Measurement of G_{Ep}/G_{Mp} to Q^2=9 GeV^2 via recoil polarization

Update of Jlab experiment 01-109, submitted to PAC 26

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Abstract

In experiment 01-109 we will obtain the ratio of the electric and magnetic form factors of the proton, G_{Ep} and G_{Mp}, by measuring the transverse and longitudinal components of the polarization of the recoiling proton in $\vec{e}p \rightarrow e\vec{p}$. With a 6 GeV beam energy two new data points are to be obtained for the ratio, nominally at Q^2=7.5 and 9 GeV^2; a test point will also be measured at Q^2=4.8 GeV^2. A scenario with slightly lower Q^2 values is available, should the beam energy be equal to the current maximum value.

The experiment requires a large solid angle detector for the electron. We are building a lead glass Čerenkov calorimeter; it will cover the solid angle of 140 msr required at the largest Q^2 of the experiment. The calorimeter is fully assembled and in the process of being connected to the readout system; several hundred channels have been tested and systematic tests on cosmics will start this Fall.

The polarization of the recoil proton will be measured in a new focal plane polarimeter (FPP) to be installed in the detector shield house of the HMS in Hall C. The FPP consists of two analyzers in series, each one followed by two drift multiwire chambers with a sensitive area of 2.06 m^2. Full assembly of the FPP is expected by the Summer of 2005.

Here we request continuation of approval for this experiment.

The full physics case was made in the original proposal which is attached as appendix, and is only briefly described in the body of this proposal. However, the matter of the disagreement between the G_{Ep}^2-values obtained in a number of Rosenbluth separation experiments, including two recent ones at JLab, and the recoil polarization results, is briefly discussed in part 2; it has received increased attention from both theorists and experimentalists. One possible explanation is that the previously neglected two-photon exchange process, in spite of its intrinsic smallness, affects the Rosenbluth separation results directly and strongly, but the polarization results only weakly.

1 Introduction

We request continued approval for JLab experiment 01-109. The goal of the experiment is to obtain G_{Ep}/G_{Mp} at two new values of Q^2: 7.5 and 9 GeV^2, by the recoil polarization method. The proposal was approved in July of 2001 by PAC 20, with rating A. As was outlined in the proposal, the plan was to build the required instrumentation in such a way as to be ready to take data in the second half of 2005. The preparations are on schedule.

In 1998 experiment 93-027 measured the ratio G_{Ep}/G_{Mp} in Hall A up to Q^2=3.5 GeV^2, with high precision. These data are published[1], and the archival PRC paper is currently undergoing revision after review. At the end of 2000, these measurements were continued with experiment 99-007, which extended the range of Q^2-values to 5.6 GeV^2; the results from experiment 99-007 are published [2] and have provided the thesis material for O. Gayou at the College of William and Mary [3].

The results from both experiments are shown together with a selection of Rosenbluth separation data in Fig. 1. Most noticeable are the consistency of the $\mu_p G_{Ep}/G_{Mp}$-values of the two recoil polarization results as well as their small systematic uncertainties, and the systematic difference between the polarization and the Rosenbluth results; for clarity only the last SLAC results of Andivahis et al. [5] and the more recent JLab Hall C cross section measurements [6] and Hall A "Super" Rosenbluth data [7] are shown. Older data show much scatter and are essentially compatible with the recent JLab cross section up to Q^2 =1 GeV^2.

The most important feature of the new JLab data has been the sharp decline of the ratio G_{Ep}/G_{Mp} with increasing Q^2, indicating that G_{Ep} falls faster than G_{Mp}. This has been the first experimental indication that the Q^2-dependence of G_{Ep} and G_{Mp} is significantly different starting at 1 GeV^2. The polarization data for G_{Ep}/G_{Mp} have created much excitement in the Nuclear Physics community, and an intriguing question is whether G_{Ep} will continue to decrease or ultimately become constant, with increasing Q^2. Another important question is what is the source of the spectacular difference between Rosenbluth data and recoil polarization data.

In the original proposal approved by PAC20 in July, 2001 (proposal 01-109), we have demonstrated the feasibility and the interest of extending the measurement of the G_{Ep}/G_{Mp} ratio to the highest possible Q^2 values with the highest available beam energy currently available at JLab in Hall C; we assumed beam energy of 6 GeV. With 6 GeV electrons the largest measurable point is at Q^2=9 GeV^2. A scenario with slightly lower beam energy will also be discussed below.

