The Silicon Vertex Tracker for the Heavy Photon Search Experiment

Per Hansson Adrian[1], on behalf of the HPS Collaboration
[1]SLAC National Accelerator Laboratory, Menlo Park, CA, USA

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 e$^+$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 [8] 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). 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'.

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.

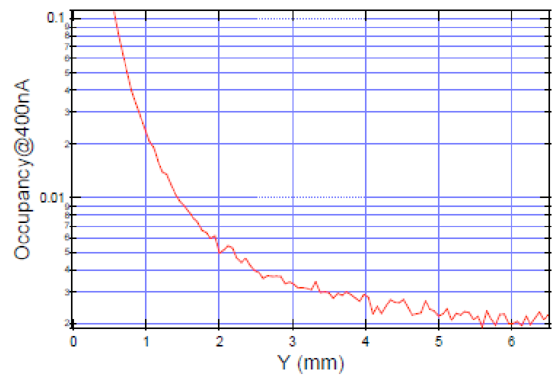

Fig. 1. Occupancy per strip (60 μm readout pitch) in Layer 1 of the SVT for 8 ns of beam at 400 nA.

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 [ref] and 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 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.

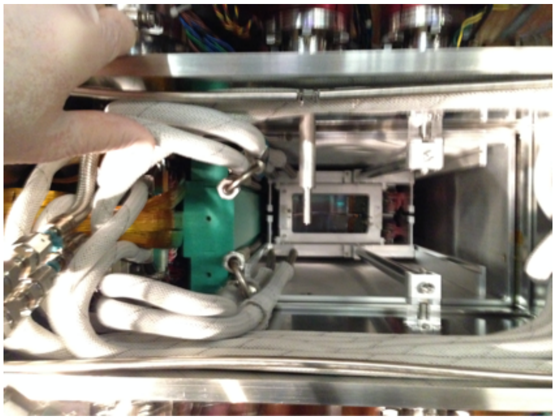

Fig. 2. View of the SVT from upstream before installation of the target and final cabling.

Layer $\rightarrow$	1-3	4-6
z pos. (cm)	10-30	50-90
Stereo angle	90°	50 mrad
Bend res. (μm)	≈ 6	≈ 6
Stereo res. (μm)	≈ 6	≈ 130

TABLE I
MAIN TRACKER PARAMETERS.

II. THE SILICON VERTEX TRACKING DETECTOR

At beam energies necessary to achieve sensitivity to A$'$ in the most interesting mass range for HPS, multiple scattering dominates the measurement uncertainty, and in particular dictates the achievable vertex position resolution for any practical material budget. The main design guidelines are therefore to minimize the material budget in the tracking volume, and the distance to the beam in order to increase acceptance for low $m_{\mathrm{A}'}$, while keeping the occupancy under control. 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. Each of the six tracking layers, arranged in two halves both above and below the beam, consists of placing Hamamatsu Photonics Corporation silicon microstrip sensors back-to-back, with 50 or 100 mrad stereo angle. These are 320 μm thick, p+-on-n, AC coupled, polysilicon-biased sensors with 60 (30) μm readout (sense) pitch, readily available at low cost from the cancelled D0 RunIIb upgrade [9]. The overall area of 1440 cm^2 has in total 23,040 channels. The optimized design, with the first layer placed only 10 cm downstream of the target to give excellent 3D vertexing performance, has a 15 mrad dead zone above and below the beam axis, putting the active silicon only 1.5 mm from the the center of the beam where hit densities reach 4 MHz/cm^2 with per-strip occupancies kept $< 1\%$, as shown in Fig. 1. To resolve overlapping hits in time and thus help to reject background and improve pattern recognition in the area closest to the beam, a 2 ns single hit time resolution is achieved by using the APV25 front-end readout ASIC initially developed for the CMS detector at CERN [10] operating in multi-peak mode. The APV25 chips, wire-bonded to the end of the sensor, are mounted on FR4 hybrid boards. A half-module is built by a sensor and hybrid glued to a polyimide-laminated carbon fiber composite backing keeping cooling and electrical services outside the tracking volume[11]. For tracking layers 4-6, double length half-modules are built with hybrids at each end to increase acceptance. 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 gives the required 3D space point resolution and conducts heat from the sensor to the cooled support structure to remove ~ 1.7 W of power per hybrid. The silicon operates at -10°C to withstand high localized radiation doses up to 1×10^{14} 1 MeV neutron eq. fluence. Critical to minimizing the multiple scattering uncertainty, a material budget of less than 0.7% X_0 per layer is obtained. Layer 1-3 and 4-6 , top and bottom modules, are mounted directly on cooled U-channels precision mounted on kinematic mounts. A lever arm extending upstream to a motor controlled high-precision vertical linear shift gives an adjustable distance to the beam plane for the L1-3 the top and bottom halves of the tracker. Mounting the four U-channel support structure on rails allows removal of the tracker from the vacuum chamber with minimal intervention. Figure 3 shows the four U-support channels complete with modules.

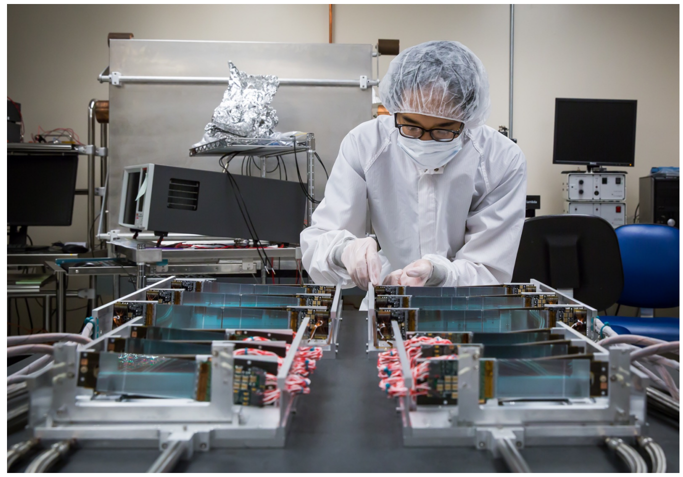

Fig. 3. The four U-channels, layers 1-3 (closest) with the detector modules mounted.

Six analog samples from the APV25 chips at 41.66 MHz from up to four hybrid boards are sent on twisted pair magnet wire to a total of 10 Front End Boards (FEB). Each FEB digitizes and transfers up to 3.3 Gb/s of data using high-speed serial links to Xilinx Zynq based data processing modules on the ATCA based SLAC RCE platform [11] 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.

Multiple scattering of the low momentum electrons are the dominant factor in limiting tracking performance. Impact parameters between 350 μm and 100 μm for track momentum between 0.25 and 1.7 GeV$/$c and a 5% momentum resolution is achieved. With a precise 3D vertex resolution from the three most upstream layers with large stereo angles, and using the $\sim$ 40 μm wide beam spot as a constraint, full track reconstruction simulation show a $\sim 10^7$ rejection of prompt backgrounds. This ensures good sensitivity for A$'$ decay lengths larger than 1 cm.

This contribution will discuss the first results from the HPS experiment. The achieved hit time resolution, tracking efficiency and momentum resolution will be presented that will pave the way for the first physics results.

Appendix A

If I need an appendix it should go here.

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, especially the last few hours of operating CEBAF6. The tremendous support from home institutions and supporting staff also needs praise from the authors.

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