Neutron and Fast Atom Spectrometry Using Natural Diamond Detectors

KRASILNIKOV Anatoli V., AMOSOV Vladimir N., GORELENKOV Nikolay N., ISOBE Mitsutaka¹⁾, JARVIS Neil O.²⁾, KANEKO Osamu¹⁾, KASCHUCK Yuri A., MEDLEY Sidney S.³⁾, NISHITANI Takeo⁴⁾, OHYABU Nobuyoshi¹⁾, PORTNOV Dimitri V., ROQUEMORE Lane A.³⁾, SADLER Guy J.²⁾, SASAO Mamiko¹⁾ and VAN BELLE Peet²⁾

Troitsk Institute for Innovating and Fusion Research TRINITI, Troitsk, Moscow region, 142092, Russia

¹⁾National Institute for Fusion Science, Toki 509-5292, Japan

²⁾JET, Joint Undertaking, Abingdon, OX14 3EA, UK

³⁾Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ, 08543, USA

⁴⁾Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Ibaraki 311-0193, Japan

(Received 18 December 1998 / Accepted 19 May 1999)

Abstract

In the period from 1993–98, several Natural Diamond Detectors (NDD) developed in Russia were used for D-T neutron spectra measurements during tritium experiments on the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET), in triton burn-up studies on JT-60U and for fast charge exchange atom spectrometry during ion cyclotron resonance heating on TFTR and neutral beam injection on the Large Helical Device (LHD). Some results of this international activity will be presented in this review paper. A number of unique properties makes the NDD very promising for neutron and high energy particles spectrometry and flux monitoring in future burning plasma and other high energy physics experiments.

Keywords:

natural diamond detector, neutron spectrometry, charge exchange atom spectrometry, fast ion energy distribution, deuterium-tritium plasma

1. Introduction

For ignition optimization and burning control in future fusion reactor it is necessary to measure a wide range of plasma characteristics. Some of these characteristics such as neutron yield, fusion power and its spatial distribution, profiles of ion temperature, pressure and plasma rotation are mostly determined by plasma ions. Hence, measurements and control of spatial and energy distributions of thermal ions, α -particles and fast ions created by Ion Cyclotron Range of Frequencies (ICRF) heating and Neutral Beam Injection (NBI) are of

great importance. Due to the high fluxes of Deuterium-Tritium (DT) neutrons, the neutron diagnostics can be one of the most important method for measurement of these characteristics for a reactor plasma. Valuable information could be also obtained by means of spectrometry and flux measurements of charge exchange atoms. Multi chord measurements with sufficient spatial resolution are necessary at least at the stage of an experimental reactor. So diagnostic systems should be as compact as possible and, of course, radiation resistant.

During 1993–98 several Natural Diamond

corresponding author's e-mail: anatoli@fly.triniti.troitsk.ru

† この論文は第15回年會にて招待講演として発表されたものを論文化したものです。

Detectors (NDDs) developed in Russia [1-3] were used for DT neutron spectra measurements [4] on the neutron generators SNEG-13 [5] and NGM-17 [6] in Russia, Frascati Neutron Generator (FNG) in Italy [7], and Fusion Neutron Source (FNS) in Japan [8]. In addition, NDDs were used during tritium experiments on the Tokamak Fusion Test Reactor (TFTR) [9-12] and the Joint European Torus (JET) [13], and during triton burn-up studies on JT-60U [14]. Several NDDs were used for fast charge exchange atom spectrometry and flux dynamics measurements during ICRF heating on TFTR [15,16] and NBI on the Large Helical Device (LHD) in 1997-98. Some results of this international activity will be presented in this review paper.

2. NDD as a DT Neutron and Fast Particle Spectrometer

Natural diamond detectors are one of the most useful choices for DT neutron, fast charged particle and atom spectrometry and flux measurements due to a number of its outstanding properties. These detectors were developed and now are routinely manufactured in Russia.

A NDD has a three layer structure (i.e., metal – semiconductor – metal structure) with Au or Ti/Pt/Au as metal and a very pure natural diamond selected from group IIa as semiconductor [1,2]. High band gap (5.5 eV), resistivity ($> 10^{15} \Omega\text{m}$) and breakdown resistance (10^7 V/cm), large saturation velocity ($2 \times 10^7 \text{ cm/s}$) and mean free drift time (10–15 ns) are crucial for materials used in radiation detectors.

