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* See annex of M.L. Watkins et al, "Overview of JET Results ",
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1. INTRODUCTION

The understanding of fast ion physics is important for modelling and interpretation of Neutral Beam Injection (NBI) in tokamak platkas. It is required for the derivation of transport coefficients and the simulation of heating and current drive in beam heated plasmas. However, simulation and measurement do not always agree, experiments on ASDEX-Upgrade have shown that the current profile broadening expected with off-axis NBI is not seen above a threshold power [1].

The JET 2-D neutron camera (figure 1) can be used to diagnose NBI fast ion behaviour by providing time and space resolved neutron profiles from fusion reactions caused by fast ions in a tokamak plasma. Previous experiments [2] from the Trace Tritium Experiment (TTE) injected short Tritium (T) beam blips (~300ms) with both on- and off-axis (beam tangent at r/a~0.4) trajectories into a Deuterium (D) plasma with plasma current 1.0 MA and toroidal fields 1.2 T ($q_{95} \approx 3.3$) and 3.0T ($q_{95} \approx 8.5$). Reanalysis of the original T beam data now shows agreement between TRANSP [3] Monte Carlo simulation and the experimental neutron profiles from DT reactions for both high and low q_{95} scenarios. Figure 2 shows DT neutron profiles for both on- and off-axis injection into a plasma with plasma current 1.0MA, toroidal field 1.2T and with 2.5MW background D NBI heating. The profiles are compared with simulations from TRANSP which have been normalised to the total neutron number in the related measured profile in order to allow a comparison of neutron profile shapes. The off-axis injection profile is not flat, as has been seen at higher toroidal field (line-integral effects will make a hollow neutron emissivity profile appear flat-topped), due to the effect of larger Larmor orbits leading to fast ions reaching the central region of the plasma. The effect of orbit size can also be seen in figure 3, which compares 2D fast ion densities calculated by TRANSP with no anomalous diffusion and 2D reconstructions of neutron emissivity for both a 1.2T ($q_{95} \approx 3.3$) and 3.0T ($q_{95} \approx 8.5$) plasma into which an off-axis T blip was injected. At high q_{95} the fast ion simulation matches the hollow neutron emission profile and high field side peak well. At low q_{95} an orbit spreading effect is seen in the simulation, mirroring the ‘filled-in’ character of the related neutron emission profile.

Pulses scanning off-axis D beam power were performed with a toroidal field 1.4T and plasma current 0.82MA ($q_{95} \approx 5.4$). Power scans with up to the available maximum of 7.7MW off-axis, or near off-axis, NBI power allowed a maximum $\beta_N = 1.8$ to be reached in a scenario with negligible thermal neutron yield, the 2.5MeV neutrons being dominated by beam-plasma reactions. The stepped power increases during the scans were spaced by 2 seconds to allow sufficient integration time for the neutron camera (due to the lower rate for DD reactions). Figures 4 and 5 compare the measured and simulated DD reaction neutron profiles, integrated over one second, from the scan which had the best diagnostic data to aid accuracy of TRANSP simulation. There are greater uncertainties in the measurement of these 2.5MeV neutron profiles compared to 14MeV, error bars have been calculated and are shown (this data may be subject to further correction for scattering effects and inter-shot efficiency variation). Over four separate power stages a maximum of 6.3MW ($\beta_N = 1.6$) was reached, and though the experimental profile is systematically more peaked than the simulation, there is no evidence of a worsening of agreement as the input power increases. Introducing modest levels of anomalous fast ion diffusion (up to $1m^2/s$) into the TRANSP simulation does not radically improve or degrade agreement with the shape of the simulated DD neutron profile at any of the power levels. This is due to orbit effects at this relatively low toroidal field causing ‘filling-in’ of off-axis injection profiles, which would obscure the effect of any present anomalous diffusion. Very similar results are seen in other power scan pulses with powers of up to 7.7MW ($\beta_N = 1.8$).

Analysis of a hybrid mode pulse from TTE with toroidal field 1.7T and plasma current 1.4MA ($q_{95} \approx 3.8$) allows an investigation of off-axis fast ion dynamics at even higher $\beta_N = 2.5$, due to 13.4MW background D NBI heating. The hybrid mode is beneficial in that, despite its low $q_{95,}$ it is free from sawteeth oscillations and their possible redistributive effects on fast ions. Figure 6 shows that for an off-axis T blip there is good agreement between the measured DT 14MeV neutron profile and TRANSP with no anomalous diffusion. There is also good agreement with the measured neutron rate for this simulation, which is degraded by introducing $0.5m^2/s$ fast ion anomalous diffusion.

CONCLUSION

T injection in combination with the 2-D neutron camera has allowed an investigation of fast ion dynamics in a wide plasma parameter space with good time resolution. Simulation using the TRANSP code now shows good agreement for the DT neutron profile in the high and low q_{95} cases and confirms that orbit effects are properly simulated for different toroidal fields. For the D beam power scans to reach high $\beta_{N,}$ the necessary low toroidal field results in a smearing of the fast ion orbits which may obscure the effect of radial fast ion redistribution. It is thus not possible to rule out some anomalous diffusion (up to ~$1m^2/s$) of fast ions in this scenario but there is no evidence of such at the available input power. The hybrid pulse case at high heating power and $\beta_{N,}$ is satisfactorily modelled without anomalous diffusion. Future upgrades to NBI power on JET will allow operation at high β_N simultaneous with high toroidal field, extending the parameter space to ITER-relevant ρ^*, thus allowing experiments in a regime where the influence of orbit effects on the detection of anomalous diffusion of fast particles will be reduced.

