Diamond detector for high rate monitors of fast neutrons beams

L. Giacomelli, M. Rebai, E. Perelli Cippo, M. Tardocchi, A. Fazzi, C. Andreani, A. Pietropaolo, C. D. Frost, N. Rhodes, E. Schooneveld, and G. Gorini

Citation: AIP Conference Proceedings **1442**, 305 (2012); doi: 10.1063/1.4706884
View online: http://dx.doi.org/10.1063/1.4706884
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1442?ver=pdfcov
Published by the AIP Publishing

Diamond detector for high rate monitors of fast neutrons beams

L.Giacomelli[a], M.Rebai[a], E.Perelli Cippo[a], M.Tardocchi[a], A.Fazzi[b], C.Andreani[c], A.Pietropaolo[c], C.D.Frost[d], N.Rhodes[d], E.Schooneveld[d] and G.Gorini[a]

[a]*Dipartimento di Fisica, Università degli Studi di Milano-Bicocca, and Istituto di Fisica del Plasma, Associazione EURATOM-ENEA-CNR, Milano, Italy*
[b]*Energy Department, Politecnico di Milano, Milano, Italy*
[c]*Dipartimento di Fisica, Centro NAST, Università degli Studi di Roma Tor Vergata, Roma, Italy*
[d]*STFC, ISIS facility, Rutherford Appleton Laboratory, Chilton Didcot Oxfordshire, United Kingdom*

Abstract. A fast neutron detection system suitable for high rate measurements is presented. The detector is based on a commercial high purity single crystal diamond (SDD) coupled to a fast digital data acquisition system. The detector was tested at the ISIS pulsed spallation neutron source. The SDD event signal was digitized at 1 GHz to reconstruct the deposited energy (pulse amplitude) and neutron arrival time; the event time of flight (ToF) was obtained relative to the recorded proton beam signal t_0. Fast acquisition is needed since the peak count rate is very high (~800 kHz) due to the pulsed structure of the neutron beam. Measurements at ISIS indicate that three characteristics regions exist in the biparametric spectrum: i) background gamma events of low pulse amplitudes; ii) low pulse amplitude neutron events in the energy range E_{dep} = 1.5-7 MeV ascribed to neutron elastic scattering on ^{12}C; iii) large pulse amplitude neutron events with E_n > 7 MeV ascribed to $^{12}C(n,\alpha)^9Be$ and $^{12}C(n,n')3\alpha$.

Keywords: Fast diamond neutron detector, digitized pulse amplitude and ToF measurements, high-energy neutron beam monitor, neutron-gamma energy discrimination.
PACS: 28.50.Dr; 29.27.Fh; 29.30.Hs; 29.40.Wk; 81.05.ug.

INTRODUCTION

High-energy neutron beams can be use to induce and control the neutron chain reaction in sub-critical fission reactor assembly [1]. The neutron beam has to feature energies > 10 MeV to exploit the neutron fission cross sections of the fuel isotopes and of the fission products. Monitoring the incoming neutron beam is a key factor to control and optimize the fission process as it is in more general neutron beam-target experiments.

Another application where the neutron beam fluence and energy need to be monitored is the irradiation of electronic microchips for accelerated experiments on neutron induced single event effects (SEE) [2]. To this aim a new irradiation beam line with neutron energies up to $E_{\mathrm{n}} \approx 800$ MeV is being built at the ISIS spallation neutron source [3]. The microchip dimensions call for small size fast neutron flux monitors such as a single crystal diamond detector (SDD) recently tested on the ROTAX beam

Fusion for Neutrons and Subcritical Nuclear Fission
AIP Conf. Proc. 1442, 305-310 (2012); doi: 10.1063/1.4706884

line at the ISIS facility (UK) [4]. The paper reports on the results of the measurement campaign.

EXPERIMENTAL

At ISIS, neutrons are produced by a double bunch structured proton beam of 800 MeV and ≈ 200 μA average current on a Ta-W target delivering about 30 neutrons / proton at 50 Hz repetition frequency. The two proton bunches are ≈ 70 ns wide and ≈ 320 ns apart. The SDD was placed in the direct beam at a distance of 14.2 m from the 95 K methane moderator. The neutron energy (E_n) spectrum features a ~10 meV peak and a $1/E_n$ tail in the fast neutron region, resembling the atmospheric neutron flux produced by cosmic rays [5][6]. A beam chopper was used along the beam line to remove the low energy component of the neutron beam. The neutron induced SDD signals are mainly due to neutron elastic scattering and to neutron capture reactions $^{12}C(n,\alpha)^9Be$ and $^{12}C(n,n)3\alpha$ depending on E_n [7]. The capture reactions occur for neutron energies $E_n > 7$ MeV. Only the $^{12}C(n,\alpha)^9Be$ reaction allows for the full neutron energy deposition within SDD.

