12 GeV Upgrade Project

DESIGN SOLUTIONS DOCUMENT

The Hall D Detector

Version 1.2

August 12, 2010

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APPROVALS

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REVISION LOG

Version No.	Description of the Changes Made	Revision Date
1.0	Original	May 2007
1.1	Revised	May 2008
1.2	Section 3.2 added "positions of two coils on left of Figure 1 swapped from original…"; Section 3.5 added description fo 48 BCAL segments and changed parameters in Table 1 "number of SiPMs"; Section 3.8, 2nd paragraph added sentence regarding "straw counts" and "channel counts"; Various minor edits throughout; Updated CAM and Hall Leader to Eugene Chudakov; Updated APM to Glenn Young on approval page.	August 2010

TABLE OF CONTENTS

ACRONYMS

AC	Alternating current
ADC	Analog-to-Digital Converter
ALARA	As low as reasonably achievable
BCAL	Barrel Calorimeter
CDC	Central Drift Chamber
CHL	Central Helium Liquefier
DAQ	Data Acquisition
DI	Deionized
DOE	Department of Energy
DX	Direct Expansion
EH&S	Environment, Health and Safety
FADC	Flash Analog-to-Digital Converter
FCAL	Forward Calorimeter
FDC	Forward Drift Chamber
FPC	Fundamental Power Coupler
ft	Feet
GlueX	Gluonic Excitations Experiment
HEPA	High-efficiency particulate air
HMS	High Momentum Spectrometer
HOM	Higher-Order Mode
Hz	Hertz
ICS	Integrated Control System
ID	Internal diameter
in	Inch(es)
JLab	Thomas Jefferson National Accelerator Facility
kV	kilovolt
kW	kilowatt
LANL	Los Alamos National Lab
LASS	Large Acceptance Solenoid Spectrometer (SLAC)
LCC	Life-cycle cost
LGD	Lead Glass Detector
LHe	Liquid Helium
LHC	Large Hadron Collider
Linac	Linear accelerator
LLRF	Low level radio frequency
MEGA	Mu-to-E-Gamma Experiment (LANL)
MHz	Megahertz
mV	millivolts
NFPA	National Fire Protection Association
ODH	Oxygen Deficiency Hazard
PPS	Personnel Protection System
QCD	Quantum Chromodynamics
R&D	Research and Development
rf/RF	Radio frequency

SiPM	Silicon Photomultiplier
SF	Square feet
SLAC	Stanford linear accelerator
SRD	System requirements document
SRF	Superconducting Radio Frequency
TDC	Time-to-Digital Converter
TOF	Time-of-Flight
WBS	Work Breakdown Structure

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1 Project 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 D, a tagged coherent bremsstrahlung beam and solenoidal detector will be constructed in support of a program of gluonic spectroscopy aimed at testing experimentally our current understanding that quark confinement arises from the formation of QCD flux tubes.

2 Hall D Detector System Requirements

- To meet the experimental goals of the experimental program, the project requires
    - 9 GeV linearly polarized photon beam,
    - detector with charge particle identification and detection over a broad angular range,
    - detector with photon detection over a broad angular range,
    - detector with good momentum and energy resolution,
    - electronics fully pipelined, and
    - detector capable of acquiring about 200k events per second with a Level-1 trigger..

- The beamline and detector must be designed and built in a manner that insures the safety of equipment and personnel.

3 Technical Approach for meeting the Hall D Detector System requirements

The GlueX detector will be housed in a new above-ground experimental hall (Hall D) located at the east end of the CEBAF north linac. A collimated beam of linearly polarized photons (with 40% polarization) of energy 8.5 to 9 GeV will be produced via coherent bremsstrahlung with 12 GeV electrons. This requires very thin, of order 20µ thick, diamond crystal radiators and a 3.5 mm collimator 75m downstream of the radiator to achieve the designed polarization.

