A Compact VLPC Photon Transducer System.

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Abstract

We have developed a compact Visible Light Photon Counter (VLPC) system. A VLPC is a solid state, silicon impurity band conduction device [1] able to transducer single photons. VLPCs have quantum efficiency of 60-70%, gain greater than 10^4 and rates capabilities of greater than 10^7 photons/sec, without decreased operating efficiency. We use the device as a transducer for scintillating fibers[2]. The complete system is capable of operating 16 cryogenic modules each containing 256 VLPC channels for a total of 4096 channels. The system uses about one litter Liquid Helium per hour and is capable of operating in various orientations. Using this compact cryogenic system we have measured the noise, gain and effect of rate verses the working temperature of the VLPCs.

I. INTRODUCTION

The original motivation for designing a compact Visible Light Photon Counting (VLPC) system was to take advantage of physics opportunities at the Superconducting Super Collider (SSC) in Texas [3,4]. However, even though this machine is canceled the design constraints that it imposed were quit general and we have gone on to complete a prototype compact VLPC transducer system. Our goal was to develop a high rate tracking system appropriate for charged particle tracking based on multimode scintillating fiber technology. Clearly this technology is very general and for example would perform well as a medical imaging transducer or as an astrophysics x-ray transducer.

II. LIQUID HELIUM CRYOSTAT

The cryostat is a forced-flow liquid helium cryostat able to maintain the VLPC modules at ±0.05K over a wide temperature range even when orientated up to 45° off of the vertical. The schematic diagram of cryostat concept [5,6] is show in Fig.1. Liquid helium is used to cool the cassette through a heat station located just above the VLPC photo-detectors. The first heat station is kept at ~5.5K. The VLPC detectors are in thermal contact with a copper plate that is heated slightly to bring the detector temperature to the desired level. The temperature of the copper heat stations in the cryostat are controlled by adjusting the flow rate of the liquid helium.

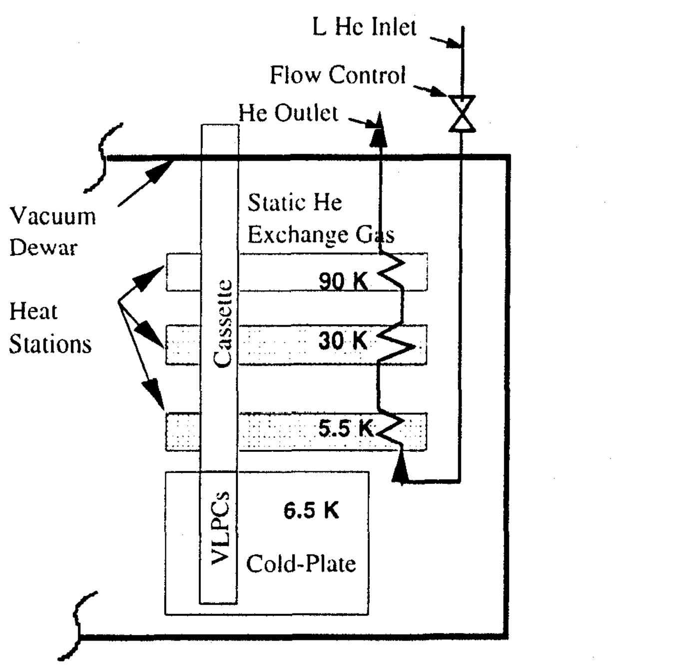

Figure 1: The compact VLPC transducer cryostat concept.

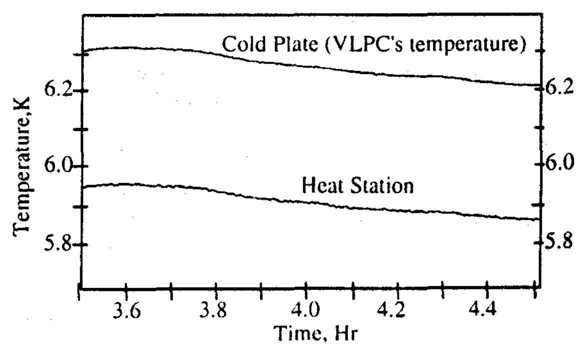

Figure 2: Temperatures of Cold Plate and First Heat Station during 1 hour period.

