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ORIGINAL PAPER

CVD diamond detectors for fast alpha particles escaping from the tokamak D-T plasma

Iwona Wodniak,
Krzysztof Drozdowicz,
Jan Dankowski,
Barbara Gabańska,
Andrzej Igielski,
Arkadiusz Kurowski,
Barbara Marczewska,
Tomasz Nowak,
Urszula Woźnicka

Abstract. Measurements of the so-called lost alpha particles escaping from thermonuclear plasma in future tokamaks (such as ITER) for energy production would be essential for monitoring the energy balance in these devices. The detection would have to be carried out in a harsh environment (with high nuclear radiation fluxes, high temperature, etc.), which limits the use of common semiconductors for charged particle detection. Diamond seems to be an attractive material for alpha particle detectors in these conditions. In this paper an analysis of properties of a diamond detector for spectrometric alpha measurements is reported. A high purity CVD (chemical vapour deposition) single crystal diamond detector was used, fabricated for this dedicated application by the Diamond Detector Ltd. The energy calibration was carried out using a triple alpha particle isotope source, AMR33 (^{239}Pu, ^{241}Am, ^{244}Cm). A very good energy resolution, ca. 20 keV at ca. 5.5 MeV had been obtained, which is comparable to that of the silicon detector. The linearity of the diamond detector amplitude response to the alpha particle energy was analyzed with the use of mono-energetic (0.4–2 MeV) ion beam from a Van de Graaff accelerator. Results of the measurements using the AMR33 source deviate at most 30 keV from the calibration line obtained in this way.

Key words: CVD diamond detector • lost alpha particles • high temperature plasma diagnostics

I. Wodniak
The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences,
152 Radzikowskiego Str., 31-342 Kraków, Poland
and Interdisciplinary Doctoral Studies,
AGH University of Science and Technology,
30 A. Mickiewicza Ave., 31-342 Kraków, Poland

K. Drozdowicz, J. Dankowski, B. Gabańska✉,
A. Igielski, A. Kurowski, B. Marczewska, T. Nowak,
U. Woźnicka
The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences,
152 Radzikowskiego Str., 31-342 Kraków, Poland,
Tel.: +48 12 662 8163, Fax: +48 12 662 8458,
E-mail: Barbara.Gabanska@ifj.edu.pl

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Introduction

According to plans, the international thermonuclear experimental reactor (ITER) would be operating at certain point with the deuterium-tritium fuel. In the fusion reactions in such a fuel neutrons and alpha particles are being generated

$$(1)\quad {}^{2}_{1}\mathrm{D} + {}^{3}_{1}\mathrm{T} \rightarrow {}^{1}_{0}\mathrm{n}\ (14\ \mathrm{MeV}) + {}^{4}_{2}\mathrm{He}\ (3.5\ \mathrm{MeV})$$

carrying away the surplus energy. Alpha particles subsequently transmit their energy to deuterium or tritium ions and helium ash, and in this way heat up the plasma. Some alpha particles escape from the core due to enhanced radial transport caused by plasma instabilities or a toroidal field ripple. They are called the "escaping alpha particles" or the "lost alpha particles". The detection of "lost alpha particles" is very important, as they might be the source of information on the energy balance in tokamak [3, 7]. However, the flux of neutrons and alpha particles in future tokamaks is estimated to be very large, which means that the detection process would have to be carried out in a harsh environment, so damage resistant detectors would be required. A total neutron flux of 2.5×10^{14} n/s/cm^2 and a maximum flux

Table 1. Physical properties of diamond and silicon [4]

Property	Diamond	Silicon
Mass density (g/cm^3)	3.5	2.33
Atomic number	6	14
Band gap (eV)	5.5	1.12
Energy to create e-h pair (eV)	13	3.6
Breakdown field (V/m)	10^7	3×10^5
Intrinsic carrier density ($1/cm^3$)	$< 10^3$	1.5×10^{10}
Resistivity (Ω·cm)	$> 10^{11}$	2.3×10^5
Electron mobility ($cm^2/(V \cdot s)$)	4500*	1350
Hole mobility ($cm^2/(V \cdot s)$)	3800*	480
Saturation velocity (km/s)	220	82

* After [11].

