ION TEMPERATURE DETERMINATION FROM NEUTRON RATE DURING NEUTRAL INJECTION IN ASDEX

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Neutron rate measurements are very often used to determine the ion temperature in ohmic discharges. We have developed software (NR code) which extends this method to neutral beam injection heating (D^0 in D plasma) by introducing a model for neutron production by fast ions. Our software is fully modular however, so that it can also be used for all kinds of thermonuclear plasmas and in future, also for non-thermonuclear neutron production, which may arise RF-heated discharges.

Relaxation time model

The local neutron rate in a plasma is simply given by

$$Q_{ab} = n_a n_b \langle \sigma v \rangle_{ab} = n_a n_b \iint \sigma_{ab} f_a(v_a) f_b(v_b)\, dv_a dv_b . \qquad (1)$$

n_a, n_b, f_a, f_b, v_a, v_b are, respectively, the densities, distribution functions, and velocities of the two reacting ion species, σ_{ab} is the corresponding cross-section, and $\langle \sigma v \rangle_{ab}$ is the reactivity of this process. For the distribution function we use the following ansatz:

$$n f = n_0 f_0 + n_1 f_1 + n_2 f_2 + n_3 f_3 , \qquad (2)$$

where the index 0 denotes the background plasma, and the indices 1, 2, and 3 the deuterons injected with full (45 keV), half, and one-third energy, respectively. For the ASDEX plasma parameters we can use a Maxwellian for f_0. We have to distinguish the following contributions to the neutron rate in the case of D^0 injection in D plasma

$$\begin{aligned} Q_{DD} = \tfrac{1}{2} n_0^2 \langle \sigma v \rangle_{00} &+ \alpha_1 n_1^2 \langle \sigma v \rangle_{11} + \alpha_2 n_2^2 \langle \sigma v \rangle_{22} + \alpha_3 n_3^2 \langle \sigma v \rangle_{33} \\ &+ n_0 n_1 \langle \sigma v \rangle_{01} + n_0 n_2 \langle \sigma v \rangle_{02} + n_0 n_3 \langle \sigma v \rangle_{03} \qquad (3) \\ &+ \alpha_{12} n_1 n_2 \langle \sigma v \rangle_{12} + \alpha_{13} n_1 n_3 \langle \sigma v \rangle_{13} + \alpha_{23} n_2 n_3 \langle \sigma v \rangle_{23} . \end{aligned}$$

The first term describes the thermonuclear production in the bulk plasma, and the terms in the second row are the beam-target reactions for the three injection energies. The remaining terms describe the different beam-beam reactions, their coefficients α taking into account possible injection in opposite directions.

As we shall see, for the ASDEX plasma the main contributions are due to the beam-target and the thermonuclear production. Because the distribution function of the bulk plasma is isotropic, the beam-target production only depends on the energy of the injected deuterons and not on their pitch angle. We can therefore use the energy distribution function for the fast deuterons, which is simply calculated from the classical relaxation of the particle energy W:

$$dW/dt = - W/\tau_W , \qquad (4)$$

where τ_W is the energy relaxation time. The resulting distribution functions are

$$n_i f_i(W) = \frac{\dot{N}_i D_i(r)}{n} \frac{n\tau_{W_i}}{W_i}, \quad i = 1, 2, 3. \tag{5}$$

Here n is the electron density, $\dot{N}_i$ are the numbers of deuterons injected per second, and $D_i(r)$ their deposition profile. The energy relaxation parameter $n\tau_W$ is a function of only the electron temperature and the energy itself.

Interpretation of neutron rate

The emission profiles for the different contributions in eq. 3 to the neutron rate and thus the volume-integrated neutron rate itself are completely determined with the geometric data of the plasma, the electron density and temperature profiles n(r) and $T_e(r)$, the profile $Z_{eff}(r)$, the deposition profile D(r) of the injected deuterons, and the plasma deuteron density and temperature profiles $n_D(r)$ and $T_D(r)$. The emission profiles for the different contributions in eq. 3 to the neutron rate and thus the volume-integrated neutron rate itself are completely determined. The densities of electrons n, deuterons n_D, and protons n_H are related by

$$\frac{Z_x - Z_{eff}}{Z_x - 1} = \frac{n_D}{n}\left(1 + \frac{n_H}{n_D}\right), \tag{6}$$

where Z_x is the charge of the dominant impurity. In a deuterium plasma without protons, n_D could therefore be determined from Z_{eff}, and thus the ion temperature T_D from the measured neutron rate Q_{DD}. If there is any information about the shape of the ion temperauture profile, the neutron emission profile $D_{DD}(r)$ can also be deduced. For plasmas with a mixture of protons and deuterons, as with H^0 injection in D plasma, one of the two parameters T_D and n_D/n_H can always be calculated from the neutron rate if the other is known.

