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Neutron Emission Studies of NB Heated JET DT Plasmas

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Neutral beams (NB) have been used to produce record fusion power plasmas during the first main deuterium-tritium experiment (DTE1) at JET in 1997. Different combinations of d and t beams of energies up to 150 keV, injected into thermal (Ohmic) plasmas, raised the ion temperature from $T_i \approx 2$ keV to a sustained level of up to $T_i \approx 25$ keV. Between these 'steady state' conditions, the NB action on the plasma caused different transients, notably, at the leading and trailing edges of the NB pulse. The fast NB ions constitute a varying supra-thermal (ST) contribution to the plasma fusion power (P_f). Information on the relative contribution of thermal (TH) and ST ion reactions can be obtained from neutron emission spectroscopy (NES). Moreover, NES can provide insight into the characteristics of fast NB ions from the time of their deposition into high-energy (HE) orbits through the subsequent slowing down to thermalization. The temperature and reactivity of the base plasma, before and after the NB pulse, were also determined with NES. Neutron measurements with these objectives were realized, for the first time, with the 14-MeV magnetic proton recoil (MPR) spectrometer during the DTE1 campaign at JET, which now form an extensive data bank, of use both to develop the NES diagnostic method and to gain unique insight into fast ion physics of fusion plasmas. Here we present new results based on systematic studies of analyzable and interpretable NB ion signatures in the neutron spectrum. These include neutron production involving HE ions in co and counter (cr) passing orbits as well as those in trapped orbits. The temperature was also determined for the bulk ions, which, in favorable cases, were split into components of TH and slowing-down (epithermal, ET) ions; the bulk plasma toroidal rotation was measured as well.

These studies were realized with the MPR neutron spectrometer [1] using its unique capability to operate at high count-rate (C_n) with a high signal-to-background ratio. This was used for time resolved measurements of the main component of the neutron emission as well as to detect components of weak intensity. The MPR *ab initio* calibration and stability were used to perform absolute measurements of neutron energy and intensity. The plasma was observed along a collimated quasi-tangential (at 47º) sight-line making a double pass through the plasma center counter to that of the plasma current and NB injection [2]. The data quality is limited by C_n, which varies with the neutron flux from the plasma and is, in turn, proportional to P_f. Consequently, the best quality NES measurements so far were done during DTE1 with $P_f \leq 16$ MW and $C_n \leq 0.61$ MHz. Here, a subset of these data is considered, namely, discharges with NB in the range P_{NB}=4-11 MW and $C_n \leq 0.2$ MHz, together with transients at the onset and ramp-down of P_{NB}. Moreover, the Ohmic phases of the discharges were also studied at C_n=1-30 Hz requiring integration over a few seconds compared to a time resolution ≤100 ms during the NB pulse.

The neutron spectrum reflects the center-of-mass motion of ion pairs, i.e., d and t in this case, so that $d + t \rightarrow \alpha + n$ reactions produce mono-energetic 14-MeV neutrons for a cold plasma and a spectrum with a certain broadening or shift relative to this energy reflecting isotropic or anisotropic ion motional states, respectively.

In order to analyze the neutron spectrum, we used two approaches. An inclusive analysis was applied to determine the lowest order moments of the spectrum to extract information on intensity, energy shift (plasma toroidal rotation, v_{tor}) and spectral width (temperature, T). In this case, the resolving power of the data (given by C_n) was used to maximize time resolution (typically ≤200 ms) for spectral analysis. The spectrum was also analyzed in terms of components based on the underlying ion reactions and defined by the velocity distributions of the d and t populations. Besides the thermal component of Gaussian shape defined by T, four supra-thermal ones were considered whose shapes were predicted based on Monte Carlo calculations of fast ions interacting with the thermal bulk ion population. The fast isotropic ions were assumed to be epithermal (same as the thermal but $T_{ET} > T_{TH}$), and high energy (HE) anisotropic ones in passing (HE_P, co and cr) or trapped (HE_T) orbits with pitch angles of 60±15º for HE_P orbits and 90±10º for HE_T. This multiple-component analysis allows us to extract maximum information on the ion reactions responsible for the neutron emission but is demanding in terms of statistics, hence, the reduced time resolution (here, typically ≥0.5 s). Much of this information is unique for NES except for the bulk properties of the plasma where detailed information exists from charge exchange recombination spectroscopy (CXRS) and also crystal x-ray spectroscopy (CXS); these also provide information on v_{tor} as does NES.

