The Silicon Vertex Tracker for the Heavy Photon Search Experiment

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***Abstract*—The Heavy Photon Search (HPS) is a new, dedicated experiment at Thomas Jefferson National Accelerator Facility (JLab) to search for a massive vector boson, the heavy photon (a.k.a. dark photon, A'), in the mass range 20-500 MeV/c^2 and with a weak coupling to ordinary matter. An A' can be radiated from an incoming electron as it interacts with a charged nucleus in the target, accessing a large open parameter space where the A' is relatively long-lived, leading to displaced vertices. HPS searches for these displaced A' to $\mathrm{e}^+\mathrm{e}^-$ decays using actively cooled silicon microstrip sensors with fast readout electronics placed immediately downstream of the target and inside a dipole magnet to instrument a large acceptance with a relatively small detector. With typical particle momenta of 0.5-2 GeV/c, the low material budget of 0.7% X_0 per tracking layer is key to limiting the dominating multiple scattering uncertainty and allowing efficient separation of the decay vertex from the prompt QED trident background processes. Achieving the desired low-mass acceptance requires placing the edge of the silicon only 0.5 mm from the electron beam. This results in localized hit rates above 4 MHz/mm^2 and radiation levels above 10^{14} 1 MeV neutron equivalent dose. Hit timing at the ns level is crucial to reject out-of time hits not associated with the A' decay products from the almost continuous CEBAF accelerator beam. To avoid excessive beam-gas interactions the tracking detector is placed inside the accelerator beam vacuum envelope and is retractable to allow safe operation in case of beam motion. This contribution will discuss the design, construction and first results from the first data-taking period in the spring of 2015.**

I. Introduction

RECENT astrophysical results [1], [2] have generated intense interest in physics models beyond the Standard Model with a new force, mediated by a massive, sub-GeV scale, U(1) gauge boson (a.k.a. the Heavy Photon, Dark Photon or A') that couples very weakly to ordinary matter through "kinetic mixing" [3], [4]. The existence of such a new force is in accord with astrophysical and cosmological constraints. Its weak coupling to the electric charge could be the only non-gravitational window into the existence of hidden sectors consisting of particles that do not couple to any of the known forces that are common in many new physics scenarios [5].

The Heavy Photon Search experiment (HPS) is a new fixed-target experiment [6] specifically designed to discover an A' with $\mathrm{m}_{\mathrm{A}'} = 20 - 500$ MeV, produced through bremsstrahlung in a tungsten target and decaying into an e^+e^- pair.

Manuscript received November 23, 2015. Work supported by the U.S. Department of Energy under contract number DE-AC02-76SF00515, the National Science Foundation, French Centre National de la Recherche Scientifique and Italian Istituto Nazionale di Fisica Nucleare. Authored by Jefferson Science Associates, LLC under under U.S. Department of Energy contract No. DE-AC05-06OR23177.

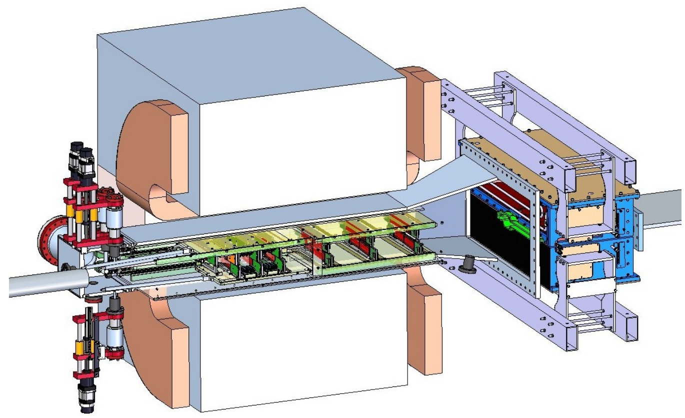

Fig. 1. A rendered overview of the HPS detector.

II. The Heavy Photon Search Experiment

The Heavy Photon Search experiment (HPS) is a new fixed-target experiment [6] specifically designed to discover an A' with $\mathrm{m}_{\mathrm{A}'} = 20 - 500$ MeV, produced through bremsstrahlung in a tungsten target and decaying into an e^+e^- pair. In particular, the HPS experiment has sensitivity to the challenging region with small cross sections out of reach from collider experiments and where thick absorbers, as used in beam-dump experiments to reject backgrounds, are ineffective due to the relatively short A' decay length (< 1 m) [7]. This is accomplished by placing a compact silicon tracking and vertex detector (SVT) in a magnetic field, immediately downstream (10 cm) of a thin ($\sim 0.125\%$ X_0) target to reconstruct the mass and decay vertex position of the A'. A rendered overview of HPS is shown in Fig. 1.

