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Title: Analysis of DST Solenoid Magnetic Measurements

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Analysis of DST Solenoid Magnetic Measurements
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25-Jan-2006

The solenoids magnets that will be used in the DST during the scaled accelerator and in the final configuration have been measured by Dave Barlow. The measurements were under the same conditions that they will be operated as described below:

- The magnets were cycled two times to a maximum current – I_{max} and back to zero or very low current before measurements were made
- The magnets were then ramped to I_{max} and the current was lowered to the measurement value
- The magnet ramp rate was specified to take approximately 2 minutes to energize from zero current to I_{max} and similarly back to zero current.

Technical notes summarizing the results of the measurements are presented in Appendices 1-4. The measured solenoid magnets are listed below:

- S1 (Larry)
- S2 (Curly)
- S3
- S4
- Thor (Moe)
- AP

Excitation Function:
The excitation function (B vs I) was measured and has been fit to the following polynomial expansion.

$$B(I) = a_0 + a_1 I + a_2 I^2 + a_3 I^3 + a_4 I^4 + a_5 I^5 + a_6 I^6$$

Here, the coefficients are defined such that the current is in amperes and the field is in Gauss. The coefficients are given in Table 1 below.

Table 1: Excitation function coefficients for the DST solenoids

Coefficient	S1	S3	S4	S2	Thor	AP
a_0	4.3921	4.1815	4.0008	2.8470	3.9569	4.1084
a_1	24.601	24.612	24.586	21.665	6.0508	4.9625
a_2	3.4871E-02	3.5116E-02	3.5932E-02	-4.5404E-05	3.9585E-03	1.5627E-03
a_3	-1.3710E-03	-1.3981E-03	-1.3920E-03	-7.1398E-06	-6.3926E-05	-1.0101E-05
a_4	2.3655E-05	2.4479E-05	2.3829E-05	4.9133E-08	-3.3892E-07	2.9283E-08
a_5	-1.8461E-07	-1.9366E-07	-1.8516E-07	-1.5399E-10	8.9990E-09	-3.7956E-11
a_6	5.0868E-10	5.4101E-10	5.0949E-10	1.2782E-13	-3.8599E-11	1.7183E-14

The accuracy of the fits is typically better than 0.1% except at the lowest excitations where it is better that 0.5 Gauss. With the exception of S2 (Curly), the total contribution from coefficients a_2 to a_6 is less than 3% at all measured currents. Because S2 operates at much higher fields the non-linear contributions are higher.

Field Shape Parameters:

The process of determining the field shape parameters is not a straightforward as determining the excitation function. The measurement data needs to be massaged prior to determining the field shape parameters. The following procedure is used for all magnets.

1. Average the data for B(z) and B(-z) to eliminate longitudinal asymmetries:

$$B'(z) = B'(-z) = \left(B_m(z) + B_m(-z)\right)/2$$

2. Subtract $B'(z_{max})$ from all data points so that the field is zero at the limits of the measurement.

$$B(z) = B'(z) - B'(z_{\max})$$

The first step eliminates measurement asymmetries due to the measurement and the apparatus.

The second step truncates the measurement to zero and is less justified. However, any iron materials in the beam line will have the effect of clamping the field and reducing the longitudinal extent of the field distribution. This approach was analyzed in detail for the S1 magnet. POISSON simulations were performed for this magnet with boundary conditions which truncated the field to zero and z_{max}. The results are compared to the measurements in Figures 1 and 2. The agreement between the measured and POISSON prediction for the focusing effective length is better than 0.5% and the agreement between the measured and POISSON prediction for the rotation effective length is about 1.0%. The POISSON prediction for the excitation function is excellent as seen in Figure 2. The residual field introduces some structure to the measured field which is accounted for by subtracting the measured residual field from the data. The drop off in the excitation function at higher currents was not predicted very well until a correction was introduced to simulate the fact that the outer shell of the magnet does not cover 2π. A thinner outer shell was modeled to approximate the absence of the outer shell where the coil leads are located. This approximation reduced the thickness of the outer shell by about 12%.

The longitudinal field shape assumes a functional form as defined in the equation below.

$$B(z) = \frac{B(0)}{(1 + az^2 + bz^4 + cz^6 + dz^8 + ez^{10})}$$

The longitudinal field coefficients were first optimized to obtain the best fit to the field distribution. This did not give the best fit to the effective length (rotational and focusing) because this expression generally underestimated the field at large z. Once the best fit was obtained, small adjustments were made to provide a better fit to the effective lengths.

The focusing effective length was fit to better than 0.02% in all cases and the rotational effective length was fit to better than .3% in all cases.

The DST solenoids generally require only the first three coefficients with the exception of the two large aperture magnets, S2 and AP. The longitudinal field coefficients are given in Table 2 below. This is followed by figures for each solenoid showing the measured field distribution and the fit to the distribution. As seen in these figures the fits are a very good approximation to the measured fields.

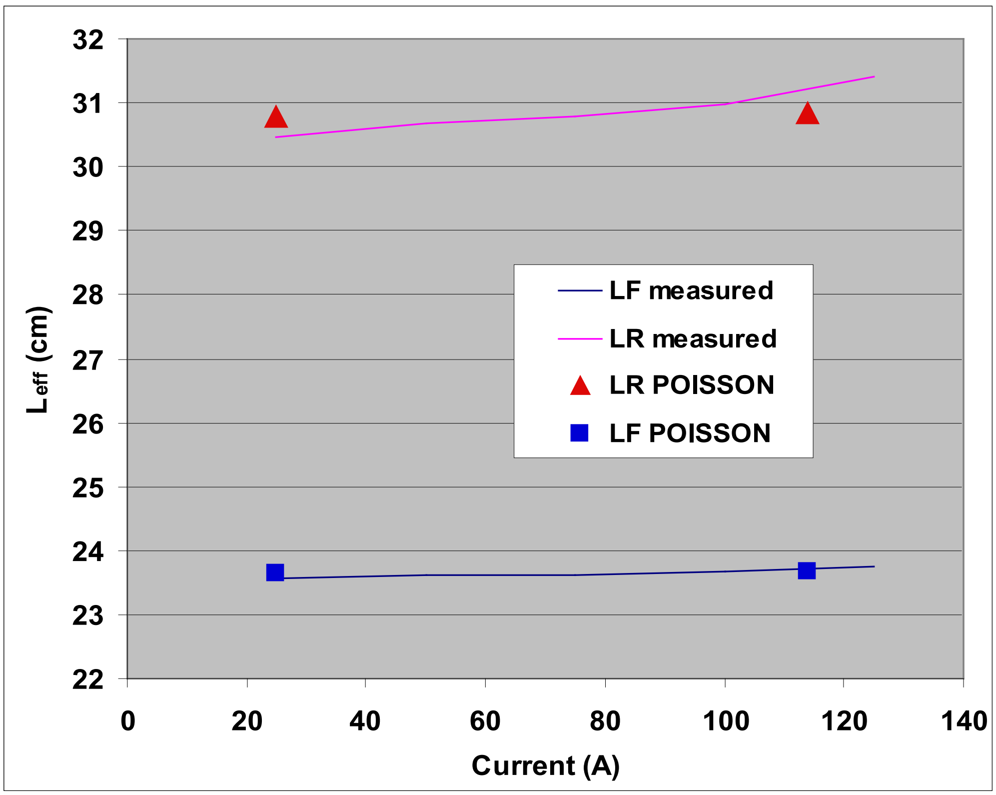


Figure 1: Measured and predicated values for the effective length.

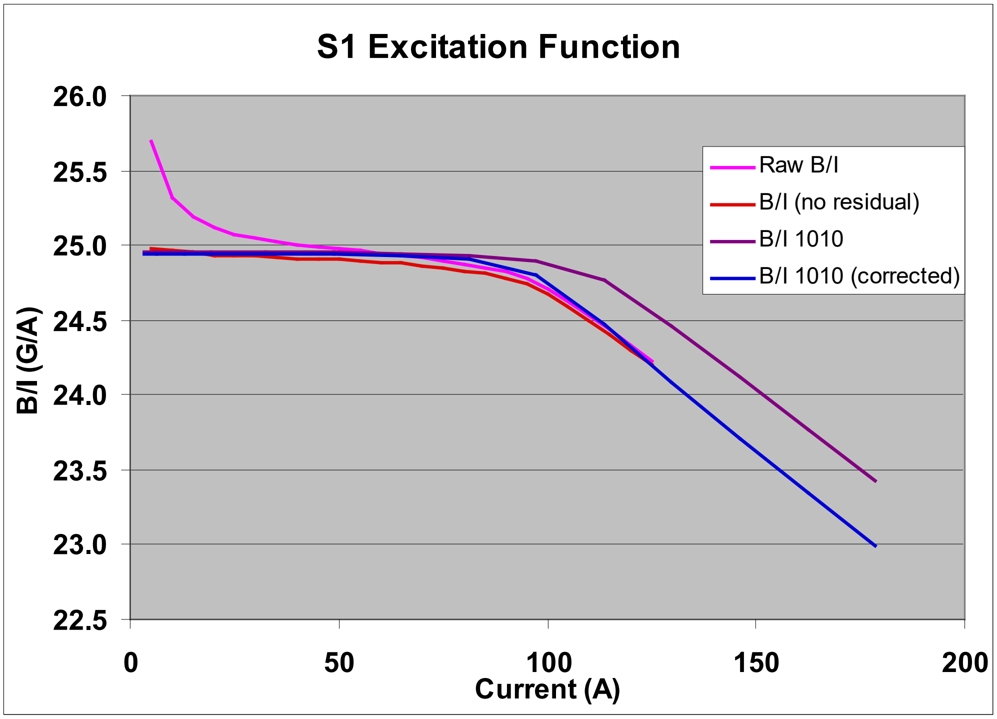
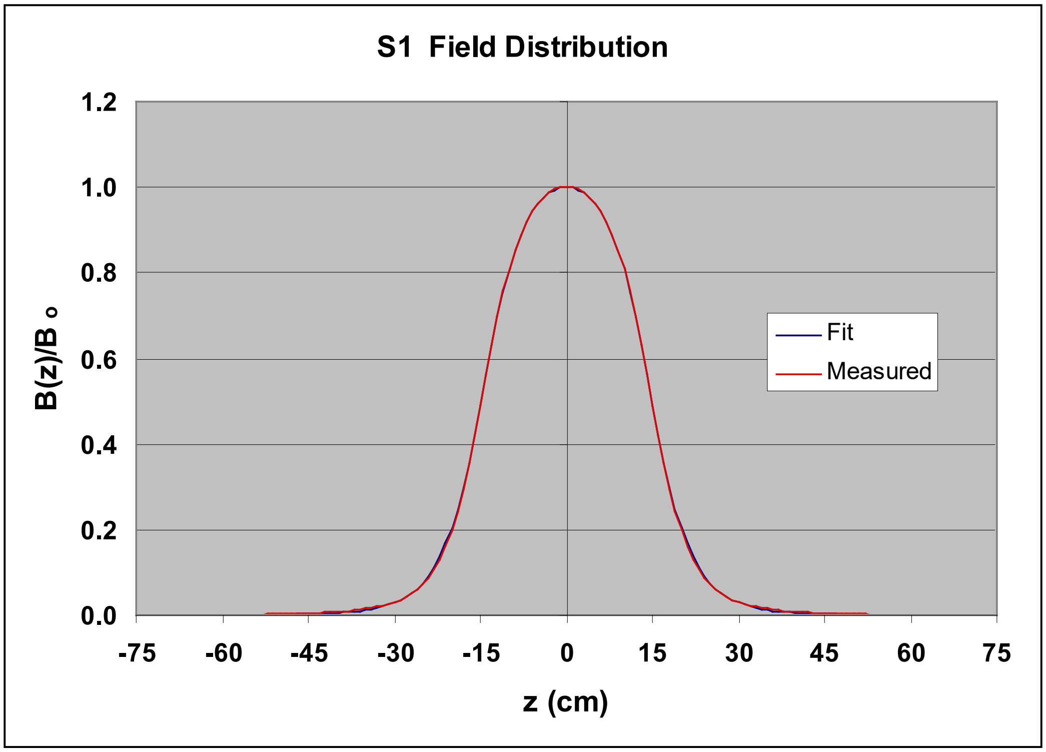
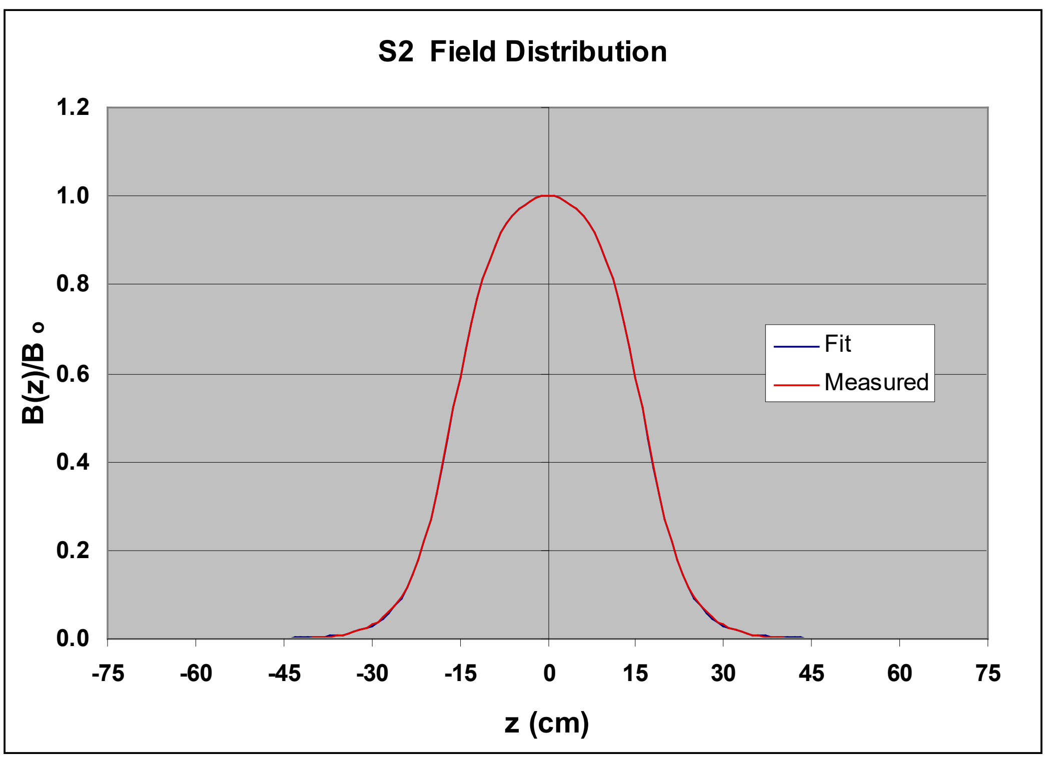


