Diamond dose rate detector testing at KURRI- A joint UK-Japan research project – 17126

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ABSTRACT

Measurements of radiation dose rates in highly active environments, such as nuclear plant decommissioning or following a nuclear disaster, is challenging due to the extreme environments encountered and restricted access. Therefore, novel radiation detector technology is required to address these challenges. One such example of a radiation detection material is diamond, as it is able to withstand and measure high radiation intensities, is chemically inert and formable into extremely small, sensitive detectors. These detectors generate small currents when exposed to radiation, and if the radiation levels are high enough this can be measured. Testing of such detectors is not possible in routine laboratories due to the requirement to have high active radiation sources. However, through a new collaboration formed through the University of Bristol- Kyoto University bilateral symposia such facilities are accessible for UK researchers at Kyoto University Research Reactor Institute. This paper presents an overview of the collaborative research project, the accessible facilities for device manufacture and testing and some early results from radiation testing of diamond detectors at KURRI.

INTRODUCTION

Bristol-Kyoto Collaboration

The collaborative research between the diamond detector research team at Bristol and researchers at KURRI stemmed from the Bristol-Kyoto Symposium. The first symposium, which is believed to have been the largest of its kind ever held in the UK, aimed to raise international awareness of Kyoto University and Bristol University, build a foundation of research collaboration for future student, faculty, and staff exchange, and promote collaboration with industry and academia built on the university partnership. The mutual interest on nuclear technology and science, including the diamond detector development was further discussed in detail at the second Symposium held at KURRI. Through this meeting researchers have applied for funding through several schemes, both in the UK and Japan, that has led to three collaborative visits to date with several planned for the near future. These visits are not only to use experimental equipment but also to discuss future funding opportunities and the optimum way to the advance the technology for use in Japan and the UK.

Background to Research

In March 2011, an earthquake and tsunami of unprecedented scale hit the east coast of Japan, exacting a deadly toll on coastal areas. The Fukushima Daiichi

Nuclear Power Plant (FDNPP) was severely stricken, and a catalogue of disasters caused Units 1-4 to contaminate the environment with significant atmospheric release of radioactive material [1]. Today, the reactor site is still operating under emergency regulations and whilst clean-up and decommissioning have been successfully progressing there has been little success with respect to entering and monitoring the physical state of the breached reactor cores. The primary challenge has been the lack of metrology technologies that can withstand the very high radiation intensity within the reactor vessels. There exists a pressing need to characterise the state and location of fuel-containing material at the base of the cores and to undertake retrievals of the material for suitable processing as nuclear waste, as discussed in a recent report [2].

One technology that may prove critical in the monitoring of the highly active environments at FDNPP, but also at other nuclear facilities worldwide, is diamond detectors. Diamond has had long use in particle detection in the ATLAS beam conditions monitor and compact muon solenoid experiments, evidenced by the RD42 collaboration at CERN [3]. Our collaborative team has translated this learning from CERN and over the past three years has been studying the feasibility of using diamond-based radiation detectors for civil nuclear applications. These tiny devices present a fantastic new opportunity for characterisation and monitoring of highly radioactive environments, providing a capability that doesn’t currently exist for civil nuclear operations. Diamond detectors offer several other advantages over conventional devices: they are not damaged by high radiation doses [4]; no cooling is required [5]; they show a low noise-to-signal ratio due to the large band gap [6]; and are intrinsically simple, with no p-n junction needed.

Diamond behaves as a radiation detector in a similar manner to many other semiconductor based devices [7], Figure 1. When ionising radiation interacts with the diamond detector, Compton scattering, the photoelectric effect and pair production create mobile charges. These drift to electrodes under the influence of an electric field with the measured charge being indicative of the energy deposited in the detection material by the ionising radiation. Without amplification the charge collected at the electrodes for a single incident photon is too small. However, should many particles arrive continuously then this signal becomes a significant measurable current. This ‘leakage current’ is the basis of a simple dose rate detector [8]. The current generated as a result of irradiation is proportional to the dose rate [9] and, for significant numbers of photon interactions, independent of the individual photon energy [10] or radioisotope producing the radioactive particles.

