CLAS12 Alignment and G_M^n Target Preparations

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This document is a proposal of work to be performed during the sabbatical of Dr. G.P.Gilfoyle at Jefferson Lab during the 2015-2016 academic year (September 1, 2015 to May 31, 2016). The focus of the work is two-fold. (1) We will prepare for the measurement of the neutron magnetic form factor G_M^n (JLab experiment E12-07-104) with the CLAS12 detector in Hall B. The work will focus on the design, study, and possible construction (depending on schedule) of the dual-cell cryo-target. (2) To prepare for commissioning and operations of CLAS12 we will develop algorithms and code for track-based alignment of CLAS12 as part of the detector calibrations.

We now describe our program to measure the neutron magnetic form factor G_M^n at high Q^2. One of the central goals of nuclear physics now is to push our understanding of QCD into the nonperturbative region. Here the nonlinear nature of QCD dominates and defies traditional mathematical solutions; forcing us to resort to phenomenological models, effective field theories, and the daunting numerical calculations of lattice QCD. Our understanding of the structure of the proton and neutron is still clouded. The neutron magnetic form factor G_M^n is one of the fundamental quantities of nuclear physics and its evolution with Q^2 characterizes the distributions of charge and magnetization within the neutron. It is central to our understanding of nucleon structure as discussed in the NSAC Long-Range Plan and in Milestone HP4 in the DOE Performance Measures. We are part of a broad campaign to measure the four elastic nucleon form factors (electric and magnetic ones each for the proton and neutron) at JLab that includes six experiments approved for running after the 12 GeV Upgrade is complete. Gilfoyle is the spokesperson and contact person for JLab Experiment E12-07-104 which will measure G_M^n with the CLAS12 detector in Hall B.

To measure G_M^n we use the ratio R of $e-n$ to $e-p$ quasielastic (QE) scattering from a deuterium target (there are no free neutron targets). By taking the ratio R we are less sensitive to uncertainties in the luminosity, electron acceptance, electron reconstruction and trigger efficiencies, the deuteron wave function, and radiative corrections. The extraction of G_M^n from R depends on our knowledge of the other three nucleon form factors, but the proton form factors are precisely known and the neutron's electric form factor G_E^n is typically small so its impact on the systematic uncertainty is limited. This technique does require precise knowledge of the neutron and proton detection efficiencies. To measure the neutron detection efficiency a unique dual-cell, co-linear, liquid-hydrogen-liquid-deuterium target will be used. The liquid deuteron part of the target will be used for production events and the liquid hydrogen cell will provide calibration events. The $ep \rightarrow e'\pi^+n$ reaction is a source of tagged neutrons. The location of the neutron in CLAS12 can be determined from the pion and scattered electron data and we scan that region for the neutron in the electromagnetic calorimeter (EC/PCAL) and the forward time-of-flight (FTOF) systems. The neutrons are detected in two, overlapping measurements with both the EC/PCAL and the FTOF systems providing a powerful consistency check on the measurements. To measure the proton detection efficiency we use elastic ep scattering on hydrogen. With the dual-cell target, these efficiency and calibration data will be collected under exactly the same running conditions as the production data - an essential feature to keep our systematic uncertainties under control. Similar methods were successful in our CLAS6 G_M^n measurement (see J.Lachniet et al., *Phys.*

Rev. Lett., **102**, 192001 (2009)).

Working with the JLab staff we have begun development of the unique, dual-cell target for the G_M^n measurement. In Figure 1 we show the current design. An upstream (left) cell will hold liquid deuterium for production running and the downstream (right) cell will hold liquid hydrogen for calibrations. The cryo-liquid cells in each design are conical to allow any bubbles formed by heating from the beam to flow more easily out of the target. The design was inspired by our experience with the CLAS6 G_M^n experiment and other targets. The cooling lines and support structures will be attached upstream of the target to minimize the material in the path of scattered particles. Here each cell is 2 cm long with a 2 cm gap in between the cells.

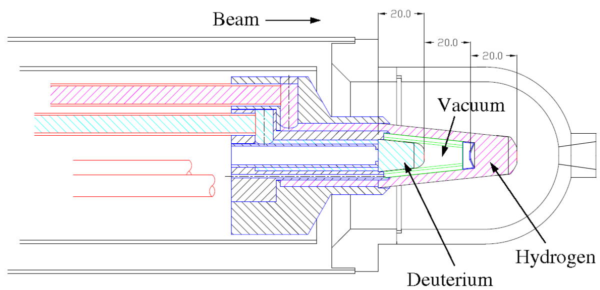

Figure 1: G_M^n target design drawing. Dimensions are in *mm*.

