CLAS-NOTE 2001-015
Will Brooks
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Specifications for the E5 (‘dual-cell’) Target

1.0 Introduction

Experiments in CLAS at Jefferson Lab are organized into ‘run periods’ which in general include several concurrent experiments sharing common experimental conditions. The relevant experimental conditions include target material, magnet currents, and incident beam type and energy.

The E5 run period is distinct from other run periods in that it requires the presence of two targets in the beam at the same time. One target (hydrogen) is used for an important calibration, and the other (deuterium) provides the data for physics analysis. The requirement for having two targets simultaneously comes essentially from the high-precision nature of the intended measurement. The quantity of interest, the neutron magnetic form factor (G_{Mn}), has been measured to moderate accuracy in a number of experiments over the past few decades. The two features of this experiment which are new are to measure G_{Mn} with high precision, and to measure it over a broad range in momentum transfer (Q^2). The experimental error is limited by systematic errors at small Q^2 (large neutron angles) and by statistical errors at large Q^2 (small neutron angle). Because of the emphasis on high precision, some considerations are more important for this experiment than for other CLAS experiments.

The E5 run period at the current time only has one approved experiment, E94-017; however, at least two other run groups have an interest in the deuterium part of the E5 data. For this reason it is of interest to make the dual-cell target design as general-purpose as possible, as long as it does not compromise the E5 experimental goals.

2.0 Summary of Specifications

The following table summarizes the critical specifications of the dual-cell target. The reasons for these design choices are discussed in the following sections.

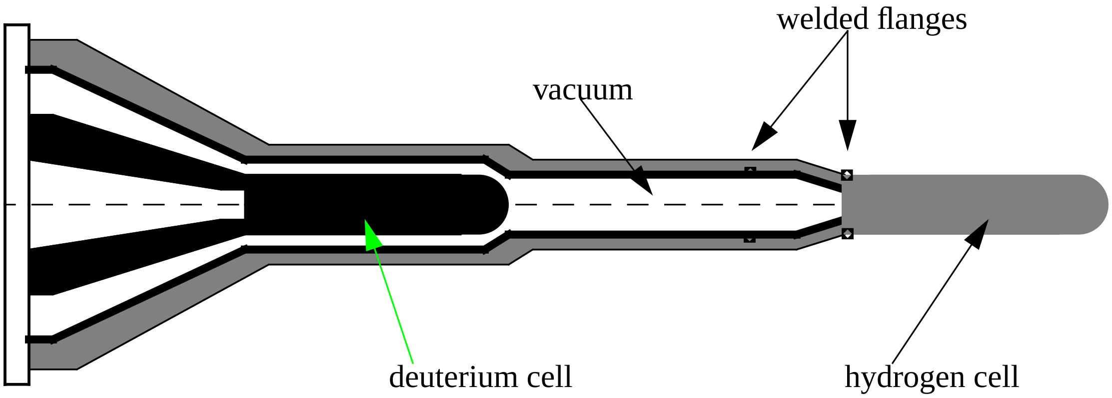
TABLE 1. Summary of dual cell target critical specifications

Length of deuterium cell	5 cm (+0.5, -0. cm)
Length of hydrogen cell	equal to deuterium cell (+/- 0.5 cm); ratio of lengths should be measurable to +/- 1%.
Separation between cells	sufficient to permit measurements down to 8 degrees. (Approximately 4 cm.)
Cell inner vacuum wall thickness	< 0.010” (aluminum)

3.0 Conceptual Design of Target

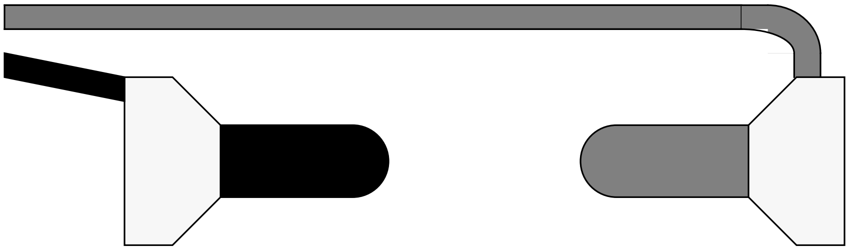
The prevailing conceptual design for the target is shown in Figure 1. The upstream cell shown in black is the deuterium cell, and the downstream cell shown in grey is the hydrogen cell. The three-dimensional shape of the target is obtained by rotating this figure around the dotted line (beam axis). Thus the supply lines are not cylindrical pipes, but rather are conical shells. The inner line shown as thicker is made of thicker material because it is supporting vacuum on the inside and one atmosphere on the outside, so it has to be more robust than all the other volumes to prevent buckling. This is referred to in this document as the 'inner vacuum wall' and its thickness is addressed in Section 7.0. The construction is entirely of aluminum, and there are only a few weld joints.

