EFDA–JET–PR(11)51

V.A. Krasilnikov, V.N. Amosov, I. Coffey, S. Popovichev, Yu.A. Kaschuk,
A.V.Krasilnikov and JET EFDA contributors

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V.A. Krasilnikov[1], V.N. Amosov[1], I. Coffey[2], S. Popovichev[2], Yu.A. Kaschuk[1], A.V. Krasilnikov[1] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]SRC RF Triniti, Troitsk 142190, Moscow Region, Russian Federation
[2]JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
** See annex of F. Romanelli et al, "Overview of JET Results",*
(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

Preprint of Paper to be submitted for publication in
Plasma Physics Reports

ABSTRACT.
To study the evolution of the distribution function of fast atoms in a real and kinetic spaces under different scenarios of additional plasma heating (injection of neutrals and ion cyclotron heating) in addition to multi-channel neutral particle analyzer a compact fast corpuscular spectrometer with a natural diamond detector was introduced at JET Tokamak. The new digital spectrometric tract at peak load allows spectrometer to reach a value 10^7 registrations per second. Established in the equatorial pipe of JET tokamak the diamond detector provides spectrometry of neutral particles in the energy range 70 – 5000keV. Flux of the charge-exchange atoms were observed both during simultaneous operation of the Ion-Cyclotron Resonant Heating (ICRH) and Neutral Beam Injection (NBI), and during only ICRH heating. The flux dynamics and spectra of the deuterium atoms with energy above 70keV in the experiments with a combined additional plasma heating are presented. The formation of a group of fast minority ions in the plasma accelerated by ICRH at the fundamental frequency, as well as the beam injected ions additionally accelerated by the ICRH through the mechanism at the second harmonic were observed.

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^{o}. 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 20keV, but in real terms due to signal noise, it rose up to 70, and in some discharges up to 100keV.

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 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^{o}. 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 Figure 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 20keV, therefore, the bremsstrahlung spectrum of electrons lies below the detection threshold of the spectrometer (70keV 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 14MeV neutron flux is several orders lower than 2.5MeV [3], the instrumental spectrum of the registration of the latter with the diamond detector is given by a uniform distribution from 0 to 800keV, 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 Pulse No: 79203, the plasma density at 63-65 seconds was about 1.5×10^{19} m^{-3}, whereas for Pulse No's: 79199 and 79202, this value was on average $2.81.5\times10^{19}$ m^{-3}. Because of this characteristic the slowing down time of the ions in the Pulse No: 79203 is more than that in Pulse No's: 79199 and 79202. Pulse No: 79203 shows a higher count rate and higher energy distribution of hydrogen atoms reported then in Pulse No's: 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 Pulse No: 79203 during the ICRH, the power of neutral injection was 5 times lower than in Pulse No's: 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 Pulse No's: 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 3MW) ICRH. 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 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 Pulse No's: 79341 and 79343 particles with energies above 200keV are registered, while in the Pulse No: 79340 particles had lower energies, that is a consequence of lower power ICRH in this discharge.

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.

ACKNOWLEDGMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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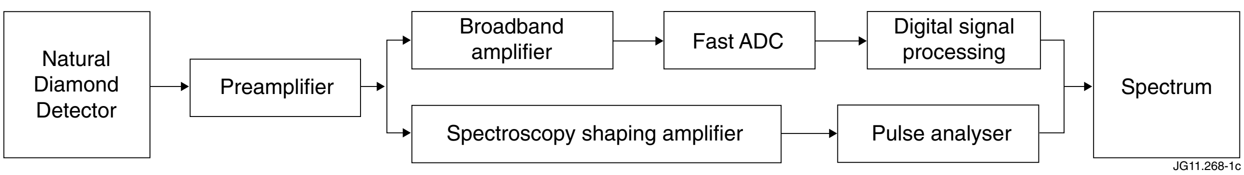

Figure 1: Block diagram of the spectrometer on the basis of natural diamond with a digital (upper branch) and analog (lower branch) signal processing.

