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Nuclear Instruments and Methods in Physics Research Section A

Volume 754, 1 August 2014, Pages 24–27

doi:10.1016/j.nima.2014.03.061

Characterisation of scCVD diamond detectors with γ sources

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Abstract

A single-crystal CVD (Chemical Vapor Deposition) diamond detector was used to measure γ rays in order to assess its performance in terms of energy resolution and linearity. For this purpose, ^{57}Co, ^{133}Ba, ^{22}Na,^{207}Bi and ^{137}Cs γ sources were used. Electrons scattered by the backward Compton process were detected in the diamond, in coincidence with (backscattered) γs measured in a NaI detector, placed at 180^o from the CVD diamond detector with respect to the source. The resulting calibration shows a linear dependence of the charge deposited in the diamond and a resolution of about 24 keV FWHM for the energy of the incident γs between 40 keV (^{57}Co) and 477 keV (^{137}Cs), comparable with the resolution of our electronic chain.

1. Introduction

Diamond is an innovative detector with many promising properties which make it suitable for applications such as neutron detection in fusion and fission reactors. Diamond detectors are sensitive to deep UV photons, X-rays, γ-rays, electrons, α particles, charged ions and neutrons, with a dynamic range in energy spanning from 5.5 eV up to the GeV range. Since its band-gap is as wide as 5.5 eV, the dark current noise at room temperature is negligible. Therefore the detector does not require any ad hoc cooling system and can operate in a high temperature environment without loss of efficiency. Another great advantage is its compactness: a fully equipped detectors can have linear size < 1 cm. Diamond has an octahedral crystalline structure, very strongly bound. It is the crystal with the highest melting point, 3800^oK, and with the largest displacement energy, 43 eV, among the ones used for neutron detection. This makes it possible to create compact devices suitable for very high radiation environments. The recent development of synthesis processes for high-quality single-crystal homoepitaxial diamond obtained by Chemical Vapour Deposition (CVD) has resulted in considerable improvements in the performance of diamond devices for applications in many different fields. As examples, interesting results have been obtained in UV and extreme UV detection in astrophysics and

plasma physics [1] [2], minimum ionising particle detection in large accelerators [3], beam monitoring [4], dosimetry for radiology and radiotherapy [6].

scCVD diamonds are semiconductor detectors, in which the charge produced by the passage of an ionising particle in the sensitive volume is collected by means of an applied bias field E. This kind of device features a large electron mobility, 200 $\mu m^2/(Vs)$, so the charge collection is very fast. Measurements with scCVD diamonds have been performed at JET, demonstrating diamond stability and reliability during 2 years of uninterrupted operation [5]. These measurements have also shown a linear counting behaviour in perfect agreement with that of standard neutron detection methods, in particular fission chambers. A simple neutron counter, however, is not sufficient to monitor the plasma condition in a fusion reactor. A high resolution neutron spectrometer is necessary. Since neutron spectra are obtained by unfolding procedures using a response matrix of the detector, a fundamental requirement is a deep knowledge of the response function of the device.

The aim of the measurements presented in this paper was to determine the deposited energy resolution of diamond detectors and to verify the linearity of their response at low energy. Such low-energy signals can be obtained by means of γ sources.

