EFDA–JET–PR(13)42

J. Eriksson, C Hellesen, S. Conroy, G. Ericsson, A. Hjalmarsson, M. Nocente,
M. Skiba, M. Weiszflog and JET EFDA contributors

Deuterium Beam Ion Diffusion in JET H-mode Plasmas Studied with TRANSP Modeling and Neutron Diagnostics

Deuterium Beam Ion Diffusion in JET H-mode Plasmas Studied with TRANSP Modeling and Neutron Diagnostics

J. Eriksson[1], C Hellesen[1], S. Conroy[1], G. Ericsson[1], A. Hjalmarsson[1],
M. Nocente[2,3], M. Skiba[1], M. Weiszflog[1] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1] EURATOM-VR, Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
[2] Dipartimento di Fisica "G. Occhialini", Universit`a degli Studi di Milano-Bicocca, Milano, Italy
[3] EURATOM-ENEA-CNR, Istituto di Fisica del Plasma "Piero Caldirola", Milano, Italy
** See annex of F. Romanelli et al, "Overview of JET Results",*
(24th IAEA Fusion Energy Conference, San Diego, USA (2012)).

Preprint of Paper to be submitted for publication in
Nuclear Fusion

ABSTRACT

The plasma transport code TRANSP has an anomalous diffusion module that can be switched on in order to make the diffusion of energetic ions stronger than neoclassical values. In this contribution we use this module to investigate the occurrence of anomalous beam ion diffusion for three high density ($n_\mathrm{e} \sim 10^{20}$ m^{-3}) H-mode deuterium (D) plasmas at JET with the ITER-like wall (Be wall and tungsten divertor). Using ion distributions obtained from TRANSP modelling, the total neutron rate and the neutron spectrum seen by the time-of-flight neutron spectrometer TOFOR are calculated. The plasmas were heated with D neutral beams and hence the neutron emission consists of D(d,n)^{3}He neutrons with energies around 2.5 MeV.

It is found that the total neutron rate is over-estimated by about 40% by TRANSP when no anomalous diffusion is assumed. An anomalous diffusion coefficient of the order of 10 m^2/s results in total neutron rates which are comparable with the measured values. However, in these TRANSP simulations the thermal neutron fraction that was derived from the TOFOR data is generally not correctly reproduced.

In all the simulations the Z_eff profile was assumed to be uniform in space, with a value obtained from visible Bremsstrahlung measurements ($Z_\mathrm{eff} \sim 1.4 - 1.8$). However, if Z_eff is increased to values above 2.0 in all or part of the plasma, both the neutron rate and the thermal to beam-thermal fraction are correctly reproduced. Thus, these results indicate that little or no anomalous beam ion diffusion is needed to obtain a consistent picture of the measured neutron emission in these discharges, provided that value and spatial profile of Z_eff is adjusted in the TRANSP simulations. The validity of this assumption could be tested further in future experiments using data from the neutron profile monitor at JET, which is currently being upgraded.

1. INTRODUCTION

It is important to understand the transport behavior of fast ions in tokamak experiments. Fast ions are ions with energies much higher than the energy of a thermal plasma ion, and are produced either in the fusion reactions between the fuel ions or via external heating systems, such as neutral beam injection (NBI) or ion cyclotron radio-frequency heating (ICRH). The fast ions heat the plasma during their thermalization, and their transport behavior therefore affects the nature of the heating. A substantial amount of research has gone into investigating fast ion transport over the years [1, 2], and most of the observations are well described by neoclassical theory. However, anomalous transport, attributed to transport by microturbulence, have been observed at DIII-D [3, 4]. Also, measurements made during trace tritium experiments at JET [5] and current drive experiments at JT-60U [6] show signs of transport exceeding the neoclassical level. The subject of fast ion transport is thus still an area of interest for investigation.

In this paper it is investigated how neutron emission spectrometry can contribute to studies of fast ion transport. The main source of neutrons in a deuterium (D) plasma is the D(d,n)^{3}He reaction, producing neutrons with energies around 2.5 MeV. The energy of such a neutron is determined by the masses and velocities of the reacting ions, which means that the energy spectrum of the neutrons contains information about the velocity distribution of ions in the plasma. In particular, it is often possible to separate the fast ion contribution to the neutron emission from the thermal contribution [7]. This possibility is exploited in the present paper, where the measured fraction of thermal neutrons is compared to the corresponding value obtained from plasma modelling using the TRANSP package [8]. The neutron spectra were measured with the time-of-flight spectrometer TOFOR [9] at JET.

TRANSP has an anomalous diffusion module that can be switched on in order to make the diffusion of energetic ions stronger than neoclassical values. The approach followed in this paper is to compare the thermal neutron fraction and the total neutron rate with TRANSP calculations, for different levels of anomalous diffusion, to see if it is possible to find a scenario where both these quantities are accurately reproduced. This was done for three high density ($n_{\rm e} \sim 10^{20}$ m^{-3}) H-mode deuterium discharges at JET. The experiments were conducted after the completion of the ITER-like wall project [10], where the carbon wall was replaced with a beryllium wall and a tungsten divertor. In general it was not possible to find a case where both the thermal fraction and the total neutron rate were correctly reproduced by TRANSP, by adjusting only the level of anomalous diffusion. However, the TRANSP simulations can be made consistent with both measurements, without introducing anomalous diffusion, by manually changing the value and spatial dependence of $Z_{\rm eff}$ in the simulations.

