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Confinement of Neutral Beam Injected Fast Ions in W7-AS

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ABSTRACT: Detailed studies demonstrate that the decrease of fast particle densities and neutron rates with decreasing plasma density is owing to a decreased deposition of the injected particles. The power deposited by neutral injection after the first particle losses is determined from the initial rise as well as from the plateau value of the neutron rate. For this the neutron counters were absolutely calibrated by means of Indium activation. The results of the studies demonstrate classical confinement of fast particles in W7-AS. Losses of fast particles are only observed during strong MHD activities.

In a previous paper [1] we reported discrepancies between measured fast particle densities as well as neutron rates and the respective values expected from beam deposition calculations of the injected power. The measured values were smaller than the expected ones for large energy relaxation times of the injected ions, i.e. for low plasma densities.

Neutron production during D-injection is a sensitive indicator for the confinement of the fast ions, as they need approximately one energy relaxation time to produce their neutrons. For W7-AS this is between 10 and 60 ms. Therefore we have carried out detailed studies of the measured neutron rates for a large number of discharges with different plasma parameters and neutral beam powers. In order to get information about the confinement of fast ions, one has to know their density deposited after the first orbit losses, i.e. the density of particles starting in the relaxation process after their injection. Therefore, the central point is an experimental determination of the deposited power, which is smaller than the primary injected power, depending on injection angle and density.

As already shown in our previous paper the initial rise of the local neutron yield $Q_i\ (t)$ produced by injected ions with energy W_i is given by the simple expression

$$\left.\frac{dQ_i\ (t)}{dt}\right|_{t\to 0} = S_i \cdot n_d \cdot \sigma\ (W_i) \cdot \sqrt{\frac{2W_i}{m_d}}\ , \tag{1}$$

where S_i is the deposition rate (number of ions/cm^3 s), n_d the deuteron density of the background plasma, σ the fusion cross-section and m_d the deuteron mass. Summation over the three species of injected ions gives the initial rise of the total local neutron yield $Q(t)$.

It is essential to note that this initial rise depends on the parameters of the injection and the plasma density only, but not on the relaxation process of the fast ions, i.e. on their energy distribution function. Therefore it is an ideal tool for determining the deposited power $P = \Sigma\ S_i\ W_i$, but it requires a sensitive and well-calibrated neutron counter. We have done careful calibrations of the two counters (BF3 and NE213) installed at W7-AS by means of indium activation but, unfortunately, the BF3 counter is not sensitive enough and the uncertainty of the NE213 calibrated at large neutron rates increases with lower count rates. Therefore the values for deposited power P_{rise} which we determine from the initial rise of the neutron signal are rather uncertain.

A second possibility for determining the deposited power is an evaluation of the full shape of the neutron signal or at least of the plateau value in the stationary state of the discharge. But this procedure requires the knowledge of the fast ion energy distribution and needs several measured plasma parameters. In order to investigate a large number of discharges we used for the ion energy distribution $f\,(W)$ the so-called high-energy approximation:

$$f_i(W) = \frac{\tau_{s\ de}}{2} \frac{W^{\frac{1}{2}}}{W^{\frac{3}{2}} + W_{crit}^{\frac{3}{2}}} \; S_i \quad . \tag{2}$$

Here $\tau_{s\ de}$ is the slowing down time for deuteron-electron collisions and W_{crit} the so-called critical energy, where electrons and background ions receive the same heating power.

As to be expected, the measured ratio $P_{rise} / P_{plateau}$, where $P_{plateau}$ is the value for the deposited power determined from the plateau, is about 1 for small neutrons rates with an error of about 50%. This is a reasonable result taking into account the error margin of the input data.

