELLE magnet using subcooler and ejector.

Test Results: For the first run, with one ejector installed, the magnet's operating temperature as measured on T-9 was typically 4.4 K with the ejector pumping the subcooler to 0.35 atm. The system's heat load and consequent mass flow exceeded the value for which the ejector had been designed. The parallel second ejector which was installed for the next run resulted in magnet operating temperatures of 4.1 K, with the subcooler pumped to 0.6 atm.

The MK II magnet's performance with forced flow was enhanced compared to the previous pool boiling results:

1. **Maximum Attainable Current.** The maximum current reached, after "training", exceeded pool boiling quench currents by > 10%.

A graphic comparison of the magnet's performance for both cooling modes is shown in Fig. 9. Magnet parameters and performance are discussed in detail in paper I-1 presented at this conference.⁹

Fig. 9 Quench history for Mark II magnet with pool boiling and forced flow cooling.

2. **Magnet Stability.** The magnet was energized at ramp rates exceeding requirements for the ISABELLE machine with a resultant temperature rise below 0.1 K as measured on T-9. The maximum attainable current was not limited by the rate of excitation at 4.1 K.

ACKNOWLEDGMENT

Many people contributed significantly to the success of this project. The work of the magnet group under the direction of A.D. McInturff and W.B. Sampson, referenced above, is of fundamental importance here. The ISABELLE design group, and Brookhaven's Shop, Division gave needed know-how and support. Special thanks to V. Buchanan, W. Franklin, D. Gilzinger, H. Hildebrand, R. Kahl, A. Schiafke, A. Werner and D. Zantopp for contributing their special talents. K. Hahn and J. Spiro gave the required direction and encouragement to implement this program.

References

1. K. Hahn, ed., "A Proposal for Construction of a Proton-Proton Storage Accelerator Facility ISABELLE" BNL Rept. 10161 (1976).
2. D.P. Brown, BNL Formal Report BNL 50514 (1976). Available from the National Technical Information Service, U.S. Department of Commerce.
3. W.B. Sampson, P.F. Dahl, A.D. McInturff, K.E. Robins, *Proc. 19th Intern. Conf. High Energy Accelerators*, SLAC, Stanford, Calif., p. 606 (1974). Available from the National Technical Information Service, U.S. Department of Commerce.
4. A.D. McInturff, P.F. Dahl, R. Damm, C. Lasky, K. Robins, W.B. Sampson, *IEEE Trans. Nucl. Sci.* NS-22, No. 3, 1133 (1975).
5. A.D. McInturff, P.F. Dahl, D. Kassner, C. Lasky, K. Robins, W.B. Sampson, *Proc. Technical Applications of Superconductivity Conf. Alushta, USSR*, (1975).
6. A.D. McInturff, W.B. Sampson, K. Robins, P. Dahl, R. Damm, D. Kassner, J. Kaugerts, C. Lasky, "ISABELLE Ring Magnets", these Proc.