The SDD detector is a commercial chemical vapor deposition high purity single crystal diamond (4.6·4.6 mm^2 surface and 0.5 mm thickness, Au electrodes) purchased from Diamond Detectors Ltd. [8]. It is connected through a fast preamplifier DBAIII [9] to a multi-channel fast digitizer CAEN DT5751 [10]. The preamplifier output pulses feature rise time < 1 ns and FWHM ≈ 2.5 ns. The fast digitizer is USB-connected to a computer and has communication software for settings the acquisition parameters and for data storage. The voltage bias applied in these experiments was $V_{bias} = +400$ V. The noise level was ≈ ±6 mV and the signal offset was ≈ +30 mV. The CAEN module was used to record the SDD signal. The proton beam signal from the accelerator was recorded in a separate channel. Each signal was sampled at 1 GHz as a 6 μs long waveform. The maximum signal peak amplitude is 1 V. The SDD waveform usually contains more than one useful detection event. A Python script [11] was developed in order to analyze the signals of the SDD waveform. The waveforms were corrected for offset; for all pulses exceeding the 30 mV threshold the time of flight (t_{ToF}), peak height, and pulse amplitude Q_T (i.e., the signal area) were determined. The t_{ToF} is calculated as difference between the time of the individual signal peak in the SDD waveform and the time of the corresponding proton beam signal. The event deposited energy E_{dep} is obtained from the pulse amplitude Q_T. Observations on the biparametric (t_{ToF}, E_{dep}) spectrum were performed over a period of about 8 days.

DETECTOR STABILITY

The radiation interacting with the SDD gives rise to electrons and holes, which follow the electric field lines of intensity V_{bias} / d (d being the thickness of the SDD depletion layer), and build up the signal at the electrodes. In a SDD, the electrons generate the signal while reaching the anode at $V_{bias} = +400$ V. The radiation also gives rise to displacements in the SDD crystal that traps the charge. This induces a local electric field opposite to the one due to V_{bias}, i.e., the polarization of the diamond. To re-establish the performance, it is necessary to switch the V_{bias} off [12].

The measurement results presented here concern two data sets relative to two acquisitions of 17 h and 94 h. V_{bias} was switched on immediately before the two acquisitions started. FIGURE 1 shows the ISIS proton beam current I_p (left hand axis) and the SDD counts (right axis) due to signals with peak height exceeding 150 mV.

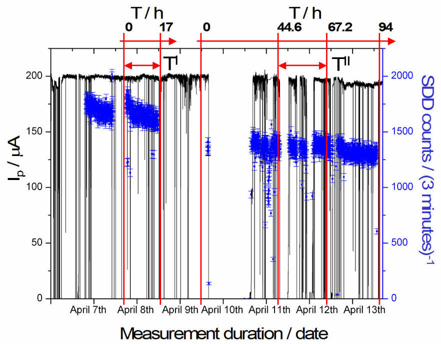

FIGURE 1. ISIS proton beam current I_p (left hand axis) and SDD counts with peak height > 150 mV (right hand axis). Two acquisition periods of 17 h and 94 h are shown on the top together with the two time intervals T^I and T^{II} considered for this study. Each SDD time bin is 3 minute long.

The ISIS proton beam current fluctuations are due to discontinuities in the accelerator operational conditions. The SDD counts decrease with time in the first few hours of operations and are nearly stable afterwards. A possible interpretation of the results would be that, after an initial reduction in sensitivity, the polarization does not affect the SDD performance. However, pulse amplitude and ToF spectra do not feature significant changes associated to the irradiation history (FIGURE 2). This suggests that the observed rate changes may be due to other causes than polarization effects that are presently not understood. Since an irradiation-dependent rate would be an undesirable feature of a beam monitor it will be further investigated in the near future.

