Appendix D

Tracking System

D.1 Tracking

As was mentioned in the original proposal, the MOLLER experiment will require a charged-particle tracking system, which will be used for diagnostic studies at very low beam currents. The motivation for such a system includes its use to help characterize background contributions, to characterize the spectrometer, and to determine the effective kinematics of the asymmetry measurement. Here we provide some detail on these motivations, and discuss our initial concepts for the tracking system design. Much of this discussion is informed by our experience from the HAPPEx experiments, E158, and most relevantly, recent experience with the Qweak tracking system.

D.1.1 Backgrounds and Spectrometer Optics

An important component to the systematic error on the asymmetry measurement will be the contributions from various background processes, including elastic electron-proton scattering ("elastic e-p's"), inelastic e-p's, neutrals (photons and neutrons), and pions and their decay muons (from real and virtual photoproduction in the target, and also deep inelastic scattering). The expected dominant dilution to the signal will be from the elastic e-p's. The inelastic e-p's will be much smaller in relative rate, however they will carry a larger and less-predictable asymmetry, and thus are a major concern as well. An important criterion for the spectrometer, detector and collimator design has been to ensure a "two-bounce" system in order to suppress neutral backgrounds, however at the high luminosity the experiment will run at, it is likely that there will still remain some neutral component to the integrated signal read out by the main detectors, which will dilute the measured asymmetry. Pions and decay muons can be produced from a variety of sources, and so their asymmetry will be hard to predict. Thus their asymmetry must be measured and their contributions to the yield must be determined, in order to correct for their effect.

Much of the background identification and suppression provided by the spectrometer and main detectors has been described in detail in the proposal. A critical feature is the high degree of segmentation of the detectors in both radius and azimuth, which then provides asymmetry measurements in r, ϕ bins, which contain different mixes of signal and background processes. As an example, Fig. D.1 shows the simulated radial distribution of Møller electrons, elastic e-p's and inelastic e-p's, demonstarting the radial part of the kinematic separation. The shapes of the distributions are sensitive to not only the spectrometer optics, but also large radiative effects and multiple scattering in our thick (17% of a radiation length) hydrogen target. However, this figure is somehat misleading: the radial segmentation of our main detectors is rather coarse on this scale. The same simulated data, binned as the detectors will be, is shown in Fig. D.2. Clearly, a meaningful comparison of the observed distributions of rates with the Monte Carlo prediction would be compromised by the coarse binning.

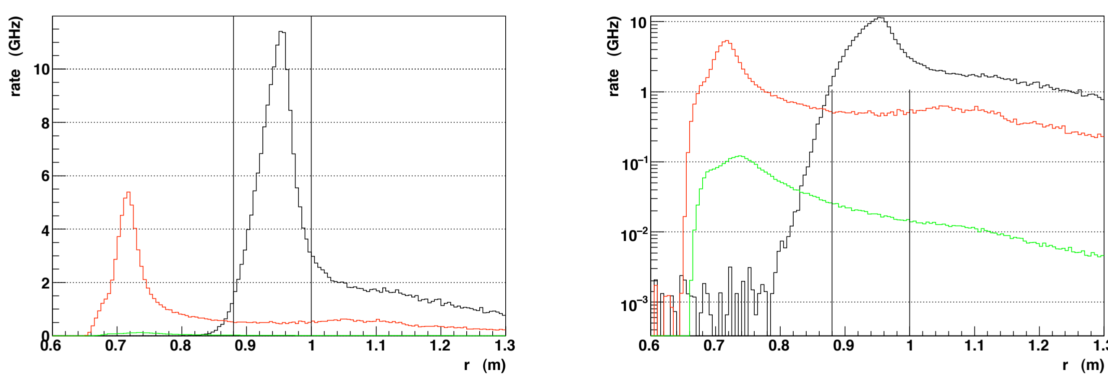

Figure D.1: *Expected rates vs. radial position for elastic e-p (red) electrons, inelastic e-p electrons (green) and Møller (black) electrons at the z location of the main detectors. Bins are 5 mm wide. The black vertical lines represent the edges of the main Møller detectors ring. Left: linear scale; Right: log scale.*

