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I. Jenkins, C.D. Challis, J. Hobirk, Yu.F. Baranov, L. Bertalot, D.L. Keeling,
V. Kiptily, S.E. Sharapov and JET EFDA contributors

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I Jenkins[1], C D Challis[1], J Hobirk[2], Yu F Baranov[1], L Bertalot[3], D L Keeling[1],
V Kiptily[1], S.E. Sharapov[1] and JET EFDA contributors*

[1]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[2] *Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany*
[3] Associazone EURATOM-ENEA sulla Fusione, C R Frascati, Frascati, Italy
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The understanding of fast ion physics is important for modelling and interpretation of Neutral Beam Injection (NBI) in tokamaks. It is required for the derivation of transport coefficients and the simulation of heating and current drive in beam heated plasmas.

The JET tokamak possesses a unique combination of tools to diagnose NBI fast ion behaviour in the ability to inject on- and off-axis tritium beams and to diagnose them using a 2-D neutron camera. The latter offers fast time and space resolved profiles both of the 14MeV neutron profiles resulting from DT reactions caused by fast tritons in a deuterium plasma and of the 2.5MeV neutrons from DD reactions (see figure 1). Experiments have been performed with the injection of short tritium beam blips (~300ms) with both on- and off-axis beam trajectories into a pure deuterium plasma. The plasma conditions were chosen so that the thermal neutron yield was negligible compared with beam-target and, in the case where deuterium beams were also used, beam-beam interactions. Data was obtained at two values of toroidal magnetic field, 1.2T and 3T, corresponding to $q_{95}\approx3.3$ and $q_{95}\approx8.5$ respectively, at the plasma current of 1MA.

Previous analysis [1] of data taken during the trace tritium experiment (TTE) showed discrepancies between the measured 14MeV neutron yield and that predicted by Monte Carlo simulations using the TRANSP code [2]. The high q_{95} experiments reported in this paper provide the simplest case to test for anomalies of this kind. They are free of ICRH heating, have minimal MHD activity and, in the case of high power D beams, allow the T beam blip to be non-perturbative. The calibration of NBI power was examined carefully and the effect of thermal tritons in both the D and T beam phases was accounted for. The influence of input data available from alternative diagnostics was examined, especially that for Z_{eff} which can be supplied from both charge-exchange spectroscopy (CXS), which assumes only carbon impurities, and from Visible Bremmstrahlung (VB) measurements. Integrating the total DT neutrons calculated by TRANSP over the time of the tritium blip (where the neutron count is dominated by the 14MeV neutrons) and dividing this by the total measured neutrons over the same period gives a neutron discrepancy ratio. Repeating this calculation for the DD neutrons in an equivalent period just before the tritium beam blip (where the 2.5MeV neutrons dominate) and plotting the DD and DT ratios against each other gives figure 2. Measurements and modelling agree when the DD and DT ratios achieve unity. Uncertainties in measured quantities such as Z_{eff}, which affects thermal fuel dilution, or temperature and density, which affect the slowing down time, introduce a similar discrepancy in the modelling of both deuterium and tritium beams. Such uncertainties would tend to move data along the $x=y$ line in figure 2. This is illustrated by the comparison of simulations using Z_{eff} from CXS (~1.1-1.5) and from VB (~3). Only causes of discrepancy that do not affect the injected deuterons and tritons in the same way can result in a departure from the $x=y$ line, such as a relative miscalibration of the D or T beam power. The error bar shows the effect of the ~10% uncertainty in the tritium power on the modelled DT neutron rate. It can be seen that the relative discrepancy between DD and DT simulations is within the uncertaintiy of the beam power, and that the absolute discrepancy between measurement and simulation is within the uncertainty of the value of Z_{eff}.

Comparing modelled neutron profiles with measurements during the DT phase shows a contrast between high and low q_{95} regimes. The simulated profiles in the following figures have been normalised to the total neutron number in the related measured profile in order to allow a comparison of the neutron profiles shapes. Two high q_{95} regimes were investigated, one with no D beam and one with a steady state high power (~12MW) D beam injected continuously before and during the T blip. In these high q_{95} cases the neutron profiles show good agreement with the measured profile shape (see figures 3 and 4). The difference between on- and off-axis (beam tangent at r/a ~ 0.4) T injection is clearly apparent in the peaked/flat nature of each profile (line-integral effects will make an off-axis beam hollow neutron emmissivity profile appear flat-topped). The agreement between the scenarios involving differing D beam power indicate there are no significant power-dependent effects causing any redistribution of fast ions. In the low q_{95} cases, although the simulation is able to match the peaked on-axis T beam neutron profile in a similar manner to the high q_{95} cases (and matches the neutron rates to within uncertainties), it has been unable to reproduce the shape of the off-axis profiles (see figures 5&6). The measured off-axis profiles from both the Bicron and NE213 neutron cameras are narrower than the simulation, indicating they are less hollow than the high q_{95} cases. This suggests anomalous fast ion radial redistribution at low q_{95}.

