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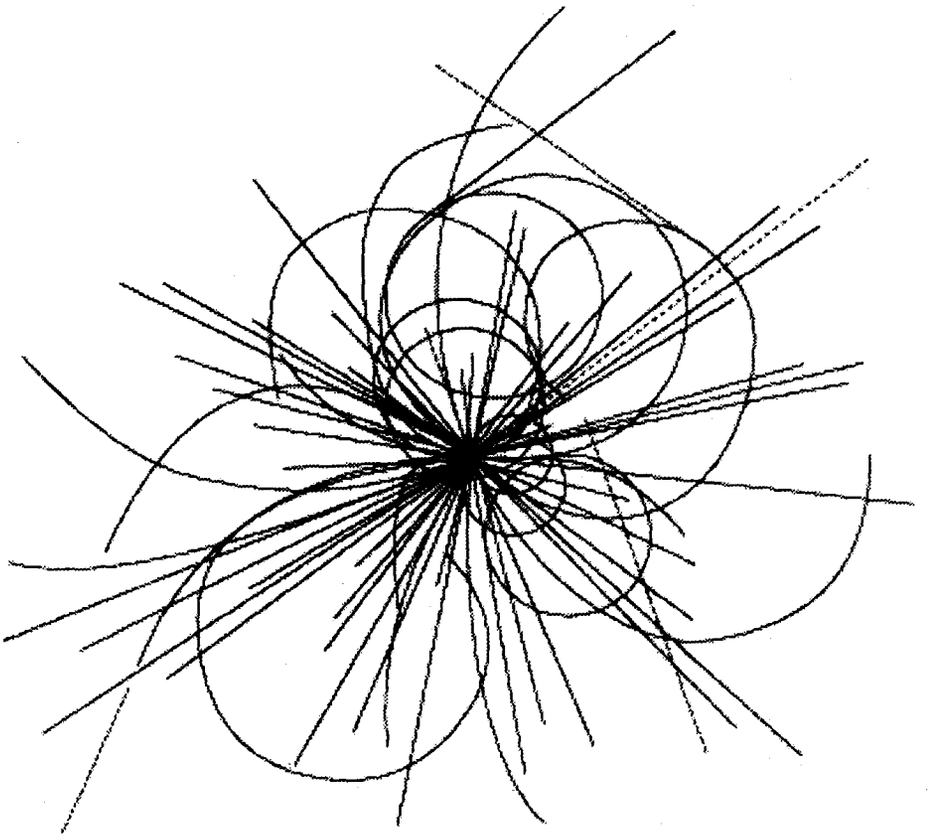

Superconducting Super Collider Laboratory

SSCL-611

Studies of Avalanche Photodiodes for Scintillating Fibre Tracking Readout

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ABSTRACT

Avalanche Photodiodes (APDs) operating in "Geiger Mode" have been studied in a fibre tracking read-out environment. A fast recharge circuit has been developed for high rate data taking, and results obtained from a model fibre tracker in the test beam at Brookhaven National Laboratory are presented. A high rate calibrated light source has been developed using a commercially available laser diode and has been used to measure the efficiency of the devices. The transmission of the light from a 1mm fibre onto a 0.5mm diameter APD surface has been identified as the main problem in the use of these particular devices for scintillating fibre tracking in the Superconducting Supercollider environment. Solutions to this problem are proposed.

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1.0 INTRODUCTION

In the Superconducting Supercollider (SSC) fibre tracking environment, a high quantum efficiency for the readout device is essential because it is necessary to detect very small numbers (4-6) of photons. In addition, a fast recovery time is needed to maximize the data taking rate from a machine with a duty cycle of 16 ns. Avalanche Photodiodes (APDs) are a possibility for such a readout device, although in the past certain characteristics of their operation had excluded them from consideration. It is shown that running in "Geiger Mode" with a fast recharge circuit can achieve the desired efficiency and recovery time.

2.0 GEIGER MODE RUNNING

An Avalanche Photodiode is a silicon device which behaves in various regions of gain in a similar fashion to a wire chamber. In all the studies that are described here, the RCA C30902S[1] APDs were used. A photon is incident on the diode and forms an electron hole pair, the electron of which drifts under the influence of the bias voltage, until it causes an avalanche. In "Linear Mode," the output signal is proportional to the number of photons incident on the diode and the response time is very short, on the order of a few ns. However, in this mode of operation, the system is not sensitive to numbers of photons less than about 10 due to the modest gain (of order 100) and the noise rate associated with any practical set of electronics. By increasing the bias voltage to a region where a breakdown occurs, in a manner analogous to a wire chamber operating in the Geiger region of gain, the diode can be run in "Geiger Mode". The characteristics of this type of operation are the ability to detect even single photons but an intrinsically long dead time, of order 1 μs. This is believed to be due to the time needed for recombination to occur, the breakdown having incorporated the whole area of the diode rather than a limited region of the surface as in linear mode.

