A compact fast corpuscular spectrometer with a detector based on natural diamond was installed at JET tokamak in addition to multi-channel Neutral Particle Analyzer (NPA) to study the evolution of the distribution function of fast plasma ions in real and kinetic spaces under various scenarios of additional plasma heating (injection of neutrals and ion cyclotron range of frequencies heating). Digital spectrometric tract allows spectrometer to operate at peak load reaching a value 107 registrations per second which corresponds to particle flux 6x10^8 particles/(cm^2s). Established in the equatorial pipe the Diamond Neutral Particle Spectrometer (DNPS) operates within the energy range 70 - 4000keV. Particle flux and spectra obtained during selected discharges of the JET campaign C27 with different regimes of additional heating are presented.

A similar spectrometer is proposed for installation in the future tokamak-reactor ITER in the NPA diagnostic channel. The schemes of proposed allocation are presented. The main characteristics of the developed spectrometer, the expected signal estimates and operation modes of the spectrometer under different scenarios of the ITER tokamak are presented.
1. INTRODUCTION

Vertical and horizontal Neutral Particle Analyzers (NPAs) that are installed at JET tokamak [1], allow one to analyze the energy distribution of ions of the tokamak plasma, the particles are separated by mass and charge, but NPAs have several disadvantages such as limited number of channels, low efficiency of registration and the cones of registration that are directed strictly perpendicular to the plasma currant. In addition to these JET diagnostics a spectrometer of fast charge-exchange atoms with a Natural Diamond Detector (NDD) with a digital signal processing, which has 100% detection efficiency [2] has been installed. Cone of the registration of the NDD spectrometer intersects the axis of the plasma at an angle of 18\(^\circ\). With high time resolution, diamond spectrometer of charge-exchange atoms can be used in studies of the effectiveness of different types of additional plasma heating, the interaction of plasma instabilities with a fast ion component.

2. NDD SPECTROMETER WITH DIGITAL SIGNAL PROCESSING

Spectrometer exchange atoms with a sensitive element of the natural diamond nizkoprimesnogo group IIa includes a specially developed fast electronics, as well as high-speed A / D converter installed in the computer industry, which produces the collection and processing of experimental data.

Figure 1 shows a diagram of the spectrometer with a digital (upper branch) and analog (lower branch) signal processing. Digital signal processing (DSP), in addition to improving the counting rate has several advantages, such as a more accurate determination of position and amplitude of the pulse, the possibility of multiple post-processing, automation and integration of data collection and processing [2]. In the bench experiments, the pulse detection threshold was about 20 keV, but in real terms due to signal noise, it rose up to 70, and in some discharges up to 100 keV.

![Fig1. Block diagram of the spectrometer on the basis of natural diamond with a digital (upper branch) and analog (lower branch) signal processing.](image)

When registering a particle with NDD at the output of a charge-sensitive preamplifier signals are formed, whose shape is shown in Figure 2. The signal from the diamond spectrometer in
the real experiment is very noisy because of interference from a vacuum pump that operates near the preamplifier, as well as from the rotors of the other diagnostics (with rotating detectors). Data processing is carried out in several stages, the main of which are:

1) quick search for a pulse with "soft" conditions - search for rapid baseline shift above a certain threshold, the accuracy of determining the position of the front at this stage equals half of its length;

2) the exclusion of false detections - check the detected events for the linearity of the front line, of segments to the left and right of the front. Here high-frequency and midrange noise as well as overlapping pulses are eliminated, the low-frequency noise does not have an appreciable effect on the detection of a pulse;

3) precise positioning of the pulse - a few areas of the proposed wavefront approximated by a given wavelet waveform, the point at which the deviation of the wavelet from the data is minimal is considered as the position of the pulse. At this stage, the position of the pulse is determined within ADC sampling step;

4) linear approximation of the two segments of data (before and after the alleged wavefront) - these segments (blue and orange lines in Figure 2) are obtained by the method of least squares;

5) calculation of the amplitude of the initial pulse, using the obtained approximation - several options are implemented to choose from by an experimenter. Depending on the duration of the pulse decay (characteristic of the preamplifier) and the length of the approximation intervals (user selectable), as well as the noise.

Fig 2. A typical processed signal. Thick lines indicate the detected wavefront.

