CONF-821108--33

CONF-821108--33

DE84 003373

ERROR FIELD GENERATION OF SOLENOID MAGNETS

J.L. Saunders

General Dynamics Convair Division
P.O. 80847, San Diego, CA 92138
MZ 16-1072

ABSTRACT

Many applications for large solenoids and solenoidal arrays depend on the high precision of the axial field profile. In cases where requirements of $\Delta B/B$ for nonaxial fields are on the order of 10^{-4}, the actual winding techniques of the solenoid need to be considered. Whereas an ideal solenoid consisting of current loops would generate no radial fields along the axis, in reality, the actual current-carrying conductors must follow spiral or helical paths. A straightforward method for determining the radial error fields generated by coils wound with actual techniques employed in magnet fabrication has been developed. The method devised uses a computer code which models a magnet by sending a single, current-carrying filament along the same path taken by the conductor during coil winding. Helical and spiral paths are simulated using small, straight-line current segments. This technique, whose results are presented in this paper, was used to predict radial field errors for the Elmo Bumpy Torus-Proof of Principle magnet. These results include effects due to various winding methods, not only spiral/helical and layer-to-layer transitions, but also the effects caused by worst-case tolerance conditions both from the conductor and the winding form (bobbin). Contributions made by extraneous circuitry (e.g., overhead buswork and incoming leads) are also mentioned.

INTRODUCTION

One of the requirements for the design of the Elmo Bumpy Torus-Proof of Principle machine is that the cumulative error field (B_r/B_0), with all of the coils energized, will not exceed 1×10^{-4} when averaged around the torus along the minor axis. Figure 1 illustrates the EBT-P machine at the time this work was performed.

A magnetic field of 4.8 tesla on axis at the coil throat is provided by 36 solenoids in a toroidal array. With the given criteria, this corresponds to a maximum error field of 4.8 gauss. Allowing for possible magnet misalignment, extraneous system circuitry, etc., the maximum error field that could be tolerated by the system due to the coils themselves was determined to be on the order of two gauss.

The question, then, was whether or not the winding technique could be responsible for generating error fields on this order and, if so, what method of winding would generate the minimum error field. It was decided that a computer simulation of various winding techniques would yield the most straightforward and accurate conclusion.

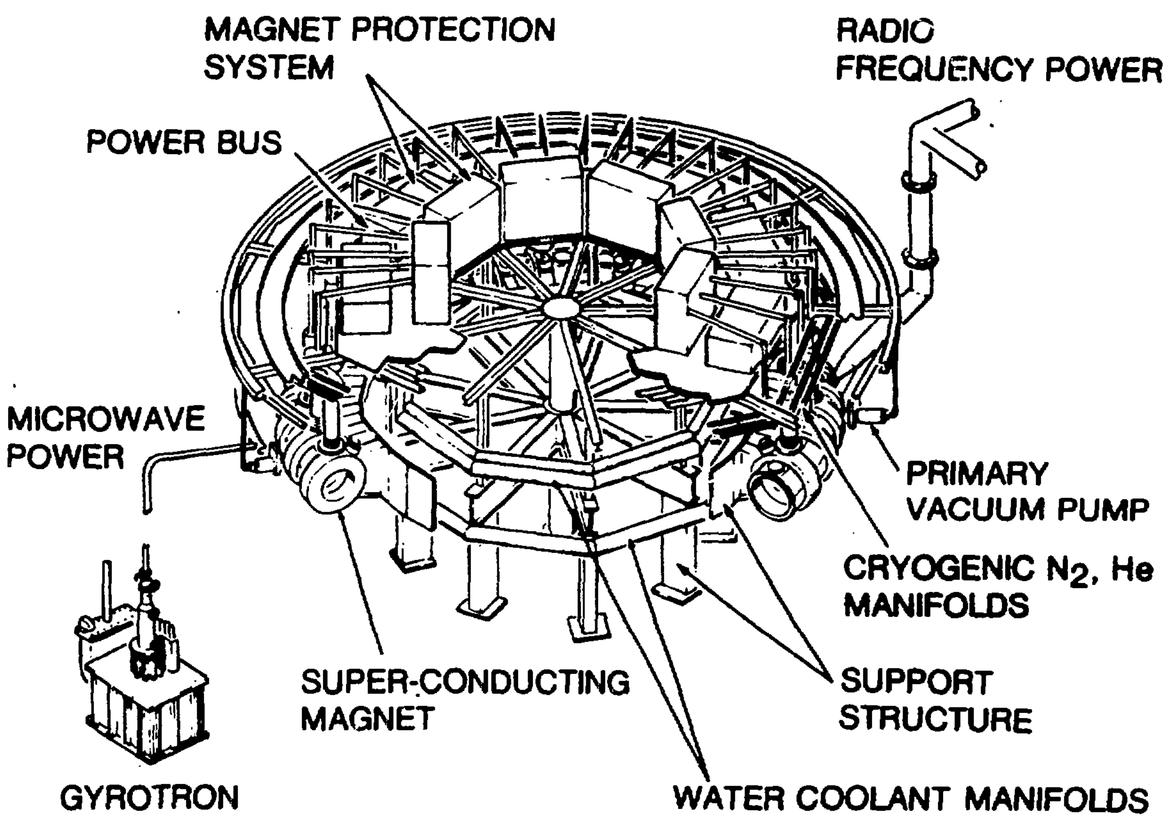

Figure 1. Elmo Bumpy Torus-Proof of Principle experiment.

