

Beam Systematics for Mott Experiment Runs I and II

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Abstract

Systematic studies of the Mott experimental asymmetry to electron beam conditions such as beam position, beam size, and energy spread measured during Runs I and II are summarized in this note.

1 Beam Lines

Beam Lines

A dipole (MDL0L02) deflects the polarized electrons to either the Mott polarimeter or a spectrometer beam line (see Fig. 1). Quads (MQJ0L02/MQJ0L02A) control transverse beam size while an SRF cavity (R028GSET/R028PSET) controls beam momentum/spread. Wire scanners IHA0L03 and IHA2D00 measure beam sizes to respectively determine the beam emittance at MQJ0L02 and the momentum spread. The Mott target is viewed by camera ITV3D01.

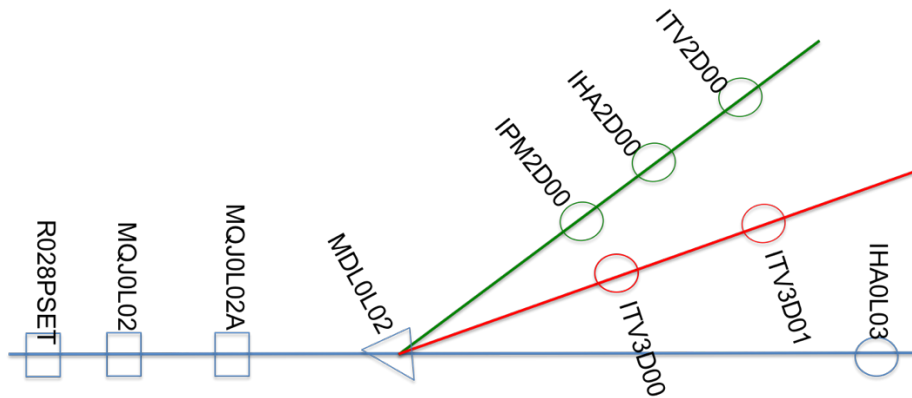


Fig. 1. A schematic of the Mott polarimeter (red) and spectrometer (green) beam lines.

Beam Line Optics Model

A beam line modelled with Elegant begins at MQJ0L02 and ends at IHA2D00 or ITV3D01.

```
"cle" ! clear whole RPN stack for safety
```

```
% 1 atan 4 * sto pi  
% pi 180 / sto cdtor  
% 180 pi / sto crtod
```

```
! DRIFT BETWEEN QUADS
```

```
D1 : DRIFT, L=0.4596
```

```
! DRIFT TO 2D LINE
```

```
D2 : DRIFT, L=1.0065  
D3 : DRIFT, L=3.1385  
D4 : DRIFT, L=0.1778  
D5 : DRIFT, L=0.1270
```

```

! DRIFT TO 3DLINE
D6      : DRIFT, L=1.0041
D7      : DRIFT, L=0.5584
D8      : DRIFT, L=0.2667
D9      : DRIFT, L=0.8113

! NORMAL MOTT
MQJ0L02: KQUAD, L=0.15, K1= -5.04003396226415
MQJ0L02A: KQUAD, L=0.15, K1= +5.00232327044025

! 2D DIPOLE
MDL0L02_2D: CSBEND, L=0.1230, ANGLE="-30.0 180.0 / -1 acos * ", &
            E1=" 0.0 180.0 / -1 acos * ", E2="-30.0 180.0 / -1 acos * ", &
            EDGE_ORDER=2, HGAP=0.013564, FINT=0.5, NONLINEAR=1, &
            N_KICKS=15, INTEGRATION_ORDER=4

! 3D DIPOLE
MDL0L02_3D: CSBEND, L=0.1278, ANGLE="-12.5 180.0 / -1 acos * ", &
            E1=" 0.0 180.0 / -1 acos * ", E2="-12.5 180.0 / -1 acos * ", &
            EDGE_ORDER=2, HGAP=0.013564, FINT=0.5, NONLINEAR=1, &
            N_KICKS=15, INTEGRATION_ORDER=4

! DIAGNOSTIC IN 2D LINE
IPM2D00: WATCH, FILENAME="%s.ITV2D00", MODE=COORD
ITV2D00: WATCH, FILENAME="%s.ITV2D00", MODE=COORD
IHA2D00: WATCH, FILENAME="%s.IHA2D00", MODE=COORD

! DIAGNOSTIC IN 3D LINE
ITV3D00: WATCH, FILENAME="%s.ITV3D00", MODE=COORD
ITV3D01: WATCH, FILENAME="%s.ITV3D00", MODE=COORD

! BEAM LINES
2D: LINE=(MQJ0L02, D1, MQJ0L02A, D2, MDL0L02_2D, D3, IPM2D00, D4,
IHA2D00, D5, ITV2D00)
3D: LINE=(MQJ0L02, D1, MQJ0L02A, D6, MDL0L02_3D, D7, D8, ITV3D00, D9,
ITV3D01)

```

2 Run I Results

Run I Energy

The electron beam kinetic energy for Run I is 4.806 ± 0.097 MeV [1] and corresponds to a momentum of 5.292 ± 0.098 MeV/c.

Run I Beam Emittance

The horizontal and vertical beam projections at wire scanner IHA0L03 were measured as a function of MQJ0L02 quad strength using the JLab software tool *qsUtility 3.21* (see Fig. 2). The beam emittance and Twiss parameters are calculated at the entrance of MQJ0L02 by SDDS toolkit utility *sddsemitproc*. Details are given in e3466292 and results are summarized in Table 1.

