Simulation and analysis of neutral particle spectra from W7-AS in combination with neutron activation measurements

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For the investigation of confinement of fast ions we present results of an experimental and theoretical study at W7-AS. It consists of the analysis of non-thermal neutral particle spectra and absolute neutron yield measurements combined with theoretical calculations.

The fast ion distribution function is measured with the neutral particle diagnostics. It consists of four neutral particle energy analysers for spatially resolved measurements. The lines-of-sight of the analysers cross a neutral particle diagnostic beam which is passing vertically through the plasma centre. For absolute neutron yield measurement indium activation samples are used which are irradiated inside the vacuum vessel near the plasma. Their γ-activation is measured with a calibrated germanium detector. Using a fluence factor which is calculated with the Monte Carlo code MCNP, the volume integrated absolute neutron yield of the plasma discharge is determined. - For the numerical simulation of the neutral particle spectra and the neutron yield the time-dependent 2D Fokker-Planck code NRFPS is used.

The local charge-exchange particle flux $S(v,\mu,t)$ from the plasma is given by

$$S\,(v,\mu,t) = g\,n_i\,n_0\,f\,(v,\mu,t)\,\langle\sigma v\rangle_{\rm cx}\cdot\exp\left[-\int_0^a \frac{1}{v}\left(n_i\,\langle\sigma v\rangle_{\rm cx} + n_e\,\langle\sigma v\rangle_e + n_i\langle\sigma v\rangle_{\rm i}\right)\right]\;. \quad (1)$$

Here, $f(v,\mu,t)$ is the ion velocity distribution, v the particle velocity, $\mu = v_{\|}/v_{\perp}$ the pitch-angle, g a geometrical factor, n_i and n_0 are the ion and neutral particle densities, $\langle\sigma v\rangle_{\rm cx}$ and $\langle\sigma v\rangle_e$ are the rate coefficients for charge-exchange and for electron impact ionisation. The exponential factor describes the absorption of the particles on their trajectory through the plasma and is calculated with respect to the real stellarator geometry.

The local neutron rate Q from the plasma is given by

$$Q(t) = \frac{n_i n_j}{1+\delta_{ij}} \iint f_i(v,t)\; f_j(v',t)\; \sigma(|v-v'|)\;|v-v'|\; d^3v\; d^3v'\,, \quad (2)$$

where $f_i(v,t)$ and $f_j(v',t)$ are the velocity distributions for the ion species i and j, $|v - v'|$ the relative velocity and σ the fusion cross section, respectively

Measurements and calculations have been carried out for a variety of W7-AS discharges with H^0 and D^0-injection with average electron densities ranging from 2.8×10^{19} to $7 \times 10^{19} m^{-3}$, electron temperatures from 0.5 to 2.8 keV and ion temperatures of about 0.32 to 1 keV. Electron temperatures and densities were taken from the Thomson scattering and ion temperatures from the neutral particle diagnostics. The deposition profile for the injected particles was calculated with the 3D FAFNER code.

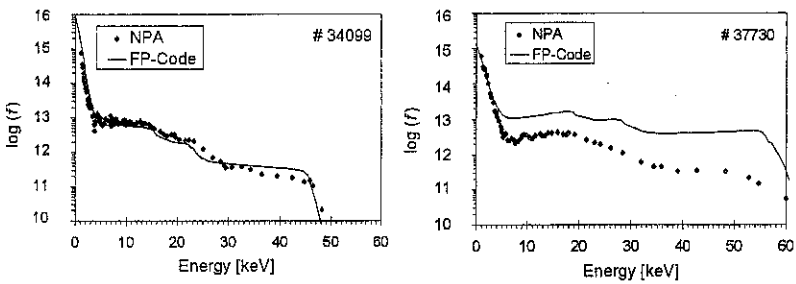

Fig. 1: Comparison of calculated neutral particle flux with experimental data.

1a: $n_e = 7,3 \times 10^{19} m^{-3}$
T_e = 0.5 keV
Ti = 0.44 keV
τ_W = 3.5 ms

1b: $n_e = 3,7 \times 10^{19} m^{-3}$
T_e = 2,8 keV
Ti = 0.83 keV
τ_W = 52 ms

Fig.1 shows as an example the calculated and measured neutral particle flux for two different plasma discharges. For the high density discharge the measurement and the calculation agree rather well. However, discrepancies occur for lower densities. The smaller the density becomes in a discharge, the larger becomes the neutral gas density and the higher the electron temperature. Increasing electron temperature and decreasing density result both in an enlargement of the energy relaxation time of the fast particles. As shown in fig.2 the discrepancies increase strongly with increasing classical energy relaxation time τ_W.

In principle, the observed discrepancies can be caused by three different processes, namely by reduced particle deposition owing to the high neutral gas density, and by particle or energy loss mechanisms with time scales comparable to the classical relaxation times.