THEORETICAL CALCULATIONS

Of course, the magnetic field on axis, generated by solenoids consisting of current loops, can be calculated very simply by applying the Biot Savart law,

$$\vec{dB} = \frac{\mu_o I}{4\pi R^3}(\vec{dL} \times \vec{R}) \qquad (1)$$

around the loops and summing for the total field.

The complication arises when the current-carrying conductor follows noncircular paths. A computer program was developed to accumulate the field, at any point, created by a multitude of straight filaments representing the actual coil-winding conductors. This computer code uses a method of computation developed for the MAGIC program at General Dynamics Convair Division.[1]

Computer models were then developed to simulate the winding of solenoidal coils. Two possible winding techniques were devised and set up for computation with the code. A model was also developed to simulate the field contributions made by the overhead buswork system and the incoming leads.

COMPUTER MODELS

The first coil-winding case to be considered deals with the field deviation which would be generated by winding the coils in a helical fashion. The second case looks at a coil that is wound by what is referred to as the "joggled" method, which will be discussed later. In comparing the two winding methods, joggle and helix, only the error fields due to the coils themselves will be discussed (i.e., excluding the leads and overhead buswork).

In each case, the magnetic model is divided into five sections (Figure 2) with the following characteristics:

- Half of the 32nd layer from the center to the left flange (helical or joggled)
- Pancake spiral from the 32nd to the first layer (actually consisting of approximately 34 spiral turns because of the two-conductor-width insulation between the 31st and 32nd layers)
- Main conductor pack consisting of 31 layers with approximately 39 turns/layer (helical or joggled)

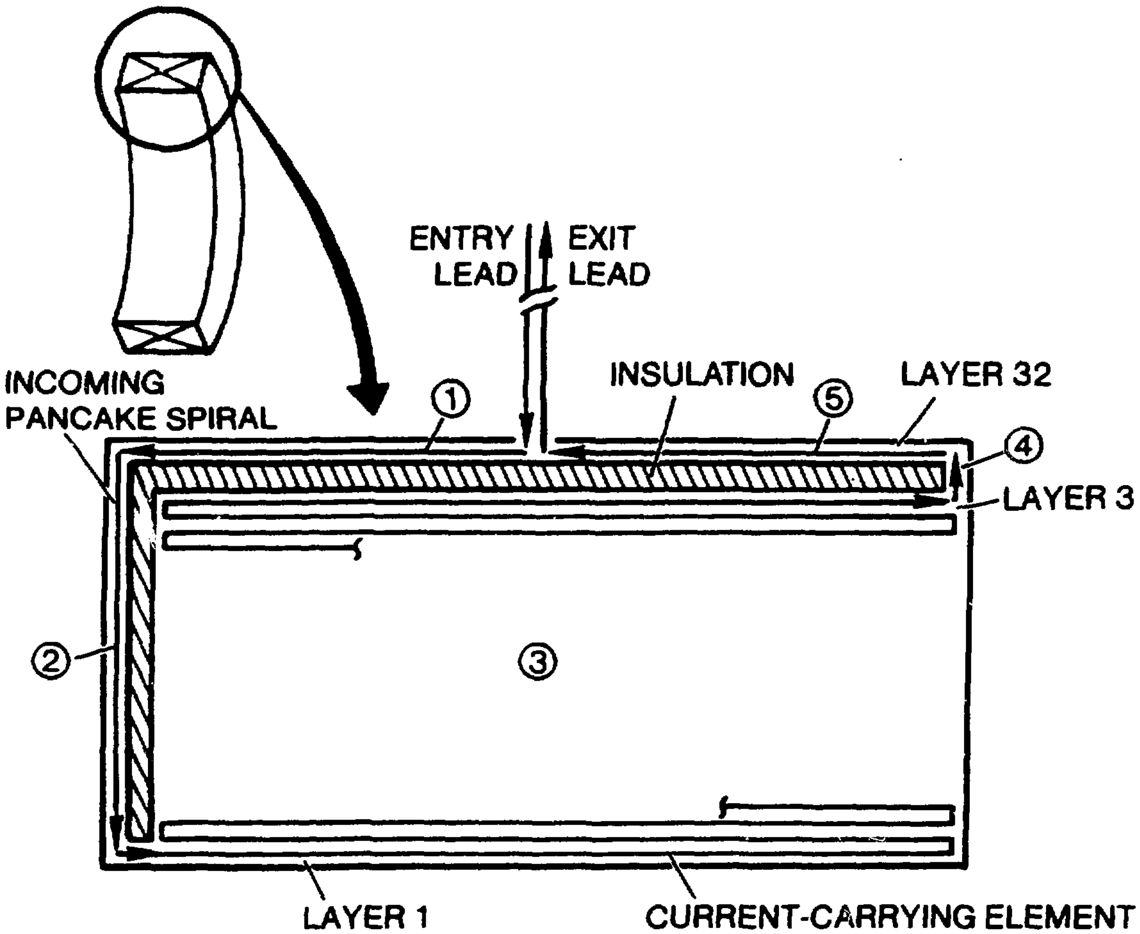

Figure 2. Coil pack winding model.

