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www.ifj.edu.pl/publ/reports/2014/

Kraków, 2014

Report No. 2068/AP

Principles of a method to use CVD diamond detectors for spectrometric measurements of particles in mixed radiation field emitted by D-D and D-T fusion plasmas

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The work has been performed within the framework of the research grant of the Polish Ministry of Science and Higher Education (MNiSW) No. NN 505 485840.

Abstract

Future thermonuclear reactors for needs of power plants will operate with the deuterium-tritium fuel. Neutron, alpha particle, and energy are created in the fusion reaction between these isotopes. Measurement of energy of the reaction products is important to control energetic balance in the thermonuclear plasma. Fast neutrons (14 MeV) should deliver energy outside the tokamak. Alpha particles are the ash of the reaction but they should also leave their energy (3.6 MeV) in the plasma to maintain the fusion reaction. Therefore, knowledge of the energy of alpha particles escaping from plasma (the lost alpha particles) is essential. Because of a short range of alpha particles the measurement has to be performed inside the tokamak, in harsh surrounding (high temperature and high particle fluxes). Diamond seems to be a proper material for use it as a semiconductor detector under those conditions.

A diamond detector (synthetic high purity CVD monocrystal) was tested in aspect of its potential application for spectrometric diagnostic of the ions in tokamaks. The energy calibration of the diamond detectors of the different thickness was performed using isotopic sources: energies around 5 MeV from the ^{239}Pu + ^{241}Am + ^{244}Cm source, and 6.8 and 8.7 MeV from the ^{212}Bi + ^{212}Po source. Additionally, monoenergetic ions beams (alpha particles and protons) were obtained from a van de Graaff accelerator in the 0.4 – 2 MeV energy range. A very good linearity of the amplitude signal vs. energy was obtained.

At any working tokamak, a mixed radiation field is present consisting of various particles, like n, α, γ, p, d, t. Their contributions fluctuate depending on a regime of tokamak work and on plasma instabilities. Thus, the CVD diamond detector response in a mixed radiation field can be properly studied only in well-defined conditions of a laboratory experiment. Detection of ions and neutrons was performed at our 14 MeV neutron generator, IGN-14, where (i) the same nuclear reaction as in the D-T plasma occurs and (ii) also other types of radiation similar as at tokamaks are observed (owing to a number of different reactions on the generator target). A new measuring chamber at IGN-14 was designed and built to make possible observation of responses of detectors placed symmetrically or at different angles in respect to the primary ion beam. Two identical or different type detectors can be compared at the same time. A complex spectrograms were obtained and analysed to distinguish signals from various particles.

1. Introduction

High temperature plasma and thermonuclear fusion research have been intensified owing to a start of the ITER (*International Thermonuclear Experimental Reactor*) project. The aim of the project is to provide opportunity of application of fusion energy to produce electricity. ITER will be a thermonuclear tokamak reactor which should to prove that the deuterium-tritium (D-T) fusion can be utilized to produce energy. Fast neutrons will deliver the energy outside, according to the reaction:

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{n} + {}^{4}\mathrm{He} + E, \tag{1}$$

where partition of energy $E = 17.6\ \mathrm{MeV}$ is following:

$14\ \mathrm{MeV}$ is taken by neutrons, and

$3.6\ \mathrm{MeV}$ is used by α particles.

The α particles should transfer their energy to plasma to sustain the plasma burning. Therefore, proper diagnostics, i.e. the measurement of energy of alpha particles leaving plasma is necessary (the so-called *escaping alpha particles* or *lost alpha particles*) [1],[2]. The measurement has to be performed inside the tokamak because of a very short range of alpha particles in the matter.

An application of diamond detectors (in harsh thermonuclear reactor conditions) to measure products of deuterium-deuterium (D-D) and/or deuterium-tritium (D-T) fusion is the actually problem, because diagnostics of different kind of radiation created in high temperature plasma give important data on fusion processes in the reactor (D + T $\rightarrow$ n + α + energy). Neutrons go up about 14 MeV energy which can be utilized for electric power production. Alpha particles go up 3.5 MeV energy which have to be used to support the energy conditions of burned plasma. The measurement of number and energy of alphas which escape the plasma volume (*lost alphas*) is one of the most important experimental challenge. For the reason of harsh conditions in plasma vessel: high temperatures, high electromagnetic, charge particles and gammas radiation fields, conventional detectors have not to be used. Diamond as the most resistant material gives the chance to build the effective detection system which could be used inside plasma vessel of thermonuclear reactors as tokamaks and stellarators.

2. Detection of charged particles and neutrons with CVD diamond detectors

Single crystal of diamond has the properties of the semiconductor [3],[4],[5]. Any radiation that generates free carriers in diamond can be detected, only just the low atomic number gives a low sensitivity for radiation UV, X-rays and γ-rays. Drift of free charges, electrons and holes, generates the electrical current in the external circuit (Fig.1). The electrons and holes have large mobility [Table 1]. This high mobility is a partial consequence of the high Debye temperature and inelasticity of the material.

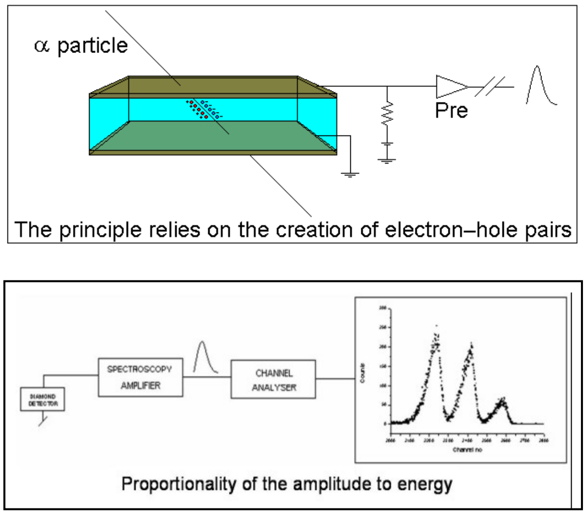

Fig. 1 Detection of charged particles by a semiconductor detector.

