27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** (2000) 412 -415

Charge-Exchange Diagnostics of Knock-on Deuterium-Tritium Ion Distribution Function in Fusion Plasma

A.V.Khudoleev, V.I.Afanasyev, A.V.Dech and A.I.Kislyakov
A.F.Ioffe Physical -Technical Institute, 194021,St.Petersburg, Russia

1 Introduction

In the contemporary plasma experiments on tokamaks the main plasma ion distribution function is frequently distorted by the development of plasma instabilities or by external additional heating. In burning deuterium-tritium plasma there is another specific mechanism which leads to the ions tails generation. Alpha-particles from the thermonuclear reaction due to hard knock-on collisions with the thermal fuel ions can create their suprathermal population. In [1] it has been proposed to use knock-on signature on neutron spectra for α–particles diagnostics. At the same time it has been demonstrated experimentally [2] that hydrogen ions in MeV energy range have sufficiently high probability to be neutralized and escape plasma. In present report we consider feasibility of charge-exchange diagnostics of knock-on d, t ions for ITER plasma parameters.

2 Numerical model for ion distribution function

In our analysis we followed the model developed in [3] where steady state Fokker-Plank equation with no spatial diffusion was solved in uniform plasma both for α–particles and d, t ions. The special emphasis in this work was made on relative contributions of Coulomb and nuclear scattering including the interference between these two types. It has been shown that in burning plasma fast knock-on concentration may be as high as 0.5 % and sufficient for diagnostic purposes. Since for a number of diagnostic applications it is important to know the time scale of the processes we solved similar nonstationary equation:

$$\frac{\partial f_z}{\partial t} = \frac{1}{\upsilon^2}\frac{\partial}{\partial \upsilon}\left(\upsilon^3 \nu_z f_z\right) + Q_z \qquad (1)$$

The source in equation (1) for α–particles is defined by nuclear reaction:

$$d + t \rightarrow \alpha\left(3.5\,MeV\right) + n\left(14\,MeV\right)$$

accounting thermal broadening of the source. For d, t ions the source appears as a result of the thermal ions interaction with the fast α–particles. The differences scheme was made for equation (1) and solved numerically. The source term was recalculated on each time step following changes in the plasma temperature and density. At the beginning the source term was defined by Monte Carlo method and then for computing acceleration approximated by Gauss curve with parameters dependent on temperatures. The input parameters of the program are ion and electron temperatures and densities. At the output we have energy distribution functions of α–particles, d, t ions and their sources. The Fokker-Plank code was run for set of different input plasma parameters corresponding to the different radial points to obtain spatial distribution of fast particles in real plasma. Typically this procedure was made for 10 sets of temperature and density which later were attributed to the different radii. For data smoothing in further computations interpolation was used.

3 **Neutralization model**

For separate measurements of hydrogen isotopes distribution functions neutral particles charge-exchange diagnostic is frequently used. The diagnostics is based on the neutral flux measurement of corresponding isotopes outside plasma. To produce experimentally measurable neutral flux fast hydrogen ions in plasma has to be neutralized. In low energy range the neutralization is predominantly determined by classical charge-exchange reaction. In the

MeV energy range the situation is more complicated and we need to consider several different neutralization processes. The detailed analysis of their relative role as well as some estimates for ITER plasma one can find in [3]. Generally speaking neutralization of MeV hydrogen ions occurs due to non-resonant charge-exchange on not fully stripped light impurity ions and some times due to direct recombination with plasma electrons. In our report we base consideration on the numerical model of neutral hydrogen isotopes and helium penetration into plasma. The program solves Boltzmann equation for neutrals in slab geometry assuming monoenergetic and homogenous neutral influx from the wall. The model allows to consider plasma containing two different hydrogen isotopes, helium and one other dominating impurity. In the program the processes of charge-exchange between these species, electron and ion impact ionization and recombination are taken into account. Also charge-exchange process between helium and carbon [6] was taken into consideration. Plasma temperature and density profiles are used as an input parameters. As a result we have radial density distribution of neutral hydrogen isotopes, neutral helium and H-like helium and light impurity in the ‘‘corona’’ model. Program also allows to introduce neutral beam into consideration. H-like impurity density in this case comes from ionization balance for the conditions $L_{beam} << \lambda_{ion} << 2\pi R_{tor}$ where L_{beam} is the beam size in plasma, λ_{ion} -ionisation length, R_{tor} is toroidal major radius which are usually fulfilled for the thermonuclear reactor parameters. Fast d, t ions are neutralized in the reactions:

