The CLAS12 Backward Angle Neutron Detector (BAND)

E.P. Segarra, F. Hauenstein^{1,*}, A. Schmidt², A. Beck³, S. May-Tal Beck³, R. Cruz-Torres, A. Denniston, A. Hrnjic, T. Kutz, A. Nambrath, J.R. Pybus, O. Hen

Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

K. Price⁴, C. Fogler, T. Hartlove, L.B. Weinstein

Old Dominion University, Norfolk, Virginia 23529, USA

I. Vega, M. Ungerer, H. Hakobyan, W. Brooks

Universidad Técnica Federico Santa María, Casilla 110-V Valparaíso, Chile

E. Piasetzky, E. Cohen, M. Duer

School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

I. Korover

Nuclear Research Center Negev, Be'er Sheva 84190, Israel

J. Barlow, E. Barriga, P. Eugenio, A. Ostrovidov

Florida State University, Tallahassee, Florida 32306, USA

Abstract

The Backward Angle Neutron Detector (BAND) of CLAS12 detects neutrons emitted at backward angles of 155° to 175° , with momenta between 200 and 600 MeV/c. It is positioned 3-m upstream of the target, consists of 18 rows and 5 layers of 7.2-cm by 7.2-cm scintillator bars, and read out on both ends by PMTs to measure time and energy deposition in the scintillator layers. Between the target and BAND there is a 2-cm thick lead wall followed by a 2-cm veto layer to suppress gammas and reject charged particles.

This paper discusses the component-selection tests and the detector assembly. Timing calibrations (including offsets and time-walk) were performed using a novel pulsed-laser calibration system, resulting in time resolutions better than 250 ps (150 ps) for energy depositions above 2 MeVee (5 MeVee). Cosmic rays and a variety of radioactive sources were used to calibration the energy response of the detector. Scintillator bar attenuation lengths were measured. The time resolution results in a neutron momentum reconstruction resolution, $\delta p/p < 1.5\%$ for neutron momentum $200 \le p \le 600$ MeV/c. Final performance of the BAND with CLAS12 is shown, including electron-neutral particle timing spectra and a discussion of the off-time neutral contamination as a function of energy deposition threshold.

Keywords: CLAS12; time of flight; plastic scintillator; ultrafast neutrons

1. Introduction

CLAS12 (12-GeV CEBAF Large Acceptance Spectrometer) [1] in Hall B of the Thomas Jeffer-

84190, Israel

^{*}Corresponding Author

Email address: hauenst@jlab.org (F. Hauenstein)

 $^{^1\}mathrm{Also}$ at: Old Dominion University, Norfolk, Virginia 23529, USA

²Current address: George Washington University, Washington, D.C. 20052, USA

³Also at: Nuclear Research Center Negev, Be'er Sheva

 $^{^4\}mathrm{Current}$ address: Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay, France



Figure 1: CLAS12 and BAND in Hall B at Jefferson Lab. The electron beam is incident from the right side. BAND is marked in red. The overall detector system is roughly 20 m in scale along the beam axis.

son National Accelerator Facility (JLab) is a multipurpose spectrometer used to detect charged and neutral particles emitted in high-energy electron scattering reactions. Tagged deep inelastic scattering studies require the detection of backward-angle recoil neutrons with momenta above 200 MeV/c [2]. This is achieved by a combination of the Central Neutron Detector (CND) [3] and the Backward Angle Neutron Detector (BAND). The CND covers angles from 40° to 120° while BAND covers from 155° to 175°.

BAND was designed to measure neutrons with momenta of 200 - 600 MeV/c, with an average detection efficiency of 35%, and with a momentum reconstruction resolution better than 1.5%. The detector is based on scintillator bars with PMT readout on both bar ends. BAND was installed in January 2019 and has since taken data in coincidence with CLAS12. Fig. 1 shows a drawing of BAND located upstream of CLAS12 in Hall B.

This paper describes the design, operation and calibration of the BAND. Section 2 presents the required time resolution, efficiency and geometry, the resulting design and layout, the selection of detector components, and results from comparative measurements of different PMTs and magnetic shields. Section 3 presents the performance of the detector after its installation in Hall B. It describes cosmic-ray and laser calibrations [4] as well as the measured time-of-flight (ToF) resolutions and neutron-photon separation from 10.6-GeV electrondeuteron data. Section 4 summarizes the results.

2. Design of the backward angle neutron detector

The major considerations for the BAND design were the constraints on geometry and areal coverage in Hall B, the time-of-flight resolution required, and neutral particle identification. To achieve the physics of interest in BAND [2], neutron ToF resolutions below 300 ps at an energy deposition threshold of ~ 2 MeVee (MeV-electron-equivalent) are required. This threshold is later optimized using neutron signal-counts-above-background, measured ToF resolutions and neutron efficiencies as a function of minimum energy deposition. Neutral particles are identified by using a thin 2-cm veto laver for charged-particle identification between the target and the first active layer of BAND. Photons are suppressed by a 2-cm thick lead wall placed downstream of the veto layer. Neutron-photon discrimination is achieved via ToF relative to the electron scattering time measured by CLAS12. Out-of-time random neutron and photon contamination in a signal region can be reduced, relative to the signal strength, by optimizing the minimum energy deposition of particles in the bars (see discussion in Neutron identification).

The following subsections describe the BAND geometry, the individual components, including the bench measurements that informed their selection, the photon shielding, the laser calibration system, the electronics and data acquisition, and the final assembly of the detector.

2.1. Geometry

The design of the BAND geometry balanced the goal of maximizing acceptance for backward angle neutrons with the space contraints in hall (see Fig. 2). BAND was designed to cover the region between the Central Detector and the target support, where the flight path of the neutrons had minimal material obstruction. In order to be installed on the support cart for the central tracking detectors, BAND had to be lowered down through an existing opening in the CLAS12 support scaffolding (referred to as the space frame, shown in black in Fig. 2). This required that BAND fit within a box



Figure 2: BAND and its close surroundings: the cryotarget and beam line components (cyan), BAND (red), the central detector region of CLAS12 (blue), the space frame (black), and the central detector support cart (grey). The beam is coming from the left side. The target is located at the center of the CLAS12 central detector.