HPS runs in Hall B at Thomas Jefferson National Accelerator Facility (JLab) using the CEBAF accelerator electron beam with an energy of 1.05 GeV and 50 nA current, with planned operation of up to 6.6 GeV and 450 nA. The kinematics of A' production typically results in final state particles within a few degrees of the incoming beam, especially at low $m_{\mathrm{A}'}$. Because of this, the apparatus must accommodate passage of the beam downstream of the target and operate as close to the beam as possible. Because background rates in this region from the scattered beam are very large, a fast lead-tungstate crystal calorimeter trigger with 250 MHz FADC readout [8] and an excellent time tagging of hits is used to select interesting data and reduce the bandwidth required to transfer data from the detector. This method of background reduction is the

Layer →	1-3	4-6
z pos. (cm)	10-30	50-90
Stereo angle (mrad)	100	50
Non-bend plane res. (μm)	≈ 6	≈ 6
Bend plane res. (μm)	≈ 130	≈ 130

TABLE I
MAIN TRACKER PARAMETERS.

motivation for operating HPS in a nearly continuous beam: in a beam with large per-bunch charge, background from a single bunch would fully occupy the detector at the required beam intensity.

III. THE SILICON VERTEX TRACKING DETECTOR

The Silicon Vertex Tracker (SVT) allows for precise and efficient reconstruction of charged particle and their trajectories. At beam energies between 1.0-6.6 GeV, the e^+e^- pair from the A$'$ decay will emanate with momenta between 0.4-2 GeV/c and an angle of 10-100 mrad from the beamline. The dominant tracking uncertainty in this regime is multiple Coulomb scattering and the SVT needs to minimize the amount of material in the tracking volume. With an approximate goal of 2% mass resolution and a $\approx$ 1 m long tracking volume (determined by existing vacuum chamber) and 0.25 T (for 1 GeV beam energy) magnetic field, a 1% X_0 or less material per 3D tracking hit and six layers was determined adequate. For low kinetic mixing angles, the A$'$ maybe be long-lived and the e^+e^- pair decay vertex might be displaced several cm's downstream of the target foil. To discover rare A$'$ displaced decays, the SVT typically needs a prompt rejection of roughly 10^7 at 1 cm vertex resolution [6]. In order to reach that performance, the first layer of the SVT needs to be placed 10 cm from the target. At that distance, the large hit rates from beam electrons undergoing Coulomb scattering in the target allows placing the first layer 1.5 mm from the beam. The intense radiation thus creates a 15 mrad "dead zone" throughout the experiment where no instrumentation can be placed. The expected radiation dose peaks at 10^{15} electrons/cm^2/month, or roughly 3×10^{13} 1 MeV neutron equivalent/cm^2/month [9], close to the beam and places further constraints on the sensor technology. Furthermore, the whole tracker has to operate in vacuum to avoid secondary backgrounds from beam gas interactions, and have retractable tracking planes and easy access for sensor replacement to increase safety. Given the high hit density, the fast time response, and good resolution and radiation hardness needed; silicon microstrip sensors are the technology of choice for the tracker. Pixel sensors suitable for instrumenting our large acceptance are either too slow or have an unacceptable material budget.

A. Layout

The SVT overall layout is rendered in Fig. 2 and summarized in Tab. I. Each of the six tracking layers, arranged in two halves both above and below the beam to avoid the "dead zone", consists of placing silicon microstrip sensors back-to-back. The first three layers have a 100 mrad stereo angle between the sensors and the last three have 50mrad in order to improve the pointing resolution to the vertex. The first layer is located only 10 cm downstream of the target to give excellent 3D vertexing performance which, with the 15 mrad dead zone above and below the beam axis, puts the active silicon only 1.5 mm from the center of the beam. Hit densities in the most active region reaches 4 MHz/mm^2 and about 1% occupancy for the strips closest to the beam, see Fig. 3.

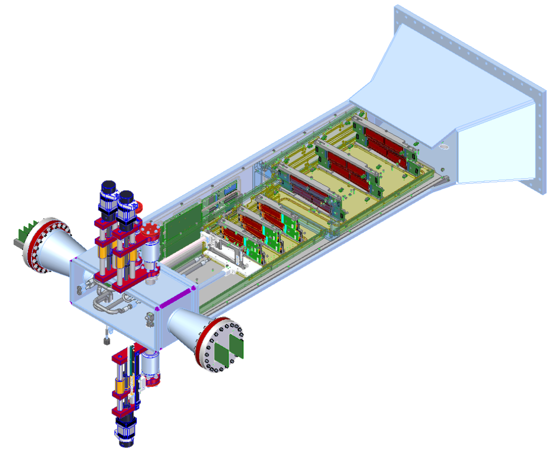

Fig. 2. A rendered overview of the SVT installed on the beamline.