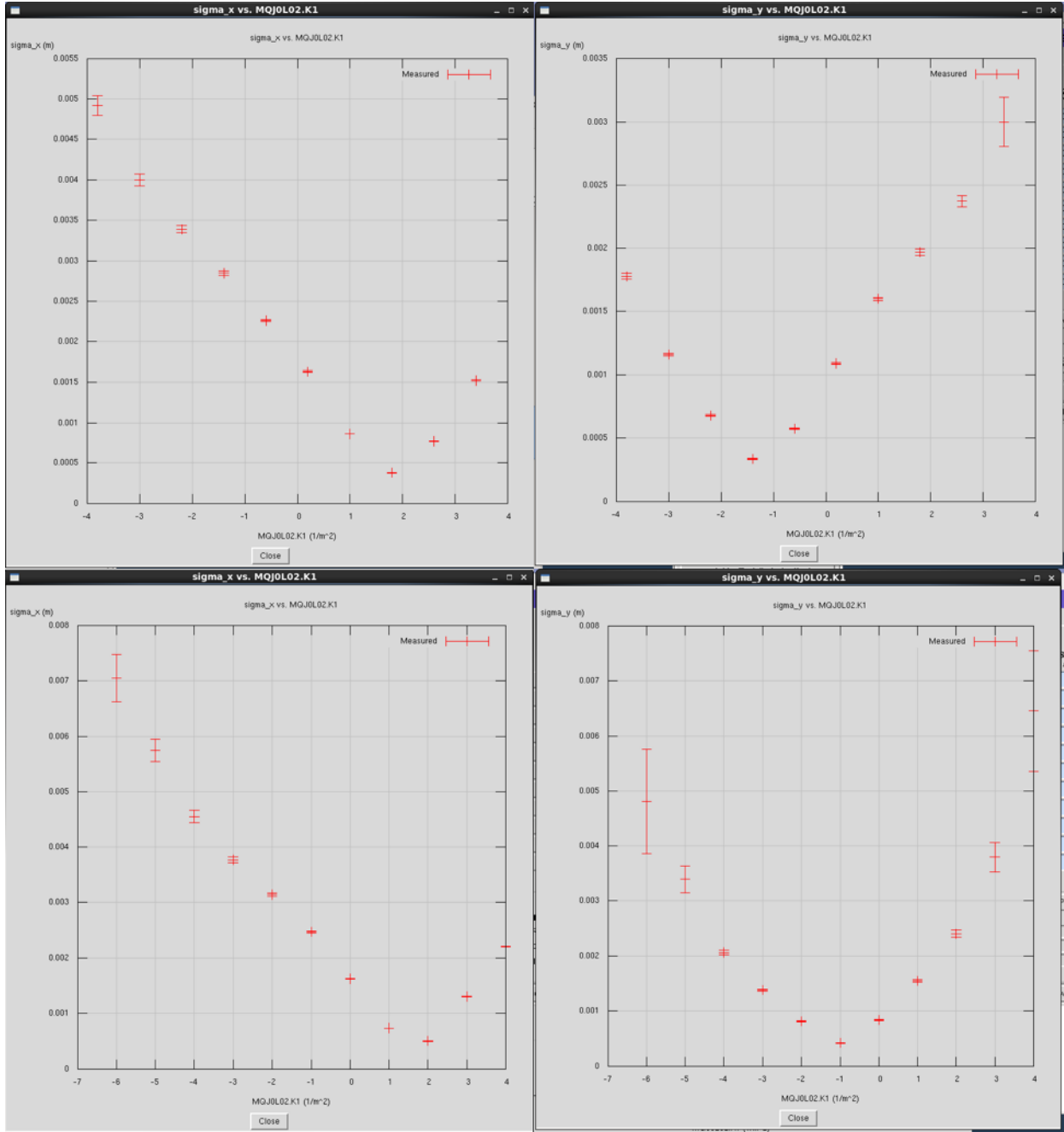


Fig. 2. Upper (lower) plots show horizontal and vertical RMS beam size at IHA0L03 as a function of MQJ0L02 quad strength on 2015-01-18_22:36 (IHA0L03_2015-01-19_17:15).

Table 1. Summary of measured normalized emittance and Twiss parameters at MQJ0L02.

$qsUtility$ (run date)	$\epsilon_{n,x}$ (μm)	β_x (m)	α_x (rad)	$\epsilon_{n,y}$ (μm)	β_y (m)	α_y (rad)
2015-01-18_22:36	0.534(3)	15.8(1)	-2.01(2)	0.342(2)	13.3(5)	-0.617(11)
2015-01-19_17:15	0.593(5)	14.4(2)	-1.42(3)	0.461(2)	11.2(2)	-0.070(06)

Run I: Asymmetry vs. Beam Energy Spread

The Mott asymmetry as a function of energy spread was studied by varying the phase R028PSET of the last QCM SRF cavity upstream of the polarimeter. The relative momentum spread (dp/p) is first determined from a measurement of the beam size at a dispersive location

$$S_x^2 = \varepsilon_x \beta_x + \left(\frac{dp}{p} \eta_x \right)^2$$

where S_x is the horizontal RMS beam size. For each value of R028PSET the beam size at IHA2D00 [IHA2D00_2015-01-19_*] (see Fig. 3) and the Mott asymmetry using both foil #15 (Au:1 μm) were measured. and summarized in Table 2.

