ELECTRON BEAM MØLLER POLARIMETER AT HALL A, JLAB

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As a part of the spin-physics program at the Thomas Jefferson National Accelerator Facility (JLab), a Møller polarimeter has been developed to measure the polarization of electron beam of energies between 0.8 and 6.0 GeV. A unique design of this polarimeter was developed. A set of three quadrupole magnets provides an angular selection of the Møller electron pairs and a dipole magnet provides energy analysis. The test procedure and commissioning of the polarimeter are presented. The results of beam polarization measurements in long-term physical experiments, the correlation for the three-beam accelerator mode and other effects are discussed.

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1. INTRODUCTION

Since 1996 JLab is the world's premier facility for studying nuclei and nucleons via the (e,e'x) reactions with a polarized electron beam. For the spin-physics program at JLab, a number of polarimeters exploiting Mott, Møller, and Compton scattering are used. In the Hall A a Møller polarimeter was designed and constructed to measure the polarization of the electron beam with energies from 0.8 to 6 GeV. It has been operating since 1998. The polarimeter was created eliminating certain disadvantages which were inherent in its predecessors. For example, the effect of Fermi motion of atomic electrons [1-2] (now known as the Levchuk-effect) was taken into account in the polarimeter design. A rotatable polarized target and a new method of target polarization measurements *in situ* were developed for this polarimeter. The polarimeter was used to measure the long-time evolution of the beam polarization for a number of experiments in the Hall A. Some of the experiments results are published already [3-8]. The Møller polarimeter was used for investigation of the dependencies of the electron beam polarization on certain parameters of the RF system of the injector at the JLab accelerator.

2. EXPERIMENTAL METHOD AND RESULTS

2.1 Polarized electron beam at JLab

CEBAF (Continuous Electron Beam Accelerator Facility) is the accelerator located at JLab in Newport News, VA, USA. The accelerator is based on superconducting RF cavities operating in a continuous wave (CW) mode. A layout of the machine is shown in Fig. 1 [9]. Two parallel linacs in a "race track" configuration increase the beam energy from 800 to 1200 MeV for each turn. The beam is recirculated up to five times to reach a maximum energy up to 6 GeV. The accelerator can deliver electrons to 3 experimental areas (Hall A, B and C) at either the same energy, or at multiples of 1/5 of the end energy. The energy spread in the beam is $\Delta E/E<10^{-4}$. Beams can be extracted at each recirculation. It provides the operation of the experimental halls with simultaneous beams of different, but correlated, energies. The 1.497 GHz RF structure allows simultaneous beams to be delivered to the halls at a frequency of 499 MHz. The microbunches can be loaded with different electron densities, which provide operations of the experimental halls with in parallel with a standard thermionic unpolarized gun.

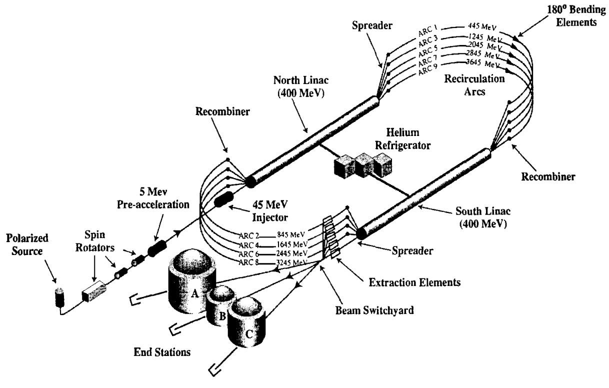

Fig. 1. *Schematics of the CEBAF accelerator [9]*

The polarized electron gun produces a continuous series of electron bunches at a characteristic RF of 1497 MHz of the accelerator. The polarized source is based on the method of photoemission from semiconductor photocathodes (strained GaAs type), which induce an incident circularly polarized laser beam. The laser system (see Fig. 2) comprises three lasers, one designed to each experimental hall. Each laser operates in a synchronized RF mode with 499 MHz frequency and produces optical pulses of ~55 ps duration (30ºRF). The beam current for each hall can be adjusted with corresponding photon beam attenuators or slit devices. Usually, the photon attenuators are fully open to minimize the current dilution between different laser beams. The slit device makes it possible to reduce the electron beam current and its phase.