FIGURE 1. Present conceptual design for E5 target.



A feasible alternative design is shown in Figure 2. This design employs two plastic cells connected by three tubes each, with plastic bases.

FIGURE 2. Alternative E5 target design.



4.0 Length of Deuterium Cell

The data of physics interest in E5 comes from the deuterium cell. The measurement in this cell is of the ratio of the differential cross section for e-n quasielastic scattering to e-p quasielastic scattering, where both the proton and neutron belong to the deuterium cell.

$$\Re \equiv \frac{\frac{d\sigma}{d\Omega}(e', n)_{quasi-elastic}}{\frac{d\sigma}{d\Omega}(e', p)_{quasi-elastic}}$$

In this quantity many experimental uncertainties ‘cancel’, such as the magnitude of the beam current or the Cerenkov counter efficiency. In general, systematic errors arise whenever it is not possible to treat the measured proton and neutron in an identical way, such as the measurement of their angles.

Any condition required of the *electrons* from e-n and e-p scattering will have identical consequences and will therefore not affect $\Re$. For example, vertex cuts made on the electron vertex will not introduce systematic errors in the ratio; they will, however, reduce the statistical information on e-D scattering. For this reason, the deuterium target should be made *long* to improve the target-to-window ratio, especially if vertex cuts are made.

Such vertex cuts may be necessary to increase the purity of the event sample. This is particularly important when the final state detected includes one neutral particle; the spectrometer gives limited information about neutral particles, making it more challenging to eliminate backgrounds for these final states.

If the target were made arbitrarily long, there would be a more complicated acceptance for particles coming from the target. However, this point is moot since the fabrication technique currently planned is limited to cells approximately 5.25 cm in length. The precise value of the cell length is not critical. Therefore the deuterium cell length is chosen to be 5.0 (+0.5, -0.) cm.

5.0 Length of Hydrogen Cell

5.1 Purposes of the Hydrogen Cell

The primary purpose of the hydrogen cell is to provide a calibration of the neutron detection efficiency (ε) through the ep -> $e'n\pi^+$ reaction, through which one can tag neutrons of well-defined energy and direction and study the reaction of the detector to them. This efficiency ε is a quantity which directly affects $\Re$. In addition, various cross checks will be available from elastic scattering from this target, such as measuring systematic errors from proton angular cuts.

5.2 Vertex Cuts on the Hydrogen Cell

Just as in the case of the deuterium cell, it may be necessary to make vertex cuts on the hydrogen cell data. Since the measurement of $\Re$ requires identification of a final state with a directly detected neutral particle, elimination of background is more of a challenge. Missing mass cuts for the neutron will eliminate much of the background, but some events from single pion production from endcap nuclei will certainly pass this cut. These events will contaminate the measurement of ε because the Fermi momentum distribution modifies the kinematic relationship between the scattered electron, pion, and neutron which holds for a proton target. It is possible that this could raise or lower the measured value of ε, depending on the cuts used.

In Figure 3 the measured value of ε is shown for no vertex cuts on the electron and for 4σ cuts, using $\sigma = 2.5$ mm. The center of the target was taken as -0.5 cm based on the raw electron vertex for all events; as may be seen in Figure 4, this produces an apparently asymmetric cut in the $e'n\pi^+$ events. There is no obvious difference before and after the cuts in Figure 3, within the statistical error; there may be a slight enhancement between 1.0 and 1.5 GeV of the open circles compared to the crosses. A full study would require data with very high statistics binned in θ.

TABLE 2. Effects of applying vertex cuts on the hydrogen target cell for 5 cm deuterium cell.

	$f = 0.25$	$f = 0.5$	$f = 1.0$
Percent loss in H_2 target length, 1σ cuts, 5 cm D_2 cell	40%	20%	10%
Percent loss in H_2 target length, 2σ cuts, 5 cm D_2 cell	80%	40%	20%

In Table 2 is a (rather trivial) statement of the effect of applying 1σ and 2σ cuts on the hydrogen cell if the deuterium cell length is taken to be 5 cm and the hydrogen cell is taken as a fraction f of that length, and $1\text{-}\sigma$ is taken to be 2.5 mm, a reasonable value according to present analyses of empty target runs. Since it is likely that at least 2σ cuts would be applied, it can be seen that the impact on the hydrogen target length is fairly severe if f is much less than 1.0, i.e., equal to the deuterium target length.

