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Eriksson J, Castegnetti G, Conroy S, Ericsson G, Giacomelli L, Hellesen C, JET-EFDA Contributors

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Deuterium density profile determination at JET using a neutron camera and a neutron spectrometer[a)]

J. Eriksson,[1,b)] G. Castegnetti,[1] S. Conroy,[1] G. Ericsson,[1] L. Giacomelli,[2,3] C. Hellesen,[1]
and JET-EFDA Contributors[c)]
JET-EFDA, Culham Science Centre, Abingdon OX14 3DB, United Kingdom
[1]*EURATOM-VR, Department of Physics and Astronomy, Uppsala University, Sweden*
[2]*Department of Physics, Università degli Studi di Milano-Bicocca, Milano, Italy*
[3]*EURATOM-CCFE Fusion Association, Culham Science Centre, Abingdon, United Kingdom*

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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 %. The method has also been applied to neutron measurements from a neutral beam heated JET discharge, which gave $n_d/n_e \approx 0.6 \pm 0.3$ in the plasma core and $n_d/n_e \approx 0.4 \pm 0.3$ towards the edge. Correction factors for detector efficiencies, neutron attenuation, and back-scattering are not yet included in the analysis; future work will aim at refining the estimated density. [http://dx.doi.org/10.1063/1.4889907]

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-Of-Flight spectrometer Optimized for Rate 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 (TN) neutron emission from the beam-target (BT) 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

$$I_{tn} = \frac{n_d^2}{2} \langle \sigma v \rangle_{tn}, \tag{1}$$

$$I_{bt} = n_d n_{bt} \langle \sigma v \rangle_{bt}. \tag{2}$$

In the above equations, the neutron emission I has been decomposed into the contributions from TN and BT fusion reactions. $\langle \sigma v \rangle_{tn}$ and $\langle \sigma v \rangle_{bt}$ denote the corresponding fusion reactivities and n_{nb} is the density of beam deuterons. The TN reactivity is a function only of the ion temperature T_i, but the BT 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 submodule NUBEAM,[6] to model the n_{nb} and the BT 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 n_{nb} 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 Eqs. (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 TN neutrons is also shown explicitly for camera channel 15, one of the central vertical channels, which also resembles the TOFOR sightline as described above. It is seen that both the total and TN 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

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[b)] Author to whom correspondence should be addressed. Electronic mail: jacob.eriksson@physics.uu.se.

[c)] See the Appendix of F. Romanelli *et al.*, Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, US.

neutron emissivity profile and the TOFOR measurement of the TN/BT-fraction.

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 Secs. II and III.

II. RESULTS

The above described framework was tested using synthetic neutron data to determine the accuracy of the estimated n_d-profile. The synthetic data were generated according to a known n_d-profile, 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 for TRANSP simulations of plasma scenarios with different NBI deposition profiles and TN/BT ratios to see if the correct n_d-profile is recovered, and how large the corresponding statistical uncertainties become. This procedure gives information about how well the method performs in the ideal case, when the model describes 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 shows the synthetic data, i.e., the number of neutrons in each of the 19 camera sightlines and the TN/BT 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 Sec. I. In other words, the camera measures the profile of the total neutron emission, and TOFOR is used to separate the emission into the TN and BT 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.