The mechanism of detection is based on the collection of charge carriers created by incident radiation interacting with a diamond. The electric charge produced within the sensitive volume of a diamond detector (i.e. the natural diamond region) is collected by means of an external electric field. Thus, the NDD is capable of detecting any particles generating charge carriers in it. These include UV radiation, x-rays, γ -rays, high energy particles such as α -particles, electrons, atoms, neutrons and others. The NDD is sensitive to 2.5 MeV neutrons and γ -rays due to ^{12}C recoil nuclei and Compton electrons produced inside the diamond detector during elastic scattering of neutrons and by γ -rays, correspondingly [7]. The possibility for using NDD for DT neutron spectrometry is ensured by the shape of the NDD pulse height spectrum in a DT neutron flux [5-8] (see Fig. 1). Such a pulse height spectrum is determined by the high energy charged particles (α , ^9Be and ^{12}C) created inside the diamond by

Fig. 1 Total NDD pulse height spectrum in 14.1 MeV neutron flux of FNS.

nuclear reactions as well as both elastic and inelastic scattering of the neutrons. Measured pulse height spectra are in excellent agreement with the results of calculations based on double differential cross sections for reactions taking place during the DT neutron interactions with a diamond [5]. Mathematical code used for these calculations was created [5] taking into account full charge collection in NDD and the fact that energy for electron-hole pair production in diamond equal to 13.2 eV. The $^{12}\text{C}(n,\alpha_0)^9\text{Be}$ reaction which creates a peak in the NDD pulse height spectrum around energy $E_n \sim 5.7 \text{ MeV}$ is the one useful for DT neutron spectrometry. In the case of our application of NDD for fusion plasma DT neutron spectrometry the broadening (FWHM) of this peak provides information about plasma ion temperature and averaged peak energy gives value of averaged velocity of participating in nuclear reaction deuterons and tritons along the detector cone of view. The absence of contributions from the other nuclear reactions to the pulse height spectrum around the $^{12}\text{C}(n,\alpha_0)^9\text{Be}$ peak, namely in the range $E_{\alpha_0+^9\text{Be}} \pm 2 \text{ MeV}$, is the unique feature of diamond in comparison with other semiconductor materials and makes the NDD a very useful tool for DT neutron spectrum measurements in hot (ion temperatures up to $\sim 50 \text{ keV}$) burning plasma [4].

Applications of NDDs to spectrometry purposes are based on the large (up to few mm) charge collection distance for selected natural diamonds. In the case of full charge collection, the detector signal is proportional to the kinetic energy of an ionizing charged particle and the detector operates as spectrometer. Crucial advantage of selected natural diamonds for spectrometric detector

development with respect to artificial CVD diamond like materials and high pressure grown diamond is the very low level of crystal lattice defects and impurities in it. This provides full free charge collection and so high energy resolution of NDD at high count rate. The energy resolution of the best NDDs is in the range 1.2–3% for 14 MeV neutrons and 5.5 MeV ^{241}Am alpha particles without any degradation at any high count rates which could be processed by spectroscopy electronics. Such high resolution coupled with the high radiation resistance of diamonds (5×10^{14} n/cm² [17]) and ability to operate in temperature range 100–450° K enables successful application for spectrometry and flux monitoring of 14 MeV neutrons [9–14], fast ions [18] and atoms [15,16] in the radiation conditions of large modern tokamaks. Extremely high radiation resistance of diamond detectors in comparison with other solid state detectors is based on very high (37–47 eV depending upon direction of displacement inside crystal lattice) energy necessary for carbon atom displacement from their crystal lattice position. Six NDDs with energy resolution 1.2 [6]–3% for DT neutrons and four NDDs with energy resolution 4–12% for fast atoms and ions were used in these experiments.

A NDD with dimensions: area –16 mm², thickness 0.2 mm and area of thin (50 nm) gold contacts –9 mm² has the following values of sensitivity: 5×10^{-4} counts/(n/cm²) total for DT neutrons; 10^{-5} counts/(n/cm²) due to the $^{12}\text{C}(n,\alpha)^9\text{Be}$ reaction for DT neutrons; 10^{-3} counts/(n/cm²) for DD neutrons; 10^{-3} counts/(γ/cm²) for ^{137}Cs and ^{60}Co gammas.

