April 28, 2011

E08-027 & E08-007
Readiness Review Document

Contents

1 Introduction

Two polarized target experiments at Jefferson Lab (E08-027 and E08-007) will extend measurements of the spin structure functions (SSF) and electromagnetic form factors (FF) to the lowest accessible momentum transfer (Q^2), and provide the definitive measurement of these fundamental quantities. E08-027 will focus on measuring the proton's structure function g_2, while E08-007 will measure the proton form factor ratio G_E/G_M in the same kinematic region as E08-027. Because of the similarities in technique and equipment, the two collaborations have effectively merged into a single cooperative known as 'g2p', which will run simultaneously. The only practical difference is that E08-007 will select elastic scattering, while E08-027 measures inelastic data.

This document aims to provide a general introduction to the experiments, including the major modifications and upgrades that are being undertaken. Before discussing the technical aspects, we will briefly discuss the physics motivation for these measurements.

1.1 E08-027: A Measurement of g_2^p and the LT Spin Polarizability

The inclusive scattering spin structure functions g_1 and g_2 are fundamental spin observables which characterize the deviation of the nucleon's spin-dependent properties from point-like behavior. Historically, measurements of g_1 provided direct tests of QCD, and also revealed that only a small fraction of the nucleon spin is carried by the valence quarks. While g_1^p has been mapped out extensively, g_2^p remains largely unmeasured, especially at low Q^2. It is the main goal of E08-027 to address the lack of knowledge of this fundamental quantity, in order to gain a more complete understanding of the proton.

The lowest momentum transfer that g_2^p has been measured is 1.3 GeV^2 by the RSS collaboration. The absence of g_2^p data is particularly unsatisfying given the intriguing results found in the transverse neutron data: The SLAC E155 collaboration found their data to be inconsistent with the proton Burkhardt-Cottingham (BC) sum rule at $Q^2 = 5.0$ GeV^2, while the JLab E94-010 collaboration found that the neutron BC sum rule held below $Q^2 = 1.0$ GeV^2. Even more compelling, it was found that state-of-the-art next-to-leading order χPT calculations are in agreement with data for the generalized spin polarizability γ_0^n at $Q^2 = 0.1$ GeV^2, but exhibit a significant discrepancy with the longitudinal-transverse polarizability δ_{LT}^n. It is rare to find such striking disagreement with theory, and this new data will be invaluable in establishing the reliability and range of χPT.

Lack of knowledge of the g_2^p structure function at low Q^2 is also one of the leading uncertainties in calculations of the hyperfine splitting of the hydrogen atom, and the Lamb shift in muonic hydrogen. In particular, the g_2^p contribution to these calculations is dominated by the region below 0.4 GeV^2 where no data currently exists and where E08-027 will measure.

1.2 E08-007: The Proton Elastic Form Factor Ratio at Low Q^2

Interest in the low Q^2 form factors have recently become very compelling. First, the form factors are fundamental properties of the nucleon that should be measured well to test our understanding of the nucleon. Second, although theory generally indicates the form factors have smooth shapes as one varies Q^2, there are an unsatisfyingly large number of theory calculations, fits, and data points that suggests this might not be the case – that there might be narrow structures in the form factors. The proposed measurement is good enough to either confirm or refute all existing suggestions of few percent structures in the form factors, or in the form factor ratio. Third, it has become apparent that the existing uncertainties in the form factors are among the leading contributions to uncertainties in determining other physics quantities, such as the nucleon Zemach radius, the strange form factors determined in parity violation, and the generalized parton distributions determined in deep virtual Compton scattering. The improvement possible with the proposed measurements is substantial.

1.3 Recent Developments

Recently, it has become apparent that poor knowledge at low Q^2 of the SSFs and FFs (which are purely QCD quantities), limits the precision of QED calculations of simple bound systems, such as the hydrogen-like atom. Energy levels in these systems can be measured to fantastic precision. As a result, the corresponding QED calculations have been pushed to a level where the finite size of the nucleon, as characterized by the structure functions and elastic form factors, has become a leading uncertainty. Of particular interest, researchers from PSI have obtained a value for the proton charge radius $\langle R_p \rangle$ via measurements of the Lamb shift in muonic hydrogen, which differs significantly from the value from elastic electron proton scattering. The deviation in $\langle R_p \rangle$ would have many troubling consequences, such as requiring a sizable shift in the fundamental Rydberg constant, so all aspects of the PSI calculations are being re-examined. The main uncertainties in the PSI results originate from the proton polarizability and from different values of the Zemach radius. These quantities are determined from integrals of the spin structure functions and elastic form factors, which due to kinematic weighting, are dominated by the low Q^2 region which will be investigated by E08-027 and E08-007. The proposed measurements, by virtue of the anticipated high precision and low Q^2 has the potential to shed light on this discrepancy by allowing a significantly more accurate extraction of the proton charge and magnetization radii, and by providing much improved determinations of the SSF and FF at low Q^2.

