

## F Coil and Containment Design and Manufacture (MW, JB)

### F.1 Electromagnet Subsystem Requirement (MW)

The electromagnet team is responsible for the design and construction of the electromagnets for the actuation system of each vehicle. The electromagnets will provide the forces and torques necessary for translational movement in the 2-D horizontal plane and for disturbance rejection. To demonstrate the concept of electromagnetic formation flight, the baseline maneuver will consist of a two-vehicle system performing a spin-up maneuver as illustrated by Figure F.1-A. In this figure, the two vehicles are represented as electromagnet dipoles in an initial perpendicular configuration. As current is applied to the electromagnets, forces and torques are induced as illustrated by the arrows in Figure F.1-B. Using a reaction wheel, these forces and torques are counteracted such that the dipoles begin to spin-up until they are aligned along a single axis in steady state rotation. Each vehicle will be floated across a smooth surface using compressed gas to reduce friction.

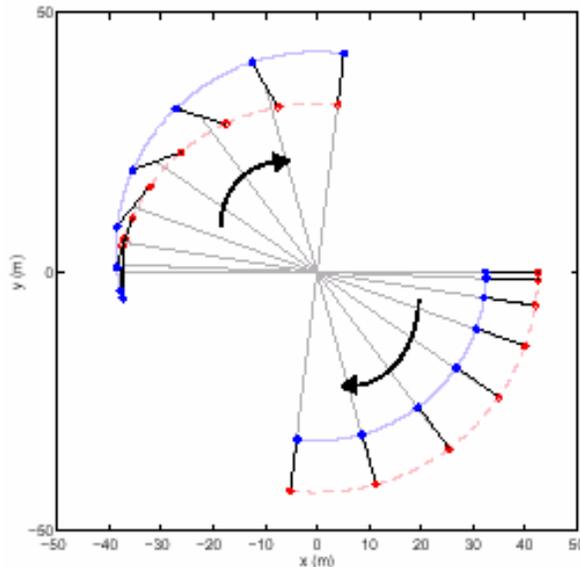


Figure F.1-A: Baseline maneuver. Two-vehicle electromagnet dipole system undergoing spin-up.

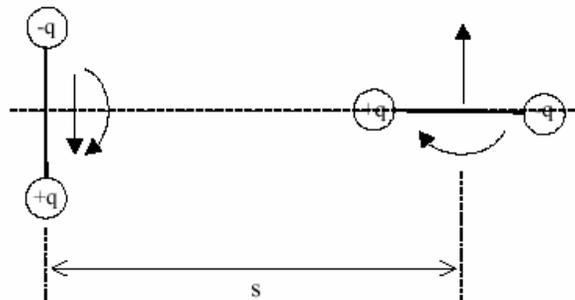


Figure F.1-B: Induced forces and torques on two dipoles.

The electromagnets must provide the forces and torques required to perform the baseline spin-up maneuver to a constant steady state angular rate of one rotation per minute, or six degrees of arc per second, at a separation distance of two meters measured from each vehicle's center of mass. The vehicles are required to maintain this rotation rate for a minimum of three rotations. In order to fulfill these actuation system requirements, the electromagnet subsystem team considered several designs for the electromagnet coil.

## F.2 Design History (MW)

The original design for the electromagnet consisted of a ferromagnetic core made of steel wrapped with copper wire to produce the force and torque necessary to fulfill the system requirements. However, since the ability of the system to spin up is dependent upon mass, it is desirable to keep the mass as low as possible. Additionally, since the EMFFORCE satellite test-bed is demonstrating a concept that should be translatable to space application, a large, heavy steel core would not necessarily be the best option due to high launch costs and payload restrictions. A coreless option was then considered.

The electromagnet team discarded the steel core and worked on resizing the copper coil such that it was able to produce the required force and torque for spin-up without the core material. However, the large copper coil could not satisfy the requirement due to the restriction on the amount of current that could safely be passed through the wire. Even with cooling systems, it would not have been feasible to use a coreless copper coil electromagnet because of the resistance of the wire creating a large amount of heat. The team then considered a new material to replace the copper that could carry higher levels of current.

An electromagnet made of high temperature superconductor wire became the chosen alternative to the copper wire electromagnet coil. American Superconductor's Bi-2223 reinforced high temperature superconductor wire is able to safely carry more than ten times the amount of current that copper can at temperatures below 110 K. Below this temperature, the superconductor wire has zero resistance allowing more than 100 amps of current to be passed safely through the wire. This amount of current made it feasible for the subsystem to produce the required force and torque necessary to spin up the system. However, since the superconductor wire must be kept below 110 K during the entire duration of the test, the superconductor wire adds the additional requirement for a coil containment system that keeps the wire below this temperature. Using the coreless superconductor coil as the choice for the electromagnet, the team began the final design and fabrication of the electromagnet subsystem.

