Study of the Vertical Component of the Beam Polarization for the 2004 HAPPEX-2 Run

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Abstract

The HAPPEX-2 collaboration would like to estimate the contribution of the vertical component of the electron beam polarization, in Hall A during their 2004 production run, to their overall physics result. To help achieve this goal, a set of injector Mott polarization measurements and injector beam polarization manipulations were made during their run period. This note summarizes that activity and offers some comments to help complete the estimatation. Additionally, the magnitude of the beam polarization for the superlattice and strained layer GaAs photocathodes used are reported in this note.

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1 Introduction

The 2004 HAPPEX-2 production run occurred between June 11 and July 25. While the experiment relies on a longitudinally polarized electron beam in Hall A, some component of the electron beam may be transverse. The vertical transverse component may contribute to the overall physics result. To determine this contribution, the collaboration organized a special 2 day test which included injector Mott polarization measurements and injector beam polarization manipulations. The aim of the Mott measurements was to estimate the amount of vertical beam polarization being delivered during their longitudinal run period. The aim of the polarization manipulations was to purposefully deliver a fully vertically polarized electron beam to Hall A so that they may efficienctly measure this contribution. The injector work and this test in Hall A occured during July 15-16, while using a strained layer GaAs photocathode in Gun2 (July 7-25). Earlier measurements, opportunistically performed on June 21, measured the polarization while using a superlattice GaAs photocathode in Gun3 (June 11-July 7). These measurements were performed to study this photocathode material and provide only and upper bound to the vertical component of the beam polarization at that time.

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Owing to the elegant geometry of the CEBAF accelerator and to the predominant need for a longitudinally polarized beam in the end stations, the manipulation of the beam polarization is usually reduced to that of a single degree of freedom. The Wien filter spin rotator, following the electron gun, is used to correct for the precession the beam polarization experiences in the 180° sections of the recirculation arcs in the accelerator and finally in the extraction arc leading to an end station. Because this correction may be accurately calculated with a precision $\delta\theta$ better than 5° the reduction in the desired polarization is small $(1 - \cos\delta\theta)$, and is considered acceptable compared to the additional time required to further tune the orientation. While the injector Mott polarimeter is well equiped to map the orientation of the beam polarization and ideally located to do so, this is not usually done. However, when measured, the vertical component of the beam polarization exiting the injector is a small, but non-zero, fraction of the total beam polarization typically amounting to an absolute value of less than 3%.

This note is organized as follows. First, the formalism used to interpret the spin rotations for Mott measurements is presented. Next, the injector polarization measurements performed during this period are analyzed. Finally, the results to help the HAPPEX-2 collaboration estimate the amount of vertical beam polarization in Hall A during their run are summarized.

2 Spin Manipulations and the Vertical Polarization in Hall A

The electrons interact with many different electromagnetic elements in the injector, however, the equation of motion of their spin is, to a very good approximation, reduced to a simple picture. First, the electron gun produces a longitudinally polarized beam, $\vec{P}_{Gun} = (0, 0, \pm P_0)$. Next, the beam may then encounter two orthogonal spin rotations in sequence, first about the vertical axis (Wien filter) and next about the longitudinal axis (pair of solenoids). Finally, the polarization measured at the Mott polarimeter following these manipulations accurately represents the polarization entering the accelerator. Once in the accelerator the total polarization experiences signficant precession by the dipole magnetic fields, however, the symmetrical arrangement of these magnets ultimately conserves the vertical component of the beam polarization exiting the injector at the end station target.

While the reader is urged to seek more detail if necessary [1] the list of assumptions and simplifications used is stated here:

- The non-counterwound solenoid magnet (MFH2I01 for Gun2 or MHF3I01 for Gun3) leaves the longitudinal polarization unchanged,
- the precession due to the bend magnet MDS1I01 (0.02°) is ignored,