2 Major Equipment

This set of experiments utilizes several new or non-standard pieces of equipment:

1. A polarized NH_3 target.
2. An upstream magnetic chicane.
3. A low power local beam dump.
4. A pair of septum magnets.

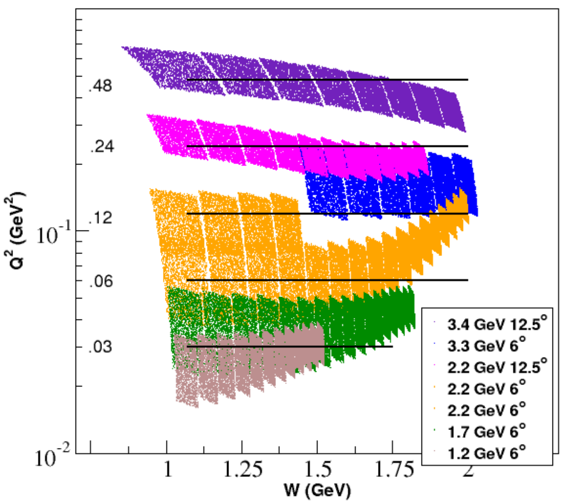

Figure 1: Kinematic coverage for E08-027. E08-007 will measure in the same Q^2 range, but specifically in the elastic (W=0.94 GeV) region.

5. Beamline modifications to enable low current beam diagnostics.

E08-027 will perform an inclusive measurement of the proton spin-dependent cross sections in order to determine the g_2^p structure function in the resonance region for $0.03 < Q^2 < 0.4$ GeV^2, as shown in Fig. 1. E08-007 will extract the form factor ratio G_E/G_M from the double spin asymmetry measured in elastic scattering over the same Q^2 range. Both techniques require a polarized electron beam, a polarized proton target, and a set of room temperature septum magnets to allow access to the 6 degree scattering angle associated with such low values of Q^2.

The UVa/JLab polarized NH_3 target will be installed in Hall A for the first time. This target has been used in several previous experiments in Hall C (SANE, RSS, GEn), and a target based on similar operating principles has been used in Hall B (EG1, EG4, DVCS). It operates at a low temperature of 1K and a strong field of 2.5–5.0 T. Installation of the target in Hall A requires modifications to the standard pivot and the mounting of nearby support platforms.

The beam current for the main production will range from 50 to 130 nA, which requires new beam diagnostic instrumentation. In particular, the tungsten calorimeter will be used, and upgrades are needed for the BPMs, BCMs, and Harp's to operate at low currents.

E08-027 requires the target field to be transverse (90°) to the beam direction, while E08-007 requires the target field to be oriented at 20° with respect to the beam direction. The transverse target field will significantly deflect the electron beam. To correct for this, a chicane system with two magnets will be used to pre-bend the incident electron beam so

Parameter	Performance Requirement	Associated Beamline Components	Comments
Beam Energy	1.159 GeV, 1.705 GeV, 2.257 GeV, and 3.355 GeV	Chicane – FZ magnets – FZ2 stand	Controlled by the MCC – requires adjustable optics system
Beam Current	50-130 nA	Tungsten Calorimeter BCMs	Desire 1% accuracy
Beam Position	Angle of incidence to 0.03°	BPMs Superharps FZ magnets BD magnets FZ2 magnet stand	Need to accommodate Qweak helicity rate of 1 kHz
Beam Diameter	Rastered to 25mm	Fast Raster (to 4mm square) Slow Raster (to 25mm round)	Spread beam energy across entire target face. May be as small as 20mm, if required.
Target Position	1) 87 cm upstream 2) At pivot	Affects articulating arm	1 superharp when upstream, 2 when at pivot
Target Vertical Position	1) 9 cm elevated 2) At "standard" height	FZ magnets FZ2 magnet stand	Need separate elevation to get low Q^2 values – requires ½ field on FZ magnets
Beamline Vacuum	1x10-6 Torr, for the entire beamline	Vacuum pumps, gauges, valves, exit window	
Alignment	Stands – to 3mm Components – to 0.25mm		Normal alignment parameters – will require fiducialization of several components.
Beam Clearance	0.5mm radially	Beam pipe – 1.5" OD	

