12 GeV Upgrade Project

DESIGN SOLUTIONS DOCUMENT

Upgrade Hall B

Version 1.2

August 9, 2010

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APPROVALS

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REVISION LOG

Version No.	Description of the Changes Made	Revision Date
1.0	Original	September 2007
1.1	Reviewed, unchanged	June 2008
1.2	Design Solutions to Fullfill the Requirements Section, Requirement #4, #5, and #6 updated with various text additions; Updated Physics APM to Glenn Young on approval page	August 2010

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ACRONYMS

AC	Alternating current
ALARA	As low as reasonably achievable
CD	Central Detector
CHL	Central Helium Liquefier
CLAS	CEBAF Large Acceptance Spectrometer
CLAS12	Upgraded CEBAF Large Acceptance Spectrometer
DI	Deionized
DOE	Department of Energy
DX	Direct Expansion
EH&S	Environment, Health and Safety
fpm	Feet per minute
FPC	Fundamental Power Coupler
ft	Feet
GPD	Generalized Parton Distribution
HEPA	High-efficiency particulate air
HOM	Higher-Order Mode
HTCC	High Threshold Cerenkov Counter
Hz	Hertz
ICS	Integrated Control System
ID	Internal diameter
in	Inch(es)
JLab	Thomas Jefferson National Accelerator Facility
kV	kilovolt
kW	kilowatt
LCC	Life-cycle cost
Linac	Linear accelerator
LLRF	Low level radio frequency
MHz	Megahertz
NFPA	National Fire Protection Association
ODH	Oxygen Deficiency Hazard
PMT	Photo-multiplier Tube
PPS	Personnel Protection System
psf	Pounds per square foot
psi	Pounds per square inch
rf/RF	Radio frequency
SBC	Standard Building Code
SF	Square feet
SRD	System requirements document
SRF	Superconducting Radio Frequency
SVT	Silicon Vertex Tracker
TBD	To be determined
UL	Underwriters Laboratories
UPS	Uninterruptible power supply
WBS	Work Breakdown Structure

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1 System Description

The 12 GeV Upgrade Project scope is divided into three major systems: 1) Accelerator System, 2) Physics System, and 3) Civil Construction System. The Physics System is further divided into four systems: 1) Hall A Upgrade, 2) Hall B Upgrade, 3) Hall C Upgrade, and 4) Hall D.

The Physics System equipment planned for the Upgrade project takes full advantage of apparatus developed for the present program. In Hall B, the CEBAF Large Acceptance Spectrometer (CLAS), which was designed to study multi-particle, exclusive reactions with its combination of large acceptance and moderate momentum resolution, will be upgraded to CLAS12 and optimized for studying exclusive and semi-inclusive reactions (emphasizing the investigation of so-called Generalized Parton Distributions and Transverse Momentum Dependent Parton Distributions) at high energy. It will also be used for selected valence quark structure studies involving neutron “tagging" or polarized targets capable of supporting only very low beam current. Most importantly, the maximum luminosity will be upgraded from 10^{34} to more than $10^{35}\ cm^{-2}s^{-1}$. The present time-of-flight counters, Čerenkov detectors, and electromagnetic calorimeters will be retained, but the tracking system and other details of the central region of the detector will be changed to match the new physics goals.

2 Upgrade Hall B System Requirements

The Hall B System shall meet the following requirements:

1) 11 GeV polarized electrons beam,
2) Capability to run at luminosities of $10^{35}\ cm^{-2}sec^{-1}$,
3) Capability of operation with a longitudinally polarized target,
4) Capability to detect the forward-going high momentum particles from 5 - 35 degrees,
5) Capability to detect the recoil baryons at large angles > 35 degrees,
6) Large momentum range for the separation of electrons, pions, kaons and protons.

The safety of personnel and equipment must be implemented in all phases of the CLAS12 detector upgrade including R&D, design, construction, and commissioning.

3 Technical Approach to meet the Upgrade Hall B System requirements

INTRODUCTION

The Hall B Upgrade system, also termed ***CLAS12*** detector, has evolved from the CEBAF Large-Acceptance Spectrometer, or CLAS, to meet the basic requirements for the study of the structure of nucleons and nuclei with the CEBAF 12 GeV Upgrade. A major focus of ***CLAS12*** will be to determine the Generalized Parton Distributions (GPDs). ***CLAS12*** will be able to carry out the core program for the study of the internal dynamics and 3D imaging of the nucleon, and quark hadronization processes. Both of these programs impose broad requirements for measuring multiple uncorrelated particles over a wide kinematics range with good resolution in momentum and angles. These studies are carried out by measuring **exclusive** and **semi-inclusive** processes from hydrogen and nuclear polarized and unpolarized targets. The access to GPDs at high photon virtuality requires use of large acceptance detectors capable of operating at high luminosity. Moreover, a program to access GPDs requires use of polarized solid state targets which can only operate at limited luminosity. ***CLAS12*** will provide the large acceptance to measure these processes well.

