Technical Report

Subject:	Analysis of JLAB Q1 field plots at JLAB	Author:	SJ
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Dist:	JLAB	CC:	NRI/PNP

1 Introduction

SJ and TAB visited JLAB to plot the magnetic field of the Q1 magnet and adjust the position of its cold mass with respect to the OCV if necessary. The report P:\P0452SPM Q1 for JLab\Field plotting\Site installation\Mapping and movement June15\Determining cold mass positions from field map - Jlab Q1.doc outlines the work done to determine the magnet position and it was agreed with the customer that no adjustment of the cold mass position was to be attempted. Field plotting was continued and the data is analysed here to show that the magnet meets specification.

2 Measurement set up

JLAB redesigned the plotting rig to bolt straight onto the side of the cryostat. The previous design, which was a free standing rig held in the magnet bore on 2 A-frames, was difficult to align with the mechanical centre and introduced even more uncertainty into the measurement. Bolting the plotting rig onto the side of the cryostat minimised this error.

The plotting rig consists of a HPE? (plastic) cylinder which is free to rotate on its axis on bearings. A rail runs along the length of the cylinder OD, into which the hall probe carriage fits and can slide in the z direction. The z positions are set by sprung ball bearings which pop into holes drilled at known positions. The angular positions are set by manually pushing a pin on the plotting rig frame into holes on the turning cylinder. Figure 1 shows the plotting rig and Figure 2 shows the hall probe set in its carriage.

JLAB wrote software to easily handle making the measurement and recording the data. It simply has an array of buttons, which, when clicked, records the measured magnetic field and magnet current measurements to the correct cell (to correspond with the angular and axial position of the hall probe) in an excel file. The hall probe was set to one z position, the plotting rig is then simply rotated and stopped at every angular position where a measurement taken. Once a measurement has been taken at all 64 angular positions then the hall probe is moved to the next axial position.

