

# Quadrupole Information for the Møller Polarimeter in Hall A

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## Abstract

This is intended to be a summary of the existing information for the Hall A Møller quadrupole magnets.

## 1 Introduction

The Hall A Møller polarimeter was originally designed with a magnetized Fe-foil target followed by a 3-quadrupole + dipole spectrometer focusing events onto a detector. Over the years modifications have been made to the target, the spectrometer and the detector package. The focus of this note is a summary of the quadrupoles. The information for this summary comes largely from <https://hallaweb.jlab.org/equipment/moller/spectrometer.html> and is meant to clarify what can be confusing and sometimes apparently conflicting information.

## 2 History

The original quadrupole magnets used in the Møller polarimeter for Hall A came from LANL. Photocopies of documentation found at [https://hallaweb.jlab.org/equipment/moller/magnets/Moller\\_quads2.pdf](https://hallaweb.jlab.org/equipment/moller/magnets/Moller_quads2.pdf) state that at least two of the quadrupoles were mapped originally in 1972, so we aren't dealing with new magnets. Four quadrupoles given the names Patsy, Jackie, Tessa and Felicia, were provided to Jefferson Lab by LANL for the Hall A Møller polarimeter. Only 3 were used in the original design since that was sufficient for the 6 GeV program. Jackie was in the worst shape and was put in storage. In 2012 a new fourth quadrupole magnet was designed to allow for the beam energies of the 12 GeV upgrade. Looking through the documentation can be confusing since these magnets were referred to differently depending on when the document was written and where they were placed on the beamline at the time. For example quadrupole 1 refers to Patsy in the 6 GeV era but generally is used to mean the new quadrupole after 2015. Some documents refer to a quadrupole 0. Table 1 is included to provide nomenclature reference.

Table 1: Reference table providing changing nomenclature for the spectrometer quadrupoles. “Eugene’s Ref.” refers to Eugene Chudakov’s summary on the following webpage [https://hallaweb.jlab.org/equipment/moller/magnets/quad\\_summary\\_simul.html](https://hallaweb.jlab.org/equipment/moller/magnets/quad_summary_simul.html).

12 GeV position	ID	Name	Eugene’s Ref.
Q1	QO1H01	New	Q4
Q2	QM1H02	Patsy	Q1
Q3	QO1H03	Tessa	Q2
Q4	QO1H03a	Felicia	Q3

Patsy and Jackie were identical magnets as were Tessa and Felicia. The new fourth quadrupole was designed to be similar to Tessa and Felicia, although it turned out to have larger contributions from higher multipole moments and. The physical information for the 4 quadrupoles (excluding Jackie) is provided in Table 2.

Table 2: Physical parameters of the four quadrupole magnets.

	New	Patsy	Tessa	Felicia
Manufacturer	?	MagnaTek	Indust. Coil	Indust. Coil
Height (in)	?	14 1/8	22 1/8	22 1/8
Width (in)	?	14 1/8	22 1/8	22 1/8
Length (in)	?	16	12	12
Effective Length (cm)	36.58(2015)	44.77 (1996) 44.73 (2012)	36.74(1996)	36.6(1996)
Bore/Aperture (in)	4.0	4.0	4.0	4.0
Max Current (A)	280	300	280	280
Pole tip field @ 300 A (T)	– (2015)	0.5801 (R=4.96 cm 1996) 0.5604 (R=4.6 cm 2012)	0.6029(R=5.00 cm1996)	0.6135(R=5.00 cm1996)

Here are key points in the history I was able to piece together.