Fig 3. Diamond detectors location at JET tokamak. Two detectors are placed in the KS6 chamber (near X-Ray & VUV survey).
level, one can use the values of the midpoints of the segments or the value closest to each other points of the two intervals (the last point of the left segment and the first point of the right segment) to calculate the amplitude of the initial pulse.

3. SPECTROMETER ARRANGEMENT

Two codirected diamond detector are located (in the chamber KS6) at the end of 20-meter vacuum channel communicating with the chamber through the JET tokamak equatorial diagnostic port in octant 6, the registration cone of the NDDs crosses the plasma axis at an angle of 18°. The preamplifier is located just outside the vacuum chamber KS6, 20 centimeters from the detectors. The signal is transferred to the rest of the equipment in a computer hall by an 80-meters cable. Two NBIs that are located in the fourth and eighth octants, each have two lines of injection - normal and tangential. Normal beam crosses plasma at a larger angle and is directed at the inner wall of the tokamak vacuum chamber, while tangential beam goes to the opposite outer wall of the chamber. As shown in Figures 3 and 4, the cone of registration of NDDs crosses tangential ray of eighth octant injector. Vertical NPA "sees" both beams while the horizontal NPA “sees” only the tangential beam of the fourth quadrant injector.

In addition to charge-exchange atoms diamond detector is sensitive to both neutron fluxes and X-ray. In the experiments discussed below, the plasma temperature does not exceed 20 keV, therefore, the bremsstrahlung spectrum of electrons lies below the detection threshold of the spectrometer (70 keV in the best discharges). The intensity of the more energetic lines at such a great distance from the tokamak is negligible. Moreover no correlation with the JET X-ray diagnostics is observed. There is also no correlation with the neutron diagnostics. In no-tritium experiments 14 MeV neutron flux is several orders lower than 2.5 MeV [3], the instrumental spectrum of the registration of the latter with the diamond detector is given by a uniform distribution from 0 to 800 keV, which does not correspond to the distributions observed in the experiments described below.
4. EXPERIMENTS WITH COMBINED ADDITIONAL PLASMA HEATING

To analyze the effect of slowing down of the particles on their energy distribution using a digital diamond spectrometer three JET pulses were analyzed. These experiments were dedicated to the study of retention of hydrogen and helium-4 plasmas. Energy spectra of atoms of hydrogen were obtained in the regimes of the tokamak with ICRH and NBI.

With He4 as the main component of plasma, He4 neutral injection and a small addition of H, the resonance ICR heating, located in the plasma, was consistent with the first harmonic of hydrogen. Time diagrams of additional heating, as well as count rates of diamond spectrometer (shown in Figure 5) confirm the assumption that the detected particles are the minority hydrogen atoms accelerated by ICRH. Spectra of the hydrogen atoms observed during three discharges with similar scenarios of additional heating are given in Figure 6. In discharge 79203, the plasma density at 63-65 seconds was about $1.5 \times 10^{19} \text{ m}^{-3}$, whereas for discharges 79199 and 79202, this value was on average $2.8 \times 10^{19} \text{ m}^{-3}$. Because of this characteristic the slowing down time of the ions in the discharge 79203 is more than that in discharges 79199 and 79202. Pulse 79203 shows a higher
count rate and higher energy distribution of hydrogen atoms reported then in pulses 79199 and 79202.

Data experiments demonstrate energy absorption by the minority ions of hydrogen on the first harmonic while without He4 injection. The dynamics of the measured flux indicates that in the presence of injection (the initial phase of ICRH) the wave energy is mainly absorbed by the high energy beam through a mechanism on the second harmonic of the ion cyclotron frequency.

It is also possible to assume that the detected particles are atoms of helium-4, accelerated by the ICRH-heating on the second harmonic, but in this case, the peak of the count-rate would be observed during the simultaneous operation of neutral injection and ICRH. Moreover, in the discharge 79203 during the ICRH, the power of neutral injection was 5 times lower than in discharges 79199 and 79202. In this case smaller count-rate should have been observed in this discharge. However, the observations are opposite.

