An Upgrade for the HPS Silicon Vertex Tracker

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1 Introduction and Motivation

The heavy photon (A′), aka a "hidden sector" or "dark" photon, is a massive gauge boson which couples weakly to electric charge by mixing with the Standard Model photon [1, 2]. Consequently, it can be radiated by electrons and subsequently decay into e^+e^- pairs, albeit at rates far below those of QED trident processes. Heavy photons have been suggested by numerous beyond Standard Model theories [3] to explain the discrepancy between theory and experiment of the muon's $g-2$ [4], and as a possible explanation of recent astrophysical anomalies, e.g. [5–7]. Heavy photons couple directly to hidden sector particles with "dark" or "hidden sector" charge; these particles could constitute all or some of the dark matter, e.g. [8, 9]. Current phenomenology highlights the $20-1000$ MeV/c^2 mass range, and suggests that the coupling to electric charge, ϵe, has ϵ in the range of $10^{-3} - 10^{-5}$. This range of parameters makes A′ searches viable in medium energy fixed target electroproduction [10], but requires large data sets and good mass resolution to identify a small mass peak above the copious QED background. At small couplings, the A′ becomes long-lived, so detection of a displaced decay vertex can reject the prompt QED background and boost sensitivity.

1.1 The HPS Experiment

The HPS experiment [11] was installed in Hall-B at JLab in late 2014 and early 2015 to search for heavy photons by directing the 1.1-6.6 GeV CEBAF12 electron beam onto a thin (0.125% X_0 – 0.25% X_0) tungsten target foil. The HPS experiment uses both invariant mass and secondary vertex signatures to search for A′ decays into e^+e^- pairs. At CEBAF energies, the A′ decay products are boosted along the beam axis with small opening angles. For couplings $\epsilon << 10^{-3}$, A′ decay lengths range from millimeters to tens of centimeters and beyond. Accordingly the tracking detectors cover opening angles down to 15 mrad and are placed just 10 cm downstream of the target.

HPS employs a 90 cm long silicon tracking and vertexing detector (SVT) located inside a dipole magnet to measure momenta and decay vertex positions. A fast $PbWO_4$ electromagnetic calorimeter downstream of the magnet provides the trigger and electron identification. Both the silicon tracker and the ECal have ∼ns timing resolution, which eliminates much of the out-of-time background from multiple scattered beam electrons. Fast front end electronics and high trigger and data rate capability and the near 100% duty cycle of the CEBAF accelerator allows HPS to accumulate the very large statistics needed to be sensitive to the highly suppressed production of heavy photons.

The HPS experiment completed a successful Engineering Run in Spring 2015, including a short period of production running resulting in a small physics-quality dataset at $E_{\text{beam}} = 1.06$ GeV. Subsequent analysis has shown that the performance of the detector meets the goals set in the proposal for the critical measurables of e^+e^- mass and vertex resolution that determine the experimental reach of HPS for hidden sector photons [12]. HPS has just completed a physics run at 2.3 GeV, collecting approximately 5 days of data and is scheduled for a longer run in 2018.

1.2 Improving Reach at Intermediate Couplings

The expected reach of the HPS experiment after one month of running is shown in Figure 1 together with the anticipated reach of other proposed experiments. Aside from the difficulty in probing masses above $\approx 2m_\mu$ the most difficult region to access is at intermediate couplings, in the range of $10^{-8} < \epsilon^2 < 10^{-6}$. While there are a number of proposals that aim to probe this region, only LHCb claims the ability to cover it completely, and not until ≈2023 after the completion of a major detector upgrade and collection of data during Run 3 of the LHC. While the HPS experiment is designed to take data for a total of 6 months, even with a complete dataset collected at all energies, HPS will leave roughly one order of magnitude in coupling unexplored in the range ≈15MeV-150 MeV.

