*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-1.043 (2002)*

# Neutron Production in High Performance Scenarios in ASDEX Upgrade

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## 1. Introduction

The neutron production in magnetically confined fusion plasma discharges is a measure of the discharge performance. Whereas in a reactor, D-T operation is necessary, in the medium sized ASDEX Upgrade tokamak ($R_0$ = 1.65 m, a = 0.5 m), only H and D plasmas are used. In D-plasmas heated by D-Neutral Beam Injection (NBI) (with injection energies of 60 kev and 93 keV in ASDEX Upgrade), a significant neutron production is observed. In this paper, we analyse $S_{DD}$, the neutron rate due to D-D fusion reactions, to characterise the performance of different plasma discharge scenarii. In particular, we investigate standard H-modes, improved H-modes [1], the high $\beta_N$-scenario [2] and ITB-discharges [3].

## 2. Experimental setup and modeling tools

In ASDEX Upgrade, a stack of 5 detectors with matched efficiencies is used to measure $S_{DD}$, covering the range 3 x $10^9$ n/s to 3 x $10^{16}$ n/s at 100 Hz sample rate with counting statistics better than 10 %. Absolute calibration is done with a PuBe source. Since the rate of this source is small compared to the maximum produced in plasma discharges, only the two detectors with highest sensitivity are directly calibrated. The source is placed at 35 different toroidal positions in the torus and summing up the individual measurements yields a calibration for a toroidal plasma. By using neutron rates measured in plasma discharges, the other detectors are calibrated in intervals of overlap.

To verify the measurements, we performed detailed simulations with the FAFNER [4] code that first calculates the beam deposition and then, using a Monte-Carlo technique, the steady-state distribution function. The code was upgraded to calculate the neutron rate using the fitted cross-sections given in [5] and taking into account finite $T_i$ for the beam-thermal reactions. The neutron rate is composed of three contributions (see e.g. [6]):

thermal reactions: $S_{th} \propto n_D^2 \langle \sigma v \rangle \propto n_D^2 T_i^{\alpha}$ with $\alpha \approx 6.27\ T[\mathrm{keV}]^{-1/3} - 2/3$ (1)

beam-target reactions: $S_{bt} \propto n_D \tau_{sd} P_{NBI} \propto T_e^{3/2} (n_D/n_e) P_{NBI}$ (2)

beam-beam reactions: $S_{bb} \propto P_{NBI}^2 \tau_{sd}^2 E_{inj}^{-2}$ (3)

where $n_D$ is the density of thermal Deuterium ions, $\tau_{sd}$ is the slowing down time of the fast ions and $E_{inj}$ the energy of the injected particles. From the approximate formulae of [6], one finds that in ASDEX Upgrade, due to the relatively high densities and the fact that only co-injection is used, the beam-beam contribution is generally small compared to the beam-target contribution; its calculation is therefore not included in FAFNER. The agreement between measurement and calculation was generally very good for steady state (less than 10 % error in $S_{DD}$, at the lower end of the accuracy with which the profiles are known).

## 3. Database

For a first overview, a database was generated with all ASDEX Upgrade discharges since 1999 to look at the maximum of $S_{DD}$. Since the neutron rate signal itself may exhibit erroneous spikes, we determined the maximum of $W_{MHD}$ and evaluated $S_{DD}$ at the same time, averaged over 20 ms. Only discharges with significant neutron rates $S_{DD} > 10^{14}$ $s^{-1}$ were considered. Obvious outliers were inspected in detail and discarded if an error was detected. Fig. 1 shows, for the whole dataset, $S_{DD}$ as function of the stored energy.