Figure 2: Theory of Operation - critical functionality from beamline.

that it will be horizontal when it reaches the target center, after passing through the first half of the target field region. The beam will be deflected again after passing through the second half of the target field region. Consequently, the downstream beam will not reach the standard dump, and a local beam dump is required.

In order to reach the lowest Q^2 possible, a pair of septum magnets will be used to bend scattered electrons at 6 degrees to enter the standard Hall A high-resolution spectrometers, whose lowest scattering angle is 12.5 degrees. These magnets will be removed near the end of the experiment to allow access to the two highest Q^2 bands shown in Fig. 1. While the septa are in use, the target must be shifted upstream from its standard position. When they are removed the target will be returned to the pivot center.

2.1 Beamline

Beamline modifications are under the direction of engineering division's **Tim Michalski**. A detailed installation schedule which is tied to 6 the six month shutdown schedule with resources identified has been produced and will be provided to the review committee. Relevant milestones have been identified. Not all material has been ordered yet, but all material is anticipated to support the installation schedule. Final BPM and BCM testing will be completed prior to the readiness review. Preliminary data indicates meeting instrumentation/diagnostics needs for g2p/GEp.

The following list details the planned changes from the existing beamline:

1. Need Transport style Beam Position Monitor (BPM) electronics for the BPMs leading from the Beam Switch Yard to the hall (qty 12 + 2 spares). This is due to the existing hardware not being required or able to provide adequate data below 1uA. This will be a permanent upgrade to the beamline for Hall A.

2. EP removed as it is not needed for this experiment.

3. Addition of the Slow Raster to allow beam energy to be distributed across the 25mm diameter target face. A new function generator has been procured via a collaborator and the system is being tested in the EEL building.

4. The Tungsten Calorimeter is being relocated to Region 1, from the long girder, as a means to accurately measure the beam current. This interrupts beam to the target, therefore it will be used as a means to calibrate the system.

5. The upside down girder in Region 2 is being removed due to needing different magnets and a larger beam pipe. It is being replaced with another girder which will have 2 BD corrector magnets, the Beam Loss Accounting (BLA) system Beam Current Monitor (BCM), superharp, vacuum components (gauges, valves), and larger beam pipe to accommodate the 25mm rastered beam.

6. The long girder is being removed from Hall A and being replaced by the FZ magnet chicane.

7. The purpose of the chicane, using 2 FZ dipole magnets, is to achieve the required beam incident angle on the target for the different energy beams.

8. The chicane has a viewer between the 2 FZ magnets.

9. There is instrumentation on the output of the FZ2 magnet (BPMs and superharps). This instrumentation will accurately determine the beams position and angle as it enters the target chamber and strikes the target.

10. The FZ2 magnet will have to be vertically repositioned and the FZ1 and FZ2 fields adjusted in order to achieve the appropriate beam optical path for the different energy levels.

11. New instrumentation electronics have been developed to accurately measure beam current and beam position at the low current levels. These support the existing BCMs and the 5.5” M15 BPMs.

12. 2 power supplies have been borrowed from Hall C in order to power the FZ magnets. Due to the current requirements and the fact that the magnets are controlled separately, 2 PSs are required. The FZ1 PS must deliver 231A and the FZ2 PS must deliver 465A.

13. An additional magnet, type AI, will be added in series on the FZ1 PS in order for it to have an adequate load (available power supply voltage).

The required functionality of the accelerator and beamline for the g2p/GEp experiment is to provide beam to the target. Key parameters that must be either controlled or monitored on the beam are detailed in Table 2.

