1. EVALUATION OF APDS FOR KOPIO:

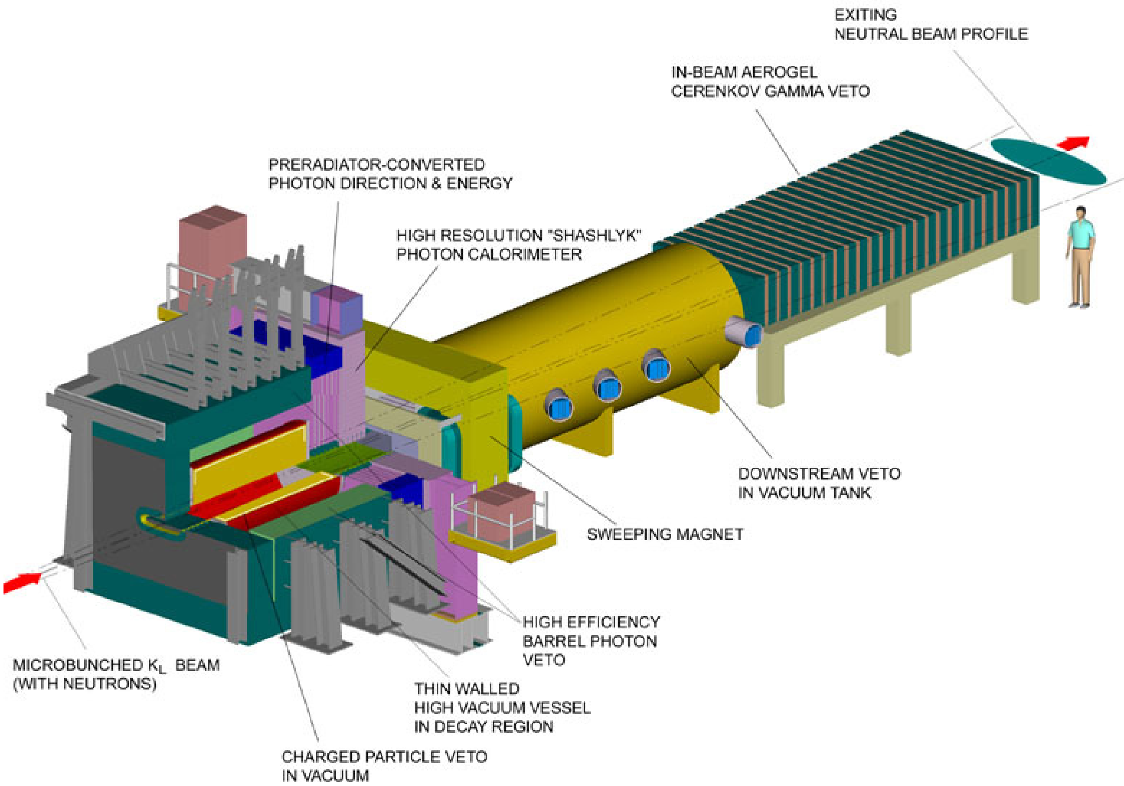

Fig. 1: Schematic of the KOPIO detector

The KOPIO experiment is expected to begin the construction phase in the coming fiscal year. KOPIO will search for the decay of a kaon via the rare decay mode $K_L \rightarrow \pi^0 \nu \nu$. The success of KOPIO will depend on the detection and rejection of the much more common decay modes that include extra gamma rays and charged particles. To be fully efficient, the gamma detectors must be sensitive to gammas from energies down to 1 MeV and up to 1.5 GeV. These gammas will be detected with lead/scintillator modules which convert the deposited energy to visible light. Low energy gammas yield very little light, making the observation of low light signals (a few photons) of great importance.

Several of the KOPIO subsystems are considering using APDs as the light detection device, provided the performance in critical areas can be achieved. These critical areas are:

- dark current, or signal-to-noise ratio and sensitivity to small light signals
- signal shape and timing, as a function of preamplifier type
- size of light sensitive area, and how this size impacts noise and timing.
-

It is crucial that we complete the study of the feasibility of using APDs for this experiment in the coming year so that construction of the detector can begin. Subsystems that are considering APD use include the Calorimeter (CAL), Outer Veto (OV), Barrel

Veto (BV), and Downstream Veto. Although the technical challenges vary, much of the APD research for the Phase II proposal is common to all of the subsystems.