The paper is organized as follows. In section 2 the relevant features of the neutron energy spectrum from a fusion plasma is described. Section 3 describes TOFOR and the JET discharges studied in the paper, and section 4 presents TRANSP simulations and TOFOR measurements from these discharges. The results of the analysis are discussed in section 5 and conclusions are presented in section 6.

2. NEUTRON EMISSION FROM A FUSION PLASMA

The energy of a fusion neutron depends on the velocities of the fuel ions that took part in the fusion reaction. The energy spectrum of such neutrons is therefore determined by the distribution of the fuel ions and the cross section of the fusion reaction under consideration. The neutron spectrum can be thought of as the sum of different emission components, arising from reactions involving different sub-populations of ions.

In the bulk plasma the fuel ions are in thermal equilibrium, and their velocities are distributed according to the Maxwellian distribution. The corresponding neutron spectrum can be shown to be of Gaussian shape, and the width is determined by the temperature of the ions [13]. This result holds when $Q \gg T$, which is a good approximation in fusion plasmas.

The fast ions produced by the NBI give rise to additional components in the neutron spectrum. These are the beam-thermal component – from reactions between beam particles and the bulk plasma – and the beam-beam component – from reactions between two beam particles – respectively. For the analysis presented in this paper, the neutron spectra corresponding to these reactions were calculated numerically, using fast ion distributions calculated with the code NUBEAM [11], which is part of TRANSP. Density and temperature profiles obtained from the TRANSP modeling were used in the calculations, as well as a detailed 3-dimensional model of the TOFOR viewing cone. This has been shown to be an accurate way of modeling the beam contribution to the neutron spectrum [12].

The intensity of a neutron component arising from reactions between ion populations a and b is proportional to the product of the ion densities n_a and n_b. For the thermal component in a D plasma, both n_a and n_b are equal to the the deuterium density n_d, which is related to the electron density n_e and the impurity charge Z_i through the definition of Z_eff,

$$Z_\mathrm{eff} = \frac{n_\mathrm{d} + n_\mathrm{i} Z_\mathrm{i}^2}{n_\mathrm{e}}. \tag{1}$$

Here, $n_\mathrm{i} = (n_\mathrm{e} - n_\mathrm{d})/Z_\mathrm{i}$ is the impurity density, in the approximation that there is only one impurity species in the plasma (assumed to be beryllium throughout this paper). The intensity of the thermal component therefore scales quadratically with n_e and Z_eff,

$$I_\mathrm{th,dd} \propto n_\mathrm{e}^2 \left(\frac{Z_\mathrm{i} - Z_\mathrm{eff}}{Z_\mathrm{i} - 1} \right)^2 . \tag{2}$$

The intensities of the beam-thermal ($I_\mathrm{bt,dd}$) and beam-beam ($I_\mathrm{bb,dd}$) components can be written down in a similar way, by noting that the beam ion density is roughly proportional to the product of the beam power P_nbi and the slowing down time τ_s. The latter is inversely proportional to n_e [2], which gives

$$I_\mathrm{bt,dd} \propto P_\mathrm{nbi} \left(\frac{Z_\mathrm{i} - Z_\mathrm{eff}}{Z_\mathrm{i} - 1} \right), \tag{3}$$

$$I_\mathrm{bb,dd} \propto \left(\frac{P_\mathrm{nbi}}{n_\mathrm{e}} \right)^2 . \tag{4}$$

Note that the n_e dependence cancels in the expression for the beam-thermal intensity.

In addition to the density dependence discussed above, the component intensities depend on several other factors, such as beam injection geometry and the temperature of the bulk plasma. These effects are taken into account in the detailed modeling by TRANSP/NUBEAM.

3. EXPERIMENTAL

Three JET H-mode discharges, carried out in March 2012, were analyzed for this paper. The discharges are similar to one another, all having densities of the order of $n_\mathrm{e} = 10^{20}$ m^{-3} and temperatures around 3.5 keV, as measured by Thomson scattering. The global value of Z_eff, obtained from visible Bremsstrahlung measurements, is between 1.4 and 1.8. The main source of heating is about 18 MW of NBI. Time traces of these parameters follow each other closely throughout the discharges, as can be seen in figure 1. The total neutron rate measured by fission chambers is shown in figure 2. The neutron rates are not as similar to each other as the other signals, both the time evolution and the peak values are somewhat different between the discharges. The reason for this difference has not been investigated in detail for this work. One contributing factor is probably that the discharges were seeded with nitrogen in the divertor, in order to study the surface heat loads and plasma detachment for different seeding scenarios. The details of the seeding were slightly different between the discharges, which could have affected the confinement, and thereby the neutron rate.

The neutron spectra from the discharges were measured with the neutron time-of-flight spectrometer TOFOR [9], which is situated in the roof laboratory, 19 meters above the JET tokamak. The line of sight goes vertically through the center of the plasma, and the width of the viewing cone is about 25 centimeters at the torus mid-plane. Neutrons are detected in two sets of plastic scintillator detectors, and the neutron energy is related to the time between the detector events. The time-of-flight of a 2.5 MeV neutron is about 65 ns. The instrument response function has been modeled in detail with particle transport calculations, using a detailed model of the detector geometry and materials [14]. The response function is needed in order to convert calculated neutron energy spectra to time-of-flight scale, which is crucial for the component analysis presented in section 4.2.