- the non-counterwound solenoid magnets (MFB1I02 and MFB1I03) rotate the polarization about the longitudinal axis, but on a cone of opening angle less than the 0.02° incurred by the dipole, and is ignored,
- the Wien filter introduces the first macroscopic rotation (θ_{Wien}) about the vertical axis followed by two co-axial solenoids MFQ1I04AB and MFA0I02AB, which introduce the second macroscopic rotation ($\phi_{S_{12}}$) about the longitudinal axis,
- the counterwound solenoids following the Wien filter that are not fully balanced, i.e., $\int B_z \cdot dz \neq 0$, will precess the polarization as if were one of the two solenoid spin rotators,
- the dipole magnet that bends the beam ($-12.4°$) to the Mott polarimeter in the 5 MeV region of the injector will precess the polarization by no more than $-0.16°$, and is ignored,
- the net vertical bend angle of the beam in the spreader and recombiner section of the recirculation arcs is zero and the net precession due to these magnets is consequently zero,
- the transverse electric fields due to the cryomodule RF couplers cancel over each cryomodule and the remaining electric field experienced by the beam is purely longitudinal,
- and finally, the beam polarization-beam orbit sensitivity which may precess the polarization into the vertical direction is a negligible contribution, likely less than 0.2%/mm of a vertical orbit amplitude; a more accurate estimate would require a thoroughly detailed analysis, beyond the scope of this note.

Because the vertical component of the beam polarization is estimated to be conserved through the accelerator, a Mott polarimeter measurement is sufficient to estimate the vertical component of the beam polarization in Hall A. However, to determine the total beam polarization or to make an estimate of the horizontal or longitudinal component of the beam polarization we must account for the spin rotations. Because the Wien filter is routinely used we rely upon the previous calibration of the device and use an uncertainty of 2°. The solenoid magnets are used infrequently as spin rotators and therefore the azimuthal rotation is calculated from each Mott measurement independently. This process is fully described in the next section.

2.1 Mathematical Formalism Used

The product of the rotations of the three spin manipulators (one Wien filter and two sequential solenoid magnets) transform the polarization vector at the electron gun, $\vec{P}_{Gun}$, to a polarization vector at the Mott polarimeter (or entrance to the accelerator), $\vec{P}_{Mott}$, in the following way,

$$\vec{P}_{Mott} = R_z(\phi_{Solenoid_2}) \cdot R_z(\phi_{Solenoid_1}) \cdot R_y(\theta_{Wien}) \cdot \vec{P}_{Gun}, \tag{1}$$

where the rotation matrices about the $y-$ and $z-$ axis are given, respectively, by

$$R_y(\theta) = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix},$$

$$R_z(\phi) = \begin{pmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{2}$$

A positive rotation angle is described by the right–hand rule. Because the rotations in the two solenoid magnets are about the ame axis and are in series they commute, so $\phi_{S_{12}} = \phi_{Solenoid_1} + \phi_{Solenoid_2}$, or

$$\begin{aligned} \vec{P}_{Mott} = & \quad R_z(\phi_{S_{12}}) \cdot R_y(\theta_{Wien}) \cdot \vec{P}_{Gun} \\ = & \begin{pmatrix} \cos\theta_{Wien}\cos\phi_{S_{12}} & -\sin\phi_{S_{12}} & \sin\theta_{Wien}\cos\phi_{S_{12}} \\ \cos\theta_{Wien}\sin\phi_{S_{12}} & \cos\phi_{S_{12}} & \sin\theta_{Wien}\sin\phi_{S_{12}} \\ -\sin\theta_{Wien} & 0 & \cos\theta_{Wien} \end{pmatrix} \cdot \vec{P}_{Gun}. \end{aligned} \tag{3}$$

$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}_{Mott} = P_0 \begin{pmatrix} \sin\theta_{Wien}\cos\phi_{S_{12}} \\ \sin\theta_{Wien}\sin\phi_{S_{12}} \\ \cos\theta_{Wien} \end{pmatrix}. \tag{4}$$

The azimuthal angle, ϕ_{S12}, is determined by comparing the ratio of the vertical to horizontal beam polarizations,

$$\frac{P_y}{P_x} = \frac{P_0 \cdot \sin\theta_{Wien} \cdot \sin\phi_{S_{12}}}{P_0 \cdot \sin\theta_{Wien} \cdot \cos\phi_{S_{12}}} = \frac{\epsilon_y/A_y}{\epsilon_x/A_x} = \frac{\epsilon_y}{\epsilon_x} = \tan(\phi_{S_{12}}), \tag{5}$$

where ϵ_x and ϵ_y are the measured horizontal and vertical experimental asymmetries sharing a common analyzing power, i.e., $A_x = A_y = A = -0.4008 \pm 0.0048$ for the $1\mu m$ thick gold target used for all of the measurements reported here. Once the azimuthal angle is calculated the total polarization P_0 can be calculated from either the equation for P_x or P_y.