of the D-T neutrons of 4.4×10^{13} n/s/cm^2 at the first wall are expected in ITER [9]. The high flux of particles and high temperature restrict the use of common semiconductors, e.g. silicon detectors. The conventional silicon detectors fail for the neutron fluence of 1×10^{13} n/cm^2. The results presented in [10] point out, however, that the single crystal diamond detector can withstand the neutron fluence of 2×10^{14} n/cm^2. Diamond-like semiconductor materials have some properties which are very useful from the point of view of high temperature plasma diagnostics, like radiation and corrosion resistance, large band gap, high breakdown threshold, high electron and hole mobility, large carrier saturation velocity, optical transparency, fast response, and low noise arising from leakage current. These attributes make it an attractive semiconductor detector for spectrometric α measurements [1, 5, 6]. These parameters ensure its usefulness especially in extremely harsh conditions found in operating tokamaks. Diamond itself is high temperature resistant (e.g. 1600°C). As a detector material it is expected to function well up to ca. 200°C with good fast particle energy resolution. (At higher temperatures the increasing crystal lattice vibrations may deteriorate energy resolution). A comparison of the properties of diamond and silicon is presented in Table 1. Any radiation that generates free carries in diamond can be detected, including: UV, X-rays, γ-rays and high energy particles, e.g. alpha particles, neutrons, and electrons. Since diamond has a lower atomic number than silicon, it is less sensitive to electromagnetic radiation [8]. The transport of the generated charge proceeds independently of the exciting radiation type. The drift of free charges, electrons and holes is a key property of the diamond detector. The applied external electric field separates the pairs of electrons and holes before they recombine. Electrons drift towards the anode, the holes to the cathode, and the charge is collected by the electrodes. The motion of free charge carriers in the electric field applied across detector generates an electric current in the external circuit. A schematic picture of the semiconductor detector is presented in Fig. 1.

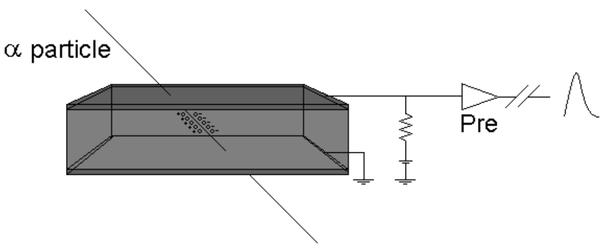

Fig. 1. Principle of α detection by a semiconductor detector.

Measurements of alpha particles using the diamond detector

Measurements were performed with a high purity CVD single crystal diamond. The diamond detector (Diamond Detector Ltd.) is a single crystal plate that has a thickness of 50 μm and size of 2.5 × 2.5 mm, and gold contacts of the thickness of maximum 20 nm. The energy calibration and the study of energy resolution of the diamond and silicon detectors had been carried out using a triple alpha particle isotopic source, AMR33 (^{239}Pu, ^{241}Am, ^{244}Cm). A schematic block diagram of the detection line is presented in Fig. 2.

The diamond detector had always been operated and stored at the room temperature. Examples of alpha spectra acquired with the use of the diamond and silicon detectors are shown in Fig. 3. The AMR33 source emits alpha particles with three main energies. Thus, three

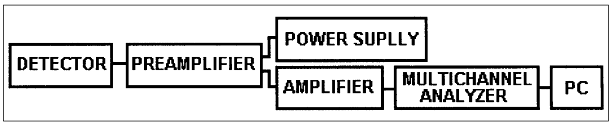

Fig. 2. Block diagram of the detection line.

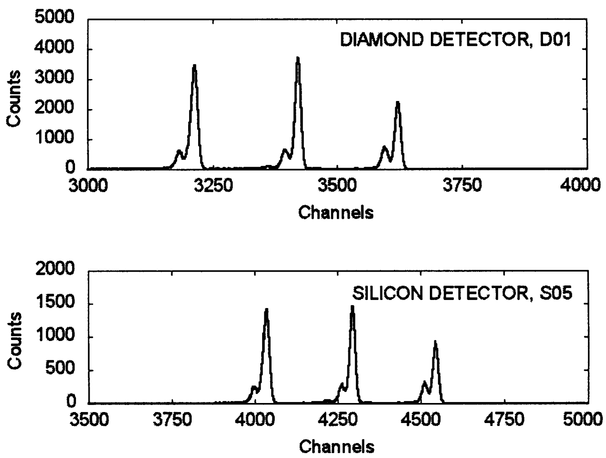

Fig. 3. Spectra of the AMR33 source recorded with the diamond and silicon detectors.

Table 2. Energy resolution of the detectors

E_t (keV)	Diamond detector		Silicon detector	
	ΔE (keV)	$\Delta E/E_t$ (%)	ΔE (keV)	$\Delta E/E_t$ (%)
5156.65	23	0.45	24	0.46
5485.68	26	0.48	20	0.36
5804.86	21	0.36	19	0.33

E_t – energy of α particles emitted by the AMR33 source.
ΔE – FWHM of the peak.

corresponding peaks are clearly visible in the spectra. The Gaussian function was fitted to each main peak of the spectrum. The obtained full widths at half maximum (FWHM) of the peaks are presented in Table 2. E_t is the energy of alpha particles emitted by the radioactive source, and E_m is their "measured" energy, i.e. the read-out from the obtained calibration line. Comparison of the energy resolution of these detectors shows that the diamond detector has as good energy resolution as the silicon one, i.e. about 20–25 keV.