The duration of electrical pulses from a spectrometric NDD operating in the counting mode is about 3 ns, so the NDD itself can successfully operate at count rates up to 5×10^7 counts/s. However, pile-up effect in the electronics may make NDD spectrometry application impossible at such high count rates. The most critical component of an electronic circuit from the point of view of high count rate applications is the linear amplifier. We used the fastest standard spectroscopy amplifiers EG&G Ortec-673 and Canberra-2024 which provided spectrometry at an input count rate of up to 3×10^5 counts/s with an output count rate up to 10^5 counts/s. An ultra fast amplifier was specially developed to provide charge exchange atom spectrometry on TFTR at a count rate up to 4×10^5 counts/s [15]. To reduce the electronic noise (which affects the spectrometer energy resolution especially during charge exchange atom measurements), the low noise EG&G 142A preamplifier were used.

3. Some Results of NDD Application for DT Neutron Spectrometry

3.1 TFTR

Three NDDs were used for DT neutron spectrometry and flux monitoring during deuterium-tritium experiments on TFTR using NBI and ICRF heating. During these studies, up to six NBI sources were aimed in the counter-direction and up to six in co-direction, with a total power of 36 MW of 105 keV DT injection. Up to 3 MW of ICRF power at 30 MHz was injected with wave phasing 60° (counter), 180° (π), and 300° (co with respect to the plasma current) during ICRF heating at the fundamental triton cyclotron frequency. The high (up to 3×10^{18} n/s) yield of 14 MeV neutrons during TFTR experiments made it possible to use neutron spectrometry to study the ion energy distributions under reactor-like conditions. The small size of the NDD housing (~1 cm³) allowed the detectors to be inserted into the TFTR multichannel neutron collimator and fusion gamma shield without interfering with other detectors operating there. These NDD positions provided perpendicular and tangential DT neutron spectrometry [9–12].

For a Maxwellian DT plasma with ion temperature T in the range 30–50 keV, the FWHM of the DT neutron energy distribution is given by

$$\Delta E_n = 178 \sqrt{T_{\text{eff}}} \quad (\text{where } \Delta E_n \text{ and } T_{\text{eff}} \text{ are in keV [15]}) \quad (1)$$

The ion component in TFTR contains both thermal and hot beam ions. Energetic ions also appear during ICRF heating. The emitted neutrons result from three channels: beam-plasma (55–75%), beam-beam (0–20%) and thermal neutrons (10–30%). The anisotropy of TFTR hot ions produces an anisotropy on the DT neutron energy distribution. To model the D-T neutron spectra measured by each of the three NDDs, the Neutron Source post-TRANSP (NST) code was developed [10]. This code utilizes TRANSP [19] to calculate deuterium and tritium plasma densities and temperatures as well as D and T beam distribution functions and applies fusion cross sections to derive the neutron emission spectra using a well known [20] formulation. In addition to the NST code, a relatively simple semi-analytical model [10] for calculations of D-T neutron spectra for plasmas with anisotropic deuteron and triton distribution functions was developed. Good agreement between the data on the evolution of the $T_{\text{eff},\perp}$ measured by NDD during 22 MW NBI and the calculated result

modeled by the NST code is obtained as shown in Fig. 5 of ref. 9.

Figure 2 shows the evolution of T_{eff} as measured by three NDD-based neutron spectrometers during experiments with NBI power of 17 MW and ICRF heating power of 2 MW. The FWHM of the neutron energy distributions for perpendicular and tangential (with respect to plasma current axis) emission are different due to the anisotropy of the hot beam ions since the majority of the neutrons from TFTR are from beam-plasma and beam-beam interactions [19]. The FWHM is a function not only of the plasma ion temperature but also of the average energy of the beam ions along the detector viewing cone, which in turn is a function of the electron density. The decrease in the effective tangential

Fig. 2 Tangential (curve 1) and perpendicular (curve 2 and 3) triton effective temperature during tritium ICRF heating experiments: NBI power 17 MW, ICRF heating power 2 MW (curve 1 and 2); without ICRF heating (curve 3).

Fig. 3 Peak energy of tangential neutron spectra during tritium ICRF heating experiments with counter (curve 1) and co (curve 2) wave phasing.

temperature (Fig. 2, curve 1) and increase in effective perpendicular temperature (Fig. 2, curves 2 and 3) during the first half of the beam phase are functions of the change of beam penetration due to the increase of plasma density. The difference between curves 2 and 3 illustrates the increase in perpendicular energy of the tritons due to ICRF heating. The triton slowing down time was estimated from the decrease of the tangential effective temperature (Fig. 2, curve 1) after deuterium and tritium beams were turned off. The derived value of about 100 ms was in reasonable agreement with calculations.