The purpose of this activity was to first measure the amount of vertical polarization being delivered for the longitudinal run and then to purposely setup the polarization orientation to be entirely vertical. Mott measurements were made at eight Wien angles including the one used for the Hall A longitudinal run period ($\theta_{Wien} = 15.95°$). The eight measurements were made to prepare for the vertical orientation setup and to improve the measurement of the full beam polarization. The experimental asymmetries measured for the eight measurements are listed in Table 1. For the case $\theta_{Wien} = 15.95°$ the vertical beam polarization is $P_y = 1.1 \pm 1.2\%$. The vertical asymmetry indicates a small non-zero rotation in ϕ, and using Eq. 5 yields the results shown in Fig. 1c. The mean and standard deviation of these measurements is $-2.98° \pm 1.01°$. The average total polarization is computed to be $\overline{P}_0 = 73.4 \pm 2.9\%$ using the Wien angle and azimuthal rotation angle from each measurement, and is shown in Fig. 1d. While the single measurement reported for $\theta_{Wien} = 15.95°$ is consistent with a zero vertical polarization, the estimate of the vertical polarization exiting the injector, based on the average of all eight measurements, is more precisely determined to be $P_y = 1.0 \pm 0.4\%$.

Table 1
The experimental asymmetries (with statistical uncertainty) are shown as a function of Wien angle.

Wien Angle	Data File	ϵ_x [%]	ϵ_y [%]
45.21°	mott5.15Jul04_11:15:02	-20.73 ± 0.46	1.08 ± 0.46
75.23°	mott5.15Jul04_11:27:41	-28.66 ± 0.65	0.70 ± 0.64
15.95°	mott5.15Jul04_11:36:06	-7.33 ± 0.50	0.45 ± 0.48
85.24°	mott5.15Jul04_11:45:36	-29.72 ± 0.76	0.99 ± 0.75
95.25°	mott5.15Jul04_11:55:13	-29.80 ± 0.50	1.90 ± 0.52
105.26°	mott5.15Jul04_12:14:07	-28.16 ± 0.61	2.05 ± 0.61
-30.20°	mott5.15Jul04_12:41:59	15.07 ± 0.69	-1.03 ± 0.67
-60.22°	mott5.15Jul04_12:51:26	26.56 ± 0.66	-1.07 ± 0.63

Next, the beam polarization was oriented vertically. This was done in two steps. First, the beam polarization was rotated to the transverse horizontal direction by setting $\theta_{Wien} = 91.08°$. The choice of the Wien angle was based on a fit of the horizontal asymmetry in Fig. 1a. Next, the beam polarization was rotated about the longitudinal direction using the pair of solenoids MFQ1I04AB and MFA0I02AB. The rotation is created by varying the quantity $\int B_z dz$ while maintaining a constant focal length (inversely proportional