The experiment for which we are seeking continuation requires a new focal plane polarimeter (FPP) to be installed in the high momentum spectrometer (HMS) in Hall C to measure the polarization of the recoiling proton, and a large frontal area lead-glass calorimeter (BigCal) to detect the electrons. Here we will

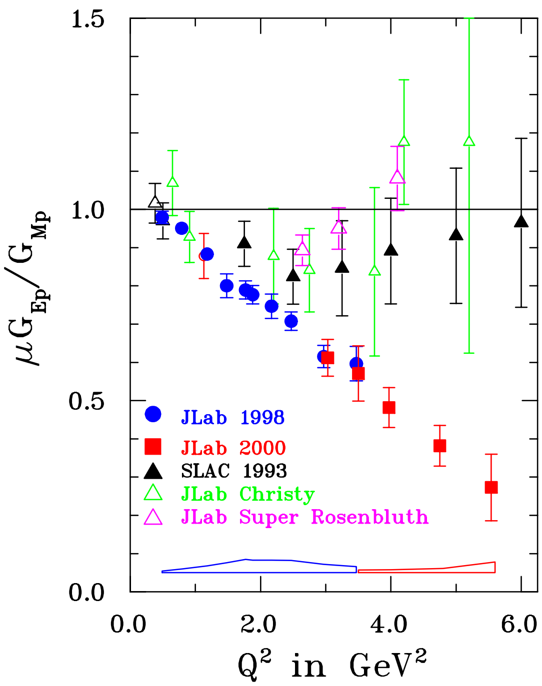

Figure 1: The ratio $\mu_p G_{Ep}/G_{Mp}$ as determined in the recoil polarization experiments 93-027 and 99-007, compared to the Rosenbluth results of Andivahis et al. [5], and the recent JLab data of Christy et al. [6] and Segel et al. [7]; the uncertainties shown for both polarization experiments are statistical only; the systematic uncertainties are of similar size.

show that:
1) the calorimeter proper is fully assembled and partially instrumented; we are currently taking cosmic data on a few hundred channels at a time.
2) the design of the new FPP is complete, and that the chambers are under construction in the Laboratory for High Energy (LHE) at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. One prototype chamber is at JLab and is undergoing extensive testing.

We received a DOE grant to build the drift chambers required for the new FPP; a total of 5 chambers will be built in the Instrumentation Division at the LHE(JINR).

The recoil polarization technique is self calibrating and will determine the analyzing power for the protons up to 5.7 GeV/c. To plan this experiment, in 2001, a calibration study was carried out at the Dubna Synchrophasotron up to 5.3 GeV/c [8]. The results of the calibration indicated that the analyzing power

A_y for protons with a CH_2 analyzer is nearly constant for proton momentum from 3.8 GeV/c at Q^2=5.6 GeV^2, for which we have JLab calibration data, to 5.3 GeV/c; these results will be discussed in section 3.1.

2 The two-photon hypothesis

One of the underpinnings of the program of experiments to study the structure of hadrons using electron beams at Jefferson Lab is the assumption that the dominant reaction mechanism is the one-photon exchange between the electron and the target hadron. Indeed, in the specific case of elastic *ep* scattering, the one-photon exchange formalism forms the basis for a direct determination of the electromagnetic form factors from either the measured cross sections, or the polarization observables. However, the striking discrepancy between the recoil polarization data and the Rosenbluth data that has been established to date has led theorists [9, 10, 11] and experimentalists alike to question the validity of the one-photon exchange process dominance, and indeed to investigate the possible contributions of two-photon exchange processes (box diagrams), which have been deemed negligible in the past.

On the experimental front, this past January, we submitted a new proposal to PAC 25 [12], to determine the contribution of two-photon exchange in elastic *ep* scattering, by measuring the ratio of the transferred polarization components P_t and P_ℓ versus ϵ, the polarization of the virtual photon; the ϵ-values for the data points of this experiment are given in Table 1 . The proposal was approved with A^- rating for 18 days if running consecutively with GEp(III) 01-109 (20 days if running separately); it will be the second experiment to use the new FPP in Hall C.

