Assembly and Bench Tests of an Active Collimator Prototype for Hall D

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Abstract

The University of Connecticut nuclear physics group has produced a design for an active collimator to be used in the GlueX polarized photon beam line in Hall D. A prototype of this detector has been built with four of the eight sectors installed. Amplifier electronics sufficient for the readout of two sectors have been purchased and tested with the prototype on the bench using the Labview data acquisition system. Results from these tests are analyzed to determine the sensitivity and bandwidth limits of the detector. These results are compared with the requirements for the Hall D photon beam. Recommendations are also made as to future work on this project.

An active collimator has been designed by the University of Connecticut group for the Hall D photon beam line at Jefferson Lab [1]. The design was borrowed from SLAC, where a similar device was needed for monitoring the alignment of their high energy electron beam. This device is described by G. Miller and D. Walz [2] as a "tungsten pin cushion" detector. It takes advantage of the "knock-on" electrons produced in electromagnetic showers generated by the incident hard photon beam in the tungsten, which result in a net flow of electrons out of the tungsten plates.

Implementation of this technique requires optimization of the knock-on emission rate and amplification of the small currents they produce. The tungsten blocks are machined to resemble pin cushions: an array of pins erected on a solid tungsten base. The pins are directed downstream from the incident beam, and present a dense material for shower and knock-on production while at the same time allowing the knock-ons to escape in the spaces between the pins. Our design employs two rings of tungsten pin cushion wedges each divided into four independent sectors for a total of eight sectors. The two rings are coaxial with the beam axis, an outer ring for coarse positioning and an inner ring for fine positioning of the beam relative to the geometric axis of the collimator. The wedges are mounted on an insulating housing and seated within a conducting shell which serves as a Faraday shield and also as a collector to catch the emitted electrons and close the current loop.

1 Prototype construction

The design of the principal components of the active collimator has been developed and its performance simulated [1]. The need for good insulation and heat dissipation (critical for components exposed to the a high energy photon beam) simultaneously has been taken into account, leading to the use of boron nitrite. The aluminum collector has been designed to fit inside the cylindrical insulator, with electrically conducting walls that divide and isolate the two rings and four quadrants.

A full-scale boron nitride insulating support has been obtained from the firm Accuratus for use in the prototype. Careful attention was given to the choice of material for this purpose. The following quotation taken from the manufacturer's documentation explains the special properties and limitations of this material.

> Boron nitride is often referred to as *white graphite* because it is a lubricious material with the same platy hexagonal structure as carbon graphite. Unlike graphite, BN is a very good electrical insulator. It offers very high thermal conductivity and good thermal shock resistance. BN is stable in inert and reducing atmospheres up to 2800°C, and in oxidizing atmospheres to 850°C. Three grades are commonly used, including a boric oxide binder system, a calcium borate binder system, and a pure diffusion bonded grade. The boric oxide containing material (Grade BO) absorbs moisture which causes swelling and property degradation. The calcium borate containing material (Grade CA) is moisture resistant. The pure BN material (Grade XP) contains no binders and is used for extremes of temperature and where purity is important. The boric oxide material is the most commonly used grade.

