GlueX/Hall-D Computing Document
GlueX-doc-2350

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for the GlueX Collaboration

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1 Introduction

This document presents the current computing plan for GlueX/Hall-D and covers both software and the computing hardware needed to analyze the expected data. This document is based on reference [1] which was prepared for the 2012 12-GeV Software Review. The material in the earlier document has been updated to reflect the work that has been carried out since that review, and attempts to present an up-to-date description of the GlueX/Hall-D software. The document is meant to be a complete and stand-alone description of our current status.

The remainder of this introduction describes the GlueX physics program and approved beam time, and then presents a timeline of activities leading up to first physics data in 2016. This section is followed by a short response to the issues raised during the 2012 Software Review. A more detailed response to the official report from that review can be found in the collaboration’s report written [2] shortly after the official report was released. Information in this document supersedes that in the earlier report. This is followed by a review of the management of the collaboration, in particular the management of the offline effort.

The remainder of the document is organized roughly the way that the software is currently used. We start with a description of the data formats, and then move on to a description of event generators and simulation of events. This is followed by a description of the relevant online systems and the triggers used in the experiment. This leads to reconstruction of events, and then physics of analysis of the reconstructed events. Data challenges are currently used to both produce large Monte Carlo samples for physics analysis as well as stress test systems on a realistic scale. We then discuss the efforts on calibration and finally the anticipated storage and compute needs of the collaboration when we are running the GlueX experiment. Various appendices provide draft versions of data management and analysis plans.

1.1 The GlueX Physics Program

Hall D at JLab was designed primarily for a single experiment, GlueX, with the design and development of both the physics program and the facilities being driven by the user community. The primary goal of the GlueX experiment is to map out the spectrum of exotic hybrid mesons [3]. The GlueX detector in Hall D has nearly 4\pi acceptance for both charged particles and photons. In order to carry out its primary physics program, it must be able to fully reconstruct final states involving many particles in a high-rate environment. The primary physics reactions are the photo production of mesons off protons using linearly-polarized photons with energy from 8.4 to 9 GeV. Figure 1 shows a cut-away rendering of the photon beam and detector.

The photon beam is derived from 12 GeV electrons impinging on a 20 \( \mu \)m thick diamond crystal that has been accurately aligned to produce linearly polarized \( \sim 9 \) GeV photons via coherent bremsstrahlung. The paths of the recoil electrons are bent in the tagger magnet, and the recoil electrons are then detected in a fine hodoscope which tags the energy of the produced photon. The tagged photons proceed down an 80 m long beam line and pass through a 3.4 mm diameter collimator before entering Hall D. They then proceed into the
GlueX detector where they interact in a 30 cm long liquid hydrogen target. During the initial phases of GlueX running, we anticipate about \(10^7 \gamma/s\) in the coherent bremsstrahlung peak incident on the target. During later running periods, this rate will be increased towards the \(10^8 \gamma/s\) design limit of the experiment.

Photons interacting in the target will produce final states involving several charged particles and photons as well as a recoil nucleon. The reactions of interest are discussed further in Section 9. The GlueX detector is in a 2.2 T solenoidal field that allows us to momentum-analyze the charged particles coming from the interactions. Charged particles pass through a thin scintillator “start counter” just outside the target that is used to provide a start time for the event. These particles are then tracked through the “central drift chamber” which is a 28-layer straw-tube based detector. They then move downstream into the “forward drift chambers” which are multi-plane drift chambers where both the anodes and cathodes are read out to provide space points along the tracks. Finally, the charged particles are detected in a downstream “time-of-flight” wall. Photons from the decay of mesons such as \(\pi^0\) and \(\eta\) are also measured by GlueX. Those emitted at angles larger than about \(10^\circ\) are detected in the “barrel calorimeter” which is a lead-scintillating fiber calorimeter with readout on both ends. Those going more forward are seen in the “forward calorimeter” which is an array of lead-glass blocks.

Events with signals in all of these detectors must be fully reconstructed and then given to the physics analysis. The development of reconstruction and analysis software by the GlueX collaboration began in 1998\(^2\). This has led to a mixture of elements in the software repository,

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1 Current safety plans call for running the magnet at about 90% of this field.
2 CVS repository entry
some of which may be considered legacy now (e.g. GEANT3) and some developed to address the current, modern landscape of multi-core computers (e.g. JANA). Experience with other experiments has shaped the collaboration to emphasize software as a major component of the GlueX experiment with considerable effort and resources applied to it early on. The data volumes\(^3\) GlueX will produce are unprecedented at JLab and are comparable to most LHC experiments.

1.2 Approved GlueX Beam time

Currently, three spectroscopy proposals have been submitted to the Jefferson Lab Program Advisory Committee for GlueX physics. The first proposal was submitted to PAC-30 in 2006 [4] with a follow-up to PAC-36 in 2010 [5]. This resulted in 120 PAC days of beam time being approved for initial running. In 2012, a proposal was submitted to PAC-39 proposing additional running at higher intensities with upgraded particle identification [6]. This proposal was conditionally approved pending more details on the planned kaon-identification system. In 2013, a separate proposal was submitted to PAC-40 describing the kaon physics that could be carried out with the baseline GlueX detector [7]. This was approved for 200 PAC days of running at five times the intensity of the initial running. In addition to the spectroscopy proposals, there are also approved experiments (using the GlueX detector) to measure the Primakoff production of the \(\eta\) meson [8] and the polarizability of the charged pion [9]. In addition, an experiment to measure rare decay modes of the \(\eta\) has been declined by the PAC [10].

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
<th>Phase IV</th>
</tr>
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<td>60</td>
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<tr>
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<td>2015</td>
<td>2016</td>
</tr>
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<td>(10^7)</td>
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</tr>
<tr>
<td>Purpose</td>
<td>Engineering</td>
<td>Commissioning</td>
<td>Physics</td>
</tr>
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</table>

Table 1: The approved beam time for GlueX divided into four phases of running. It will not be until 2016 that running with 12-GeV electron beams on a diamond radiator to produce linearly-polarized photons will first occur. Photon rates are average values.

1.3 Timeline to GlueX Physics

As noted in Section 1.2, the first running with full-energy electron beam on a diamond radiator to produce linearly-polarized photons is currently scheduled for 2016. In April of 2014, the electron beam will be brought to the tagger hall. However, no photons are expected in Hall D at that time. In October of 2014, first photon beam in Hall D is expected, but the beam energy, intensity and quality are not expected to be optimal. In 2015, it is expected

\(^{3}\text{estimated at 3 PB/yr of raw data}\)
that there will be a longer engineering run with unpolarized photon beams in Hall D, which would lead up to the 2016 running.

In Figure 2, we present the expected beam and runtime overlaid on a timeline from fall 2013 through 2017 (and beyond). This timeline also shows (in broad swaths) the activities that will be occurring throughout that period. Until about the middle of 2014, installation of the detector and readout will continue in the hall. As detector systems are installed, they will be cabled to the electronics and then implemented into the data acquisition system. Roughly speaking, the FCAL will be first in November of 2013, followed shortly after by the BCAL. The TOF system will be installed in December of 2013, and should be ready to readout in early 2014. The FDC will be next, with the detectors installed and cabled by January of 2014. This is followed by the CDC which should be ready about a month later. The start counter is not anticipated to be installed before the summer of 2014.

In the tagger hall, there is a desire to avoid full installation until after the April 2014 beam in the tagger hall, but this will need to be ready by the time of beam in the Hall later in 2014. Other smaller systems such as the pair spectrometer will be installed in early 2014. That all said, as soon as detector systems are ready to read out, it is expected that the calibration and commissioning activities that can be done with cosmic rays will start. This activity needs to be completed before the beam in 2015 arrives on target, and should be able to take advantage of the beam delivered in late 2014. These activities are described in Section 12.
In Figure 3 we summarize the current status of the GlueX/Hall-D software. As will be noted throughout this document, the major activities that remain to be completed are calibration and commissioning and the development of physics analyses.

Figure 3: The status of the GlueX/Hall-D simulation, reconstruction and analysis software. The brown shading of the boxes indicates the fraction of the work that is complete. The major piece of work left to do is calibration plugins for the detectors and developing physics analyses.
2 Response to the 2012 Software Review

Several issues and questions were raised about the GlueX/Hall-D software during the 2012 12-GeV Software Review. Shortly after the report from that review came out, the GlueX Collaboration developed a written response to the report [2]. In this section, we identify relevant comments by the review committee and summarize the GlueX/Hall-D response. The responses in this document supersede those in the earlier report.

2.1 Summary Comments

Plans delineating specific testing programs and milestones to measure progress towards at-scale production running were mixed. Hall efforts included well developed plans for successive Data Challenges progressively scaling up testing of the software and computing systems; we recommend such plans be made general practice, and make full use of JLab's available computing resources for realistic scaling tests. Such plans will be key not only to software and computing readiness but to a smooth transition from development to operations. When data taking begins, computing operations at realistic data taking levels should not be a new experience.

As described in Section 10 we carried out a large-scale data challenge in December 2012 [11]. This challenge ran on a combination of the Open Science Grid (OSG), the JLab compute farm and on the Carnegie Mellon cluster. During this challenge, about $5.3 \times 10^9$ triggers were simulated. These events are available from both Jefferson Lab and on SRM disks hosted at the University of Connecticut. Assuming typical down times, this sample represents the physics output from about 88 days of running at $10^7 \gamma/s$. This represents a significant fraction of the physics data sample expected from the Phase III running in 2016. The second large-scale data challenge is being planned for late 2013 or early 2014 and will at least double the size of the 2012 challenge.

The Committee heard little on data management plans despite the fact that this will be an important part of the infrastructure. Also plans for workload management were unevenly developed among the Halls. These are particularly important for the more data and processing intensive programs of Halls B and D. Plans in these areas should be carefully developed, and are good candidates for common solutions.

As noted in Sections 4 we have now defined most of our data formats. We have also run a large scale data challenge and these data were used to develop the PAC proposal submitted in 2013 [7]. Jefferson Lab has also established a working group to identify the needs of the physics program and develop processing tools suitable for handling this. With regard to the long-term stewardship aspects of data management, both the lab
and the collaboration have draft plans in place. The Jefferson Lab plan is reproduced in Appendix A and the GlueX/Hall-D plan is in Appendix B.

2.2 General Comments and Recommendations

Presentations in future reviews should cover end user utilization of and experience with the software in more detail. Talks from end users on usage experience with the software and analysis infrastructure would be beneficial.

With the development of our analysis package as described in Section 9 we have seen a large increase in the number of people able to carry out high-level physics analyses. The collaboration also ran a two-day workshop for over thirty people in July 2013 [12]. This went from event simulation through reconstruction, physics analysis and event selection and then to an amplitude analysis. Participants were actively involved through a detailed series of exercises. The Workshop was taped, and all the material is available on the GlueX Wiki here: https://halldweb1.jlab.org/wiki/index.php/GlueX_Analysis_Workshop_2013

2.3 Data Acquisition

Once a modest all-way data path is established, plan a mock data challenge with fake data, in particular with nominal data rates from GlueX.

As discussed in Section 10, the first online data challenge was carried out in August of 2013 [13]. This injected events in EVIO format into the event builders, moved them through the level-3 trigger processors and then transferred data to the tape silos at Jefferson Lab. As soon as the electronics are installed in the hall, and the final networks are put in place, a follow-up challenge will occur where the data is read out from the crates and sent through to the data acquisition system and then to tape storage.

2.4 Experimental Halls - General

There is good attention to multi-threading/multi-processing support to accommodate new computing architectures. Event-level, but not subevent-level (or at least not before considering event level) parallelism is being pursued, consistent with trends in HENP.

Evaluate standard code evaluation tools, such as valgrind, clangs scan-build, cppcheck, Gooda, ... for inclusion in the software development cycle. We suggest looking at an Insure++ license as well.
As discussed in Section 3.10, we do some of these tests irregularly, but we are now looking at the issues involved in making them part of our release cycle. The biggest issue at the moment is the large number of “false positives” from the tools and filtering them out.

Run a code validation suite such as valgrind as part of the routine software release procedure.

As discussed in Section 3.10, we do occasionally run valgrind, but not as part of our normal release cycle. We are now looking at the issues involved in making them part of our release cycle. The biggest issue at the moment is the large number of “false positives” from the tools and filtering them out.

Give full and early consideration to file management, cataloging and data discovery by physicists doing analysis. Report on this area in future reviews.

With the 10 terabyte output of our first data challenge, we have started to address this through the use of grid tools. In particular, the data are available to the collaboration from “storage resource management” (SRM) discs hosted at the University of Connecticut. The collaboration is expecting a similar resource at Jefferson Lab for distributing data. This is will continue to evolve as our analysis efforts expand with our second large-scale data challenge.

2.5 Hall D Specific

A series of scale tests ramping up using JLab’s LQCD farm should be planned and conducted.

As noted above, the first large-scale challenge was run in December 2012. This utilized around 140 cores on the Jefferson Lab farm, and peaked at about 8000 cores on the OSG. Since that time, we have been able to get about 350 cores on the JLab farm, this represents about $\frac{1}{3}$ of the available cores. (See reference [11] for details.)

The data volume and processing scale of GlueX is substantial but plans for data management and workload management systems supporting the operational scale were not made clear. They should be carefully developed.
A committee has been formed in an effort led by the IT division to develop a workflow system designed around the needs of 12GeV data processing at JLab. The committee contains members from multiple halls who are working closely with the IT developers to develop the system. (See Section 11 and Appendix D for more details.)

Consider ROOT (with its schema evolution capabilities) as a possible alternative for the HDDM DST format.

The collaboration considered using ROOT for the DST format. However, the collaboration has considerable experience with HDDM which still makes it an appealing choice for us. While it does not contain full schema-evolution, it does contain the schema of the data file in its header. In addition two developments since the last review give us confidence in this scheme: 1.) The successful development and use of the REST format under HDDM (see section 4.4). 2.) The development of the hddm2root tool for semi-automatic conversion of HDDM files into ROOT trees. Finally, we should point out that we do use ROOT at the next level of analysis after events have been selected from the REST format files. This is the stage where end users are most likely to use the ROOT facilities.
3 Software Coordination and Organization

This section presents the details of organization, staff resources, and development tools relevant to the offline software in GlueX and Hall D. The efforts are coordinated within the GlueX collaboration, and, at present, nearly all groups are involved at some level in the software effort, either directly in its development or through physics analysis to test the performance and identify areas that need work. As will be noted, the collaboration has a good picture of what fraction of the various software elements described in this document are done and what effort is needed to finish things. There also appears to be a reasonable match between the manpower available to complete these tasks and the expected effort needed to complete them. The collaboration also feels that the majority of our software is deployed, and actively being used for physics analysis by members of the collaboration. The majority of the remaining work is in calibration procedures that require the detectors to be in place and connected to the data acquisition system to complete. The required installation is already completed for some detector elements (FCAL) and is expected to be finished for both calorimeters, all the tracking chambers and the time-of-flight system by early 2014. The tagger system is expected to be in the same state by the late spring of 2014. While there will always be modifications to parts of the code to improve overall performance. What is needed to carry out full simulation and physics analysis has been in place since early 2013. Thus, beyond the calibration and alignment work that needs to be done, the majority of our future work with the software will be devoted to stressing the system with realistic physics analyses and then implementing needed improvements and fixes. With some beam expected to be delivered to the detector (of unknown quality) in late 2014, and a full-scale engineering run scheduled in 2015, the collaboration is confident of its ability to quickly capitalize on the first physics running expected in 2016.