Similarly, the azimuthal distribution of tracks at the main detectors provides another tool for separating backgrounds. Figure D.3 shows the (r, ϕ) distribution of Møller and e-p electrons at the z location of the main detectors. As described in the proposal, the detectors will also be segmented azimuthally, with each sector of the spectrometer divided into four ϕ segments. This segmentation will provide some handle on verifying this distribution, but a detailed acomparison with the simulated rates would require a finer spatial resolution than the detector segmentation will provide.

Thus, we propose a fast tracking system that will allow us to measure these rate

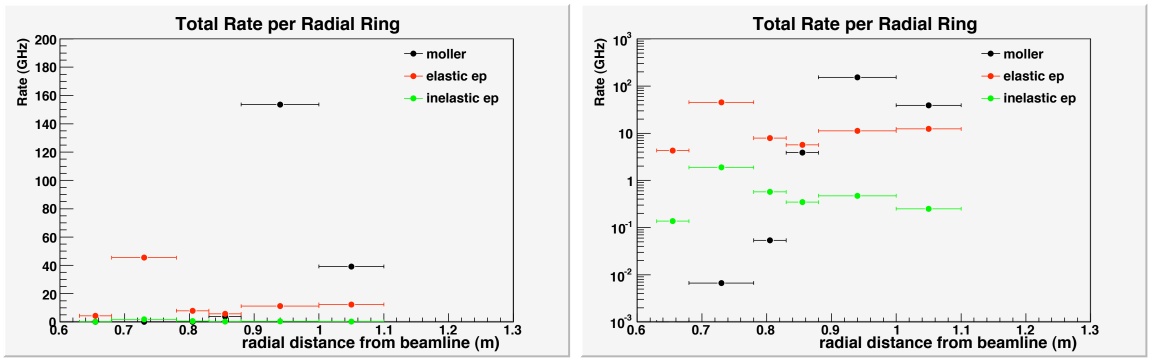

Figure D.2: *Same as Fig. D.1, except binned by the sizes of the various main detector rings. Left: linear scale; Right: log scale.*

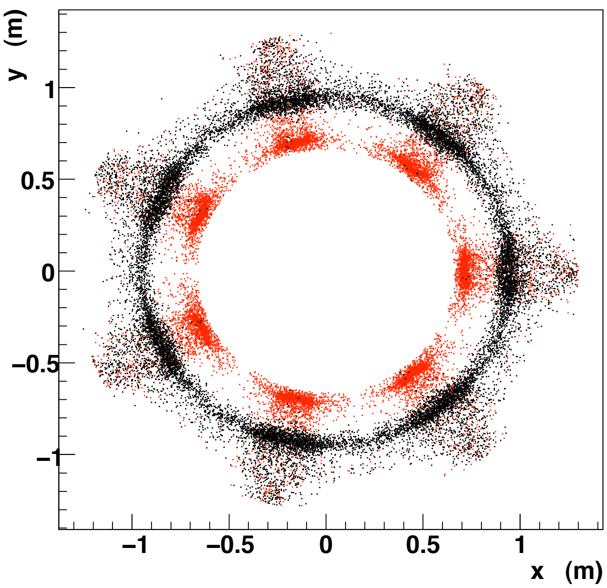

Figure D.3: *Expected distribution of events at the z location of the main detector from Møller electrons (black) and e-p electrons (red).*

distributions with fine position resolution (of order 250 μm). The tracking system will be run with the beam current turned down to the scale of 100 pA, which will produce a total electron flux after the second toroid of $\approx$ 150 kHz over the full azimuth, corresponding to a modest flux of $\leq$ 200 Hz/cm^2 at the main detectors. This should not tax the capabilities of conventional tracking detectors. The ability to stably deliver such a low-current calibration beam for similar tracking measurements has been demonstrated in Hall C for the Qweak experiment, which similarly relies on using a tracking system for background and kinematics measurements, at a beam current 6 orders of magnitude lower than used for the primary asymmetry data-taking.

