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Magnetic field effects on large area avalanche photodiodes at cryogenic temperatures

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ABSTRACT

We present results for detection of X-rays by large area avalanche photodiodes (APDs) in strong magnetic fields and at cryogenic temperatures. Whereas at room temperature we observe essentially no effects on the response, at cryogenic temperature we observe significant distortion when the magnetic field is in the plane of the APD surface (and thus perpendicular to the electric field in the APD). At all temperatures, effects are minor when the magnetic field is normal to the APD surface (and thus parallel to the electric field in the APD). We performed measurements of the response of an APD to illumination by X-rays in fields between 0 and 4.6 T, for temperatures between 77 and 250 K. Measurements were performed using ^{241}Am and ^{55}Fe sources, and 1.5 keV X-rays produced by aluminum fluorescence. The data indicate that the effects are associated with those X-rays that are absorbed in the drift region of the APD.

1. Introduction

In a recent experiment to study neutron radiative decay [1,2], we employed a detector consisting of a bismuth germanate (BGO) crystal coupled to a 13.5 mm by 13.5 mm avalanche photodiode (APD) [3] to detect gamma-ray photons in the 15–340 keV range. The particle and photon detection methods employed for this experiment are described elsewhere [4]. The detector was operated near 77 K and in a 4.6 T magnetic field produced by a solenoidal, superconducting magnet. APDs can also be used to directly detect X-rays [5–8]. For a new experiment we have also directly detected X-rays in the 0.1–30 keV range with 28 mm by 28 mm APDs [3,4,9]. Whereas the scintillator detector operated with the magnetic field normal to the APD surface (and thus parallel to the APD electric field), the first version of the direct detector operated with the magnetic field in the plane of the APD surface (and thus perpendicular to the APD electric field). In this paper we will refer to these as the "parallel" and "perpendicular" configurations. We found a significant distortion of the response of the APD to 5.9 keV X-rays from an ^{55}Fe source. This phenomenon was not expected, as past studies had reported only minor effects for detection of X-rays with APDs for fields up to 5 T [10,11], regardless of the direction of the magnetic field. Upon revising our detector so that the magnetic field was normal to the APD surface, we saw only minor effects from the field. Further experiments in a different apparatus revealed that the significant effects that we observed for the perpendicular configuration only occur at low temperatures, hence were not observed in prior studies at room temperature [10,11]. In this paper we present results for the perpendicular configuration.

2. Apparatus and results

Fig. 1 shows a photograph of the first direct detector, which consisted of four 28 mm by 28 mm APDs [3] that surrounded the neutron beam. To provide a continuous monitor of the energy calibration, an ^{55}Fe source [12] was mounted on the detector assembly. The APD signal was sent to a preamplifier [13], followed by an amplifier set for a 3 μs shaping time constant. The output of the shaping amplifier was registered by a multi-channel analyzer (MCA) [14]. The APD was operated at a bias of 1346 V (≈ 45 V below breakdown) in the bore of the magnet employed for the radiative decay experiment. We observed the response of the APD to the 5.9 keV X-rays for magnetic fields between 0 and 4.6 T. As the magnetic field was increased, a portion of the peak was displaced to decreased photoelectron yield. At the maximum field of 4.6 T, the yield for this displaced portion was an order of magnitude lower than that of the

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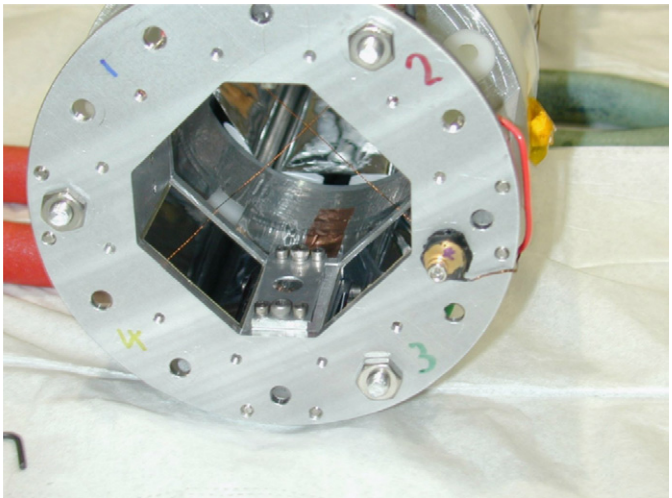

Fig. 1. First version of the direct detector, in which the APDs were in the perpendicular configuration. The neutron beam passed through the center of the octagonal structure and the magnetic field was parallel to the beam. At the bottom of the photograph, the mount for the ^{55}Fe source can be seen.

zero-field peak. These effects were only observed for the perpendicular configuration.