3.0 THE FAST RECHARGE CIRCUIT

A fast recharge circuit has been developed at SSCL[2] to sense the breakdown early on in the process and at this moment to lower the bias voltage across the diode to prevent a full breakdown from occurring. Figure 1 shows the circuit in which a comparator senses the breakdown after a few ns and enables at the same time a tri-state buffer and an RC timing circuit. The tri-state buffer lowers the bias voltage across the APD by 5 V thus discouraging the breakdown from continuing. After the time determined by the RC circuit (30-40 ns), during which recombination occurs, the tri-state buffer goes low, returning the bias voltage to normal. The comparator is turned off and the tri-state buffer is disabled. The output from the comparator is used as a convenient digital signal for data acquisition. The lower trace shown in Figure 2 shows the

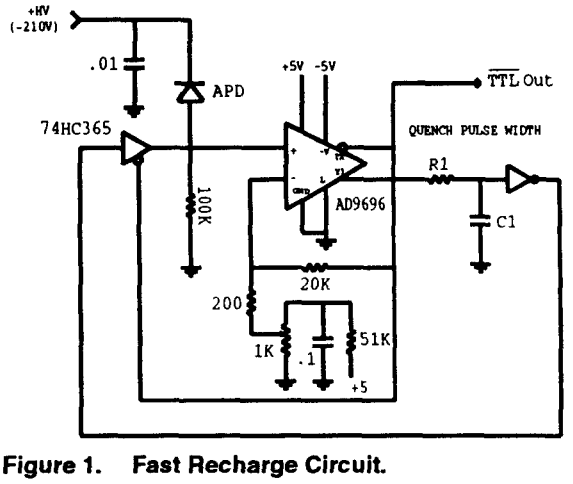

Figure 1. Fast Recharge Circuit.

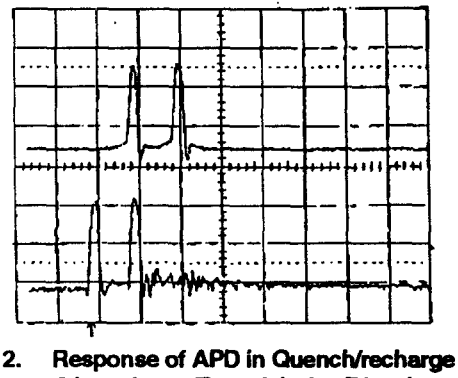

Figure 2. Response of APD in Quench/recharge Circuit to Two Light Flashes Separated by 50 ns. Upper trace shows output signal from APD, lower is input pulse to laser diode.

current through a laser diode (two pulses separated by 50 ns), light from which is coupled to the APD via a plastic optical fibre. The upper trace shows the output of the APD taken at its anode. It can be seen that the circuit has been successfully recharged and is ready for the next pulse about 50 ns later.

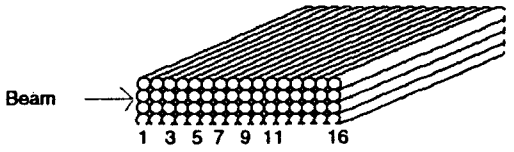

Figure 3. Model Fibre Tracker.

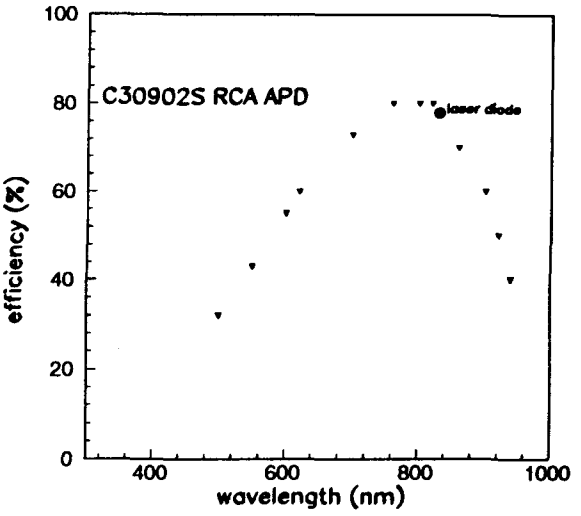

Figure 4. APD Quantum Efficiency as a Function of Wavelength.

