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Author

DeWitt, R.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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R. DeWitt

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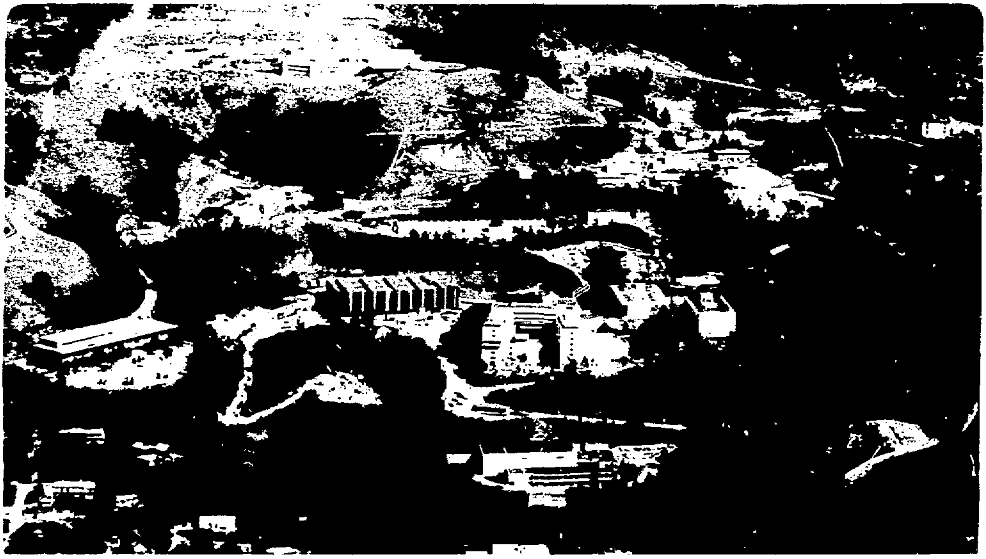

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FINAL DESIGN AND PERFORMANCE OF A TWO GAP MAGNET*

R. DeWitt
UNIVERSITY OF CALIFORNIA
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Introduction

The Doublet III (DIII) Neutral Beam Injection System (NBIS) magnet is unique. It must operate in the non-uniform external field of the Tokamak and still reflect two (2) high power ion beams. Currently, the incoming beams consist of mixed particles, mostly ionized, of nearly 8 MegaWatts each, over a half-second duration. Higher power beams and longer times may be required in the future.

The basic magnet design considerations have been detailed previously.[1] This paper elaborates on the choices made and correlates the actual performance with those final design criteria.

Safety devices are mentioned. These devices are prolific due to the high power levels in the beams.

Yoke

The yoke was designed to carry the return flux from the gap and the DIII Tokamak fringe field flux (Fig. 1) for the worst case. The worst case here refers to both fields being aligned in the return yoke steel after the DIII upgrade takes place. (See Fig. 4 and 5)

The yoke has two (2) gaps, one for each beam. The beams are focused on a single port in the DIII torus. The center yoke is tapered to accomodate the convergence angle of 8°40' between the sources.

Each gap is 18 cm high normal to the beam. This allows space for the expanded ion beam and the shields which absorb the stray ions. These water-cooled shields keep the temperature within acceptable limits and also protect the yoke surface from sputtering.

All of the mild steel pieces are nickel plated to prevent corrosion. In addition, the plating process reduces problems associated with outgassing. Both electroless nickel and electroplated nickel pieces were used. Samples were tested to corroborate the material acceptability.[2]

The calculations were done for C1010 steel, which was available at that time. When the purchase order was placed, C1008 was available for the same cost. Naturally, LBL bought the better magnet steel. Although a softer steel is more sensitive to corrosion, the plating would protect it adequately until it was placed in the hydrogen atmosphere. The magnetic parameters, however, were improved slightly.