4. RESULTS

4.1. TRANSP SIMULATIONS OF THE JET DISCHARGES

The discharges have been modeled with the plasma transport solver TRANSP [8]. Four different simulation cases, A through D, are presented in this paper, using different values of anomalous diffusion or Z_{eff}. A summary of the simulation cases can be found in table 1. An example of the thermal and beam-thermal neutron emissivity profiles calculated by TRANSP is shown in figure 3, together with the field of view of TOFOR. It can be seen that a large part of the beam-thermal emission takes place in the outer part of the plasma, in contrast to the thermal emission which comes from the core. This is a consequence of the comparatively high density in these discharges; most of the injected beam particles cannot penetrate very far into the plasma before being ionized.

In simulation cases A, B and C Z_{eff} was assumed to be the same everywhere in the plasma, with a value obtained from the visible Bremsstrahlung measurements shown in figure 1, i.e. between 1.4 and 1.8. In case A the beam ion diffusion was assumed to be purely neoclassical, whereas in cases B and C 5 and 10 m^2/s of anomalous beam ion diffusion was prescribed, in order to see what effect this has on the neutron production. The left panel of figure 4 shows a summary of the TRANSP output. The total neutron rate given by TRANSP for the different values of anomalous diffusion is compared with the measured neutron rate. It is seen that the neutron rate is overestimated by about 40-50% for the case without anomalous diffusion. When anomalous diffusion is introduced the calculated neutron rate is reduced, and for a diffusion coefficient of 10 m^2/s the calculated and measured values are generally in agreement.

In cases B and C above, the calculated neutron rate is reduced since the anomalous diffusion reduces the number of beam particles. Another way to obtain the same effect is to reduce the density of deuterons in the bulk plasma, by increasing the value of $Z_{\rm eff}$ in all or parts of the plasma. This is done in simulation case D (see table 1). For discharges 82812 and 82817, the $Z_{\rm eff}$ value is increased to 2.2-2.35 in the outer part of the plasma, outside $\sqrt{\psi_{\rm tor}} = 0.4$, and for discharge 82816 $Z_{\rm eff}$ is set to 2.0 throughout the plasma. These particular choices of $Z_{\rm eff}$ are motivated by the result of the TOFOR analysis presented in section 4.2, and is discussed in section 5. The results are shown in the right panel of figure 4. The calculated and measured neutron rates are in agreement for all three discharges.

4.2. TOFOR ANALYSIS

From the TRANSP simulations presented in section 4.1 it is seen that the measured neutron rate can be reproduced either by adding around 10 m^2/s of anomalous beam ion diffusion, or by increasing the value of $Z_{\rm eff}$, possibly also changing its spatial dependence. In this section it is investigated whether these simulations are consistent with measurements of the neutron energy spectrum performed with the TOFOR spectrometer (see section 3), by comparing the fraction of thermal neutrons seen by TOFOR with the corresponding value obtained from TRANSP. The different simulation cases are expected to result in different relative intensities of the neutron emission components, since anomalous diffusion only affects the beam neutrons, whereas a change in $Z_{\rm eff}$ affects both the thermal and the beam-thermal intensities, according to the scaling relations (2) and (3).

Examples of the TOFOR analysis is shown in figure 5. Three neutron emission components are fitted to the data; a thermal component, a beam-thermal component and a back-scatter component, taking into account neutrons scattering in the divertor region and back towards TOFOR [15]. The beam-thermal component is obtained from the fast ion distribution and the density profile obtained from TRANSP/NUBEAM, by calculating the neutron spectrum, as discussed in section 2. In figure 5 the integration times for the TOFOR data (about 2-2.5 seconds) are specified for each discharge. The fast ion distributions from TRANSP are averaged over the same time interval. The beam-beam contribution is very low in these plasmas, about 1-2$\%$ of the total neutron emission according to the TRANSP simulations. This is due to the high density, and the fact that the beam-beam intensity is inversely proportional to the square of the density, according to (4). This component is therefore not included in the analysis. In total there are four free parameters in the fit; the temperature of the thermal component and the intensity of each of the three components. In addition to the best-fit values of the parameters, the corresponding statistical uncertainties are extracted from a Monte-Carlo sampling of the likelihood function around the optimal parameter values. The reduced χ^2 of the fits are between 0.6 and 0.9, which indicates that the fitted spectra describe the data well.

The thermal neutron fraction is obtained by forming the ratio between the thermal and total direct neutron fluxes, $\Gamma_{\rm th}/\left(\Gamma_{\rm th}+\Gamma_{\rm bt}\right)$, where $\Gamma_{\rm th}$ and $\Gamma_{\rm bt}$ are the thermal and beam-thermal neutron fluxes measured by TOFOR, i.e. the best-fit value of the intensities of the respective components in the fit. In this way it is possible to obtain the TOFOR estimate of the thermal fraction for each of the simulation cases (A through D) presented in table 1, as well as the TRANSP prediction of the same quantity. A summary of the results is presented in the right panel of figure 5. These plots show the thermal neutron fraction that is obtained from TOFOR (blue squares with error bars), using the beam components obtained from TRANSP simulations with different levels of anomalous diffusion. Also shown in the plots are the simulated thermal fractions for each case. The red circles correspond to cases A, B and C, and case D is represented by a green cross, in order to distinguish it from case A, since both these simulations are without anomalous diffusion. The thermal fractions are plotted against the value of the anomalous diffusion coefficient used in the respective TRANSP simulations.

In discharge 82812, the calculated thermal fractions are within the error bars of the TOFOR estimate for the two simulations without anomalous diffusion, i.e. simulation cases A and D. For discharge 82816, agreement is obtained only for simulation case D, in the other cases the TRANSP calculations are significantly different from the TOFOR results. In discharge 82817, agreement is obtained for all cases except case A, where the TRANSP value is slightly lower than the value from TOFOR.

