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Journal Item

An implantation Diamond detector as a beam monitor for an intense radioactive ion beam

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Abstract. We present the characterization of a Diamond detector and its response as a beam rate monitor with full stopping of radioactive ion beams of high intensity. The detector has been implemented in the VAMOS focal plane at GANIL and utilised in conjunction with AGATA and MUGAST detector systems. In the present experiment, for the first time, the beam has been fully stopped, rather than being recorded by a transmission detector. The Diamond detector has been tested for use as a particle counter for monitoring a high intensity, radioactive ion beam in the study of the alpha transfer reaction ^{7}Li(^{15}O,t)^{19}Ne. The present experiment, which took place in July 2019, has used a ^{15}O radioactive beam with a high intensity of 10^{7} particles per second due to the weak reaction population and it has been measured using the VAMOS spectrometer and the AGATA and MUGAST arrays. Detailed monitoring of beam intensities in the range of $10^{6} - 10^{7}$ particles per second is particularly challenging in radioactive ion beam experiments. Thus, the chosen method involves the diamond detector due to its sub-nanosecond response time as well as its radiation hardness. The study of the alpha transfer reaction ^{7}Li(^{15}O,t)^{19}Ne will be performed to determine the radiative alpha capture rate on ^{15}O which is a key breakout route from the Hot-CNO cycle which leads to a explosive nucleosynthesis in X-ray bursts.

1. Introduction

The understanding of X-ray bursts' mechanisms on neutron star surfaces and the subsequent nucleosynthesis relies on the study of key reactions taking place on them. The surface of the neutron star is burning hydrogen into helium via the hot CNO cycle. With an increase of temperature a breakout of the cycle takes place leading to the r-process through two key reactions ^{15}O(α, γ)^{19}Ne and ^{18}Ne(α, p)^{21}Na [1].

Determining the α + ^{15}O reaction rate through the 4.033 MeV state in ^{19}Ne has been a long-standing challenge. Thus, a new measurement of the α + ^{15}O capture reaction has been performed via the indirect transfer reaction ^{7}Li(^{15}O, t)^{19}Ne. The experiment took place using the state-of-the-art set-up formed by the VAMOS spectrometer [2], MUGAST [3] silicon array and AGATA HPGe detector array [4], located at GANIL. A triple particle coincidence was achieved by the three different components of the set up coupled together for the first time, achieving a better selectivity.

Monitoring the beam was a challenge during this particular experiment due to its characteristics. Low intensity beams up to 10^5 pps can be monitored by plastic scintillators or silicon detectors. On the other hand, high intensity beams of about 10^9 pps or more are easily monitored using a current integrated faraday cup. However, for this experiment a radioactive ^{15}O beam at 10^7 pps was needed, intensity too high to use a plastic or a silicon detector and too low to be able to use a faraday cup. Thus, a new technique for monitoring this particular intensity was applied during the experiment, using a diamond detector as a beam rate monitor with full stopping of high intense radioactive ion beams.

2. Diamond detector characteristics

Diamond has the great advantage of being a semiconductor material with a band gap of 5.6 eV [5], big enough to be able to operate in room temperature conditions, and achieving a breakdown field strength of 10^7 V/cm [6]. Being a covalent solid means that diamond is composed by atoms instead of being composed for ions. Its chemical composition makes diamond a non electrical conductor. Within its properties can be highlighted its radiation hardness, very robust material with great tolerance to high particle intensities.

The high mobility and charge carrier saturation provide diamond a extremely good timing resolution, meaning short, uniform rising times $<$ 100 ps, experiencing high counting rate capability of 10^9 pps. Thus, a resolution of picoseconds is achieved, given by the high mobility of charges (e-h saturation velocity 10^7 cm/s) [7]. Timing limitations are given by the resolution of the electronics and the quality of the diamond detector [8].

The diamond detector used during the experiment is shown in figure 1. It has a size of (2x2) cm^2 and 0.5 mm thick. It was located at the focal plane of the VAMOS spectrometer. The electronics used to process the signal was a Diamond Broadband Amplifier [5], fast enough to collect the signal.