Table 1. Comparison of the physical properties of diamond and silicon.

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 [MV/cm^1]	10	0.3
Resistivity [Ωcm]	$>10^{11}$	$2.3 \cdot 10^5$
Electron mobility [cm^2/Vs]	1800	1350
Hole mobility [cm^2/Vs]	1200	480
Radiation length [cm]	12	9.4

The diamonds detectors used in the experiments manufactured by the Diamond Detector Ltd. and CIVIDEC GmbH are a high purity CVD (Chemical Vapour Deposition) single crystal. There are two types of scCVD diamond detectors from Diamond Detector Ltd:

- a single crystal plate that has a thickness of 50 µm, size of 2.5 mm × 2.5 mm
- a single crystal plate that has a thickness of 500 µm, size of 4.7 mm × 4.7 mm.

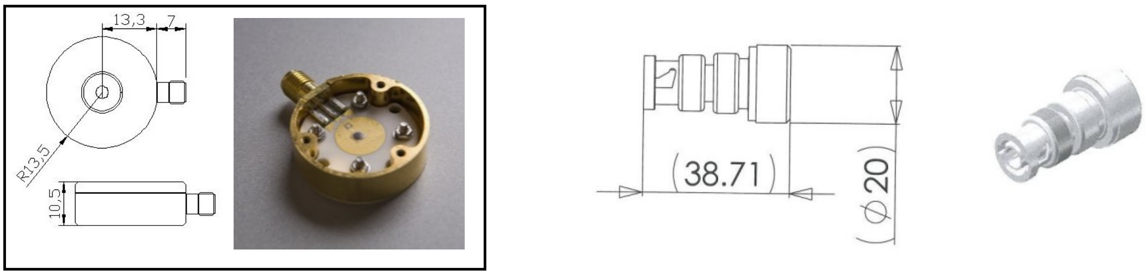

Fig. 2 Two type of connectors – SMA right angle (a) and axial BNC (b) of the diamond detector.

Each diamond detector was evaluated using the detection line consisting with the SMA or BNC (Fig.2) connector to the charge preamplifier ORTEC 142A, the spectroscopy amplifier ORTEC 672, the multichannel analyzer ORTEC 927 and a computer (Fig. 3).

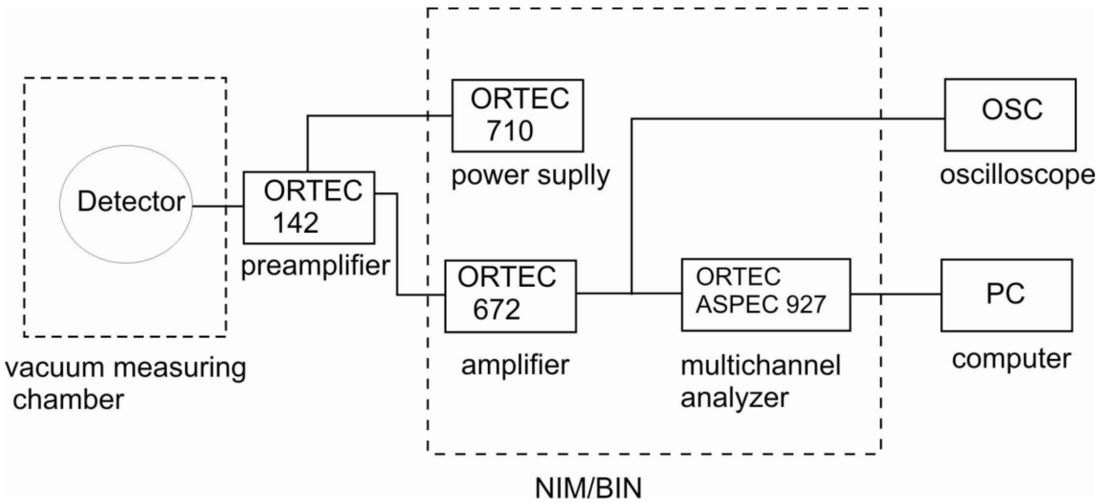

Fig. 3 Block diagram of the detection line.

3. Energy calibration of the CVD detector

The precise calibrations of diamond detectors [6],[7] using alpha particles of defined energies from isotopic sources were done with a triple alpha particle isotope source, ^{239}Pu + ^{241}Am + ^{244}Cm, (AMR33) (Table 2) and from a ^{212}Bi + ^{212}Po source (Table 2 and Table 3).

Table 2. Energy of α particles emitted by the AMR-33 source.

^{239}Pu		^{241}Am		^{244}Cm	
E_α (keV)	P_α (%)	E_α (keV)	P_α (%)	E_α (keV)	P_α (%)
5156.65	70.76	5485.68	84.4	5804.86	76.6
5143.9	17.16	5442.98	13.1	5762.74	23.4
5105.89	11.92	5388.40	1.65		
E_α – energy of α particles P_α – fraction of α particles that have energy E_α.					

Table 3. Energy of α particles emitted by the ^{212}Bi + ^{212}Po source.

^{212}Bi		^{212}Po	
E_α (keV)	P_α (%)	E_α (keV)	P_α (%)
6050.92	25.1	8785.06	100

The results of the calibrations are shown on the Fig. 4 and Fig. 5:

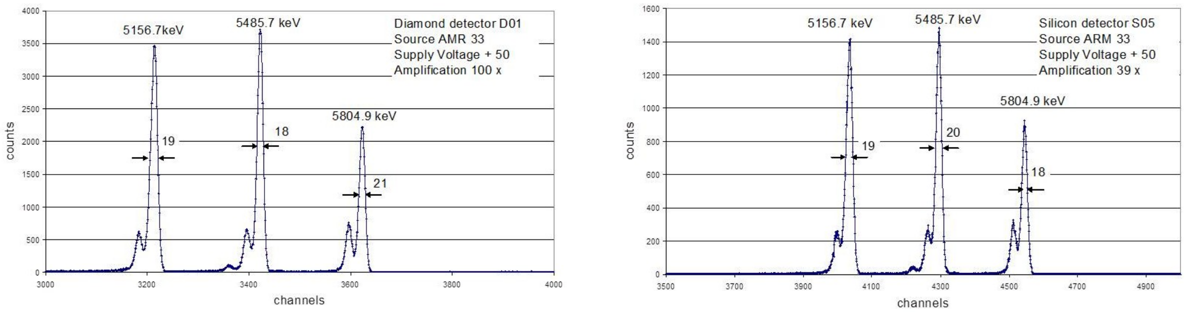

Fig. 4 Energy spectra of the AMR-33 source recorded with the diamond and silicon detectors.