$$He^{+}+\left(d,t\right)^{+}\rightarrow He^{2+}+\left(d,t\right)^{0}$$

$$C^{5+}+\left(d,t\right)^{+}\rightarrow C^{6+}+\left(d,t\right)^{0}$$

$$\left(d,t\right)^{+}+e^{-}\rightarrow\left(d,t\right)^{0}$$

$$H^{0}+\left(d,t\right)^{+}\rightarrow H^{+}+\left(d,t\right)^{0}$$

The outcoming flux of neutrals may be calculated as:

$$\frac{d\Gamma}{dE}=\frac{1}{4\pi}\int_{l}\frac{dn}{dE}\left[n_e\langle\sigma_{rec}\upsilon_e\rangle+\sum n_z\langle\sigma_{cx}\upsilon_{rel}\rangle\right]\exp\left(-\tau(E,x)\right)dx \qquad (2)$$

where σ_{rec}, σ_{cx}- recombination and charge-exchange cross-sections, $\tau(E,x)$ - flux attenuation factor.

4 Computational results.

We made our computations for one variant of the thermonuclear reactor project. The major input parameters were :

$$a_p = 2\,m, T_e(0) = 29\,keV, T_i(0) = 22\,keV, n_e(0) = 10^{20}m^{-3}, n_d(0) = n_t(0) = 4.5\cdot 10^{19}m^{-3};$$

$$n_{He}/n_e = 10\%,\ n_C/n_e = 2\%$$

For temperatures were selected profiles rather peaked in the plasma center when electron density assumed nearly constant over radius. The relative ion densities were taken constant over radius as well. For active measurements we assumed Diagnostic Neutral Beam (DNB) to be installed on reactor with following parameters:

$$P_{DNB} = 1.5MW, E_{inj} = 100\,keV/amu, S = 0.30\times 0.30\,m^2$$

Flux in the model is integrated over view line passing through plasma center perpendicular to major plasma axis and laying in the equatorial plane . DNB supposed to stay in the adjacent port so that viewing line nearly coincides with the injection line. In this position experimental signal will loose in active spatial resolution but gain in magnitude.

Distribution functions in fig.1 were calculated under assumption that there are no losses of fast ions in plasma. That means radial distribution of knock-on ions depends just on the intensity of the α–particles source and on drag term. Time relaxation constant for ions is typically of the order of local slowing down time which varies by more then two orders of magnitude from the center to the edge. Outcoming flux defined by integral (2) has different origin places for different energies. As a result neutral fluxes have different relaxation times for plasma parameters perturbation. Without losses population of d, t is rather high even at the periphery. At the same time calculation of the neutralization target demonstrate sharp increase toward the plasma edge as shown in fig.2. If in the plasma center the dominant process is re-combination than closer to the periphery the target is determined by charge-exchange with hy-drogen neutrals. Any kind of particle transport will distort the initial distribution shown in fig.1. Since the main aim of this work was to make general estimate of the fast neutral flux for diagnostic purposes we did not consider specific transport mechanisms for knock-on ions. To give just the rough idea of the scale we performed calculations for two variants - with fully classical slowing down in whole plasma and with zero density outside r = 0.75 a. The fluxes for these two cases are shown in fig.3. Low energy part of the spectra goes down significantly when high energy part defined by recombination stays at the same level. Computation of the active signal shows the that DNB can provide reasonable contrast ~ 5 times only for energies below 0.5 MeV. Higher energies are dominated by passive signal. To get the idea of possible signal intensity we can assume ‘‘ideal neutral particle analyzer’’ with the parameters: Efficiency α=100%, acceptance $-\varpi S = 10^{-4}$, energy resolution ΔE/E = 10%, so for 1 MeV transform coefficient from flux to count rate equals to 10^{-5}. We see that knock-ons produce small but principally measurable flux. This flux may be applied for example to the isotope composition control. In low energy range neutrals suffer from severe plasma opacity and can provide information about plasma composition on the periphery [5]. For fast particles attenua-tion factor is relatively small and varies from 2 to 10 for different energies. It makes the ex-perimental data in this range less sensitive to plasma conditions. Fast d and t flux ratio for ac-tive and passive variants are shown in fig.4. In our model we did not consider fast triton from *d* - *d* reaction which give [3] about 10% correction so appropriate energy range for plasma composition measurements is from 1 to 2 MeV.