FIGURE 3. Neutron detection efficiency vs. momentum for no vertex cuts and for a 4-σ vertex cut.

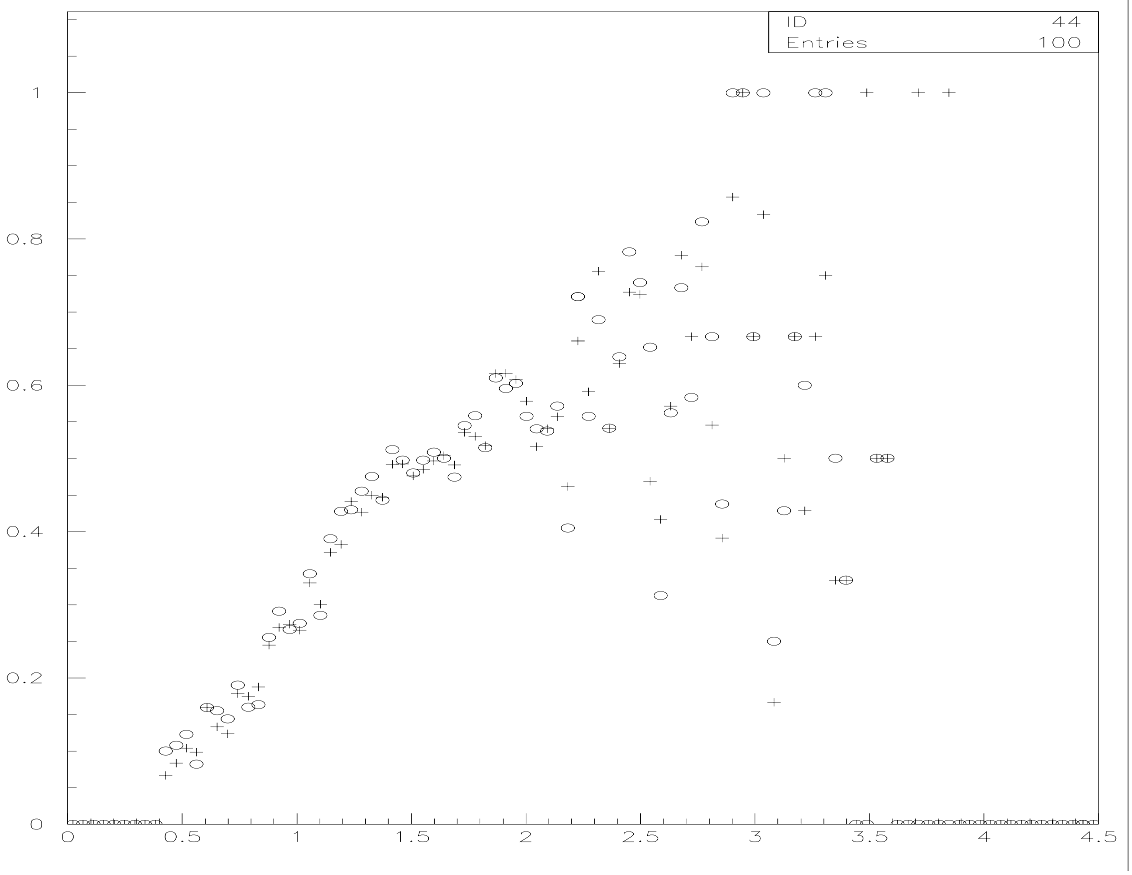
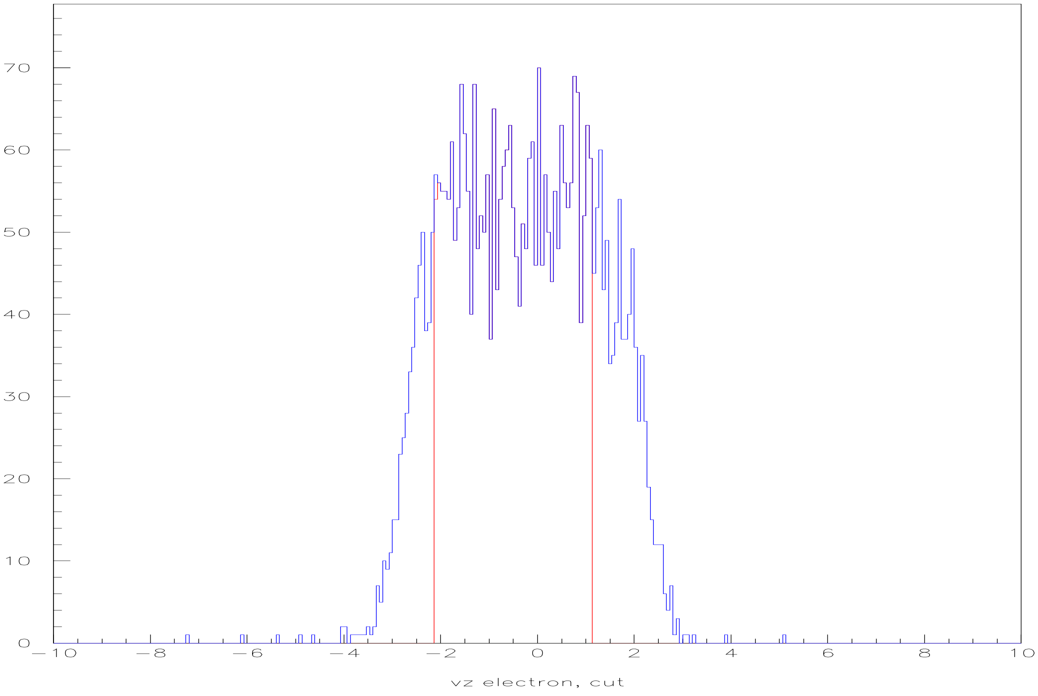