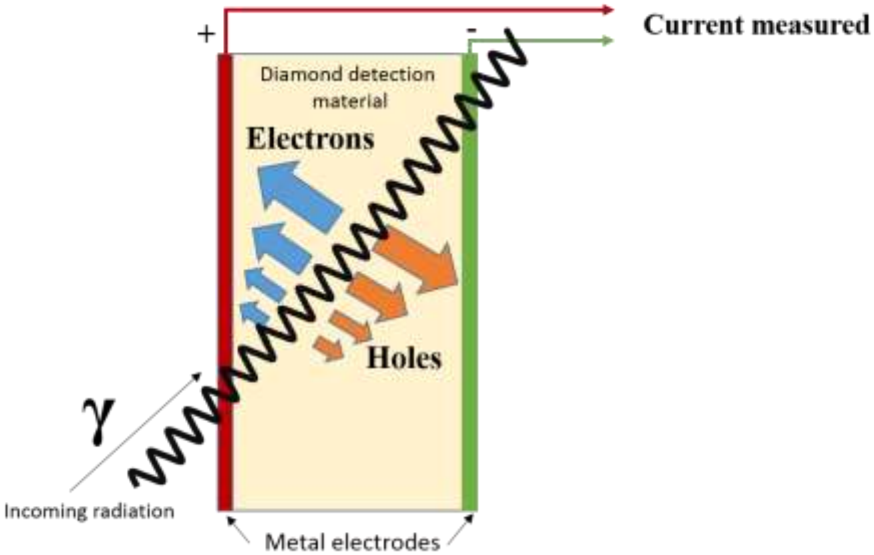

Figure 1. Principle of radiation detection in a diamond detector

METHODS

Dark current characterisation

Three commercial diamond detectors were tested, two from Cividec (C1 and C2) and one from Diamond Detectors Limited (S1). All three contain single crystal CVD diamond with dimensions of 4 mm x 4 mm x 0.5 mm and gold electrodes on either face. Firstly, an initial test of performance, especially in the characterisation of the metal coating contact, was performed. This is known as the dark current which is attributed to the small electric current that flows through a detector device when no incident particles are arriving at the device. The method for testing this involves sweeping the bias voltage from +1000 V to – 1000 V and measuring the current recorded, with the exact details the same as those described in detail in [11].

Response to irradiation

Subsequent to dark current testing the three devices were exposed to varying dose rates using a Co-60 irradiation facility at Kyoto University Research Reactor Institute (KURRI), Figure 2 This facility houses a Co-60 source in a large irradiation room that allows exposure to a large range of dose rates from approximately 0.1 Gray/hour up to >4000 Gray/hour. The diamond detectors were located on the end of a 50 metre cable run, Figure 2, and controlled using custom built software that applies a 300 V bias voltage and records current data every 50 ms. For each dose rate a background was recorded for 30 seconds before and after the source was introduced, with 60 seconds of data collected while the diamond was exposed to the source. The mean and standard deviation of the current recorded was calculated for each dose rate and background measurement. A background subtraction, between the start background and measurement current, was performed to allow the current generated by irradiation to be plotted.

Figure 2. (Left) diamond detector C1 in Co-60 irradiation facility and (right) diamond detector S1 located at the end of a 50 m cable run.

RESULTS AND DISCUSSION

The results from the dark current measurements for the three detectors are shown in Figure 3. For an ideal detector there should be very little variation in current over the whole bias voltage range. As can be seen, detector S1 follows this pattern with a total variation of approximately 12 nA. This is representative of a good metal electrical contact and is highly indicative of a reliable detector. However, the other two detectors (C1 and C2) do not exhibit this behavior. These detectors vary by several hundred nA over the bias range and are not stable, indicating insufficient detector performance for reliable dose rate measurement in a civil nuclear application. One caveat to these analyses is that the applied detector bias voltage during use may be within an apparently stable region. These results highlight that although a detector may respond in a linear fashion to dose rate, it does not necessarily make the detector suitable for use and a combination of dark current measurements and controlled dose measurements are required to determine the suitability of a detector for reliable use.