5 Conclusions

Measurements of fast d, t knock-on atomic fluxes are feasible in the thermonuclear re-actor plasma.

These measurements will be able to provide ratio N_d/N_t on the bases of flux measure-ments in the 1 - 2 MeV energy range. Time resolution of the method is about 1 s.

Active variant of the diagnostic is also possible but in the present layout cannot pro-vide spatial resolution. Application of the NBI for plasma heating will increase signal level and improve sinal to noises ratio.

Special attention must be paid to the fast particles transport events which may lead to ion redistribution in plasma. In some cases they can appear close to the edge where neutraliza-tion probability is high and may corrupt N_d/N_t measurements.

Referencies

1. R. K. Fisher et al., Diagnostics for Experimental Thermonuclear Fusion Reactors, Plenum Press, pp. 485-503 (1996).
2. M.P.Petrov et al., 19th EPS, 16CII-1031 (1992)
3. L.Ballabio et al., Phys.Rev.E, Vol.55, No.3, pp. 3358-3368 (1997)
4. A.A.Korotkov et al, Nuclear Fusion, Vol.37, No. 1 (1997)
5. A.V. Khudoleev et al., Plasma Physics Reportes, Vol.24, No. 2, pp. 161-164 (1998)
6. F.Sattin et al., Plasma Phys. and Contr. Fusion, Vol. 42, pp. 15-20, (2000)

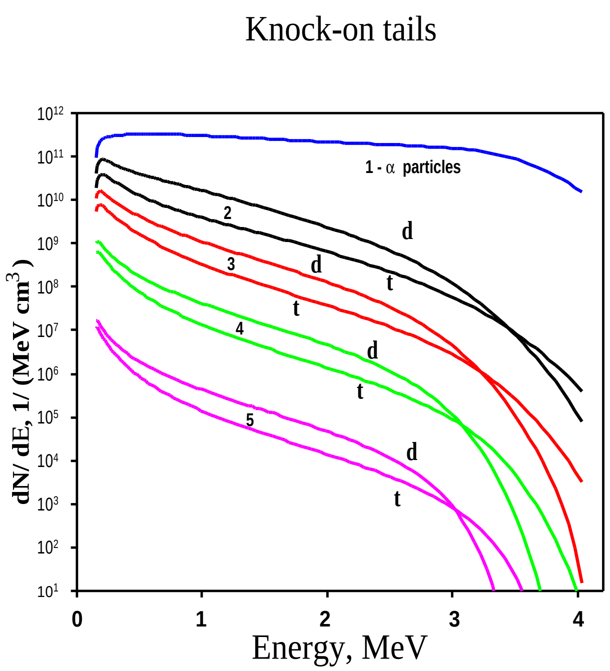

Fig.1 Ion distribution functions. 1 - α - particles in plasma center. 2, 3, 4, 5 - knock-on d and t at radii r / a = 0, 0.5, 0.75, 0.9 .