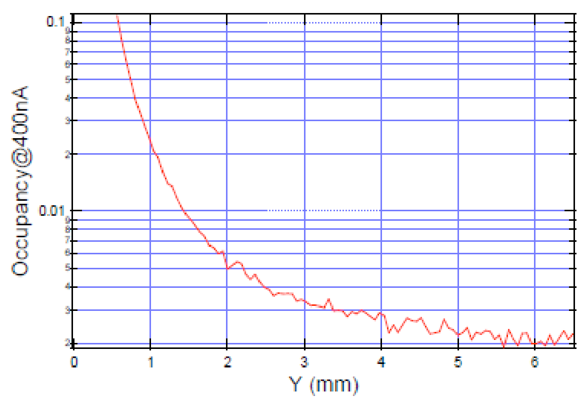

Fig. 3. Occupancy per strip (60 μm readout pitch) in Layer 1 of the SVT for 8 ns of beam at 400 nA [6].

B. Sensors and Front-End Readout

The sensors are p+-on-n, single-sided, AC-coupled, polysilicon-biased microstrip sensors with 30 (60) μm sense (readout) pitch fabricated by Hamamatsu Photonics Corporation for the cancelled DØRun 2b upgrade [10]. These sensor are 4×10 cm^2 and 320 μm thick, matching the required material budget and single hit resolution (better than 50 μm). The sensors were qualified to withstand at least 1 kV bias in order to tolerate the 1.5×10^{14} 1 MeV neutron equivalent/cm^2 for a six month run without much degradation.

One of the key requirements for the SVT is hit time resolution of about 2 ns in order to reject background and improve pattern recognition for tracking close to the beam where occupancies are high. This is achieved by using the APV25 front-end readout Application Specific Integrated Cir-

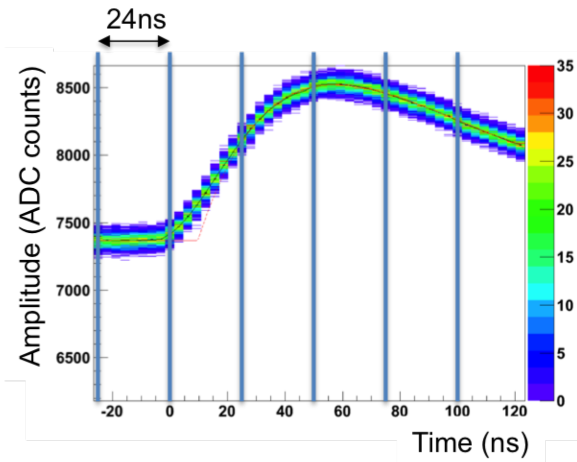

Fig. 4. Pulse shape of the APV25 ASIC.

Technology	0.25 μm
Channels	128
Input pitch	44 μm
Noise [ENC e$^-$]	$270 + 36\times$C (pF)
Power consumption	350mW

TABLE II
MAIN APV25 ASIC PARAMETERS.

cuit (ASIC) [11], developed for the Compact Muon Solenoid experiment at the Large Hadron Collider. The APV25 is an analog pipeline ASIC with 128 channels of preamplifier and shaper, feeding a 192 long pipeline ASIC with analog memory. In the so-called "multi-peak" readout mode, the APV25 presents three consecutive samples of the pipeline upon an APV25 readout trigger signal. By sending two APV25 readout triggers for every trigger signal from the electromagnetic calorimeter, six analog samples of the pulse shape, see Fig. 4, is obtained at a sampling rate of 41 MSPS. This pulse shape can be analyzed and fitted to extract the t_0 of the hit [12]. The details of the APV25 ASIC is shown in Tab. II: the 44 μm pitch, low noise and operation using either polarity together with the proven robustness and radiation hardness is a good fit for the SVT. The sensor and APV25 chip can be seen in Figure 5.

