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PROPOSED MAGNET SYSTEM FOR EBT-P*

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Since EBT-P, and other EBT devices, depends on having closed field lines for its successful operation, a very tight tolerance (on the order of 6 parts in 10^4) must be imposed on certain components of the field error. This is a global tolerance that influences the design of each magnet, its leads, the electrical bus, and the relative position of each magnet to its neighbors. ~~To make sure the overall system has the proper field error tolerance, each magnet must be tested before it is put into EBT-P. The test procedures will be determined during the magnet prototype phase.~~ This paper discusses the design, ~~proposed magnet tests,~~ and field error analysis of the ORNL reference design for EBT-P.

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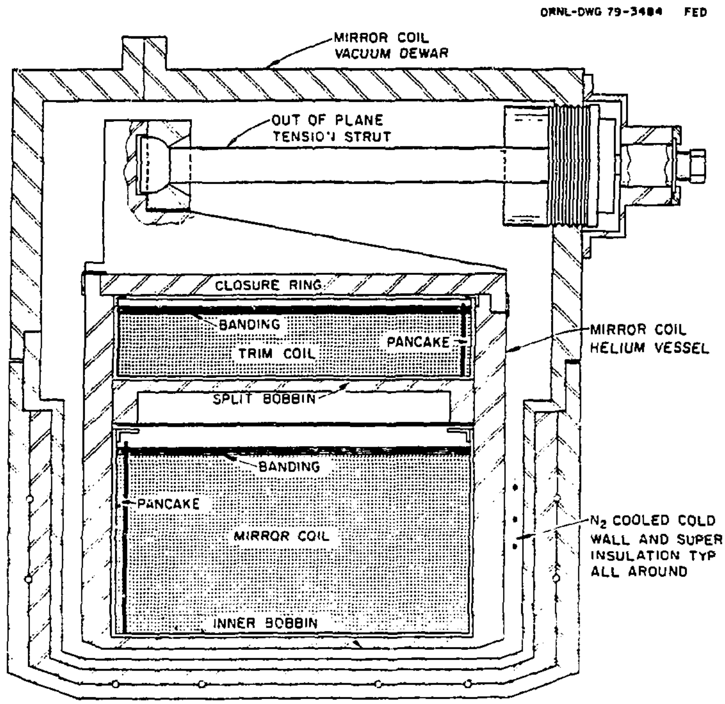
Introduction

A new Elmo Bumpy Torus (EBT) will be constructed and operated in the early 1980's. The reference design for this device, EBT-P, will be selected later this year. As input to the selection process, ORNL and each of four industrial groups are preparing conceptual design reports. This paper discusses the superconducting magnet design, the protection system for the magnets, and the coil positioning system in the ORNL conceptual design report (Ref 1).

EBT-P will be a staged device. The first stage will have a 5.6-m major radius and 36 mirror coils. Each magnet will consist of two concentric superconducting solenoids, one wound inside the other. As shown in Fig. 1, the inner coil is the mirror coil and the outer coil is the trim coil. The general magnet parameters are shown in Table 1. This arrangement of coils will allow the mirror ratio to be changed, in the range of 1.96 to 2.3, by adjusting the relative currents in the two magnets. The size, shape, maximum field, and maximum current densities of the windings were set in a series of tradeoffs between plasma physics requirements and reasonable goals for a moderate risk magnet system.

One important aspect of EBT's is that they are closed field line devices. Ref. 2 reports some of the experimental work done to verify the importance of closed field lines. Many design choices have been made on the basis of keeping the global field errors low. One such decision was to provide for coil position adjustment within the dewar while the coil is cold. Another is the design of the bobbin for the mirror and trim coils.

Fig 1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MIRROR COIL VACUUM DEWAR
OUT OF PLANE TENSION STRUT
CLOSURE RING
BANDING
PANCAKE
TRIM COIL
MIRROR COIL HELIUM VESSEL
SPLIT BOBBIN
BANDING
PANCAKE
MIRROR COIL
N_2 COOLED COLD WALL AND SUPER INSULATION TYP ALL AROUND
INNER BOBBIN