We will begin design studies to optimize the target performance. These studies require an event generator for QE events from deuterium that includes the effects of the Fermi motion. This feature is in the program QUEEG used in the CLAS6 G_M^n experiment and which we have updated and improved for CLAS12 (see CLAS-NOTE 2014-007). We will use the program GENEV and other programs to generate inelastic events. We will also need a simulation of the target cell that can be incorporated into the CLAS12, Geant4 simulation *gemc*. We have already taken the first steps toward this goal and have developed the geometry for an earlier design.

There are a number of issues to address in the target design. The dual-cell target is used to perform *in situ* calibrations to measure the proton and neutron detection efficiencies under the same running conditions as the production measurements. One difference between the calibration and production targets is their position. The small target size in CLAS12 should reduce this effect, but we want to investigate it now in simulation. Very forward angle QE events from the deuterium cell can pass through the hydrogen cell. The impact of different materials and thicknesses in the cell walls, *etc.* will be studied. Our experience with CLAS6 showed the dominant source of multiple scattering is the drift chambers, but we should inventory all the contributions and see where reductions in thicknesses could be made while maintaining the structural integrity of the target (see CLAS-NOTE 2001-015 for a full discussion of the CLAS6 target). We have discussed the target development with the Dr. V. Burkert, the Hall B Group Leader, and members of the engineering staff at JLab (D. Kashy, S. Christo, C. Keith).

The second focus of this sabbatical is on track-based alignment of CLAS12 as part of the calibration and commissioning of the detector. We are part of the team developing software for CLAS12 in preparation for the start of experimental running. The goal is to be ready to calibrate CLAS12 and analyze the data when beam arrives. In planning this project we met with the leader of the CLAS12 Software Group (JLab staff scientist V. Ziegler) and the other members of the group to discuss priorities, unassigned tasks, and the the steps necessary to meet the Laboratory goal. Considering the current schedule for CLAS12 startup and the fact that Gilfoyle will be on sabbatical during the year before startup we have decided to focus on track-based alignment for CLAS12.

Reaching the CLAS12 design specifications requires understanding the geometry of the detector components as they are built and installed and during their operation. Differences between the nominal geometry and the detector built in Hall B can degrade the resolution and lead to systematic biases in the data reconstruction - distorting the physics results. This task is more important for the new CLAS12 detector relative to CLAS6 because of the increased segmentation of some components (Silicon Vertex Tracker (SVT), panel 1b of the FTOF, *etc.*). Our focus here will be on track-based alignment as opposed to complementary tasks like surveying. The alignment is important for all the CLAS12 experiments.

The actual positions of detector components (drift chamber wires, silicon strips) may differ from the nominal, design values causing the reconstruction software to return flawed values for the track parameters. We start by considering two general approaches to this problem - iterative and closed form. In the iterative approach, a track model (*e.g.*, a solution to the passage of a charged particle through a magnetic field) is fit to the hit positions from the detector by minimizing the χ^2. The residual distributions are used to adjust the geometry of the detector (they should average to zero) and the process is repeated until the χ^2 converges to a satisfactory value. This technique is less complex than others, but does not include correlations between the track parameters of the fit and changes to the detector geometry.

To account for correlations one can use the closed form approach. A least squares fit is performed simultaneously on the track parameters and the detector geometry parameters so it naturally accounts for correlations. However, for a detector like CLAS12 the number of detector parameters is large so the computational demands may be prohibitive. Nevertheless, there are possible solutions. One is Millipede II, a program for linear least squares fits with a large number of parameters based on the minimization of the χ^2 (see V.Blobel et al., *Comput. Phys. Comm.*, 182:1760-1763 (2011)). The method takes advantage of the difference between local parameters (fit parameters for individual tracks) and global ones (the positions, orientations, deformations, *etc* of the detector components). This difference manifests itself in the structure of the least squares matrices so the dimension of the matrix equation is determined by the global (detector) parameters regardless of the number of local (track) parameters - significantly decreasing the size of the problem. This matrix equation is then solved by inversion and the inverse matrix is the covariance matrix of the global parameters. Fits with as many as 100,000 global parameters are possible (see `https://www.wiki.terascale.de/index.php/Millepede_II)`.

There are two issues to consider in the results of our alignment program. (1) The 'weak modes' problem is one where some eigenvectors have small eigenvalues and little impact on the χ^2 making the fit results for the local parameters ambiguous. This ambiguity in the local parameters can effect the physics results. To mitigate this problem requires a large, diverse sample of events (both simulated and real) that illuminate all of CLAS12, *e.g.*, cosmic rays, straight tracks ($\vec{B} = 0$), and curved ones ($\vec{B} \neq 0$) over a wide range of kinematics. (2) The other issue is validation. The χ^2 should be well behaved and the residuals should be largely independent of the fit parameters. A residual that increases with, for example, the azimuthal angle ϕ is a sign the alignment is off. The track results can also be tested with 'standard candles', well-known quantities like elastic scattering, invariant masses and widths of known resonances, and others. During Gilfoyle's sabbatical year we will develop programs to align CLAS12 and start collecting and analyzing the data sets for the track-based alignment.