C. Module Design

Five APV25 chips are mounted on FR4 hybrid boards and wire-bonded to the end of the sensor. The hybrid boards, located outside the tracking volume, provide power and filtering circuitry for the high voltage bias and a temperature sensor. A hybrid and a sensor, glued to a polyimide-laminated carbon fiber composite backing, make up a so-called "half-module" for the first three layers. To increase acceptance, the half-modules for layers 4-6 have two sensors mounted next to each other and are read out from opposed ends. Space constraints required these hybrids to be slightly smaller for those half-modules and instead of Teflon-coated twisted pair wires soldered directly to the FR4 board as in layer 1-3, these have BGA mounted high density connectors to transfer signal, power and high voltage bias on and off the hybrid. Figure 5 and 6 shows a complete layer 1-3 and a 4-6 half-module under assembly, respectively.

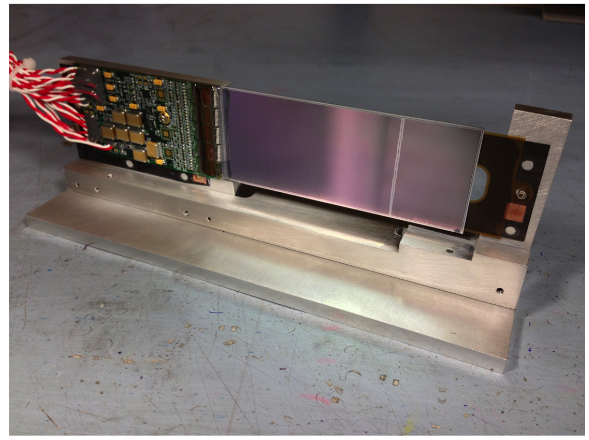

Fig. 5. Half-module used to build modules for the three most upstream layers.

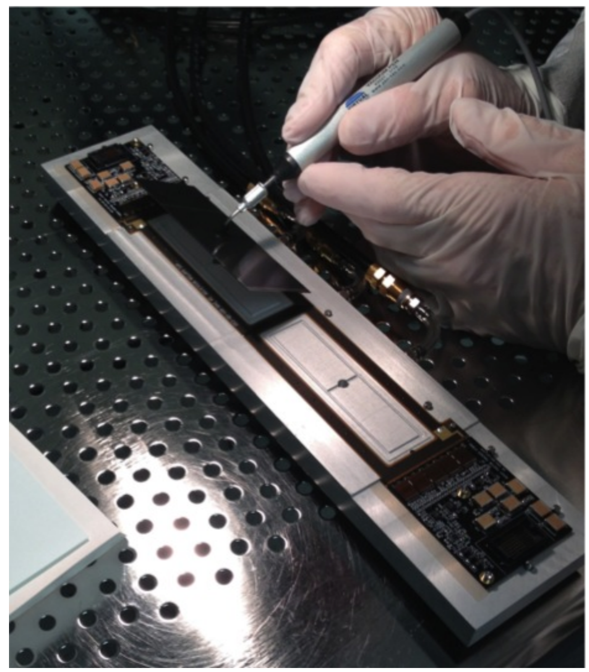

Fig. 6. Half-module used to build modules for the three downstream layers.

Modules are built from placing two half-modules, with each hybrid end sandwiched around an aluminum cooling block, back-to-back with a 50 or 100 mrad stereo angle which gives the required 3D space point resolution. The cooling block extends a few millimeter under the sensor in order to more efficiently transfer heat out of the sensors. For layer 1-3 modules, the cooling block serves as the fixed part of a support where the opposed end of the half-modules are screwed to an aluminum bar with a pivot engaging a screw-adjusted spring, see Fig. 5. This spring-tensioned module support allows keeping the sensors, with its carbon fiber backing, straight with essentially zero support material and to absorb thermal expansion mismatch. The same principle is used for layer 4-6 where one of the cooling blocks are pinned to the spring.

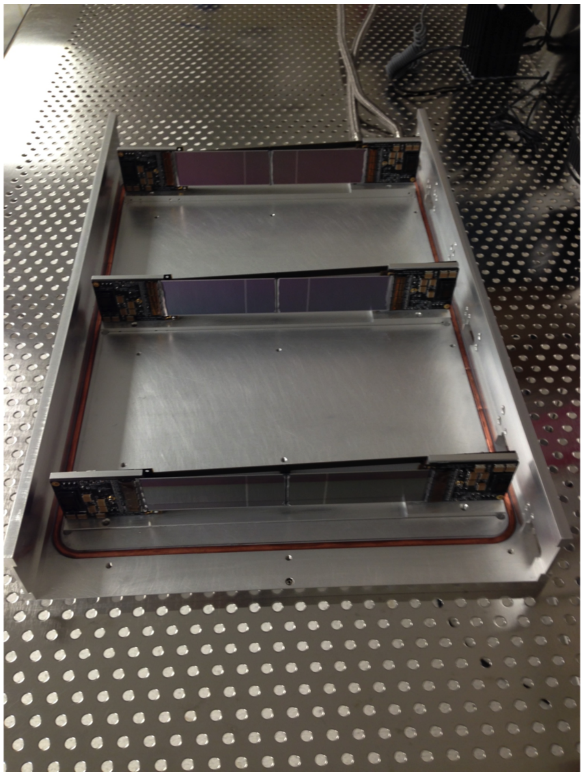

Fig. 7. A u-channel for layer 4-6 holding three detector modules.