Tangential DT neutron spectra measured by NDD during TFTR tritium minority ICRF heating experiments enabled the estimation of the averaged tangential velocity of resonance tritons for the cases of co- and counter-wave phasing. These velocities were derived from measured DT neutron peak position shifts (with respect to 14.16 MeV) shown in Fig. 3. During the first half of the heating time, the measured shift corresponded to averaged triton tangential velocities of $\pm 10^7$ cm/s and during second half to $\pm 7 \times 10^6$ cm/s. The decrease in the average triton tangential velocities can be explained by the increase of plasma density during NBI.

Measurements of tangential TFTR neutron spectra during pure co (5 sources of total power ~ 10 MW) and pure counter (4 sources, ~ 7 MW) deuterium beam injection into deuterium-tritium plasma enabled the estimation of the averaged tangential velocity of the injected beam deuterons. The peak of the tangential neutron energy distribution was shifted 0.44 MeV downward to lower energies during co injection (spectrum 1 of Fig. 4) and 0.43 MeV upward to higher energies during counter injection (spectrum 3 of Fig. 4) with respect to balanced injection case. The accuracy of these measurements was ± 60 keV. Taking into account that energies of beam deuterons are essentially higher than energies of plasma tritons, we can write the following equation for the relation between averaged deuteron tangential velocity and the energy of the neutron spectrum peak [12]:

$$E_n = 14.1 + 0.56 \times E_d + 2.13 \times \cos \theta \sqrt{E_d} \quad (2)$$

(where all E in MeV)

Averaged deuteron tangential energies estimated using equation (2) from data presented in the neutron spectra of Fig. 4 are 43 keV and 41 keV for co- and counter- injection, respectively. These values were in good agreement with the averaged deuteron tangential

Fig. 4 Tangential DT neutron energy distribution during co (1, upper spectrum), balanced (2, middle spectrum) and counter (3, lower spectrum) deuterium injection into TFTR DT plasma. Spectra (1) and (2) shift on 40 and 20 counts for better view. Arrows show energy distributions peaks positions.

energy obtained from measurements of the neutron spectra broadening during balanced deuterium injection.

3.2 JT-60U

On JT-60U [13], the NDD was used for DT neutron spectrum and DD and DT neutron flux measurements in experiments with deuterium plasmas. A NDD with an energy resolution of 2.5% was installed in the equatorial plane outside the torus vacuum chamber at a distance of about 0.5 m without a collimator. This was an actually the first attempt to measure the 14 MeV neutron spectrum coming from triton burnup. The studies of triton behaviour have been carried out before in deuterium discharges of several tokamaks by using mainly the absolute yield measurement.

The NDD application for DT neutron spectrometry during these enabled measurement of the averaged energy of tritons appearing inside deuterium plasma due to nuclear reactions during and after 100 keV deuterium NBI with power up to 30 MW. In order to see the triton behaviour, the DT neutron spectra were studied after beam turn off. Figure 5 shows NDD pulse height spectra accumulated during 300 ms of 69 JT-60U shots before (a) and after (b and c) NBI was turned off. The

measured averaged triton energy was 410 keV during beam injection and 250 keV at ~200 ms after the beam was turned off. The triton slowing down time was estimated from this measurements as 400 ms.

In JT-60U experiments NDD was sensitive to DT and DD neutrons. DD neutron induced pulses were in energy range 0–0.9 MeV (ADC channels 1–15). Taking into account this fact and also the fact that DD neutron yield was ~1,000 times higher than DT neutron yield we estimated the dynamics of JT-60U DT and DD neutron yields after beam turn off from evolution of the total numbers of NDD pulse height spectrum counts in channels with $N > 20$ ($E > 1,120$ keV) and channels with $N < 15$, correspondingly. These evolutions calculated from Fig. 5 data are shown in Fig. 6. The measured decay time (800 ms) of the DT neutron flux was essentially higher than that for DD neutrons

Fig. 5 NDD pulse height spectra accumulated in 69 JT-60U shots during 300 ms of beam time (a), first (b) and second (c) 300 ms after beam was turned off.

(300 ms). This is due to longer slowing down time of sub-MeV tritons compared to beam deuterons with energies ~ 100 keV.