The reason for the gap in sensitivity at intermediate couplings is simple. For a pure resonance search, the irreducible backgrounds from radiative tridents are quite large, so only for couplings where the signal is also relatively large is there sensitivity. This situation only changes at couplings low enough that the entire prompt background can be eliminated by requiring a separated vertex. Below that, there is no background, opening up a new region of sensitivity at low couplings that extends downward in coupling until the production cross

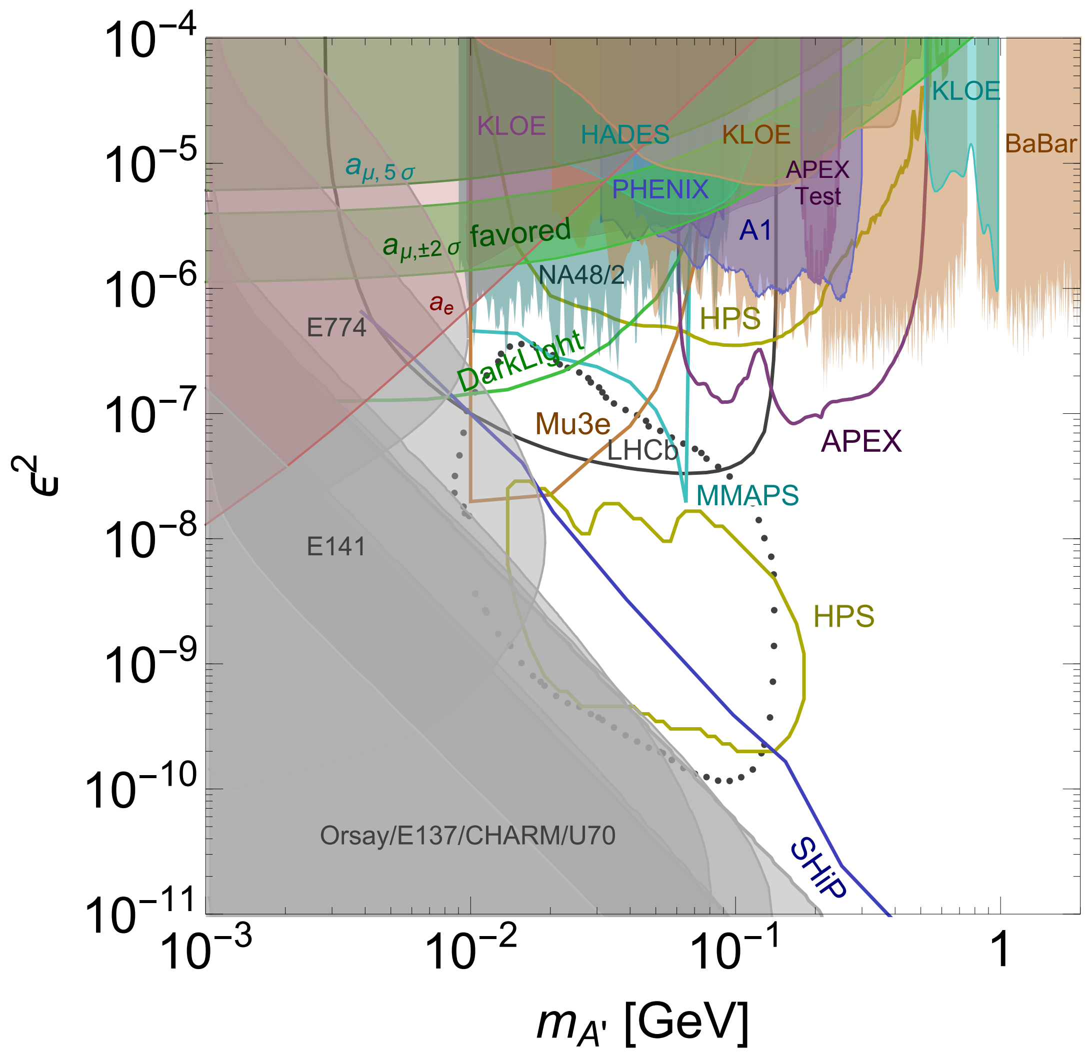

FIG. 1: The current expected reach of the HPS Experiment for 1 month of running together with current exclusions (solid) and projected reach of other proposed experiments in the next decade. A full 6 month run of HPS would close the gap at intermediate couplings to roughly one order of magnitude in coupling.

section becomes so low that there are no signal events remaining. This leaves the following options for HPS to close the gap at intermediate couplings:

1. Close the gap from above in the resonance search with improved S^2/B via operation at much higher luminosity or much larger acceptance to collect larger datasets, or vastly improved mass resolution to reduce backgrounds.