2. Experimental set-up

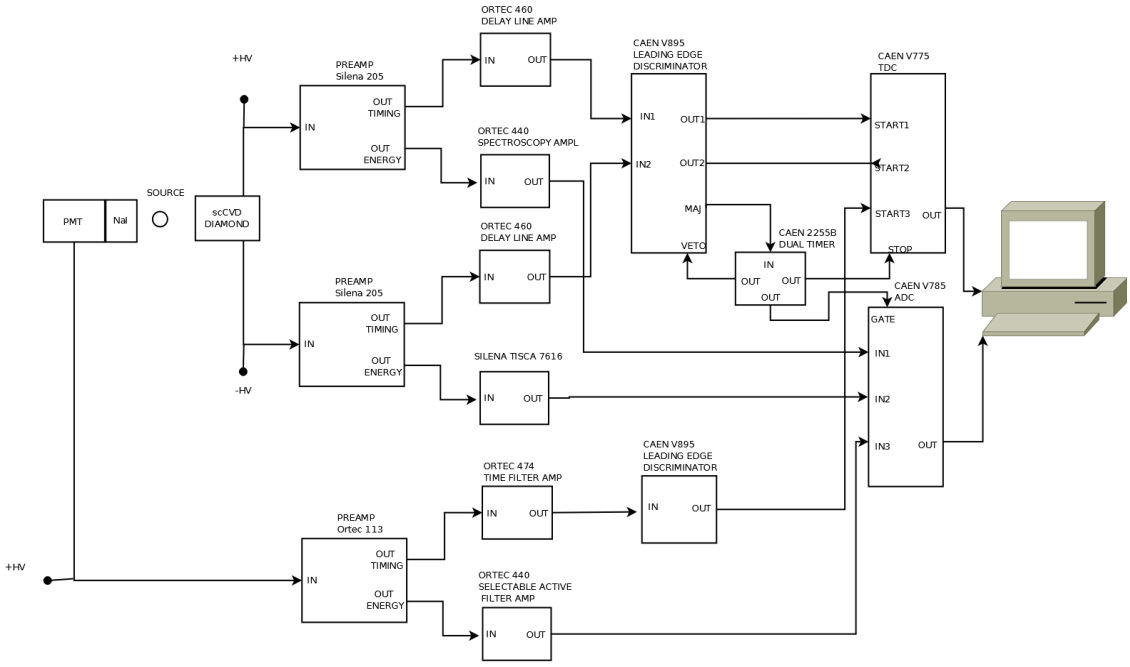


Fig. 1: Data acquisition system for coincidence measurements of backward Compton scattering from scCVD diamond

γ sources were used to study energy resolution and linearity of a scCVS diamond. The Compton electrons were detected in the the diamond, in coincidence with the backscattered γs detected in a NaI detector. The NaI detector was placed at 180^o from the diamond with respect to the source. The detector used in this setup is made by a commercial [9] single crystal CVD diamond with are dimensions of $4.7 \times 4.7\ mm^2$ and 500 μm of thickness, covered by Au electrodes on both faces. The diamond was polarized by 1 V/μm bias, +250 V on one side and -250 V on the other side, using an ORTEC 710 power supply. When an ionising particle passes through the sensitive volume of the detector, it produces electron-hole pairs, the average energy necessary to produce a pair being $< E_{eh} > \simeq 13eV$. The charge collected on

source	E_γ [keV]	P (%)	E_e^{max} [keV]	E'_γ [keV]
^{57}Co	122.1	85.6	39.5	82.6
^{133}Ba	302.9	18.3	164.3	138.6
^{133}Ba	356.0	62.1	207.3	148.8
^{22}Na	511.0	99.9	340.8	170.3
^{207}Bi	569.7	97.7	393.3	176.4
^{137}Cs	661.7	85.1	477.4	184.3

Table 1: Energy of γs from ^{57}Co, ^{133}Ba, ^{22}Na, ^{207}Bi and ^{137}Cs sources. P (%) is the branching ratio of the line considered. The maximum energy of recoil electrons (E_e^{max}) and the corresponding minimum energy of backscattered γ (E'_γ) are also given.

each electrode was sent to two SILENA 205 charge pre-amplifiers. Each SILENA 205 pre-amplifier had two outputs: one was used for the measurement of the deposited energy, while the other was used to perform a time coincidence. Two different electronic chains were used for the two different purposes: the energy output was sent to a spectroscopy amplifier (ORTEC 440 and Silena TISCA 7616 respectively for each electrode) and then to a CAEN V785 Peak Sensing ADC Module. The timing output was sent to a Delay Line Amplifier (ORTEC 460 for both the electrodes), then to a CAEN V890 leading edge discriminator and finally to a CAEN V775 TDC. The read-out used for the NaI detector was similar. The signal from the PMT was amplified using a ORTEC 113 charge pre-amplifier. The energy output was sent to a ORTEC 440 Selectable Active Filter and then to the ADC. The timing pre-amplifier output was sent to a ORTEC 474 Timing Filter Amplifier, then to a CAEN V890 Leading Edge Discriminator and finally to the TDC. The CAEN V890 Discriminator Majority signal was set > 1, which corresponds to the situation in which both signals from the two electrodes of the CVD diamond were over the threshold. In this way accidental signals due to electronic noise in one of the two chains were avoided. The Majority signal was used as the "GATE" signal for the ADC. The START inputs for the TDC were the discriminated signals from the two CVD diamond electrodes and from the NaI detector, while the "COMMON STOP" signal was the Discriminator Majority, delayed by 300 ns. The Data Acquisition System configuration used in this measurement is shown in Figure 1.

3. Measurements

The coincidence measurements between the diamond detector and the NaI detector were performed using the following γ sources: ^{22}Na,^{57}Co, ^{133}Ba, ^{137}Cs and ^{207}Bi. The same sources were used to calibrate the NaI detector. The energies of the main lines from each source are listed in Table 1, together with the corresponding branching ratio. For each line, the energy of the backward Compton γs and of the forward βs are also listed.