- Pancake spiral which bypasses the insulation at the right flange
- Half of the 32nd layer from the right-hand flange to the center

The field was calculated at several points along the coil axis and then averaged to get the approximate mean radial error field.

In the first model, the current element helically progresses from the insulation on the left-hand side to the flange on the right-hand side (as seen in Figure 2) for the main section of the coil pack. Each turn of the helix is divided into 360 straight-line segments.

Each time a left- or right-hand boundary dimension is met, a layer transition automatically occurs. During a layer transition, the current element travels a path tangent to the helix at the point where it contacted the boundary. This tangent takes the element to the next layer, along the boundary, and then begins its helical traverse back to the other side of the coil.

For the model simulating the "joggle-wound" coil, the field is calculated due to small (360/loop) straight-line current segments which incrementally follow the path of the joggled loop.

The angular position where the current element stops following the circular loop to "joggle" to the next turn is determined by the dimensions of the wedge (Figure 3), which are input variables to the program. An additional input variable is used to determine the angular precession of these joggles as the winding progresses from turn to turn along the layer (Figure 4).

At each flange, the current element follows a circular path along the flange, ramps up to the next layer, and continues the circular path along the flange until it meets a diametrically placed wedge and joggles to the next turn to complete the new layer.

The overhead buswork was also modeled to determine its contribution to the error field. The buswork consists of a system of current-carrying segments which repeat every 40 degrees for a total of nine sections (refer to Figure 5). Only those leads which carry current during normal operation were considered; that is, all power supply leads and dump circuitry were ignored. This buswork was then

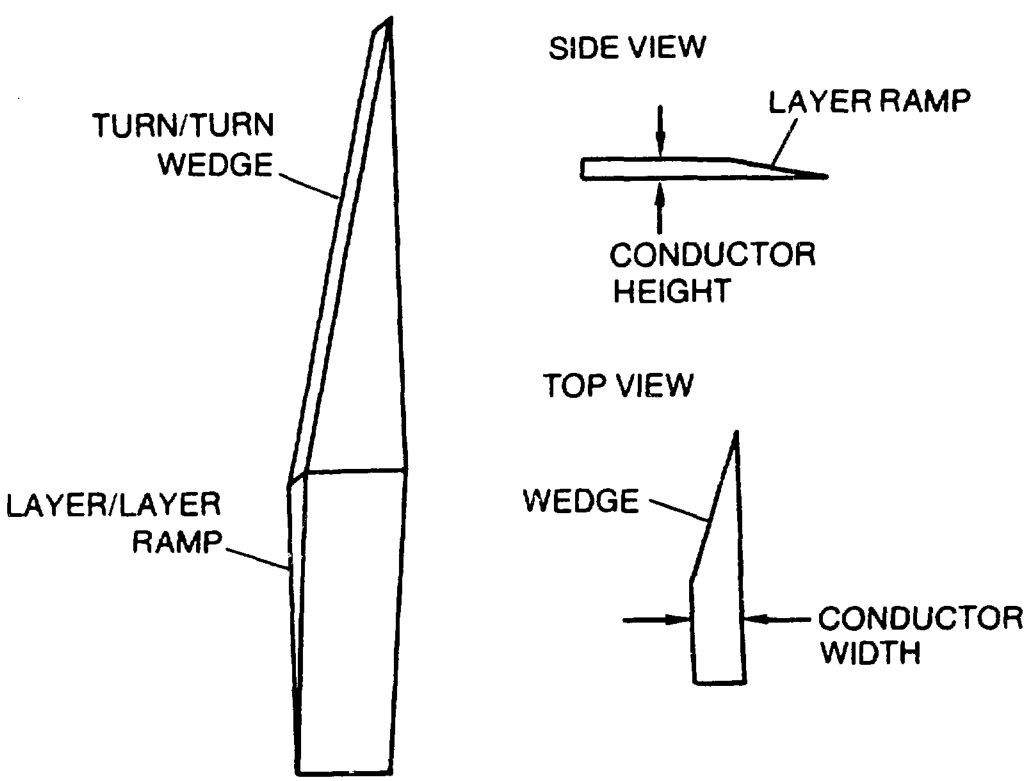

Figure 3. Wedge/ramp for joggled winding method.

