Nuclear Instruments and Methods in Physics Research A 859 (2017) 69–75

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The Heavy Photon Search beamline and its performance

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A R T I C L E I N F O

Keywords:
Electron beam
Collimator
Heavy photon
Silicon microstrips
Electromagnetic calorimeter

A B S T R A C T

The Heavy Photon Search (HPS) is an experiment to search for a hidden sector photon, aka a heavy photon or dark photon, in fixed target electroproduction at the Thomas Jefferson National Accelerator Facility (JLab). The HPS experiment searches for the e^+e^- decay of the heavy photon with bump hunt and detached vertex strategies using a compact, large acceptance forward spectrometer, consisting of a silicon microstrip detector (SVT) for tracking and vertexing, and a $PbWO_4$ electromagnetic calorimeter for energy measurement and fast triggering. To achieve large acceptance and good vertexing resolution, the first layer of silicon detectors is placed just 10 cm downstream of the target with the sensor edges only 500 μm above and below the beam. Placing the SVT in such close proximity to the beam puts stringent requirements on the beam profile and beam position stability. As part of an approved engineering run, HPS took data in 2015 and 2016 at 1.05 GeV and 2.3 GeV beam energies, respectively. This paper describes the beam line and its performance during that data taking.

1. Introduction

The Heavy Photon Search (HPS) experiment [1] at the Thomas Jefferson National Accelerator Facility is a search for a new 20 – 500 MeV/c^2 vector gauge boson A′ ("heavy photon", aka "dark photon" or "hidden sector photon") in fixed target electro-production. Such a particle would couple weakly to electric charge by virtue of "kinetic mixing" [2]. Consequently A′ s could be produced by electron bremsstrahlung and decay to electron/positron pairs or pairs of other charged particles. Since the expected coupling is ϵe, with $\epsilon \leq 10^{-3}$, A′ production is small compared to standard QED production of e^+e^- pairs. To identify A′ s above this copious trident background, HPS looks for a sharp bump in e^+e^- invariant mass and, for very small couplings, separated decay vertices. It does so with a compact 6-layer silicon vertex tracker (SVT) situated in a dipole magnetic field. A highly segmented $PbWO_4$ electromagnetic calorimeter (ECal), located just downstream of the magnet, provides the trigger [3]. Observing a statistically significant signal in the presence of a large background requires sufficient luminosity such that the number of signal events is large compared to the square root of the background (for the bump hunt), or a means of reducing the background so that it is negligible compared to the signal (for the vertex search). This is accomplished with the continuous wave (CW) CEBAF beam, utilizing very fast electronics, a high rate trigger, and high data rate capability. To minimize the multiple scattering of the incident beam into the detector, HPS employs very thin target foils and relatively high (~100s nA) average beam currents. HPS avoids most of these scattered beam electrons as well as those that have radiated and been bent in the horizontal plane by the dipole magnet, by splitting the SVT and ECal vertically into top and bottom sections, situated just above and below the beam. The beam is passed through the entire apparatus in vacuum to minimize beam gas backgrounds.

The kinematics of the reaction are such that A′ s are produced at very forward angles with energy approximately that of the incident beam (1 – 6 GeV for HPS). For A′ masses of interest, the A′ decay products are very forward peaked, so the detectors must be placed as close to the beam as possible. Similarly, good vertex resolution requires the silicon tracker to be as close as possible to the target. The HPS detector accepts vertical scattering angles greater than 15 mrad. The first silicon layer is positioned 10 cm downstream of the target, so the

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http://dx.doi.org/10.1016/j.nima.2017.03.061
Received 9 January 2017; Received in revised form 10 March 2017; Accepted 30 March 2017
Available online 04 April 2017

physical edge of the silicon sensor is placed just 500 μm above and below the beam (the sensor has a 1 mm wide guard ring). Proximity to the beam imposes stringent requirements on acceptable beam size, stability, and halo; necessitates protection collimation; and demands real time monitoring and circuitry to protect against errant beam motion. The innermost silicon detectors see high but tolerable radiation levels and roughly 1% strip occupancies close to the beam. Crystals in the innermost rows of the upper and lower halves of the ECal, situated about 3 cm above and below the beam, see maximum rates of about 1 MHz near the exiting electron beam, which is transported in a vacuum chamber between them.

This paper will discuss HPS's beam requirements, the design of the HPS beamline, and its performance. It will review the beamline instrumentation used to measure and monitor performance and to protect against errant beam motion. The excellent quality and stability of the CEBAF beams coupled with HPS protection systems lets HPS take data safely with its silicon detectors just 500 μm from the electron beam.