### F.3 Design Overview (MW)

The design for the electromagnet subsystem consists of two perpendicular, vertically oriented coils made of high temperature superconductor wire. Two perpendicular coils are used to allow for variability in the direction of the magnetic field. Since the superconductor coils must operate at temperatures below 110 K, they are immersed in liquid nitrogen at 77 K for the duration of the test. The liquid nitrogen and coil are contained within a toroid-shaped casing, and the liquid nitrogen is replenished from a reservoir on top of the coil casings. Figure F.3-A shows the configuration of the perpendicular coils.

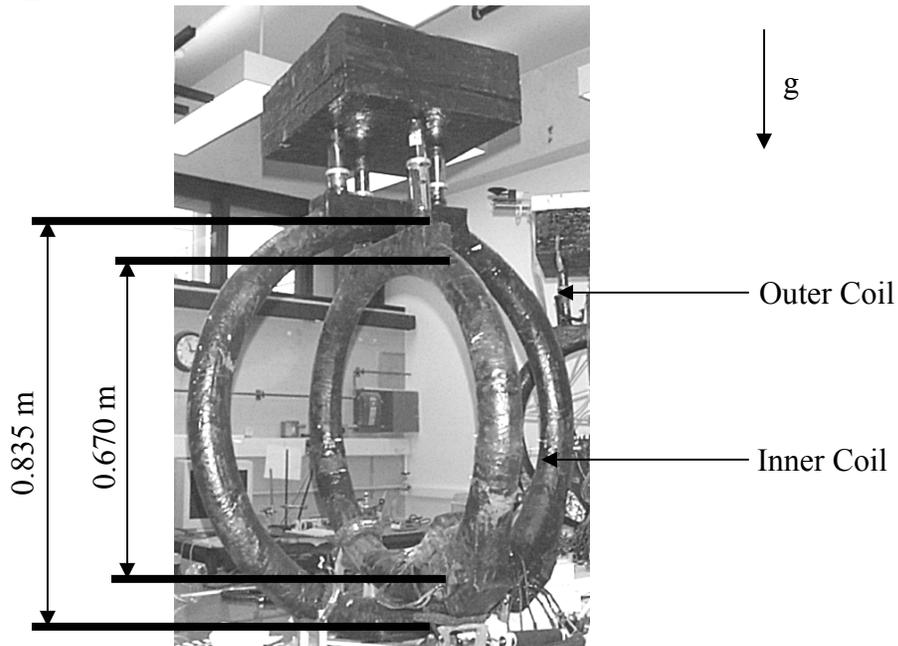


Figure F.3-A: Electromagnet Coil Design Overview.

## F.4 Electromagnet Coil Sizing (MW)

The first task to be completed was the sizing of the electromagnet coil. In order to determine the size of the coil, the electromagnet team first calculated the strength of the coil necessary to meet the design requirements. To do this, the team considered the baseline spin-up maneuver of two vehicles to a steady state rotation of one rotation per minute. Each vehicle is modeled as a dipole. Figure F.4-A shows the two dipoles at a separation distance ( $s$ ) and at dipole angles of ( $\alpha$ ) and ( $\beta$ ). The two vehicles undergoing spin-up during the baseline maneuver are modeled as magnetic dipoles.

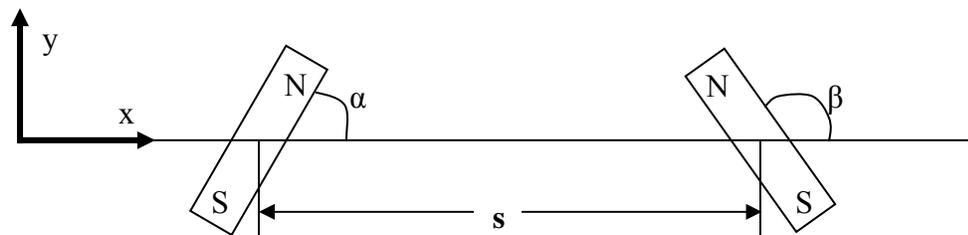


Figure F.4-A: Two Magnetic Dipoles.

Calculating the force in the radial (x) direction and the force in the tangential (y) direction, the following equations are obtained where ( $\mu_0$ ) is the permeability constant and ( $\mu_A$ ) and ( $\mu_B$ ) are the magnetic moments of the dipoles (Schweighart 2002):

Axial force:

$$F_x = \frac{3}{4\pi} \frac{\mu_0 \mu_A \mu_B}{s^4} (2 \cos \alpha \cos \beta - \sin \alpha \sin \beta)$$

**Equation F.4-1**

Tangential force:

$$F_y = -\frac{3}{4\pi} \frac{\mu_0 \mu_A \mu_B}{s^4} (\cos \alpha \sin \beta + \sin \alpha \cos \beta)$$

