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GlueX/Hall-D Solenoid Studies

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Introduction

Studies have been carried out on the impact of reducing the Hall-D solenoid current from its nominal $1500\,A$ to around $1300\,A$. This reduction in current could affect several aspects of the experimental program.

- For a fixed photon rate on target, the electromagnetic background rates in the detector will rise as the magnetic field strength is reduced. This can affect the ability of some detector elements to take data as well as impact the lifetime of detectors.
- The momentum resolution of charged particles will be reduced as the magnetic field is reduced.
- The ability to reconstruct final states at a particular purity may be affected by the change in magnetic field.

In order to study these effects, the GlueX Collaboration has undertaken a series of studies using the GEANT based simulation of the detector as well as the full reconstruction and physics analysis tools.

The results of these studies indicated that for solenoid magnetic fileds associated with solenoid currents in the 1300 to $1500\,A$ range, the impact on GlueX physics appears minimal. As the field is lowered beyond this, there is a degradation in the experimental capabilities of the detector. For most of the interesting physics reactions in GlueX, a solenoid current of $1350\,A$ will be close to the optimal value. The details from these studies are presented in this report.

Electromagnetic Backgrounds

As a reference, the GlueX detector was designed to handle rates corresponding to $10^8\,\gamma/s$ in the coherent photon peak. This beam will be generated with a $12\,GeV$ electron beam impinging on a a $20\,\mu m$ thick diamond radiator on the Hall-D Tagger Hall. These rates nominally corresponds to an electron beam current in the tagger hall of $1\,\mu A$.

The electromagnetic rates in various detectors in GlueX have been examined [1] for magnetic field currents of $1500\,A$ (nominal), $1200\,A$ (80% of nominal) and $1050\,A$ (70% of nominal). This study also looked at the affect of the size of the dead region around the beam line in the Forward Drift Chambers (FDC). Since the time of the report, both the start counter and the hole size in the FDC have been changed based on information in the report. As such, we avoid using the absolute normalization numbers from this report, but use how fast the electromagnetic background rates in several of the detectors close to the beam line increase as the magnetic field is decreased. From this study, the detectors most affected by the electromagnetic backgrounds are those closest to the beam. In particular, the forward drift chambers and the start counter.

Taking the data from this study [1], we can normalize the rates in the FDC and the start counter to those observed at full solenoid current. The normalized values are given in Table 1. We plot these for the two detectors as a scale factor by which the rate increases against the solenoid current, as shown in Figure 1. In the FDC, the rates electromagnetic

Solenoid Current (A)	FDC Rates	Start Counter Rates
1050	2.40	1.89
1200	1.67	1.44
1500	1.00	1.00

Table 1: The rates in the Forward Drift Chamber and the Start Counter as a function of the solenoid current, normalized to the rate at nominal current ($1500\,A$).

background rates appear to increase by about 30% for a drop in the solenoid current of $100\,A$. In the start counter, the increase is about 20% for the same drop in current. Thus, for a solenoid current of $1300\,A$, we would expect that the electromagnetic background rates in the most sensitive detector elements will be 40% to 60% higher than they would be a $1500\,A$ solenoid current. We have fit these data to a linear expression as

$$\begin{aligned} R_{FDC} &= -(2.98\times 10^{-3}\,A^{-1})\,I + 5.42 \\ R_{ST} &= -(1.91\times 10^{-3}\,A^{-1})\,I + 3.83\,, \end{aligned}$$

where the 2.98 and 1.91 coefficients correspond to the 30% and 20% numbers as quoted above.