CLAS12 makes use of many existing detector components. Major new components include the superconducting torus coils that cover only the forward angle range, a new gas Čerenkov counter for electron/pion separation, additions to the electromagnetic calorimeters, and the central detector. In the following the modifications and new components are briefly described.

Forward detector: The forward detector system will use several of the existing components: the low threshold gas Čerenkov counters, all electromagnetic calorimeters, and the time-of-flight scintillators. New components include the high threshold Čerenkov counter, the torus magnet, and the forward drift chambers, which will cover an angle range from 5 to 40 degrees. The large drift chambers in CLAS will be replaced by smaller ones that will cover the 5 - 40 degree angle range. Two of the existing detector systems, the time-of-flight system and the electromagnetic calorimeter system, need some upgrading to allow measurement of high momentum forward going particles. A pre-shower detector will be inserted in front of the existing CLAS electromagnetic calorimeters to allow high energy photon detection and separation of single photons from neutral pion events. Improved particle identification will be accomplished by several means: the timing resolution of the scintillation counters will be improved by adding an additional layer of scintillators with 1/3 of the widths of the existing layer and by using PMTs with better timing characteristics.

Central detector (CD): A main component is a compact superconducting solenoid magnet, which has a triple function: it provides magnetic shielding of all tracking detectors from charged electromagnetic background, mostly Møller electrons and particles from secondary interactions. It provides the magnetic field for the momentum analysis of charged particles at large angles, and it provides the uniform 5 Tesla field needed for the operation of a dynamically polarized solid state target. The CD will detect charged particles from 35 degrees to 125 degrees. Several layers of silicon strip sensors will provide momentum analysis. Particle identification is achieved by the combination of momentum analysis and time-of-flight measurements in the scintillation counters.

Beamline and targets: Most of the existing beamline components will be re-used without changes. This includes the photon tagger and pair spectrometer, the polarized photon instrumentation, a polarized target for photon experiments, and beam position and current monitors.

DESIGN SOLUTIONS TO FULFILL THE REQUIREMENTS

Requirement 1 (11 GeV beam capability) is satisfied by upgrading to 11 GeV the Hall B beamline transporting electrons from the extraction region into the hall. This scope resides within the Accelerating Systems Beam Transport WBS 1.3.4 and the Hall B Upgrade Beamline WBS 1.4.2.5.

Requirement 2 (luminosity capability) requires a factor of 10 increase over the existing CLAS luminosity. This requirement drives two parts of the Hall B upgrade: the development of improved Moeller electron shielding, and changes in the drift chamber geometries.

<u>A. Improved Moeller electron shielding</u>
The present luminosity limit for electron scattering experiments comes from Moeller electrons produced in the target that interact either directly (first region of drift chambers) or through primary photons and the production of secondary particles in the support structures and Torus coils with all three regions of drift chambers. A large fraction of the Moeller electrons affecting the first region are already shielded using a small toroidal magnet that does not block higher-energy charged particles from reaching the drift chambers, but which deflects the Moeller electrons into the outer surface of massive shielding where they are absorbed. This method allows CLAS to operate at a luminosity of 10^{34} $cm^{-2}s^{-1}$. In the course of CLAS operation of polarized targets using Helmholtz coils, it was determined that solenoidal shielding would be more effective at suppressing Moeller electrons, because these electrons are ‘trapped’ starting at their point of origination and they can be transported and dumped on the interior of a conical pipe, rather than on an exterior surface. Subsequent simulations have validated this conclusion, and in addition showed that a strong solenoidal field with a large $\int Bdl$ gains another factor of ~1.5 in luminosity increase, showing the luminosity increase is expected to be a factor of ~3 in this approach. However, use of solenoidal shielding is not practical in the current CLAS except for experiments where the particles of interest are confined to small angles, since a solenoid magnet will block larger-angle particles that are needed for many experiments. The technical solution for CLAS12 is to use solenoidal shielding where detector elements within the magnet bore cover the angles that would otherwise be blocked. The discussion of Requirement 5 will elaborate further on this solution. Requirement 4 (forward angle range from 5-35 degrees), which specifies a minimum angle of 5 degrees at 50% acceptance in azimuthal angle for measured particles, means that the cone of Moeller electrons must be confined to a significantly smaller angle so as to not flood the active detector volumes with low-energy tracks. This requires that the $\int Bdl$ provided by the solenoid magnet downstream of the target must be sufficiently high to confine the Moeller electrons into a small forward cone where they can be safely absorbed. In detailed simulations of the field needed for this it was determined that a 5 T

field was required with $\int Bdl \geq 2.5$ Tm downstream of the target, thus fixing the maximum solenoid field specification and its length. The other limit of Requirement 4, a maximum angle of 35 degrees, constrains the geometry of the massive components of the magnet. This requirement means that the downstream end of the solenoid needs to be a conical aperture allowing 35 degree particles from the cryo-target to pass through, thus fixing the downstream geometrical specification of the solenoid magnet.