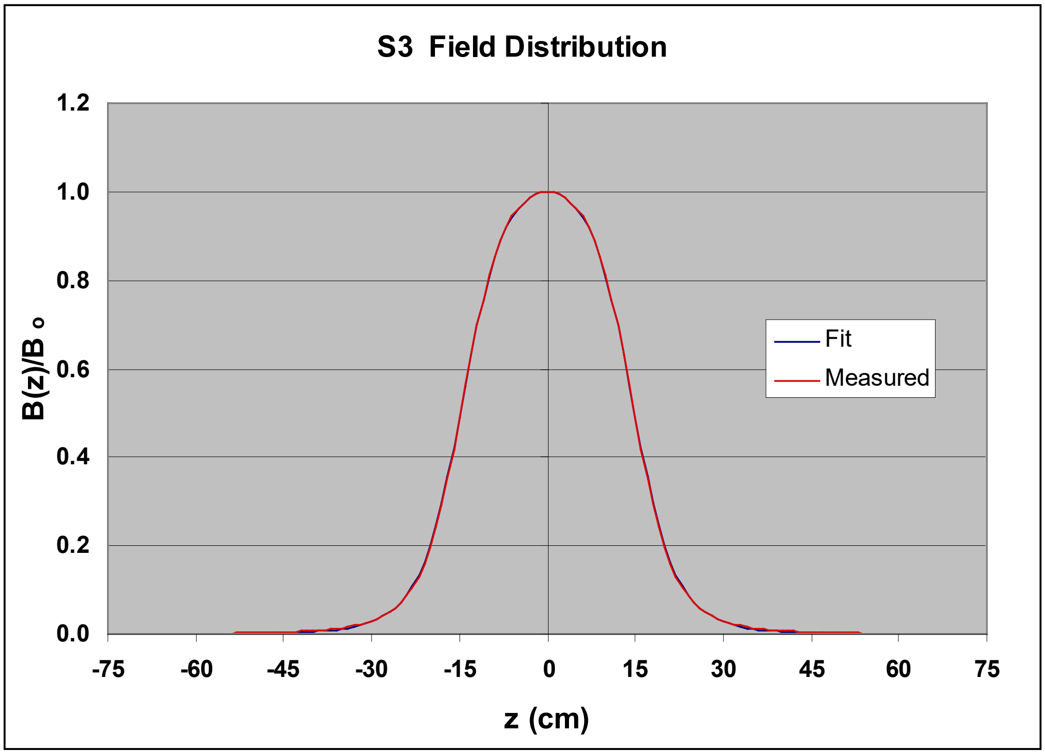
Figure 2: Measured and predicted values for the excitation function

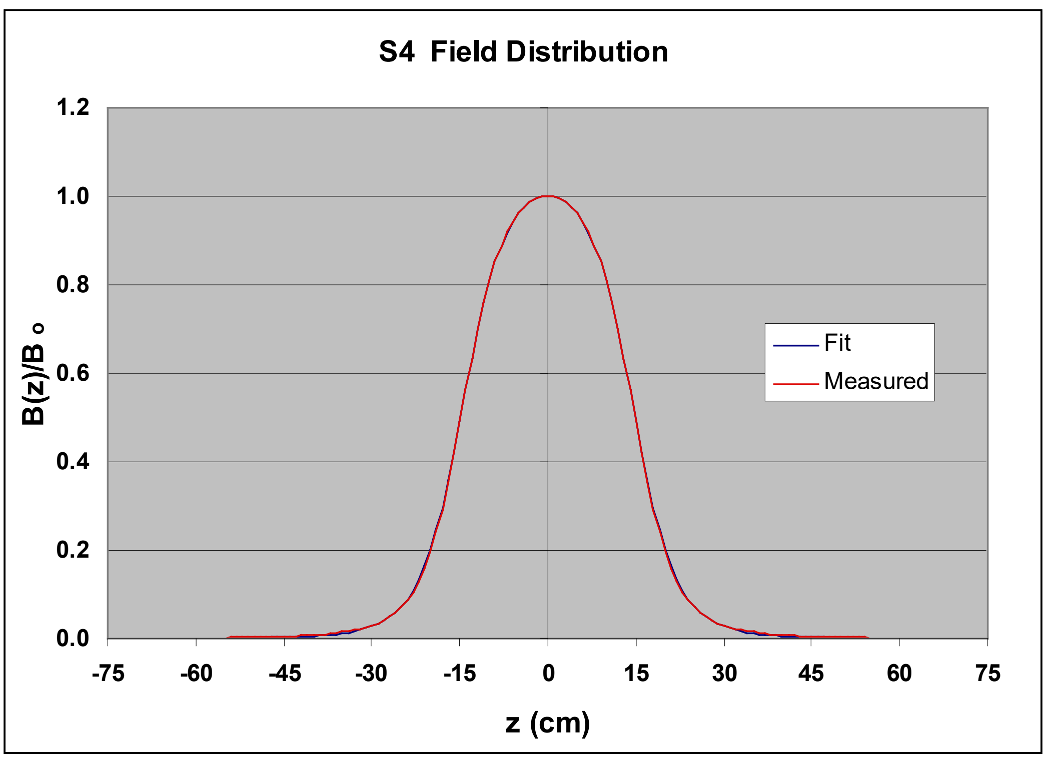
Table 2: Longitudinal field shape coefficients.

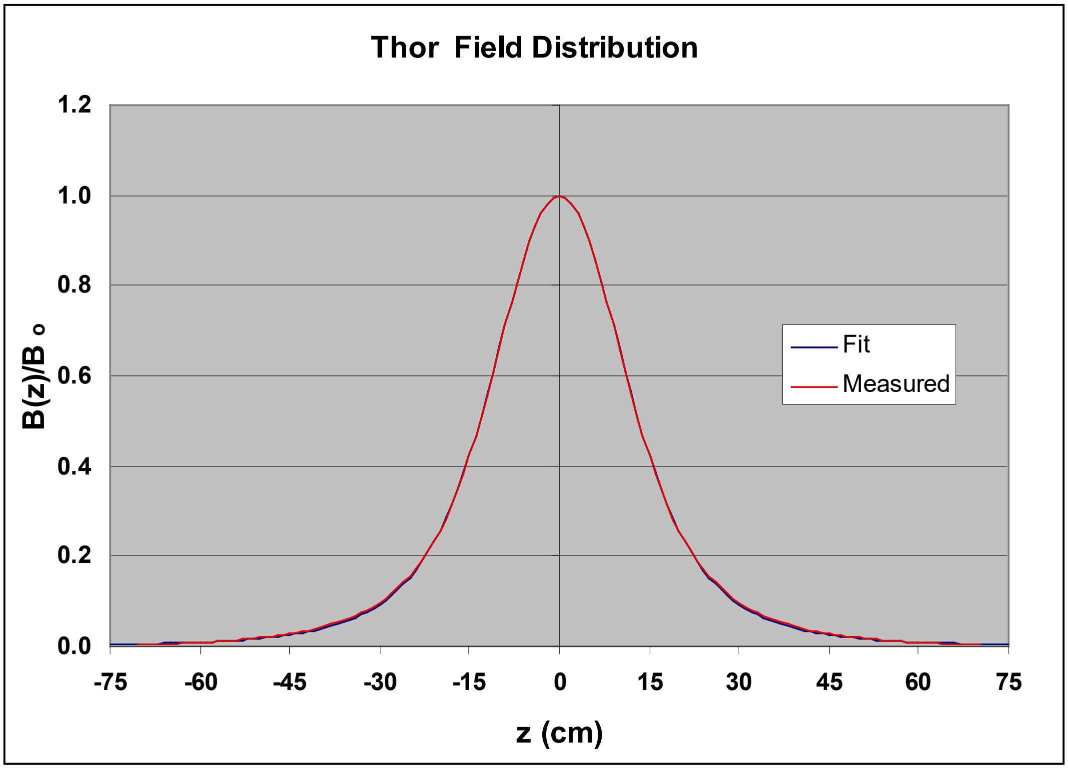
Magnet	S1	S2	S3	S4	Thor	AP
Current	100	50	75	75	75	675
a	1.44E-03	1.09E-03	1.48E-03	1.48E-03	4.42E-03	3.18E-03
b	5.53E-06	4.26E-06	4.71E-06	4.71E-06	7.10E-06	5.17E-06
c	3.82E-08	1.62E-08	4.10E-08	4.08E-08	1.01E-12	4.01E-11
d	0	1.86E-11	0	0	0	0
e	0	6.30E-15	0	0	0	3.9E-17

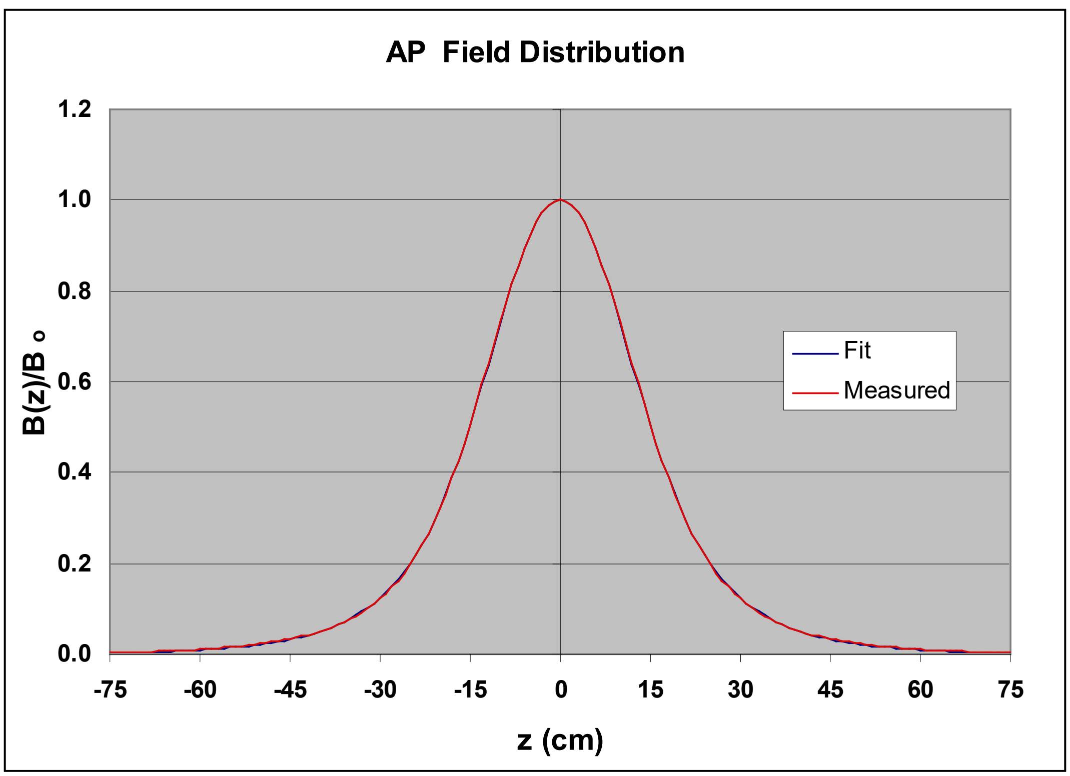

S1 Field Distribution
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B(z)/B o
-75
-60
-45
-30
-15
0
15
30
45
60
75
z (cm)
Fit
Measured


S2 Field Distribution
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B(z)/B o
-75
-60
-45
-30
-15
0
15
30
45
60
75
z (cm)
Fit
Measured


S3 Field Distribution
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B(z)/B o
-75
-60
-45
-30
-15
0
15
30
45
60
75
z (cm)
Fit
Measured


S4 Field Distribution
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B(z)/B o
-75
-60
-45
-30
-15
0
15
30
45
60
75
z (cm)
Fit
Measured


Thor Field Distribution
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B(z)/B o
-75
-60
-45
-30
-15
0
15
30
45
60
75
z (cm)
Fit
Measured


AP Field Distribution
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B(z)/B o
-75
-60
-45
-30
-15
0
15
30
45
60
75
z (cm)
Fit
Measured

Appendix 1: LANSCE-ABS:05-022 (TN) - Dec. 19, 2005 – David Barlow
Tests and Measurements of the DARHT S1, S3 and S4 Solenoids

This memo will give a brief description of the measurements and results along with plots of the data. The actual tables of data are given in the accompanying spread sheet labeled "DARHT Solenoids.xls". These three solenoids had been mapped previously, see LANSCE-1:03-001. A sketch of the solenoids is shown in Fig. 1. The solenoid labeled S1 is also known as Larry.

Cooling and Power

A plot of the flow rate as a function of pressure drop for the three solenoids is shown in Fig. 2. S1 was measured to have a lower flow rate that the other two solenoids because its water manifold was equipped with 0.75" water fittings rather than the 1.00" fittings of S3 and S4. At 100 A the average voltage drop across the terminals of the magnets was measured to be 71 V at an average coil temperature of 81° F.

Conditioning

The magnets were conditioned prior to the start of the magnetic measurements by ramping the current at a ramp rate of 2 A/s through the following cycle; 0 A $\rightarrow$ 125 A $\rightarrow$ 12 A $\rightarrow$ 125 A $\rightarrow$ 12 A $\rightarrow$ 125 A. The current was changed in 12.5 A steps with a 10 s pause between steps. The value of 12 A was used rather than 0 A to avoid transients that typically occur when the DC power is turned off and then back on. The magnet was always reenergized to 125 A before the start of every measurement sequence and measurements were always made on the downward branch of the hysteresis loop

Measurement Setup

The field was measured by a Group-3 Hall probe which can measure the field with a random uncertainty of 0.1 G and systematic uncertainty of about 1 G. The Hall probe was located on the tip of the boom of a three axis point mapper. The *x*, *y*, and *z* axes of the point mapper were aligned with respect to the mechanical axes of the solenoid with sufficient accuracy that the center of the active area of the Hall probe has an uncertainty of 1 mm in *x*, *y* and *z* with respect to the mechanical axes of the solenoid. The current was measured by a Danfysik "zero flux" current transducer. The error in the current measurement is less than 0.01 A.

Central Field

The axial field at the center of each solenoid was measured as a function of current. A plot of B_o/I vs. I for all three solenoids is shown in Fig. 3.

Axial Field vs. Z

The axial field was measured along the mechanical axis of the solenoid at currents of 125 down to 0 A in steps of 25 A. A typical plot of B_z vs. z at 125 A is shown in Fig. 4. The integral of $B_z.dz$ is consistent with a 616 turn solenoid. A plot of B_z vs. z near z=0 indicates an offset in the magnetic center of S1 and S3 that is greater than the measurement error, Fig. 5. These offsets are believed to be due to the fact that there is about 4 mm of tolerance between the inside of the iron yoke and the outside length of the potted coil. The potted coils of S1 and S3 appear to be shifted about 1 mm in the $-z$ direction with respect to the center of the iron yoke while the potted coil of S2 appears to be shifted about 1 mm in the $+z$ direction.