4.0 TEST BEAM RESULTS FROM A MODEL FIBRE TRACKING DEVICE

In the following test beam work, the fast recharge circuit was not used, mainly because the particles in the test beam come at 1-10 μs intervals and so it would not have been useful to employ the circuit under these conditions. Figure 3 shows the tracker set up. An array of 4 × 16 fibres were oriented towards the beam as shown allowing an easy measure of the efficiency due to much redundancy in identifying tracks.

During the test, four different coloured fibres were used. These were Red: SCSF-81Y7R3 and Orange:SCSF-81Y7O2 from Kuraray and Green:BCF-28 and Blue:BCF-10 from Bicron. The motivation to study different coloured fibres is expressed in Figure 4,where the quantum efficiency as a function of wavelength is shown for the C30902S RCA APDs. However, there are competing effects: the longer the wavelength, the higher the quantum efficiency but also additional fluors are needed to produce that wavelength. For each fluor there is associated a new inefficiency for the conversion of photons from one wavelength to another. Further, the quantum efficiency, which is the efficiency to create an electron hole pair in the silicon and is determined optically by the manufacturer, is not the whole story. There is also a detection efficiency to be taken into account which is the efficiency to produce a breakdown (or Geiger) from one electron hole pair. This has been calculated by Lightstone and McIntyre[3] as shown in Figure 5.

The setup consisted of the scintillating fibres (30 cm long), attached to 2 meters of clear fibre by a connector whose transmission was measured to be 90%±5%, and 64 channels of APDs. Two scintillators attached to photomultiplier tubes (PMTs) in coincidence acted as the track trigger. The APDs were cooled to 18°C and kept constant to within ±1°C. The schematic is shown in Figure 6.

The clear fibres were connected to the APDs by means of a ball lens as shown in Figure 7. It was necessary to use such a setup because the active diameter of the APDs was 500 μm but the diameter of the

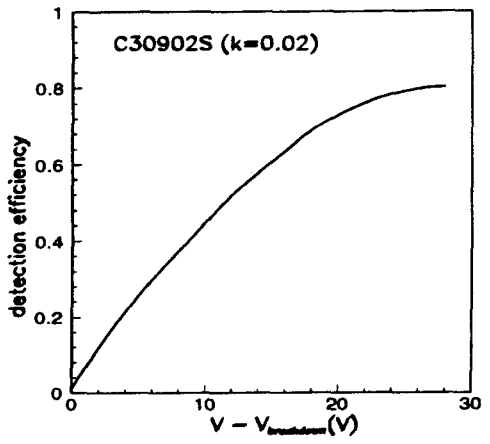

Figure 5. Probability That a Photoelectron Will Produce a Geiger Avalanche.

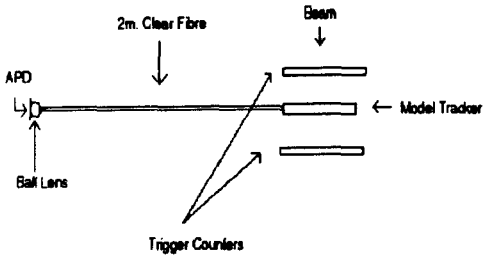

Figure 6. Schematic of Beam Test Setup.

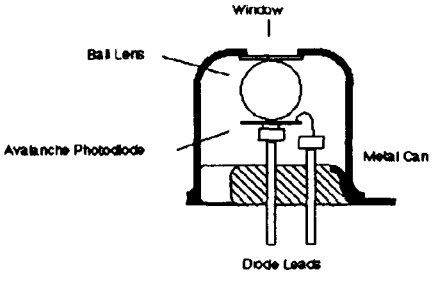

Figure 7. Ball Lens Used to Focus Light From a 1-mm Fibre Onto a 500 -μm APD.

fibre was 1mm. The ball lens (diameter 1.5 mm) focuses the light from a larger to a smaller diameter circle, but obviously has some intrinsic inefficiency.

The efficiency of the fibre+APD was measured by looking for tracks in the tracker using only even (or odd) numbered fibres in a column and looking at the efficiency for the odd (or even) ones. A simple Monte Carlo gave us confidence that our track finding algorithm did not bias our efficiency measurements. A certain inefficiency is allowed in the selection which can permit slanting tracks into the sample which miss the end fibres. If this were not properly taken into account, it would produce anomalously low efficiencies for the end fibres.