3.1 The GlueX Collaboration

Software development is coordinated within the existing management structure of the GlueX collaboration. The collaboration is headed by an elected spokesperson who works closely with the Jefferson Lab Hall D group leader. The spokesperson also chooses a deputy spokesperson who is then vetted by the collaboration. These three people form the executive group in the collaboration. In addition to the executive group, there is a six-member elected collaboration board that serves primarily in an advisory role. The actual work within the collaboration is carried out by the technical working groups. This structure including the working groups that existed at the time of the June 2012 Software shown in in Figure 4. Groups can be added or eliminated by the Spokesperson. Since the time of the first software review, several new working groups have been created to respond to the evolving state of the experiment. These include a “PID upgrade” group, an ”Installation” group, a “Level-3 Trigger” group and we have formed the “Calibration” group. This latter group will take over much of the effort in the hardware groups as this will be the major activity of those members. We also created a “Data Challenge” group in 2012 that prepared for and ran the first the 2012 large-scale data challenge. That group then dissolved.
While membership in the GlueX collaboration is formal, membership in any of the technical working groups by collaboration members is not. Any collaboration member wishing to participate in meetings and either speak or vote on working group decisions is welcome to do so at any time. The working groups have overlapping memberships with most collaborators participating in two or more working groups. The collaboration is also in regular communication through video conferences at all levels. Each working group holds a video conference once every two weeks, where detailed issues are discussed and critical decisions made. Most of these working group meetings also have at least one member from the executive group present. The collaboration holds a video conference every two weeks where all the working groups report. Finally, the collaboration holds meetings at Jefferson Lab three times a year where more detailed information and discussion occur. It is also possible to participate in these collaboration meetings via video conference as well.

### 3.2 The Offline Working Group

The primary offline activities are carried out in the “Offline Software Working Group” which is responsible for coordinating the development of the offline software and responding to issues that arise when it is used. The group also organizes workshops and tutorials on use of the GlueX software and maintains a wiki-based “how-to list”\(^4\). Because of these activities,

\(^4\)https://halldweb1.jlab.org/wiki/index.php/Offline_HOWTO_List
the offline group works closely with several other working groups in the collaboration. In Figure 4, the offline group is called out in the larger box and the other groups that are involved in this effort are marked with an asterix (*).

The offline working group is led by the Software Coordinator who is an individual from the collaboration elected every two years by participants of the group. The responsibilities of the Software Coordinator are detailed as follows.

The primary responsibility is the overall coordination of the offline software effort. This includes coordinating with other working groups on software issues as well as the actual software development. The coordinator sets and enforces software related policies to maintain suitable standards. This occurs both by implementing “consensus policies” and making unilateral decisions in the case of unresolvable controversy. The coordinator is also responsible for watching the software repository and notifying responsible parties when build problems occur. The coordinator is also the primary contact for problems encountered in the software and maintains the offline software wiki page.

The coordinator organizes and chairs the biweekly offline meetings and reports of the groups activities at the larger collaboration-wide meetings, both the biweekly video conferences and the collaboration meetings. The offline coordinator is the primary person for maintenance of the software subversion repository. This work includes periodically checking out and building the software, and if this fails, getting the appropriate person to fix the issue. The Coordinator also creates and releases tagged versions of the software on a regular basis and maintains “hook scripts” and the “build systems” for the software.

The offline working group is currently responsible for coordinating and running the large-scale data challenges in the collaboration.

3.3 The Online Working Group

The Online Working Group (OWG) has overall responsibility for data taking and transfer of data to the JLab tape storage facility, configuration, control and monitoring of the GlueX detector, data quality monitoring and all aspects of experiment operation and the counting house environment visible to operators. In order to accomplish this the OWG must work very closely with the various detector groups, the Engineering group, the Trigger Working Group and the Offline Working Group.

In particular, in order to reconstruct event data the offline group needs information about the exact state of the detector at the time the data was taken. This includes translation tables, pedestals and offsets, details of the trigger used, readout mechanism used, which detectors were read out, innumerable controls settings (e.g. HV and LV), etc.

The main mechanism we plan to deploy involves database entries with time stamps and historical version information included. A few types of database schemas will be used, the exact set is currently being refined.
3.4 The Trigger Working Groups

There are two trigger groups. One handles the level-1 trigger which runs entirely in hardware on the front-end electronics. The primary software responsibility of this group is providing an accurate trigger simulation that can be applied to data. The second group is developing and implementing the software-only level-3 trigger. This group has a closer connection with the offline software effort because much of the level-3 software is based on existing offline software.

3.5 The Physics Working Group

The physics working group is the primary user of all offline and analysis software and typically the group that identifies performance and usability issues. There are currently several ongoing physics analyses of simulated data, and in the first half of 2013, there was a very large effort within this working group to fully understand the performance and limits of the baseline detector in developing the physics case for the recently approved proposal for high-intensity GlueX running. We simply quote from the PAC-40 report [14] here.

By means of detailed full simulations of several processes of interest containing strange mesons and hyperons the GlueX collaboration showed that this increase in statistics, coupled with a sophisticated multivariate analysis which uses the Boosted Decision Tree (BDT) algorithm, will result in a signal of $10^4$ events per $10^{-1}$ MeV/c$^2$ mass bin, while keeping the background contamination within 10%. Thus the experiment will be able to carry out a significant exploratory study of final states containing kaons and hyperons using the baseline GlueX setup, in which kaon identification up to 2 GeV/c is provided by time-of-flight (in the forward direction); additional kaon identification is provided by TOF in the barrel calorimeter and dE/dx in the drift chamber. Furthermore, this increase in data volume will increase the sensitivity of GlueX to reactions that may have been statistically limited in the first phase.

The PAC report went on to say

The PAC was impressed by the level of sophistication of the GlueX software and analysis which is essential for the achievement of a significant kaon and hyperon program even in the absence of dedicated hardware.

As the experiment moves forward, the physics analysis will be an ever increasing part of the software effort.

3.6 The Calibration Working Group

The collaboration has recently established the calibration working group. Institutional responsibility has been identified for this task, and this group is in the process of participating in all the detector working groups to understand globally all of the calibration plans in the
experiment. In addition, this effort is identifying all of the information that will be stored in the calibration data base, and developing a plan for how it will be implemented as well as how the calibration procedures will update this information. So far, work has started with the calorimeters, the tracking chambers and the time-of-flight system.

3.7 Manpower

Manpower commitments dedicated to software from collaborating institutions have been gathered and condensed into a form that estimates the annual available manpower over the next 3 years (2014-2016). Many of the commitments are not backed by a formal MOU, but do represent the collaboration’s good faith estimate of the software manpower that will be available. The estimates have been broken down into different categories of workers as seen in Figures 5 and 6. Figure 5 contains an “efficiency factor” as a means to normalize the units of FTEs into units of useful work. This accounts for the expectation that 1 hour of undergraduate time will generally not be as productive as 1 hour of a full professor’s time due to the difference in experience levels. The efficiency factors are subjectively derived, but have an overall effect of lowering the total manpower estimates by 16%. The first commissioning beam is expected in 2015 and the first physics beam is in 2016, so over the next three years, we estimate that about 47 FTE-years are available to work on software projects and developing physics analyses. This breaks down to roughly 14.5 FTE-years in 2014, 18 FTE-years in 2015 and 15 FTE-years in 2016. The manpower available in 2014 alone is enough to complete about 75% of the remaining tasks.

In addition to the available manpower, the progress on software tasks is also maintained in a spreadsheet. This is shown in Figure 7 where the basic tasks are listed. Also given are the estimated effort needed, the percent complete and the person responsible for the task. The total effort listed in this table has gone up by about 25% from the estimate made at the time of the 2012 Software Review. This is due to including new activities. Namely, the addition of online activities, a new category for “reconstruction and analysis Q&A”, addition of resources for regular data challenges and other smaller activities. While the needed effort estimated to complete the project increased, we also saw nearly a doubling in available manpower from the estimate made for the 2012 software review. This came about from several sources. Groups with construction projects are shifting manpower from construction to calibration efforts as completed detectors are being installed. Groups are also bringing on graduate students to work on GlueX, and much of what they will be doing is software related. Finally, several new groups have joined where the primary contribution will be in software. The bottom line is the estimated manpower went from about 25 FTE-years in the 2012 survey to about 47 FTE-years available now. From the table, the total software effort is now estimated to be 45 FTE-years and with 56% done, we anticipate needing an additional 20 FTE-years. This is well below the 47 FTE-years available within

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5 The spreadsheet where these numbers are kept is maintained in the subversion repository and can be found here: https://halldsvn.jlab.org/repos/trunk/docs/offline/ProjectProgress/manpower_survey.ods

6 The spreadsheet is maintained in the source code repository here: https://halldsvn.jlab.org/repos/trunk/docs/offline/ProjectProgress/OfflineComputingActivities2013.xlsx.
Figure 5: Spreadsheet summarizing the expected manpower contributions for software over three calendar years.

the collaboration. Figure 8 shows pie charts of both the total effort needed on each part of the software as well as what is remaining.

### 3.8 Subversion Repository

Hall D software is stored in a subversion repository\(^7\). The repository uses SSL to provide secure, web-based access from anywhere in the world. The URL can be used by a web-browser to browse the code or a subversion client to access the repository. Anyone can check out the code anonymously, but a username and password to an active JLab CUE account that is a member of the “halld” unix group is required to check anything in. The JLab IT division maintains the filesystem holding the repository with regular backups. They also maintain the web server that provides access to the repository.

The structure of the repository is set up to keep the large core of offline software in a package called *sim-recon*. The detector geometry is maintained in a separate package called *hdds*. Both of these are required to build the simulation and reconstruction software for Hall D. Versions of these are tagged separately (see Section 3.8).

The reconstruction code is written using the JANA framework described in section 8.1. The JANA framework is maintained in a separate repository that was set up to hold software

\(^7\)The repository is located at [https://halldsvn.jlab.org/repos](https://halldsvn.jlab.org/repos).
Figure 6: Bar chart summarizing the data in the “Adjusted Total” table shown in fig. 5. Only the adjusted totals are shown, where efficiency factors based on worker type are applied to estimate the effective available manpower.

used in common with other experimental halls\textsuperscript{8}. Currently, only Hall D uses JANA, but its design is kept free of Hall D specific code to facilitate others use of it.

All major software packages in the repository are tagged periodically in order to maintain standard versions by which simulation studies may be compared. Tagged versions are created on an as-needed basis, but this tends to happen about once per month. Tagged revisions are named based on the date on which the tag was made. For example:

\textit{sim-recon-2012-03-12}.

### 3.9 Third-party Software Packages

We utilize several 3rd party software packages in the Hall D software base.

- GEANT3
- XERCES (XML Parser)

\textsuperscript{8}The common repository is located at \url{https://phys12svn.jlab.org/repos}. 

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<tr>
<th>Responsible Institution</th>
<th>Responsible Persons</th>
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<th>UConn</th>
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<td>0%</td>
<td>UConn/CUA</td>
<td>Franz Klein/Richard Jones</td>
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Figure 7: Offline software activity schedule. This is a snapshot of the spreadsheet where this information is kept and tracked. See text for location where spreadsheet is maintained.
Figure 8: Software manpower needs for Hall D. The chart on the left indicates the fractions of the overall project for the listed software categories based on the activity schedule shown in figure 7. The chart on the right separates work that has already been completed for each category indicating the breakdown of work still needed.

- ROOT
- CLHEP
- PYTHIA

Since the last software review, work has begun on a GEANT4 implementation of the simulation code. Once released, it will be vetted against the existing GEANT3 code over a period of multiple months. The expectation is that the collaboration will rapidly shift from GEANT3 to GEANT4, which will make long-term code maintenance much easier. In addition, the XERCES code was updated from version 2 to version 3, which will also help with long-term maintenance. External support for ROOT and CLHEP is expected to continue, so maintenance issues from these are probably minimal. Finally, PYTHIA is heavily used to model the hadronic backgrounds in our physics samples. This stand-alone GlueX/Hall D code will need to be maintained throughout the life of the experiment, but it is a standalone package which isolates it from the remainder of the software and makes long-term support much easier.

New packages are scrutinized carefully to try and ensure that they will be supported for the length of the GlueX experiment and will bring value to the code base. These packages are maintained by the physicists and users outside of the IT division.

3.10 Code Validation and Testing

Nightly Builds

For several years, an automatic build of the GlueX/Hall-D software has been carried out nightly on all of the supported platforms. This build sends a summary including both warnings and errors to people subscribing to the appropriate mailing list. These summaries are monitored at the highest levels of the collaboration.
Nightly Jobs

Two classes of simulation and reconstruction jobs are run several times per week and the output histograms are stored for reference. Output from these jobs is also distributed via a mailing list and watched by members of the collaboration. This activity has also been going on for several years, however the histograms and output has been changed several times to reflect the needs of the collaboration.

Bug Tracking

To help track bugs and feature requests we utilize the web-based Mantis system⁹. Multiple projects are tracked using the system, but issues such as Offline software can be isolated using features of the Mantis system. The Mantis DB is reviewed at every Offline Software working group meeting.

Code Validation

Code validation tools such has VALGRIND have been looked at by the offline working group on a semi-regular basis, but no standard schedule has been set up. The challenging issue are the large numbers of false problems reported and the need to develop tools that sit on top of the output to filter this out. Manpower has not been identified to fully develop these tools.

Software Performance

Reports are typically made at our triennial collaboration meetings on the performance of the software. There has been steady improvement in both the speed of the code and the overall efficiency of the code over the last 18 months. We do anticipate taking a speed hit to the software when the collaboration switches from GEANT-3 to GEANT-4 (see Section 5.3).

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⁹The Hall D Mantis server can be accessed here: https://halldweb1.flab.org/mantisbt.
4 Data Formats

Most of the data formats used in Hall D are contained in the Hall D Data Model (HDDM) format \[15\]. This is an XML format with embedded binary that can flexibly handle many types of data. Since it is coupled to XML, the format is self-defining, while the bulk of the data is stored in the binary sections making it more compact. Within GlueX/Hall-D, several of these formats within HDDM are defined, as described in the following. Event generators output an HDDM file that is then read in by the simulation programs. HDGEANT writes as an output file in an HDDM format known as Simulated Event Storage (SEST) format. This format can be read in by the reconstruction code in JANA and the output format from these is a fairly compact Reconstructed Event STorage (REST) format. The reconstruction code can also read the online EVIO formatted data that will be produced by the experiment, and a plugin exists that can convert the SEST data into the EVIO format. Finally, higher level analysis libraries, in the JANA framework, can read in the REST data and then either write out their own REST files, or Physics Analysis ROOT TTree (PART) files. The PART files can then be used to set up input for an amplitude analysis within the amp-tools framework. All of these exists and are in common use throughout GlueX/Hall-D.

4.1 Online Data Format (EVIO)

Online event data is written to mass storage by the event recorder in EVIO format. This binary format was developed by the JLab DAQ group and has been in use since the lab began operations. It was designed to allow for very compact storage and employs a bank hierarchy where banks consist of a one- or two-word bank header followed by an array of binary data. It is used for all DAQ systems at JLab as well as for some offline applications.

The JLab DAQ group provided a facility (mc2coda) that allows us to write simulated raw data files from Monte Carlo digitizations indexed by crate/slot/channel. The facility currently implements only the most common front end board readout mode, pulse integral mode, out of the many available. It further only implements single event block mode, which is expected to be used upon experiment startup; multi-event block used for high-rate data taking will be eventually added.

mc2coda produces simulated front-end data exactly as it comes out of the front-end boards. This data is somewhat redundant, including information needed by the event builders but not thereafter. Also, some data is duplicated by every front-end board, e.g. the trigger time, so it appears many times in the EVIO record even though one copy would suffice. For this reason we developed a compression algorithm that strips the EVIO record of redundant data, and we plan to implement the algorithm in the front-end processors. Preliminary testing showed a significant reduction in the size of the event record, by as much as a factor of three, but the input test data was not realistic enough to be sure of the average reduction factor.