Axial Field vs. X and Y

The axial field was also measured along the x and y axes for $z = 0$, Fig. 6. These results indicate that the magnetic and mechanical centers coincide within the 1 mm uncertainty of the measurements.

Rotating Coil Measurements

S1 was mapped with a rotating coil to see if there were any anomalous transverse field components and to check that the magnetic axis of the solenoid was aligned with its mechanical axis. The coil was a standard quadrupole mapping coil with an OD of 6" and active length of 44". The coil's axis of rotation was aligned with respect to the ID of the solenoid to within ±0.25 mm of x and y at both ends of the 324 mm-long magnet. The coil's measurement of the various multipole components is listed in Table I. None of these components appear to be anomalously large. The coil's measurement of the dipole component as a function of current is shown in Fig. 7. In principle the dipole field measurement will only depend on the tilt of the coil's axis of rotation with respect to the solenoid's magnetic axis and not on the transverse offset of one axis with respect to the other. This assumption was verified experimentally by measuring the dipole component as the coil was tilted and offset by known amounts, Figs. 8 and 9. Fig. 8 suggests that the magnetic axis might be tilted about 2.5 mr in the horizontal plane with respect to the mechanical axis. However the systematic error of these results is about 1.5 mr and more experience is needed with this procedure before any conclusions can be made. With a little practice and a some extra attention to alignment the rotating coil technique might be capable of determining the tilt of the magnetic axis with respect to the mechanical axis with an uncertainty approaching 1 mr.

Table I
Multipole components measured for S1 at 125 A.

Component	Amplitude	
n=1	$1.11\text{x}10^{-4}$	T-m
n=2	$2.27\text{x}10^{-4}$	T
n=3	$1.76\text{x}10^{-3}$	T/m
n=4	$2.92\text{x}10^{-2}$	T/m^2
n=5	$7.03\text{x}10^{-2}$	T/m^3

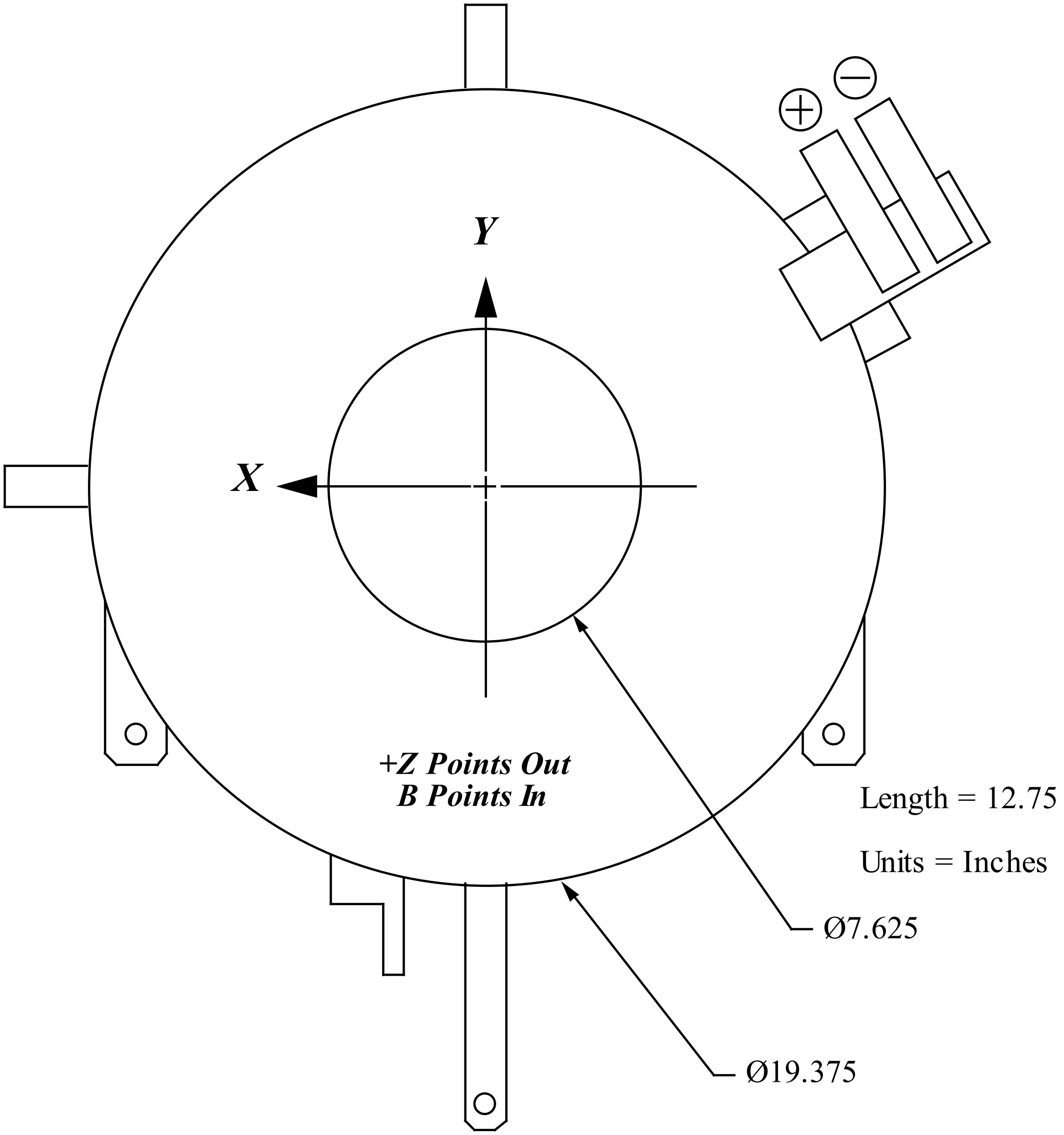


Fig. 1 A rough sketch of a S1, S3 and S4 solenoids. The magnet is held in this orientation by a set of kinematic mounts (not shown). X, Y and Z are defined to be zero at the center of the solenoid. The field points in the -z direction for the current polarity shown.

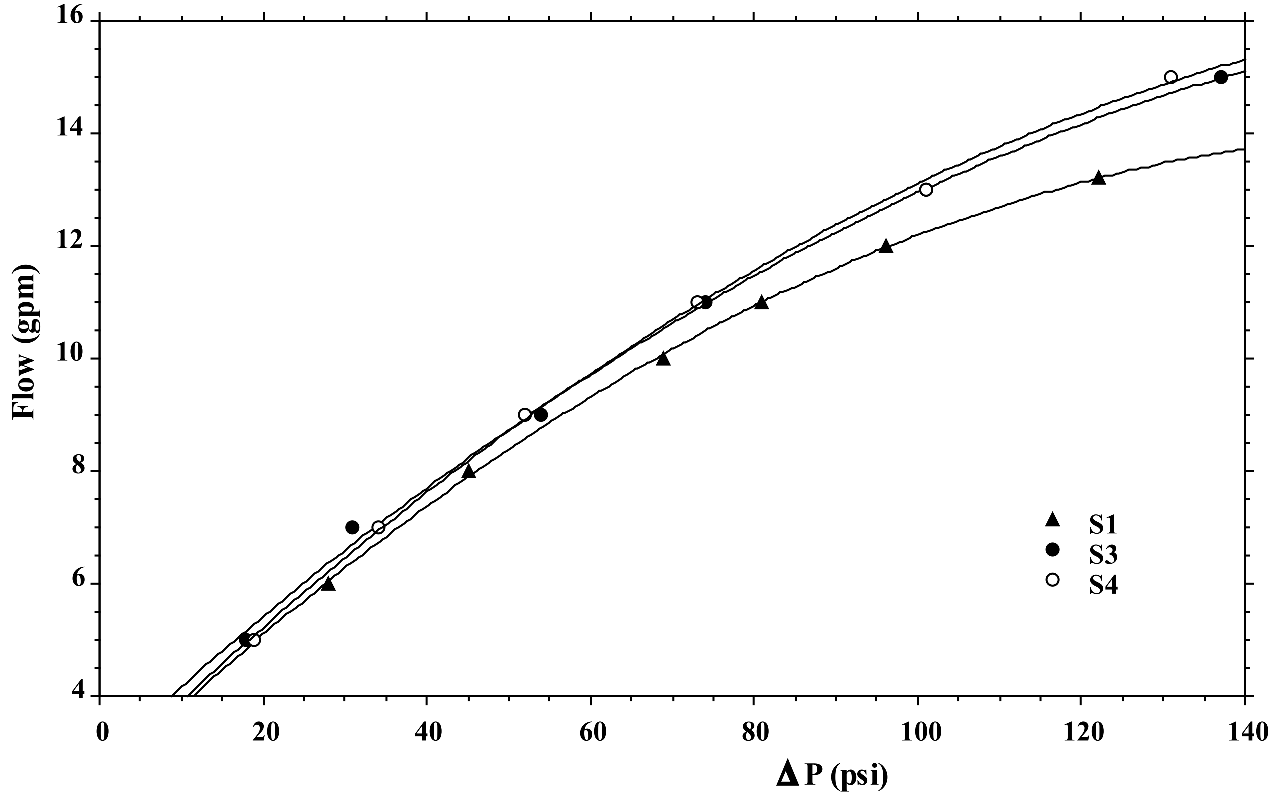


Fig. 2 Flow rate vs. pressure drop. Note that the water manifold of S1 was equipped with smaller fittings than that of S3 and S4.

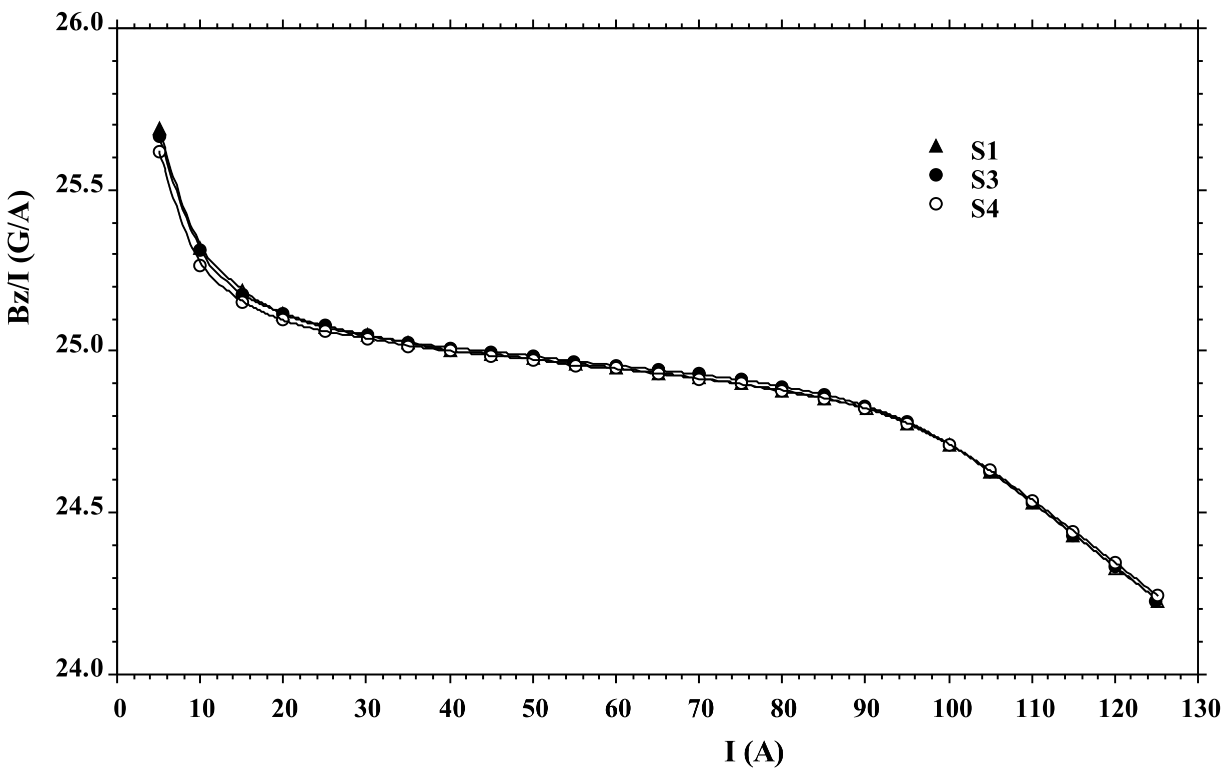


Fig. 3 B_o/I vs. I.

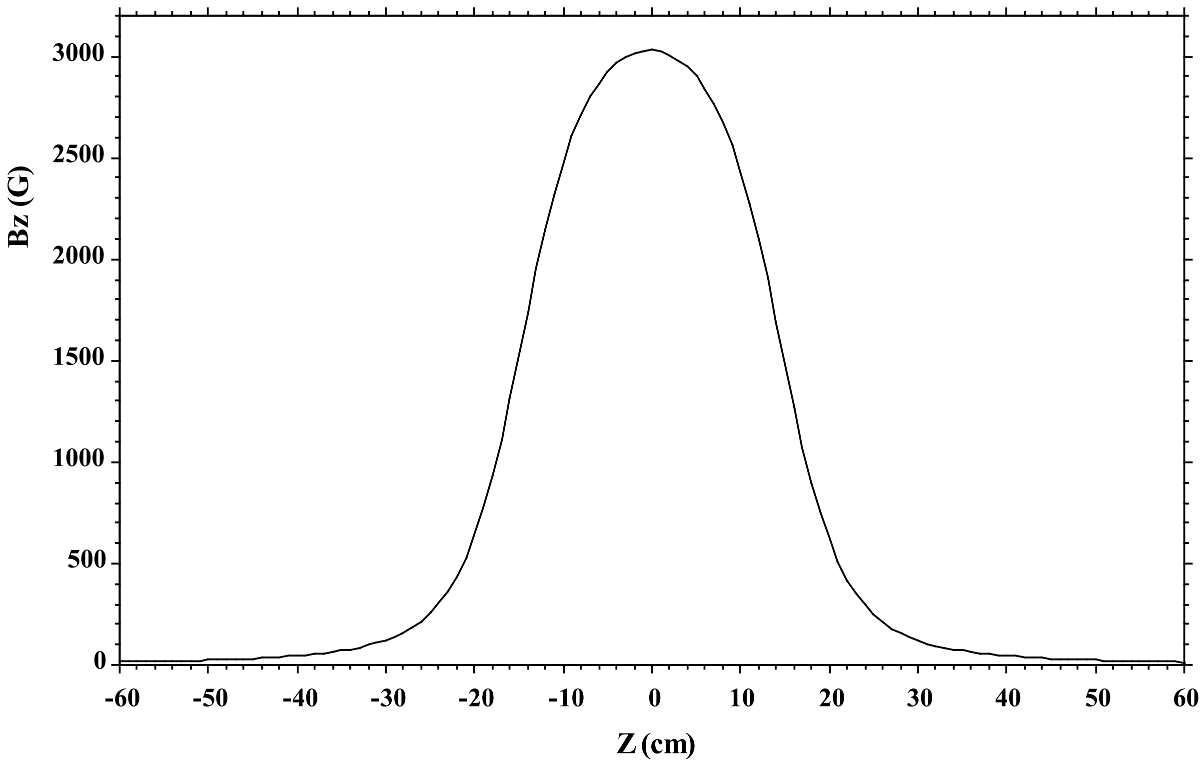


Fig. 4 A typical axial field measured along the *z* axis at a current of 125 A.