2.1 Calorimeter and Outer Veto

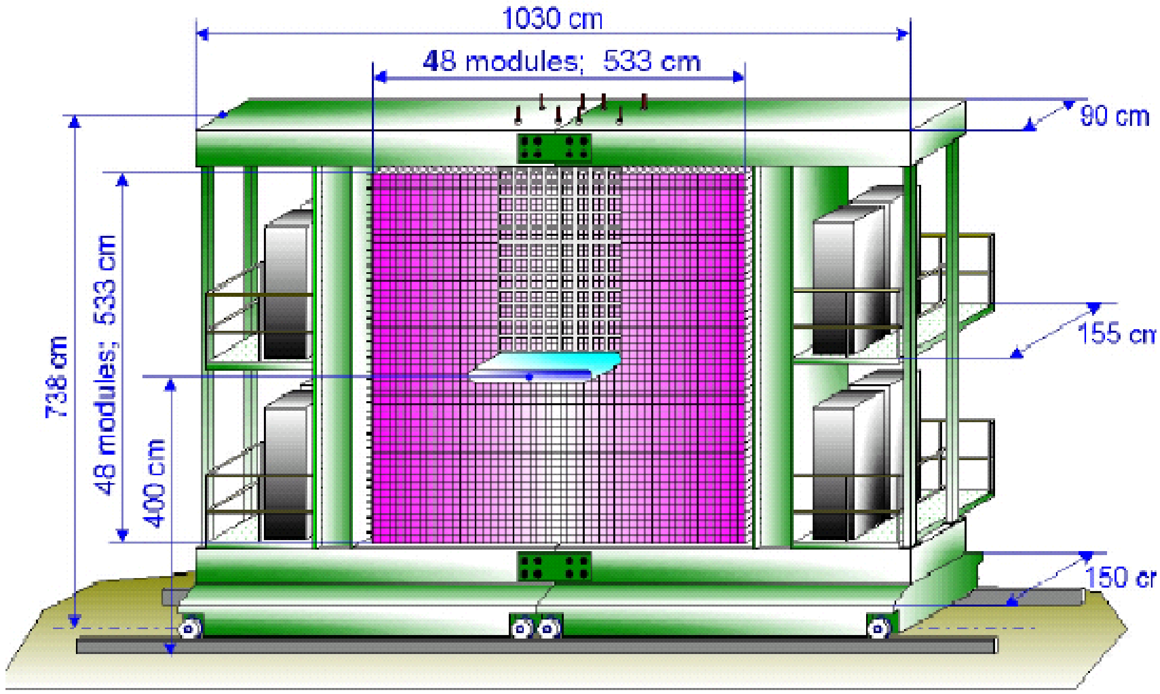

Fig. 2: Perspective view of the KOPIO Calorimeter array, 2500 modules.

The KOPIO Calorimeter (CAL) requires 2500 APDs, each with an active area of about 1.5 cm^2. The Outer Veto (OV) requires an additional 600 APDs of the same dimension. The performance requirements of the CAL and the OV are identical. Each APD views the light transmitted by 144 wavelength-shifting fibers, 1mm in diameter. This can be accomplished with circular APDs of 15 mm diameter. We are currently testing devices of this size as part of the Phase I proposal. APDs are preferred over photomultiplier tubes (PMTs) for this application, because of the need to operate the light collection devices in regions of high magnetic field, where conventional PMTs would not function. The APDs reading out the calorimeter are only a few centimeters from a large magnet, with fringe fields in the range of hundreds of gauss. Standard PMTs suffer loss of gain in such fields. Although there are some field-tolerant PMTs that make use of mesh dynode structure to reduce the effect of the magnetic field, they sacrifice performance and cost significantly more than APDs.

