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Study of the triton-burnup process in different JET scenarios using neutron monitor based on CVD diamond

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We present the results of analysis of triton burn-up process using the data from diamond detector. Neutron monitor based on CVD diamond was installed in JET torus hall close to the plasma center. We measure the part of 14 MeV neutrons in scenarios where plasma current varies in a range of 1-3 MA. In this experiment diamond neutron monitor was also able to detect strong gamma bursts produced by runaway electrons arising during the disruptions. We can conclude that CVD diamond detector will contribute to the study of fast particles confinement and help predict the disruption events in future tokamaks.

I. INTRODUCTION

The realization of diagnostic systems in future tokamaks ITER and DEMO has limitations due to high neutron fluxes, harsh environmental conditions and engineering aspects of integration. For these machines, the use of relatively small, radiation hard neutron diamond detectors having high energy resolution is foreseen. In this work, we present the results of analysis of triton confinement produced at 1 MeV in D+D=T+p reaction using the data from diamond detector. Such tritons have similar orbits as 3.5 MeV alpha particles in DT plasma. Therefore, study of triton confinement is necessary for operation of future tokamaks.

Tritons with 1,01 MeV are produced in D+D reaction with equal probability as 2.5 MeV neutrons. Maximum reactivity of D+T reaction is about 200 keV[1], so if the tritons are confined and slowing down, they can lead to 14 MeV neutrons. Measuring of DT and DD neutron yields by means of neutron spectrometry can provide the information about fast particles confinement. In previous investigations made on JET it has been shown that the DT/DD neutron ratio varies in different scenarios depending mainly on plasma current[1-3].

In this work, it is also worth noting that CVD diamond neutron monitor installed in torus hall in the low energy area of spectrum was able to detect strong gamma bursts produced by runaway electrons arising just before the disruptions. Based on these data we can conclude that in addition to the measurement of neutron yield CVD diamond detector will contribute to the study of fast particles confinement and help predict the disruption events in future tokamaks.

II. EXPERIMENT

Neutron monitor based on CVD diamond with geometrical sizes 5x5x0.5 mm was installed in JET torus hall close to main horizontal port. Distance from the plasma center at the detector location was about 3m[4]. Calculated neutron flux in this point was up to 10^8 n/cm^{2}s and total count rate on the detector in this location reached in some pulses 10^5 Hz, which allows us to have proper count statistics and good temporal resolution. Detector operates as a threshold counter. The maximum deposited energy from 2.5 MeV neutrons in diamond crystal doesn't exceed 800 keV, so fluxes of DD neutrons interact with carbon nuclei only through elastic scattering. Otherwise, 14 MeV neutrons produced during triton burn-up cause carbon ionization also in (n, alpha) reaction. Using spectrometric channel of measurement we distinguish response from DD and DT neutrons. We measure the part of 14 MeV neutrons at different scenarios where plasma current varies in a range of 1-3.5 MA. Counts from the detector have been recorded within 12 ms time window.

III. RESULTS OF MEASUREMENTS

To calculate DD and DT yield the following technique is applied. Using neutron transport calculations incident neutron spectra E_1 from DD and DT plasma sources at the detector location has been determined. Based on these results we build the response function of the diamond detector to 2.5 MeV and 14 MeV neutron sources[5]. It can be presented as:

$$W(E_p)=\frac{dN(E_p)}{d(E_p)}=\int_{E^1_{\min}}^{E^1_{\max}} K(E_p,E_1)F(E_1)dE_1=\int_{E^1_{\min}}^{E^1_{\max}} \alpha\sum_i \sigma_i(E_1)f_i(\mu,E_1)\frac{\partial\mu}{\partial E_p}F(E_1)dE$$

Here E_p is an energy deposited in crystal, i - process of interaction, $\sigma_i(E_1)$ - its cross-section, α=nVt, n – concentration of carbon, V – detector volume, t –exposure time, $f_i(\mu,E_1)$ is a probability mass function for the neutron to be scattered in cosine of the angle from μ to (μ + dμ). Based on this response function the total neutron yield as well as DT neutron yield are restored. For the most JET pulses the total neutron yield recalculated from the diamond detector corresponds with appropriate accuracy to

KN1 fission chambers – main diagnostic system for the JET neutron yield (see fig. 1).