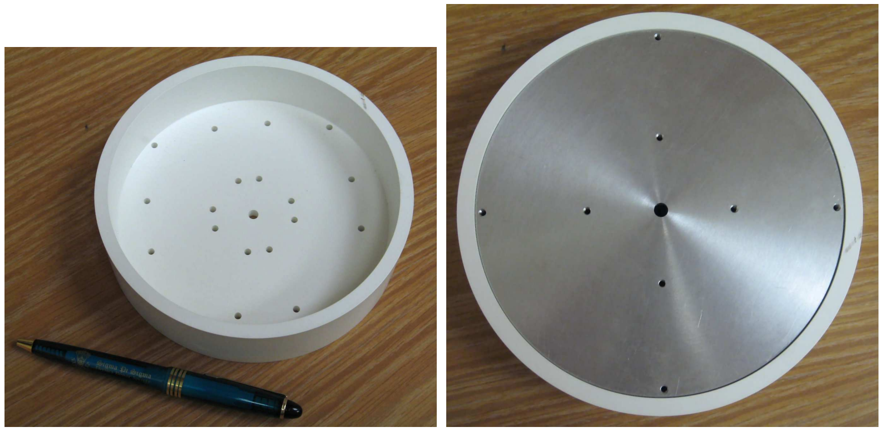

Figure 1: Photographs showing the boron nitride insulating support cylinder on which the tungsten pin cushion wedges will be mounted. Each wedge is supported by bolts that pass through the holes in the base of the support. The holes at the outer perimeter of the support are used to attach the aluminum quadrant divider insert to the insulating support shown in its attached position in the second panel.

The material used for the active collimator prototype used a calcium borate binder to avoid the problems with humidity-dependent dimension changes that affect the boric-oxide-based material.

The manufacturer machined the piece to our specifications, including the mounting holes that support the tungsten wedges. The reference surface for this piece is the outer cylindrical surface, which was specified to be cylindrical to within ± 50 μm. Two holes to support each tungsten wedge were placed with the same precision around the circumference of the two rings, and a central hole provided to allow the uncollimated beam to pass through without interaction. Photographs of this piece are shown in Fig. 1.

The tungsten wedges for the active collimator were fabricated starting from solid blocks of machinable tungsten material of composition 97%W : 2.1%Ni : 0.9%Fe by weight. This alloy was chosen because of of its machinability (Class 4 ROC 28) in contrast to pure tungsten that is too hard and brittle to machine at room temperature. Rows and columns of square pins of dimension approximately 0.5×0.5 mm^2 by removing the material in between using a process called electric discharge machining (EDM). This work was done for us by the Physics Department machine shop at Florida State University, Tallahassee, FL. We are grateful to Prof. Paul Eugenio at Florida

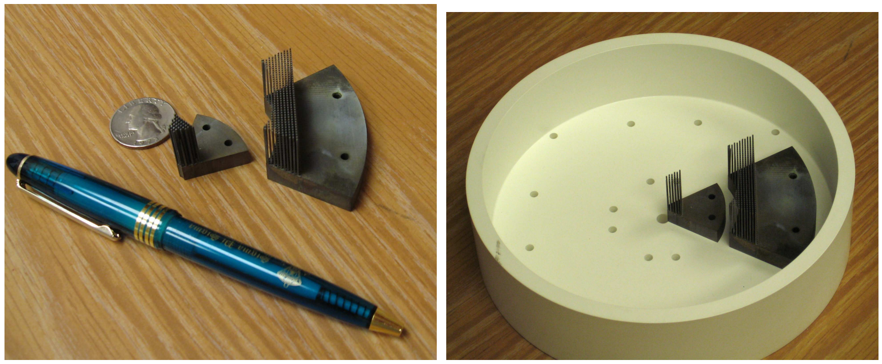

Figure 2: Photographs showing the tungsten pin cushion wedges and the boron nitride cylinder on which they will be mounted. The second panel shows one inner and one outer wedge in the positions where they will be mounted when the prototype is assembled.

State for his assistance in the fabrication of these specialty components. Photographs of these pin cushion wedges are shown in Fig. 2. Fig. 3 shows photographs of the assembled prototype detector with coaxial connectors installed.

Mechanical constraints due to the expected temperature variation have been checked, showing that the assembly fits together without internal stress over the temperature range $0 - 40^\circ$ C.

2 Readout electronics

The assembly of the collimator with the connections to the readout electronics has been tested. On the data acquisition side of the project, low and high-level software support for the DAQ cards has been explored within the framework of Labview. Various Labview virtual instruments have been made to test data acquisition. A screen shot of the prototype readout interface is shown in Fig. 4. Data acquisition with this interface has also been tested.