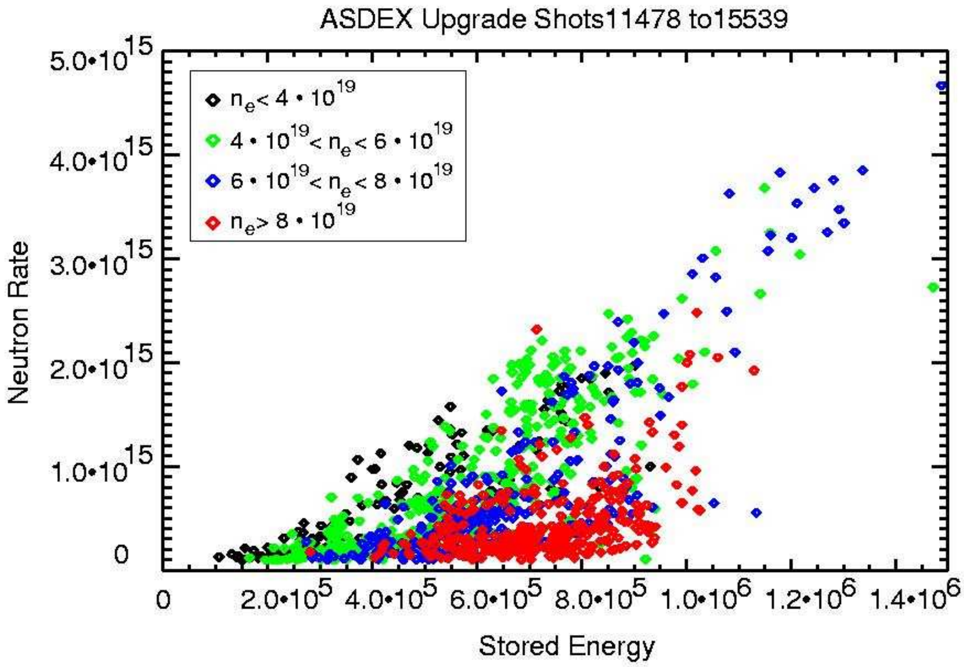


*Fig. 1: Neutron rates for ASDEX Upgrade discharges since 1999.*

As can be seen, the maximum $S_{DD}$ scales roughly linear in $W_{MHD}$. Also, for given $W_{MHD}$, the lowest density discharges produce the highest neutron rates. This can be explained by the different neutron production mechanisms in NBI heated ASDEX Upgrade discharges. As will be shown in section 4, the dominant contribution in the discharges with the highest neutron rates is usually the beam-target reaction, and the thermal reactions can account for a comparable contribution at higher temperature. Since the lowest density in the experiment is essentially fixed by technical reasons (NBI shine-through), we expect a scaling somewhat stronger than linear from (2). This can indeed be seen for the envelope of the individual density classes. Note that for $T_i < 10$ keV, also (1) yields a significant variation with $n_e$ at fixed $W_{MHD}$, since only above 10 keV, $\langle\sigma v\rangle \propto T_i^2$ and $S_{DD}$ is strictly proportional to $W_{MHD}^2$ without density dependence.

**4. Detailed analysis of the different scenarii**

The highest values of $S_{DD}$ (and $W_{MHD}$) are achieved transiently in ITB discharges with an H-mode edge. Here, $W_{MHD}$ rises almost linearly until the first ELM sets in; the discharge then converts to ELMy H-Mode. Fig. 2 shows an example, actually the one with the record $S_{DD}$ achieved at present. In this case, FAFNER modelling is not successful in reproducing the measured $S_{DD}$, since it assumes steady state which is clearly not the case here (the slowing down time of 100 ms is actually comparable to the duration of the high performance phase). $S_{DD}$ calculated by FAFNER is roughly twice the measured value. The calculations indicate that under these circumstances, the composition of $S_{DD}$ would be 50 % beam-target and 50 % thermal reactions if steady state was achieved.

Also shown in Fig. 2 is $Q_{DT}$, the equivalent value of $Q = P_{fus}/P_{NBI}$ if 50% Tritium were used. To obtain this number, we multiplied $S_{DD}$ by $\langle\sigma v\rangle_{DT}/(2\langle\sigma v\rangle_{DD})$ which is between 90 and 110 in the temperature range of interest [6]. No account was taken of dW/dt or an increased confinement with Tritium due to the isotope effect. A thorough discussion of the significance of the equivalent $Q_{DT}$ is given in [7].