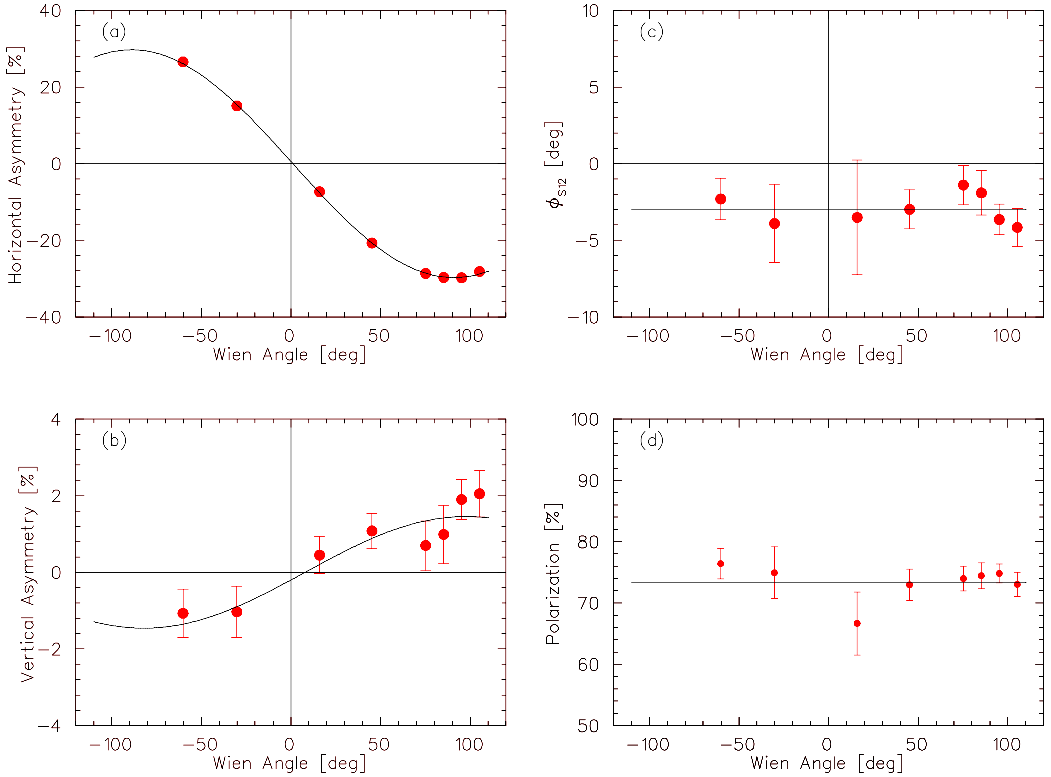

Fig. 1. The four plots summarize the measurement of the beam polarization for the Hall A longitudinal run period. Plots (a) and (b) show the horizontal and vertical experimental asymmetries with statistical uncertanties. Plot (c) shows the effective rotation angle $\phi_{S_{12}}$ from each measurement. Plot (d) shows the calculated total beam polarization.

to $\int B_z{}^2 dz$). To accomplish this we create a difference between the power supply current for each half of the solenoid magnet ($\Delta I_{AB} = I_B - I_A$, see Ref. [1] for more detail). The weaker of the two solenoids, MFA0I02AB, was set for the maximum rotation it could provide, about 40°. Next, the solenoid MFQ1I04AB was set to about 45° and Mott measurements were made as the rotation was varied, to determine which rotation produced the maximum vertical beam polarization. The measured asymmetries are reported in Table 2 and shown in Figs. 2a and 2b. The calculated rotation angle is plotted in Fig. 2c versus ΔI_{AB}. A linear fit of this data yields the rotation due to the solenoid MFA0I02AB and any incorporated errors ($\phi_0 = -39.3° \pm 0.5°$) and the slope yields the sensitivity of the solenoid MFQ1I04AB ($\Delta\phi/\Delta I = 0.0368 \pm 0.0003$ deg/mA). The solenoid MFQ1I04AB was finally set at $\Delta I_{AB} = -1395.96$ mA ($\phi_{S12} = 90.7° \pm 0.6°$). For this final orientation the vertical component of the beam polarization was measured $P_y = 76.8 \pm 1.6\%$. The total polarization is computed using the Wien angle and the calculated solenoid rotation angle for each measurement and is shown in Fig. 2d. The average total polarization is $\overline{P}_0 = 75.1 \pm 1.9\%$. The estimate of the vertical polarization exiting the injector is $P_y = 75.1 \pm 1.6\%$.

Table 2
The Mott polarimeter experimental asymmetry with statistical uncertainty is shown for the measurements at eight different solenoid settings.

MFQ1I04A	MFQ1I04B	Data File	ϵ_x [%]	ϵ_y [%]
-505.89 mA	809.37 mA	mott5.15Jul04_13:43:36	-28.37 ± 0.44	-4.38 ± 0.45
-370.89 mA	674.37 mA	mott5.15Jul04_14:06:47	-30.76 ± 0.46	0.27 ± 0.45
-303.39 mA	741.87 mA	mott5.15Jul04_14:15:55	-30.44 ± 0.43	0.35 ± 0.45
505.89 mA	-809.37 mA	mott5.15Jul04_14:31:05	-1.47 ± 0.50	30.03 ± 0.49
235.89 mA	-539.37 mA	mott5.15Jul04_14:43:40	-10.76 ± 0.59	27.24 ± 0.59
775.89 mA	-1079.37 mA	mott5.15Jul04_14:55:36	9.83 ± 0.59	29.16 ± 0.58
546.24 mA	-849.72 mA	mott5.15Jul04_15:35:37	-0.83 ± 0.54	30.81 ± 0.53
542.01 mA	-845.49 mA	mott5.15Jul04_15:43:46	1.05 ± 0.55	29.97 ± 0.55

