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High-Resolution Energy and Intensity Measurements with CVD Diamond at REX-ISOLDE

Erich Griesmayer (corresponding author)**,**
Heinz Pernegger, Daniel Dobos CERN/ATLAS
Fredrik Wenander CERN/REX-ISOLDE
Julien Bergoz, Hervé Bayle Bergoz Instrumentation, France
Helmut Frais-Kolbl, Johann Leinweber Fachhochschule Wiener Neustadt, Austria
Thomas Aumeyr Royal Holloway, University of London

Abstract

A novel beam instrumentation device for the HIE-REX (High In-tensity and Energy REX) upgrade has been developed and tested at the On-Line Isotope Mass Separator ISOLDE, located at the European Laboratory for Particle Physics (CERN). This device is based on CVD diamond detector technology and is used for measuring the beam intensity, particle counting and measuring the energy spectrum of the beam. An energy resolution of 0.6% was measured at a carbon ion energy of 22.8 MeV. This corresponds to an energy spread of ± 140 keV.

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1 Introduction

A novel beam instrumentation device for REX-ISOLDE based on chemical-vapor deposition (CVD) technology has been developed and tested at CERN. This paper presents the test results of a charged-particle solid-state detector based on CVD diamond. CVD diamond detectors are used in the ATLAS experiment at the LHC collider as beam conditions monitor [1]. Amongst many other advantages, CVD diamond detectors have a high radiation tolerance and a high charge mobility.

The purpose of this test is to measure the beam intensity in the full dynamic range of REX-ISOLDE, which is a few particles per second and up to a few pA. The second goal is the precise measurement of the energy resolution for spectroscopical applications. All measurements presented in this paper are made with a carbon ion beam.

1.1 Principles of diamond detectors

In Figure 1 the basic principle of diamond as a particle detector is shown [2]. A bias voltage is applied across a diamond. The incoming ions penetrate the CVD diamond. On their path through the material, they ionise material and create free charge carriers (electrons and holes). The energy to create an electron-hole pair is 13 eV. Depending on the polarity of the bias voltage, either the electrons or holes are collected. The drift of these charges produces a signal that can be measured. For single crystal CVD (sCVD) diamond, the charges drift through the whole detector. In polycrystalline CVD (pCVD)

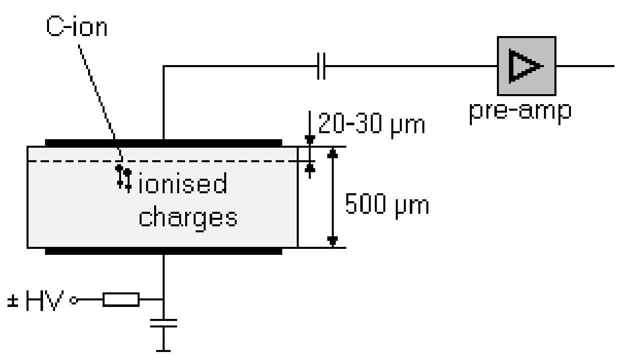

Figure 1: Basic principle of diamond as a particle detector

diamond, the drifting charges are trapped within the "charge-collection distance" (ccd), which is typically 200 μm.

In the used setup, the diamond detector has a thickness of 500 μm. Typical ISOLDE beam energies are 2-3 MeV/u. According to SRIM simulations, at these energies carbon ions penetrate the CVD diamond about 10-20 μm . The longitudinal straggling is about ± 1 μm [3].

2 Beam characteristics

The REX-ISOLDE cavities operate with an RF frequency of 101.28 MHz for beam energies up to 2.25 MeV/u and at 202.56 MHz above. The RF period of 9.87 ns defines the micro-structure of the beam. The macro-structure, i.e. the gate length, is 50 μs. The period time is variable between 10 ms and 2 s, depending on the particle type to be accelerated. During the diamond test the period was set to 40 ms. This timing structure of the REX-ISOLDE ion beam can been seen in Figure 2.