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The flow is controlled at the entrance to the cryostat, where the helium is a single-phase, sub-cooled liquid. The flow rate.is easily held constant so that the temperature of the heat stations remain very stable

During our tests of the system we have used a Heli-Tran® transfer line to deliver liquid helium to the system. The transfer rate was found to be very stable. This is evidenced by the stability, ±0.05K, of the coldest heat station during a one hour period as illustrated in Fig. 2. Since the coldest heat station, lays just above the VLPC detector elements and is cooled to below the VLPC operating temperature, a small amount of heat is added to the cold-plate to achieve the desired VLPC operating temperature. All the cassettes are inserted into a common heat sink which allows a single heater and temperature sensor to control the entire system. This greatly simplifies the temperature control scheme and improves system reliability.

The helium used to cool the heat stations is contained inside conduits and does not mix with the static helium in the body of the cryostat. The static helium serves to equalize the pressure within the system and acts to improve the heat exchange between the cassettes and the heat stations. By separating these two functions there is no contamination of the helium supply and re-circulation is easily accomplished. Non-vertical operation requires only that the void regions in the cryostat be filled with an insulating material to prevent convection currents in the static helium.

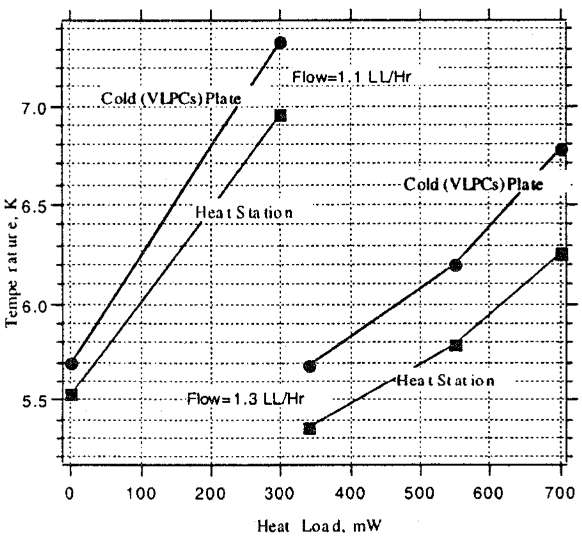

Figure 3: Temperatures of Cold Plate and first Heat Station vs. applied heat load for 1.1 and 1.3 LL./Hr helium flow rate.

Tests have shown that the cryostat operates stability as a function of time well within its design parameters. With 1 test-cassette and 15 dummy modules in place the cryostat used 1.1 liter of liquid helium/hour. (Fig.2 and Fig.3). We used a LakeShore Autotuning Temperature Controller [7] for automatic control of the cold-plate's heater and easily maintained the temperature of the VPLCs to within ±0.05K over a 24 hour period. The cryostat has operated reliability during more than 25 "cool-down" and "heat -up" cycles.

III. VLPCs CASSETTE DESIGN

Several factors influenced the high channel density design of the SSC cassette [3,4]. The cassette(designed by Rockwell) and the dewar (designed and built by APD[5,6]) had to operate near the highly valuable space of the collision region, limiting the number of lines to the cryogenic source and demanding high density electrical connections and cables, because of the intense competition for space. Another purpose of this cassette was to test new assembly techniques such as edge mounting of VLPCs and the use of unshielded cables with micron thick copper lines. Such techniques were intended to reduce the cost of a million channel VLPC. The goal was to reduce the number of mechanical parts and construction steps to the absolute minimum in order to make such a large system affordable. Our construction techniques were not intended for small systems, or even medium size system[8,9] deployments, where cost per channel may well be less critical. The amount of development work required for full scale production of the this design can only be recovered when spread out over a large number of channels.

The VLPCs used in these cassette are designated HISTE (IV) and (V) by Rockwell International [2,10]. Each VLPC chip is an 8x1 pixel array, each pixel being 1 mm in diameter. Each VLPC pixel is aligned to a 0.965mm diameter polystyrene multiclad, multimode waveguide fiber .