5. DISCUSSION

From the results presented in figure 4 and figure 5 several observations can be made.

- When using the measured value of $Z_{\rm eff}$, the total neutron rate is overestimated by TRANSP. If anomalous diffusion coefficients around 10 $\rm m^2$/s are introduced in the simulations, the agreement between the TRANSP calculations and the experimentally measured neutron rate is significantly improved.
- When anomalous diffusion is introduced to reproduce the neutron rate, the TRANSP simulations generally do not reproduce the thermal neutron fraction derived from TOFOR data. This is particularly evident for discharge 82816, where the TRANSP results are significantly higher than the TOFOR results.
- Both the total neutron rate and the thermal fraction can be correctly reproduced by changing the $Z_{\rm eff}$ used in the simulations. No anomalous diffusion is needed in this case.

Thus, these results indicate that little or no anomalous beam ion diffusion is needed to obtain a consistent picture of the measured neutron emission in these discharges, provided that the value and spatial profile of $Z_{\rm eff}$ is adjusted in the TRANSP simulations. Also, for discharges 82812 and 82816, it was not possible to correctly reproduce both the neutron rate and the thermal fraction only by introducing anomalous diffusion.

The choices of Z_{eff} for simulation case D were motivated by the results of the TOFOR measurements, and by the scaling relations (2) and (3) for the intensities of the neutron emission components. To exemplify this, consider discharge 82812. As seen from figure 5, the thermal fractions from TOFOR and from TRANSP were in agreement already for simulation case A, both results being close to 0.4. These values reflect the thermal fraction in the core of the plasma, which is where the significant thermal neutron production occurs, as seen from figure 3. This means that the TOFOR measurements are compatible with core Z_{eff} values close to the visible Bremsstrahlung measurements. Therefore, in simulation case D, Z_{eff} was increased mainly in the outer part of the plasma. The effect of this is a reduction of the calculated total neutron rate, without any change in the thermal neutron production in the core. In this way it was possible to match both the total neutron rate and the thermal neutron fraction for discharge 82812. The same reasoning was applied when adjusting Z_{eff} to match the measurements for discharge 82817.

For discharge 82816 on the other hand, both the neutron rate and the thermal fraction were overestimated by TRANSP in simulation case A. This indicates that TOFOR does not see the amount of thermal neutrons corresponding to the Bremsstrahlung measurements of Z_{eff} in this discharge. In this case, an increase in Z_{eff} from about 1.4 to 2.0, throughout the plasma, was necessary in order to obtain agreement between the calculated and measured values.

Thus, the TOFOR measurements give a strong indication about the value of Z_{eff} in the core for these discharges. Regarding the Z_{eff} values prescribed for the outer part of the plasma, these are motivated by the requirement that the total neutron rate should also be reproduced by the TRANSP simulations. One way to further investigate the validity of these assumptions on Z_{eff} would be to include the JET neutron profile monitor in the analysis. An upgrade of this instrument is currently being finalized. Measurements of the neutron emissivity profile could greatly contribute in the assessment of the Z_{eff} profiles in future studies similar to the one presented in this paper. Charge exchange recombination spectrometry can also give information on impurity density profiles. This diagnostic were not available during the discharges studied in this paper, but could also make an important contribution in future studies.

It can be seen from the TOFOR results in figure 5 that the estimate of the thermal fraction are somewhat different between the different simulation cases. This reflects the fact that different values of anomalous diffusion in the TRANSP simulations results in calculated beam components of slightly different shapes, which affects the fit. However, for most of the simulation cases studied here, the difference between the TOFOR estimates corresponding to different simulation cases is always smaller than the statistical uncertainty of the fit. Simulation case C ($D_{\text{a}} = 10$ m^2/s) in discharge 82816 is an exception, but apart from this outlier the TOFOR estimates for a given discharge all have partially overlapping error bars. This indicates that the determination of the thermal fraction from TOFOR data is robust, and not very sensitive to variations in the modelling of the beam ion distribution.

5.1. SYSTEMATIC UNCERTAINTIES

The error-bars on the TOFOR estimates of the thermal neutron fractions presented in figure 5 are the statistical uncertainties from the fit of the neutron emission components to the data. In addition to these uncertainties, there are some possible sources of systematic errors that should be pointed out.

Uncertainties in the width of the viewing cone could result in errors when integrating the calculated neutron spectrum to obtain the TOFOR neutron components and thermal fraction. However, a sensitivity study has been made where the width of the viewing cone was varied by as much as a factor of two (between about 15 and 30 centimeters) and the corresponding relative changes in the calculated thermal fractions were always less than $\sim 3\%$, which is smaller than the statistical error-bars. It is therefore concluded that uncertainties in the modeling of the viewing cone width is of little importance for the results presented in this paper.

The response function of TOFOR requires input in the form of detector thresholds, which are set in the analogue electronics of the data acquisition system. During a recent calibration (June 2013) it was seen that the thresholds had drifted slightly since the previous calibration in 2009. The nominal value is 380 keV, but the new calibration indicated that the thresholds were higher, about 400-450 keV. This means that there is some uncertainty about the threshold values for the pulses studied in this paper. The TOFOR analysis presented in section 4.2 was made with a response function corresponding to thresholds set at 440 keV. The same analysis has been performed assuming that the thresholds were 380 keV, and the resulting thermal fractions that are obtained are again within the error-bars shown in figure 5. In future studies the threshold values will be better known, and this source of uncertainty will be even smaller.