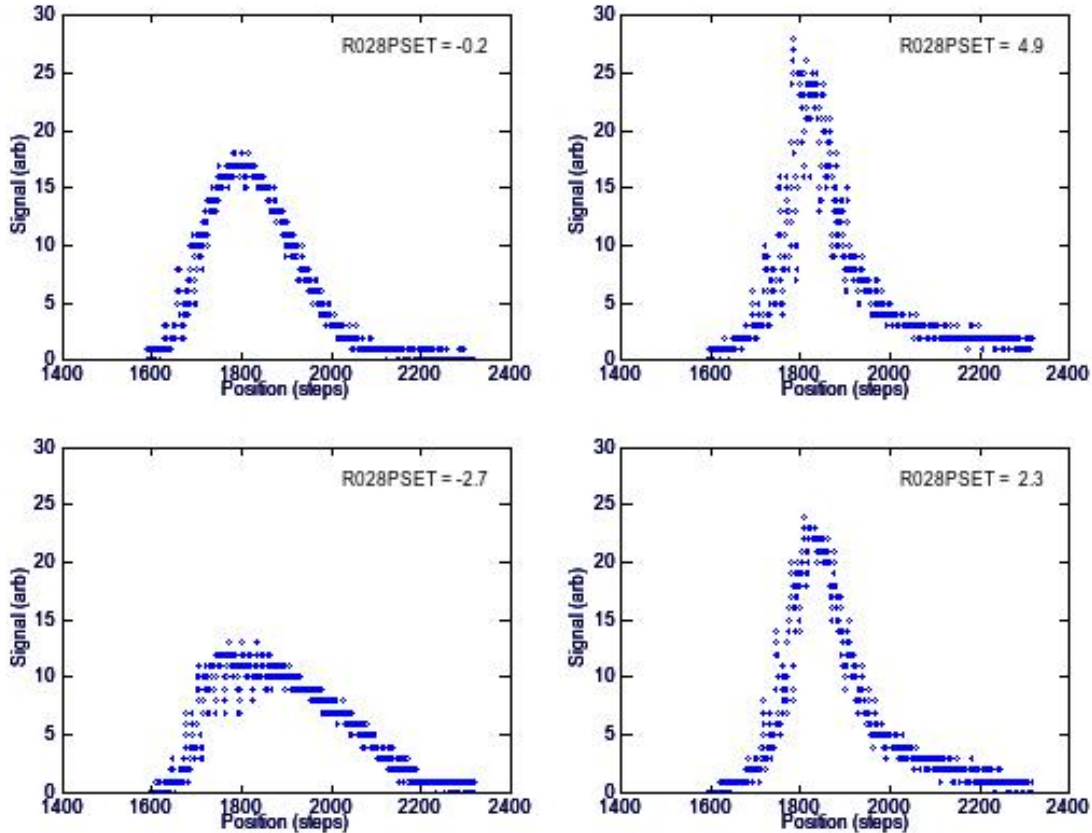


Fig. 3. The horizontal wire scanner signal as a function of motor position for four values of R028PSET are shown. The wire scanner reports a position calibration of 0.02041 mm/step.

The non-dispersive beam size at IHA2D00 was computed to be 0.21 mm using the measured emittance (2015-01-19_17:15) and quad set points: MQJ0L02 = -133.65 G ($K = -5.048 \text{ m}^{-1}$), MQJ0L02A = 132.95 G ($K = 5.010 \text{ m}^{-1}$). The horizontal dispersion function at IHA2D00 was computed to be $\eta_x = -1.946 \text{ m}$. The calculated relative momentum spread ($\delta p/p$) and energy spread (δT) vs. R028PSET is summarized in Table 2 and Fig. 4. The horizontal and vertical RMS beam size at Mott target including energy spread is computed is also reported in Table 2, where the dispersion at the Mott target ITV3D01 is $\eta_x = -0.3767 \text{ m}$. The spot diameter is computed as the ellipsoidal quadratic mean diameter and the largest value of the four cases is 0.63 mm. Finally, the Mott physics asymmetry vs. phase offset and energy spread is shown in Fig. 5.

Table 2. Parameters and results of energy spread measurements.

<i>R028-PSET</i>	Δ - <i>PSET</i>	<i>R028 GSET</i>	<i>MAD 3D00H</i>	<i>Mott Runs</i>		<i>File</i>	<i>S_x (RMS) IHA2D00</i>		$\delta p/p$	δT	<i>S_x ITV3D01</i>	<i>S_y ITV3D01</i>
<i>deg</i>	<i>deg</i>	<i>MV/m</i>	<i>G-cm</i>	<i>IN</i>	<i>OUT</i>		<i>steps</i>	<i>mm</i>	10^{-3}	<i>keV</i>	<i>mm</i>	<i>mm</i>
-0.2	0.0	4.81	0	8180	8181	22:55	76.00	1.55	0.79	3.46	0.76	0.37
4.8	-5.0	4.82	20	8182	8183	22:44	136.29	2.78	1.00	4.41	0.80	0.38
-2.7	2.5	4.81	-9	8184	8185	22:53	137.63	2.81	1.02	4.45	0.80	0.38
2.3	-2.5	4.81	11	8186	8187	22:51	118.55	2.42	0.87	3.83	0.78	0.38