Two current-sensitive high-gain preamplifier-amplifiers have been obtained for testing. These are the PMT-5R current-sensitive preamplifier made by Advanced Research Instruments Corporation. These devices support 7 different gain settings, from 10^{-6} A/V to 10^{-12}A/V. Expected currents from individual tungsten wedges under nominal GlueX running condi-

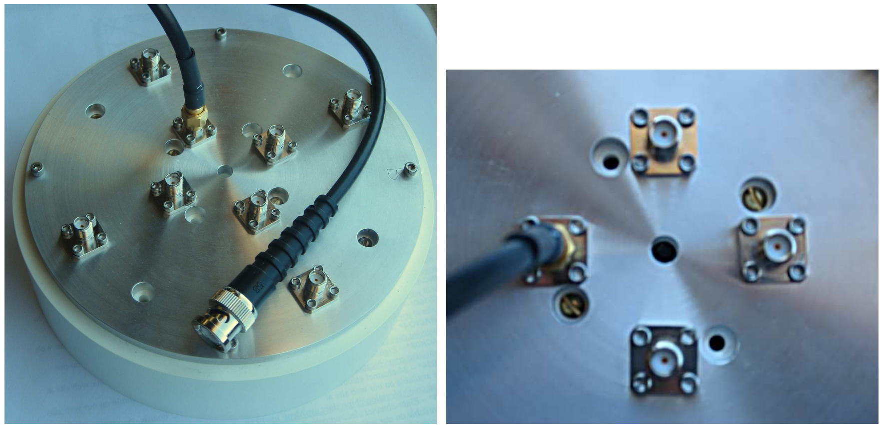

Figure 3: Complete assembly of the collimator (with one row of tungsten pin cushions.)

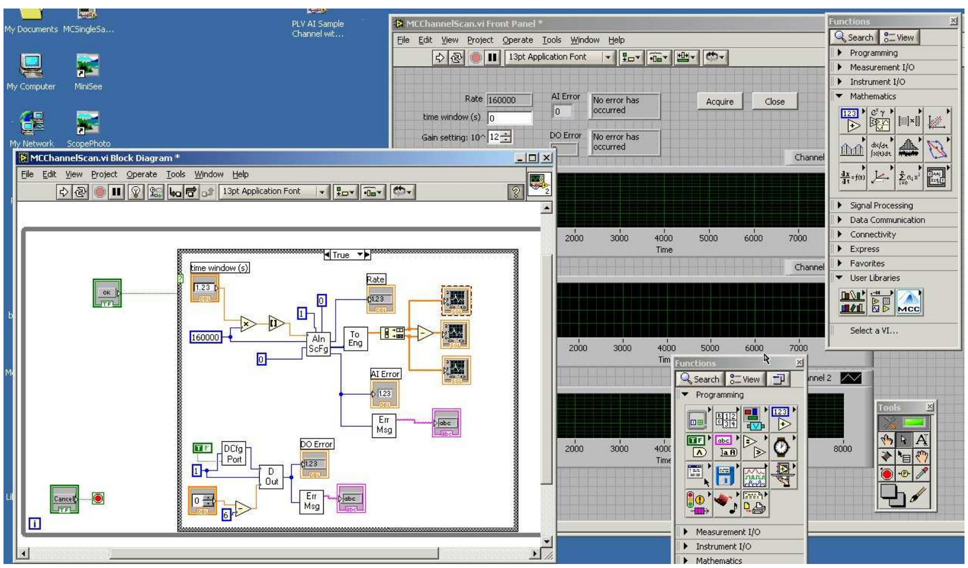

Figure 4: A screen shot of a virtual instrument in Labview. The window on the lower left provides a schematic of the data flow, including routines called, program flow control, triggering and the "back end" of the visual objects used to output the data. The window behind it shows the graphical run-time controls. The toolbars on the right are used to design the visual and back-end aspects of the virtual instruments.