Structure of the NR software

To take care of all these possibilities, our software has a fully modular structure. The scheme is shown in Fig. 1; firstly, the software DATA FILES reads all input data. It is thus easy to adapt changes in the ASDEX data files or to introduce new data which become accessible with the development of new diagnostics. An example of the last is the new $Z_{eff}(r)$ measurement from visible bremsstrahlung which is now availiable at ASDEX.

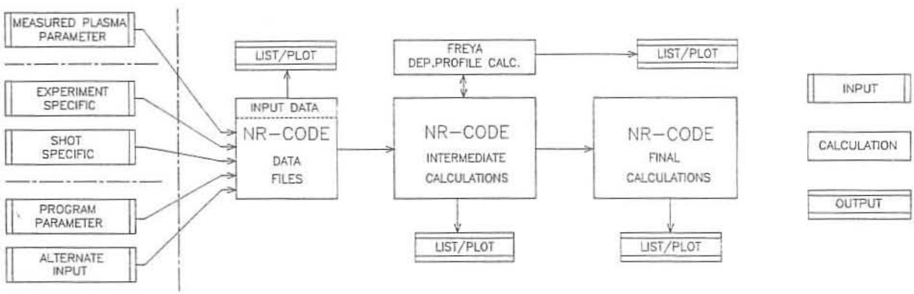

Fig.1: Software scheme

Secondly, the reactivities and the distribution functions are determined in INTERMEDIATE CALCULATIONS and the input data for FREYA code calculation of the deposition profile D(r) are prepared. In the FINAL CALCULATIONS one of the parameters Q_{DD}, T_D, and n_D can always be calculated, the other two being taken as ALTERNATE INPUTS. The software thus allows not only determination of the ion temperature or density, but also prediction of neutron rates and therefore detailed studies of the influence of relevant plasma parameters on the neutron rate.

By this modular structure all components of eq. 3 can be separately discussed. Furthermore, if this becomes advisable, it would be easy to change the model for neutron production by fast ions and use, in particular, more sophisticated distribution functions, even for the target plasma. Last but not least, the flexibility of the software allows us to treat, besides D^0 injection, not only ohmic discharges but also H^o injection in deuterium plasmas and ICR and LH heating. For most of these cases the hydrogen content of the plasma is the main problem.

D^0 injection in deuterium plasma

As an example of the treatment of D^0 injection in deuterium plasma, we consider two discharges, one with a high ion temperature of about 3.5 keV (#17061, injection: 4.15 MW, 1.1 - 1.4 sec) and another with a relatively low ion temperature of about 2.0 keV (#16910, injection: 3.1 MW, 1.1 - 1.5 sec). Figure 2 shows for both discharges the time development of the neutron rate Q and the central electron temperature, as well as the time-dependent central deuteron temperature calculated from Q. Table 1 gives for discharge #17061 for some times the components Q_{00}, Q_{01}, Q_{02} (the indices correspond to those in equation 3) and the ratio T_D/T_e, calculated for a content of 10% protons.

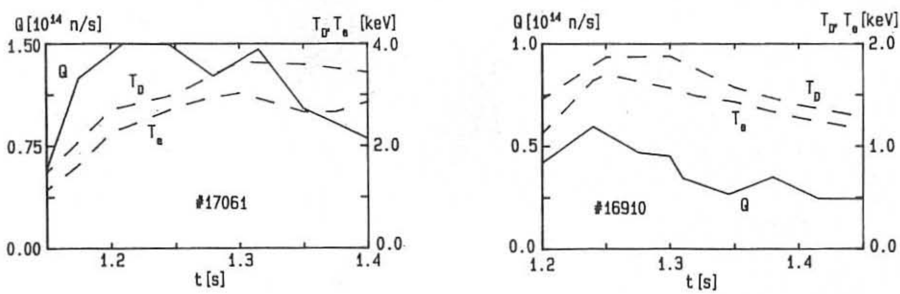

Fig. 2: Neutron rate (Q), electron (T_e) and deuteron (T_D) temperatures

The dominant neutron production is due to the full energy beam reactions with the target plasma Q_{01}. The half-energy beam (Q_{02}) contributes about 10% of Q_{01}. At the beginning of the injection this is appreciably higher than the thermonuclear production Q_{00}. But during injection the temperatures increase, causing an increase in the beam-target reactions (owing to T_e and T_D) as well as in Q_{00}. At the maximum of the neutron rate Q_{00} is about twice Q_{02}. The scatter in the results for T_D/T_e reflects the uncertainty of the temperature determination.