To analyze the effect of additional heating on the energy distribution of ions in the plasma JET discharges 79340, 79341 and 79343 were selected. In these experiments with ICRH at several frequencies [3] - a 1st harmonic resonance for the main component of plasma (H), a 2nd harmonic resonance for injected particles (D) and a 1st harmonic resonance for minority (He3, the near-wall resonance) - particle flux in the diamond detector were observed only during operation of the injector number 4 at a time with a powerful (more than 3 MW) ICRH. (See Figure 7) If we assume that the detected particles are a product of the charge-exchange of the main component of plasma on the hydrogen-like atoms of carbon, emerging in the plasma as a beam effect, then in this case, the presence of energetic hydrogen ions would be observed in other time windows as a result of Fig 7. Additional heating powers for discharges 79340, 79341 and 79343, as well as the counting rates of the diamond spectrometer for these discharges.
exchange of these ions on the atomic hydrogen present in plasma and charge-exchange on which is more likely than on carbon. However, this is not observed, therefore, the flux of atoms formed by charge exchange of ionized atoms of the beam, accelerated by ICRH at the second harmonic were measured. In discharge 79341 and 79343 particles with energies above 200 keV are registered, while in the discharge 79340 particles had lower energies, that is a consequence of lower power ICRH in this discharge.

5. Proposal for ITER

A diamond-detector-based neutral particle spectrometer (Diamond Neutral Particle Spectrometer, DNPS) is proposed for ITER plasma diagnostics as a supplementary part of the Neutral Particle Analyzers (NPA) system. In different regimes of ITER operation the DNPS is capable to provide either charge-exchange atoms’ or neutrons’ flux and spectra. Diamond Detectors have been applied at several tokamaks [4,5,6] including JET [7,8] for both charge exchange atoms and neutrons spectroscopy and monitoring. The application of diamond as a sensitive element for spectroscopy is determined by its high radiation hardness (at least 2 orders of magnitude higher than that of silicon) along with wide band gap, high breakdown voltage and small charge collection time. The detector’s have very high radiation resistance - maximum acceptable fluence (up to which it maintains its spectrometric properties,) is about 5x10^{14} n/cm², that is at least 100 ITER discharges, considering detector position. Then it should be replaced. Pure electronic grade CVD diamond plates used as sensitive elements of the detectors are now commercially available.

The main purposes of the DNPS as a charge-exchange atom spectrometer for ITER are:

- Investigation of the dynamics of fast ion energy and spatial distributions during various plasma instabilities. In the process of the instability development a fraction of high-energy ions moves outside of the plasma core to the periphery where they can charge-exchange and the

Fig 8. Energy distributions of detected particles in discharges 79340, 79341 and 79343.
resulting atoms can reach the diamond detector. The energy spectrum of this fraction of ions can provide information on the peculiarities of the instabilities development in plasma.

- Additional heating (NBI, ICRH) efficiency studies. The energy spectrum of ICRH-accelerated and beam injected ions after their charge exchange inside plasma could be measured by DNPS. This will provide information on the efficiency of the RF waves coupling and fast ion confinement.

- Studies of charged fusion products (alpha-particles, protons, tritons) generation, confinement and slowing down.

Operating as a neutron spectrometer the DNPS can provide ion temperature measurements of the deuterium-tritium plasma and data for fast deuterium and tritium energy distributions studies. It will also provide the neutron flux monitoring.

The proposed DNPA system is dual-channel. Each channel consists of a diamond detector and a preamplifier. The detectors are different in the aperture and the size of diamond plates (Ø3 mm and Ø8 mm) and therefore have different sensitivities to provide wide range of the counting rates. The preamplified signals are digitized using 2-channel ADC (2x400 MHz, 16 bit) with preliminary processing and stored in the database for post-analysis.

The preamplifier can be located at most 3 meters away from the detector. It allows the preamplifier to be placed behind the neutron shielding.

The electronics and data processing software, which define the maximal counting rate of the DNPS, are able to operate at loads of $10^6$ counts per second. The lower energy detection threshold is determined by the noise level of the electronics and for various regimes builds up to 50÷100 keV. The upper limit of the spectrometry is defined by the thickness of the crystal and for 100 µm equals 4 MeV ($^1$H atoms).

Two diamond detectors are to be installed in the vacuum pipe of the NPA system, in front of the High Energy Neutral Particle Analyzer (HENPA) (Fig. 4), combined with the front mirror of the H-alpha diagnostic. The H-alpha front mirror system is to be placed between two vacuum valves. Such location allows it to have a mechanism of mirror replacement without depressurizing.
the analyzers. The 2 DDs are attached to the mirror holders and are removed down from the pipe along with the mirror, as shown in Fig. 5 by pink arrow. There are 2 cylindrical holes (Ø10mm each) in the mirror for the DDs, as they are placed behind it.

