Draft Run Plan for RG-F

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This document provides a rough outline of the run plan for the run of RG-F, scheduled from February 12, 2020, to May 2, 2020. In particular, we provide the rationale for the time to be assigned to various auxiliary and background measurements.

CONTENTS

I. INTRODUCTION

Hall-B Run Group F is scheduled to run from February 12, 2020, to May 1, 2020. The run will use 10.4 GeV (5-pass) electron beam with currents up to 200 nA impinging on a 40 cm long, 0.6 cm diameter gaseous deuterium target (D_2) at 6-7 atm pressure. The anticipated luminosity will be 2×10^{34} nuclei/cm^2 e^-/s. At the beginning of the run, we require two 100% efficient ("PAC") days of 1-pass running (2.2 GeV) for calibration and commissioning purposes at somewhat lower luminosity (depending on observed rate). We also anticipate several runs interspersed throughout the 3-month period with ordinary hydrogen (H_2) or helium (^{4}He) gas filing the target at the same pressure (6-7 atm) as well as "nearly empty" target runs with 1 atm H_2. To save time, the latter will be run with 400 nA beam if possible. Following the recent approval of a second experiment (DVCS on the neutron) within Run Group F, we require high beam polarization and we will measure this polarization with Möller runs.

The Hall B CLAS12 forward detector will be used in its standard configuration, with the toroid magnet (most of the time with in-bending polarity), HTCC Cherenkov Counter, Drift Chambers, Scintillation counters, and electromagnetic calorimeter. The configuration of LTCC and RICH Cherenkov counters will be left unchanged from run group B (November - January run). The forward tagger will not be used (detectors turned off) and the Moller shield will be installed in the "FT off" configuration with extra shielding. The Central Detector will include the superconducting solenoid at full field, and the CTOF and CND scintillation counters. The central vertex tracker consisting of barrel micromegas gas detectors and silicon-strip detectors will be replaced by the custom-built BONuS12 Radial Time Projection Chamber (RTPC) which surrounds the 40 cm long target, and a new forward micromegas tracker (FMT) with 3 layers provided by Saclay. We also anticipate to re-install the BAND neutron detector upstream of CLAS12.

This Document gives some guidance and supporting information on the optimal sequence and duration of various run configuration periods within Run Group F. We do not address specifically any additional runs that may be required to commission and calibrate the new FMT or BAND, although we anticipate that the configurations described below should largely be sufficient for that purpose. We expect to take pedestal and cosmic ray runs whenever there is no beam in the Hall but the CD and RTPC are available. Furthermore, as stated above, we will conduct a Moller run (with ancillary harp scans etc.) about once every 1-3 weeks, depending on changes in the injector setup, number of passes or beam energy.

II. BEFORE INSTALLATION

At present, we have 2 completed RTPC detectors, and 1 additional one will be build (expected completion in mid-February). This allows us to pick the RTPC with the best performance for initial installation and keep a second RTPC for tests, optimization of parameters, and as a "hot swap-out" to minimize downtime in case of a failure of the in-beam RTPC. Until installation in the Hall, we are checking out both RTPCs and all ancillary systems, including gas panel, detector gas monitoring system (DMS), slow controls, DAQ and data taking and reconstruction software with ^{90}Sr sources and cosmic rays. We are characterizing RTPC performance and calibration as a function of operating parameters, and train run-time RTPC operators ("experts"), while completing all documentation.

III. BEFORE BEAM

The present switch-over plan foresees the begin of installation of the RTPC on the Hall B beamline beginning Friday, February 7. This leaves 5 days for installation, connecting all service and control systems (for both RTPC and FMT), and survey. During this time, we will once again check out all systems and DAQ. As time permits, we will take pedestal runs and cosmic runs without and with solenoid (trigger: opposite sides of CToF).

IV. ESTABLISH BEAM

Beam delivery to Hall-B for RG-F is planned to begin Wednesday, February 12. The following is the anticipated sequence to first establish beam; subsequently, a similar procedure will be followed each time beam is (re-)established to the Hall after lengthy down times or significant configuration/energy changes.