**Equation F.4-2**

The radial force due to the magnetic dipoles is required to counteract the centripetal acceleration of the rotating vehicles. The tangential force provides the necessary angular acceleration ( $\dot{\omega}$ ) for the vehicles to spin up. These relations provide the following equations:

$$F_x = \frac{3}{4\pi} \frac{\mu_o \mu_A \mu_B}{s^4} (2 \cos \alpha \cos \beta - \sin \alpha \sin \beta) = m \omega^2 \left( \frac{s}{2} \right)$$

**Equation F.4-3**

$$F_y = -\frac{3}{4\pi} \frac{\mu_o \mu_A \mu_B}{s^4} (\cos \alpha \sin \beta + \sin \alpha \cos \beta) = m \dot{\omega} \left( \frac{s}{2} \right)$$

**Equation F.4-4**

Solving for the magnetic moment of a dipole and assuming that both vehicles have identical coils and masses and that  $\beta = 0^\circ$ , the following equation is obtained where ( $m$ ) is the mass of the vehicle and ( $\omega$ ) is the rotation rate of the system (Schweighart 2002):

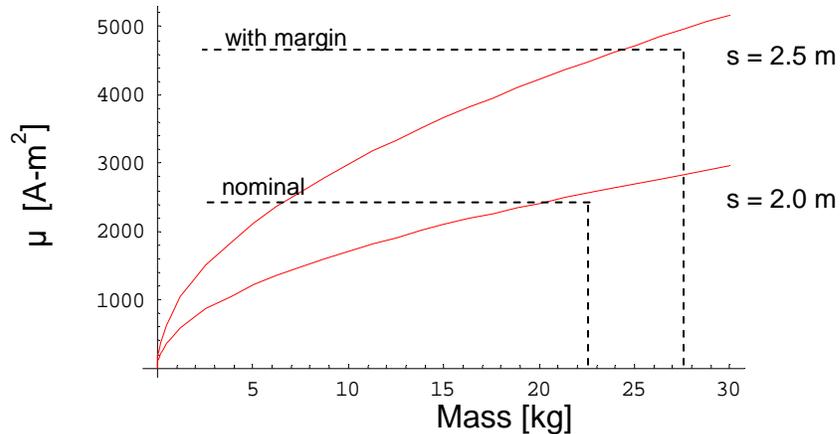
$$\mu_A = \mu_B = \left( \frac{32\pi}{3} \frac{m \left( \frac{s}{2} \right)^5 \sqrt{4 \dot{\omega}^2 + \omega^4}}{\mu_o} \right)^{1/2}$$

**Equation F.4-5**

This equation provides the instantaneous magnetic moments necessary to maintain a rotation rate ( $\omega$ ) for a vehicle of mass ( $m$ ) at a separation distance ( $s$ ) from another vehicle where the permeability constant ( $\mu_o$ ) is  $4\pi * 10^{-7}$ . The mass estimate of the vehicle is approximately 20 kg. Using the set requirements for steady state rotation and separation distance and setting angular acceleration ( $\dot{\omega}$ ) equal to zero, the required magnetic moment for one dipole is 2418 [A-m<sup>2</sup>].

In order to determine the size of the coil, the electromagnet team increased the mass estimate and separation distance requirement by a margin of 25% for safety. Calculating the required magnet strength for 25 kg vehicles at a separation distance of 2.5 meters,  $\mu_A = \mu_B = 4723$  [A-m<sup>2</sup>].

Figure F.4-B shows the dependency of magnetic moment on mass and separation distance. The required magnetic moment for each dipole, in order to fulfill the baseline maneuver requirements for the nominal case and for the case with a 25% margin of safety factored into the mass and separation distance, is denoted by the dashed lines.



**Figure F.4-B: Magnetic Moment vs. Mass for 2.0 and 2.5-meter separation distances.**

For the electromagnet coils,  $\mu = nIA$  where  $n$  is the number of turns of the superconductor wire,  $I$  is the current, and  $A$  is the area enclosed by the coil. The current was set at 100 amps, which is a safe level of current that may be passed through the superconductor wire. Since there are two coils per vehicle, the outer coil was sized such that it exceeded the required magnetic moment for the system with margin while leaving enough room for the inner coil to be sized to meet the original requirement.

The outer coil diameter was set at 0.835 m with 99 turns of superconductor wire. For these coil properties and 100 amps of current,  $\mu_{\text{outer}} = 5421$  [A·m<sup>2</sup>]. The inner coil diameter was set at 0.670 m with 120 turns of superconductor wire. For these coil properties and 100 amps of current,  $\mu_{\text{inner}} = 4231$  [A·m<sup>2</sup>]. At the diameters and number of turns set for the outer and inner coils, each coil requires the same length of superconductor wire and allows room for the coil casings to fit around each coil.