2.1.1 Safety – PSS/FSD

1. Uses standard BLA system components - BCM (on upside down girder) and ion chambers.

2. Monitoring FZ magnet PS current – limits set to ensure beam is controlled successfully through the chicane.

3. FSD masking for Calorimeter Operation.

4. Thermocouples on LC dump – monitor temperature – elevated temperature may indicate too high a beam current.

5. Viewer in chicane – allows MCC Operators to view beam for steering confirmation.

6. Viewer on LC dump – allows MCC Operators to view beam for steering confirmation.

7. Update PSS sweep procedure as required after walk-through, equipment installation.

2.1.2 Requirements for Successful Accelerator Operations

The following items satisfy their requirements:

1. Must have capability to successfully steer the beam to the Hall A dump or Low Current (LC) dump.

2. Adequate instrumentation/diagnostics in order to perform item 1.

   (a) Viewer on the hall and LC dumps.
   (b) Thermocouples on the LC dump.
   (c) BLA and BCMs.
   (d) BPMs.
   (e) Ion chambers.

3. Appropriate EPICS control screens for all instrumentation/diagnostics.

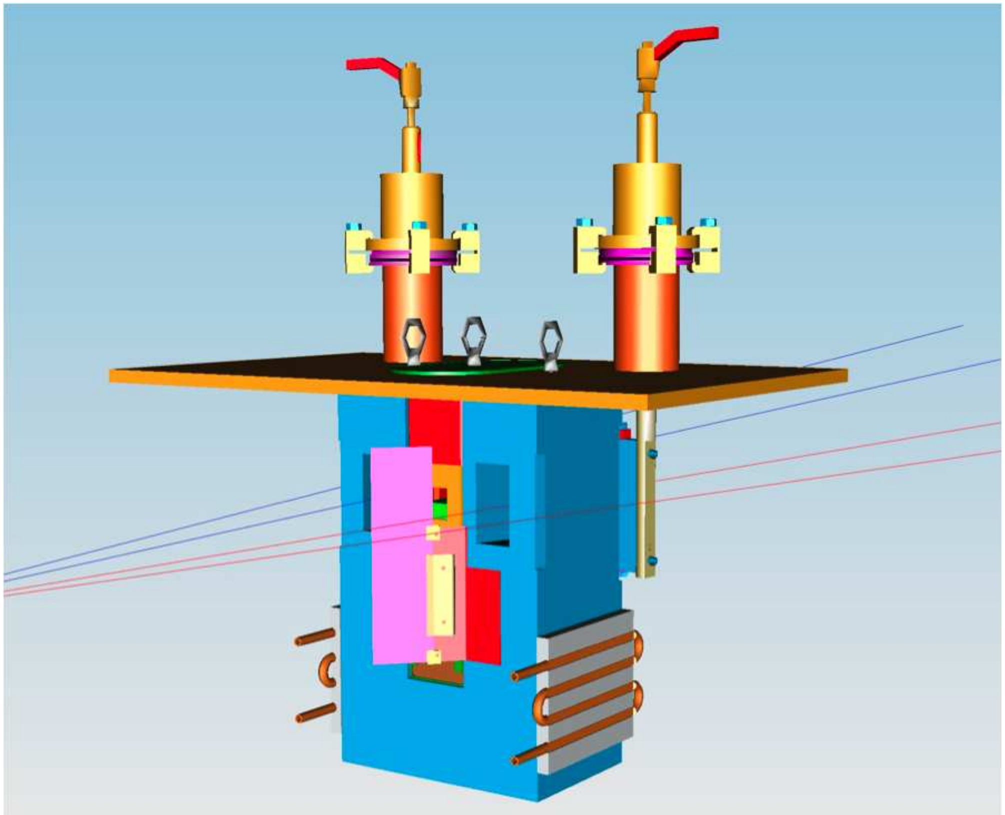

Figure 3: Low Power Dump placement for g2p.

4. Spares for any new systems or electronics.

5. Trained maintenance personnel.

2.2 Low Power Dump, Septa Magnets and Pivot

The beam dump for g2p is located between the target chamber and the septum magnet for the upstream target position and maintains its relative position to the target when the target chamber is moved on to the pivot (septum removed). See Fig. 3. The dump assembly consists of a main core machined from Tungsten fitted with temperature sensors and embedded in a Lead shield. A removable cartridge assembly, which serves a dual purpose, is located upstream of the core. The primary function of the cartridge is to shield personnel during configuration changes. In addition, the cartridge will hold foils consisting of several materials which will be analyzed by RADCON to provide empirical data for future radiological models. Sieve slits provided for the "Septum in" run are mounted on rotary assemblies which are precisely located with respect to the Lead shielding which also collimates the scattered particles entering the septum. A thin Beryllium Oxide plate is mounted upstream of the dump to provide visual confirmation of the beam location during operations. The entire Dump assembly is located inside a Helium enclosure which extends from the scattering

