CEBAF Program Advisory Committee Seven Update Cover Sheet

This proposal update must be received by close of business on November 23, 1993 at:

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Present Conditionally Approved Proposal Title and Number

PARITY VIOLATION IN ELASTIC SCATTERING FROM the PROTON: PLANS FOR The FIRST RUN

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Experimental Hall: A
Total Days Requested for Approval: 42 days
Minimum and Maximum Beam Energies (GeV): 4 GeV
Minimum and Maximum Beam Currents (μAmps): 100μA

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By: gp

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Update to the CEBAF PAC

PARITY VIOLATION IN ELASTIC SCATTERING FROM THE PROTON: PLANS FOR THE FIRST RUN

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Abstract

We present a detailed plan for running a first point in Hall A to measure the parity-violating asymmetry for the elastic scattering of polarized electrons from hydrogen at 12.5° and at a Q^2 of 0.7 $(\mathrm{GeV/c})^2$. The result will measure the contributions of the combination of strange quark form factors $F_1^s + 0.36F_2^s$ with a precision of ± 0.03. Technical issues raised by the PAC and the Barish panel are addressed. This represents the initial point for the program outlined in CEBAF proposal PR-91-10. With the success of this run, we will plan to continue our program to include a significant Q^2 range for hydrogen, quasielastic scattering from deuterium, and a few precision points on ^{4}He.

PARITY VIOLATION FROM ELASTIC SCATTERING FROM THE PROTON AND ^{4}He

I. INTRODUCTION

Experiment PR-010-91, "Parity Violation in Elastic Scattering from the Proton and ^{4}He" is one of three parity experiments conditionally approved in 1992. These proposals describe a series of measurements designed to investigate the contribution of strange quarks to the form factors of the nucleon. In the summer of 1992, the Strange Currents/Parity Experimental Proposals Review Committee, chaired by Barry Barish, examined three parity proposals that had been presented to the PAC both in terms of physics and technical issues.

We point out several of the conclusions from that report: 1. "The unique capabilities of CEBAF and the timeliness of such attempts to learn about the strangeness content of the nucleon make this a very high priority of the Laboratory." 2. "The committee also agrees with the conclusions drawn by the PAC on the appropriateness of the Hall A proposals. While the impact on the entire program in Hall A is likely to be large, the importance of parity studies at CEBAF seems to warrant this." 3. "The Committee feels that the complete set of measurements proposed in PR-91-004, PR-91-010, and the revised PR-91-017 are worth pursuing. We also feel that from the perspective of this particular point in time some priority should be given to an initial measurement of the elastic proton asymmetry at a selected value of momentum transfer."

This document presents our plans, consistent with the recommendations of the Barish Committee, to perform an initial measurement on the proton at a Q^2 of 0.7 (GeV/c)^2. We will address the issues identified by the Director's Technical Advisory Committee, which are listed in Appendix A. This list includes the issues raised by the PAC as well as other issues considered by the Barish Committee.

II. PHYSICS MOTIVATION

We briefly review the physics justification for a parity experiment in Hall A.[1] A more detailed account is given the original proposal. The existence of the neutral weak boson, the Z_0, provides a new current for the nucleon

$$\langle p|J^Z_\mu|p\rangle = \overline{U}\left(\gamma_\mu F^Z_{1p}(Q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N}F^Z_{2p}(Q^2) + \gamma_\mu\gamma_5 G_{Ap}(Q^2)\right)U$$

where U is the nucleon spinor. Thus there are three new form factors for the proton, F^Z_{1p}, F^Z_{2p}, and G_{Ap}, which are fundamental quantities that are important to measure as a function of Q^2. In the Standard Model[2], the couplings of the Z^0 to the quarks are known[3], and it is possible to express the weak form factors in terms of the electromagnetic ones:[4]

$$F_{ip}^{Z} = \frac{1}{4}\Big((1 - 4\sin^2\theta_W)F_{ip}^{\gamma}(Q^2) - F_{in}^{\gamma}(Q^2) - F_i^s(Q^2)\Big), \qquad 1$$

where $i = 1, 2$. Here $F_{ip}^{\gamma}(Q^2)$ and $F_{in}^{\gamma}(Q^2)$ are the electromagnetic form factors for the proton and neutron, respectively, and the $F_i^s(Q^2)$ are a new pair of form factors which result from the presence of strange quark-antiquark pairs in the nucleon.[5,6] The $F_i^s(Q^2)$ are isoscalar. If the electromagnetic form factors are known with sufficient precision[6], the $F_i^s(Q^2)$ may be determined by measuring F_{ip}^Z.

One way to measure these new form factors is to determine the parity-violating asymmetry for the scattering of polarized electrons from the proton[6]

$$\mathcal{A}^{PV} = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L),$$

where $\sigma_L(\sigma_R)$ is the differential cross section for the scattering of electrons with left (right) helicity. The asymmetry at forward angles, a kinematic condition apropriate for Hall A, is

$$\mathcal{A}^{PV} \approx \frac{G_F Q^2}{\pi\alpha\sqrt{2}} \times \frac{F_1^{\gamma} F_1^Z + \tau F_2^{\gamma} F_2^Z}{(F_1^{\gamma})^2 + \tau (F_2^{\gamma})^2},$$

where $\tau = Q^2/4M_p^2$.

Our main motivation for this experiment is to obtain information about the F_{ip}^Z because they are a fundamental property of the nucleon. Presently the greatest interest in these form factors stems from the possibility that they have a substantial contribution from strange quarks.[7] Results from spin-dependence in deep inelastic scattering of polarized electrons from polarized protons,[8] deuterons,[8] and ^{3}He,[9] have given credibility to the idea that strange quarks may have nonzero matrix elements in ordinary nucleons and significantly contribute to the form factors. According to simple arguments using vector dominance, however, one might expect that this contribution should be negligible.[10] Indeed, measuring the weak form factors may be one of the most practical ways to settle this issue.

The role of strange quarks on the above asymmetry is most transparent in the approximation where $\sin^2\theta_W = \frac{1}{4}, Q^2 \approx 0$, and $F_{1n}^{\gamma} = 0$: Then

$$\mathcal{A}^{PV} \approx -\frac{4 G_F M_p^2 \tau^2}{\pi\alpha\sqrt{2}} \times \frac{\frac{2}{3} M_p^2 r_s^2 - \mu_p(\mu_n + \mu_s)}{1 + \tau\mu_p^2}$$

where $r_s^2 = -6[dF_1^s/dQ^2]_{Q^2=0}$ and $\mu_s = F_2^s(0)$. In this approximation and in the absence of strange quarks, the asymmetry is proportional to $\mu_n = F_2^n(0)$, the neutron magnetic form factor.

At larger Q^2, the asymmetry provides a measure of the combination $F_1^s(Q^2) + \tau\mu_P F_2^s(Q^2)$, assuming that the electromagnetic form factors have the same dipole form. The experiment is, however insensitive to the axial term G_{Ap}^Z whose theory is uncertain due radiative corrections.[11,12]

In our opinion, however, measuring $\mathcal{A}^{PV}$ for the proton presents one of the best practical opportunities for experimentally establishing statistically significant strange matrix elements in the nucleon. The first point we are planning, if different from the prediction without strange quarks, will provide strong evidence for these effects. Ongoing[13] and subsequent measurements on hydrogen listed in our proposal will establish the Q^2 dependence of the effect. Once strange quarks are established, we can continue with our program on ^{4}He and separate F_1^s from F_2^s.[14] Quasielastic scattering from the deuteron will provide additional information. Other relevant experiments for separating the form factors include PR-91-017, which will study lower Q^2 and also backward angles, elastic scattering form ^{4}He at higher Q^2 as in proposal PR-91-004, or by neutrino scattering.[15]

The only theoretical estimates that we have for strange form factors come from rather speculative models. Usually they are presented in terms of r_s^2 and μ_s. A number of such predictions for $r_s^2$and μ_s appear in the literature[10,16] and are presented in Table I. There seem to be two classes, those with $|r_s^2| < 0.01$ fm^2 and those with $|r_s^2| > 0.05$ fm^2. Establishing the validity of one of the large predictions would be important. Establishing a value near the low prediction (vector dominance) would indicate that strange quarks are unimportant for the vector form factors.

Table I. Predictions for Strange Quarks in the Nucleon

Model	r_s^2(fm^2)	μ_s	R_{μ_s}	R_{r_s}
SU(3) Skyrme Model	-0.19	-0.33	0.20	0.87
Skyrme, broken symmetry	-0.10	-0.13	0.15	0.42
Skyrme, vector mesons	0.05	-0.06	-0.12	0.27
Jaffe, 8.1	0.11	-0.25	-0.27	0.49
Jaffe, 8.2	0.22	-0.24	-0.13	0.97
Jaffe, 7.1	0.16	-0.43	-0.32	0.70
Vector Dominance	0.01	-0.003	-0.04	0.04

Two ratios, $R_{\mu_s} = 3\mu_p\mu_s/2M_p^2r_s^2$ and $R_{r_s} = 2M_p^2r_s^2/3\mu_p\mu_n$, are also given. The first gives the ratio of the contribution of F_2^s to that of F_1^s at low Q^2. For the models listed, $R_{\mu_s} < 1$, suggesting that F_1^s will dominate our result. The ratio R_{r_s} indicates roughly how large the contribution of the strange quarks is relative to the asymmetry in the absence of strange quarks.

Figure 1 shows the Q^2 dependence of F_1^s for several of these models[10,16,17,18]. Again, it is not clear how seriously these predictions should be taken. For the Jaffe parameterization, the higher the Q^2 the better, at least up to Q^2=0.5 (GeV/c)^2. These predictions should be compared with our expected error of ± 0.03 in the quantity $F_1^s(Q^2) + \tau \mu_P F_2^s(Q^2)$ at Q^2=0.7 (GeV/c)^2.

Figure 2 shows the fractional change in the parity asymmetry for hydrogen using the same models. The effects are quite large (20-50% or more) at our kinematics. Our experiment will have a dramatic impact if the strange quarks do indeed contribute that much to the structure of the proton.