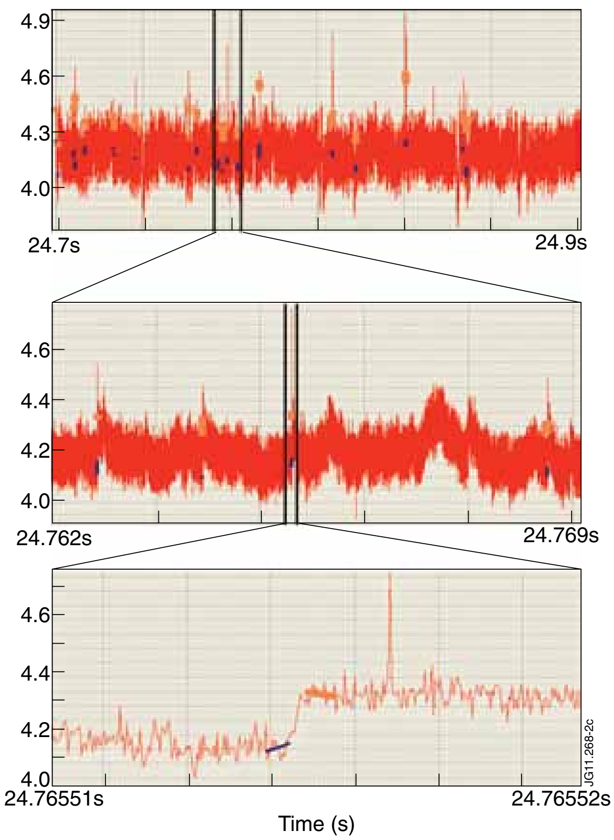

Figure 2: A typical processed signal. Thick lines indicate the detected wavefront.