The second requirement of calorimeter readout is that it must be sensitive to very low light levels. The KOPIO experiment relies upon the detection of gammas down to less than 1 MeV in energy. A 1 MeV gamma will produce enough visible photons to deliver approximately 57 visible photons through the wavelength shifting fibers. In order to achieve good efficiency at such low light levels, we must be able to convert those photons into electrical signal in a way that preserves good signal-to-noise ratio, S/N. The quantum efficiency for the APDs is currently measured in the range 70-80% for light from the wavelength shifting fibers. This gives 40 photoelectrons for the APD, but only 11 for a standard PMT. This makes the choice of APDs seem very attractive. However, the APD signal has noise contributions that are much greater than PMTs. With currently available APDs, we find that we must set a threshold for gamma detection at 1 MeV, while for PMTs the threshold is 0.25 MeV. The reduction of noise is an area of research that requires great attention before the decision to use APDs can be made. Additional improvement in the quantum efficiency will also be investigated as part of the Phase II proposal. The inherent QE of silicon can be above 90%. We will determine the how best to optimize the QE of the APDs proposed for the CAL and OV.

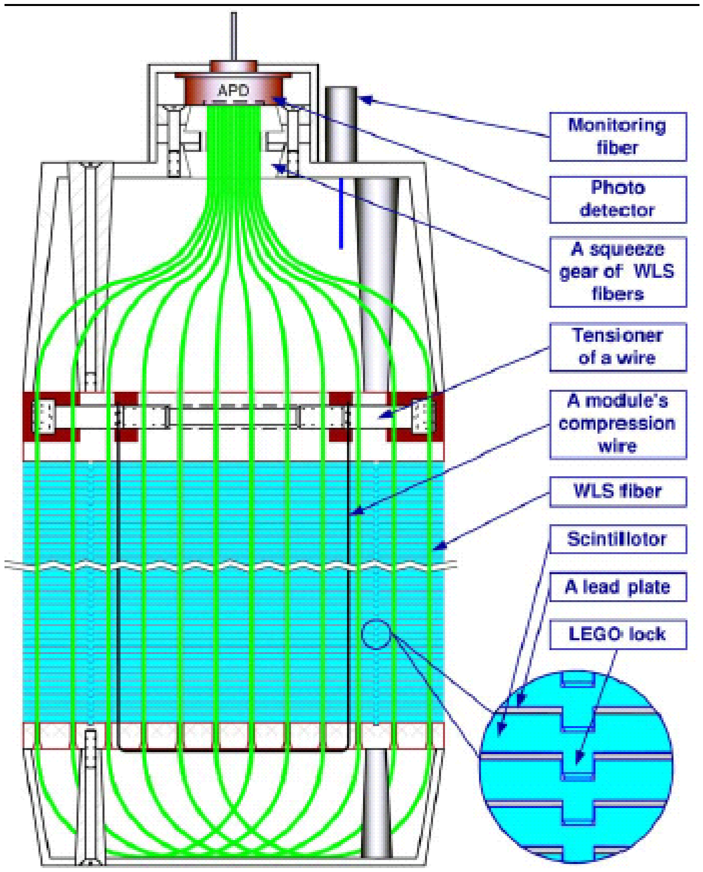

Fig. 3: Components of the KOPIO Calorimeter module.

APD noise is compounded by an Excess Noise Factor that is much larger than PMTs. The Excess Noise Factor (F) describes how the response function in a detector with gain like an APD differs from a perfect photodetector with a resolution that was determined by Poisson statistics only. A typical PMT has an F of 1.4. We have made measurements of F of 2.4 for APDs. In general the F of APDs is gain dependent[Hayat,1999], growing as the gain increases. Because KOPIO is extremely sensitive to noise and the resolution of small signal levels, understanding and control of F is a top priority for the Phase II R&D with KOPIO.