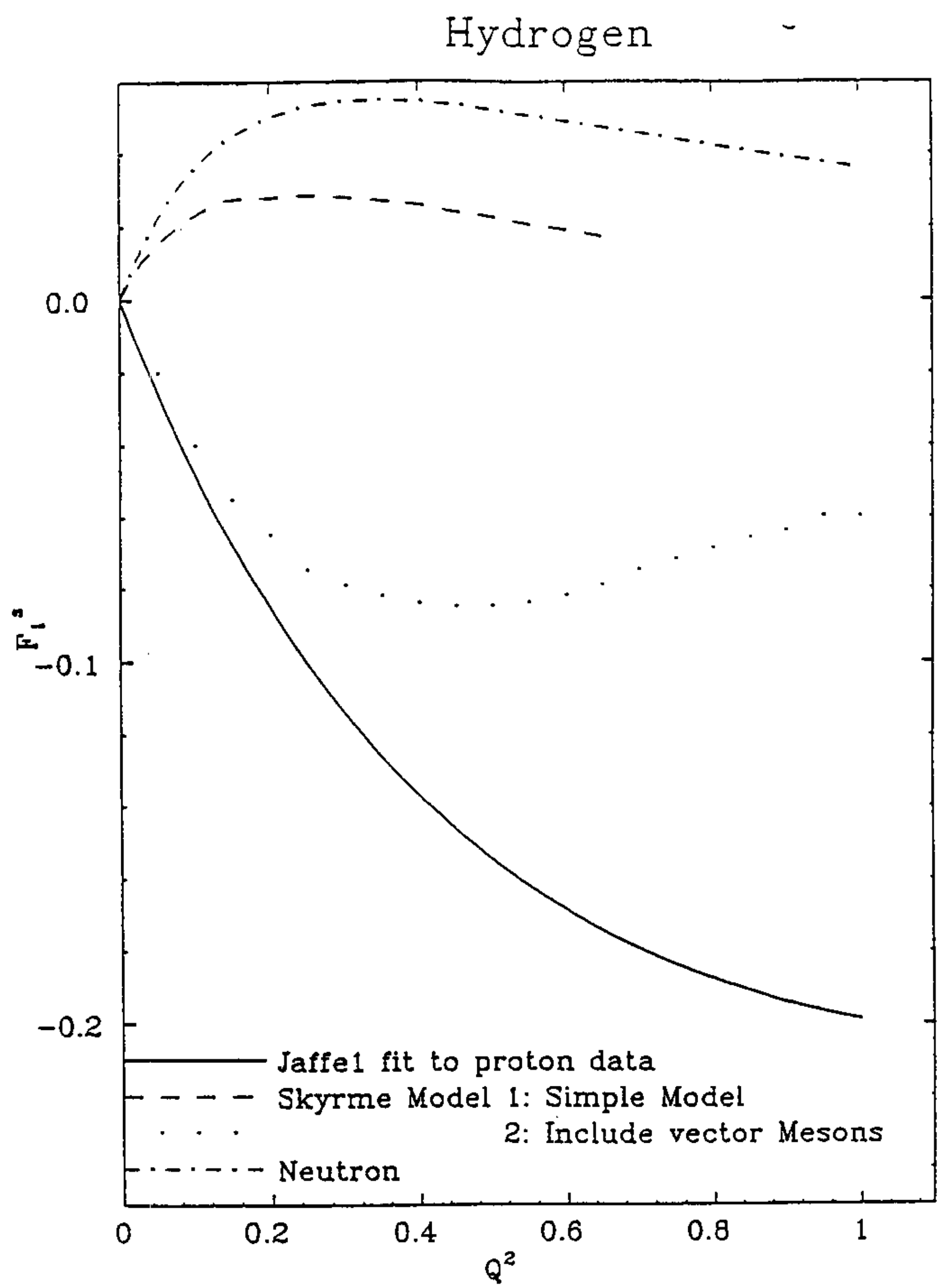


Figure 1. F_1^s as a function of Q^2 for various models. The curve labeled Jaffe is the smallest of his three estimates for F_1^s.

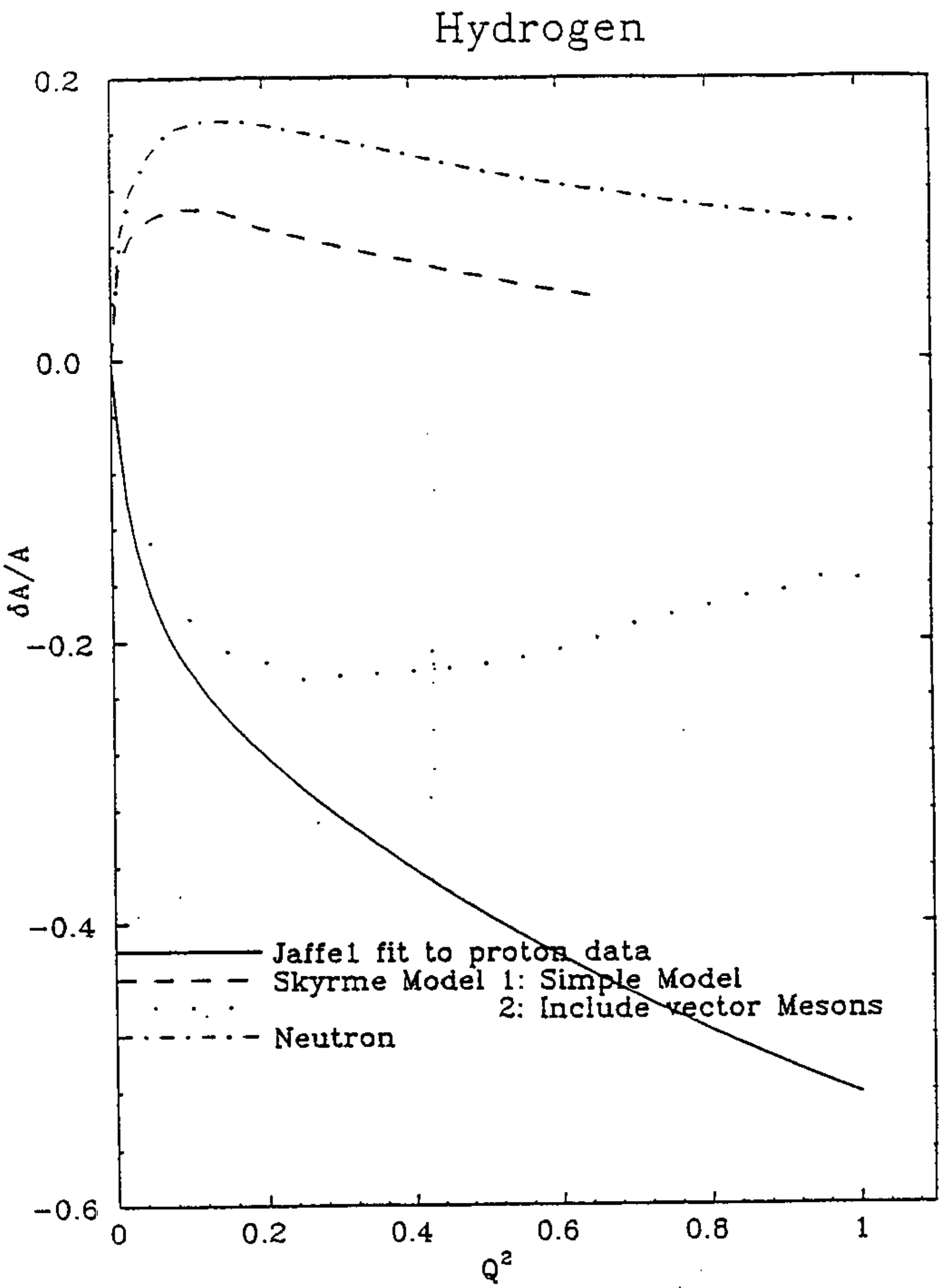


Figure 2. Effect of strange quarks on the parity asymmetry for hydrogen at small angles as a function of Q^2. The curve labeled Jaffe is the smallest of his three estimates, a second is $\sim$ 50% bigger and the third is twice as big.

II-B. CHOICE OF KINEMATICS

For our first point, we plan to run at the highest possible energy, 4 GeV, and the most forward angle, 12.5°. For this point, the fractional error for a given amount of running time is optimal, as shown in Fig. 3. In addition, the expected asymmetry is large, 30 ppm. This is a factor of about 15 higher than the asymmetry of the ^{12}C experiment at Bates.[19] Thus systematic errors associated with helicity reversal will be negligible even if they are considerably worse than they were at Bates. Moreover, by running this point, we will gain the experience and confidence to efficiently run the interesting points with smaller asymmetries in the future.

The details of our point are as follows:

$E_0 = 4$ GeV

$\theta_0 = 12.5°$

$\langle Q^2 \rangle = 0.71(\mathrm{GeV/c})^2$

Form Factor Combination Measured $= F_1^s + .36F_2^s$

$\langle d\sigma/d\omega \rangle_{Avg} = 0.32\mu\mathrm{b/sr}$

Loss due to radiative corrections: 1/1.3 (App. A. #1)

Total Yield=1.91×10^{12} counts/400 hours

$\langle \mathcal{A} \rangle_{Avg} = 2.9 \times 10^{-5}$

$h = 49\%$ (Beam Helicity)

$\langle h\mathcal{A} \rangle_{Avg} = 1.4 \times 10^{-5}$

Total running time, including background subtraction and Møller runs=500 hours

$\delta\mathcal{A}/\mathcal{A} = 8\%$

$\delta(F_1^s + .36F_2^s) = \pm 0.03$

In order to obtain the beam time estimate we assumed an average beam current of 100 μA, and a target thickness of 1.0 gm/cm^2, and a spectrometer solid angle of 7.2 msr (14.4 msr total for both spectrometers). With these assumptions a 5% measurement of the asymmetry can be made in 400 hours. A list of all of the sources of errors is summarized in Table II at the end of the document.