NaI and diamond spectra were analysed off-line to remove accidental coincidences. In the NaI spectra, backward γ peak events were selected around the E'_γ energy. The timing information from TDC spectra was used to reject accidental coincidences. In principle, coincidence events should present always the same delay between the NaI and the diamond signals, therfore the quantity $TDC_{NaI} - TDC_{dia}$ should be constant. Using a leading edge discriminator, however, two signals arriving at the same instant could have different discriminator peak-off times according to their amplitude ("time walk"). In particular, the smaller is the signal, the bigger is the delay in the discriminator peak-off time. The correlation between $ADC_{NaI} - ADC_{dia}$ and $TDC_{NaI} - TDC_{dia}$ was analysed to find the the coincidence region and ad hoc selections were performed, as shown as an example for the ^{22}Na source in Fig. 2. In the plot, the coincidence region lies between the solid curves. In particular, as ^{22}Na decays β^+, two 511 keV γs are emitted at 180^o. For this reason, two spots of correlation are present for this source. The one in the $ADC_{NaI} - ADC_{dia}$ range [0,1000] and the smaller time difference is due to the coincidence between the direct γ in the CVD and the back-scattered γ in the NaI. The second correlation spot, around $ADC_{NaI} - ADC_{dia} \simeq 2000$ and with the greater time difference, is due to the coincidence of the two direct 511 keV γs emitted by the source at 180^o. There are other two distributions in correspondence of $ADC_{NaI} - ADC_{dia}$ between -1000 and 0 and between 3000 and 4000. These distributions represent the accidental coincidence events with 511 keV or 1275 keV ^{22}Na γs. The selected events are shown in Fig. 3. The resulting diamond spectra are quasi Gaussian distributions around the forward Compton electron energies. The low

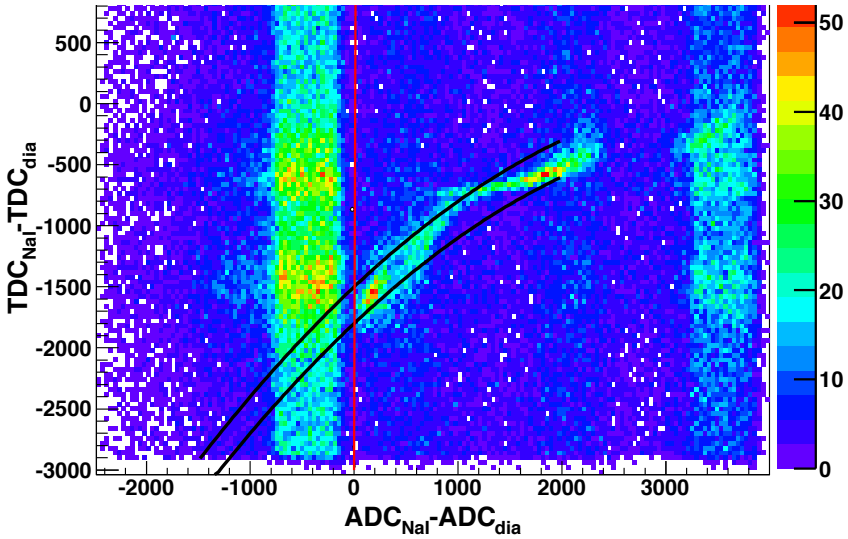


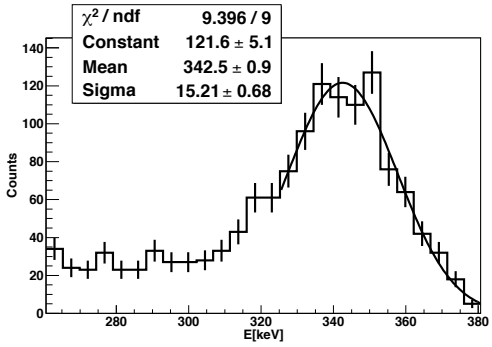
Fig. 2: $ADC_{NaI} - ADC_{dia}$ and $TDC_{NaI} - TDC_{dia}$ correlation for ^{22}Na source. The region of correlated events is between the two black solid curves and for $ADC_{NaI} - ADC_{dia}$ >0 (red curve). The correlation spot in the $ADC_{NaI} - ADC_{dia}$ range [0,1000] is due to the coincidence between the direct γ in the CVD and the back-scattered γ in the NaI. The second correlation spot, around $ADC_{NaI} - ADC_{dia} \simeq 2000$, is due to the coincidence of the two direct 511 keV γs emitted by the source at 180^o. The distribution in the $ADC_{NaI} - ADC_{dia}$ range [-1000,0] is due to the accidental coincidence events with 511 keV ^{22}Na γ, while the distribution in the $ADC_{NaI} - ADC_{dia}$ range [3000,4000] is due to the accidental coincidence events with 1275 keV ^{22}Na γ.

energies tails are mainly due to Compton electrons that leave the diamond without depositing all their energy. The charge collected in the two electrodes is the same within the experimental errors.

