Using Spin Precession to Infer the Strength of Solenoid MFL0I07

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Abstract
Precession of the radial component of the electron beam polarization passing through the CEBAF injector solenoid MFL0I07 is used to measure the integrated axial magnetic field of the magnet. A measurement of the precession provides a means to infer the presently unknown number of coil windings and thus a means to model and predict the magnetic strength of this element.

Introduction
CEBAF solenoid MFL0I07 focuses the electron beam into the cryounit, yet the strength of the magnet is unknown. Also referred to as "Lens7" or "500keV solenoid" the external dimensions of MFL0I07 exactly match that of JLAB DWG 34131-0003 (March 1989). Unfortunately, the winding number of the two internal coils is not mentioned. The only reference to winding number is a personal logbook entry from July 1995 [1] indicating both coils were re-wound for 600 turns. To verify this requires removing the magnet for inspection, which is cumbersome. Instead, the magnetic strength may be inferred from either the effect of the magnet on the beam size (focusing) or polarization (precession). The latter is approach is taken in this note.

The precession of the transverse component of the beam polarization is proportional to the integral of the longitudinal solenoid field along the near-axial path the beam takes traversing the magnet and is given by,

$$\eta_\varphi = \frac{ge}{2p}\int B_z\, dz \qquad (Eq.1),$$

where $g=2.002319$ is the electron gyromagnetic factor, e the electronic charge, p the beam momentum and B_z is the longitudinal magnetic field component. The CEBAF Mott polarimeter is ideally suited to determine the precession angle by measuring the transverse component of the beam polarization (P_x and P_y) with angular resolution of <1˚. Thus, for known configurations of the solenoid and beam polarization the axial field integral ($\int B_z\, dz$) may be calculated. This value is simply proportional to the coil winding number, where the constant of proportionality is given by modeling the solenoid form factor using the given drawing.

Modeling MFL0I07 in POISSON

An ironic complication is that MFL0I07 is a so-called counter-wound (CW) solenoid. In the CW configuration the two coils produce opposing fields to purposefully null the field integral ($\Delta\phi = \frac{ge}{2p}\int B_z\, dz = 0$) and have no effect on the beam polarization. However, reversing the leads of one coil produces a single-wound (SW) configuration, allowing the non-zero measurement to be made. The POISSON model of MFL0I07 derived from the drawing is provided in Appendix A where drawing dimensions are rounded to 0.05 cm (<2 mil). For clarity, the SW and CW configuration magnetic profiles (assumes 600 A-turn) are shown in Fig. 1.

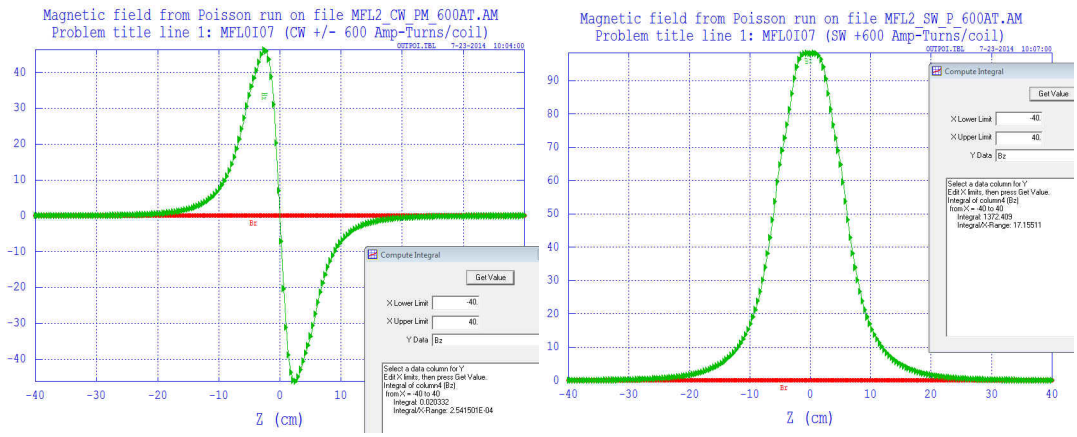

Fig. 1. With 600 turns/coil the usual CW configuration (left) provides a null integral, whereas the temporary SW configuration (right) produces 1372 G-cm.

Measurement of the Spin Precession

Mott measurements were made in one polarity of the CW configuration and both polarities of the SW configuration. For each configuration four runs were made, alternately reversing the sign of the beam polarization using an optical wave-plate (either *IN* or *OUT)* at the polarized source. The Mott runs are summarized in Table 1.

Table 1. Vertical (P_y) and horizontal (P_x) components of the beam polarization were measured for various conditions of MFL0I07 and optical wave-plate (IHWP).