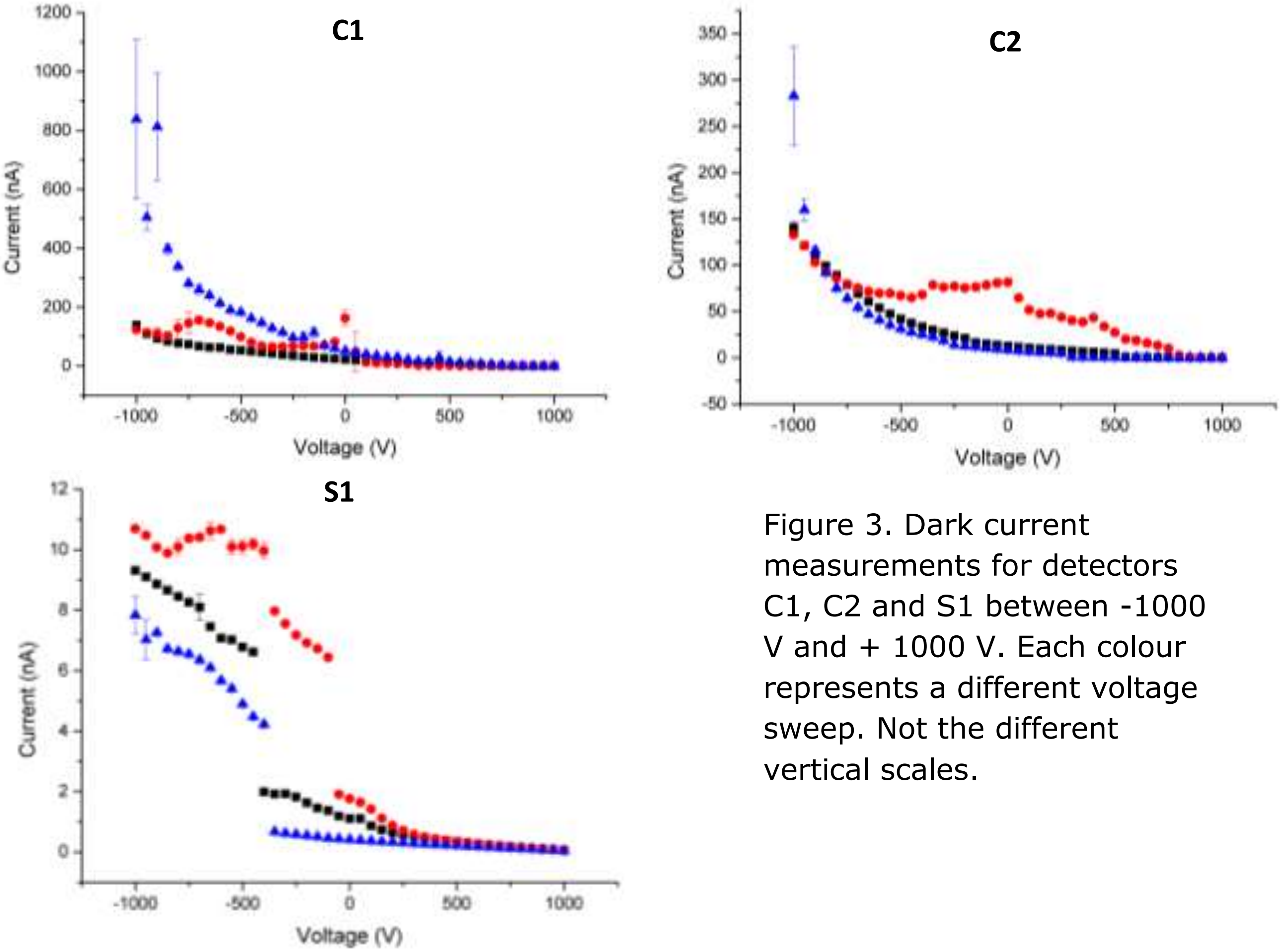

Figure 3. Dark current measurements for detectors C1, C2 and S1 between -1000 V and + 1000 V. Each colour represents a different voltage sweep. Not the different vertical scales.

