EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(04)03-20

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2002 (Proc. 19th IAEA Fusion Energy Conference, Lyon (2002).*

Preprint of Paper to be submitted for publication in Proceedings of the
31st EPS Conference,
(London, UK. 28th June - 2nd July 2004)

ABSTRACT.

The neutron emission from fast tritons in plasmas with different magnetic shear configurations has been investigated in a dedicated experiment on JET. Short pulses of neutral beam injection were used to deposit fast tritons in deuterium plasmas. By comparing the measured neutron yield with predictions based on DT reaction calculations, fast triton losses can be assessed. The latter are expected to be very low according to neoclassical predictions based on Fokker-Planck simulation [1]. Much larger "anomalous" beam-ion losses (up to 40%) have been reported in TFTR experiments for plasma conditions with reversed magnetic shear [2]. The TFTR experiments indicated an excess DT rate in the simulation and, to a lesser extent, in the DD rate and plasma stored energy. This was interpreted as anomalous beam-ion loss associated with reverse shear due to an unidentified loss mechanism. Evidence of a similar effect was searched for in the JET experiments reported in this paper.

1. NEUTRON EMISSION FROM BEAM-INJECTED FAST TRITONS

JET is equipped with a comprehensive set of neutron measurements [3] including the time resolved diagnostics of the DT rate and total (DD+DT) rate. Independent measurement methods [4] ensure an absolute error of <10% (Fig.1).

In the experiments reported here short pulses (up to 150 ms) of 100 keV triton beams are injected in a deuterium plasma. The neutron emission components are well separated under these conditions as shown in Fig.2.

The experiments were carried out on JET plasmas featuring four different "advanced" scenarios [6] commonly used at JET, with magnetic q-profile ranging from monotonic (type 1, "optimised shear" [7]) to flat (type 2, "hybrid") to reversed (type 3, "long pulse ITB" and 4, "current hole" [1]). The tritium beam was injected both on-axis and off- axis for each type of discharge. The injection time was chosen to fall within a phase with internal transport barrier where applicable. All discharges were generally well behaved, e.g. without significant MHD activity.

2. PLASMA SIMULATION AND RESULTS

The absolute fusion neutron emission from plasmas with neutral beam injection is the result of a sequence of processes: beam deposition, beam slowing down, and fusion reactions between fast and thermal ions. The most comprehensive model for these processes is built into the TRANSP simulation code [8], which has been upgraded over the years for use on JET plasmas. The following diagnostics data were available for most discharges and used as input to the TRANSP simulations: LIDAR n_e, T_e profiles; CXRS T_i and Z_{eff} profiles; MSE q profile (used with constraints on q-value on axis). Some smoothing of the input data was applied where required. Uncertainties on individual plasma parameters are typically 10-20%. The error on the measured triton and deuteron beam power is at most 15%.

A first noticeable result is that the measured and simulated stored energy (diamagnetic energy) are in agreement within 5% typically. The results on DD and DT neutron emission depend on discharge type as summarised in Fig.3. Figure 4 illustrates two extreme cases of disagreement between simulated and measured neutron rates.

The following observations can be made on the results of Fig.3:

- The simulated DD rate (Fig.3(a)) agrees with the measurement for Type 1 and Type 3 discharges; it is 30-50% too large in Type 2 and 4. The reference low density H-mode discharge is intermediate between the two cases.
- The simulated DT rate (Fig.3(b)) is always above the measurement by 25-75% depending on discharge type. An exception is the second beam pulse in Type 1 discharges (Fig.4) where the simulated DT rate is about twice and 4 times the measurement for on- and off-axis injection, respectively.
- The ratio between the data of Fig.3 (a) and (b) con be used as an indication of a common behaviour for DT and DD neutrons. The ratio is close to 1 for Type 2 and 4; it is well above 1 for Type 1 and 3; the reference H mode is intermediate.

The neutron camera DT measurements (not shown) provide the following evidence: the discrepancy between simulation and measurement is more or less uniform across the neutron brightness profile for Type 2 and 4 discharges. In Type 1 and 3 discharges the discrepancy is largest in the outer part of the profile irrespective of the injection being on- or off-axis. An exception is the late injection where the discrepancy is very large everywhere.

CONCLUSION

The simulated DT neutron rate is systematically above the measurement, in line with TFTR observations. The simulated plasma stored energy, on the other hand, is essentially in agreement with the measurement. The q-profile does not have a clear relation with the evidence of missing DT (and DD) neutrons; nor does the presence of a transport barrier.

There is no major element of physics that is not built into the TRANSP model and could explain the discrepancy. For instance ICRH 2 nd harmonic absorption is not included in TRANSP but its effect on the neutron rate is at most a few % for an ICRH power of 4MW.

An obvious question to ask is whether the discrepancy can be removed by adjusting the input data within their uncertainty boundaries. The adjustment required, however, would have to be rather extreme: unlike the case of thermal neutron emission, where the neutron emission is a strongly nonlinear function of plasma temperature, beam-target emissivity is nearly linear with plasma parameters such as T_e (affecting the slowing down time) and the target deuteron dilution. For Type 1 and 3 it is tempting to assume that the NBI power is overestimated by 15% for T and underestimated by 15% for D. This does not account for the extreme case of late, off-axis injection in Type 1 discharges.