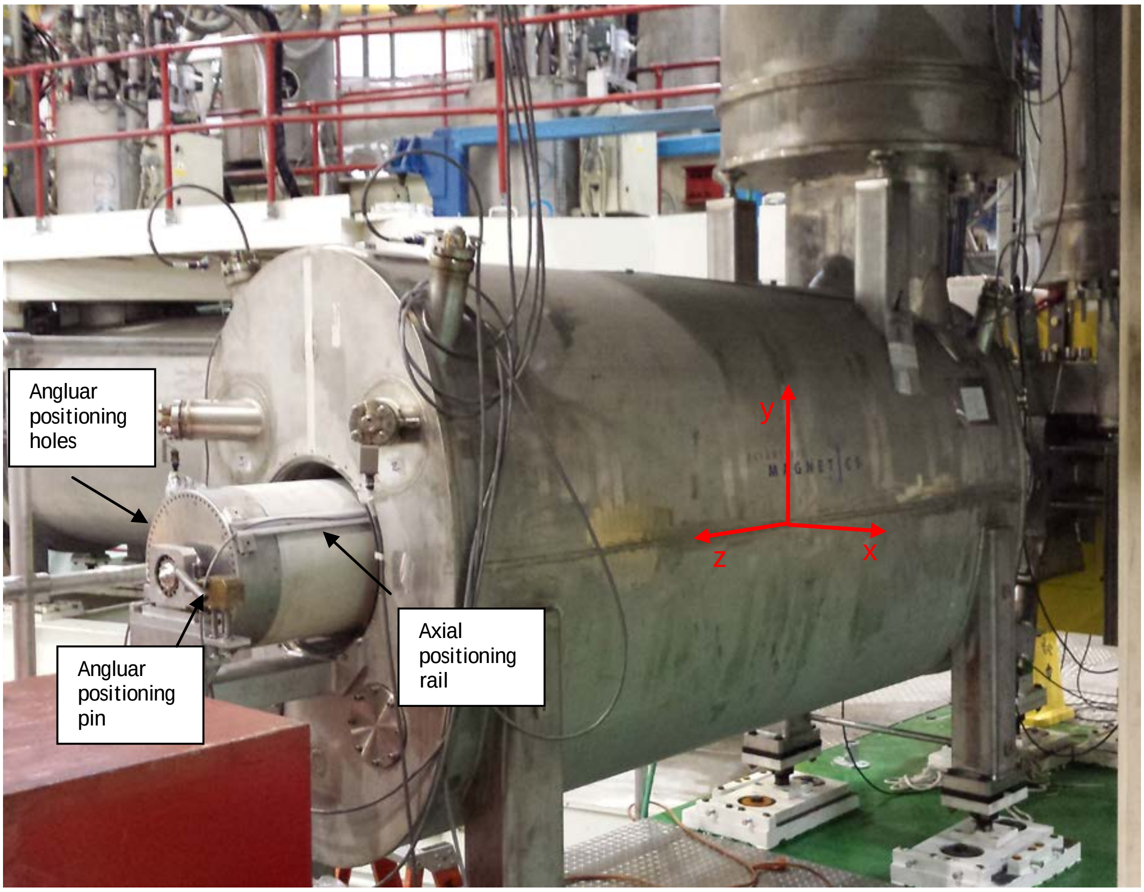

Figure 1: Plotting rig installed into Q1 magnet at the JLAB facility.

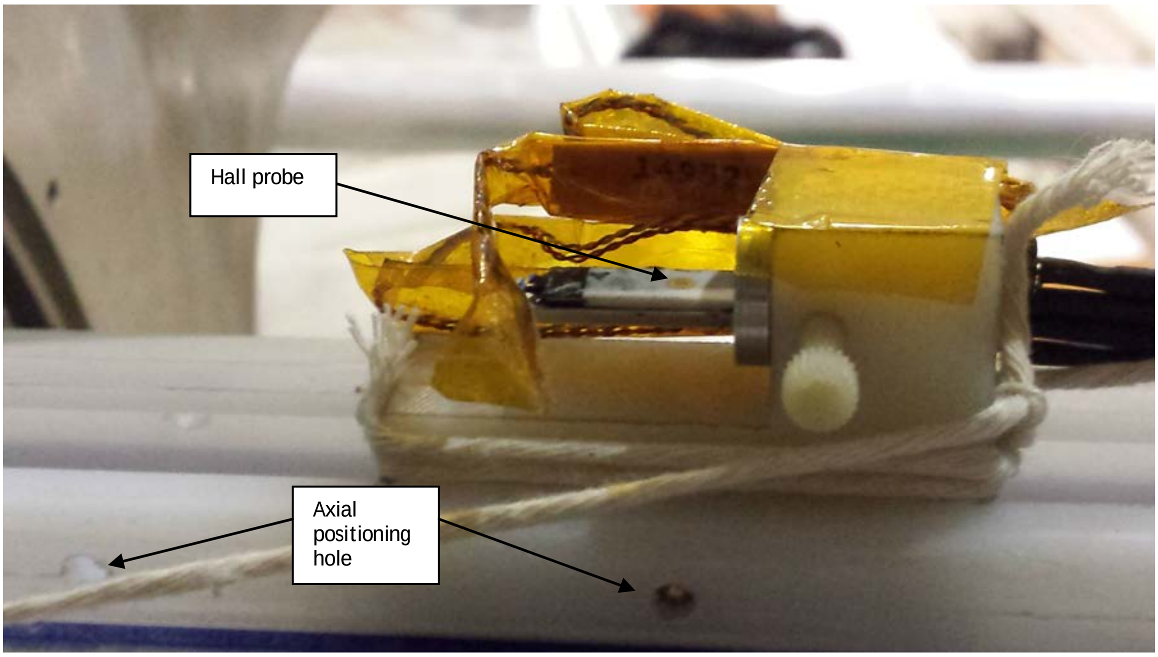

Figure 2: Hall probe in its carriage

3 6 Gev field plot

The magnet was ramped to 1228 A as this corresponds to 6 GeV/c beam line momentum. A half of the magnet is plotted – this means full 64 point slices from z(3) (axial position 3) to z(24). This assumes the magnet is symmetrical in the analysis and we ignore z(1) and z(2) as the field is close to zero here. Additionally, slices z(22) and z(23) were also omitted as the field is quite flat in the middle of the magnet and can be assumed to be similar to the surrounding slices. The reason for omitting these slices was due to time constraints. Each slice takes about 15 minutes accounting for the time to move the hall probe carriage in z. Each full magnet plot doing all 47 slices would have taken about 11 hrs.