TABLE 1

time [sec]	Q_{00}	Q_{01} [10^{13} neutrons/sec]	Q_{02}	T_D/T_e
1.15	0.036	4.41	0.35	1.30
1.20	0.72	10.5	1.03	1.20
1.25	2.07	12.9	1.29	1.10
1.30	2.32	8.31	0.91	1.20
1.35	1.14	7.36	0.83	1.35
1.40	0.39	6.60	0.68	1.20

Table 2 gives the different particle densities $n_i = \int n_i f_i dW$ on the plasma axis. They are of the same order for all components of the beam, but about one order of magnitude smaller for the beams than for the target plasma.

Table 2 Deuteron densities on axis at maximum neutron production

	n_0	n_1	n_2	n_3	
#17061	4.16	0.64	0.45	0.16	10^{13} deuterons/cm^3
#16910	3.37	0.45	0.17	0.12	10^{13} deuterons/cm^3

Table 3 gives for discharge #16910 at 1.3 sec all components of eq. 3, for injection of the total power in one direction and for the hypothetical case of balanced injection with half the power in each beam. Here, owing to the low ion temperature the thermonuclear production is of the same order as the production by the one-third energy beam component, which itself amounts to only 1.5% of the beam production. The production by reactions between the beam particles clearly shows a dependence on the relative velocity, as is to be expected. But owing to the small densities in the beams compared with the target plasma the beam-beam productions are smaller than the one-third energy beam-target production, even in the hypothetical case of balanced injection, and so it is always negligible.

Table 3

	neutron rate [neutrons/sec]	
	unidirectional inj.	balanced inj.
Q_{00}	7.99×10^{11}	7.99×10^{11}
Q_{01}	4.39×10^{13}	4.39×10^{13}
Q_{02}	3.71×10^{12}	3.71×10^{12}
Q_{03}	7.39×10^{11}	7.39×10^{11}
Q_{11}	7.35×10^{7}	1.44×10^{11}
Q_{12}	1.47×10^{8}	8.20×10^{10}
Q_{13}	1.86×10^{8}	2.94×10^{10}
Q_{22}	7.18×10^{5}	3.19×10^{10}
Q_{23}	6.42×10^{5}	8.54×10^{9}
Q_{33}	7.39×10^{3}	2.12×10^{9}

H^0 injection in deuterium plasma

As an example of the treatment of H^0 injection in deuterium plasma we consider the discharge #21502 (1.35 MW, 1.0 - 3.0 sec). In this case we have only the thermonuclear production Q_{00}. Figure 4 shows the measured neutron rate and the ratio n_D/n_H from CX measurements. Figure 5 gives the deuteron temperature calculated with our software and, for comparision, the electron temperature from ECE measurements. Here again we find $T_D/T_e \approx 1.2$. The decrease in the neutron rate is caused by the small decrease in the ion temperature.

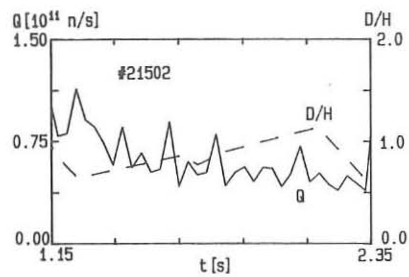

Fig. 4. Neutron rate and n_D/n_H for discharge #21502

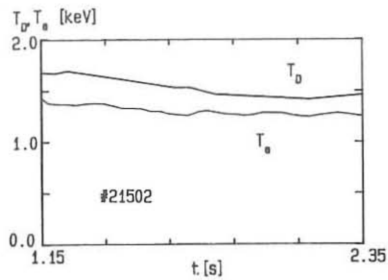

Fig. 5: Ion and electron temperature for discharge #21502