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Neutron emission spectroscopy of DT plasmas at enhanced energy resolution with diamond detectors[a)]

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This contribution focuses on the superior energy resolution synthetic single crystal diamonds (SD) offer for spectral studies of Deuterium-Tritium (DT) fusion neutrons. SD response function measurements of 1-20 MeV neutrons were carried out at Peking University nuclear accelerator. Results show 1% SD energy resolution for incoming 20 MeV neutrons, which, together with 1% detection efficiency, opens up to new prospects for fast ion physics studies in high performance nuclear fusion devices, especially with regard to DT plasmas discharges heated by neutral beam injection and, specifically, to shed light on the discrepancy between simulated and measured neutron yields at JET.

I. INTRODUCTION

Neutron emission spectroscopy (NES) is a diagnostic technique that allows for energy measurements of neutrons born from nuclear reactions. The application of neutron spectrometers based on different detection principles (magnetic proton recoil, time of flight and compacts) includes studies at nuclear facilities as well as the development of diagnostic systems for fusion tokamaks[1,2,3,4]. The Joint European Torus[5] (JET, Culham, UK) has a special role in this respect as advanced spectrometers for 2.5 MeV and 14 MeV neutrons have been here developed for the first time and used to demonstrate measurements of the neutron spectrum from Deuterium (D) and Deuterium-Tritium (DT) plasmas with unprecedented accuracy. One important outcome of these results has been to establish NES as a key diagnostic for fast ion studies in high performance plasmas[6,7,8,9,10].

Progress in chemical vapor deposition techniques have recently made it possible to grow single crystal synthetic diamonds (SD), which can be used for NES applications[11,12,13,14,15,16,17]. Single crystal diamonds of so called electronic grade have been produced reliably with dimensions up to a 0.5 mm thickness and 4.5x4.5 mm^2 area. The neutron detection principle is based on elastic scattering for neutrons up to 6 MeV and on ^{12}C(n,α)^{9}Be (Q_{value} = -5.7 MeV) reactions at 14 MeV, of relevance for DT plasma discharges.

In this contribution we focus especially on the superior energy resolution offered by SDs for spectral studies of DT fusion neutrons. Measurements of the SD (0.5 mm thickness and 4.5x4.5 mm^2 area with Gold based contacts) neutron response function were carried out at the State Key Lab of Nuclear Physics and Technology of Peking University (Beijing, China) using the Van de Graaff Accelerator[18,19]. The SD was exposed to neutrons in the energy range of 1-20 MeV created either by 3.3 MeV protons or 3.3 MeV deuterons on a tritiated Titanium target at different angles. The impinging neutron beam at the SD position has been calculated by modeling the target (geometry and materials) and the beam-target reactions with the code TARGET[20]. Results show that for incoming neutrons of E_n = 20.0 MeV, the neutron beam mean energy has a Doppler shift of 114 keV while the neutron peak of the ^{12}C(n,α)^{9}Be reaction (FIG. 1) features a full width at half maximum (FWHM) broadening of 183 keV (FIG. 2). This demonstrates an SD contribution to the measurement, i.e., an SD energy resolution[21] $\eta = 1\%$ with 4% efficiency in the ^{12}C(n,α)^{9}Be peak.

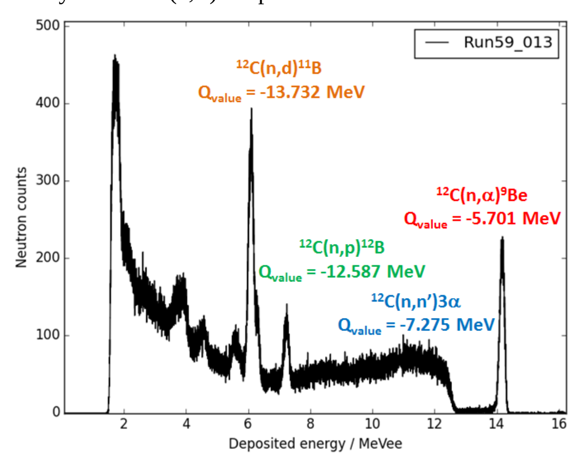

FIG. 1. (Color online). Pulse height spectrum measured by SD for 20 MeV neutrons.

