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Detector development for Jefferson Lab's 12 GeV Upgrade

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ABSTRACT

Jefferson Lab will soon finish its highly anticipated 12 GeV Upgrade. With doubled maximum energy, Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) will enable a new experimental program with substantial discovery potential, addressing important topics in nuclear, hadronic and electroweak physics. In order to take full advantage of the high energy, high luminosity beam, new detectors are being developed, designed and constructed to fit the needs of different physics topics. The paper will give an overview of various new detector technologies to be used for 12 GeV experiments. It will then focus on the development of two solenoid-based spectrometers, the GlueX and SoLID spectrometers. The GlueX experiment in Hall D will study the complex properties of gluons through exotic hybrid meson spectroscopy. The GlueX spectrometer, a hermetic detector package designed for spectroscopy and the associated partial wave analysis, is currently in the final stage of construction. Hall A, on the other hand, is developing the SoLID spectrometer to capture the 3D image of the nucleon from semi-inclusive processes and to study the intrinsic properties of quarks through mirror symmetry breaking. Such a spectrometer will have the capability to handle very high event rates while still maintaining a large acceptance in the forward region.

1. Introduction

Jefferson Lab's 12 GeV Upgrade presents a unique opportunity for the nuclear physics community to expand its reaches into unknown scientific areas and has been ranked the highest priority in the 2007 Long Range Plan written by the U.S. Department of Energy and National Science Foundation's Nuclear Science Advisory Committee. The 12 GeV Upgrade project includes doubling the maximum energy of Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF), major enhancements to the equipment in the existing experimental areas – Hall A, B and C, and the construction of a new experimental area, Hall D, with a new detector. The upgraded CEBAF will be able to provide electron beams to the existing Halls A, B and C with beam energy up to 11 GeV and the maximum energy to Hall D will be 12 GeV. In order to take advantage of the physics opportunities offered by the greatly improved energy and quality of the beam, the experimental equipment in each of the halls will have significant improvements, such as the SuperBigBite Spectrometer (SBS), the Möller Spectrometer, the Solenoidal Large Intensity Device (SoLID) in Hall A, the CLAS12 detector and the detector for the Heavy-Photon Search (HPS) in Hall B, the Super-High Momentum Spectrometer (SHMS) in Hall C, and the GlueX detector in Hall D. This paper will focus on the detector technologies developed for Hall D's GlueX program and Hall A's SoLID program.

2. The GlueX program of Jefferson Lab's Hall D

The GlueX experiment [1,2] (Fig. 1) is the flagship program of the new experimental Hall D. The major mission of the GlueX experiment is to study the gluon field inside meson by studying the spectrum of exotic mesons. These types of particles are beyond the standard picture of a meson in which a quark and an anti-quark are bound together by a gluon field at the ground level. Exotic mesons explicitly manifest the gluonic degrees of freedom and provide an unambiguous way of studying states with excited glue that are predicted by QCD. Experimentally, such a measurement is extremely challenging due to limited statistics and non-uniform detection efficiency. GlueX is designed for a high-energy, high-luminosity photon beam and a solenoid-based hermetic detector system, making it the first of its kind with the capability to systematically study the family of exotic mesons and unravel their origin. It has been the core motivation of Jefferson Lab's 12 GeV Upgrade.

GlueX will use a linearly polarized photon beam with energy between 8.4 and 9.0 GeV created using the coherent Bremsstrahlung technique in which 12 GeV electrons are passed through a thin (~20 μm) diamond radiator. The level of linear polarization will be

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enhanced by having the photon beam pass through a 25 μrad active collimator sitting 75 m away from the radiator. After the radiator, the electrons will be swept away by a 1.5 T dipole magnet and detected by two hodoscopes to tag the energy of the associated photons. A finely segmented Microscope Tagger (Fig. 2) consisting of 500 scintillator fibers placed in 100 columns will cover the 8.4–9.0 GeV coherent peak with an energy resolution of 0.1%, while the broader range of photons between 3 and 11.6 GeV will be tagged by the Fixed Array Hodoscope made of scintillator paddles.

The GlueX spectrometer uses a geometry based on a 2 T superconducting solenoid that is 4 m long and has a bore of 1.8 m. The charged particles will be reconstructed using two tracking systems (Fig. 3): the Central Drift Chamber (CDC) [3] around the target and the Forward Drift Chambers (FDC) in the downstream half of the magnet. The CDC is a 28-layer, 1.5 m long straw tube chamber with approximately 3500 straw tubes. It is made from alternating sections of axial and stereo (6° angle with respect to the beam direction). This allows the track's polar angle to be determined when multiple layers are considered. Overall, the CDC straw tubes have a position resolution of ~150 μm. The FDC consists of four separate packages, each with six cathode-plane drift chambers. Both the upstream and downstream cathode planes are instrumented for readout. This provides information on the position along the hit wire, improving the pattern recognition. The CDC provides 3D space points with ~200 μm resolution in the coordinate perpendicular to the beam line. Together, these detectors will track particles from threshold up to nearly 8 GeV with a momentum resolution about $\sigma_p/p \approx 1$–3%.