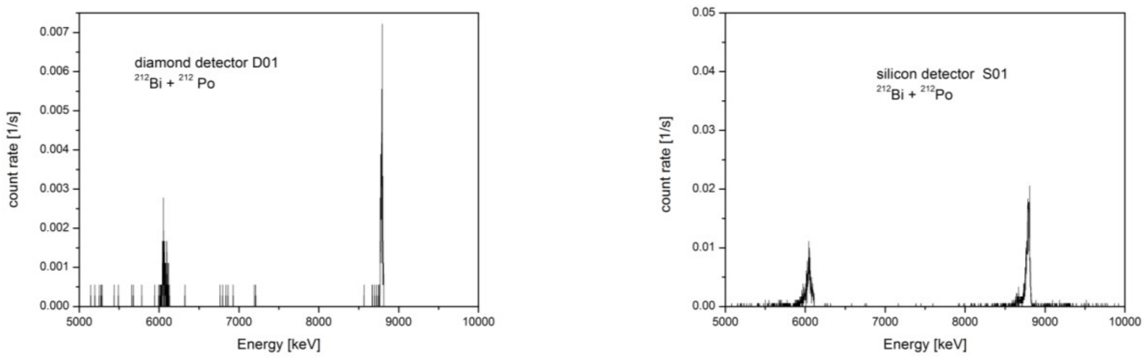

Fig. 5 Energy spectra of the ^{212}Bi + ^{212}Po source recorded with the diamond and silicon detectors.

The problem is that the calibration energies of alpha particles from the isotopic sources are higher than the maximum α energy from the fusion reaction, 3.5 MeV Eq. (2):

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

Therefore monoergetic ions beams (0.4 MeV – 2 MeV) produced by van de Graaff accelerator were used to diamond detector calibrations in the range of energy below 3.5 MeV. The experiments with monoenergetic proton beams (van de Graaff accelerator at the Institute of Nuclear Physics PAN, Kraków) and beams of protons, deuterons and alpha particles obtained from a van de Graaff, "Lech", at the National Centre for Nuclear Research in Otwock-Świerk, Poland, were done (Fig. 6).

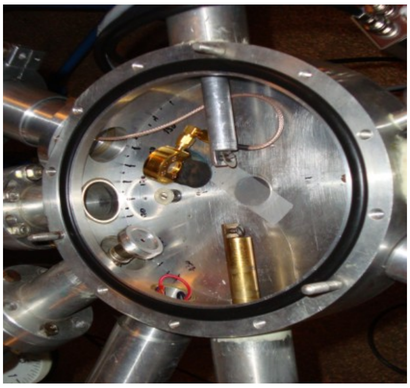

Fig. 6 The vacuum chamber in the experiments on the van de Graaff, "Lech"

In these measurements we used the RBS geometry (Rutherford Backscattering Spectrometry) to get better energy resolution and dodge the issue of high flux of particles.

The accelerated ions (protons, deuterons and alpha particles) bombarded thin foil of gold and were scattered. The backscattered ions under 150 degree angle in respect to the ion beam had a well defined energies. They were measured with a number of the diamond detectors. A silicon detector was used as the reference counter in all measurement series. The scattering foil and the detectors were placed in a vacuum chamber (Fig. 7).

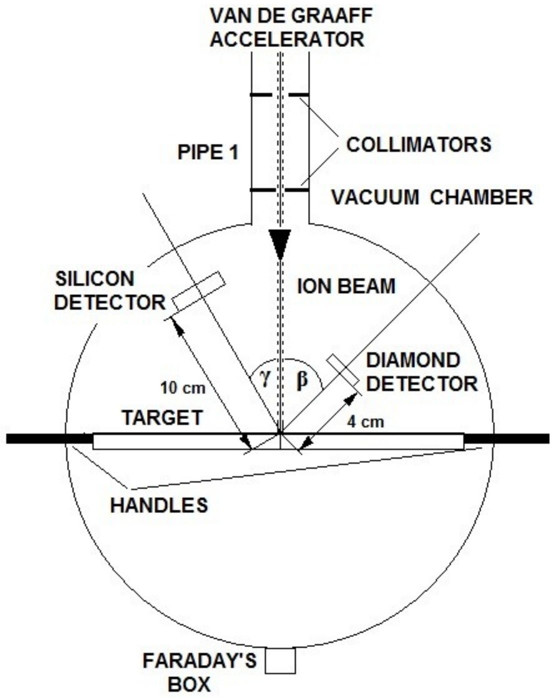

Fig. 7 Geometry of detection of the backscattered ions.