- 1972: Tessa and Felicia are mapped at LANL.
- 1996: Patsy, Jackie, Tessa and Felicia are all mapped at LANL before being given to JLab. Quadrupole and higher order multipoles are measured. The multipole measurements are recorded in an LANL document apparently first copied into a document at UK which was then poorly photocopied into the first 6 pages of document MiscQuadInfo.pdf. It appears pg.1 was written by someone at UK. Pages 2-6 contain photocopies of a LANL document with measurements recorded from 1996 and including some information on the plots on page 6 from 1972. Page 14 (labeled pg 1 of a document by Sirish Nanda made in 2000) appears to simply replicate the information in the tables of the LANL data in pages 2-3. It is not clear where the effective length values come from.
- 1997: Magnetic fields of Patsy, Tessa and Felicia remeasured by the University of Kentucky. Multipole components do not appear to be remeasured. The measurements at UK are not clearly labeled so it is difficult to know which ones they are. Perhaps the hysteresis curves shown on pages 15-19 of MiscQuadInfo.pdf. It is not clear what the information is on pages 7-12 of this document. Is it a UK measurement? There is a hand-written note saying these are from EPICS field maps. Not sure what to make of this. Regardless, pages 7-12 don't provide much additional information except to say the quads are essentially linear at the parts per thousand level up to 150 A or about half max.
- 1998: Møller polarimeter commissioned.
- 2012: Patsy removed from beam line and mapping performed by magnet group at Jefferson Lab. Multipoles and gradient measured.
- 2012: New 4th magnet (now Q1) manufactured similar in design to Tessa and Felicia.
- 2013: Four quadrupole configuration installed.
- 2015: 11 GeV beam tested in Hall A Møller

Insights and questions from this history:

1. All our information for the two most downstream quadrupoles are from decades ago. To what accuracy were they mapped and can we still trust the decades old information?
2. Patsy was remeasured in 2012. How consistent were those results with the 1996 and 2000 maps?
3. The new quadrupole was mapped most recently. How well do we know that mapping?

We will address these questions individually in the sections ahead.

### 3 New quadrupole (Q1 or QO1H01)

The new quadrupole was mapped in 2012. The raw data is found in the spreadsheet QO1H01\_Summary1.xlsx. Four (at least) different data sets were taken.

#### 3.1 Effective length

Effective length was measured moving a Hall probe along Z at R=4.035 cm. The effective length was found to be 36.58 cm and the value at the center (Z=0) was 0.51404 T. The data are shown in Fig. 1.

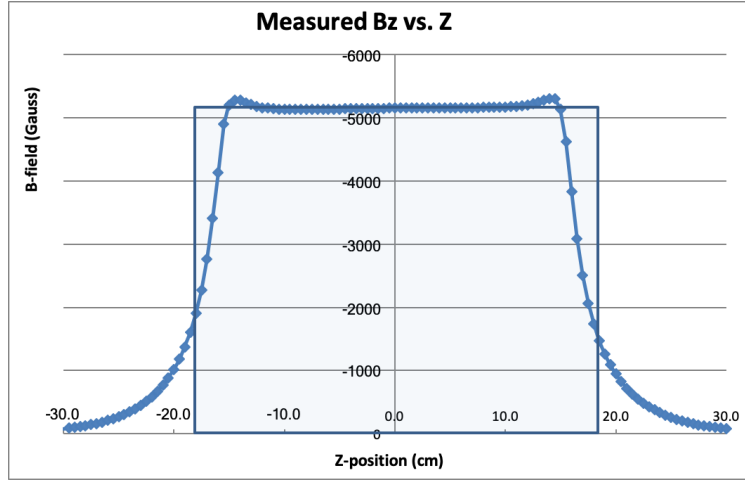


Figure 1: Hall probe measurements taken along Z for QO1H01 at r=4.035 cm. The effective length, 36.58 cm, is shown as the shaded region.

#### 3.2 Harmonics: multipole expansion

The magnetic field in a region free of current can be approximated in a truncated multipole expansion. For cylindrical coordinates the radial,  $B_r$  and azimuthal,  $B_\phi$  components of the field can be expressed in terms of sines and cosines as

$$B_r = \sum_n A_n \left( \frac{r}{r_0} \right)^{n-1} \sin(n\phi - \alpha_n), \quad n = 1, 2, \dots$$

$$B_\phi = \sum_n A_n \left( \frac{r}{r_0} \right)^{n-1} \cos(n\phi - \alpha_n),$$

where  $A_n$  are constant coefficients dictating the relative strength of the contributions.  $\alpha_n$  is an offset term in case the coordinate system has an offset azimuthal angle relative to the field axes. The index  $n$  gives the multipole order.  $n = 2$  gives the quadrupole term with 2 negative and 2 positive poles in the azimuth and is proportional to  $r$ . To determine the