3-m wide, 1.5-m high, and 1-m deep, and include a hole in the middle for the beam pipe.

To maximize the active detector volume within these constraints, we chose to use rectangular scintillator bars stacked (in x-y), perpendicular to the beam direction (z), see Fig. 3. The cross section of each scintillator bar determines our position granularity in y, z (vertical and longitudinal directions relative to the beam pipe), and should be comparable to our time-resolution-dependent position resolution along the bar (in x). Given our timeresolution specification of 300 ps (discussed below), 7.2 cm by 7.2 cm scintillator bars were chosen to optimize fiducial volume, granularity, and cost.

The active detector area (excluding the veto layer) consists of 116 scintillator bars, arranged in 5 z-layers with 18 vertically stacked rows of bars. The arrangement of the bars is shown in Fig. 3. The bottom three rows each have only four layers due to obstructions from the cart below BAND (see grey cart in Fig. 2).

Three different bar lengths are used: 15 bars of length 164 cm, 43 bars of length 202 cm, and 58 bars of length 51 cm. The shorter bars were used in the vicinity of the beam pipe. All bars have light guides attached to both sides, and the bars are read out by 51 mm PMTs. The PMTs are either Hamamatsu R7724 [5] or Electron Tubes (ET) 9214KB [6] (see Table 1).

The veto layer, which is installed on the downstream face of BAND (i.e., between BAND and the target), consists of 24 scintillator bars with a cross



Figure 3: BAND design of bars in the main detector and the veto layer. The 164-cm long bars are shown in red, the 202-cm bars in white and the short, 51-cm bars in cyan. The position of the PMTs for each bar is also shown. The beam direction corresponds to the z-axis.

section of 2 cm by 7.2 cm. The veto bars have the same lengths as the corresponding BAND bars, such that the whole downstream surface is covered by the veto, see Fig. 3. Each veto bar is only read out on one side by a single ET 9954KB [7] 51 mm PMT.

Each bar has an assigned sector and layer number. The layer number corresponds to the position along the beam line (in z) starting from upstream (1) to downstream (5) for the active area and (6)for the veto bars. The sector numbering follows from top to bottom. Sector 1 consists of three rows of 164-cm long bars (red bars in Fig. 3). Sector 2 has seven rows of 202-cm long bars, below Sector 1. Sector 5 also consists of the 202-cm long bars, two rows on the bottom of the detector. The white bars in Fig. 3 show the locations of Sectors 2 and 5 in each laver. The short 51-cm bars to the left of the beam hole (negative x) are in Sector 3, while the ones on the right side (positive x) are in Sector 4 (both are shown in cyan in Fig. 3). Table 1 summarizes the geometry parameters and PMTs for each sector and layer.

2.2. Components

The timing resolution of the scintillator bars is affected by many factors, and each component was

^aLayer 5 is missing due to obstructions from the central detector support cart below BAND

	Dimensions $(w \times h)$	PMT		
Sector 1, $L = 164$ cm				
Layer $1-5$	$7.2 \times 7.2 \text{ cm}^2$	R7724		
Layer 6	$2 \times 7.2 \text{ cm}^2$	9954 KB		
Sector 2, $L = 202$ cm				
Layer $1-5$	$7.2 \times 7.2 \text{ cm}^2$	R7724		
Layer 6	$2 \times 7.2 \text{ cm}^2$	$9954 \mathrm{KB}$		
Sector $3 / 4$, $L = 51$ cm				
Layer $1-4$	$7.2 \times 7.2 \text{ cm}^2$	9214KB		
Layer 5	1.2×1.2 CIII	R7724		
Layer 6	$2 \times 7.2 \text{ cm}^2$	9954 KB		
Sector 5, $L = 202$ cm				
Layer $1 - 4^{\rm a}$	$7.2 \times 7.2 \text{ cm}^2$	R7724		
Layer 6	$2 \times 7.2 \text{ cm}^2$	$9954 \mathrm{KB}$		

Table 1: Parameters for bars and PMTs for the different BAND sectors and layers.

optimized considering both cost and design constraints. We selected Bicron BC-408 [8] scintillant for its light output, time response and attenuation length. The bulk attenuation length of 380 cm is much longer than the length of the BAND bars. To enhance reflectivity, we wrapped each bar with 3M Enhanced Specular Reflector foils [9]. In order to select the optimal PMTs and thickness of magnetic-shields, we bench-tested a variety of options described in the following text.

2.2.1. Bench Measurements

Bench measurements were used to guide the PMT and magnetic shielding selection. A diagram of our test setup and electronics is shown in Fig. 4, featuring a coincidence setup between a "test" scintillator bar and a "reference" scintillator bar. Each bar has two PMTs coupled to its ends; the test bar has the PMTs whose time resolution we wish to study. Both bars are wrapped in an optical reflector, and placed in a dark-box. The reference bar was kept fixed during all measurements. Five different 51-mm PMTs were tested (see Table 2, [10], and [6]), assembled on 200- to 250-cm long bars.

The signal for our measurement is given by a 60 Co source which is placed between the two bars. The 60 Co source yields two γ rays with energies of 1.17 and 1.33 MeV. The two γ -rays were collimated by two lead bricks to ensure they each hit a specific location along each bar, allowing us to study individual PMT time resolution and measured energy as a function of hit location.

Measurements with different ⁶⁰Co source loca-



Figure 4: Schematic of the bench test setup (top) and its read-out system (bottom) to measure PMT time resolutions.