There are two points of interest with respect to the two-photon exchange issue which we wish to highlight; the first relates to the possible effect of the two-photon amplitude in the kinematics of this experiment. Chen et al [13] have calculated the effect of including two-photon exchange processes on the polarization observables at the parton level. They assume that the two-photon process proceeds through scattering off a single parton, and use the generalized parton distributions to evaluate the amplitudes. The limit of application of this calculation is given as $(s, -u, Q^2 >> M_p^2)$; the condition on Mandelstam u corresponds to a condition $\epsilon > 0.4$ for Q^2=2.6 GeV^2 and $\epsilon > 0.16$ for Q^2=9 GeV^2. The overall absolute correction factor to the form factor ratio, $\mu_p G_{Ep}/G_{Mp}$ is shown in the figure below (Fig. 2)as a function of Q^2 and ϵ; the crucial feature to note is that the effect on the ratio is overall small compared to our projected statistical uncertainties.

Both for the cross section and polarization observables in *ep* elastic scattering, the two-photon process manifests itself through an altered ϵ dependence compared to that seen in the one-photon exchange case; in the case of the polarization observables, the one-photon exchange approximation predicts no ϵ

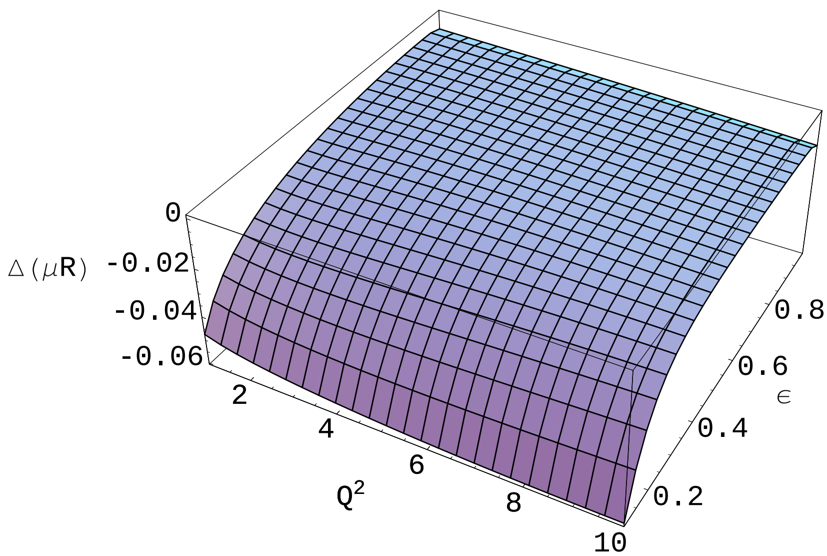

Figure 2: Overall absolute correction to the form factor ratio originating from two-photon exchange, assuming that the ratio decreases linearly as established in JLab experiments 93-027 and 99-007; R is the ratio G_{Ep}/G_{Mp} and μ is the proton magnetic moment.

dependence at all.

The two-photon contribution to both the cross section and the polarization components are small; however, they are not negligible when compared to the electric part of the cross section, and that is why they affect the Rosenbluth form factor separation results strongly.

This brings us to the second major point of interest, which is that the polarization transfer technique (or a complementary polarized target experiment) appears to be the only viable method of extracting the elastic electromagnetic form factor ratio, G_{Ep}/G_{Mp}.

3 Status of the Preparations

3.1 The Calorimeter BigCal

Design of the new calorimeter BigCal was started at the end of 2001. The frame and platform for the lead glass stack became available in the fall of 2002 and the stacking of the 1744 bars of glass was completed in the summer of 2003. The photomultipliers and photomultipler bases are now attached and connected to their respective patch panels and to the multiplexer/amplifier units installed on the calorimeter platform.