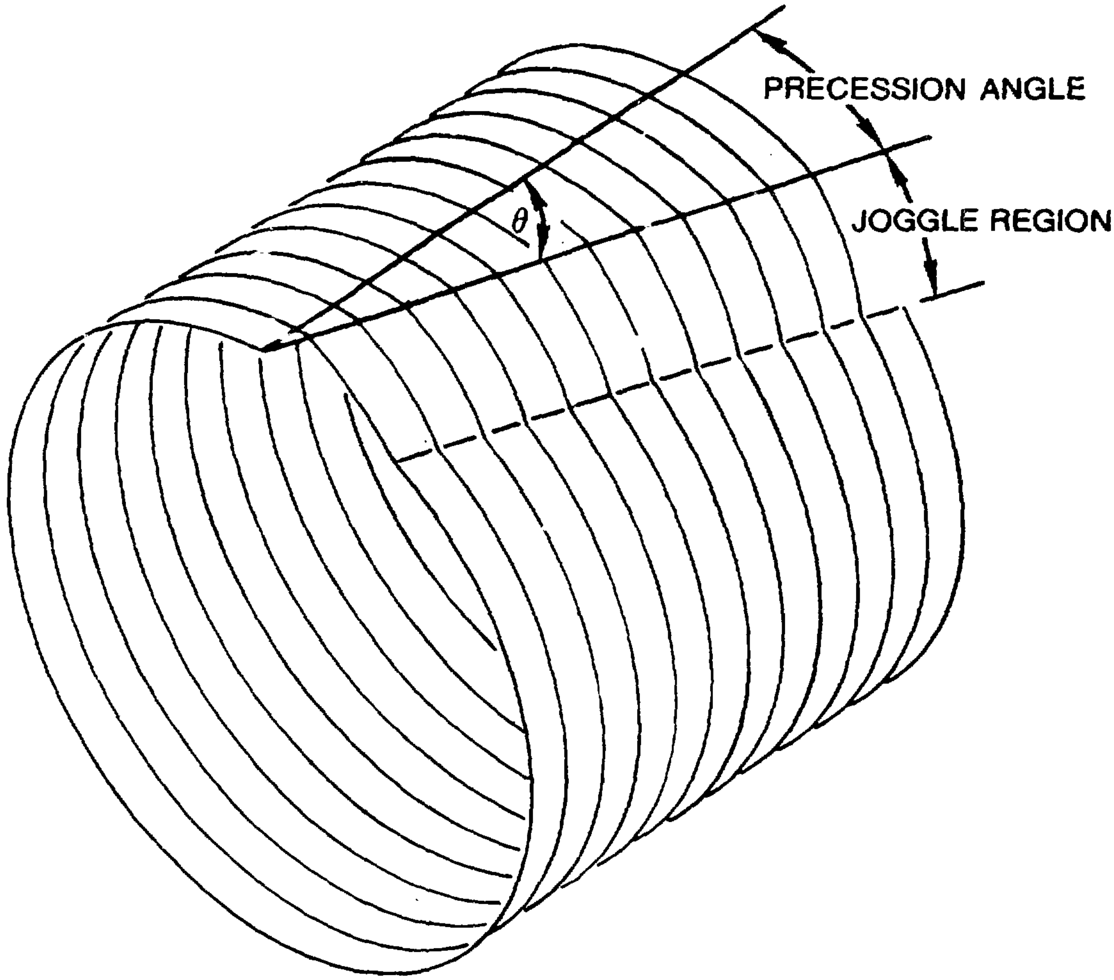

Figure 4. Joggle precesses angularly as winding progresses from turn to turn (θ = angle of precession).

simulated as a network of straight-line segments, and the error field contributions were calculated in the bore of a coil (coil throat) and at the midplane between two coils to get a worst-case approximation (Figure 6).

RESULTS

Computer simulation of both of the chosen winding techniques disclosed that the error field generated by a helically wound coil, excluding leads, overhead buswork and all other extraneous circuitry, would be less than one gauss. The same method determined the error field generated by the joggle-wound case to be greater than three gauss.