The resulting measurements are loaded into the MathCad spread sheet – can be found at [Harmonic field expansion - Half magnet plot1228A.xmcd](). Each angular position is integrated along Z and then the integrated fields are expanded as a Fourier series. The sextupole, octupole and higher order terms are expressed as a % of the main quadrupole term and these are shown below.

$$\mathrm{Res} = \begin{pmatrix} 0.098 \\ -1.257 \\ 0.044 \\ -0.068 \\ -0.203 \end{pmatrix} \%$$

Specification

Integrated Harmonic as a percentage of A_2 Limit

A_4/A_2 -1.7 to 0 %
A_6/A_2 -3.0 to 1.0 %
A_8/A_2 -0.5 to 0%
A_{10}/A_2 -1.2 to 0%
$A_{>10}/A_2$ -0.5 to 0%

Most of the terms fall into the specification range - only A_4 and A_8 do not but they are very small. The same values are calculated from the ideal model in Opera at 1228 A and are shown below. The origin of the circle in Opera is offset to match the position of the plotting rig. It is clear here that the Res values don't fall into the specification bracket either. This shows that they may be sensitive to movement of the plotting rig.

$$\mathrm{Res} = \begin{pmatrix} 7.673 \times 10^{-3} \\ -1.834 \\ 3.454 \times 10^{-4} \\ -0.146 \\ 0.013 \end{pmatrix} \%$$

Specification

Integrated Harmonic as a percentage of B_2 Limit

A_4/A_2 -1.7 to 0 %
A_6/A_2 -3.0 to 1.0 %
A_8/A_2 -0.5 to 0%
A_{10}/A_2 -1.2 to 0%
$A_{>10}/A_2$ -0.5 to 0%

The field gradient is calculated as the field as the main quadrupole magnitude at the radius of the measurement circle, R0, divided by R0. The field gradient at z=0mm (z(24)) is calculated from the measurements to be 4.226 T/m at 1228 A.

The effective magnetic length is calculated as the integrated field divided by the central field. This is calculated from these measurements to be 1.869 m and the specification is 1.861 m

4 Middle slice at increasing currents

A full set of angular measurements on the middle slice at z=0 is taken for 4 different currents. These correspond to 6 GeV, 8 GeV, 10 GeV and 11 Gev. Table 1 shows the the operating currents for a given beam energy. The measured data was loaded into the MathCad spread sheet [Harmonic field expansion - Middle circle at different currents.xmcd]. Figure 3 shows measured data at each of the currents (Y axis in Tesla). One point was missed at 1672 A and was saved as zero. This affects the higher order terms a lot and also introduces some error into the lower order terms that we are interested in so a linear interpolation between neighbouring points was used to estimate the field at this point. The dipole terms and the skewed quadrupole terms are shown in table 2 for the different currents.

Table 1

Beam energy (GeV)	Magnet current (A)
6	1228
8	1672
10	2169
11	2454

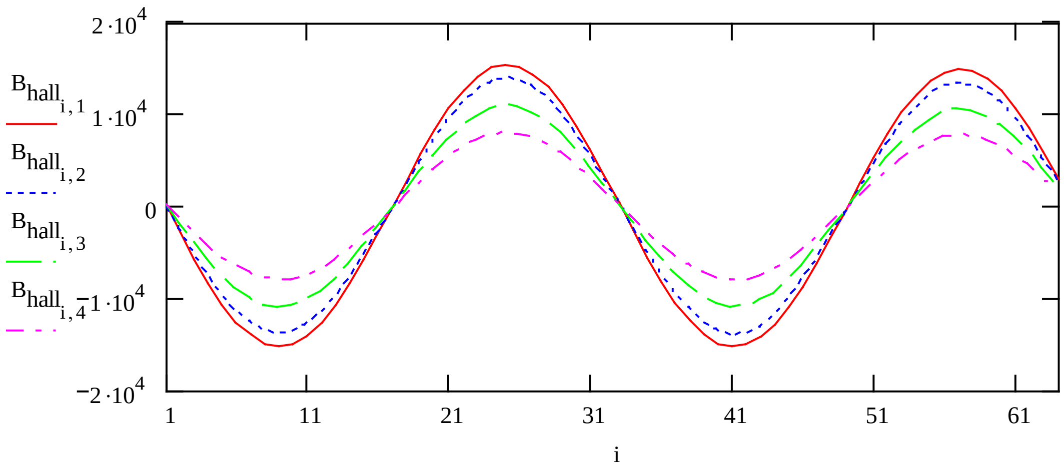

Figure 3: Measured data around a slice at z=0 for different currents. i is the angular index and the field is shown in Tesla.