3. Diamond sample preparation

The sample used was a electronic grade polycrystalline material purchased from Diamond Detector Ltd. UK. In order to adjust the diamond detector to the set-up, a few changes were needed. First of all, the sample was cleaned using acetone, IPA, piranha solution and finally O_2 plasma Asher. The following step was the evaporation of the contacts upon the diamond. The back contact was 15nm of Cr followed by 55nm of Au and the front contact was 15nm of Cr followed by 65nm of Au.

After the contact layers were finished we proceeded to do the wirebonding. In order to fix the substrate onto the carrier we used two-part silver epoxy placing four dots at the corners of the carrier and then aligning it. Secondly, a small wire loop was prepared and, placing one dot of epoxy on the front corner of the substrate and another one on the carrier contact, placed the wire loop into the two dots. Finally, the entire carrier was baked with substrate at 375 K for 2 hours.

4. Time performance test

Two different time response tests were done with a triple α source (Am-Cm-Pu) at University of York. The first test was performed in order to make sure that the diamond sample was in working order. The second test was performed after mounting the substrate on the new frame with the new contacts. These tests confirmed that the detector was working fine. For the performance test we located the detector and the α source inside a vacuum chamber. The distance between the source and the detector was 15mm.

We could also measure the shaping time and the rise time. A CAEN Desktop Digitizer model DT5730 was used in order to process the signal and record a copy of the data.

Figure 1. Diamond detector frame and substrate. The board was mounted on the movable part of the VAMOS focal plane. The contact junctions were done using silver epoxy. The total size of the boar is 3.45 x 2.20 cm^2.

A third test was performed with a Cf-202 source once the diamond detector was properly located on the VAMOS focal plane. This test allowed us to ensure that the electronics was working and we also could adjust the threshold in order to avoid noise and get a clean signal of the pulses.

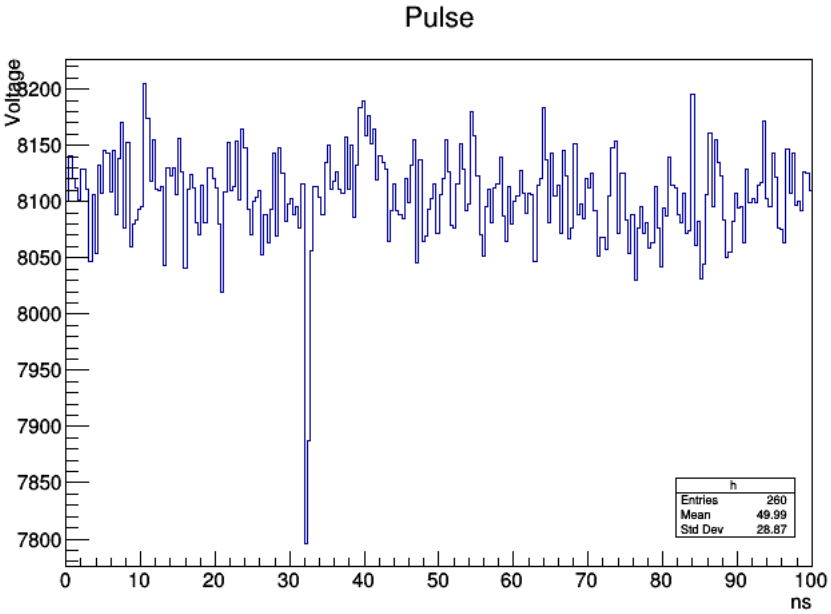

Figure 2. Time response of the diamond detector. Units of voltage in (mV) and units of time in (ns). A single pulse is shown on the image, corresponding to one single alpha particle signal. The very fast response is noticeable on the spectrum. A shaping time of about 2 ns can be appreciated.