Table 2: Bench test configurations. Length refers to the length of the scintillator bar. σ is the time resolution for 2-MeV central-equivalent energy deposit in the middle of the bar extrapolated from data. The 9214KB PMT [6] is manufactured by ET-Enterprises and the other PMTs are manufactured by Hamamatsu [10].

PMT	Length (cm)	σ (ps)
R7724	200	~ 240
R7724-100	250	~ 210
R13089	250	~ 210
R13435	200	~ 310
9214 KB	200	~ 260

tions were combined by using the measured attenuation in the bar to convert the energy measured by the PMT to the "center-equivalent energy deposit," the energy that would have been deposited at the center of the bar to give the same measured energy. For example, by placing the source close to one PMT one can achieve a center-equivalent energy deposit significantly greater than the 1 MeV 60 Co Compton edge.

Fig. 5 shows the PMT time resolution as a function of center-equivalent energy deposited for different source placements. Each individual data set explores the response of the PMT over the entire Compton distribution for a single source placement. Since the individual data sets are consistent within error bars, the measurements were combined to



Figure 5: PMT time resolution as a function of centerequivalent energy deposit for different placements of the 60 Co source along the bar for Hamamatsu R13089 PMT. The labels indicate the distance of the source to the PMT.

cover a center-equivalent energy deposition range up to 1.8 MeV.

Fig. 6 shows the measured single-PMT time resolution for the different test configurations. The lines indicate fits to data extrapolated beyond 1.8 MeV. All PMTs except the R13435 met the timingresolution design specification of 300 ps at 2-MeV energy deposition (see Table 2). To reduce costs, a combination of Hamamatsu R7724 [5] and Electron Tube 9214KB [6] PMTs for BAND were selected. For the veto layer, available Electron Tube 9954KB PMTs were used. See Table 3 for details of the selected PMTs.

After BAND was assembled and installed, the time resolution of each bar was measured using the laser calibration system (see Sec. 2.4 and [4]). The time resolution as a function of the energy deposit in the center of the bar is shown in Fig. 7 for a representative 202-cm bar with R7724 PMTs. The resolution is below 150 ps from 2 to 8 MeV center-deposited energy, indicating the good performance of the bars and PMTs. One should note that Fig. 7 is the bar ToF resolution, while 6 is the PMT resolution. In Fig. 7, the energy deposition is measured from both PMTs (reconstructed as the geometric mean and corrected for attenuation).

2.2.2. Light Guides

The light guide design was constrained by the available space, the sizes of the scintillator bars and PMTs, and the length of the mu-metal shielding. The design utilizes a modified Winston cone to op-



Figure 6: Single-PMT time resolution as a function of centerequivalent energy deposit for the five PMTs tested. For each PMT, data, such as that of Fig. 5, are combined to a single set and weighted averages are taken to reduce error given the density of points. The lines are fits to data (only the blue and yellow data points are shown). The functional form used, $\sigma_{PMT} = ae^{-b\cdot E_{dep}} + c$, reflects that at sufficiently high energy deposition, PMT resolution becomes constant. At 2 MeV energy deposition all PMTs except R13435 achieve a time resolution below 300 ps.

timize light collection by concentrating light from a large area at the scintillator onto a smaller active area of the photomultiplier. CAD drawings of the light guides for the main detector and the veto bars are shown in Fig. 8. In total, they are 8.9 cm long. Each light guide has a 4.9-cm long cylindrical section with a 4.6-cm diameter, which is connected to the active photocathode area of the 51-mm diameter PMTs. The cylindrical length allows for the magnetic field shielding to extend more than 51 mm (i.e., more than a PMT diameter) beyond the photocathode (see next section). The other end of the light guide matches the cross section of the scintillator. The light guide is glued to the scintillator bar with a DYMAX UV curing glue [11] and attached to the PMT with MOMENTIVE RTV615 silicone rubber compound [12]. The light guides were designed, optimized, and manufactured by Florida State University.

2.2.3. PMT Magnetic shielding

The fringe field of the CLAS12 solenoid magnet [13] is between 20 and 120 G at the location of BAND, requiring all PMTs to have magnetic shielding. The transverse field (perpendicular to the axis of the PMT) in the PMT region ranged from 10 to 110 G and the longitudinal field ranged from 10 to

Table 3: Properties of the PMTs used in BAND.

	R7724 [5]	9214KB [6]	9954KB [7]
Company	Hamamatsu	ET	ET
Diameter	$51 \mathrm{mm}$	51 mm	$51 \mathrm{mm}$
Dynode stages	10	12	12
Spectral response	$300-650~\mathrm{nm}$	$290-630~\mathrm{nm}$	$290-680~\mathrm{nm}$
Max. wavelength emission	420 nm	350 nm	380 nm
Quantum eff. maximum	26%	30%	28%
Gain	$3.3{ imes}10^6$	$3.0{ imes}10^7$	$1.8{ imes}10^7$
Max. anode current rating	200 µA	100 µA	100 µA
Anode dark current	6 nA	4 nA	8 nA
Anode pulse rise time	2.1 ns	2.0 ns	2.0 ns
Electron transit time	29 ns	45 ns	41 ns



Figure 7: Time resolution as a function of center-deposited energy for one bar with R7724 PMTs using the BAND laser system after installation. The energy deposition is the geometric mean of both PMTs at the end of the bar, and is corrected for attenuation effects. The deposition is in the center of the bar due to the installation of the fiber there.

50 G.

A dedicated test stand was used to examine different thicknesses of passive magnetic shielding. Two 56-turn Helmholtz coils, with a radius of 0.5 m, separated by 1 m, were constructed. A prototype detector was also used, consisting of a 2cm thick, 5-cm diameter scintillator disc, coupled to two 7-cm long, 5-cm diameter cylindrical acrylic light guides and two PMTs. The detector was lightproofed with Tedlar(R) and stabilized on a simple plastic stand at the center of the Helmholtz coils.