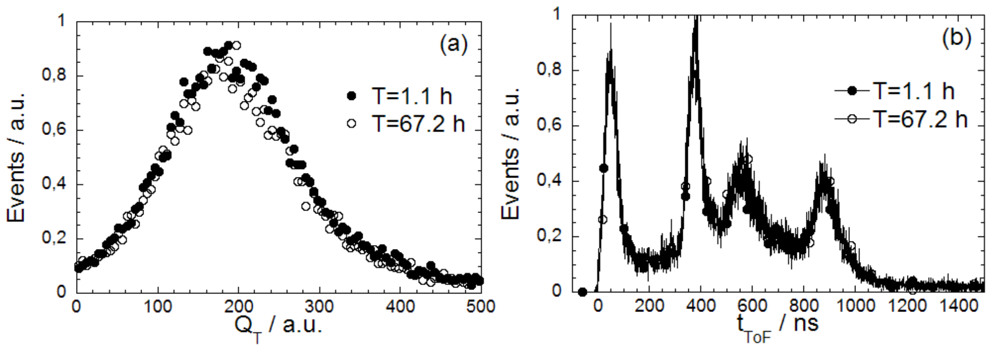

FIGURE 2. Comparison of the normalized pulse amplitude distributions Q_T (a) and of the t_{ToF} spectra (b) at $T = 1.1$ h and at $T = 67.2$ h.

BIPARAMETRIC ANALYSIS

FIGURE 3(a) shows the biparametric (t_{ToF}, E_{dep}) spectrum obtained by adding the data of the two acquisitions periods T^{I} and T^{II} shown in FIGURE 1 for a total of 114 h. The radiation from a thin foil of natural uranium placed on the detector provided a means to calibrate the energy deposited in the SDD [13][14][15].

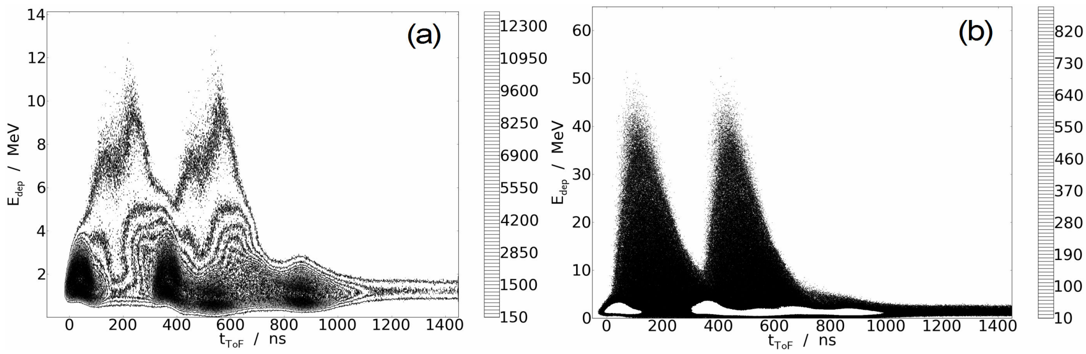

FIGURE 3. Biparametric (t_{ToF}, E_{dep}) contour plot for the 114 h long measurement at the ROTAX beam line (a). The total number of events is $9.1{\cdot}10^{7}$. (b) same as (a) but with a different grey scale showing the events with high deposited energy.

Different regions are visible in the biparametric spectrum. The peaks at $t_{\mathrm{ToF}} \approx 50$ ns and $t_{\mathrm{ToF}} \approx 370$ ns and $E_{\mathrm{dep}} \approx 1.8$ MeV are interpreted as due to γ rays from the target/moderator assembly. The remaining events are mostly due to elastic and inelastic neutron collisions/reactions with Carbon. Elastic collisions are the main contribution at low deposited energies including the peaks with $t_{\mathrm{ToF}} \approx 550$ ns and $t_{\mathrm{ToF}} \approx 870$ ns and $E_{\mathrm{dep}} \approx 1$ MeV which is associated with the elastic cross section peak at $E_{\mathrm{n}} \approx 3.5$ MeV (see FIGURE 4).

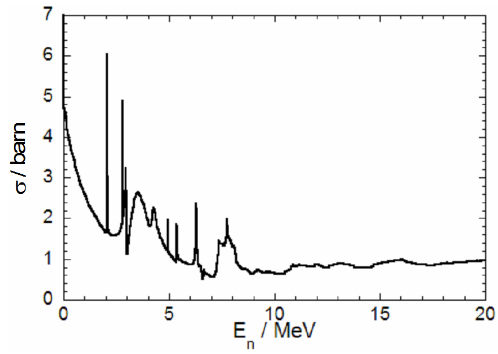

FIGURE 4. Cross section values for neutron elastic scattering on Carbon [7].

The neutron events with t_{ToF} > 1000 ns involve multiple scattering along the beam line collimator before reaching SDD or they are events related to the activation of the detector itself. FIGURE 5 shows the projections of the data in FIGURE 3(a) along the t_{ToF} (a) and E_{dep} (b) axes. In FIGURE 5(a), the double peaks due to prompt γ's (≈ 70 ns wide) and 3.5 MeV neutrons are clearly recognizable. The log scale energy distribution of the events displayed in FIGURE 5(b) shows events with energy deposition E_{dep} up to 60 MeV. Most of the events have E_{dep} < 4 MeV.