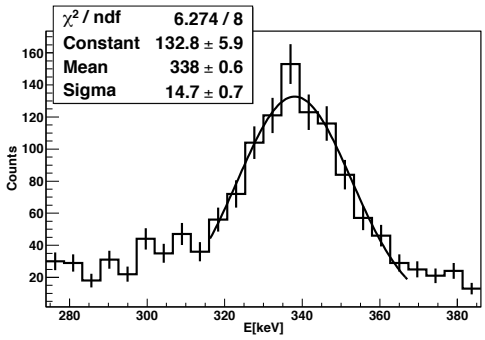
The spectra of the deposited energy for each source were fitted with a Gaussian function and a calibration procedure was performed for the signal from each electrode separately and for their sum (Fig. 4). The difference in the relation between the deposited energy and the ADC values for the two electrodes is due to a slightly different gain in the electronic chains. The obtained energy resolution is shown in Fig. 5. The electronic chain contribution to the resolution was tested using a ORTEC 480 Pulser. The FWHM value from the electronics alone was 24.3 keV. The FWHM values found for the single electrode signals with the γ sources are compatible with the value obtained with the pulser, thus the electronic chain gives the main contribution to the total resolution. The Fano factor for the diamond is about 0.08 [7], therefore the contribution due to the fluctuation in the number of pairs is negligible. The energy resolution of the sum of the two signals is compatible with $\frac{\sigma_{pulser}}{\sqrt{2}}$, as expected. The deviation of the ^{22}Na and of the ^{137}Cs resolutions from the average was due to a larger background contribution: 2 γs coincidence for ^{22}Na and accidental coincidence for ^{137}Cs, which presented the higher activity among the sources used. The linearity of the detector was also studied. The relation between the collected charge and the deposited energy was fitted by a 1^{st} order and a 2^{nd} order polynomials. The difference between the two polynomials represents the deviation from the linear behaviour and the non-linearity of the instrument. The differential non-linearity was found to be smaller than 5% and the main deviations from the linear behaviour were observed in correspondence of deposited energies close to the β range in the diamond. The integral non-linearity in the energy range [40 , 477] keV was smaller than 0.1% .

4. Conclusions

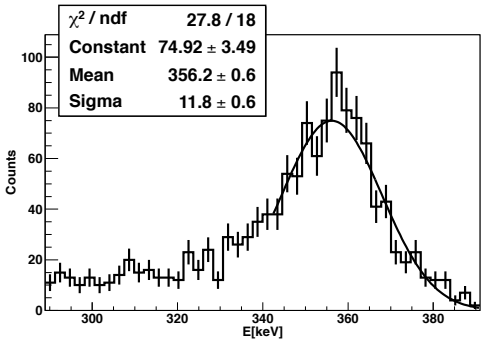
γ rays from ^{22}Na, ^{57}Co, ^{133}Ba, ^{137}Cs and ^{207}Bi sources were measured with a scCVD diamond detector in order to determine the deposited energy resolution of this device and to verify the linearity of its response. Measurements were performed in coincidence with a NaI detector, placed at 180^o from the diamond detector with respect to the source. This setting was suitable to select only backward Compton scattering. Post-processing of acquired spectra was necessary to remove accidental coincidences. NaI spectra were analysed and only the backward Compton γs events were selected. The correlation between $ADC_{NaI} - ADC_{dia}$ and $TDC_{NaI} - TDC_{dia}$ was also analysed. Due



(a) ^{22}Na scCVD spectrum for electrode 1.



(b) ^{22}Na scCVD spectrum for electrode 2.



(c) Sum of both the electrodes signals from ^{22}Na source.

Fig. 3: scCVD spectra after removing accidental coincidences. The peak corresponding to the deposited energy distribution of the forward Compton electrons was fitted with a Gaussian. The low energies tails are mainly due to the Compton electrons that leave the diamond without depositing all their energy and to two independent Compton scatterings by the two 511 keV γs.

