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THE DESIGN AND CONSTRUCTION OF AN EBT-P DEVELOPMENT COILS*

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Abstract

The ELMO Bumpy Torus Proof-of-Principle (EBT-P) plamsa physics device is a large mirror fusion machine scheduled to begin operation in 1985. It will have 36 superconducting mirror magnets arranged in a bumpy torus on a 4.5 m radius. Presented here are several of the design parameters and supporting design/analysis that have not been published until now due to contractural arrangements between ORNL and the EBT-P subcontractors.

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Introduction

Historical Perspective

The EBT-P magnet development program began in May 1979 to support the construction schedule by taking advantage of the time between the start of the EBT-P program and the selection of the industrial subcontractors to perform some of the magnet development work. Briefly stated, the basic plan was for ORNL to design, build, and test two full-sized development magnets (D1 and D2) and transfer the technical information obtained during the development work to the industrial manufacturer in charge of magnet construction. The magnet manufacturer will then wind a prototype magnet, with basically the same design parameters, which will be tested in a three magnet array simulating the magnetic conditions of EBT-P.

The EBT-P magnet design parameters were agreed to during Phase I of the EBT-P project by ORNL FED staff members, DOE-OFE staff members, and the four competing industrial teams during a series of meetings in the fall of 1979. Naturally, the chosen parameters were the result of a series of compromises among several factors the most significant of which are (1) EBT physics constraints, (2) EBT-P performance goals, (3) acceptable risk levels, and (4) projections of available funding.

Present Status

To date ORNL has fabricated and successfully tested magnets D1 and D2 (for the details of the tests see Ref. 3 which is a companion paper to this one and also located in the proceedings of this conference). ORNL is presently transferring the technical information gleaned from the magnet development work to General Dynamics Convair Division (the industrial manufacturer in charge of magnet construction for EBT-P). The remainder of this report presents some of the more interesting aspects of and novel ideas for the ORNL EBT-P development magnets.

DISCLAIMER

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EBT-P Design Parameters

The 36 mirror magnets are solenoids wound in a U-shaped winding cavity. The winding pack has a length of 21.1 cm with inner and outer radii of 24 and 34 cm, respectively. A schematic of the winding design, to be discussed, is shown in Figure 1. The peak magnetic field at the windings with the magnets assembled as a bumpy torus will be 7.4 T. This magnetic field is achieved with an average current density over the winding pack of 10,000 A/cm^2.

The conductor is a 2.9 x 5.0 mm compacted monolith[4] of copper and NbTi. The measured critical currents are 3600 A at 7.5 T for the high field conductor; and 4300 A at 6 T and 3020 A at 7.5 T for the low field conductor.[3] D1 is wound with both conductor grades. D2 is wound with only low field conductor, due to other concerns. The high field conductor was delivered with a 71% copper fraction and the low field conductor was delivered with a 76% copper fraction. The expected operating current for the magnets is about 1700 A for 7.4 T at the windings when operated in the full EBT-P torus. When tested separately, these magnets require about 6% more current for 7.4 T to make up for the effect of the other magnets in the torus. The total stored energy in the magnet is about 1.5 MJ.

Of course, these magnets can not be cryostable at these fields and average current densities but as stable a design as possible was chosen. Dresner[1] indicate that a conductor with a copper fraction of about 75% and an operating current to critical current ratio of about 50-60% for a pool-boiling cooled magnet is the optimum for this configuration. Pool boiling was chosen because of high expected X-ray heat load on the magnet's windings. Nomex lacing tape (applied in a spiral wrap with 50% coverage) was chosen as an insulation because of our previous experience with this material and because it is easy to use.

EBT-P Development Magnet Construction

The bobbin and closure ring for the first and second development magnet (D1 and D2) were fabricated from 304L stainless steel. A U-shaped bobbin was chosen to minimize the required spatial envelope and to provide an accurately machined winding cavity. The ground wall insulation consisted of a single 0.94 mm thickness of solid G-10 next to the bobbin and then a 1.12 mm thick perforated G-10 sheet next to the windings. This sheet was perforated to allow for improved helium circulation. The corners were insulated with Mylar tape.

A layer winding scheme was not used because of the magnetic field error that would have been created by the distance that separated the leads and a pancake winding was avoided because of the number of splices that would have been required. A hybrid scheme, which we appropriately termed layer-cake, was developed for the winding. With this scheme, a single pie or 1/2 pancake was wound on one side and the remainder of the coil was layer wound, thus permitting both leads to come out close together near the middle of the last layer. Besides minimizing the magnet field error due to current leads, this scheme also had the advantages of (1) not requiring any splices if the conductor was long enough and (2) not requiring any connection to or penetration of the steel bobbin. The conductor was wound with 800 N of tension and strain gauges on the bobbin bore were used to monitor the prestress added by each layer[5]. A justification for the stated superconductor pretension is presented in the next section. A special device spiral-wrapped nomex insulation onto the rectangular superconductor during winding and was geared to give 50% coverage. The sequence of steps used to produce the hybrid winding is shown in Figure 2 and given below:

(1) Mount both bobbin (B) and superconductor (SC) which is on spool #1 (S1) on winding machine (WM). Attach leader (1) and route through tensioner (T). Start leader on spare spool #2 (S2).

(2) Pull a pancake (PC) and 1/2 layer length of superconductor through tensioner and wind on spare spool #2.

(3) Form crossover of the superconductor and firmly attach to bobbin. Apply tension to superconductor and wind pancake and extra conductor.

(4) Remove superconducting spool #1 with the remaining superconductor from winding machine without cutting the superconductor.