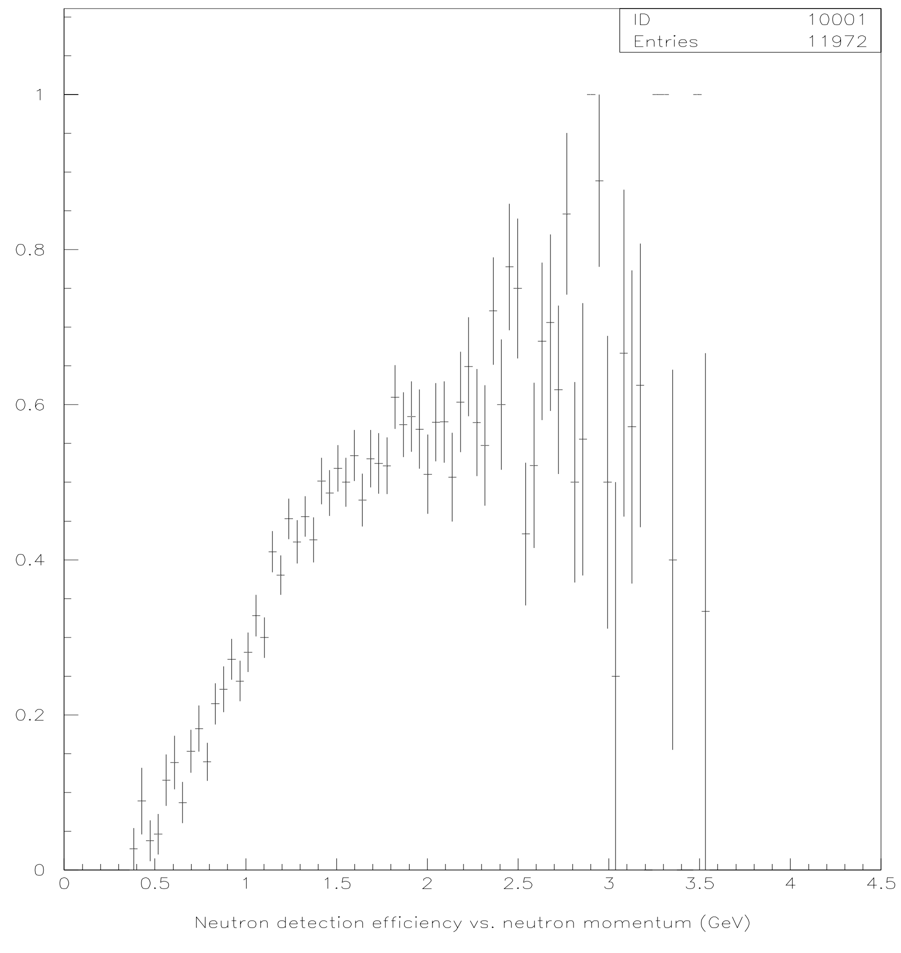
FIGURE 4. Vertex distribution for e’np$^+$ events showing the 4-σ vertex cut.