More recent simulations yielded a data size (uncompressed) of about 18 kB per event, giving us confidence we can achieve 15 kB per event or less after compression. Note that EVIO data expected to dominate the storage footprint of GlueX, so these results are re-
assuring. Work is under way to include electromagnetic backgrounds and improved noise injection in the simulated data which should allow us to make more accurate estimates of the true data size and the effectiveness of compression.

4.2 PYTHIA Events

Events from the bggen generator (Section 5.1) are output in an HDDM format file that is typically 800 bytes per event. These are read in by the HDGEANT program and processed. The output from this step is a SEST HDDM file.

4.3 Simulated Event Storage Format — SEST

The “smeared” output of the GEANT-based event simulation is stored in our Simulated Event Storage Format, SEST. It contains the simulated hitView structure properly factorized into pure hits and pure truth tags plus a hook for appending the reconstructed data structure (see below for REST) for people who want both hits and reconstructed results for studies. It also contains a small handful of other extended truth tags that have been introduced over the years to facilitate studies. A tool will be available to strip arbitrary SEST files down to bare hits. Such “bare hits” files will also be valid SEST files, but missing the information contained in the extra structures (in particular truth information). The rawevent plugin can read any SEST file and properly handle situations where various types of information are available or not, according to the factory schema. In particular, it is possible to convert SEST files into the Online Data Format for testing and studies.

For large-scale Monte Carlo production, the the SEST file output by GEANT is immediately processed by mcsmear and the reconstruction code and the only file retained is the output of the reconstruction software. The large-footprint SEST file is not typically stored for future use.

4.4 Reconstructed Event Storage Format — REST

A schema for a DST format was developed using HDDM. Code has been developed using this which has been successfully used in the analysis of several Monte Carlo data sets. The self-describing nature of HDDM formats and the collaboration’s extended experience with HDDM made it an appealing choice. At the same time, it is recognized that at the next step in the analysis, where we move to MicroDSTs, that the ROOT package would be the appropriate choice.

Based on this, a format built on the Hall D Data Model (HDDM) was developed known as the REconstructed STorage format (REST). The Online Data and the SEST data becomes REST data after it has been passed through the reconstruction code, dana, and the hits information and simulation-truth elements are suppressed. This REST format fully contains all information needed for physics analysis, but will yield a DST data footprint about 1% of the size of our raw data files. We gain a factor of 10 in the reduction of the event size. There is a second factor of 10 reduction due to eliminating events which are outside the tagged
window. Because of this large reduction, much of this data can be disk-based to facilitate physics analysis.

4.5 Physics Analysis ROOT TTree — PART

The Physics Analysis ROOT TTree (PART) format: This format is used to store physics data after performing an analysis with the Physics Reaction Analysis Library. There is one TTree entry for each combination of particles that potentially match the reaction that is being studied. It contains all of the relevant information needed to perform further physics analysis in ROOT. Each entry contains the kinematics of each particle in the event, along with the kinematics of any thrown particles, the kinematic fit results, PID information, and other information necessary for later analysis. This information can be pipelined into a ROOT Boosted Decision Tree to perform further signal/background separation.
5 Simulation

The simulation package for GlueX is constructed within a framework that wraps the core simulation code inside of a larger package that handles event generation, geometry and calibrations, and production of “hits” as a part of the simulated data stream. It is written in such a way that multiple core generation packages could be plugged into the same framework. This allows for exactly the same geometry and digitization to be used. The current production system uses GEANT-3 as its core simulation code, but the collaboration is well along on the transition to GEANT-4. The entire package of simulation and reconstruction is known as the sim–recon package. Within the package, the geometry description is known as HDDS[16], the core Monte Carlo is hdgeant, and the detector response is mcsmear.

5.1 Event Generators

GlueX has several Monte Carlo event generators available for use as part of the sim–recon package. These provide a variety of events that are useful for testing software, studying detector efficiency, understanding backgrounds and carrying out physics analysis. Each of these will be described in the following sections.

In addition, the hdgeant package has the built-in ability to overlay electromagnetic background on top of simulated events. It does this by simulating photons sampled from the coherent bremsstrahlung spectrum for a configurable time range and a configurable beam rate. Most of these “beam” photons will pass right through the target, but a few will interact with material in the beam line (dominated by the target) giving the correct electromagnetic background.

A PYTHIA-based event generator—bggen

The photon beam in GlueX contains not only the coherent photons, but also an incoherent component that extends from 0 up to the 12 GeV electron energy. Any photon with energy larger than that needed for single-pion photo production can undergo a hadronic interaction in the GlueX target. The purpose of our “PYTHIA-based” event generator is to simulate all of these hadronic interactions for the GlueX photon beam. This PYTHIA generator is the primary event generator for the experiment. It is used in the large-scale data challenges and is the one that will be used to produce the large Monte Carlo samples used in defining the event filtering procedures in physics analysis.

Because PYTHIA does not accurately simulate these reactions below $E_{\gamma} = 3$ GeV, a modified generator has been built that simulates eleven photo-production reactions. Above the 3 GeV energy, standard PYTHIA is used. Figure 9 shows the contribution of these channels and the total hadronic cross section as a function of the photon energy. This generator is known as bggen. In the future, it may prove necessary to tune the the bggen generator to more accurately reflect the true photo-production rates, but for the foreseeable future it appears to be quite suitable for the needs of the experiment.
Figure 9: Low energy $\gamma p$ cross-section data along with the distributions produced by the $bggen$ generator. Below $E_\gamma = 3 GeV$, a mixture of the 11 reactions listed is used. Pythia is used for higher photon energies.

**A tunable particle gun**

The simplest event generator is a “built-in” particle gun that allows one to shoot single particles through the detector simulation. The particle type, vertex location, momentum range and angular range can all be controlled by external parameters. This generator is particularly useful for studying particular parts of the detector, or the response to particular particle types.

**A coherent bremsstrahlung event generator**

The coherent bremsstrahlung event generator simulates the coherent photon beam which is produced at the bremsstrahlung target. These photons can then be propagated through the beam-line simulation to simulate and understand the beam-related and electromagnetic backgrounds that will be observed in the detector.
A simple $t$-channel process event generator—\textit{genr8}

The physics processes that are of interest in GlueX are $t$-channel production of mesons. The \textit{genr8} event generator allows the user to specify a photon beam energy and a $t$-slope for the photo production. This is then used to generate a specified meson, which is then allowed to decay via a user-specified decay chain. The decays account for the mass of the particles, but do not include any spin or angular momentum information. For a given value of $s$ and $t$, it is essentially a phase-space generator.

Physics event generators based on amplitude analysis tools

Going beyond the simple \textit{genr8} generator, it is possible to use the physics analysis tools discussed in Section 9 to produce a set of Monte Carlo events that are weighted by any desired physics amplitude. This generator is needed to be able to test the amplitude analysis as it allows one to fully include spin, angular momentum in the decay of a resonance. It also allows for the inclusion of quantum mechanical interferences between two or more resonances that all decay to the same final state.

5.2 The Geometry Description—\textit{HDDS}

The geometry definition of the GlueX detector for use in both simulation and reconstruction is maintained using the HDDS system. This is a set of XML files based on the ATLAS AGDD format. In addition multiple tools have been developed that parse the XML and output the information in other formats. Specifically, in GEANT3 compatible FORTRAN code as well as ROOT compatible C++ code. An example of the format can be seen in figure 10.

The reconstruction code also has access to the HDDS geometry via a JANA (see Section 8) interface. The interface allows extraction of any attribute from the XML using xpath\textsuperscript{10} formatted strings.

Numerous wiki pages exist that document the HDDS format and describe how to use HDDS. They can be found on the GlueX wiki in the Offline Software HOWTO pages linked from main Offline Software wiki page.

5.3 The Core Simulation Code—\textit{HDGeant}

As noted above, \textit{hdgeant} is the core detailed Monte Carlo that tracks particles through the detector. It allows for the particles to interact with material in the detector, and to record the energy and timing of signals in the active areas of the detector elements.

The GEANT-3 Code

The main work-horse of current Hall-D/GlueX simulation is a detailed GEANT-3 code known as \textit{hdgeant}. In order to run this code, it is linked to the geometry subroutines written by

\textsuperscript{10}See http://www.w3schools.com/xpath for info of path.
Figure 10: Example of HDDS formatted file defining the Forward TOF geometry.
the HDDS system, and then reads in events from one ore more event generators. The code includes not only a detailed description of all the detector elements and material, but also a detailed \( \phi \)-symmetric map of the Hall D solenoid both inside the magnet volume and in the region from the down-stream bore of the magnet to the lead-glass forward calorimeter.

**The GEANT-4 Code**

During the Summer of 2013, work on a GEANT-4 version of hdgeant was started in earnest. The most challenging aspect of this is due to the strict volume checking in GEANT-4 relative to GEANT-3. This required a substantial clean-up of the geometry definitions which has now been completed. It has also been back-ported so that both the GEANT-3 and GEANT-4 versions now use the same geometry definition.

We anticipate that the new GEANT-4 version will be tested and checked over the next several months, and expect that it will quickly replace the GEANT-3 version which we would like very much to retire.

**5.4 Truth Information**

For simulated data, it is possible to know the “truth” information about what is in the event. Over the last year, a rewrite of a number of the data structures has been undertaken to cleanly separate the truth information from the data stream. This makes it very easy, if desired, to drop this information from the data stream.

A related problem that has come to light due to our data challenge is we have not had complete recording of the decay/interaction chain of simulated particles. This was partially confused by different Monte Carlo code schemas from different packages, and partially by some bugs that had gotten into the event generators. The collaboration is now finalizing how this information will be carried forward with Monte Carlo events so it is possible to understand both reconstruction efficiencies and backgrounds in reconstructed event samples.

**5.5 Detector response simulation—mcsmear**

Much of the digitization and detector resolution effects of the simulation have been placed in a separate program called mcsmear. This allows tuning of these effects in the mcsmear code without incurring the overhead of the full simulation at every cycle of the development. Things such as drift time resolution, cathode strip resolution, SiPM dark hits, etc., are implemented in mcsmear. Eventually, this will also apply dead channel and efficiency maps to the simulated data to better reflect the actual detector conditions for a given run period. Such information will be derived from the calibration system, but the mechanism not been developed at this time. This package is common to both the GEANT-3 and GEANT-4 core code.
6 Online Software

The CODA3 software toolkit, developed by the JLab DAQ group, provides the framework that the Hall-D DAQ group customizes to create its DAQ system. CODA3 supplies front-end board readout libraries, a framework application that runs on the front-end single-board computers that must be customized for each particular crate, event builders and event recorders, packages the implement interprocess transfer of events and messages, a run control system and a package for working with EVIO formatted data.

The GlueX DAQ system employs approximately 60 front-end VXS/VME crates housing custom and commercial DAQ boards, mainly ADC’s and TDC’s, to read out all the detector elements. Readout Controllers (ROCs), Linux-based single board computers housed in the crates, use the VME bus to read data out of the DAQ boards, typically at a 1kHz rate. Note that for high-rate running the trigger rate is about 200kHz, so many triggers are read out of the front-end boards at one time by the ROCs (this is called “block readout mode”).

The front-end board delivers data to the ROC in such a way that data from multiple triggers appears in the same record, so simple concatenation of the data from multiple boards by the ROC yields “entangled” records, i.e. where data from a single event is not contiguous in memory. We plan to run a disentangling algorithm in the ROCs to reorder the data so that data from a single event is contiguous in memory, allowing for simpler analysis downstream.

Multiple event builder processes running on multi-core computers in the counting house gather data from the ROCs, build them into partial events, then pass the partial event records to a final-stage event builder which builds complete events. Buffers of complete events are then sent to the monitoring/Level-3 triggering farm.

During initial production running ($10^7 \gamma/s$) the farm will just monitor events for data quality and pass them on to an event recorder, which will write them to RAID storage at approximately 300 MB/s (for 15 kB/event). Eventually a Level-3 rejection algorithm with 10% acceptance will be applied in the farm while at the same time the tagged photon rate will be increased by a factor of 10, thus keeping the rate to tape constant at full luminosity.

The RAID system has enough capacity to hold several days worth of data. In normal operation data on the RAID device will be transferred to the JLab central tape storage facility at the same rate it is being accumulated, so the RAID system will only fill up if the tape storage facility is not available. Note that this has only rarely happened during the previous 15 years of JLab operation.

6.1 Data Quality Monitoring

A fraction of the events passing between the final event builder and the event recorder will be analyzed in the monitoring/Level-3 trigger farm. The monitoring processes use the analysis framework developed by the offline group but with custom plugins that generate ROOT histograms appropriate for online monitoring purposes. These plugins will be written by the Hall-D DAQ group and by detector groups within the GlueX collaboration. Many have been written already and some have been tested in a recent online data challenge.

The RootSpy facility, written by members of the GlueX collaboration, will be used to
collect histogram data from the monitoring processes and present it graphically to operators. RootSpy has also been tested in a recent online data challenge and other halls are considering using RootSpy as well.

6.2 Conditions and Calibration Data

The offline analysis effort requires detailed information about experiment conditions during data taking in order to properly analyze the raw data. Conditions data will be made available to offline analysis programs via a shared database application.

This system is under development, but the basic strategy is to use a simplified version of the full offline calibration database that gets mirrored onto servers available to the analysis farms. The online system will write sets of data to this conditions database indexed by time and run number. This will happen directly as part of data taking runs as well as after the fact via sweeps of relevant data from other online archive systems (e.g. from the EPICS archive, where only a small fraction of the data is relevant to offline analysis). A major reason to sweep data from online archive systems into the conditions database is to eliminate the need for offline analysis programs to access online control and archive systems, which may not be running when the raw data is analyzed.
7 Triggers

There are two trigger groups in GlueX/Hall-D. One handles the level-1 trigger which runs entirely in hardware on the front-end electronics. The primary software responsibility of this group is providing an accurate trigger simulation that can be applied to simulated MC data. The other trigger group handles the Level-3 trigger software which runs on nodes in the online computer farm. This group is responsible for developing, testing and implementing the algorithms to select the desired events to be written to disk.

7.1 The Level-1 Hardware Trigger

The level-1 trigger runs on the front-end electronics and is designed to reduce the event rate at $10^7 \gamma/s$ running to a level that can be written to tape. Because this is all hardware based, it is very difficult to have an exact simulation process for this trigger. Currently, an very good approximation of the trigger is implemented for simulated events. Work is ongoing to improve this, particularly as it is important in developing the level-3 trigger.

7.2 The Level-3 Software Trigger

The GlueX detector is designed to handle a maximum photon flux of $10^8 \gamma/s$ in the peak of the coherent bremsstrahlung spectrum ($8.4 \text{ GeV} < E_\gamma < 9.0 \text{ GeV}$). At this intensity, the level-1 trigger is expected to reduce the event rate to about 200 kHz. With a typical raw event size of 15 kB, the expected data rate of 300 MB/s will saturate the currently available bandwidth to disk for rates higher 20 kHz. A level-3 software trigger is therefore being developed to reduce this data rate to disk by roughly an order of magnitude. In addition to reducing the disk footprint and reconstruction CPU time require, this will ultimately enhance physics analysis efficiency.

For physics analyses, one is primarily interested in only those events in and above the coherent peak around 9 GeV. The level-3 trigger is designed to efficiently select events which are consistent with a high energy $\gamma p$ collision from the data stream while reducing the low energy photon events as much as possible. Due to the high photon flux required, the GlueX photon tagger will receive accidental hits from photons outside the desired RF bunch, preventing it from uniquely identifying the photon energy of the triggered interaction. Therefore, information from the downstream GlueX detector systems are utilized in the level-3 trigger selection.