The GlueX detector uses an existing 2.2 T superconducting solenoid that is currently being refurbished. An existing 2800-element lead-glass electromagnetic calorimeter for detecting photons will be reconfigured to match the downstream aperture of the solenoid. Immediately upstream of the lead-glass is located a scintillator hodoscope for triggering and for time-of-flight (TOF) measurements. The barrel calorimeter, which lines the inside of the solenoid coil cryostat and consists of alternating layers of lead and scintillating fibers bonded together with optical epoxy, will provide position and energy measurement for photons and flight time information for charged particles. A start counter will surround the 30 cm long liquid hydrogen target to be included in the trigger and to give the start time for the time-of-flight system. This counter will be surrounded by cylindrical straw-tube drift-chambers (CDC), which will fill the region between the target and the barrel calorimeter. Planar drift chambers will be placed inside the solenoid downstream of the CDC to provide accurate track reconstruction for charged particles going in the forward direction.

This detector configuration has close to a 4π hermeticity and momentum/energy and position information for charged particles and photons produced from incoming 9 GeV photons. This detector has been optimized to carry out partial wave analysis of many particle final states. Extensive parametric Monte Carlo studies for a wide variety of final states have been carried out to certify the design parameters and the suitability of the detector for carrying out the final analysis. In particular, the geometrical acceptance of the detector for final state particles is typically above 95% and is quite uniform over the detector. A well understood acceptance is crucial to being able to carry out precision partial wave analysis.

The close to hermetic design for the detector makes it an ideal tool to determine the masses and quantum numbers of mesons in the mass range from 1.5 to 2.5 GeV/c^2. The detector will be sensitive to hybrid mesons produced with cross sections as low as a few percent of well known mesons and can also be used to map out normal mesons and baryons.

3.1 Photon Tagger

The purpose of the photon tagging system is to provide a tagged flux of up to 10^8 Hz of linearly polarized photons from coherent bremsstrahlung in a thin (20μm), oriented, diamond crystal. The tagging spectrometer is located immediately downstream of the radiator and 75 m upstream of the collimator hut and experimental area Hall D. The energies of photons are determined by tagging the energy-degraded bremsstrahlung electrons in the spectrometer. The photon energy will be determined with fine resolution (less than 0.1% r.m.s. of the incident beam energy, E_0) for a photon energy, E_γ, between 70% and 75% of E_0. The tagging system consists of one dipole magnet, a vacuum chamber and the associated focal plane detectors. The dipole is run at about 1.5 T, with a magnetic length of 6m and a field-integral of 9 Tm.. The pole shoe surfaces are part of the vacuum chamber. The focal plane detector array is located just outside the vacuum chamber. One set of 190 fixed scintillation counters spans the broad energy range from 25% to 95% of E_0. A second, movable, *microscope* of 124 narrow channels will be used to accurately measure the photon energies in the energy range 70 to 75% of E_0.