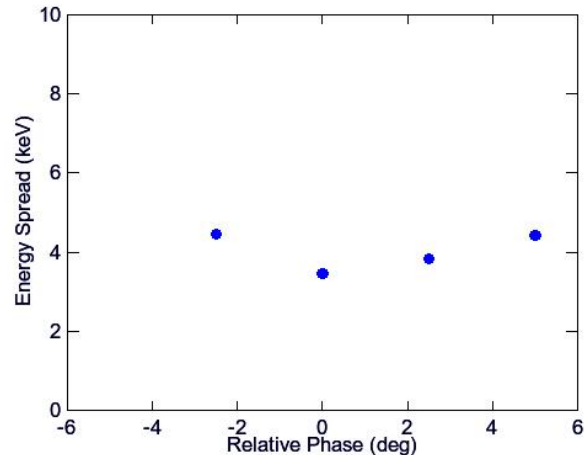


Fig. 4. Absolute energy spread (δT) vs. relative phase about Run I operating set point.

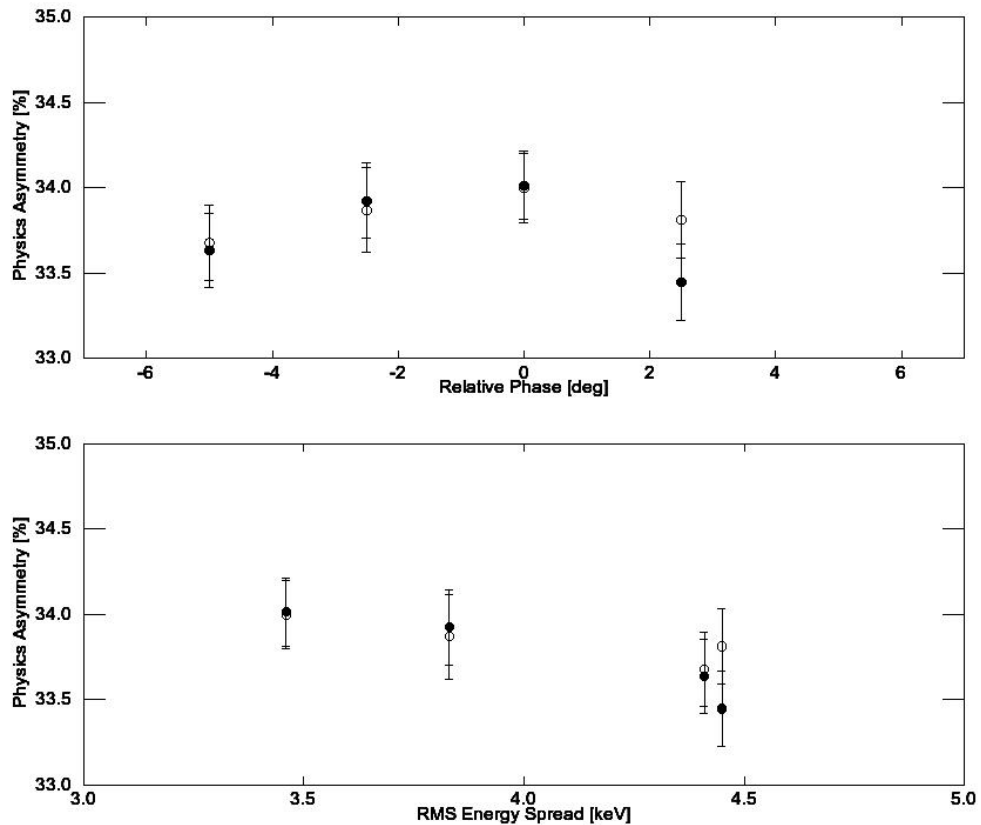


Fig. 5. Physics asymmetry versus relative phase (top) and RMS energy spread (bottom).

Run I: Asymmetry vs. Beam Spot Size

The Mott asymmetry using foil #15 (Au:1 μm) was measured vs. beam spot size by varying the quad strengths MQJ0L02 and MQJ0L02A about their nominal operating set point. The calculated horizontal and vertical RMS beam spot sizes at the Mott target using the measured emittance (2015-01-19_17:15) and relative momentum spread (7.9×10^{-4}) are summarized in Table 3 (runs with visually poor spectra are listed in **bold**) and plotted in Fig. 6. The spot diameter is computed as the ellipsoidal quadratic mean diameter (see Appendix B). The Mott asymmetry for spot sizes less than 1 millimeter is 0.3380.

Table 3. Summary of spot size measurements. “Name” is estimated size during Run I and “Fig.” corresponds to the OTR image in e3318205. Runs with visually bad spectra are in **bold**.