A thin foil of gold was bombarded by the beam of ions during the measurements. The incident ions (energy E_0) penetrated the foil of gold and interacted via either inelastic collisions with electrons or elastic collisions with the atoms of gold. Then the final energy of the scattered ions, E_1, is defined Eq.(3) by the relation

$$E_1 = K \cdot E_0 = \left[\frac{\left(M_1^2 - M^2 \sin^2\theta\right)^{1/2} + M\cos\theta}{M_1 + M} \right]^2, \qquad (3)$$

where M is the ion mass, M_1 is the gold atom mass, and $\theta = 180° - \gamma$ (Fig. 8)

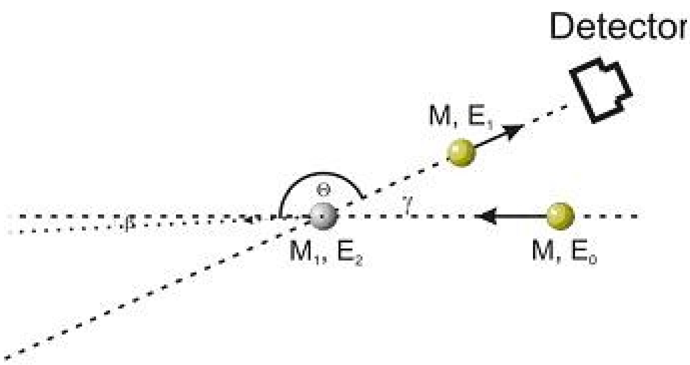

Fig. 8 Principle of the RBS geometry (Rutherford Backscattering Spectrometry)

Spectrometric properties of the detectors from different manufacturing series and detectors of different thicknesses (50 μm and 500 μm) were compared in a few series of the experiments. Three kinds of ion beams were used: alpha, protons or deuterons with energy from 0.4 MeV to 2.1 MeV. A silicon detector was used as the reference counter in all experiments.

For each type of the diamond detector in each experiment the same method of determination of the maximum energy was used:

- the position (number of channel) of the experimental peak is fixed as the point intersection of the tangent to a curve (at the point in the half-high of back slope of experimental peak) with the axis of abscissa Fig. 9,

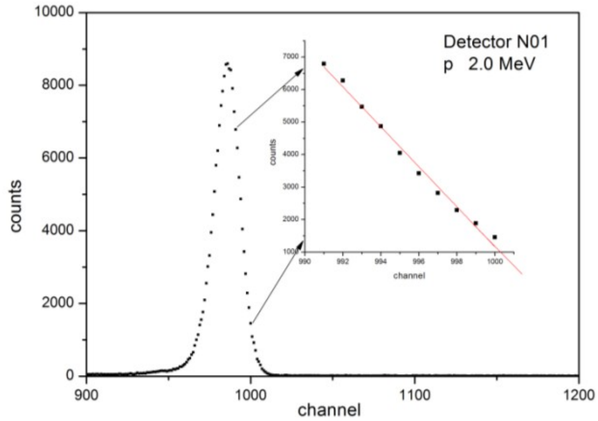

Fig. 9 Method of the pinpoint of the experimental peak.

- the energy of the ion is determined from calibration line for the diamond detector,
- the energy of the ion is CVD determined from calibration line for the Si detector used as the reference: $E_{CVD} = a^* E_{Si} + b$. A corresponding plot is shown in Fig. 10

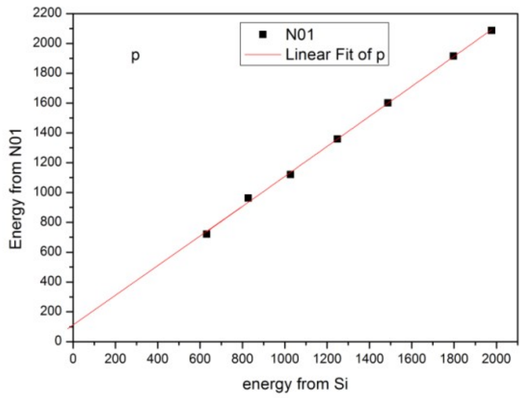

Fig. 10 Energy of the peaks from a diamond detector versus energy from the Si detector (Example: N01 detector, 2.0 MeV proton beam).

For all CVD detectors the calibration lines were obtained using various ions (examples in Fig. 11– 14).

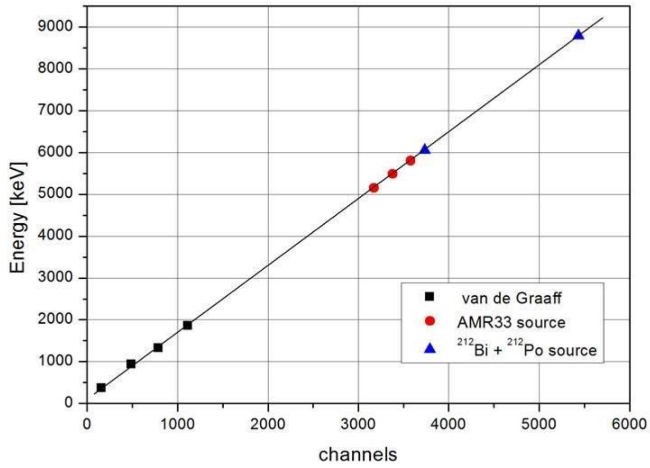

Fig. 11 Response of the CVD 50 μm diamond detector to the α calibration sources and to monoenergetic ions.

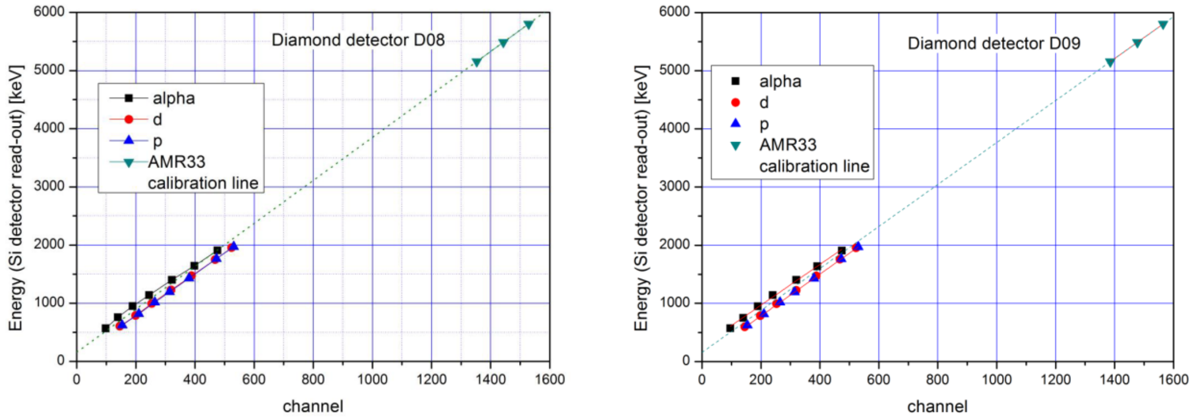

Fig. 12 Response of diamond detectors D08 and D09 (both 50 μm) to the α calibration source and monoenergetic ions.