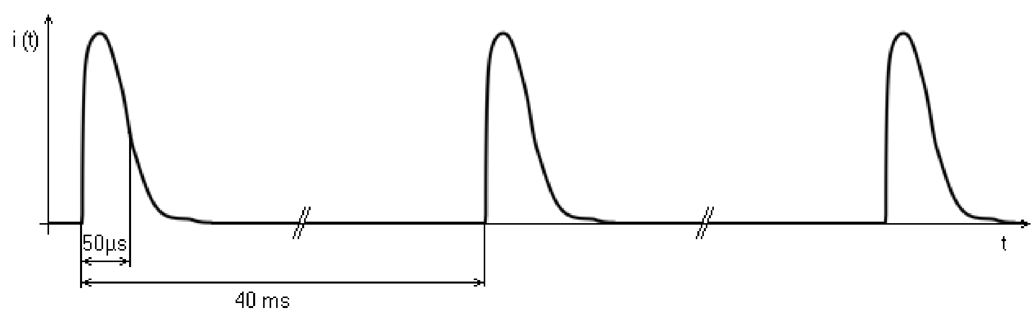

Figure 2: Timing structure of the REX-ISOLDE ion beam

For the measurements, a $^{12}C^{4+}$ beam is used. The beam energies are 1.9 MeV/u and 2.85 MeV/u, i.e. the total energy is 22.8 MeV and 34.2 MeV respectively.

3 Setup

Figure 3 shows the setup of the measurement. The Faraday cup is used to measure the incident beam intensity after the collimator, which is made of aluminium and has an aperture of 3 mm and a thickness of 1 mm.

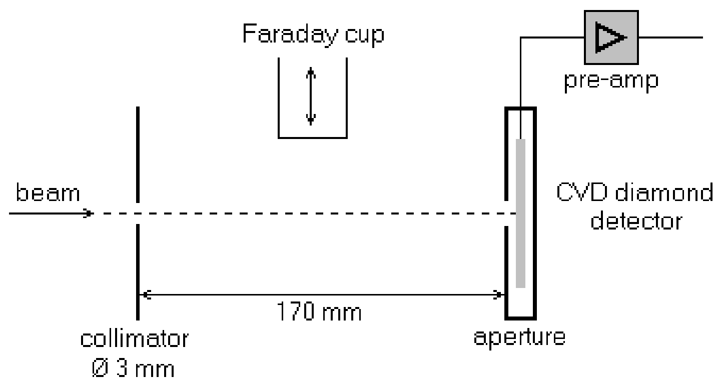

Figure 3: Setup of the diamond inside the beam line

Two different types of CVD diamond are used for the tests. The pCVD diamond measures 10×10 mm^2 and is 500 μm thick. Two 25 nm thick and 8×8 mm^2 Al electrodes are plated on the substrate top and bottom.

The sCVD diamond measures 5×5 mm^2 with a thickness of 500 μm. Two 500 nm thick Au electrodes with a diameter of 3 mm are plated on the substrate top and bottom. Both detector types have a grounded guard ring on the signal electrode side.

For the measurements, due to the difference in detector size, the aperture diameter is 5 mm for the pCVD diamond and 2 mm for the sCVD diamond.

4 Measurements

The detector pulses are preamplified with 40 dB and an analogue bandwidth of 1 GHz. Diamond has a relative permittivity of 5.7. Therefore, the capacity of the detector is 6.5 pF for the pCVD diamond and 0.7 pF for the sCVD diamond. The load resistance for the bias voltage is 1 MΩ, the load capacitance against ground is 1 nF. The DC path has 1 MΩ against ground. The input to the RF amplifier is AC coupled with 1 nF, the output is AC coupled with 100 nF.

The beam intensity measurements run in two modes. In the low intensity range of 0 - 10^6 ions/s, the particles are counted with a scaler. In the high intensity range above 10^6 ions/s, the detector current is measured with a picoammeter (see Figure 4). For the read-out as well as for data recording, a LeCroy WaveMaster 8600A sampling oscilloscope with 1 GHz bandwidth and

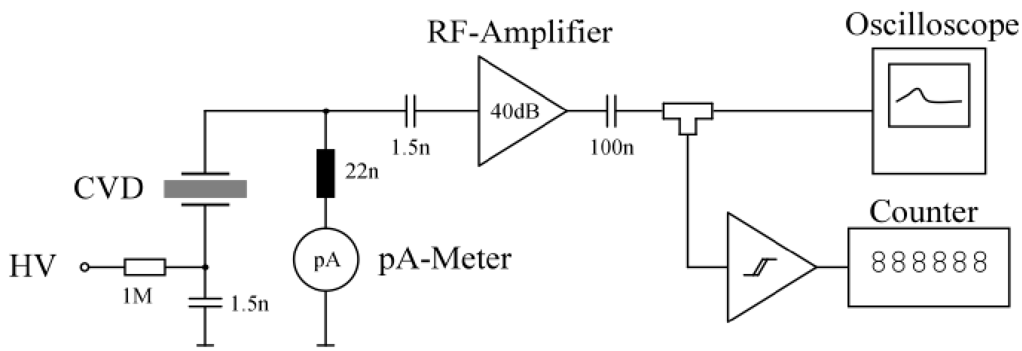

Figure 4: Setup of the measurement

a sampling rate of 10 GS/s is used. Measurements and statistical analysis are performed on-line with the oscilloscope.