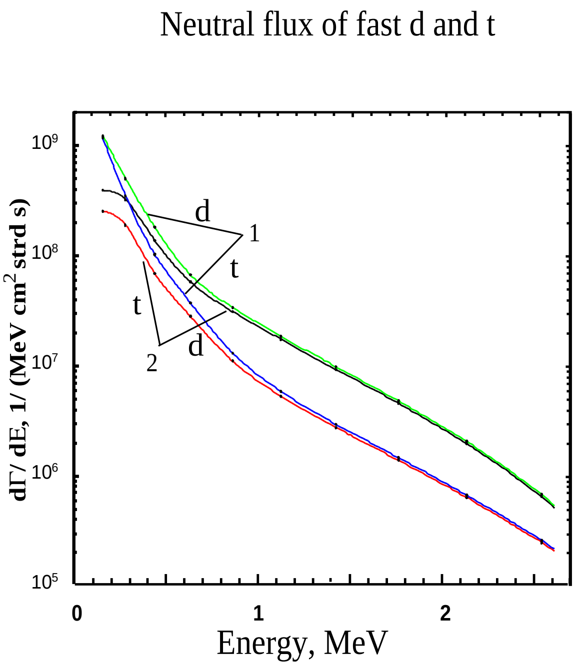

Fig.2 Neutral flux of d and t knock-ons. 1 - classical slowing down in whole plasma. 2 - classical within r/a=0.75 and 0 outside.

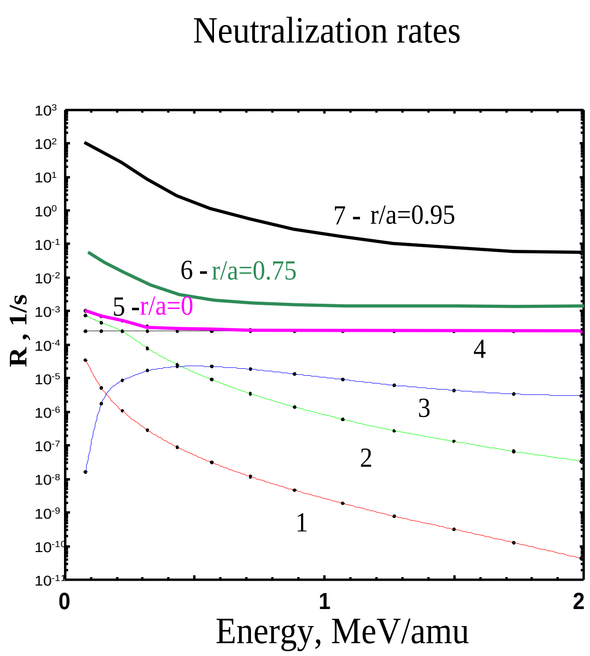

Fig.3 Neutralization at different radii. 1, 2, 3 charge exchange on H, He and H-like C in the plasma center. 4-recombination. 5, 6, 7 - total rates..

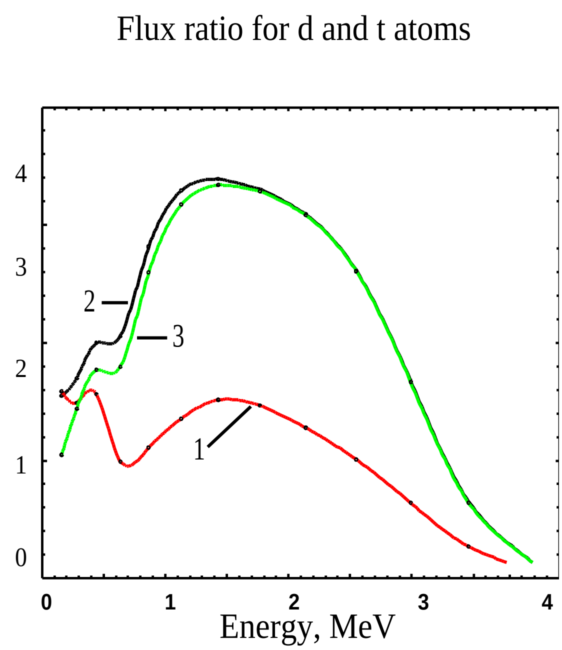

Fig.4. Ratio of outcoming fluxes of d and t. 1 - with diagnostic beam. 2 - passive; for classic slowing down in whole plasma . 3 - passive; with no prticles outside r/a= 0.75..