Considering the SD response to 2.5 MeV neutrons, the measured neutron spectrum features a plateau extending up to a shoulder about a deposited energy E_{dep} = 0.7 MeVee which

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corresponds to the maximum energy ^{12}C deposits in the 0.5 mm SD thickness after the elastic collision with a backscattered neutron from the beam. Modelling the shoulder of the measured pulse height spectrum as a Gaussian convoluted step function, it results in broadening of about 99 keV FWHM. This combined with 38 keV broadening of the TARGET[20] incoming 2.5 MeV neutron beam indicates that the SD diamond contributes for $\eta = 13\%$ at this neutron energy.

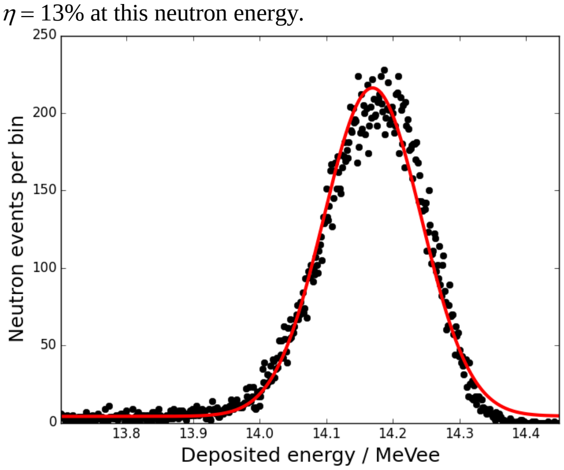

FIG. 2. (Color online). Detail of FIG. 1: Fit of the ^{12}C(n,α)^{9}Be peak resulting in a FWHM = 183 keV.

These results allow for an assessment of the SD contribution to the resolution of the measurements for various incoming neutron energies which defines $\eta = f(E_{dep})$ relationship. In view of the different electronic chains (pre-amplifiers and amplifiers[22,23]) designed for 2.5 MeV D and 14.0 MeV DT neutron measurements at JET and considering the electronic noise as the major contribution to the SD energy resolution, it results $\eta = f(E_{dep}) = 0.093E_{dep}^{-1}$ for $E_{dep} <= 1.0$ MeVee and $\eta = 0.143E_{dep}^{-1}$ for $E_{dep} > 1.0$ MeVee, respectively: This corresponds to $\eta = 1.7\%$ for the ^{12}C(n,α)^{9}Be peak from 14 MeV DT neutron measurements. For comparison, the most important NES results in DT plasmas to date were obtained with a magnetic spectrometer that had a resolution of ~3% and ~10^{-4} detection efficiency, although with a wider dynamic range and better sensitivity to weak spectral components[1].

Potentials offered by SDs for physics studies in DT plasmas are addressed in this article, especially with regard to measurements of the neutron spectrum in discharges heated by Neutral Beam Injection (NBI). In particular, we discuss here the potential use of spectral information at unprecedented resolution to shed light on the ubiquitous discrepancy between simulated and measured neutron emissions at JET.

II. DETERMINATION OF THE SD RESPONSE FUNCTION

The SD response function[24,25,26] to 0.1-18.2 MeV neutrons has been obtained considering $\eta = f(E_{dep})$ assessed from the measurements at the Van de Graaff Accelerator[18,19], and calculations performed with the code MCNPX[27]. To verify the effects of the cross sections on this analysis, different cross section libraries, namely, the Evaluated Nuclear Data File (ENDF/BVII.1)[28], the Fusion Evaluated Nuclear Data Library (FENDL-3)[29] and the Talys Evaluated Nuclear Data Library (TENDL-2014)[30] were used in the calculations. FIG. 3 displays the comparison for neutrons of $E_n = 14.0$ MeV. The ^{12}C(n,α)^{9}Be peak is at $E_{dep} = E_n - Q_{value} = 8.3$ MeVee and it is the same for the three libraries. The spectral region of $E_{dep} < 7.0$ MeVee instead features differences with the largest in magnitude for ENDF/BVII.1. For larger neutron energies, i.e., $E_n > 15.7$ MeV, the discrepancies affect also the peak region.