Table 1. Magnet parameters

	Mirror coil	Trim coil
Winding dimensions		
Inner radius (cm)	27.0	49.5
Outer radius (cm)	42.5	54.5
Axial length (cm)	30.0	30.0
Number of turns per coil	2000	700
Current density in winding (A/m^2)		
Mirror ratio (MR) = 2.3	6600	0
MR = 1.96	5000	6700
Operating current (A)		
MR = 2.3	1535	0
MR = 1.96	1163	1568
Peak operating field (T)	8	2
Winding type[a]	Hybrid	Hybrid
Cooling type	Pool boiling	Pool boiling
Conductor size[b] (mm)	2.9 x 5.0	2.9 x 5.0
Conductor material	NbTi	NbTi
Number of grades	2	1
Insulation turn to turn	50% covered Barber pole wrap 0.5-mm thick	50% covered Barber pole wrap 0.5-mm thick
Minimum copper:superconductor[c]	3	To be determined
Critical current (all grades) (A)	2800	2800
Stored energy (total all magnets) (MJ)		
MR = 2.3	109	
MR = 1.96	152	

[a] A hybrid winding is a particular combination of pancake and layer winding; see text for explanation.

[b] Because of dimensional tolerance and strength requirements, a cable or a braid will not be used.

[c] The copper:superconductor ratio will change from one grade of conductor to another. The final ratio will be determined by the conductor manufacturer after the other conductor parameters are met.

Coil Design

The winding scheme for the mirror coils must be chosen carefully to keep the field errors low. These errors are introduced by crossovers, by layer-to-layer transitions in the magnet, and by leads. The largest potential error is the leads as they leave the winding. The choice of the winding scheme strongly influences the lead placement. An inappropriate layer winding scheme would feed the conductor on to the bobbin through a hole in a side plate and then after the coil's layers are wound the other lead will be on the outside diameter. The bad feature of this scheme is that there is an uncompensated current lead the length of the coil build. It is possible to design a layer wound coil that eliminates this problem, but it requires conductor joints at one end of the magnet. One can also make a design of an inappropriate pancake-wound coil with uncompensated leads on each end of the coil. Pancake-wound coils for this application have another disadvantage. If the conductor is graded, there must be two joints in each pancake to make the change of grade and two more joints to connect the pancakes electrically. All joints take considerable time to make, thus increasing the overall winding cost. But as in the layer-wound case, proper designs of pancake-wound coils are also possible, e.g., the mirror magnets for EBT-S.

A hybrid winding scheme has been chosen for the EBT-P coils. Basically, this design consists of a layer wound coil with a ~~pie (one-half of a~~ pancake) wound on one end to bring the conductor next to the bobbin to the outside diameter as a lead. There will be an even number of layers and the same number of ~~shims~~ turns as layers in the pie so that the two leads end up on the outside diameter on the same end of the coil. The leads can then be brought out close together for good field error compensation. The lead-to-lead spacing will be set to standoff ~~by the~~ he~~lium breakdown~~ the voltages developed during a dump.

In the inner coil there will be two grades of conductor. A conductor with a 3:1 Cu:SC ratio will be used in the high field regions. A conductor with the same dimensions and a higher copper to superconductor ratio ~~less superconductor~~ will be used in the low field regions to help reduce costs. The hybrid scheme requires only one joint between the two conductor grades. The actual number of joints in the magnet depends on a number of things, such as the maximum length of conductor that can be manufactured, but in any case there should be fewer joints than in a pancake-wound coil.

The trim coil is not wound directly onto the inner coil's turns (see Fig. 1) because structural banding is needed on the inner magnet to keep the turns nearest the bobbin pressed against the bobbin insulation when the coil is fully energized. It is not practical to wind the outer coil on the banding of the inner coil. Therefore, the outer coil will have its own bobbin with space left between the outer bobbin and the outside diameter of the inner coil to serve as a small helium plenum and lead space.

The alignment of the inner and outer coils is important because the field error has to be small when one or both coils are used. The proper alignment of the coil axis is the best way to ensure this. At first thought it seems reasonable to put each coil on its own bobbin and then attach the two bobbins, but this is difficult when one also designs for the possible out-of-plane fault loads. The bobbin can be made self-aligning by welding circular end plates large enough to accommodate both coils onto a cylinder. The cylinder will be machined to the proper dimensions, and then be used as the bobbin for the inner coil. The bobbin for the outer coil is made in two C-shaped cylinders that will be aligned with respect to the inner bobbin with pins and bolted to the end plates. Once the inner coil is wound, and the leads are brought to the outside diameter of the bobbin, the outer coil bobbin will then be put into place. Covers will be seal-welded over the countersunk pins and bolts. The bobbin insulation for the outer coil will be put in place, and the outer coil will be wound. The leads will be put in position and the outer cover plates bolted onto the side plates and seal-welded.