Examples of the neutron emission components that are of interest to describe NB heated plasmas are shown in Fig.1 (left). The epithermal d and t components (assuming T_{ET}=25 keV) are compared with the thermal one (T_{TH}=5 keV) in the lower panel. The results on passing and trapped high-energy d and t components, in the upper panel, show a double-humped shape that is characteristic for the anisotropy in the underlying ion motions. For the HE_T ions we see the effect of the gyro-motion perpendicular to the magnetic field while there is no (or negligible) net effect of the parallel motion. The gyro-motion is also responsible for the shape of the HE_P ions with a superimposed energy up- or down-shifted depending on the net parallel velocity being co or cr to the plasma current with the MPR viewing in the co-direction. The measured spectra are typically well described by the model (Fig.1, right), the components of which, besides the energy shift reflecting the presence of v_{tor}, were determined by fitting.

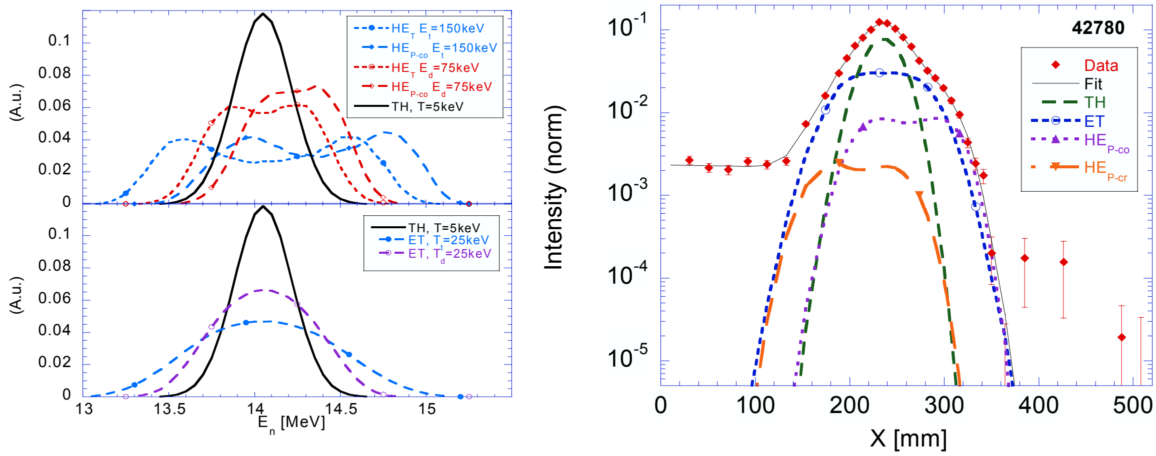

Fig. 1. Spectral components (left panel) used to describe the neutron emission from NB plasmas and applied in the analysis of MPR data for JET discharge #42780 (right panel).

The JET discharge #42780 was heated with tritium NB, NB(T°), resulting in an ion temperature in the range of T_i = 5.5 to 4 keV according to CXRS. The NES results (Fig. 2b) confirm these T_i-results during the NB-pulse and that it was raised to that level from a base of about 2 keV which it also fell back to after the pulse. The NB pulse also resulted in an ET component of T_{ET}=35 keV. The neutron rate shows an increase of almost four orders of magnitude (Fig. 2a), which must be due to ET and HE ion reactions. From the detailed analysis of the neutron spectrum we find that about 80 % of the fusion power is due to supra-thermal ion reactions at the beginning of the NB-pulse decreasing to 40 % at the end. The same time evolution can be predicted with the TRANSP equilibrium calculations but generally with higher values than our measurements. Moreover, experimentally we find that the ST contribution is dominated by ET but with a significant