2. Close the gap from below in the vertexing search with better vertex resolution.

The brute force approach, an experiment with much higher luminosity and/or acceptance, cannot be achieved within the current footprint of HPS. Although not impossible, an entirely new experiment is required. Furthermore, at the very low level level of S/B implied by a high-statistics resonance search, systematic uncertainties in the background shape may limit the sensitivity unless they can be made vanishingly small. However, it should be noted that improvements that enhance resonance searches by reducing the effective background do not share this shortcoming and will extend the reach of resonance searches without any drawbacks. In particular, HPS expects to improve the resonance search significantly by using the reconstruction of the recoiling incident electron to improve mass resolution and reduce backgrounds, which will offer increased reach in the resonance search region that are yet to be quantified.

Meanwhile, significant improvements in vertex resolution can be achieved by adding a new SVT layer closer to the target, a project that appears possible within the framework of the current SVT, which already has facilities in place that would serve to support an additional layer, both mechanically and electrically. Therefore, we propose to add a new layer, Layer 0, located at $z = 5$ cm, directly between the target at $z = 0$ cm and Layer 1 at $z = 10$ cm. This additional layer would utilize thinned sensors to reduce the material by a factor of two in comparison to the other layers of the SVT.

1.3 Impact of a New SVT Layer 0

For A$'$ that decay only to Standard Model particles, the decay length is proportional to ϵ^2, so the large-coupling boundary of the vertex reach in Figure 1 improves linearly with decay length resolution and therefore with impact parameter resolution, as well. Studies performed for the Snowmass exercise in 2013 [13] verified this expectation with simulation and experience with data confirms that the vertex tails, upon which our sensitivity depends, scale with the core resolution. It is simple then to deduce that the two improvements offered by the addition of Layer 0 will expand the large-coupling boundary of the vertex reach by a factor of $2\sqrt{2}$. First, because the impact parameter resolution is dominated by multiple scattering in the first plane, reducing the material by a factor of two improves the impact parameter resolution by $\sqrt{2}$. Second, with the distance between the target and the first plane cut in half, the impact parameter resolution at the target is roughly halved also. Together, these improvements greatly expand the vertexing reach and close the gap in sensitivity significantly at intermediate couplings.

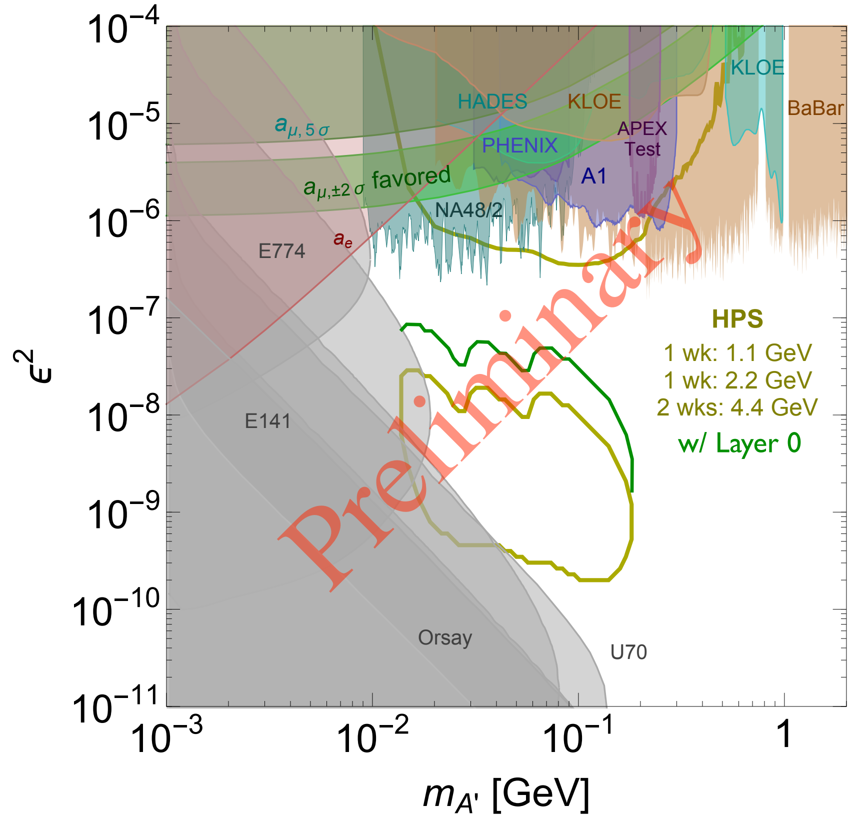

FIG. 2: A rough projection of the reach improvement expected with the addition of Layer 0 to the SVT for one month of running.