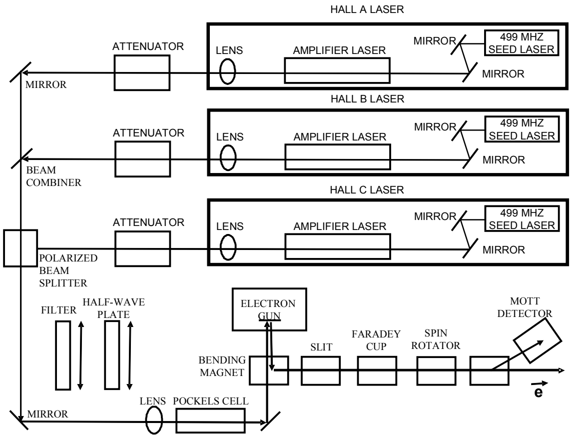

Fig. 2. Layout of the laser system and polarizing optics [9]

2.2 The Hall A Møller polarimeter

The polarimeter exploits the process of Møller scattering [10] $e^{\rightarrow}+e^{\rightarrow}\rightarrow e+e$. Its cross-section depends on the beam and target polarizations P^{beam} and P^{target} as:

$$d\sigma^{Moll}/d\Omega^* = (d\sigma_o^{Møll}/d\Omega^*)\times(1+\Sigma\, P_i^{beam} A_{ii} P_i^{target}), \quad (1)$$

where i=x,y,z defines the projections of the polarizations, and $d\sigma_o^{Møll}/d\Omega^*$ is the cross-section of non-polarized Møller scattering. The analyzing power A_{ii} depends on the scattering angle in the CMS frame Θ_{CMS}. Assuming that the beam direction is along the zaxis and that the scattering happens in the zx plane:

$$d\sigma^{Moll}/\, d\Omega^* = (\alpha^2\gamma^{2}/4m^2)\times(4 - \sin^2\Theta^*)^2/\sin^4\Omega^*, \quad (2)$$

$$A_{zz} = -(7 + \cos^2\Theta^*)\sin^2\Theta^*/(3 - \cos^2\Theta^*)^2. \quad (3)$$

At $\Theta_{CMS}=90^o$ the analyzing power has its maximum $(A_{zz})_{max}=-7/9$. A beam transverse polarization in the scattering plane also leads to an asymmetry, though the analyzing power is lower: $(A_{xx})_{max}=1/9$. The main purpose of the polarimeter is to measure the longitudinal component of the beam polarization.

For the polarized electron target the Møller polarimeter of Hall A (see Fig. 3) uses ferromagnetic foils magnetized in a magnetic field of about 240 Oersteds along the beam axis. The target foil can be tilted at various angles to the beam axes in the horizontal plane; therefore the target polarization has both longitudinal and horizontal transverse components. The spin of the incoming electron beam may have a horizontal transverse component due to precession in the accelerator and in the extraction arc, coupling with the target transverse polarization.

In order to cancel out the horizontal component, the asymmetry is measured at two target angles of about 20º and 160º and the average is taken, since the horizontal contributions have opposite signs for these target angles. Additionally, this method reduces the impact of uncertainties in the target angle measurements. At a given target angle two sets of measurements with opposite directions of the target polarization are taken. Averaging the results helps to cancel some false asymmetries, as one coming from the residual helicity driven asymmetry of the beam flux. The target polarization was derived from the foil magnetization measurements. For the Supermendur foil used in 19981999 a polarization of 7.95±0.23% was obtained.