Members of the GlueX collaboration have developed and implemented the software trigger for the LHCb experiment, which is one of the most sophisticated software triggers ever developed [17, 18]. Building off this experience, we have begun developing the algorithms for a GlueX level-3 trigger using a Boosted Decision Tree (BDT). By utilizing characteristics of the event such as the charged track momentum sum, calorimeter energy deposits, start counter and time of flight hits, the BDT is trained using MC simulated events to select high energy $\gamma p$ collisions. Reconstruction of some objects, such as charged tracks in the drift chambers, require much more CPU time than others. To increase the speed of the algorithm
(and reduce the required CPU for the online farm), the algorithm is staged to make decisions quickly with simpler reconstructed objects, such as calorimeter energies, before spending the CPU time to reconstruct tracks. An initial version of the algorithm was used in the 2013 Online Data Challenge which is discussed further in Section 10.4.

For high-intensity running of GlueX, it is estimated that a trigger farm with about 1000 compute cores will be needed to keep up with the data. For initial GlueX running at $10^7 \gamma/s$ in the coherent peak, it is estimated that about 200 cores will be sufficient. Thus, we anticipate having the ability to implement the level-3 software trigger at a very early stage of the experiment. As noted, it would initially be run in a mode where it tags events with the trigger decision, but allows all events through. After sufficient study of its performance, it would be run in an active triggering mode.
8 Reconstruction

Reconstruction is one of the most manpower intensive parts of the software effort. Its primary function is to extract particle properties (charge, momentum, mass) from the raw data. It needs to combine information from various detector systems and a priori knowledge of the detector to calculate these properties in physical units with accurate covariance matrices. Physics analyses can begin only after reconstruction has been performed.

Many collaborators contribute to the reconstruction code base, so a framework is required that allows them to work independently while still maintaining a coherent reconstruction package. Standard software practices such as modularity and reusability are utilized in the Hall-D software. Reconstruction is done using C++ in the JANA framework[19, 20]. JANA is a framework developed at JLab for Hall D. The framework is designed to allow multi-threaded event-level parallelism. Reconstruction is broken up into several modules called factories. Factories use data objects as inputs and produce other data objects as outputs. Figure 11 shows the current relationship between reconstruction factories.

8.1 JANA Framework

JANA implements a data-on-demand paradigm that can improve overall efficiency by limiting the algorithms run on a particular event to only those that are needed and guaranteeing that each unique algorithm is only run one time per event. JANA is designed to allow event-level parallelism via multi-threading using the pthreads package. Each processing thread contains a complete set of factory objects making it capable of completely reconstructing an entire event independent of of threads. JANA has been extensively tested to verify that the rate scales well with the number events on machines containing as many as 48 cores.

8.2 Charged Particle Tracking

Extensive work has been done on charged particle tracking software to date [21, 22, 23]. The goal of the charged particle tracking code is to use the raw hits in the Forward and Central Drift Chambers to determine the momenta of charged particles traversing the field of the solenoidal magnet. The first stage of the tracking reconstruction is the track finding or pattern recognition stage. Adjacent hits in successive layers of the forward drift chambers are associated together into segments and these segments are linked together to form track candidates using a helical model to determine initial guesses for the track parameters. Similarly, adjacent hits in successive CDC layers are linked together to form a seed for a circle fit from which an estimate for the transverse momentum can be determined. At this stage the angle of the track relative to the beam line and the z-position at a particular reference radius are determined and a CDC track candidate is formed.

In the angular range of $\sim 5^\circ - 20^\circ$ with respect to the beam line, a charged particle will produce hits in both the CDC and the FDC. The code finds candidates for FDC and CDC hits separately and matches them to form single candidates where possible. The list of track candidates provides the input to the second stage of the reconstruction: wire-based fitting.
Figure 11: Call graph produced by reconstructing simulated $b_1\pi$ events.
The rough track parameters (using a helical model) determined by the first stage are used as a seed for the fitting algorithm. We are using a Kalman Filter. At the wire-based stage, we do not use the drift-time information from the CDC wires; nevertheless this stage provides an improved guess for the track parameters because we employ knowledge of the full magnetic field (as opposed to assuming a constant magnetic field everywhere – a condition implied by using a helical model at the earlier stage). The FDC provides very precise coordinates along the wires due to the cathode readout; we found that we do not need to use the drift time information from the wire readout to get good momentum resolution.

The result of the wire-based stage provides the input to the final fitting stage: *time-based tracking*. Here we use the drift time information from the CDC wires. At this stage we have implemented *hit pruning* and *broken track recovery*. Because the track parameters determined by the earlier stage can be somewhat crude, sometimes hits due to delta rays or hadronic interactions can be associated with the track even though they may be fairly far removed from the “true” trajectory. These extra hits may cause the $\chi^2$ of the track fit to become large or cause the fit to fail entirely. Another source of poorly-fit tracks is a kink in the trajectory due to hard scattering or particle decay. We prune the hits that are too far away from the projected position along the trajectory to be considered consistent with the current trajectory. Since we are primarily interested in the track parameters near the interaction point, if the code detects a kink in the trajectory, it attempts to recover these tracks by dropping the hits beyond the position of the kink and refitting the track with the reduced set of hits closest to the target.

During the 2012 large-scale data challenge (see Section 10), about 8% of the jobs failed to complete. This was identified as being due to low-momentum charged particles spiraling in the CDC. The software tends to find many “broken tracks” rather than a single spiraling trajectory. The first fix to this was to abort events with too many found tracks. A *bandaid* to allow work to continue. During the summer of 2013, a major rewrite was done to the core track finder in the CDC. This incorporates both the axial and stereo straws equally at an early stage. This combined with other changes produced an algorithm that produces significantly fewer “broken tracks”, and hence much less chance to have too many tracks in an event. This rewrite is now part of the standard tracking code release. The overall reconstruction efficiency is slightly improved from this, but the major improvement has been substantially faster code because it no longer needs to thrash on large numbers of track candidates.

### 8.3 Calorimetry

Reconstruction code has been written for both the Forward Calorimeter (FCAL) and Barrel Calorimeter (BCAL). The FCAL code is based on algorithms successfully implemented for a similar lead-glass detector used for the Rad-$\phi$ experiment at JLab. The original BCAL code was derived from the KLOE fortran code (converted into C)\cite{24} since the KLOE calorimeter design is similar to that implemented for the GlueX BCAL.

A new BCAL reconstruction package has been implemented in 2013. This has been written specifically for GlueX, and allows for better handling of large angle tracks as well as
incorporating detailed information on the performance of the BCAL. This performance has been implemented in the GEANT simulation. The BCAL and FCAL packages reconstruct clusters independently with no attempt to combine information for single showers that may have sprayed particles from the end of the BCAL into the FCAL. The fringe field of the magnet is strong enough in that region and the gap between BCAL and FCAL large enough that it has been shown that such reconstruction would not be possible.

The reconstructed showers that are not matched to charged tracks are combined into a single list of DNeutralShowerHypothesis objects. A figure of merit is calculated for shower as being either a photon or a neutron. Neutrons are not reliably reconstructable in the GlueX calorimeters so showers with a low photon FOM and a high neutron FOM will likely lead to the reconstructed shower (and possibly entire event) being dropped from the analysis.

Work done on studying calorimetry has substantially improved performance over the last 18 months. A significant problem has been reconstructing too many neutral clusters. Utilizing information such as timing, and measured performance of the calorimeters has substantially reduced this. Work is also currently underway to see if a multivariate analysis may help improve this further. However, it is believe that this section of the code is substantially done.

![Reconstruction efficiency for 1 GeV γ](image)

**Figure 12:** Reconstruction efficiency for 1 GeV photons as a function of $\theta$ angle. The dip near 11° is due to the boundary between the BCAL and FCAL detectors.

### 8.4 Event Reconstruction

Full event reconstruction consists of numerous pieces:
• identifying all charged particles,
• identifying whether calorimeter clusters are due to photons or another type of particle,
• grouping particles together that come from the same vertex, and
• grouping vertexes together that belong to the same event.

A complete set of classes have been defined that should allow this information to be represented. Particle ID software generates a confidence level for each charged particle hypothesis and a figure of merit for each non-track-matched calorimeter cluster. Currently, the FOM is calculated using the projected and measured time difference. This can be used to help distinguish photons and non-photons.

The default tracking code fits $\pi^+$, $K^+$ and proton mass hypotheses for positive tracks but only $\pi^-$ and $K^-$ for negative tracks. The masses fit are taken from the configuration parameters MASS_HYPOTHESES_POSITIVE and MASS_HYPOTHESES_NEGATIVE which can be set at run time to include other particle types.

At this stage of the analysis, the event is classified by the number of positively-charged particles, the number if negatively-charged particles, and the number of neutral objects reconstructed. The assignment of actual particle type is made at a later stage of the analysis when the event can be examined as a whole, rather than relying only on information from individual particles.
9 Physics Analysis

In the following section we present a conceptual overview of the method for taking the outputs of reconstruction and simulation and conducting a full physics analysis. Since the core focus of GlueX is spectroscopy and the search for exotic mesons, we will primarily discuss how such searches will take place. The same general analysis principles are applicable to other types of physics analyses. Since the Fall of 2012, all of the tools needed to carry out these analyses have been in place, and members across the Collaboration have been actively using them to study physics reactions in GlueX. In particular, a major thrust was made to develop the proposal that was submitted to the Jefferson Lab PAC in summer of 2013 [7]. In addition, a two-day workshop was held in the summer of 2013 where around 30 people learned how to use the full suite of GlueX software [12]. Both of these are described later in this section.

Briefly, GlueX will study reactions of the type $\gamma p \rightarrow X^+n$ or $\gamma p \rightarrow X^0p$, where $X$ is an intermediate resonance of interest that decays to a collection of stable hadrons. For the initial phases of GlueX running, the stable hadrons of interest are $\pi^\pm$, $\pi^0$, $K^\pm$, $K_S$, $\eta$, $\omega$, and $\eta'$. The goal is to isolate some collection of stable hadrons, e.g., $\pi^+\pi^-\pi^+$, and then study the initial state and intermediate resonances. For example, the final state $\pi^+\pi^-\pi^+$ may be populated by decays $a_2^+(1700) \rightarrow f_2(1270)\pi^+$ followed by the decay $f_2(1270) \rightarrow \pi^+\pi^-$ or $\pi_2^+(1670) \rightarrow \rho^0\pi^+$ followed by $\rho^0 \rightarrow \pi^+\pi^-$.  

For any collection of final state particles we want to identify all such initial states $X$ and measure the quantum numbers (total angular momentum $J$, parity $P$, and charge conjugation $C$) of $X$, its $J^{PC}$. The quantum numbers of the initial state are determined by performing an unbinned maximum likelihood fit to the angular distributions of the data, this is discussed in more detail below. In summary the analysis process has two key steps: (1) the selection of a signal-rich sample of events in which a particular collection of final state hadrons is produced, and (2) the subsequent “amplitude analysis” of the angular distributions of these events in order to extract intermediate resonances and their quantum numbers.

9.1 Event Selection

In order to carry out an analysis, the reconstructed events, as described in Section 8.4 need to be skimmed to produce a relatively pure sample of the desired final state. The first stage in this analysis process is to define the selection criteria that isolate a particular set of final state particles. To do this, the analysis relies on the Physics Reaction Analysis Library. This library contains a set of high-level tools to facilitate analysis, all of which are accessed through simple plug-ins to the JANA framework. Because this lives within the JANA framework, it allows users to read in and write out nearly all possible data formats. It also provides a uniform access to both the data, and the high-level tools to analyze the data [25].

The workhorse of the Physics Reaction Analysis Library is sophisticated kinematical fitting software. This tool has access to the reconstructed momentum and energy of each particle in an event, as well as the full covariance matrix of errors associated with them. It knows about the multiple panicle-type hypotheses for each particle, and has access to the
primary photon information. The tool is able to use momentum and energy conservation, multiple invariant mass constraints and vertex information (primary, secondary and tertiary vertices) from the event. The fits are driven by a simple interface that identifies the desired reaction. The library is then able to set up all the possible combinatorics for a particular event, run multiple fits based on all of these, and then return the resulting confidence level (and other information) for each hypothesis that converges. While it would be possible to use this kinematic fit information directly as an analysis cut, this in turn is used as input to a multivariate analysis.

Within GlueX, the “TMVA Toolkit for Multivariate Data Analysis with ROOT” [26] is used for carrying out multivariate analyses, with the prevalent tool being the “Boosted Decision Tree.” The boosted decision tree utilizes all reconstruction variables that may be able to help resolve the actual event topology. This includes the obvious things like the confidence level from the kinematic fit, missing transverse momentum, secondary vertex information, individual track goodness of fit, particle identification information such as time-of-flight and energy loss, etc.... Utilizing the these methods, the event samples are tuned for purity and efficiency. In order to avoid unintentional bias at this stage in the analysis we use large samples of inclusive Monte Carlo generated with the version of PYTHIA tuned for photo production, bggen to create background and signal samples for training the multivariate decision process. These large samples come from the large-scale data challenge (see Section 10) as well as smaller samples consisting only of the desired final state.

As noted earlier, the multivariate analysis can be tuned to optimize the purity of an event sample, but the higher the purity, the lower the efficiency for reconstruction. A rough rule of thumb in amplitude analysis is that the smallest signal that one can reliably extract is of the same size as the background in the sample. Thus, a sample that is 90% pure would allow us to extract a signal that is about 10% of the sample size. A sample that is 99% pure has 10 times the sensitivity of the 90% sample. For most of the initial studies in GlueX, we expect that the samples will be at least 90% pure. The other advantage of this method is that it allows us to understand the dominant backgrounds for a particular analysis and develop subsequent tools that may allow us better sensitivity than the simple rule of thumb from above.

While the GlueX collaboration has studied a sample of several final states, we are planning a major push with the results from our next large-scale data challenge 10.3 where a systematic study will be carried out with all final states of interest for the first physics in GlueX. Such a list is given in Sections 9.3 and 9.5. The goal is to have many of these analyses worked out well before any data is recorded so that the resulting physics analysis can proceed quickly.

At this point in time, these analyses utilize the PYTHIA data available via SRM disks as well as smaller samples generated locally. The SRM tools have provided a useable way to skim through the large data samples on disk, either on a local disk, or by submitting a job to the OSG. The exact mechanism for conducting and managing these large-scale skims is still evolving in that we would like to efficiently accommodate a variety of user preferences. We are continuing to examine systems such at EventStore [27], used by CLEO-c, which essentially provides a mechanism to efficiently index events and provide random access to
lists of events. On the other end of the spectrum would be the skims we are currently
doing that produces a either a smaller REST file, or a RootTTree tuned for each analysis.
While such an approach results in duplication of data, it tends to make subsequent analysis
tasks easier for some users and would be ideal for sparse skims of the data. By having
several options available, users may choose the technique that provides highest efficiency for
a particular analysis.

9.2 Amplitude Analysis

Once an analyzer has decided on a set of event selection criteria to select a final state of
interest, the amplitude analysis procedure can be started. The goal of amplitude analysis
is to use all of the physical observables, e.g., decay angles and invariant masses, to extract
information about the intermediate resonances. In order to do this, one constructs a model
probability density function that describes the density of events in the multi-dimensional
phase space of observables. This model contains free parameters, which are typically pro-
duction amplitudes, masses, or widths of various resonances that are determined through an
unbinned maximum likelihood fit to the data. Typically three collections of events are input
to the fit:

(a) the actual data that pass all event selection criteria;

(b) a sample of generated signal events, uniform in phase space, that is several times larger
    than the data; and

(c) the sample (b) after it has been subjected to the event selection criteria used to select
    the data events.

The Monte Carlo samples (b) and (c) are used to incorporate the acceptance of the detector
and event selection algorithm into the physics model that describes the decay. It is expected
that the amplitude analysis process will be repeated many times during the course of an
analysis as the analyzer systematically tries different parameterizations of the physics model.
Some analyses may require hundreds or thousands of fits to be performed on the data to
evaluate systematic uncertainties in the analysis.