Name (mm)	Fig.	MQJ0L02		MQJ0L02A		IHWP IN	IHWP OUT	Sx mm	Sy mm
		G	l/m	G	l/m				
0.100	1	-133.00	-5.0231	153.00	5.7785	8163	8164	0.40	0.30
0.250	2	-115.00	-4.3433	139.00	5.2497	8165	8166	0.47	0.23
0.500	3	-164.00	-6.1939	153.00	5.7785	8167	8169	0.66	0.68
1.000	4	-188.00	-7.1003	141.00	5.3252	8170	8171	1.17	1.05
2.000	5,6	-264.00	-9.9707	130.00	4.9098	8172	8173	2.34	2.10
0.750	7	-182.00	-6.8737	148.00	5.5896	8174	8175	0.94	0.94
1.500	8,9	-225.00	-8.4977	135.00	5.0986	8176	8177	1.74	1.57
0.475	10	-133.65	-5.0477	132.65	5.0099	8178	8179	0.76	0.38

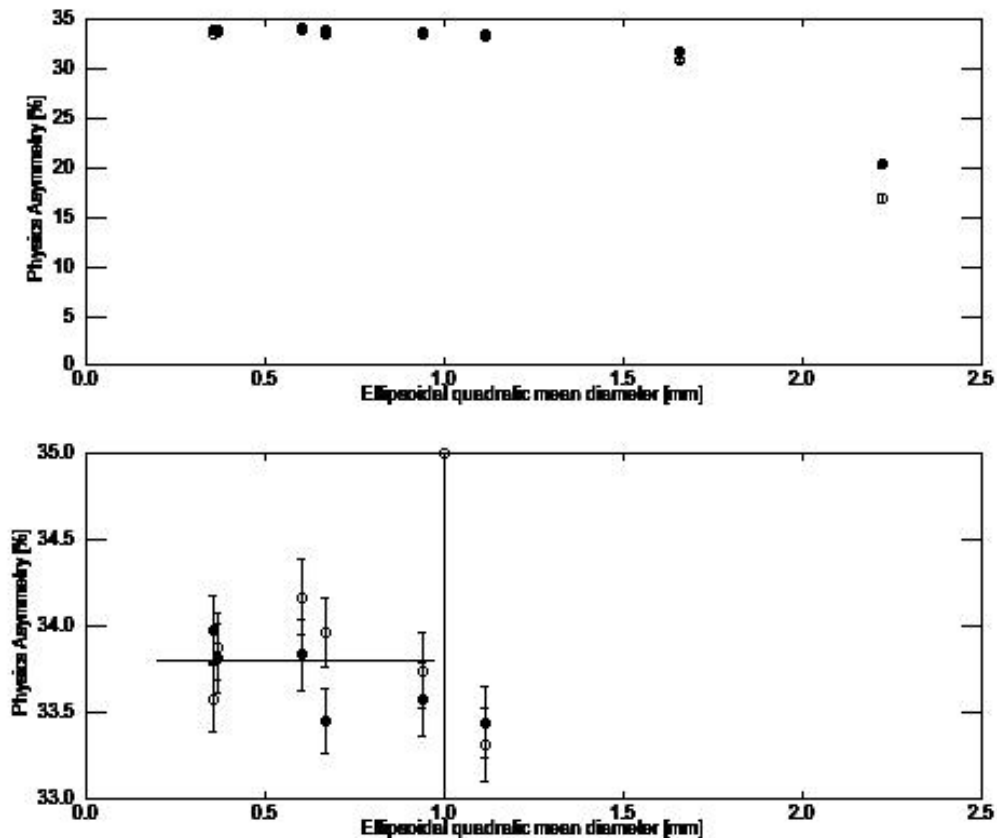


Fig. 6. Mott asymmetry vs. spot size.

Run I: Asymmetry vs. Beam Position

The Mott asymmetry vs. beam position was studied by varying two upstream steering coils MBH0L01AH and MBH0L01AV to locate the beam at 6 locations within one spot size of the operating position. At various positions the Mott asymmetry was measured using foil #15 (Au:1 μ m) e3318095 and foil #1 (Au:0.225 μ m) e3318137 and an OTR camera image was recorded. Three steps are applied to transform the OTR image to the beam position at the foil:

- Software *ImageJ* refines the camera PNG image to one that is 165 by 165 pixel with absolute resolution of about 2 pixels. The OTR beam centroid coordinates are computed within the camera reference frame,
- The camera coordinates are transformed to target foil coordinates. The transformation between the (c)amera pixels and the (b)eam pixels is given by (see Appendix A for details):

$$\begin{pmatrix} x_b \\ y_b \end{pmatrix} = \begin{pmatrix} -0.579 & -0.579 \\ -0.819 & 0.595 \end{pmatrix} \begin{pmatrix} x_c \\ y_c \end{pmatrix}$$

- By taking images of the ladder for known linear vertical motion a calibration of the transformed pixel size to real vertical size is determined to be 37.9 px/mm.

Results are summarized in Table 4 and the corresponding Mott asymmetry is shown in Fig. 7.

Table 4. Summary of position measurements.