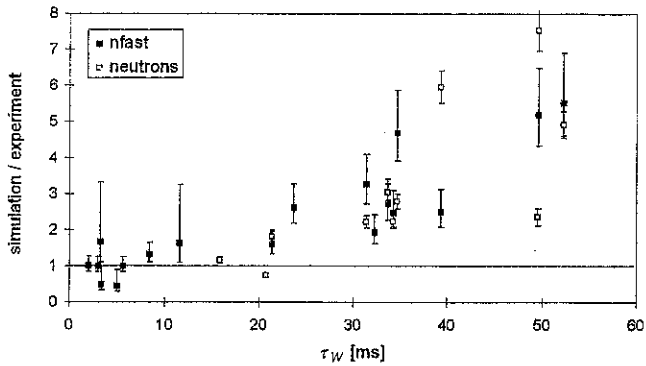

Fig.2: Comparison between calculated and measured fast particle density and between calculated and measured neutron yield in dependence of τ_W.

These three processes will influence the time behaviour of the plasma signals in a different way. First of all it is of interest to investigate the initial rise of the plasma signals at the onset of the injection. To that end it is sufficient to use the relaxation time model which takes into account only the relaxation of energy $dW/dt = -W/\tau_W^*$ and leads to the simple approximation

$$f(W) = \frac{dn(W)}{dW} = \frac{\tau_W^*}{W}\left(S - \frac{n(W)}{\tau_n}\right) \tag{3}$$

for the energy distribution function of fast particles. Here, τ_W^* is the total energy relaxation time, resulting from classical and anomal energy losses ($1/\tau_W^* = 1/\tau_W + 1/\tau_{W,anomal}$). S is the density of injected particles per second and τ_n the time constant of direct particle losses. From this expression follows that the initial rises of the plasma energy E_f and of the neutron-rate Q at the onset of the neutral beam injection are solely determined by the particle injection properties:

$$\left.\frac{dE_f(t)}{dt}\right|_{t\to 0} = S\,W_0, \qquad \left.\frac{dQ\,(t)}{dt}\right|_{t\to 0} = S\,n_e\,\sigma(W_0)\sqrt{\frac{2W_0}{m}}. \tag{4}$$

Here, W_0 is the injection energy, m_f the mass of the injected ions. An example for the initial rise of the plasma energy and the neutron signal. is shown in fig.3. The dotted lines indicate the theoretical rise according to eq.4. Agreement with the measured signals is obvious for the high density discharge but - owing to the statistical fluctuations in the signals - not as clear for the low density one.

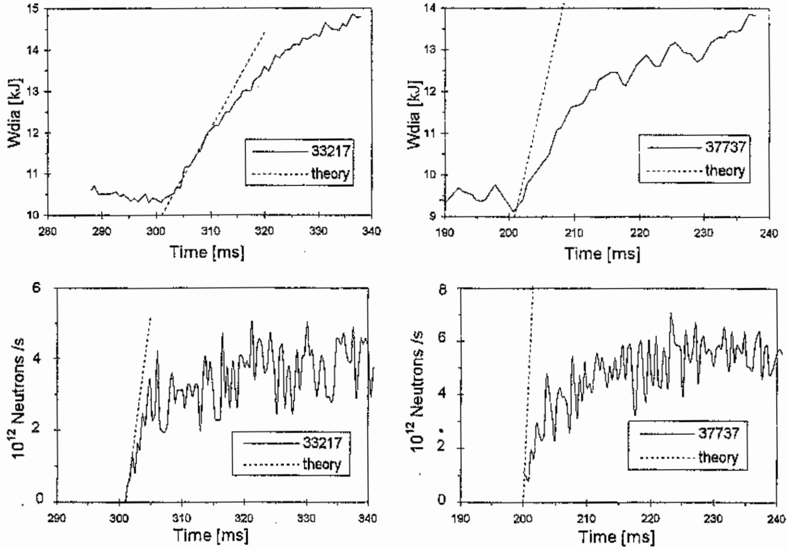

Fig. 3: Initial rise of the plasma energy and the neutron signal.

3a: n_e=5.7x10^{19} m^{-3}
T_e=1.2 keV
τ_W= 21 ms

Fig.3b n_e=3.9x10^{19} m^{-3}
T_e=2.7 keV
τ_W= 50 ms

Although further investigations are required this may be an indication that the observed discrepancies are not caused by a reduced deposition but by a loss mechanism. Moreover, from the FAFNER calculations it follows that the neutral gas density at the plasma edge has to be at the level of 2.5x10^{10}cm^{-3} in order to explain the observed effects. This seems to be a rather high value. On the other hand, a direct particle loss owing to radial diffusion would require a diffusion coefficient in the order of 1 m^2/s, this may be a reasonable value. Finally, up to now we have not detected plasma mode activities which correlate with the observed discrepancies and thus could lead to an anomal energy relaxation by ion-plasmon interactions. Thus, in conclusion, though we can presently not exclude definitely the other two processes, it seems that enhanced radial diffusion of the fast ions may be the reason for the observed reduction in fast particle density and neutron emission in low density discharges.