Run	*Config*	*PS [mA]*	*IHWP*	P_y *(%)*	σ_{Py} *(%)*	P_x *(%)*	σ_{Px} *(%)*
7673	CW	2240	OUT	91.45	2.35	2.12	2.30
7674	CW	2240	IN	-83.92	2.40	-4.00	2.34
7675	CW	2240	OUT	89.07	2.37	5.38	2.31
7676	CW	2240	IN	-87.38	2.39	-4.55	2.32
7677	SW	1400	OUT	73.02	2.39	-51.62	2.22
7678	SW	1400	IN	-73.97	2.25	49.46	2.12
7679	SW	1400	OUT	71.73	2.42	-54.37	2.25
7680	SW	1400	IN	-70.90	2.43	52.19	2.27
7681	SW	-1400	OUT	68.48	2.37	56.66	2.22
7682	SW	-1400	IN	-65.01	2.48	-57.02	2.29
7683	SW	-1400	OUT	66.65	2.50	52.47	2.31

7684	SW	-1400	IN	-63.21	2.51	-57.28	2.31

For each configuration the four runs are statistically averaged (taking into account the wave-plate reversal) and the azimuthal angle of the beam polarization is computed as $\phi = \tan^{-1}\left(\frac{P_y}{P_x}\right)$. Finally, the precession angle between the non-zero SW configurations and the null CW configuration $\Delta\phi = \phi_{SW} - \phi_{CW}$ may be calculated, (see Table 2).

Table 2. The azimuthal angle (ϕ) of the beam polarization as determined from Mott measurements in shown above, followed by the calculated precession angle (Δϕ) between either of SW and the CW configuration.

Measured Azimuthal Angle	ϕ	σ_ϕ
CW +2400 mA	87.39°	0.46°
SW +1400 mA	125.57°	0.45°
SW -1400 mA	49.71°	0.47°
Calculated Spin Precession Angle	$\Delta\phi$	$\sigma_{\Delta\phi}$
(SW +1400) - (CW +2400)	38.18° ccw	0.65°
(SW -1400) - (CW +2400)	37.68° cw	0.66°

The SW (+1400 mA) configuration is found to have rotated the polarization counter-clockwise (ccw) by 38.18°. The sense of rotation is consistent with the sign of the axial magnetic field (Bz < 0), indicated by careful Hall probe measurements over the entrance and exit steel surfaces. When reversing the solenoid polarity SW (-1400 mA) the beam polarization precessed in the opposite clockwise direction (Bz > 0) by a similar amount 37.68°. For clarity, the measured azimuthal angles for the three configurations are depicted in Fig. 2.

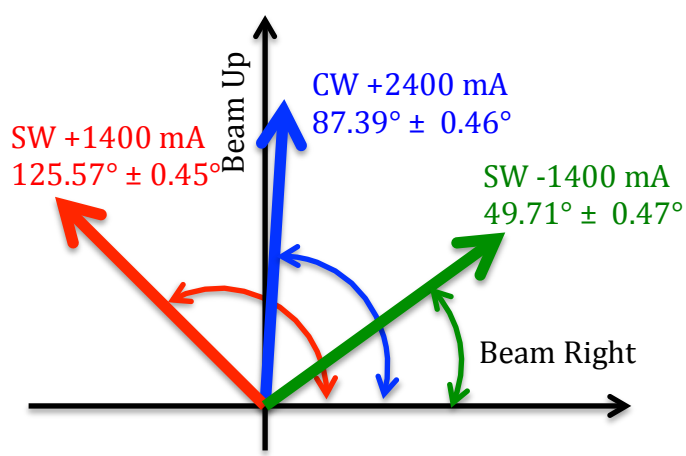

Fig. 2. Measured azimuthal orientation of the transverse polarization for the three configurations.

Measurement of Beam Momentum

In order to determine the axial magnetic field integral the beam momentum must be known. The momentum was measured [2] using the 1D spectrometer by comparing the spectrometer dipole MBO0I06 control value of the un-deflected beam (9.2 G-cm) against the value necessary (1699.0 G-cm) to deflect the beam +30° to the end of the spectrometer. The systematic uncertainty of the dipole magnet is 0.5% based upon the most recent 2006 analysis [3] to quantify reproducibility, field uniformity and account for nearly ~4% saturation at this operating set point. The systematic uncertainty in bend angle is 2.1% based upon positioning the beam within 1 cm of ideal coordinates at the various viewers used to establish the beam deflection. Finally, the beam momentum is determined to be p = 1.01 $\pm$ 0.02 MeV/c.

Calculation of Axial Magnetic Field and Coil Winding of MFL0I07

Using Eq. 1 the axial magnetic field integral is computed for both SW configuration polarities and reported in Table 3. The average value at 1400 mA is 2234.4 +/- 61.0 G-cm.

Table 3. Axial magnetic field integrals computed using Eq. 1.