The efficiency results are shown in Figures 8 and 9. It was found that blue and green fibres gave the highest efficiency although it can be seen in the plots that the channel count was reduced (a few fibres have zero efficiency). It was determined that this was due to water damage from condensation on the electronics. It was concluded that the inefficiency from the presence of additional flours in the red and orange fibres overwhelmed the gain in quantum efficiency at the longer wavelengths.

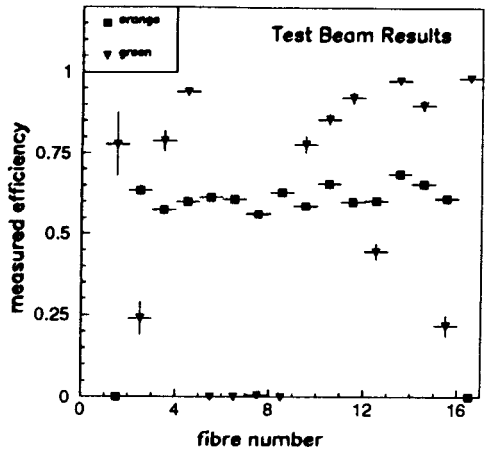

Figure 8. Efficiency Results for Green and Orange Fibres.

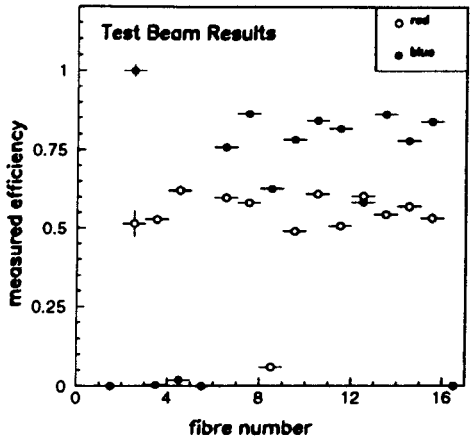

Figure 9. Efficiency Results for Blue and Red Fibres.

5.0 CALIBRATED LIGHT SOURCE

The efficiency of the blue and green fibres (+APDs) for detecting minimum ionizing particles was measured to be in the range from 70%-90%. With the 2-m length of clear fibre (with an attenuation length of the order of 9 m) and the measured efficiency of the connector, one would expect the measured efficiency to be higher since basic calculations predict that the number of γs/mm of scintillating fibre which are captured is between 60 and 70. In order to decouple the APD efficiency from the yield and transmission effects of the fibres, it was necessary to build a light source capable of putting out very short pulses of very few photons.

The source used for this was a commercial laser diode of wavelength 830 nm. It was pulsed at 100 kHz with pulses of varying length and the light yield was measured with a PIN diode connected to an electrometer capable of measuring current to a few pA accuracy. The PIN diode sees a constant current and so the number of γs/pulse can be calculated from the following relation:

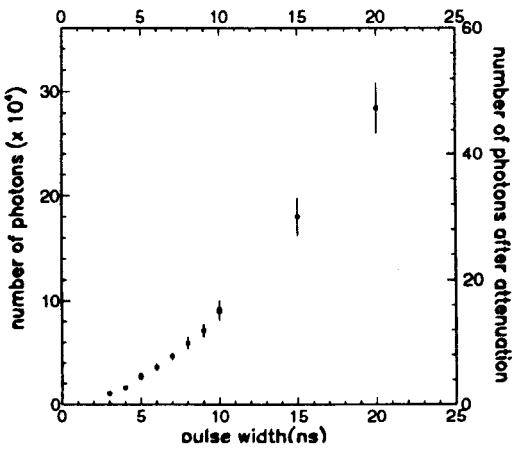

Figure 10. Plot Showing Number of γs/pulse as a Function of Pulse Width.

$$N\gamma = I / \{(hc/\lambda) \bullet f \bullet R\}$$

where I is the current read from the PIN diode, λ is the wavelength of the light, f is the pulsing frequency and R is the diode responsivity which is determined by the manufacturer as a function of wavelength.

The calibration curve for the number of γs/pulse as a function of pulse width is shown in Figure 10. The number of γs is seen to be functionally dependent on the pulse width. However, the number of γs is very large and an attenuator of order 10^4 is needed to reduce this number to a few. This was achieved in the following way: A simple attenuator was formed by reflecting light coming out of one fiber off the diffuse white interior of a small light tight box. Only light which managed to be captured by a second fiber coming out of the box was transmitted. The laser was pulsed at 20 MHz in order to collect enough light at the PIN diode to measure. This reading was compared with the PIN diode reading with no attenuator and the attenuation was measured to be 6×10^3. It is assumed that this attenuation does not depend on the pulse width or the frequency. The right hand scale on Figure 10 shows the number of γs/pulse after attenuation. The results are very robust: many different measurements achieve approximately the same result for the attenuation. The central value and error were determined to be $6\pm1 \times 10^3$.