The Møller scattering events pass through a magnetic spectrometer (see Fig. 3) consisting of a sequence of three quadrupole magnets and a dipole magnet to detector. The spectrometer selects the electrons scattered close to the horizontal plane, in a kinematical range of about $75° < \Theta_{CMS} < 105°$. The polarimeter can be used at beam energies from 0.8 to 6 GeV, by setting the appropriate fields n the magnets. The detector consists of lead-glass calorimeter modules, split into two arms in order to detect two scattered electrons in coincidence. The helicity asymmetry of the coincidence counting rate (typically of about 10^5 counts/sec) is used to derive the beam polarization. Additionally, for detecting the counting rates, about 300 counts/sec of "minimum bias", the events containing the amplitudes and timings of all the signals are recorded with a soft trigger from one arm. These data are used for various checks and tuning, and also for studying the non-Møller background. The ratio of the single arm rate to the coincidence rate is about 2 for the beam energy higher than 1.5 GeV, while it rises up to 5 at the lowest beam energy used of 0.8 GeV. A comparison of the asymmetries measured with the single arm signal and the coincidence indicates that about 30% of the single arm rate is caused by nonMøller sources. The estimated accidental rate level in comparison with the coincidence rate is below 1%.

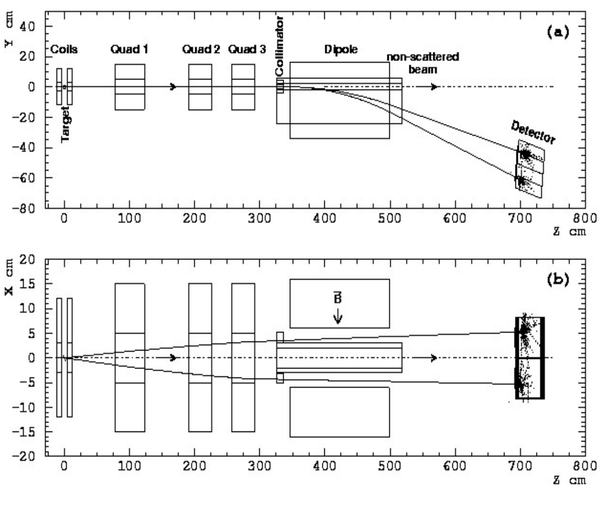

Fig 3. Layout of the Møller polarimeter, top presents the side view, bottom presents the top view. The trajectories displayed belong to a simulated event

of Møller scattering at $\Theta_{CMS}=75°$ and $\Theta_{CMS}=105°$, at a beam energy of 4 GeV

The polarimeter was used in all Hall A experiments with polarized beam for the beam polarization measurements. For the first experiments, when a bulk GaAs photocathode was used in the polarized gun, a typical beam polarization was ~35%, and for the strained GaAs photocathode typical polarization it is of about 75-80%. A typical statistical error for a 1 hour measurement with the beam current of about 0.5 μA is ~0.2%, and the absolute systematic error is ~2.5%.

2.3 "Spin-dance" measurements

Let the particle's momentum to rotate by an angle Θ. Then its spin would turn with respect to the momentum by an angle:

$$\alpha = \gamma\times\Theta\times(g - 2)/2, \qquad (4)$$

where $\gamma=E/m$, Θ is an angle of the momentum rotation and $(g-2)/2 = 0.00115965$ for electrons. So, spin turns to the same direction as the momentum and by a larger angle at higher energy.

The total expected spin rotation angle for the halls A, B, C at CEBAF is calculated in [10]. The value of α depends on the number of passes and on the angle in the hall's extraction arcs, taking into account the beam acceleration:

$$\alpha=(E_L/m)\times(g-2)/2\times(2n^2-n\times(1-2a+b))-$$

$$a\times(1+b/2)\times180°, \qquad (5)$$

where E_L is the linac's energy, n is the number of passes, $m=0.51099906$ MeV/c^2 is the electron mass, $a=0.1125$ is the ratio of the injector energy to the linac's energy, $b=-1/2.4$ for Hall A, $=0$ for Hall B and $1/2.4$ for Hall C; this factor comes from the extraction arc.

Let us assume Hall A is running five passes at $E_L=0.55836$ GeV, so $\Theta= 4.5\times360°$. Then spin makes an angle of about $30.487\times360°$ to the momentum. Measuring the spin precession with an accuracy of 5° one can potentially measure the electron energy with accuracy on about 0.05%. However the initial spin angle is not defined with a precision comparable to that and a better way of measuring the spin precession is to compare the synchronously measured beam polarizations from two halls running at different energies. This procedure is nicknamed "spin-dance". The direction of spin is changed on the injector and by convention the positive direction is clock-wise, as the direction of accelerated electrons is. It is convenient to run at a so-called "magic" energy when both halls should have a zero transverse polarization at the same angle at the injector. Since at the zero point the accuracy of the phase measurement is the highest, both halls should be able to measure this point at the same angle at the injector.