As a baseline, responses to 90 Sr and 137 Cs sources were measured with zero magnetic field and no shielding. The sources were placed either 0 or 5 cm away from the scintillant. PMT event rates, time



Figure 8: CAD drawing of the light guides for the main detector (left) and the veto bars (right). The top parts are connected to the PMTs while the lower parts are connected to the bars.

differences between the left and right PMT signals, and peak energies were measured at nominal operating voltages.

The same quantities were subsequently measured with different shielding configurations at different longitudinal and transverse magnetic fields, up to 80 G (limited by heat dissipation in the Helmholtz coils).

Mu-metal shielding of thicknesses of 0.9, 1.5, 1.8, 2.4 and 3 mm were tested, as well as two soft-iron pipes. The magnetic field, amount of detector covered by the shielding, the thickness of the shielding, and the angle of the detector to the field were all varied.

In Fig. 9, the event rate from a 90 Sr source as a function of magnetic field strength is shown for different thickness of mu-metal shields and a reference measurement without any shield. The shield was positioned to cover 5 cm beyond the photo-



Figure 9: Magnet shielding test results with a ⁹⁰Sr source, a longitudinal field. The shields were placed to cover 5 cm beyond the PMT photocathode. Event rates with increasing field and no shielding are shown in red. Results with 0.9, 1.5, 1.8, and 2.4 mm mu-metal thickness are shown in yellow, green, blue, and purple, respectively.

cathode. The longitudinal magnetic field degraded the PMT performance the most. While the 1.5-mm mu-metal shield was not sufficient, the 1.8-mm mumetal shield maintained PMT performance up to 80 G. The soft-iron pipes performed worse than the 1.5-mm mu-metal (not shown in Fig. 9). The magnetic shields performed best when they extended 5 cm (one diameter) beyond the PMT photocathode. In order to be conservative, 2.6-mm thick mu-metal shields were selected.

2.2.4. PMT and bar quality test measurements

Before the final assembly of BAND (see Section 2.6), all PMTs and bars have been tested for quality assurance. These measurements were conducted with a picosecond pulsed UV-LED.

The test setup for each PMT had a 6.4-cm long scintillator disc attached between the LED and the PMT inside of a light-tight dark box. Gains and time resolutions for each PMT were measured. The PMTs were then matched in pairs to be then glued to a bar. Pairs were determined by minimizing gain different and time resolution difference between the PMTs of a pair.

For each bar the attenuation length was measured by moving the LED pulser along the bar. This was done without a wrapping material around the bar and with no light guides attached, in a light tight black-box. The bars with the worst attenuation length were selected as back-up bars.



Figure 10: Connection of a fiber to bar after UV-cure gluing. The fiber is positioned in the center of the bar and is covered by both layers of wrapping material, ESR [9] and Thorlabs Aluminium foil [14].

2.3. Lead shielding

To minimize background from backward-going photons, a lead wall was installed on the downstream face of BAND (between the CLAS12 target and BAND). This lead wall consists of individual 2-cm thick blocks stacked in front of the veto layer. Each block is covered on both sides with an aluminum layer to safely handle. The lead wall can be seen in the final assembly photographs shown in Fig. 13.

2.4. Laser Calibration system

A UV laser system to calibrate BAND and monitor its performance was implemented during datataking. The design and performance of the system is fully described in Ref. [4].

The main component of the system is a picosecond pulsed diode laser (Teem Photonics STV-01E-140, [15]) with a wavelength of 355 nm. The laser can be triggered externally between 10 - 4000 Hz. The light is only transported within fibers. Further components of the system are a mode scrambler, a 90:10 splitter whose outputs are connected to a reference photodiode (10% output) and a variable optic attenuator [16] (90% output). The attenuator allows to vary the pulse intensity sent to the detector. It is connected to a custom SQS Vláknová Optika 1×400 splitter which distributes the light to every bar of BAND.

Each bar has an optical fiber glued to its center with UV-curable glue (see Fig. 10). We used an exposed fiber for the fiber-scintillant connection since



Figure 11: Electronic schematic of the BAND read-out. Every PMT signal is split and ADC and TDC information are obtained. Additional outputs of the discriminators are used to create single bar and cosmic-laser triggers from BAND.

it was a stable, reliable and easy option. The other end of the fiber is connected to the splitter through a patch panel attached to the BAND frame.

The photodiode provides reference time for the laser system. The output signal of the photodiode is inverted and shaped before it is sent to the BAND read-out system. The photodiode signal is then digitized by the same ADCs and TDCs which are used for the PMT signals.

2.5. Electronics and DAQ

The high voltages for each PMT are provided by a multi-channel CAEN SYS4527 mainframe with eleven A1535SN cards with 24 channel each [17, 18].

A schematic drawing of the read-out electronics and its components is shown in Fig. 11. The signal of each PMT is split to an ADC and TDC, read out independently. The signal splitters are custom made and have been used in previous experiments at Jefferson Lab. From the splitter one signal is sent to a 250-MHz sampling flash-ADCs [19] (FADC) while the other signal is sent to discriminators. The discriminated time signal goes to a TDC (CAEN VX1190A [20]) with 100-ps resolution per channel.

In total, the system consists of 16 flash-ADCs in one VXS crate, 16 discriminators and two TDCs in a VME crate and 16 splitters. A trigger signal distribution card for the flash-ADCs and trigger interface boards are installed in the crates. All components are part of the standard CLAS12 electronics [21, 22].

The detector is read out either by a trigger from the main CLAS12 trigger system [22] or by standalone BAND triggers. The stand-alone triggers are used for tests and calibrations with cosmic rays, radioactive sources and the laser system. They are implemented by a programmable CAEN V1495 logic board [23]. Such triggers include a single bar trigger for source measurements and a coincidence bar trigger for cosmics and laser measurements. The coincidence trigger is also fed to the central CLAS12 trigger system to allow monitoring of the detector by recording laser data during experimental data taking. This laser-monitoring trigger rate is usually about 10 Hz, compared to the $\sim 15 - 20 \,\mathrm{kHz}$ trigger rate from electron interactions in the target.