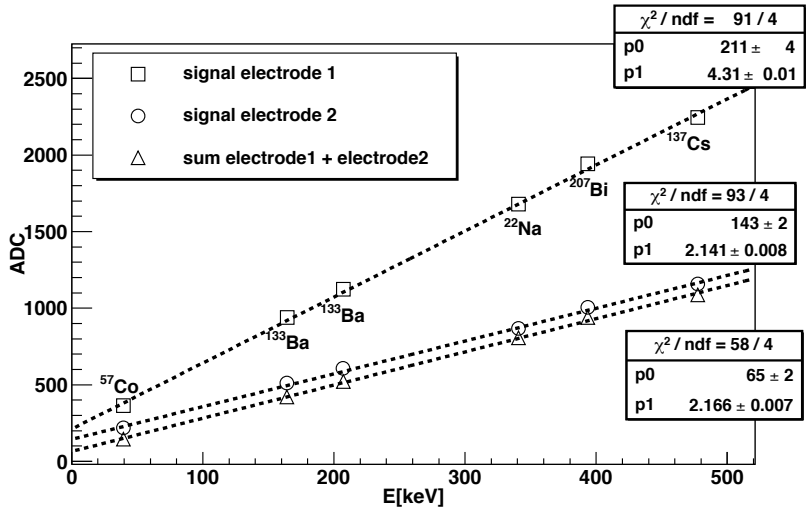


Fig. 4: Charge collected in the diamond detector as a function of deposited energy for each electrode signal and for their sum. Each set of data has been fitted by a linear function "$p0 + p1 \times E_{dep}$". The difference in the relations between the deposited energy and the ADC values in the two electrodes is due to different gain in the electronic chains.

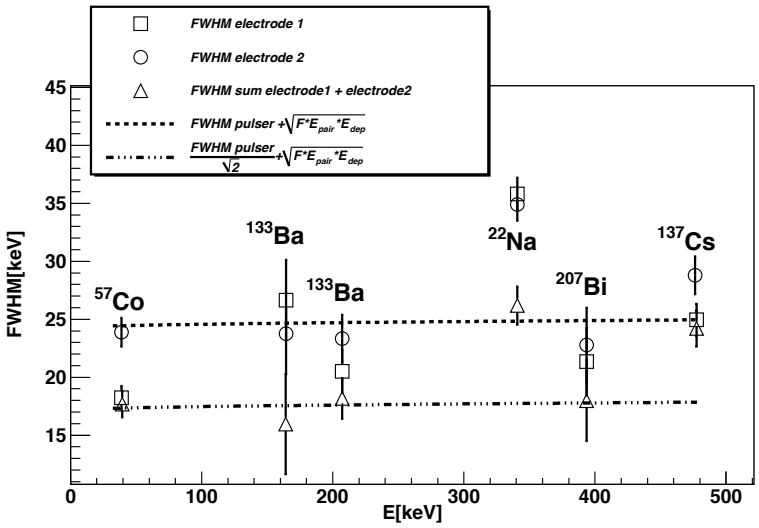


Fig. 5: Deposited energy resolution of diamond detector as a function of deposited energy for both electrodes signals and for their sum. The function $\sigma_{pulser} + \sqrt{F \times E_{pair} \times E_{dep}}$ is also shown. σ_{pulser} = 24.3 keV and represents the contribution due to the electronic chain. F is the Fano factor and its value for the diamond is 0.08. E_{pair}=13 eV is the mean energy necessary to create a pair electron-hole in the diamond. The resolution of the sum is compatible with $\frac{\sigma_{pulser}}{\sqrt{2}}$. Deviation of the ^{22}Na and of the ^{137}Cs resolution from the average was due to a larger contribution of the background.

to the time walk, the $TDC_{NaI} - TDC_{dia}$ is not a constant value but depends on the $ADC_{NaI} - ADC_{dia}$ value. The coincidence regions were identified for each source and ad hoc selections were performed. After post-processing, the diamond spectra were found to be quasi Gaussian distributions around forward Compton βs energies. These distributions were fitted with a Gaussian and the calibration of the detector was performed. The charge collected by the two electrodes was found to be the same within experimental errors. The resolution was compatible with that of the electronic chain ($FWHM_{pulser}$=24.3 keV). The resolution of the sum of the signals from the two electrodes was compatible with $\frac{FWHM_{pulser}}{\sqrt{2}}$. The contribution due to the fluctuation in the number of pairs was found to be completely negligible. Deviation from linearity was smaller than 5% for differential non linearity and smaller than 0.1% for integral non-linearity in the energy range [40 , 477] keV.

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