## F.5 Coil Wrapping (MW)

Once the sizing for each coil was determined, the electromagnet team began fabrication on the first vehicle's inner coil. The wire used for the electromagnet coil is Bi-2223 reinforced high temperature superconductor wire manufactured by American Superconductor. In order to prevent the coil from shorting out, the superconducting coil is layered with DuPont Kapton insulator tape with adhesive on one side of the tape. Figure F.5-A shows the dimensions of the superconductor wire, and Figure F.5-B shows the dimensions of the Kapton insulator.

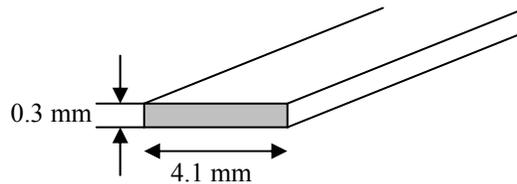


Figure F.5-A: Reinforced High temperature superconductor wire.

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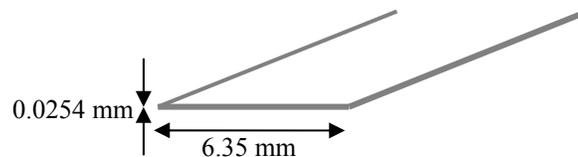


Figure F.5-B: Kapton insulation tape.

Each coil consists of three individual coils of superconductor wire layered with insulator. This design allows for a more compact casing to be constructed around the coil than would be required for a single tall stack of the required number of wire turns. Figure F.5-C shows a cross-section and dimensions of both the outer and inner coils. The outer and inner coil stacks each contain 33 and 40 layers, respectively, of superconductor wire layered with Kapton insulator tape.

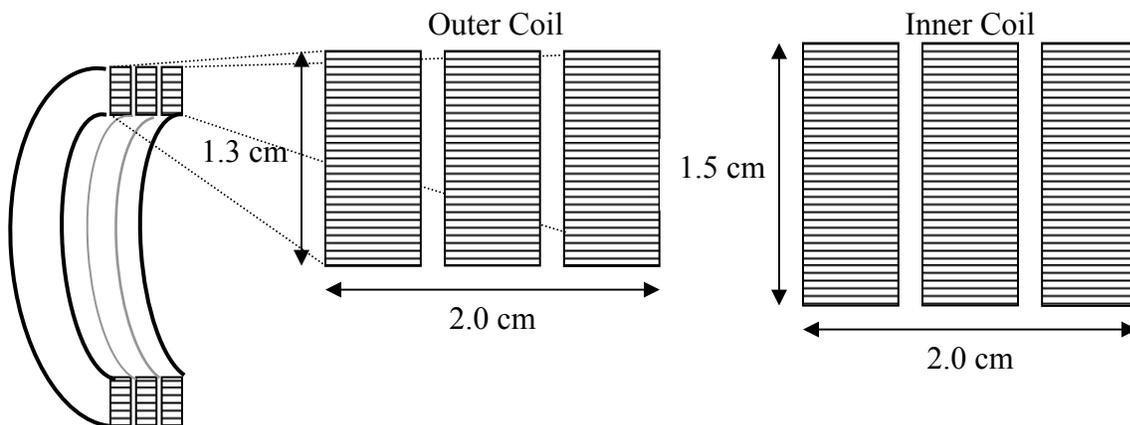


Figure F.5-C: Outer and inner electromagnet coil cross-sections

In order to wrap each coil stack, a spindle for the outer coil and another spindle for the inner coil were fabricated out of three layers of Plexiglas to match the inner dimensions of each coil. The superconductor wire and Kapton tape were layered onto the spindle as it was slowly rotated until each stack was complete. Figure F.5-D is a side-view of the wrapping assembly, and Figure F.5-E is a side-view of the spindle. The three layers of Plexiglas are held together by wing nuts that allow the coil stack to be removed. The spindle aligns the superconductor wire and Kapton tape during the wrapping process. The Plexiglas pieces are separated by removing the wing nuts. This allows the coil stack to be removed once it is finished.