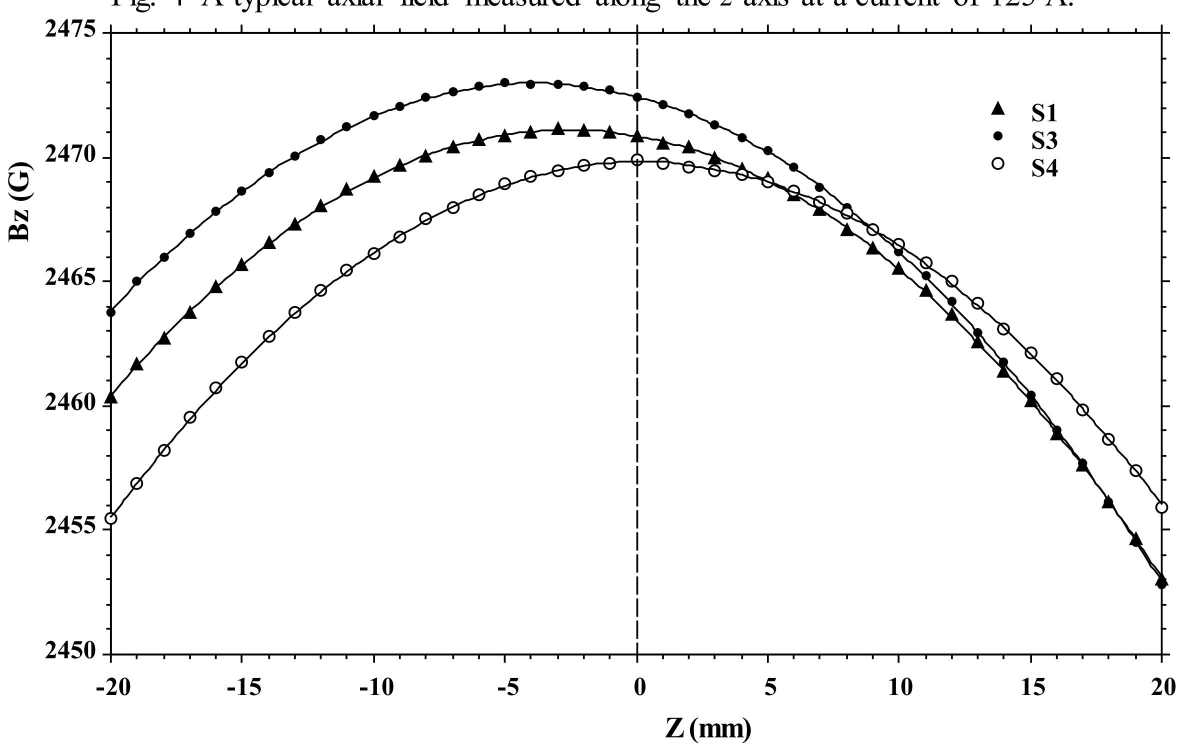


Fig. 5. B_z vs. z near z=0 measured at 100 A.

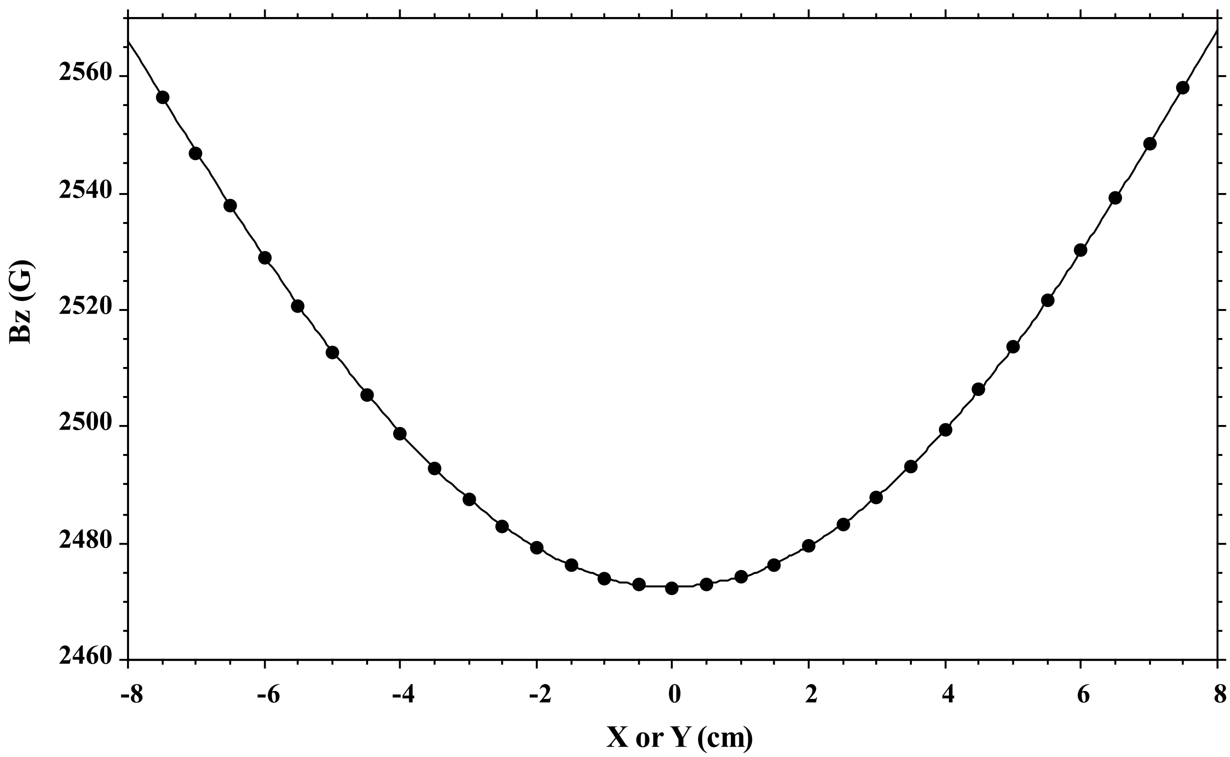


Fig. 6 A generic plot of the axial field measured along the *x* or *y* axes at a current of 100 A.

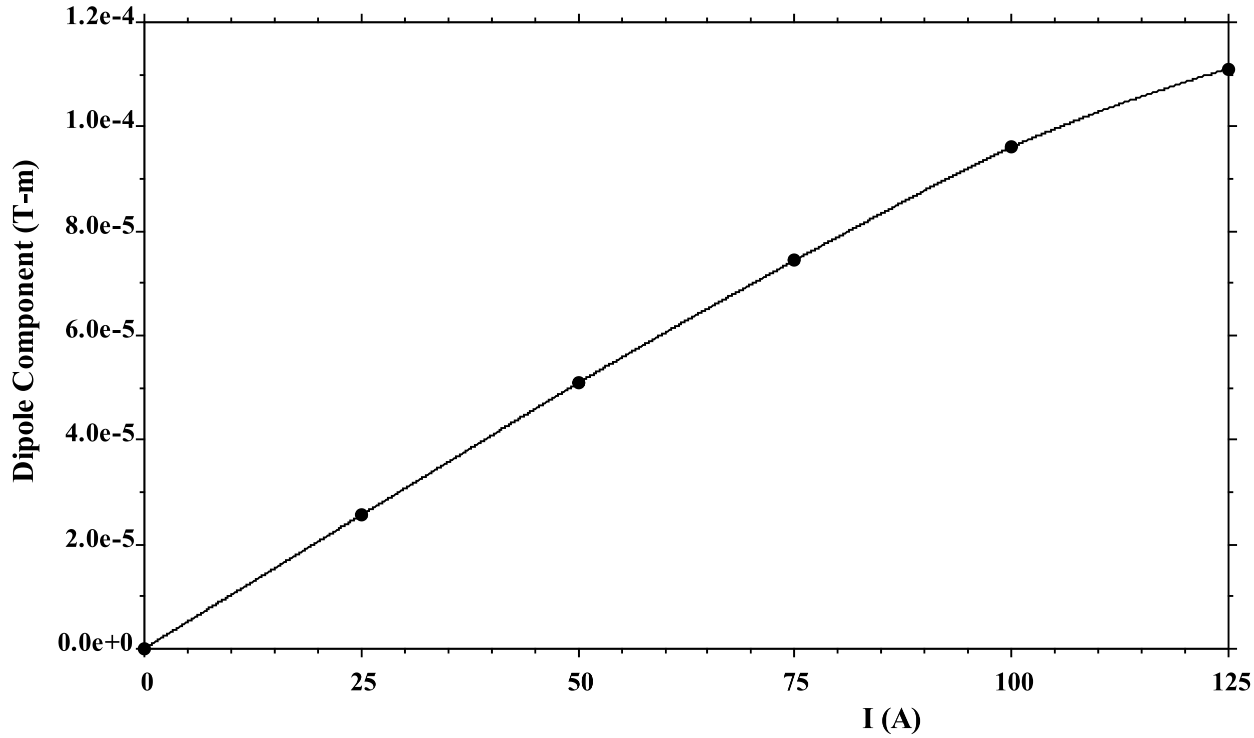


Fig. 7 The dipole component vs. current measured for S1. The 1.3×10^{-5} T-m contribution of the Earth's field, (measured with the magnet turned off), has been subtracted out.

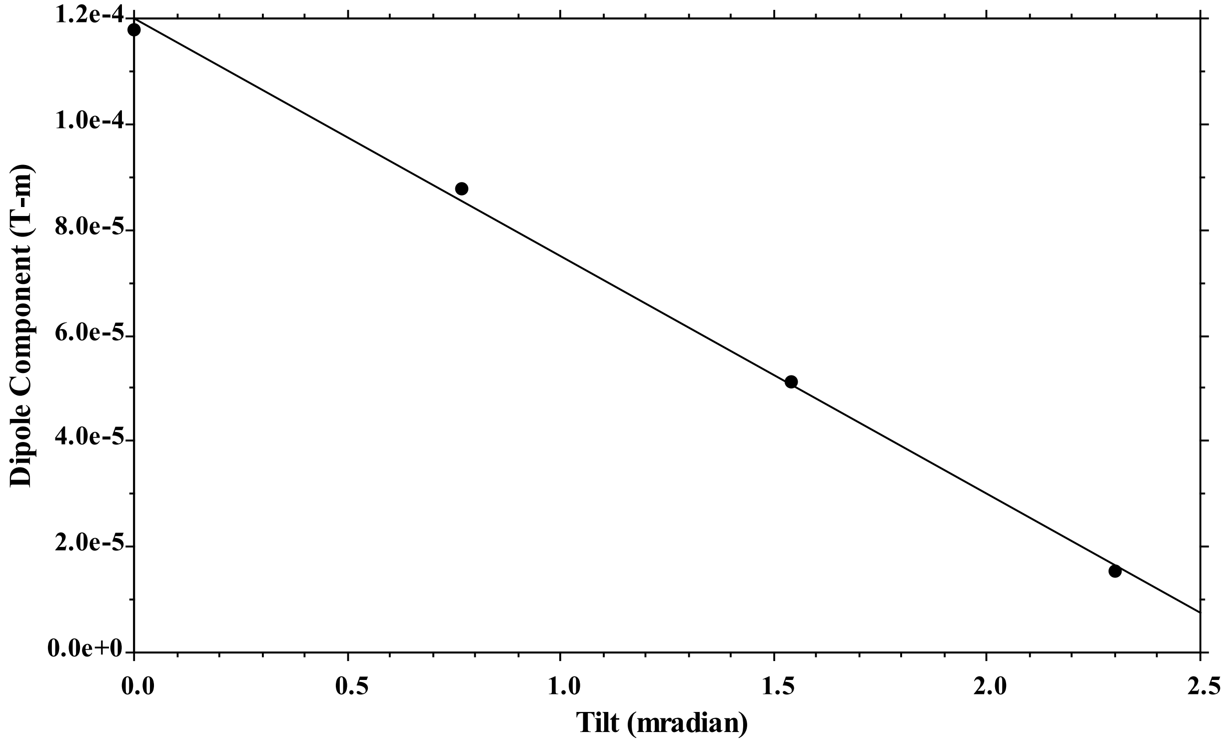


Fig. 8 The dipole field measured at 100 A as the coil's axis of rotation with respect to the magnet is tilted in the horizontal plane.

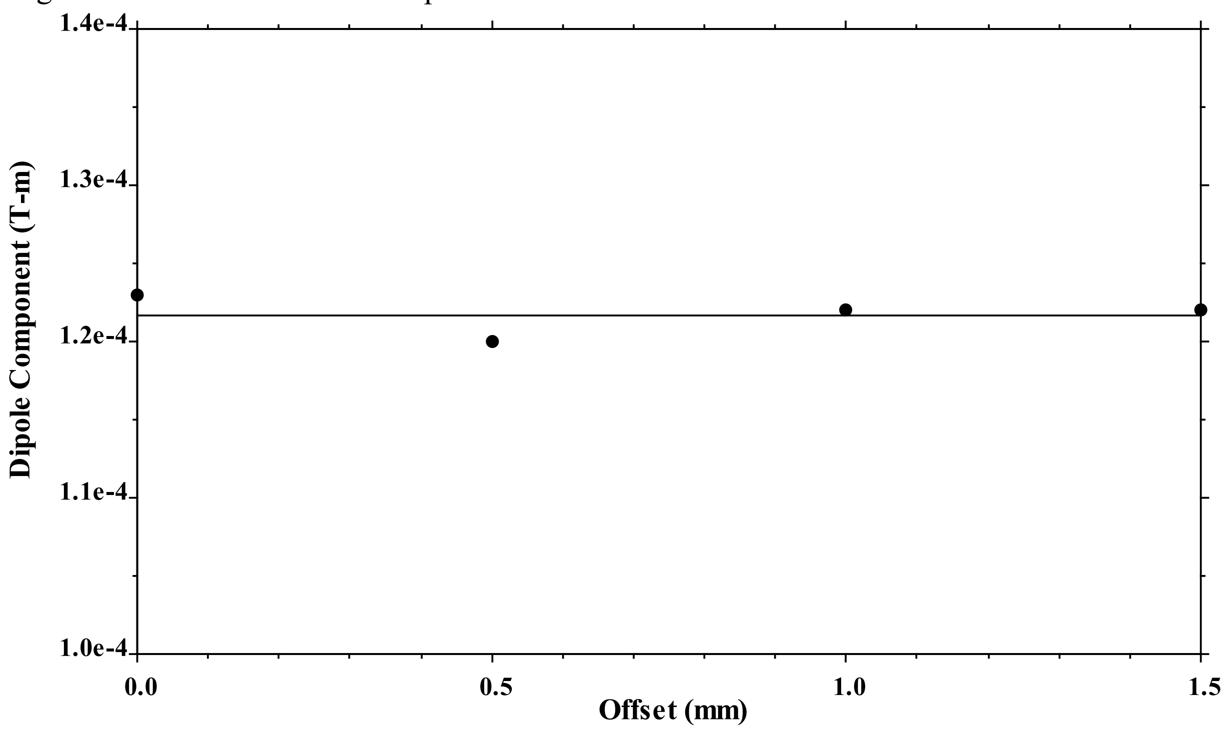


Fig. 9 The dipole field measured at 100 A as the coil's axis of rotation with respect to the magnet is offset in the horizontal plane.