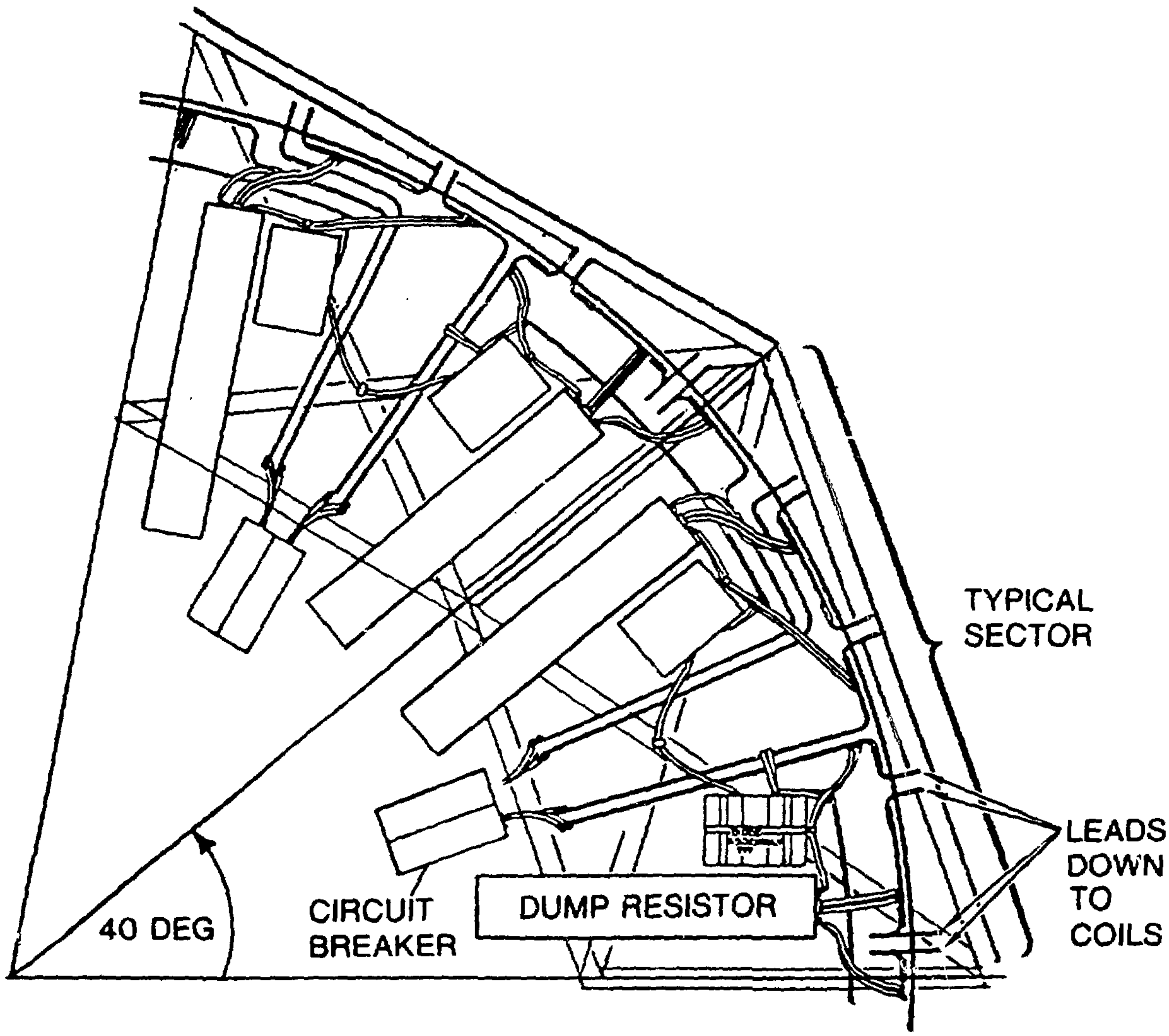

Figure 5. Overhead bus system consists of nine symmetric sectors (40 degrees per sector).

The variance of radial fields between the two methods of winding, joggled versus helical, can also be seen intuitively. To perceive this, first observe the field generated by helical turns of current. Each successive layer places helical turns directly above the preceding layer with the radial field components in the opposite direction. This tends to cancel the generated radial fields.

Now consider the field generated by a joggled turn that is basically, an uncompleted circular loop. There is no radial field produced by the circular portion of this loop since all of the segments are perpendicular to the two axes defining the radial direction. All of the radial field is generated by the relatively short section of arc which goes from one circular turn to the next. There are no antipodal portions in this

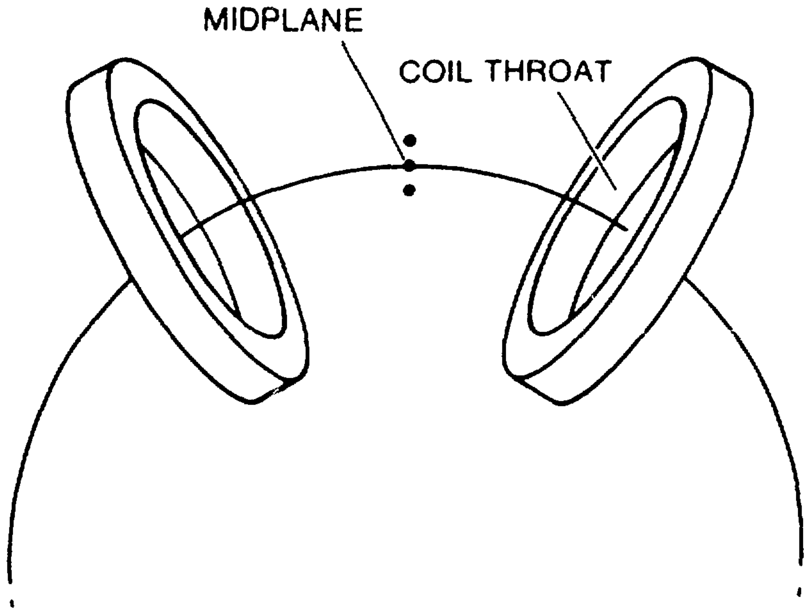

Figure 6. Error field contributions due to the overhead buswork were calculated at points in the coil throat and the midpoint between two coils.

turn to cancel the radial field. In addition, depending on the angular precession of these joggles as the turns progress along a layer, the radial fields are inclined to accumulate rather than cancel. In the next layer, the radial fields tend to cancel somewhat because the joggles are going in the opposite direction; however, since these joggles are not directly above those in the previous layer, neither axially nor circumferentially, this cancellation is minimal.

This same technique was used to determine the effects due to certain types of manufacturing tolerance errors on the conductor and bobbin sizes. For example, worst-case tolerance effects were determined to simulate the largest winding area and smallest conductor sizes possible. This case was modeled using the helical winding technique and resulted in a change in the total magnetic field magnitude of approximately 1.4% and a change in the radial field on axis at the center of the coil throat of approximately 0.2G.

Since this method of modeling magnetic fields results in a discretization of the coil loops, the computational error was calculated to determine the degree of accuracy. This was performed by simply calculating the field due to a circular turn of current and comparing it to the field produced by a turn consisting of 360 straight-line segments. The field deviation was on the order of 10^{-5} and was determined to be small enough to give fairly accurate results.