Measurements of the mono-energetic helium ion beams

The calibration energies of alpha particles from the AMR33 source are higher than the maximum α energy from the synthesis reaction, 3.5 MeV, Eq. (1). Spectrometric properties of the diamond detector at lower energies had been investigated using a Van de Graaff accelerator in the Institute of Nuclear Studies (Otwock/Świerk, Warsaw Branch, Poland), which provided mono-energetic beams of helium ions. The whole arrangement with the diamond detector was placed in a vacuum chamber (Fig. 4), which was connected with the accelerator through pipe 1. The ion beam was passing through the pipe 1, which was introduced into the vacuum chamber, and then was falling on a scattering thin foil. The diamond detector was placed at the β angle (45°) with respect to the beam of the ions and at the distance of 4 cm from the scattering foil. Only the ions scattered back under the β angle were detected. The electronic line was identical to that used in the calibration measurements with the AMR33 source.

The beam of helium ions ${}^4_2\mathrm{He}^+$ (energy E_0) was incident on a thin gold foil. The superficial mass of the gold foil was equal to 100 μg/cm². The beam ion of mass M penetrates the foil and interacts via either elastic collision with atoms of gold of mass M_1 or inelastic collision with electrons. The final energy E_1 of ions scattered by the angle θ = 180° – β = 135° may be calculated from the relation [2]:

$$E_1 = E_0 \left[\frac{(M_1^2 - M^2 \sin^2 \theta)^{1/2} + M \cos\theta}{M_1 + M} \right]^2 \tag{2}$$

The following energies E_0 of the incident helium ions were used: 400, 1000, 1500 and 2000 keV. The energies of the scattered ions were found from Eq. (2), which is exactly fulfilled for one-atomic layer of gold. The results of the calculation (E_1) and the values of the measured energies of the helium ions (E_m) are collected in Table 3. The energy spectra of helium ions

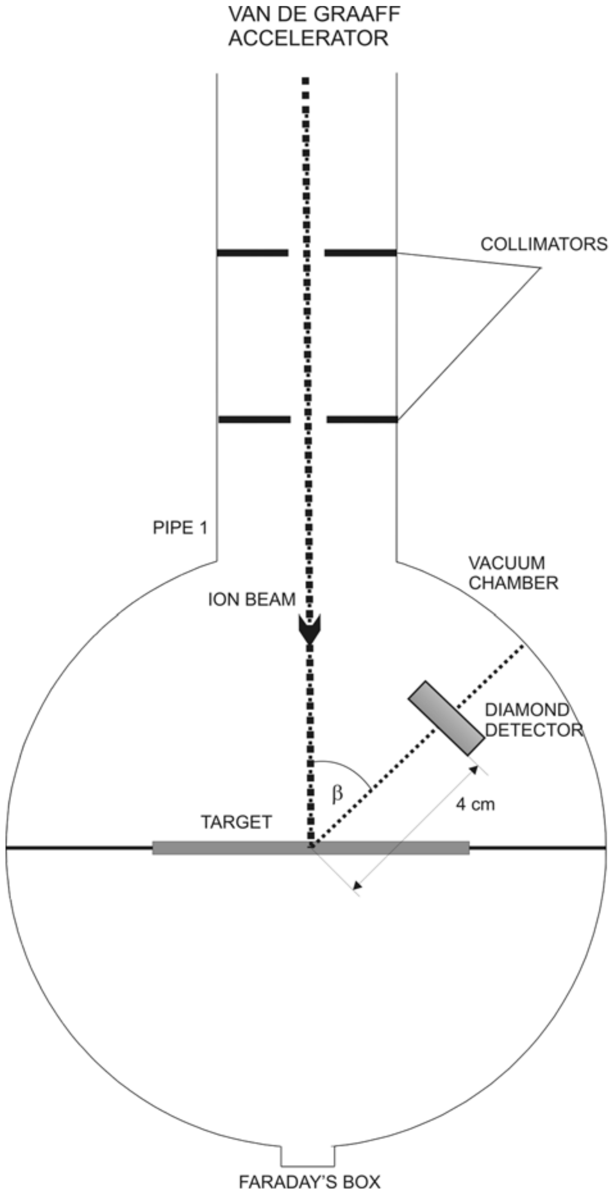

Fig. 4. Geometry of the detection of the backscattered ions.