The response of the three detectors to various dose rates from Co-60 are shown in Figure 4, where the data point is a mean of 60 seconds of data and the error bars are one standard deviation to give an indication of detector stability. Detector S1 shows a stable and linear response, with an increasing dose rate being proportional to an increase in current measured. This predictable response would allow the use of this detector in civil nuclear applications as a reliable calibration factor can be derived. The two Cividec detectors (C1 and C2) show a different response, especially C2. Both these detectors show deviation from the linear and so use of these detectors in the civil nuclear sector would not be possible without significant investigation to get a valid calibration. This includes variations in the error which may be due to background fluctuations or other interferences. This is especially pertinent for detector C2 as at the lower dose rates the signal current produced is negative, which is not a reliable result. This negative current is likely an artefact of the unstable background readings and thus inadequate background subtraction. Another notable observation is that even though detectors C1 and C2 are nominally the same, there are large variations in the current produced (approximately a factor of 2) for the same dose rate. Figure 5 shows the differences between background current before and after irradiation. In an ideal detector there should be very little difference between the two as the detector should be restored to a stable state after use. This is required so that an accurate measurement of current generated can be made. As can be seen, detectors C1 and C2 have some significant variations in background current due to exposure to dose. These differences will create difficulty in their use in the civil nuclear sector, as there is no clear indication of what value needs to be subtracted to calculate the signal current generated. However, the difference in background for detector S1 is small, normally below 1nA immediately after the irradiation source is removed. This background level continues to decrease and after approximately 2 minutes it is at approximately the same level as before irradiation. From the combined observations it is clear that the manufacture of a reliable diamond detector device is not straightforward, with the metal electrodes and contacts needing to be of high quality to avoid polarisation effects and ensure mechanical adhesion. It is also clear that each detector needs to be thoroughly examined and tested before any potential use in the civil nuclear sector, as each detector is likely to be individual.

Future Research Through the Bristol-Kyoto Collaboration

The results presented here show early results from the testing of three diamond detectors using the Co-60 irradiation facility at KURRI to assess their suitability for use in monitoring highly radioactive environments in the civil nuclear sector. This has led to the training of researchers at KURRI on the use of the experimental kit and one full set of experimental apparatus developed at Bristol being present at KURRI for future use. This allows any diamond detectors developed at Bristol to be routinely tested using the Co-60 facility without the need for the Bristol team to travel considerable distance. This includes detectors manufactured from both commercial single crystal diamond and diamond wafers grown at the University of Bristol CVD diamond laboratory.

Following testing using the Co-60 facility, any detectors that show promise for use, such as S1, will be tested further using the other facilities present at KURRI. This will include exposure to different energy gamma radiation such as Cs-137, to establish if the incident gamma energy has any effect on detector response. Additionally, upon restart of the Kyoto University Research Reactor (KUR) and Kyoto University Critical Assembly (KUCA) the detector response in highly active gamma and neutron/gamma mixed fields can be investigated. Together with the irradiation using Liner Accelerator (LINAC) this is essential in determining whether there is any response to neutron irradiation that may be misconstrued as gamma irradiation and also to test the detectors in environments that are not possible to achieve in the United Kingdom.