Beryllium was assumed to be the only impurity species in the TRANSP simulations. This is a limitation, since other impurities – e.g. tungsten or some of the nitrogen that was seeded in the divertor – may also have penetrated into the confined plasma. This adds some uncertainty to the values of Z_{eff} that is needed in TRANSP in order to match the neutron rates. Specifically, if some of the impurities would have a higher charge than beryllium, the required Z_{eff} would be higher. As stated above, charge exchange measurements could reduce this limitation in future experiments.

Uncertainties in the input to TRANSP affect the results of the simulations presented in this paper. This has been investigated, by varying the input electron density and temperature within 10% of their measured values and re-running TRANSP. The result is that slightly different values of Z_{eff} are needed in order to match the neutron rate and the thermal fraction. A systematic study of how these uncertainties affect the results is beyond the scope of this work. However, the qualitative observation pointed out in this paper does not change: a consistent picture of the neutron emission can be obtained without introducing anomalous diffusion.

CONCLUSIONS

Neutron emission spectrometry can contribute to studies of fast ion transport, by comparing calculated neutron spectra based on TRANSP simulations for different transport scenarios with the measured neutron spectrum. For the three JET discharges studied in this paper, it was possible to obtain a consistent picture of the total neutron rate measured by fission chambers and the neutron spectrum measured by TOFOR, assuming only neoclassical fast ion transport, by adjusting the value and spatial distribution of Zeff used in the TRANSP simulations. The total neutron rate could also be reproduced by TRANSP by introducing an anomalous diffusion coefficient of 10 m2/s, but in this case the calculated neutron spectrum did not match the spectrum measured by TOFOR, in two out of the three discharges studied.

In future experiments, the assumptions made on the Zeff profile could be further validated by including data from the newly upgraded neutron profile monitor, as well as impurity density profiles measured by charge exchange recombination spectrometry, in the analysis.

ACKNOWLEDGMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]. Heidbrink W.W. and Sadler G.J. 1994 Nuclear Fusion **34** 535

[2]. ITER Physics Expert Group on Energetic Particles, Heating, and Current Drive et all 1999 Nuclear Fusion **39** 2471

[3]. Heidbrink W.W. et al 2009 Physical Review Letters 2009 **103** 175001

[4]. Heidbrink W.W. et al 2009 Plasma Physics and Controlled Fusion **51** 125001

[5]. Baranov Y.F. et al 2009 Plasma Physics and Controlled Fusion **51** 044004

[6]. Suzuki T. et al 2008 Nuclear Fusion **48** 045002

[7]. Hellesen C. et al 2010 Review of Scientific Instruments **81** 10D337

[8]. Ongena J. et al 2012 Trans. Fusion Technology **61** 180

[9]. Gatu Johnsson M. et al 2008 Nuclear Instruments and Methods A **591** 417

[10]. Matthews G.F. et al 2011 Physica Scripta **T145** 014001

[11]. Pankin A. et al 2004 Computer Physics Communications **159** 157

[12]. Hellesen C. et al 2010 Plasma Physics and Controlled Fusion **52** 085013

[13]. Brysk H. 1973 Plasma Physics **15** 611

[14]. Hjalmarsson A. 2006 Development and construction of a 2.5MeV neutron time-of-flight spectrometer optimized for rate (TOFOR) PhD Thesis Department of Neutron Research, Uppsala University, http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-7198

[15]. Gatu Johnson M et al 2010 Plasma Phys. Control. Fusion **52** 085002

TRANSP case	D_α	Z_{eff}
A	$0m^2/s$	Flat Z_{eff}, from visible Bremsstrahlung measurements.
B	$5m^2/s$	Flat Z_{eff}, from visible Bremsstrahlung measurements.
C	$10m^2/s$	Flat Z_{eff}, from visible Bremsstrahlung measurements.
D	$0m^2/s$	Pulse No: 82812: $Z_{eff} = 1.85$ inside $\sqrt{\psi_{tor}} = 0.4$, $Z_{eff} = 2.2$ outside. Pulse No: 82816: $Z_{eff} = 2.0$ throughout the plasma. Pulse No: 82817: $Z_{eff} = 1.7$ inside $\sqrt{\psi_{tor}} = 0.4$, $Z_{eff} = 2.35$ outside.

Table 1: Summary of the different TRANSP simulation cases, specifying the value of the anomalous diffusion coefficient, D_α, and commenting on the assumptions made on Z_{eff} for each case.