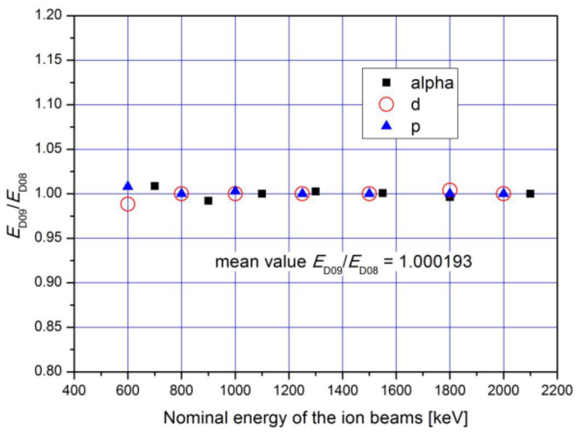

Fig. 13 Comparison of detectors D08 and D09.

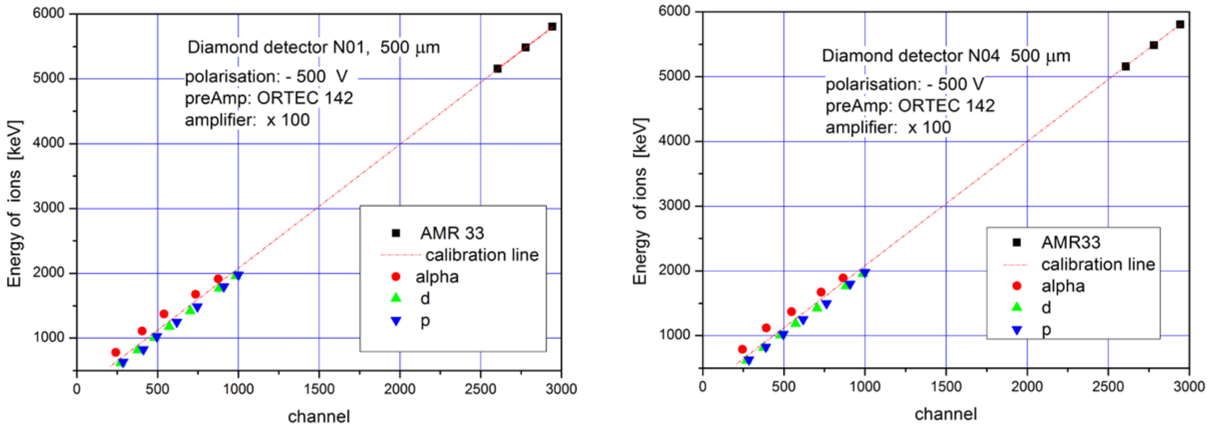

Fig. 14 Results of measurements of various ions with the N01 and N04 scCVD (500 µm) diamond detectors.

Reproducibility of response of various detectors is shown in Fig.15.

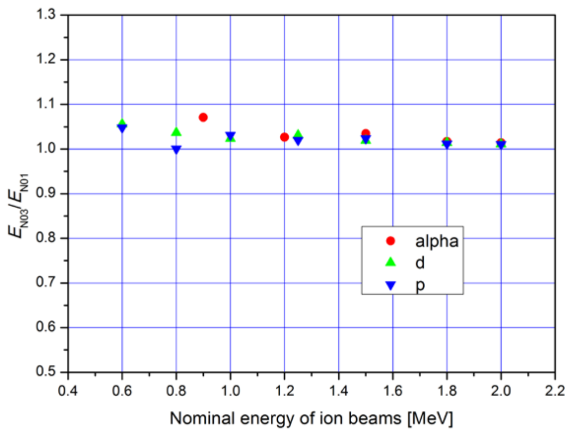

Fig. 15 Reproducibility of response of various detectors. Plot of the ratio of detector N03 to N01 spectrometric response.

A visible small deviation between the points measured for alpha particles and deuterons or protons was observed also for thin detectors (example in Fig. 16). It is probably related to very different ranges of these particles in diamond and then to the charge collection region. However, a difference of about 0.1 MeV is not crucial for measurement of the escaping fast ion energy. Note that the polarization voltages, 500 V at N01 and 50 V at D09, create the same electrostatic field of 1 V/µm.

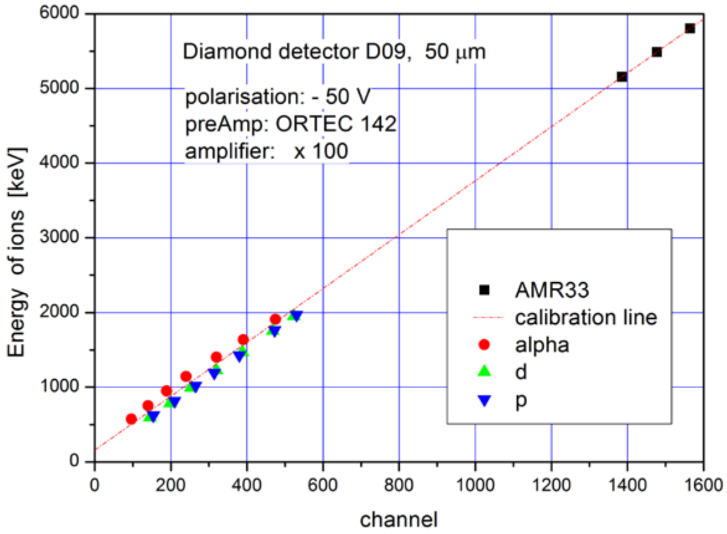

Fig. 16 Results of reference measurements of various ions with the D09 50 μm scCVD diamond detector.

