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ABSTRACT

In this work we estimate the fuel ion density profile in deuterium plasmas at JET, using the JET neutron camera, the neutron time-of-flight spectrometer TOFOR and fusion reactivities modeled by the transport code TRANSP. The framework has been tested using synthetic data, which showed that the density profile could be reconstructed with an average accuracy of the order of 10 percent. The method has also been applied to neutron measurements from a neutral beam heated JET discharge, which gave $n_d/n_e \approx 0.6$ in the plasma core and $n_d/n_e \approx 0.4$ towards the edge. Correction factors for detector efficiencies, neutron attenuation and backscattering are yet to be included in the analysis; future work will aim at refining this analysis.

I. INTRODUCTION AND METHOD

Accurate measurements of the densities of deuterium (n_d) and tritium (n_t) are essential for the operation and control of a burning fusion plasma. Neutron diagnostics offer the possibility to perform these kinds of measurements, since the neutron rate from a given point in the plasma is related to the fuel densities at that point. Neutron spectrometry has previously been used to estimate the average value of the fuel ion ratio (n_t/n_d) in the core of deuterium-tritium plasmas at JET [1].

In this work we test the principles of fuel ion density profile measurements with neutron diagnostics in deuterium (D) plasmas at JET, using the JET neutron camera [2] and the neutron time-offlight spectrometer TOFOR [3]. The neutron camera measures the neutron emission along 19 radial lines-of-sight, 10 horizontal and 9 vertical. TOFOR measures the time-of-flight spectrum of the emitted neutrons, with a line-of-sight similar to the central vertical sightline of the camera. From the TOFOR measurements it is often possible to separate the thermo-nuclear (TH) neutron emission from the beam-target (NB) emission [4], which is exploited in the present work.

We consider the case of a D plasma heated with neutral beam injection (NBI). The basis of the method is the fact that the DD neutron emissivity corresponding to a given deuterium density is given by

$$I_{\text{th}} = \frac{n_{\text{d}}^2}{2} \langle \sigma v \rangle_{\text{th}} \tag{1}$$

$$I_{\text{nb}} = n_{\text{d}} n_{\text{nb}} \langle \sigma v \rangle_{\text{nb}} \tag{2}$$

In the above equations, the neutron emission I has been decomposed into the contributions from TH and NB fusion reactions. $\langle \sigma v \rangle_{\text{th}}$ and $\langle \sigma v \rangle_{\text{nb}}$ denote the corresponding fusion reactivities and n_{nb} is the density of beam deuterons. The thermonuclear reactivity is a function only of the ion temperature T_i, but the beam-target reactivity depends on the details of the slowing down distribution of the injected beam ions. In this work we use the plasma transport code TRANSP [5], and its sub-module NUBEAM [6], to model the beam ion density and the beam-target reactivity. This modeling requires that T_i as well as the electron density (n_e) and temperature (T_e) are known. When the reactivities and nnb have been obtained, it is possible to calculate the number of neutrons going into in each sightline of the measuring instruments for a given n_d-profile, by integrating Equations (1) and (2) over the corresponding viewing cones. Under the assumption that the beam slowing down is unaffected by the fuel ion density, it is thus possible to set up a model of the neutron emission seen by each diagnostic, parameterized in terms of the density profile. This model can be used in a fitting procedure to find the density profile that gives the best match to both the neutron camera and the TOFOR measurements.

The basic idea is illustrated in Figure 1. This figure shows the calculated number of neutrons going into each sightline of the neutron camera, for two different density profiles. The density profile is specified as the average density in four regions along the normalized flux coordinate ρ, i.e. the model of the neutron emission depends on four free parameters in this case. In addition to the total number of neutrons, the contribution from thermonuclear neutrons is also shown explicitly for camera channel 15, one of the central vertical channels. It is seen that both the total and TH neutron emission depends on the density profile, and hence it is possible to estimate the density by finding the profile that reproduces both the camera measurement of the total neutron emissivity profile and the TOFOR measurement of the TH/NBfraction. This method for estimating the deuterium density profile has been tested using synthetic data, and the framework has been used with real data from a NBI heated JET discharge. The results are presented and discussed in the following sections.