harmonics of the magnetic field a wire coil of radius 3.699 cm rotating at a fixed frequency was used. The signal from the coil was analyzed using a lock-in amplifier to pick out the harmonics. The coil had a radius of 3.699 cm whereas the pole tip is at 5.08 cm. Only the  $n=2$  (quadrupole) and  $n=6$  (dodecapole) contributions were measured to be significant as can be seen in Table 3. The  $n=6$  contribution was found to be 1.44% of the quadrupole at  $R=3.699$  cm. Since the dodecapole depends on the  $r^5$  whereas the quadrupole on  $r$  this translates into a  $n=6$  contribution of 5.12% at the pole tip.

Table 3: Newest quadrupole (QOH01) showing the harmonic multipole contributions relative to the quadrupole contribution measured at  $r = 3.699$  cm. Multipoles up to  $n=20$  were measured. Shown here are all harmonic contributions above 0.01% of the quadrupole.

Current (A)	n=2 (arb)	n=3 (%)	n=4 (%)	n=5 (%)	n=6 (%)	n=7 (%)	n=10 (%)
100.0	44217.253	0.035	0.035	0.114	1.438	0.012	0.056
200.0	87505.650	0.035	0.036	0.116	1.439	0.012	0.056
300.0	118079.471	0.035	0.036	0.116	1.441	0.012	0.056

### 3.3 Gradient-length (GL)

GL measurement versus current from -300 A to 300 A using a stretched wire to determine the non-linearity of the quadrupole from saturation.

### 3.4 Map of Bdl

A map of Bdl was made using a stretched wire at 5 different X-positions and at 22 different currents ranging from -300 A to 300 A. These data were also analyzed to assess the multipole components. The full map can be found in QO1H01\_Summary1.xlsx.

In Eugene's quadrupole summary page an analysis of these data was performed. Using the rotating coil analysis, the contribution of  $n=6$  was fixed at 4.8% at  $r=5$  cm and GL and an X-offset were allowed as fit parameters (see the following webpage: <https://hallaweb.jlab.org/equipment/molle>). The fits to the data have rather apparent large residuals although they are not tabulated and the X-offset was found to be 0.4 mm. GL was found to be 4.76 T at 300 A. I was not able to replicate these results using the same data. Figure 2 shows the fits and residuals following the same procedure. I find much better agreement with data (small residuals), an X-offset of  $7 \pm 27 \mu\text{m}$  consistent with zero and a GL at 300 A of 4.72 T. The source of these discrepancies is not clear.

Redoing the analysis, but allowing the  $n=6$  contribution to be a fit parameter gives improved results. I did not find that allowing other multipole contributions than quadrupole and dodecapole improved the  $\chi^2/NDF$  significantly, but rather made the fits unstable. The improved results are shown in Fig. 3. With the exception of low current data where the small denominator produces large fluctuations, residuals are less than  $\pm 3\%$  and generally much less