The first step of the assembly process, is to precision mount the eight channel VLPC array onto the silicon substrate using a set of jigs. The VLPC is held in place with epoxy (Fig.4).

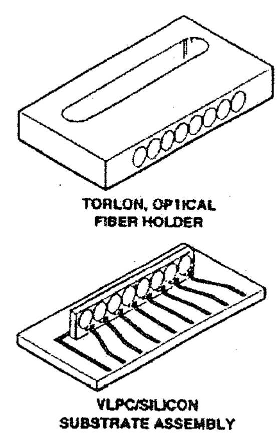

Figure 4: VLPC mounting system.

The electrical traces on a silicon substrate and VLPC are connected using a drop of conductive epoxy. Then, a flat kapton unshielded cable with micron thick copper traces is soldered to the substrates electrical traces. Two VLPC chips (16 channels) are connected to a single cable. A precision molded torlon fiber holder is then epoxied to the silicon substrate; it is positioned using precision jigs. The precut and polished multimode waveguide fibers are then epoxied into the torlon fiber holder. The fibers are positioned against the VLPCs while warm, but at liquid Helium temperature they contract away from the VLPC surface leaving a gap of approximately 100μm. Every effort has been made to minimize the thermal stress in the design and construction of VLPC module by careful selection of all materials used. Finally the warm end of the cable is soldered to miniature electrical connectors with center to center conductors 0.6mm apart. At the end of this step we have a submodule which consist from 2 VLPC chips (16 pixels), connected to a single flat cable and 16 guide fibers.

For this test only eight submodules were mounted inside a single G10 (phenolic) housing. The cassette is designed to accommodate 16 submodules, but for this development work only 8 submodules were used. The space between each submodule was filled with black felt to prevent visible light and infrared radiation from the warm end of the cassette from reaching the VLPC. The cross-section of the G10 housing is 0.610 x 2.395 inches with a wall thickness of 0.030 inches. At the cold end of cassette, the VLPCs extend past the G10

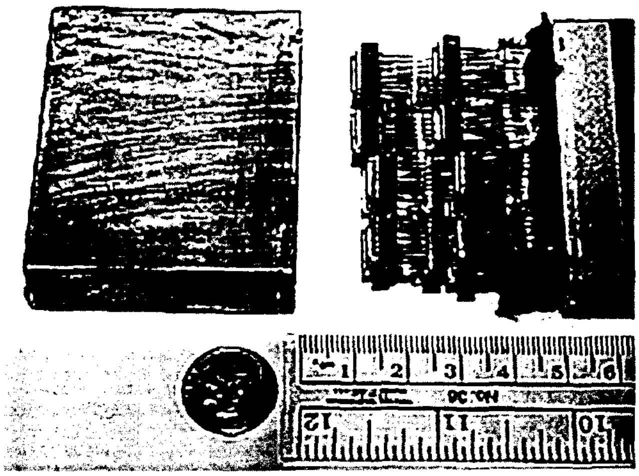

Figure 5: The bottom (cold end) of VLPC cassette. Copper end piece are separated from G10 cassette housing.

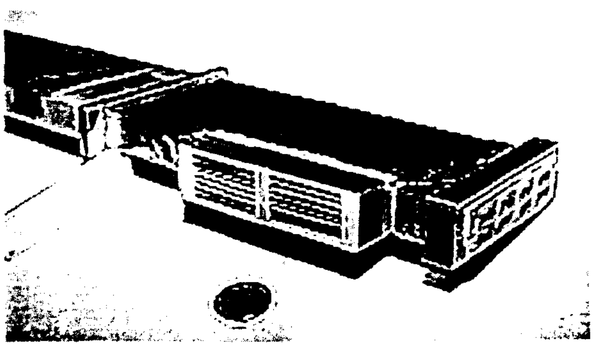

Figure 6: The top (warm end) of VLPC cassette. Optical and electrical connectors.

housing by 4.2 cm. Attached to the end of the G10 housing is a copper cover, which establishes an isotherm surrounding the VLPCs. This housing is shown in Fig.5. At the top of the cassette (warm end), waveguide fibers are glued into the optical connector shown in Fig. 6 and then diamond cut and polished. At this point the cassette is ready for operation.