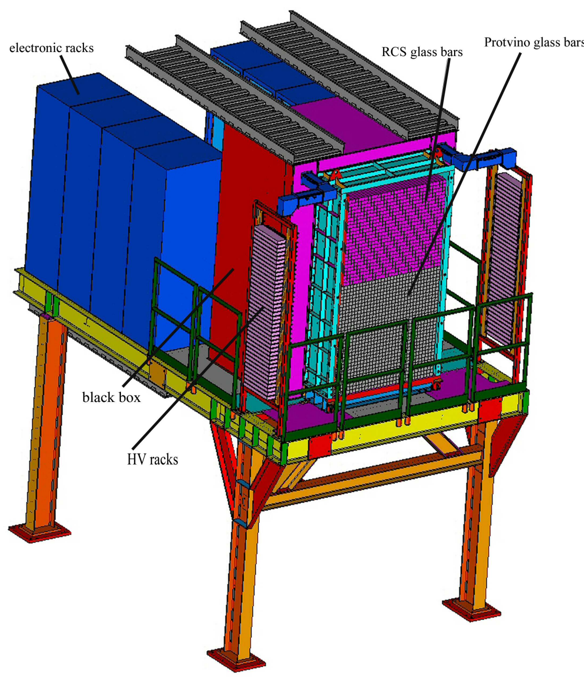

Figure 3: Design of the BigCal platform, showing the frame containing the 1744 lead glass bars, the platform proper and the two rows of racks containing the multiplexing electronics

The signal delay cables to the ADCs and TDCs will be connected and checked this summer; each is 100 m long and all 2000 of them are stored on a cable storage rack built for this purpose. The experiment requires 120 multiplexer units and 90 are available; the remaining 30 are expected in the next few weeks. Each unit contains two octets of inputs, each with amplified outputs for the ADC, as well as summed signals from each octet for timing purpose.

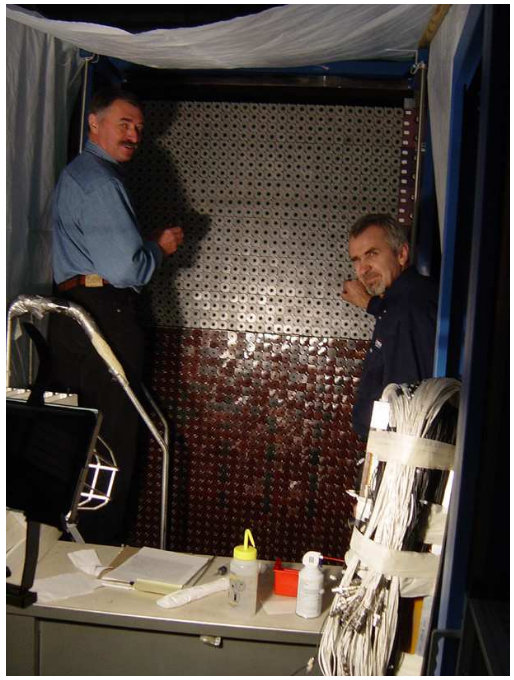

Figure 4: View of BigCal in Jan. 2004, at the point when all PMs have been installed. Now the PM bases and patch panels have been installed and the whole is contained in a light tight black box.

BigCal consists of 32 columns times 32 rows of 3.8×3.8 cm^2 bars of Protvino lead glass blocks at the bottom, and 30 columns times 24 rows of 4.0×4.0 cm^2 from RCS (Yerevan blocks) placed on the top. The total frontal area is thus 2.63 m^2. When used for the largest Q^2 in this experiment, the front of the glass will be 4.35 m away from the target, offering a solid angle of 140 msr to the electrons of the ep reaction and providing optimum kinematical matching (see section 4 below). The pulse height from every lead glass bar will be digitized. In addition, after splitting in the multiplexer/amplifier circuit, a copy of the original signal is added in groups of 8 channels for time digitization. The multiplexers will be wired in such a way that the 8 neighboring glass bars of each individual bar are in different octets, so as to have time information for each of them; interpolation over the charge sharing in neighboring bars is expected to improve the position resolution from the canonical $d/\sqrt{12} \sim 1.2$ cm, where d is the bar's transverse size, to about 0.5 cm. The timing information will help distinguishing noise from true charge sharing.

In the Fall of 2004 we will start a systematic test of the calorimeter with cosmic muons. Preliminary test results confirm expectation that these muon tracks will provide a good initial calibration. More accurate calibration will be obtained from the on-line analysis of elastic *ep* events during the experiment proper.