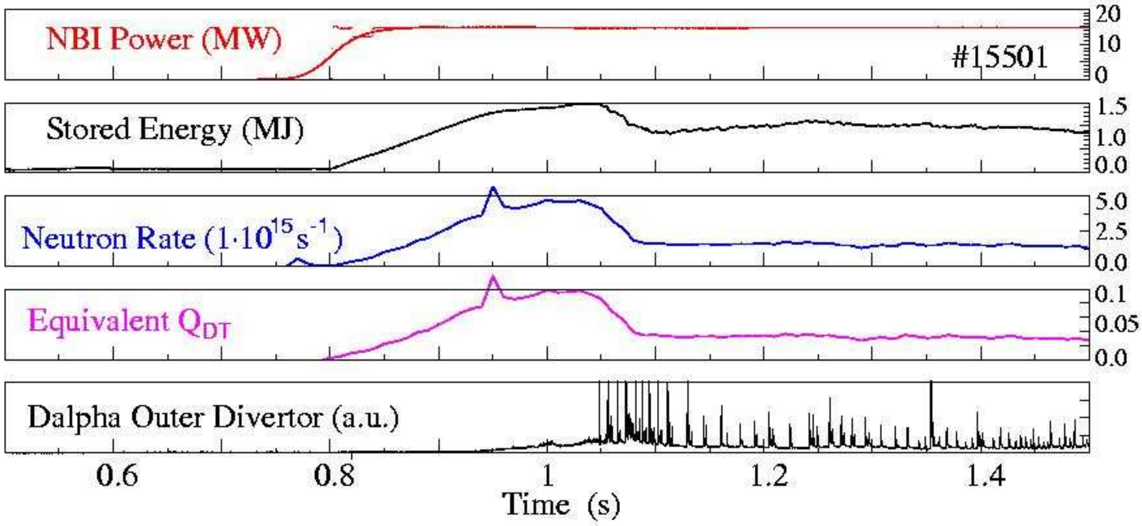


*Fig. 2: ITB discharge with record values of stored energy and neutron rate.*

As can be seen, $Q_{DT}$ reaches 0.1. However, this is not the highest value achieved in ASDEX Upgrade, since a relatively large heating power is applied. In fact, the highest $Q_{DT}$ is achieved in the so-called 'improved H-mode' scenario, which is an H-mode regime with peaked density profile and $T_i > T_e$. Fig. 3 shows an example.

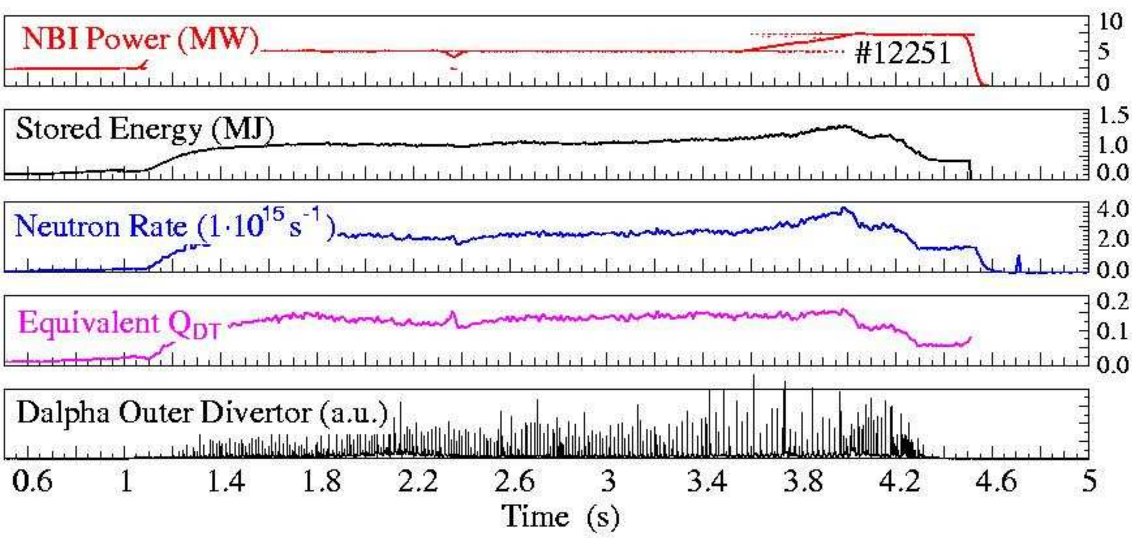


*Fig. 3. Steady state improved H-mode discharge with record value of equivalent $Q_{DT}$.*