5.3 Statistical Requirements for the Calibration Reaction

The quantity ε in the CLAS electromagnetic calorimeters is a function of the neutron momentum, as shown in Figure 5. The momentum of the neutron in quasielastic scattering is higher than that for any other reaction by definition, and so the momenta of the neutrons from the e’nπ^+ final state are too low to use directly. The efficiency must be extrapolated up to the quasielastic momentum. A plot of the neutron momenta from the e’nπ^+ final state and the ep elastic final state is shown in Figure 6. The vertical scale has been adjusted on this plot to simulate the relative statistics for e-n quasielastic scattering up to θ = 45 degrees.

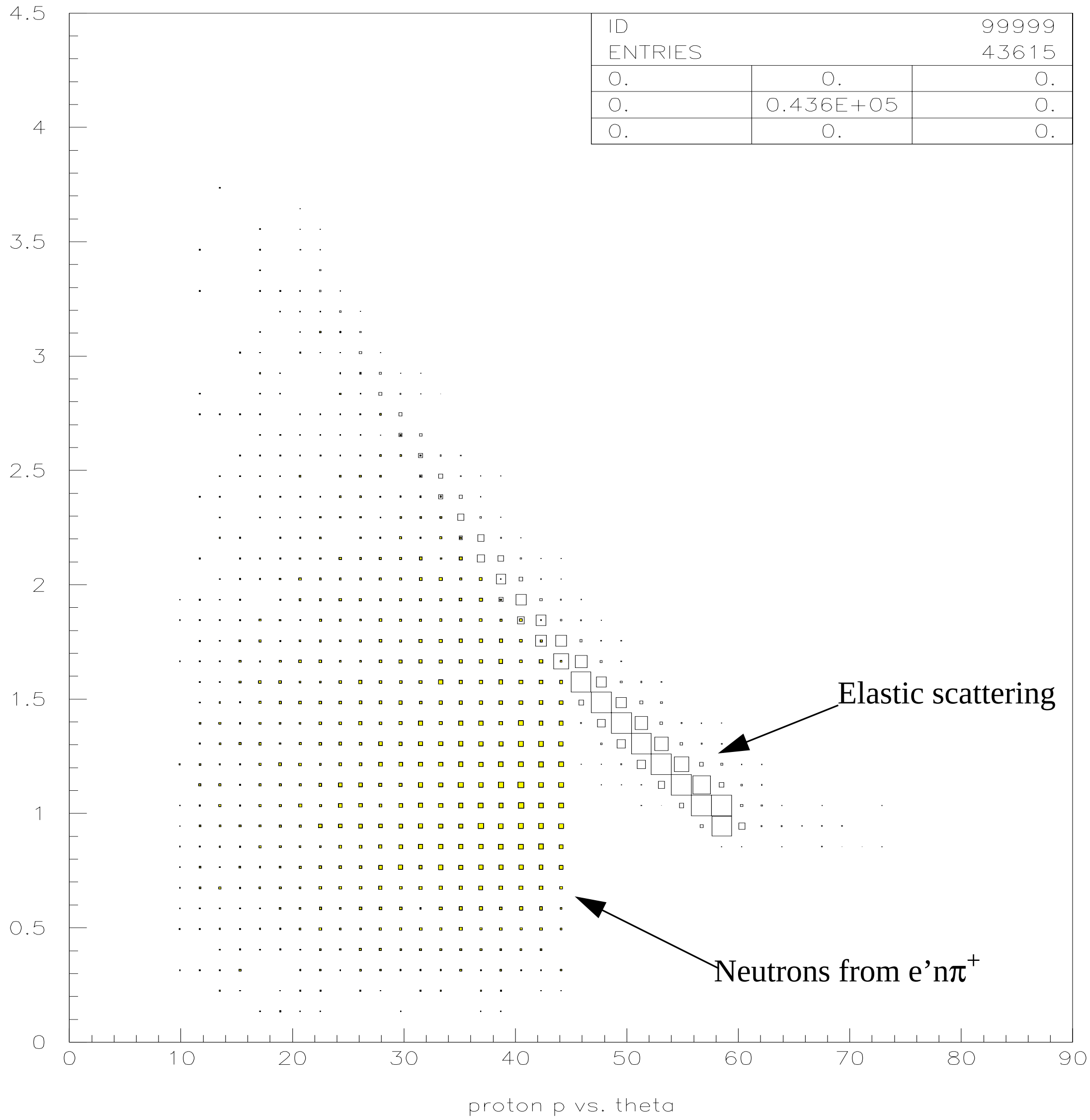
FIGURE 5. Neutron detection efficiency ε in the CLAS forward electromagnetic calorimeters.