From Figure 1, it is clear that a simple linear model may not be the most accurate description of the data. As such, we have also used a quadratic expression in the current, where the results to these fits are given as

$$\begin{aligned} R_{FDC} &= (5.93\times 10^{-6}\,A^{-2})\,I^2 - (1.82\times 10^{-2}\,A^{-1})\,I + 15.0 \\ R_{ST} &= (3.29\times 10^{-6}\,A^{-2})\,I^2 - (1.04\times 10^{-2}\,A^{-1})\,I + 9.15\,. \end{aligned}$$

This model would predict somewhat lower electromagnetic rates for $1300\,A$ than the linear model. However, as the solenoid current continues to be lowered, the linear model would under predict the quadratic model. An another study, see reference [2] used the quadratic model to estimate the electromagnetic rates, and then assumed that the beam current would need to be decreased to maintain constant electromagnetic rates. The study also looked at the degradation of the width of narrow states. The overall conclusion of that study was that

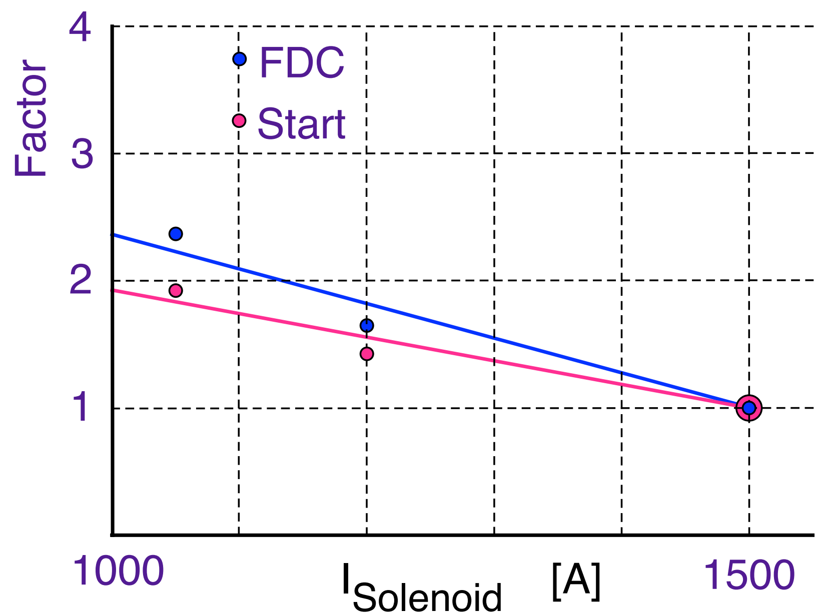

Figure 1: The scale factor by which the electromagnetic rate increases as a function of the solenoid current. The data suggest that for each drop of $100\,A$ in the current, the electromagnetic background rates increase by about 30% in the FDC and by about 20% in the start counter.

there was a degradation effect that went with B^2 for the electromagnetic backgrounds and B for the resolution of the detector, leading to an increase in run time that scaled like B^{-3}.

We need to caveat this with the fact that while the experiment is designed for $1 \times 10^8\,\gamma/s$ running, we do not know how close we will be able to come to this with full field running. Thus, we do not know the starting point, and probably will not until we have started taking data. We also not that the high-intensity running that has been approved assumed an average flux of 5×10^7—a factor of two below the design value. Thus, if we are at the limits of the rate that the detector can handle, we may need to increase the running time at lower rates, this may have already been accounted for in the beam time estimates.

Momentum and Angular Resolution

It is expected that the momentum resolution should scale directly with the strength of the magnetic field, and hence the solenoid current. This is indeed verified for for the π^+ and π^- momenta, but is not exactly true for the proton's momentum. In the latter case, other effects such as energy loss and multiple scattering tend to limit the effect, and the degradation in the proton is less than what would be expected. [3]

To the level that we have been able to check, the angular resolutions (in the lab frame) are not affected by the magnetic field strength. We have also examined the angular resolution in the Gottfried-Jackson frame for the decay of the ω. These angular resolutions also do not appear to depend on the magnetic field strength.

Finally, for the ω channel as studied above, we have examined the post-kinematic fit invariant mass resolution for the ω. For a 20% decrease in the magnetic field strength, we see a 10% increase in the width of the ω meson.