tions at 10^8 tagged photons per second are on the order of several hundred nA near nominal beam alignment. It is important for the active collimator readout to be sensitive to currents on the order of pA in order to monitor the photon beam during beam line commissioning and early running at 10^6 - 10^7 γ/s. A current noise of 1 pA corresponds to roughly 5% in the asymmetry between opposing wedges at a beam intensity of 10^7 γ/s, which just satisfies the required photon beam alignment accuracy of ± 200 μm rms. The bandwidth of the current amplifier should be at least 300 Hz in order to be able to cancel beam motion at 60 Hz and its low-order harmonics in an active feedback circuit. Electronic noise will limit the usable bandwidth of this device at reduced operating currents, but it is a design goal for the active collimator to achieve $\sigma_x = 200$ μm at the full 300 Hz bandwidth for a photon beam intensity of 10^7 γ/s.

Two sources of noise must be distinguished in this context: electromagnetic interference (EMI) and random thermal noise (TN). EMI typically occurs at characteristic frequencies, whereas TN is spread over all frequencies up to the bandwidth of the channel, with amplitude proportional to the square root of the bandwidth. There is a fundamental lower bound coming from thermodynamics on the input noise of a current amplifier with input resistance R operating at temperature T of

$$I_{rms}(\text{thermal}) = \sqrt{\frac{4k_B T \Delta f}{R}} \tag{1}$$

where Δf is the bandwidth of the amplifier in Hz. Fixing $\Delta f = 300$ Hz and $I_{rms} = 1$ pA gives an ideal minimum input impedance $R = 5\text{M}\Omega$. According to Eq. 1, increasing R would seem to further reduce the noise at fixed bandwidth, but this ignores the fact that the input device has some capacitance C which provides an independent upper bound on the bandwidth of the observed signal. An appropriate value for the input device capacitance is 50 pF (75Ω coaxial cable is typically 0.7 pF/cm), which combines with $R = 5\text{M}\Omega$ to give a source bandwidth of 600 Hz. Thus it should be possible by using high-gain electronics that operates with 5MΩ input impedance near the Johnson noise limit, and restricting the distance from the detector to the preamplifier to less than 1 m, to achieve 1 pA current sensitivity at 300 Hz bandwidth.

EMI is a more formidable challenge because it is more difficult to calculate or predict. The primary source of EMI within the relevant frequency range is 60 Hz pickup. The position signal from the active collimator is based on current differences between wedges, so the readout can benefit from common-mode rejection in trying to control noise levels from EMI. The only reliable way to determine the noise levels from EMI is to build a prototype circuit and measure them.

Bench tests were carried out of the PMT-5R preamplifiers using an unterminated 50Ω coaxial cable connected to the input. The results are shown in Fig. 5. Several things should be noted regarding these results. First, the 60 Hz EMI is by far the dominant source of noise. Second, the straight-line fit to the 60 Hz amplitude data follows the expected behavior with output proportional to the nominal gain setting, except for the top point (nominal gain 10^{12}) which lies significantly below the line and distorts the fit. This observation calls into question the claimed gain of the preamp at the 10^{12} setting, which we investigate further below. Third, in contrast to the 60 Hz pickup signal, the thermal noise output from the preamplifier rises slowly with gain, increasing by about one order of magnitude between the 10^6 and 10^{12} V/A settings. There is no fundamental reason why the thermal noise should be relatively stable across 6 orders of magnitude in gain, but it makes sense from the design viewpoint in that lower input impedance and higher bandwidth are generally preferable as long as the output noise remains at the mV level. Finally, the non-60Hz noise level of 15 mV rms at the 10^{12} V/A gain setting seems too low in view of Eq. 1, assuming a bandwidth on the order of 300 Hz and an input resistance of 5MΩ.