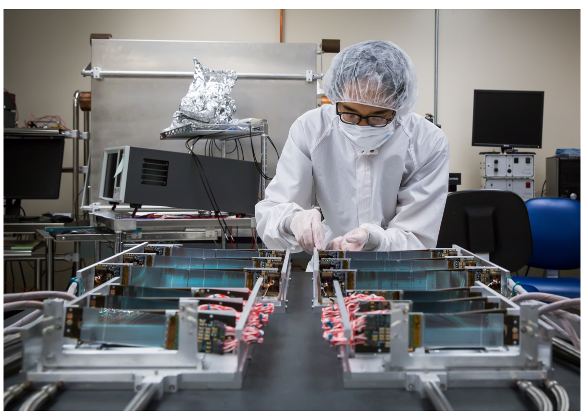

Fig. 8. All four u-channels (layers 1-3 closest) with detector modules mounted. The flexible cooling hoses and support rods for layer 1-3 can be seen extending towards the camera view.

D. Support and Cooling

Three modules are screwed directly on to a aluminum "u-channel", see Fig. 7 and 8, that are actively cooled by coolant circulating in a 1/4" copper tube pressed into a machined grove. Four U-channels, two for L4-6 and two for L1-3, roll in to a rigid support box on guide rails to precision kinematic mounts. The support box, shown in Fig. 9, sits inside the JLab Hall B analyzing magnet magnet chamber on four adjustable supports, essentially matching the inner size to within a few millimeters. In order to provide the rigidity needed for precision mounting of the u-channels, a square "support ring" is located at the inner mounting point for the u-channels. That support ring also provide guiding holes and

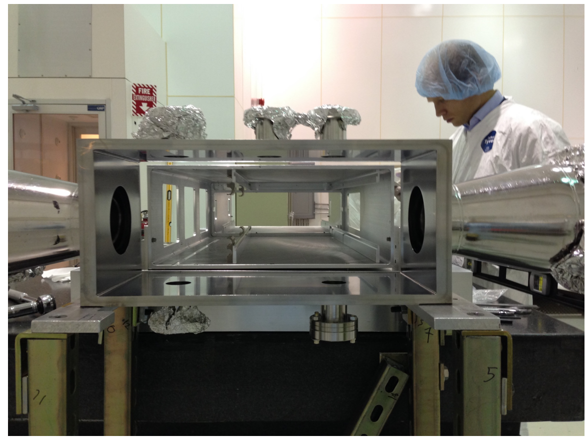

Fig. 9. The SVT support box with the upstream vacuum box for services.

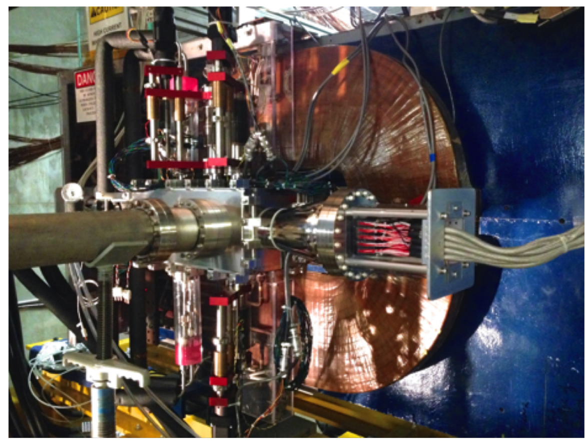

Fig. 10. View from upstream, electron side, of the SVT after installation on the beamline. The vacuum box, that interfaces the beamline with the vacuum chamber, can be seen with its three linear shifts, two on the top and one on the bottom side. The flange holding the power and high-voltage sensor bias vacuum penetration boards extends to the right from the support box.