If the two reactions are assumed to be symmetric in the laboratory ϕ angle (except for small acceptance differences), then the extrapolation can be made by summing over ϕ and extrapolating for a given range in θ. Thus the extrapolation goes vertically upward in Figure 6 to the quasielastic momentum for that angle.

As can be seen in Figure 6, the extrapolation from the e’nπ^+ reaction requires extrapolating from a region of higher statistics to a region of lower statistics at the quasielastic momentum. The accuracy of the extrapolation is likely to always improve given more statistics, for practical integrated luminosities. In principle, the shape of the extrapolated function is not known exactly, although it is known to plateau for higher momenta (cf. Figure 5). Much more will be known after the data is taken and studied as to what will be the limit on the accuracy of the neutron detection efficiency. At the present time it is not possible to rule out that the limit may be the statistical accuracy of the data sample. The goal as stated in PR94-017 was to determine this quantity to 1% absolute accuracy. This is clearly an experimental challenge, but may be possible.

FIGURE 6. Momentum vs. angle for neutrons from single pion production and elastic scattering off a proton target. The vertical scale is adjusted to simulate neutron quasi-elastic statistics up to 45 degrees.



In conclusion, it is undesirable to make the hydrogen cell too short relative to the deuterium cell because good statistics are required for the calibration reaction.

5.4 Luminosity Limitations in CLAS

The luminosity limit in CLAS has an influence on the choice of hydrogen cell length. Once a luminosity limit has been established, making the hydrogen cell longer decreases the available luminosity on the deuterium cell. The luminosity limit is basically imposed by the product of beam current and orbital electron density of the target (Z). For example, if the CLAS luminosity limit is attained with a given beam current on a hydrogen target of a given length, this limit is then attained with the *same* current on a deuterium target of the *same* length, while the luminosity (number of scatters per nucleon) is *doubled* on the deuterium target. The impact of this interplay is analyzed below.

Consider a deuterium target of length L, and an hydrogen target of length $f \cdot L$, where f may vary from 0 to 2 for practical targets. If the maximum luminosity is obtained with current I_o for $f = 0$ (no hydrogen target at all), calculate the change in deuterium luminosity as a function of f.

I is the beam current ($I < I_o$ if $f \neq 0$); ρ_{nD}, ρ_{pD}, ρ_{pH} are the deuterium and hydrogen *nucleon* densities, $\mathcal{L}$ is the luminosity, c is a constant.

$$\mathcal{L}(D\ \ only)^{max} = cI_o L(\rho_{pD} + \rho_{nD})$$

$$\mathcal{L}(D\ \ and\ \ H)^{max} = cIL(\rho_{pD} + \rho_{nD} + f\rho_{pH})$$

The luminosity limit is based on the *proton* luminosity. The *proton* luminosity is equal in the above two cases, which results in:

$$cI_o L\rho_{pD} = cIL(\rho_{pD} + f\rho_{pH})$$

and so

$$\frac{I}{I_o} = \frac{1}{\left(1 + f \cdot \frac{\rho_{pH}}{\rho_{pD}}\right)} \qquad (1)$$

Since the deuteron luminosity is just proportional to the beam current, the relative change in beam current I/I_o gives the relative change in deuteron luminosity, as shown in the following table in which ρ_{pH}/ρ_{pD} is taken as 0.84:

TABLE 3. Impact of H_2 cell on deuterium luminosity for several cell lengths (equation 1)

	$f = 0$	$f = 0.25$	$f = 0.5$	$f = 1.0$	$f = 2.0$
Fractional change in deuterium luminosity (I/I_o)	1.0	0.83	0.70	0.54	0.37
Percent change in deuterium luminosity (I/I_o) relative to two equal-length targets	+85%	+52%	+30%	0%	-31%
Percent change in deuterium statistical accuracy relative to two equal-length targets	+36%	+23%	+14%	0%	-13%

As can be seen from the above table, the impact on the statistical error in the deuteron quantities is not very large. The largest errors quoted in PR94-017 were 5.6% for the neutron statistical error at $Q^2 = 5.1$ GeV^2. According to Table 3, if a half-length hydrogen cell were used instead of a full-length cell, this error would drop to 4.9%. At the same time, the statistical uncertainty on the data used to determine the neutron detection efficiency would increase by 41%. Only a small part of the deuterium measurement is dominated by statistical errors ($Q^2 > 4$ GeV^2), while statistical errors in the neutron detection efficiency affect all of the data used to derive $\mathfrak{R}$.