The Hall A Møller polarimeter was cross-calibrated by simultaneous measurement of the beam polarization with three Møller polarimeters in halls A, B and C, the Compton polarimeter at the Hall A and the Mott polarimeter of the injector [12]. The results of the spin-dance are presented on a Fig. 4 and Tables 1 and 2. Experimental data were fitted with a curve: $P(1)\times sin((x-P(2))\times\pi/180°n)$, where n is a number of the beam passes in the accelerator. Parameters $P(1)$ and $P(2)$ are presented on the Fig. 4.

Table 1*. Final results of spin-dance measurement for $E_{injector}$ = 0.06289 GeV and E_{linac} = 0.55836 GeV. 1-Mott (injector), 2-Compton (Hall A), 3 Møller (Hall A), 4- Møller (Hall B), 5- Møller (Hall C)*

Pola-rimetr	Total precession angle, degrees	Phase, degrees	Polari-zation,*%
1	0.	88.79±0.34	72.22±0.21
2	10975.2	-175.79±0.75	72.52±0.45
3	10975.2	-176.12±0.62	75.50±0.14
4	10494.7	60.41±0.51	69.33±0.48
5	10014.2	-56.95±0.63	73.60±0.23

** - only statistical errors of the electron beam polarization measurement are presented.*

Table 2. *Summary of energy measurement results comparing only end-station polarimeters [12]*

Polari-meters	Δα degrees	Beam energy, E, MeV	ΔE/E
Møller A - Møller B	+37.4908±0.0100	5685.67±9.53	1.68×10^{-3}
Møller A - Møller C	+74.9687±0.0046	5650.71±5.19	9.18×10^{-4}
Compton A - Møller B	+37.4908±0.0100	5689.55±10.81	1.90×10^{-3}
Compton A - Møller C	+74.9687±0.0046	5652.65±5.77	1.02×10^{-3}
Møller B - Møller C	+37.4779±0.0110	5615.75±9.67	1.72×10^{-3}

All measurements and calculations were done for the injector energy $E_{injector}$=0.06289 GeV and the linac energy E_{linac}=0.55836 GeV. All three halls were running with the same beam energy.

The angle shift Δα between the dial and measured angles is explained by the energy shift ΔE. As it is shown in the Table 2, ΔE is approximately the same for all halls and it is not proportional to the electron beam energy. It means that the angle shift Δα is connected to the error in the injector energy definition, which is the same for all three halls.

2.4 Laser's phase influence on the polarization

The electron beam in the injector with energy 5 MeV is deflected and rotated around a ring in the plane perpendicular to the beam direction, synchronously with RF of the accelerator and the polarized injector laser RF structure (~500 MHz). An absorber disk is placed in this plane, with 3 radial slits for each hall's phase. This system, called a "choper", provides the RF structure even for a DC and unpolarized electron sources.

It was found that the polarization measured may depend on the slit-attenuator configuration in the injector. Typical Hall A experiments were running with