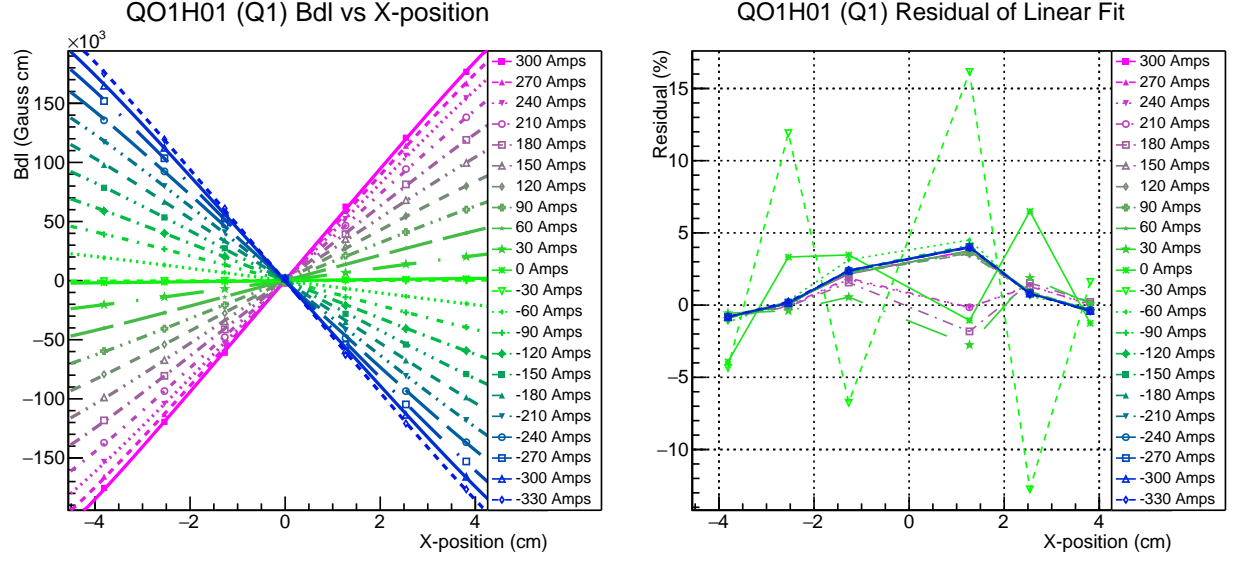


Figure 2: Attempted replicated of Eugene's results fixing the contribution of  $n=6$  to 4.8% at  $r=5$  cm. QO1H01 Bdl measurements for 5 different X-positions and 22 currents. The following fit equation is utilized where square brackets indicate fit parameters:  $Bdl = [GL](x - [x_0]) \left( 1 - 0.048 \left( \frac{x - [x_0]}{5.0} \right)^4 \right)$ .

than this. Table 4 gives the fit results for the X-offset and  $n=6$  relative contribution. Once

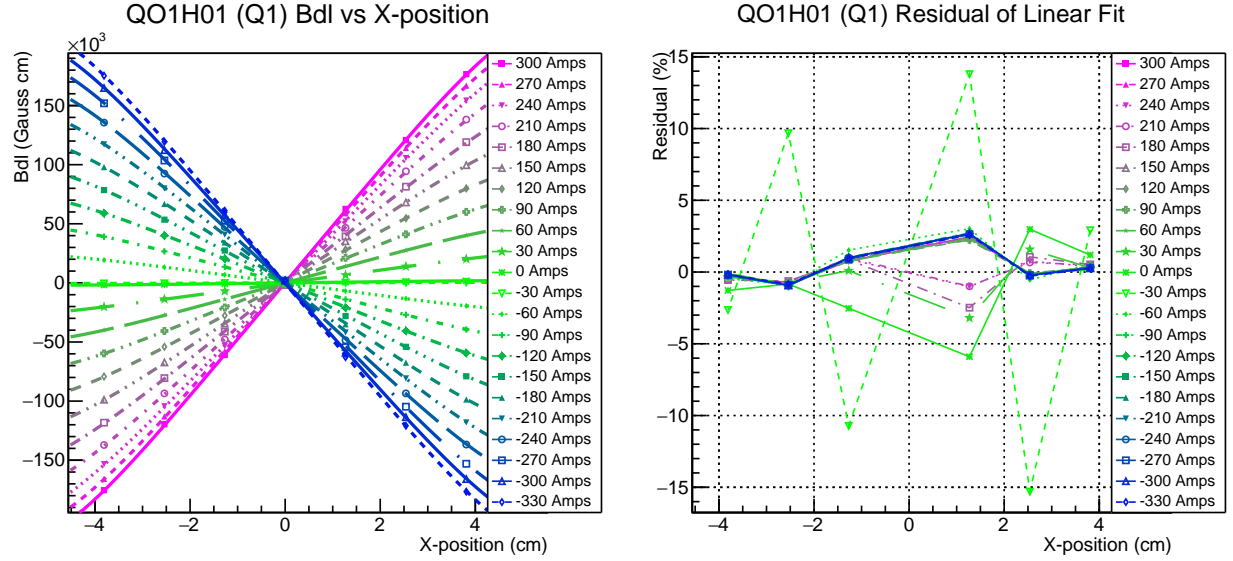


Figure 3: QO1H01 Bdl measurements for 5 different X-positions and 22 currents allowing the  $n=6$  contribution to come from the fit. The following fit equation is utilized where square brackets indicate fit parameters:  $Bdl = [GL](x - [x_0]) \left( 1 - [A_6] \left( \frac{x - [x_0]}{5.08} \right)^4 \right)$ .