Foil	Motion		MBH0L01A Relative		Image	Mott Run		Image Pixels		Image Rel Pixels		Foil Rel Pixels		Foil Rel (mm)		
	Real	OTR	Hor	Ver		IN	OUT	X	Y	Xc	Yc	Xb	Yb	X	Y	R
15	0	0	0	0	run1-foil15-fig7.png	8132	8131	80.2	93.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	U	U	0	30	run1-foil15-fig5.png	8134	8133	61.9	107.5	-18.4	14.3	2.4	23.5	0.1	0.6	0.6
15	D	D	-0.2	-30	run1-foil15-fig6.png	8136	8135	99.4	75.8	19.1	-17.4	-1.0	-26.0	0.0	-0.7	0.7
15	R	L	29.8	0	run1-foil15-fig8.png	8138	8137	65.2	78.6	-15.1	-14.6	17.2	3.7	0.5	0.1	0.5
15	L	R	-30	0	run1-foil15-fig9.png	8140	8139	97.4	109.8	17.2	16.6	-19.5	-4.2	-0.5	-0.1	0.5
15	LD	RD	-30	-30	run1-foil15-fig10.png	8142	8141	114.5	95.2	34.3	2.0	-21.0	-26.9	-0.6	-0.7	0.9
15	RU	LU	30	30	run1-foil15-fig11.png	8144	8143	46.4	97.0	-33.9	3.8	17.4	30.0	0.5	0.8	0.9
1	0	0	0	0	run1-foil1-fig3.png	8146	8145	86.0	95.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	LD	RD	-30	-30	run1-foil1-fig4.png	8149	8147	121.2	92.8	35.1	-2.6	-18.8	-30.3	-0.5	-0.8	0.9
1	LU	RU	-30	30	run1-foil1-fig5.png	8151	8150	83.7	125.2	-2.3	29.8	-15.9	19.6	-0.4	0.5	0.7
1	RU	LU	30	30	run1-foil1-fig6.png	8153	8152	52.1	99.4	-34.0	4.0	17.3	30.2	0.5	0.8	0.9
1	RD	LD	30	-30	run1-foil1-fig8.png	8155	8154	86.2	62.6	0.2	-32.8	18.8	-19.7	0.5	-0.5	0.7
1	D	D	0	-30	run1-foil1-fig9.png	8157	8156	102.4	78.8	16.3	-16.6	0.1	-23.2	0.0	-0.6	0.6
1	L	R	-30	0	run1-foil1-fig10.png	8159	8158	101.7	106.8	15.7	11.4	-15.7	-6.0	-0.4	-0.2	0.4

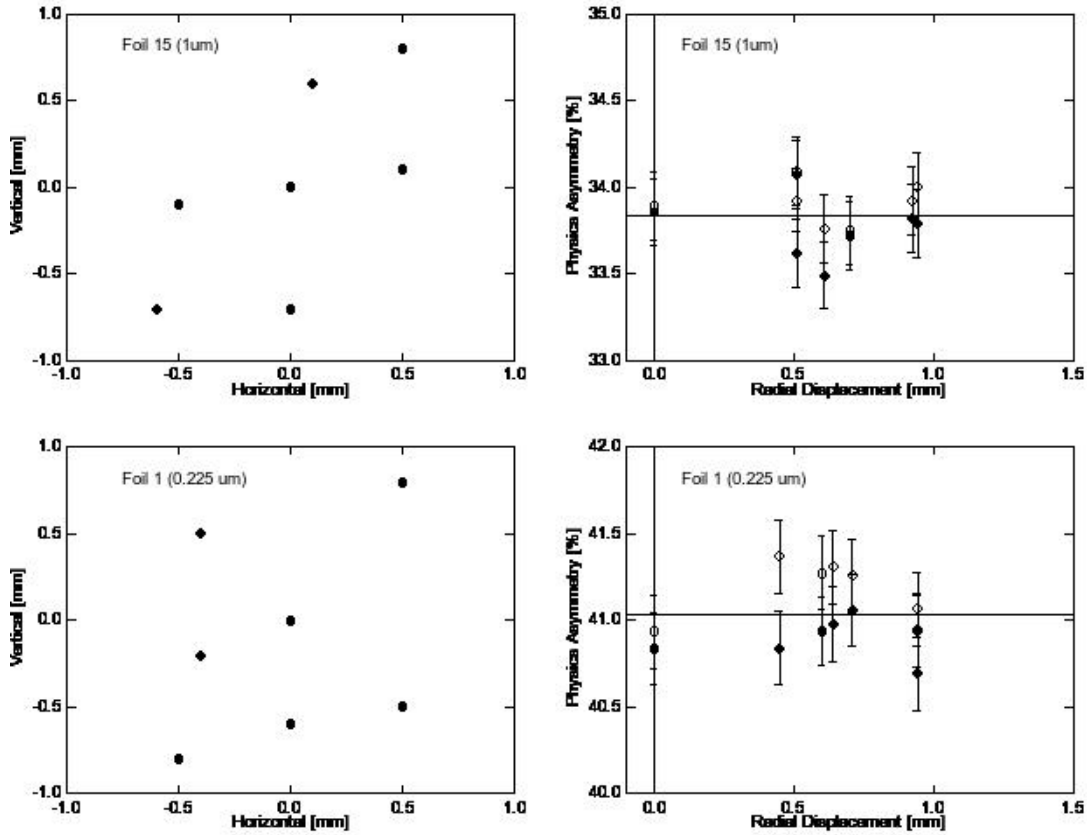


Fig. 7. Physics asymmetry vs. radial position foil #15 (Au: 1.0 μm) and foil #1 (Au: 0.225 μm). The left plots show the position relative to nominal operating point (0,0) and the right plots show a scatter of asymmetry vs. radiation displacement from (0,0).

3 Run II Asymmetry vs. Beam Energy

The Mott asymmetry was measured vs. at four beam energies about the operating set point by varying QCM R028GSET while minimizing energy spread with R028PSET. The Mott asymmetry was measured using foil #15 (Au:1 μm) and foil #14 (Au:0.35 μm). The electron beam energies [1] and Mott runs are summarized in Table 5. Mott asymmetries are shown in Fig. 8.