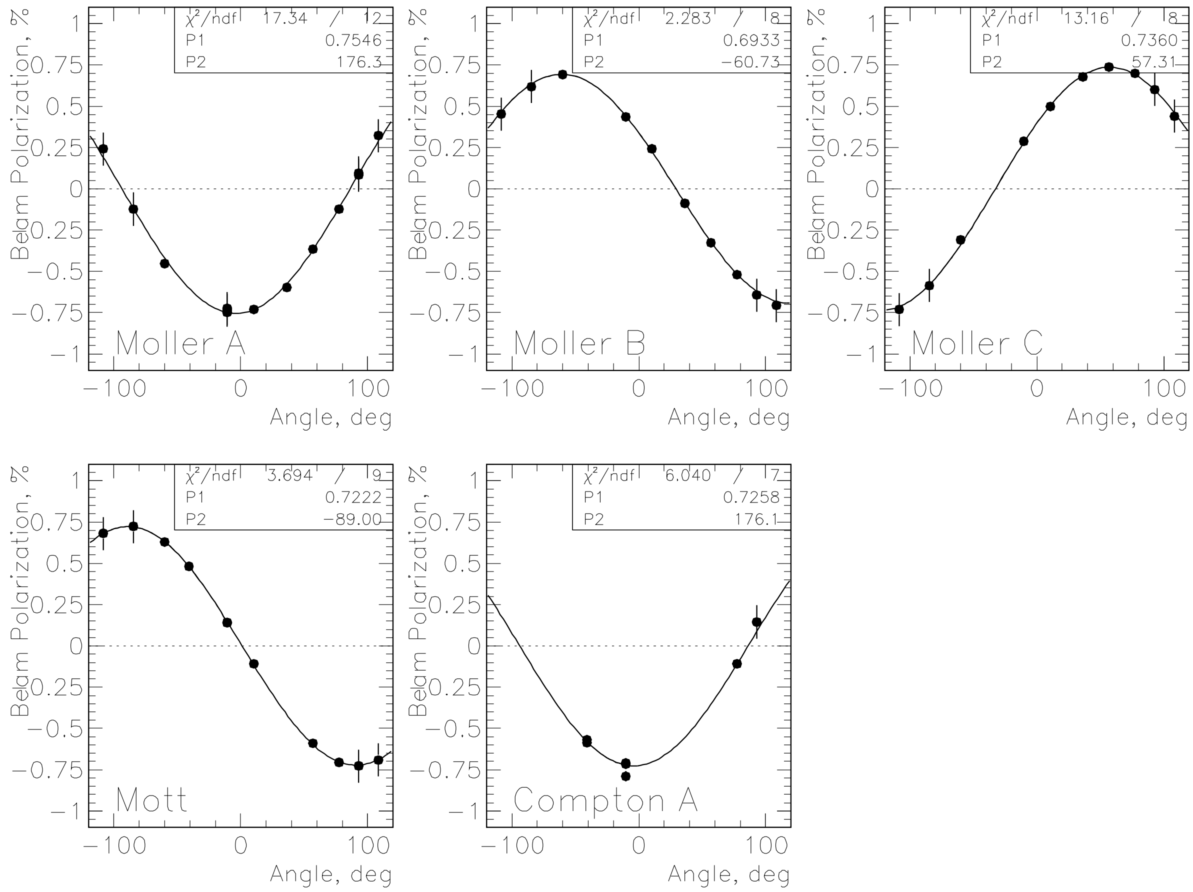

Fig. 4. Results of spin precession measurement with five polarimeters

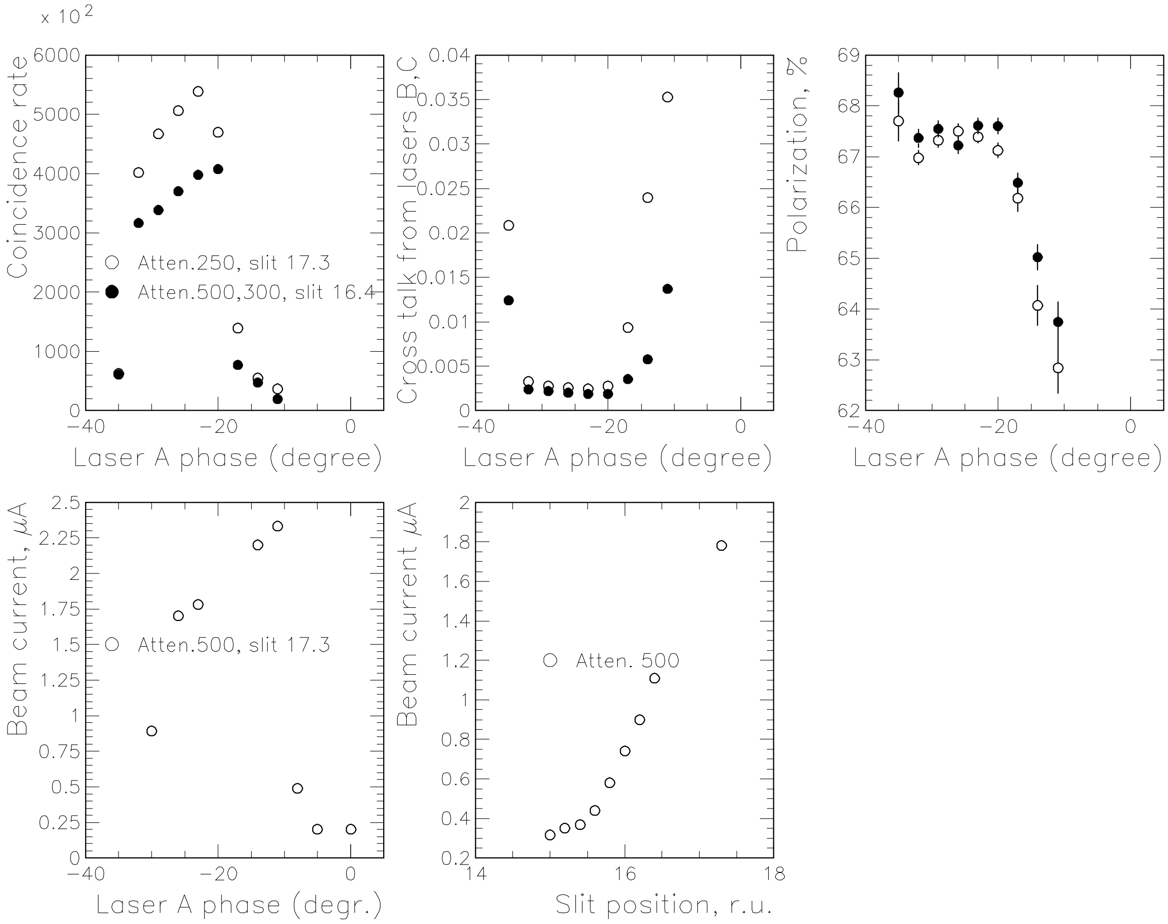

Fig. 5. Hall A electron beam polarization dependence of the injector laser phase

the slit completely open and no laser attenuation while the Møller measurements typically used configurations with the slit tight and no attenuation. The latter was done in order to minimize "cross-talks" (see 2.5) from the lasers of Halls B,C running at a phase opposite to Hall A laser. Additional important parameter of the polarized gun is "phase". With a narrow slit the "phase" defines what time phase of the laser RF pulse comes through the slit, which may vary from the maximum of the pulse to a tail, while with the open slit practically all the pulse passes through whatever is the "phase" parameter. The "phase" was readjusted 2-3 times per week.

The influence of the phase adjustment on the polarization was measured at the conditions as follows:

— for a given combination of attenuation, slit and phase parameters. six Møller runs were taken, for the polarization and the beam rate the average values were calculated;

— for the measure of the beam intensity the 2-arm coincidences of the Møller setup were used;

— the cross-talk from the laser B and C was measured by turning the laser A off.

The results are presented on a Fig. 5 which shows:

1. The Møller coincidence rates depending on the phase, for the slit parameters of 16.4 and 17.3 (in arbitrary units. The higher value is the wider slit. At 16.4 the measurements were done at attenuations of 500 and 300 (in arbitrary units). The lower value of attenuator parameter corresponds to stronger laser beam attenuation. The results were all normalized to 300, while at 17.3 the measurements were done at attenuation 250. For the narrower slit of 16.4 the shape of the peak is sharper than for the wider 17.3 slit.

2. The relative cross-talk from the lasers B and C depends on the phase. The results were corrected for this "cross-talk".

3. The beam polarization is flat on the peak top but drops by about 10% at the tail of the peak. Therefore, if during the Møller measurements the phase is adjusted to the tail of the peak, the results should be systematically lower than the average for the whole distribution.

4. The beam current in the injector was measured the next day. For some reason the peak became broader and a phase shift occurs with respect to the previous day.