The DDs are 10 meters away from ITER first wall; the aperture in the first wall is 20 cm, detectors’ apertures are 3 and 8 mm.

Two extreme scenarios of ITER operations were applied for calculating the DNPS counting rates. These are Inductive mode with cold and dense plasma and Steady State mode with hot and more diluted plasma. The parameters of the scenarios are available through IDM (IDM UID 2V2XYR and 2V3FDF respectively). Other scenarios will represent intermediate parameters and thus counting rates.

DNPS’s neutrons counting rate may be estimated with the following formula:

$$\frac{dN}{dt} = \dot{\Phi} \cdot \alpha,$$

where $\Phi$ – total neutron flux in the detector location, $\alpha$ – sensitivity of the detector:

$$\alpha = \frac{\pi R^2 h \cdot \rho \cdot \sigma \cdot N_A}{A_r},$$

where $\pi R^2 h$ – volume of the detector, $\rho$ – carbon density (g/cm$^3$), $A_r$ - atomic weight, $\sigma$ – interaction cross section. $N_A$ – Avogadro constant. Total neutron fluxes in the location of the detectors are estimated at $\dot{\Phi}_{DD} = 5 \cdot 10^7 \frac{n}{cm^2 \cdot s}$ for D-D phase and $\dot{\Phi}_{DT} = 10^{10} \frac{n}{cm^2 \cdot s}$ for D-T phase. Using these estimations the neutron counting rates are calculated and presented in the table below.
To calculate the atom counting rate for DNPS the collimator geometry was adopted from the “Allocation” section of this document. Deuterium and tritium charge exchange atom flux were previously calculated for the NPA system [10,11] as:

D plasma:
\[ F_D = 2 \times 10^{14} \text{ l/(m}^2\text{*ster}*\text{s}), \quad F_T = 1 \times 10^{11} \text{ l/(m}^2\text{*ster}*\text{s}) \] for Steady State mode and
\[ F_D = 3 \times 10^{13} \text{ l/(m}^2\text{*ster}*\text{s}), \quad F_T = 1 \times 10^{10} \text{ l/(m}^2\text{*ster}*\text{s}) \] for Inductive mode;

D-T plasma:
\[ F_D = 1.05 \times 10^{14} \text{ l/(m}^2\text{*ster}*\text{s}), \quad F_T = 6.70 \times 10^{13} \text{ l/(m}^2\text{*ster}*\text{s}) \] for Steady State mode and
\[ F_D = 1.50 \times 10^{13} \text{ l/(m}^2\text{*ster}*\text{s}), \quad F_T = 4.73 \times 10^{12} \text{ l/(m}^2\text{*ster}*\text{s}) \] for Inductive mode

Taking into account 100% efficiency of Diamond Detector in the case of fast atom measurements, the counting rate of DNPS for charge exchange deuterium or tritium atom flux can be calculated using the following formulae:

\[ \frac{dN_{d,t}}{dt} = F_{d,t} \cdot \omega \cdot S, \]

where \( F_{d,t} \) are given above; \( \omega \) – solid angle (cone of measurements); \( S \) – surface of the detector.