ACKNOWLEDGEMENTS

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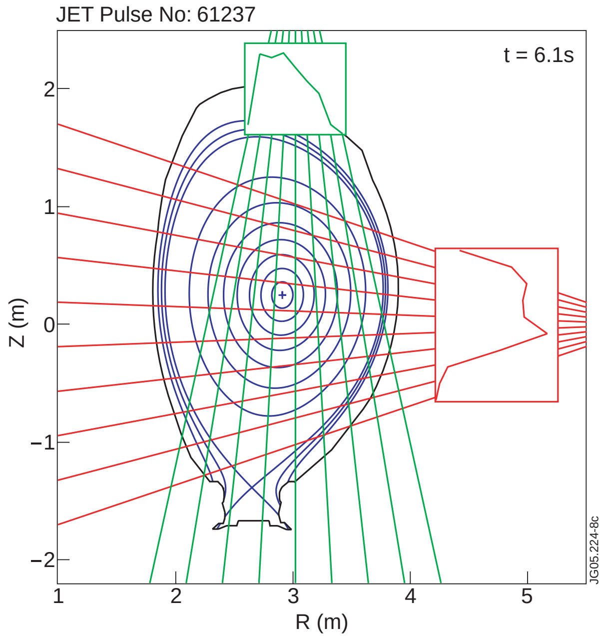


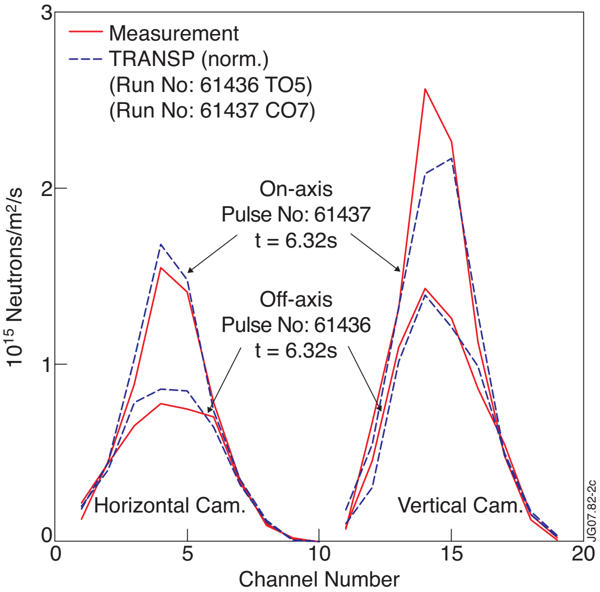


Figure 1. Views of the neutron camera on JET with typical profile shapes from off-axis NBI injection.

Figure 2. 14MeV neutron camera profiles for low q95 regime showing on- and off-axis T-beam deposition.