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LANSCE-ABS File	LANSCE-ABS	H817

Appendix 2: LANSCE-ABS:05-019 (TN) - Dec. 19, 2005 – David Barlow
Tests and Measurements of the DARHT S2 Solenoid a.k.a. Curly

This memo will give a brief description of the measurements and results along with plots of the data. The actual tables of data are given in the accompanying spread sheet labeled "DARHT Solenoids.xls". A sketch of the DARHT S2 solenoid known as "Curly" is shown in Fig. 1.

Cooling and Power

A plot of the flow rate as a function of pressure drop for the magnet is shown in Fig. 2. At 450 A the voltage drop across the terminals of the magnet was measured to be 92 V at an average coil temperature of 92° F.

Conditioning

The magnet was conditioned prior to the start of the magnetic measurements by ramping the current at a rate of 2 A/s through the following cycle; 0 A $\rightarrow$ 550 A $\rightarrow$ 10 A $\rightarrow$ 550 A $\rightarrow$ 10 A $\rightarrow$ 550 A. The value of 10 A was used rather than 0 A to avoid transients that typically occur when the DC power is turned off and then back on. The magnet was always reenergized to 550 A before the start of every measurement sequence and measurements were always made on the downward branch of the hysteresis loop

Measurement Setup

The field was measured by a Group-3 Hall probe which can measure the field with a random uncertainty of 0.1 G and systematic uncertainty of about 1 G. The Hall probe was located on the tip of the boom of a three axis point mapper. The x, y, and z axes of the point mapper were aligned with respect to the mechanical axes of the solenoid with sufficient accuracy that the center of the active area of the Hall probe has an uncertainty of 1 mm in x, y and z with respect to the mechanical axes of the solenoid. The current was measured by a Danfysik "zero flux" current transducer. The error in the current measurement is less than 0.01 A.

Central Field

The axial field at the center of the solenoid was measured as a function of current. A plot of B_o/I vs. I is shown in Fig. 3.

Axial Field vs. Z

The axial field was measured along the mechanical axis of the solenoid at currents of 550 A down to 50 A in steps of 100 A with one final measurement at 0 A. A plot of B_z vs. z at 550 A is shown in Fig. 4. The integral of $B_z.dz$ is consistent with a 576 turn solenoid. Measurements of B_z vs. z near z=0 indicates that the magnetic and mechanical centers coincide within the 1 mm uncertainty of the measurements.

Axial Field vs. X and Y

The axial field was also measured along the x and y axes for z = 0, Fig. 5. These plots also indicate that the magnetic and mechanical centers coincide within the 1 mm uncertainty of the measurements.

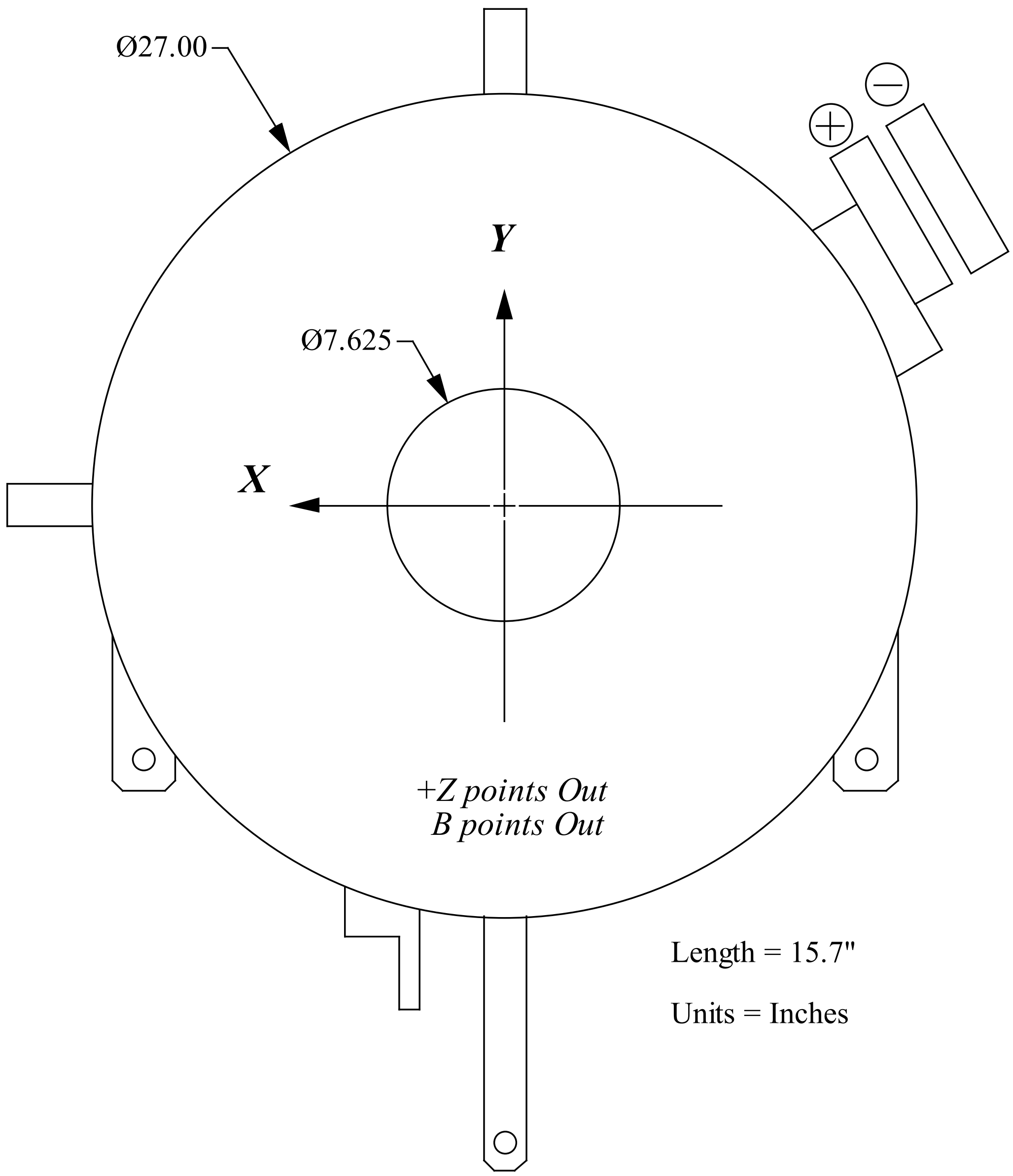

Fig. 1 A rough sketch of the S2 solenoid known as Curly. X, Y and Z are defined to be zero at the center of the solenoid. The solenoid is held in this orientation by a set of kinematic mounts (not shown). The field points in the $+z$ direction for the current polarity shown.

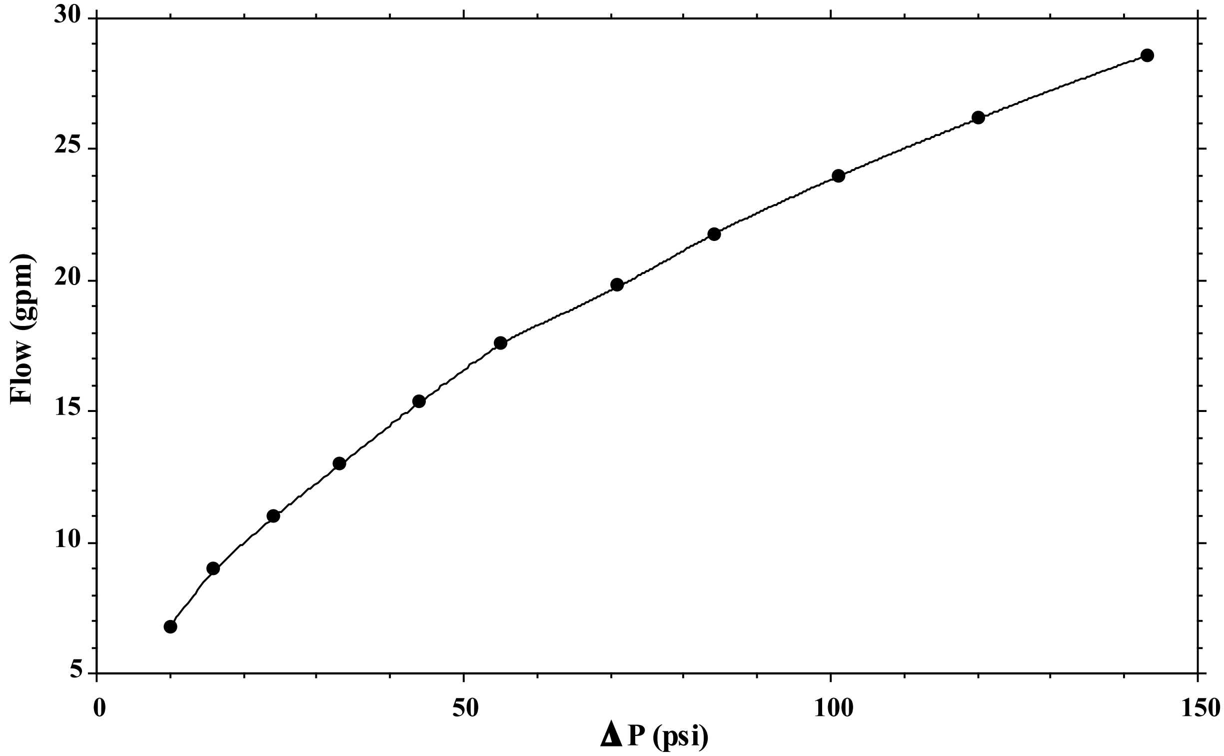

Fig. 2 Flow rate vs. pressure drop.

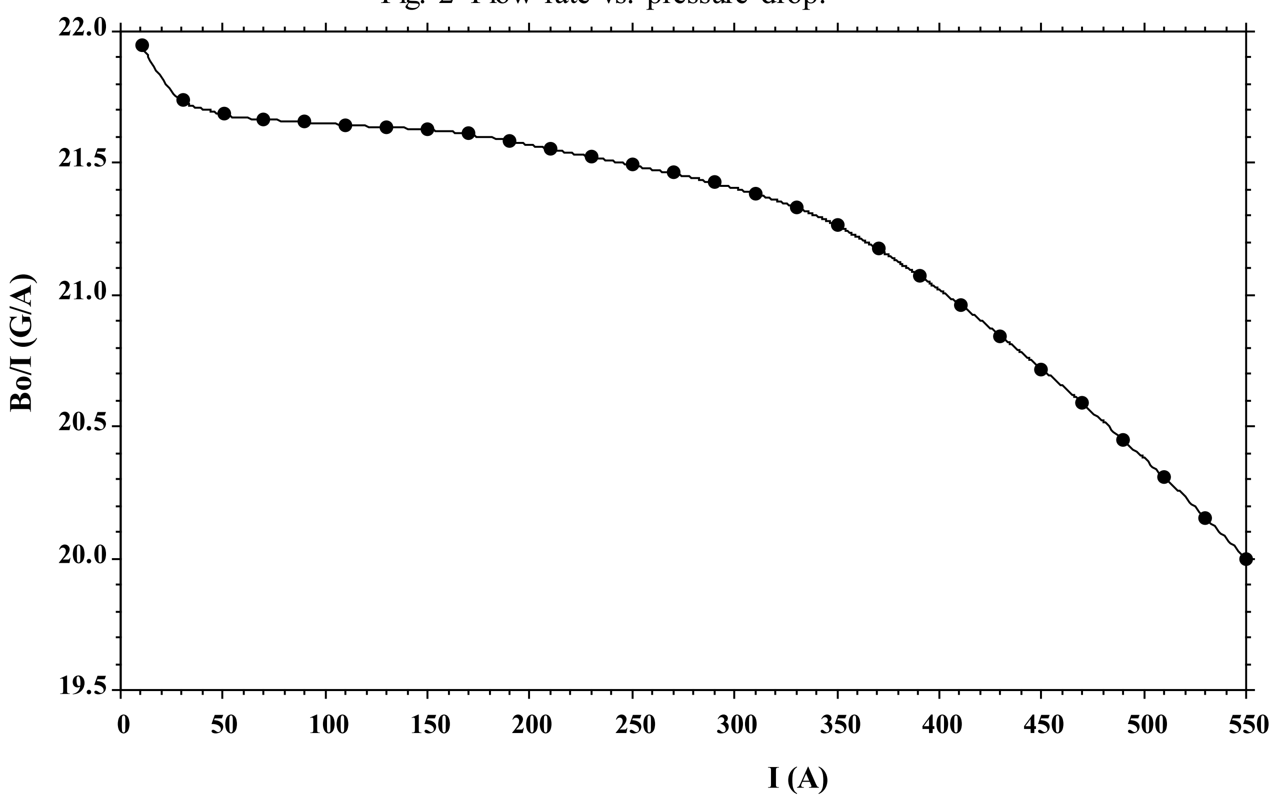

Fig. 3 B_o/I vs. I.

