The "neutron deficit" in JET baseline H-modes and hybrid regimes

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**see the Appendix of F. Romanelli et al, Proc 25th IAEA Fusion Energy Conference, 2014, St. Petersburg, Russia*

1. INTRODUCTION.

We refer as «neutron deficit» to a situation where the measured neutron rate falls short of expectations based on codes such as TRANSP, assuming only collisional fast ion orbit diffusion or no radial fast ion transport at all. The neutron deficit affects JET-C and JET-ILW discharges alike and can range from 0 to 50% typically. Frustratingly, despite being well characterised by the study here presented, the neutron deficit has so far eluded all attempts at identifying its causes. In JET, unlike ITER, neutrons are primarily from beam-thermal reactions and the causes of the neutron deficit are believed to due to processes affecting the fast ion-thermal reactivity, such as fuel dilution, NBI deposition and fast ion transport. Previous studies of the neutron deficit in JET have focussed on the trace Tritium campaign in 2003 [1,2]. The study presented here is based on Deuterium discharges, mostly from the JET carbon phase under EFDA (JET-C) and cover a wide range of plasma conditions in baseline H-mode, hybrid scenarios, together with a few L-modes. A subset of 317 samples, presented here, covers the following ranges:

$0.8\text{MA} \le I_p \le 4\text{MA}$, $1\text{T} \le B_T \le 3.4\text{T}$, $2\text{ MW} < P_{NBI} < 23\text{MW}$, $2.1 \le q_{95} \le 4.7$,
$1.5\times10^{19} \le \langle n_e \rangle \le 9.4\times10^{19}\text{m}^{-3}$, $0.002 \le \langle n_C \rangle / \langle n_e \rangle \le 0.06$, $1.4 \le Z_{eff}(\text{VB}) \le 4$, $0.06 \le \tau_E \le 0.5\text{s}$,
$0.47 \le \text{H98} \le 1.4$

Here n_C refers to the carbon density from CXRS, the brackets refer to volume averages, Z_{eff}(VB) is the effective charge as measured by visible bremstrahlung, τ_E is the energy confinement time based on the kinetic stored energy calculated from the plasma profiles and H98 is τ_E normalised to the IPB98(y,2) scaling. Discharges with $P_{ICRH}/P_{NBI}>0.1$, increased toroidal ripple, 3D fields from internal coils and the entire trace T campaign were excluded. Neutron rates were measured using the JET fission chambers, as recently recalibrated [3].

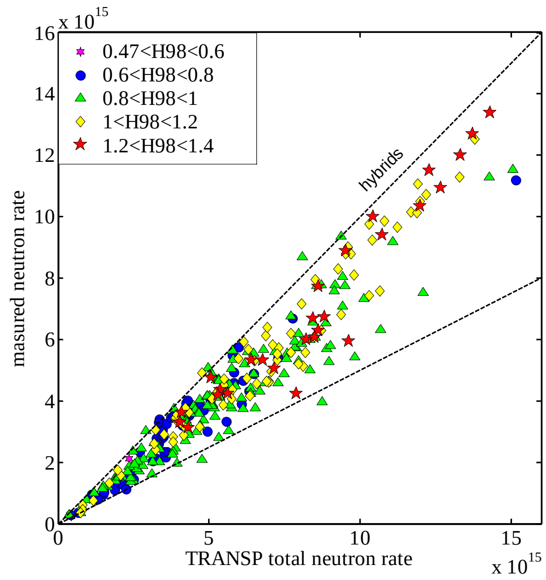

Fig.1 Measured v expected neutron rates in JET-C

TRANSP simulations for the 317 samples from JET-C were produced using T_i, the toroidal rotation ω_ϕ and the dilution inferred from n_C from CXRS and electron density and temperature from LIDAR Thomson scattering. Importantly, no ad-hoc adjustments to the measurements were made with the purpose of improving agreement between calculations and measurements. The measured neutron rates are in the range 50-100% of the total neutron rate expected from TRANSP, as seen in fig.1 The symbols refer to classes of H98.