- Tune beam with tagger on
- Set target to "empty" (= 1 atm H)

- Take low-intensity (a few nA) beam to FC, complete harp scans. We require less than 0.3 mm (1σ) beam width and halo below 10^{-4}.
- Center beam on target, using rates in BOM and downstream beam monitors. Establish range where beam starts directly interacting with target walls and take middle.
- Engage orbit locks and ascertain that they are stable.
- Set alarms and interlocks.
- Collect data with standard trigger at low beam current and check occupancy, rates, and trigger rates.
- Ramp up current to desired value (about 200 nA for production running, up to 450 nA for "empty" target; lower for 2.2 GeV and outbending configurations), while recording trigger rates, DC and RTPC occupancies, dead times and overall data rate.
- Re-check alarms and interlocks, rates and occupancies and make adjustments as necessary

V. CALIBRATION AND COMMISSIONING AT 1 PASS (2.2 GEV)

For the following runs, the Solenoid will be at full field except for one run with no magnetic fields at all. The trigger will be the standard CLAS12 electron trigger (coincidence between HTCC and EC, the latter with a threshold of at least 300 MeV actual electron energy).

A. Outbending Configuration, $^1H_2$ target (about 1 day)

Torus will be at 1/2 of maximum field, electron-OUTbending polarity. Target will be first 1 atm, then full pressure hydrogen. The trigger will be the standard single electron trigger without requiring road matching; the beam current will be reduced as needed to keep the trigger rate well below 2 kHz. We estimate a maximum current of about 10 nA will suffice for this purpose, except in the "empty target" configuration (1 atm of H_2).

We will do one set of runs with several beam currents to establish reconstruction efficiency vs. occupancy for both the RTPC and the DC. After that we will take data for about 2 shifts (about 100 M events). These data will be used to calibrate the RTPC (using the ^{1}H$(e, e'p)$ reaction) and trouble-shoot all other detectors. At the end of this period, the torus will be ramped down to zero field and 1 run will be taken in this configuration. Then the solenoid will also be ramped down to take one run of zero field data for alignment. (Beam current reduced accordingly). Afterwards, the solenoid will be ramped back up and the torus will be changed into inbending polarity but still 1/2 of full field $\Rightarrow$

B. Electron-Inbending Configuration, $^1H_2$ target

Flush target and take one run in "empty" target configuration. Then fill target with standard pressure hydrogen gas and take data for about 1 shift at the highest acceptable luminosity consistent with less than 2 kHz trigger rate. The goal of these data is to help with RTPC calibration (using the ^{1}H$(e, e'\pi^+\pi^-p)$ reaction).

C. Electron-Inbending Configuration, $^2H_2$ target

Flush target and take one run in "empty" target configuration. Then fill target with standard pressure deuterium gas and take data for about 1 shift at the highest appropriate luminosity. The goal of these data is to check out spectator reconstruction, tracking efficiency in the RTPC as function of occupancy, and to cross-check with previous BONuS data taken at 2.2 GeV.

VI. RUNNING AT 10.4 GEV / 5 PASS

After completion of the 2.2 GeV part of RG-F, we will ask for maximum beam energy (5 pass) and begin our production data taking. Depending on the results of the 2.2 GeV running, we may need another zero field run for alignment purposes (after the first 5 weeks - see below), but otherwise all runs will be with full torus field (inbending or outbending polarity) and full solenoid field. The steps to establish beam initially will follow Section IV.

The trigger will be the standard CLAS12 electron trigger (HTCC*EC) with an EC threshold of 1 GeV actual electron energy, augmented by Road matching. We will take a couple of runs with full target (hydrogen or deuterium) at reduced luminosity ($<$ 2kHz trigger rate) using the Roads from simulation (downloaded into the trigger module but only in tagged mode). Once we have ascertained that the Road finder is close to 100% efficient, we will use these roads in the trigger to reach full luminosity. After a few more runs runs with full target (hydrogen or deuterium) have been taken, we will extract new Roads from these data for the trigger, download them, and once again check their efficiency. Next, we will take a sequence of runs with different beam currents to establish the optimum running condition regarding data rate, occupancy, tracking efficiency, etc. Afterwards, we will run with the maximum luminosity compatible with these conditions, or the beam limit of about 450 nA in Hall B.

