Neutron Production during Deuterium Injection in Deuterium Plasmas in ASDEX

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Measurements of neutron energy spectra and time dependent neutron rate are presented. They agree well with the results of a simple classical deuteron relaxation model. Determination of the plasma deuterium temperature seems possible from the energy spectra as well as from the neutron rate.

Energy spectra: The energy of neutrons produced by reactions between fast injected deuterons and plasma deuterons is shifted from 2.45 MeV towards higher energies for forward emission and towards lower energies for backward emission. On ASDEX with 45 keV injection energy, neutron energies of 2.70 and 2.24 MeV, respectively, are expected (broken lines in Fig. 1). Spectral measurements by means of nuclear emulsions along tangential lines of sight in the co- and counter direction of the injection beam show shifted peaks with maxima at 2.65 and 2.32 MeV (Fig. 1). Due to integration over a finite space angle of neutron emission the measured spectra cannot show the maximum energy shift.

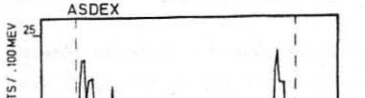

Fig. 1 Neutron energy spectra

The 2.45 MeV line is caused by thermonuclear reactions in the bulk plasma. From its FWHM we obtain a deuteron temperature of 1.9 keV integrated over the observation volume and the injection time. Using the measured electron density profile $n_e(r)/n_e(0)$ for deuteron density and temperature profiles, $n_D(r)/n_D(0)$ and $T_i(r)/T_i(0)$, we calculate $T_i(0)$ = 2.0 keV. This value is about 10 % above the

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central electron temperature. The error of the ion temperature determination is at least 20 % in this case.

Neutron rate, classical relaxation model: The energy of an injected fast deuteron with initial energy W_o decreases in a plasma as $W(t) = W_o \exp(-t/\tau_w)$. τ_w is the energy relaxation time. The number of neutrons Y_D produced by one fast deuteron during its relaxation is given by

$$Y_D = \int_o^{\tau} n_D \sigma \sqrt{\frac{2W}{m}}\, dt = (n_D/n) \int_{W(\tau)}^{W_o} \sqrt{\frac{2}{mW}}\, \sigma\, n\tau_w\, dW.$$

Here m is the mass of a deuteron, n the electron density, n_D the deuteron density and τ the confinement time of the fast deuteron. Due to the strong decrease of cross-section σ with energy the neutron production occurs mainly during the first half of the energy relaxation time, i.e. approximately 15 ms in ASDEX. For our plasma data the energy relaxation parameter $n\tau_W$ depends only on the electron temperature. Hence the neutron production by injected deuterons depends essentially on the electron temperature of the target plasma. On the other hand the cross-section σ is a function of the ion temperature. For temperatures in the region of some keV it may be approximated by

$\sigma(W,T_i) = \sigma(W,0) + 1.16 \times 10^{-28}\sqrt{W} \cdot T_i$ barn (W and T_i in keV).

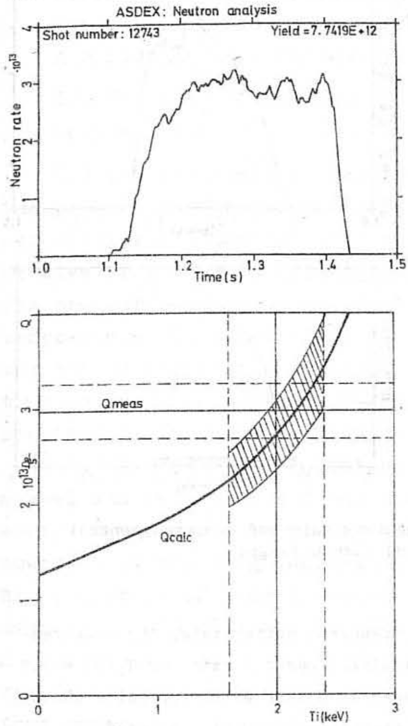
The neutron rate is calculated by integrating the product of Y_D times the deposition profile for fast deuterons over the plasma volume.

Due to the lack of a direct measurement we assume that the deuteron density is a constant fraction of the electron density, the total neutron rate may then be expressed by

$Q(T_i) = (n_D/n)\, Q_{inj}(0) \cdot (1+\gamma T_i) + (n_D/n)^2 Q_{therm}(T_i)$

where Q_{therm} is the thermonuclear rate of the bulk plasma. Here both, Q_{inj} and Q_{therm} are calculated with the electron density profile. Using this relation one can get the bulk ion temperature from the total neutron rate.