The photons are detected by two electromagnetic calorimeter systems (Fig. 4): a lead-scintillating fiber Barrel Calorimeter (BCAL) [4] inside the bore of the magnet and a lead-glass Forward Calorimeter (FCAL) [5] in the forward direction. The BCAL consists of 48 modules. Each module is 4 m long and made from approximately 17,000 scintillating fibers sandwiched between layers of lead. All 48 modules are stacked to form a cylindrical shape that is inserted into the GlueX solenoid as a whole. The BCAL detects photons emerging from the target with $\theta > 12°$ and has energy resolution of $(5.54/\sqrt{E} + 2.0)$%. With double-ended readout using silicon photomultipliers (SiPM) [6,7] it is able to measure the photon position with a resolution of $0.5/\sqrt{E}$ cm. The SiPMs are chosen for their resistance to strong magnetic field and compact size. The FCAL consists of 2800 $4 \times 4 \times 45$ cm^3 lead-glass blocks stacked in a circular frame. Each block is read out by a PMT (Photo-Multiplier Tube) powered by a Cockcroft–Walton low voltage base. This calorimeter detects photons between 2° and 11°, and has an energy resolution of $(5.7/\sqrt{E} + 1.6)$% with a position resolution of $0.64/\sqrt{E}$ cm.

The particle identification (PID) system (Fig. 5) consists of a scintillator Start Counter around the target, the forward Time-Of-Flight (TOF) wall [8], time-of-flight in the BCAL, and dE/dx information from the CDC. The start counter consists of 30 3 mm thick scintillator paddles. It is used to identify the beam bunch (coming every 2 ns) from which the interaction at the target occurs. The TOF wall will measure the flight time of charged particles relative to the beam's RF bunch time in a roughly 11° wide cone about the beam axis with 100 ps accuracy. At larger angles, the time-of-flight will be measured in the BCAL, which is expected to have a resolution of 200 ps. Finally, the CDC will measure dE/dx information for identifying particles below 0.45 GeV. Combining all these detectors, the efficiency to identify pions is over 96% and the efficiency to identify protons is about 90%. However, the identification of kaons with the existing system is very limited. Assuming a 4σ or greater separation for pions and kaons, the TOF can cleanly identify kaons up to 2.2 GeV while the BCAL only reaches 1.2 GeV.

3. The SoLID program of Jefferson Lab's Hall A

The SoLID (Solenoidal Large Intensity Device, Fig. 6) project [9,10] is developing a large-acceptance spectrometer capable of handling very high rates. It is designed to satisfy the requirements of several highly anticipated experiments in Hall A, including a precision test of the Standard Model through parity-violating deep inelastic scattering (PVDIS) [11] of electrons from a deuteron target, 4D mapping of nucleon's transverse momentum dependent structures through Semi-Inclusive Deep Inelastic Scattering (SIDIS) [12–14] , and a fully exclusive measurement of the electroproduction of J/ψ mesons from protons near threshold [15]. SoLID will also become the base equipment for a continued program of physics in the 12 GeV era at Jefferson Lab that requires both high luminosity and large acceptance. We have chosen the CLEO II magnet for the SoLID spectrometer. It is a solenoidal magnet with a uniform axial central field of 1.5 T, a large inner space with a clear bore diameter of 2.9 m and a coil of 3.1 m diameter.

The SoLID spectrometer requires high-resolution track reconstruction under high-rate conditions over a large area. A cost effective solution is provided by the Gas Electron Multiplier (GEM) technology (Fig. 7). The GEM is based on gas avalanche multiplication within small holes (on a scale of 100 μm), etched in a Kapton foil with a thin layer of copper on both sides. The avalanche is confined in the holes resulting in fast (about 10 ns rise time) signals. Several GEM foils (amplification stages) can be cascaded to achieve high gain and stability in operation. The relatively small transparency of GEM foils reduces the occurrence of secondary avalanches in cascaded GEM chambers. All these properties result in very high rate capabilities of up to 100 MHz/cm^2 and an excellent position resolution of 70 μm. The University of Virginia group recently completed the fabrication of a large prototype GEM module with a dimension of $100 \times (21$–$38)$ cm^2, approaching the proposed size of the largest SoLID GEM sectors. Such a module has been successfully tested using a hadron beam at Fermi National Lab.

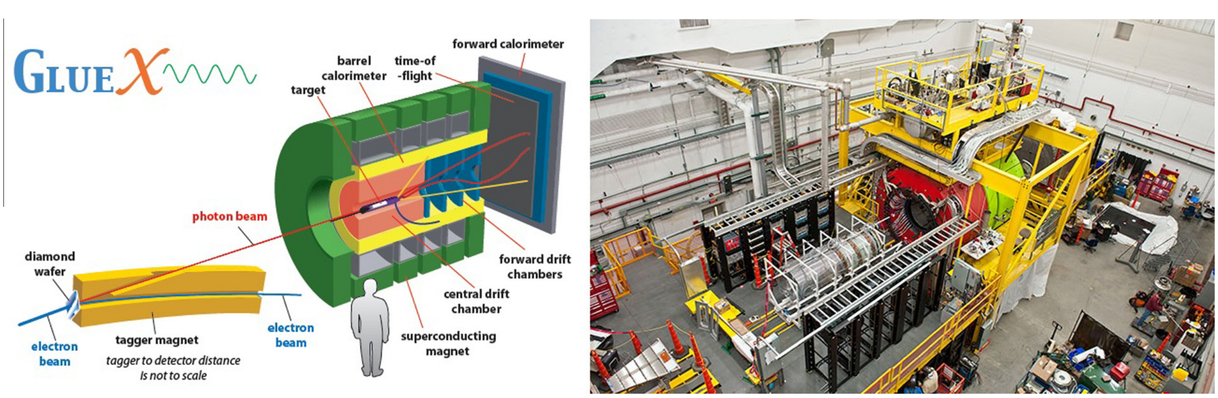

Fig. 1. (Left) experimental setup of GlueX; (Right) the GlueX detector inside Jefferson Lab's Hall D.