2.6. Final Assembly

Each scintillator bar was assembled and individually tested, following this procedure:

- 1. Select a pair of matched PMTs.
- 2. Wrap the assembled scintillator with ESR foil [9], leaving a window-flap for the laser-system optical fiber (see Fig. 10).
- 3. Glue the PMTs to the light guides with MOMENTIVE RTV615 silicone rubber compound [12].
- 4. Glue one light guide/PMT assembly to each end of the bar with DYMAX UV curing glue [11].
- 5. Wrap with light-tight foil^b, leaving a windowflap for attaching the laser-system optical fiber.
- 6. Glue the optical fiber to the center of the bar and reseal the foil window.
- 7. Install the mu-metal shields on the PMTs.
- 8. Search for and fix light leaks by measuring the PMT dark currents with a pico-ammeter.
- 9. Install each bar in the BAND support frame.
- 10. Connect the optical fibers and signal and HV cables to patch panels mounted on the upstream side of BAND.
- 11. Final test for light leaks.

Fig. 12 shows some of the steps in the assembly process, including one bar wrapped with ESR foil, a fully wrapped bar with the optical fiber shown, a

^bBlack 50- μ m thick Tedlar® foil [24] was used to wrap the short bars. The long bars were wrapped with Thorlabs black Aluminium foil [14]



Figure 12: BAND construction. From ESR [9] wrapped bars (left) to assembled detector (right). The intermediate steps show the fully wrapped bars with the optical fiber and the assembled bottom row of the detector.

row of four bars installed in the BAND frame, and the fully assembled BAND seen from the upstream side with the patch panels for HV, signal cables, and optical fibers.

After assembling the bars in the support frame, the lead wall was installed on the downstream side of BAND. BAND was then craned into its position on top of the central vertex tracker support cart upstream of CLAS12. Fig. 13 shows a design drawing and a photograph of the upstream side of BAND.

Fig. 14 shows the upstream side of BAND in Hall B with about 3/4 of the cables installed. All cables are connected to electronics which is installed outside of the photograph on the left side.

3. Performance

In this section, we first describe the performance of the individual scintillator bars and their calibrations. We next describe the performance of the BAND as a whole, with a focus on neutron identification and efficiency.

3.1. Individual bar performance

3.1.1. Gain matching

In order to have a similar response to a given energy deposit across all PMTs of BAND, each PMT's HV was optimized using cosmic rays. Cosmic ray spectra were measured with a range of HV and then combined to produce a gain curve for each PMT. These data were collected with a cosmic trigger which required a cosmic ray passing through a single vertical layer of BAND to select nearly-vertical cosmic rays. This corresponds to a relatively high energy deposition of 14.2 MeV. For each HV setting we fit the ADC spectrum with a Landau distribution and an exponential background to obtain the cosmic peak position. A representative ADC spectrum is shown in Fig. 15 (top). The obtained gain curve for this PMT is shown in the bottom panel of Fig. 15. The dashed lines indicate the final HV setting to position the cosmic peak at ADC channel 15000. This desired peak position of cosmic rays was chosen to avoid signal overflows in the sampling FADCs for neutron-induced signals, which deposit less energy as compared to cosmic rays. These overflows dominate above ADCs of 20000.

Each PMT gain curve was fit with a power law with parameters α and β

$$ADC = \alpha \cdot \left(\frac{\mathrm{HV}}{1500}\right)^{\beta},$$
 (1)

where the division by 1500 V was an arbitrary normalization to improve fit convergence. The value of the fit parameters for each PMT are shown in Fig. ?? (top). The Hamamatsu R7724 PMTs (red) are more uniform than either of the two ET PMTs, 9954KB (green) or 9214KB (blue)^c. However, the cosmic ray ADC peaks are well aligned after adjust-

^cWe obtained similar results when using the pulse amplitude of the ADC signal instead of the integral





Figure 13: (left) CAD drawing of the downstream side of BAND and its frame. The lead wall is shown in cyan, the scintillators are in magenta, and the support frame is in black. (right) Photograph of the downstream side of BAND installed in Hall B. The reflective surface in the photograph are the aluminum covers of the lead blocks.



Figure 14: BAND in Hall B. Upstream side with first set of cables installed.

ing the HV based on the obtained gain curves (see bottom panel in Fig. 16).

3.1.2. Energy deposit calibration

The ADC response of each PMT is converted to MeV energy deposition by measuring the response to multiple radioactive sources and to cosmic rays. The sources ⁶⁰Co, ²²Na, and ¹³⁷Cs were chosen due to the gamma rays that have Compton edges of 0.963 and 1.118, 0.477, and, 1.062 and 0.341, respectively (in MeV). The response to each source was measured in the center of the bar. Using the ADC response to all sources, in combination with the attenuation length of the bar, the ADC response can be converted to MeV. These measurements were done for a subset of the BAND bars (ones that were accessible following installation) after the bars were gain matched (see previous section).

A typical response of a PMT to 60 Co is shown in Fig. 17 along with a fit of the Compton edge by a parametrization described in [25]. The extracted Compton edges for various bars are quite similar which gives us confidence in applying these measurements to all bars.

3.1.3. Time-walk calibration

Time-walk calibrations were performed for each PMT with the laser system [4] by using the fiber optic attenuator [16] to vary the amount of light delivered to each bar. Waveforms and times were measured as the attenuator scans from 40 dB to 0 dB. The photodiode output is used as a reference time for any calibrations performed with the laser system, and is external to the variable attenuator.