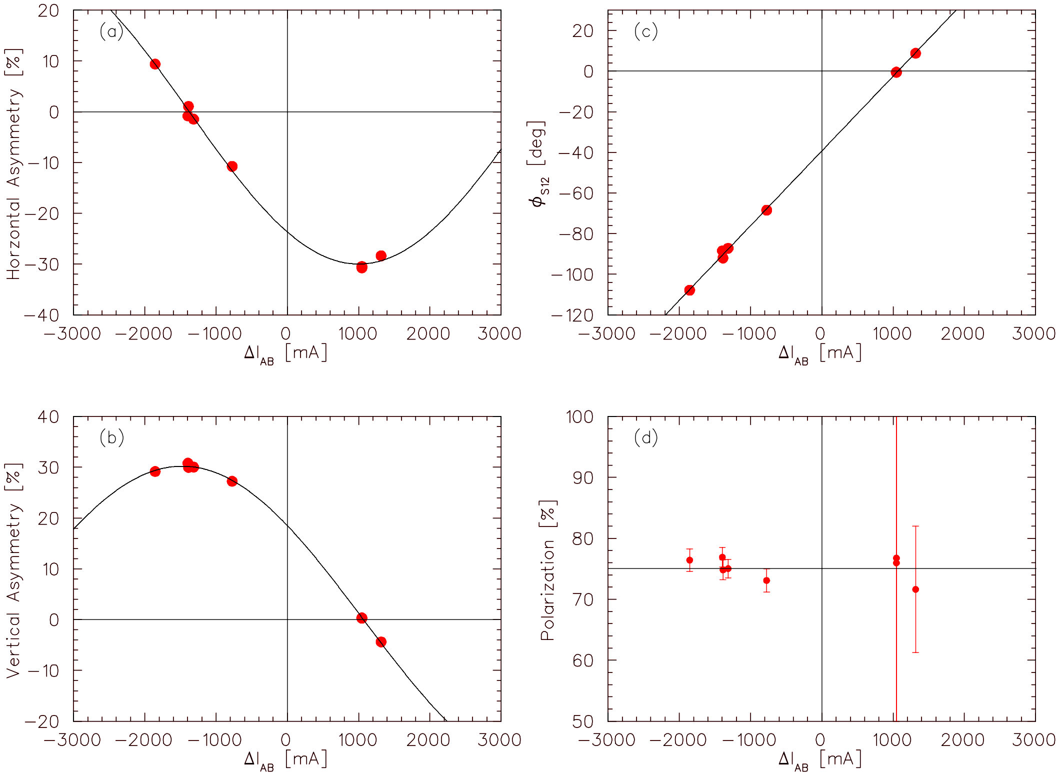

Fig. 2. The four plots summarize the measurement of the vertical beam polarization in Hall A. Plots (a) and (b) show the horizontal and vertical experimental asymmetries. Plot (c) shows the total rotation angle $\phi_{S_{12}}$ for each measurement. Plot (d) shows the calculated total beam polarization for each solenoid rotation angle.

2.3 Mott Measurements on June 21, 2004

The beam polarization of a superlattice GaAs photocathode in Gun3 was opportunistically measured on June 21 using the Hall A beam. The Wien angle

