NON-THERMONUCLEAR NEUTRON PRODUCTION IN HYDROGEN-BEAM-HEATED ASDEX PLASMAS

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Abstract

Investigations on hydrogen-beam-heated ASDEX deuterium discharges reveal an intense non-thermal (nt) neutron emission. Its fraction ($Y_{nt} \le 7 \cdot 10^{11}$) reaches up to 4 times the thermonuclear fusion yield ($T_i \le 3.4$ keV) at 3.2 MW injection power with maximum values in H-mode discharges. Strongly non-thermonuclear neutron energy spectra show several intensity maxima besides the thermonuclear line and give the evidence for fast deuteron motion along both toroidal directions. From detailed analysis some indication for fast deuteron generation caused by particle-wave interaction is found. Time-resolved neutron energy spectra indicate a strong dependence of the nt-neutron production on time.

Introduction

For present day tokamaks with high DD-neutron yields and for future machines such as INTOR or NET investigations on the fusion neutron emission are becoming important concerning quantitative information about e.g. ion energy distribution, ion temperature and fast-ion transport /1/. Particularly the T_i-determination via total neutron yield is, however, generally based on the theoretical assumption that neutrons produced in $H^0 \rightarrow D^+$ discharges are entirely of thermonuclear origin. Detailed investigations on neutron energy spectra emitted from hydrogen-beam-heated ASDEX discharges show that this simple picture does not describe the experimental data. In ASDEX the neutron emission is clearly dominated by nt-production.

Experiment

In the experiments described here the discharge conditions were as follows: $R = 165$ cm, $a = 40$ cm, $B_t = 2.2$ T, $I_p = 320...380$ kA, $\bar{n}_e = 2...4 \times 10^{13}$ cm^{-3}. In all runs the magnetic divertors (double-null configuration) were active. The two beam lines are oriented tangentially to the plasma (tangency radius 140 cm) and can deliver up to 3.2 MW (hydrogen with $E_o = 40$ keV) for 200 ms.

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Always co-injection was performed. The spectral investigations were carried out by means of two neutron spectrometers using nuclear track emulsions as detectors. Each spectrometer consists of a collimating-shielding system looking tangentially to the plasma axis towards the direction of neutral beam injection. One of both registrated the spectral neutron emission time-integrated over entire discharges, the other system is a three-channel spectrometer allowing the measurement of three time-resolved spectra within single shots with time-resolution down to 4 ms. The effective energy resolution is $\Delta E_n/E_n \simeq 4\%$.

Results and Interpretation

In all energy spectra measured so far on ASDEX fusion neutrons are observed outside the energy range for thermonuclear production. Fig. 1 shows a spectrum obtained over a series of shots at high injection powers ($P_{NI} \geq 2.4$ MW). Besides the thermonuclear neutron line at 2.45 MeV additional peaks occur at lower and higher energies which have to be caused by nt-effects. Since this spectrum is the sum of one space-and time resolved spectrum and of two volume-integrated spectra the intensity ratio of different lines cannot be interpreted easily.
The absolute nt-neutron yield as well as its ratio to the thermonuclear part depends on neutral beam power. As shown in Fig. 2 the ratio of the high-energy nt-neutron yield to the thermonuclear emission rises from 0.4 at 1.2 MW injected power to about 1 at 2.4 MW for L-type discharges. Further, a dependence on discharge-type is found: in H-mode shots /2/ the ratio increases by a factor of about 2 compared to the L-mode. Note that nt-intensity below the energy of the thermonuclear line is about equal to the high energy nt-yield. In the range of neutral beam power 1.2 MW $\leq P_{NI} \leq$ 3.2 MW the total nt-neutron yield increases by 2 1/2 orders of magnitude and reaches 7×10^{11} per shot.
An interpretation of the nt-neutron production can be deduced by detailed analysis of the spectral shape. It is well known that non-3-dimensional ion velocity distribution lead to a change of the neutron line shape and to a shift on the energy scale. Particularly for the DD-beam target reaction between an ion beam with E_d and a thermal plasma ($kT_i \ll E_d$) the neutron line shift from 2.45 MeV to E_n can be expressed as

$$E_n = 0.126\, E_d \ \left(\cos\theta + \left(\cos^2\theta + 5.92\ (3.27/E_d + 0.33) \right)^{1/2}\right)^2 \qquad (1)$$