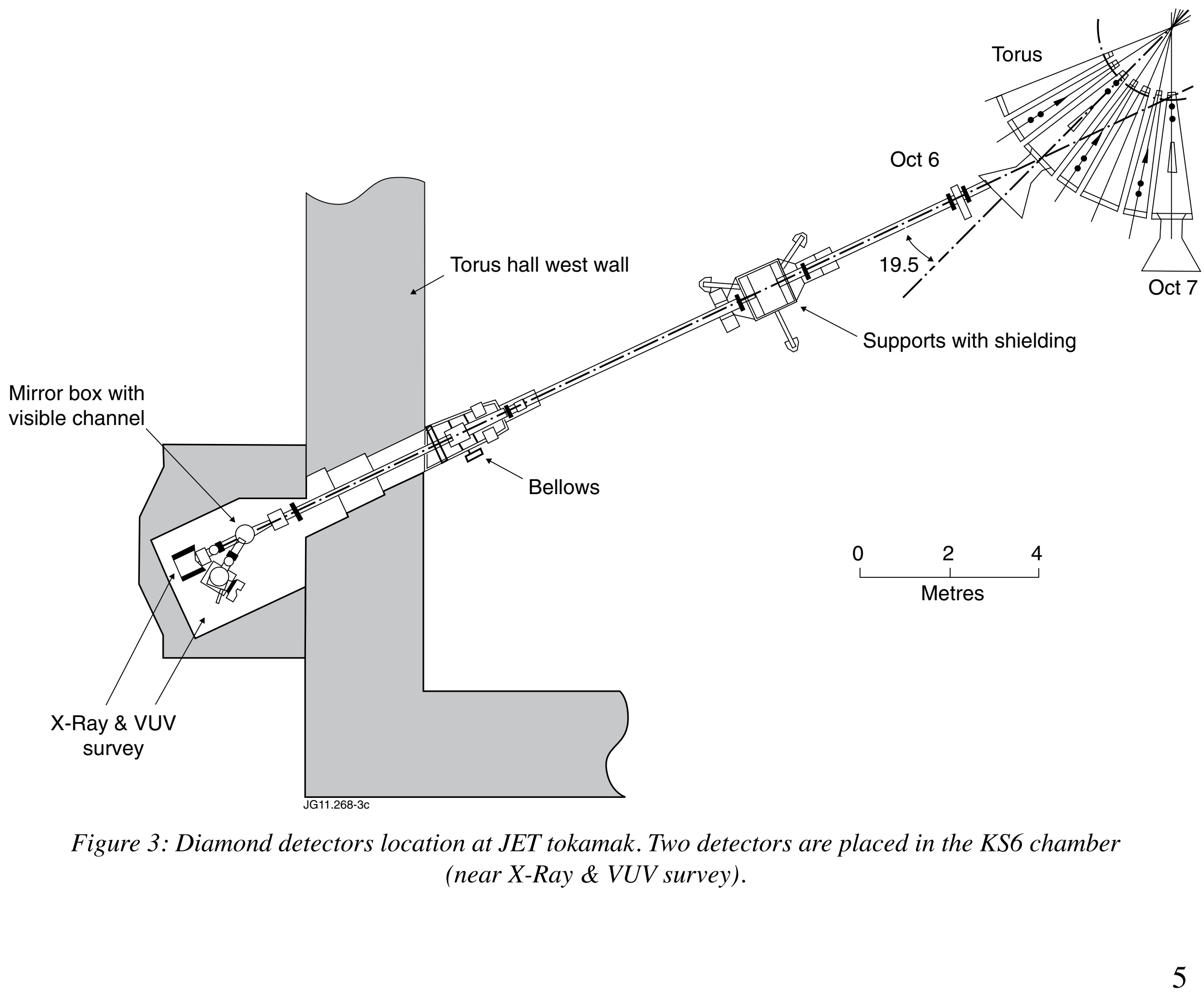

Figure 3: Diamond detectors location at JET tokamak. Two detectors are placed in the KS6 chamber (near X-Ray & VUV survey).

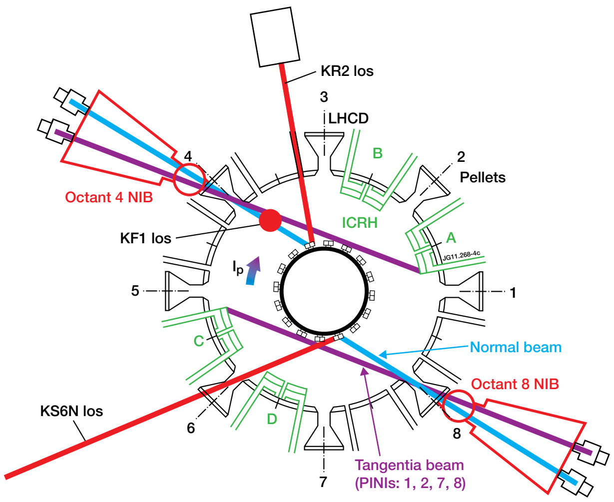

Figure 4: Beams of neutral injectors, line of sight of diamond spectrometer (KS6N) and two neutral analyzers (vertical KF1 and horizontal KR2).

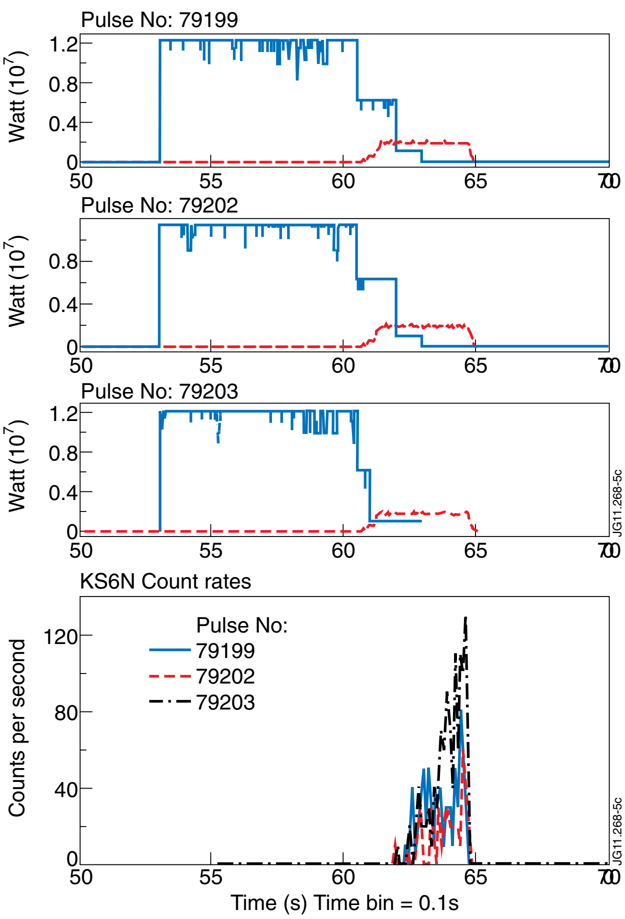

Figure 5: Additional heating powers for JET Pulse No's: 79199, 79202 and 79203, as well as the counting rates of the diamond spectrometer for these discharges.