Here, $Q_{DT}$ reaches a value around 0.15. It should be mentioned that an ordinary H-mode at higher density needs 12.5 MW of NBI power instead of 7.5 MW in the example above to reach the same $W_{MHD}$ and $S_{DD}$. For the example shown in Fig. 3, FAFNER reproduces the measured $S_{DD}$ within less than 5 %. The composition of the neutron rate is 75 % beam-

target and 25 % thermal, indicating that even at these high temperatures (*$T_i(0)$*=12 keV) but low densities ($\overline{n}_e = 4.2 \times 10^{19}$ m$^{-3}$), still the beam-target part dominates.
This is even more pronounced at high density but lower temperature, where the improved H-mode regime transits into the 'high $\beta_N$'-regime characterised by strong shaping and therefore high density $n/n_{GW} > 0.8$ (i.e. $\overline{n}_e = 1 \times 10^{20}$ m$^{-3}$ at 1 MA) at good confinement and high $\beta_N$. Fig. 4 shows an example:

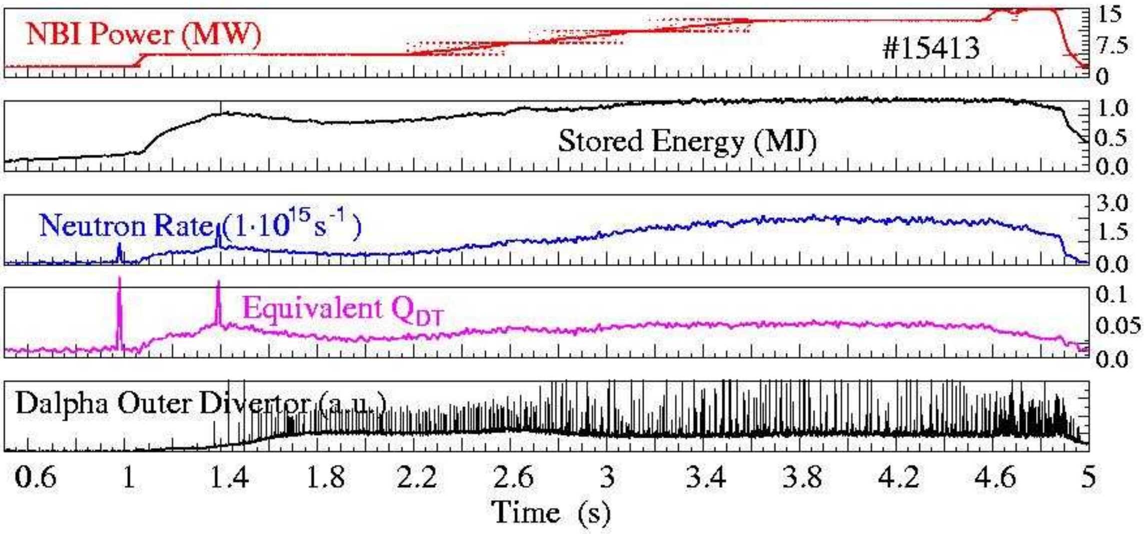


*Fig 4:High $\beta_N$ discharge at high density.*

The discharge reaches about half the neutron rate of the improved H-mode, although the stored energy is only 20 % lower, indicating a different composition of the neutron rate. Indeed, FAFNER (again reproducing $S_{DD}$ within 5%!) now indicates 90% beam-target and only 10 % thermal reactions, mainly due to the relatively low temperature ($T_i(0)$ = 3.5 keV) which drastically reduces the thermal contribution, pointing to the fact that in present devices, the interpretation of neutron rates is only sensible in the context of the individual discharge.

## 5. Summary and conclusions

We have analysed the neutron production in D-NBI heated ASDEX Upgrade discharges. The highest neutron rates are achieved in instationary ITB discharges, but steady state discharges in H-mode, improved H-mode and the high $\beta_N$-scenario show significant neutron production, too. The equivalent $Q_{DT}$ is highest in the improved H-mode scenario, where high $T_i$ is reached due to low density. With higher density in ordinary H-mode and the high $\beta_N$-scenario, the beam-target contribution is dominant due to the relatively low $T_i$.

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