3.2 The FPP for the HMS

The overall design of the new FPP to be installed in the detector hut of the HMS in Hall C is seen in Fig. 5; it is similar to the one built in Hall A and used very successfully in a series of experiments there, including GEp(I) and GEp(II). The main difference between the Hall A and the new FPP is that the new FPP

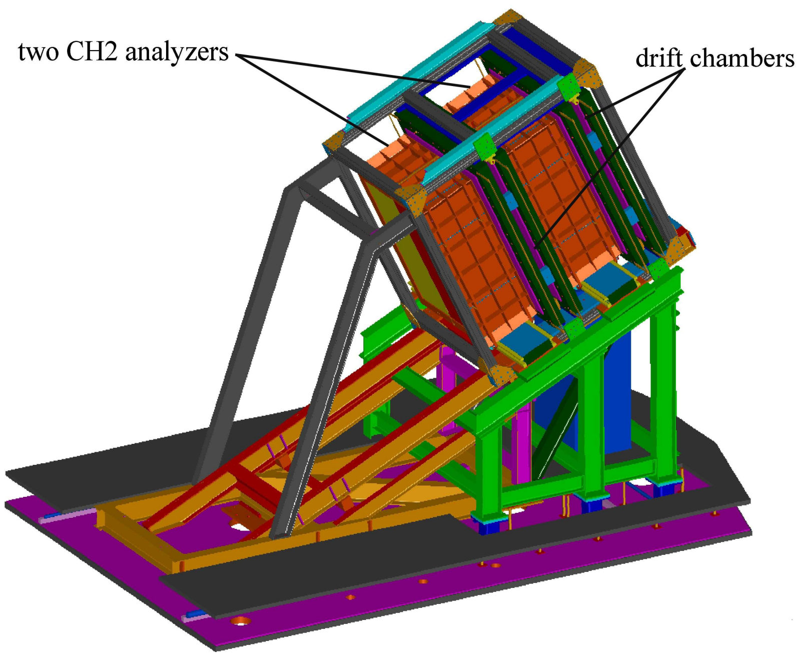

Figure 5: The FPP in the HMS in Hall C as currently designed.

will consists of two polarimeters in series to maximize the efficiency defined as the fraction of protons scattered in the analyzer material. Figure 6 shows the two independent CH_2 analyzer blocks, each 56 cm thick, 143 cm high and 112 cm wide; they are supported on a structure independent of the HMS detector support structure to avoid deforming it. Each analyzer block divides into two

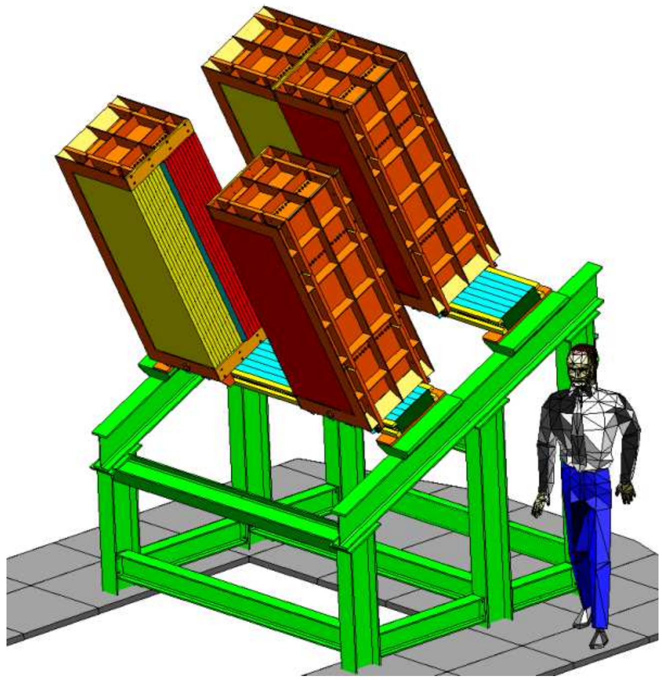

Figure 6: The structure supporting the massive CH_2 analyzer blocks is independent from the HMS detector support beams, to avoid loading them; here the front analyzer is shown in the "open" position to allow straight thru tracks to be recorded.

halves which can be moved horizontally to allow straight thru trajectories.

The idea of putting two FPP in series was verified by the results of a calibration experiment performed in Dubna in 2001 with polarized protons up to 5.3 GeV/c [8]. These data can be seen in Fig. 7; it is remarkable that they show no decrease in analyzing power up to 80 g cm^{-2} of CH_2; the two analyzers in the new FPP will have a surface density of 51 g cm^{-2} each. By placing two identical polarimeters in series we will catch a fraction of those protons which did not interact in the first analyzer, in the second analyzer.