To study these effects further, we carried out experiments in another magnet, in which we also varied the APDs temperature between 77 and 250 K. A single APD was mounted in the perpendicular configuration and illuminated by an ^{55}Fe source that was located 37 mm from the APD and attenuated with thin aluminum. Fig. 2 shows the response of the APD to the 5.9 keV X-rays for magnetic fields between 0 and 4.6 T; the behavior observed was the same as had been seen in the magnet for the radiative decay experiment. The relative standard uncertainty and homogeneity in the field strength are less than 5%. The temperature was measured using a thin film resistance cryogenic temperature sensor located near the APD, with a standard uncertainty and stability of 1 °C.

Because such effects had not been reported previously in room temperature experiments, we repeated these studies at higher temperatures. Fig. 3 shows the APD response to 5.9 keV X-rays from an ^{55}Fe source at temperatures of 77, 113, 143, 193, and 250 K. The APD bias voltage was adjusted so that the undisplaced peak remained at about the same channel on the multichannel analyzer. Tests were also performed with an attenuated ^{241}Am source, which produces X-rays between 10 and 35 keV that yielded a broad peak in the response from the APD with a maximum at $\approx$20 keV. Fig. 4 shows the APD response to the ^{241}Am source at temperatures of 77, 140, 190, and 250 K. In Figs. 3 and 4 the APD operating voltage for each temperature is shown in each plot. At 77 K, the effect of increasing the field from 0 to 4.6 T is similar to that observed for decreasing the temperature from 250 to 77 K at a fixed 4.6 T magnetic field. These data explain why we observed magnetic field effects at 77 K that had not been observed in prior studies at room temperature.

The clear breakup of the peak for the ^{55}Fe source indicates that a portion of the detected X-rays is suffering a reduction in collection efficiency for the photoelectrons produced. As the penetration depth of X-rays varies with energy, we employed X-ray fluorescence from aluminum to study the magnetic field effects for 1.5 keV X-rays. Whereas 5.9 keV X-rays penetrate the entire active region of the APD, 90% of 1.5 keV X-rays are absorbed