The SD response function was then calculated convoluting $\eta = f(E_{dep})$ with the MCNPX response for FENDL-3 (FIG. 4). The SD pulse height spectrum corresponding to 14 MeV DT neutrons has been then used to assess the capability of the SD as a high resolution neutron spectrometer for studying fast ions in DT fusion plasmas subjected to NBI auxiliary heating[31].

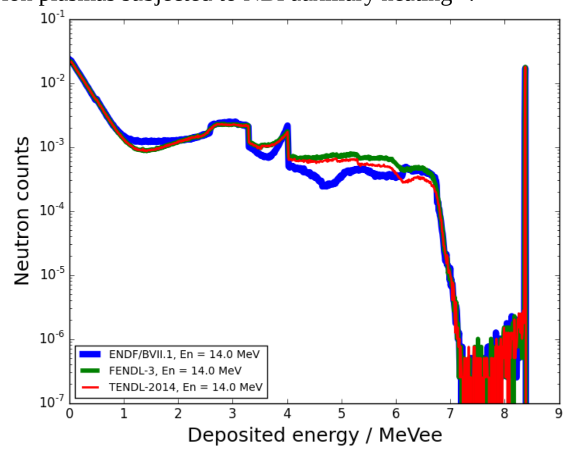

FIG. 3. (Color online). Comparison of the 14.0 MeV neutron spectra calculated with MCNPX using three different cross section libraries.

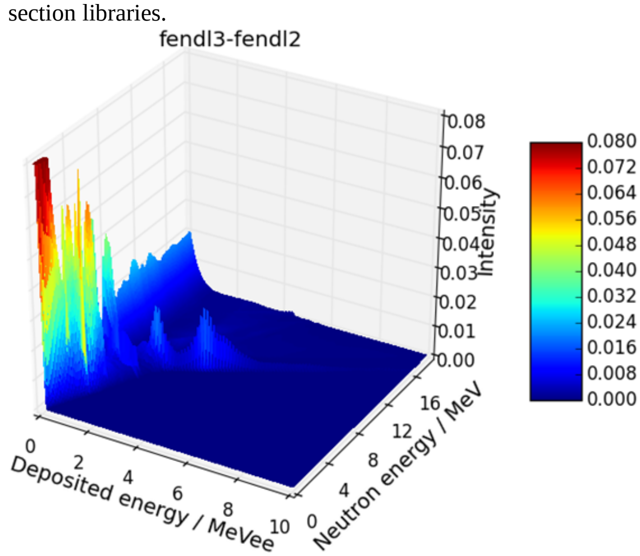

FIG. 4. (Color online). SD response function for 0.1-18.2 MeV neutrons.

III. ANALYSIS OF THE NEUTRON EMMISSION FROM NBI FAST IONS IN DT PLASMAS

Operations at ITER[32] towards high performance rely on the good confinement and classical slowing down of the neutral beam ions. These will be used for heating and fueling purposes and are essential to sustain the plasma discharge. Experiments on mid-size tokamaks have shown that, under some circumstances, there can be intrinsic and extrinsic processes that lead to deviations from the expected classical behavior. An example of the former processes are magnetic islands, that lead to enhanced diffusion of the beams well before the flux surfaces are destroyed and the field lines become stochastic[33,34]. Among the extrinsic processes, we especially recall resonant magnetic perturbations

(RMP) that are planned to mitigate edge localized modes at ITER, allowing for tolerable first wall loads in steady state operations. RMP can however cause distinctive additional losses of the beam ions that need to be monitored[35,36].