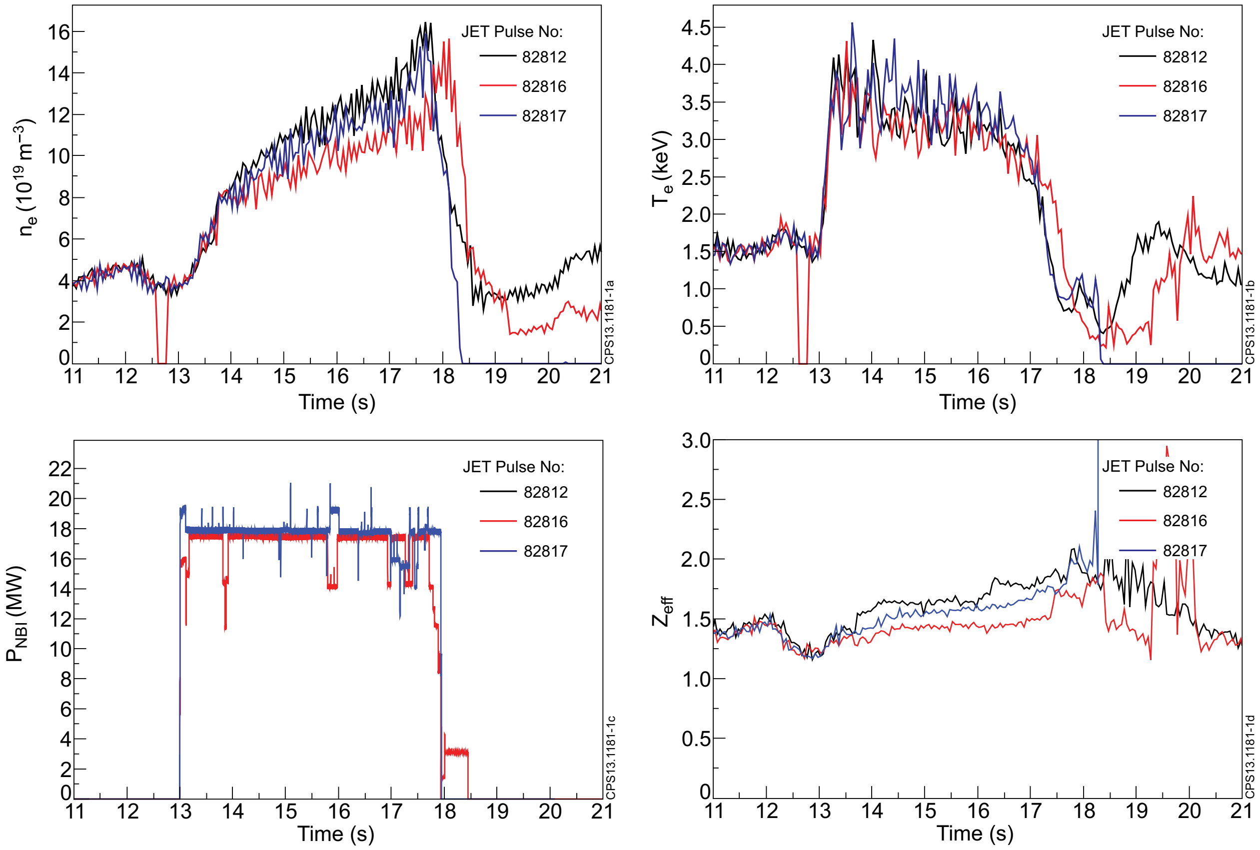

Figure 1: Time traces of central electron density, central electron temperature, NBI power and Z_{eff} for JET Pulse No's:82812, 82816 and 82817.

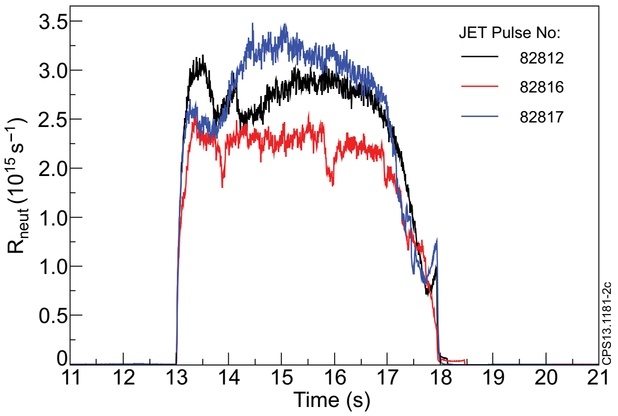

Figure 2: Time trace of the neutron rate for Pulse No's: 82812, 82816 and 82817.