3.3 JET

Four NDDs were used for DT neutron spectrometry and flux monitoring [14] during high power NBI and ICRF heating in tritium experiments at JET in 1997 [21]. Two NDDs were installed at a distance ~ 25 mm from each other 20 m away from the plasma axis behind collimator which viewed the JET plasma in the equatorial plane at angle of 50° with respect to the current axis. One of these NDDs in parallel with spectrometry was used as a flux monitor collimated to the center region (diameter 100 mm) of plasma. A third detector was installed inside the JET vertical neutron collimator (concrete, 1.2 m length, 2 cm diameter) at a distance of 17 m from plasma and measured the perpendicular neutron spectrum. The total count rate in each of NDD-based spectrometers did not exceed 8.5×10^4 counts/s, so the pile-up rejection feature was not used during these experiments. A fourth detector (NDD2) was installed in the equatorial plane of the torus 3 m away from the plasma axis without shielding and was used for DT neutron rate monitoring. This system provided DT neutron rate monitoring with useful count rate up to 6.7×10^5 counts/s at total throughput up to 8.3×10^7 s $^{-1}$. Regarding radiation damage, the characteristics of this NDD were almost the same at the end of this JET tritium experimental campaign as at the beginning. During this campaign detector accumulated fluences: $\sim 1.2 \times 10^{13}$ n/cm 2 plasma DT neutrons and $\sim 1.2 \times 10^{13}$

n/cm 2 scattered neutrons.

The highest fusion power at JET was produced during hot ion mode (HIM) experiments. These were shots with up to 22.8 MW NBI and 3–6 MW of ICRF heating. Plasma electron density increased almost linearly from 2 up to 5×10^{19} m $^{-3}$ during NBI. Perpendicular and 50° effective temperatures and plasma toroidal rotation velocities deduced from NDD DT neutron spectra accumulated during one of the highest fusion power (13 MW) hot ion mode shot (42676) are shown in Fig. 7.

Results of DT neutron spectra measurements made by perpendicular and 50° NDD based spectrometers during HIM (Fig. 7) and optimized shear experiments demonstrate that ion energy distribution functions were almost isotropic during these JET experiments. At the beginning (first 0.8 second) of NBI, beam-plasma neutrons dominate the plasma-plasma ones due to low plasma density. The broadening of the DT neutron spectrum during this time is mainly connected with the energy of beam particles and so effective temperatures are essentially higher than the ion temperature measured by charge exchange recombination spectroscopy (CXRS). But during the high plasma density and temperature phase (end of beam time and after beam

Fig. 6 The evolution of DT and DD neutrons fluxes measured by NDD after turning off deuterium NBI in JT-60U.

Fig. 7 a) Perpendicular (●) and 50° (○) effective temperatures (eV) and b) effective value of plasma toroidal rotation (rad/s) measured by NDDs during one of the highest power JET HIM shots (42676), in comparison with CXRS data. c) Center electron density (m $^{-3}$), and d) measured by NDD2 DT neutron rate evolution (a.u.).

termination), plasma-plasma neutrons dominate the beam-plasma ones. Averaged energies of beam particles on this stage diminish due to slowing down in a plasma with higher density and the ion temperatures measured by NDDs are in good agreement with CXRS data. Values for the toroidal rotation velocity deduced from the 50° DT spectrum (Fig. 7) are averaging over DT neutron birth profile along detector cone of view. That is why these values were 30 – 40% lower than shown on this figure value of toroidal rotation velocity measured by CXRS on the axis of plasma.

The high energy resolution of the diamond detectors provided measurements of the non-Gaussian DT neutron energy distributions during plasma regimes strongly dominated by beam-plasma neutrons.

The mean energies of fast beam and ICRH ICRF heating driven ions were estimated from measured spectra using a previously developed [10] semi-analytical model. The almost linear increase of measured perpendicular energy of the resonant deuterons with increasing ICRF heating power during deuteron minority heating demonstrated good confinement of high energy particles in JET plasmas.

Dynamics of the DT neutron count rate from the center plasma region (diameter 100 mm) and of the DT neutron rate produced in the total plasma volume measured by NDDs during shots with strong sawtooth oscillations are shown in Fig. 8. These data illustrate the sensitivity of the DT neutron flux from plasma center to sawtooth crash induced fast ion redistribution.

4. NDD Application for Fast Charge Exchange Atom Spectrometry and Flux Monitoring

4.1 Hydrogen charge exchange atom measurements during H⁺ minority ICRF heating on TFTR

NDDs were used for the first time for fast ($E > 225$ keV) charge exchange H⁰ atom spectrometry and flux dynamic measurements [15,16] during TFTR H⁺ minority ICRH experiments in deuterium plasma. Energy range ($E > 225$ keV) was chosen to be sure that gamma quanta do not produce noticeable contribution into measured spectra. The NDD was installed inside the midplane vacuum flight tube 4 m from the plasma axis with an observation line at a toroidal angle of 3.3° to the major radius direction. The detector cone of view value was equal to 1.5° with a diameter of 10.8 cm at the plasma axis. Therefore only deeply trapped ions with pitch angles in a narrow range of $V_{\parallel}/V = -0.058 \pm 0.014$

Fig. 8 The evolution of DT neutron fluxes from plasma center (d), and hole plasma volume (b) measured by NDDs, in JET discharge with strong sawtooth oscillations shown by x-ray flux in (d), in comparison with uncollimated fission chamber data (c).

were studied. The solid angle of the NDD atom spectra measurements was determined by a 0.9 mm diameter circular aperture in the NDD housing. A very small NDD was chosen to provide a count rate not exceeding 7×10^5 counts/s during passive measurements. A spectroscopy amplifier operating with pile-up inspection at such input count rates was specially developed.