The noise measurements described above seemed to indicate a problem with the highest preamplifier gain setting of 10^{12} V/A. On the other hand, this setting is the most important one for the active collimator because it promises the highest signal/noise if the nominal value is actually correct. To check it, a low-current injection circuit was built that transforms a a 100mV-level low-impedance signal from a function generator to a pA-level high-impedance (current-source) waveform and connected to the PMT-5R preamplifier input. The injector was built from a compact array of passive SMD components. A large-area ground plane around the injection circuit was necessary to limit the EMI pickup.

Using the well-known lock-in amplifier technique, it was possible to the injected signal even at high frequencies where the amplifier gain has dropped by several orders of magnitude. The lock-in was achieved by triggering the oscilloscope on the sync from the function generator and averaging over many cycles of the amplifier output waveform. At each frequency, the amplifier gain and phase shift were recorded. The gain is shown in the first panel of Fig. 6. It was not possible to measured much below 10 Hz using the lock-in technique, but it is reasonable to expect that the gain does not vary much below 10 Hz. By changing the value of one resistor in the current

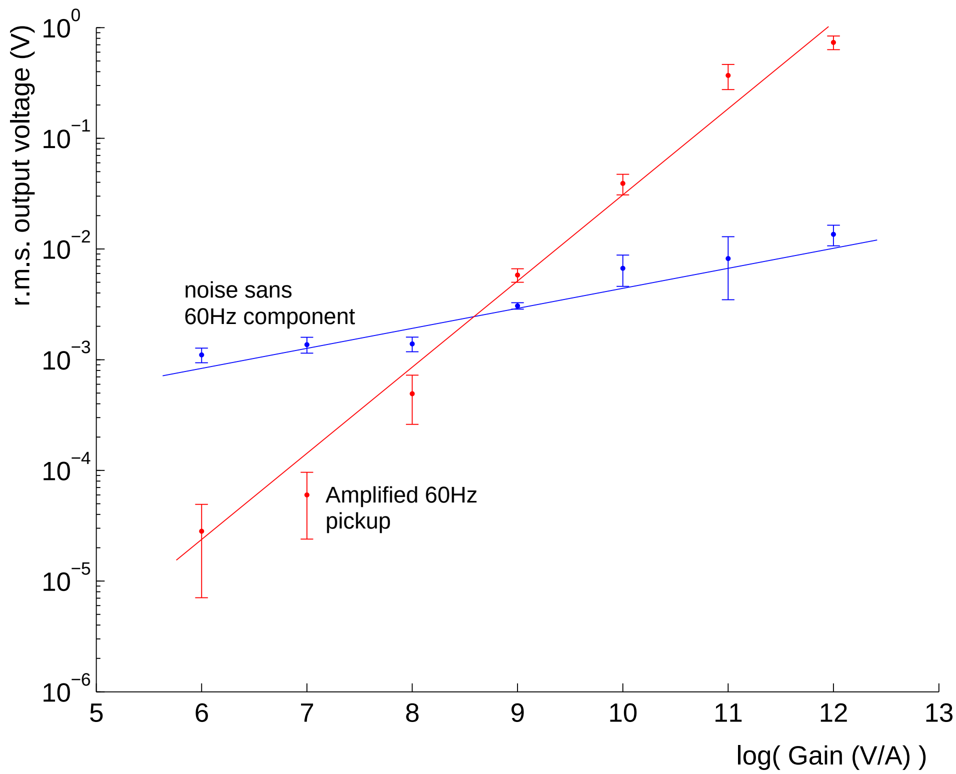

Figure 5: Noise as a function of gain is shown for both random noise and 60Hz pickup, collected with an unterminated coaxial cable attached to the input.

