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Neutral Beam Injection on JET : Effect on Neutron Discrepancy and Energy Balance.

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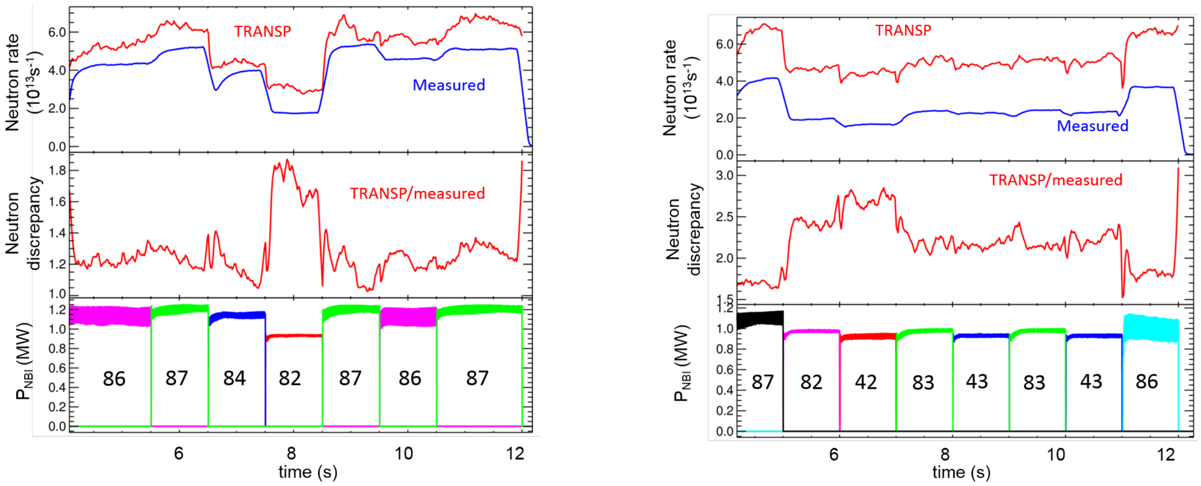
There has been a consistent discrepancy between neutrons predicted and measured during JET pulses, with the measured neutrons typically being lower than interpretive simulation results. A number of investigations into this have been carried out [1] with many explanations excluded. Further to this the energy balance on JET has shown a discrepancy of 25% [2] while the power balance calculations have shown good agreement [3]. The neutron production on JET is split between thermal fusion reactions and beam-target reactions, with beam-target reactions typically making the larger contribution in most deuterium-deuterium discharges.

Given this dominance of beam-target reactions and the ubiquity of neutral beam (NBI) heating in JET plasmas it is important to have a good understanding of both the behaviour of JET NBI in the plasma and the NBI power calibration. NBI on JET is made up of 16 beams (PINIS) over two separate beamlines (octant 4 and octant 8) To improve this understanding a series of experiments were carried out and analysed using the TRANSP [4] code to determine how the predicted & measured neutrons varied with PINI selection. To further aid the analysis beam emission spectroscopy was also carried out and the change in plasma stored energy (W) at beam turn-on was analysed and compared with the beam power.

The neutral beam power on JET is calculated from the beam voltage, extracted beam current, neutralisation efficiency and transmission. The beam voltage & current are measured electronically to a high accuracy. The neutralisation efficiency is measured directly on the JET NBI calorimeter. This is done by carrying out pulses on the calorimeter with composite beams and neutral beams only. By comparing thermocouple temperature rises in such pulses there is a direct measurement of the fraction of the beam that is neutralised. The largest source of error in the NBI power comes from the transmission as there is no direct measurement available. Transmission is estimated by combining neutral beam test bed data with ray tracing simulations

* See the author list of “Overview of the JET results in support to ITER” by X. Litaudon et al., Nucl. Fusion 57 (2017) 102001

giving a value of 75%. The total error in the NBI power is $\sim$ 10%



(a) *Pulse 90559*

(b) *Pulse 90881*

Figure 1: *Neutron rate from experiment and TRANSP (first pane), neutron discrepancy (second pane) and NBI power with PINI selection (third pane)*

Pulses were performed in stationary L-mode plasmas with a single PINI being used at any time. In some cases the same PINI was used throughout the pulse and in others the PINI was switched every 1s. The plasma current and toroidal field of these pulses was 1.2MA and 3.0T, these were used to avoid large sawteeth that could affect the results. Both the neutrons and energy balance were examined for different PINIs used and no significant difference in energy balance with PINI selection was found [2].

For each pulse interpretive TRANSP simulations were carried out. Neutron rates are calculated from kinetic profiles, beam inputs and other plasma parameters. Ion temperature measurements were available from charge exchange spectroscopy for times when PINIs viewed by that system were on. The Neutron discrepancy varies from pulse to pulse but changes within pulses can be directly compared. Due to the low power and low plasma temperature these pulses were dominated by beam-target neutrons (> 95% of the total).

In pulse 90559, shown in Fig. 1 the neutron discrepancy was $\sim$ 20 % for most of the pulse but higher ($\sim$ 80%) for PINI 8.2. The distribution of the beam between full, half and third energy (known as the species fraction) can have a significant effect the neutron rate. To check this beam emission data was collected in these pulses, this data agrees with the species fractions given in [5]. To examine this and compare the same PINI trajectory on different beamlines, further pulses were carried out, these showed that the higher discrepancy for this trajectory exists on both beamlines and that PINI 3 also had a higher discrepancy, see Fig. 1b. As the result is the same on each beamline it indicates that there is not a technical fault with a specific PINI that is causing the variation in neutron discrepancy.