As expected, performing an unbinned likelihood fit with many parameters to a large
set of data presents a computational challenge. However, the problem lends itself well to
parallel computing since evaluating the log likelihood at each fit iteration reduces to com-
puting several large sums over the input event samples. Each term in the sum is essentially
the probability of producing a given event subject to the values of the fit parameters for
that iteration. Once the event samples have been distributed to multiple host machines
these sums can be computed in parallel. The only information exchange between the “fit
manager” and the compute nodes is then the values of partial sums and updated sets of
parameters. For large data samples, the fit time scales like $1/N$ where $N$ is the number
of nodes used to compute sums. Recently, graphical processing units (GPUs) have been
utilized as an economical means of performing the parallel computing needed for amplitude
analysis. Commodity GPUs available for several hundred dollars have provided one to two orders of magnitude increase in the speed at which amplitude analysis fits can be performed. Large data sets can be spread over multiple GPUs hosted by multiple CPUs. In such a configuration the popular Message Passing Interface (MPI) toolkit for parallel processing can be used to conduct fits on multiple GPUs simultaneously. The collaboration has developed an amplitude analysis framework for performing such fits. Given the easy access to GPU hardware, it is expected that most collaborating universities will be able to accomplish amplitude analysis tasks with a modest collection of GPU resources at their home institution. For each event, one only needs to input the four vectors of the final state particles into the amplitude analysis software; therefore, the disk size of the event samples is comparatively small (tens to hundreds of GB), which will facilitate easy analysis away from the centralized Jefferson Lab computing resources.

9.3 The Physics of the PAC-40 Proposal

In June 2013, the GlueX collaboration submitted a proposal to the Jefferson Lab PAC asking for 200 PAC days of high-intensity running to enable us to start of program involving final states with strange particles. An initial study of mesons and baryons containing strange quarks with GlueX [7]. Critical to this proposal was a detailed understanding of the performance of the baseline GlueX detector to correctly identify relevant final states. The driving physics is the study of the isoscalar hybrid mesons which are mixtures of \((u\bar{u} + d\bar{d})\) and \((s\bar{s})\) quarks. To disentangle these, one needs to be able to reconstruct final states containing kaons.

This proposal focused on four “typical” reactions that would be relevant for the study of hybrid mesons. The first considered the well known normal meson, \(\phi_3(1850)\) in the reaction

\[
\gamma p \rightarrow p \phi_3(1850)
\]

with the subsequent decay

\[
\phi_3(1850) \rightarrow K^+K^- ,
\]

We then looked at two expected hybrid mesons that are thought to be largely \(ss\), the \(\eta'_1(2300)\) and the \(h'_2(2600)\). These would be produced through the photo-production reactions

\[
\gamma p \rightarrow p \eta'_1(2300) \\
\gamma p \rightarrow p h'_2(2600)
\]

with the subsequent decay of the \(\eta'_1\) through

\[
\eta'_1(2300) \rightarrow K^* K_S \\
\rightarrow (K^+\pi^-)(\pi^+\pi^-) \\
\rightarrow K^+\pi^-\pi^+\pi^-,
\]
which would have a secondary vertex. The $h'_2$ was allowed to decay to the $KK\pi\pi$ final state with no secondary vertex as
\[
\begin{align*}
h'_2(2600) &\rightarrow K^+_1K^- \\
&\rightarrow (K^*(892)\pi^+)K^- \\
&\rightarrow K^+K^-\pi^-\pi^+.
\end{align*}
\]
Finally, we considered the $Y(2175)$ state which may be the $s\bar{s}$ counterpart of $c\bar{c}$ $Y(4160)$ state. There is some evidence the the $Y(4160)$ may be a non-exotic $c\bar{c}$ hybrid meson. We considered the photo production
\[
\gamma p \rightarrow p Y(2175)
\]
and subsequent decay
\[
Y(2175) \rightarrow \phi f_0(980) \\
\rightarrow (K^+K^-)(\pi^+\pi^-).
\]

<table>
<thead>
<tr>
<th>Meson Decay</th>
<th>Tracking Resolution</th>
<th>Signal Purity</th>
<th>Selection Efficiency</th>
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</tr>
<tr>
<td>$Y(2175) \rightarrow \phi f_0(980)$</td>
<td>Degraded</td>
<td>0.90</td>
<td>0.49</td>
</tr>
<tr>
<td>$\eta'_1(2300) \rightarrow K^*K_S$</td>
<td>Degraded</td>
<td>0.90</td>
<td>0.31</td>
</tr>
<tr>
<td>$h'_2(2600) \rightarrow K^+_1K^-$</td>
<td>Degraded</td>
<td>0.90</td>
<td>0.25</td>
</tr>
<tr>
<td>$\phi_3(1850) \rightarrow K^+K^-$</td>
<td>Nominal</td>
<td>0.95</td>
<td>0.67</td>
</tr>
<tr>
<td>$Y(2175) \rightarrow \phi f_0(980)$</td>
<td>Nominal</td>
<td>0.95</td>
<td>0.31</td>
</tr>
<tr>
<td>$\eta'_1(2300) \rightarrow K^*K_S$</td>
<td>Nominal</td>
<td>0.95</td>
<td>0.15</td>
</tr>
<tr>
<td>$h'_2(2600) \rightarrow K^+_1K^-$</td>
<td>Nominal</td>
<td>0.95</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 2: Efficiencies for identifying several final states in GlueX. The efficiencies do not include the reconstruction of the final state tracks.

Detailed studies were carried out for all four of these final states that included a simple request for both 90% and 95% purity and then what would happen if the position resolution of the drift chamber system were degraded by 50%. Table 2 summarizes the results of these studies for the four final states of interest. It is clear that the detector has reasonable efficiency for 90% purity, with expectations of at least $10^4$ events in each 10 $MeV$ wide bin in mass for all four final states. This is more than sufficient for a preliminary study of all of these (and related) reactions.
Prior to the 2012 Software Review, GlueX carried out a full physics analysis including an amplitude analysis of mock data to study the $\pi^+\pi^-\pi^+$ system produced in $\gamma p$ collisions. The collaboration considered this exercise its first data challenge (Section 10.1) which generated an event sample corresponded to what we might expect to accumulate in several hours of data taking at beam intensities comparable to those planned for the first production physics runs at GlueX. The Pythia-based generator, bggen, was used to generate inclusive $\gamma p$ photo production at $E_\gamma = 9$ GeV. The signal events ($\gamma p \rightarrow \pi^+\pi^-\pi^+n$) were generated at a level of about 2.5\% of the total hadronic cross section. After optimizing all analysis criteria a signal selection efficiency of 25\% and a purity of 66\% were achieved. About 20\% of the total background originated from kaons misidentified as pions. The other backgrounds included protons being misidentified as pions or extra $\pi^0$'s in the event that went undetected. This study, conducted in 2011, motivated a more detailed simulation of particle identification systems and tracking resolution along with enhancements in tracking efficiency.

The sensitivity to small amplitudes that is provided by the GlueX detector acceptance and resolution was tested by performing an amplitude analysis on a sample of generated $\gamma p \rightarrow \pi^+\pi^-\pi^+n$ events that has been subjected to full detector simulation and reconstruction as discussed above. Several conventional resonances, the $a_1(1270)$, $\pi_2(1670)$, and $a_2(1320)$, were generated along with a small ($<2\%$) component of exotic $\pi_1(1600)$. Because at the time of this work, the sample purity was insufficient for amplitude analysis, a pure sample of signal events was used to test the amplitude analysis machinery. The result of the fit is shown in Figure 13. In such a fit, the data are divided into bins of 3$\pi$ invariant mass. Each bin is fit independently, and the fit parameters are production amplitudes and phases of the different resonances that ultimately populate the 3$\pi$ final state. In this mock data sample, all of the 3$\pi$ resonances are modeled by a simple Breit-Wigner, and one can see that the both the Breit-Wigner line shape and phase can be extracted from the small exotic wave decaying into 3$\pi$ as well as the other, dominant resonances. This study indicates that with a pure sample of reconstructed decays, the GlueX detector provides excellent sensitivity to rare exotic decays. The analysis of $\gamma p \rightarrow \pi^+\pi^-\pi^+n$ represented the first full end-to-end analysis of simulated GlueX data. While the statistics are only a fraction of what we expect to collect with the final experiment, the exercise has motivated continued refinement of the reconstruction algorithms.

With the extensive work done since the 2012 Software Review including the development of the physics analysis library and the implementation of multivariate techniques, the collaboration felt that it was important to develop training for new collaboration members on the use of all the GlueX software. To do this, a two-day long software workshop was run at Jefferson Lab during the summer of 2013. Over 30 participants attended either locally or through a video conference. The event is summarized in a GlueX report [12], but we summarize the activities as follows.

The idea was to take all participants through the entire simulation, reconstruction, event selection and amplitude analysis process. This was done using a series of short lectures, followed by exercises that each participant carried out. To make sure that not time was
Figure 13: A sample amplitude analysis result for the $\gamma p \rightarrow \pi^+ \pi^- \pi^+ n$ channel with GlueX. (top) The invariant mass spectrum as a function of $M(\pi^+ \pi^- \pi^+)$ is shown by the solid histogram. The results of the amplitude decomposition into resonant components in each bin is shown with points and error bars. (bottom) The exotic amplitude, generated at a relative strength of 1.6%, is cleanly extracted (red points). The black points show the phase between the $\pi_1$ and $a_1$ amplitudes.

wasted in getting everyone’s computer to the same state of software, and “virtual box” image of a stable build of the software was distributed to each participant on memory stick
at the start of the workshop.

The workshop focuses on the $3\pi$ reaction that had been studied in 2011. Participants ran $\text{bggen}$ to produce a background sample as well as a simple physics generator to produce a three-pion sample. These events subsequently run through HDGEANT and then reconstructed using the standard software. The resulting event samples were then analyzed using kinematic fitting an other elements of the physics analysis library, and then each participant trained an ran a boosted decision tree on their signal and background samples to produce an event set. Finally, everyone ran an amplitude analysis on the resulting sample to extract the underlying physics.

Of note is that while in 2011, we had a sample purity of 66% with a 25% efficiency, in 2013 with the full suite of GlueX analysis tools, a 95% pure sample with higher efficiency than in 2011 was achieved. All of the activities of the workshop have been linked to the GlueX wiki pages, and the lectures given during the workshop were recorded so that in the future, people can watch them. It is expected that such a workshop will become a mainstay in the collaboration for training new users and updating existing ones on improvements in tools and procedures.

9.5 Physics Analyses for GlueX

The physics working group coordinates the ongoing activities for physics analysis in GlueX. This activity is both highly dependent on the GlueX/Hall-D software as well as being the group in the best position to access both performance and usability of the software. A major effort of this group took the output of the 2012 large-scale data challenge, and developed the physics case in the PAC-40 proposal (Section 9.3). The group is now identifying, and trying to develop full physics analyses for many channels of interest in GlueX with the goal of having many of these fully worked out well before first physics data in 2016. Here, we list some of these channels, and why they are seen as important first physics.

The first class of these events is single-meson photo production. The cross sections for many of these reactions can be compared to earlier (low-statistics) measurements. In addition, there are spin observables that are accessible for both unpolarized photons as well as linearly polarized photons that will allow us to demonstrate that the detector performance is fully understood. Many of these reactions are listed in the following.

\[
\begin{align*}
\gamma p & \rightarrow p\pi^0, n\pi^+ \\
\gamma p & \rightarrow p\eta, \quad \eta \rightarrow (\gamma\gamma, \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0) \\
\gamma p & \rightarrow p\omega, \quad \omega \rightarrow (\pi^+\pi^-\pi^0, \pi^0\gamma) \\
\gamma p & \rightarrow p\eta', \quad \eta' \rightarrow (\eta\pi^+\pi^-, \eta\pi^0\pi^0, \gamma\gamma) \\
\gamma p & \rightarrow p\phi, \quad \phi \rightarrow (K^+K^-, \pi^+\pi^-\pi^0) \\
\gamma p & \rightarrow \Lambda K^+ \\
\gamma p & \rightarrow \Sigma^0 K^+ \\
\gamma p & \rightarrow \Sigma^+ K_S
\end{align*}
\]
There are also initial studies to search of exotic hybrid mesons in GlueX that will be carried out quite early. These will initially focus on the simpler final states that have either been seen coupling to exotics, or those expected to couple to exotics (see reference [3] for details). These include the following reactions

\[
\begin{align*}
\gamma p & \rightarrow p\eta\pi^0 \\
\gamma p & \rightarrow n\eta\pi^+ \\
\gamma p & \rightarrow p\pi^+\pi^-\pi^0 \\
\gamma p & \rightarrow n\pi^+\pi^+\pi^- \\
\gamma p & \rightarrow p\omega\pi^0 \\
\gamma p & \rightarrow n\omega\pi^+ \\
\gamma p & \rightarrow p\eta'\pi^0 \\
\gamma p & \rightarrow n\eta'\pi^+ \\
\gamma p & \rightarrow p\omega\pi^+\pi^- \\
\gamma p & \rightarrow n\omega\pi^0\pi^+ \end{align*}
\]

There is also interest in both hyperon and cascade baryon photo production in GlueX. Beyond the simple $\Lambda$ and $\Sigma$ photo production listed above for calibration, there are other opportunities as well

\[
\begin{align*}
\gamma p & \rightarrow \Xi^- K^+ K^+ \\
\gamma p & \rightarrow \Xi^0 K^+ K_S \\
\gamma p & \rightarrow \Xi^- \pi^0 K^+ K^+ \\
\gamma p & \rightarrow \Xi^- \pi^+ K^+ K_S \\
\gamma p & \rightarrow \Xi^0 \pi^+ K^+ K^- \\
\gamma p & \rightarrow \Lambda\pi^0\pi^+ \\
\gamma p & \rightarrow \Lambda\eta\pi^+ \end{align*}
\]

Finally, while the opportunities listed in the PAC-40 proposal may not be possible until high-intensity running is done in 2017, work is ongoing to look at these and related channels in GlueX. As noted, this work is now considered a very significant and important part of the software activity in GlueX/Hall-D as it both trains users in the use of the software tools, but also drive the development of new tools and fixes to the exiting code.

### 9.6 Event Viewer

GlueX has an event viewer that has been used to aid code development since 2005 (see figure 14). The viewer provides four 2-D views of the detector and couples directly into the JANA framework. Various options can be selected and deselected on the fly to inspect a single event. Alternate reconstruction algorithms can be displayed to make it easy to visually compare their output.
Figure 14: ROOT-based event viewer *hdview2* and one of its options windows. This has been used extensively for code development, but we are currently exploring the option of using the CLAS12 developed framework *bCNU*. 
A second generation event viewer is currently under development based on the CLAS12 event viewer framework: $bCNU$. This framework is written in Java and so cannot be compiled directly into the same executable as the JANA-based reconstruction (C++). However, an effort is being undertaken (summer of 2012) to develop a communication mechanism between the two that will tightly couple the reconstruction and viewer programs to give similar functionality as achieved with $hdview2$. 
10 Data Challenges

GlueX has been carrying out Data Challenges since early 2011. These have been crucial in identifying problems with the software and providing benchmarks for improvements to the code. The first of these challenges was presented during the 2012 12-GeV Software review, and since that time two additional challenges have been carried out with two additional ones being planned for late in 2013 and follow-up ones after that.