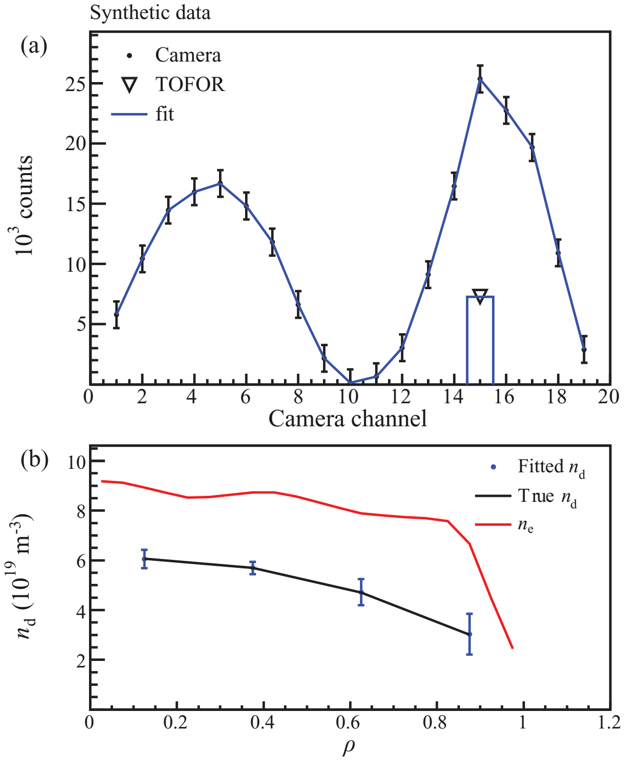

FIG. 2. (a) Synthetic neutron camera (black dots) and TOFOR data (black triangle) for a high density H-mode plasma. The TOFOR data point is the estimated TN/BT ratio, normalized to the number of counts in camera channel 15 (the error-bar is smaller than the marker). The blue line is the calculated neutron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

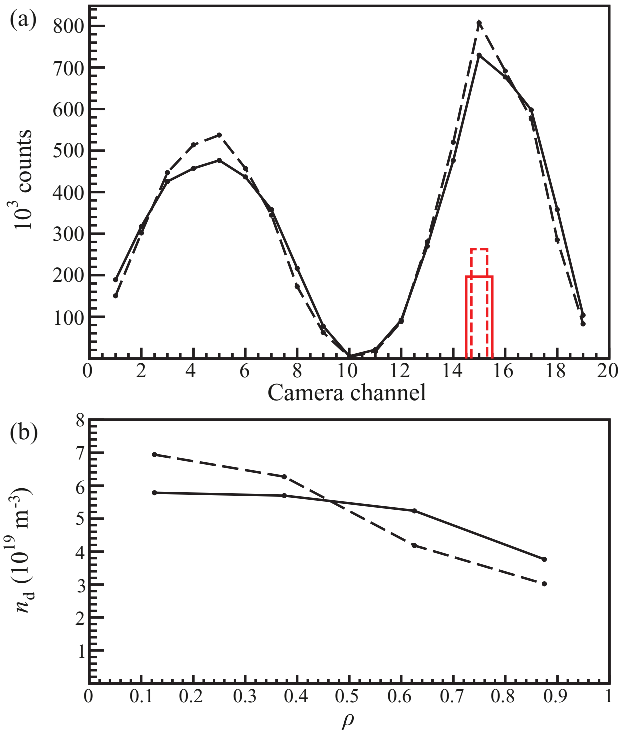

FIG. 1. (a) Calculated neutron emission for two n_d-profiles (solid and dashed lines). The number of neutrons going into each camera sightline is shown. The bar in channel 15 represents the TN emission in this sightline. (b) The two n_d-profiles used in the calculations.

For the example shown in Figure 2 the n_d-profile is correctly recovered, with an average statistical uncertainty of about 12%. 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% of the average number of counts per sightline, and the uncertainty in the TN/BT ratio obtained from TOFOR was also assumed to be 10%. If this value is changed to 5% or 20%, the uncertainty in the estimated n_d changes to 6% or 25%, respectively.

Real data from the neutron camera and TOFOR have been used to estimate the n_d-profile for JET discharge 82816.