5 Results

5.1 pCVD Pulses

Figure 5 shows a single ion pulse from the pCVD detector which is operated at -500 V bias. The pulse height is -16.6 mV. The FWHM width of the signal is 1.26 ns. The fall time is 0.83 ns and the rise time is 2.45 ns.

The single pulse agrees well with the response of the pCVD detector averaged over 1000 pulses. The pulse height of the average pulse is -9.18 mV with an FWHM pulse width of 2.06 ns. The leading edge is 0.70 ns and the trailing edge is 4.37 ns. This average pulse corresponds to a collected charge of 3.78 fC.

A decrease in amplitude and an increase in pulse width was observed with increasing dose deposition. This effect might be caused by charge trapping due to defects in the lattice [4].

5.2 sCVD Pulses

Figure 6 shows a single pulse from the sCVD detector which is operated at +500 V bias. There is less space charge effect with positive polarity, therefore the signals are cleaner. The pulse height is 109 mV. The FWHM width of

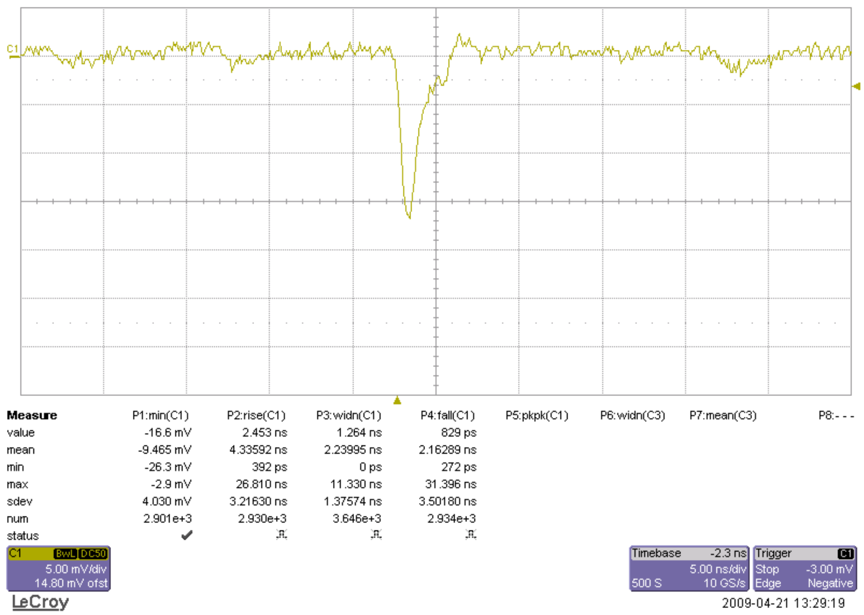

Figure 5: Single pCVD pulse for a $^{12}C^{4+}$ ion with a total energy of 34.2 MeV