where θ is the neutron emission angle with respect to the beam. Assuming that the nt-emission originates from the interaction of fast deuterons with the bulk plasma relation (1) allows an analysis of the different neutron lines with regard to the corresponding deuteron energies. The most striking aspects are the follows: a) The observed spectral structures below and above the thermonuclear line evidence clearly a fast-deuteron motion in both toroidal directions; b) The existence of separate peaks at energies $E_n \simeq$ 2.25 MeV, 2.64 MeV and 2.92 MeV (Fig. 1) indicate a nt-neutron production by fast deuterons with $v_d = \alpha \cdot 2.5(\pm\, 0.5) \cdot 10^8$ cm/s (α = 1,2) resp. $E_d \simeq$ 64 keV and 260 keV. The results give some evidence for an ion-wave coupling converting about 100 kW out of 2000 kW absorbed neutral beam power into fast deuterons (up to 1.5% of the total ion content) which in turn produce up to 80% of the total neutron yield; c) Since the amount of neutrons with $E_n > 2.7$ MeV cannot be explained by beam-beam processes of the circulating v_d-deuteron component, additional deuterons at 2 v_d (about 4% of the particle content at v_d) have to be created in the plasma, giving further

some evidence for particle-wave interaction.
Fig. 3 shows the dependence of the total neutron intensity Q on time (at P_{NI} = 3.2 MW) compared to the thermonuclear and non-thermonuclear neutron intensity Q_{therm} and Q_{non-th}. The time resolution for the spectrally resolved fluxes is Δt = 55 ms and 85 ms, respectively. Though the ion temperature increases at the start of neutral beam injection (NI) from 0.6 to 2.1 keV the further increase in T_i during NI is moderate (2.1 to 2.7 keV). On the other hand, the deuteron density becomes strongly reduced during high power hydrogen injection resulting in a thermonuclear neutron production phase that has a maximum in the first half of the NI-phase. The nt-production, however, increases when the thermal emission falls down, lasting then with high intensity till the end of NI. Time-resolved neutron energy spectra reveal that the lines do slightly shift on energy scale during the neutron production phase. There is some evidence for a change of the nt-neutron producing high energy tail of the fast deuteron energy distribution during neutron production. Also weak indication for an intensified deuteron generation at higher harmonics of v_d at the start and the end of neutral beam injection is observed. The nature of nt-neutron emission, and vice versa the basic properties of the nt-fast deuteron generation is found to be independent on injected power and discharge-type respectively. Appropriate candidates for explaining the physics of fast deuteron production seem to be ion cyclotron and magneto-hydrodynamic waves. Fast deuteron generation by H-D head-on collisions or by injection of deuterium possibly existent in spurious concentration in the H-beam lines play no significant role.

References

/1/ Strachan, J.D., et al., Nucl. Fusion 21 (1981) 67.
/2/ Wagner, F., et al., Phys. Rev. Lett. 49 (1982) 1408.

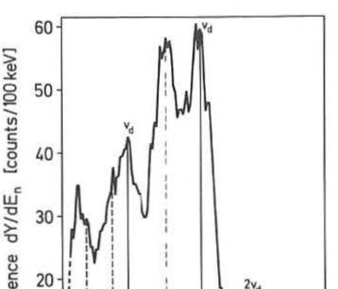

Fig. 1: Neutron energy spectrum emitted from high power NI-heated discharges.

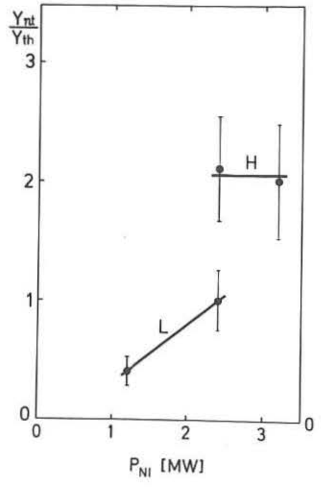

Fig. 2: Dependence of high energy non-thermonuclear to thermonuclear neutron yield on NI-power.

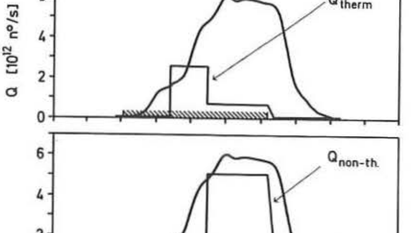

Fig. 3: Total, thermonuclear and total nt-neutron flux versus time during a NI-heated discharge.