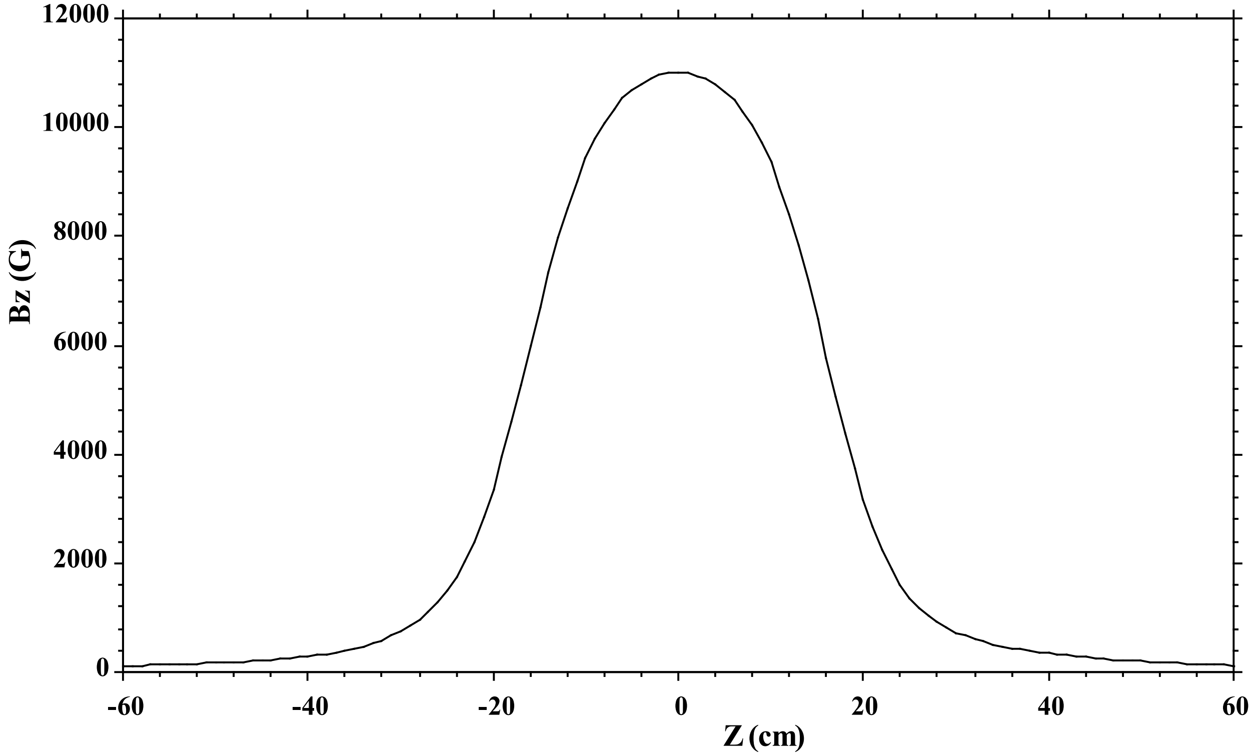

Fig. 4 Axial field measured along the z axis at a current of 550 A.

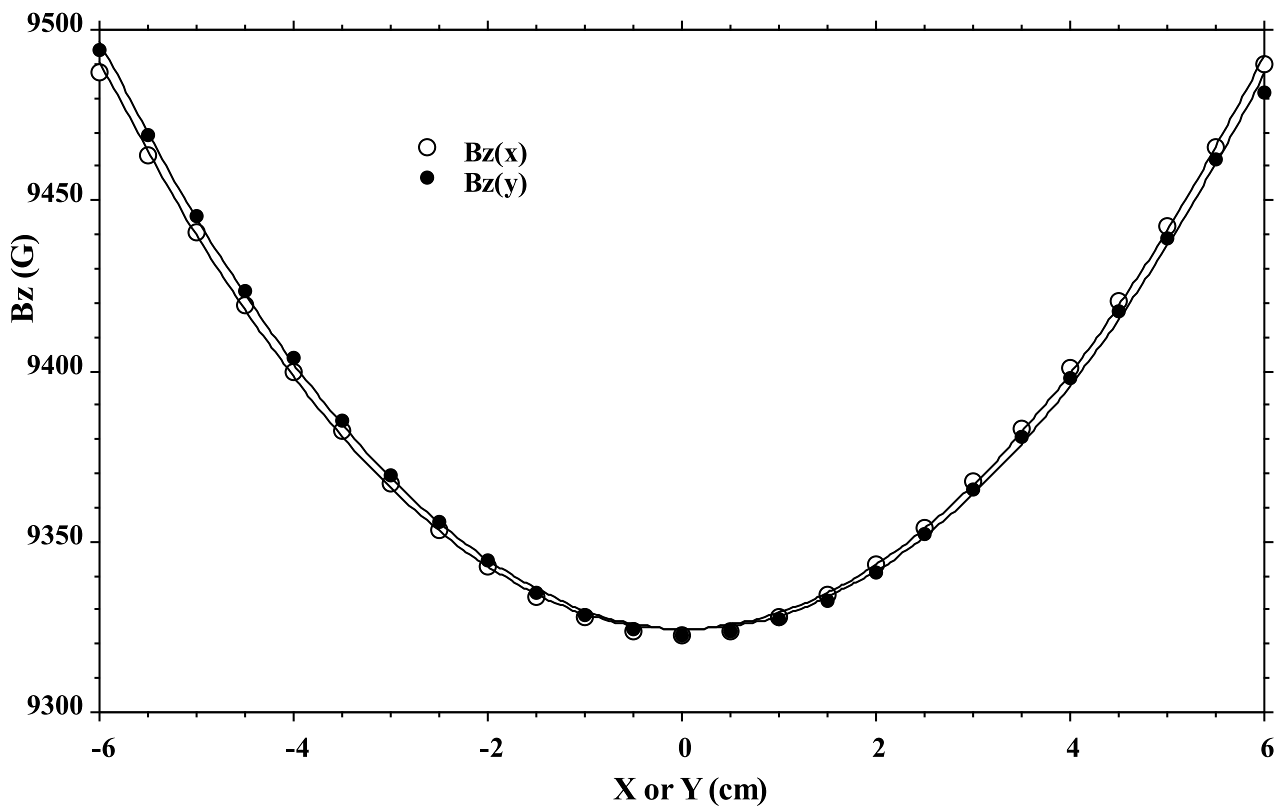

Fig. 5 Axial field measured along the x and y axes at a current of 450 A.

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Appendix 3: LANSCE-ABS:05-020 (TN) - Dec. 19, 2005 – David Barlow
Tests and Measurements of the DARHT Solenoid know as Moe a.k.a. Thor-003

This memo will give a brief description of the measurements and results along with plots of the data. The actual tables of data are given in the accompanying spread sheet labeled "DARHT Solenoids.xls". A sketch of the Moe a.k.a. Thor-003 is shown in Fig. 1.

Cooling and Power

A plot of the flow rate as a function of pressure drop for the magnet is shown in Fig. 2. At 100 A the voltage drop across the terminals of the magnet was measured to be 10 V at an average coil temperature of 81.5° F.

Conditioning

The magnet was conditioned prior to the start of the magnetic measurements by ramping the current at a rate of 2 A/s through the following cycle; 0 A → 125 A → 12 A → 125 A → 12 A → 125 A. The current was changed in 12.5 A steps with a 10 s pause between steps. The value of 12 A was used rather than 0 A to avoid transients that typically occur when the DC power is turned off and then back on. The magnet was always reenergized to 125 A before the start of every measurement sequence and measurements were always made on the downward branch of the hysteresis loop

Measurement Setup

The field was measured by a Group-3 Hall probe which can measure the field with a random uncertainty of 0.1 G and systematic uncertainty of about 1 G. The Hall probe was located on the tip of the boom of a three axis point mapper. The x, y, and z axes of the point mapper were aligned with respect to the mechanical axes of the solenoid with sufficient accuracy that the center of the active area of the Hall probe has an uncertainty of 1 mm in x, y and z with respect to the mechanical axes of the solenoid. The current was measured by a Danfysik "zero flux" current transducer. The error in the current measurement is less than 0.01 A.

Central Field

The axial field at the center of the solenoid was measured as a function of current. A plot of B_o/I vs. I is shown in Fig. 3.

Axial Field vs. Z

The axial field was measured along the mechanical axis of the solenoid at currents of 125 A down to 0 A in steps of 25 A. A plot of B_z vs. z at 125 A is shown in Fig. 4. The integral of $B_z.dz$ is consistent with a 156 turn solenoid. Measurements of B_z vs. z near z=0 indicates that the magnetic and mechanical centers coincide within the 1 mm uncertainty of the measurements.

Axial Field vs. X and Y

The axial field was also measured along the x and y axes for z = 0, Fig. 5. These plots also indicate that the magnetic and mechanical centers coincide within the 1 mm uncertainty of the measurements.

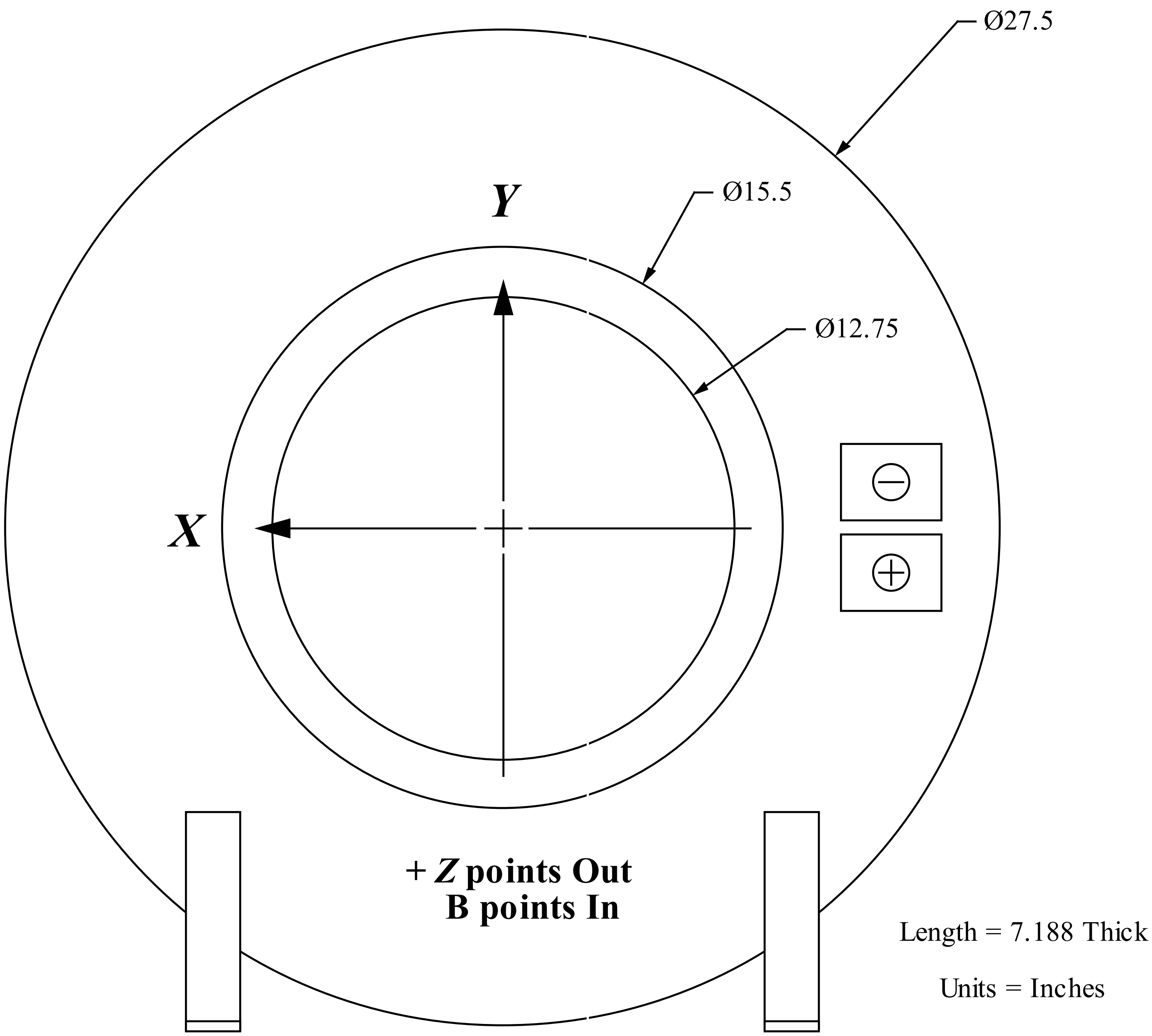

Fig. 1 A rough sketch of the solenoid known as Moe. X, Y and Z are defined to be zero at the center of the solenoid. The solenoid is equipped with a set five 0.25" thick by 12.75" ID homogenizer rings spaced on 1.5" centers. The field points in the -z direction for the current polarity shown.

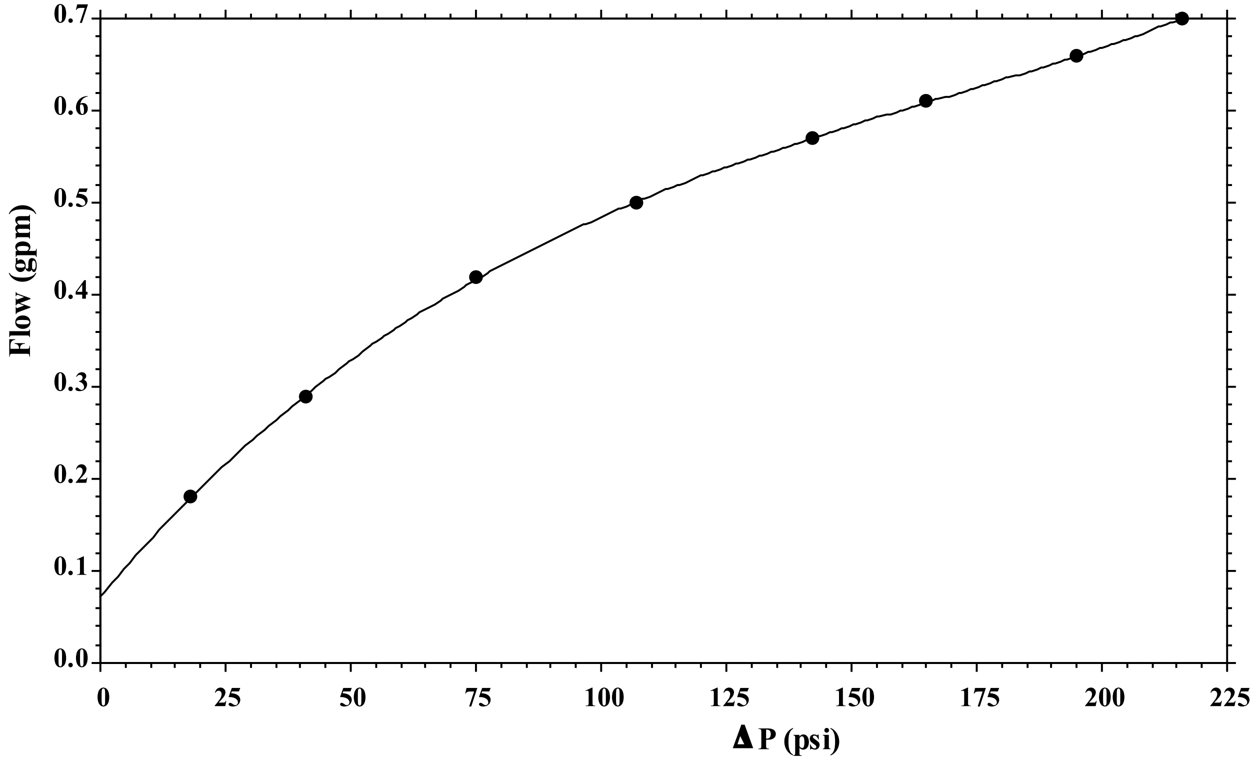

Fig. 2 Flow rate vs. pressure drop.