The aim of the measurements was to study the efficiency of the resonant hydrogen minority ion energetic tail formation, the characteristics of their redistribution by sawtooth crashes and subsequent stochastic ripple diffusion during center and off-center (30 cm outward the magnetic axis) H⁺ – minority ICRF heating on TFTR. To study the behaviour of ICRF-driven fast H⁺ – minority ions during sawteeth and TAE activity and mechanism of their diffusion, the measured charge exchange atom flux was compared with fast proton losses measured by three escaping charged particle detectors [22] located at 20, 45, and 60° below the outboard midplane. In contrast with NDD, these detectors saw non deeply trapped banana particles with the peaks of pitch angle distribution (in detector positions) at 61, 52 and 67° respectively. Full correlation between the H⁰ and escaping protons fluxes was observed. Sharp sawtooth induced spikes of fast H⁰ flux were measured during discharges with ICRH power higher than 1.8 MW when sawtooth the crash amplitude

became large enough (see Fig. 9). The amplitude of the spikes increased with increasing sawtooth amplitude. Particularly large spikes were measured during the giant sawtooth crash shown in Fig. 9 at time 3.9 s for the shot with ICRF heating power equal to 3.6 MW. The ICRF heating power, x-ray flux and fast proton losses were also shown in Fig. 9. The rise time of the H^0 spikes was of the order of the sawtooth crash time and the decay times of the ordinary sawtooth induced crashes were ~ 10 ms for center ICRH and ~ 2 ms for off-center heating. As shown in Fig. 9, these spikes were correlated with an increase of H^+ losses. Dynamics of the measured charge exchange atom flux and proton losses were in a reasonable agreement with previously developed models for sawtooth crash induced fast ion redistribution [23] and stochastic ripple diffusion [24]. As could be seen in Fig. 9, in contrast with non deeply trapped fast ions AE (Alfvén Eigenmode) activity did not noticeably affect the spatial distribution of deeply trapped fast ions.

Since the NDD and the particle charge exchange (PCX) analyzer had almost the same cones of view, it was possible to compare the spectra and fluxes measured by the two diagnostics. Fig. 10 presents examples of the charge exchange H^0 spectra accumulated by the NDD (1) and the PCX analyzer (2) [25] during 2 seconds of a shot with 3 MW of ICRF heating power. Points with error bars in Fig. 9 present the evolution of effective perpendicular H^+ ion temperature derived from measurements of the NDD charge exchange atom

Fig. 9 The H^0 atom flux and effective perpendicular temperature measured by NDD together with ICRF heating power, x-ray flux, and $60^\circ H^+$ losses during TFTR shot 104897 with center ICRH.

Fig. 10 Charge exchange H^0 atom spectra accumulated by NDD (1) and particle charge exchange analyzer (2) during 2 seconds of RF-heating shots with ICRF heating power equal to 3 MW.

spectra accumulated during 100 ms time windows. Spectrometry measurements made by the NDD gave information concerning the efficiency of minority ion heating at different ICRF heating powers and resonance layer positions in TFTR experiments.

4.2 Heating beam ion energy distribution measurements on LHD

The specially developed NDD with very thin graphite contacts enabled its application to charge exchange atom spectrometry in an energy range of about 35–100 keV in experiments on the Large Helical Device [26]. NDD was used in pulse height analysis mode. Only charge exchange atoms produced counts in the energy range 35–100 keV of NDD pulse height spectrum during LHD experiments with hydrogen and helium plasmas. The NDD was installed inside the midplane vacuum flight tube 8.25 m from the plasma axis with an observation line tangential to the plasma axis. Its cone of view value was equal to 0.47° with a diameter of 13.4 cm at the plasma axis. Therefore the energy distribution of only counter passing untrapped fast beam ions was studied. Almost no counts corresponding to fast charge exchange atoms were accumulated during beam injection only in co-direction. The solid angle of the NDD atom spectra measurements (1.2×10^{-8} steradians) was determined by a 1 mm diameter circular aperture installed in 15 cm in front of NDD which had a diameter of 2 mm. Such a small diameter aperture was chosen to provide count rates $\leq 2 \times 10^5$ counts/s over a wide range of LHD plasma

Fig. 11 Tangential charge exchange H^0 atom spectra accumulated by NDD during counter 100 keV H beam injection of indicating duration into hydrogen LHD plasmas with densities: $0.5 \times 10^{12} \text{ cm}^{-3}$, 10^{13} cm^{-3} , and $2.5 \times 10^{13} \text{ cm}^{-3}$.