Table 5. Run II Beam Momentum and Kinetic Energy

R028 GSET	Momentum		Kinetic Energy		Mott Runs		Mott Runs	
	P MeV/c	δP MeV/c	T MeV	ΔT MeV	Foil #15 (1 μm)		Foil #14 (0.35 μm)	
					In	Out	In	Out
3.350	5.025	0.012	4.540	0.012	8457 8459	8458 8460	8462 8464	8461 8463
3.740	5.219	0.013	4.733	0.012	8445 8447	8446 8448	8450 8452	8449 8451
4.120	5.404	0.013	4.917	0.013	8433 8435	8434 8436	8438 8440	8437 8439
4.500	5.603	0.013	5.115	0.013	8466 8469	8467 8470	8473 8475	8471 8474
4.890	5.785	0.014	5.297	0.014	8477 8479	8478 8480	8482 8484	8481 8483

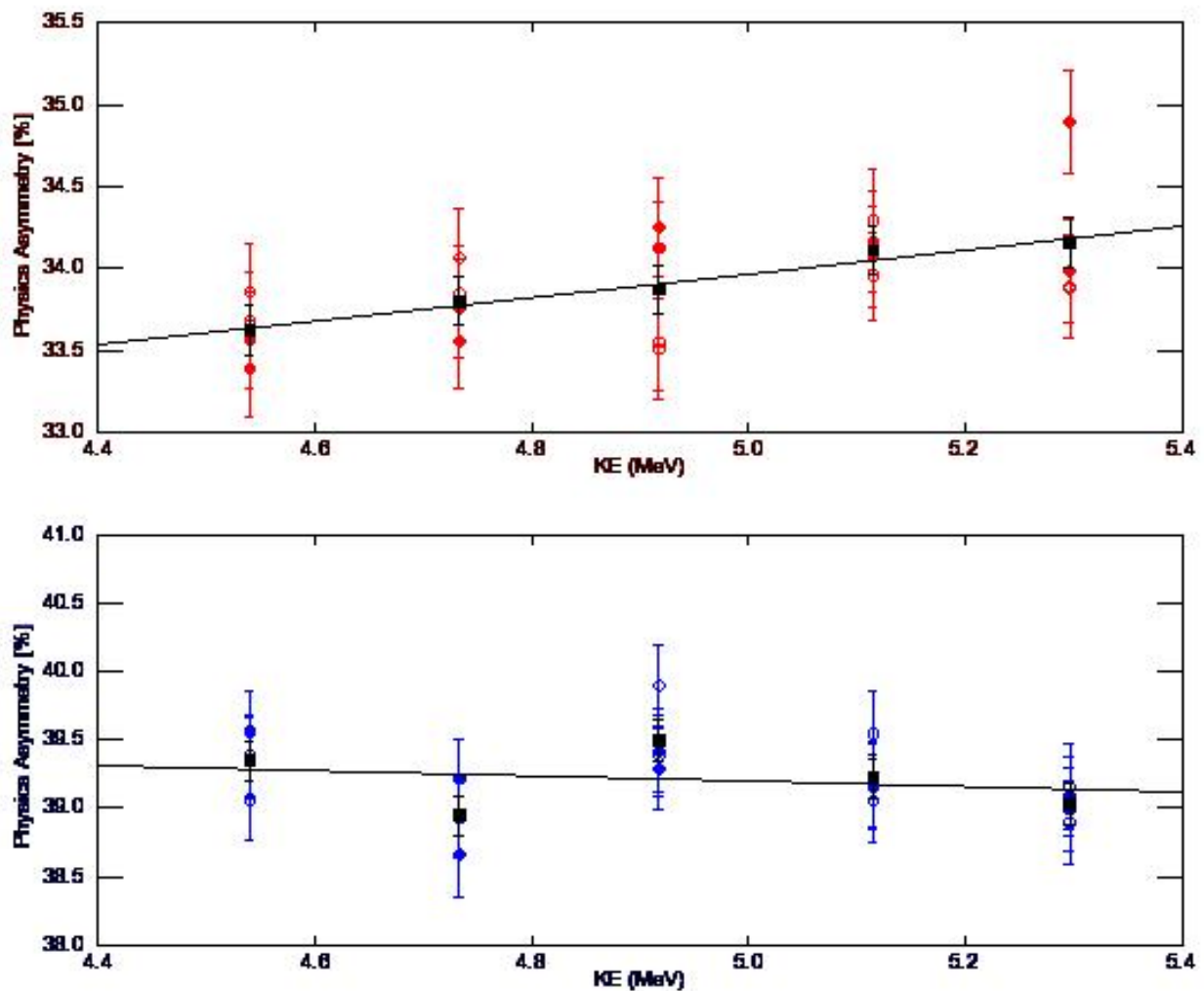


Fig. 8. Mott asymmetry vs. kinetic energy for foil #15 (Au: 1.0 μm) and foil #14 (Au: 0.35 μm).

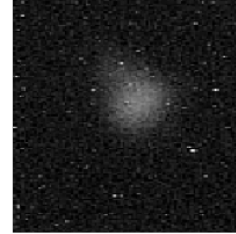
The variation with energy is 0.022/MeV for foil #15 and -0.0046/MeV for foil #14. The variation with asymmetry is consistent with the Sherman function variation with energy in the region of 172.5-173.5 degrees.