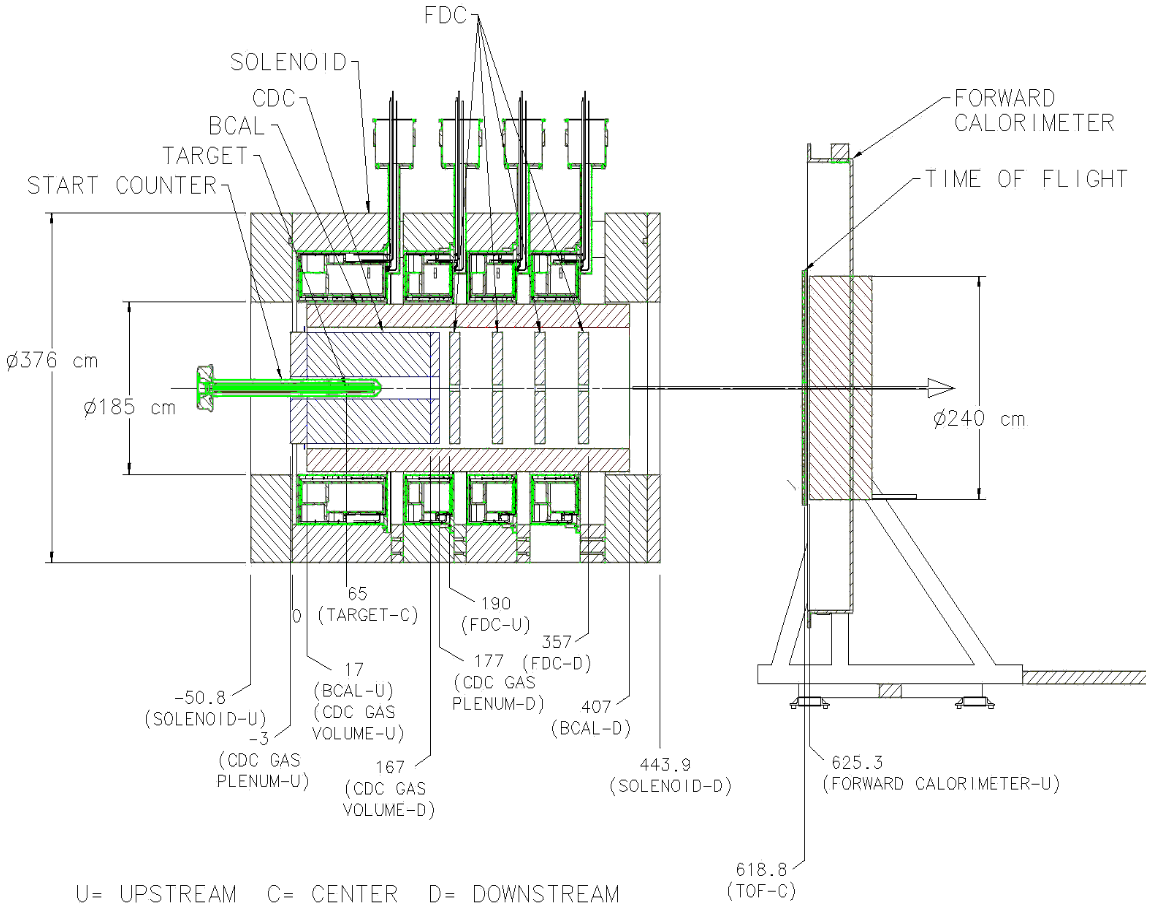

Figure 1: Elevation view of the Hall D detector.

3.2 Superconducting Solenoid

The solenoid is the magnetic element selected to provide momentum analysis in the tracking chambers. The solenoid is a 73-inch warm bore super conducting (SC) device that produces a nominal maximum central field of 2.2 Tesla at 1800 Amps. The magnet is 195 inches long and weighs approximately 300 tons. The solenoid was originally designed in 1970 as the Large Acceptance Solenoid Spectrometer (LASS) spectrometer at SLAC and was subsequently used as the MEGA spectrometer at Los Alamos National Lab (LANL). The solenoid was mothballed in place in 1995 and first inspected by JLab/Hall D in 2000. The solenoid was designed as a highly reliable cryogenically stabilized superconducting magnet. The typical field quality of the solenoid (dB/B ~ 1%) is consistent with the requirements for momentum resolution. The solenoid was designed with a slotted yoke and four separate cryostats to accommodate the large planar wire chambers used at LASS. The specific magnetic geometry of the original solenoid had the unfortunate side effect of creating large external magnetic fields, particularly in regions where phototubes would likely be present. Many of the solenoid's systems were inconsistent with JLab operations due either to design or obsolescence. The solenoid had a history of internal leaks and electrical shorts and had accumulated a substantial amount of wear and tear during its 30 year history. Despite these problems, the robust design and the good state of preservation made the selection of this solenoid a cost effective choice for Hall D, even after the necessary costs of modernization and maintenance were taken into consideration.

After the initial evaluation of the solenoid, the first modifications were to redesign the yoke magnetic geometry to match the solenoid to the requirements of Hall D and to substantially reduce the external fields. The modifications entail filling the yoke slots and adding steel at the end and mid-section of the central yoke to reduce yoke saturation and the escape of internal fields, thus reducing the external fields by creating a symmetric yoke with a large upstream opening. The positions of the two coils on the left in Figure 1 were swapped from the original configuration operated at SLAC in order to minimize and balance forces on the coil support columns in the new geometry. Further refurbishment included repairing LN_2 leaks in three coils and a leak in the LHe vessel of the fourth. The shield thermometry is being upgraded to modern PT-102 Pt resistance thermometers, and the coil support strain gauges and the deteriorated multi layer super insulation are all being replaced. New solenoid systems are planned that include a new DC power supply and energy dump system. A new cryogenic interface with JLab compatible automatic valves and connections and a new control and instrumentation package will be added, following the successful implementation of a similar (JLab-designed) system for Hall C's HMS spectrometer.