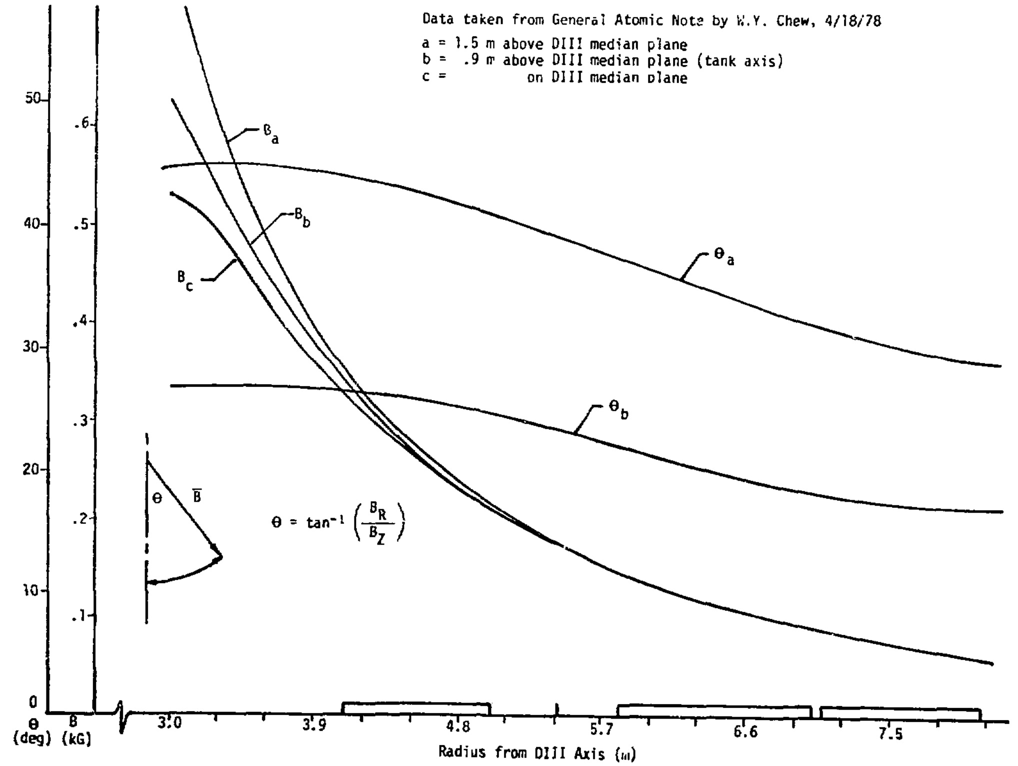

Fig. 1

TOKAMAK FRINGE FIELD

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Coils

The coils were wound from hollow square copper conductor. Copper was chosen for water system compatability and electrical characteristics. Hollow conductor to carry a larger mass of coolant water.

The coils are made from two (2) subcoils (double pancakes) of two (2) layers of eight (8) turns each. There are thirty-two (32) turns per coil and two (2) coils per gap. Each coil is connected electrically in series and hydraulically in parallel.

Each water circuit has two (2) sets of thermal switches. The first set is rated for 1 Amp and is set for ∿ 95°C. The switches open on rising temperature and are connected in series through the power supply interlock system. The second set of switches are set for only ∿ 90°C and also open on rising temperature. These are to be interfaced to the computer monitor. They serve only as a warning device. The system can run at even higher temperatures for short periods of time. Typically, however, the coils will operate at ∿ 70°C for full energy beams. The magnet is designed for continuous operation (DC) at full power.

The coils are epoxy potted, and can outgas long chain organic molecules. Vacuum tight cans are welded around the coils to seal them. The cans are made from 1/8" stainless and all of the joints are of welded construction. Seals between mating pieces are made with O-rings and are bolted together.

Field Shaping

The field shape needs to be very closely constrained for reflecting the beam of ions. The field needs to be uniform with a sharp rise. Field clamps make the field rise sharp, while field shims control the uniformity of the field. The calculations for the size and shape of the shims, and the resultant field shape, were done by Jitendra Singh (then at UCLBL, currently with Hewlett-Packard). Calculations were done using the program MIRT and another program written by Mr. Singh called BEAM. The hardware design then proceeded in earnest.

The original calculations were completed before the final requirements were known. The result required a wider pole than originally designed. The pole was expanded 1/2 inch to keep the high power line focus inside the uniform region.

Special shielding fingers were attached to the magnet to reduce the field along the incoming beams to nearly zero. The calculations for them were done by Dr. Klaus Halbach of UCLBL. The material for the special shielding is discussed elsewhere.[3] This material did not need to be plated as the alloy is already ∿ 50% nickel.

Energy Shielding

The pole shields (discussed above) kept stray beam from being deposited on the upper and lower horizontal surfaces. Additional shields were placed on the sides to accomodate the negative ions and the high momentum particles. These were also water cooled. Only the devious ion shield was not water cooled.

Collimators were placed on the neutral beam entrance and exit. These are heavy wall water-cooled copper plates to limit the beam expansion. They were made to absorb the beam power during alignment of the source and to control the beam shape. Detectors measure the temperature change so the power absorbed from each shot can be calculated and the beam alignment trimmed.

Mechanical Adjustments

The magnet is to be adjusted prior to final assembly in its spool. The adjustments can be refined after final assembly, but large adjustments will be unwieldy due to the weight (8 tons). The magnet can be adjusted in three (3) planes and rotated about 3-axes, but the maximum combined motion cannot exceed 1 inch.