Dependence of a typical PMT time on pulse height is seen in Fig. 18 (left). To correct for time-walk, we parameterize this dependence on the pulse height of the ADC signal, A, as:

$$t_{\rm PMT} - t_{\rm photodiode} = \alpha + \frac{\beta}{\sqrt{A}}.$$
 (2)

The residual difference, after the time-walk correction, $t_{\rm PMT} - t_{\rm photodiode}$, is shown in Fig. 18 (right). At pulse heights close to threshold, the parameterization is not flexible enough and underestimates the strong dependence on pulse height. However, signals with pulse heights this low are not of interest, as we found they are dominated by background, rather than by neutrons (see Section 3.2.3). Any residual corrections that are needed at higher pulse



Figure 15: Gain curve measurement. (Top) Typical ADC spectrum for a representative PMT with cosmic rays and the fit with a Landau distribution and an exponential background. (Bottom) Gain curve for the same PMT. The dotted lines indicate the final HV setting to set the cosmic peak to ADC channel 15000.

heights are corrected for iteratively, using the same equation as above.

3.1.4. Effective velocity

The relative time delays between PMTs on the same bar and the speed-of-light in that bar are extracted using cosmic ray data. The effective light speed in a given bar is extracted from the width of the relative timing distribution between its left and right PMTs and the bar's physical length:

$$t_L - t_R = -\frac{2x}{v}$$

$$-\frac{L}{v} \le t_L - t_R \le \frac{L}{v},$$
 (3)

The relative left-right PMT time offset is given by the center of the distribution (see Fig. 19 left).



Figure 16: (Top) Gain parameters for each PMT. One sees a greater spread in the Electron Tube PMTs (green and blue) than in the Hamamatsu PMTs (red). (Bottom) ADC_{cosmicpeak} position for each bar (vetos not shown) after gain matching. All bars are well aligned.



Figure 17: ADC spectrum for a 60 Co placed on the center of the bar along with the fit of the Compton edge.



Figure 18: Time-walk calibration: Typical PMT-reference photodiode time difference versus pulse height spectrum for one PMT before time-walk correction (left) and after time-walk correction (right).

This procedure is done after the PMT timing information has been time-walk corrected. The obtained effective velocities for each bar are shown in Fig. 19 (right) distinguished between short bars (boxes) and long bars (circles). The observed difference is due to geometrical effects from the different bar lengths.

3.1.5. Attenuation length

We measured the effective attenuation length of each completed (assembled and wrapped) bar from cosmic ray data by using the ADC amplitudes (A_L, A_R) and times (t_L, t_R) measured by the two PMTs:

$$A_L(x) = A_0 e^{-\frac{1}{\mu}(L/2 - x)}$$

$$A_R(x) = A_0 e^{-\frac{1}{\mu}(L/2 + x)}$$

$$R(x) \equiv \ln \frac{A_L(x)}{A_R(x)} = \frac{2x}{\mu} = \frac{-v(t_L - t_R)}{\mu}$$
(4)

where x is the location of the cosmic-ray hit, μ is the attenuation length, A_0 is the amplitude of cosmic ray interaction, and v is the effective speed of light in the bar. A typical plot of R(x) as a function of $t_L - t_R$ is shown in Fig. 20 (left). We fit the slope of the central part to obtain the attenuation length. The change in slope of the amplitude ratio closer to the edges of the bar is caused by light reflections from the light guides, which affected the amplitude and signal timing for events close to one PMT. We verified this by seeing the reflections in the unintegrated Flash ADC spectrum. We also see this using the integral of the signal (over 80 ns) rather than its amplitude (its peak) for R(x), see Fig. 20 (right). The distribution is linear over the whole bar since most of the reflections are included in the large integration window of 80 ns. However, the attenuation lengths from the integrated signals are very different from the bulk attenuation lengths and those measured in the bench tests due to the multiple reflections.

3.1.6. Individual Bar offsets

After all bars are individually calibrated, relative time delays between bars can still remain, and require correction to combine statistics from all bars. The alignment of all bars can be done quickly using the laser calibration system, as the laser pulse arrival time to each bar should be within the timing resolution. Any residual offset between bars can be corrected later by using the photon arrival time at each bar with respect to electrons detected in the CLAS12 forward detector.

We used the laser calibration system to send light pulses to all the bars. We aligned the average time of each bar, $t_{avg,i} = \frac{1}{2} (t_L + t_R)_i$, with respect to a reference bar in its layer and then we aligned the reference bars to that of layer 5. For example, the alignment for bar *i* in layer *j* is done as follows:

$$\mathcal{O}^{ij} = \langle t^i_{avg} - t^j_{avg} \rangle$$

$$\mathcal{O}^j = \langle t^j_{avg} - t^{ref}_{avg} \rangle$$

$$\overset{i,j}{corr} = t^i_{avg} - \mathcal{O}^{ij} - \mathcal{O}^j,$$

(5)

where t_{avg}^{ref} is the average time of the global reference bar chosen on the most downstream layer of BAND,



Figure 19: (Left) Typical time-walk corrected $t_L - t_R$ time spectrum in a single bar. The red dotted line indicates the LR offset value from 0. (Right) Effective light-speed for each bar. The differences in effective speeds between long bars (circles) and short bars (boxes) are due to geometrical effects.



Figure 20: (Left) Log ratio of ADC amplitudes from both PMTs on a bar as a function of time difference of the PMTs. (Right) Log ratio of ADC integral from both PMTs as a function of time difference.

and t_{avg}^j is the average time of the reference bar chosen in layer j. Then only one global offset is needed to correct the offset of t_{avg}^j if there are no residual offsets between bars.

3.2. BAND performance

3.2.1. Global offset

A final global time offset is required to align BAND with CLAS12. The CLAS12 time is determined by the time of the electron detected in the forward detector, as traced back to the target.

Fig. 21 shows the uncorrected electron-BAND time difference spectrum offset by the photon travel time for each bar. There was a 2-MeV energy deposition cut to reduce the random coincidence background. The uncorrected spectrum includes only time walk corrections but no offset corrections. One can see several sharp photon peaks between 50 and 60 ns, far away from the expected zero value.