The total efficiency will be ≈50%; the typical efficiency in the Hall A experiments with 85 g cm^{-2} of C has been 30%; this is a direct reduction of 66% on the time required to achieve a given statistics!

The double polarimeter configuration was already tested in Hall A in 2002 during the Real Compton Scattering experiment (JLab 99-114), and the deuteron photo disintegration experiment, JLab 00-007. In Fig. 8 we show the double polarimeter results from Hall A. The top panel shows that at 2.98 GeV/c the

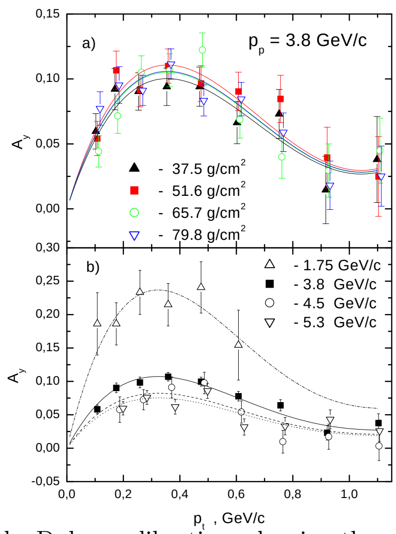

Figure 7: Results of the Dubna calibrations showing the analyzing power for a range of CH_2 thicknesses (top) and its energy dependence (bottom).

analyzing power for CH_2 is significantly larger than for C. The intermediate panel compares the results for 100 cm and 44 cm of CH_2 at 2.92 GeV/c, confirming the Dubna result that the analyzing power is nearly constant over a large range of analyzer thicknesses; the lower panel compares C analyzer data for 3 different proton momenta.

Based on our long time collaboration with the Laboratory for High Energy at the Joint Institute for Nuclear Research (LHE at JINR) in Dubna, Russia, we chose to have the 4 drift chambers built in the Instrumentation Division of the LHE; the construction of the 4 drift chambers and prototype is funded by an instrumentation grant from DOE [14]. Each chamber has a sensitive area of 116×178 cm^2, and sense wires with a spacing of 2 cm, alternate with anode wires with the same spacing, thus providing a drift space of 10 mm on either side of each sense wire. The chamber operates with -2200 V on the field wires and the cathode planes which consist of wires with 3 mm spacing to guarantee planarity over the relatively large surface area of the chambers. The number of wire planes per chamber is 3, and the wires are oriented at +45 °, 0° and -45°, or along the u, x and v directions.

It was determined in the Spring of 2003 that the project would benefit from the construction of a full scale prototype, which can then be used as a spare during the experiments. The prototype chamber is shown in Fig. 9; it was delivered to JLab in late October 2003, with its full complement of amplifier/discriminator readout cards which can be seen in Fig. 10. Two physicists from instrumentation

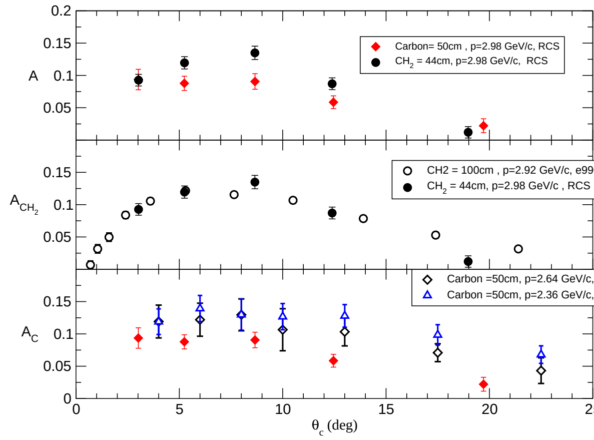

Figure 8: Hall A data for two polarimeters in series. See explanation in text.