Fig. 12 Tangential charge exchange H^0 atom spectra accumulated by NDD during counter 100 keV H beam injection of indicating durations into helium LHD plasmas with densities: $0.2 \times 10^{12} \text{ cm}^{-3}$, $0.5 \times 10^{13} \text{ cm}^{-3}$, $1.25 \times 10^{13} \text{ cm}^{-3}$, and $2.5 \times 10^{13} \text{ cm}^{-3}$.

parameters to reduce pile-up effects in using an EG&G Ortec 673 spectroscopy amplifier operating with a shaping time constant $0.25 \mu\text{s}$. The energy resolution of the NDD used was previously measured with an ^{241}Am α -source and was equal to 5.9%. The energy resolution of this NDD for 100 keV hydrogen atoms was estimated before to have a value of better than 12%. The energy resolution of these measurements was determined primarily by the EG&E Ortec 142A preamplifier plus the EG&G Ortec 673 spectroscopy amplifier noise. Measured using a generator of standard pulses, the energy resolution was equal to 16 keV.

The hydrogen atom charge exchange spectra measured by NDD in experiments with 100 keV H^0 injection into hydrogen and helium plasmas with electron and ion temperature up to 1.5 keV are shown in Fig. 11 and Fig. 12, respectively. Spectra measured in experiments with very low ($\leq 5 \times 10^{11} \text{ cm}^{-3}$) plasma densities demonstrate peaks of charge exchange atom energy distribution close to injection energy. In the case of helium plasma density $5 \times 10^{12} \text{ cm}^{-3}$ H^0 charge exchange atom flux onto detector is essentially higher than that in the previous case ($\leq 5 \times 10^{11} \text{ cm}^{-3}$) due to increase of beam deposition in a plasma, and the peak position moves to 65 keV due to fast ion slowing down. Spectra measured during shots with plasma densities $1\text{--}2.5 \times 10^{13} \text{ cm}^{-3}$ also illustrate the effect of beam ions slowing down in LHD plasmas. Noticeable difference in the shapes of fast hydrogen atom spectra measured in cases of hydrogen and helium plasmas with densities higher than 10^{13} cm^{-3} can be explained by the energy dependence of corresponding charge exchange cross sections. Reduction of atom flux with increase of plasma density higher than 10^{13} cm^{-3} is connected with charge exchange flux attenuation and with reduction of H^0 , He^0 and He^+ densities on plasma axis.

5. Conclusion

The high energy resolution, radiation resistance, small size of NDDs and their ability to operate at high count rates provided successful applications of several NDDs for DT neutron spectrometry and flux monitoring in experiments on TFTR, JT-60U and JET and for fast charge exchange atom spectrometry on TFTR and LHD.

Using multi cone of view NDD-based DT neutron spectrometry systems on TFTR and JET made it possible to measure

- anisotropy of ion effective temperatures during NBI and ICRF heating;
- averaged energies of fast beam and ICRF driven

particles;

- dynamics of DT neutron rates from plasma center and whole plasma volume.

Application of NDD for fast (0.2–3 MeV) charge exchange atom spectrometry and flux monitoring during ICRF heating on TFTR enabled the study of the efficiency of resonant proton acceleration by ICRF waves, their redistribution during sawtooth crashes and the subsequent diffusion. A possibility to use NDD for charge exchange H⁺ atom spectrometry in energy range 35–100 keV was demonstrated for the first time in NBI experiments on LHD.

The number of unique properties makes the NDD very promising for neutron and high energy particle spectrometry and flux monitoring in future burning plasma and other high energy physics experiments.

Acknowledgments

We are grateful to Drs. E.A. Azizov, A.G. Alekseev, R.V. Budny, D.S. Darrow, A. Iiyoshi, O.V. Ignatyev, L.C. Johnson, H. Kishimoto, V.S. Khrunov, R. Majeski, O. Motojima, M.P. Petrov, M. Pillon, P.E. Stott, K.M. Young, S.J. Zweben and many other members of TFTR, JT-60U, JET and LHD teams for useful discussions and for the support of the collaborations in which frames reviewed in this paper works were done.