Table 2

Beam energy (GeV)	Normal dipole term (Y displacement) (G)	Skew dipole term (X displacement) (G)	Skew quadrupole terms (G)
6	188	-168	258
8	169	-158	229
10	133	-125	210
11	89	-84	189

Table 3 shows the multipole terms as a percentage of the main quadrupole terms for each of the different currents the measurement was taken. These are plotted in Figure 4 and compared with the ideal case in the Opera models. As before, the origin of the circle in Opera was offset to match the real plotting rig positions.

Table 3

Current (A)	1228	1672	2169	2454
A4/A2	0.044%	0.063%	0.156%	0.337%
A6/A2	-0.907%	-0.868%	-0.603%	-0.254%
A8/A2	0.037%	0.032%	0.078%	0.102%
A10/A2	-0.040%	0.012%	0.056%	0.115%
An/A2	-0.017%	0.077%	0.029%	-0.012%

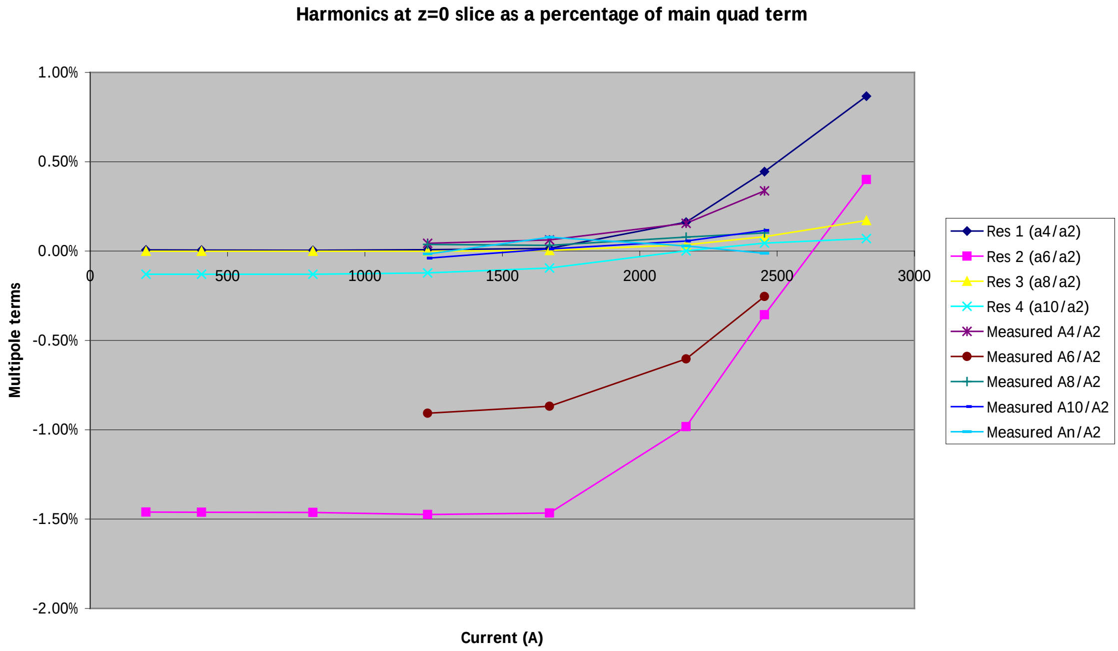

Figure 4: Multipoles as percentages of main quadrupole term - measured vs Opera

The field gradient for different currents is plotted in Figure 5 along with the field gradient from the Opera model. The model matches the measured data well here.