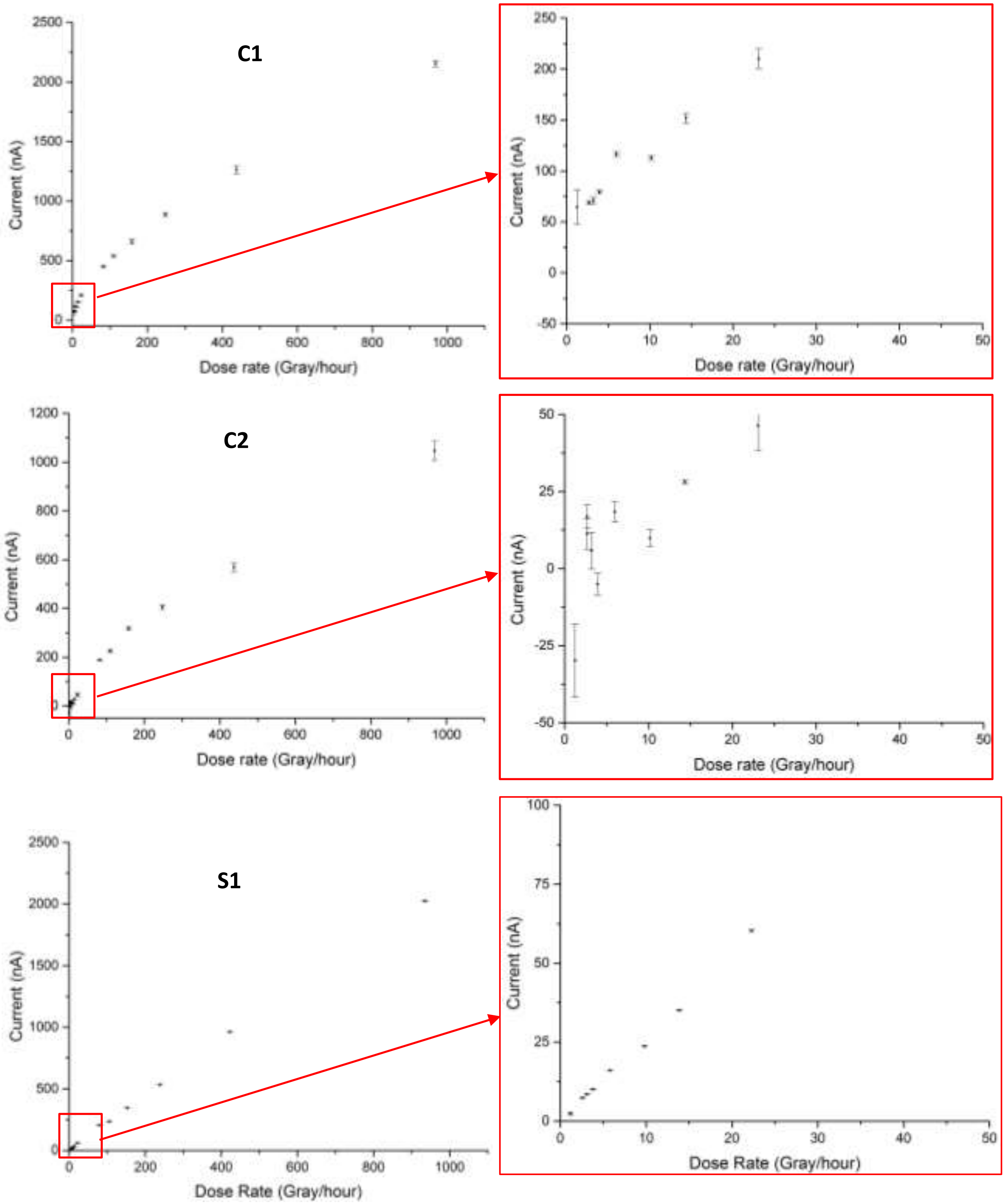

Figure 4. Detector response to Co-60 irradiation at varying dose rates for detectors C1, C2 and S1. Red box represents zoomed in area. Error bars represent one standard deviation.