2. RESULTS

In order to investigate how accurately the density profile can be determined, the framework described above was tested using synthetic neutron data, generated according to a known density profile, i.e. by prescribing values for the density in the four regions shown in Figure 1, and adding error-bars that reflect the assumed neutron count rate and systematic uncertainties. This was done using TRANSP simulations of plasma scenarios with several different beam deposition profiles and TH/NB ratios, to see if it the correct density profile is recovered, and how large the corresponding statistical uncertainties become. This procedure gives information about how well the method can be expected to perform in the ideal case, when the model is assumed to describe the neutron emission perfectly.

An example of a fit to synthetic data is shown in Figure 2, for a high density ($n_e \sim 10^{20}\ m^{-3}$) H-mode plasma. The upper panel of this figure shows the synthetic data, i.e. the number of neutrons in each of the 19 camera sightlines and the TH/NB fraction measured by TOFOR. The latter data point is visualized by normalizing it to the total number of neutrons in channel 15, which closely resembles the TOFOR sightline, as described in Section I. In other words, the camera measures the profile of the total neutron emission, and TOFOR is used to separate the emission into the TH and NB components in channel 15. In addition to the synthetic data, the neutron emission corresponding to the best-fit density profile is also shown. This density profile is shown in the lower panel of Figure 2, along with the statistical error-bars arising from the fit. The error-bars are obtained by a Monte-Carlo mapping of the likelihood function around the optimum. This means that they are fully unconstrained, i.e. that any correlations between the fitting parameters (the density values in the four regions) are properly taken into account.

For the example shown in Figure 2 the n_d-profile is correctly recovered, with an average statistical uncertainty of about 12 percent. The uncertainty is lower in the plasma core and higher towards the edge. This uncertainty depends on the magnitude of the error-bars assumed for the synthetic data, which can have contributions from both counting statistics and other systematical uncertainties, e.g. due to the neutron/γ separation in the camera detectors. In Figure 2 the systematical uncertainty for the camera data was assumed to be 10 percent of the average number of counts per sightline, and the uncertainty in the TH/NB ratio estimated from the TOFOR measurement was also assumed to be 10 percent. If this value is changed to 5 percent or 20 percent, the average uncertainty in the estimated density changes to 6 percent or 25 percent, respectively.

Real data from the neutron camera and TOFOR has been used to estimate the deuterium density profile for JET Pulse No: 82816. The data was collected during two seconds during the NBI period (18MW), when the plasma was in H-mode. The central electron density and temperature, as measured by Thomson scattering, were 1×10^{20} m^{-3} and 3 keV, respectively. For the TRANSP modeling, the assumption $T_i = T_e$ was used, since no direct measurements of T_i were available. This assumption is motivated by the high plasma density, which is expected to make the ion-electron equilibration time short compared to the time scales of interest here. The total neutron rate was about 2×10^{15} s^{-1}, which gave a count rate of 30–40kHz in the central camera channels. The TOFOR spectrum contained about 10^4 neutrons, and the TH/NB ratio was fitted to be 0.33 ± 0.05. The camera data is shown in Figure 3, together with the TOFOR data point representing the TH/NB ratio.

The camera data represents the number of neutrons detected in each of the 19 sightlines. When comparing these numbers to each other it is necessary to correct for differences in the detector efficiencies, for neutron attenuation due to scattering in different parts of the reactor structure, and for back-scattering of neutrons off the reactor wall and back towards the detectors. However, the neutron camera is just becoming operational after a major hardware upgrade and these correction factors are not yet included in the analysis. The result presented here should therefore be considered as a preliminary estimate of the density. Calculations with the Monte-Carl particle transport code MCNP will be performed to determine these correction factors.

In order to account for the unknown correction factors the absolute magnitude of the calculated camera data is taken to be a free component in the fit. Hence, only the shape of the camera data is used when estimating the density profile. The extra fitting parameter makes the fitting procedure more difficult. To compensate for this the two outer density parameters are combined into one, so that the density is only determined in three regions in ρ. Furthermore, differences between the correction factors for individual channels are taken into account by assuming a systematical uncertainty of 5000 counts for each channel. This essentially means that the relative differences between the correction factors are assumed to be about 10–20 percent for the central channels and of the order of 100 percent for the edge channels.

Under these assumptions, it is possible to get a preliminary estimate of the n_d-profile for JET Pulse No: 82816. The result is shown in Figure 3. In addition to the fitted profile, the systematical uncertainty due to a 10 percent uncertainty in n_e, T_e and T_i is shown with dashed lines. The measured electron density profile is also shown for comparison. It is seen that the nd-profile has a shape comparable to the electron density profile, with $n_d/n_e \approx 0.6$ in the plasma center and $n_d/n_e \approx 0.4$ towards the edge. The reduced χ^2 of the fit is 1.5.