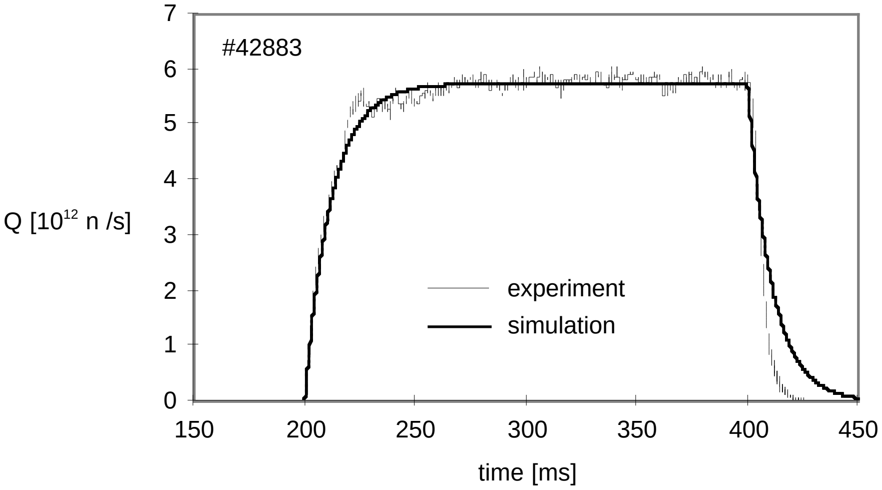

Fig. 1: Comparison between simulation and NE-213 neutron measurement for discharge type 1. Neutral particle deposition calculated from the plateau value of the neutron signal.

For 7 discharges we compared the results for the deposited power determined using this approximation with the values from a time-dependent 2D Fokker-Planck simulation of the distribution function and the related neutron rate. Both results agreed within ± 20%, which is less than the error of the values for P determined from the neutron signals. Generally, a time dependent simulation of the neutron rate using the value $P_{plateau}$ reproduces very well the rise of the neutron rate (Fig. 1). For about $^2/_3$ of the investigated plasma discharges the simulation reproduces the full time history of the neutron rate. For less than $^1/_3$ we observe a lack of neutrons in a part of the signal (Fig. 2), starting typically after half of the rise time and lasting until half of the stationary state. During this time interval strong MHD activity of the plasma is observed in those discharges, which obviously causes a loss of fast particles.

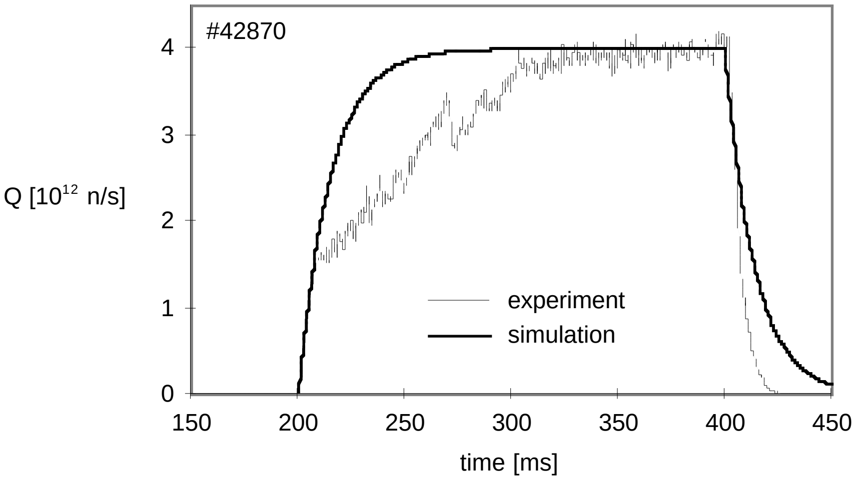

Fig. 2: Comparison between simulation and NE-213 neutron measurement for discharge type 2. Neutral particle deposition calculated from the plateau value of the neutron signal. The lack of the measured neutrons is associated with strong MHD activity.

In quiescent discharges where the electron temperature after the turn off of the neutral beam was almost kept constant using additional ECR heating the decay of the neutron signal is also well reproduced by a numerical simulation using $P_{plateau}$ (Fig. 3).