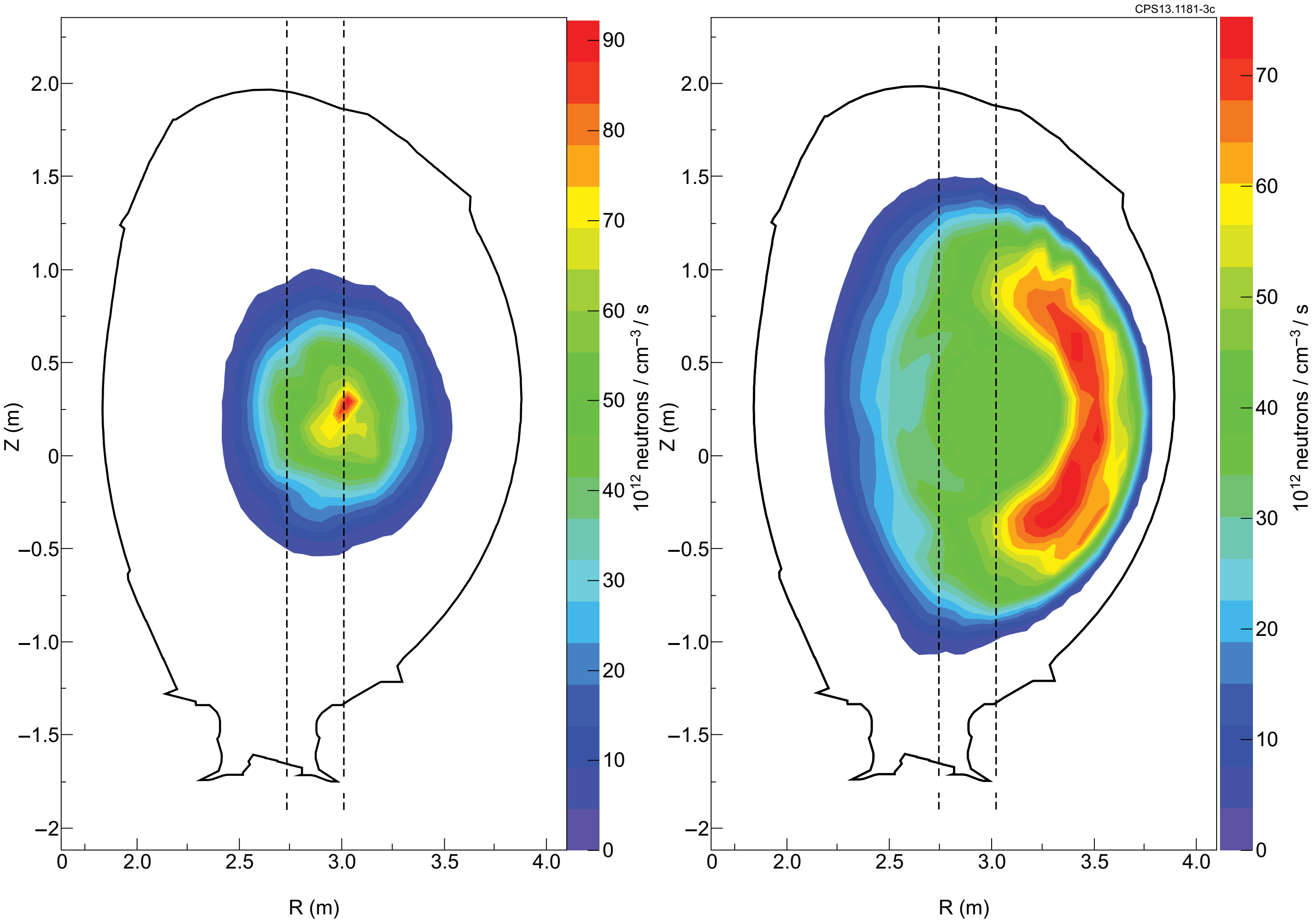

Figure 3: Thermal (left) and beam-thermal (right) neutron emissivity profiles calculated by TRANSP for Pulse No: 82812, simulation case D (see table 1). The field of view of TOFOR is indicated with dashed vertical lines.