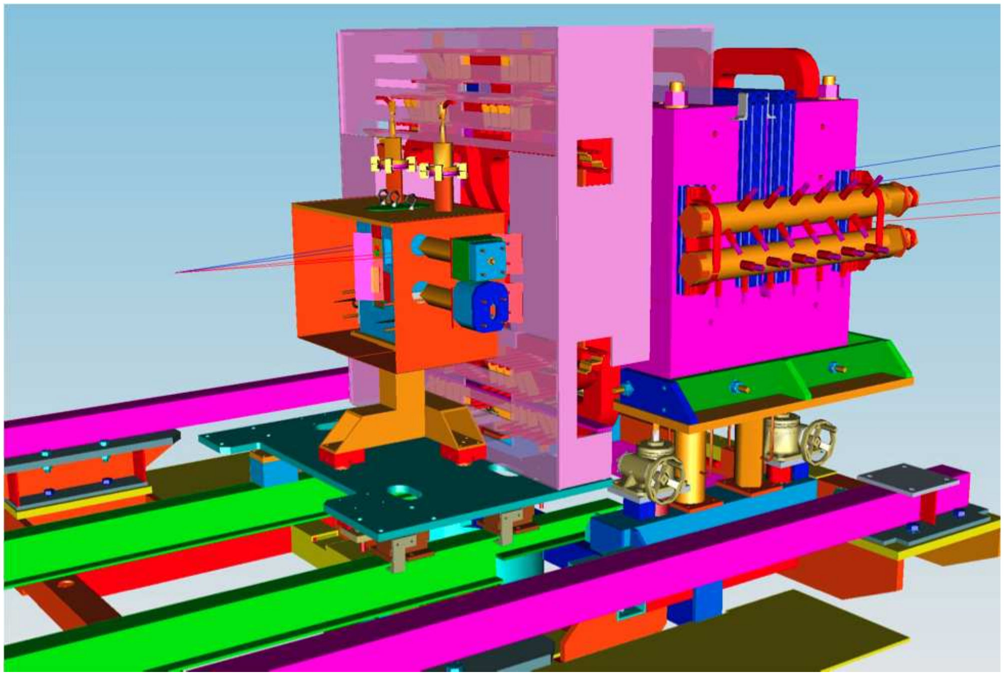

Figure 4: Septum Magnet.

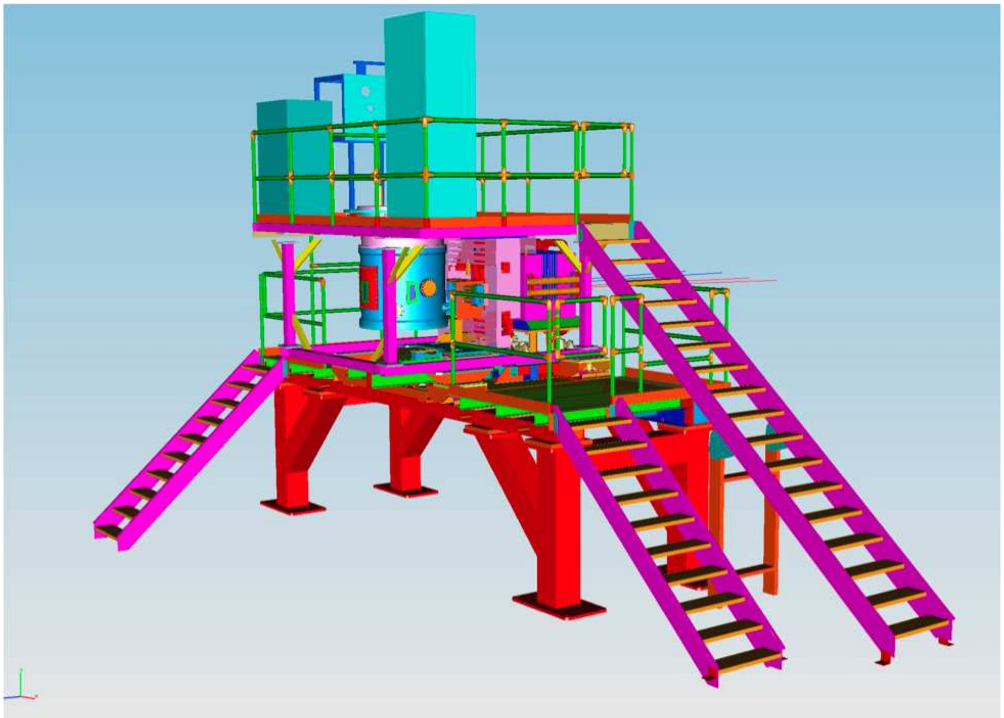

Figure 5: Overview of the target pivot, displaying the polarized target vacuum chamber, and support platforms.