support for the flexible hoses connecting to the press-fit tube in the layer 4-6 u-channels. The upstream end of the layer 1-3 u-channels are attached to a rigid support rod extending upstream to vertical linear shifts. Moving the vertical linear shifts allows the layer 1-3 u-channels to rotate up to 1.3° and the layer 1 sensors to move more than 7 mm from the beam, allowing clean passage of the beam during beam setup. The linear shifts, one for top and one for bottom, penetrate vacuum through bellows and are remote-controlled by a precision stepper motor that allows the placement of the layer 1 sensors that are closest to the beam with 6 μm steps and < 50 μm reproducibility after calibration under vacuum. A similar linear shift setup is used to hold and move the target in the right position. The flanges for vacuum penetration are located on a custom support box that attaches to the upstream end of the JLab Hall B analyzing magnet as seen in Fig. 10. In addition to the linear shift flanges, it has flanges for cooling lines and electrical services and the upstream interface to the beamline.

An aluminum plate with data acquisition boards, see Fig. 11, slide in to the chamber in a machined grove in the support box. HFE coolant is circulated through the u-channels (at about -

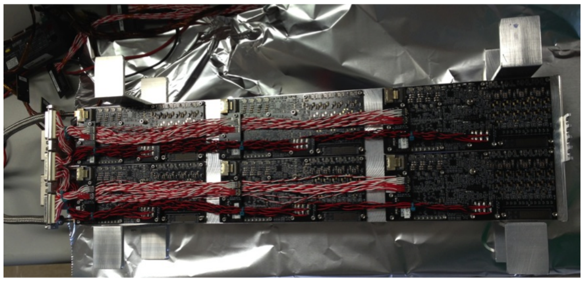

Fig. 11. The partially cabled data acquisition front end boards screwed to the aluminum support plate before installation .

Fig. 12. One COB ATCA blade used in the RCE platform.

20° C) keeping the silicon at approximately at roughly -10°C to withstand the high localized radiation dose. Water at 20° C is used to cool the data acquisition boards.

E. Data Acquisition

Six analog samples at 41.66 MSPS from the APV25 chips, from up to four hybrids, are sent on twisted pair magnet wire to a total of 10 Front End Boards (FEB) seen in Fig. 11. Each FEB digitizes and transfers data at up to 3.3 Gb/s using high-speed serial links to Xilinx Zynq based data processing modules on the ATCA based SLAC RCE platform [13] for zero suppression and event building. Each FEB also handles power regulation and monitoring as well as high voltage sensor bias distribution to each of the attached hybrids. To shorten the distance of analog signal transfer, the FEBs are fitted inside the vacuum chamber, pressed against thermal pads on each side of a 1/2" cooled support plate on the upstream positron side, which has a less intense radiation environment. Borated high-density polyethylene is used to further lower the risk of damage from radiation emitted by the nearby target. Data from three or four FEBs are routed via short, flexible mSAS cables to four flange boards. These are FR4 boards potted through slots in the 8" vacuum flange on the upstream positron side of the vacuum box. On the air side of the boards, signals are converted to optical and transferred to the DAQ platform about 30 m away. A similar mechanical technique is used on the opposite side of the vacuum box to bring in low voltage power and high voltage sensor bias into the chamber; this can be seen in Fig. 10.

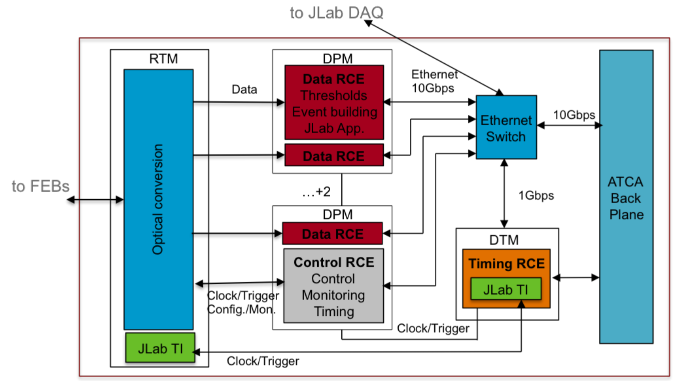

Fig. 13. Schematic overview of the SVT DAQ.