Reconstruction Efficiency

Several physics channels that share features with many of the channels to be analyzed in GlueX have been studied. All of these likely contain more specific final states, but in order to carry out an analysis, it is necessary to be able to exclusively reconstruct these.

$$\gamma p \rightarrow p\pi^+\pi^-\pi^+\pi^-\gamma\gamma \quad (1)$$
$$\gamma p \rightarrow p\pi^+\pi^-\pi^+\pi^- \quad (2)$$
$$\gamma p \rightarrow p\pi^+\pi^-\gamma\gamma \quad (3)$$

In studying these reactions, a sample containing 10^7 PYTHIA events were thrown and simulated for each solenoid current, and for each of two background photon rates. These studies include the full hadronic cross section for $7\,GeV$ photon energy up to the endpoint ($\sim 12\,GeV$). The two photon rates correspond to electromagnetic backgrounds rates expected for the initial GlueX running and for the longer running at higher intensity. The latter was approved by the PAC in 2013 and 2014. Neither of these represent the design rate (10^8) of the experiment, which is twice as large as both the assumed rate used in the proposals and the maximum simulated background rates in these studies.

The reactions were extracted using simple analyses that employed reconstruction cuts and kinematic fitting of the exclusive final states. No effort was made to optimize the cuts to a given setting; rather a common cut was used in all cases. The most selective element of the cuts was the convergence of the kinematic fit to some small, but non-zero confidence level.

Because the events were simulated, knowledge of the actual reaction in each event was retained. Thus, the actual number of events for each of the reaction types is known. We also know the number of these events selected in the final sample (signal), and the number of events that were not the correct reaction that were accepted in the final sample (background). From these, we form three measures of the performance of our reconstruction:

- *Reconstruction Efficiency* given as the number of signal events divided by the number of thrown events of the correct type.
- *Signal Purity* given as the fraction of all selected events that are the correct topology.
- *Signal/Background* given as the number of signal events divided by the number of background events in the resulting sample.

In the following tables, we present these quantities for the three reactions of interest. Table 2 gives them for the events in reaction 1, Table 3 for reaction 2, and Table 4 for reaction 3. Figure 2 shows the reconstruction measures as a function of the solenoid current for reaction 1, Figure 3 shows them for reaction 2 and Figure 4 shows them for reaction 3.

I_S (A)	γ/s	Reconstruction Efficiency	Signal Purity	Signal/Background	$S/\sqrt{B}$
750	1×10^7	5.82%	75.9%	3.15	354
1200	1×10^7	5.45%	84.1%	5.31	445
1350	1×10^7	4.64%	87.0%	6.71	461
1500	1×10^7	4.38%	86.8%	6.55	442
1200	5×10^7	4.60%	83.7%	5.12	403
1350	5×10^7	4.20%	86.9%	6.66	407
1500	5×10^7	4.00%	87.3%	6.90	432

Table 2: The reconstruction information for the $\gamma p \to \pi^+\pi^-\pi^+\pi^-\pi^0$ reaction.

I_S (A)	γ/s	Reconstruction Efficiency	Signal Purity	Signal/Background	$S/\sqrt{B}$
750	1×10^7	12.5%	83.6%	5.086	674
1200	1×10^7	10.5%	90.8%	9.893	859
1350	1×10^7	9.6%	91.8%	11.231	1048
1500	1×10^7	8.5%	93.0%	13.288	928
1200	5×10^7	9.7%	90.4%	9.430	891
1350	5×10^7	8.9%	91.2%	10.407	914
1500	5×10^7	8.0%	92.9%	13.052	808

Table 3: The reconstruction information for the $\gamma p \to \pi^+\pi^-\pi^+\pi^-$ reaction.

I_S (A)	γ/s	Reconstruction Efficiency	Signal Purity	Signal/Background	$S/\sqrt{B}$
750	1×10^7	19.71%	83.0%	4.89	388
1200	1×10^7	19.42%	89.0%	8.07	498
1350	1×10^7	17.86%	92.9%	13.07	505
1500	1×10^7	17.86%	91.1%	10.26	517
1200	5×10^7	17.3%	88.9%	8.037	465
1350	5×10^7	16.1%	92.6%	12.593	438
1500	5×10^7	16.6%	91.1%	10.175	498

Table 4: The reconstruction information for the $\gamma p \to \pi^+\pi^-\pi^0$ reaction.