chamber exit window to both spectrometers and to the entrance window of the rigid down steam beam-line that extends to the high power dump. The Low Power Dump absorbs four hundred Watts and requires forced cooling. This cooling is provided by a welding cooler which pumps water through two commercially available cooling plates attached to the Lead shield.

The room temperature septum magnet was originally used in the PREX experiment. For the g2p run it has been fitted with an additional set of coils. See Fig. 4. The addition of these coils made it necessary to refit the cooling water manifolds and install a new set of Plexiglas safety shields. The beam line extending through the magnet was destroyed during its removal at the end of the PREX run and will be replaced.

The equipment located on the pivot cannot be installed in situ given the lack of crane access and the configuration of the components. See Fig. 5. The construction of the target system along with related platforms and equipment will be assembled on a movable structure located on the left side of the beam line. The structure will be inserted in to the beam line and lowered onto the pivot. This structure; first used for the E94-107 (Kaon) run and more recently for PREX, is employed here with some minor modifications. The balcony that supports the target is designed with a symmetric mount which allows it to be used for both target positions by simply rotating it 90 degrees.

2.3 Target

The g2p and gep experiments use a solid, spin polarized target composed of NH_3. The target is dynamically polarized using a high magnetic field, low temperatures and microwave radiation. Polarization is measured using an NMR system. The target is the same one that has been used for several experiments at SLAC and in Hall C at Jefferson Lab. Safety documentation for the SANE experiment in Hall C will be used as a guide for the measures that should be taken for this pair of experiments. These documents will be updated to reflect all changes in target configuration.

The magnetic field is generated using a superconducting Helmholtz coil manufactured by Oxford. The 1 Kelvin temperatures required are achieved using a He evaporation refrigerator. The microwaves are supplied by an extended interaction oscillator (EIO). Due to damage to the system during the previous run, and the specific rotation requirements of switching between the g2p and gep experiments in a repeatable and efficient manner, both the magnet and the cryogenic sub-systems needed to be refurbished extensively. The magnet was sent back to the manufacturer for service, while the Jlab target group has repaired and redesigned aspects of the refrigeration system. This includes the design of a rotatable high vacuum seal, an extended refrigerator, new target insert, and the purchasing of new vacuum pumps. The repaired magnet recently returned to Jlab from Oxford, and all other tasks are proceeding on schedule.

2.4 Hall A Installation

Installation of the target, chicane, septa magnets and local beam dump are under the direction of **Ed Folts**. A detailed installation schedulehas been produced and will be provided to the review committee. Relevant milestones have been identified.

3 Safety Documentation

The following safety documentation is in preparation:

1. *The Conduct of Operations* (COO) will detail the experiments organization and standard operating procedures. Special procedures for access to the target pivot area, including work on any of the platforms will be detailed in the COO.

2. *The Experiment Safety Assessment Document* (ESAD) will describe hazards arising from the polarized target, local dump, septa magnets and chicane, and mitigation of said hazards. This document will also clearly specify which personnel are authorized to operate each apparatus.

3. The *ESAD for base Equipment* will describe specific hazards existing from the base equipment in Hall A, and mitigation of said hazards.

4. *The Radiological Safety Analysis Document* (RSAD) will identify the radiation budget for the experiment, the verification process for the radiation budget, and controls with regard to production, movement, or import of radioactive materials.

5. *Safety Guidelines for Radiation surveys* will be written to detail the unique safety hazards associated with the polarized target located on the pivot.

6. *Brief Hazard Awareness for RadCon group and ARMS* will describe hazard mitigation for the RadCon group arising from presence of the polarized target.