Electrical Controls

The magnet field is dependent upon the current in the coils. Therefore, the current needs to be controlled. The power supply has an external control network built in. The manual describes how to choose either voltage or resistance programming. Before a controlled change can be made, however, the desired value must be compared to the existing value.

The current can be monitored by inserting a current shunt in the coil circuit. An A/D converter allows the computer to understand and make whatever correction is required. A similar converter, across the coils, which measures the applied voltage, will allow the computer to calculate the average temperature in a set of coils.

The field is also monitored by either of two (2) Hall devices in each gap. The devices are located in the corners of the pole face. The readout device is a digital Gaussmeter that has a BCD output to interface with the computer directly. The probe is non-linear, as all Hall devices are, but is calibrated to better than 0.1% linearity. The device reads a consistant 3% below the gap center value because of the edge location. Final values need to be kept in an operations log.

Power Supply

The power supply design calls for 250 Amps @ 30 VDC. Two separate power supplies, H-P model 6469C, were purchased so the gaps could be tested independently. Free-wheeling diodes were added across the output to protect the power supply from the inductive loading of the magnet. The diodes must be protected from spikes, so varistors are placed in parallel with the diodes.

The diodes chosen were IN3739. They have a D.C. I_{ave} = 350A and I_{surge} = 3,000A for .08 sec. and a PRV of 500 Volts. Also, they were on hand. The varistors are 130 Volt 10 joule devices, and are mounted in pairs. A single 30 joule device would have been simpler, but the 10 joule units were in stock.

These power supplies are air-cooled units that have 300 Amps at 36 VDC. The test set up much simpler. Later units could be dual-channel, water-cooled power supplies for better cost effectiveness. These units remain for a test area.

The rear of the power supply has a terminal block with a variety of options. One of the jumpers must be in place during operation. This jumper is replaced with the normally closed switch circuit. Whenever a switch opens, the power supply shuts off. This jumper then becomes the safety interlock system. Testing was done with a water flow switch (NO) in this circuit. The flow closed the contacts permitting the operator to turn on the power supply current.

Testing

The magnet was tested using two (2) different systems. The magnet was located near a large magnet with a small fringe field to try to simulate the Tokamak field. No response was noted, but the external field was much less than the Tokamak will produce. Therefore, no conclusion can be drawn at this time.

Hall probes were calibrated a 1 kilo-Gauss and used to test the field as a function of current. The Hall devices operate over a very small active area (.010" dia.). The smaller the area, the more accurate the measurements in high gradient fields. The Hall response is non-linear, but can be compensated. The probe used had a 0.1% linearity over a 10 kilo-Gauss range and so was quite good for the fields being measured.

In addition, an integrating coil was used. The active region of the coil is large (∿ 1" dia.), so the absolute accuracy is poor in gradient fields. However, the coil has a linear response over the range of the integrating amplifier. The integrating capacitor needs to be a "low leakage" type, such as polystyrene.

The calculated values were plotted with dashed lines in Fig. 2. Then the actual test data was plotted in solid lines. The solid lines cover the dashed lines except the area where the pole was extended. The solid curve, however, matches the dashed curve to within the width of a pencil line. The fit is almost too good to believe, for the normalized values.

The maximum field value plotted is a few Gauss higher than calculated. The higher field probably is due to the better grade magnet steel, but joint assumptions and actual dimensions also vary over the machine tolerances. The normalization can be adjusted in real life by varying the current in the coils.

The field vs current (B-I) graph was also plotted (see Fig. 3). The graph is a straight line because the field in the steel is only about 6,500 Gauss. The steel won't approach the design value of 14,000 Gauss until the Tokamak fringe field surrounds the yoke. At that time, the B-I curve will show some non-linearity. The lower line is generated by increasing the current from the last value. The upper line is generated by decreasing the current.

The temperature switches all operated properly. The temperature was calculated from the voltage rise under constant current conditions. The water flow was shut off, and the time needed to trigger the temperature switches was monitored. The sequence triggered properly on each coil and at the proper temperature. However, the time required to reach the trigger point was longer than calculated for the upper coils. The reason lies in the simplifying assumptions. Under actual conditions all coils will have the same water pressure. Under the test conditions, the upper coils had a lower pressure than the lower coils. The water motion carried heat away from the system. In addition, very little air will be able to move, as the coil cans are in vacuum.