(5) Temporarily, wind entire length of superconductor on bobbin. Attach leader to superconductor and route through tensioner to spare spool #2. Remove spool #1.

(6) Wind all of the remaining superconductor on spool #2.

(7) Apply tension and wind superconducting layers on bobbin. The last layer would be an even numbered layer. Wind layer lead to the middle and band.

(8) Unwind the excess conductor from the pancake and then rewind on the last layer to bring the leads together on the center.

The spiral wrap and tension machine required one end of the lead to be threaded through them. A number of the above steps could be eliminated [such as (5) and (6)], with an advanced design that allowed conductor to be inserted from the side with the ends on different spools.

As shown in Figure 1, insulation is required between the panckae and layer wound section and between the last and next to last layers. The insulation design provided a safety factor greater than 2 (including the effects of voltage enhancement at corners) while also allowing for free helium circulation.

Polycarbonate double wedge shaped pieces were used to form joggles and to provide a ramp-up from one layer to the next. Experience has shown the joggles to be easier to wind than a pure helical winding for this size coil.

Splices were required on the first and second coil because the conductor length on a single spool was insufficient for a complete coil. Also, the first coil used two grades of conductor requiring a splice at the end of the high field region. Three potential solders were evaluated experimentally. They were (a) 50 Sn, 50 Pb; (b) 97.5 Pb, 2.5 Ag; (c) 97.5 Pb, 1.5 Ag, 1 Sn. Pull tests on soldered conductor samples were accomplished at room termperature, 80 K and 4.2 K. Both high lead solders (b and c) were significantly stronger at 4.2 K than the 50-50 solder (a). Solder (b) was slightly stronger than (c) and was selected for the high field grade splice. Our results were consistent with the findings given in Ref. 7. A typical splice and ramp is shown in Figure 1.

Since this magnet is wound in a U-shaped bobbin, special care was required to ensure a tight winding pack in the axial direction. Special, angled-face micarta blocks were fabricated for use while winding. The windings were axially compressed by hammering on these blocks. During winding, the spread of the side flanges was measured to determine the effectiveness of this technique.

Copper lead blocks and G-10 pieces were fabricated to allow the layer side and pancake side leads to pull against each other without connection to the bobbin (see Figure 3).

The last layer and G-10 side wall insulation is 19 mm below the radius at which the closure ring will be welded to the side walls of the bobbin. With this separation, the peak insulation and conductor temperatures can be kept below approximately 120°C during the welding operation which General Dynamics Convair Division will perform.

EBT-P Winding Pack Stress Analysis

In this section an application of solenoid stress analysis with gaps is shown as it predicts the radial and tangential stress distributions in the winding pack of the EBT-P development magnets. Due to several external design constraints, chiefly high magnetic field (7.4-T) and conductor current density (11,725-A/cm^2) requirements and small dimensional limitations for bobbin thickness (0.96 cm), a satisfactory design could not be achieved that maintained a compressive interface pressure between the inner turns of the superconducting windings and the outer bobbin surface. Applying more winding preload to overcome this defi- would have exceeded the room temperature design-allowable compressive yield stress of the bobbin. (The design-allowable yield stress was chosen to be two-thirds of the material yield stress.) A simple linear calculation was not sufficient to predict the state of stress in the superconductor when the magnet is fully energized, see Figure 4, since a tensile radial stress exists at the bobbin-insulation-superconductor interface of this well-ventilated magnet design. A nonlinear theory described in Ref.8 was used to predict the stress state in the superconductor when the magnet is fully energized, as shown in Fig. 5.

Notice that the tangential force which was fictitiously permitted to accumulate in the bobbin with the linear calculation is redistributed mainly over the first few turns of the superconductor with the nonlinear calculation. The calculated current for lift-off of the winding from the bobbin is approximately 10% higher than that experimentally measured for a virgin energization after cooldown. Subsequent energizations without warmup produce decreasing changes in strain at lift-off thus indicating more complex mechanical behavior within the magnet's winding pack. An analytical method to predict this behavior is being developed.

EBT-P Magnet Case Stress Analysis

The EBT-P magnet case is 19 mm thick on each piece except the inner bobbin which has a 9.5 mm thickness. An axisymmetric finite element model using PAFEC[3] was developed using approximately 500 4-mode quadrilaterial elements to model the behavior of the model were uniformly chosen to be that of stainless steel (200 GPa). No attempt was made to take into account the conductor stiffness; only the coil case itself was modeled - a conservative and generally accepted engineering practice in magnet design/analysis.

This model simulates the cold mass support system by artifically restraining the center-outside-top node of the outer ring against movement in the axial direction. No restraint was supplied in the radial direction.

Three load cases were defined. The first two were defined as 1.6 MPa side pressure load (due to a hypothetical fault condition) and a 6.8 MPa inner bobbin pressure load (attained from STANSOL calculations early in the conceptual design phase). The third loading case was chosen to be a 1.4 MPa uniform internal pressure acting upon the four inner surfaces of the coil case - thus simulating a quench multiplied by a factor of four (since there is some error involved in accurately calculating this number).

Linear superposition of the three loading cases combines all the loads that we have assumed to occur during a worst case fault condition. The combined loading case is dominated by loading case two and is shown in Figure 6. The deflections have been greatly exaggerated so that they could be visually interpreted on this plot. Also, the shades of darker grey represent areas of progressively larger von Mises stress. This model predicts that design allowable stress (2/3 of the yield stress) will not be exceeded even with the conservatively magnified loads.

Summary

Both development coils have been tested in a large general purpose laboratory dewar. Each coil met or exceeded design specifications. The tests and results will be presented in another paper in this conference.

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