CONF-830841--9-Draft
Draft

CONF-830841--9-Draft

DE83 017288

SINGLE-MAGNET TEST RESULTS OF THE FIRST EBT-P DEVELOPMENT MAGNET*

J. W. Lue, S. S. Shen, J. K. Ballou, T. J. McManamy, and C. T. Wilson

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

INTRODUCTION

The first development coil (D1) for the Elmo Bumpy Torus Proof-of-Principle (EBT-P) machine was successfully tested[1] in a large "bucket" dewar — the "open dewar test". Since then, it has been welded closed and installed in an individual dewar by a McDonnell Douglas/General Dynamics magnet development team. During the open dewar test, the bath contained 500 to 600 liters of liquid helium surrounding the coil. In contrast, there is only a volume of about 15 liters left for helium inside the individual dewar. This, plus the heat load introduced by the support structure, changed the cryogenic environment of the coil. litres

The main purpose of the present test was to see if the coil still operates reliably, especially under the simulated X-ray heating load. Thermal performances of the dewar, stack, and support structure shielding were also being investigated.

FACILITY SETUP

Magnet and Dewar

The EBT-P D1 coil was designed to produce a peak field of 7.4 T on the conductor at an average current density of 10,000 A/cm^2 in the winding cavity. It was wound with copper-stabilized NbTi superconductor in a ventilated layer-cake winding. The winding ID is 48 cm, OD is 69 cm, and the axial length is 21 cm. Details of the coil design and construction are given elsewhere.[2]

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

The D1 coil was installed in an individual dewar which was compatible with the cryogenic and mechanical environment expected in the EBT-P machine. The dewar conforms closely to the coil winding and consists of a closure ring, titanium support straps, liquid nitrogen shield, vent stack, and vacuum enclosure. The overall dewar has a warm bore of 42 cm, OD of 109 cm, and axial length of 30 cm. Details of the dewar will be reported elsewhere.[3]

Cryogenic System

The D1 magnet in its individual dewar was mounted on an aluminum stand anchored beneath a test platform (Fig 1). The dewar top which contains all the penetration to the cold mass, vapor-cooled leads, cryogen fill lines, instrumentation feedthrough, and pump port, etc., was sticking up to the upper level of the test stand for easy access. A plexiglass box was built around the vapor-cooled leads and nitrogen-gas was flowing through it to prevent ice ball formation.

A schematic of the cryogenic hookups is shown in Fig 2. Cooldown from room temperature to liquid nitrogen temperature was accomplished by using the building gaseous nitrogen. The incoming nitrogen-gas was divided into a stream passing through a liquid nitrogen heat exchanger and a room temperature stream. Inlet temperature and mass flow of the nitrogen-gas were adjusted through the separate valve settings of the two streams. Outgoing gas from the magnet vent line was fed to the liquid nitrogen shield trace-line. This was disconnected after the nitrogen cooldown was completed and the latter was reconnected to the liquid nitrogen supply.

Cooldown from 80 to 4.2 K was accomplished by transferring liquid helium to the bottom fill line which contains sprinkle rings to spray helium directly into the coil winding. A 500-litre supply dewar sitting on the test stand was used to supply the liquid helium.

All gas flow from the magnet passed through a flow control and metering box. Hastings mass flow meters are used for the primary gas flow measurements.

Instrumentation

A 300 V, 2000 A, fast response bipolar power supply was used to charge the magnet. In addition to supply up to 1850 A for the dc ramp test, this power supply was also able to add a ripple current on top of the dc current to produce ac losses to simulate X-ray heating. Fig 3 shows a schematic of the power supply and quench protection circuit of the magnet.

The power supply was remotely controlled by a ramp signal generator for ramping the coil current and a function generator for generating the sinusoidal signal used for the superimposed current ripple. A switching module was used in series with the dump resistor to connect it to the coil in the event of a dump or quench. Since the power supply is bipolar, the switching module consists of two legs of SCR's, each for one of the current directions. To ensure firing of the SCR's, two parallel circuits were placed on each leg.

Quench detection of the coil was based on a compensation module, which subtracted inductive voltage from the coil voltage. The inductive voltage came from a modified Rogowski pickup coil system which was made up of a primary bus, a secondary coil, and a noise compensation coil. The primary bus consisted of two turns of water-cooled copper conductor in series with the magnet. The secondary was a simple solenoid with about 2000 turns of fine copper wires wound on a nylon mandrel and was placed inside the primary bus. The noise compensation coil was identical to the secondary coil and was located outside the primary bus. The output of the noise compensation coil was subtracted from the output of the secondary coil. When the noise compensation coil was oriented properly (about anti-parallel to the secondary coil), a factor of 10 reduction in noise was achieved with this arrangement.