2. HPS Beamline

Fig. 1 shows the downstream end of the beam line in experimental Hall B, where the HPS setup is located in the alcove downstream of the CLAS spectrometer [4]. The HPS setup is a forward spectrometer based on a dipole magnet, 18D36 (pole length 91.44 cm, max-field of 1.5 T) as shown in Fig. 2. The target and SVT are installed inside a large vacuum chamber within the gap of the dipole magnet. The calorimeter (ECal) is mounted behind the magnet, 134 cm downstream of the target, and split above and below a vacuum chamber that connects the SVT vacuum chamber to the downstream beam line and the beam dump. The ECal vacuum chamber was designed to allow the innermost ECal crystals to be mounted just 20 mm from the beam plane. It has two wider openings, one to accommodate most of the multiple scattered beam electrons and the other, the bremsstrahlung photons created in the target.

In order to transport the electron beam to the beam dump, two small dipole magnets (pole length 50 cm, max-field 1.2 T) have been installed upstream and downstream of the spectrometer, forming a three magnet chicane with zero net integrated field along the beam path. The electron beam is deflected to beam's left in the first chicane dipole. It impinges on the target, which is located at the upstream edge of the spectrometer magnet, 6.8 cm to the left and at a horizontal angle of 31 mrad with respect to the original beam line. The bremsstrahlung photon beam generated in the target continues in that direction after the target, while the electron beam is bent back by the spectrometer magnet toward the second small dipole, which in turn restores the beam to its original direction in line with the dump. Behind the chicane there are two shielding walls that separate the HPS setup from the downstream tunnel. A photon beam dump (a lead cave with a tungsten insert) was installed after the first shielding wall, ~7 m downstream of HPS. A Faraday cup cage and the Hall B electron beam dump are behind the second shielding wall.

The HPS experiment will run with beam energies from 1 GeV to 6.6 GeV, and beam currents up to 500 nA using 0.125% radiation length, or 0.25% for high energy runs, tungsten foils as targets. The beam parameters required to run the SVT and ECal in close proximity to the beam plane have been established using simulation and are presented in Table 1. Requiring a small beam spot improves mass and vertex resolution when beam position constraints are included in the track and vertex fits. The tracking resolution at the target, which is much better in the vertical than horizontal direction, is reflected in the disparate beam size requirements in x and y. A small vertical beam size is also essential for keeping beam tails away from the Layer 1 silicon sensors.

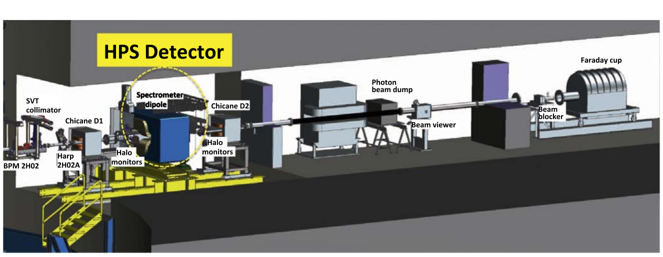

Fig. 1. The downstream end of the 2 H beam line with the HPS setup.

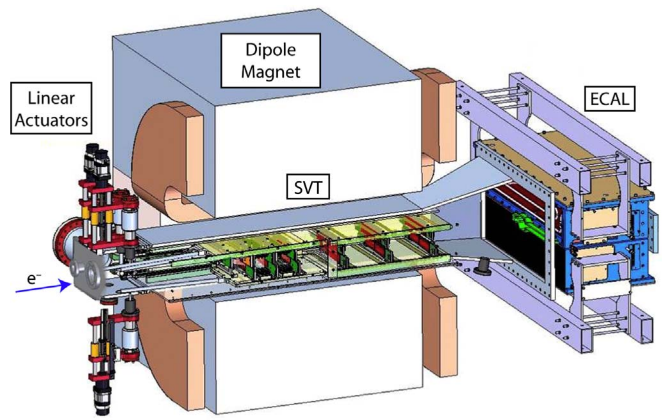

Fig. 2. Partial cut-out view of the HPS setup.

Table 1
Required beam parameters.

Parameter	Requirement	Unit
Beam Energy (E)	1 to 6.6	GeV
δE/E	$<10^{-4}$	
Beam Current	50 to 500	nA
Current Stability	~5	%
σ_x	<300	μm
σ_y	<50	μm
Position Stability	<30	μm
Divergence	<100	μ*rad*
Beam Halo (>5σ)	$<10^{-5}$	

The Hall B beamline is well equipped to deliver high quality beams which meet these requirements. Small, stable beams have been routinely delivered for experiments in Hall B [5] using the CLAS detector [4] where targets are positioned at the center of the experimental hall.

2.1. Description of the Hall-B beamline

The Hall B beamline is divided into two segments, the so called "2C" line, from the Beam Switch Yard (BSY) following the beam extraction from the CEBAF accelerator to the hall proper, and the "2H" line from the upstream end of the experimental hall to the beam dump in the downstream tunnel. The "2C" part of the beamline features an achromatic double bend (dogleg) that brings beam up to the hall's beamline elevation from the BSY. For most experiments, where the targets are located upstream of the center of the hall, instrumentation on the "2C" line is sufficient to shape the beam profile and position it. The beam line instrumentation on the "2H" line is then used only for monitoring beam properties.