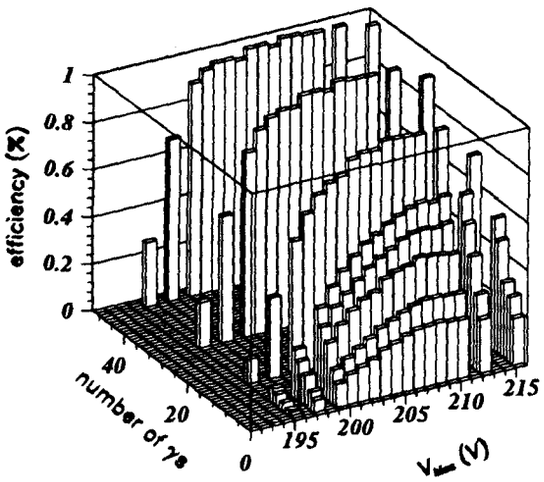

Figure 11. Efficiency as a Function of Bias Voltage for Several Different Numbers of Incident γs.

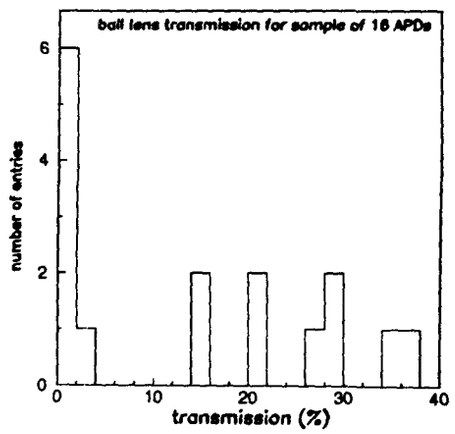

Figure 12. Fit Values of T_b for 16 APDs. Four of the entries in the lowest bin represent non-functioning channels

6.0 EFFICIENCY MEASUREMENTS

Figure 11 shows the efficiency as a function of bias voltage for one APD for eight different incident light intensities. It can be seen that the observed efficiency is lower than expected taking into account only the detection efficiency and quantum efficiency (QE). This points to poor transmission of light from the fibre to the APD. Using the calculated breakdown efficiency from Figure 5 and the measured efficiency for different numbers of incident γs as a function of V_{bias}, it is possible to fit for the transmission of the ball lens, T_b. Figure 12 shows the fit values of T_b for 16 different APDs. The transmission varies wildly from 10 -36% at best. Four of the entries in the zero bin correspond to non-working devices in our sample of 16.

7.0 WORK IN PROGRESS

Two solutions present themselves. The first is obvious: 1 mm APDs could be matched directly with the incoming fibre with very little light loss. At present EG&G is in the process of furnishing us with a couple of 1 mm APDs. Also, RMD Inc.[4] in Boston manufactures 1 mm APDs which we will test in the next few weeks.

The second solution is more challenging. Tapering the fibre from 1 mm to 500 μm could result in a gain over the ball lens. Initial attempts achieved a 30% transmission along the tapered region, similar to that achieved for the best ball lens. However, the light leaks out around the taper as the critical angle is no longer achieved by the light due to the taper angle. A reflective coating around the taper is one option and a mirrored cone connector is another. AT&T has made some advances in this kind of technology and we will try to extract some ideas from them.

Money is clearly needed for both the above efforts to input to the companies involved.

The efficiency plateaus in Figure 11 show that the most efficient running voltage is ≥ 15V above breakdown. Clearly, the present quench-recharge circuit, which is limited to providing a 5-V pulse, is not sufficient for running at such a voltage. We are attempting to modify the circuit to use ±15-V components.

Finally, the QE vs. λ relationship can be shifted towards the blue by about 10% by using a different anti-reflective coating on the APD surface. It would be very useful to test the fabrication of bluer sensitive APDs. Conversely, the manufacture of high Stokes shift red fibres must be encouraged by this work, especially because red fibres are more radiation hard than the shorter wavelength scintillator.

8.0 CONCLUSIONS

Geiger mode running of APDs has been thoroughly tested and fast (50 ns) operation in this mode has been demonstrated. The main drawback has been identified as the light loss incurred when trying to take light from a 1 mm fibre and put it on to a 500 μm APD. The solutions to this problem are being studied at present. If this final hurdle could be overcome, it would revolutionize the fibre tracking industry with easy to use, readily available room temperature devices.

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