III. APPARATUS

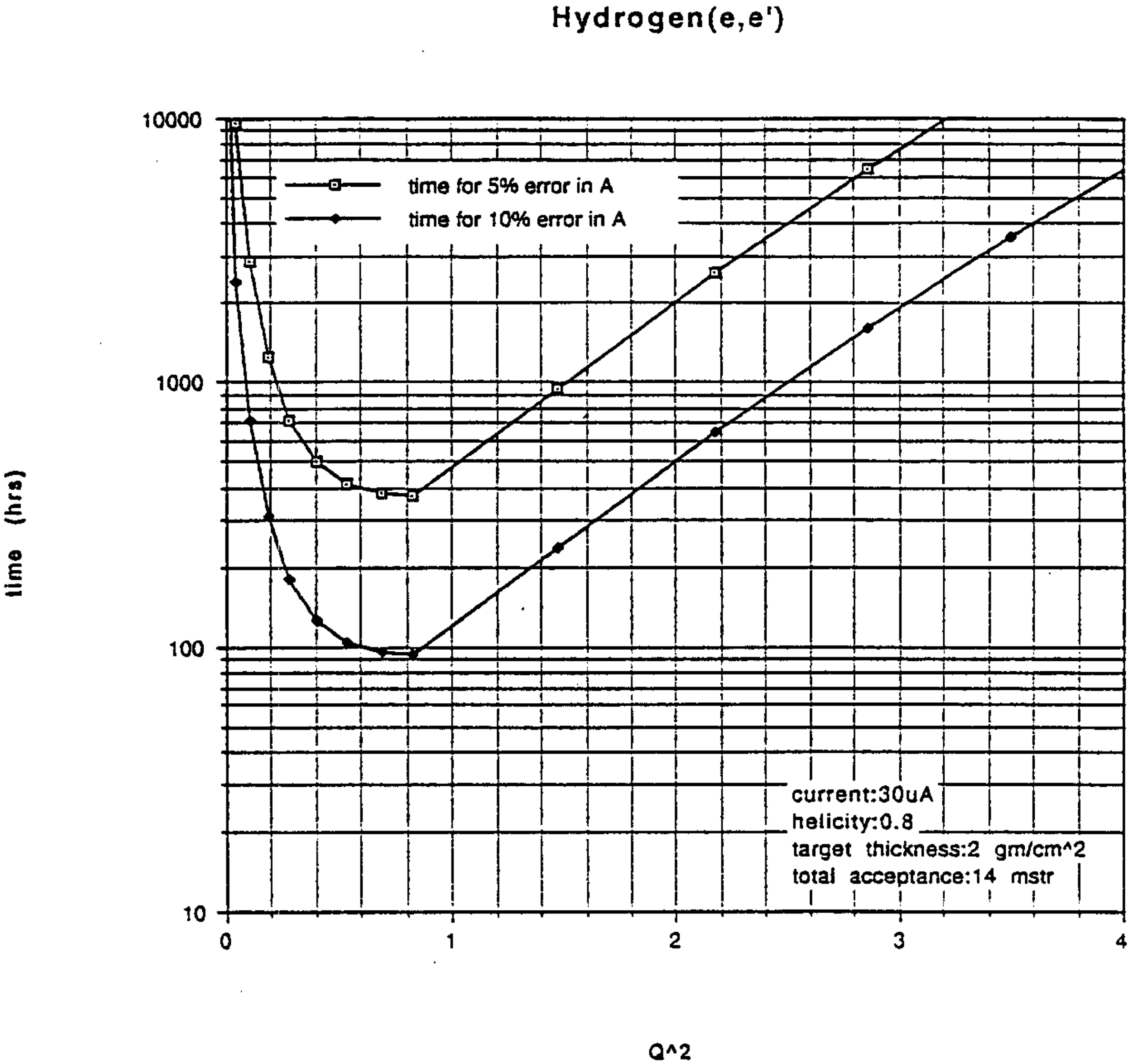


Figure 3. Achievable precision in $\mathcal{A}$ for hydrogen as a function of Q^2. The point we have chosen is near the minimum. (The absolute minimun occurs at an energy greater than 4 GeV.) Further increasing Q^2 requires larger scattering angles than 12.5° Note that this curve only gives the Q^2 dependence; the beam and target assumptions are unrealistic.

The implementation of this experiment requires an extensive amount of apparatus. Major systems include a pair of spectrometers, detectors, a high-power liquid hydrogen target, an instrumented beam transport line, an electron polarimeter, a polarized electron source, and associated electronics.

Much of this equipment is planned for use in other experiments. The major equipment unique to the parity experiment includes the detector package, sensitive beam monitors, and electronics. A summary of our time table for completing this apparatus is given in Appendix C. The groups responsible for the various tasks are listed in Appendix D.

III-A. Spectrometers

Hall A will have excellent facilities for parity measurements ***at forward angles***. The ideal parity spectrometer might have a $\Delta\theta/\theta$ acceptance of $\sim 20\%$, a ϕ acceptance of 2π, and a momentum acceptance of the detector of $\sim 2\%$. The cost of such a device designed for a 4 GeV/c beam would be prohibitive. On the other hand, at the minimum θ of 12.5° of the Hall A spectrometers, the solid angle coverage is about 25% of the ideal. In addition, the resolution is excellent. Thus Hall A at CEBAF is ideal for the forward angle part of a program to measure the F_{ip}^{Z}.

The proposed point will use both standard Hall A spectrometers positioned at the most forward angle of 12.5°. The spectrometers have been designed to operate at this angle at full beam, and will be able to withstand the radiation produced.[20] (App. A. #13). The distribution of the elastically scattered events at the location of our detector is shown in Figure 6. For clarity, the scales for both the x (dispersion) and y (scattering angle) directions are the same scale. The second order aberrations of the spectrometer are seen to spread out the elastic peak by about 5 cm at the edge of the acceptance. Since the detector in not located precisely at the focal plane, there is also smearing in the center of the detector, but this effect is smaller than the aberrations. Also shown are events at the kinematic limit for background (single pion production). There is a gap of at least 5 cm between the elastic and inelastic events, so elastic events can be identified simply by their locaton. Thus we can cleanly isolate the elastic peak from inelastic channels (App. A. #1).

III-B. Detectors

The detector for each spectrometer will be a lead glass array made of 6 SF5 blocks 30cm deep by 15 cm wide by 90 cm in the effective dispersion direction. This is the same type of lead glass blocks that are used for the standard detector package for the electron arm. Our requirement, 12 blocks, can be met with blocks originally reserved for the preradiator.

The location of the lead glass array is shown in Fig. 5. This position is chosen to achieve reasonable separation from all inelastic events as shown in Fig. 6. while

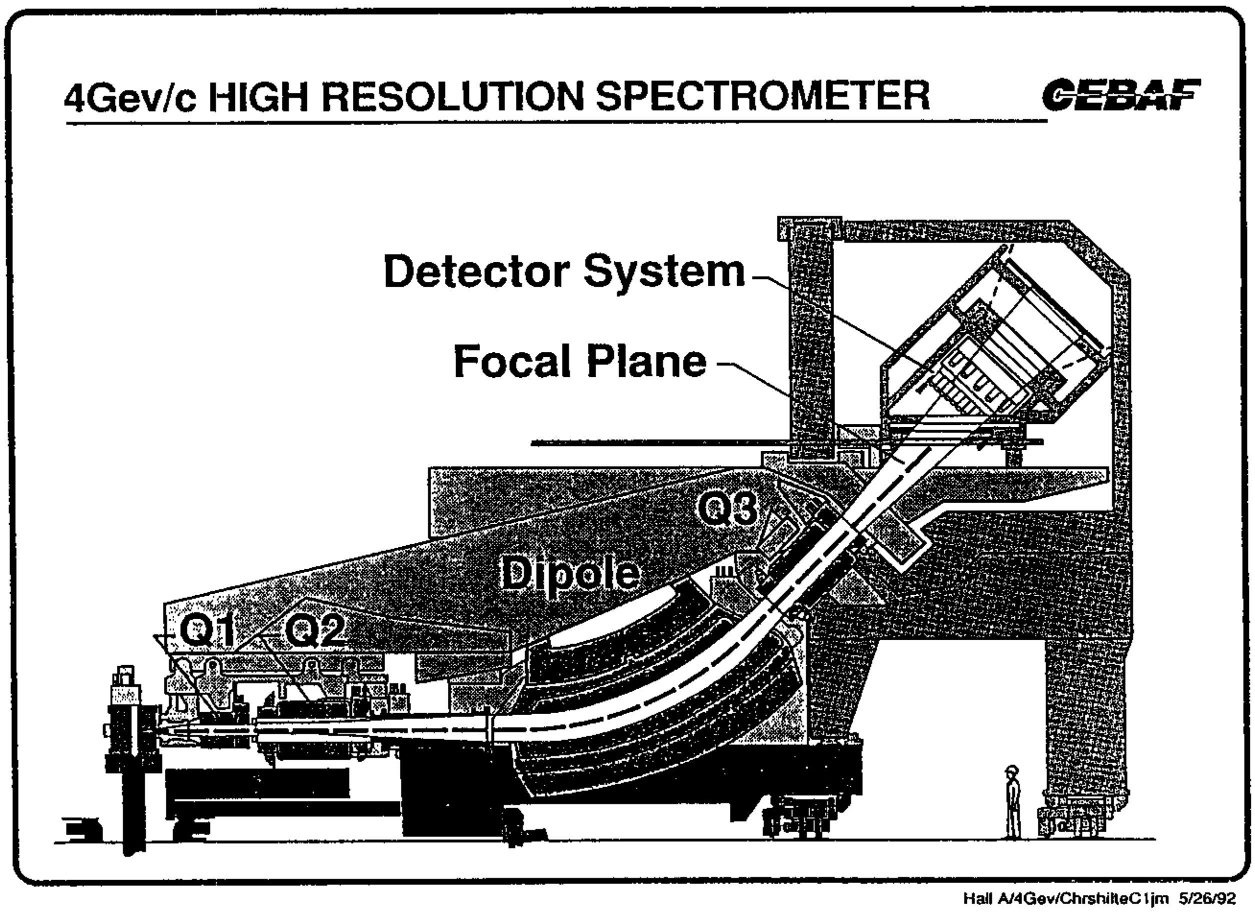


Figure 4. View of one Hall A spectrometer. Our lead glass array is positioned just past the focal plane.