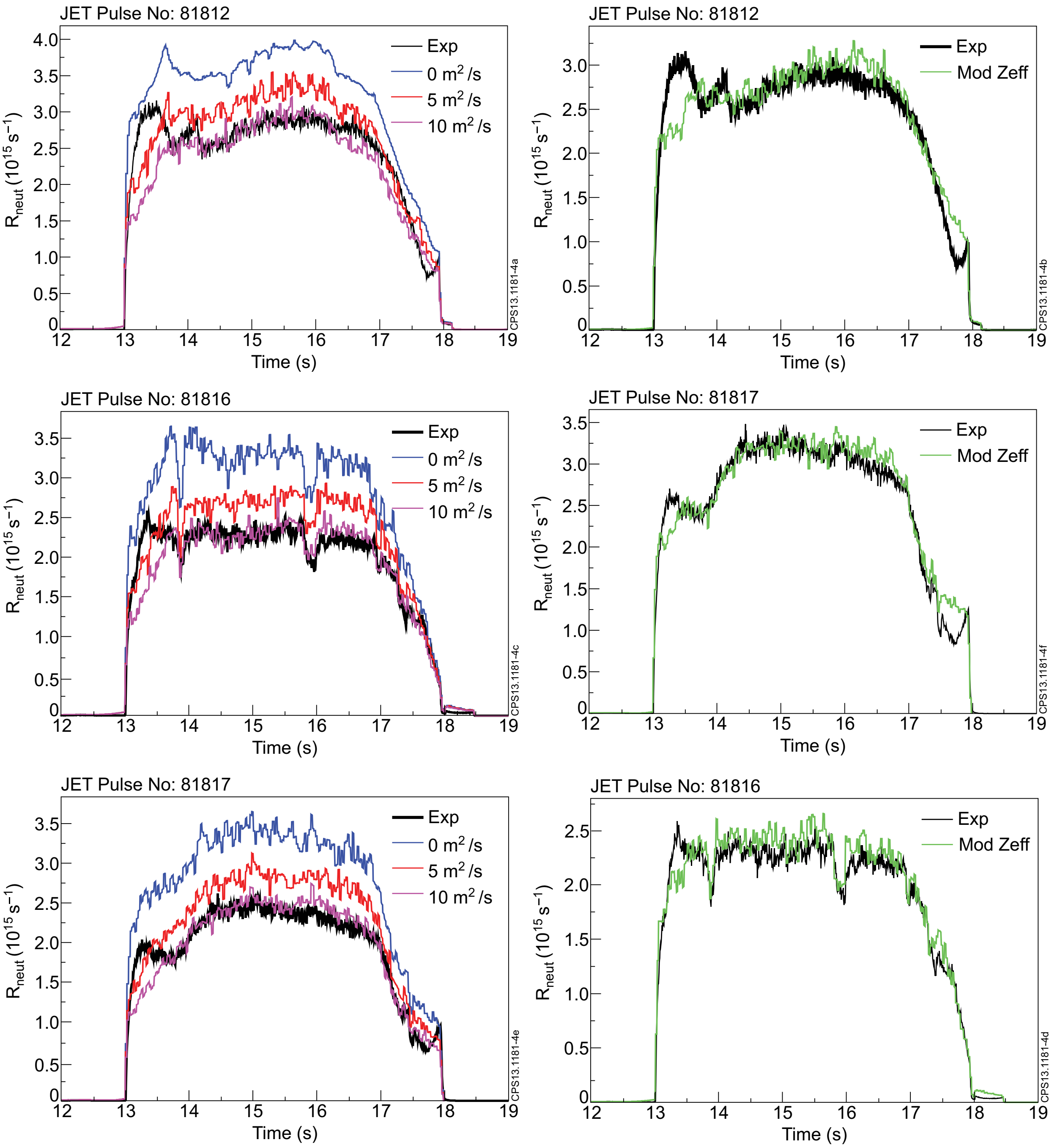

Figure 4: Left: total neutron rates calculated by TRANSP for different values of anomalous beam ion diffusion, compared with the measured neutron rate. Right: total neutron rates calculated by TRANSP for artificial Z_{eff} profiles (see table 1), compared with the measured neutron rate.

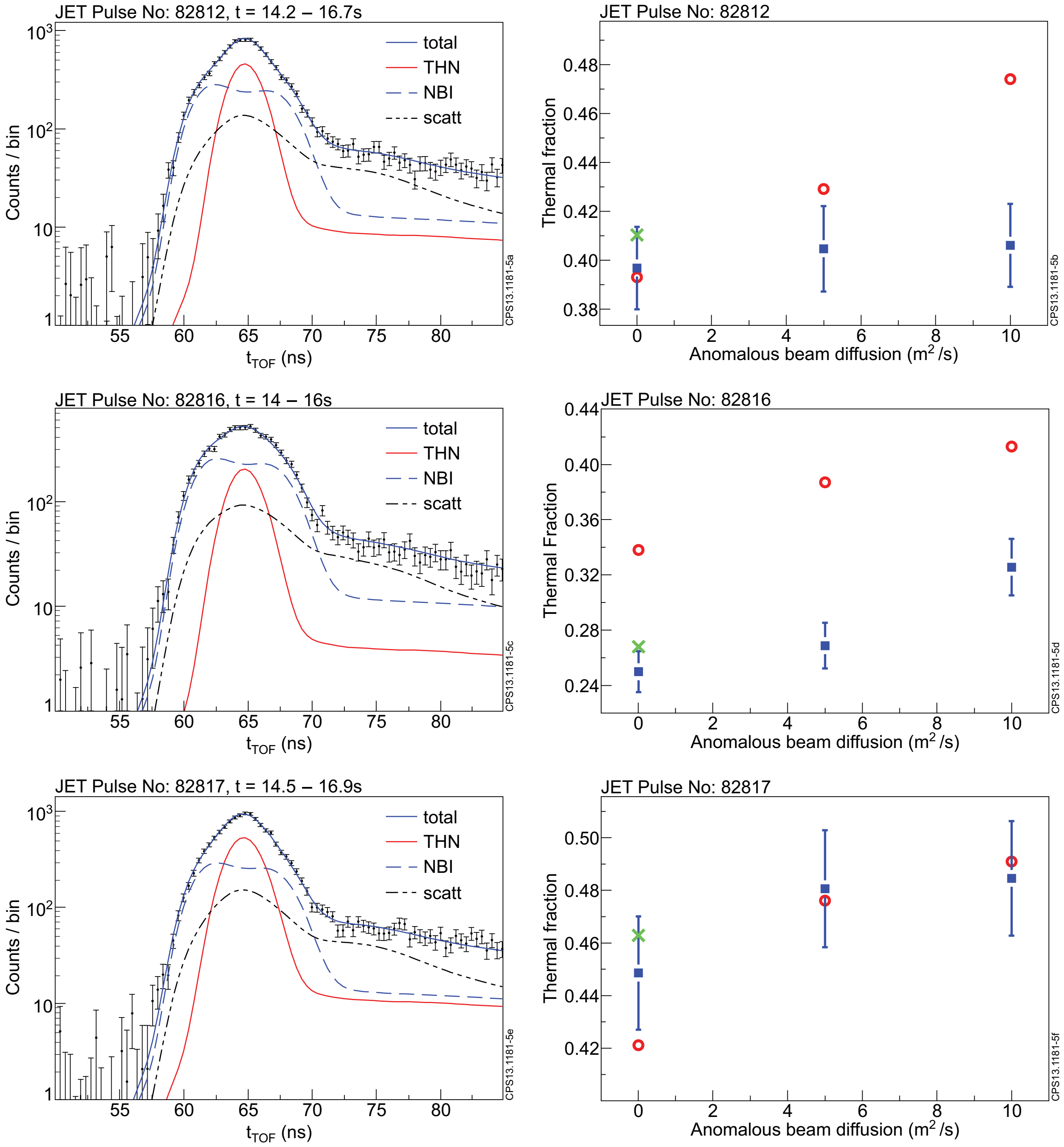

Figure 5: Left: Examples of the TOFOR analysis performed to extract the thermal neutron intensity. Thermal (red line), beam-thermal (blue dashed line) and back-scatter (black dash-dotted line) components are fitted to the TOFOR data (points with error bars). The beam components correspond to simulation case A in these examples. Right: Thermal neutron fractions derived from TOFOR data (squares with error bars), compared with TRANSP calculations of the same quantity (red circles and green cross). The red circles represent simulation cases A, B and C, and the green cross represents simulation case D (see table 1). The data points are plotted against the value of the anomalous diffusion coefficient used in the TRANSP simulations.