The fact that this behaviour occurs at low q_{95} suggests a possible link with MHD behaviour related to the q=1 surface since the location of this surface is expected to move as q_{95} is varied. Sawtooth oscillations, as detected in central Soft X-Ray (SXR) signals, are present in the low q_{95} cases, but the profiles presented here are before the first sawtooth crash of the T blip phase. This relaxation has been shown to flatten the neutron profile with on-axis beams [3], suggesting prompt fast ion redistribution, but no significant effect was seen for the off-axis case in this experiment, although the sawtooth inversion radius is close to the off-axis deposition location. No other MHD phenomena have been detected using Mirnov coils. In fact no systematic change in plasma parameters between the high and low field cases has been found that would explain this behaviour. Orbit effects due to the lower field in the low q_{95} cases are already accounted for in the simulation. Applying an anomalous diffusivity to the fast ions in the simulation makes the calculated profile more symmetric in the off-axis case, but broader than the measurement. In the on-axis case the same process degrades the agreement between calculation and measurement (the measured profiles for on-axis injection are at least as peaked as the calculations for both low and high q_{95} cases) indicating that an enhanced diffusivity does not model the observed anomalies.

In conclusion, simulation using the TRANSP code can reproduce the DT neutron rate within uncertainties in plasma purity and beam power for the high $q_{95,}$ high NBI power plasmas studied here. The neutron profile shapes in the high q_{95} plasmas for both high and low NBI power cases show good agreement with the simulations and are thus consistent with the classical picture of fast ion physics. For the low q_{95} cases the neutron profile for off-axis beam injection is not well modelled suggesting an anomalous fast ion radial redistribution process which is not explained by a simple enhancement to the diffusivity. Anomalies related to neutral beam injection have also been reported elsewhere, for example ASDEX-Upgrade [4] and TFTR [5]. However it is not clear if these have a common cause with the results presented in this paper. Future experiments and analysis are required to validate NBI modelling in conditions approaching those to be found in ITER.

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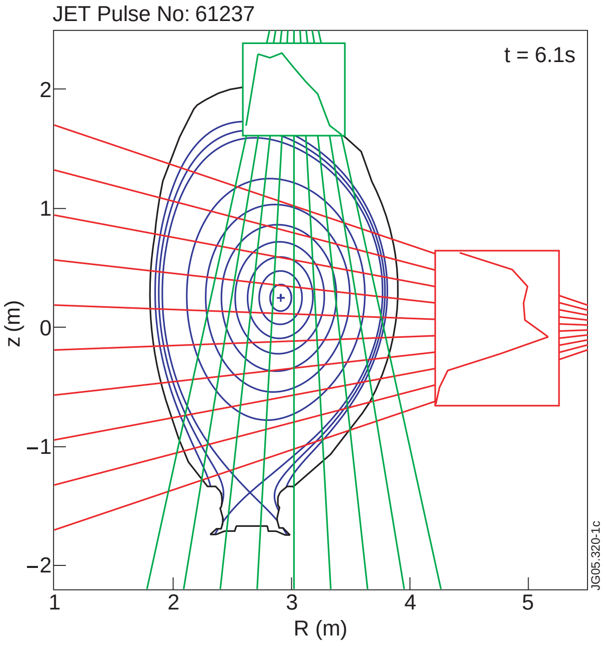


Figure 1: Views of the neutron camera on JET with typical profile shapes from off-axis NBI injection.