After applying the individual offset corrections from the previous section, we determined a timing offset for each bar from the location of its photon timing peak. Applying these offsets results in the corrected spectrum, which displays a well-aligned photon peak with a width of $\sigma = 294$ ps, consistent with the design value. The periodic 4-ns spikes in the remaining spectrum are due to photons correlated with out-of-time electrons from other beam bunches.



Figure 21: Relative electron-BAND time difference spectrum for all bars offset by the photon travel time for each bar: (red) after time-walk corrections, but not offset corrections, and (green) after all corrections. The bars are well aligned with a width of the photon peak of $\sigma = 294$ ps. A 2-MeV energy deposition cut is applied to reduce the random background. The periodic 4-ns spikes in the remaining spectrum are due to photons correlated with out-of-time electrons from other beam bunches.

3.2.2. Time of Flight resolution

The time resolution of each bar was measured independently using laser calibration data and using the electron-BAND time difference spectrum. The laser data allows us to measure the time resolution over the whole energy deposition range from 0.5 to 7 MeV (see Fig. 7).

The laser-based resolutions are obtained from a Gaussian fit of the difference of the average time of a bar to the reference photodiode as a function of energy deposited, see Fig. 22. The resolutions for the 1- and 5-MeV cuts are well below the 300-ps design goal. For the 5-MeV cut, which is a realistic neutron-selection energy deposition cut (see Section 3.2.3) the resolutions are better than 150 ps.

Fig. 22 (right) shows the time resolutions from the measured electron-photon arrival time difference with an energy deposition cut of 2 MeV. We used a high-statistics data run where electrons are detected in CLAS12. The data was also used for the global offset corrections presented in Sec 3.2.1. These measured resolutions include additional uncertainties from the pathlength of the target photons to the bar ($\sigma \approx 70$ ps) and from the time resolution of the electron beam bunch ($\sigma \approx 25$ ps). The laser data does not have these uncertainties.

3.2.3. Neutron identification

We identified neutrons from the electrondeuteron, d(e, e')X, production data by cutting on the time-of-flight per pathlength (ToF/m), where ToF is the time difference between the time that the electron interacted in the target and the particle arrival time measured by BAND (see Fig. 23 for data with a minimum energy deposition cut of 5 MeV). There are well-separated peaks for photons and for neutrons on top of a flat background from accidental coincidences.

The minimum energy deposition for neutron signals is optimized using the neutron signal-tobackground ratio, see Fig. 24. The signal region includes times for neutrons with $200 \leq p_n \leq 600$ MeV/c. The accidental background was estimated by fitting a constant to the left of the photon peak (see Fig. 23). The signal is defined as the integral of the spectrum over the signal region minus the scaled background. As the minimum energy deposition cut increases, the signal decreases, but the signal to background ratio increases. With a 5-MeV energy deposition, the signal-to-background ratio is almost three. The optimal cut will be somewhere between two and seven MeV and will be determined by minimizing the experimental uncertainties.

3.2.4. Neutron efficiency

The efficiency of BAND for neutron detection was studied using a Geant4 simulation, the results of which are shown in Fig. 25. As expected, the efficiency depends both on the energy threshold as well as the neutron momentum.

The Geant4 study did not include the effects of the material between BAND and the CLAS12 target, aside from the lead wall upstream of BAND. Neutrons of different fixed momenta were simulated according to a flat solid-angle distribution, and the efficiency was calculated to be the number of events registering only a single hit with energy deposition above threshold divided by the number of fired neutrons with trajectories hitting BAND. This efficiency is therefore an average over different incident angles and hit positions in BAND. This efficiency will be reduced by the effects of neutron multiple scattering in the material between BAND and the CLAS12 target.

The simulation indicates that BAND can achieve an efficiency at or above the design goal of above 35% using thresholds between 2- and 5 MeVee, even for higher-momentum neutrons. Running with higher thresholds to suppress background



Figure 22: Time resolution for every bar. (Left) as measured with the laser calibration system for two separate energy deposition cuts. (Right) as measured from the electron-photon time difference spectrum with a 2-MeV energy deposition cut. All bars are at or below the required 300-ps resolution.



Figure 23: Time-of-flight per meter of BAND hits in coincidence with electrons measured in CLAS12. A sharp photon peak and a broad neutron peak are visible over a flat background from accidentals. The dashed lines indicate the range of neutrons with momenta between 200 and 600 MeV/c.

may be possible without significantly compromising BAND's neutron detection efficiency.

4. Summary

The Backward Angle Neutron Detector (BAND) of CLAS12 detects neutrons emitted at backward angles of 155° to 175° and momenta between 200 and 600 MeV/c. It is positioned 3-m upstream of the target and consists of 18 rows and 5 layers of 7.2-cm by 7.2-cm scintillator bars with PMT readout on both ends to measure time and energy depo-



Figure 24: Signal counts (blue) and accidental background counts (red) in the neutron signal region of $200 \le p_n \le 600$ MeV/c. The signal-to-background ratio (green) shown with a possible minimum energy deposition cut of 5 MeV.

sition in the scintillator layers. Between the target and BAND there is a 2-cm thick lead wall followed by a 2-cm veto layer to suppress gammas and reject charged particles.

Timing calibrations were performed using a novel picosecond-pulsed laser system, along with cosmic and $ed \rightarrow e'n$ data. Energy calibrations utilized a wide range of radioactive sources.

After timing and energy calibrations performed, the measured time resolution is below our design goal of 300 ps, better than 250 ps (150 ps) for energy depositions above 2 MeV (5 MeV), yielding a momentum reconstruction resolution of $\delta p/p < 1.5\%$.