While in mid-size machines fast ion loss detectors (FILD) are the reference diagnostics to understand the behavior of the beam ions, the situation in large size, high power tokamaks, such as JET or ITER, is different. Here, FILD find some limitations, both due to the more limited fraction of ions that get lost in these machines and because of some practical constraints (e.g., high heat loads) that are common to the actual implementation of all edge probes. There is some evidence that the neutron emission spectrum is also modified when beam ions are lost from the plasma which requires a rather dramatic change in the measured spectrum to be detected by the present neutron spectrometers, which have, at their best, a resolution of the order of 2.5% around 14 MeV[31]. We here suggest instead that, thanks to their enhanced energy resolution (<2% at 14 MeV), this limitation may be overcome with super resolution SDs, making NES a useful probe of the non-classical slowing down of the beam ions in high performance tokamaks.

In order to quantitatively support this argument, we have considered the analytical model of Gaffey[37] that describes the evolution of the distribution function $f_b(v)$ of a beam of ions with initial velocity v_b, and in which we have added an "anomalous", albeit simplistic, loss term L(f) of the form

$$L(f) = \frac{f_b}{k\tau_s}\left(\frac{v_b}{2v}\right)^{\alpha} = \frac{f_b}{\tau_a(v)} \tag{1}$$

where τ_s is the Spitzer slowing down time. The characteristic time scale of the anomalous losses, say τ_a, is given by $k = \tau_a/\tau_s$ at $v = v_b/2$. The exponent α controls the effect of the losses on ions of different energies. When $\alpha < 0$, ions with velocities $v > v_b/2$ are lost preferentially. By expanding $f_b(v)$ in terms of Legendre polynomials $P_l(\xi)$ as in [37], i.e.,

$$f_b(v) = \sum_{l=0}^{+\infty} f_l(v) P_l(\xi) \tag{2}$$

where l is an integer and ξ indicates pitch, we find that the coefficients $f_l(v)$ satisfy

$$\frac{df_l}{dv} + \frac{(3v^3 - Z_2/2l(l+1)v_c^3 - \frac{\tau_s v^3}{\tau_a(v)})}{v(v^3+v_c^3)} f_l = 0 \tag{3}$$

where the critical velocity v_c and effective charge Z_2 are defined as in [37]. If we assume that all beam ions start at a pitch ξ_b and have initial velocity v_b, $f_l(v)$ must satisfy the boundary condition

$$f_l(v = v_b) = \frac{1}{v_b^3 + v_c^3}\frac{\tau_s}{2}(2l+1)S_0 P_l(\xi_b) \tag{4}$$

where S_0 is the number of ions/m^3/s that are injected. We now observe that equation (3) is an ordinary differential equation subject to the initial condition (4) and that can be solved by standard numerical techniques.

FIG. 5 shows $f_b(v)$ as obtained from (2), (3) and (4) for a typical JET NBI scenario of tritons with $E_b = 0.5mv_b^2 = 120$ keV and $\xi_b = 0.5$ in a DT plasma. The classical solution in panel (a) is compared to the cases when $\alpha = -4$ and $k = 0.5$ and 0.25 in panels (b) and (c), respectively. The Monte Carlo code GENESIS[38,39] has been used to calculate the corresponding normalized neutron spectra as displayed in panel (d). Here we observe that, depending on the extent of the anomalous losses, there is indeed a measurable change in the neutron spectrum which requires a high resolution instrument, such as an SD, to fully appreciate the effect. Together with lower neutron yields, anomalous transport affects the neutron spectrum for $E_n < 14.0$ MeV where different shapes are visible with respect to the classical slowing down distribution due to fast ions losses.

To verify the capability of the super-resolution SD neutron spectrometer to recognize such details of FIG. 5 (d), the SD response function of FIG. 4 have been used to determined corresponding pulse height spectra SD would measure. The results are presented in FIG. 6 in terms of $^{12}C(n,\alpha)^9Be$ peak containing 10000 and 100000 counts, respectively. Poissonian counting statistics has been taken into account to mimic real experimental data. SD features about 1.6 % neutron detection efficiency in $^{12}C(n,\alpha)^9Be$ peak. Applying an 1 MeVee data acquisition (DAQ) threshold for dedicated 14 MeV neutron measurements of DT plasmas, the super-resolution of the SD would allow for good statistics in 1 s acquisition time at 0.3 MCounts/s which is not a problem in view of the >1 MCounts/s capability of the DAQ system implemented in the SD setup.