Fig.2 shows that the neutron deficit also affects JET-ILW (i.e. after JET was equipped with Tungsten and Be PFC's) plasmas by comparing pairs of baseline H-modes in JET-C and JET-ILW with matching I_p=2.5MA, B_T=2.7T, $\langle n_e \rangle$ and P_{NBI} (in the range 14-17MW) and triangularity, as detailed in [4]. CXRS ion temperature measurements were not available for the JET-ILW discharges, however they were chosen to have high enough density ($7\times10^{19}m^{-3}<\langle n_e \rangle <10^{20}m^{-3}$) to safely assume $T_i=T_e$. The JET-ILW discharges had a clearly lower confinement (H98≈0.63 on average) than the JET-C cases (H98≈0.9). The deficit was also somewhat larger, with the ratio of measured to expected neutrons rates, $R_N/R_{N\ TRANSP}$≈0.7 for the 10 JET-C samples and $R_N/R_{N\ TRANSP}$≈0.64 on average for the 10 JET-ILW samples.

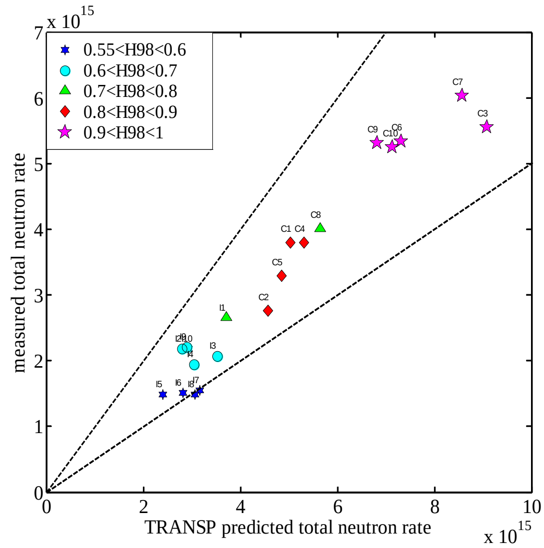

Fig.2 Measured versus expected neutron rates for 10 pairs of discharges with members from JET-C (labelled C1-C10) and JET-ILW (labelled I1-I10). I1,I2 and I3 were nitrogen seeded with Z_{eff} not exceeding that of their JET-C counterparts.

2. PARAMETER DEPENDENCIES AND MODELLING

The deficit correlates with plasma parameters, being smallest or absent in discharges with high T_e, T_i, and β_N, such as hybrid scenarios. Contrary to widespread belief, Z_{eff} and dilution appear to play at best a minor role. The peakedness of the NBI power deposition profile, expressed as $\langle q_{NB}(\rho<1/3)\rangle/\langle q_{NB}(\rho<1)\rangle$, ranging from 0.4 (hollow) to 5 (very peaked), is uncorrelated with the deficit, showing that potential errors in the beam stopping calculations do not explain the neutron deficit. Simple linear regressions of the ratio $R_N/R_{N\ TRANSP}$ (measured/expected), as shown in fig.3, using a small number (3-4) of plasma parameters achieve standard deviations near 10%, well within the best expectation, given that the key parameters governing the neutron rate (e.g. T_e, T_i, P_{NBI}, n_e, n_C) are quoted with errors of the order of 10%. They demonstrate that the neutron deficit is at least to a large part a matter of plasma physics, but do not exclude the possibility that systematic experimental errors, such as calibration errors, may also play a role. The parameters in the example regression are β_N, $T_i(\rho=1/3)$, $T_{slow}(\rho=1/3)/\tau_E$ and $\beta_{fast}= W_{fast}/(B^2/2\mu_0)$. The latter has a negative coefficient, suggesting that fast ion pressure driven modes may play a role. $T_{slow}(\rho=1/3)$ is the fast ion slowing down time from the birth energy to thermal evaluated at 1/3 of the minor radius. Note that these parameters should not be interpreted as being causally related to the deficit.

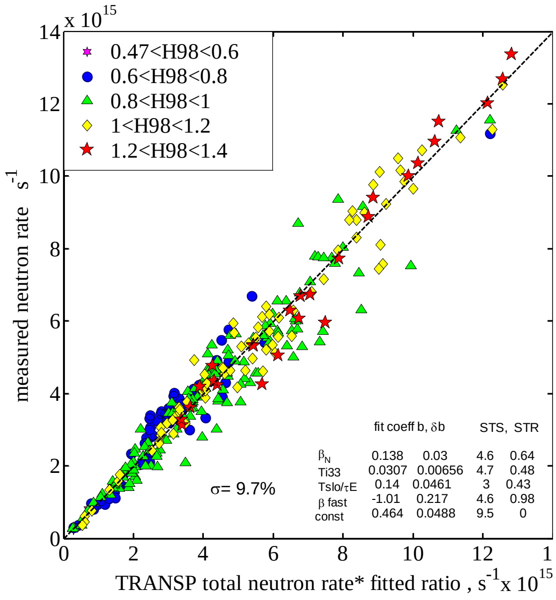

Fig.3 Measured neutron rate versus TRANSP prediction corrected with a regression. STS is the statistical significance for a 90% confidence interval and STR is the normalised statistical relevance.