4 Manpower

There is a large group of JLab staff and university collaborators working on experimental preparations for g2p. Overall coordination and management is provided by Hall A physicist **Jian-ping Chen** (project manager), **Tim Michalski** (project coordinator for the Engineering Division) and the collaboration contacts for each experiment **Karl Slifer** and **Guy Ron**. Manpower for the beamline modifications, as identified in the 6-month-down schedule and resources, are mostly provided by the engineering division and accelerator division. This will be closely coordinated with Hall A staff (**Jian-ping Chen**), engineering and design (**Al Gavalya**) and the installation team (**Ed Folts**). From the collaboration side, a PhD student (**Pengjia Zhu**, USTC) and a Hall A physicist (**Alexandre Camsonne**) are working together with the engineering and accelerator groups on instrumentation and data acquisition.

Manpower for the polarized target comes mainly from the JLab polarized target group headed by **Chris Keith**. Users will provide support from the UVa group (**Don Crabb, Donal Day**), from the UNH group (**James Maxwell**, **Karl Slifer**) and from several graduate students.

Engineering and design of the beam dump, hall infrastructure and septum magnets are being done by the Hall A engineering/design team (**Robin Wines**, **Al Gavalya**) with input from the collaboration. Postdocs **Jixie Zhang** and **Kalyan Allada** and PhD student **Min Huang** are providing cross checks with simulation.

The detectors, DAQ, optics and simulations are being worked on by several postdocs (**Kalyan Allada**, **Jixie Zhang**), PhD students (**Min Huang, Chao Gu, Pengjia Zhu**) and staff (**Alexandre Camsonne**).

In general, the following postdocs are expected to dedicate near fulltime effort to g2p:

1. **Kalyan Allada** (Hall A)
2. **James Maxwell** (UNH)
3. **Jixie Zhang** (Hall A)

In addition, the following postdocs are expected to dedicate part-time effort to g2p: **Sarah Phillips** (UNH), **Xiaohui Zhan** (ANL), **Narbe Kalantarians** (UVa), **Hovhannes Baghdasaryan** (UVa).

The following graduate students will perform their PhD work on g2p:

1. **Tobias Badman** (UNH 2nd year, advisor:Slifer) will be onsite starting 5/2011.
2. **Melissa Cummings** (W&M 2nd year, Averett) will be onsite starting 5/2011.
3. **Chao Gu** (UVa 2nd year, Liyanaga) is currently onsite, working on optics and the 3rd arm luminosity monitor.
4. **Min Huang** (Duke 3rd year, Gao) is currently onsite, working on simulations and optics.
5. **Pengjia Zhu** (USTC 3rd year, Yunxiu Ye) is currently onsite, working on beamline and target.
6. **Ryan Zielinski** (UNH 2nd year, Slifer) will be onsite starting 5/2011. Is currently working on rate estimations.

Graduate student **Nick Kvaltine** (UVa) is providing part-time support of the polarized target. In particular, he is the primary responsible for preparing polarized target material for the run. We anticipate additional PhD students from Temple University, Rutgers University and Hebrew University of Jerusalem.

The following staff and faculty are/will soon be working fulltime on g2p.

1. **Alexandre Camsonne** (JLab).
2. **Jian-ping Chen** (JLab).
3. **Guy Ron** (HUJI).
4. **Karl Slifer** (UNH).

Additional significant contributions are anticipated from a dedicated technician (HUJI), **Doug Higinbothan** (JLab), **Ron Gilman** (Rutgers) and the other spokesmen of the two experiments: **Don Crabb** (UVa), **Donal Day** (UVa), **John Arrington** (ANL) and **Adam Sarty** (SMU).

E (GeV)	θ (deg)	Target Field(T)	Target Elevation(cm)	PAC days	Real days	Overhead days	Total days
2.2	6.0	5.0	9.0	4.4	8.8	2.5	11.3
1.2	6.0	2.5	9.0	3.0	5.9	1.7	7.6
1.7	6.0	2.5	9.0	5.3	10.6	3.1	13.7
2.2	6.0	5.0	0.0	0.6	1.1	0.3	1.4
3.4	6.0	5.0	0.0	3.4	6.7	2.0	8.7
2.2	12.5	5.0	0.0	7.1	14.2	4.2	18.4
3.4	12.5	5.0	0.0	9.2	18.3	5.0	26.3
				32.8	65.6	18.8	87.4

Table 1: Estimated Runtime. 'Real days' assumes 50% efficiency. The overhead is distributed evenly.

5 Beamtime Allocation

We are in the process of optimizing the beamtime allocation between E08-027 and E008-007. The values in Table 1 will be optimized in order to reduce overhead and better combine the running time allocated to the two experiments.