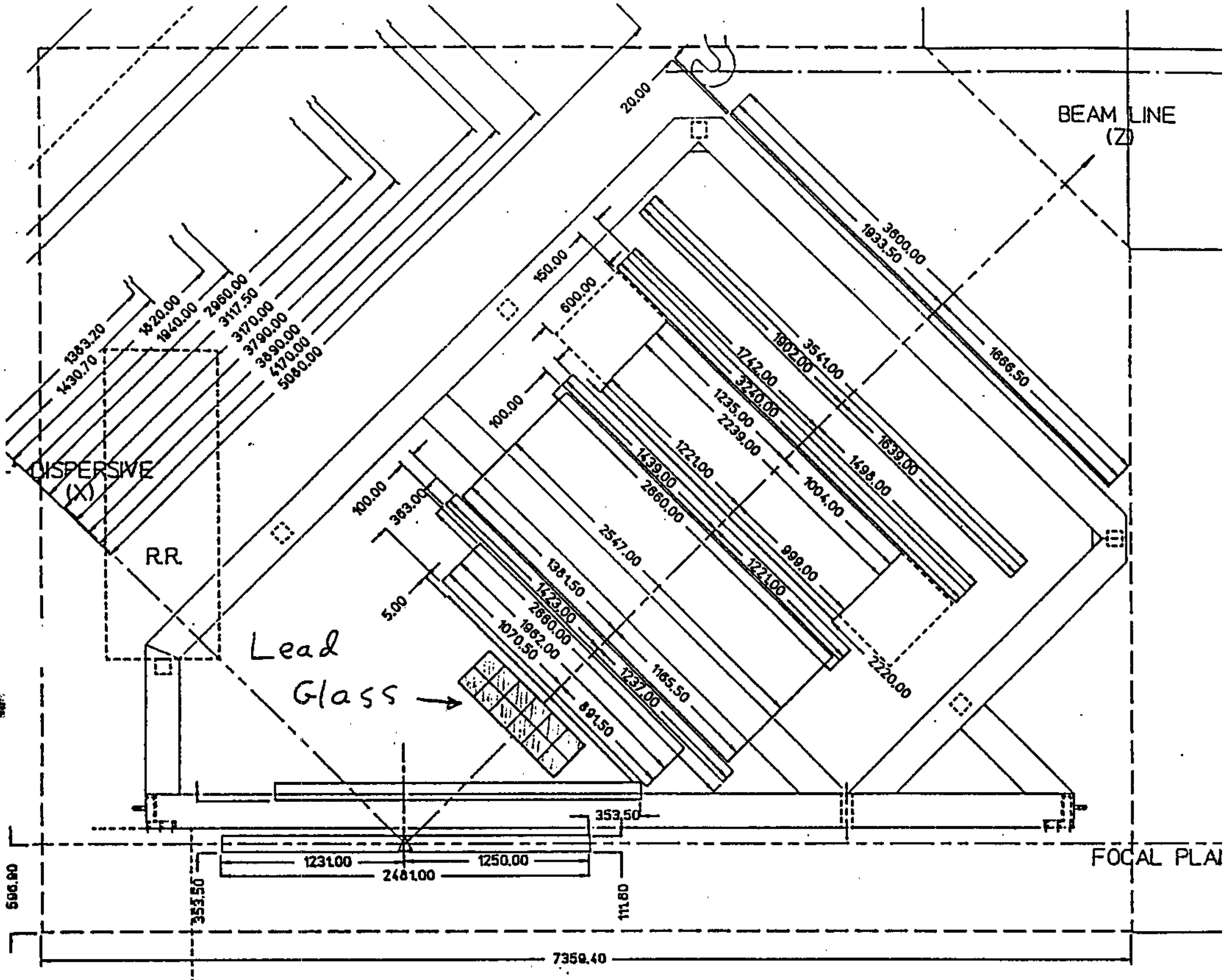


Figure 5. Location of our lead glass in the focal plane.

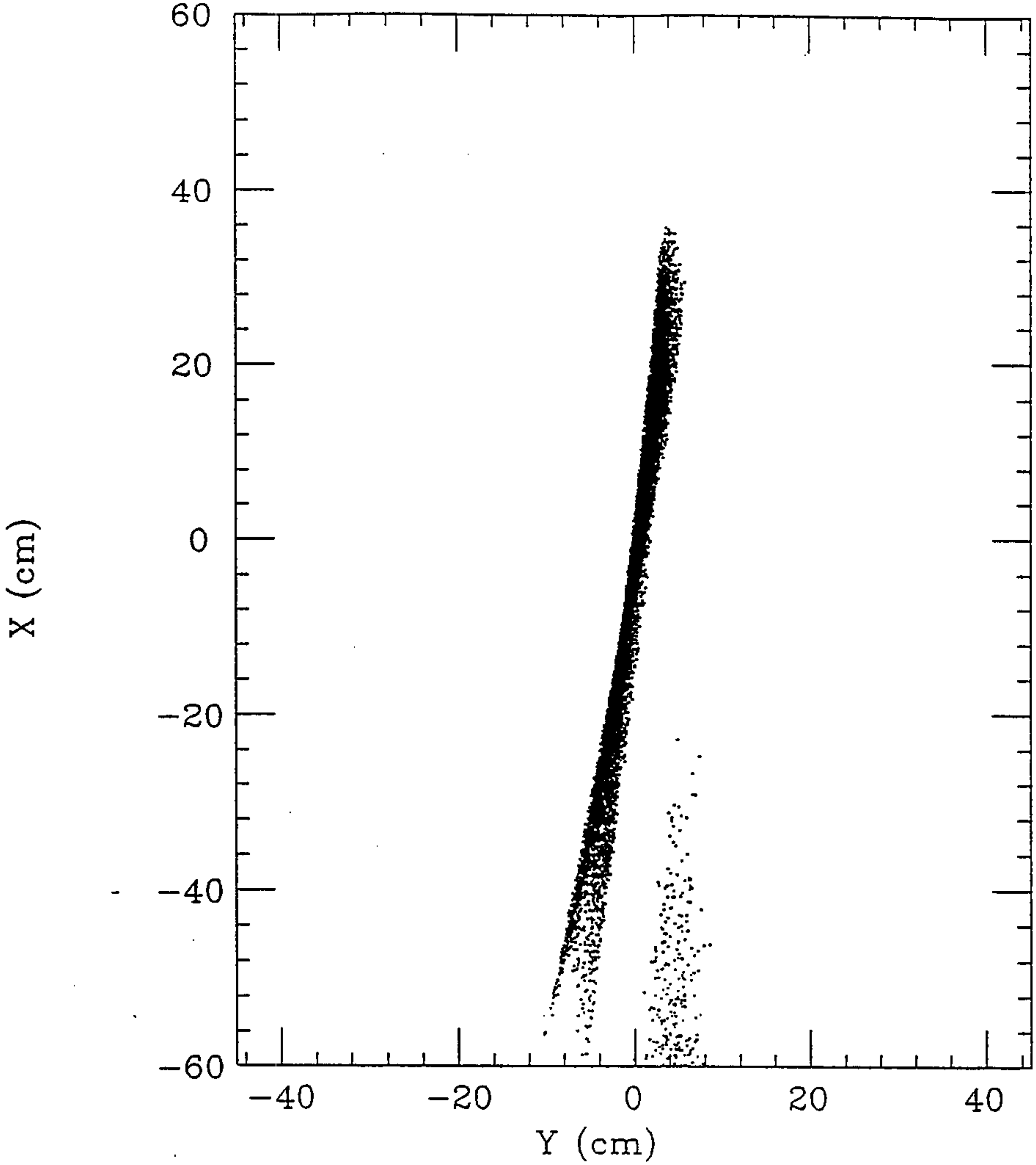


Figure 6. Position of elastically scattered electrons at the center of the lead glass. Second order aberrations are included. Also shown is a less dense band to the right which corresponds to pion production, which is the threshold for any background. We will position the lead glass so that it can only detect the dense band of elastic events.

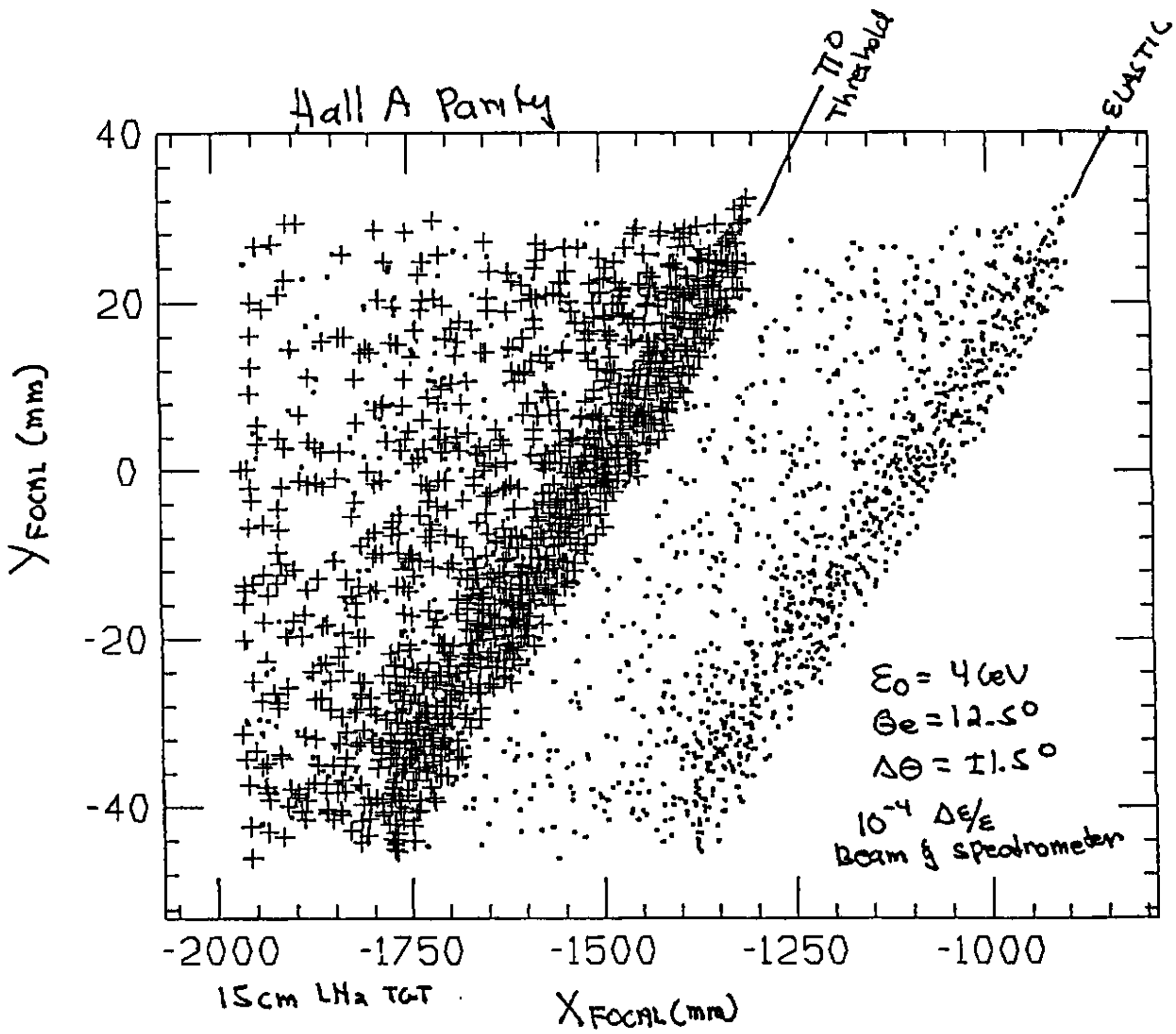


Figure 7. Smearing due to radiative tails. Events at the pion threshold are assumed to be monoenergetic and copious for this background study. In reality, the spectrum will be even cleaner.

minimizing the impact on the rest of the instrumentation in the spectrometers. (App. A #12) Indeed, we can run without removing the wire chambers in the focal plane, whose precise location is most critical. Installing the lead glass is the only change in hardware required.

The expected pulse height spectrum and also the number of photons per incident electron, based on a GEANT simulation, are given in Fig. 8. The mean energy deposited $\overline{E}$ is 3.7 GeV and the RMS spread σ is 0.2 GeV. There is plenty of signal, 10^5 photons are produced by each detected electron. As shown in Fig. 9, the response of the lead glass is fine even for events ~ 1 cm from the edges.

As stated in App. A #6, an important decision is whether to integrate the signals or count individual events. For event counting, it is easier to reject background events and other noise. The statistical error in the asymmetry is just $1/\sqrt{N}$, where N is the total number of events. However, at high rates, corrections due to dead time can be severe.