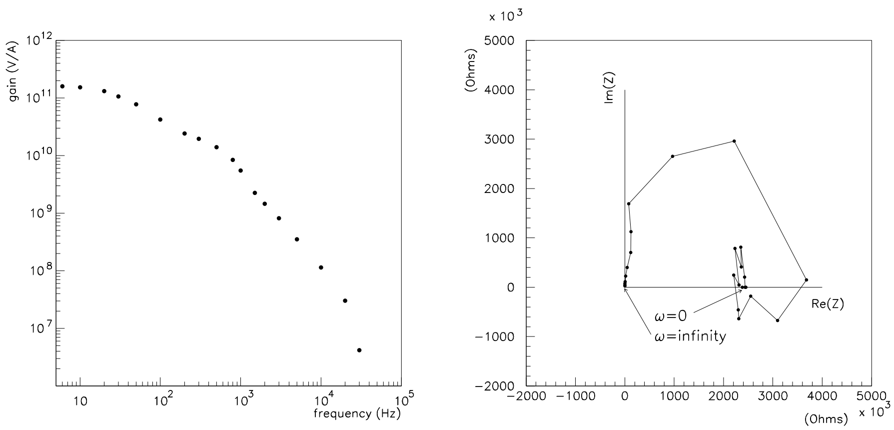

Figure 6: Measured gain (first panel) and complex impedance (second panel) of the PMT-5R preamplifier operating at the 10^{12} V/A setting. The sequence of data points is the same in the two plots. By following the connecting lines in the complex impedance plot, it is possible to reference the gain plot and look up the frequency corresponding to that measurement. The vanishing of the input impedance at high frequency is a consequence of the non-zero parasitic capacitance of the input.

injector circuit and repeating the measurements, it was possible to independently determine the amplifier gain and input impedance as a function of frequency. The second panel in Fig. 6 shows the results for the complex input impedance. The Z value at 10 Hz is pure real within errors, as expected if it represents the dc limit.

These data show that the gain at the top gain setting is indeed lower than 10^{12} V/A as suspected, by almost an order of magnitude. However in order to cancel the common-mode EMI noise it is essential that the EMI waveform not exceed the linear output range ($\pm$10V) of the amplifier. According to Fig. 5, this might happen if the gain at the top setting were larger by an order of magnitude. On the other hand, there is little motivation to further amplify a signal whose irreducible noise floor is already at the level of 15 mV rms. Based on these considerations, the 10^{12} V/A setting of the PMT-5R provides close to the maximum sensitivity achievable for the active collimator.

The bandwidth of the PMT-5R at the high-gain setting is measured to be 70 Hz from the 3dB point in Fig. 6. This is somewhat less than the design bandwidth of 300 Hz, but the gain is still 2×10^{10} at 300 Hz and does not drop off rapidly until above 1kHz. These results demonstrate that the preamplifiers can boost pA currents to about one order of magnitude above the thermal noise floor at 30 Hz bandwidth. A 1 pA signal at 300 Hz has a signal/noise ratio of approximately unity, in agreement with the design requirement. We conclude that the preamplifier is capable of measuring currents with gain and noise characteristics that match the active collimator requirements.

3 Future work

Having verified the basic performance parameters of the electronics, the prototype must now be tested in a photon beam. The following steps are recommended.

1. Obtain two more PMT-5R preamplifiers so that all four installed sectors can be read out simultaneously. Test the four readout channels on the bench to verify that the data acquisition system can multiplex between several channels at the full bandwidth without aliasing effects.

2. Design and build a translation table to hold the active collimator that has a translation stage in x capable of relative motion with a 0.1 mm accuracy.

3. Ship the prototype, mount, and data acquisition system to Jefferson Lab and install in the Hall B alcove in preparation for beam tests. Obtain a survey of the initial position in the alcove and align the collimator with the beam axis to within 1 mm.

4. Take data with a 4 GeV photon beam in Hall B, recording the signal and noise from the prototype over as wide a range in beam currents as possible. During access periods, do manual translation of the mount to expose the detector at various horizontal offsets from the photon beam axis.

5. Analyze the data and determine if the prototype meets the requirements for Hall D.

References

[1] C. Gauthier, "Simulation of a Position-Sensitive Tungsten Pin-Cushion Detector" *GlueX-doc-244* (2004).

[2] G. Miller and D.R. Waltz, Nucl. Instr. and Meth. **117** (1974) 33.