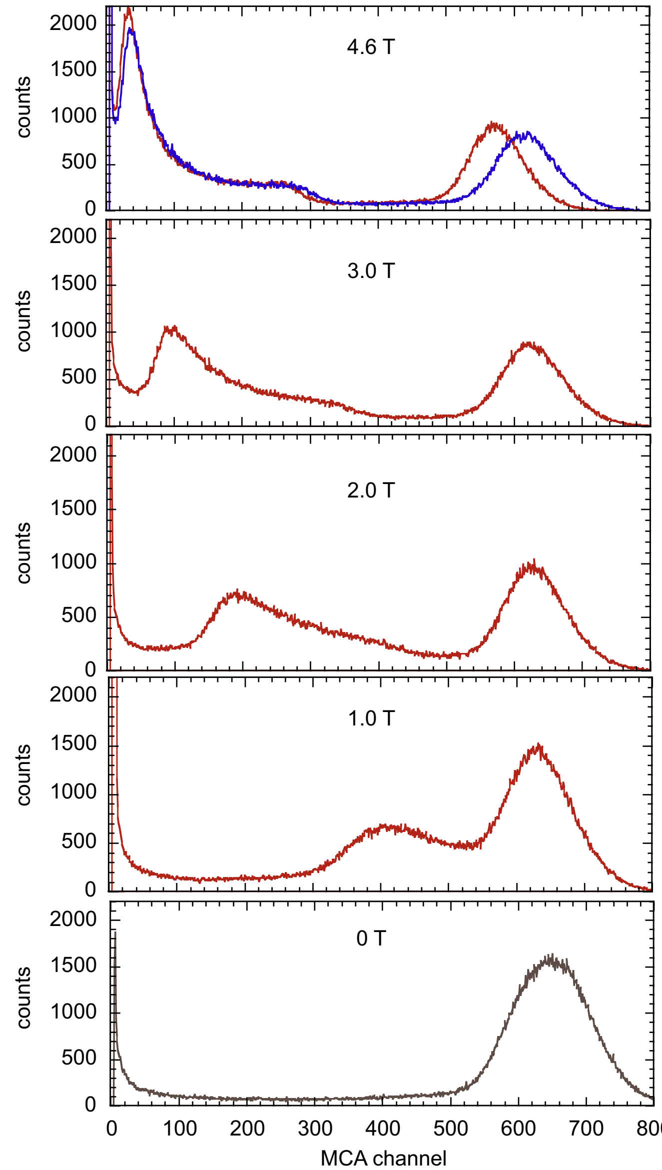

Fig. 2. Response of the APD in the perpendicular configuration to 5.9 keV X-rays from an ^{55}Fe source, for magnetic fields of 0, 1.0, 2.0, 3.0, and 4.6 T, at a temperature of 77 K. Due to a small temperature drift the gain of the APD varied slightly during these studies; we show the 4.6 T results for data taken at the beginning (red) and end (blue) of the series. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in the first 20 μm of the APD. To obtain X-ray fluorescence with a minimum of 5.9 keV X-rays, we employed a small block located 5 mm in front of the ^{55}Fe source to prevent the 5.9 keV X-rays from directly reaching the APD. X-rays from the source that passed around the block were allowed to reach aluminum that was located close to the APD. For this scheme, the height of the 1.5 keV peak was nearly an order of magnitude higher than that of the 5.9 keV peak. For this test, the source was only covered with 0.005 mm thick polyimide, so as to maximize the relatively weak fluorescence. The results are shown in Fig. 5 for a temperature of 78 K, and indicate that the APD response for almost all of the 1.5 keV X-rays are affected by the magnetic field. The magnitude of the displacement of the peak for a given field is comparable

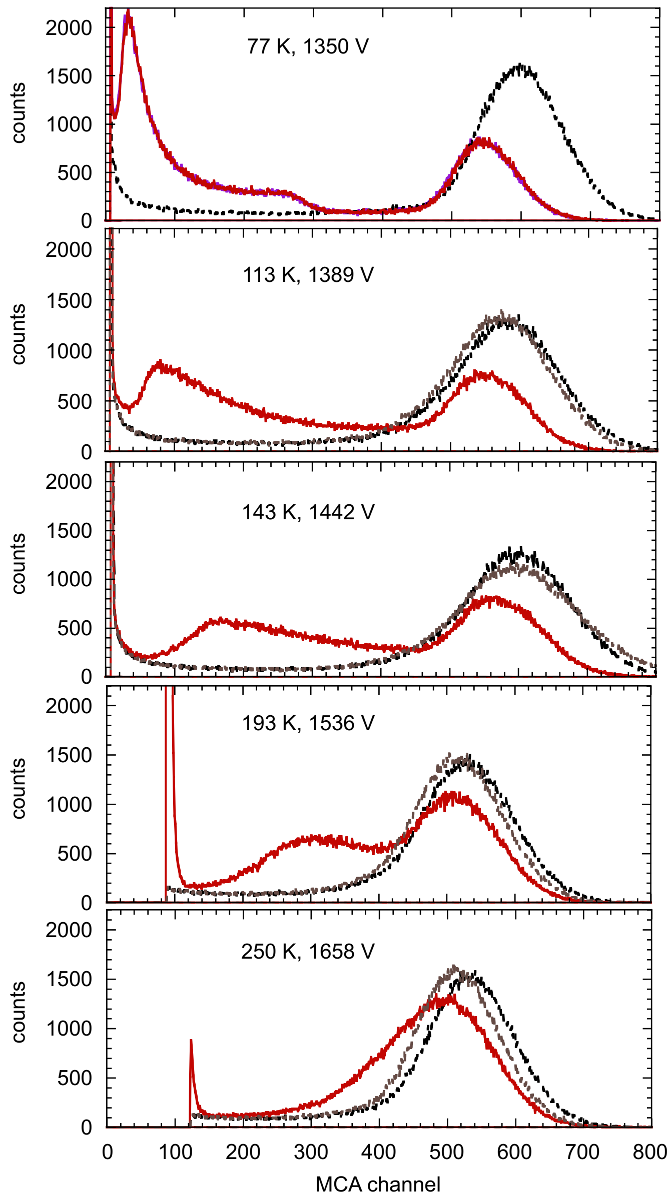

Fig. 3. Response of an APD in the perpendicular configuration to 5.9 keV X-rays from an ^{55}Fe source in a magnetic field of 4.6 T, for temperatures of 77, 113, 143, 193 and 250 K. For each temperature scans at 0 T were taken before (black, dotted line) and after (brown, dotted line) the scan at 4.6 T (red, solid line). The small difference between these two scans at 0 T is due to drift of the APDs temperature. At 193 and 250 K the use of a thermometer introduced noise on the APD signal, resulting in increased thresholds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