Neutron rate, experimental results: The neutron rate measurements have been carried out with BF_3- and U-238 counters which have been calibrated independently by a Pu-238-B neutron source /1/ and by the nuclear emulsion technique. Figure 2 shows the measured neutron rate for the discharges to which the energy spectra of Fig.1 belong. The discharges are of the H-type /2/ with I_p = 420 kA, $\bar{n}_e = 4.9 \cdot 10^{13}$ cm^{-3} and P_{inj} = 1.85 MW at 45 kV. In Fig. 2 $Q(T_i)$ is calculated using the measured profiles of the electron temperature (ECE) and electron density (HCN interferometer), Z_{eff} as derived from the loop voltage (for determination of n_D/n) and the deuteron depositon profile as computed by the FREYA code /3/. T_i was determined by the neutron spectra. The shadowed areas indicate the measurement errors. For $Q(T_i)$ they are mainly caused by some uncertainties in n_D/n. Within the limits of the errors all values agree well, thus indicating classical relaxation for the fast deuterons as assumed in the model.



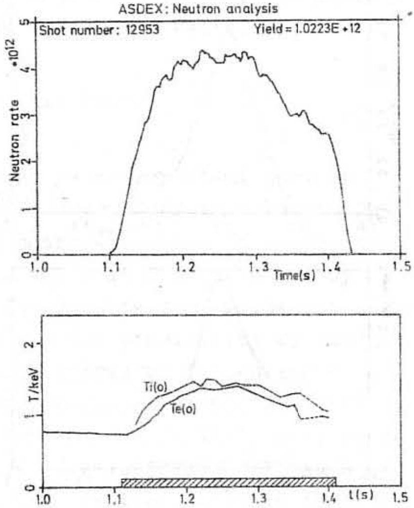


Fig. 3: Measured neutron rate (top), measured central electron temperature and calculated central deuteron temperature for injection with 29 keV and 8 beam lines (bottom).

Fig. 2: Measured neutron rate Q(t) (top), and calculated $Q(T_i)$ for t = 1.25 s for injection with W_o = 45 keV and 4 beam lines (bottom).

Next, results are presented for three other discharge types on ASDEX:

A) P_I=1.3 MW, 8 beam lines, W_o=29 keV, I_p=420 kA, $\bar{n}=6.3\times10^{13}cm^{-3}$, L-type

B) P_I=3.9 MW, 8 beam lines, W_o=45 keV, I_p=275 kA, $\bar{n}=4.4\times10^{13}cm^{-3}$, H-type

C) P_I=2.9 MW, 6 beam lines, W_o=45 keV, I_p=420 kA, $\bar{n}=4.9\times10^{13}cm^{-3}$, H-type

Figure 3 shows the measured neutron rate and central electron temperature for case A. Further $T_i(0)$ is shown as calculated from the neutron rate. It is again about 10 % higher than the electron temperature, demonstrating the validity of the model also for low injection energies and L-type discharges.

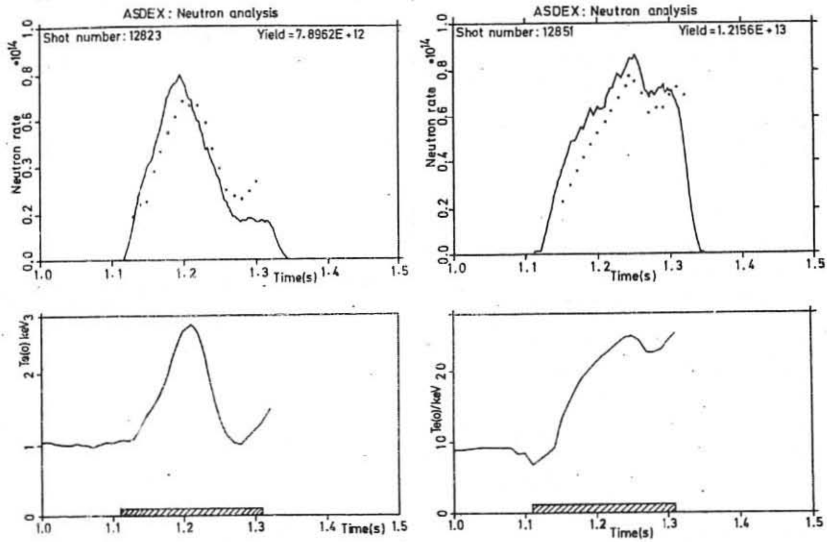


Fig. 4: Measured and calculated (dots) neutron rate and measured central electron temperature for case B (left) and case C (right).

For the cases B and C, Fig. 4 shows the measured neutron rate, the measured central electron temperature and the calculated neutron rate for $T_i(0) = 1.2\, T_e(0)$. Case B is a discharge of the burst-free H-type which typically shows a strong decrease of neutron production after about 100 ms injection. Our results for Q_{calc} demonstrate the dependence of neutron production on target electron temperature. In case C the electron temperature, and accordingly the neutron rate, remain nearly constant during injection.

Part of this work was supported by the Deutsche Forschungsgemeinschaft.

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