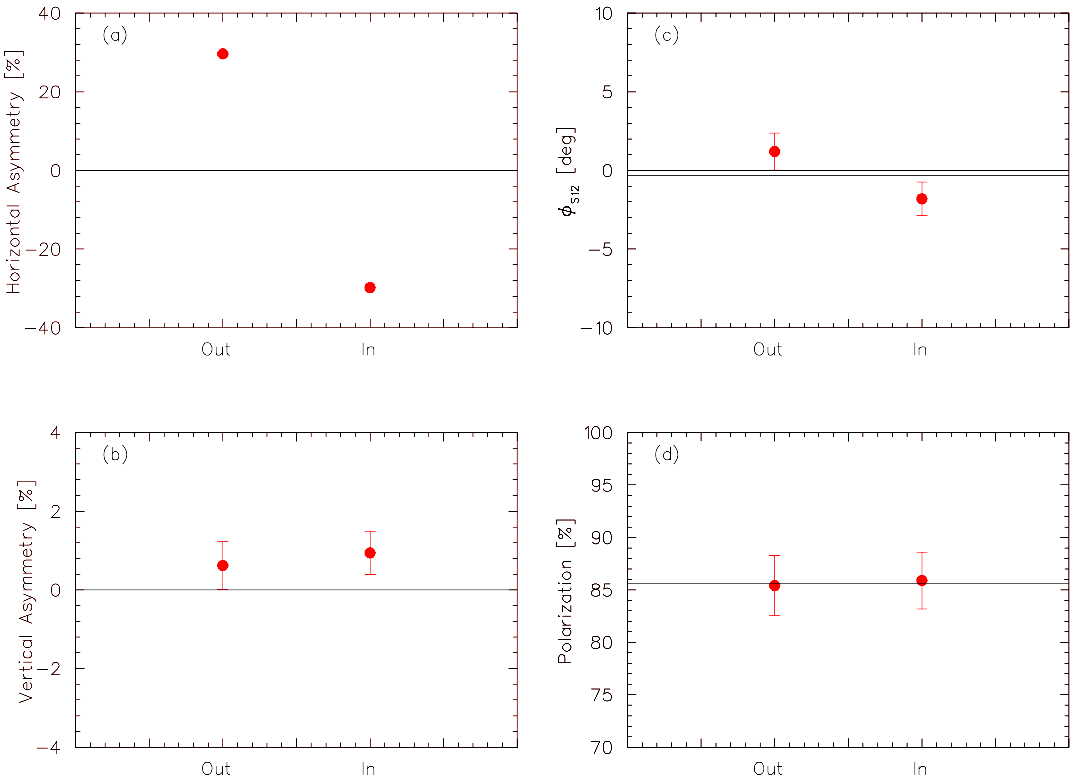

Fig. 3. The four plots summarize two measurements of the Hall A beam for the insertable half-waveplate both In and Out, during the longitudinal run period when using the superlattice photocathode from Gun3.

was first changed from 15.95° to 40.0° and the polarization was measured with the insertable half-waveplate both In and Out. The experimental asymmetries for the two measurements are listed in Table 3 and are shown in Figs. 3a and 3b. Because the half-waveplate reverses the overall sign of the beam polarization the experimental asymmetry should also reverse. While this occurs for the horizontal asymmetry, the vertical asymmetry does not reverse sign. Without additional measurements it is not clear if the source of the discrepancy is an unaccounted systematic effect or some real change to the orientation of the beam polarization. The usual rotation angle and total polarization, as previously calculated in this note, are shown in Figs. 3c and 3d, respectively. The average total polarization is $\overline{P}_0 = 85.7 \pm 2.3\%$. Based on the average of the two measurements of the vertical asymmetry an upper bound of $2 \pm 1\%$ is estimated for the vertical polarization in Hall A.

Table 3
The experimental asymmetries (ϵ_x and ϵ_y) are reported for the Hall A laser when the insertable half-waveplate (IHWP) is Out and In.

IHWP	Data File	ϵ_x [%]	ϵ_y [%]
Out	mott5.21Jun04_12:07:35	29.64 ± 0.77	0.62 ± 0.61
In	mott5.21Jun04_12:14:22	-29.80 ± 0.70	0.94 ± 0.55

3 Conclusion

Injector Mott polarization measurements were performed to help estimate the vertical beam polarization in Hall A during the 2004 HAPPEX-2 production run. The results are summarized in Table 4. As stated earlier, fine tuning of the polarization orientation or measurement of the vertical component of the beam polarization is not usually done. However, with some planning these measurements can be made to provide a higher degree of precision. It may be worthwhile in the future to adjust the polarization orientation to make available the entire full polarization of the photocathode.

Table 4
Summary of estimates for the 2004 HAPPEX-2 production run.

Event (Date)	Gun/Cathode	$\overline{P_0}$ [%]	P_y (single) [%]	P_y (average) [%]
Production (7/15)	2/Strained	73.4 ± 2.9	1.1 ± 1.2	1.0 ± 0.4
Vertical (7/15)	2/Strained	75.1 ± 1.9	76.8 ± 1.6	75.1 ± 1.6
Production (6/21)	3/Superlattice	85.7 ± 2.3	$< 3\%$	$< 3\%$

References

[1] J.M. Grames, Ph.D. thesis, University of Illinois at Urbana-Champaign, 2000, ftp://ftp.jlab.org/pub/grames/thesis.pdf.