Because the addition of Layer 0 can be undertaken at minimal cost in a very short time period, this improvement can be made quickly enough that the vast majority of the data taken by HPS will have this improvement in place. In that case, the additional sensitivity it offers will allow HPS to probe most of the parameter space below $M_{A'} < 150$ MeV by ≈2020.

2 HPS SVT Layer 0 Design

The addition of a Layer 0 to the HPS SVT must overcome a few key obstacles. First, a layer half the distance from the target must instrument a region closer to the beamline than Layer 1 by the same factor in order to maintain the full acceptance of the SVT. Second, the use of thin silicon to reduce the material in the first layer by a factor of two reduces the signal yield. Finally, space and facilities inside the vacuum chamber limit the feasible options for addition of another tracking plane. The proposed design for Layer 0 is shaped by these requirements.

The first layer of the current SVT, Layer 1, is located at z=10 cm downstream of the thin tungsten target and enables angular acceptance down to 15 mrad from the beamline, necessary for sensitivity to low-mass A$'$ decays, by placing the edge of the active silicon 1.5 mm from the beam. Utilizing standard radiation-tolerant microstrip sensors which have a $\approx$1 mm inactive border, the physical edge of the silicon in Layer 1 is therefore a mere 500 μm from the center of the scattered primary beam. Such sensors are obviously unusable for Layer 0, which must have an active region that begins 750 μm from the beamline in order to maintain the same angular acceptance when placed at z=5 cm. While there are a number of options for producing slim-edge sensors, the scribe-cleave-passivation processing of standard sensors can easily be used for the small number of sensors required here and has been shown to result in sensors capable of withstanding the high bias voltages needed for radiation tolerance [14]. Meanwhile, the dominant backgrounds from scattered primary beam will be higher in Layer 0 than in the current SVT. While one might naively expect background occupancy to increase by a factor of 4 ($\propto 1/r^2$), it is important to remember that microstrips do not sample the areal density of hits. Simulation shows that background occupancy at z=5 cm increases by only a factor of 2.5 relative to Layer 1, as shown in Figure 3. To bring occupancies back to acceptable levels, we propose to split the readout strips on the sensors in half so that the sensors are read out from both ends. This arrangement will cut the occupancy in half, or only 25% more than current occupancies in Layer 1, preserving clean pattern recognition for vertexing with Layer 0. Finally, long range tails of the HPS beam generate measurable occupancies in Layer 1 which will be larger in Layer 0 due to the proximity of the beam. Measurements of the beam tails using Layer 0 of the SVT in the engineering run, fitted to a Gaussian, predict that the resulting occupancy at the edge of Layer 0 will be roughly a factor of 1.5 higher than in Layer 1 after accounting for the reduction from splitting the readout strips. While it is anticipated that this occupancy will be acceptable at lower currents, it could become a limiting factor for operation of the SVT at the high currents envisioned for running at 4.4 GeV and 6.6 GeV. Therefore, further study will be required to assess the impact of Layer 0 on the vertexing reach at higher running energies. In the worst case, lower currents and longer running times might be required to enable HPS to deliver the best vertexing reach at higher beam energies. Finally, since the

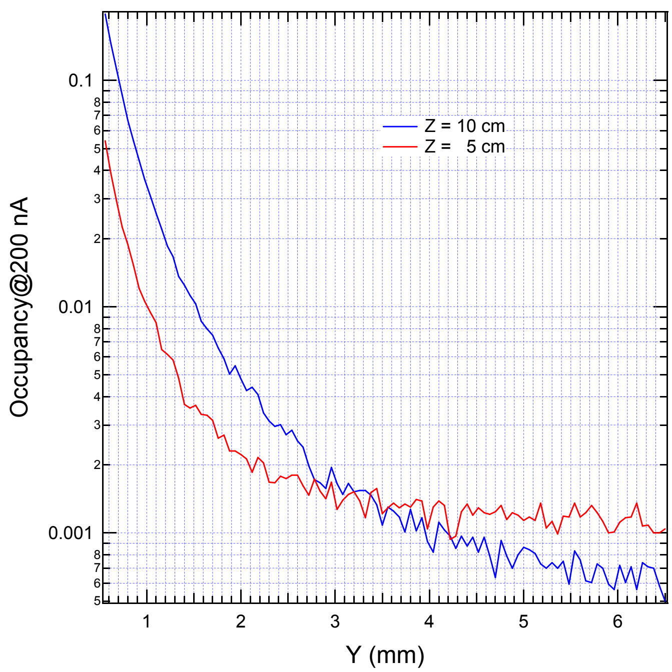

FIG. 3: The occupancy in a horizontal 60 μm readout strip as a function of vertical distance from the beam plane for sensors placed at z =5 cm and z =10 cm from the beam. The occupancy at 15 mrad for a Layer 0 at z =5 cm, 750 μm from the beam, is roughly 2.5× the occupancy for the current Layer 1 with the same 15 mrad coverage, 1.5 mm from the beam.