During our test measurements we cycled our test-cassette more than 20 times from room temperature to 5K. No broken electrical or optical connections inside the cassette were observed. Measurements of dark counts and bias current drawn by VLPC at different bias voltages and temperatures suggest that the background count rate due to infrared radiation is very low. Also the method of edge mounting the VLPC chips was robust and did not induce noise into the system [11].

IV. VLPCs PARAMETERS MEASUREMENTS

Using this compact VLPC system we explored the parameter space of our VLPCs. The signal flow diagram for the VLPCs test-station is shown in Fig.7.

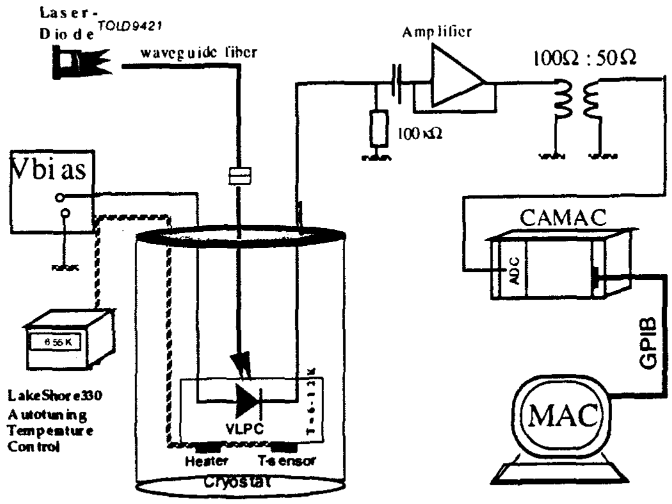

Figure 7: Signal flow diagram for the VLPC test-station.

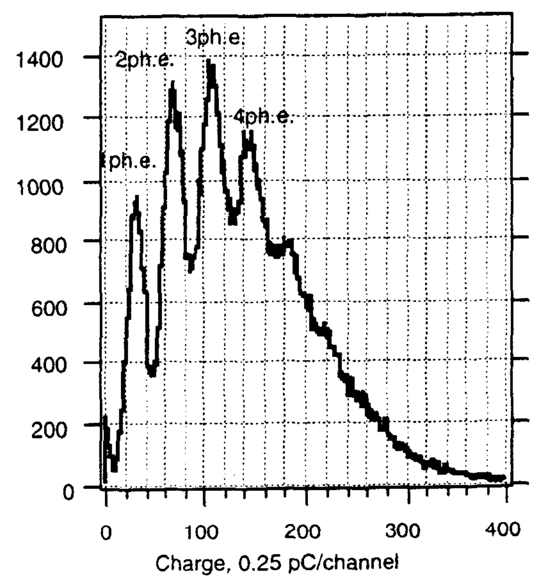

Figure 8: Typical pulse height distribution spectrum from VLPC pixel at T=6K and V_{bias}=7.0V.

A typical pulse height distribution (PHD) spectrum of a VLPC at 6K with a bias voltage of 7.0V is shown at Fig.8. There is clean separation between the pedestal and each of the first five photoelectrons peaks. These PHD spectra illustrate the fact that at this temperature the VLPCs have small gain dispersion [2,10,12,13], low noise as shown in Fig. 9 and high gain, approximately 10^4.