Figure 25: The efficiency of BAND for neutron detection as determined using a Geant4 simulation. (Left) Efficiency as a function of neutron momentum for various energy thresholds, without the effect of the lead wall upstream of BAND (top) and including the lead wall (bottom). (Right) Efficiency as a function of energy threshold for various neutron momenta without the effect of the lead wall upstream of BAND (top) and including the lead wall (bottom).

The expected neutron efficiency from simulation is 35%. In the future, we will measure the efficiency using exclusive $ed \rightarrow e'pn$ events collected at Jefferson Lab.

Acknowledgements

We thank Jefferson Lab's Hall B technical crew for the immense efforts during the BAND assembly, installation, and commissioning, especially Denny Insley, Calvin Mealer and Bob Miller. Thanks to Sergey Boyarinov, Ben Raydo, Chris Cuevas and Armen Stepanyan for providing crucial support in setting up the readout system.

We thank Bill Briscoe from George Washington University for generously providing PMTs and voltage dividers for the veto bars. We would like to thank MIT Bates for building the BAND support frame.

We also would like to thank Hall B staff for their unwavering support, especially Stepan Stepanyan for setting up an assembly and testing area at Jefferson Lab and Eugene Pasyuk for organizing components. The development of the calibration, reconstruction, and analysis software benefited greatly from discussions, advice, and assistance by Daniel Carman, Raffaella De Vita, and Cole Smith. Finally, thanks to Run Group B of Hall B in Jefferson Lab, and our run-group coordinator, Silvia Niccolai, for their support during datataking.

This work was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Numbers DE-FG02-94ER40818, de-sc0020240, DE-FG02-96ER-40960, DE-FG02-93ER40771, and DE- AC05-06OR23177 under which Jefferson Science Associates operates the Thomas Jefferson National Accelerator Facility, the Israel Science Foundation under Grant Nos. 136/12 and 1334/16, the Pazy foundation, the Clore Foundation, and the Chilean FONDECYT grant No. 1201964.

References

- V. Burkert, et al., The CLAS12 Spectrometer at Jefferson Laboratory, Nucl. Instrum. Meth. A 959 (2020) 163419. doi:10.1016/j.nima.2020.163419.
- [2] O. Hen, et al., In medium proton structure functions, src, and the emc effect, JLab PAC Proposal (2015). URL https://misportal.jlab.org/pacProposals/ proposals/1159/attachments/93263/E12-11-003A. pdf
- [3] P. Chatagnon, et al., The CLAS12 Central Neutron Detector, Nucl. Instrum. Meth. A 959 (2020) 163441. doi:10.1016/j.nima.2020.163441.
- [4] A. Denniston, et al., Laser Calibration System for Time of Flight Scintillator Arrays, Nucl. Instrum. Meth. A 973 (2020) 164177. doi:10.1016/j.nima.2020.164177.
- [5] Hamamatsu R7724: https://www.hamamatsu.com/ resources/pdf/etd/R7723_R7724_R7725_TPMH1315E. pdf.
- [6] ET 9214, http://et-enterprises.com/products/ photomultipliers/product/p9214b-series.
- [7] ET 9954KB, http://et-enterprises.com/products/ photomultipliers/product/p9954b-series.
- [8] BC408 Scintillant: https://www.crystals.saint-gobain.com/sites/ imdf.crystals.com//files/documents/ bc400-404-408-412-416-data-sheet.pdf.
 [9] 3M Enhance Specular Reflector: https://www.
- [9] 3M Enhance Specular Reflector: https://www 3m.com/3M/en_US/company-us/all-3m-products/ ~/3M-Enhanced-Specular-Reflector-3M-ESR-/?N= 5002385+3293061534&rt=rud.
- [10] Overview over Hamamatsu PMTs: https: //www.hamamatsu.com/resources/pdf/etd/High_ energy_PMT_TPMZ0003E.pdf.
- [11] DYMAX Ultra Light-Weld 3-20262, http://www. dymax.com/images/pdf/pds/3-20262.pdf.
- [12] MOMENTIVE RTV615 silicone rubber compound, https://www.momentive.com/en-us/ /products/tds/rtv615?productId= 64616a84-08ff-4372-a2a2-a58eb45be627.
- [13] R. Fair, et al., The CLAS12 superconducting magnets, Nucl. Instrum. Meth. A 962 (2020) 163578. doi:10. 1016/j.nima.2020.163578.
- [14] Thorlabs black Aluminium foil, https://www. thorlabs.com/thorproduct.cfm?partnumber=BKF12.

- [15] Teem Photonics: https://www.teemphotonics.com/ laser/microchip-laser-355-nm-1e-4khz-600ps.
- [16] OZ Optics: https://www.ozoptics.com/products/ attenuators.html.
- [17] CAEN SY4527: https://www.caen.it/products/ sy4527/.
- [18] CAEN A1535SN: http://www.caen-group.com/ servlet/checkCaenManualFile?Id=9315.
- [19] JLab 250 MHz FADC manual. URL https://www.jlab.org/Hall-B/ftof/manuals/ FADC250UsersManual.pdf
- [20] CAEN VX1190A: https://www.caen.it/products/ v1190a-2esst/.
- [21] S. Boyarinov, et al., The CLAS12 Data Acquisition System, Nucl. Instrum. Meth. A 966 (2020) 163698.
 doi:10.1016/j.nima.2020.163698.
- [22] B. Raydo, et al., The CLAS12 Trigger System, Nucl. Instrum. Meth. A 960 (2020) 163529. doi:10.1016/j. nima.2020.163529.
- [23] CAEN V1495: https://www.caen.it/products/ v1495/.
- [24] Dupont Tedlar foil, https://www.dupont.com/ content/dam/dupont/products-and-services/ membranes-and-films/pvf-films/documents/DEC_ Tedlar_GeneralProperties.pdf.
- [25] M. J. Safari, F. Abbasi Davani, H. Afarideh, Differentiation method for localization of Compton edge in organic scintillation detectors arXiv:1610.09185.