The calculations made concerning the buswork system above the torus indicate that the worst-case radial field contributions would be approximately one gauss located in the coil throat at the top of the toroidal array. The beauty of this type of computation, where the current-carrying conductors are discretized into finite elements, is that it enables the modeling of any geometrical configuration. In the case of EBT-P, this technique was also used to determine field values at various locations due to the incoming vapor-cooled leads.

ACKNOWLEDGMENT

The author expresses her appreciation to D.W. Lieurance, G.D. Magnuson, and to W.E. Toffolo for their useful discussions and input to this project.

REFERENCES

1. R.W. Baldi and D.W. Lieurance, "Magnetic Integrations Calculations Computer Program," CASD-ERR-77-051, December 1977.

ERROR FIELD GENERATION OF SOLENOID MAGNETS

J.L. Saunders

General Dynamics Convair Division
P.O. 80847, San Diego, CA 92138
MZ 16-1072

ABSTRACT

Many applications for large solenoids and solenoidal arrays depend on the high precision of the axial field profile. In cases where requirements of $\Delta B/B$ for nonaxial fields are on the order of 10^{-4}, the actual winding techniques of the solenoid need to be considered. Whereas an ideal solenoid consisting of current loops would generate no radial fields along the axis, in reality, the actual current-carrying conductors must follow spiral or helical paths. A straightforward method for determining the radial error fields generated by coils wound with actual techniques employed in magnet fabrication has been developed. The method devised uses a computer code which models a magnet by sending a single, current-carrying filament along the same path taken by the conductor during coil winding. Helical and spiral paths are simulated using small, straight-line current segments. This technique, whose results are presented in this paper, was used to predict radial field errors for the Elmo Bumpy Torus-Proof of Principle magnet. These results include effects due to various winding methods, not only spiral/helical and layer-to-layer transitions, but also the effects caused by worst-case tolerance conditions both from the conductor and the winding form (bobbin). Contributions made by extraneous circuitry (e.g., overhead buswork and incoming leads) are also mentioned.

INTRODUCTION

One of the requirements for the design of the Elmo Bumpy Torus-Proof of Principle machine is that the cumulative error field (B_r/B_o), with all of the coils energized, will not exceed 1×10^{-4} when averaged around the torus along the minor axis. Figure 1 illustrates the EBT-P machine at the time this work was performed.

A magnetic field of 4.8 tesla on axis at the coil throat is provided by 36 solenoids in a toroidal array. With the given criteria, this corresponds to a maximum error field of 4.8 gauss. Allowing for possible magnet misalignment, extraneous system circuitry, etc., the maximum error field that could be tolerated by the system due to the coils themselves was determined to be on the order of two gauss.

The question, then, was whether or not the winding technique could be responsible for generating error fields on this order and, if so, what method of winding would generate the minimum error field. It was decided that a computer simulation of various winding techniques would yield the most straightforward and accurate conclusion.

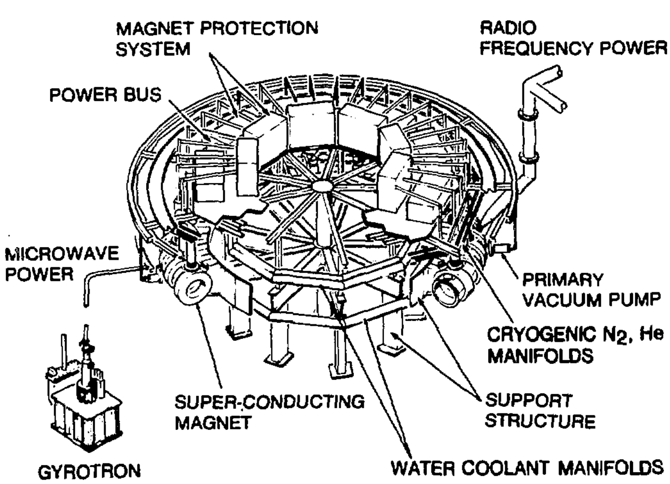

Figure 1. Elmo Bumpy Torus-Proof of Principle experiment.

THEORETICAL CALCULATIONS

Of course, the magnetic field on axis, generated by solenoids consisting of current loops, can be calculated very simply by applying the Biot Savart law,

$$\vec{dB} = \frac{\mu_o I}{4\pi R^3} (\vec{dL} \times \vec{R}) \tag{1}$$

around the loops and summing for the total field.

The complication arises when the current-carrying conductor follows noncircular paths. A computer program was developed to accumulate the field, at any point, created by a multitude of straight filaments representing the actual coil-winding conductors. This computer code uses a method of computation developed for the MAGIC program at General Dynamics Convair Division.[1]

Computer models were then developed to simulate the winding of solenoidal coils. Two possible winding techniques were devised and set up for computation with the code. A model was also developed to simulate the field contributions made by the overhead buswork system and the incoming leads.

COMPUTER MODELS

The first coil-winding case to be considered deals with the field deviation which would be generated by winding the coils in a helical fashion. The second case looks at a coil that is wound by what is referred to as the "joggled" method, which will be discussed later. In comparing the two winding methods, joggle and helix, only the error fields due to the coils themselves will be discussed (i.e., excluding the leads and overhead buswork).