4. Mixed radiation field at the neutron generator

A T/Ti target (which contains tritium in titanium, deposited on a copper substrate) was used in the experiments. It was bombarded with ~100 keV deuteron beam. In this case the neutron generator produces fast neutrons and alpha particles in the reaction:

$$^{2}\mathrm{D} + {}^{3}\mathrm{T} \rightarrow \mathrm{n}\ (14.1\ \mathrm{MeV}) + {}^{4}\mathrm{He}\ (3.5\ \mathrm{MeV}), \qquad Q = 17.6\ \mathrm{MeV} \tag{4}$$

After some time of the use the target contains deuterium implanted from the bombarding ion beam and the following reactions occur:

$$^{2}\mathrm{D} + {}^{2}\mathrm{D} \rightarrow {}^{3}\mathrm{He}\ (0{,}82\ \mathrm{MeV}) + \mathrm{n}\ (2{,}45\ \mathrm{MeV}), \qquad Q = 3{,}27\ \mathrm{MeV} \tag{5}$$

$$^{2}\mathrm{D} + {}^{2}\mathrm{D} \rightarrow {}^{3}\mathrm{T}\ (1{,}01\ \mathrm{MeV}) + \mathrm{p}\ (3{,}02\ \mathrm{MeV}), \qquad Q = 4{,}03\ \mathrm{MeV} \tag{6}$$

Tritium decays ($T_{1/2} \approx 12.5$ years) to ^{3}He and, therefore, some amount of ^{3}He appears in older targets. ^{3}He reacts with deuterons and alpha particles (^{4}He) are emitted:

$$^{2}\mathrm{D} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + \mathrm{p}, \qquad Q = 18{,}3\ \mathrm{MeV} \tag{7}$$

All reaction products, Eqs (4) – (7), emitted from the target and the backscattered deuterons reach the diamond detector shielded with a thin aluminium foil (1.5 mg/cm^2) to avoid gathering an electrical charge.

- **Chamber for measurements with diamond detectors in vacuum**

A special new vacuum measuring chamber was designed, built and installed at the ion guide of the IGN-14 generator. Any of the three openings can be used as an inlet of the deuteron beam and the detectors can be placed at the remaining ones.
In this way a possibility is achieved either to observe a response of the identical detectors placed under different angles or of different type detectors placed under the same angle (symmetrically to the deuteron beam direction) - Fig. 17.

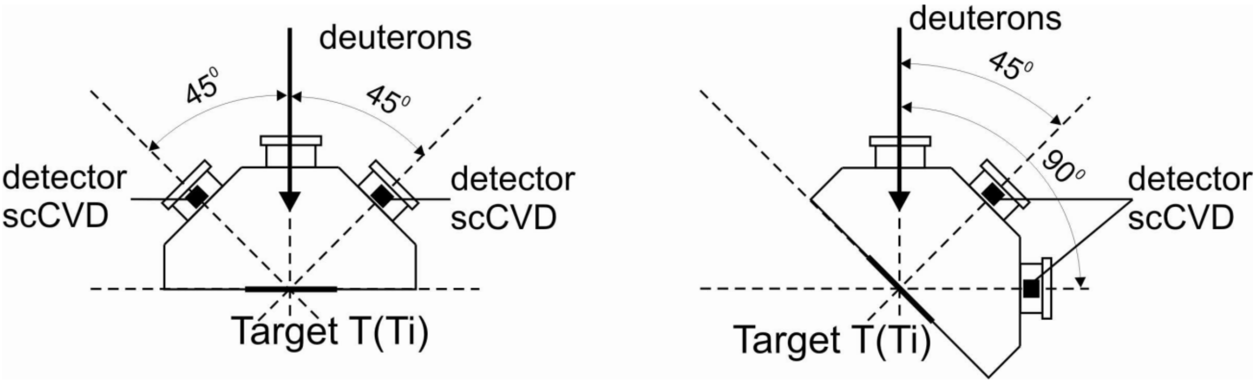

Fig. 17 Example of positioning of the deuteron beam and directions of ion measurements.

The view of the chamber is on the Fig. 18:

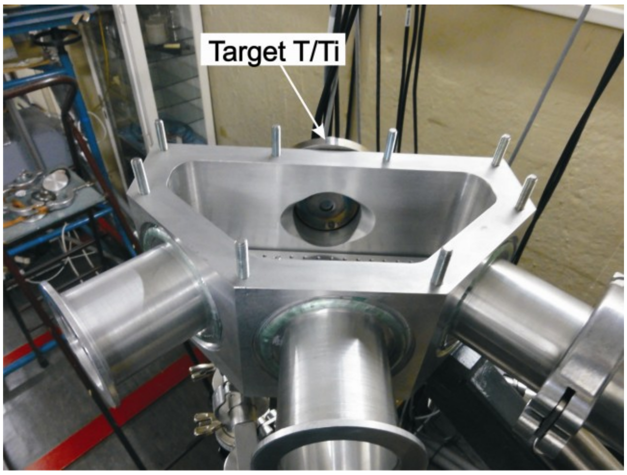

Fig. 18 View of the vacuum measuring chamber at the IGN-14 neutron generator (IFJ PAN).

- **Monte Carlo simulations of radiation distribution in the measuring chamber**

Monte Carlo modelling of radiation distributions in the measuring vacuum chamber was undertaken in order to support interpretation of the energy spectra obtained from the scCVD diamond detectors. The MCNPX code [8] was used for the MC simulations. The input data were prepared using SIMRA [9] and MATLAB [10] codes. An example of the spatial distribution of alpha particles in the chamber volume from the D-T reaction is shown in Fig. 19.