MFL0I07	BL (G-cm)	σ_{BL} (G-cm)
(SW +1400) - (CW +2400)	2249.0	58.7
(SW -1400) - (CW +2400)	-2220.0	58.7
Average	*2234.5*	*41.5*

Finally, the winding number may be calculated by comparing the measured and modeled parameters like so,

$$N_{windings} = \frac{(BL)_{meas}/I_{meas}}{(BL)_{model}/I_{model}} = \frac{\frac{(2234.5 \pm 41.5)\ G-cm}{(1.400\ \pm 0.010)\ A}}{\frac{1372\ G-cm}{600\ A}} = (698\ \pm 14)$$

Conclusion

Measurement of the precession of the transverse component of the beam polarization while passing through a solenoid magnet is measured. Along with a model of the magnet using POISSON the winding number of the internal coils is determined to be 698 $\pm$ 14 turns. Given that coils are often specified in "round" numbers it is quite reasonable to infer the coils were specified for 700 turns (rather than the 600 mentioned in Ref. [1]). Given sufficient scrutiny it is reasonable that MFL0I07 may now be modeled with greater confidence for use in the control system and modeling of the CEBAF injector.

References

[1] C. Sinclair, CEBAF Logbook #1.
[2] Y. Wang, https://logbooks.jlab.org/entry/3276850
[3] K. Baggett, M. Beck, T. Hiatt, K. Sullivan, "*BO Magnet Measurement Results June, 2006*", JLAB-TN-06-038 (August, 2006)

Appendix A – POISSON deck for MFL0I07
MFL0I07 (JLAB DWG 34131-0003, tolerance 0.05cm)

```
&
reg kprob=0,          ! Poisson or Pandira problem
mode=-1,              ! Materials have fixed permeability
icylin=1,             ! Cylindrical symmetry
dx=.025,dy=.025,      ! Mesh size intervals
nbslo=0,              ! Dirichlet boundary condition on lower edge
nbsup=0,              ! Dirichlet boundary condition on upper edge
nbslf=0,              ! Dirichlet boundary condition on left edge
nbsrt=0,              ! Dirichlet boundary condition on right edge

XMINF=0., XMAXF=0., YMINF=-40, YMAXF=40,
LMIN=1, LTOP=200, KMIN=1, KTOP=1,

; Define X (physical) and K (logical) line regions:
xreg1=2.0, kreg1=20, xreg2=10.0, kreg2=75, kmax=150,

; Define Y (physical) and L (logical) line regions:
yreg1=-5, lreg1=50,  yreg2=5, lreg2=150, lmax=200

 $PO X=00.0,Y=-40.0$
 $PO X=20.0,Y=-40.0$
 $PO X=20.0,Y=+40.0$
 $PO X=00.0,Y=+40.0$
 $PO X=00.0,Y=-40.0$

 $REG MAT=2,NPOINT=9$
 $PO X=1.90,Y=+0.65$
 $PO X=2.55,Y=+0.65$
 $PO X=2.55,Y=+0.30$
 $PO X=8.90,Y=+0.30$
 $PO X=8.90,Y=-0.30$
 $PO X=2.55,Y=-0.30$
 $PO X=2.55,Y=-0.65$
 $PO X=1.90,Y=-0.65$
 $PO X=1.90,Y=+0.65$

 $REG MAT=2,NPOINT=9$
 $PO X=1.90,Y=+0.65$
 $PO X=1.90,Y=+4.15$
 $PO X=8.90,Y=+4.15$
 $PO X=8.90,Y=+0.30$
 $PO X=8.25,Y=+0.30$
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$PO X=8.25,Y=+3.50$
$PO X=2.55,Y=+3.50$
$PO X=2.55,Y=+0.65$
$PO X=1.90,Y=+0.65$

$REG MAT=2,NPOINT=9$
$PO X=1.90,Y=-0.65$
$PO X=1.90,Y=-4.15$
$PO X=8.90,Y=-4.15$
$PO X=8.90,Y=-0.30$
$PO X=8.25,Y=-0.30$
$PO X=8.25,Y=-3.50$
$PO X=2.55,Y=-3.50$
$PO X=2.55,Y=-0.65$
$PO X=1.90,Y=-0.65$

$REG MAT=1,CUR=700,NPOINT=5$
$PO X=2.80,Y=0.60$
$PO X=2.80,Y=3.25$
$PO X=8.00,Y=3.25$
$PO X=8.00,Y=0.60$
$PO X=2.80,Y=0.60$

$REG MAT=1,CUR=700,NPOINT=5$
$PO X=2.80,Y=-0.60$
$PO X=2.80,Y=-3.25$
$PO X=8.00,Y=-3.25$
$PO X=8.00,Y=-0.60$
$PO X=2.80,Y=-0.60$
```