In each case, the magnetic model is divided into five sections (Figure 2) with the following characteristics:

- Half of the 32nd layer from the center to the left flange (helical or joggled)
- Pancake spiral from the 32nd to the first layer (actually consisting of approximately 34 spiral turns because of the two-conductor-width insulation between the 31st and 32nd layers)

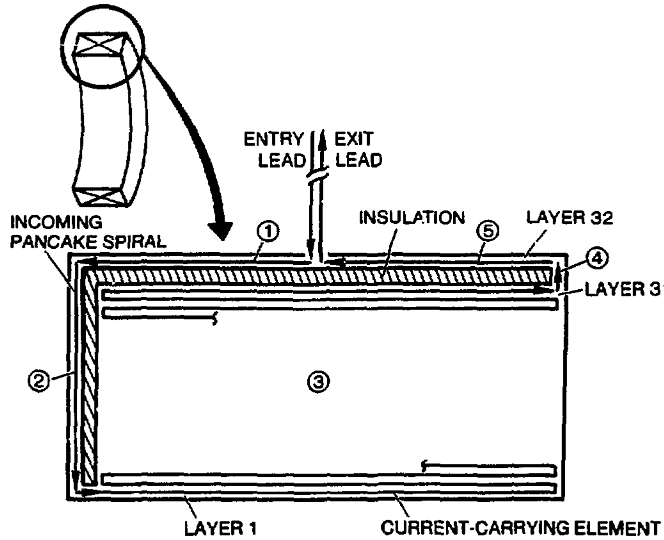

Figure 2. Coil pack winding model.

- Main conductor pack consisting of 31 layers with approximately 39 turns/layer (helical or joggled)
- Pancake spiral which bypasses the insulation at the right flange
- Half of the 32nd layer from the right-hand flange to the center

The field was calculated at several points along the coil axis and then averaged to get the approximate mean radial error field.

In the first model, the current element helically progresses from the insulation on the left-hand side to the flange on the right-hand side (as seen in Figure 2) for the main section of the coil pack. Each turn of the helix is divided into 360 straight-line segments.

Each time a left- or right-hand boundary dimension is met, a layer transition automatically occurs. During a layer transition, the current element travels a path tangent to the helix at the point where it contacted the boundary. This tangent takes the element to the next layer, along the boundary, and then begins its helical traverse back to the other side of the coil.

For the model simulating the "joggle-wound" coil, the field is calculated due to small (360/loop) straight-line current segments which incrementally follow the path of the joggled loop.

The angular position where the current element stops following the circular loop to "joggle" to the next turn is determined by the dimensions of the wedge (Figure 3), which are input variables to the program. An additional input variable is used to determine the angular precession of these joggles as the winding progresses from turn to turn along the layer (Figure 4).

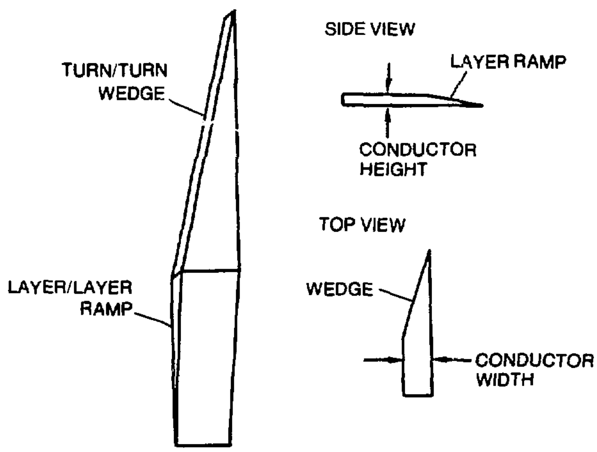

Figure 3. Wedge/ramp for joggled winding method.

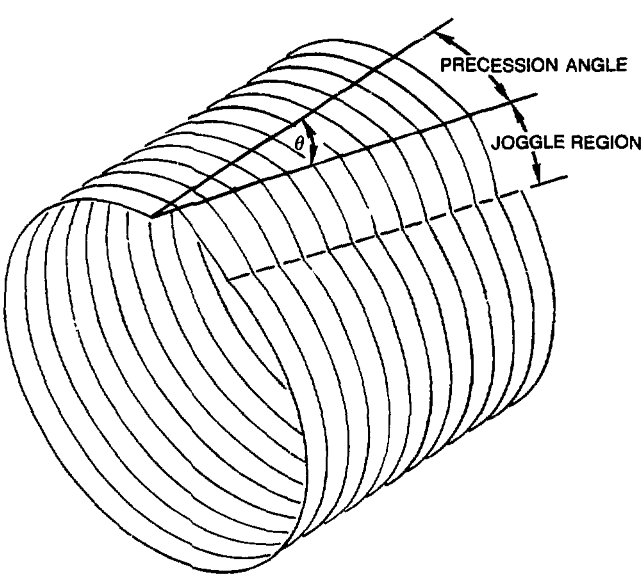

Figure 4. Joggle precesses angularly as winding progresses from turn to turn (θ = angle of precession).

At each flange, the current element follows a circular path along the flange, ramps up to the next layer, and continues the circular path along the flange until it meets a diametrically placed wedge and joggles to the next turn to complete the new layer.