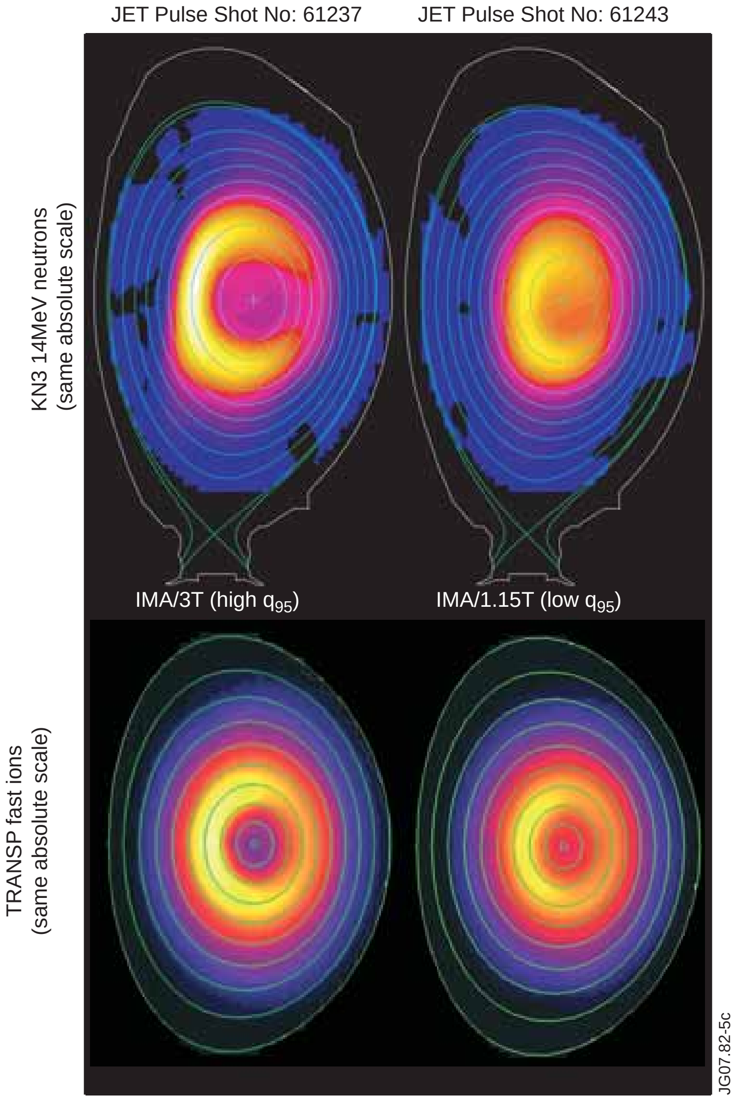
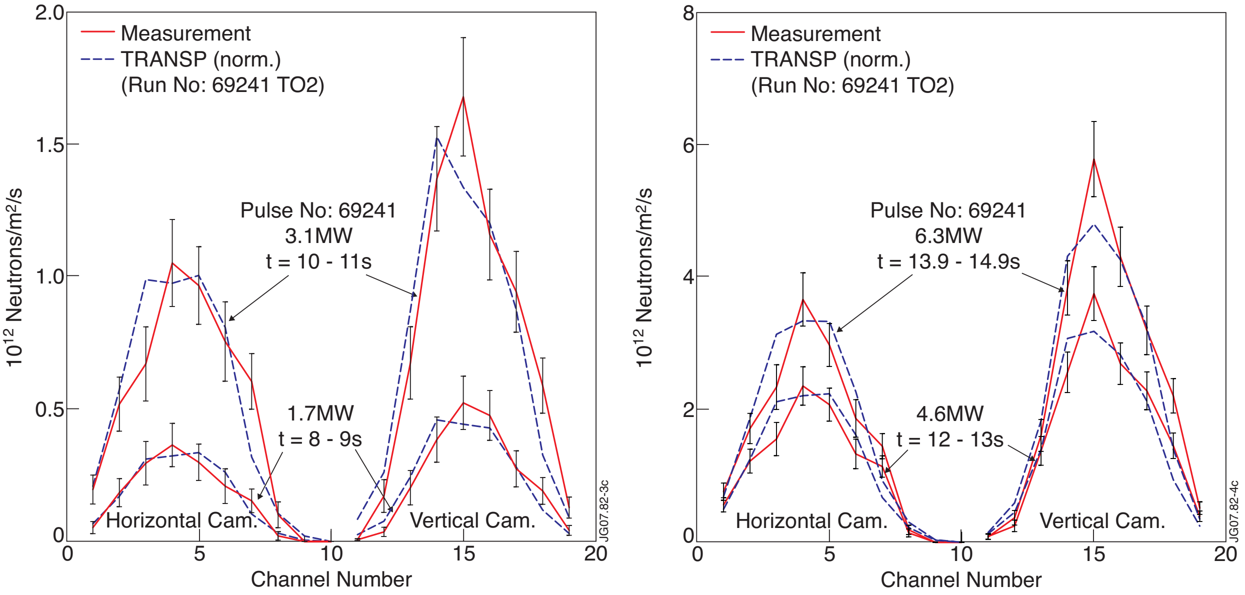


Figure 3: *2D plots of 14MeV neutrons plotted above related TRANSP fast ion density for off-axis T beam pulses. TRANSP simulations (61237C31 at 6.25s and 61243T01 at 6.2s) are displayed on up-down symmetric equilibria.*



Figures 4 and 5. Neutron camera profiles compared with simulation for scan in off-axis NBI power (Pulse No: 69241) with powers of 1.7MW, 3.1MW (figure 4, left), 4.6MW and 6.3MW (figure 5, right).

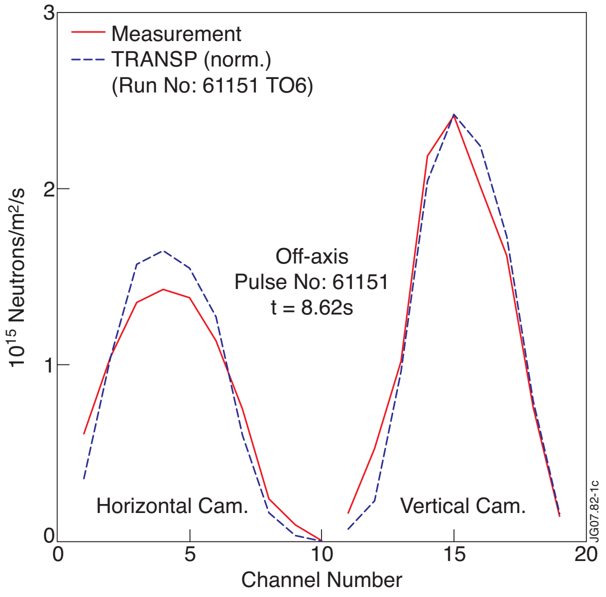


Figure 6: 14MeV Neutron camera profiles for off-axis T beam in a _N=2.5 hybrid mode.