The field error due to one perfectly positioned coil is $\sim 10^{-5}$. The coil alignment procedure has not been worked out in sufficient detail yet to discuss here, so there is no estimate for this error component. The error field due to the bus work is on the order of 10^{-6}. It is low because the current is fed back on itself so the error field is low.

The turn-to-turn insulation is a 50% covering of the conductor surface with a barber-pole wrap of 0.5-mm-thick Nomex lacing tape. The voltage per turn in the mirror coil during a system dump is $\sim$0.3 V; the maximum voltage between adjacent turns is then $\sim$30 V.

The insulation between the bobbin and the windings will be slotted G-10 sheets covered with a solid G-10 sheet to electrically insulate the winding cavity from the bobbin. The helium circulation next to the bobbin is designed to remove the x-ray heat deposited in the bobbin and to remove the heat conducted through the support struts. During steady-state operation, the helium in the windings will remove the x-ray heat in the windings. Helium circulation to the mirror coil is provided by slots machined on the ends of the trim coil's bobbin and by the slotted insulation between the trim coil and the side plates. There will be enough slots to vent the helium in the inner coil during a quench without an excessive pressure buildup.

All of the mirror coils will be operated in series from one power supply and all of the trim coils will be operated from another power supply. Separate power supplies for these two systems is needed so that the mirror ratio can be varied. But the chief advantage is that it will force the current in each mirror (trim) coil to be nearly the same. (There is a very small effect of the dump resistor always being in parallel with the coil.)

Coil Positioning

Since EBT-P is a closed field line device the coils must be accurately placed to prevent field errors. In EBT-S the water-cooled copper coil's position was determined with a transit, but in EBT-P only the dewars can be aligned with such a simple method.

In EBT-P, the final coil adjustment will be made with the coils in the dewars and cold. The coil will be supported on a system of struts with ball joint fittings to the coil case and the dewar case (Fig. 1). Coil position adjustments will be made by turning threaded members mounted on the dewar case. The threaded member on the dewar case shown in Fig. 1 is simplified to make the figure easier to understand. In fact it will also be a ball joint system like the one shown in Fig. 2. The ball joint in Fig. 2 is actually the warm end ball joint that carries the centering force load to a post ;mounted in the floor. There will be three sets of coil supports: one set for gravity loads; one set for the centering force; and one set for the out-of-plane loads. The out-of-plane loads can only occur in the event of a quench and a particular failure in the protection system.

The maximum centering force is 4.89×10^5 N (1.1×10^5 lb) and the maximum out-of-plane force is 1.16×10^6 N (2.6×10^5 lb). The out-of-plane forces can only occur if the coil system quenches and there is a simultaneous failure in the protection system.