were obtained using AMR33 source calibration line. These spectra are presented in Fig. 5. The linearity of the amplitude signal was investigated as well. The measured peak energy values E_m as a function of the known values of the scattered helium ion energy E_1 and of the peak positions E_t of the AMR33 source are plotted in Fig. 6. By presenting the results in such a way we may compare the results obtained at slightly different energy-to-channel adjustment in different series. The points from AMR33 source lie on the calibration line which has been obtained from measurements with the mono-energetic

Table 3. Calculated (E_1) and measured (E_m) energies of helium ions

E_0 (keV)	E_1 (keV)	$\sigma(E_1)$ (keV)	E_m (keV)
400	373	11	325
1000	933	27	852
1500	1399	40	1332
2000	1866	54	1846

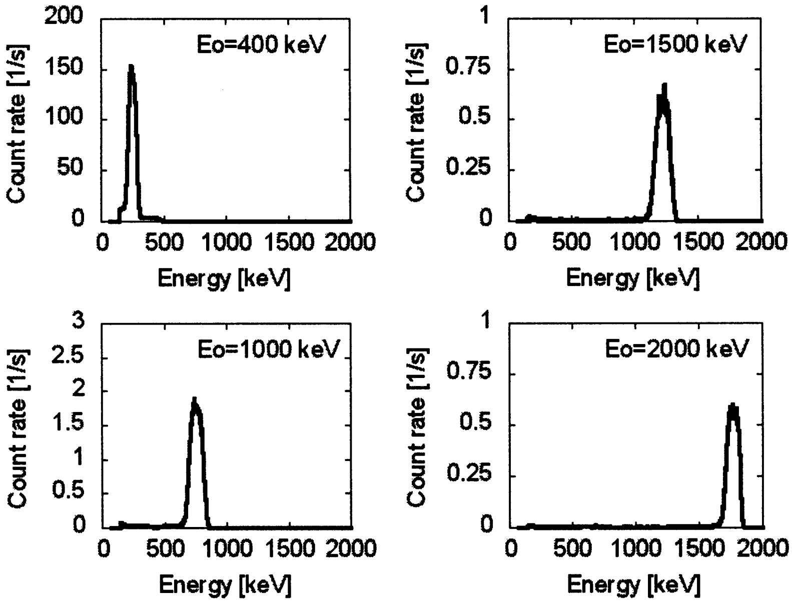

Fig. 5. Energy spectra of helium ions scattered on a gold foil of 100 μg/cm², recorded using the diamond detector.

beams. A maximum difference is 31 keV. In this way we checked whether the calibration made only in one range is good for a distant range of energies.

Conclusions

Our measurements indicate that the energy resolution of the diamond detector is comparable with that of the silicon detector. A very good linearity of the detector amplitude signal vs. the helium ion energy was recorded, including also results obtained with the AMR33 source that emits α particles with the energies about 5.5 MeV. The differences between energies E_m (E_t) of alpha particles emitted by the AMR33 source and the energies

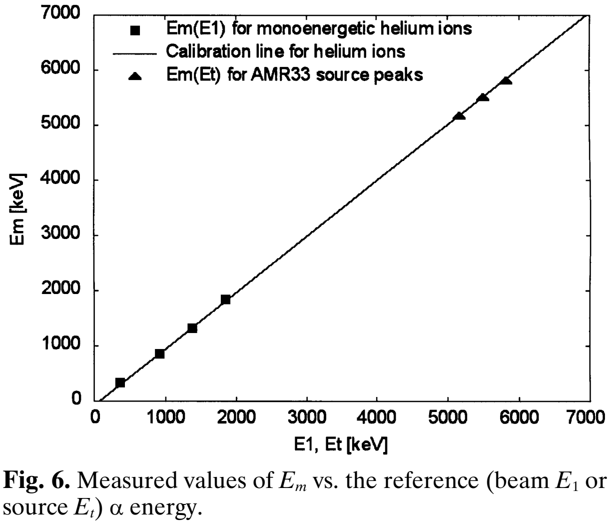

Fig. 6. Measured values of E_m vs. the reference (beam E_1 or source E_t) α energy.

of alpha particles E_m (E_1) calculated using the ion calibration line do not exceed 31 keV. The differences are of the order of 0.5% of the measured energies. This shows that mono-energetic helium ion beams may be useful for calibration of the diamond detectors in the range of energies below the maximum energy of alpha particles from the thermonuclear reaction (2). The obtained results are very promising as far as the application of the diamond detectors for the spectrometric detection of the escaping alpha particles is concerned.

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