The electronics used included a diamond broadband amplifier DBA-IV connected to the detector, to a power supply (+12 V) for making the detector work and biased with 400 V. In figure 2 a pulse obtained during the test is shown. It is noticeable how fast the detector is, having a shaping time of around 2-3ns. We used two different types of electronics: the DBA-IV and also a Diamond Charge Amplifier CSA1 purchased from CIVIDEC instrumentation. With the CSA1 we only got a shaping time of around 9ns whereas with the other we had better shaping time (of about 3ns). The impedance matching of the detector to the electronics was not optimised. The performance was good enough for the test we wanted to perform, so we did not make any particular effort on optimising it. In our case the CSA1 amplifier was not adequate thus, during the experiment we used the DBA-IV electronics.

During the tests we concluded that for the aim of monitoring the beam on the focal plane the diamond detector was a good solution that was worth trying, due to its extremely fast timing resolution and its characteristic radiation hardness.

5. Implementing the diamond counter on the VAMOS focal plane

The diamond detector was mounted on the movable mechanism of the VAMOS spectrometer focal plane, allowing us to locate it in the right position once the magnetic rigidity was selected to focus the 8^+ charged state of the beam on the detector. The diamond was located directly to stop the non-reacted beam. Stopping the beam on the detector allowed us to monitor it by counting the particles impacting on the diamond detector. If the beam position does not change, the count rate should scale with the beam intensity. If the beam slightly moves, the detector rate is reduced as the beam is no longer centered on the diamond detector. If the beam switches off, the detector rate drops. In figure 3 we can see the signal of the diamond detector. It is largely constant around 7500 s^{-1} and it drops to zero at around 06:53 where the beam was stopped. This is a very nice way to monitor our beam, seeing the signal and being able to graphically determine the amount of time where the beam was not available. Instabilities on the beam intensity were also monitored during the experiment.

Unfortunately we experienced some limitations during the experiment. Working with a radioactive beam such as ^{15}O means that the beam production and optimization is not straightforward and is the reason why the beam spot ended up being too big to cover with the detector. During the experiment we also needed to move the beam to the right of the centre of the detector for technical reasons. only a percentage of the full beam signal was detected, although we need to analyse the data to give a certain value. Further information will be given in later publications. Between the limitations of the detector performance in terms of time resolution, the electronics is the main one, as it has to process a very fast signal. We used Diamond Broadband Amplifiers (DBA-IV) [5] signal processors.

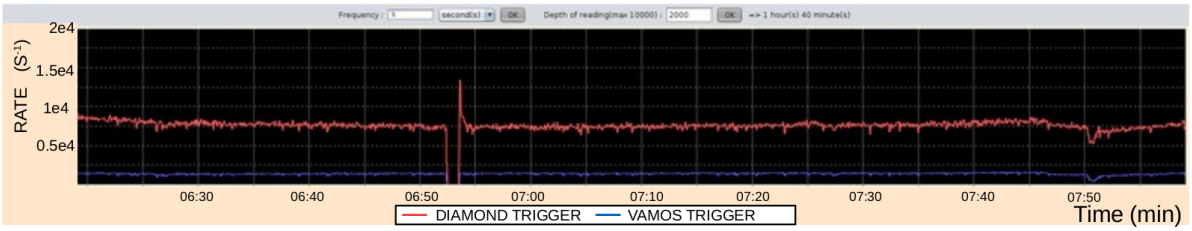

Figure 3. Online graphic monitor of the diamond detector used during the experiment. Trigger rate (y-axis) units in s^{-1} and time (x-axis) units in minutes. A constant signal is shown, only perturbed by a few minutes' cut. This cut is caused by a beam loss in chamber.

6. Conclusions

For the first time a diamond detector was located to fully stop a radioactive ion beam with a high intensity of 10^7 pps, proving that this technique could easily be implemented on set-ups such as the one used during this experiment. Further improvements on the design have to be done, such as an increase on the size of the diamond, necessary to cover the full beam spot that these particular heavy-ion radioactive beams are characterized by. However, this first test implementing the diamond detector on the set-up has proved to be a very good option to consider.

Monitoring the beam counting its particles with this technique is promising. As part of a future project for monitoring high-intense, radioactive beams an investment on a 3cm x 10cm diamond detector array for position sensitivity in beam monitoring and normalisation is proposed.

In conclusion, using a diamond detector as a beam monitor has been successful and it seems a promising technique for both monitoring and normalising high intense radioactive ion beams.

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