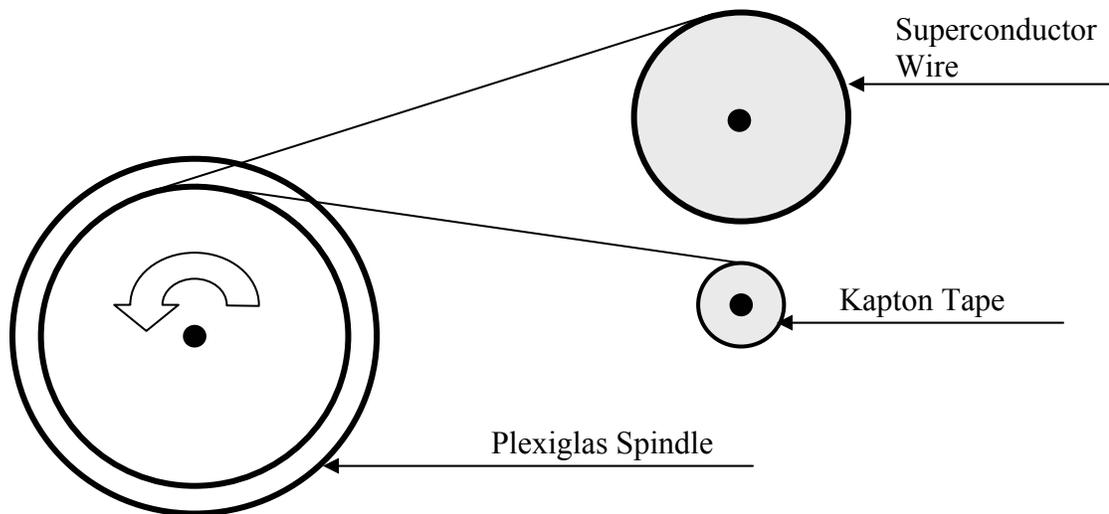


Figure F.5-D: Side-view of the wrapping assembly.

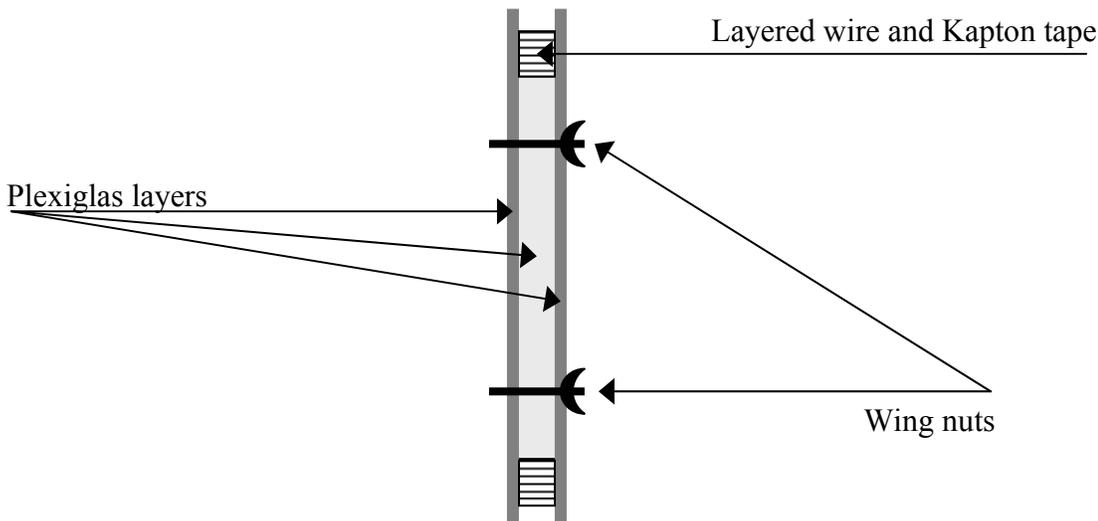


Figure F.5-E: Side-view of wrapping spindle.

## F.6 Coil Testing (MW)

One layer of the inner coil was tested to determine whether it exhibited superconducting properties below 110 K and to measure the magnetic field for comparison with the expected values from the model derived by Samuel Schweighart from the equations found on <http://www.netdenizen.com/emagnet>. The model for the field strength in the axial direction is given by Equation 6, and the model for the field strength in the radial direction is given by Equation 7 where ( $a$ ) is the coil radius, ( $n$ ) is the number of wire turns, ( $i$ ) is the current, ( $r$ ) is the radius of the measurement point, and ( $h$ ) is the height of the measurement point. *EllipticK* denotes a complete elliptic integral of the first kind, and *EllipticE* denotes a complete elliptic integral of the second kind. In order to simplify the model, consider the following substitutions:

$$\alpha = \frac{r}{a} \quad \beta = \frac{h}{a} \quad \gamma = \frac{x}{r} \quad q = \left(1 + \left(\frac{r}{a}\right)\right)^2 + \left(\frac{x}{a}\right)^2$$

**Equation F.6-1**

The resulting equations for magnetic field strength in the axial and radial directions are:

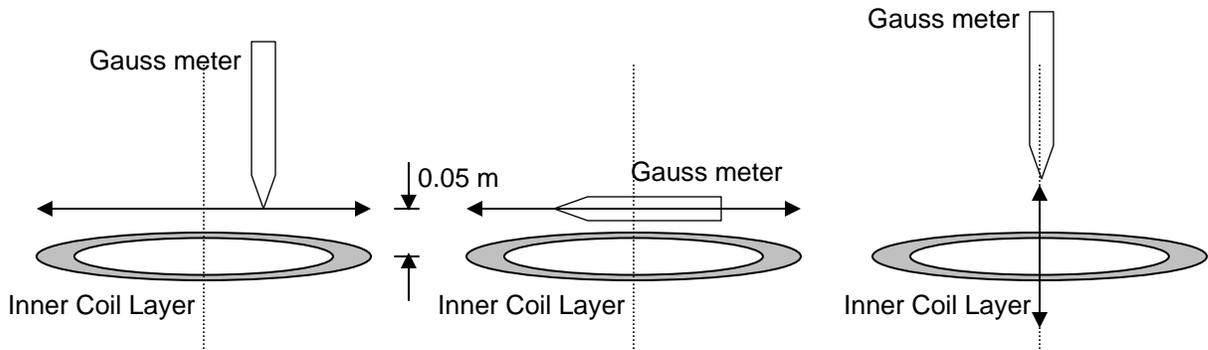
$$B_{axial} = \frac{n\mu_o i}{2a\pi\sqrt{q}} \left( \left( \frac{1 - \alpha^2 - \beta^2}{q - 4\alpha} \right) \text{EllipticE} \left[ \frac{4\alpha}{q} \right] + \text{EllipticK} \left[ \frac{4\alpha}{q} \right] \right)$$

**Equation F.6-2**

$$B_{radial} = \frac{n\mu_o i \gamma}{2a\pi\sqrt{q}} \left( \left( \frac{1 + \alpha^2 + \beta^2}{q - 4\alpha} \right) \text{EllipticE} \left[ \frac{4\alpha}{q} \right] - \text{EllipticK} \left[ \frac{4\alpha}{q} \right] \right)$$

**Equation F.6-3**

The resistance of one layer of the inner coil at room temperature was measured at 0.37 ohms. The layer was then immersed in liquid nitrogen at 77 K, and the measured resistance was zero, indicating that the wire was superconducting at that temperature. Thirty amps of current were applied to the immersed coil, and magnetic field (or B-field) measurements were taken using a Gauss-meter. Figure F.6-A illustrates the experimental setup for the axial B-field measurements taken at varying radii, Figure F.6-B illustrates the setup for the radial B-field measurements taken at varying radii, and Figure F.6-C illustrates the setup for the axial B-field measurements taken at varying height.



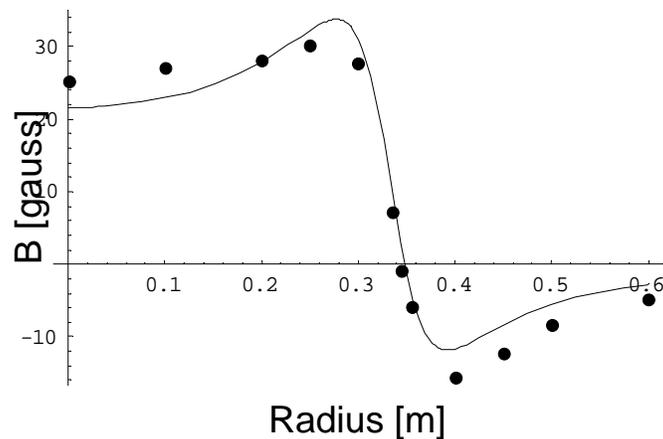
**Figure F.6-A: Axial B-field measurement at varying radii.**

**Figure F.6-B: Radial B-field measurement at varying radii.**

**Figure F.6-C: Axial B-field measurement at varying**

The experimental data was plotted against the field strength model to determine how well the model predicted the induced magnetic field.

Figure F.6-D is a plot of axial magnetic field strength at varying radii, Figure F.6-E is a plot of radial magnetic field strength at varying radii, and Figure F.6-F is a plot of axial magnetic field strength at the center of the coil at varying heights.



**Figure F.6-D: Magnetic Field in Axial Direction vs. Radius.**

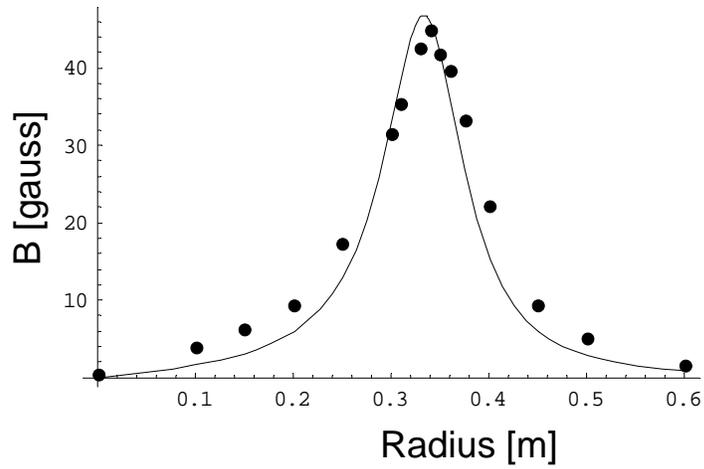


Figure F.6-E: Magnetic Field in Radial Direction vs. Radius.