When the compensated coil voltage went beyond the preset quench threshold, the detector opened up the circuit breaker. Voltage across the switching module built up until the Zener diode conducted. This, in turn, fired the SCR and the dump resistor was connected across the coil to dissipate its stored energy. Two different quench thresholds were used. Compensated coil voltage of up to 2 V lasting for 270 ms or in excess of 6.5 V would trigger a dump. The low quench threshold, however, had to be raised to about 6 V during simulated X-ray heating. This was because applied voltages of up to 60 V were required to produce 20 W of ac heating, and the 95% compensation left a compensated coil voltage of about 3 V.

A Doric Digitrand 240 process monitor was used to scan the data from strain gauges; CLTS, and thermocouple temperature sensors within the magnet; pressure transducer and helium level in the dewar; and helium flow rates. A strip chart recorder and a PDP-12 monitored the coil during current tests.

TEST RESULTS

Cooldown and Cryogenics

A finite element analysis[4] was performed on the magnet bobbin for thermal stress during cooldown. The result indicated that maximum von Mises stress occurred in both corners (inner bore to sidewall and closure ring to sidewall), demonstrating that as the sidewall shrank, it forced the inner and outer rings to bend. In order to keep the von Mises stress in the coil case to below 15 ksi during cooldown, the closure ring temperature should be no lower than 20 K below the sidewall temperature. This limitation could be relaxed somewhat as the bobbin temperature lowered. After 80 K was reached, then no schedule was necessary and liquid helium could be sprayed directly into the coil.

The nitrogen-gas supply was regulated to a maximum of 35 psig to prevent damage to the magnet dewar in the event of a total blockage of the vent lines. The maximum achievable flow rate with this pressure head and the restrictions of the piping was about 10 g/s. With an average mass flow of 8.0 g/s and ΔT limitations discussed above, it took about 72 hours to cool the magnet and its bobbin down to 90 K. Liquid nitrogen was then fed into the coil until it was ready for further cooling and magnet test.

Cooldown from liquid nitrogen temperature to liquid helium temperature took about 4 hours by direct liquid helium transfer and about 200 litres were required.

Helium boil-off rate of the dewar was approximately 14 L/hr, and agreed quite well with the design estimation. However, the 80 K heat stationing for the cold mass supports appeared to only reduce the support temperature to 100 K, introducing an extra heat leak of about 2 W. The 80 K heat stationing plate in the stack floated almost as if it were not heat stationed at all. It was at a much lower temperature during the test. The dewar vacuum space was valved off after helium transfer began. It maintained a vacuum of 10^{-6} Torr or less during the test. Thus, the dewar vacuum is judged to be sufficient.

Magnet Ramp Tests

After several low current testing to check the quench protection system and power supply, the coil was ramped to 1240 A (the 60 GHz resonance field operating level) at a rate of 2 A/s. The ramp rate was later increased to 4 A/s, 8 A/s, and 12 A/s. All ran smoothly. The maximum field on the coil was 5.0 T. The coil was held twice at this field for about 30 minutes - once with a trickle flow to maintain the liquid helium level, once without helium fill to demonstrate steady state operation. It was further charged successfully to its full rated current of 1820 A (7.4 T maximum field, 90 GHz resonance level).

The coil was manually dumped from both 5.0 and 7.4 T maximum fields. The helium-vent relief valve was set at 3 psi, but the fast rising pressure registered a maximum dewar pressure rise of 4.4 psi on the 5.0 T dump and 6.7 psi on the 7.4 T dump. The coil discharge voltage trace and measurements made shortly after the dumps indicated that the coil did not quench from the 5.0 T dump. It quenched from the 7.4 T dump, and bobbin sidewall indicated a temperature rise of about 20 K.

X-ray Simulation Heating

X-ray simulation test was successfully performed on the coil at 5.0 T field. A 0.5 Hz sinusoidal ripple current was superimposed on the dc magnet current. The amplitude of the ripple current was increased steadily from 2 A to 20 A. According to the calibration made in Ref. 1, the maximum equivalent heating was about 20 W. This heating was applied for 10 minutes. The magnet held up at 5.0 T while helium level was maintained by a trickle flow from the bottom fill-tube. During this time, no active pumping was applied and the dewar pressure increased to 17.5 psia, causing bath temperatures to rise to about 4.4 K.

After the heating test, the ripple current was removed. Helium transfer was stopped, and the dewar pressure and helium boil-off were returned to normal. The magnet current remained at 5.0 T level for another 20 minutes without any ill symptoms.

CONCLUSIONS

The D1 coil performed well in its tightly enclosed individual dewar. The coil could be charged to the 5.0 T maximum operating field in less than 2 minutes. Steady-state operation was demonstrated at this and the full rated field of 7.4 T. The coil was allowed to warm up towards liquid nitrogen temperature at the end of each day's test before refilling with liquid helium for the next test. No training nor quench was encountered in any of the tests performed requiring an emergency discharge.