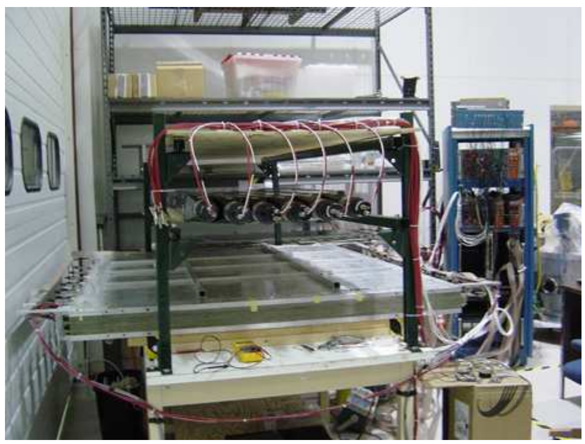

Figure 9: The FPP prototype drift chamber in the clean room.

division of LHE/JINR stayed at JLab each 1 month to assemble the chamber and performed an initial test using CO_2 as a quencher. We are currently preparing to continue these tests, using 2 SOS spare drift chambers, each with two u, v and x wire planes to do tracking and measure properties like drift spectrum, efficiency and plateau over the sensitive area of the prototype chamber, using the better quencher gas ethane. The data obtained will also be used to further develop and test the tracking software.

The support structure for the FPP chambers is fully designed; we expect to have it at JLab in the Fall of 2004. The next two Dubna chambers should arrive here in early Winter 2004, and will be immediately tested with cosmics, in place within the support structure. The last two Dubna chambers should arrive in the spring of 2005, and they in turn will be immediately tested. All

Figure 10: View of the prototype drift chamber, showing the 8-channel amplifier cards along one edge of the chamber. The chamber window is protected with a cover.

parts of the FPP should be available for pre-assembly on the floor of Hall C in the Summer of 2005.

4 Measurements

We are preparing to measure 3 data points: 9 and 7.5 GeV^2, and as a control point 4.75 GeV^2. These Q^2 values require a 6 GeV beam energy. Some kine-

Table 1: The 3 kinematics of this proposal for 6 GeV beam energy (the proposal values). χ is the spin precession angle.

Q^2	E$_e$	θ_e	E$_{e'}$	θ_p	p$_p$	ϵ	$d\sigma/d\Omega_e$	χ	$\Delta\Omega_e$	rate
GeV^2	GeV	deg	GeV	deg	GeV/c		cm^2/sr	deg	msr	Hz
4.75	3.6	68	1.07	11.5	3.3	0.32	$3.4.0 \times 10^{-36}$	165	61	63
7.5	6.0	46	2.0	17	4.8	0.46	1.1×10^{-36}	236	37	12
9	6.0	68	1.2	11.4	5.66	0.24	1.4×10^{-37}	274	135	6

matical details for this beam energy are shown in Table 1. The statistical error bars and the beam on target time required to achieve the error bars are shown in Table 2; they require 40 days, as originally approved.

Note that we have increased the Q^2 of the test point to 4.75 GeV^2 from the proposal value of 4.2 GeV^2; there are 2 advantages in doing so: at the larger momentum transfer squared the precession angle $\chi = 180°$ is in the acceptance,

Table 2: Absolute uncertainties, including systematics, and times required for 6 GeV beam energy. $\Delta(\mu G_{Ep}/G_{Mp})$ is the anticipated absolute uncertainty, assuming $\mu G_{Ep}/G_{Mp}$ follows the fit to the JLab polarization data, but the absolute uncertainty is only weakly dependent of $\mu G_{Ep}/G_{Mp}$.

Q^2	E_e	absolute $\Delta(G_{Ep}/G_{Mp})$	time
GeV^2	GeV		hours
4.75	3.6	0.05	40
7.5	6.0	0.08	200
9	6.0	0.09	720
		TOTAL TIME	960 or 40 days

Table 3: The modified 3 kinematics for a beam energy of 5.74.

Q^2	E_e	θ_e	$E_{e'}$	θ_p	p_p	ϵ	$d\sigma/d\Omega_e$	χ	$\Delta\Omega_e$	rate
GeV^2	GeV	deg	GeV	deg	GeV/c		cm^2/sr	deg	msr	Hz
4.6	3.444	71	1.0	17	3.2	0.30	3.6×10^{-36}	162	67	71
7.1	5.74	47	2.0	19	4.6	0.47	1.9×10^{-36}	226	35	15
8.6	5.74	69	1.16	11.5	5.44	0.23	1.7×10^{-37}	264	115	7

thus providing at the same time data to check the spin transfer calculation in COSY, by determining the momentum for which the normal component of the polarization in the focal plane, P_n^{fpp}, crosses zero; this information has proven invaluable in both previous G_{Ep} experiments in Hall A. Second, the calorimeter angle is the same as for the Q^2=9 GeV^2 point, meaning that the 3 points of this experiment can be obtained with the calorimeter positioned at two angles only.