For integrating, dead time errors are not present, but background is added to the signal. The statistical error, which is

$$\delta A = \sqrt{(1 + \frac{\sigma^2}{\overline{E}^2})/N}$$

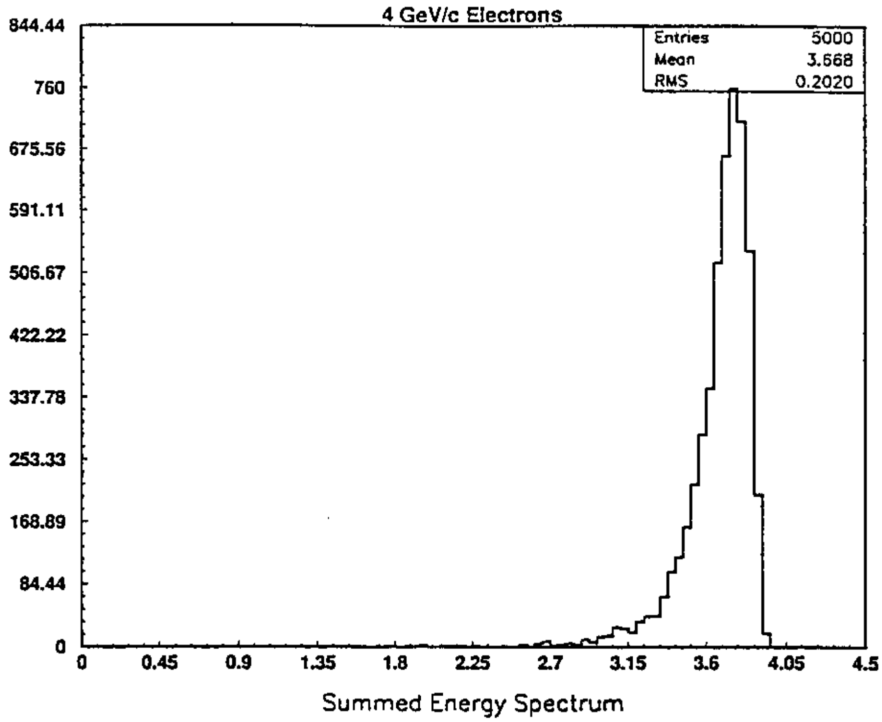
may also be increased if there are large fluctuations in the response of the detector from event to event.

For our case, the focussing of the spectrometer eliminates background electrons. Phototube noise will be small compared to the 10^{11} photons/s produced by $\sim 10^6$ events/s. Low energy backgrounds, such as $\sim$ 5MeV gamma rays from neutron capture, would contribute a negligible signal even if the rate were as high as 10^6/s (App. A. #1). According to the simulation, $(\sigma/\overline{E})^2 = .003$ is small, so there is negligible loss in statistics due to integrating. Therefore, we plan to integrate our signals. We note that for our first point the event rate of 10^6/s is small enough for counting, and thus we also plan to count our events as a diagnostic. The parity experiments at SLAC,[21] Mainz,[22] and Bates[19] all used integration.

III-C. Polarized Electron Source

The heart of any parity experiment at CEBAF will be the polarized electron source[23]. The quality of the operation of the source will determine the beam polarization, intensity, and duty factor. In addition, and of equal importance, is the fact that the source creates many of the possible systematic errors.

The CEBAF source will be based on photoemission from a GaAs crystal. We are planning our first point assuming that 100μA of 49% polarized electrons will be



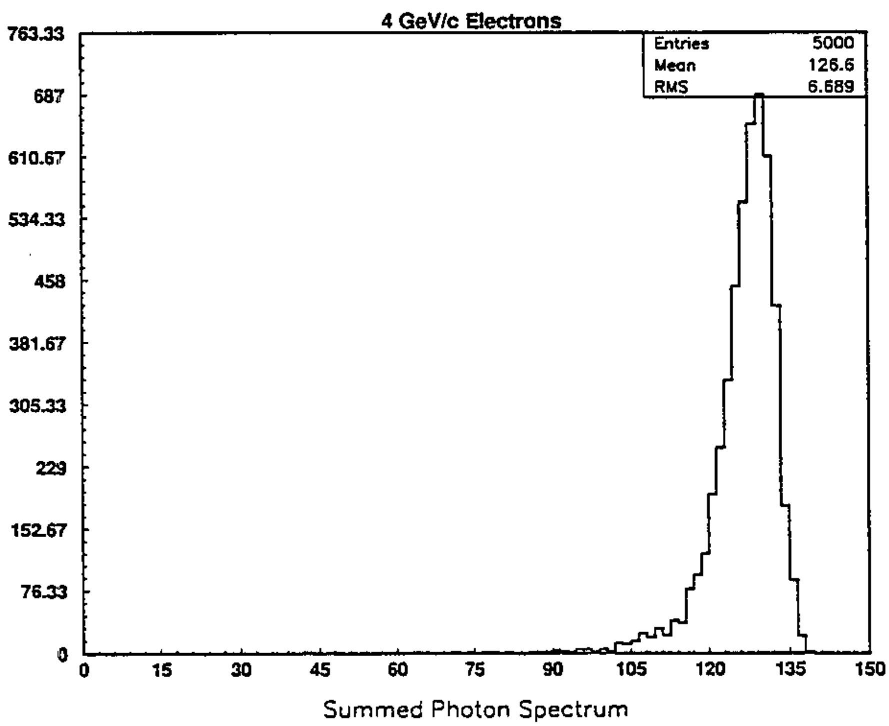


Figure 8. Top: Energy deposited by 4 Gev electrons in one of our lead glass blocks. The resolution is excellent for our purposes. Bottom: number of photons generated *divided by 1000.*

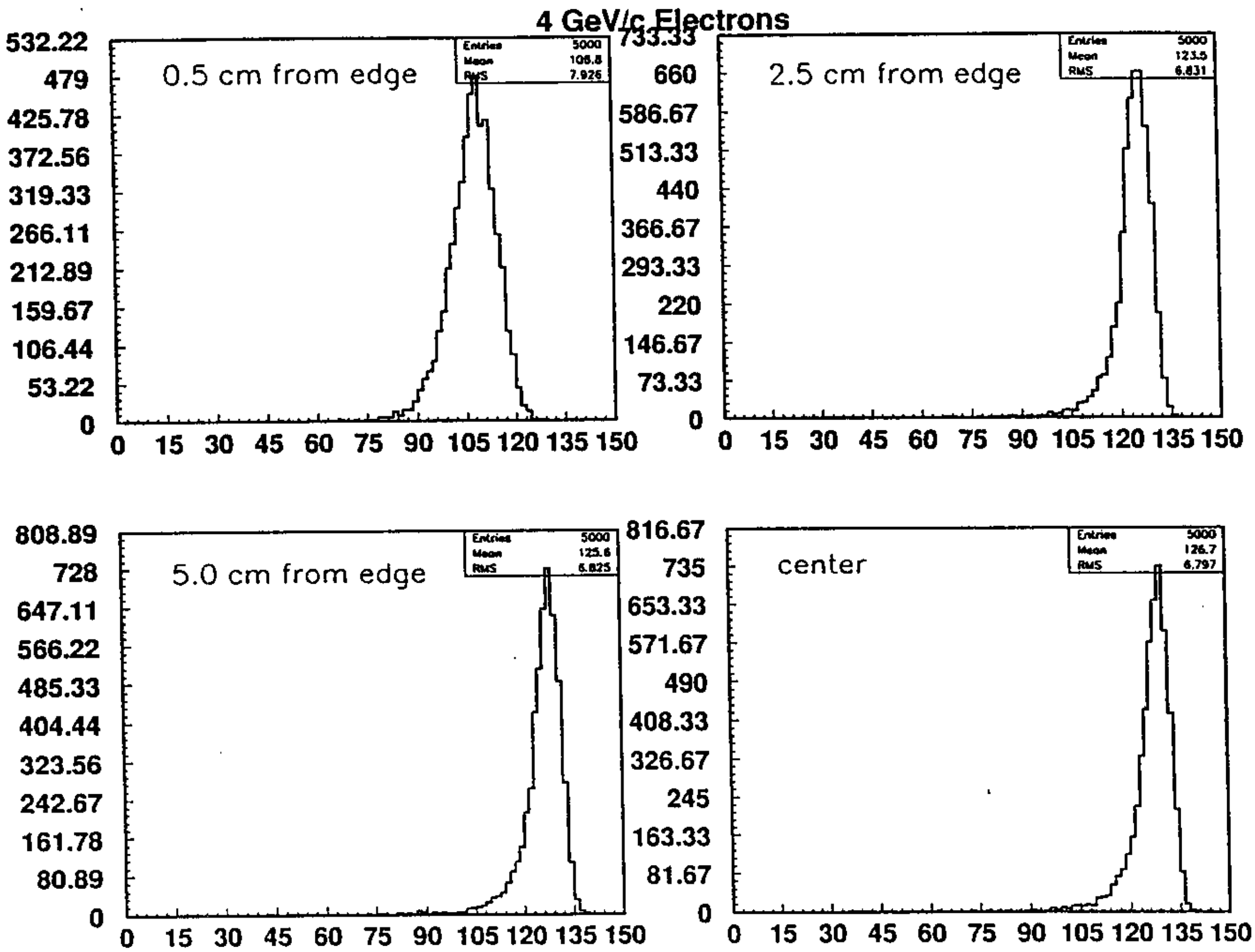


Figure 9. Response of lead glass as a function of distance from the edge of a block. We note that events 2.5 cm from the edge have negligible losses. Even events 0.5 cm from the edge contribute with more than 80% weighting.

available in Hall A. We require no special time structure apart from that necessary for the microwave cavity monitors to operate. We do not need to chop the beam during helicity reversal. (App. A. #8) We do not anticipate that our requirements will have any exceptional impact on the operation of other Halls. (App. A. #11)

Sources of systematic error arising from the electron gun include helicity correlations in intensity and position. For the ^{12}C experiment, we achieved an average intensity difference asymmetry of $\sim$ 1ppm and position differences $\sim 1\mu$. We plan to do as well at CEBAF; this would make all corrections due to helicity correlated beam differences negligible.

Small correlations are not automatic; even a carefully prepared optical system for the polarized source can give rise to helicity correlated intensity difference asymmetry in the electron beam at the level of 10 ppm. From our work on the Bates experiment, we have considerable expertise in the understanding of this effect and its impact on the experimental measurement. Correlations can be reduced by implementing a feedback scheme coupling the helicity correlated intensity difference in the electron beam to the voltage of the Pockels cell from which the circular polarization of the laser beam is derived. We plan to work closely with the laboratory to help implement this scheme, which can be used for all CEBAF parity experiments.