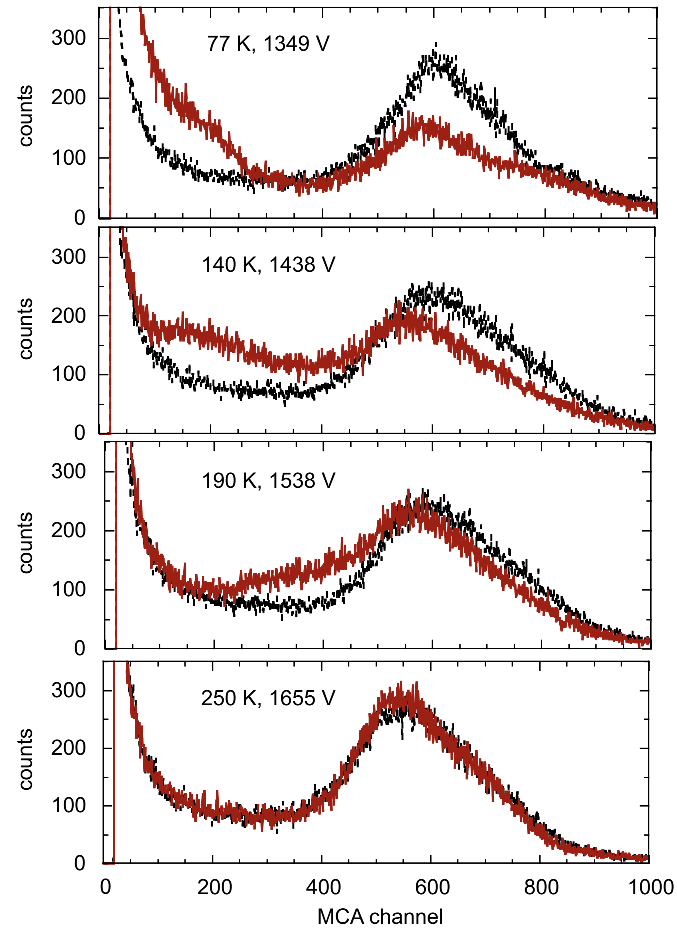

Fig. 4. Response of an APD to an ^{241}Am source in a magnetic field of 4.6 T, for the perpendicular configuration, for temperatures of 77, 140, 190 and 250 K (red, solid lines). The black, dotted lines show the response at 0 T. The maximum response of the APD to the ^{241}Am X-rays was at $\approx$20 keV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to the displacement observed for the affected portion of the ^{55}Fe peak.

3. Discussion and conclusions

To interpret the breakup of the peak for the ^{55}Fe data, we first checked that the total number of counts was constant. For a few fields this was not the case, but the apparent increased rate was found to be due to noise from the magnet power supply that caused the real time required for the scan to be substantially longer than the live time. For the data shown in Fig. 2 this problem is only relevant to the 1.0 T data. For seven scans between 2 and 4.6 T as well as one at 0 T, the real time was 1.03 ± 0.01 times the live time. For this group, the total number of counts was constant to within $\pm 1\%$. Hence we conclude that the photoelectron yield is different for a subset of the detected X-rays. The X-rays for which this could be relevant are those absorbed in the drift region of the APD. Fig. 6 shows the typical construction of the APDs employed in these studies. Whereas photoelectrons produced in the depletion region are swiftly accelerated across the junction, those produced in the drift region do not immediately see a strong electric field. Whereas motion towards the depletion region would be unaffected by a magnetic field normal to the APD surface, this motion would be significantly affected by a magnetic field in the plane of the APD surface. This hypothesis is supported by the 1.5 keV X-ray results, as these X-rays would be almost entirely absorbed in the drift region. For the ^{55}Fe X-rays we expect that 57% of the X-rays that would be absorbed somewhere within the active region of the APD are absorbed in the drift region, which was 19 μm for the particular APD tested. We find that the ratio of the number of counts in the displaced peak to the total number of counts is consistent with this value.