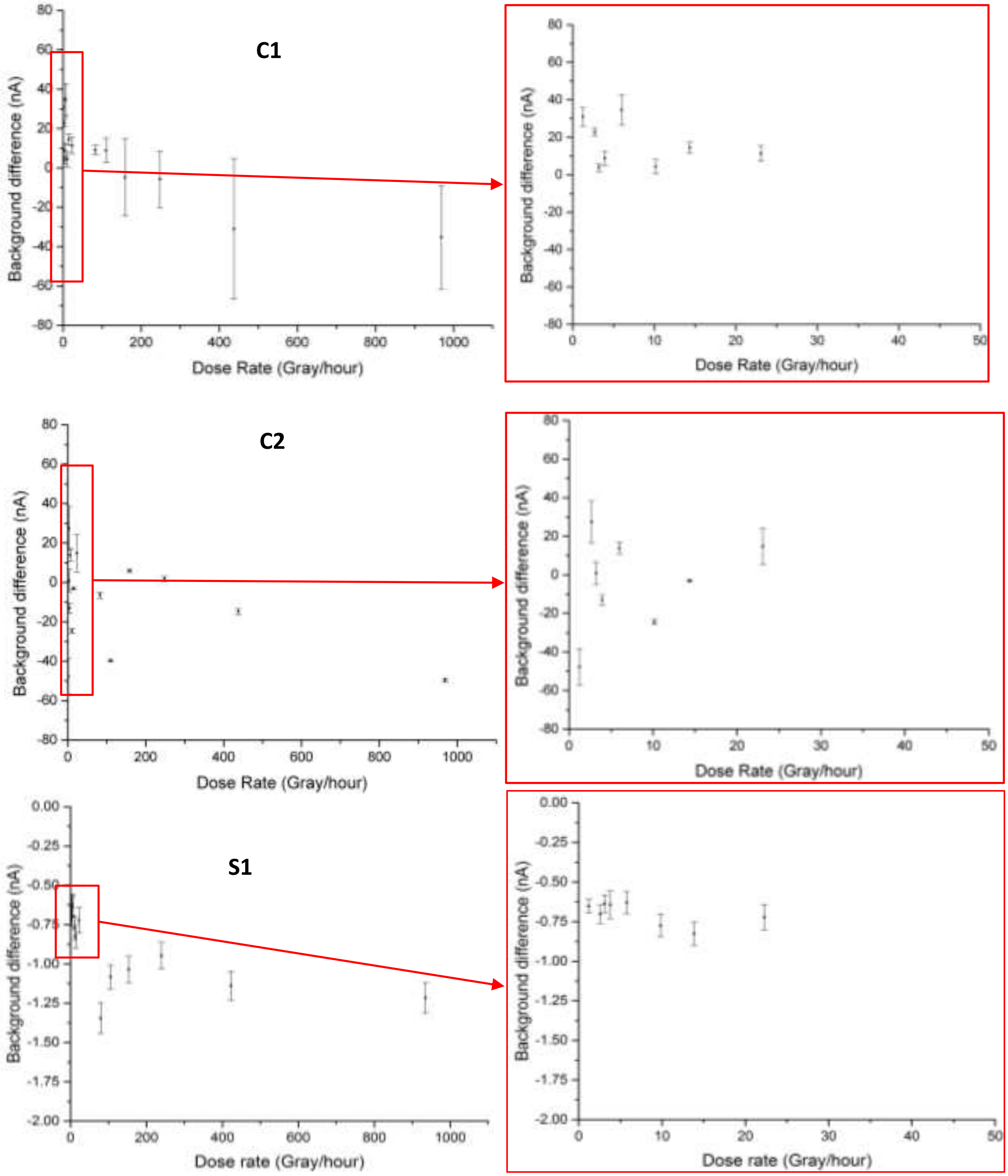

Figure 5. Difference in background measurements before and after irradiation for detectors C1, C2 and S1. Red box represents zoomed in area. Error bars represent one standard deviation.

CONCLUSIONS

This paper describes a collaboration between the University of Bristol and Kyoto University Research Reactor Institute to assess the performance of three single crystal CVD diamond detectors of different manufacturing origins. This aimed to determine their suitability to measure high radiation dose rates in civil nuclear applications. This was achieved by characterisation of the dark current response over a range of bias voltages to determine the quality of the metal contacts and connections, and then testing in a controlled radiation environment, using Co-60, to determine current response to a variety of dose rates over a large range (approximately 1-1000 Gray/hour).

It was established that the dark current measurements for detectors C1 and C2 indicate that these detectors are not stable and may not be reliably used in the civil nuclear sector. This was confirmed by the response to Co-60 irradiation which showed a non-linear response with large variations in background currents. Conversely, the dark current measurement for detector S1 suggested it is a good quality detector. This is confirmed with the linear and stable response to Co-60 irradiation over a large range (approximately 1-1000 Gray/hour) of dose rates. This stable and linear response allows a robust calibration plot to be generated so that this detector can be used to determine the dose rates present on civil nuclear sites.

The differences in detector responses highlight that not all detectors are of suitable quality for their reliable use in civil nuclear applications, with reliability absolutely essential in the nuclear industry. Therefore a method for testing and quantifying the quality of the diamond detector is required and this has been developed here, with a combination of dark current measurements and controlled exposure to Co-60 over a large range of dose rates.

Further testing of subsequent diamond detectors is planned using the fleet of facilities available at KURRI, which are not readily accessible in the UK, to ensure that the devices can be reliably used in the civil nuclear sector including at FDNPP.

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