3.3 Target

The main physics program pursued with the Hall D detector system will be conducted with a low-power liquid hydrogen target. The planned target is 30 cm long and somewhere between 1 and 3 cm in diameter. Such targets normally employ Mylar target cells. The Mylar cell will be mounted on a metal base to provide for liquid entry ports and a reliable means of positioning the cell. The beam enters through a thin window mounted on a reentrant tube at the base of the cell. The target cell is connected to a condenser located upstream of the cell. The maximum power deposited in the target by the beam is 100 mW. Natural convection is sufficient to remove heat from the target cell and a circulation pump is not required.

3.4. Start Counter

The start counter will be used in the Level 1 trigger. The start counter is also providing a start signal for time of flight measurements and to identify the beam pulse associated with the observed event. In order to be independent of particle momenta and trajectories, the start counter is located as close to the target as possible. To be able to identify beam pulses the detector needs a minimal time resolution of 300 ps. The start counter for the Hall D detector system is an array out of 40 scintillator strips of 10 mm width and 500 mm length. The scintillator strips are bent to point to the target resulting in a 20 mm diameter opening for the photon beam. The angular coverage of the start counter is 3^o to 134^o over the full length of the target. Due to the fringe field of the solenoid care has to be taken for the readout electronics. There are 2 possibilities which would work SiPMs of similar type as for the BCal or PMTs of the type R5924-70 from Hamamatsu. These tubes operate without gain loss in 0.5 Tesla magnetic fields.

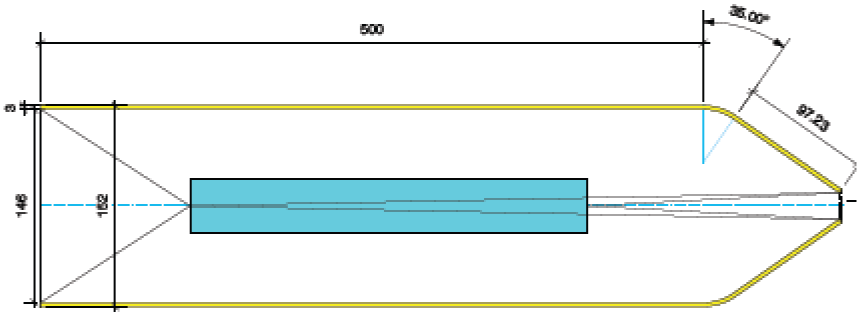

Figure 2: A schematic view of the start counter surrounding the target.

3.5 Calorimeter – Barrel

The purpose of the barrel calorimeter (BCAL) is the detection and energy determination of photons from the decays of the neutral π^{o}, the η and other mesons decaying into photons. Any charged particles that are swept by the magnetic field to fall within its volume, mostly in the momentum range of 0.3 to 1.0 GeV/c, will also be detected. Spatial information can also be extracted from the timing information relative to the two read-out ends of the BCAL and from the information provided by the independent read-out cells in each end. The design of the BCAL is based on that of the KLOE calorimeter at DAFNE in Italy, which had a reported energy resolution of 5.4% / ($\sqrt{E}$ (GeV)) with a negligible constant term and a timing resolution of 54 ps / ($\sqrt{E}$ (GeV)) $\oplus$ 140 ps. The BCAL parameters are summarized in Table 1. The physical layout of the BCAL is a ring consisting of 48 modules (segments) at an inner radius of 65 cm and an outer radius of 90 cm. Thus, its approximate thickness is 25 cm corresponding to approximately 16 radiation lengths. The nominal length of each module is 390 cm. Each module is constructed as a matrix of 96-1mm diameter double clad scintillating fiber optic strands (SciFi+IBk-s), embedded on grooved Pb sheets of 0.5 mm thickness. Thus, each module consists of approximately 190 layers of Pb/SciFi and special optical epoxy composite. The Pb: SciFi: Epoxy ratio (by volume) is 37:49:14. The high magnetic field - and the limited space available for read out - present an area of particular concern and several emerging photo-detection technologies, such as Silicon Photomultiplier Tubes, or SiPM's, offer an attractive solution. An intensive R&D effort is ongoing in order to finalize the type of readout devices and the required channels. Each module has a two sided readout, with each side divided in an inner and outer readout section. The inner section is segmented in 6x4 readout channels and the outer one in 2x2. Each of the 48 BCAL segments has 40 optical sensors on each end, for 3840 total sensors. The radially inner layers of readout are grouped into a 6x4 matrix, with the summed amplitude from groups of three sensors digitized by FADC-250 and also sent to a leading-edge discriminator and thence to an F1TDC set for 60ps. The outer layers consist of 4 groups of 4 sensors each, with the summed amplitude of each group digitized by an FADC-250. This results in 1152 total FADC channels and 768 total F1TDC channels.