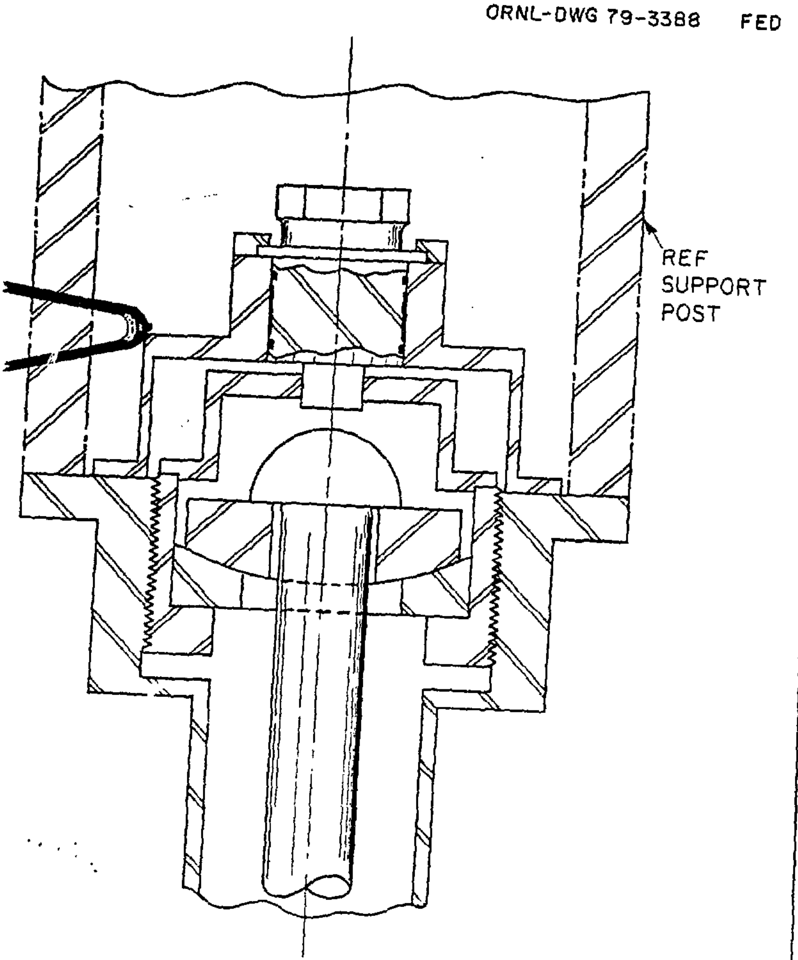

Fig 2

Protection System

The purpose of the protection system is to ensure the integrity of the magnet in case of a quench and other fault events. For the operating current and conductor cross section/composition, the energy stored in the magnet needs to be removed in a fairly short time (~10 sec) to prevent excessive temperature use. During this amount of time, it is not possible to absorb the stored energy (4.3 MJ/magnet) internally because the normal zone propagates slowly (~2 m/sec), switching is required to dump the energy externally and keep the coil-to-ground voltage low.

The number of switches required depends on the acceptable level of transient voltage to ground. For the pool-boiling magnet proposed, a 600-V limit is used. This implies that each mirror coil has its own dump resistor and that each pair of trim coils has a dump resistor.

Details of the protection circuit are shown in Fig. 3. Characteristics of the protection system are shown in Table 2. There will be two of these circuits, one for the mirror coils (36 sections) and one for the trim coils (18 sections). During normal operation all mirror (trim) coils are connected in series to minimize the field error. There will be a little current in the dump resistor even during normal operation because they are in parallel with the bus work to the vapor-cooled leads and the vapor-cooled leads. The error field produced is small enough to be acceptable.

If a quench is detected in any section, all S_B switches are closed first, then all of the S switches are opened to discharge the coils; each section through its own dump resistor. The power supplies are protected by the diodes from transient high voltage during dump. The

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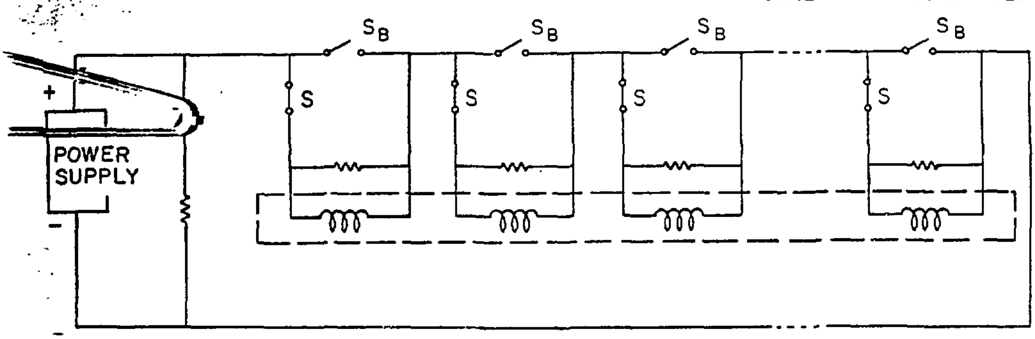


Fig 3

Table 2. Protection characteristics

	Inner coils		Outer coils
Inductances			
Self (H)	92.1		26.8
Mutual (H)		31.1	
Dump resistor/section (Ω)	0.375		0.36
Number of coils per section	1		2
Peak voltage (V)			
MR = 2.3	576		200
MR = 1.96	436		564
Percent of stored energy dumped in the resistors			
MR = 2.3	85.6%		14.4%
MR = 1.96	63.2%		36.8%

S_B switch is needed to avoid high transient voltage to ground as some S switches may open before others. Since S_B switch merely provides current an alternative path, it can be compact with low duty rating. Additional S switches may be used to improve reliability and minimize ground loop problems. Although this needs to be trade-off with available space and cost factor, the power supplies and magnets are floated to aid ground fault detection.