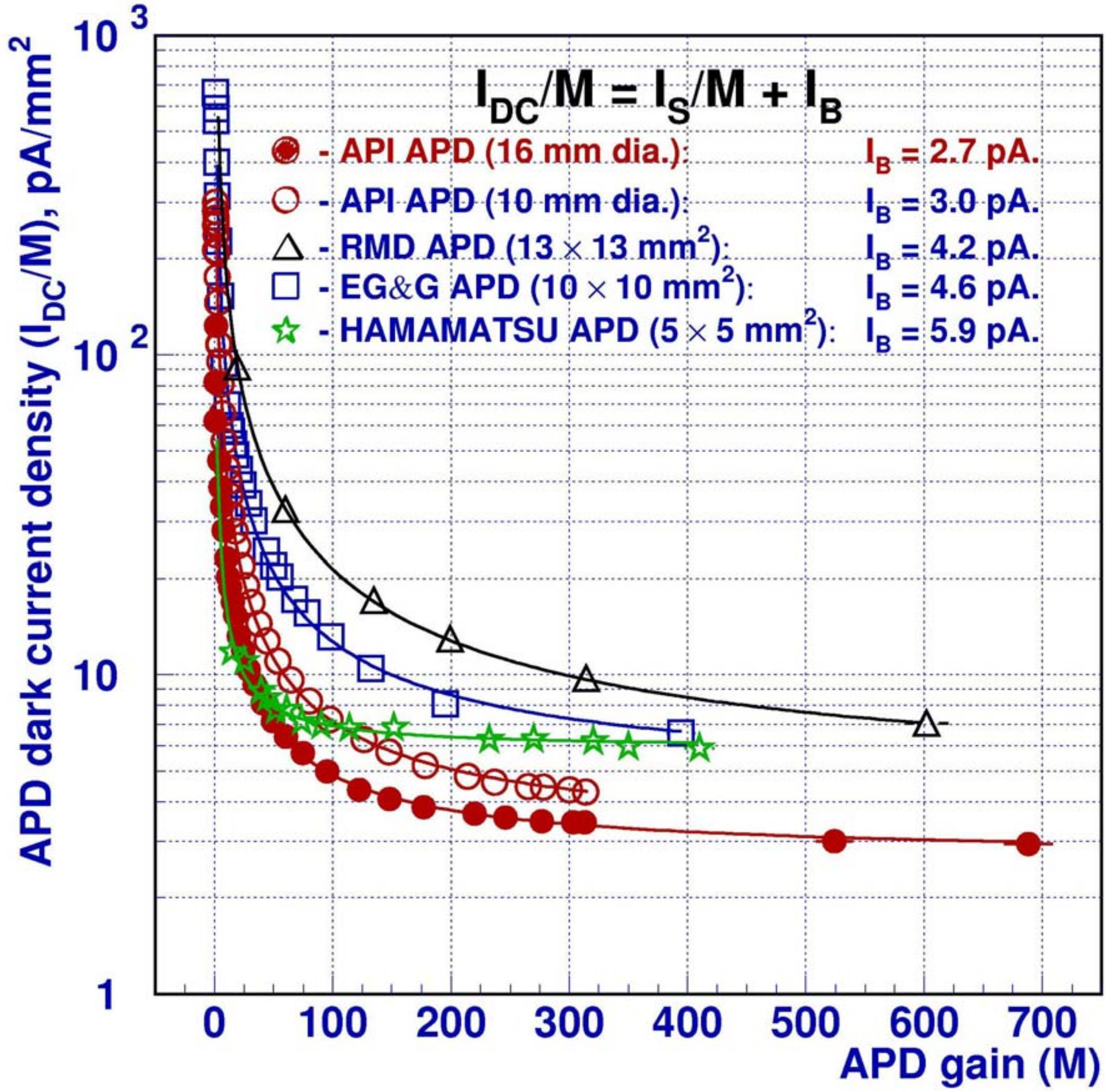

Fig. 4: APD dark current density as a function of APD Gain for a variety of APDs.