The most satisfying result was that it survived the simulated X-ray heating test at the 60 GHz resonance field level. The original design criteria was 10 W at 90 GHz field and the expected 60 GHz field heating was on the order of 2.5 W. Therefore, it was quite pleasing to see that almost an order of magnitude over the anticipated heating, or 20 W could be sustained by the magnet for a steady-state period, some 10 minutes, without any difficulty although the dewar pressure was increased and caused the bath temperature to rise to about 4.4 K.

Because of the limited inventory of helium inside the dewar, the coil was not tested to its full capabilities. However, in every respect it was tested, no degradation in performance was evident compared to the previous open dewar test.[1] The trickle flow used to maintain the helium level inside the dewar during ramp rate and heating tests was very similar to the flooded system being planned for EBT-P. The coil operated well under these conditions was a good boost to the flooded design.

Helium consumption rate of the dewar was within design margin. However, better heat stationing of the cold mass supports and the 80 K plate or modification of the stack design is desirable.

REFERENCES

1. J.R. Miller, J.W. Lue, and S.S. Shen, "Proc. 9th Symp. Eng. Prob. of Fusion Research", IEEE Pub. No. 81CH1715-2 NPS, 2012 (1981).
2. J.K. Ballou, T.J. McManamy, R.L. Brown, W.H. Gray, and M.S. Lubell, "Proc. 9th Symp. Eng. Prob. of Fusion Research, IEEE Pub. No. 81CH1715-2 NPS, 543 (1981).
3. S.L. Ackerman, et al, to be published at MT-8, Grenoble, France (1983).
4. W.H. Gray, private communication.