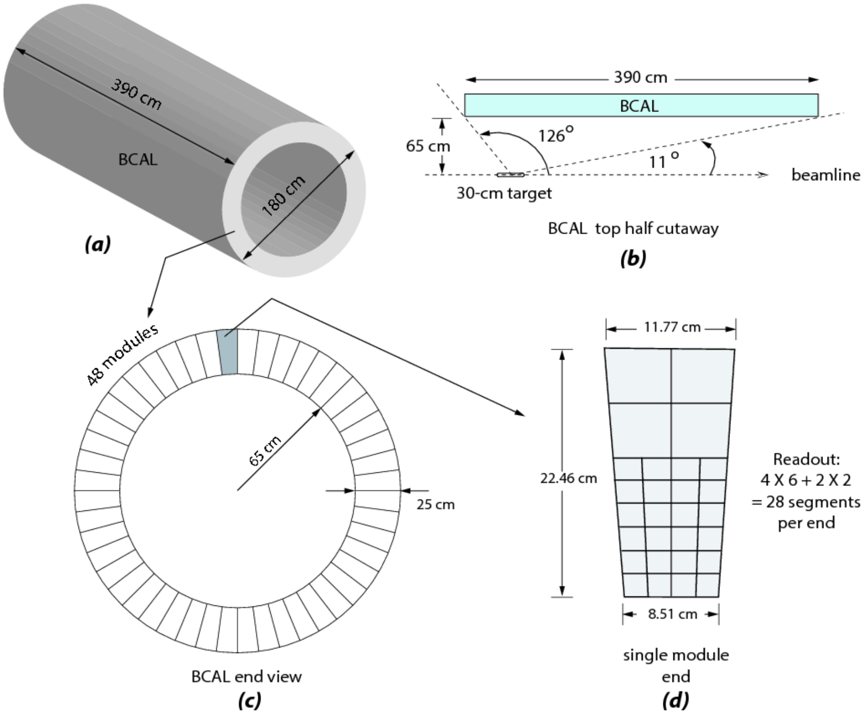

Figure 1. BCAL geometry

Table 1: Main parameters of the Barrel Calorimeter.

Parameter	Size
Length	390 cm
Inner radius	65 cm
Outer radius	90 cm
Fiber diameter	1 mm
Lead Sheet thickness	0.5 mm
Number of Fibers	780,000
Number of SiPMs	3840
Mass	22 metric tons

3.6 Calorimeter – Forward

The purpose of the forward calorimeter (FCAL) is also to detect and measure the energy and position of photons from the decays of π^0, the η and other mesons. Lead glass (F80-00) detectors of similar construction were used in experiments at Brookhaven (E852 - using a pion beam) and JLab (the "Radphi" experiment -using a photon beam). The energy resolution is given by $\sigma(E)/E = 0.036 + 0.073/\sqrt{E}$. Shower positions at the FCAL plane are reconstructed with a resolution of $\sigma_r = \sqrt{(7.1/\sqrt{E})^2 + (X_0 \sin\theta)^2}$ mm where X_0 is the radiation length of the lead glass (30 mm) and θ is the photon angle measured with respect to the normal to the FCAL (energies in GeV). This leads to mass resolutions of 10 MeV/c^2 and 30 MeV/c^2 for the π^0 and η respectively. The detector consists of 2800 lead glass blocks of dimensions $4\times4\times45$ cm^3 arranged in a nearly circular stack of radius ~ 1 m. The Cerenkov light from each block is viewed by a FEU-84-3 Russian phototube. The phototube bases are of a Cockcroft-Walton (CW) design. The phototubes are registered with respect to the glass using a cellular wall that includes soft-iron and μ-metal shielding. Since the FCAL is the furthest downstream subsystem in the Hall D detector, the mass presented to particles is not an issue. A 1 GeV photon produces about 800 photoelectrons corresponding to a phototube signal of about 0.5 V and a rise-time of 10 ns. No further amplification is required. The signal will be digitized with a 12-bit 250 MHz Flash Analog-Digital Converters (FADCs) – see later.