Initially, the torus will be in the electron-inbending configuration at full field. We will take data following the sequence below for about 5 weeks in this configuration. After that, we will take about 2 weeks of data with electron-outbending torus polarity (and appropriately reduced luminosity; again, we may use the simulated Roads initially since they contain both inbending and outbending particles, and then replace them - after efficiency testing - with Roads extracted from data). The remaining 4-5 weeks will be run again in inbending configuration, but potentially higher luminosity and with a high-Q^2 trigger (see Section VII). In all cases, we will follow the same sequence of runs[1] outlined below. The rationale for the relative weight given to each of these run conditions is explained in Section VI B.

A. Sequence of standard runs

1. **(MT):** The sequence begins with the target "empty" (1 atm hydrogen gas) and after being flushed several times.

2. **(H):** The target is filled with the maximum amount of hydrogen gas (6-7 atm). Take one run of data.

3. **(MT):** The target is empty. About once a month (and the first time with each configuration), take one run of data (at maximum current).

4. **(D):** Fill target with standard pressure deuterium gas. Take 7-8 runs of production data.

5. **(MT):** Empty and flush target. Either begin cycle at 1., or (once a week and the first time with each configuration) continue as below:

6. **(He):** Fill target with 6-7 atm helium-4 and take one run of data. These data are for background subtraction and to calibrate the RTPC energy loss determination.

7. **(MT):** Empty and flush target. Begin cycle at 1.

Intersperse Moller runs as needed.

B. Optimizing background and ancillary runs

In this subsection, we give the rationale behind the relative weight (time) assigned for each of the 10.4 GeV segments of the run group. We are trying to optimize the final statistical uncertainty of the desired Physics observable, which depends not only on the amount of data taken in the standard configuration (maximum luminosity on deuterium with inbending torus polarity) but also on sufficient statistics taken for each of the auxiliary measurements necessary to address backgrounds and other supplemental information needed to extract Physics results. In the following, we designate the total run time of the 10.4 GeV part of the experiment with T and the fraction of that time spent for a specific configuration "Y" as X_Y.

[1] A standard run should take about 2 hours and contain about 10-20 M events except for background runs.

1. BONuS12 observables

During RG-F, we will operate the experiment with the following different configurations:

D: Standard running with e^- inbending torus field on a maximum density (6-7 atm) deuterium gas target (D) with nominal luminosity (about 200 nA beam) resulting in a *nuclear* luminosity of $\mathcal{L}_D = 2 \times 10^{34}$/s/cm^2. The total number of counts within a given bin $(\Delta Q^2, \Delta x)$ of electron kinematics (and integrated over the VIP proton kinematics) for the entire experiment will be

$$N_D = X_D \mathcal{L}_D T \left[\Delta\sigma_n \epsilon_{tag}(1 + f_{acc}) + f_{He}\Delta\sigma_{He} + f_W \Delta\sigma_W + \Delta\sigma_{e+e-}\right] \tag{1}$$

Here, $\Delta\sigma_n$ is the cross section for inclusive scattering off the neutron in the deuteron (we ignore the small correction due to the n motion remaining even after selecting VIP kinematics). ϵ_{tag} is the overall efficiency of tagging a VIP during a scattering process on the neutron, i.e., the probability for a spectator proton to be emitted with momenta between 0.07 and 0.1 GeV and with an angle greater than 110 degrees relative to the q-vector, multiplied with the acceptance and efficiency of the RTPC for detecting such a proton. The first part is of order 10%, while the latter part may be as low as 0.5, yielding an overall factor of $\epsilon_{tag} \approx 0.05$. The quantity f_{acc} accounts for accidental coincidences; we assume it will be in the 10%-30% range. For simplification, we will ignore this quantity in what follows - we assume that all measured counts have already been corrected for accidental coincidences (with minimal impact on their statistical uncertainties). The remaining terms describe various background contributions to the measured deuteron counts:

(a) Helium contamination of the target. f_{He} is the contamination fraction in terms of Helium atoms per Deuterium atom and $\Delta\sigma_{He}$ is the cross section for an electron to be scattered from a Helium atom into the same kinematic bin while simultaneously releasing a proton in ^{4}He that falls within the VIP range. For a partial helium pressure of 0.7 psi = 5% of the surrounding buffer or 1% of the deuterium pressure, f_{He} is about 0.005, see below. The cross section $\Delta\sigma_{He}$ is at least 6 times larger than $\Delta\sigma_n$, just by counting nucleons and assuming that the cross section on a proton is at least twice that on a neutron. Depending on the probability of coincident proton emission within the VIP range, the true value could be much larger. Taking just the RTPC acceptance and efficiency into account, it seems reasonable to assume $\Delta\sigma_{He} \approx 10 \times \Delta\sigma_n \epsilon_{tag}$, leading to a 5% background.