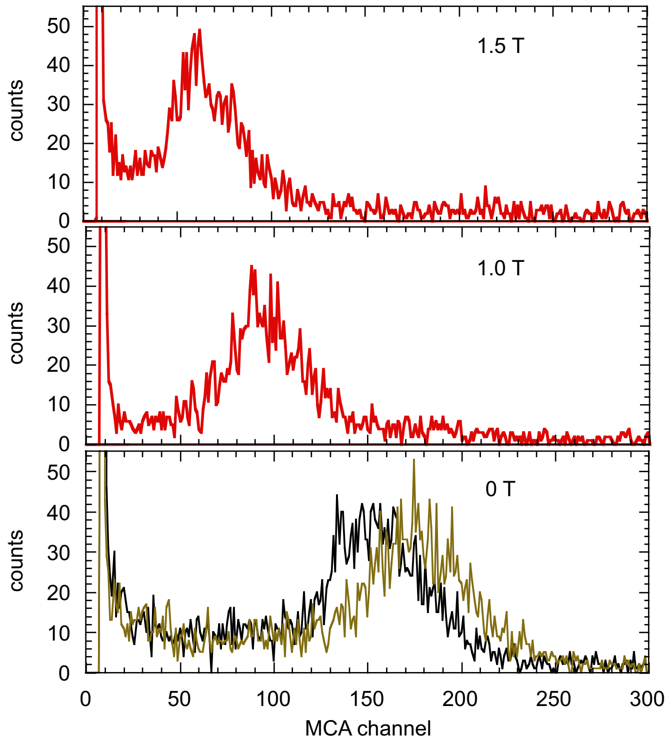

Fig. 5. Response of an APD at 78 K to 1.5 keV aluminum X-ray fluorescence, for magnetic fields of 0, 1.0, and 1.5 T, in the perpendicular configuration. Scans shown for 0 T taken at the beginning (black) and end (brown) of the series differ due to slight drift of the APDs temperature. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

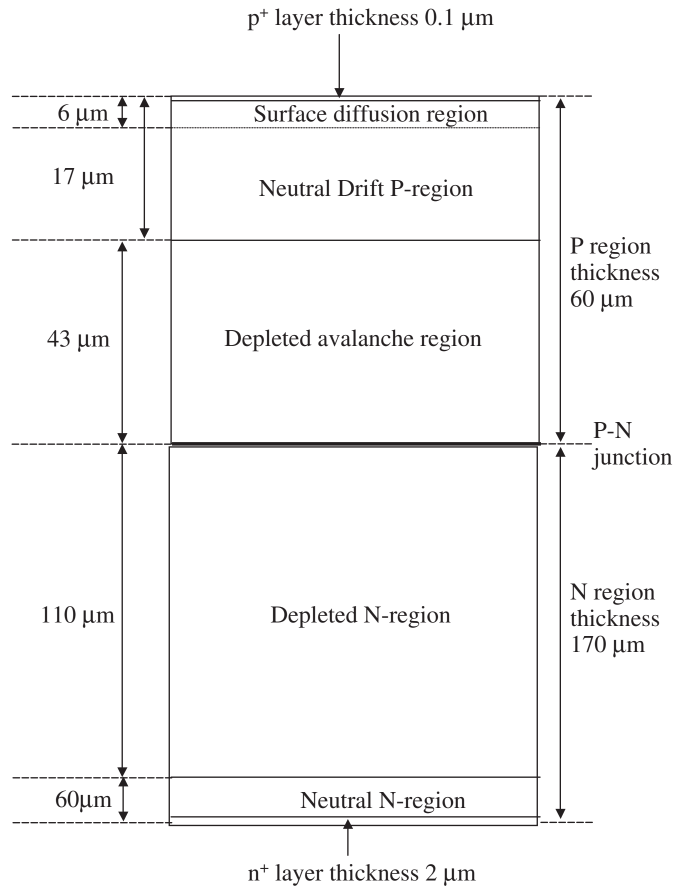

Fig. 6. Schematic diagram of the typical construction of the APDs employed in this study. X-rays absorbed in the neutral drift p-region produced photoelectrons that do not experience a strong electric field until they reach the depletion region.

We have limited this report to the significant effects observed in the perpendicular configuration. For the actual radiative decay experiment, which will be described in future publication, we operated three APDs in the parallel configuration in a 4.6 T magnetic field at a temperature of 77 K. An ^{55}Fe source was employed for a continuous calibration of the APD response. In this case, we observed only a small (less than 10%) decrease in the location of the peak from the 5.9 keV X-rays, but also a decrease of up to nearly a factor of two in the width of the peak. The small shift and the degree of improvement in the resolution varied between the three APDs.

In summary, we have shown that a strong magnetic field in the plane of a large area APD has a dramatic effect on the response at cryogenic temperatures. The data support the hypothesis that those X-rays that are absorbed in the drift region produce a lower yield of photoelectrons, and this yield decreases by an order of magnitude as the field is increased from 0 to 4.6 T. For a given temperature, we found that the effect of increasing the magnetic field strength was similar to the effect of lowering the temperature for a given field strength. The magnetic field effects we observed may be larger than for some other APDs due to the relatively large drift region in the APDs we employed. Whereas the data clearly indicate that the drift region is the area affected by the field, a detailed understanding of the effect of the magnetic field and temperature on the photoelectrons will require detailed modelling of the APD, which is beyond the scope of this experimental report.

Acknowledgements

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