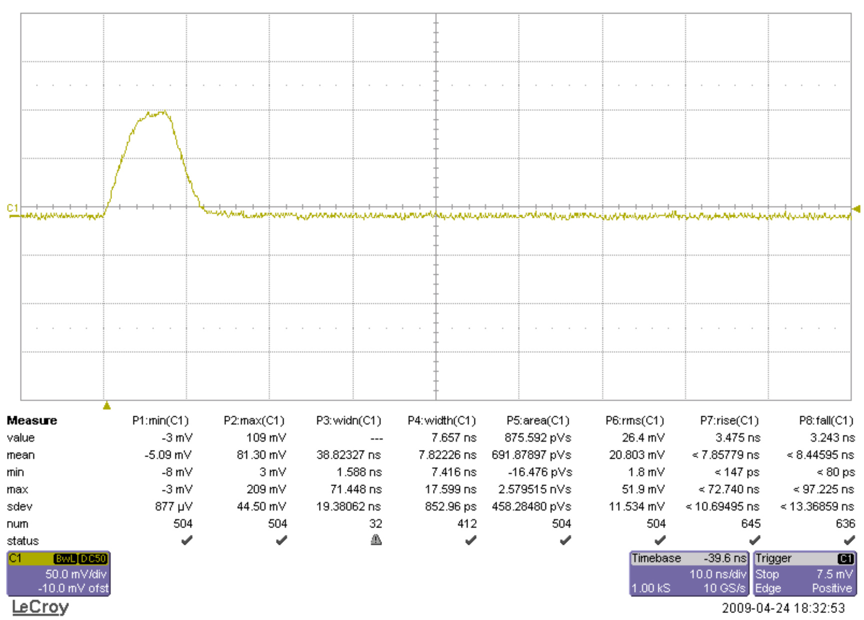

Figure 6: Single sCVD pulse for a $^{12}C^{4+}$ ion with a total energy of 34.2 MeV

the signal is 7.66 ns. The leading edge is 3.48 ns and the trailing edge is 3.24 ns.

The single pulse agrees well with the response of the sCVD detector averaged over 1000 pulses. The pulse height of the average pulse is 96.95 mV with an FWHM pulse width of 7.73 ns. The rise time is 4.38 ns and the fall time is 4.14 ns. This average pulse corresponds to a collected charge of 159.7 fC.

The pulse shape of the sCVD detector changed with increasing charge deposition in the form of higher beam intensity. A fast rise time of about 1 ns, a flat top during charge drift and a fast fall time would be expected. Figure 6 shows slow increase and decrease of the signal. This is caused by space-charge effects in the detector [4].

The leakage current of the sCVD detector was stable throughout the energy measurements.

5.3 Timing structure

The following three images show persistence traces of detector signals. Operating the scope in persistence mode superimposes multiple waveforms on the same view, with more frequent data in brighter colors than less frequent ones. The areas of the trace that have the highest population density are red, while the areas with the lowest population density are blue.

In Figure 7, the RF buckets of the REX-ISOLDE machine can be seen. The RF frequency is 101.28 MHz and the RF period is 9.87 ns. This is the so-called micro-structure of the beam. Figure 7 also shows a histogram of the signal pulse heights (see Section 5.5).

Figure 8 shows a macro-pulse from the REX-ISOLDE machine. The core of the pulse shows a width of about 50 μs, followed by a DC component. In Figure 9, the 40 ms period of the REX-ISOLDE beam is shown.

5.4 Beam intensity

The counting mode was tested with positive and negative polarities of the bias voltage. The particle counting efficiency, that is the number of detected particles compared with the incoming flux, shows big variations depending on the bias voltage polarity which could be explained by charge trapping of the pCVD which leads to a decreasing efficiency. For sCVD, using a collimator aperture of 2 mm and bias voltages of +500 V and -500 V, the

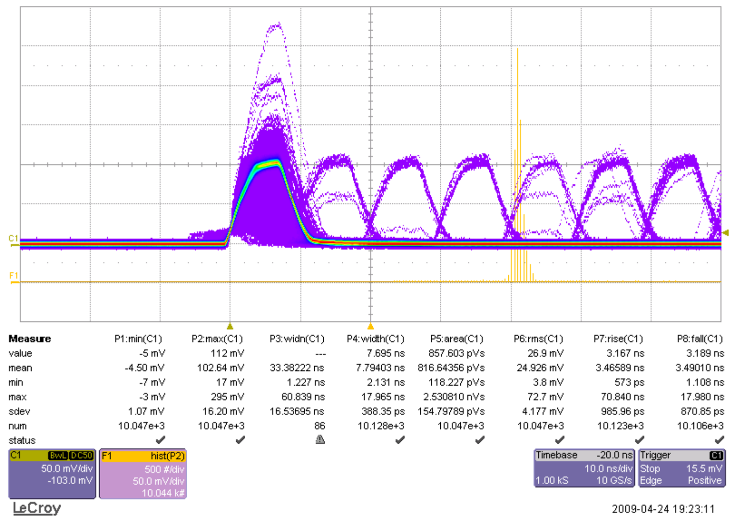

Figure 7: Persistence trace showing the filled 9.87 ns RF buckets of the REX-ISOLDE machine, which corresponds to an RF frequency is 101.28 MHz. This plot was taken with a sCVD diamond detector and a $^{12}C^{4+}$ ion beam with a total energy of 22.8 MeV.