same backgrounds dominate the radiation dose to the sensors that limit their lifetime through bulk damage effects proportional to the areal density of hits, sensors in the same technology used in the rest of the SVT will last only 25% as long as in Layer 1, or approximately 1.5 months. Given the short run periods expected for HPS, such a short lifetime may be acceptable with planned periodic replacement of Layer 0. However, the same technologies used to produce more radiation tolerant sensors for the LHC experiments could be used here to avoid this scenario and will be investigated.

In order to achieve the desired material reduction, the silicon must be half as thick as that in the other layers of the SVT, or roughly 150μm of silicon with no support. While such silicon is available from a number of vendors, the more significant issue is that thinning the silicon results in a commensurate loss of signal. The ability to fit periodic samples of the shaped signal pulses to extract the hit time with a precision of ≈2 ns is fundamental to reducing un-triggered, random backgrounds in the SVT to acceptable levels for high-purity vertexing. Since hit time resolution degrades rapidly for S/N<20, the loss of signal from thin silicon must be compensated with lower noise. [15] This is naturally achieved with smaller sensors, since studies show that the Layer 0 sensors can be as short as 2 cm and achieve full efficiency for both A′ decay daughters and recoiling electrons, as shown in Figure 4. With readout strips split in half to reduce occupancy, as previously described, the

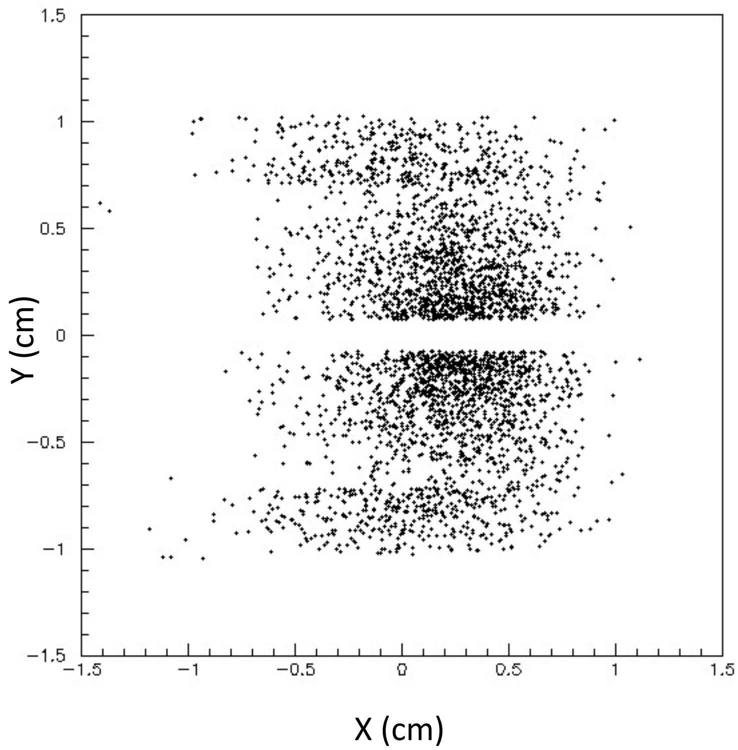

FIG. 4: The distribution of hits from electron recoils that also produce hits in Layers 1 and 2. Together with the beamspot constraint, such recoils can be reconstructed with high efficiency. Including the recoil in a kinematic fit significantly increases the sensitivity of the resonance search.

noise will be approximately 1/3 that of the other layers of the SVT for the same readout technology, resulting in even higher S/N than in the rest of the SVT. Finally, it is important to remember that lowering both signal and noise in Layer 0 will result in lower readout thresholds. Because of this, the 10 keV L-shell x-rays generated from the action of the beam on the tungsten target will deposit enough energy in the silicon to consistently pass threshold cuts, in contrast to the situation in Layer 1 where these x-rays are at or slightly below threshold in most channels. Simulations show that the small size of the sensors for Layer 0 together with thickness that results in only ≈70% absorption at this energy in each sensor give rise to less than 1/2 hit in Layer 0 per 8 ns time window. This uniform 0.07% occupancy has no significant effect on tracking performance.