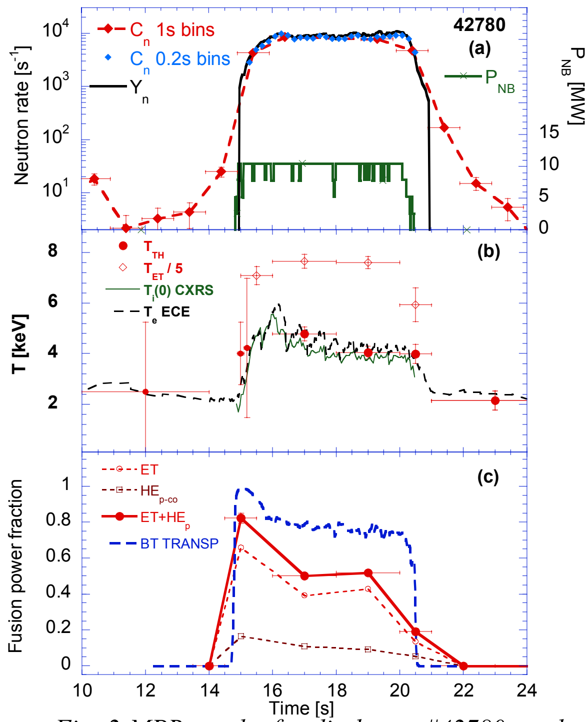

Fig. 2 MPR results for discharge #42780 on the time evolution of count rate C_n (a), temperatures (b), and fusion power fractions (c) compared with other data

addition from co-passing ions. It is also noteworthy that the experiment shows a significant ST contribution (including HEP) in the end of the NB-pulse (Fig. 2c), which is also clear from the C_n parameter shown in Fig. 2a.

The toroidal plasma rotation was deduced for discharges with NB(T°) and NB(D°,T°) both from the inclusive and detailed analysis of the neutron spectrum (Fig. 3). The results of the detailed analysis are found to confirm those of the inclusive one, performed with much higher time resolution, so that a comparison can be made with the results on the time evolution from the CXRS diagnostic. We thus find that the leading edge of the pulse show a steeper rotation increase than displayed in the CXRS. These features form a recurrent phenomenon whose significance is not quite clear. Another difference is that both diagnostics indicate changes during the NB pulse but they seem not to be co-variant with each other. Finally, it can be noted that the NES measurement show finite rotation velocities after the NB pulse is shut off.

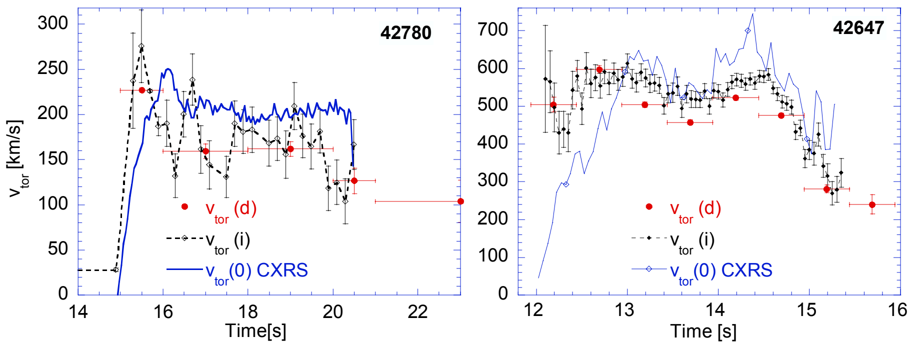

Fig. 3 Inclusive and detailed study of toroidal rotation as compared with CXRS data for #42780 heated with NB(T°) (left) and #42647 heated with NB(D°,T°) (right).

The present studies show that NES diagnosis of fusion plasmas start to be possible in detail at fusion power levels of a few tenths of MW in DT plasmas. The high quality regime is for pulses of 10 MW and above, which would be routine on ITER. Similarly, JET-EP would offer more favorable NES diagnostic conditions. The same NES diagnoses of D-plasmas are not yet possible but are envisaged to be realizable with a 2.5-MeV spectrometer (TOFOR) for JET at power levels of 1/100 of those for DT. Another line of development is a spectrometer that can measure the emission of 2.5 and 14-MeV neutrons, which will be afforded with the upgrade of the MPR spectrometer (MPRu) for JET-EP [3].

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