In order to use VLPCs in a specific application it is important to understand how the properties of the VLPC changes as a function of the flux of photons [13]. This "Rate effect" results in a decrease of the output signal and loss of

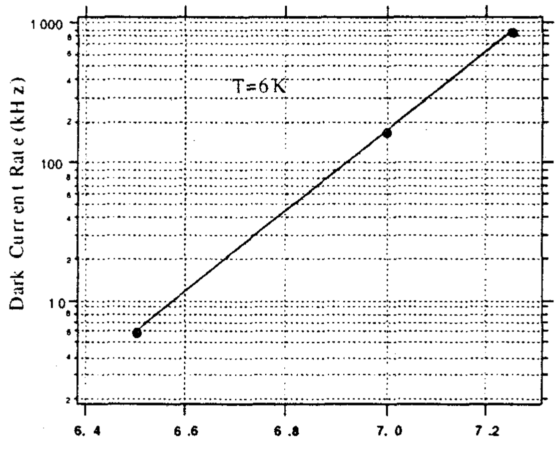

Figure 9: Direct measurements of dark current rates, defined as any signal above 1/2 photoelectron, as function of bias voltage for T=6K.

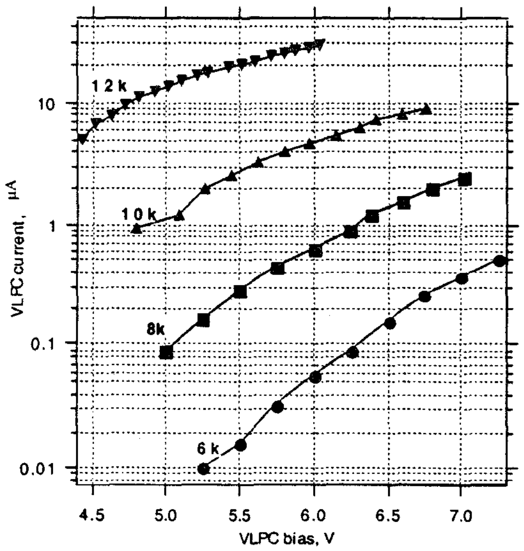

Figure 10: Bias current through VLPC for temperatures 6K, 8K, 10 and 12K.

quantum efficiency as a function of the light intensity. This effect may limit the use of VLPCs as a phototransducer for high luminosity collider experiments. Recent measurements [13] show that increasing the temperature of the VLPC is one of way to extend the effective operating rate of the device.

We have concentrated our effort measuring the VLPC parameters at high temperatures. Direct measurements of bias current as a function of bias voltage for different temperatures are presented in Fig. 10. Each isotherm shows the limit of VLPC operation. At the high voltage end of the curve the device suddenly go into a "break-down" type operating mode with a very high noise rate. At the highest temperatures the currents are so high that the device may have a limited lifetime.

The results of measurements of the VLPC output signal as a function of illumination are presented in Fig. 11. In order to measure the effect of high photon fluxes on the device we used two light source coupled to a single VLPC fiber. One source acted as the "reference" pulsing at a constant frequency of about 100Hz while the other acted as the "background" source set to the desired rate.

For our measurement s each reference and background light pulse was set at about 100 photons. This choice of source intensity kept the pulse in the VLPC linear response range[14] and while the noise contribution to the pulse height distribution was negligible.

The measurement for each temperature curve was normalized to 1.0 at a background rate of 0Hz. The curves show that an increase in temperature of ΔT=3K extends the operating rate of the VLPC by a factor of about 50.

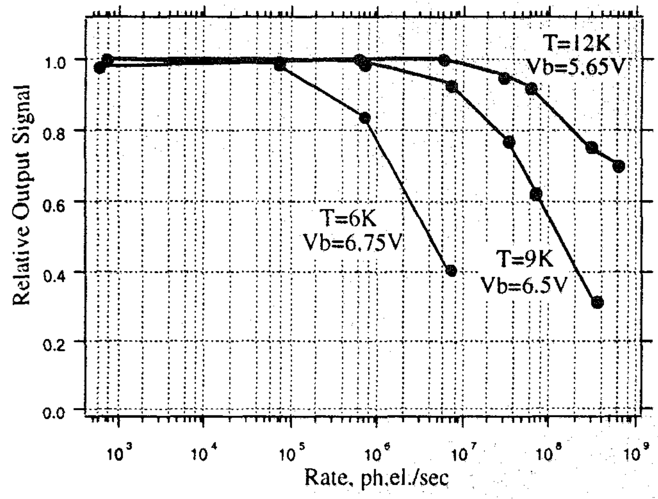

Figure 11: Effect of rate on VLPC output signal at: (1) T=6K, V_{bias}=6.75V; (2) T=9K, V_{bias}=6.5V;. (3) T=12K, V_{bias}=6.5V;