With the feedback scheme, it is possible to keep the helicity correlated intensity differences to within a fraction of the statistical error to which these differences are determined. We emphasize that the feedback scheme achieves this suppression of false asymmetries concomitant with data taking. This precludes the need to run actual beam tests to achieve the required level of precision for the presence of false asymmetries, which might easily require as much beam time as required to run the actual experiment. Further, the suppression of helicity correlations in the beam characteristics leads to less stringent requirements on the linearity of the detectors and the readout electronics.

Ground loops (App. A, #7) are another problem that can induce spurious signals in the detectors. One problem is cross talk between the voltage applied to the Pockels cell controlling the helicity and the detectors. We plan to use the technique we used at Bates, namely carefully isolating the Pockels electronics by using optical isolators. In addition, the effects of ground loops can be canceled by taking equal quantities of data with the two possible orientations of the linear light entering the Pockels cell. This serves to change the sign of the expected asymmetry with no other changes in the hardware.

The plan of isolating the ground loops at the origin, the source, eliminates the necessity of isolating all of the rest of the detectors; current monitors, position monitors, and the detectors of the scattered particles. Another problem is logic signals that control the helicity and tag the helicity for the data acquisition system. We plan to have the choice of helicity made at the source end, and to transmit this information several macro pulses later and during the time the electronics are gated off. This method will solve that ground loop problem.

III-D. Polarization Reversals

As indicated in App. A #6, the CW nature of CEBAF is quite different from the pulsed structure of the accelerators used for previous parity experiments. In particular, with a pulsed accelerator, the helicity of the laser beam is changed between pulses, so instabilities of the beam during reversal are not a problem. In addition, the gates for integrating all signals, detectors of scattered events, current monitors, and position monitors, are set slightly larger than the pulse length, avoiding timing problems.

At CEBAF, we plan to reverse the helicity at 30 Hz. Helicity reversal will be done in terms of pairs of macro pulses. The helicity of the first will be randomly selected, and the helicity of the second will be the complement of the first. Thus an asymmetry may be formed for each pair of pulses.

The frequency will be phase locked to the 60Hz line frequency, which will eliminate any noise introduced by line noise in the beam. Flipping the helicity will take on the order of 100μs, the majority of the time spent waiting for ringing in the Pockels cell doing the flipping to settle down. The beam will be on the entire time, but the integrating electronics will be gated off during this 100 μsec. Since the gate widths are uncorrelated with helicity, stability at the 0.1% level will be sufficient. Alignment of the gates relative to each other only needs to be accurate to $\sim$10μs .

III-E. Target

The target is an important technical challenge (App. A #4,5). The target must absorb $\sim$400 W of power from the beam. The highest power target previously used in an experiment of which we are aware had a load of 250 W. However, the overall requirements for our experiment are at the same level as other Hall A experiments, and we believe that these targets are feasible.

Our experiment, measuring high rates and small asymmetries, places special requirements on the performance of a cryogenic target. Density fluctuations are perhaps the greatest concern. For experiments measuring cross sections, small variations occuring over long time periods are a potential source of systematic error. For a parity experiment, measuring an asymmetry by rapidly reversing the helicity of the beam eliminates this problem. However, larger fluctuations due to boiling that might average out during a cross secton measurement might add noise to the data that would appear as statistical fluctuations significantly larger than predicted by counting statistics and increase the running time required for the experiment.

Presently the SAMPLE[13] experiment is testing a 500 W target (40 μA beam on 40 cm of LH_2) for a parity experiment at Bates. We are keeping in touch with the progress of that project. Their requirements are quite similar to ours. The success of that experiment will demonstrate that a hydrogen target of this power can indeed be used for a parity experiment using a high intensity electron beam.

For our point the statistical error is ~0.6% per 33 ms macro pulse. Thus the density fluctuations from macro pulse to macro pulse must be less than ~ 0.2%. This is less severe than the requirement of the SAMPLE experiment, which has 20 times the event rate.

The beam will be rastered to a size of 0.1 mm x 2 mm in order to distribute the beam power over a reasonable volume. The horizontal spot combined with the vertical flow effectively accomplishes this. During the rastering, the beam will traverse different amounts of LH_2 due to the curvature of the windows. The size of this efffect is $\delta L/L = x^2/LR$ where $L = 15$ cm is the target length, $R = 1$cm is the radius of curvature of the window, and $x = \pm 1$ mm is the maximum displacement of the beam from the center of the target. Thus $\delta L/L = 7 \times 10^{-4}$ is much smaller that the statistical error in a macro pulse and can be neglected.

Reversing the helicity at a higher rate (up to perhaps 600 Hz) would greatly reduce this requirement and can be implemented if necessary.

Vibrations in the target are another source of fluctation that would average out for a cross section measurement but could produce a significant lengthening of the running time for a parity experiment. For example, the hydrogen flows through the target loop at a speed of ~10m/s driven by a vane-axial pump rotating at a maximum speed of 57.5 revolutions per second. Thus a 57.5 Hz vibration may be present. The amplitude of such vibrations should result in small fluctuations compared to the 0.2% mentioned above, and randomly reversing the helicity of the beam will eliminate any coherent signal. Again the requirements of the similar SAMPLE target are more severe.

Rastering the beam (App. A #5) will be required to keep the beam spot large enough to prevent boiling. We plan to use the methods specified in CEBAF-PR-93-005.

The thickness of the aluminum end windows for the normal target cells is 0.011 in each or 0.15 g/cm^2 total. Assuming that the cross section per nucleon is the same as for deuterium, 10% of the events will come from the windows and will be accepted by the spectrometer. This would increase our errors by about 10%. Short background runs (5% of the beam time) either with an empty target (to measure the size of the cross cestion) and with a dummy target (to measure the asymmetry) will also be required to make the corrections. For the parity runs, we plan to reduce the thickness of the end windows by a factor of at least two. This will keep the corrections comparable to our projected error and also reduce the time required to measure the corrections to about 10% of the production beam.

The target window has a 1 cm radius, which will cause the thickness of the target as seen by an off-center beam to vary with position. The size of the effect for a 1 mm displacement and a 0.1μ helicity-correlated displacement is 0.1 ppm, negligible compared to our -17 ppm predicted asymmetry. For the proposed point we see little reason to use a flatter window on the target.

III-F. Electronics

The detected light from the photomultiplier tubes which will collect light from the lead glass counters will be integrated over the duration of the pulse and then digitized. The ADCs will be required to have 16 significant bits to ensure sufficient sensitivity at rates of 100 kHz. Total linearity of 0.1% should be sufficient since the systematic error scales as the nonlinearity times the largest helicity correlated asymmetry in the system. We note that a properly designed feedback scheme should keep all such asymmetries at the same level as the expected experimental asymmetry. The differential nonlinearity will be required to be better than about 1 least significant bit. The sensitivity to the differential nonlinearity will be alleviated by adding a pseudorandom DC level to each integrated signal which will later be subtracted offline.

ADCs conforming to these characteristics with conversion times less than 20 microseconds are available. We propose to develop a prototype of the integrator-ADC system beginning in early 94, to be ready for testing at CEBAF in the summer.

The same electronics will also be used to integrate and digitize the signals from the microwave beam monitors mentioned in section IV-B. below. The signal from the beam current monitor will be used to normalize the signals from the detectors, eliminating helicity correlated beam intensity differences as a direct systematic error. The signals from the microwave position monitors will be used to monitor and correct systematic errors from other helicity correlated beam differences.

Detector linearity is another problem. Again, the relevant criterion is the ratio of the largest asymmetry present relative to the desired error. For experiments where there is a large helicity correlated difference in intensity and/or large background in the detectors, this can impose stringent requirements. However, if ample care is taken at CEBAF, the largest asymmetry in the experiment will be caused by parity violation! Linearity at the 1% level will then be ample.

IV. SYSTEMATIC ERRORS

Introduction

For the case of parity experiments with polarized electrons, the major problems in the past have had more to do with attaining sufficient electron intensity and in controlling the beam current than in dealing with systematic errors arising from the small asymmetries. Moreover, in terms of proposing a new experiment at CEBAF, there is much to be learned from previous work at SLAC[21], Mainz[22], and Bates[19] that can be applied to eliminate spurious asymmetries at the required level. Indeed, the achievement at Bates of an uncertainty in the asymmetry of 0.02 ppm is compelling evidence that we can achieve our goals. In our proposal, we detailed our general philosophy about methods to eliminate systematic errors. Here we will address the issues raised by the Directors TAP (see App. A.).

IV-B. Beam Monitors

Helicity correlated differences in the first order beam parameters, assumed to be position, angle and energy, are measured by using beam position monitors (BPM's). In the Hall A beam transport line, there will be an XY pair within 2 m of the target, an XY pair 8 m upstream (Fig. 9), and a BPM in the bend where there is substantial dispersion (Fig. 10). The first four determine position and angle by tracking, and the fifth gives the energy. The differences in these monitors are denoted δM_i.