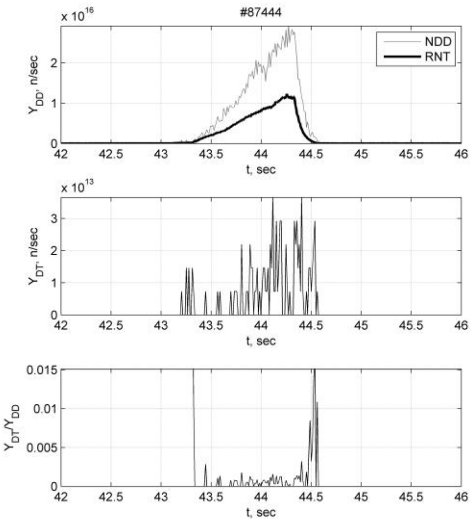

FIG. 1. On the top: comparison of DD neutron yield recalculated from diamond detector (blue) and from KN1 fission chambers (red). On the middle: DT neutron yield. On the bottom: DT/DD ratio. Pulse #86650, Ip=2.5 MA

IV. PULSES WITH LOW PLASMA CURRENT

As mentioned above in the most JET scenarios there is a good agreement with total neutron yield measured by fission chambers and CVD detector counts. Nevertheless, in several pulses with low plasma current (<2MA) and high NBI power (up to 25 MW) we found a significant discrepancy between data from two diagnostics (see fig. 2).

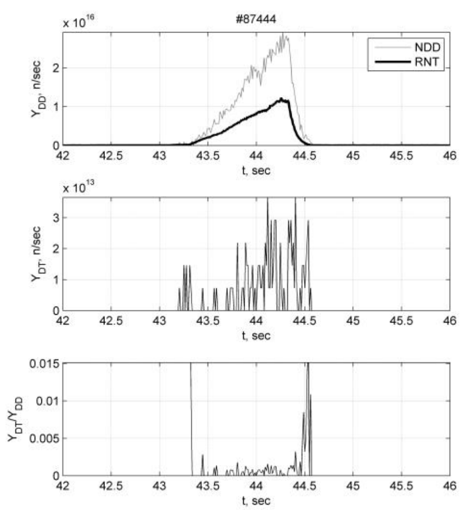

FIG. 2. On the top: comparison of DD neutron yield recalculated from diamond detector (blue) and from KN1 fission chambers (red). On the middle: DT neutron yield. On the bottom: DD/DT ratio. Pulse #87444, Ip=1.5 MA, NBI power – 25 MW.

Such discrepancy can be explained by the lack of the restoring technique for beam neutron source. To get the detector response function we use incident spectra E_1 calculated for thermalized plasma source.

V.DT/DD RATIO IN DIFFERENT PLASMA SCENARIOS

Production of 14 MeV neutrons depends on the conditions of 1.01 MeV triton confinement and thermalization. Such process is easily to achieve in the pulses with higher plasma current in a view of reducing triton Larmor radius.

In this work, we investigate how the ratio between measured DT and DD neutron yields depends on other plasma parameters. As one can see from the figures 3a and 3b, we found the correlation between measured DT/DD ratio and plasma current or electron temperature. For example for the pulses with numbers 87526, 87520, 87528, 87505, 87407 with plasma current 2,5 MA electron temperature varies 3,5 keV, 3,5 keV, 3 keV, 4 keV, 5.5 keV.

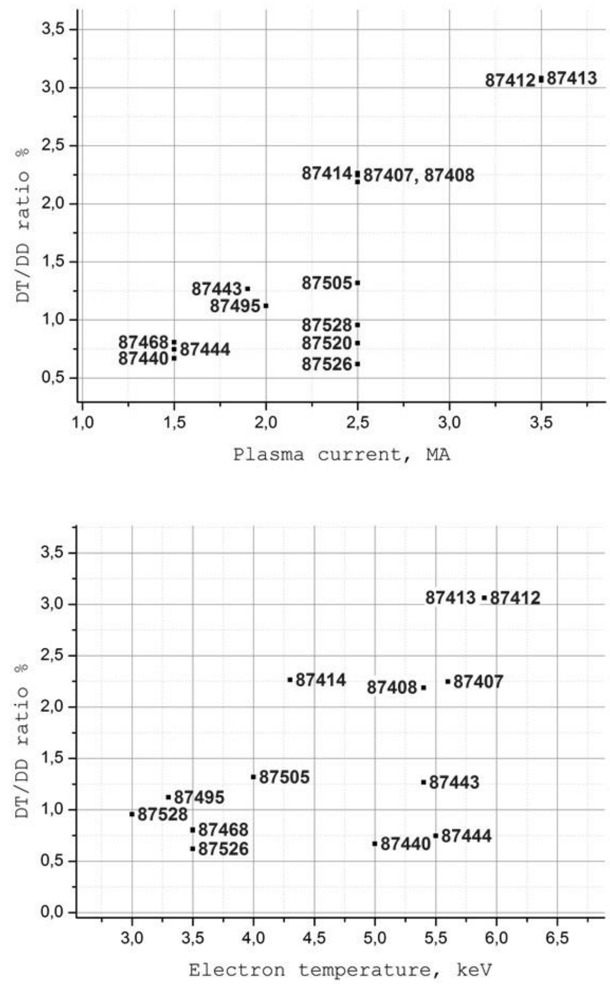

FIG. 3. DT/DD ratio against plasma current and electron temperature

VI. ESTIMATION OF TRITON SLOWING DOWN TIME

One can see from the fig. 2, there is a peak of DT/DT ratio at 44.5s. The triton burn-up neutron emission goes with some delay relative to the birth time of triton. It corresponds with slowing down time of triton to the energy of the DT maximum reactivity (about 170-200 keV). This delay is observable during the experiment. To calculate it we use the convolution of normalized DD and DT signals (fig. 5).