The overall noise in APDs can be reduced through cooling. Initial studies have given very promising results for what can be achieved with low cost refrigeration techniques. KOPIO would like to continue the noise studies as a function of temperature, to see what level of cooling is required for single photoelectron sensitivity. We will be investigating the use of Thermoelectric Cooling devices (TECs) that can be bonded to each APD and used to cool the APD by 40-50 degrees C. We plan to purchase enough TECs to test with a prototype APD and see if the performance we measure is sufficient for the KOPIO calorimeter modules. This study will complement our Phase I refrigerator study with a final design for mounting cooled APDs on the back of the calorimeter modules. We will measure the effective energy threshold for detecting gammas with APD readout and PMT readout, as a function of APD gain and temperature.

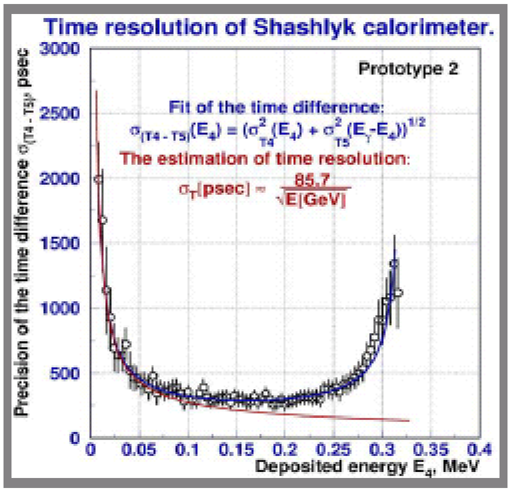

Fig. 5: Time resolution of KOPIO Calorimeter with APD readout, from test beam study.

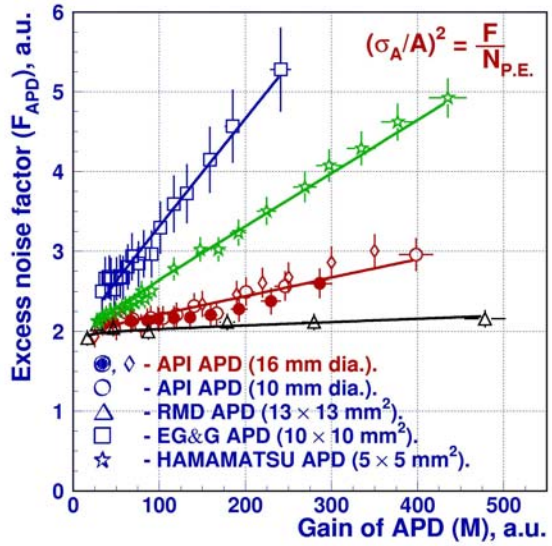

Fig. 6: Excess Noise Factor as a function of APD gain, for various APDs.

Timing of the APD signals is a concern for KOPIO. In order to distinguish between signal gammas and background gammas, one of the most powerful tools is the timing of the hit in the calorimeter. The timing will be determined either by a threshold discriminator and Time to Digital Converter (TDC) or a Wave Form Digitizer (WFD). We hope to achieve a timing resolution of 60 ps/√E(GeV) in the calorimeter. Although the readout scheme for the calorimeter has not yet been finalized, we expect we will require APD signal rise times of several nanoseconds in order to achieve the time resolution specified. Some of this study will be devoted to the design of a preamplifier. Voltage sensitive preamps usually have faster risetime, but greater noise. Charge sensitive preamps give reduced noise, but at the cost of slower rise times. As part of Phase II, we will investigate the best compromise between noise and speed to give the KOPIO calorimeter the optimum performance.

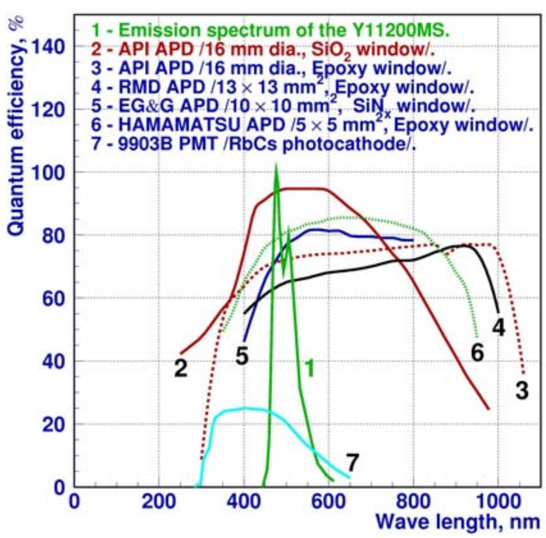

Fig. 7: APD Quantum efficiency vs wavelength.