(b) Background from the target entrance and exit windows. f_W is the product of the relative density of the windows vs. the gas target multiplied with the fraction of events from the windows that end up within fiducial cuts, and $\Delta\sigma_W$ is the cross section for an electron to be scattered from an aluminum atom into the same kinematic bin while simultaneously releasing a proton in aluminum that falls within the VIP range. In the following, we assume that this background is ignorable (since we will cut out the windows by our vertex-z selection). We will still take some "empty" target measurements with only 1 atm of hydrogen, for calibration, vertex reconstruction and similar purposes, but the fraction of the run time for such runs will be very small and will be ignored here.

(c) Pair symmetric background. $\Delta\sigma_{e+e-}$ is the cross section for production of an electron-positron pair, with the electron kinematics falling into the same kinematic bin, and coincident production of a proton within the VIP range. This background comes mostly from direct or π^0 decay photons that convert into e^+e^- pairs close to the target. The magnitude of this background depends highly on kinematics and is largely unknown for the case of tagged production. However, taking into account what is known about inclusive electron scattering, we can assume that $\Delta\sigma_{e+e-} = 0.02 - 0.1 \times Delta\sigma_n \epsilon_{tag}$. The higher number corresponds to low electron momentum and thus lower x; since we are only statistics-limited at high x, we will use the smaller number to evaluate the required amount of outbending runs.

Auxiliary measurements needed to correct for these backgrounds are discussed below under "He" and "outb".

H: Since our most prominent Physics goal is the ratio $F_{2n}/F_{2p} \approx \Delta\sigma_n/\Delta\sigma_p$, we will measure directly the cross section on ordinary hydrogen to form this ratio, thus canceling several input quantities with systematic uncertainties. Assuming that we will run with the same conditions (same beam current and target pressure), the *nuclear* luminosity will be the same and we can write

$$N_H = X_H \mathcal{L}_D T \Delta\sigma_p \tag{2}$$

(In principle, there are also small contributions from ^{4}He and from pair-symmetric processes, but the former will be largely suppressed if we don't require a spectator and the latter can be taken care of by simply measuring the same fraction X_H of hydrogen target time with outbending configuration - see below.)

He: For the same pressure, a pure ^{4}He gas target contains roughly 1/2 as many atoms as a deuterium gas target, yielding 1/2 of the luminosity. Assuming we will still run with the same beam current (200 nA) to minimize Moller and accidental backgrounds, this means that

$$N_{He} = X_{He}\frac{\mathcal{L}_D}{2}T\Delta\sigma_{He} \tag{3}$$

outb: To correct for pair-symmetric background, we will run for some fraction of the time with outbending torus polarity, which means that the positrons from the pair will follow the exact trajectories of the electrons for inbending polarity. Hence, by counting the number of positrons in the same kinematic bin, we can subtract the pair-symmetry contribution. Accounting for the fact that we may have to lower the luminosity for outbending runs, the total counts will be

$$N_{e+} = X_{outb}\mathcal{L}_{outb}T\Delta\sigma_{e+e-}. \tag{4}$$

We can now combine these measurements to extract the "clean" D(e,e')X cross section:

$$\Delta\sigma_n = \left[\frac{N_D}{X_D\mathcal{L}_D T} - f_{He}\frac{2N_{He}}{X_{He}\mathcal{L}_D T} - \frac{N_{e+}}{X_{outb}\mathcal{L}_{outb}T}\right]/\epsilon_{tag} \tag{5}$$

$$= \frac{1}{\mathcal{L}_D T}\left[\frac{N_D}{X_D\epsilon_{tag}} - \frac{f_{He}2N_{He}}{X_{He}\epsilon_{tag}} - \frac{N_{e+}\mathcal{L}_D}{X_{outb}\epsilon_{tag}\mathcal{L}_{outb}}\right] \tag{6}$$