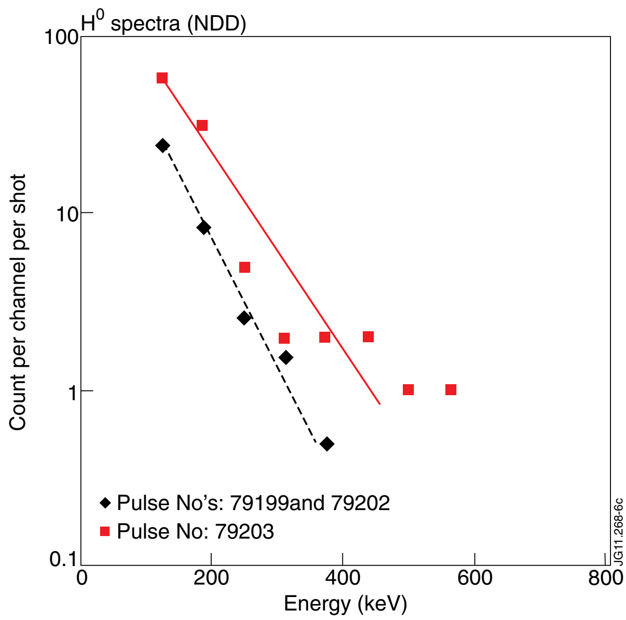

Figure 6: Energy distributions of detected particles in Pulse No's: 79199, 79202 and 79203.

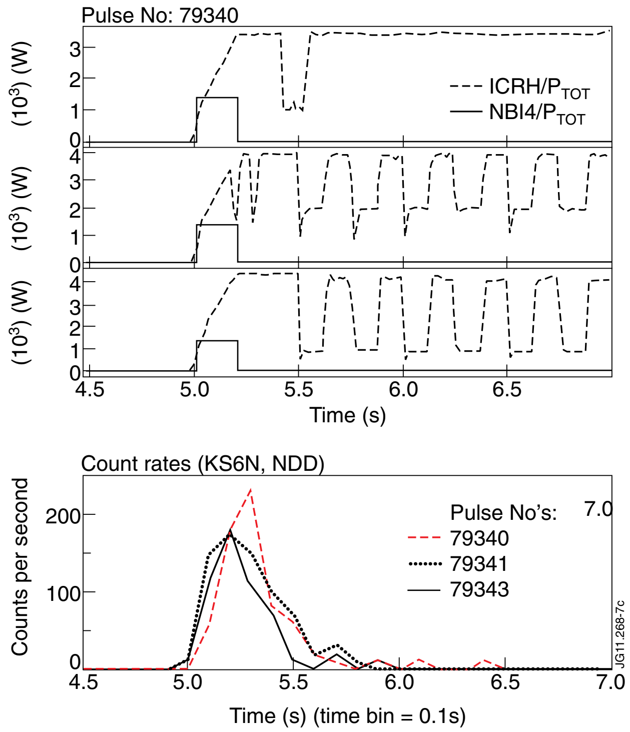

Figure 7: Additional heating powers for Pulse No's: 79340, 79341 and 79343, as well as the counting rates of the diamond spectrometer for these discharges.

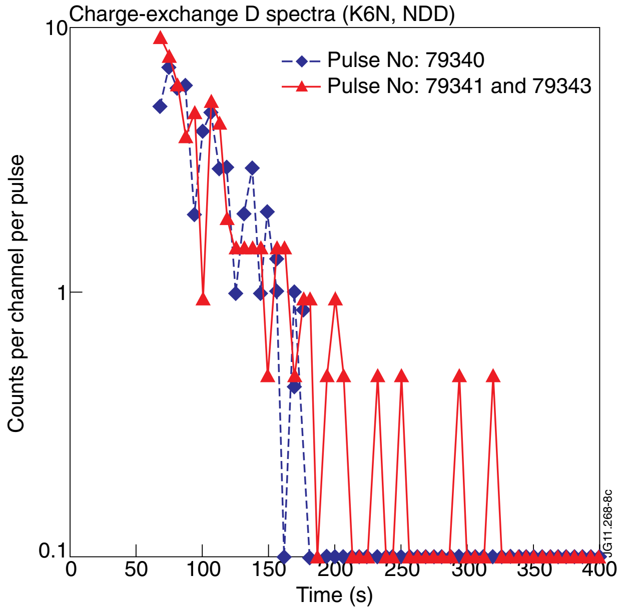

Figure 8: Energy distributions of detected particles in Pulse No's: 79340, 79341 and 79343.