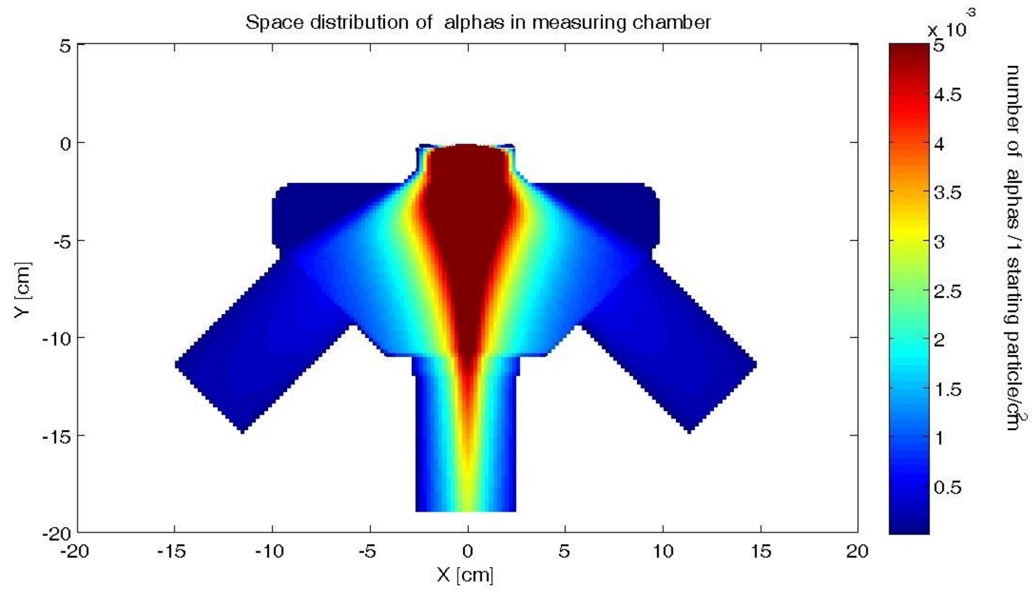

Fig. 19 Distribution of alpha particles inside the vacuum chamber from the D-T reaction on the target.

- **Results**

A placement of the detectors symmetrically to the incident beam direction allows comparing responses of the same type detectors or responses of different detectors (here, 50 μm and 500 μm thick) exposed to the same conditions of the radiation field. Positioning under different angles to the incident beam direction supplies from the same reaction ions which have different energies.

Fig. 20 a shows example of the α spectra (D-T reaction) when two 50 μm scCVD detectors are placed at the same angle, θ = 135°. Maximum energy of the alpha particles is about 3.2 MeV. In Fig. 20 b a comparison of the detector responses different angles is shown. The maximum under 90° is about 3.7 MeV. The results are compatible with a theoretical prediction.

a) b)

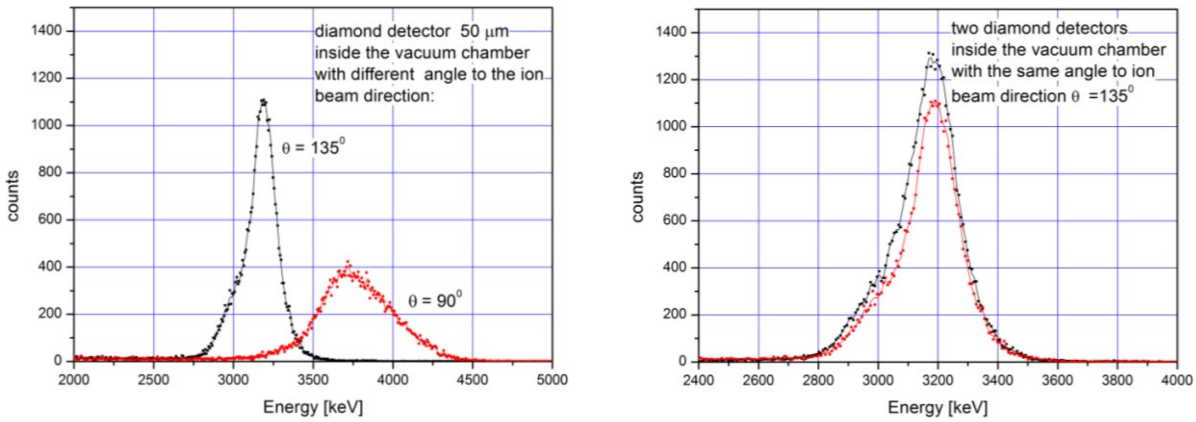

Fig. 20 Comparison of the α spectra of the α particles (D-T reaction) obtained from the scCVD detectors in the vacuum chamber at different angles.

Another experiment was made to compare sensitivity of the 50 μm and 500 μm diamond detectors to the 14 MeV fast neutron and 3.5 MeV α particles. The detectors were placed symmetrically under the θ = 135° angles. The result is shown in Fig. 20 b. The thin detector repeats, of course, the spectra shown in Fig. 20 a. Its thick is, however, insufficient for fast neutrons to react on this distance with carbon nuclei and no neutron signal is observed. The second detector (500 μm, red line) detects neutrons with the essential peak ~8.4 MeV from the threshold reaction, $^{12}C(n,\alpha)^{9}Be$, with a negative Q = –5.70 MeV.

The result means that a 50 μm scCVD diamond detector, placed in a tokamak vessel and destined to measure energy spectra of the escaping alpha particles, will be insensitive to the accompanying D-T neutron radiation [11], [12].

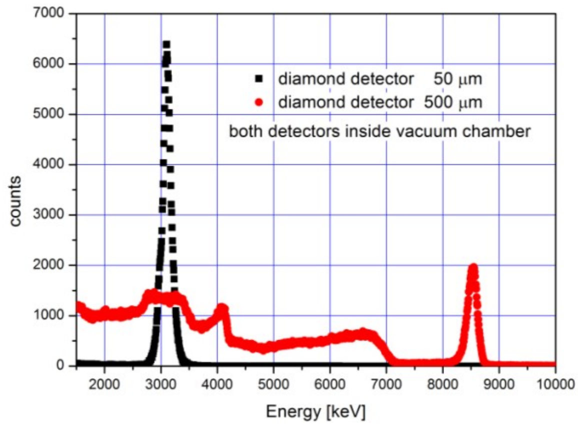

Fig. 20 Detection of alpha particles and neutrons by the 50 μm and 500 μm diamond detectors.