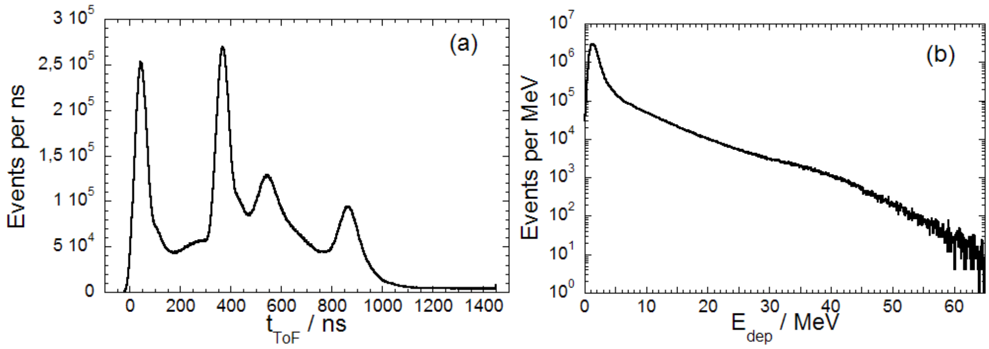

FIGURE 5. t_{ToF} (a) and E_{dep} (b, in log scale) spectra obtained as projection of the biparametric (t_{ToF}, E_{dep}) spectrum of FIGURE 3(a).

CONCLUSIONS

The SDD performance was tested at the ROTAX beam line of the ISIS spallation neutron source. SDD proved capable of detailed measurements of the time structure and energy of the incoming radiation beam. New SDD tests with a mixed (^{239}Pu, ^{241}Am, ^{244}Cm) α source in vacuum and new calculations will be performed to verify these results [13][14][16][17]. New SDD tests are also planned at the VESUVIO beam line at ISIS [18]. The spectroscopic capabilities of the SDD make it an interesting choice as a detector system for neutron experiments where high rate capability is required.

ACKNOWLEDGMENTS

This work was supported within the CNR-CCLRC Agreement No.01/9001 concerning collaboration in scientific research at the spallation neutron source ISIS. The financial support of the Consiglio Nazionale delle Ricerche in this research is hereby acknowledged.

REFERENCES

1. J. Källne *et al.*, contribution to this conference.
2. R.D. Schrimpf and D.M. Fleetwood, http://www.worldscibooks.com/engineering/5607.html.
3. http://www.isis.stfc.ac.uk/instruments/Chipir/.
4. http://www.isis.stfc.ac.uk/index.html.
5. http://www.jedec.org/standards-documents/docs/jesd-89a.
6. webstore.iec.ch/preview/infoiec62396-1%7Bed1.0%7Den.pdf.

7. http://www.nndc.bnl.gov/exfor/endf00.jsp.
8. Diamond Detector Ltd. BCMS-SCD464650A – BCM.
9. P. Moritz, "Broadband Preamplifiers for Fast Particle Detectors", GSI - Gesellschaft für Schwerionenforschung mbH, Planckstr. 1, D-64291 Darmstadt, Germany.
10. http://www.caen.it/csite/CaenProd.jsp?parent=14&idmod=632.
11. http://www.python.org/.
12. M. Angelone *et al.*, "Radiation hardness of a polycrystalline chemical-vapor-deposited diamond detector irradiated with 14 MeV neutrons", *Rev. Sci. Instrum.* **77**, (2006) 023505. G.J. Schmid *et al.*, "A neutron sensor based on single crystal CVD diamond", *Nucl. Instr. and Meth. A* **527** (2004) 554-561.
13. A. Pietropaolo *et al.*, "Fission diamond detectors for fast-neutron ToF spectroscopy", *Europhysics Letters* **94** (2011) 62001.
14. M. Rebai *et al.*, "Fission diamond detector tests at the ISIS spallation neutron source", *Nuclear Physics B* Proceedings Supplements **215**, Issue 1, (2011) 313-315.
15. http://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html.
16. A. Pietropaolo *et al.*, "Single-crystal diamond detector for time-resolved measurements of a pulsed fast-neutron beam", *Europhysics Letters* **92** (2010) 68003.
17. L. Giacomelli *et al.*, "Diamond detectors for fast neutron irradiation experiments", *Nuclear Physics B* Proceedings Supplements **215**, Issue 1, (2011) 242-246.
18. http://www.isis.stfc.ac.uk/instruments/vesuvio/.