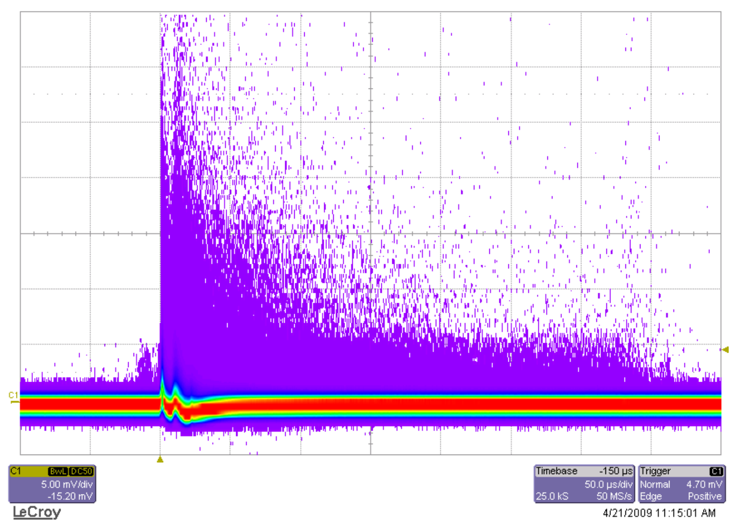

Figure 8: Persistence trace showing the time-structure of the REX-ISOLDE macro-pulse, with the main part of the beam found within the first 50-100 us, followed by a DC component for as long as the accelerating RF is on (in total 350 us). This plot was taken with a pCVD diamond detector and a $^{12}C^{4+}$ ion beam.

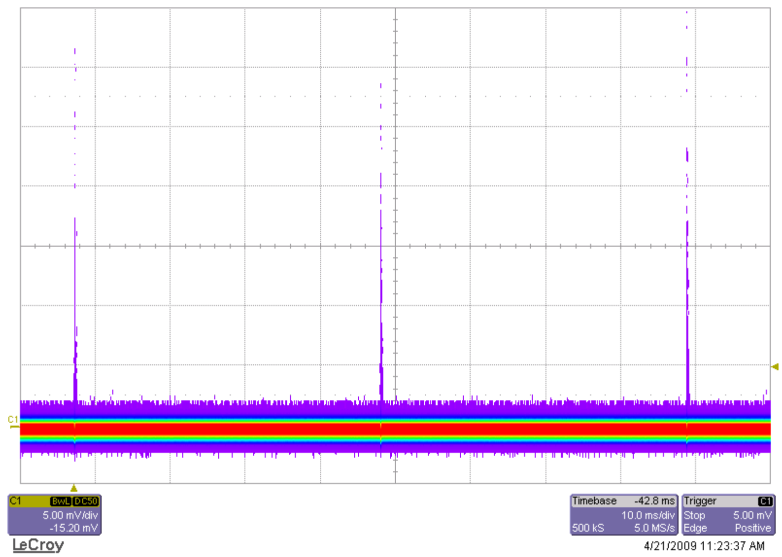

Figure 9: Persistence trace showing the 40 ms period of the REX-ISOLDE machine. This plot was taken with a pCVD diamond detector and a $^{12}C^{4+}$ ion beam with a total energy of 22.8 MeV.

counting efficiency is tested for beam intensities up to 10^4 ions/s and it shows consistent values for both polarities.

The pCVD detector shows unstable leakage currents which vary with time, bias voltage, polarity and dose, changing from some tens of pA to few nA. This effect is known, possible mitigations have to be studied. The sCVD detector was not used in current mode.

5.5 Energy resolution

The energy resolution is measured using the sCVD diamond detector operated at a bias voltage of +800 V. The beam energy is 1.9 MeV/u, which corresponds to a total energy of 22.8 MeV. The energy resolution of the $^{12}C^{4+}$ beam is shown in Figure 10. The distribution has $N = 1653$ entries.

The gaussian fit shows a mean value of 131.23 mV and a sigma of 1.46 mV. The resulting energy resolution is 1.11%. Note that this value is convoluted with the energy spread of the beam that is estimated to 0.9% FWHM. If the energy spread of the beam is deconvoluted, an energy spread of the CVD detector of 0.6% is gained. This corresponds to an energy spread of $\pm$140keV.