A result of a supplementary experiment is shown in Fig. 20 (when the 50 μm and 500 μm diamond detectors were placed inside vacuum chamber) and in Fig. 21 when detectors were placed outside the vacuum chamber with the inner tritium target. The alpha particles, due to their very short range in the matter, are stopped by the construction materials and are absent outside. On the other hand, this is almost no screen for the 14 MeV neutrons. The 500 µm diamond detector registers the energy spectrum (red line) as it was inside the chamber. Response of the 50 µm diamond detector to the neutrons is almost zero (about 0.1 %). The black line in Fig. 21 corresponds to the data multiplied by 10.

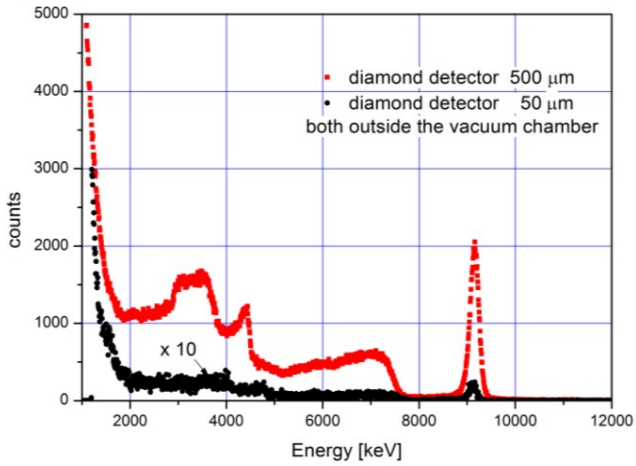

Fig. 21 14 MeV neutron energy spectra recorded by diamond detectors of 50 µm and 500 µm widths.

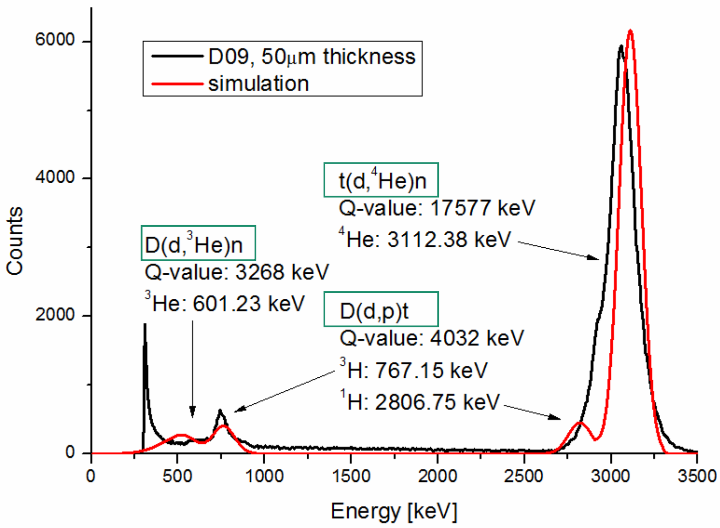

Fig. 22 Example of the spectrum of alpha particles, protons, tritons, and He-3 ions, obtained by 50 µm thick diamond detector (D09) inside the vacuum measuring chamber at the 14 MeV neutron generator and the simulation prepared by SIMRA code [9].

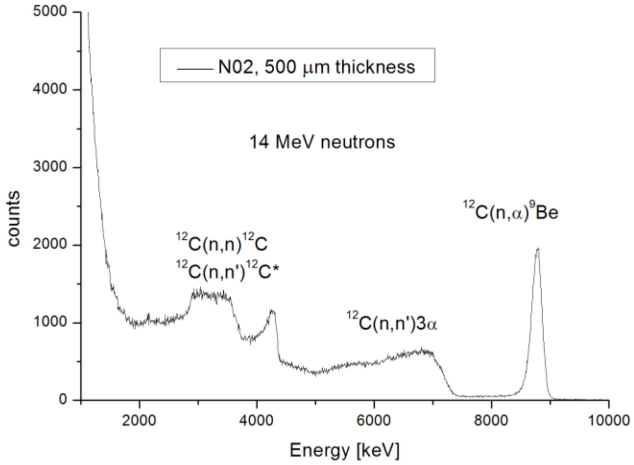

Fig. 23 Example of a response of the 500 μm thick scCVD diamond detector (N02) at 14 MeV neutron generator (neutrons outside the measuring chamber)

5. Conclusions

Usability of the scCVD detectors in diagnostic of the thermonuclear plasma was confirmed experimentally. Spectrometric properties of detectors have been verified for different ions as alphas, protons, deuterons and fast neutrons.

The base of the spectrometric diagnostic with diamond detectors in the mixed nuclear fields was elaborated.

The experiments that have been carried out demonstrated linearity and high resolution of the diamond detector in a wide range of the α particle energies (0.4 – 8.8 MeV) (isotopic source and beams from van de Graaff accelerators). Calibration of detectors with alpha sources is valid for the other ions. Also the scCVD diamond detectors of 500 μm thickness are destined for spectrometric measurements of 14 MeV neutrons at the neutron generator. They are, of course, sensitive also to ions which leave tokamak plasma (in the case when the detector is placed inside the vessel). Therefore, response of the detectors for different ions was investigated. The spectrometric properties of the 500 μm thick detector were found the same as of 50 μm detectors which are thought to be used for alpha particle (and other ions) detection. A very good reproducibility of various detectors responses was stated. Therefore, a combination of thin and thick detectors is possible to be used in order to get demanded information when the detectors are used in mixed irradiation fields, which is present at tokamaks. The test experiments for the elaborated method will be continued at the COMPASS tokamak in Prague (Czech Republic).

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