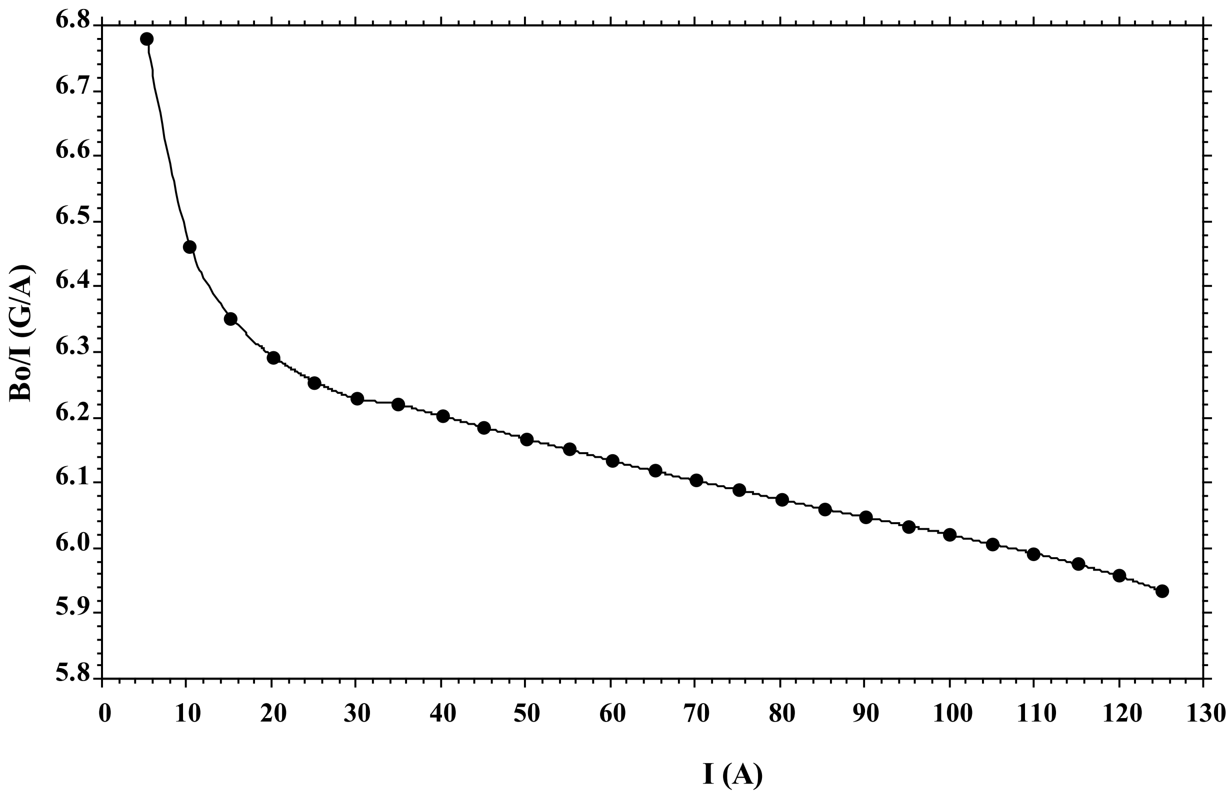

Fig. 3 B_o/I vs. I.

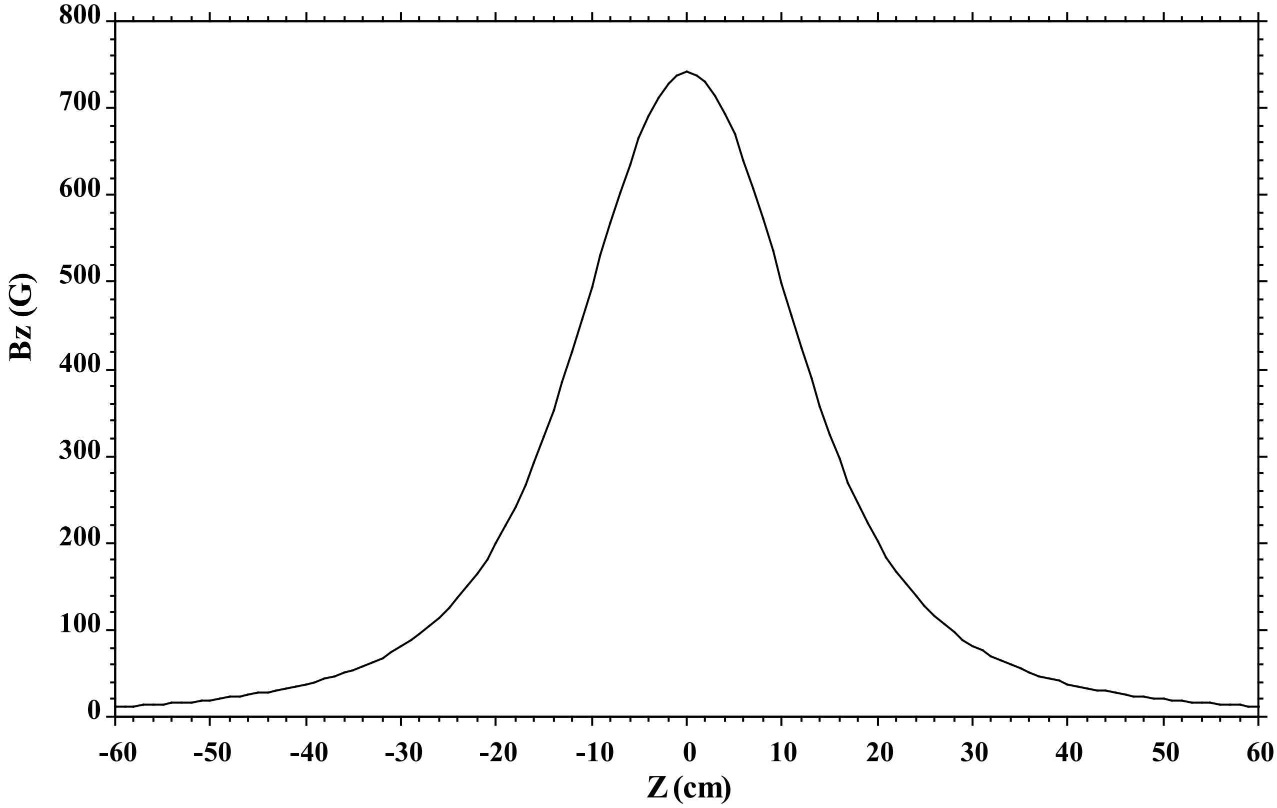

Fig. 4 Axial field measured along the *z* axis at a current of 125 A.

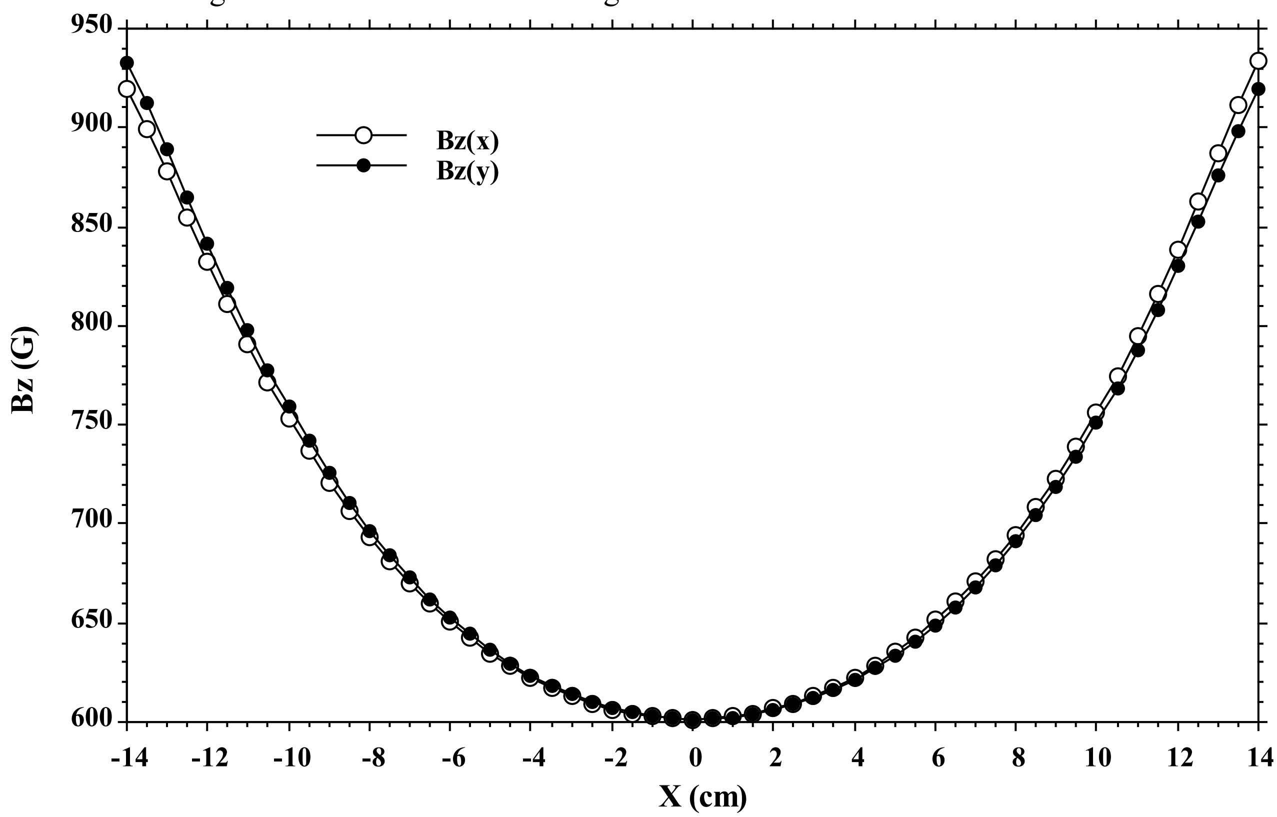

Fig. 6 Axial field measured along the *x* and *y* axes at a current of 125 A.

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Appendix 4: LANSCE-ABS:05-021 (TN) - Dec. 19, 2005 – David Barlow
Tests and Measurements of the DARHT Solenoid know as the AP Magnet

This memo will give a brief description of the measurements and results along with plots of the data. The actual tables of data are given in the accompanying spread sheet labeled "DARHT Solenoids.xls". A sketch of the AP Magnet is shown in Fig. 1.

Cooling and Power

A plot of the flow rate as a function of pressure drop for the magnet is shown in Fig. 2. At 700 A the voltage drop across the terminals of the magnet was measured to be 31.6 V at an average coil temperature of 91.5° F.

Conditioning

The magnet was conditioned prior to the start of the magnetic measurements by ramping the current at a rate of 2 A/s through the following cycle; 0 A $\rightarrow$ 725 A $\rightarrow$ 10 A $\rightarrow$ 725 A $\rightarrow$ 10 A $\rightarrow$ 725 A. The value of 10 A was used rather than 0 A to avoid transients that typically occur when the DC power is turned off and then back on. The magnet was always reenergized to 725 A before the start of every measurement sequence and measurements were always made on the downward branch of the hysteresis loop

Measurement Setup

The field was measured by a Group-3 Hall probe which can measure the field with a random uncertainty of 0.1 G and systematic uncertainty of about 1 G. The Hall probe was located on the tip of the boom of a three axis point mapper. The x, y, and z axes of the point mapper were aligned with respect to the mechanical axes of the solenoid with sufficient accuracy that the center of the active area of the Hall probe has an uncertainty of 1 mm in x, y and z with respect to the mechanical axes of the solenoid. The current was measured by a Danfysik "zero flux" current transducer. The error in the current measurement is less than 0.01 A.

Central Field

The axial field at the center of the solenoid was measured as a function of current. A plot of B_o/I vs. I is shown in Fig. 3.

Axial Field vs. Z

The axial field was measured along the mechanical axis of the solenoid at currents of 725 down to 625 A in steps of 25 A with one final measurement at 0A. A plot of B_z vs. z at 725 A is shown in Fig. 4. The integral of $B_z.dz$ is consistent with a 144 turn solenoid. Measurements of B_z vs. z near z=0 indicates that the magnetic and mechanical centers coincide within the 1 mm uncertainty of the measurements.

Axial Field vs. X and Y

The axial field was also measured along the x and y axes for $z = 0$, Fig. 5. These plots also indicate that the magnetic and mechanical centers coincide within the 1 mm uncertainty of the measurements.

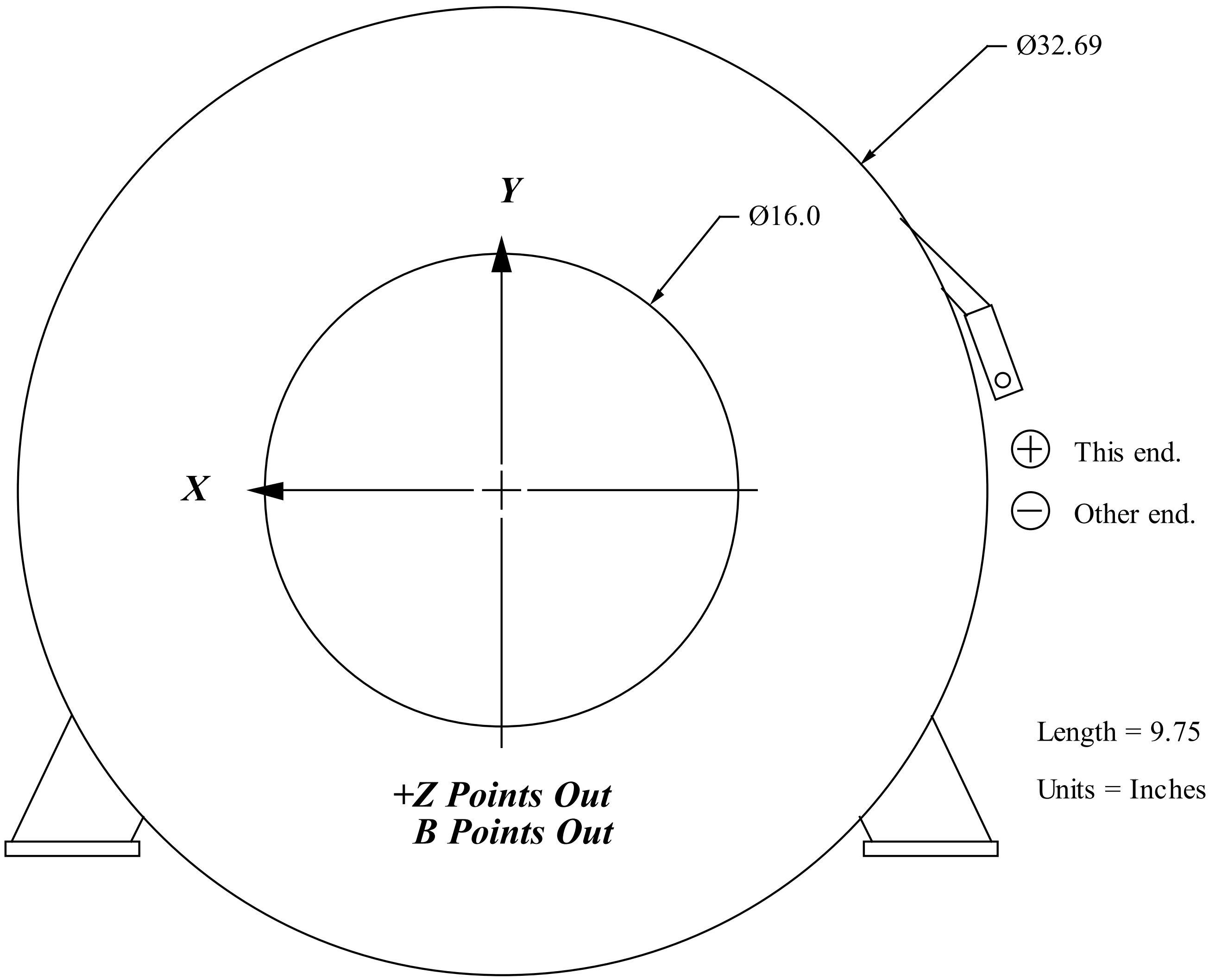

Fig. 1 A rough sketch of the AP Magnet. X, Y and Z are defined to be zero at the center of the solenoid. The field points in the $+z$ direction for the current polarity shown.