These ongoing challenges are meant to serve many purposes, and test many different aspects of the full system. Thus, the GlueX collaboration has moved to a model where the challenges are focused on a specific need or test. The first challenge, in 2011, was meant to be a proof of principle that we could generate, reconstruct and then analyze a reasonably large data set. The first large-scale challenge in 2012 was meant to satisfy the physics needs of several working groups as well as test are production capability at JLab, on the Open Science Grid, and at an outside institution. It also allowed us to set up a way to easily distribute Monte Carlo data to many institutions. The online data challenge was meant to test data flow from from the Hall D event builders to the tape farms, and then test all the activities that occur when data are being taken. Unlike the previous two challenges, the data moved around was not meant for any other purpose.

As we move forward, there are three collaboration needs that will be satisfied by different types of data challenges.

- Large-scale data challenges: these data challenges will focus on simulating and reconstructing very large physics data samples (comparable to all of the running in 2016). The data needs will primarily be driven by the physics working group in the efforts to develop full analyses for the first channels that will be studied in GlueX. These will most likely continue to be primarily run on OSG resources, with a sizable parallel component at Jefferson lab, and smaller efforts on clusters outside JLab. These jobs are run using the generator files as a starting point, and only outputting the resulting REST (DST) files. The intermediate GEANT output (SEST) is not saved.

- Online data challenges: these will continue to run, with data originating at sources as close to the detector as the installed hardware and networks will allow. It will also provide a environment to fully develop the monitoring software, as well as develop alarm systems, and provide a realistic testing ground for level-3 trigger development. It will also make sure that the data pathway from Hall D to the tape silos is robust, and that failure systems work. While these data may serve some informational purpose, they are unlikely to be used for physics analysis.

- Production data challenges: these will test the ability of the JLab farm to handle the production load expected from running of the experiment. Initial testing will need to demonstrate that first 1000 and then several thousands of cores can simultaneously be running GlueX jobs with a high probability of successful completion. This can be tested as part of a large-scale challenge, as long as there is sufficient priority to get the
needed cores. A second, and perhaps more important part of this would include the
testing of running a large-scale production of jobs using data files on the tape-silos.

10.1 The 2011 Data Challenge

In order to test the GlueX analysis framework, we decided to attempt to carry out a full
GlueX analysis on simulated data. This included an amplitude analysis of mock data to
study the $\pi^+\pi^-\pi^+$ system produced in $\gamma p$ collisions.

The Pythia-based generator, bggen, was used to generate inclusive $\gamma p$ photo-production
events at $E_\gamma = 9$ GeV. The event sample corresponded to what we might expect to accumulate about a day of data taking at beam intensities comparable to those planned for the first production physics runs at GlueX ($10^7 \gamma/s$). In addition, signal events ($\gamma p \rightarrow \pi^+\pi^-\pi^+n$) were generated at a level of about 2.5% of the total hadronic cross section. In fact, this event sample was limited by the available disk storage (~ 50 tera bytes) and the use of the SEST format for storing the output of the GEANT simulation (see Section 4.3).

During this study, a number of issues with the charged tracking, particle identification calorimeter reconstruction and overall management of the data were observed. In the end, after optimizing all analysis criteria available, a signal selection efficiency of 25% and a signal-to-background ratio of 2:1 were achieved. This purity is not good enough for an amplitude analysis, so a final amplitude analysis studies had to be done on pure signal samples.

These results spurred a large effort devoted to improving many aspects of the offline software. In particular, a significant improvement was the development of a compact format as output from the reconstruction code, the REST format (see Section 4.4).

10.2 The 2012 Large-scale Data Challenge

Detailed planning for the next data challenge started shortly after the 2012 12-GeV Software Review, but the need was solidified by work within the collaboration to study and compare several proposed schemes to add a kaon identification system to GlueX. This work pushed the development of a physics-analysis package (see Section 9) and the need for a much larger bggen sample to study events containing kaons.

A number of small tests led up to the December 2012 run of the data challenge. About 5.3 billion photo-production events in the narrow window in $E_\gamma$ where we will have linearly polarized photons (8.4 to 9.0 GeV). This sample corresponds to about 88 days of actual running at $10^7 \gamma/s$ on target, as expected in 2016. A detailed report was written on this work [11].

The 2012 challenge ran on a combination of the OpenScienceGrid (OSG), the JLab compute farm and a 600-core cluster at Carnegie Mellon. Of the $5.3 \times 10^9$ triggers simulated, about $4.0 \times 10^9$ were produced on the OSG, about $1 \times 10^9$ were produced at JLab, and the remaining $0.3 \times 10^9$ were generated at Carnegie Mellon. The entire production took about 2 weeks (with hiccups), but not all resources ran at 100% efficiency. During the peak, about 7000 cores on the OSG, 140 cores at JLab and 200 cores at Carnegie Mellon were utilized.
The original plan had been to produce $10^{10}$ events, but the challenge was ended early after it was discovered that about 8% of the jobs failed to end, and then timed out on the clusters. At both JLab and Carnegie Mellon, these jobs simply vanished, but on the OSG, they kept getting resubmitted, so after a several days of running, nearly all the OSG jobs were ones that would never finish. As noted in Section 8.2, these problems were caused by low-momentum charged particles that spiraled in the CDC. The reconstruction code tended to reconstruct these as a very large number of short track segments that filled memory. Even with these problems, these events were extremely useful, and were made available from both Jefferson Lab and on SRM disks hosted at the University of Connecticut. As discussed in Section 9, they have been central to all of the physics analysis carried out since they were generated. We refer to this effort as Data Challenge I.

### 10.3 Future Large-scale Data Challenges

A follow-up large-scale data challenge is also being planned for late in 2013 or early 2014. This challenge would aim to reach the $10^{10}$ trigger point that was the goal of the 2012 challenge. This is also driven by physics analysis needs, with much of the on-going work wanting an event sample produced with the most-up-to-date version of the software. In addition, background and noise will be included in this sample, as well as keeping events outside of the narrow photon-energy window where we have linear polarization. We refer to the next large data challenge as Data Challenge II.

### 10.4 The 2013 Online Data Challenge

In addition to the Offline Data Challenge discussed in Section 10.2, understanding how the online system works with GlueX-sized data samples is also quite important. The first major test of this was carried out in August 2013 and is summarized in a report [13]. Since the front-end crates were just being installed and the powerful servers planned to run event builder processes had not arrived, events were injected into the system by a simulated final-stage event builder that just got events from a simulated raw data file (\texttt{bggen} sample converted from SEST to EVIO format). The full system downstream of the final event builder was tested, however.

The data path past the final event builder is as follows. From the simulated final event builder events were transferred to the level-3 trigger farm, and then on to an event recorder that wrote data to RAID storage. The data was then copied to the JLab tape storage facility. The level-3 farm initially ran in a “pass-through” mode where events simply moved through with no action. More sophisticated level-3 algorithms were also tested, but software problems prevented extensive running in this mode. This test ran for several days and was able to exercise all the hardware and network connections that were in place at the time.

A fraction of the events prior to and after the level-3 farm were transferred to monitoring farm nodes for online analysis. Note that it is important to compare the pre- and post-level-3 event samples to check that the rejection algorithm does not introduce unacceptable biases.
The basic data flow and monitoring operation are portrayed in Figure 15. We refer to this first online effort as *Online Data Challenge I*. 

**Figure 15**: A schematic showing the data flow tested during the 2013 online data challenge. See the text for a full description of the figure.

### 10.5 Future Online Data Challenges

Once enough crates are installed in the Hall and network connections have been established to them, we plan to hold a follow-up online data challenge where the data originates in the crates in the hall (rather than in a simulated final-stage event builder). Data will then be transferred by the ROCs to the two-stage event builder system where data from the individual crates gets built into full events. From there the events will pass through the L3 farm to the event recorder and then to RAID storage. About 10 TB of data will be transferred to the tape storage facility via the production automated transfer system (currently working). As in the previous data challenge, pre- and post-L3 monitoring will be performed, and histograms will be presented to operators via the RootSpy system.

It is anticipated that this will be done in late 2013, and similar challenges will continue as more of the experiment comes online. These efforts will be important in the development of full monitoring software and alarm systems. They will also be a realistic testing ground for level-3 trigger development. We refer to the next online challenge in late 2013 or early 2014 as *Online Data Challenge II*. 

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10.6 Production Data Challenges

In addition to the large-scale data challenges which generate data needed for physics analysis in GlueX, it is also critical to test the data production tools (hdgeant, and JANA) directly on the JLab farm nodes where the real data will ultimately be processed. Some of this was tested during the 2012 large-scale data challenge (Section 10.2), where about $10^9$ events were produced on the JLab clusters. However, due to farm priorities set at the time, this effort had a sustained usage of about 150 cpu cores. In work currently leading up to the next large-scale data challenge, this has now peaked at about 350 JLab cores. This effort is expected to scale up to about 1000 core by the time of the next large-scale data challenge (as long as there is sufficient priority).

Another aspect of these data challenges will be to test production of data at Jefferson Lab, where the data are stored on tape. This is the anticipated running mode of GlueX/Hall-D and testing the tape staging systems in conjunction with the Hall-D/GlueX software is quite important. Such an effort will require prepositioning sufficient GEANT output (either SEST or EVIO format) on the JLab tape silos to be able to saturate offline production. As these GEANT files are not typically saved, a special Monte Carlo run will need to be made to produce these. Fortunately, these do not need to all be unique events as long as enough of them are unique. It will likely be reasonable to only generate $10^8$ of these events, and then put many copies of each on tape. Thus, the production system can be tested, but the actual output from this effort is not likely to be useful for physics. Production of such a Monte Carlo sample could easily be produced in a day or so of running on the JLab farms. We refer to the first of these efforts as Data Challenge III and anticipate that it will occur in early 2014.
11 Workflow Tools

11.1 Tools Used During the Data Challenge

During the GlueX/Hall-D Data Challenge I, the events were broken into jobs each containing 50,000 events. Thus, over 100,000 DST files in REST format were produced. Tools were also written to combine multiple files into larger files. Management of these has mostly proceeded using Open Science Grid tools with the srm facility. For jobs run on the Open Science Grid, OSG tools exist to both manage workflow as well as cataloging the output jobs.

For GlueX/Hall-D, a set of Perl scripts, backed with a MySQL database, were developed to manage jobs at JLab for Data Challenge I. These functioned but it is expected that the new workflow tools will supersede them. The jobs run at Carnegie Mellon were managed by hand using the PBS system at CMU and the output was then copied to the UCONN srm disks.

11.2 Development with the JLab IT Division

A joint effort between IT Division’s Scientific Computing Department at JLab and the Experimental Halls in the JLab Physics Division has started to develop workflow tools: a set of software objects to aid large-scale computing tasks, principally the processing of real or simulated event-based experimental data. A committee was put together in the summer of 2013 by Chip Watson, the head of Scientific Computing, and it has produced a set of requirements [28] (see Appendix D) based on numerous discussions and meetings. A working group has recently been formed to turn those requirements into a more formal software specification.

The goal is to provide a set of tools to facilitate management of a processing project consisting of a large number (tens of thousands) of individual computing jobs. At the Lab, heretofore, only job-level management tools have existed. A simple and common case has each job processing one input data file and producing a corresponding output file and other auxiliary files. More complicated scenarios should also be supported, of course. The tools will provide a job submission function, job accounting, output file accounting, a facility for optional re-submission of failed jobs, with users having the ability to customize each function or decision based on the specific nature of the project.

Such efforts are not unique in high energy and nuclear physics, but after a study of the available products the committee concluded that, at least to start, a local solution would be developed. Tools available for the grid were considered heavyweight and not trivially adapted for the JLab Farm. Products from the life sciences are not oriented toward event-based data.

One complication in development of a Lab-wide tool is the contrasting computing paradigms used by Hall B and Hall D, the two major customers for the product. Hall B uses the Clara framework, a service-oriented architecture, where the jobs are managed by the Clara Orchestrator, whereas Hall D uses a traditional batch job submission style using the Auger system that has long been supported by Scientific Computing. Despite this difference, the
committee thought that the core concept of a "job" can be abstracted so the workflow tools can manage projects effectively independent of the underlying processing model. As the tools develop, GlueX/Hall-D is ready to serve as a test bed for them.
12 Calibration

In order to be able to extract physics from the data collected in GlueX, it is necessary to have procedures in place to calibrate the detector elements. Calibration data must be stored in a robust calibration database that both allows easy access to the correct calibrations as well as a simple mechanism for updating these as a function of run conditions and run periods. The database package CCDB [29] has been designed for GlueX and the software interfaces to the package. While only a fraction of the calibration constant sets that will be necessary have been fully specified, work is ongoing to realize them fully. Implementing the calibration software into the analysis chain and developing robust procedures for getting updated calibrations and alignments into the data base, and in use in the analysis software is estimated to be the largest remaining offline software effort to complete in terms of estimated FTE-years (see Section 3.7).

To facilitate this work, the JANA framework provides a well-defined API for accessing calibration constants from the reconstruction code[30]. In addition, a shell-like tool exists that allows one to browse the and modify the database.

12.1 Calibration and Conditions Databases

The Calibration and Conditions DataBase (CCDB) was designed based largely on experience with CLAS at JLab. The design accommodates the JANA API making it easy to begin using it with the sim-recon package. The CCDB can use multiple technologies on the backend, specifically MySQL, SQLite, and ASCII files in a well-defined directory tree.

12.2 Detector Calibration and Alignment

Implementation of calibration procedure for each of the major detector systems is currently underway with the work starting in the relevant technical working group (see Section 3), but being coordinated by a single person. This work will shortly shift to a calibration working group. The activity within the groups to develop tools that will be needed for these calibration and alignment procedures is ongoing. In the following, we discuss the current state for the major detector systems.

Beam line

Calibration of the photon beam for GlueX consists of measuring the photon energy boundaries and relative time offsets for the tagging counters, the energy boundaries and time offsets for the pair spectrometer counters, the absolute tagging efficiency of each of the tagging counters, and the relative normalization of the coincidence rates in the pair spectrometer to the rates in the tagger. The order of the photon beam energy calibration is as follows. First, the coincidence rate spectrum in the pair spectrometer (PS) is taken and fitted in the end-point region to an empirical function to locate the end-point. This information is used, together with the electron beam energy provided by the accelerator, to set the absolute
energy scale in the PS. A look-up table based on the field map of the spectrometer and the known positions of the PS counters is used to transfer this absolute calibration to the entire photon spectrum covered by the PS. A similar look-up table will be available for the tagging counters as well, providing a well-established relative energy calibration within the tagger arrays. Coincidences between the pair spectrometer and the tagger will be used to transfer the absolute energy calibration from the pair spectrometer to the tagger arrays.

The order of relative timing calibration within the tagger and PS counters is as follows. The PS is equipped with a second array of low-segmentation counters which are designed for precise timing of pair tracks. The relative time offsets between these counters will be calibrated by taking coincidences between all possible pairs of left-right counters, and adjusting the timing so that all of the offsets are aligned with one of them. Once this is done, the time measured in the pair spectrometer provides a single reference against which all of the counters in the tagger arrays will be calibrated. The same calibration dataset which is used to establish the timing calibration will also be used to measure the relative beam intensity normalization between each counter in the tagger and the corresponding coincidence rate in the PS. Absolute calibration of the photon beam rate in terms of the rates in the individual tagger counters will be performed using special runs at very low beam intensity, in which a total absorption counter is placed in the beam.

A data needed to perform this calibration procedure are contained within the standard GlueX data stream. Software to analyze the data and store calibration constants in the calibration database will be written in the form of a standard consumer within the GlueX offline framework. This software has not been written yet, but will be simple to implement and debug, taking advantage of cross-checks between the tagger and the PS. Calibration of the gains and offsets for the real-time measurement of the photon beam centroid in the active collimator will be performed in special scans to be carried out at the start of a run, and at regular intervals throughout a run period as required. Special software for calibration and monitoring of the beam position signal from the active collimator has been prototyped using test data collected with this device in the Hall B photon beam, with the final version currently under development.