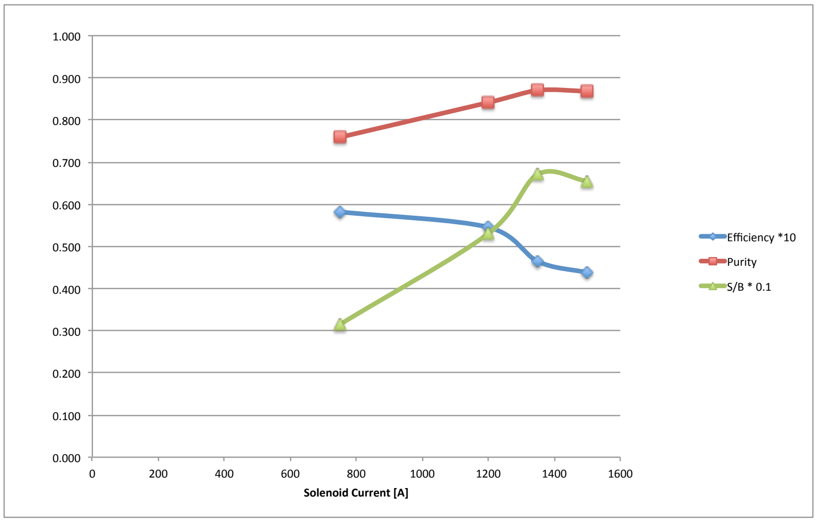

Figure 2: Plots for the reaction $\gamma p \to p\pi^+\pi^-\pi^+\pi^-\pi^0$. The *Reconstruction Efficiency* (blue), the *Signal Purity* (red) and the *Signal/Background* (green) as a function of the solenoid current. The three quantities have been scaled as indicated in the figure caption so that they are all visible on the same vertical scale. The *Signal/Background* shows little change in the $1300\,A$ to $1500\,A$ region, but then starts to deteriorate rapidly as the solenoid current decreases.

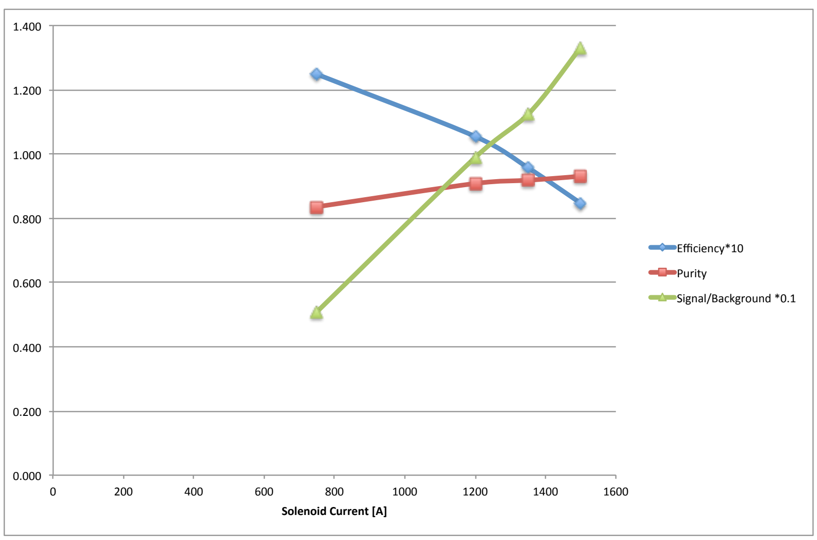

Figure 3: Plots for the reaction $\gamma p \to p\pi^+\pi^-\pi^+\pi^-$. The *Reconstruction Efficiency* (blue), the *Signal Purity* (red) and the *Signal/Background* (green) as a function of the solenoid current. The three quantities have been scaled as indicated in the figure caption so that they are all visible on the same vertical scale. The *Signal/Background* falls steadily from the highest solenoid current to the lowest. This is different from the reactions where there is a π^0 in the final state.