A simple model was used for assessing a hypothetical relation between fast ion transport and thermal energy transport. It calculates the radial diffusion of fast ions, assuming $D_f \propto \chi$, together with the fast ion slowing down and associated neutron production. Neutron rates are reduced by transport because of the increased (unproductive) slowing down on the electrons at the lower T_e experienced by fast ions having moved outwards, as well as due to the reduced $\langle\sigma v\rangle_{DD}$ at lower T_i. Fig.4 shows the observed ratio $R_N/R_{N\ TRANSP}$ versus the ratio obtained from assuming $D_f=\chi_i$ from the power balance and $D_f=0$ using the model. It is plain that the observed dependencies are not reproduced by the model. In particular, ions with

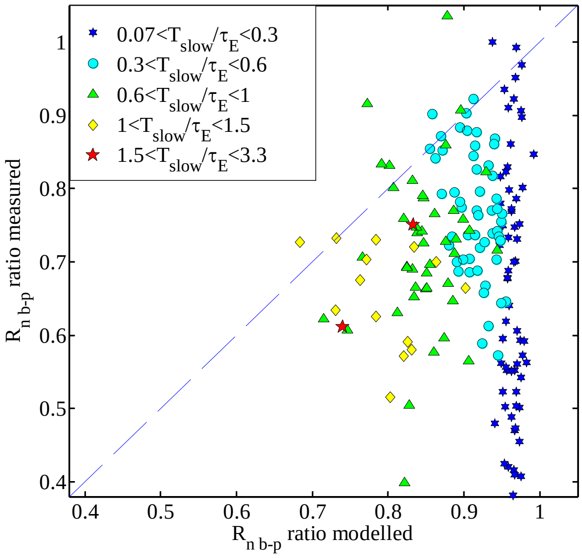

Fig.4 Measured versus modelled beam-thermal neutron deficit, assuming $D_f=\chi_i$ and $D_f=0$

$T_{slow}(\rho=1/3)/\tau_E<0.3$ (blue stars) should be to a large degree immune to transport at the time scale of τ_E, but the results show, to the contrary, that this class of data spans the whole range, from no deficit to the worst in the database.

3. MHD

Fast ion redistribution by a variety of MHD modes, such as sawteeth, NTMs and fishbones, provides a potential explanation. Neutron rates in most baseline H-modes are too low for measuring sawteeth using the JET neutron camera. This drawback has been overcome by the boxcar-ing of 2600 quasi-identical sawteeth with 0.5ms time resolution from 132 repeated pulses, using a central ECE signal for crash timing. The result shows that neutron sawteeth (reflecting those of the underlying fast ions) are very similar to those of other plasma parameters such as T_e, with a ~16% crash for the central channel and inverted neutron sawteeth outside the inversion radius. Ad-hoc modelling of the mixing, as well as the (selectable) sawtooth model in TRANSP, show that mixing by sawteeth can account at best for a few % of the neutron deficit on a sawtooth cycle averaged basis, when sawteeth are present at all. Boxcar-ing of 18000 ELMs has revealed no discernible effect of the ELMs on the neutron rates. A still ongoing analysis of MHD activity based on the JET high resolution toroidal array and spanning the mode number range -10<N<10 has so far revealed no significant correlation between mode activity and the neutron deficit. It is tempting to see this as supportive of ASCOT simulations of fast ions in the 3D fields of NTM's, which show that NTM's can only account for a modest reduction in neutron rates below expectations and are far from being able to account for the largest deficits, even for island chains spanning the minor radius [5]. However, as the observed modes have not yet been categorised into types such as NTM's, fishbones, kinks etc, the lack of a correlation between MHD activity and the neutron deficit may simply indicate that the modes producing the largest signals at the probes may not be the most potent ones at causing fast ion transport.

References

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