The solid angle of the cone of measurements for the geometry discussed in previous chapter equals \( 3 \times 10^{-4} \) steradian. The detectors’ diamond plates may be from 1 to 10 mm across diameter and from 0.05 to 0.2 mm thick. Two detectors with Ø3 x 0.075 mm and Ø8 x 0.075 mm crystals would provide spectroscopy within wide flux range and will cover energy range up to 3 MeV for hydrogen measurements. The following table contains results of DNPS counting rate calculations for chosen ITER modes.
<table>
<thead>
<tr>
<th></th>
<th>Ø3 x 0.075 mm</th>
<th>Ø8 x 0.075 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D plasma</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutrons counting rate</td>
<td>1.0e+4</td>
<td>7.1e+4</td>
</tr>
<tr>
<td>Gamma counting rate</td>
<td>1.7e+3</td>
<td>1.2e+4</td>
</tr>
<tr>
<td><strong>Inductive mode</strong></td>
<td></td>
<td></td>
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<tr>
<td>D counting rate (0.1 - 2MeV)</td>
<td>7.0e+4</td>
<td>5.0e+5</td>
</tr>
<tr>
<td>T counting rate (0.1 - 2MeV)</td>
<td>2.3e+1</td>
<td>1.6e+2</td>
</tr>
<tr>
<td><strong>Steady state</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D counting rate (0.1 - 2MeV)</td>
<td>5.0e+5</td>
<td>3.0e+6</td>
</tr>
<tr>
<td>T counting rate (0.1 - 2MeV)</td>
<td>2.0e+2</td>
<td>1.6e+3</td>
</tr>
<tr>
<td><strong>DT plasma (ratio 1:1)</strong></td>
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<td></td>
</tr>
<tr>
<td>Neutrons counting rate</td>
<td>1e+6</td>
<td>7.1e+7</td>
</tr>
<tr>
<td>Gamma counting rate</td>
<td>7e+5</td>
<td>5e+7</td>
</tr>
<tr>
<td><strong>Inductive mode</strong></td>
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<td></td>
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<tr>
<td>D counting rate (0.1 - 2MeV)</td>
<td>3.5e+4</td>
<td>2.4e+5</td>
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<tr>
<td>T counting rate (0.1 - 2MeV)</td>
<td>1.0e+4</td>
<td>7.5e+4</td>
</tr>
<tr>
<td><strong>Steady state</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D counting rate (0.1 - 2MeV)</td>
<td>2.3e+5</td>
<td>1.6e+6</td>
</tr>
<tr>
<td>T counting rate (0.1 - 2MeV)</td>
<td>1.5e+5</td>
<td>1.0e+6</td>
</tr>
</tbody>
</table>

During the ITER tokamak operation with deuterium plasma both detectors can operate as charge exchange spectrometers. Atom counting rates are expected to be one order of magnitude higher than the counting rates for neutrons. At maximum atom flux in the steady state operation scenarios the detector with a larger diamond will work in near-critical load regime, in this case the more reliable signal will be provided by the detector with smaller crystal.

![Graph](image1)

**Fig 12.** Total diamond detector DT-neutron pulse height spectrum.

**Reactions:**
1. Elastic and non-elastic scattering,
2. $^{12}$C (n, n') $^4$He

**Fig 13.**

- **a)** Estimated energy distributions of the gamma fluxes in the position of diamond detectors [13],
- **b)** Estimated response function of the (Ø3x0.075mm) diamond detector to the gamma flux with energy distribution given above [14].
In the DT-campaign detector with the smaller crystal will provide necessary counting rates, so the other one will provide the higher dynamic range of the measurements working at lower neutron yield or may be replaced with the same small size crystal and closed aperture. In the latter setup the second detector will be registering exclusively neutrons. Subtracting one spectrum from the other will provide the spectrum of charge-exchange atoms without neutron background. Although in D-T plasmas gamma counting rate is comparable to the one for neutrons, the useful part of neutron spectrum may be separated from gamma background because of its significantly higher response energy. The reaction $^{12}$C (n, $\alpha_0$) $^9$Be has a dedicated peak in the pulse height spectrum at 8.4 MeV (see Fig. 6) [12], while the main part of the response function for gamma rays is below 2.5 MeV (see Fig.7) due to Compton-electrons escaping the small diamond plate.

For atom spectroscopy during the deuterium phase with 10-channel spectrum 5000 counts are required for average 10% statistical accuracy of each energy channel below 1.5 MeV. This means that counting rate of $5 \times 10^4$ cps will result in time resolution of 100ms.

For neutron spectroscopy only 5% of registered neutrons have entered the reaction without secondary neutron and only these 5% are useful [7]. Therefore at the counting rates of $10^6$ cps time resolution of 20 ms is achievable with at least 10% statistical accuracy for each energy channel between 7.5 and 8.5 MeV.
6. CONCLUSION

For the first time the fast charge-exchange atom spectrometer based on a natural diamond detector with a digital signal processing was experimentally implemented at JET tokamak. Spectrometer has demonstrated its efficiency in the world's largest thermonuclear facility. The data obtained by the spectrometer allows to analyze the influence of plasma parameters on the characteristics of energy distributions of ions, as well as the effectiveness of joint use of such methods of additional heating of the plasma as the injection of fast neutral particles and ion cyclotron heating.

The proposed DNPS system for ITER is able to provide charge-exchange atom spectroscopy for 'official' (as of Dec'10) ITER scenarios - Inductive and Steady State in deuterium phase with required accuracy (10%) and time resolution (0.1s). The charge-exchange atoms spectra acquired by the DNPS will have a wide range of applications and interpretations depending on the task of the experiment.

Acknowledgments

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