As part of our Phase I research we have operated with APD gains on the order of 10,000, larger than the gains in most applications. In Phase II we will explore the limitations to the stable operation of APDs at gains of 10,000 or greater. We would also like to explore with RMD and the BNL Instrumentation Group the possibility of the development of monolithic APD/Preamp chips, eliminating the need for external preamps.

2.2 Barrel Veto

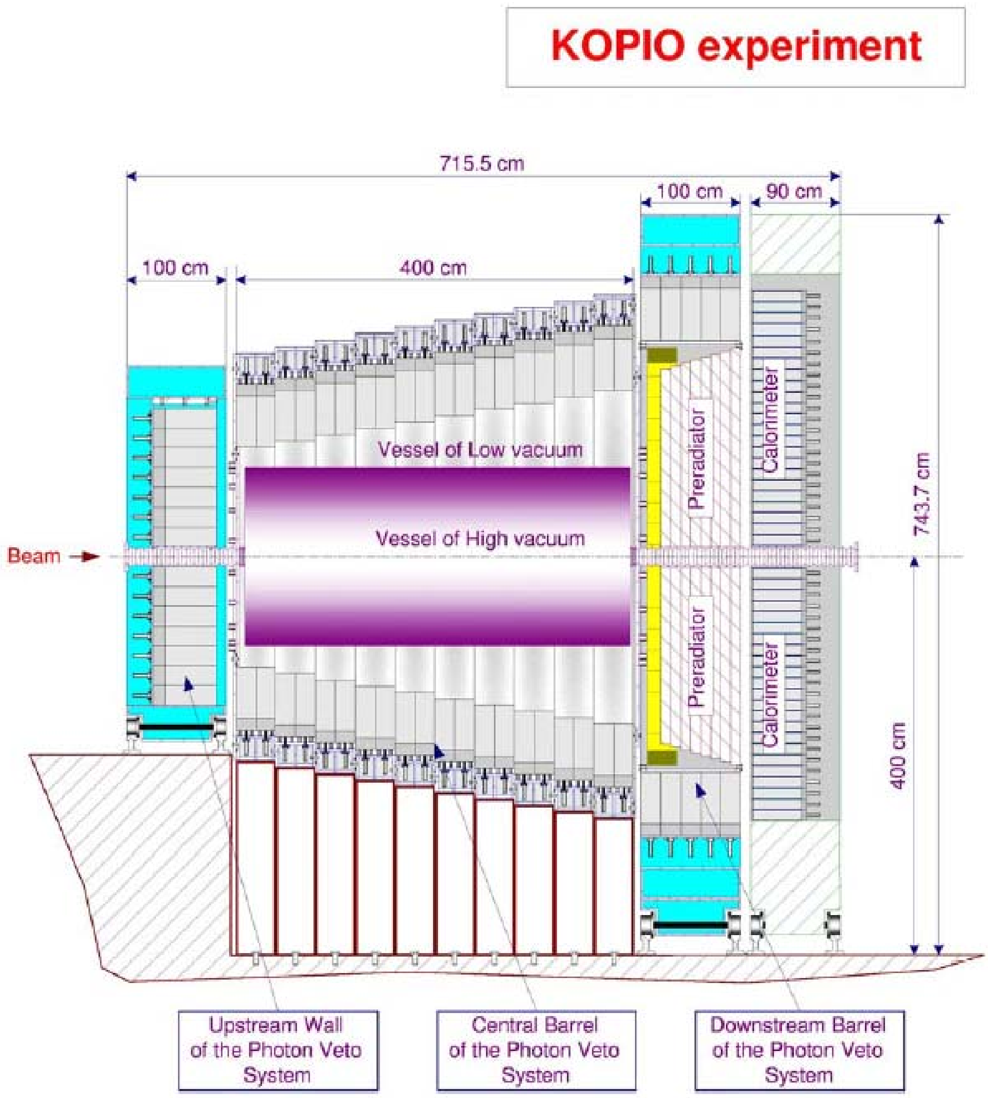

Fig. 8: Schematic of the KOPIO Barrel Veto, Shashlyk option.