An overview of the data flow across the RCE platform is shown in Fig. 13. Data from 10 FEBs are split and sent to 14 processing nodes on two ATCA blades, called Cluster On Board (COB). The processing nodes, known as Reconfigurable Cluster Elements (RCE) are based on Xilinx Zync 7000 series system-on-chip which has a dual ARM Cortex A9 processor tightly coupled to a 28nm FPGA fabric. The independent operating nodes receive data from up to four hybrids, applies calibrated thresholds and builds event frames in the firmware. A readout application from the JLab DAQ, running on the ARM processor, pulls the event frames from memory via DMA and transfers the event frames to the JLab CODA event builder over 10 Gb/s ethernet. The COB also hosts a special RCE that handles the trigger and timing distribution across the processing nodes on each COB. This RCE implements the JLab trigger interface firmware and accepts the master and derived clocks together with trigger information from the JLab DAQ from a special fiber attached on the custom rear transition board. One of the RCEs is allocated to handle control, trigger and timing signals to and from all the hybrids. It also hosts the slow control and environmental interfaces to the EPICS control system.

During running the system operated at about 20 kHz and with data rates up to 150 MB/s. It has been tested to 50 kHz and 200 MB/s.

F. Performance

HPS first run with an electron beam was carried out in the spring of 2015. The primary goals of this engineering run was to prove existing outstanding operational principles. Thanks to a 2-week extension of the running schedule HPS was able to take data with a fully functional detector, beam current and size as specified in the requirements and the SVT in its design nominal position with sensors only 0.5 mm from the the center of the beam. In addition to commissioning, roughly 1/3 of a week of physics data was taken at the nominal operating point with 1.05 GeV beam energy.

The SVT was operated with 180 V sensor high-voltage bias and had only five bad channels out of 23,040. Beam halos and occupancy was measured as expected (see Fig. 3). The preliminary results presented below shows that key performance variables behave as expected at this early stage, where

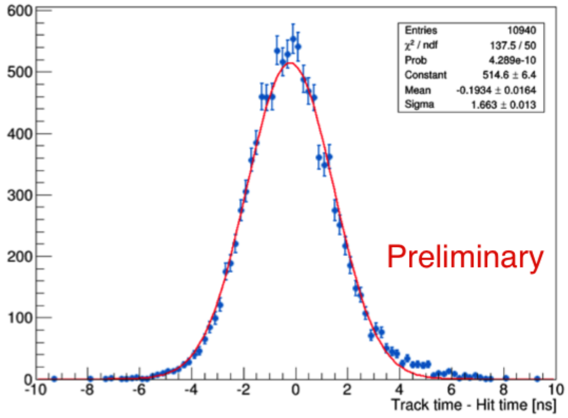

Fig. 14. Difference between the track time and hit time.

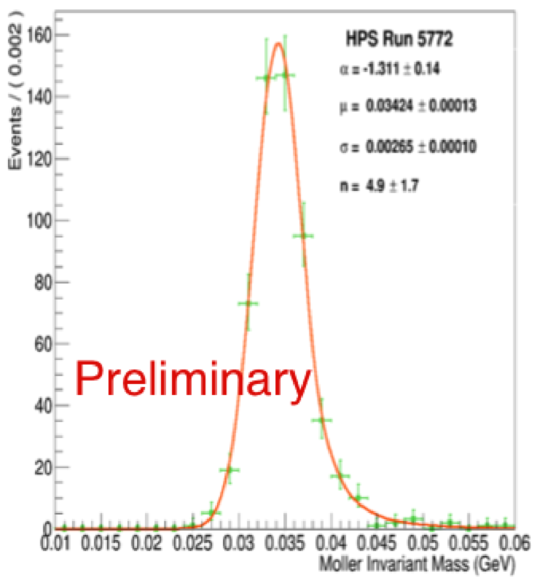

Fig. 15. Invariant mass of selected e^-e^- pairs compatible with Moller kinematics in a fraction of the data collected.

improvements in calibration and alignment is underway. A 2.2 ns time resolution can be extracted from the difference between the hit and track time (average of the hit times on the track) seen in Fig. 14. Further optimizations on the pulse shape fit will likely improve this. For the A′ searches, the mass and vertex resolutions are key observables. The mass resolution are calibrated using e.g. Moller events, see Fig. 15, and data show good agreement with the expected distribution from simulated events. The vertex resolution, and with particular emphasis on it's positive tail, show reasonable agreement with simulation at this stage. The vertex distribution of e^+e^- pairs after a QED trident selection is shown in Fig. 16. Understanding the tails of these type of distributions is fundamental to the displaced vertex search. Ongoing data analysis results from this run is expected in 2016.