and

$$\frac{\Delta\sigma_n}{\Delta\sigma_p} = \frac{1}{\mathcal{L}_D T}\left[\frac{N_D}{X_D\epsilon_{tag}} - \frac{f_{He}2N_{He}}{X_{He}\epsilon_{tag}} - \frac{N_{e+}\mathcal{L}_D}{X_{outb}\epsilon_{tag}\mathcal{L}_{outb}}\right]/\frac{N_H}{X_H\mathcal{L}_D T} \tag{7}$$

$$= \left[\frac{N_D}{X_D\epsilon_{tag}} - \frac{f_{He}2N_{He}}{X_{He}\epsilon_{tag}} - \frac{N_{e+}\mathcal{L}_D}{X_{outb}\epsilon_{tag}\mathcal{L}_{outb}}\right]/\frac{N_H}{X_H} \tag{8}$$

The total statistical uncertainty on the cross section ratio is therefore (using standard error propagation and Poisson statistics for all counts):

$$\sigma^2\left(\frac{\Delta\sigma_n}{\Delta\sigma_p}\right) = \left[N_D\frac{1}{(X_D\epsilon_{tag})^2} + N_{He}\frac{(2f_{He})^2}{(X_{He}\epsilon_{tag})^2} + N_{e+}\frac{\mathcal{L}_D^2}{(X_{outb}\epsilon_{tag}\mathcal{L}_{outb})^2}\right]/\left(\frac{N_H}{X_H}\right)^2 + \tag{9}$$

$$+\left[\frac{N_D}{X_D\epsilon_{tag}} - \frac{f_{He}2N_{He}}{X_{He}\epsilon_{tag}} - \frac{N_{e+}\mathcal{L}_D}{X_{outb}\epsilon_{tag}\mathcal{L}_{outb}}\right]^2/\frac{N_H^3}{X_H^2} \tag{10}$$

We make one further simplification: Since most of the N_D counts come from $\Delta\sigma_n$, we approximate N_D in the upper row (eq. 9) with the leading term: $N_D = X_D\mathcal{L}_D T\Delta\sigma_n\epsilon_{tag}$. In this case, and by replacing all counts by the expressions for each run configuration, we get

$$\sigma^2\left(\frac{\Delta\sigma_n}{\Delta\sigma_p}\right) = \mathcal{L}_D T\left[\frac{\Delta\sigma_n}{X_D\epsilon_{tag}} + \frac{2f_{He}^2\Delta\sigma_{He}}{X_{He}\epsilon_{tag}^2} + \frac{\Delta\sigma_{e+e-}\mathcal{L}_D/\mathcal{L}_{outb}}{X_{outb}\epsilon_{tag}^2}\right]/\left(\mathcal{L}_D T\Delta\sigma_p\right)^2 + \tag{11}$$

$$+\left(\mathcal{L}_D T\right)^2\Delta\sigma_n^2/(X_H\mathcal{L}_D T\Delta\sigma_p)/\left(\mathcal{L}_D T\Delta\sigma_p\right)^2 \tag{12}$$

$$= \frac{\Delta\sigma_n}{\Delta\sigma_p}\frac{1}{\mathcal{L}_D T\Delta\sigma_p\epsilon_{tag}}\left[\frac{1}{X_D} + \frac{2f_{He}^2\Delta\sigma_{He}/(\Delta\sigma_n\epsilon_{tag})}{X_{He}} + \frac{(\mathcal{L}_D/\mathcal{L}_{outb})\Delta\sigma_{e+e-}/(\Delta\sigma_n\epsilon_{tag})}{X_{outb}} + \frac{\Delta\sigma_n\epsilon_{tag}/\Delta\sigma_p}{X_H}\right] \tag{13}$$

The expression in front of the square brackets is a constant, so to optimize the statistical uncertainties, we have to find a combination of values for all X_Y that minimizes the expression within the square brackets. Of course, we have the constraint that $X_D + X_{He} + X_{outb} + X_H \equiv 1$.