The Barrel Veto (PV) is an array of lead/scintillator detectors surrounding the decay volume of the KOPIO experiment. Its purpose is to detect any gammas that accompany the signal, indicating the presence of a background. The BV must be sensitive to gammas of energies below 1 MeV, up to energies of 1 GeV; similar in performance to the CAL. Like the CAL, the BV must be capable of fast timing measurements, and low noise.

There are approximately 1200 light detectors on the BV. In distinction to the CAL, the BV must collect the light from over 400 fibers, so the active area must be larger. APDs of 25 mm diameter would be adequate. This requires larger APDs than we have worked with in Phase I, and it will be a challenge to achieve the same APD performance with a larger area device.

As part of the Phase II R&D program, we plan to compare the gain, timing, resolution and noise behavior of these larger 25 mm diameter APDs.

2.3 Downstream Veto

The Downstream Veto includes a gamma veto (DGV) similar to the BV and a charged particle veto (DCPV). The gamma veto must function inside a strong magnetic field, making PMT use impossible. Performance for the DGV are just as stringent as the CAL and BV; sensitivity to gammas down below 1 MeV, with fast rise time and low noise. APD size requirements are not completely specified for the DGV yet, but will be similar to the CAL.

The Downstream Charged Particle Veto (DCPV) is a different design from the gamma vetoes. Each DCPV will be a single scintillator tile with wavelength shifting fiber readout. This means that the light collection area will be quite small; a few square mm. For this application, smaller APDs would be appropriate. This makes achieving the low noise operation somewhat easier, and could improve the response time compare to the larger area APDs. As part of Phase II we plan on investigating the design of APD readout of the DCPV.

[Hayat] Hayat, Majeed M., Chen, Zikuan, and Karim, Mohammad, An analytical Approximation for the Excess Noise Factor of Avalanche Photodiode with Dead Space, IEEE Electron Device Letters, V.20, No.7, p 344, 1999.

Milestones:

1) Low noise operation
   a. Development of a triggerable low light output pulser system. — 31 Dec 2004
   b. Acquisition of low noise preamps, voltage sensitive and change sensitive. — 31 Dec 2004
   c. Improved data acquisition for low noise study. — 31 Dec 2004
2) Excess Noise Factor study
   a. Acquisition of precision pulser to calibrate APD response. — 31 Aug 2004
3) Cooling study
   a. Acquisition and implementation of Thermoelectric Cooling devices. — 31 Aug 2004
   b. Design study of system-wide application of TEC. — 31 Dec 2004
   c. Measure gain and noise response as a function of temperature. — 31 Dec 2004
4) Timing study
   a. Acquisition of fast TDC and WFD for subnanosecond timing study. — 28 Feb 2005
   b. Optimization of preamp selection and system design. — 30 June 2005
   c. Comparison of voltage sensitive vs charge sensitive preamps. — 30 June 2005

Budget:

Equipment:		
Pulser for noise study:		
BNC-6040 Universal Pulse Generator with		$5850
BNC-201E Rise Time Module		$4105
Low noise charge sensitive preamp:		
Cremat CR-110	25 @ $55/pc =	$1375
Low noise voltage sensitive preamp:		
SRS SIM910	$975/pc =	$975
Thermoelectric cooling devices		$250
Data Acquisition PC Dell Precision 650 w/ PCI		$2500
VME Crate 6023/620		$5827
SIS3100 VME-PCI Interface/Crate controller		$3800
VME test/diagnostic unit and bus display		$1609
CAEN 32 channel TDC: V775		$4980
CAEN 32 channel ADC: V792		$4810
Total Equipment		$36081
Technical Support		
6 man-months @$50.13/hr fully burdened		$48124
Total Budget		$84205