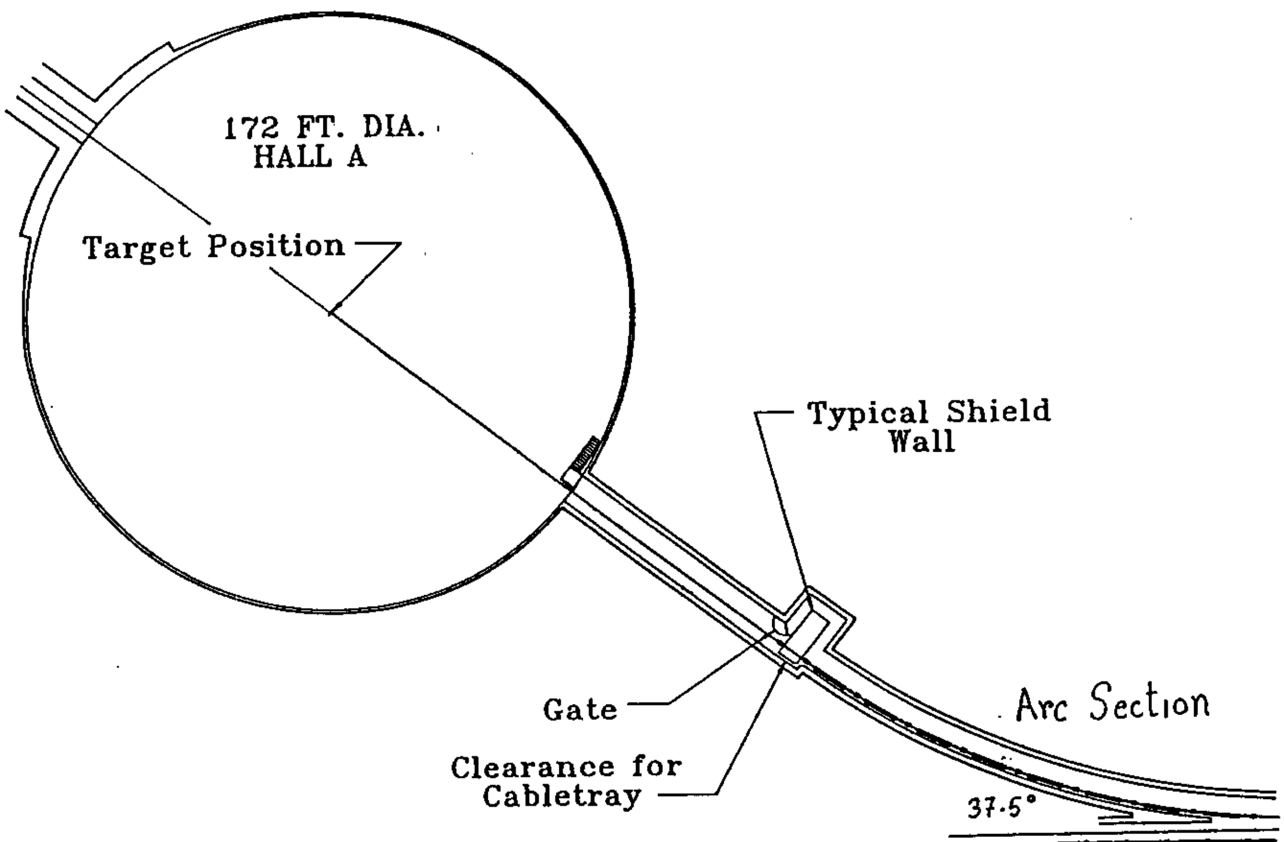
The required relative precision of the beam monitors is estimated as follows. The cross section for electron scattering is very sensitive to energy; with $\sigma \sim E^n$. For our first point, n is 5, which is in fact typical for almost any experiment. For a 33 ms gate, we require $\Delta E/E < \frac{1}{100}\frac{1}{n}\Delta\sigma/\sigma \sim 0.01\%$. (The $\frac{1}{100}$ factor assures that the resulting errors will be totally negligible.) With a dispersion of $\sim$ 2 cm/%, this corresponds to a position of 20 μm.

The situation for beam angle and position is similar. The sensitivity of the cross section to scattering angle is 3.3%/mr. This resolution can be achieved with a 20 μm position resolution with a $\sim$ 10 m lever arm. (In fact, this sensitivity will cancel because we are using symmetric spectrometers.) One requirement on position sensitivity is that the change in path length through the target due to changes in position Δx of the beam when the beam is rastered x = 1mm off the axis due is negligible. Then $\delta L/L = 2x\Delta x/LR$, where L is the target length and R=1 cm is the radius of curvature of the windows. This requires a resolution of 50 μm with the $\frac{1}{100}$ safety factor. Another potential problem is the effects of radiative tails missing the detector. We have evaluated these effects and found them to be slightly smaller that the other sensitivities reported here. In conclusion, monitors with a resolution of $\sim$ 20 μm each 33 ms macro pulse are very conservative. Our requirements are summarized in Appendix B.

It is also possible that there are helicity correlated differences in second order beam parameters such as phase space. There are many second order parameters and it would be difficult or impossible to unfold them all in a quantitative fashion. However, based on our experience at Bates, we expect them to be negligible. Moreover, by reversing the beam helicity with the spin rotator in the injector, we can monitor the net contribution of such effects and cancel them by averaging. (App. A #2,3).

For our position monitors, we plan to use microwave cavities such as those used at SLAC and Bates and the version developed for the Los Alamos/NBS microtron project[24]. The latter had a resolution of $\sim$ 20 μm for a 100 μA beam with a 40 ns gate. Since we will integrate for 30 ms, our resolution should be much better, although the quoted number is sufficient for our needs.

We plan to also use microwave cavities to measure the beam current. The Los Alamos/NBS monitor had a resolution of 8%. Integration over 10^6 times more time should easily reduce the noise to below our requriement of 0.1% per macro pulse.



HALL A BEAM LINE

Figure 10. Hall A beam line. The positon monitor in the center of the Arc Section will determine the helicity correlated energy difference.

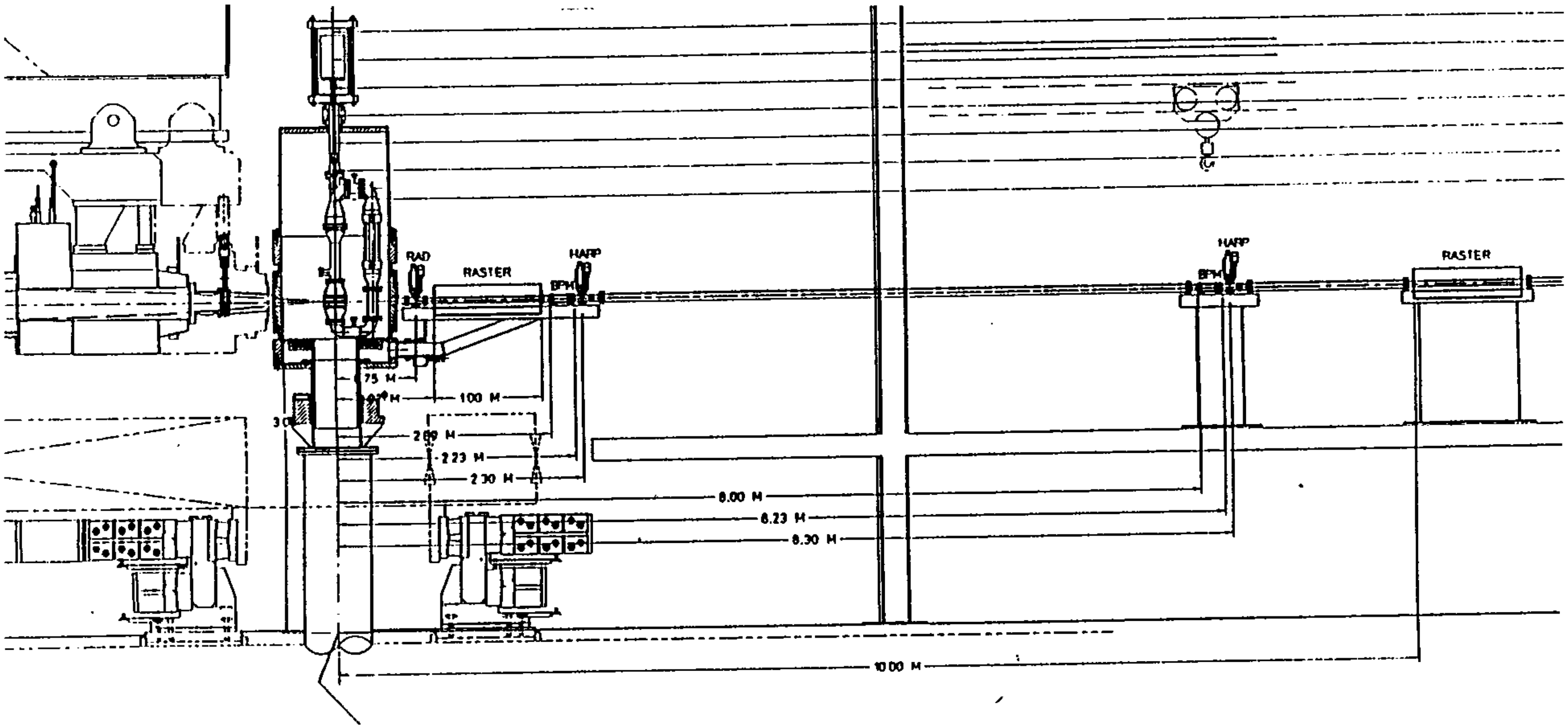


Figure 11. Detailed view of the beamline and target. Position monitors are located ~2 m and 8 m from the target.

Although these devices are very sensitive, they are subject to many problems when performing absolute measurements. Fortunately, we do not need them for absolute measurements for this experiment. Since the asymmetry is computed for each pair of adjacent pulses, the calibration constant of the current monitor cancels if it is stable over only hundreds of ms. The position monitors are continuously calibrated by the coil ramping.

IV-C. Calibration

We have argued that the helicity correlated changes in beam properties will be small enough to be neglected, and that we can measure that they are small to ample precision with microwave cavity monitors. During the experiment, we will *prove* that this is true by using the calibration method that we developed at Bates. This is achieved by varying the beam parameters in a controlled way by ramping steering coils and the beam energy. This method was effectively demonstrated for the ^{12}C parity experiment at Bates, and a similar method should work well at CEBAF. Note that this ramping is totally separate from the faster rastering required to prevent problems with the LH_2 target.

To correct the raw asymmetries, we use the equation

$$A_{exp} = A_{raw} - \Sigma a_i \delta M_i,$$

where A_{raw} is the uncorrected asymmetry, δM_i are the differences in the beam monitors correlated with helicity, and the a_i are correction coefficients. Data obtained while the steering coils in the beam line are ramped are used to compute the correction coefficients involving the position and angle of the beam.

The coefficients a_i, which are really $\partial\sigma/\partial M_i$, are computed by first measuring the response of the spectrometer and the monitors to the coils C_i: $\partial\sigma/\partial C_i$ and $\partial M_j/\partial C_i$. Then the equation

$$\frac{\partial\sigma}{\partial C_j} = \frac{\partial\sigma}{\partial M_i}\frac{\partial M_i}{\partial C_j} = a_i\frac{\partial M_i}{\partial C_j}$$

is solved by matrix inversion to obtain the a_i. The key of the method is to ramp under computer control a complete set of parameters with devices (steering coils and an energy vernier) placed upstream of all of the monitors. Steering coils upstream of the most upstream monitor, the energy monitor, serve to control the position and angle. There are important dynamic range criteria here. First, the coils must vary position and angle with ample independence so that the matrix $\partial M_i/\partial C_j$ is far from being singular. The amplitude of the ramping must be large enough so that it exceeds the size of the normal beam jitter, yet small enough so that the effect of the ramping is small compared to the statistical error on the cross section. Achieving these requirements simultaneously was accomplished at Bates and should be easier at CEBAF because the beam should be quieter and we know the relevant criteria prior to establishing the design of the beam transport system. This method is key to simultaneously taking production data and studying systematic errors. We are presently studying this issue with members of the Hall A staff.

For calibrating the effects of energy variations, we plan to modulate the energy of the beam on our target. Varying the energy by $\pm 10^{-4}$ at 1Hz will be sufficient. This can be done in the accelerator by using the device used to test that the arcs in the accelerator are isochronous. (App. A. #9).

The computer steering control system might also be used to keep the average beam parameters at values minimizing the sensitivity of the apparatus to systematic errors. Hitting the precise center of the target is one possibly important example.