5. This plot shows the beam current, measured on the injector, depending on the slit parameter. The phase was at -14° - at the top of the beam current profile. The open and filled circles present the data taken at the laser attenuation of 500 and 600. The data were approximated with a polynomial with the coefficients as follows: 0.32209, -0.01468, 0.29857, 0.21897, -0.09835.

6. This plot shows the relative beam current, measured on the injector, depending on the laser attenuation. Since the measurements were done at different slit sizes, the results were normalized to a certain slit size using the polynomial defined in 5). The data can be approximated with a curve $a\times\sin((x-x_0)\times\pi/(2\times550))^2$, with $x_0=0$. The beam current dependence on the laser power parameter was not calibrated.

A potential source of systematic errors was found, associated with the fact that Møller polarimeter typically runs at a beam current of about 1% of the current used by the experiments. There are two reasonable ways to reduce the current to such a low value:

1. Attenuate the laser beam
2. Attenuate the electron beam using a slit with a variable width.

The 1-st method is not acceptable if the other halls are running because of a considerable "cross-talk" from the dark currents of the other lasers, typically polarized in a direction, opposite to the laser of Hall A. At no attenuation the effect of the cross-talk is below 0.1%, but may reach a few per cent at a strong attenuation. The second method looks preferable, but one has to be sure that the narrow slit selects the plateau of the laser RF structure, but not a tail where the beam polarization is lower by 4-10%. The "phase" parameter of the injector setup is used for appropriate adjustments.

2.5 "Cross-talk" between the halls

Separation of the beam between the halls is performed using the RF phase of the electron bunches. This phase matches the RF phase of the laser in the given hall (see Fig. 2). In the process of the electron beam polarization measurement with the Hall A Møller polarimeter a strong "cross-talk" from the halls B and C was found. This effect can be explained by the dark currents of the halls B and C lasers. A sign of hall A laser helicity is opposite to the sign of halls B and C. Thus, the polarized electrons emitted with the hall B and C lasers have an opposite sign of the polarization and can reduce the Hall A electron beam polarization. The leakage from halls B and C was measured by turning the hall A laser off. The results of the measurements are presented in the Table 3.

***Table 3**. Results of measurements of Hall B and C laser beam leakage to Hall A*

Run	Polari-zation,*%	Current, μA	Comments
1	67.95±0.18	0.55	Lasers A, B, C are on
2	72.03±0.19	0.55	Lasers A, B are on, laser C is off
3	-74.08±1.0	0.02	Laser A is off, lasers B, C are on
4	-	0.00015	Laser A, C are off, laser B is on

**- only statistical errors of the beam polarization measurements are presented*

During the regular electron beam polarization measurements in the Hall A care is taken in order to minimize the effect of the "cross-talk", using the optimal combination of the laser attenuation and slit size.

3. CONCLUSIONS

The Hall A Møller polarimeter is operating from 1997 for the electron beam polarization measurement. It provides:

— the electron beam polarization measurement with the relative systematic error <3%;

— control of long-time beam polarization evolution along the experiments with high statistical accuracy of ~0.2%;

— measurement of both, longitudinal and transverse, components of the beam polarization;

— measurement of each component of the polarized beam helicity;

— control of the beam energy with accuracy of ~10^{-4} together with another hall polarimeters;

— investigation of phase- and time-resolved properties of the polarized electron beam together with polarized injector.

The JLab injector system design offers additional advantages to investigate the phase-resolved effects, and also the synchronization pulse delay for generating a laser pulse for any of three halls in the relation to the time pulse of the accelerator RF-structure. The use of the minimal slit size, which corresponds to the electron bunch duration of about 0.5 psec, permits high time-resolution investigations of the time structure of electron bunches. The preliminary results of these investigations were obtained. The beam current and polarization were studied as functions of the laser attenuation and slit position for the Møller polarimeter current range. The effects of "cross-talk" between the lasers of three halls were investigated. The data analysis is now in progress and additional measurements are desirable. Simultaneous measurement of the beam polarization with different spin orientations gives an additional control of the spin orientation and makes it possible to measure the beam energy with accuracy of about ~10^{-4}.

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