The overhead buswork was also modeled to determine its contribution to the error field. The buswork consists of a system of current-carrying segments which repeat every 40 degrees for a total of nine sections (refer to Figure 5). Only those leads which carry current during normal operation were considered; that is, all power supply leads and dump circuitry were ignored. This buswork was then simulated as a network of straight-line segments, and the error field contributions were calculated in the bore of a coil (coil throat) and at the midplane between two coils to get a worst-case approximation (Figure 6).

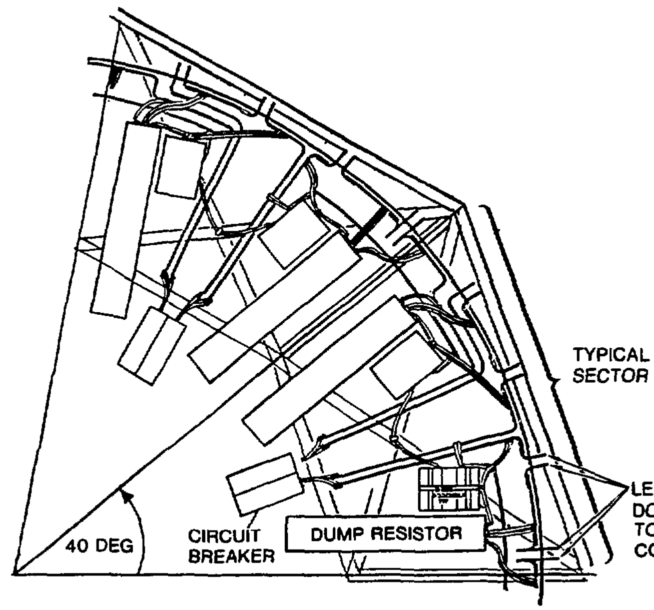

Figure 5. Overhead bus system consists of nine symmetric sectors (40 degrees per sector).

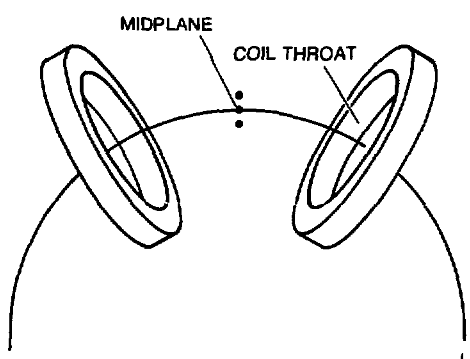

Figure 6. Error field contributions due to the overhead buswork were calculated at points in the coil throat and the midpoint between two coils.

RESULTS

Computer simulation of both of the chosen winding techniques disclosed that the error field generated by a helically wound coil, excluding leads, overheau buswork and all other extraneous circuitry, would be less than one gauss. The same method determined the error field generated by the joggle-wound case to be greater than three gauss.

The variance of radial fields between the two methods of winding, joggled versus helical, can also be seen intuitively. To perceive this, first observe the field generated by helical turns of current. Each successive layer places helical turns directly above the preceding layer with the radial field components in the opposite direction. This tends to cancel the generated radial fields.

Now consider the field generated by a joggled turn that is basically, an uncompleted circular loop. There is no radial field produced by the circular portion of this loop since all of the segments are perpendicular to the two axes defining the radial direction. All of the radial field is generated by the relatively short section of arc which goes from one circular turn to the next. There are no antipodal portions in this turn to cancel the radial field. In addition, depending on the angular precession of these joggles as the turns progress along a layer, the radial fields are inclined to accumulate rather than cancel. In the next layer, the radial fields tend to cancel somewhat because the joggles are going in the opposite direction; however, since these joggles are not directly above those in the previous layer, neither axially nor circumferentially, this cancellation is minimal.

This same technique was used to determine the effects due to certain types of manufacturing tolerance errors on the conductor and bobbin sizes. For example, worst-case tolerance effects were determined to simulate the largest winding area and smallest conductor sizes possible. This case was modeled using the helical winding technique and resulted in a change in the total magnetic field magnitude of approximately 1.4% and a change in the radial field on axis at the center of the coil throat of approximately 0.2G.

Since this method of modeling magnetic fields results in a discretization of the coil loops, the computational error was calculated to determine the degree of accuracy. This was performed by simply calculating the field due to a circular turn of current and comparing it to the field produced by a turn consisting of 360 straight-line segments. The field deviation was on the order of 10^{-5} and was determined to be small enough to give fairly accurate results.

The calculations made concerning the buswork system above the torus indicate that the worst-case radial field contributions would be approximately one gauss located in the coil throat at the top of the toroidal array. The beauty of this type of computation, where the current-carrying conductors are discretized into finite elements, is that it enables the modeling of any geometrical configuration. In the case of EBT-P, this technique was also used to determine field values at various locations due to the incoming vapor-cooled leads.

ACKNOWLEDGMENT

The author expresses her appreciation to D.W. Lieurance, G.D. Magnuson, and to W.E. Toffolo for their useful discussions and input to this project.

REFERENCES

1. R.W. Baldi and D.W. Lieurance, "Magnetic Integrations Calculations Computer Program," CASD-ERR-77-051, December 1977.