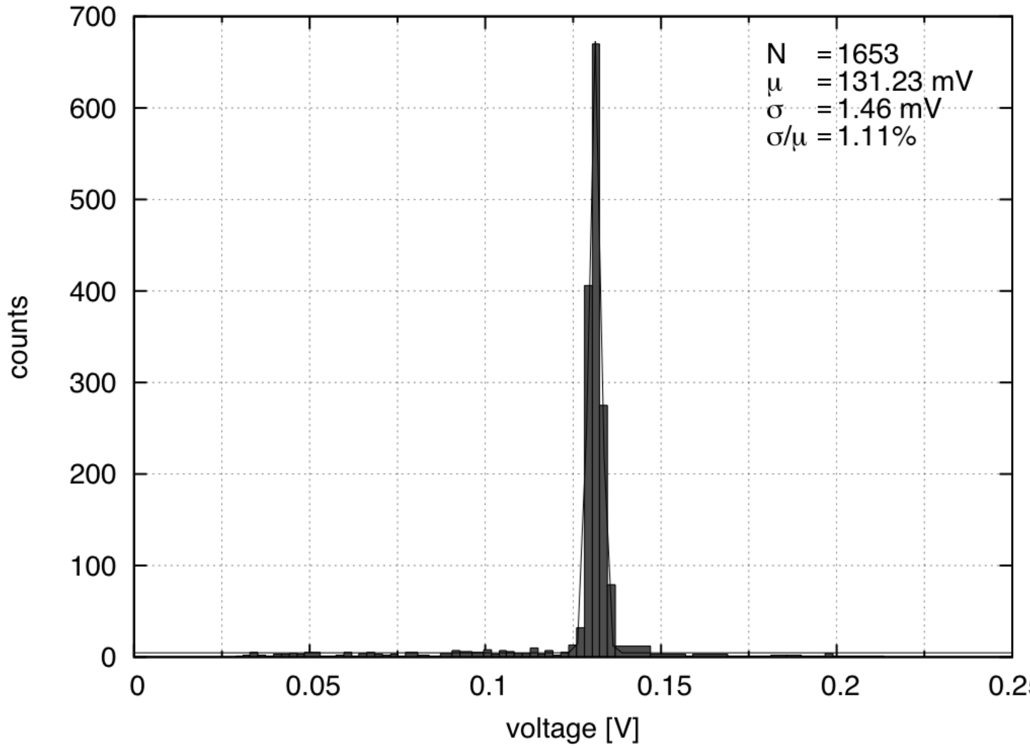

Figure 10: Energy resolution of the $^{12}C^{4+}$ beam with 1.9 MeV/u. The resulting energy resolution is 1.11%. Quantisation effects of the ADC are not compensated. This value is convoluted with the energy spread of the beam that is estimated to 0.9% FWHM. If the energy spread of the beam is deconvoluted, an energy resolution of the CVD detector of 0.6% is gaine. At a total energy of 22.8 MeV, this corresponds to an energy spread of $\pm$140 keV
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6 Conclusion

A novel beam instrumentation device for REX-ISOLDE has been tested. The beam intensity as well as the energy resolution were measured. The measurements were carried out with pCVD and sCVD diamond detectors. A carbon ion $^{12}C^{4+}$ beam was used with 1.9 MeV/u, i.e. a total energy of 22.8 MeV.

In the pCVD diamond detector the pulse height decreased with increasing dose deposition. The reason for that is charge trapping in the lattice structure of the diamond. The counting efficiency decreased with time and it also changed with the bias voltage polarity. The leakage current was not stable during irradiation, but varied from some tens of pA to a few nA.

When measuring the intensity, the sCVD diamond detector showed unstable dark current behavior during irradiation. The counting rates decreased with irradiation time and showed no dependence on the polarity of the bias voltage. The measurement of the energy distribution shows an energy spread of 1.1%, and 0.6% if the energy spread of the beam is subtracted,.

7 Acknowledgements

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References

[1] V. Cindro, E. Griesmayer, et al. The ATLAS Beam Conditions Monitor. *Journal of Instrumentation P02004*, 3, 2008.

[2] H. Pernegger, S. Roe, P. Weilhammer, V. Eremin, H. Frais-Kölbl, and E. Griesmayer. Charge-carrier properties in synthetic single-crystal diamond using the transient-current technique. *Journal of Applied Physics*, 97(7), 2005.

[3] M. Pavlovič and I. Strašík. Supporting routines for the SRIM code. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 257(1-2):601 – 604, 2007.

[4] C. Tuvè et al. Pulse height defect in pCVD and scCVD diamond based detectors. *Diamond and Related Materials*, 15(11-12):1986–1989, 2006.