again a negligible offset is assessed at  $20 \pm 30 \mu\text{m}$ . The dodecapole contribution is favored to be much larger (around 12%) than that found by the rotating coil. **This suggests that we need to include the dodecapole in the simulation and that there may be some flexibility in adjusting its relative contribution.**

Table 4: Newest quadrupole (QOH01) offset and n=6 multipole fractional component as determined from fitting the gradient-length versus X-position data at 22 different currents. These are the fit results shown in Fig 3. These are extrapolated to the pole tip at R=5.08 cm. The average dodecapole contribution is about 12%, more than double that assessed by the rotating coil analysis.

Current (A)	Offset (mm)	Dodecapole Coeff (frac)
300.0	-0.06	-0.114
270.0	-0.04	-0.114
240.0	0.04	-0.091
210.0	0.05	-0.091
180.0	0.08	-0.082
150.0	-0.04	-0.111
120.0	-0.05	-0.114
90.0	-0.03	-0.114
60.0	-0.04	-0.117
30.0	0.12	-0.071
0.0	0.31	-0.289
-30.0	0.57	-0.196
-60.0	-0.02	-0.123
-90.0	-0.06	-0.118
-120.0	-0.06	-0.112
-150.0	-0.05	-0.115
-180.0	-0.05	-0.115
-210.0	-0.06	-0.115
-240.0	-0.06	-0.115
-270.0	-0.06	-0.117
-300.0	-0.06	-0.116
-330.0	-0.08	-0.117
Average	0.02	-0.121

## 4 Patsy (Q2 or QM1H02)

Patsy was measured in 1996 at LANL and its GL and pole tip field measured versus current and its multipoles contributions measured. In 1997, the hysteresis curves were measured at the University of Kentucky. The results can be found in MiscQuadInfo.pdf as well. These



were also transcribed in 2020 into the spreadsheet `quadrupole.info.xlsx`. Figure ?? shows the results of the most recent measurement as well as a 5-deg polynomial fit and the existing 5-deg polynomial parametrization used in the GEANT4 simulation. The new parametrization does a better job at low currents and the two are equivalent at currents above  $\pm 150$  A. This new parametrization is recommended.

Fig. 5 shows a comparison of the 2012 JLab and 1997 UK measurements of Q2 (Patsy) GL versus current along with 5 degree parametrizations for each data set. The absolute difference  $\times 100$  between the 2012 parametrization and the 1997 measurements shows differences ranging from  $-0.08$  T to  $+0.05$  T. The percent difference between the two parametrizations is also shown and varies from several percent at low current to about 1% near the maximum. The reason for these differences is not clear. Are they real or the result of measurement error? No matter how they arise, they suggest that the uncertainty in the magnetic field of Q2 is at the level of a 1-2% at high current and larger at lower current.