References

- [1] E.A. Konorova and S.F. Kozlov, *Sov. Phys. Semicond.* **4**, 1600 (1971).
- [2] A.E. Luchanskii, S.S. Martynov, V.S. Khrunov and V.A. Cheklaev, *Sov. At. Energy* **63**, 639 (1987).
- [3] A.V. Krasilnikov, V.N. Amosov and Yu.A. Kaschuck, *IEEE Trans. Nucl. Sci.* **45**, 385 (1998).
- [4] A.V. Krasilnikov, *Diagnostics for ITER*, P.E. Stott *et al.*, Ed. (Plenum Press, New York and London, 1995) p.435.
- [5] A.V. Krasilnikov, *Sov. Voprosi Atomnoy Nauki i Tehniki, Ser.: Termoyad. Sintez* **1**, 36 (1995).
- [6] V.N. Amosov, Yu.A. Kaschuck, A.V. Krasilnikov, D.V. Portnov and S.V. Siromukov, *Rev. Sci. Instrum.* **70**, 1104 (1999).
- [7] M. Pillon, M. Angelone and A.V. Krasilnikov, *Nucl. Instrum. Meth. B* **101**, 473 (1995).
- [8] A.V. Krasilnikov, J. Kaneko, M. Isobe *et al.*, *Rev.*

- Sci. Instrum.* **67**, 1720 (1996).
- [9] A.V. Krasilnikov, E.A. Azizov, A.L. Roquemore *et al.*, *Rev. Sci. Instrum.* **68**, 553 (1997).
- [10] A.V. Krasilnikov, N.N. Gorelenkov, R.V. Budny, L.C. Johnson and A.L. Roquemore, *Controlled Fusion and Plasma Physics (Proc. 23th EPS Conference, Kiev, 1996, EPS, Geneva 1996)* Vol. 20C, p.995.
- [11] A.V. Krasilnikov, A.L. Roquemore, N.N. Gorelenkov and R. Budny, *Proc. 16th IAEA Fusion Energy Conference, Montreal, 1996*, p.293.
- [12] A.V. Krasilnikov and A.L. Roquemore, *Plasma Phys. Rep.* **24**, 158 (1998).
- [13] A.V. Krasilnikov, V.N. Amosov, P. Belle, O.N. Jarvis and G.J. Sadler, *to be published in Nucl. Fusion*.
- [14] M. Isobe, T. Nishitani, A.V. Krasilnikov *et al.*, *Fusion Eng. Des.* **34-35**, 573 (1997).
- [15] A.V. Krasilnikov, S.S. Medley, N.N. Gorelenkov *et al.*, *Rev. Sci. Instrum.* **70**, 1107 (1999).
- [16] A.V. Krasilnikov, S.S. Medley, N.N. Gorelenkov *et al.*, *to be published in Nucl. Fusion*.
- [17] S.F. Kozlov, R. Stuck, M. Hage-Ali *et al.*, *IEEE Trans. Nucl. Sci.* **NS-22**, 160 (1975).
- [18] A.G. Alekseev and G. Martin, *Proc. 25th EPS Conference Plasma Physics and Controlled Fusion, Prague, 1998*, F101.
- [19] R.V. Budny *et al.*, *Nucl. Fusion* **35**, 1497 (1995).
- [20] S.V. Putvinskij, *Reviews of Plasma Phys.* **18**, 211 (1990).
- [21] J. Jacquinot and the JET Team, JET-P(98)05, *submitted to Nucl. Fusion*; see also JET Team, TFTR Team (*presented by Jacquinot*) *Proc. 25th EPS Conf.*, Prague, 1998, A13.
- [22] D.S. Darrow *et al.*, *Rev. Sci. Instrum.* **66**, 476 (1995).
- [23] N.N. Gorelenkov, R.V. Budny, H.H. Duong *et al.*, *Nucl. Fusion* **37**, 1053 (1997).
- [24] R.B. White and M.S. Chance, *Phys. Fluids* **27**, 2455 (1984).
- [25] S.S. Medley *et al.*, *Rev. Sci. Instrum.* **67**, 3122 (1996).
- [26] M. Fujiwara *et al.*, *Proc. 17th IAEA Fusion Energy Conference Yokohama, 1998*, IAEA-CN-69/EX2/3; see also NIFS-572.