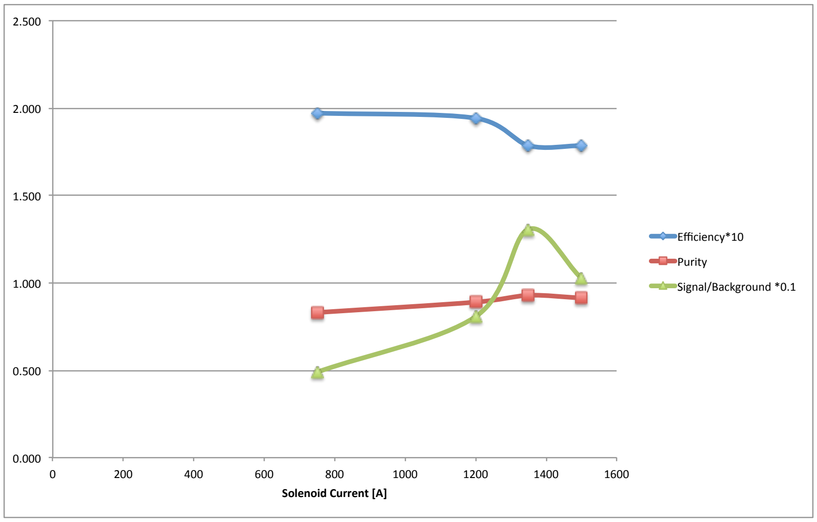

Figure 4: Plots for the reaction $\gamma p \to p\pi^+\pi^-\pi^0$. The *Reconstruction Efficiency* (blue), the *Signal Purity* (red) and the *Signal/Background* (green) as a function of the solenoid current. The three quantities have been scaled as indicated in the figure caption so that they are all visible on the same vertical scale. The *Signal/Background* shows little change in the $1300\,A$ to $1500\,A$ region, but then starts to deteriorate rapidly as the solenoid current decreases.

Interpretation

The results of the reconstruction measures present an interesting picture. In all three reactions, there is a steady increase in the signal purity as the magnetic field strength is increased. This is directly coupled to the improvement in momentum resolution. A quantity that is proportional to the magnetic field strength. If we were to only consider the purity and the electromagnetic backgrounds, it would clearly argue for running the experiment at the highest magnetic field possible.

However, the results on reconstruction efficiency paint a different picture. Here we see a steady degradation of this efficiency as the magnetic field is increased. This somewhat counter-intuitive result can be traced to the ability of the experiment to handle tracks which spiral in the central drift chamber (CDC). For tracks of low-enough transverse momentum, and thrown in a range of polar angles centered at $90°$ in the lab frame, the charged particles will execute one or more full spirals in the CDC. These confuse the pattern recognition, and reduce the probability of correctly reconstructing the final state. The exact transverse momentum for which spiralling occurs depends on the magnetic field, and increases linearly with the magnetic field strength.

Thus, we have two competing effects. One which improves performance with increasing magnetic field, and a second that degrades performance with increasing magnetic field. Which wins depends on the physics of the reactions being studied. In the typical GlueX reactions, which are well represented by the three reactions studied here, there tends to be a sharp cut-off for low momentum particles in the angular window of interest. Moving the field up or down by a small amount can significantly increase or decrease the number of particles that can spiral in the CDC.