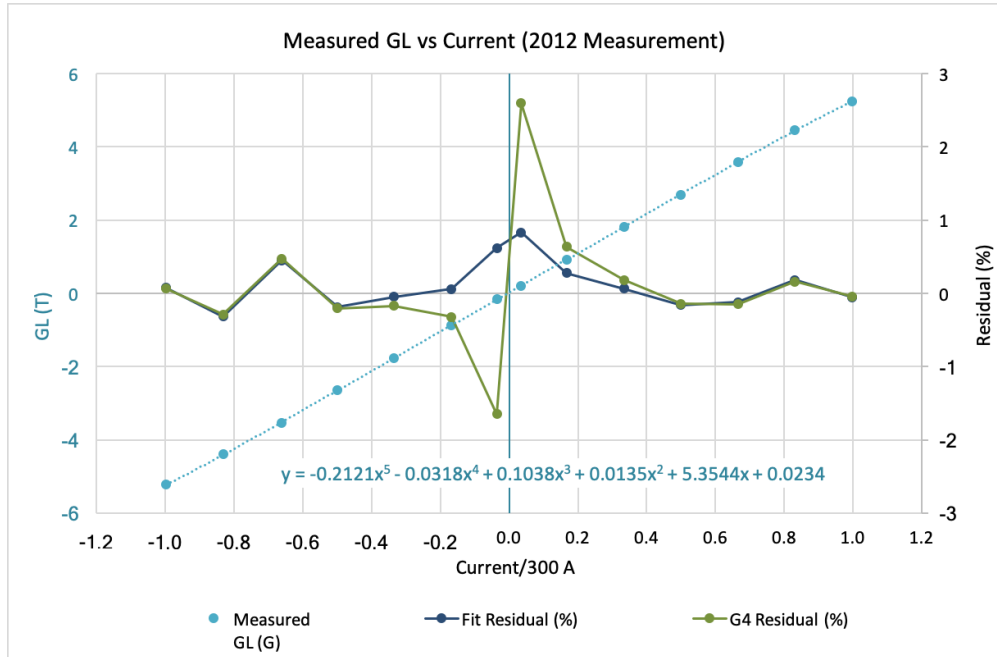


Figure 4: Results of the 2012 JLab measurement of Q2 (Patsy) GL versus current. A 5 degree polynomial parameterization is shown along with the existing parametrization in G4. The new parametrization is better at low currents less than 100 A but is essentially identical above this.

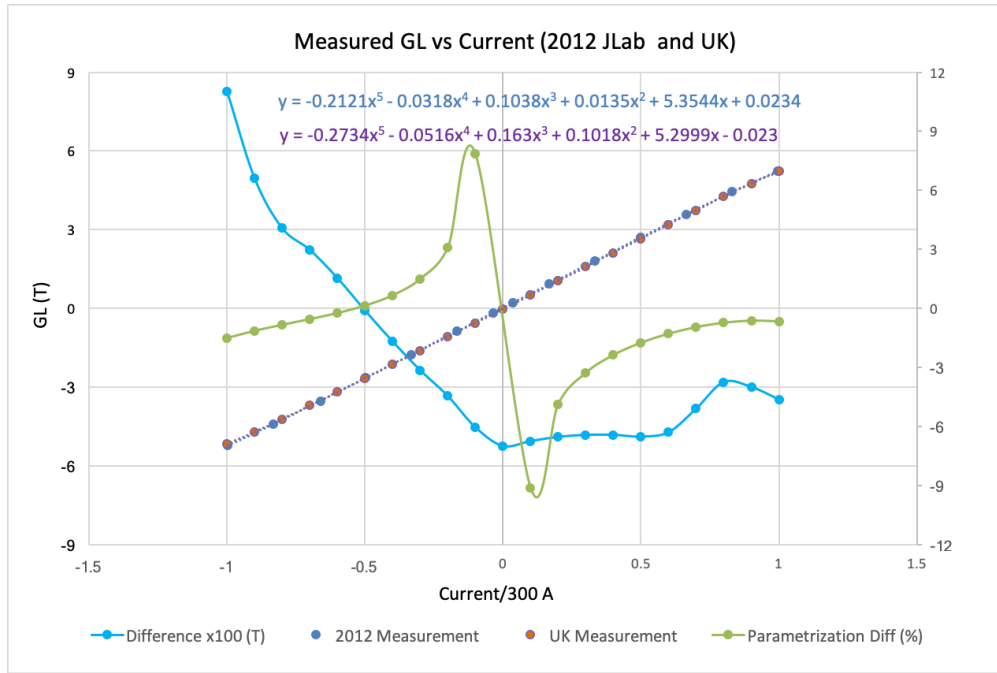


Figure 5: Comparison of the 2012 JLab and 1997 UK measurements of Q2 (Patsy) GL versus current. 5 degree parametrizations are also shown for each data set. Since the data sets are taken at different current comparisons were made using the parametrizations where required. The absolute difference  $\times 100$  between the 2012 parametrization and the 1997 measurements shows differences ranging from -0.08 T to +0.05 T. The percent difference between the two parametrizations is also shown.