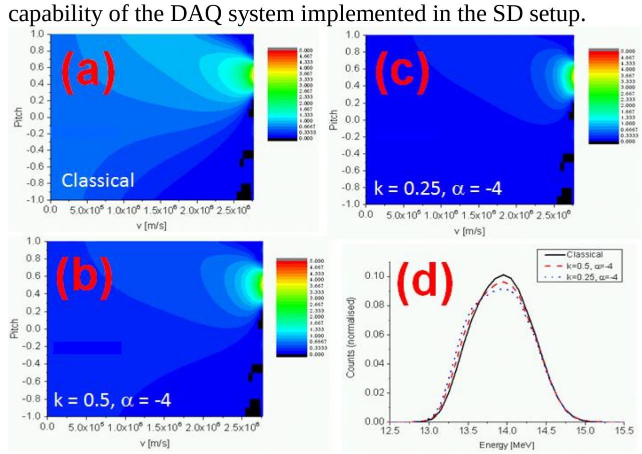

FIG. 5. (Color online). Calculations of the slowing down distributions of NBI tritons in a DT plasmas using both classical (a) and "anomalous" models with $(k,\alpha) = (0.5,-4)$ (b) and (0.25,-4) (c), respectively. The corresponding effects on the shape of the normalized neutron spectrum are highlighted in (d).

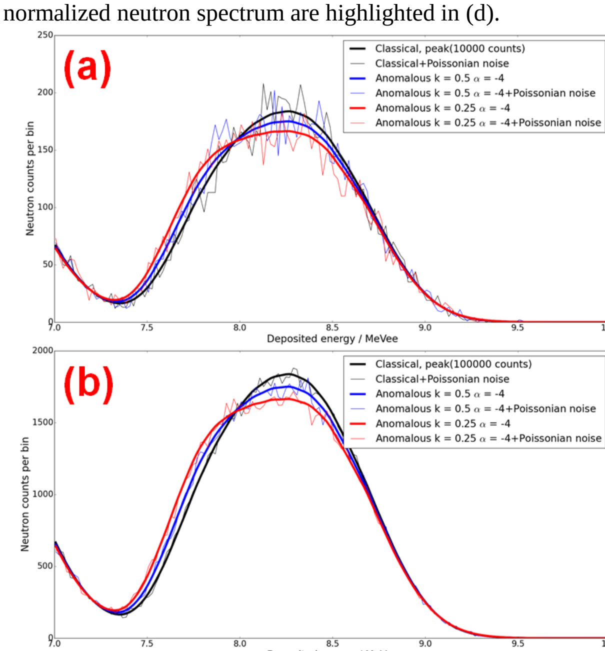

FIG. 6. (Color online). Comparison of the pulse height spectra SD would measure with 10000 and 100000 counts in the $^{12}C(n,\alpha)^9Be$ peak positioned at about $E_{dep} = 8.3$ MeVee for the neutron spectra shown in Fig. 5 (d). Poissonian statistics has been added to mimic real experimental data.

With our simplified model we have found that changes in the neutron spectrum are more pronounced for small k and negative α. Little to no changes are observed in the spectrum when $\alpha > 0$, i.e., when the slower ions are preferentially lost, for example as a result of micro-turbulence which is thought to play a minor role on energetic ion transport[40].

As DT plasma diagnostic, SDs need to operate in stable conditions, namely, avoiding polarization effects[14], which can be mitigated by inverting the applied high voltage. Moreover, the SDs physical properties of resilience at high temperatures and insensitivity to magnetic fields, make the SDs a valuable candidate as high resolution neutron spectrometer for present and future nuclear fusion facilities as ITER and DEMO[41].

IV. ACKNOWLEDGMENTS

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