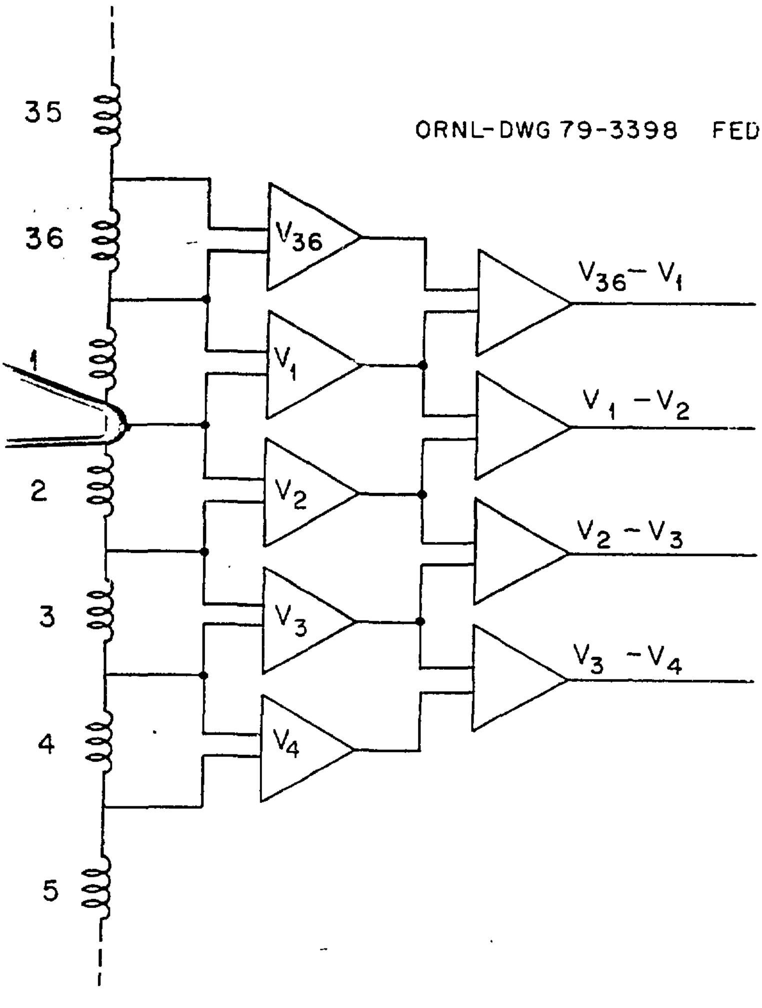
The same scheme may be used for 48-coil systems because the protection characteristic is determined by energy stored in the coil.

A scheme similar to the present one has been proposed for ISABELLE ring magnets.[2,3]

Voltage differences across each magnet (Fig. 4) are monitored by voltage taps and differential amplifiers. Because coils are identical and carry the same current during normal operation, the voltage drop across each coil should be the same. The voltage between neighboring coils is compared by a second stage of differential amplifiers. Deviation from zero indicates quench or shorts.

If V_1 has quenched, it will show up in both channel V_1-V_2 and channel $V_{36}-V_1$. Hence, the particular magnet that has problems can be located.

A similar scheme has been proposed for short detection in TFTR toroidal field magnets.[4,5]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35
36
1
2
3
4
5
V36
V1
V2
V3
V4
V36 − V1
V1 − V2
V2 − V3
V3 − V4

Fig 4

Conclusion

There is a good design for EBT-P because it has a cooled bobbin, ventilated winding scheme ,can tolerate large x-ray heat loads, low field errors due to winding scheme, and the coil position can be changed while it is cold. The protection system is adopted from a proven system.

References

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3. W. B. Sampson, *Proc. Magnet Technology*, MT-6, p. 460 (1977).

4. K. E. Robbins, W. B. Sampson, and M. G. Thomas, *IEEE Trans. Nucl. Sci.*, NS-24, 3, p. 1318 (1977).

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Figure [illegible]. Cross section through coil, dewar [illegible] shield. One of eight tension struts that carry the possible out of plane loads and allow coil position adjustment is also shown. The strut's connection to the dewar wall is simplified.

Figure 2. Detail of strut connection to a room temperature wall. This also shows the connection to a post that will carry the centering force.

Figure 3. Protection circuit schematic

Figure 4. Quench detection circuit.