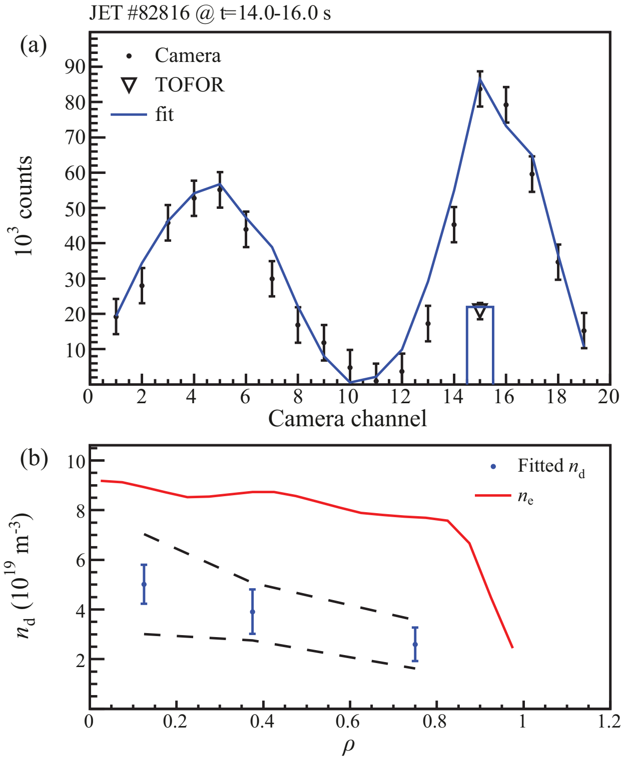

FIG. 3. (a) Neutron camera (black dots) and TOFOR (black triangle) data for JET discharge 82816. The TOFOR data point is the estimated TN/BT ratio, normalized to the number of counts in camera channel 15. The blue line is the calculated neutron emission corresponding to the best-fit n_d-profile (blue dots), shown in (b). The dashed lines are estimates of the systematical uncertainty (see text). The measured n_e-profile (red line) is also shown for comparison.

The collected data are integrated over two seconds during the NBI period (18 MW), when the plasma is in H-mode. The central electron density and temperature, as measured by Thomson scattering, are 1×10^{20} m^{-3} and 3 keV, respectively. The total neutron rate, measured by fission chambers, is about 2×10^{15} per second, which gives a count rate of 30–40 kHz in the central camera channels. The TOFOR spectrum contains about 10^4 neutrons, and the TN/BT ratio is fitted to be 0.33 ± 0.05. The camera data is shown in Figure 3, together with the TOFOR data point representing the TN/BT ratio.

For the TRANSP modeling, the T_i profile is assumed to be equal to the measured T_e profile, since no direct measurements of T_i are available for this discharge. 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 T_i predicted by TRANSP deviates from the measured T_e by no more than about 10% during the part of the discharge studied here, which corroborates this assumption.

The camera data represent 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 first wall of JET 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 Carlo N-Particle transport code MCNP[7] 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 n_d-profile. The extra fitting parameter makes the fitting procedure more difficult. To compensate for this the two outer density parameters are combined, so that n_d is only determined in three regions in ρ. Furthermore, differences between the correction factors for individual channels are accounted for 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% for the central channels and of the order of 100% for the edge channels.

Under these assumptions, it is possible to get a preliminary estimate of the n_d-profile for JET discharge 82816. The result is shown in Figure 3. In addition to the fitted profile, the systematical uncertainty due to a 10% 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 n_d-profile has a shape comparable to the electron density profile, with $n_d/n_e \approx 0.6 \pm 0.3$ in the plasma center and $n_d/n_e \approx 0.4 \pm 0.3$ towards the edge. The reduced χ^2 of the fit is 1.5.

III. DISCUSSION AND CONCLUSION

The study with synthetic data demonstrates that it is possible to correctly estimate the n_d-profile from measurements of the neutron emission profile and the neutron energy spectrum, if n_e, T_e, and T_i are known. 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[8] and neutron camera measurements.[9]

As remarked in Sec. II, the result for discharge 82816 is still preliminary and should be interpreted with care. The lack of correction factors for efficiency, attenuation, and back scattering introduces systematical uncertainties which are difficult to estimate. The error-bars for the fitted n_d-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 n_d-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, allowing for a more systematic evaluation of the method, 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 82816 studied here, the BB is typically low (∼1%-2% 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 discharge 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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