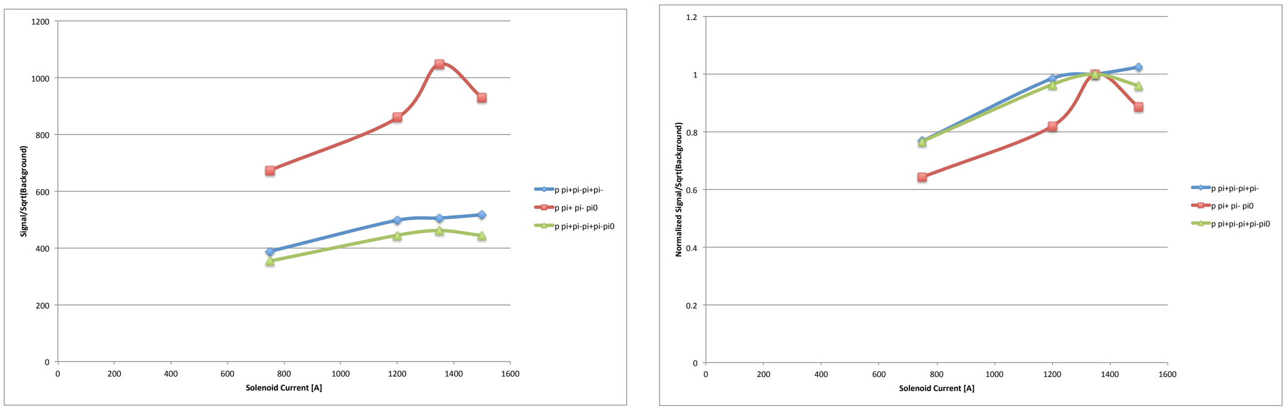

Figure 5: (left) The signal divided by the square root of the background, $S/\sqrt{B}$, as a function of the solenoid current for the three reactions. (right) $S/\sqrt{B}$ normalized to the values at $1350\,A$ solenoid current as a function of solenoid current. The green curve is reaction 1, the blue curve is for reaction 2 and the red curve is for reaction 3.

In order to fully access this, we use the measure of the signal divided by the squareroot of the background, $S/\sqrt{B}$. This is presented numerically in the above tables, but we plot it for the three reactions of interest in the left-hand of Figure 5. For reactions 1 and 2, this is approximately constant for currents above $1300\,A$, and degrades below this. For reaction 3, the behavior is somewhat different. Here the measure is roughly the same at 1200 and $1500\,A$, but shows a peak at $1350\,A$. We also show $S/\sqrt{B}$ normalized to the values at $1350\,A$ in the right-hand plot of Figure 5. This just reiterates the summary as discussed above. These results suggest that for low-multiplicity reactions, it may be possible to optimize the field setting somewhat to improve performance, while for higher multiplicity reactions, there is plateau once $1300\,A$ is reached. Based on these, a field of about $1350\,A$ is a better field setting than the nominal $1500\,A$.

Caveats

The above studies are based on our best knowledge of running conditions in GlueX, from both simulation and initial commissioning running in Fall of 2014. Realistic running conditions may differ from those that are expected, and could impact the value of the optimal magnetic field.

- If the electromagnetic backgrounds are higher than are expected, increasing the magnetic field strength might be able to decrease the rates seen in the detectors. Only real data under realistic running conditions will be able to address this.

- The physics processes simulated for GlueX which produce the low-momentum tracks that reduce reduce the reconstruction efficiency as the field increases may not reflect the actual physics processes that are observed in GlueX. The event generator has been tuned to match the existing data for photo production in the GlueX energy regime, but that does not preclude it from not correctly reflecting all the physics. In particular, a decrease in the number of low-momentum tracks in real data could change the conclusions about the optimal filed setting.

- Improved pattern recognition and rejection software could improve the experiment's ability to reconstruct events with low-momentum tracks. However, a major rewrite of the tracking code that deals with these tracks was undertaken 18 months ago, and the benefits of that work are captured in this report. While this does not preclude a second rewrite of the code providing large gains, a big improvement seems unlikely given the work that has already gone into this effort.

Summary

While there are caveats that could push the optimal magnetic field choice to a larger value, our present understanding of the physics and the experiment indicate that GlueX physics will not be adversely affected by running at solenoid currents down to about 1300 A. While it does appear that tuning of the magnetic field can enhance the performance for individual reactions, the plans for running GlueX call for an open trigger where no one reaction is favored over another. Based on this, physics running at a solenoid current of 1350 A is a good choice for the overall physics program, and for most channels of interest, will lead to better detector performance than running at 1500 A.

References

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[3] M. Staib, **Investigating the Resolution of Reconstruction for the Reaction** $\gamma p \to p\omega\pi^+\pi^-$, GlueX-doc-2538, (2014).

[4] R. Mitchell, **A Simple Analysis of a Few Reactions using Pythia MC**, GlueX-doc-2552, (2014).