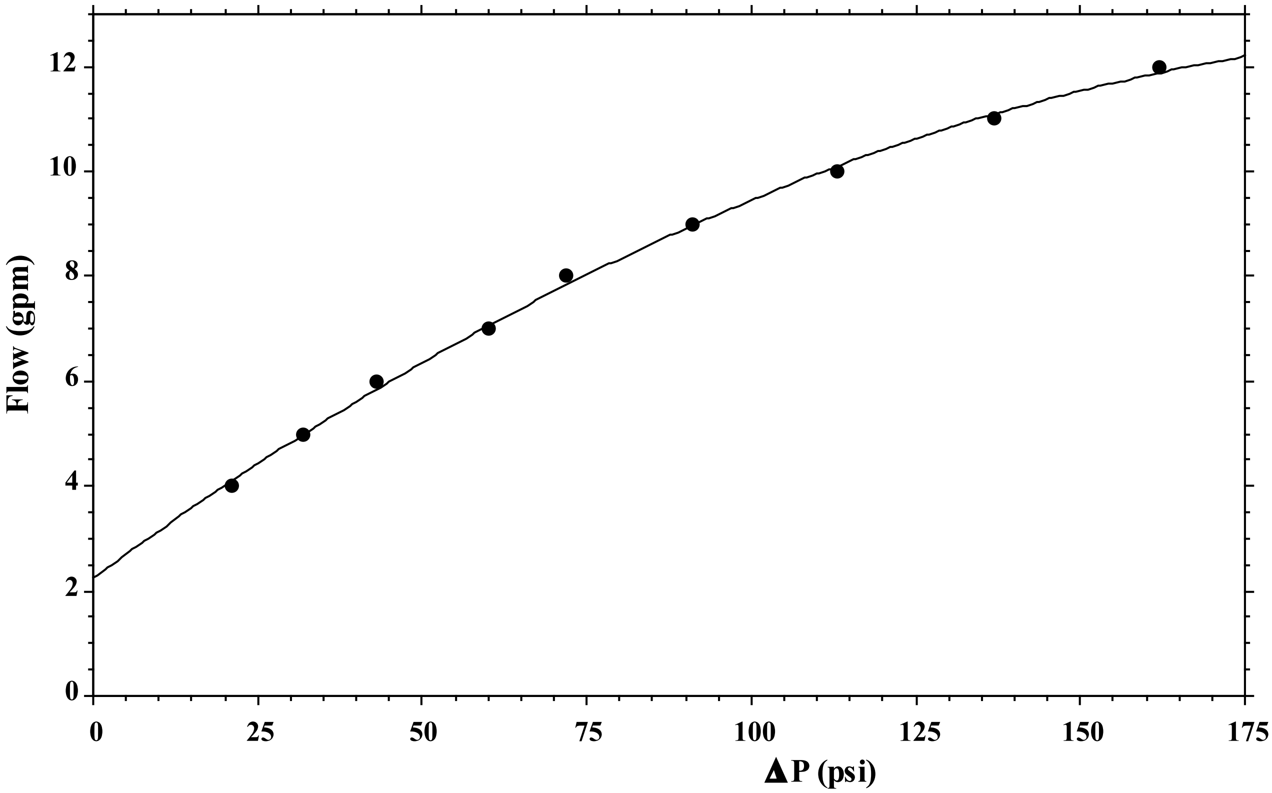

Fig. 2 Flow rate vs. pressure drop.

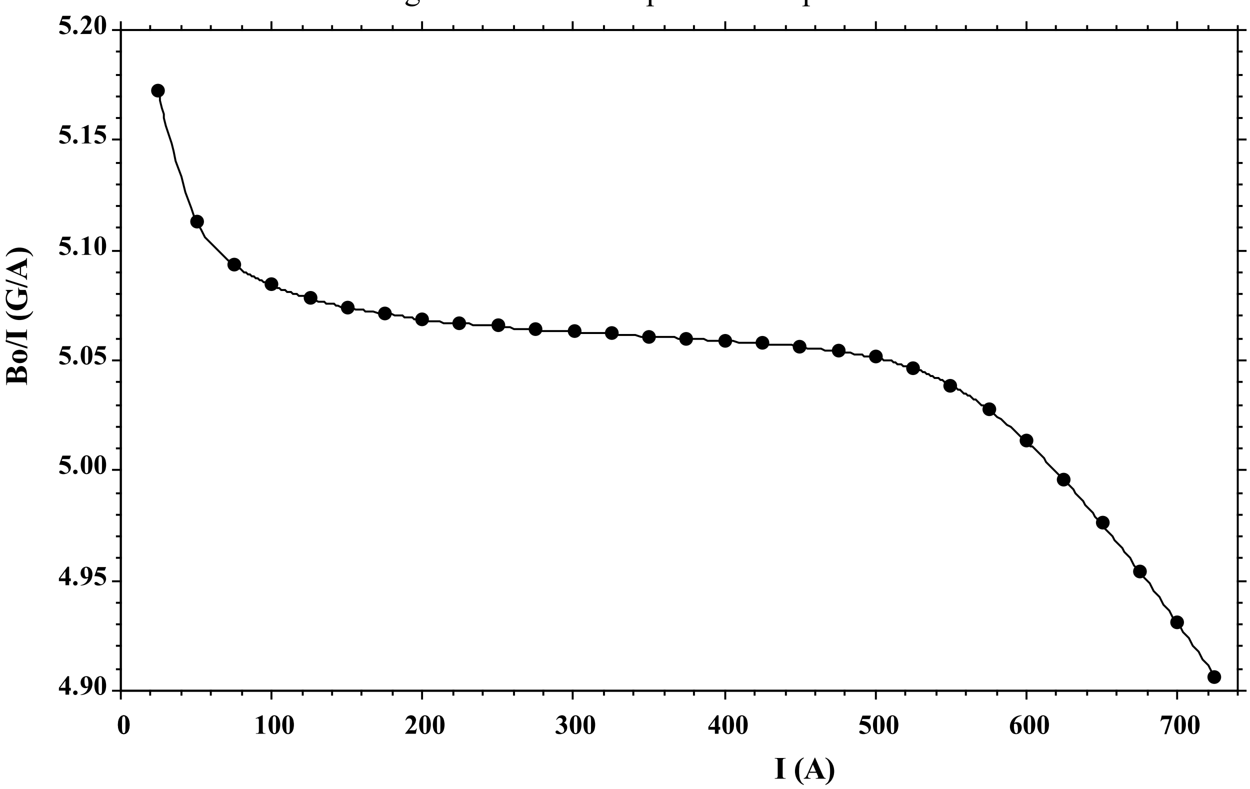

Fig. 3 B_o/I vs. I.

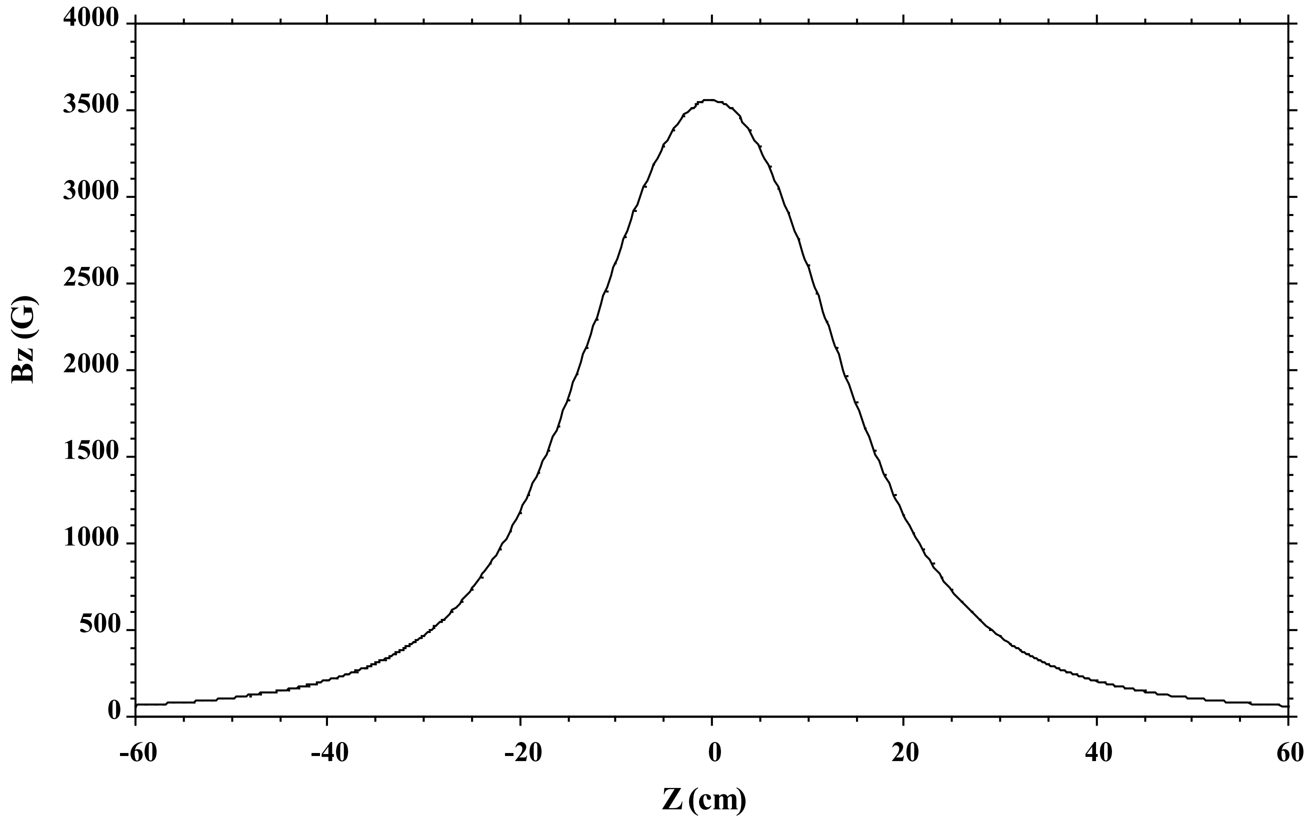

Fig. 4 Axial field measured along the *z* axis at a current of 725 A.

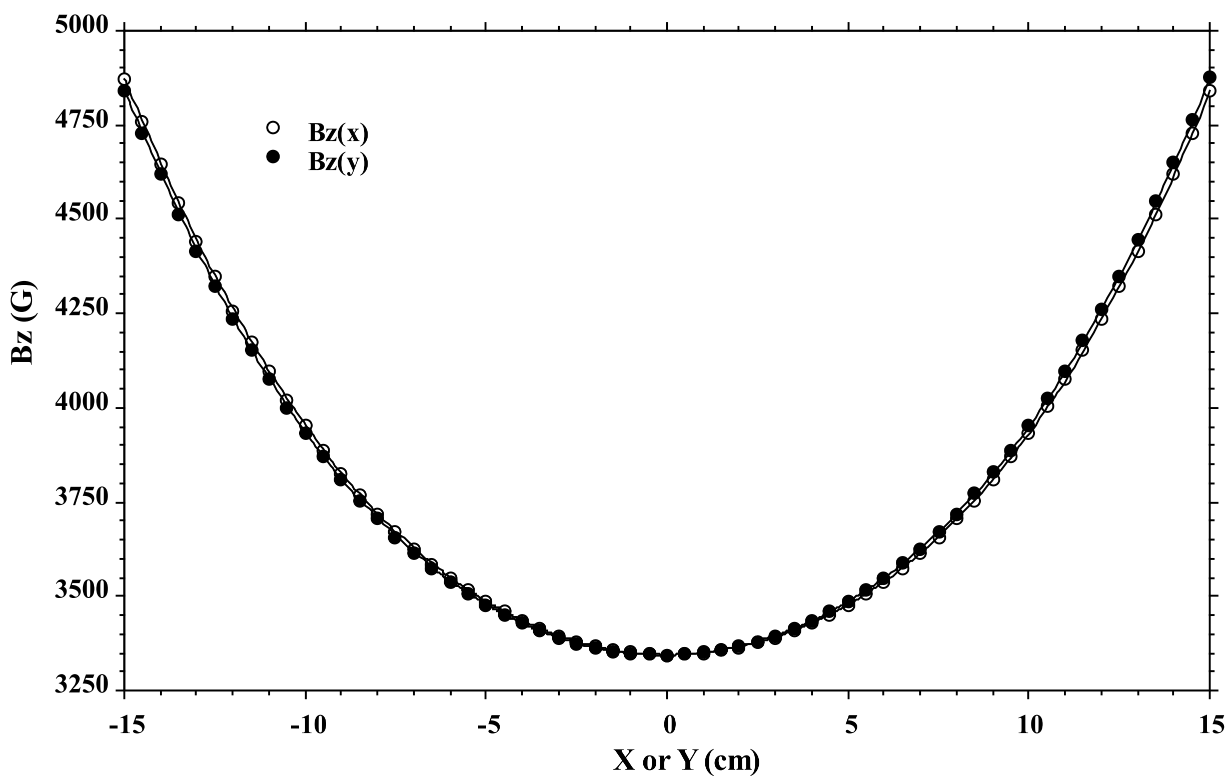

Fig. 5 Axial field measured along the *x* and *y* axes at a current of 675 A.

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