The observations can alternatively be interpreted in terms of fast ion losses. For Type 1 and 3 discharges it can be assumed that the fast tritons are preferentially (relative to the deuterons) expelled from the outer part of the plasma, and from most of the plasma in the extreme case. However no other evidence for this was found other than the missing neutrons. In conclusion, there is a clear overestimate of the DT neutron rate in the JET simulations. This can be interpreted either as due to large errors in the input plasma parameters or as evidence of fast ion losses. Neither interpretation is totally convincing. The interpretation in terms of preferential T losses in some advanced plasma scenarios should be tested by high power DT experiments where the power fraction between T and D beams is varied. Some evidence on this may be found in the JET DT experiments performed in 1997.

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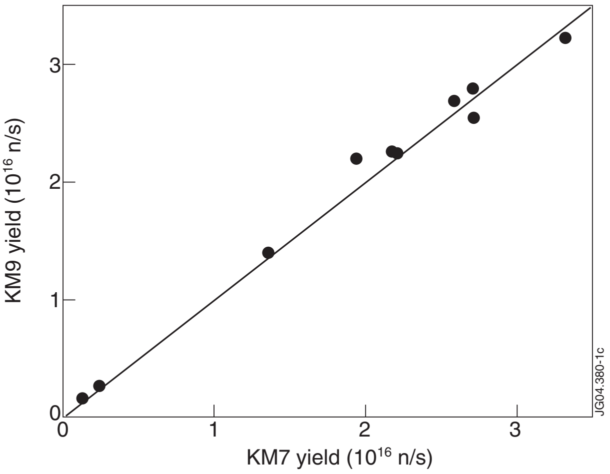

Figure 1: *Comparison between the integrated DT neutron yield measured with the MPR neutron spectrometer (KM9) and the silicon diode neutron counters (KM7) in the plasma discharges selected for this experiment.*

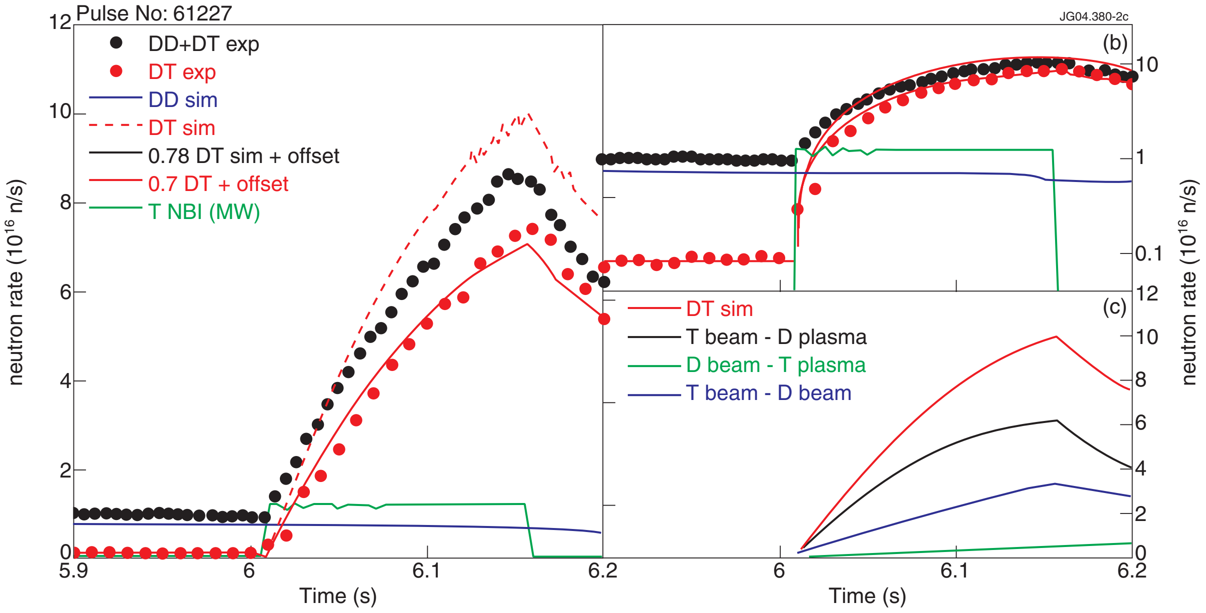

Figure 2: *(a) Experimental and simulated DD and DT neutron rate in a typical tritium beam pulse experiment. Also shown is the tritium NBI power trace. The peak neutron rate consists of DT neutrons from injected tritons plus the small offset emission level measured before injection. This is mostly DD, with a DT contamination of typically 10-20%, which is best seen in log scale (b). The DT pulse emission up to the peak is mostly due to fast (beam) tritons: it is typically one third T beam - D beam neutrons and two thirds T beam – D plasma neutrons. The emission from thermalised tritons becomes rapidly dominant after the beam is switched off, as studied in [5]. In this example the curves providing a best fit to the DD+DT and DT measurements are obtained by scaling the simulated DT rate by a factor of 0.78 and 0.7, respectively. This discharge is of “Type 1” (see text).*