The PINI Positions 2 and 3 both pass through the lower part of the plasma, where the plasma is at lower n_e/T_e compared with other trajectories. The possibility that a small error in the relative position of beam and plasma could have a larger effect for these PINIs was investigated by varying the vertical position of PINI 2 in TRANSP but the results showed that such an error was not significant. The position of PINIs 2 & 3 in the beamline is such that the losses from beam scraping are higher than other PINIs, but is insufficient to explain this neutron discrepancy.

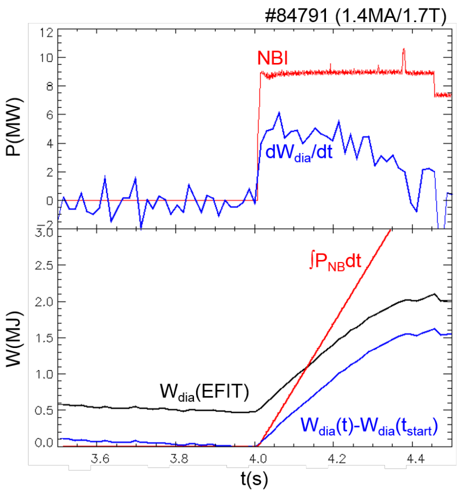


Figure 2: *Transient plasma stored energy compared with neutral beam power (first pane) and stored energy compared with integral of neutral beam power (second pane).*

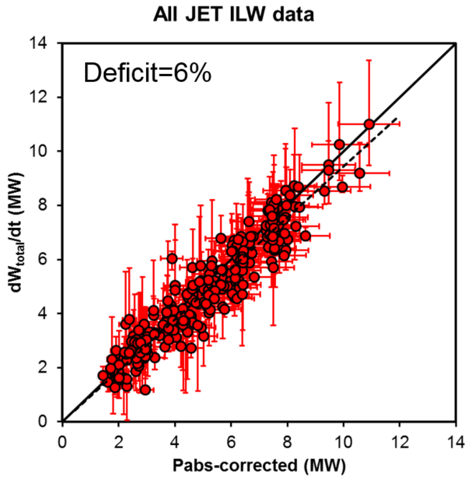


Figure 3: *Comparison of neutral beam power calculated by NBI calibration and transient stored energy for all suitable JET-ILW pulses*

At the point the NBI power first switches on the transient increase in plasma stored energy can be compared with the NBI power. High time resolution EFIT is used with MHD and diamagnetic signals combined to give a value for W. As the dW/dt signal is noisy W is instead compared with $\int$P.dt as in Fig. 2. The plasma must be stationary at beam turn-on for this analysis to work; there must be no ICRH or LHCD during this time window, radiation & ohmic heating must be steady. All pulses from the JET-ILW period that meet these criteria have been analysed. The beam shinethrough power is calculated from interferometer data and subtracted. Fast ion orbit losses and charge exchange losses will lead to lower W so must be corrected for, they are both estimated from TRANSP to give a combined effect of $\sim$5% at beam turn-on. Any delay in the time to reach full beam power at turn on will also affect this analysis so the rate of power rise has been estimated using fits to data from the single PINI test pulses. The comparison between W and NBI power, including these corrections is shown in Fig. 3. It is found that difference is 5-6%, which is within stated errors of NBI power.

The high time resolution TRANSP runs performed also allow for simulated fast ion slowing down behaviour to be compared with experiment. The decay of neutron rate after the NBI power is switched off has been fitted for both the experiment and TRANSP calculations, shown in Fig. 4. The decay rates disagree in the pulse shown by ∼35% compared to a ∼50% neutron discrepancy, indicating the slowing down of the fast ion population is a significant contribution to the neutron discrepancy. This analysis requires more data from multiple PINIs to confirm fully.

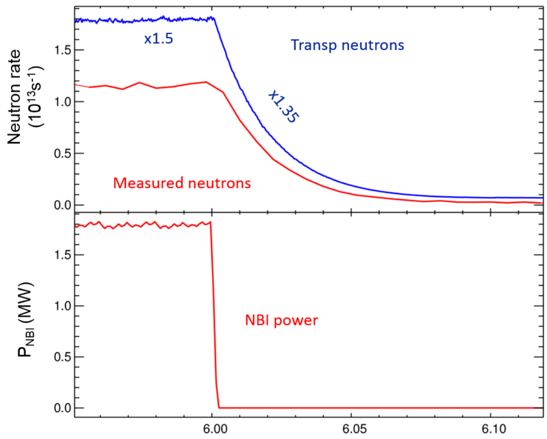


Figure 4: *Decay of neutron rate in experiment and TRANSP calculation for pulse 92250*

The analysis has shown that energy balance on JET is not significantly affected by the PINI selection while there is a larger neutron deficit for PINIs 2 & 3 than for other PINIs within these pulses. There are transmission & trajectory differences for PINIs 2 & 3 but these effects are not large enough to explain the lower neutron discrepancy. An analysis of stored energy at beam turn-on corroborates the beam power calibration used, implying that inaccurate NBI power is not the cause of the neutron discrepancy. The discrepancies in neutron rate and decay of neutron rate are comparable. The pulse type developed for this experiment can be used to expand this analysis further given more experimental time and it has also been used for testing of NBI parameters to improve performance.

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