For the project to be feasible, it must fit within the existing mechanical and DAQ framework of the SVT. This requirement is easily accommodated, since the upper and lower cooling structures of the SVT extend upstream to approximately z =5 cm, where Layer 0 would be mounted and where the SVT beam scan wires are currently located, as shown in Figure 5. By incorporating the scan wires into the Layer 0 modules, their function can be

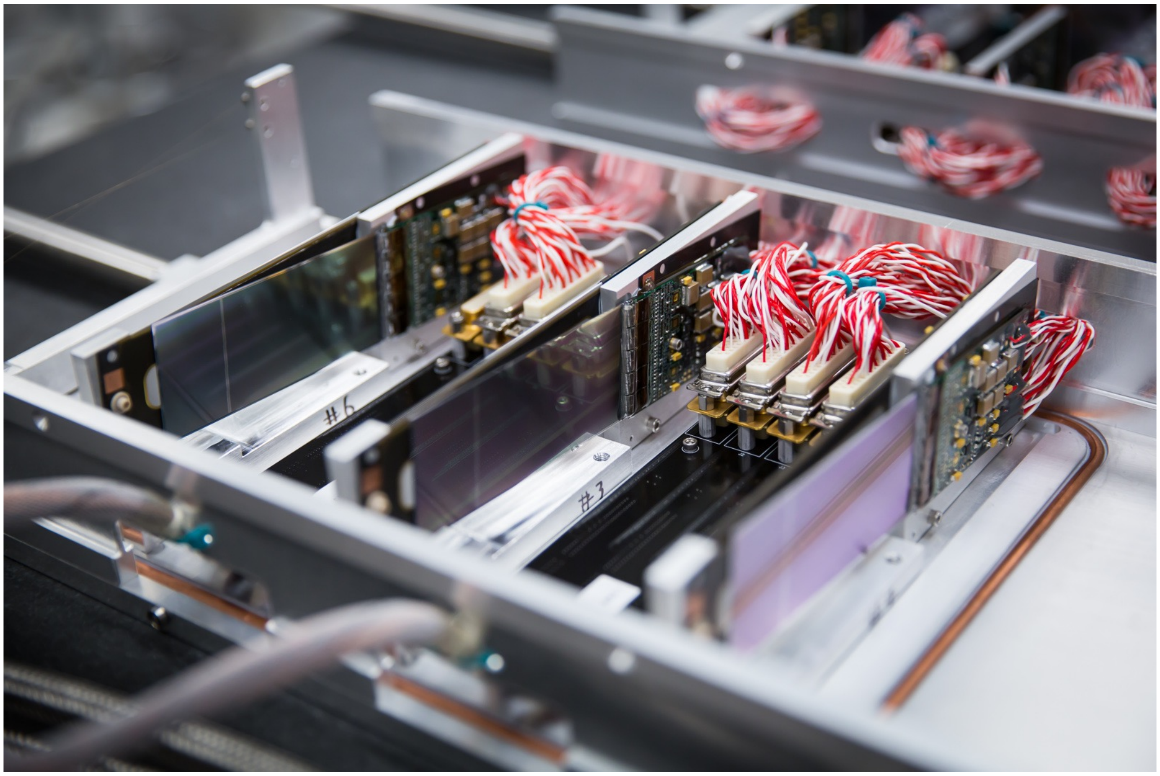

FIG. 5: A photograph of the u-channel support structure that holds the Layer 1-3 modules of the SVT. Layer 0 would be mounted on this support in roughly to same position as the wire scanner support seen at left, with scan wires incorporated into the Layer 0 module. The crossover boards that provide power and readout for the modules can be seen between the SVT modules, where the two unused connections on the crossover board between layers 1 and 2 can be used for Layer 0.

retained in the upgraded system. Meanwhile, the DAQ for the current SVT has the excess capacity needed to accommodate the new layer. This includes connectivity for the modules on the cooling structures between Layers 1 and 2, the Front End Boards (FEBs) that provide control and power to the modules and digitize signals from them, and the optoelectronic vacuum feedthrough boards that relay signals from the FEBs to the remotely located RCE DAQ and power supplies. In short, the entirely of the power and DAQ needed for Layer 0 was already installed and tested in the SVT and SVT DAQ as originally built.

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