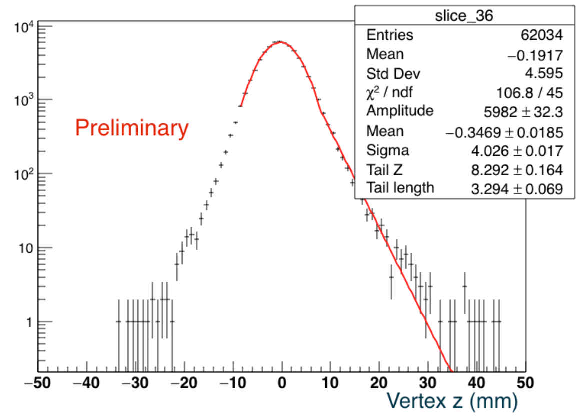

Fig. 16. Fitted vertex distribution of e^+e^- pairs selected using a QED trident events for a small fraction of the data.

G. Summary and Outlook

The HPS experiment is a new fixed-target experiment in Hall B at JLab searching for a heavy photon, or A′, produced in a bremsstrahlung-like process with the CEBAF accelerator beam interacting with a thin tungsten foil. HPS searched for visible decays of the A′ to an e^+e^- pair in the A′ 20-500 MeV/c^2 mass range. The signal signature is two-fold: a bump-hunt search in the invariant mass spectrum on top of a large continuous QED trident background and a low background displaced vertex search to discover A′ if they are long-lived.

The experiment employs a silicon vertex tracker (SVT), triggered by a fast lead-tungstate electromagnetic calorimeter with good time resolution, to measure the trajectories of the A′ decays. The SVT has six layers of silicon microstrip sensor pairs with 50-100 mrad stereo angle distributed over approximately 80 cm. In order to reach the prompt vertex rejection needed, the first layer is placed only 10 cm behind the target. To avoid the majority of the scattered beam, the SVT is split in two halves around the beam plane with a 15 mrad dead zone placing the innermost sensors 0.5 mm from the center of the beam. In addition to the design challenges of having a retractable, actively cooled silicon detector in beam vacuum the material in the tracking volume needs to be minimized with typical electron momenta between 0.5-2 GeV/c. Spring-tensioned, carbon fiber backed, tracking modules are built with less than 0.1% radiation length of support material for each 3D space point. A 2 ns time resolution, needed to reject out-of-time background in the nearly continuous beam, is obtained by reading out and fitting six samples of the pulse shape from APV25 ASIC. The SVT was installed, commissioned and operated under nominal conditions during an engineering run in 2015. Preliminary results suggests expected performance and blinded A′ searches based on roughly 1/3 week of data are underway.

ACKNOWLEDGMENT

The authors are grateful for the support from Hall B at JLab and especially the Hall B engineering group for support during installation and decommissioning. They also would like to commend the CEBAF personnel for good beam performance during the spring run of 2015. The tremendous support from home institutions and supporting staff also needs praise from the authors.

REFERENCES

[1] O. Adriani *et al.* [PAMELA Collaboration], Nature **458**, 607 (2009)
[2] M. Ackermann *et al.* [Fermi LAT Collaboration], Phys. Rev. D **82**, 092004 (2010)
[3] N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer and N. Weiner, Phys. Rev. D **79**, 015014 (2009).
[4] B. Holdom, Phys. Lett. B **166**, 196 (1986), P. Galison *et al,* Phys. Lett. B **136** (1984) 279
[5] J. L. Hewett, *et al.*, "Fundamental Physics at the Intensity Frontier," arXiv:1205.2671 [hep-ex].
[6] A. Grillo *et al.* [HPS Collaboration], JLab PAC37 PR-11-006, http://www.jlab.org/exp prog/PACpage/PAC37/proposals/Proposals/
[7] J. D. Bjorken, R. Essig, P. Schuster and N. Toro, Phys. Rev. D **80**, 075018 (2009) [arXiv:0906.0580 [hep-ph]].
[8] E.Jastrzembski and H. Dong, https://coda.jlab.org/drupal/content/vme-payload-modules
[9] Rashevskaya *et al.*, Radiation damage of silicon structures with electrons of 900-MeV, Nucl. Instr. Meth. A, **485**, 126-132, (2002)
[10] D. S. Denisov and S. Soldner-Rembold, FERMILAB-PROPOSAL-0925.
[11] M.J. French *et al.*, Design and results from the APV25, a deep sub-micron CMOS front-end chip for the CMS tracker , Nucl. Instr. Meth. A, **466**, 359-365 (2001)
[12] Friedl *et al.* (2009), Readout of silicon strip detectors with position and timing information, Nucl. Instr. Meth. A, **598**, 82-83 (2009)
[13] P. Hansson Adrian *et al.* [HPS Collaboration], The Heavy Photon Search test detector, Nucl. Instr. Meth. A 777 (2015), 91-101, http://dx.doi.org/10.1016/j.nima.2014.12.017