3. DISCUSSION AND CONCLUSION

The study with synthetic data demonstrates that it is possible to correctly estimate the nd-profile from measurements of the neutron emission profile and the neutron energy spectrum. When performing this study it was found that the combination of profile information and spectroscopic information is crucial. If the TOFOR data point is omitted it is sometimes possible to find density profiles which give good fits to the camera data, but are significantly different from the true profile. Accurate modeling of the slowing down of the injected beam ions is also essential for the analysis presented here. The TRANSP/NUBEAM modeling used in this work has previously been validated both against TOFOR measurements [7] and neutron camera measurements [8]. As remarked in Section II, the result for Pulse No: 82816 is still preliminary and should be interpreted with care. The lack of correction factors for efficiency, attenuation and back-scatter introduces systematical uncertainties which are difficult to estimate. The error-bars for the fitted nd-profile in Figure 3 reflect the assumption that the systematical uncertainty is 5000 counts in each camera channel, but the validity of this assumption should be investigated further. With this in mind, it can still be noted that the basic features of the fitted nd-profile are reasonable; the density is higher in the core than at the edge, and always lower than the electron density. The fitted n_d-profile corresponds to a Z_{eff}-value of about 2.3 ± 1 in the core and 2.8 ± 1 towards the edge (assuming only Beryllium impurities). For comparison, the line integrated Z_{eff}-value along one single visible Bremsstrahlung chord was around 1.4 for this discharge. Thus, within the uncertainties of the estimated n_d-profile, these values are consistent with each other. Once the required correction factors for the neutron camera are available it will be possible to make a refined estimate of the density, and a more systematic evaluation of the method can be performed, using data from more discharges.

The contribution from beam-beam (BB) reactions to the neutron emission has been neglected throughout this project. For high density discharges, such as Pulse No: 82816 studied here, the BB is typically low (~1-2 percent according to the TRANSP simulations), due to a short slowing down time of the NBI ions. However, for a different plasma scenario (e.g. lower density) the BB contribution could be non-negligible. The BB intensity does not depend explicitly on the fuel density, so this component would be a fixed "background" component in the analysis.

In conclusion, a framework has been developed which allows for the estimation of the fuel ion density profile in D plasmas at JET, using TRANSP modeling of the NBI slowing down and neutron emission measurements from the JET neutron camera and the TOFOR spectrometer. The framework has been tested with synthetic data, and applied to real data from JET Pulse No: 82816. Correction factors for detector efficiencies,neutron attenuation and back-scattering are yet to be included in the analysis of the neutron camera data, and the results so far should therefore be interpreted with care.

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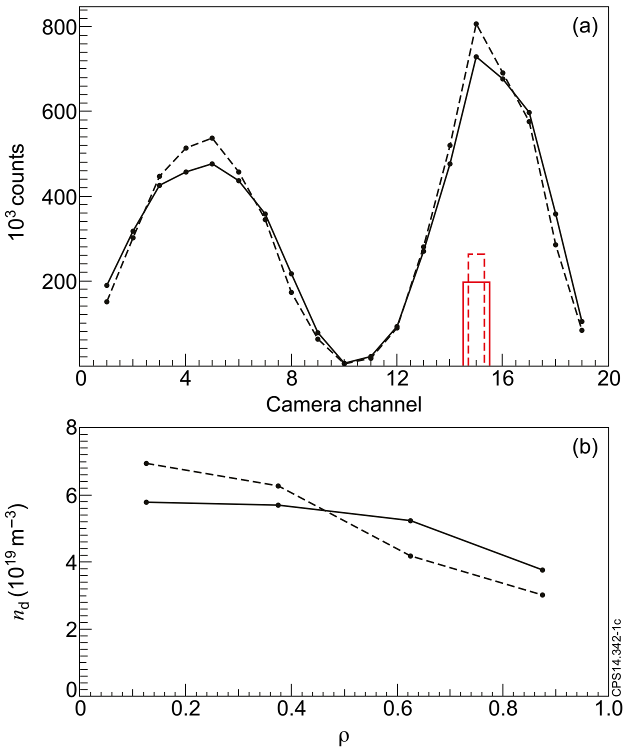

Figure 1: (a) Calculations of the neutron emission for two n_d-profiles (solid and dashed lines). The number of neutrons going into each of the 19 camera sightlines is shown. The bar in channel 15 represents the TH emission in this sightline. (b) The two density profiles used in the calculations.