At a fixed light level input, the VLPC output signal is a convolution of the VLPC gain and quantum efficiency. It is important to understand the gain and quantum efficiency individually as a function of temperature. The measurement of absolute quantum efficiency however is very difficult. In this work we instead measure only the relative quantum efficiency by comparing the number of photoelectrons for each VLPC bias and temperature at a fixed light intensity. The results are shown in Fig. 12. We observe that the quantum efficiency saturates at high temperature just as it has been shown to saturate at low temperature [4,10] and that the saturation value appears to be fixed, independent of temperature. We also observe that the voltage at which the saturate point is achieved decreases with increasing temperature.

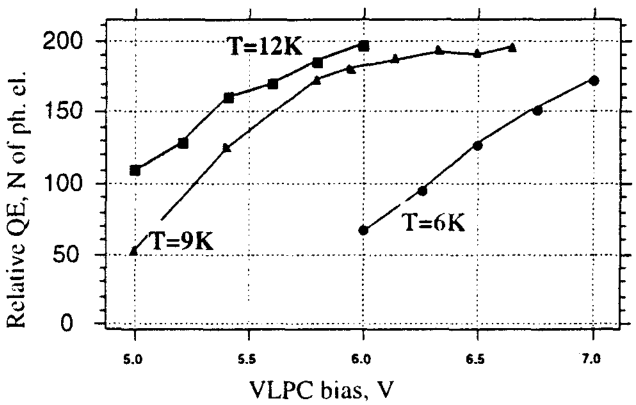

Figure 12: VLPC relative quantum efficiency as a function of bias voltage for temperatures 6K, 9K and 12K.

The gain can be calculated by dividing the output signal by the observed number of photoelectrons. The results are shown in Fig. 13. The results show that at high temperature the VLPC have the same linear gain increase as a function of bias voltage as has been observed a low temperature. We also observe that the gain does not saturate but suddenly changes into a noisy none linear mode.

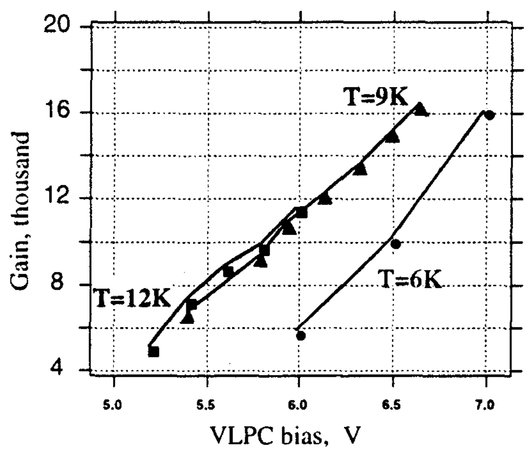

Figure 13: VLPC gain as a function of bias voltage for temperatures 6K, 9K and 12K.

The results we have shown are representative of HISTE(IV) and HISTE(V) VLPC devices. Newer VLPC devices HISTE(VI) show more attractive characteristics [13], having dark currents 10 times less than the devices we have worked with and 2-3 times higher gain. However, the general trends we observe are independent of VLPC generation. We have found that the main disadvantage of working with VLPCs at higher temperatures is the increase of dark current counts. For light sources with high intensity, 10 photoelectrons or greater this increase in dark current can be eliminated by an increase in threshold.

V. CONCLUSION.

We have completed the construction and testing of a high channel density compact Visible Light Photon Counter (VLPC) system, which was originally designed to be used at the Superconducting Super Collider (SSC). The design goal of a low cost highly stable system have been shown to be successful. The cryostat has operated stably at ±0.05K with low LHe consumption, about 1 liter LHe/hour for 4096 channels. The mechanical properties of the cassette have been shown to with stand the thermal stress of multiple cycles. The cassette design was also successful in blocking infrared background.

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