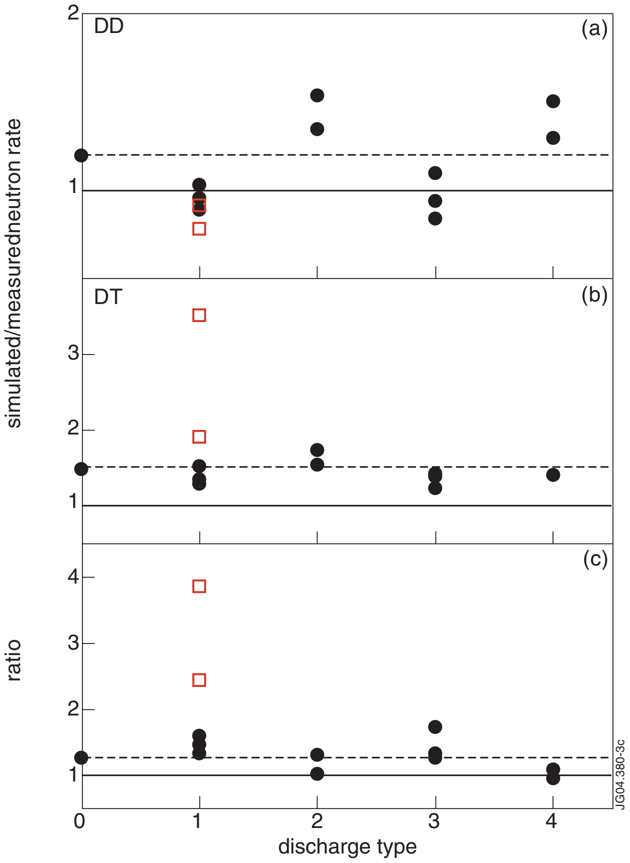

Figure 3: Ratio between simulated and experimental total neutron rates for the four discharge types used in this experiment. The points on the vertical axis are for a reference H mode discharge and provide the reference values shown as a horizontal dashed line. The net DD rate is taken just before the injection of the tritium beam pulse. The net DT rate (after offset subtraction) is taken at the switch-off time of the tritium beam, which is also the time of the peak neutron rate values. The bottom graph shows the ratio between the DT and DD values. The data marked as empty red squares refer to the injection of a second beam pulse at a later time of Type 1 discharges.

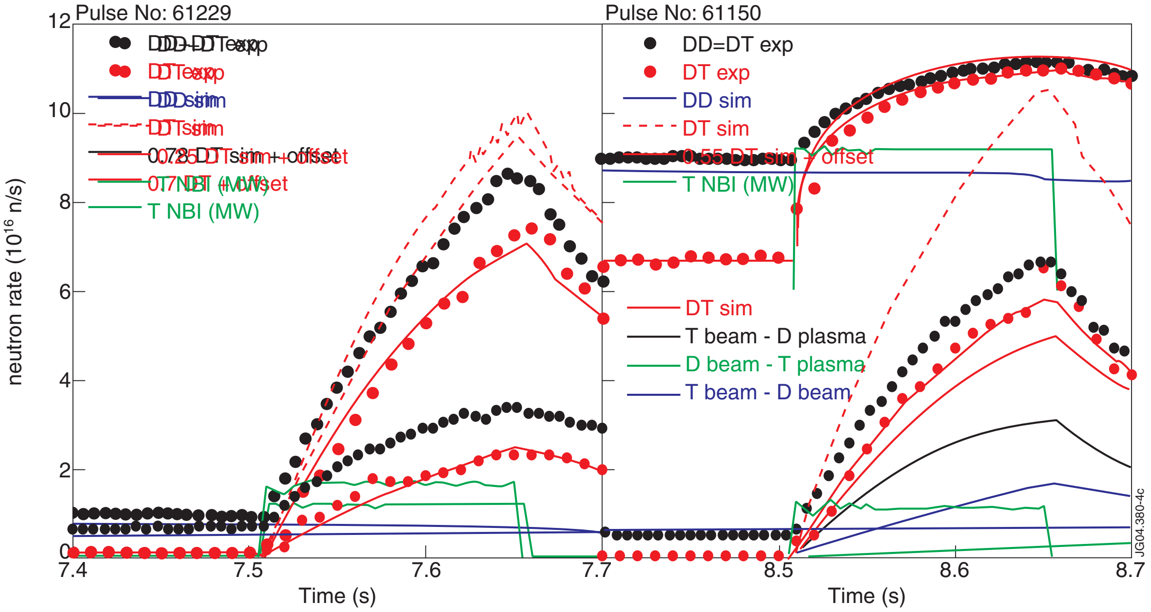

Figure 4: Extreme examples of experimental and simulated DD and DT neutron rate in tritium beam pulse experiments. In the first example (Type 1 discharge) the simulation matches the DD rate but overestimated the DT rate by a factor of 4. In the second example (Type 2 discharge) both DD and DT rate are overestimated by about 35% and 75%, respectively.