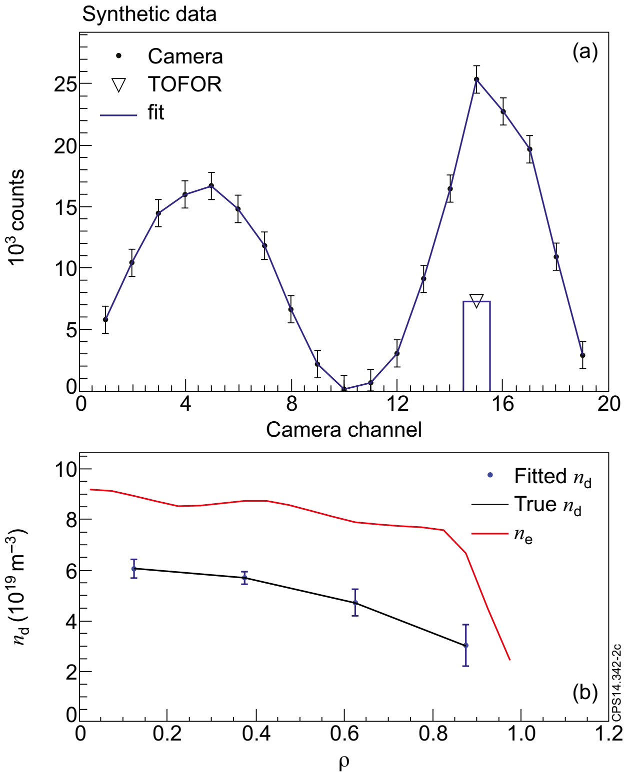

Figure 2: (a) Synthetic neutron camera (black dots) and TOFOR data (black triangle) for a high density H-mode plasma. The TOFOR data point is the estimated TH/NB ratio, normalized to the number of counts in channel 15 of the camera (the error-bar is smaller than the marker). The blue line is the calculated neutron emission corresponding to the best-fit n_d-profile, shown in (b). The true ndprofile (black line) and the ne-profile (red line) are also shown for comparison.

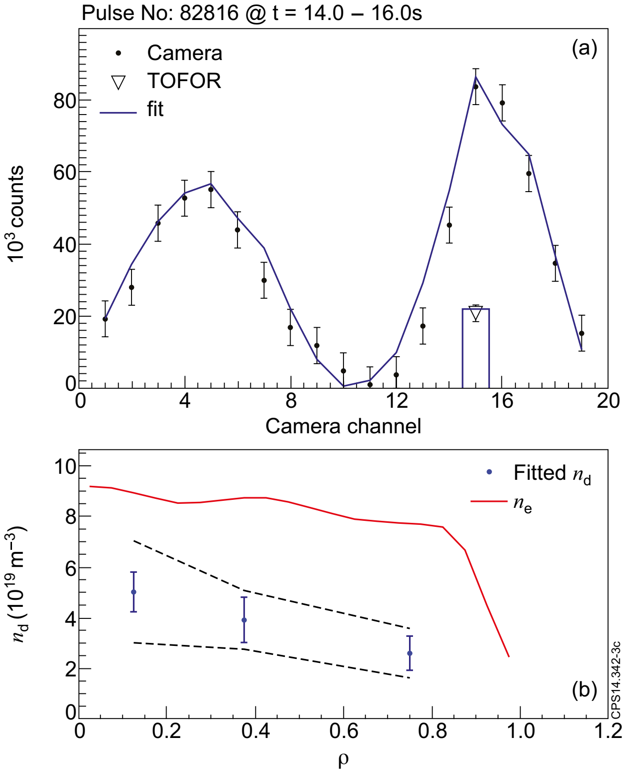

Figure 3: (a) Neutron camera (black dots) and TOFOR (black triangle) data for JET Pulse No: 82816. The TOFOR data point is the estimated TH/NB ratio, normalized to the number of counts in channel 15 of the camera. The blue line is the calculated neutron emission corresponding to the best-fit nd-profile (blue dots), shown in (b). The dashed lines are estimates of the systematical uncertainty (see text). The measured ne-profile (red line) is also shown for comparison.