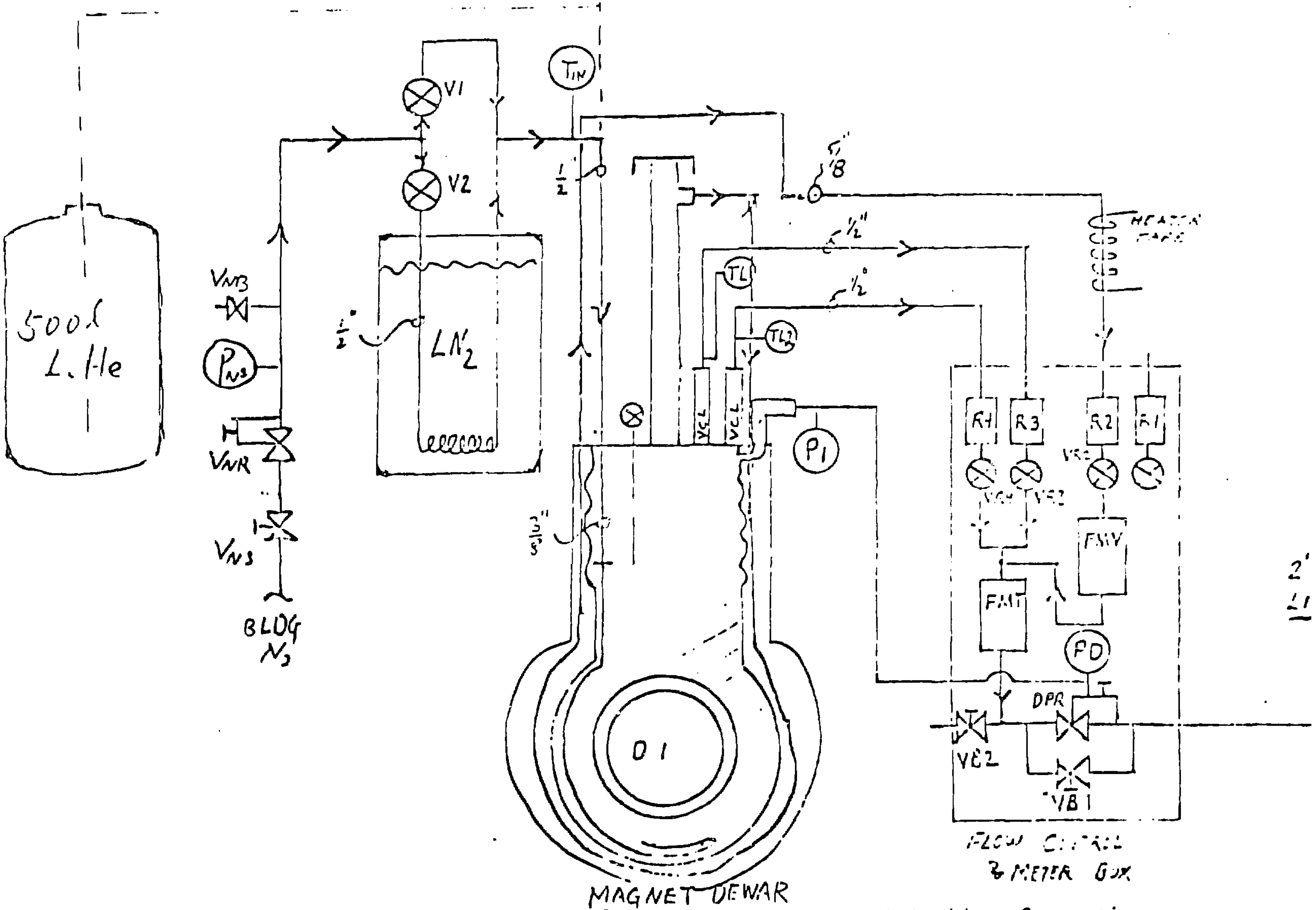

Fig. 2 ~~300K to 100K Initial Cooldown Connections~~

Fig. 2

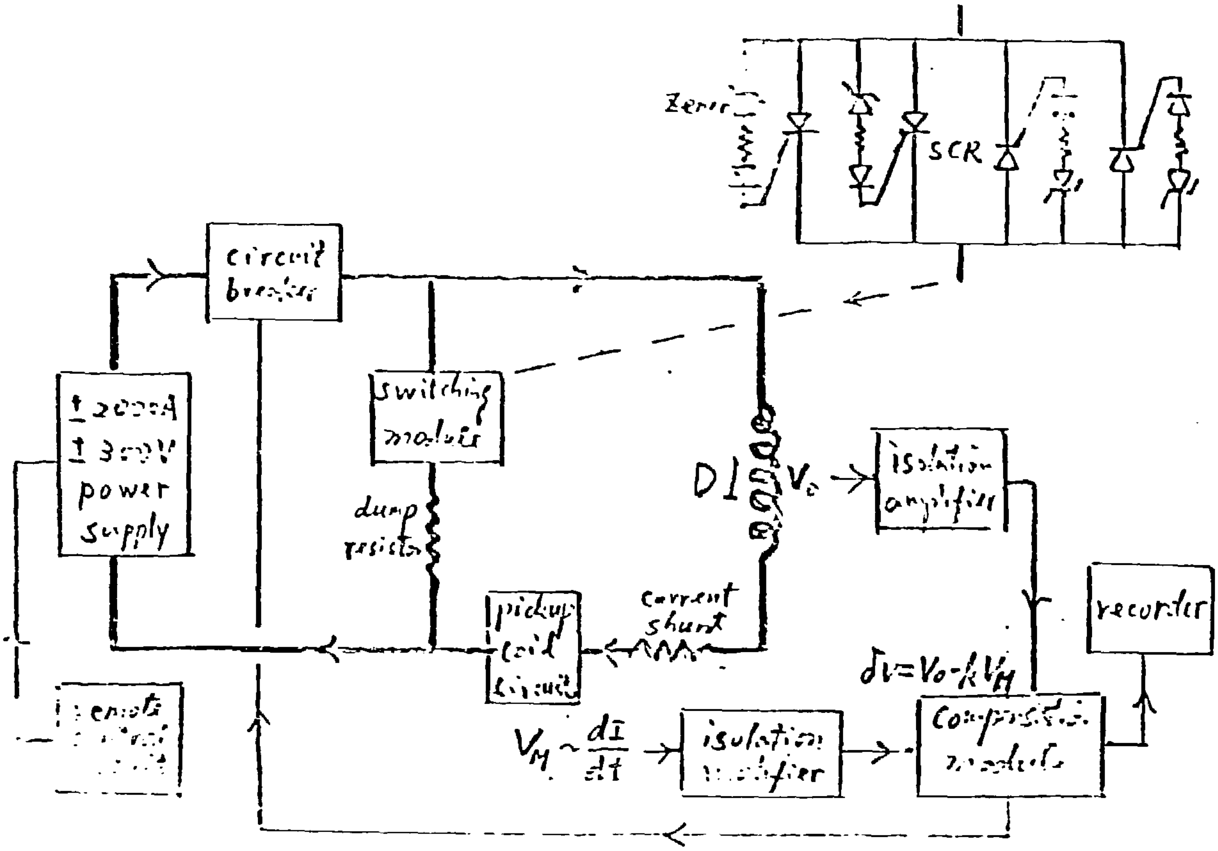
Zener
SCR
circuit breaker
switching module
± 2000A
± 300V
power supply
dump resistor
DI
V_0
isolation amplifier
recorder
current shunt
pickup coil circuit
$\delta V = V_0 - kV_H$
compensation module
$V_M \sim \frac{dI}{dt}$
isolation amplifier

Fig. 3