2. Mathematical Interlude

Lemma:
Let $A = \Sigma a_i/X_i$ be a function of the X_i for which we want to find a set of X_{i0} that minimizes A, under the condition that $\Sigma X_i = 1$. Then each of the X_{i0} will be proportional to $\sqrt{a_i}$.
Proof:
We implement the constraint by setting $X_1 = 1 - \Sigma_{j>1} X_j = 1 - S$. Then $A = a_1/(1-S) + \Sigma_{j>1} a_j/X_j$. To find the minimum, we require that the derivative of A with respect to every one of the X_j is zero:

$$\frac{\partial A}{\partial X_j} = \frac{a_1}{(1-S)^2} - \frac{a_j}{X_j^2} \equiv 0 \Rightarrow X_j^2 = \frac{a_j}{a_1}(1-S)^2. \tag{14}$$

This is a set of equations for the X_j which has a unique solution within the range $0 \leq X_j \leq 1$. The solution can be most easily found by observing that

$$S = \Sigma_{j>1} X_j = (1-S)\Sigma_{j>1}\sqrt{a_j/a_1} \Rightarrow S = \frac{\Sigma_{j>1}\sqrt{a_j/a_1}}{1+\Sigma_{j>1}\sqrt{a_j/a_1}} \Rightarrow X_{10} = 1 - S = \frac{1}{1+\Sigma_{j>1}\sqrt{a_j/a_1}}. \tag{15}$$

Therefore, for $j > 1$ but also for $j = 1$, it follows that ,

$$X_{j0} = \frac{\sqrt{a_j}}{\sqrt{a_1} + \Sigma_{j>1}\sqrt{a_j}} = \frac{\sqrt{a_j}}{\Sigma_i \sqrt{a_i}}, \tag{16}$$

q.e.d.

3. Application to RG-F

From subsection VI B 1, we can identify the a_i in the result above as follows:

1. $a_1 = a_D = 1 \Rightarrow \sqrt{a_1} = 1$.

2. $a_2 = a_{He} = 2 f_{He}^2 \Delta\sigma_{He}/(\Delta\sigma_n \epsilon_{tag}) \Rightarrow \sqrt{a_{He}} = f_{He}\sqrt{2\Delta\sigma_{He}/(\Delta\sigma_n \epsilon_{tag})} \approx 0.005\sqrt{20} = 0.022$.

3. $a_3 = a_{outb} = (\mathcal{L}_D/\mathcal{L}_{outb})\Delta\sigma_{e+e-}/(\Delta\sigma_n \epsilon_{tag}) \Rightarrow \sqrt{a_{outb}} \approx \sqrt{0.04} = 0.2$, assuming we want to optimize for the highest x and that the outbending luminosity is 1/2 the inbending one.

4. $a_3 = a_H = (\Delta\sigma_n \epsilon_{tag})/\Delta\sigma_p \Rightarrow \sqrt{a_H} \approx \sqrt{0.02} \approx 0.14$, where we assume $\Delta\sigma_n/\Delta\sigma_p = 0.4$ at high x and $\epsilon_{tag} = 0.05$.

Obviously, these are all initial rough estimates that can be refined based on data collected during RG-F. Plugging them into our results from the previous subsection, we find $\Sigma_i \sqrt{a_i} = 1.36$ and

1. $X_D = 0.734$

2. $X_{He} = 0.016$

3. $X_{outb} = 0.15$

4. $X_H = 0.1$

In other words, we should run roughly 15% of our available beam time with outbending torus field (which is also needed for tracking calibrations), and 10% hydrogen as well as 1.6% helium. The remainder, nearly 75%, will be production data taking on deuterium.

VII. HIGH-Q^2 RUNNING

Depending on the results from the first few weeks of running (in particular the amount of accidental background and occupancy we can tolerate in the RTPC), we may try to increase the beam current for the second part of inbending running. This can be compensated in part by implementing a filter in the road-based trigger that selects only events at higher Q^2, as this is where BONuS12 is most "statistics-hungry". In particular, we could trigger only on events with electron scattering angles above 12 degrees and $Q^2 > 3$ GeV^2 (the latter requires that $E' * \theta_e^2 > 0.29$, where θ_e is in radians and E' in GeV).

The goal is to keep the total trigger rate below 2kHz (or whatever was established as safe running condition for the DAQ). The DC occupancies will not be a concern as they are already very low (according to simulation). The only potential issue might be that we will have too many hits and too many accidental tracks in the RTPC to reliably reconstruct VIPs and remove background. This will have to be studied using the initial running before increasing the beam current.