Central drift chamber

The central drift chamber (CDC) needs to be both accurately aligned with the other tracking elements, but also include accurate time-to-distance relations for converting measured drift times to coordinates along the track. Software will also need to be able to track changing conditions within the detector, such as pressure and temperature, that may affect these calibrations. Such procedures were developed and used on a small prototype built in preparation for the final detector, and the results of this work have been published [31].

Small scale efforts have been carried out to accurately align the position of each wire in the CDC, but to date have been limited by the small number of channels that could be read out with the chamber at Carnegie Mellon. The detector was delivered to Jefferson lab at the end of October and is scheduled for installation in Hall D in early 2014. After that time, it will be possible to readout the entire chamber utilizing cosmic events. This will allow a
full-scale alignment of all the wires in the CDC.

Time-to-distance calibrations are based on functions matched to GARFIELD calculations with different gas mixtures. Interpolation between mixtures is done to get the optimum table. This final calibration can be tested with cosmics, but the final calibration will need to wait for full magnetic field, and will probably be with first engineering beam in the hall.

Work is currently ongoing to make sure that all the relevant tables and constants are defined in the database and development of JANA plugins to do the calibrations will start soon.

**Forward drift chamber**

The forward drift chambers (FDC) face similar issues as the CDC, and similar work has been carried out with prototypes. It is expected post-survey alignment will be done using photon beam with the magnetic field off. The resulting “straight-line tracks” can then be used to align both the individual FDC packages to each other, but also the relative alignment of the CDC and FDC. The code to carry out this straight-line tracking has recently been written.

The FDC is currently in Hall D with installation expected to be finished by the end of 2013. While some studies will be possible with cosmic rays, due to the geometry of the detector, full calibration and alignment will need to wait for engineering beam in the hall.

As with the CDC, work is currently ongoing to make sure that all the relevant tables and constants are defined in the database and development of JANA plugins to do the calibrations will start soon.

**Forward calorimeter**

Currently, the forward calorimeter (FCAL) is the most advanced in calibration; a full calibration has been performed using simulated data. The procedure is fairly standard in calorimeters, and will utilize $\pi^0$s where both decay photons are observed in the FCAL. Constants for individual channels are then tuned to optimize the resulting two-pion invariant mass at the mass of the $\pi^0$.

The FCAL is fully installed in Hall D, and studies with cosmic rays are expected to start by late 2013. The work remaining is to integrate it into the JANA framework and the calibration database.

**Barrel calorimeter**

Work on the the calibration of the barrel calorimeter (BCAL) is only beginning, although it is anticipated that a similar procedure as is done in the FCAL will ultimately be used. Studies need to be carried out to determine the best choice of photons to use.

The BCAL is installed in Hall D and it is expected that initial calibration work will be carried out using comics in conjunction with the CDC. This pair of detectors will allow us to know the position of cosmic muons with high precession. All procedures still need to be integrated in JANA and the constants need to be defined in the database.
Time of Flight

The time of flight (TOF) is a crossed, two-layer scintillator hodoscope, with each bar read out at both ends. The modules have been tested and give the accuracy required for GlueX, but the final procedure for calibration has not yet been worked out and implemented in the database.

All of the modules have been delivered to Jefferson Lab and installation is planned for late 2013.
13 CPU, Storage, and Bandwidth Requirements

13.1 CPU Requirements

The scale of the computing resources need to analyze GlueX data is set principally by the trigger rate, running time, the size of events, and the time it takes to reconstruct an event. In addition to the real data, simulated data sets will have to be generated to calculate efficiencies and study systematic effects in the real data. Any estimate of computing must take into account this simulation. Statistical errors from analysis of the simulated data must be comparable or preferably smaller that that coming from the real data, therefore the amount of simulated data is also driven by the raw data rate.

The GlueX hardware trigger is designed to accept the entire hadronic rate in the hydrogen target. The hardware trigger rate is therefore set by the beam intensity and the hadronic cross section. For Phase II and Phase III running, at $10^7 \gamma/s$, this means a rate of about 20 kHz.

In later phases of running we will have higher beam intensity but will also have a Level-3 software trigger that will keep the rate being written to tape close to that of Phases II and III. As a result many of the assumptions that apply to these early phases will hold at least approximately for later GlueX running. For early phase running, the computing farm infrastructure for a Level-3 trigger farm will exist, but not with the computing power necessary for the high rate running in later phases when a software trigger decision must be rendered for every event. Initially the farm will be used for data monitoring and to prototype trigger algorithms in a mark-and-pass (non-cutting) mode.

The time to reconstruct a simulated event has been measured on a 2.8 GHz Nehalem processor to be 133 ms. The measurement was done on a sample of minimum-bias events, including all significant sources of hadron photo production on the proton. A simulated hardware trigger was applied to the generated data sample before inclusion in the sample.

To make an estimate of the amount of CPU power required we take a steady-state model, based on Phase III running assumptions. We assume that GlueX data is being produced at an average rate which takes into account running efficiency and machine shutdown periods and that this goes on ad infinitum. We enumerate all of the computing tasks that are generated from this incoming data stream, including the generation of simulated data and any repetition factors (see below) for real or simulated data processing, and calculate the resulting rate of consumption of computing resources. Any offline compute complex must provide this rate of computing or the data taking will overtake the computing and an ever lengthening backlog will develop, year-over-year. Capacity higher than this rate means that there will be idle time on some compute nodes, but the latency for each step will be reduced. Note that we do not make any assumptions about the latency of any component step; these are set by requiring a rate of event processing that keeps up. We view this level of computing power as an acceptable lower limit on the size of the offline farm.

Commonly, large-scale reconstruction of the real data, as well as simulation and/or reconstruction of Monte Carlo data, is done more than once. Each iteration generates lessons for the next. We account for this possibility with a independent repetition factor for each
Parameter | Value
--- | ---
trigger rate | 20 kHz
event size | 15 kB
running time per year | 35 weeks
time to reconstruct an event | 133 ms
ratio of simulated events to real events | 2
time to generate a simulated event | 67 ms
time to reconstruct a simulated event | 133 ms

Table 3: Basic assumptions for computing requirements. All computing times are for a single core.

<table>
<thead>
<tr>
<th>Activity</th>
<th>CPU-need, 1 iteration</th>
<th>Number of iterations</th>
<th>CPU-need</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>45</td>
<td>2</td>
<td>89</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>894</td>
<td>2</td>
<td>1,789</td>
</tr>
<tr>
<td>Skims/mini-DST</td>
<td>89</td>
<td>5 × 2</td>
<td>894</td>
</tr>
<tr>
<td>Physics Analysis</td>
<td>89</td>
<td>10 × 1</td>
<td>894</td>
</tr>
<tr>
<td>Simulation</td>
<td>2,683</td>
<td>2</td>
<td>5,366</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>9,033</strong></td>
</tr>
</tbody>
</table>

Table 4: CPU needs. All needs are in terms of cores on a 2.8 GHz Nehalem processor.

step in our estimate, e.g., every raw data event will have to be reconstructed twice. In other words, maintaining steady-state almost certainly means having enough computing to do some things more than once.

In addition to the main tasks of reconstruction and simulation, we account for other computing tasks:

**Calibration** We assume that some fraction of the data will need to be reconstructed for calibration purposes. The resulting data is not appropriate for physics analysis.

**Skims/mini-DST production** The production of skims for various topologies and the production of corresponding mini-DST files will require some resources.

**Physics Analysis** We account for the JLab-resident physics analysis effort. This is exclusive of GPU-based amplitude analysis (see Section 9).

The basic assumptions that we use here are for generic running in Phase III. These are shown in Table 3. Table 4 shows assumptions for each computing task and the size of the corresponding CPU requirement in this model expressed as a number of cores. The computing complex needed to keep up with all activities is then equivalent to about nine thousand cores.
<table>
<thead>
<tr>
<th></th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days of running</td>
<td>60</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Trigger rate (kHz)</td>
<td>2</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Number of events</td>
<td>$5.18 \times 10^9$</td>
<td>$5.18 \times 10^{10}$</td>
<td>$1.04 \times 10^{11}$</td>
</tr>
<tr>
<td>Reconstruction time (days)</td>
<td>0.8</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Simulation time (gen. + recon.) (days)</td>
<td>2.4</td>
<td>24</td>
<td>48</td>
</tr>
<tr>
<td>Recon. + Sim. time (days)</td>
<td>3.2</td>
<td>32</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 5: Wait times for all steps shown in table 4 on a 10,000 core farm for approved GlueX running. (includes multiple passes)

Another view of these estimates is to ask how long some of these steps will take on a given compute farm to process 1 year of data. Table 5 shows the number of days required to complete a single pass at reconstruction and simulation for the three Phases, using the same assumptions as above, on a farm with 10,000 cores. Note that these times will only be obtainable if all cores are dedicated to these activities. For Phase III then, to do a complete cycle of reconstruction on the entire data set will take about two weeks, to do reconstruction and the required simulation about two months.

### 13.2 Tape Storage Requirements

The steady-state model described in the previous section implies a rate of events of various types being read and written to tape. Even if the data is meant to be accessed from disk, we intend to archive all data on tape, with the exception of the pre-reconstruction simulated data. We assume that the reconstructed DST data is 1.5 kB per event (a factor of 10 compression from the raw data) and that all events will be reconstructed. We also include repetition factors, despite the possibility that some of the tapes from early iterations may be recycled. The amount of data written to tape is summarized in Table 6.

The bulk processing being described also implies an average bandwidth to and from tape. To estimate this, the bandwidth for reading input as well as writing output is included. The sum of all activities, in steady state is 1.0 GB/s. Physics analysis is not included. Current tape technology in the JLab tape library can go at 100 MB/s. On average then, 10 drives will be need to support data analysis.

### 13.3 Disk Use

Disk storage is driven by the size of data sets necessary to support various analysis activities. The following classes of data will have to be permanently accessible from disk:

**Calibration disk** Disk space to support on-going calibration development and production.

**Coherent-peak skim DST** Reconstructed data selected from the coherent bremsstrahlung peak. This is the principal data set for GlueX.
Data Type | Rate to Tape (PB/year)
---|---
Raw data | 3.2
Calibration | 0.06
DST (Reconstructed) | 1.3
Skims | 0.6
Simulation DST | 2.5
Total | 7.7

Table 6: Average rate of writing data to tape.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration disk</td>
<td>62 TB</td>
<td>124 TB</td>
</tr>
<tr>
<td>Coherent-peak skim DST</td>
<td>25 TB</td>
<td>50 TB</td>
</tr>
<tr>
<td>Inclusive background simulation DST</td>
<td>265 TB</td>
<td>531 TB</td>
</tr>
<tr>
<td>Individual analysis skims (10 analyses)</td>
<td>207 TB</td>
<td>415 TB</td>
</tr>
<tr>
<td>Mini-DST’s for amplitude analysis</td>
<td>7 TB</td>
<td>15 TB</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>567 TB</strong></td>
<td><strong>1134 TB</strong></td>
</tr>
</tbody>
</table>

Table 7: Disk requirements for analysis in terabytes.

**Inclusive background simulation DST** Simulation of minimum bias events with appropriate cross-section weighting. This represents the background for all physics channels of interest.

**Individual analysis skim** Skims of the coherent-peak DST and the inclusive simulation DST for individual analyses. These are used to study cuts and perform the physics analysis, tailored to a particular analysis. Events may contain additional analysis dependent data.

**Mini-DST’s for amplitude analysis** “4-vector” files appropriate for amplitude analysis.

The total disk footprint for each are summarized in Table 7 separately for Phases II and III. (Phase I data is not a significant contribution.)

In addition to the disk space above, there will be a need for a general work disk of about 300 TB for staging files and scratch space. The total of all of these areas comes to 2.0 PB.
A The Jefferson Lab Data Management Plan

Summary Jefferson Lab [33] requires that valuable data generated in connection with the lab's research program be managed in a way that allows future and outside researchers to be able to work with the data, either to validate a result or to conduct additional studies on the same data. The scope of this mandate includes the preservation of the data, documentation of the data format, the preservation of associated data such as run conditions and calibration databases, and the preservation of software used to read and process the data.\footnote{This Jefferson Lab Data Management Plan (DMP) is distinct from the DMP which will be required by DOE for all new research proposals submitted in response to solicitations issued on or after 10/01/2013, but can be referenced as part of writing a research DMP.}

Responsibilities Researchers and collaborations conducting publicly funded research at Jefferson Lab are responsible for having and following a data management plan to preserve their data and the ability at some future date to reanalyze that data. The laboratory makes available to the researchers a number of capabilities and tools to facilitate fulfilling this responsibility.

The following data and metadata must be addressed by the researchers' data management plan:

1. raw data
2. processed data, where the processing involved significant computing resources, or where the processed data is much more accessible for additional investigations (example: first pass event reconstruction, where the processed data includes tracks, energy deposition, etc.)
3. run conditions (machine energy, polarization and intensity, target, etc.)
4. electronic log books containing pertinent data for subsequent data analysis (e.g. periods of for which the data is known to be of poor quality)
5. calibration database(s)
6. geometry database(s)
7. analysis software sources, make files or build scripts, documentation for building and using the software, and the for all software upon which the analysis software depends.

All valuable raw and processed data should be stored in the tape library in a timely fashion, typically within one week of acquisition. All remaining should be stored at a reasonable frequency (e.g. quarterly), using tools provided by the IT Division and using a file naming system or directory naming system that any of these snapshots to be recovered the future. Snapshots of databases must be stored in externalized human readable form, such mysql-dump for MySQL databases, and the must list the commands used for taking snapshots and
for their recovery. This externalization must also be performed for all metadata. Binary versions may also be kept, but cannot be the sole backup for any item except event data.

Collaborations may develop a plan that covers all or most elements of a data management plan, such that a researcher may reference that plan and specify any necessary additional items needed to make the plan complete for his or her research. The collaboration plans may reference this document to cover those aspects of a complete plan that are being provided by the IT Division (listed below).

Data Management Plans must be submitted to the division in which the research takes place.

Major long lived collaborations are also responsible for testing their ability to go back and rebuild software and run a standard analysis job at least once every two years. Every decade this process must touch a snapshot from every five year period for which the snapshots exist. If third party software becomes completely unavailable, then alternatives will be investigated for running an older operating system as a virtual machine, and then keeping an older machine operational for some period of time.

The laboratory will conduct additional random tests of the snapshot system to ensure that it is functioning properly.

**IT Division Data Management Systems**  The following capabilities can be by research groups and collaborations in building a data management process and plan:

1. a robotic tape library and associated software and servers for writing and reading files to and from tape
2. an archival tape storage room to hold duplicate copies of high-value files for which this is appropriate
3. a disk server cluster and distributed file system for staging files to and from tape

In addition, Jefferson Lab manages in an automated and checked fashion the following processed:

1. automatic duplication of raw data from an experiment (triggered by writing the files into one of a specified number of raw data directories)
2. automatic duplication of additional directories for the purposes of preserving both data, metadata and data provenance
3. an ongoing process of duplicating tapes from older generations to newer generations so that the ability to read files is preserved

User tools documentation:

1. Raw data duplication: http://scicomp.jlab.org/doc/<tbs>
2. Metadata, databases and source code snapshots (TBS)
3. Tape library commands: (TBS)

4. File & disk system commands (TBS)

5. Additional general scientific computing information available at http://scicomp.jlab.org/doc

Quality Assurance  The Data Management processes will be overseen by the Deputy Director for Science. Under his direction, the laboratory will conduct periodic self-assessments of its Data Management processes. A readiness review of Data management will be conducted prior to the start of 12 GeV research.

Point of contact for additional information: Chip Watson watson@jlab.org Head of Scientific Computing.
B The Draft Data Management Plan for Hall D

Summary: The Jefferson Lab data management plan document details the lab’s plan to responsibly manage the scientific data generated in connection with the lab’s research program. This document sets out the plan of Experimental Hall D and is intended as a reference for the plans of individual experiments conducted in the Hall.