The tracking system will be used to verify the expected ratio of Møller to e-p distributions in both r and ϕ, to look for backgrounds from collimator punch-through and scraping, to study neutral backgrounds (by running in anti-coincidence with the main detectors), and, along with a PID system, to determine the π and μ backgrounds.

The utility of such a fast tracking system for studying backgrounds has recently been demonstrated in the commissioning of the Qweak experiment, where the "Region 3" vertical drift chamber system has been useful in understanding and limiting soft backgrounds in the Qweak main detectors.

In addition, we anticipate that the tracking system will prove useful for initial "tuneup" of the magnetic optics of the spectrometer. Comparison of the measured track distributions with simulated results as a function of magnetic field and target (liquid hydrogen, gaseous hydrogen, various solid targets) will be an essential way to "benchmark" the simulation and to verify spectrometer operation.

D.1.2 Effective Kinematics

The central value of Q^2, weighted by acceptance and detector response, must be determined to 0.5% for this experiment. In principle, Q^2 can largely be determined from survey measurements of the collimator apertures and knowledge of the target location and length, along with the standard Hall A beam energy measurement ("Arc-energy"). The detectors should cover the full acceptance of events that pass through the collimators, so, to first order, precise measurement of their locations should not dominate the Q^2 determination. However, their analog response will come into play: in an integrating experiment such as this, the relative weight of a detected event in the asymmetry is determined by the amount of light detected at the PMT. If this analog response varies with Q^2, it will skew the effective Q^2 distribution, and modify the central Q^2. In the Qweak experiment, the effect on the central value of Q^2 is 2.5%. For that measurement, measuring this effect, and monitoring it during the course of the experiment, was one of the main motivations for their tracking system. While we don't yet have a simulated estimate for this effect on this experiment (this awaits detailed detector design), we anticipate that it may be significant here as well. Mapping out and monitoring this analog response will be a major goal of the tracking system.

In addition, the large amount of multiple scattering, dE/dx and radiative losses due to the thick target, coupled with the large kinematic acceptance, and the rapid variation of the asymmetry with Q^2, means that the Monte Carlo simulation of the effective Q^2 seen by each detector segment needs to be validated carefully. Again, a tracking system with high spatial and angular resolution will be critical for this validation.

D.1.3 Conceptual Design

The present concept is that the tracking system will be located after the second toroidal magnet; it will measure the positions and angles of the tracks emerging from that magnet. Unlike the Qweak tracking system, we do not plan on having tracking elements located before the spectrometer magnets. The system will be removable for the primary asymmetry measurement, but will be periodacally moved into place for tracking measurements. We are considering the use of two widely-separated planes of gas electron multiplier (GEM) chambers located in the evacuated drift region, followed by a final plane (in air) of either GEMs or straw-tube chambers, positioned just upstream of the main detector array. We are considering the possibility of a "Roman Pot" [9] arrangement for mounting the first two planes of GEMs, however we note that GEMs have been used under vacuum succesfully [10].

D.1.4 Focal Plane Scanner

Another useful diagnostic will be a simple, small, movable detector that can operate at both the full beam flux and at the low beam currents needed for the tracking measurements. This "focal plane scanner" would consist of a small single Cerenkov detector made of fused silica, read out by PMTs, mounted on an x, y motion stage covering one sector of the acceptance, and located just upstream of the main detectors. Such scanners have been used in E158, HAPPEx-II, and one is now being used by Qweak. This device can be used to confirm that the rate distribution as measured at low beam currents by the full tracking system is not sigificantly different than that seen at full luminosity. It also would allow periodic rapid monitoring of the distribution during production data-taking, to ensure stability of the effective kinematics and to signal any changes in backgrounds.