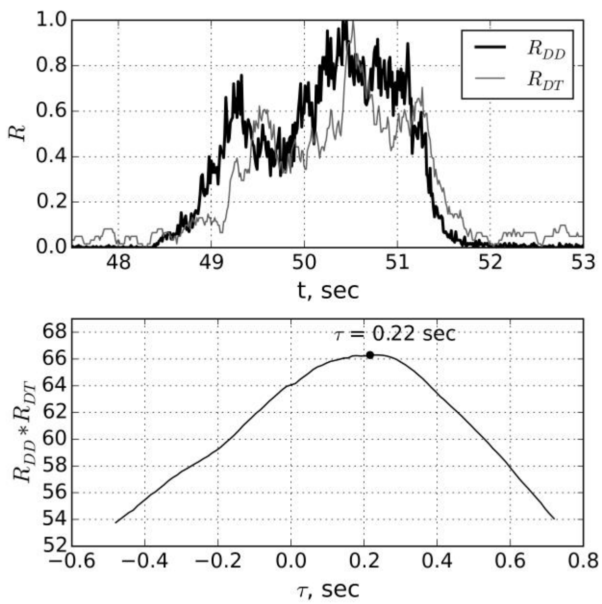

FIG. 5 Calculation of triton burn-up neutron emission delay time. On the upper picture is the normalized yields of DD and DT neutrons, on the bottom – convolution of them. Pulse #87413, Ip=3.5 MA.

In the most typical JET pulses, the value of DD and DT neutron delay τ is about 0.2s. Nevertheless, for several pulses with low plasma current and high NBI power (as #87444 with Ip=1.5 MA, P_{NBI}=25 MWT) calculated value of τ were lower (about 0.16s). It gives us an assumption, that in such case DT reaction goes with not fully slowing down tritons.

VII. SENSITIVITY TO GAMMA RADIATION

In our experiment for measurement of total neutron yield, we use 300 keV energy registration threshold for the detector response. In a view of our diamond crystal used is relatively small we consider that effect of gamma produced on its response using this threshold is negligible compare to the neutrons. In the energy range of 100keV – 10 MeV dominated process of interaction of photons with carbon is Compton effect. One can assume that scattered photon leaves the detector without repeated interaction and only part of the recoiling electron energy is deposited in the crystal. Nevertheless, in the low energy area of spectrum during the current disruption detector registered in several pulses a strong gamma burst arising from runaway electrons (see fig. 6). Further analysis has shown that similar signal observed as well in some scenarios where the plasma current grows and Hard X-Ray Monitor registered the emission from runaway electrons. We consider that observation of this effect on CVD detector is important, because of future tokamaks such ITER and DEMO have some limitations on integration of gamma diagnostics and signal from relatively small and radiation hard CVD diamond detectors can be useful.

VIII. CONCLUSIONS

Diagnostic system created is able to determine DD and DT neutron yield in scenarios with different plasma parameters (current, electron temperature). Using the data from the CVD diamond neutron monitor we found the scenarios with the best triton confinement and estimated the triton slowing down time. This data can be used for the analysis of the fast particles confinement.

Developed detector model can be used for the evaluation of DD and DT neutron yield of the JET with acceptable accuracy. But we found significant discrepancy of the diamond detector counts with the data from KN1 fission chambers in some plasma charges which requires more modelling on the beam neutron source.

Diamond detector is sensitive to the gamma radiation. We found that diamond neutron monitor was able to detect strong gamma bursts produced by runaway electrons in the low energy area of the spectrum.

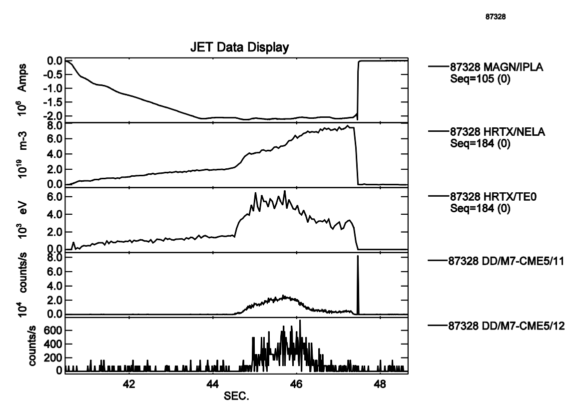

FIG. 6. Time traces for the pulse#87328. From the top down: plasma current, electron density, electron temperature, diamond detectors counts with 300 keV registration threshold and with 1.9 MeV threshold. Peak during current disruption is observed.

IX. ACKNOWLEDGMENTS

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