4 Reference

1. J. Grames, "Mott Experiment Run I/II Beam Energies", JLAB-TN-17-001 (2017).
2. J. Grames "Fall 2014 Mott Target Replacement and Ladder Position Re-Calibration", JLAB-TN-14-026 (2014).

5 Appendix A

Step 1. The ELOG entry images were saved as PNG files and cropped to 165 x 165 pixels. An example is shown here and summarized for all images below.



FILENAME	WIDTH	HEIGHT	CEN X	SIG X	FWHM X	CEN Y	SIG Y	FWHM Y
run1-foil15-fig10.png	165	165	114.5	12.9	30.5	95.2	18.6	43.9
run1-foil15-fig11.png	165	165	46.4	13.2	31.0	97.0	12.0	28.2
run1-foil15-fig1.png	165	165	47.2	13.8	32.6	117.7	14.5	34.2
run1-foil15-fig5.png	165	165	61.9	12.5	29.5	107.5	19.0	44.7
run1-foil15-fig6.png	165	165	99.4	13.2	31.0	75.8	14.1	33.3
run1-foil15-fig7.png	165	165	80.2	13.8	32.4	93.2	13.8	32.6
run1-foil15-fig8.png	165	165	65.2	13.9	32.6	78.6	16.4	38.6
run1-foil15-fig9.png	165	165	97.4	12.9	30.4	109.8	16.4	38.7
run1-foil1-fig10.png	165	165	101.7	15.3	36.0	106.8	17.4	40.9
run1-foil1-fig3.png	165	165	86.0	14.7	34.6	95.4	15.4	36.4
run1-foil1-fig4.png	165	165	121.2	15.3	35.9	92.8	16.5	38.9
run1-foil1-fig5.png	165	165	83.7	15.4	36.4	125.2	18.9	44.4
run1-foil1-fig6.png	165	165	52.1	15.6	36.7	99.4	14.5	34.2
run1-foil1-fig8.png	165	165	86.2	14.2	33.5	62.6	14.7	34.6
run1-foil1-fig9.png	165	165	102.4	14.4	34.0	78.8	17.6	41.6

Step 2. The true beam position at the target is reduced in the plane of the target-mirror-camera by the projected distance of the mirror-foil vector relative to the beam axis. This value is estimated from drawings to be 13° from drawings however actual alignment of the mirror and its support fixture may result in a variation by as much as $\pm 6^\circ$. This sub-tended image is collected along a target-mirror-camera plane of about 45° cw with respect the horizontal beam plane and is thus coupled. The image is also inverted by the mirror. Finally, the true beam position (x_b, y_b) is related to the camera pixel position (x_p, y_p) by the following transformation:

$$\begin{pmatrix} x_c \\ y_c \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}_{Inv} \begin{pmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{pmatrix}_{\phi=-45^\circ} \begin{pmatrix} 1 & 0 \\ \cos \theta & 1 \end{pmatrix}_{\theta=13^\circ} \begin{pmatrix} x_b \\ y_b \end{pmatrix}$$

$$\begin{pmatrix} x_c \\ y_c \end{pmatrix} = \begin{pmatrix} -0.726 & -0.707 \\ -1.000 & 0.707 \end{pmatrix} \begin{pmatrix} x_b \\ y_b \end{pmatrix}$$

This 2 x 2 matrix is inverted to finally yield true beam position as a function of camera pixels.

$$\begin{pmatrix} x_b \\ y_b \end{pmatrix} = \begin{pmatrix} -0.579 & -0.579 \\ -0.819 & 0.595 \end{pmatrix} \begin{pmatrix} x_c \\ y_c \end{pmatrix}$$

Step 3. On a separate occasion images of the target ladder were saved for small 200 step increments of the target ladder. The transformed position of a specific item may then be calibrated to the known physical motion of 4464 ladder steps = 25.4 mm of linear vertical travel [2]. The table below shows the transformed images indicate purely vertical motion of the target ladder and indicate a calibration of 37.9 +/- 1.1 pixels/mm.

Image ABS Pixels		Image REL Pixels		Foil REL Pixels		Ladder ABS Steps	Ladder REL Steps	Ladder (mm)	pixels/mm
-421	476	0	0	0.0	0.0	-73800	0	0	
-392	447	29	-29	0.0	-41.0	-73600	200	1.14	-36.03
-362	419	59	-57	-1.2	-82.2	-73400	400	2.28	-36.13
-329	385	92	-91	-0.6	-129.5	-73200	600	3.41	-37.93
-299	355	122	-121	-0.6	-171.9	-73000	800	4.55	-37.77
-267	322	154	-154	0.0	-217.8	-72800	1000	5.69	-38.27
-235	290	186	-186	0.0	-263.0	-72600	1200	6.83	-38.52
-204	259	217	-217	0.0	-306.8	-72400	1400	7.97	-38.52
-171	226	250	-250	0.0	-353.5	-72200	1600	9.10	-38.83
-140	194	281	-282	0.6	-397.9	-72000	1800	10.24	-38.85

6 Appendix B

An approximation for the average/mean radius of an ellipse's circumference, Er , is the elliptical quadratic mean:

$$Er \approx Er_q = \sqrt{\frac{a^2 + b^2}{2}}$$

(where a is the central, horizontal, transverse radius/semi-major axis
and b is the central, vertical, conjugate radius/semi-minor axis)