3.8 Particle Tracking –Central Drift Chamber

The purpose of the Central Drift Chamber (CDC) is to accurately measure (r, ϕ, z) coordinates along charged-particle tracks. In conjunction with the Forward Drift Chamber (FDC – see below), it will be used to reconstruct the momentum vector of each track and the primary and secondary vertices of the event. The momentum resolution is a function of particle momentum and the number of hits in both the CDC and FDC. Monte Carlo studies indicate that an $r\phi$-spatial resolution, $\sigma_{r\phi}$ on the order of 150 μm is sufficient to satisfy the physics goals of the experiment. The *z*-coordinate is obtained using 6° stereo layers. The resolution is given as $\sigma_z = \sigma_{r\phi} / \sin 6^\circ$. The CDC also needs to provide dE/dx information sufficient for identifying protons with momentum below 0.5 GeV/c.

The chamber is built using 28 layers of 1.6 cm diameter, 100 μm-thick aluminized Kapton, 1.5 m-long straw tubes. The layers are arranged as a series of nested cylindrical shells, with straw counts ranging from 42 straws on the innermost up to 209 straws on the outermost layer. The signal is registered using a 20μ diameter gold-plated tungsten wire strung under 55 g of tension. Layers 9-12 and 21-24 are $+6^\circ$ stereo while layers 5-8 and 17-20 are -6° stereo. The total channel count is 3500 channels.
A minimum ionizing track produces about 30 primary ionizations per centimeter of traversed gas. Path length in a straw-tube depends on both the distance away from the wire as well as the polar-angle θ of the track, but typical values vary between about 0.5 cm to a few cm. The chamber will be run such that the gas amplification is about 10^4. The signals will be read out using capacitive coupled preamps mounted directly on the upstream end plate of the detector and then fed into 12 bit FADC and digitized at 125 MHz. Due to the 2.2 T magnetic field, the maximum drift times will be on the order of 800 ns for a typical gas mixture of 50/50 Ar/CO_2.

3.9 Particle Tracking – Forward Drift Chamber

The forward drift chambers (FDCs) include 4 separate packages of disk-shaped horizontal drift chambers to measure the momentum of all charged particles emerging from the target at angles of up to 30° relative to the photon beam line. Each chamber is 1.2 m in diameter and consists of 6 wire planes, each one flanked on either side by cathode planes divided into thin strips. The strips are oriented at $\pm 75^\circ$ with respect to the wires and 30° with respect to each other. Neighboring chamber layers will be rotated by 60° with respect to each other to improve track reconstruction decisions on the corresponding left/right ambiguities in the wire planes, therefore improving the overall resolution.

The spatial resolution of the FDC is expected to be better than 200 μm. Each wire plane consist of alternating field and sense wires, with a sense to field wire separation of 5 mm and a wire plane to cathode plane separation of 5 mm. The wires that cross through the beam line will be deadened to beam spray out to a radius of 3.5 cm. The nominal design for the cathode planes calls for a strip pitch of 5 mm and a strip-to-strip separation of 1 mm. The strips will lie on a 1-mil thick Kapton backing. The strips themselves will be copper with a thickness of 2 μm. To minimize the material seen by the photon beam the cathode planes have a whole corresponding to a scattering angle for charged particles of less then 1^o. A ground plane is included between neighboring cathode planes to ensure minimal signal cross-talk. The sense wires will be at a positive high voltage, the field wires at a negative high voltage and the cathode planes will be at ground. The number of sense wires on each wire plane is 96 and the number of field wires is 97. Each cathode plane consists of 216 cathode strips. The total number of anode wires per FDC package is 576 and the number of cathode strips per FDC package is 2592. The total number of readout channels for the full FDC system is 12672.