B. Drift chamber geometry

Since improving the Moeller shielding yields a factor of ~3 increase in the luminosity limit, a remaining factor of 3-4 needs to be obtained relative to the existing drift chambers by reducing the solid angle of the drift chamber cell sizes in order to achieve Requirement 2. The rate due to charged particles is approximately proportional to the drift chamber cell radius for fixed distance between the target and the chamber. The new Region I forward chamber will be at a 2.5 times larger distance from the target than the existing chamber (200 cm vs. 80 cm), which by itself will provide a luminosity limit increase of approximately a factor of 2.5. Further rate reduction (factor ~2) is obtained by using a reduced time window due to the use of a higher field gradient, a slightly reduced wire spacing, and an additional reduction due to the better shielding of the large $\int Bdl$ of the solenoid field. The 5-35 degree angle coverage in Requirement 4, together with the design choice of six-layer superlayers (to maintain the existing level of redundancy) and the wire spacing reduction, determines the forward drift chamber channel counts. All three regions have 112 channels/layer/sector, and there are 12 layers per region, which for six sectors yields a total channel count of 112x12x3x6 = 24,192 drift chamber cells. Region 2 and region 3 also need significantly lower rates which are achieved by a combination of reduced production of secondary background particles and the reduced solid angle coverage due to the larger distance from the target, although this effect is smaller for the region 2 (factor ~1.7) and the region 3 (factor ~1.3) than for region 1 (factor 2.5). The combined increase in luminosity due to improved Moeller electron shielding and the reduced sensitivity of the drift chamber cells was obtained in a detailed simulation and event reconstruction analysis with realistic physics background that resulted in comparable occupancies and reconstruction efficiencies for the CLAS12 and CLAS configurations at 10 times higher luminosity for CLAS12.

Requirement 3 (capability with longitudinally polarized target) is satisfied by adapting the design of the existing polarized target to the geometry and conditions resulting from addressing Requirement 2 as discussed above. Specifically, the polarized target cell operates in magnetic fields of high intensity, typically 3 - 5 Tesla, and high uniformity, and that is oriented along the beam axis. The 5 T solenoid field required to satisfy Requirement 2 can be used for this purpose as long as the field uniformity required can be achieved. The field uniformity required is 10^{-4} within a cylindrical volume 2.5 cm in diameter and 9 cm in length. This requirement sets the field uniformity specification for the solenoid magnet. The CLAS12 polarized target itself is not part of the 12 GeV Upgrade, but the implications for the CLAS12 design have been integrated.

Requirement 4 (capability to detect high-momentum particles from 5 to 35 degrees) has been partially discussed under Requirement 2 above. High-momentum charged particles are detected by the combination of the forward part of the silicon vertex tracker, the drift chambers, the magnetic field from the torus magnet, and the time-of-flight scintillators. The silicon vertex tracker is addressed in the discussion of Requirements 5 and 6. The design solution for the drift chambers that satisfies Requirement 2 as discussed above is adequate to satisfy Requirement 4 as well. The resolutions achievable with the wire spacing given and the planned drift chamber gas are consistent with the missing mass resolution needed to measure missing particles. The timing information from the time-of-flight counters is needed to perform the time-based tracking needed for the drift chamber analysis. The magnetic field needed to momentum-analyze the detected charged particles is determined by the energy ranges of the particles and the geometries of the detectors and magnets. The maximum field value and the profile of its intensity have been determined and specified by these considerations. While the maximum field is approximately the same as the existing torus, the field volume is smaller by approximately a factor of two. The azimuthal angle coverage extends down to polar angles of 5 degrees where it is 50% of 2π. The minimum angle coverage in CLAS standard configuration is limited to about 10 degrees and covers a smaller range in azimuthal angle. The fall-off in integrated field strength is also significantly different from the existing torus, and is well-matched to the momentum spectra of the charged particles anticipated.