5.5 Summary of Hydrogen Cell Length Issues

The hydrogen cell length is chosen to be the same length as the deuterium cell length because:

- this minimizes the loss of data due to vertex cuts
- it provides needed statistics for the calibration reaction
- its impact on the statistical quality of the deuterium data (because of luminosity limitations), while negative, is not large

6.0 Cell Separation Distance

There are two issues which could impact the cell separation specification: the vertex resolution, and the angle at which particles from the upstream target start to hit the downstream target (minimum accepted angle).

6.1 Vertex Resolution

The vertex resolution has been shown to be approximately 2.5 mm from empty target data. In E5 it is required to know from which target the scattered electron originated. The uncertainty on this should be 1% or less. In the absence of sector-dependent misalignments and non-Gaussian tails, this implies a minimum separation of 1.5 cm; using a reasonable safety factor, this could be ‘rounded up’ to 2 cm.

6.2 Minimum Accepted Angle

The minimum accepted angle from existing data can be estimated by looking at CLAS data for electrons and positive pions for low magnetic fields. In Figure 7 is shown the distribution in the direction cosine with respect to the z axis for electrons (top) and positive pions (bottom) for 1.5 GeV data where the torus current was 750 A. It may be seen that the cutoff for the upper plot is approximately 0.9765, whereas for the lower plot it is 0.9900. The former value corresponds to $\theta = 12.4$ degrees, while the latter corresponds to $\theta = 8.1$ degrees.

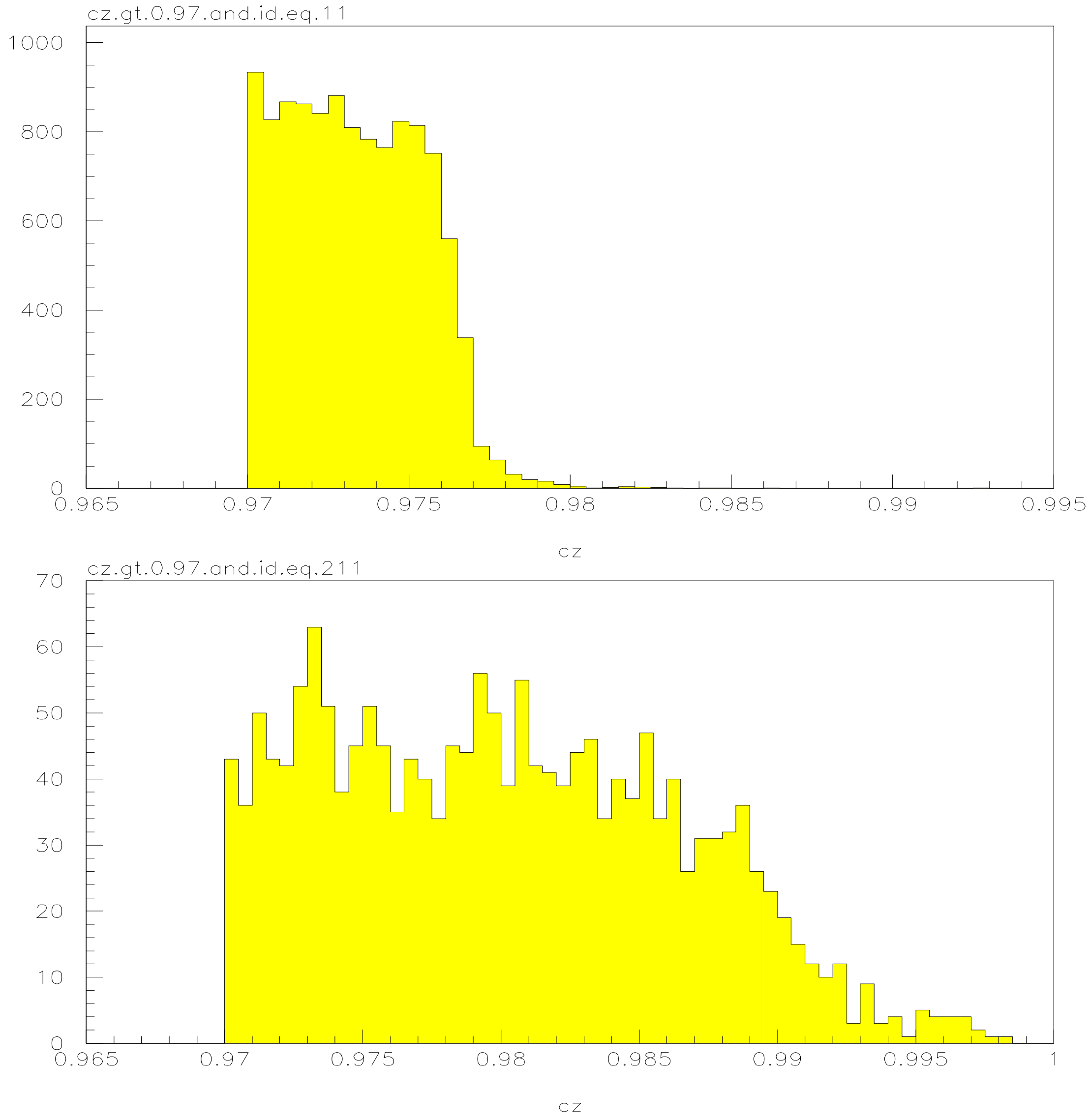
In proposal PR97-017, the proposed running conditions included reversed-field running; in practice, that condition may or may not be needed to achieve the lowest reliable values of Q^2. For reversed field, the 8 degree limit would apply to electrons, while the 12 degree limit would apply if only ‘normal’ field polarity were used. A conservative approach is to specify the target to be able to take advantage of either condition, i.e., to specify that the minimum angle allowed by the target is 8 degrees.