IV-D. Beam Polarization

For our first run, we will use the tested method of Møller scattering to measure the beam polarization. (App. A #10) The precision will be about 4%.

We are also hoping to have a precision Compton polarimeter to measure the beam polarization. It will measure the polarization simultaneously with data taking, eliminating errors due to time variation in the polarization. The precision will be a few percent or better. Of course, implementation of this device is a significant challenge.

IV-E. Magnetized Iron

Polarized electrons striking magnetized iron can produce an asymmetric background (App. A #1) because of the spin dependence of the interaction with the polarized electrons in the iron. These effects are small: the electron polarization in iron is 7%, the maximum analyzing power is 5/9, only a few percent of the energy loss is due to interaction with the electrons (.02), the magnetization of most of the iron is perpendicular to the beam (.05), and the true signals in the detector swamp the background (0.001). Putting these factors together gives a false asymmetry of $< 10^{-8}$, which is comfortable.

IV-F. Errors in Evaluating the Theoretical Prediction

To evaluate the theoretical expression for the parity asymmetry in hydrogen, (App.

A, Theory #1) the following expression is useful:

$$A_{ep}^{PV} = 3.167 \times 10^{-4}\tau \Bigg[(3\tilde{\gamma} - \tilde{\alpha}) \left(\frac{\varepsilon G_{Ep} G_{En} + \tau G_{Mp} G_{Mn}}{\varepsilon G_{Ep}^2 + \tau G_{Mp}^2} \right)$$
$$+ (3\tilde{\gamma} + \tilde{\alpha}) \left(1 \right)$$
$$+ (\tilde{\beta} - \frac{3}{5}\tilde{\delta}) \left(\frac{\sqrt{1-\varepsilon^2}\sqrt{\tau(\tau+1)} G_{Mp} G_A}{\varepsilon G_{Ep}^2 + \tau G_{Mp}^2} \right)$$
$$+ 2(\tilde{\gamma} + \epsilon_{av}^{es}) \left(\frac{\varepsilon G_{Ep} G_{Es} + \tau G_{Mp} G_{Ms}}{\varepsilon G_{Ep}^2 + \tau G_{Mp}^2} \right) \Bigg]$$

where $\tau = Q^2/4M_p$ and $\varepsilon = \left(1 + 2(1+\tau)\tan^2(\frac{\theta}{2})\right)^{-1}$. G_{Ep}, G_{En}, G_{Mp} and G_{Mn} are the usual electromagnetic form factors for the proton and neutron. The values of the coupling constants in the Standard Model are given by:

	Standard Model	$\sin^2\theta_W = 0.23$
$\tilde{\alpha}$	$-\rho(1 - 2\sin^2\theta_W)$	-0.54
$\tilde{\beta}$	$-\rho(1 - 4\sin^2\theta_W)$	-0.08
$\tilde{\gamma}$	$\frac{2}{3}\rho\sin^2\theta_W$	0.15
$\tilde{\delta}$	0.	0.00
ϵ_{av}^{es}	$\frac{1}{2}\rho(1 - \frac{4}{3}\sin^2\theta_W)$	0.35

where the numerical value for $\sin^2\theta_W$=0.23. Thus the coefficients to the first $(3\tilde{\gamma} - \tilde{\alpha})$ and fourth $(\tilde{\gamma} + \epsilon_{av}^{es})$ terms are unity, and those of the second and third are < 0.1.

There are a number of problems involved in evaluating the above prediction for the parity asymmetry in hydrogen. Most of the asymmetry comes from the first term, which is proportional to the neutron form factors. The size of the errors on these form factors is a somewhat controversial issue, both in terms of the present limits to our knowledge and in terms of what will be learned in the near future from experiments at Bates, Mainz, and CEBAF.

To set the context of the scale of errors, we will consider predictions about the contributions of the strange quarks to the charge form factor. If the predictions of Jaffe are right, strange quarks change the asymmetry by more than 50%, and will overwhelm most other errors. One of the Skyrme model predictions gives 20% contributions, and determining if this is true is a reasonable goal for a first round experiment. The Skyrme model prediction of 8% will be more challenging to establish; this might represent the ultimate goal of the program.

The question that has received the most attention in the literature is the value of G_{En}, the neutron electric form factor. The difference in the parity asymmetry between G_{En} being its nominal value[34] and zero is about 15%. In addition, the error in G_{Mn}, on the order of 10%, is important because the parity asymmetry is approximately proportional to that quantity. Experiments are planned or underway at CEBAF to reduce the error on G_{En} to about 15% of itself and at Bonn and Mainz to improve G_{En} to better than 3%. This should be sufficient for our first work.

Another issue is radiative corrections.[11,12] Due to the excellent resolution (compared to SAMPLE) of the spectrometers, most of the radiative tail will be rejected, simplifying that part of the calculation. The more difficult problem is the electroweak radiative corrections related to the composite nature of the nucleon. These effects are often described in terms of percent corrections, which can become very confusing because the effects under consideration are often small or zero; some have a factor of $1-4\sin^2\theta_W \approx 0.08$ and others are strictly zero. Indeed, at low Q^2 and forward angles, the first term in the above equation, which is small, dominates. For our kinematics, however, the second term, involving G_{Mn}, is largest. Its coefficient is 1 instead of 0.008. Moreover, the radiative corrections are multiplied by $1-4\sin^2\theta_W$, reducing their importance. The calculated corrections should be reliable to at least a few percent (ignoring top quark mass problems) and uncalculated box diagrams which are the analog to two photon exchange diagrams should also be tractable.

Table II. Estimated Errors in $\delta\mathcal{A}/\mathcal{A}$

SOURCE	ERROR
Statistics	5%
Energy and position monitors	<1%
Electronics	< 1%
Magnetized iron	1%
Background	1%
Beam Polarization	4%
Radiative Corrections	4%
Form Factors (neutron G_E and G_M)	3%
Total	8%

V. RUN PLAN

A large number of tests must be done prior to running our experiment. First we list projects that can be accomplished without modifying the normal apparatus in Hall A as follows:

Test the beam monitors.

Test the beam monitor integrating electronics and software.

Test the coil ramping–control system, software.

Study possible effects of target boiling on counting rates.

Check that the data behaves statistically.

Measure the sensitivity of the apparatus to beam parameters.

Search for electronic cross talk due to ground loops.

Test source feedback system.

Test the Møller polarimeter.

Much of this work can be done as a part of the commissioning stage. For tests that go smoothly, the time required will be modest; the production beam time needed for each test is probably $<$ one hour. Thus most of this extensive work can be done in a parasitic mode with minimal impact on the rest of the program. For example, studies of target boiling, which do not need background rejection, can be done by counting pulses in the standard lead glass package. Of course, we may run into some unexpected problems that will require much more work.

Once we have completed the parasitic studies mentioned above, we will be ready to make a serious measurement. As suggested by the Barish Commettee, we request 6 weeks of production beam. For this run, we will install and calibrate our lead glass. This will give our projected result even if our production data occupies only half of the scheduled beam time.

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APPENDIX A
Issues Identified by the Director's Technical Advisory Panel

Experimental Issues

1 Capability of the proposed instrumentation to isolate the reaction of interest - backgrounds, inelastic channels, radiative tails.

2 Sensitivity to changes in the beam properties - position, emittance, angle, energy, current.

3 Resulting limits on helicity correlated changes and proposed methods of control and verification.

4 Cryotargets - feasibility, maximum current, impact of vibration, density variation, background from windows, window stability, and target length effects.

5 Requirements for rastering and/or large spot size.

6 Anticipated problems with helicity reversal for CEBAF's CW beam (reversal frequency, macro pulse duration, gap?)

7 Detector systems - integrating or counting, dead times, efficiencies, noise, ground loops, etc.

8 Polarized source requirements.

9 Requirements for energy variation.

10 Proposed method for polarization measurement.

11 Impact on running the other Halls.

12 Changes requrired in the standard equipment of the Hall.

13 Can cryogenic magnetic elements (if present) withstand forward radiation produced?

14 Schedules and manpower.

Theoretical Issues

1 Do G_E^n, meson exchange currents, dispersive (second order) contributions, or separation of form factors cloud the interpretation?

2 What level of accuracy is required for a useful measurement?

Appendix B

BEAM AND TARGET PROPERTIES

Frequency of beam reversal (Hz):	30
Time Period of measurement (ms):	33
Space between beam micro bunches (ns):	-
Beam polarization error (%)	4
Target Length (cm)	15
Power deposited in target (W)	400
Beam Radius (R) on target incl. rastering (mm)	1
Average beam current (μA)	100

BEAM MONITOR SENSITIVITIES FOR ONE TIME PERIOD OF MEASUREMENT

Time period of measurement (msec)	33
Beam position monitor sensitivity (microns)	20
Beam intensity monitor sensitivity (%)	0.1
Beam energy monitor sensitivity (10^{-4})	1
Beam jitter–Energy (10^{-4})	1
Beam jitter–position (μ)	200

Appendix C

SCHEDULE FOR HALL A HYDROGEN PARITY

Status	CD	D	P	R	
Target loop		93		95	
Target gas system	93	94		95?	descoped
Møller	93	94		96?	descoped
Spectrometers				95	
Lead glass	93	95		96	
Integrating electronics	94	94	94	95	
Polarized source				95	
Helicity reversal		94	94	96	
Coil ramping	93	94		95	
Microwave cavity monitors			95	96	

Key

CD Conceptual design

D Design

P Prototype

R Ready for experiment

Appendix D

Responsibilities of Participants

- CEBAF: S. Nanda –Spectrometer, beam line.
- CSULA: Epstein et al.– Hydrogen Target.
- CEBAF: J. Gomez et al.– Target
- CUNY: M. Lubell–Beam diagnostics, Source.
- Harvard: R. Wilson–Electronics
- MIT/Bates: W. Bertozzi et al.–Spectrometer calibrations.
- Princeton: K. S. Kumar – Integrating electronics, source systematics.
- Kent State: G.G. Petratos: Polarized backgrounds
- Maryland: C. Halli et al.– Lead glass calibration.
- ODU: P. E. Ulmer et al.– Spectrometer calculations.
- Syracuse: P. A. Souder et al. –Detectors, Analysis.
- UVA: R. Lourie et al.–Spectrometer calibrations.
- Kharkov: P. Sorokin et al, Møller Polarimeter
- William and Mary: J. M. Finn et al. – Data acquisition software, Analysis.

Appendix E

Special Experimental Equipment

Shared equipment with the general Hall A program includes the two HRS spectrometers, high powered cyrogenic targets, a beam line polarimeter and standard beam line monitors. Additional equipment that is required especially for the parity experiment are listed below.

1. Integrating electronics for the detectors

2. Control electronics for the source, beam steering, and beam monitors ($50k).

3. Cavity monitors