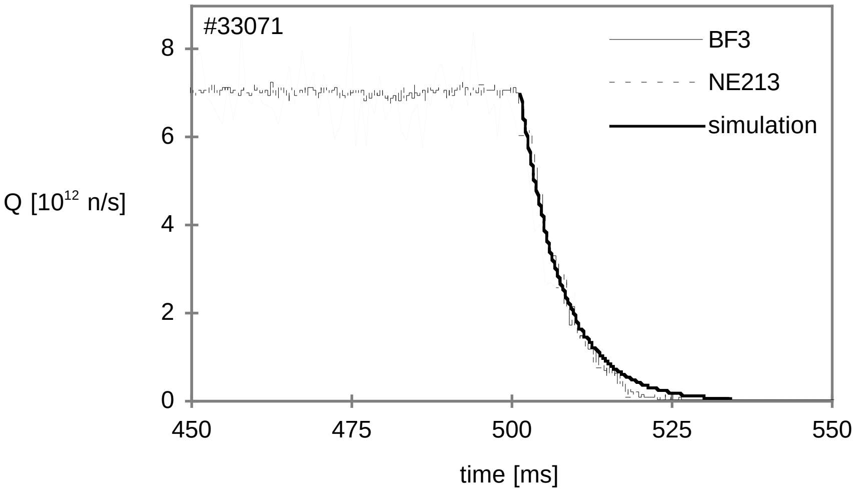

Fig.3: Comparison between calculated and measured neutron decay after turning off the neutral beam injection. During the decay, the electron temperature is kept constant by ECRH heating.

Finally, there are a few discharges for which the analysis of the measured data gives inconsistent results. It is an open question whether this is due to erroneous measurements or due to a very special plasma configuration.

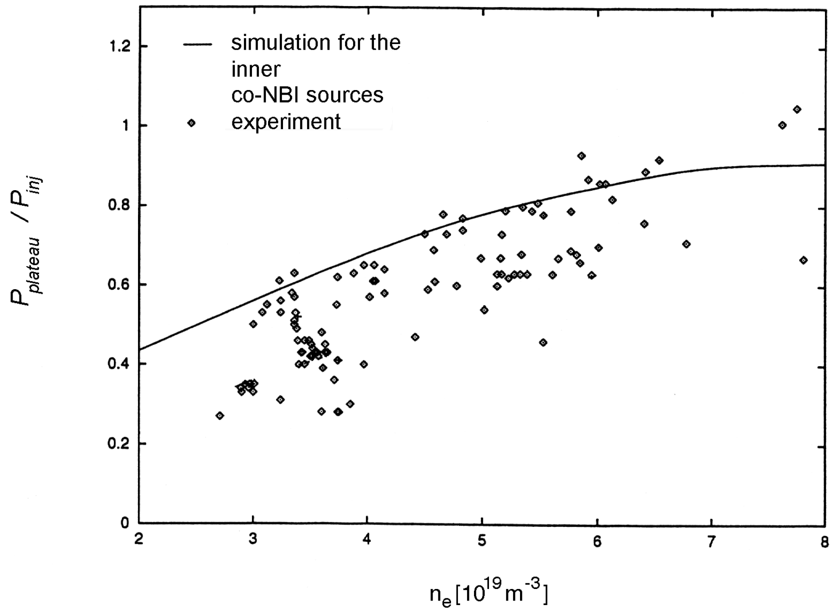

Fig. 4: Fraction of neutral beam deposited power to the input power via the central density.

Fig. 4 shows the ratio of $P_{plateau}/P_{inj}$, where P_{inj} is the injected power as a function of the electron density, i.e. the deposited fraction of the injected power, which decreases with decreasing electron density because of rising shine through and charge-exchange losses. The injected power was calculated by the beam deposition code FAFNER. The solid line gives the values obtained with FAFNER for the case of the inner sources, which are injecting almost tangentially. For most of the discharges we used the inner co-NBI sources. The experimental values are widely spread. This is mainly caused by the errors of the plasma data, which are to be used in the determination of $P_{plateau}$. In the mean the measured values are smaller than the calculated ones. In addition some measurements were made with outer sources, which have a larger injection angle. As expected their ratio of $P_{plateau}/P_{inj}$ is in the mean lower than for the inner sources. But this decrease is smaller than the spread of the values.

From our observations we can draw three essential conclusions. Firstly, the deposited power is in tendency smaller for the examined density region than it is expected from FAFNER calculations. This explains the formerly observed discrepancies between the measured and expected neutron rates and fast particle densities. Secondly, the relaxation process of injected ions is a classical one in W7-AS, at least for the period of one energy relaxation time. This follows from the excellent reproduction of the rise as well of the decay of the neutron signal in numerical simulations using the value of deposited power determined from the plateau. Thirdly, the fast ions are confined in W7-AS at least over one energy relaxation time as long as there are no plasma perturbations by mode activities.

[1] N. Rust, e.a., Controlled Fusion and Plasma Phys., 24 (4) 1621-1624 (1997)