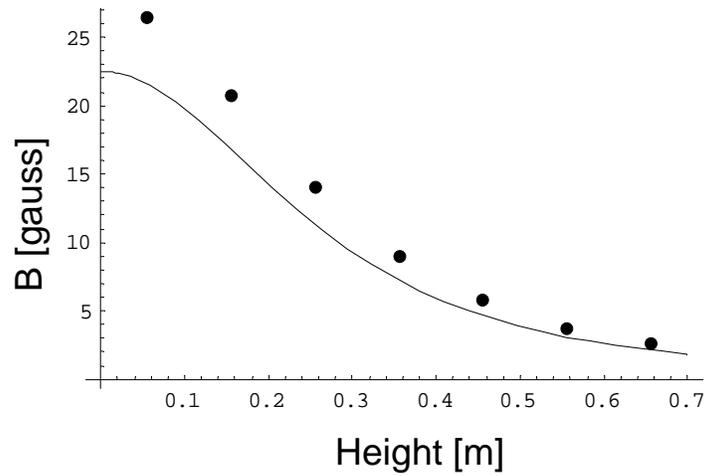


Figure F.6-F: Magnetic Field in Axial Direction vs. Height.

## **F.7 Containment System (JB)**

### **F.7.1 Requirements:**

- The super conducting wire must be immersed in liquid nitrogen at all times during operation
- Insulate from the environment the wire and the liquid N<sub>2</sub>. A better insulation will allow a slower boil off, which means less liquid nitrogen will be needed to maintain the required temperature, and thus the EM subsystem will be lighter, which is more desirable for overall design of the vehicles
- Stiff enough to support liquid N<sub>2</sub> container, its own weight, and the weight of other components that will be attached to it. As shown in the diagram of the vehicle, the containment system is the main structure; therefore it needs to have attached points and be strong enough to support the weight of the different components

**F.7.2 Parts**

- 2 coil containments per vehicle. Manufactured and designed specifically for EMFF
- 1 tank per vehicle. Manufactured and designed specifically for EMFF
- 4 pipes per vehicle. 1 inch in diameter, 1 foot long made out of brass

## F.7.3 Design and Manufacturing

### F.7.3.1 Coil containment

In order to hold the coils and the liquid nitrogen that surrounds it, and achieve the desired insulation, STYROFOAM extruded polystyrene insulation was used to build a toroidal shape container.

The size constraints come from the coil Figure F.7-A. The wire goes through the center of the toroid shaped container.



**Figure F.7-A: Coils on the Vehicle**

Since there are two coils, which need to be perpendicular to each other, one of the containers is small enough fit inside the other. The dimensions of the coils are shown in Figure F.7-B and Figure F.7-C, respectively.

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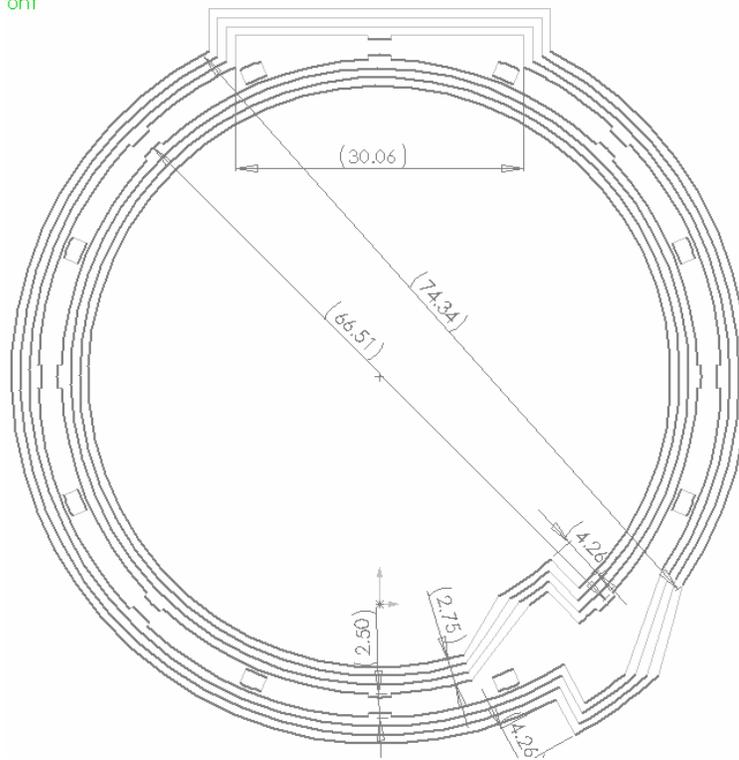


Figure F.7-B: Cross Section of the Inner Coil (cm)