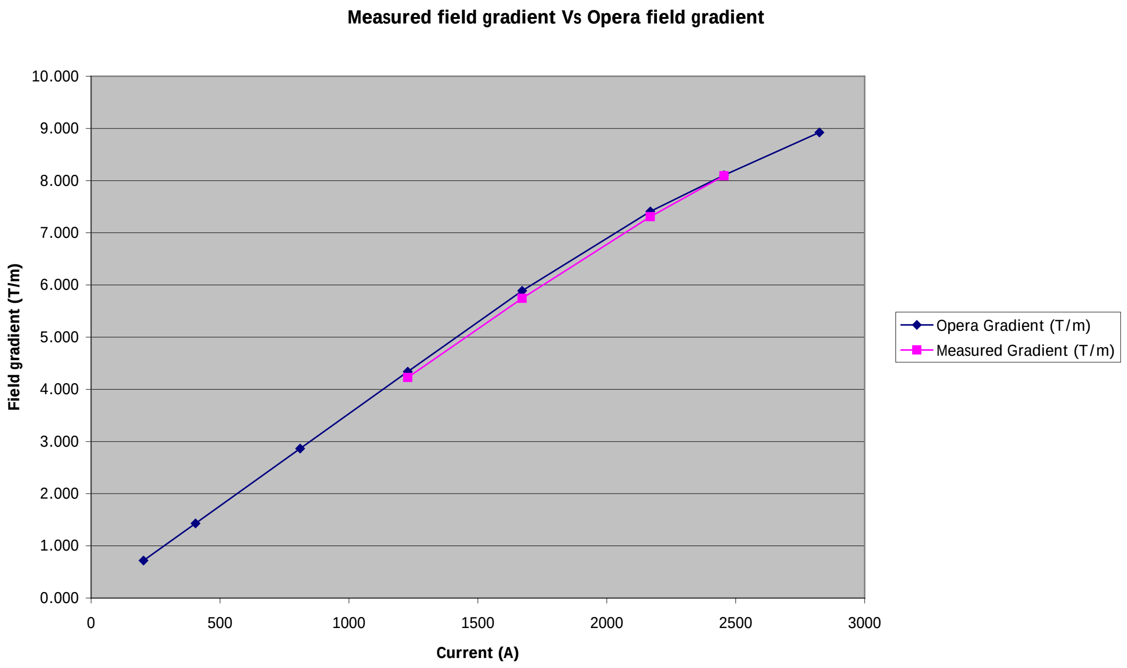

Figure 5: Measured field gradient vs Opera field gradient

5 Plots along z

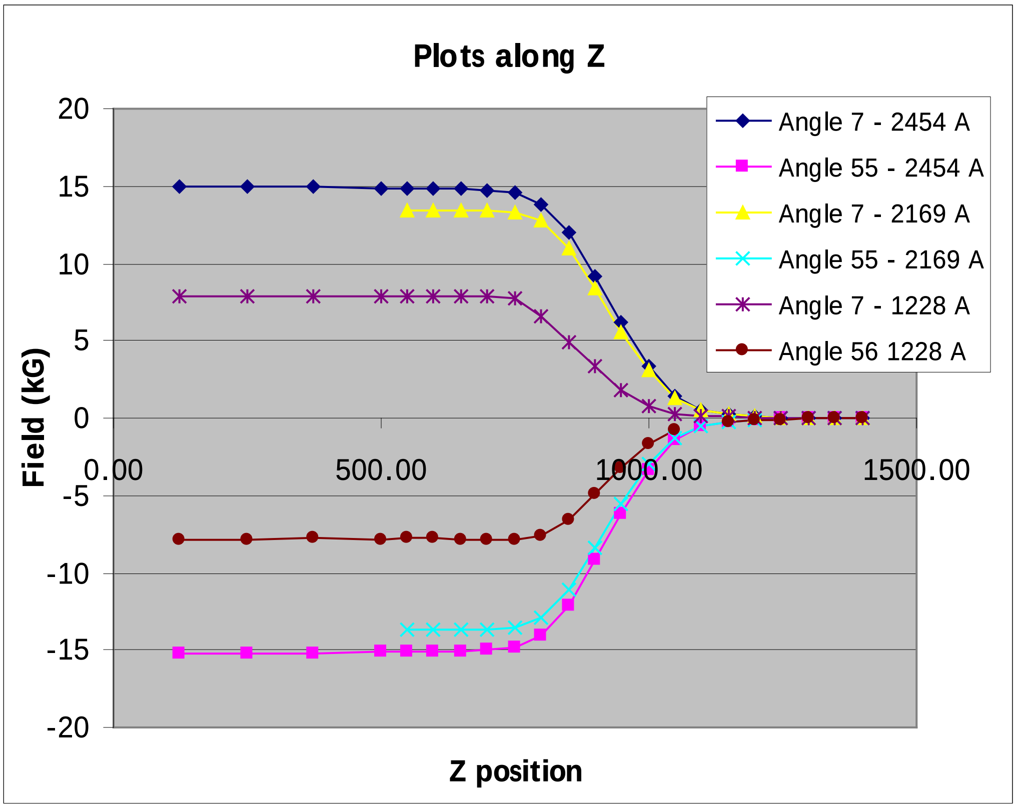

Figure 6: Plots along X at +/- 45 deg at various currents.

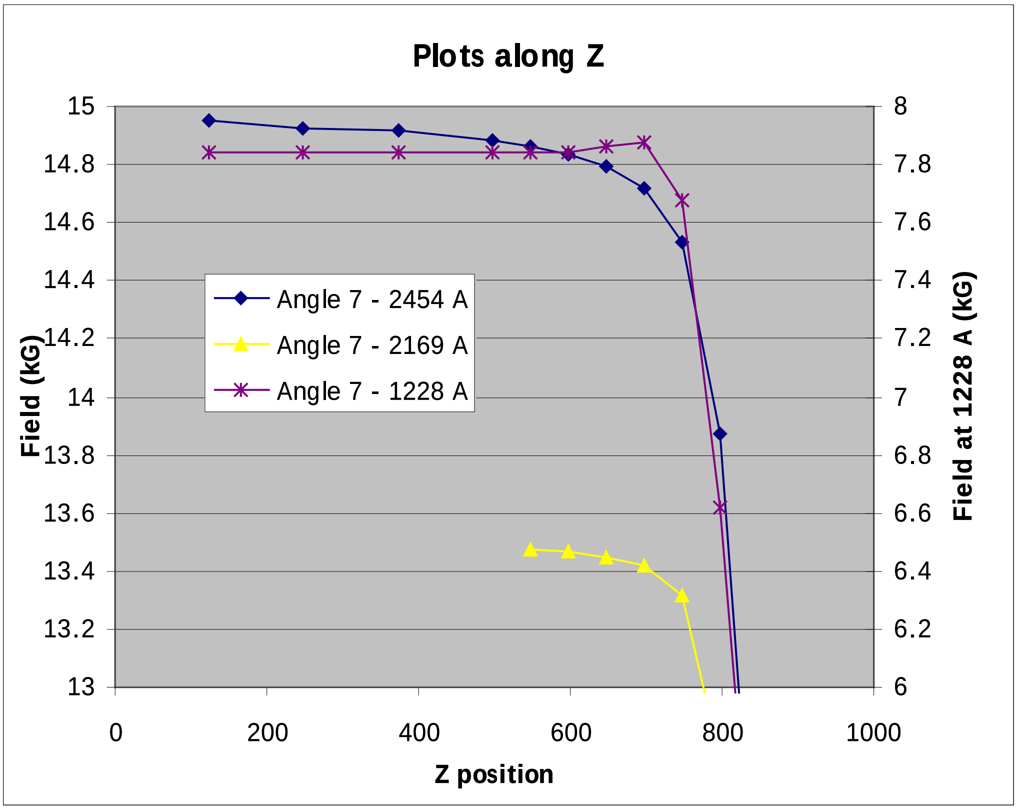

Figure 7: Zoomed in plots along z at +45 deg.

Figure 6 and 7 show plots of the field along z for different currents. Note that the field pattern is slightly different in the lower current plot than in the higher current plot. This is a consequence of the increase of multipole terms with current, which is a result of the non-linear magnetisation of the iron.

6 Conclusion

- From the field plot at 1228 A multipole expansion terms are mostly within specification with two being just outside specification but still a very small number. It looks as though all the terms become more positive as you increase the current, which means they will look worse at higher currents. This could just be due to the offset of the magnet and the uncertainty of the plotting rig positions
- At 1228 A the effective magnetic length of the magnet is 1.869 m - a close match to the specification of 1.861 m.
- The field gradient is a good match to the modelled field gradient
- Recommend that JLAB complete a full magnet field plot at all points and at a the Operating current for 11 GeV or 12 GeV.