Neutral particles at high energies will be detected using the forward calorimeters. Because of the increased beam energies, neutral pions at high momentum are no longer able to be detected with the existing CLAS forward calorimeter, necessitating the addition of the pre-shower calorimeter which has a finer-grained readout that can resolve the two photons from the neutral pion decay. The parameters of the pre-shower calorimeter have been optimized for this purpose, determining the specifications for the device. It will have 6 triangular sectors to follow the torus and forward calorimeter geometry and be composed of alternating lead and scintillator layers. The lead is 2.2mm thick and the scintillator bars are 4.5cm x 1 cm in cross section. The scintillators are arranged in an x-u-v arrangement, not unlike the existing forward calorimeter. Each slat has two full-length holes, which each are filled with two wavelength-shifting optical fibers. The fibers are readout by photomultiplier tubes, 192 per sector (1152 overall). Neutrons will be detected in the pre-shower calorimeter as well as the existing calorimeter, increasing the overall efficiency of neutron detection. The increase in granularity also translates into an improved angular resolution for neutrons detected in the pre-shower calorimeter. While the design was optimized for neutral pions as driven by Requirement 4, the improvement in neutron detection is an important additional benefit.

It should be noted that the fulfillment of Requirement 4 is supported in an important way by Requirement 6 (particle identification over wide momentum range), since ‘detecting’ a particle generally requires a determination of the particle type.

Requirement 5 (detecting recoil baryons at large angles) is addressed by the central detector package. This detector set is mounted inside the solenoid magnet. It includes the barrel portion of the silicon vertex tracker, a time-of-flight array, and the provision of space for a compact detector for neutral particle detection. Determination of the charged particle momentum is performed by recording the hit positions of the helical trajectories in the silicon vertex tracker in the solenoid magnetic field. Identification of the particle type is performed by combining the momentum information with the time as measured by the time-of-flight system. The central time of flight consists of 50 scintillator bars read out on each end by photomultiplier tubes coupled using UVT acrylic light guides. The light guides are bent to clear the active polar angle zone, and the photomultipliers are shielded from the solenoidal field outside the main bore of the solenoid.

The parameters of the barrel portion of the SVT such as strip pitch, level of redundancy, and thickness of materials are chosen to optimize detection of recoil particles. The sensors are 320 microns thick n-type silicon and have a readout strip pitch of 156 microns and a stereo angle that varies from 0 to 3 degrees across a sensor. The preamplifier ASIC is the model FSSR2 developed earlier at FNAL.

Requirement 6 (particle identification over a large range in momentum) has been addressed by a number of design choices. A second gas Cerenkov counter that has a higher pion detection threshold was added to increase the range of electron-pion separation to approximately 5 GeV. This High Threshold Cerenkov Counter (HTCC), which is located in front of the Region 1 drift chamber, is designed to have minimal mass to reduce its impact on the tracking information. The HTCC has 6 sectors containing the thin mirrors on foam substrates, with each sector read out by eight 5" quartz-faced ET-9823QKB photomultiplier tubes. To further reduce the impact of this added mass, the forward part of the Silicon Vertex Tracker (SVT) was added, which samples tracking information before the particles arrive at the HTCC and provides a track vector to match to the forward drift chambers.

The location of the HTCC just downstream of the target and before the Torus magnet and the drift chamber system is a natural choice that does not add much length along the beam line to the overall length of CLAS12. The relative positioning of the Solenoid and the Torus magnet is largely determined by the out-of-plane forces the transverse magnetic field of the Solenoid exerts on the current in the Torus coils. The transverse magnetic field must be limited to < 50 Gauss to limit distortions of the Torus coil panels to acceptable levels, which requires a distance of at least 220 cm from the Solenoid center (target center) to the Torus coils. This space is ideally suited for inserting the HTCC detector which requires an overall length of approximately 150 cm beginning 30 cm downstream of the target center.

A second component of the particle identification scheme is to use the existing panel of time-of-flight scintillators in the forward region and add a second layer with smaller scintillator widths and new photomultiplier tubes to construct new time-of-flight detectors with better timing resolution. This requirement is the basis for the specifications for their performance. This new forward time-of-flight array has 6 sectors, each with 64 counters of 6cm x 6cm cross section and read out from each end by compact fast linear-focused photomultiplier tubes. The slat lengths vary from 13 to 260cm depending on their radial position in the sector. A third component is the time-of-flight counters within the solenoid magnet, part of the central detector, which was mentioned in the discussion of Requirement 5. Identification of the particles in this lower-momentum region is important and it drives the performance requirements for these detectors.

Finally, as already discussed for Requirement 4, the pre-shower calorimeter is required to identify neutral pions at the highest energies. While it has been optimized for this purpose, it will also improve the identification of electrons, pions, and neutrons.