Should the 6 GeV not be available at the time of this experiment, but only the maximum energy of 5.74 GeV achieved in the recent past, the largest Q^2 value will have to be lowered to 8.75 GeV^2. The relevant kinematical quantities are shown in Table 3, and the expected error bars in table 4. The 3 data points expected from this experiment are shown together with the data from the first two Hall A G_{Ep} experiments in Fig. 11. The experiment requires time to measure the background in Hall C, to install the calorimeter and test it, to check the optical alignment of the HMS, and to install the FPP in the HMS shield hut and test it. Table 5 shows an outline of the approximate times required.

A test with a 25 channel calorimeter prototype was done in 2003, in a single arm geometry to verify rate predictions; the rates observed where within the expected range . We are expecting to get 2 to 3 days of beam time in Hall

Table 4: Absolute uncertainties, including systematics, and times required for 5.74 GeV beam energy.

Q^2	E_e	absolute $\Delta(G_{Ep}/G_{Mp})$	time
GeV^2	GeV		hours
4.6	3.6	0.05	40
7.1	6.0	0.08	200
8.6	6.0	0.08	720
		TOTAL TIME	960 or 40 days

Table 5: Approximate times for pre-testing, assembling and final testing of components in Hall C.
* can be done concurrently with calorimeter installation.

when	what	goal	duration
2004	trigger from HMS, calorimeter prototype		6-9 shifts
2004-5	HMS optics		twice 1 shift
2005	calorimeter	install	1 month
2005	calorimeter	test	3 shifts
2005	polarimeter	install	1 month*
2005	polarimeter	test	3 shifts

C in June 2004; the same prototype with realisitic readout will be placed at several angles in the Hall and operated in coincidence with the HMS. It is planned to install electronics to create a proton trigger in the HMS hut, which will be used to open a window for the ADCs of the calorimeter. As many components of the experiment as possible will be identical to the actual ones; in particular, the multiplexers/amplifiers will be used to obtain time information in the multiplexing mode of the actual experiment. This test will be used to test various softwares required to optimize the spatial resolution of the calorimeter.

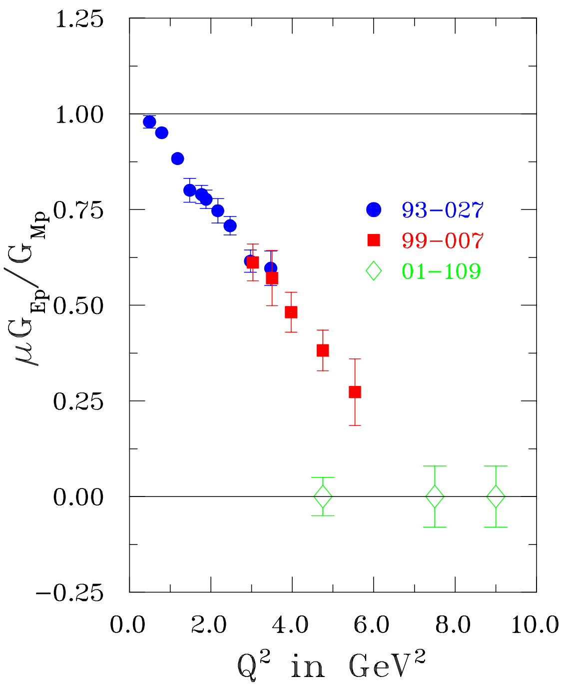

Figure 11: The anticipated error bars for this experiment(01-109), compared to the ratio $\mu_p G_{Ep}/G_{Mp}$ data from experiments 93-027 and 99-007

5 Conclusions

The original proposal to measure the ratio G_{Ep}/G_{Mp} up to 9 GeV^2 in Hall C, by detecting the proton in the HMS and the electron in a large solid angle lead glass calorimeter is unchanged.

All the new components required for this experiment, the calorimeter (BigCal) and the proton polarimeter (FPP), are well along in their construction; they both will have been tested with cosmics before our readiness target date of August 1, 2005. No cause for delay can be identified at this time.

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