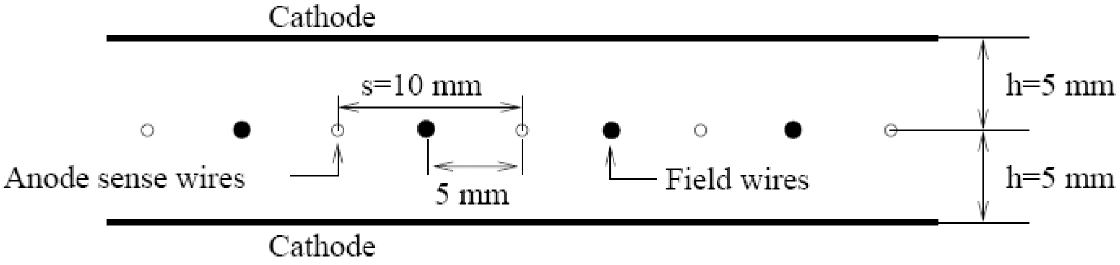

Figure 2: Schematic end-view defining the nominal electrode geometry of the FDC system.

Each signal from the FDCs (anodes and cathodes) will be sent to a chamber-mounted charge-sensitive preamplifier that drives a pulse-shaping amplifier. The signals from the anode wires that are above some pre-determined voltage threshold will be discriminated and then digitized by 125 ps LSB resolution F1 TDCs. The signals from the cathodes will be digitized with 125 MHz 12-bit flash ADCs.

3.10 Particle Identification –Time-of-flight

The purpose of the time-of-flight detector (TOF) is to serve as part of the particle identification system in conjunction with a Cerenkov detector for forward-going charged particles. The goal is to separate $\pi^{\pm}$ from $K^{\pm}$ for momenta up to 2.5 GeV/c and for the given geometry a 95% separation efficiency is achieved at the highest momentum with a time resolution of at least 80 ps. The TOF will use two planes of scintillator bars located immediately upstream of the lead glass detector (LGD), rotated by 90^o to each other. Based on simulations and prototype studies the bars will be 252 cm long, 6 cm wide and 2.5 cm thick. Thus the mass presented by the detector immediately before the LGD corresponds to 5.0 cm of scintillating plastic. Each bar apart from the 2 central ones is read out at both ends with a photomultiplier. The 2 central bars of both planes are split in the middle to provide a central hole to allow for the passage of the beam. The channel count is 168.

3.11 Electronics

The electronics will amplify, discriminate, and digitize raw detector signals storing them for later readout at level 1 trigger rates of 200 kHz at 10^8 γ/s without incurring dead time. The detector includes approximately 13868 125MHz FADC and 4470 250 MHz FADC channels as well as 3640 TDC and 1336 discriminator channels.

A pipelined approach is required due to the high trigger rate. The digitized information must be stored for several microseconds while the level 1 trigger is formed. Multiple events must be buffered within the digitizer modules and read or transmitted while the front ends continue to acquire new events. The raw data rate from the detector is about 4 Gbyte/second. A sophisticated timing system is required to synchronize the pipelines in the front-end modules. Energy sums from the calorimeters comprise the level 1 trigger.

3.12 DAQ System

The Hall D science program requires an LHC-era state of the art data acquisition system, and the architecture is being designed for a flux of 10^8 photons/sec. Although at experiment startup the incident flux will only be 10^7 photons/sec, the architecture must be appropriate for the full flux to avoid a costly redesign. The architecture scales such that components can be added as needed as the flux increases.

The DAQ must be a dead-timeless system capable of accepting a 200 kHz trigger rate (at 10^8 incident photons/sec), transporting the resulting 3 GB/sec of data from the front-end detector electronics into builder nodes, building the data into single events (event size 15 kB), and delivering the events to the Level 3 farm. The rate to mass storage is 300 MB/sec. At startup the Level 3 farm provides little filtering, but at 10^8 the farm must reduce the event rate by a factor of 10. Finally, the DAQ must deliver a small subset of the events to calibration and monitoring systems.

3.13 Online Systems

The online effort is the umbrella under which all efforts related to taking data and writing it to mass storage will be organized, and includes overall responsibility for designing, installing, and maintaining everything related to controlling and running the experiment. This effort includes the experiment network design and installation, counting house and operator environment, integration and customization of the JLab DAQ system, run management and control, construction and maintenance of Level 3, developing the slow controls system, and alarms systems.