In the present conceptual design of the target, a minimum angle of 8 degrees implies a separation distance of 4.5 cm, while a minimum angle of 12 degrees would allow a separation of 3 cm. The constraint is not given by the downstream cell itself, but rather by a required welding flange between the two cells. Any misalignments of the beam and the target would decrease the minimum accepted angle rapidly. Given the parameters of the deuterium and hydrogen cells as listed above, specifying 8 degrees instead of 12 degrees gives an overall target length increase of 11%, which is not a large impact on the target acceptance and allows for more flexibility.

6.3 Summary of Cell Separation Distance Issues

It seems best given the present conceptual design to specify a minimum angle of 8 degrees. If the design can be modified so that the intruding flange can be moved, a minimum separation of at least 2 cm is required, based on existing vertex resolutions, in addition to the 8 degree requirement.

FIGURE 7. Minimum z-axis cosine for electrons (top) and positive pions (bottom)



7.0 Aluminum Cell Vacuum Wall Thickness

An ***approximate*** accounting of the materials encountered by scattered particles at a 45 degree angle is given in Table 4. This assumes the deuterium cell is in the upstream position and is therefore surrounded by a thin jacket of liquid hydrogen, and it assumes the thin aluminum walls needed to contain the cryogenic liquids. It does NOT include the thicker aluminum tube needed to isolate the two cells with vacuum. Drift chamber wire materials, gas bags, etc. have not been included.

As may been seen from the table, the dominant term is the thickness in radiation lengths of the drift chamber gas. Using the numbers below and the simplest multiple scattering expression, the characteristic angle is equal to $0.1/(\beta p)$ degrees, where beta = v/c and p is the particle momentum in GeV. This produces a range for CLAS from 0.025 degrees for 4

GeV electrons to 2.5 degrees for 200 MeV/c protons (for E5 quasielastic protons the practical lower limit is greater than 500 MeV/c).

In E5 the critical issue is to minimize systematic uncertainties. Placing a cut on an angle quantity which is uncertain by a random resolution should not produce systematic errors as long as the resolution function does not vary significantly in the region of the cut, that is, the number of events which ‘scatter into’ the cut should be the same as the number which ‘scatter out.’ Therefore, a small degradation in the angular resolution due to increased multiple scattering should have no appreciable effect on the measurement of $\Re$.

TABLE 4. ***Approximate*** accounting of the materials encountered by a 45 degree particle in CLAS.

Material	**Number of radiation lengths**
Deuterium liquid	0.0022
36 microns of aluminum	0.00041
Hydrogen liquid	0.00057
Air	0.0053
Drift chamber gas	0.0127
Total	0.021

For the sake of argument, consider the impact of choosing 0.010” for the thickness of the additional vacuum tube. This contributes an additional radiation length thickness of 0.0029, an increase of 14%, and the increase in the characteristic angle is 7%, a small increase. There will also be a very small increase in the energy loss (135 keV additional energy loss for minimum ionizing particles).

Naturally it is desirable to minimize this thickness to the extent feasible, however, any value below 0.010” should have a negligible impact.