Responsibilities: With the assistance of the Scientific Computing group in IT division the Experimental Nuclear Physics (ENP) division management is responsible for the data management of nuclear physics data. The maintenance of this document, the plan that it describes and its implementation are the responsibility of the scientific staff of Hall D.

Experimental Nuclear Physics Data Management processes: The data management processes are listed as follows according to the broad categories of data that they address:

- **Raw Data**: Newly acquired raw data is stored on disk and moved to the tape library in a timely fashion using tools provided by IT division. IT division also makes a duplicate copy of raw data at a later date on tapes that are removed from the library and stored.

- **Processed Data**: Processed data is initially stored on disk and migrated to tape using IT tools as required. Intermediate data files may or may not be archived on tape at the discretion of the researcher(s). It is not standard practice to duplicate processed data except in cases where it is moved offsite or as requested by the data owner.

- **Processing Meta-Data**: Histograms and log files created as a by-product of processing will also be archived to tape. Other meta-data will be resident in databases (see relevant section below).

Run Conditions: Run conditions, (machine energy, beam polarization and intensity, target type, etc.) are stored in the experiment logbook and/or other databases.

Databases: Database servers are managed by IT and regular snapshots of the database content are stored along with the tools and documentation required for their recovery. Examples are:

- **Log Books**: Jefferson Lab uses an electronic logbook system with a database backend.

- **Calibration databases**: These databases are operated by ENP staff and users but the servers are managed and backed up by IT.
• **Other databases:** There are several databases used by the online systems (for example the one recording run conditions) which are physically in the Hall D Counting House. Management practices follow closely those used by IT to maintain the calibration databases, using the same tools and backup regime.

**Analysis software source code and build systems:** Data analysis software is a combination of packages from several sources, lab staff and users, off-site lab collaborators and third parties. Examples of third party software are the ROOT and GEANT packages from CERN. Locally written software source code and build files, along with contributions from collaborators are stored in a version management system (Subversion). Third party software is managed by software maintainers under oversight of the Software Support Committee. Source code repositories and managed third party packages are backed up by IT. Data analysis software is tagged and released on a regular schedule and before major data analysis efforts to assure reproducibility of the code base in the future. Binaries from production runs are archived and stored in the tape library.

**Documentation:** Documentation is available online in several locations depending on the type of content.

• **Formal documents.** These are stored in a document database. DocDB is used. It is maintained by collaboration users at the University of Regina.

• **Web pages.** Most web content is contained in a wiki maintained and backed up by IT. Mediawiki is used. It is maintained by IT at JLab.

**Quality Assurance:** As stated in the lab data management plan document, the data management plan process is overseen by the Deputy Director for Science. Periodic reviews of data management will be made.
C Draft GlueX/Hall-D Analysis Plan

Introduction

To facilitate rapid publication of GlueX/Hall-D results, while maintaining a high-level of quality control over the analysis procedure, the GlueX Collaboration has adopted a set of rules named the GlueX/Hall-D Analysis Plan. This plan relates to the use of analysis software, the managing of calibrations and data production, and the simulation of Monte Carlo events need for analysis. All analyses that expect to be published must adhere to these rules. The relevant working groups (e.g. Offline, Calibration, Physics, ...) will establish appropriate vetting procedures to both validate appropriate versions of code, and enforce the use of validated tools and approved data in all publishable analyses. This policy does not exclude the development and testing of new procedures, code and calibrations, and in fact encourages these activities with the ultimate goal being the adoption of such improvements at the collaboration level for global use.

This document will refer to the Jefferson Lab Data Management plan which can be found at http://scicomp.jlab.org/DataManagementPlan.pdf.

Software

Code Management All official software will be maintained in a master code repository inside of a code management system. These repositories are to be maintained at Jefferson Lab with the understanding that regular backups occur as part of the activities of the Jefferson Lab I.T. division. Regular tagged releases of all packages will be made and current accepted release of these will be clearly identified in the appropriate place on the GlueX wiki. Tagged releases will also be made for all production runs of data, simulation code to match production runs, and code used in large-scale data challenges. These versions will also be maintained on the GlueX wiki.

At the time this plan was written, the svn package in in use for offline and analysis tools, while git is for the online environment.

Code Validation Code validation is a crucial aspect of software. The GlueX collaboration will endeavor the run nightly build a fairly encompassing set of code, and quickly respond to errors that occur. The collaboration will also endeavor to regularly run an appropriate set of test jobs to both make sure that code is functioning and to track changes in the code’s performance over time.

As part of Data Management, the GlueX collaboration will setup a schedule to verify that older tagged versions of the code that were used for “Data Production” which are still deemed valid will be run through the nightly build procedure and some standard test jobs on a semi-regular basis for a suitable subset of of the supported platforms.

At the time this plan was written, nightly builds were running on multiple platforms and both “single particle” and ”$b_1 \pi$” event samples were run several times per week.
**Code Development**  The appropriate working groups will establish procedures for adding code repositories, and for code becoming part of the official analysis libraries of GlueX/Hall-D.

**Data Analysis**

In analyzing both real and simulated data in GlueX/Hall-D, it is very important to be able to reproduce the analysis at a later stage. For this, it is important that exact version of code and constants can be recovered at a later data.

**Data Production in GlueX**  Data production meant for use in physics analyses must be done using tagged releases of all relevant code. The collaboration will maintain a list mapping data period to production run and tagged code information, and all physics analyses that are to be published must use an officially tagged version of the code. These official produced data samples in REST format will be the starting point for all physics analyses.

This policy does not apply to data sets being analyzed to obtain calibration constants, geometrical alignments, and for development runs to improve code performance, or for algorithm development.

The data produced under these official production runs is considered part of the GlueX/Hall-D data that falls under the purview of Data Management plans. These data are expected to be produced at JLab, and have copies on tape storage. If a data sample is reprocessed using a newer tagged version of the code, then after one year, the collaboration can define the early production as no longer valid and remove it from management. As long as data from a particular production is being analyzed by members of the GlueX/Hall-D collaboration, it is considered useable and to be regularly checked. Once data are no longer under active analysis, procedures will be set up to make sure that the files remain readable by GlueX/Hall-D software.

**Simulation Data Production in GlueX**  It is expected that an official GEANT simulation for each run period in GlueX will be developed, and this version will then be tagged and the tag paired with the tag used in the data production. All Monte Carlo simulation that will support physics analyses intended for publication must utilize the appropriate tagged version of the simulation code in conjunction with the correctly tagged version of the reconstruction code. The pairings of these lists will be maintained by the offline working group.

Large scale Monte Carlo production simulating the full hadronic event rate as well as backgrounds in the experiment will be managed as a collaboration activity and the output files from these made available to the collaboration to enable development of high-level analysis cuts and procedures.

Smaller, more specialized, Monte Carlo runs are also required to use the appropriate tagged versions, but may be run either as a collaboration effort, an effort of a working group, or by individuals. If these results are to be used in an analysis, an effort should be made to make sure that they are available to the collaboration as a whole.
The simulated under an official simulation production run is also considered part of the GlueX/Hall-D data that falls under the purview of Data Management plans. These data are expected to be copied to JLab, where copies will be made onto tape storage. If a simulated data sample no longer matches a valid production data set, the collaboration can define the simulation sample as no longer valid and remove it from management. As long as data from a particular production is being analyzed by members of the GlueX/Hall-D collaboration, it is considered useable and to be regularly checked. Once data are no longer under active analysis, procedures will be set up to make sure that the files remain readable by GlueX/Hall-D software.

**Large-scale Data Challenges**  Large-scale data challenges follow most of the rules of a “simulation data production” other than the tagged version of the code may or may not be tied to a particular run period. The largest of these will be managed as a collaboration activity, while smaller runs are expected to be performed by groups and individuals. The particular tagged version of code used to do these needs to be retained in a public place.

Data from the large-scale data challenges are not considered to be part of data management plans. They likely do not match data production runs and do not lead to physics publications.

**Physics Analysis**

Physics analysis is defined as the step in going from the DST files produced both from the data and the simulated data in GlueX, and leading to a publishable result. This is broadly divided into two parts: “event selection” and “final analysis”. Each are described here.

**Event Selection**  Event selection is the process of finding and isolating the relevant events from a large production run for use in a specific analysis. This may be identifying a particular final state, or a broad class off events. It is expected that this process will be carried out using tools and techniques developed, vetted and maintained by the collaboration. Also, as much as possible, it is expected that the collaboration will strive to develop a standard set of choice and cuts to be made in carrying out these analyses.

The collaboration, working through the appropriate working groups will strive to establish as many standards as possible during this stage of the analysis, and from this, maintain appropriate methods and tools for assessing errors and uncertainties for these. The expectation is that this part of the analysis should not occupy a major part of any analysis review as long as standard procedures are followed. If standard procedures are not followed, and no justification can be found, the collaboration reserves the right to prohibit the publication of said work.

**Physics Results**  Depending on the exact physics analysis being carried out, there may not be standard tools in place to go from the selected event samples to physics output. To the extent that these tools are available, (amplitude analysis, extraction of cross sections and
polarization observables, *etc....*), they should be used, but it is clear that not all cases can be covered. The collaboration will establish rules for the appropriate level of documentation, and encourage developers of new methods to work to establish them as standard tools.

**Conference and Publication Reviews** The collaboration will establish a set of policies for reviewing data and results prior to public dissemination. In all cases, this will require a detailed analysis note, it is expected that a Ph.D. thesis could satisfy the criteria for an analysis note. It is also expected that all documentation on the analysis shall be entered in the the GlueX/Hall-D document database system. It is also expected at a time no later than the publication of a result, that the analysis note will become publicly available.

It is expected that near the time of publication of results, a final data sample of suitable form will fall under the purview of the data management plan. Unless there is a very strong need to do so, intermediate samples leading to the final result are not expected to fall under a data management plan.

**Published Physics Results** The collaboration will establish procedures for assuring that the numerical results shown in publications, including errors are archived in a publicly accessible way.
Jefferson Lab Workflow System Requirements

In this appendix, we reproduce the text from reference [28].

Introduction

Jefferson Lab (Jlab) offers physicists large computing resources to carry out data analysis and simulation. The resources are managed and operated in a batch computing mode. Physicists submit many jobs to the batch system. Each job processes one or many files. These files are fetched from the Jlab tape library automatically if they are not on disk file systems. In the past few years, Jlab has managed to meet the ever increasing demand for computing power and has provided excellent computing services for the physics community. However, the current mode of job submission and data analysis prevents scientists from analyzing large quantities of data in a streamlined fashion. In particular, the Jlab batch system is a job-centric platform instead of a work-centric environment, which forces scientists to focus on each individual job rather than to concentrate on an overall activity.

To improve efficiency of data analysis and to better serve the Jlab physics community, we propose a workflow software system that enables a large set of jobs that make up a analysis or simulation activity to flow through the Jlab computing cluster with a highly successful rate, high throughput, and less human intervention while it utilizes the computing resources efficiently.

This document summarizes the feature requirements for the new system. The requirements are the results of fruitful discussions among the authors. The discussions were carried out during several dedicated meetings, through casual hallway interactions, and by email communication. This document only specifies minimal functionalities in the new system; it does not serve as a software design document.

Workflow Types

There are many types of workflow involved in physics data analysis. However, there are only a few types of workflow encountered frequently at Jlab. Fig. 16 illustrates the 3 different types of workflow that the new workflow system is going to manage.

In the figure, type (a) presents a simplest workflow that a set of $N$ jobs process a set of $M$ data files where $N$ and $M$ can be 1. There is no dependency among the jobs. The output of the jobs appear on disk and some or all of the output files eventually end up in the tape library. Type (b) presents a similar workflow that is partially managed by an external process management system such as CLARA. Finally, type (c) workflow happens less often and it expresses a multi-staged data analysis, which consists a series of jobs each of which cannot start until the previous job finishes or the output files from the previous job are available.
Figure 16: Three different types of workflow.

**Feature Requirements**

1. **Submit a named workflow of type (a).**
   
   (a) A user can submit a workflow that processes a set of files. The files can be a list of files, a single name with either wide card symbols or a name contains a regular expression.
   
   (b) A user can submit a workflow that analyses all files from an experiment. These files could be specified by an experimental run.
   
   (c) A workflow can specify one or $N$ executables. Each executable can process one or $M$ files.
   
   (d) A workflow has to specify resource requirements.
   
   • On a workflow level: minimum/maximum number of cores, set of files that are pinned throughout the workflow,...
   
   • On a job level: Memory, disk, wall-clock, ...
   
   • **Option**: The resource requirement of a job may be adjusted based on the resource usages of finished jobs.
   
   (e) A workflow can specify output files in a list corresponding to the input file list or specify a pattern for output files.

2. **Submit a named workflow using a list of specified jobs.**

   (a) A named workflow (group) contains many jobs specified as Auger jobs.
   
   (b) The jobs can be rearranged according to the locations of input files.
   
   (c) A new job can be resubmitted to join the workflow inside a job script.
(d) There will be no hierarchy of workflows, i.e. a workflow cannot contain another workflow.

3. **Interface with an external process manager.**
   
   (a) The external manager needs to name a workflow for an analysis.
   
   (b) The workflow system provides APIs to the manager so that the manager can ask the system to stage input files. The workflow system may provide APIs to let the manager monitor the progress of the staging of the files.
   
   (c) The manager submits many jobs to the system. Each must specify a workflow name so that the system can track the workflow.
   
   (d) The manager needs to notify the system when files are no longer needed.

4. **Submit a workflow of type (c).**
   
   (a) A workflow is specified by a sequence of job and data.
   
   (b) *Can this type workflow be specified by a sequence of simple workflows?*

5. **Monitoring the progress of a workflow or a group of jobs by a name.**
   
   (a) The system should offer a nice web view showing statistical information about a workflow such as the number of successful jobs, the number of processed data files, the number of successful output files, and so on.
   
   (b) The system should offer suggestions and tips to users about their finished jobs. At the minimum, these suggestions should include memory usage, disk usage, and wall-clock time. These suggestions can appear in emails, job output files, and on web pages. *(Some of the job resource usage information is available now through web and a job output file.)*
   
   (c) The system provides users an option to be notified on error conditions through email.
   
   (d) The system should provide an easy way to get the history and statistics of workflows and jobs.
      
      - By a workflow name, a group name, a user name and so on.

6. **Error recovery**
   
   (a) If a job fails within a workflow, this job can be resubmitted for a pre-specified number of times to a different set of nodes. This is only an option.
   
   (b) The exit status of a job may determine the location of the output files. **The exit status of 0 always means success.**
   
   (c) **Option:** A job can provide a validation script upon the finish of the job. The exit status of the script will determine the status of the job. **The exit status of 0 means success.** Specific status definition comes in the software design phase.
7. Data Provenance Support

(a) The system provides more job submission tags (fields) which can be used to specify meta data information about a job.

- Users specify meta data information about a job or a workflow. The following fields could be presented upon a job or a workflow submission: major third party libraries/packages, compiler, database used, software version, software build environment, and a comment field.

(b) If there is no meta information provided by a job submission, the system will inspect its executable and tries to figure out some of the meta information.

(c) The meta information of a job or a workflow is stored along with other information of the job or the workflow. The meta information can be easily obtained through a simple search of a job or a workflow.

Conclusion

It is clear that Jlab workflow software system will not handle general workflows that are usually described by a DAG (Direct Acyclic Graph). The frequent encountered types of workflow at Jlab are relative simple. However, the lack of a workflow system at Jlab impedes the efficient analysis of large quantities of experimental data. This document serves as the first step to the realization of a workflow system within the scientific computing software arena at Jlab.
References