Summary

The magnet tested slightly better than designed, in spite of changes during fabrication. The system will be assembled at General Atomic shortly. The real testing will begin then. But the magnet has met all of its initial tests with success. I suspect that if all goes as well as expected, the system will be upgraded. The magnet can be pushed to handle higher energies by using larger power supplies. It could also be operated as a pulsed DC magnet.

Acknowledgements

Much of the work on the NBIS project was a group interaction. It is with pleasure and pride that I mention certain individuals that contributed in areas that made the project possible and the system a reality. Not all of them helped directly on the magnet, but all helped develop the system: M. Fong, J. Gunn, N. Hawks, R. Hintz, K. Halbach, L. Resnick, J. Singh and R. Yamamoto. My thanks to J. Sundance and W. Low for their assistance in preparing this paper.

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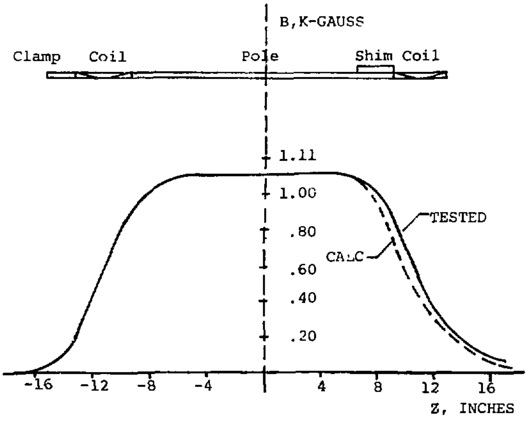

Fig. 2

FIELD PLOT

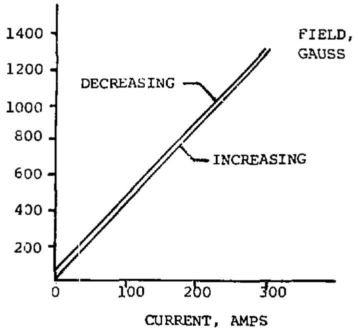

Fig. 3

B-I GRAPH

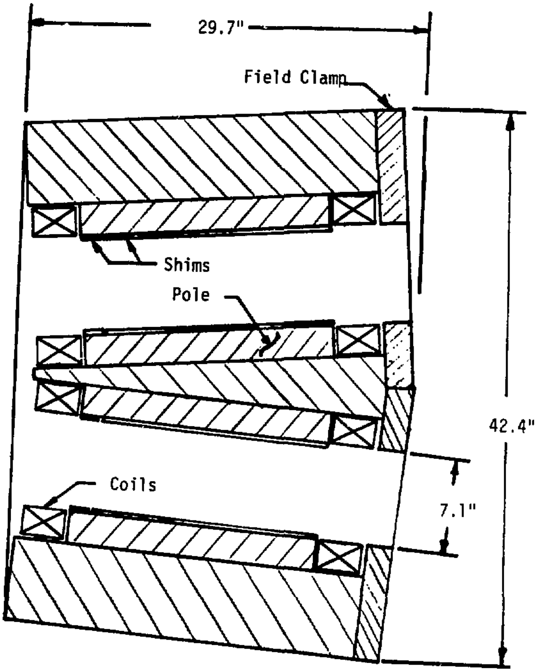

Fig. 4

ELEVATION, CUT-AWAY

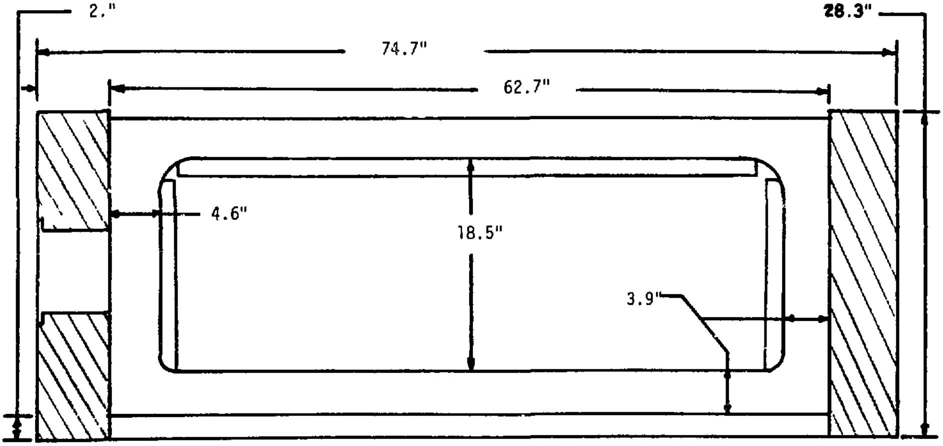

Fig. 5

PLAN VIEW, CUT-AWAY