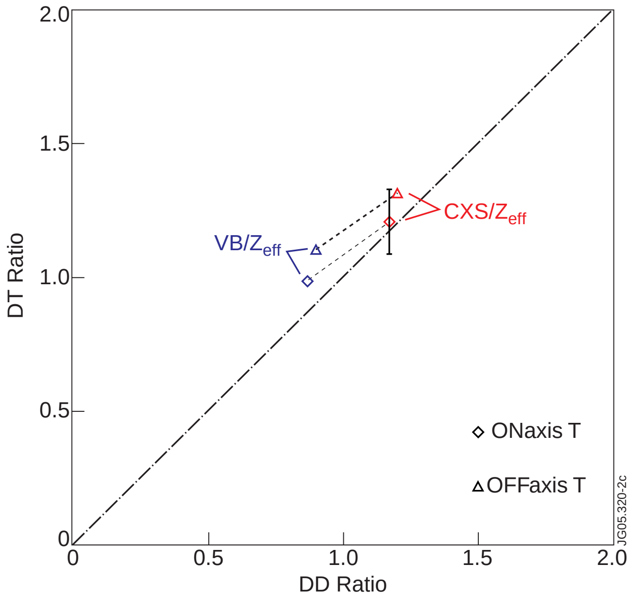
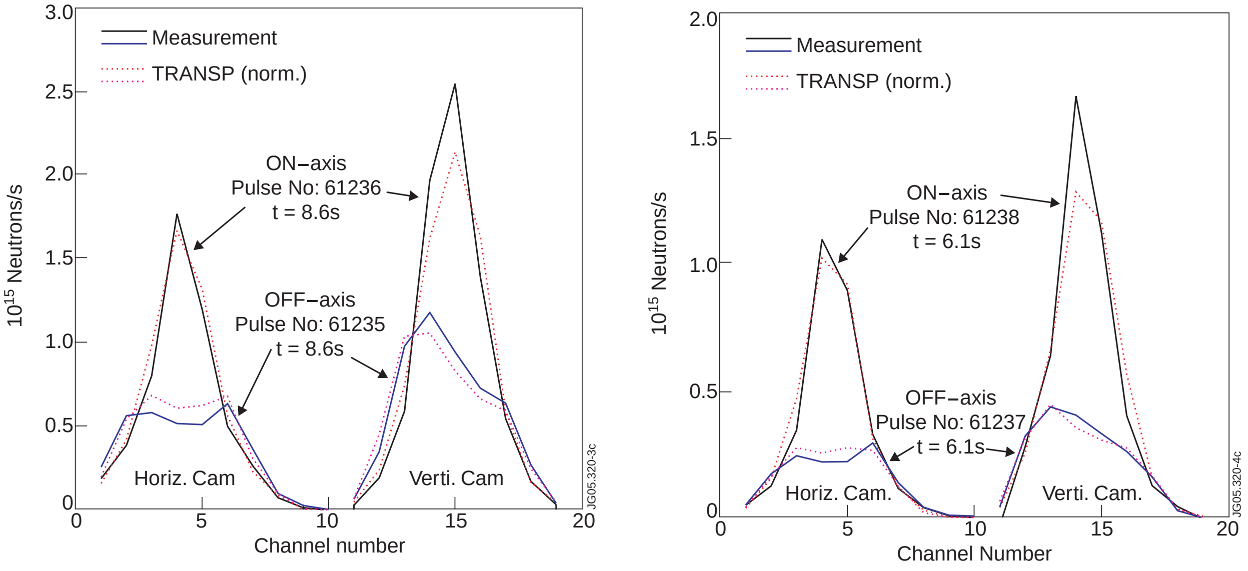
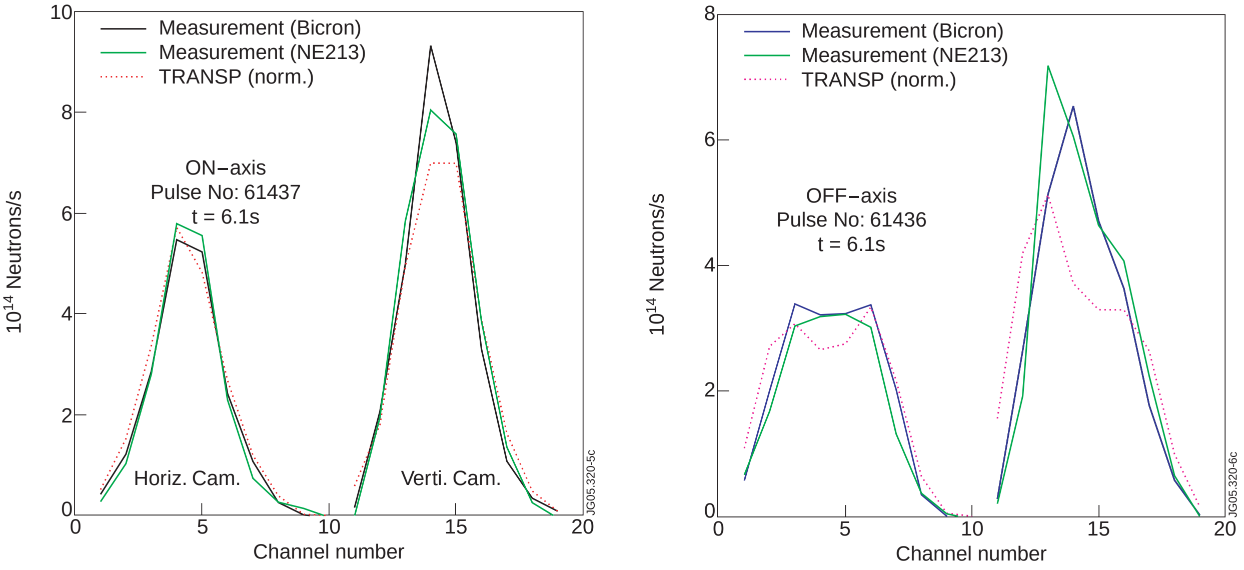


Figure 2: Ratio of time-integrated neutron counts from TRANSP over measurement for DD and DT phases.



Figures 3 and 4. Neutron camera profiles for high power (left) and low power (right) high q_{95} regime showing on-axis (peaked) and off-axis (flattened) T deposition and comparing simulation with measurement (Bicron).



Figures 5 and 6. Neutron camera profiles for on-axis (left) and off-axis (right) T beam at low q_{95} comparing simulation with measurement.