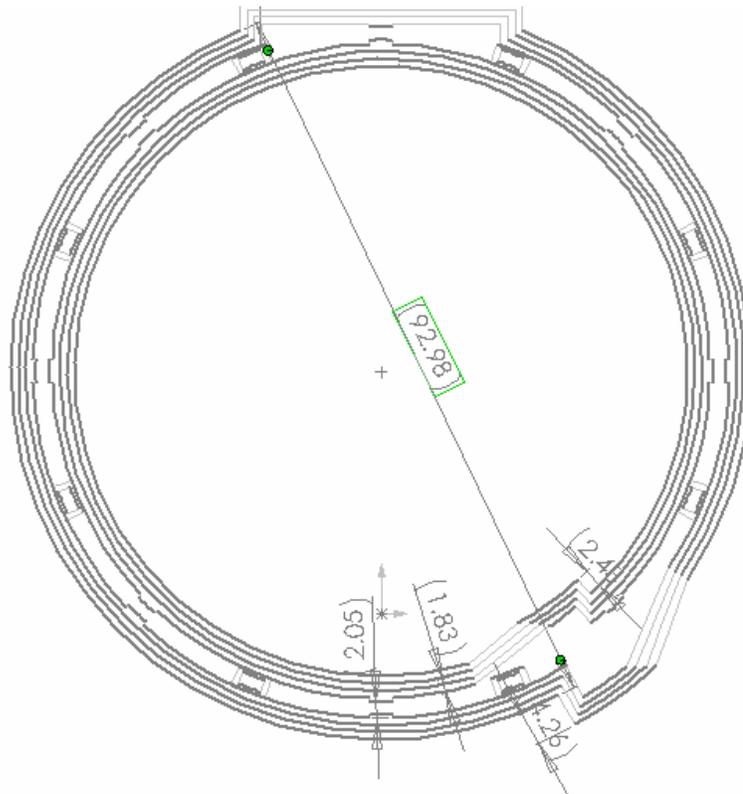


Figure F.7-C: Cross Section of Outer Coil (cm)

In order for the liquid nitrogen to flow better through the container, spacers were included on the sides of the wire. These are shown in the cross section figures for the coils. Figure 0-D shows the details of the spacers on the side and bottom for the male part of the container. Another part that has the mirror shape of this one, attaches to the top creating more space for the liquid N<sub>2</sub>.



**Figure F.7-D: Spacers for the Male Part of the Container**

The manufacturing of the containers is a time consuming process. For every container tested there at least six to ten hours of only manufacturing time. There is also time to epoxy the different parts, which is about an hour and finally the curing time, which is from sixteen to 24 hours for every layer of epoxy.

The containers were built in two parts, each part having had four pieces each. These pieces were made in a milling machined programmed in mastercam 9. The first part was the “Male” piece and the second one was the “Female” piece, since they were negative of each other.

After putting each part together with epoxy the super conducting wire was put into the female piece, where all the extra wiring took place.

Before epoxing the two halves together, tests were performed to make sure that current could flow through all the wires.

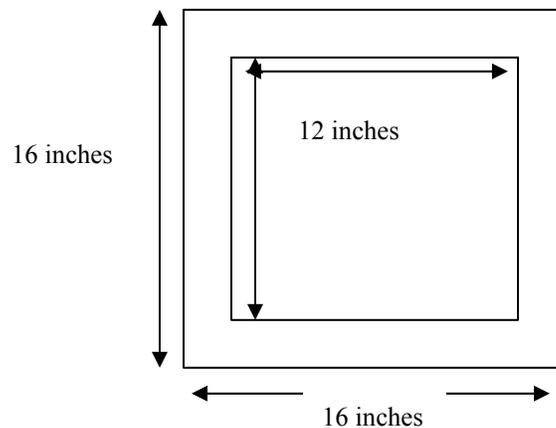
Once the two main parts’ assembly had dried, fiberglass and cryogenic epoxy were applied to the outside for leak proofing and to make the structure stiff.

Finally, the containers have to be thermo cycled about ten times, in order to stress relieve the foam. This causes many cracks on the foam, but once it has gone through enough number of cycles it will stop cracking and leaking.

### F.7.3.2 Tank

The purpose of the tank is to hold liquid nitrogen, in order to keep the wires immersed as the nitrogen boils off. The volume the tank has to hold is directly related to the amount of time the system is expected to operate. Based on boil off testing on the coils and the fact that the limiting factor for operational time is the air carriage system, which can run for 8 minutes, the tank was designed to carry enough nitrogen to keep the coils immersed for 10 min.

If at some point the desired volume is increased, the current design for the tank allows to simply add another layer of foam and the volume would be increased by whatever thickness this new layer has. This is clearer in Figure F.7-E.



**Figure F.7-E: Area of the Tank**

The tank was constructed in a similar manner as the coils containment. A foam frame was made and epoxied together and fiberglass with epoxy was applied to the outside.

The foam frame was composed of a square base and two square layers of the same size but the inside was cut off, leaving a squared ring.

Finally, 4 pipes were connected to the coils (2 for each coil) as shown in Figure F.7-F.



**Figure F.7-F: Tank**