PLASMA KINETICS MODELS FOR FUSION SYSTEMS BASED ON THE AXIALLY-SYMMETRIC MIRROR DEVICES

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A numerical model of ion kinetics is considered for the axially symmetrical magnetic trap. The trap contains warm Maxwellian plasma and strongly non-Maxwellian high-energy (fast) ions. The steady-state fast ion population is supported by the ionization of high-energy neutral atoms injected into the plasma. The physical model is based on the kinetic equation with the two-dimensional Fokker–Planck collision operator in the velocity phase space. Regimes of plasma exhaust through the mirrors are considered taking into account the possibility of electrostatic barrier formation. Parameters of power balance are discussed for the system under consideration.

I. INTRODUCTION

The kinetics of the plasma with high-energy ions in an axially symmetric magnetic trap is considered in the present work. The central section of the trap consists of a long solenoid and two end mirror coils constricting magnetic field lines. The trap contains warm Maxwellian plasma and strongly non-Maxwellian high-energy (fast) ions. Fast ions appear in the plasma due to the ionization of neutral particles injected into the configuration.

The general scheme of the magnetic trap for plasma confinement under consideration is like the system known as Gas Dynamic Trap (GDT) [1]. The physical concept of the dense plasma dynamics in GDT based on the classical mechanisms of gas exhaust through small hole from the balloon into the vacuum space. In this case linear magnetic field constricted at the ends of the system play the role of such balloon. Plasma is stored in the system during relatively small time but very large energy density is achieved due to the heating by high-energy beams. Such plasma can be used for technological applications and fundamental research. Experiments on GDT device at the Budker Institute of Nuclear Physics in Novosibirsk demonstrate essential achievements in the following directions: stable magneto-hydrodynamic equilibrium of the high-pressure plasma; suppression of electron heat transport along magnetic field lines; high efficiency heating by high-energy particle beams. Ambipolar confinement during the formation of electrostatic barrier at the ends of the system was demonstrated in experiments with compact plugging mirror SHIP [2].

In the case of deuterium-tritium (D–T) plasma mixture the powerful neutron source for technology and nuclear power engineering is an attractive prospect of GDT application [3].

Recently the concept of the powerful thermonuclear neutron generator operating in the kinetic collisionless plasma regimes was formulated [4].

Injection of high-energy (fast) particles into warm thermal plasma affects essentially on the gas dynamic regime. Fast particles heat the plasma and initiate nuclear reactions. The energy distribution of fast component is non-equilibrium. To calculate the heat transfer between fast particle and warm plasma kinetic models and numerical codes developed at the Thermal Physics Department of the Bauman Moscow State Technical University are used [5–7].

The fast ion kinetic model for GDT device conditions was developed earlier neglecting the losses due to the effect of the angular scattering [8]. Kinetic models [5, 6] applied in the present study take into account angular scattering and nuclear reactions of fast ions. Numerical modeling is based on FPC2 code [7] developed for the problem of fast ion kinetics in magnetic mirror trap.

II. MODELS OF PLASMA KINETICS

Time-dependent kinetics of fast ions is considered under the assumption of homogeneous plasma parameters in the trap. Coulomb interactions are described by the two-dimensional Fokker–Planck operator in the velocity space [9]. The Fokker–Planck equation generally includes both differential and integral operators [10, 11]. Here we use the differential approximation of Fokker–Planck operator [5, 6]. It decreases numerical calculation time essentially. In the high-energy range the effect of fast with fast particles collisions is negligible in comparison with the effect of fast with thermal particles collisions. Thermal populations are assumed to be Maxwellian for the calculation of the effects of injected particle slowdown and scattering. At very high energies (> 1 MeV) collision operator takes into account nuclear elastic scattering [12] which can become important in the processes of slowing down and scattering of charged products of nuclear reactions.

The Fokker–Planck equation in coordinates velocity v and angle θ between velocity and magnetic induction vectors is presented in the following form:

$$\frac{\partial f_a}{\partial t} - \frac{1}{v^2}\frac{\partial}{\partial v} v^2 \left[D_{vv}^C \frac{\partial f_a}{\partial v} - (A_v^C + A_v^N) f_a \right]$$
$$- \frac{1}{v^2 \sin\theta}\frac{\partial}{\partial \theta} \sin\theta D_{\theta\theta}^C \frac{\partial f_a}{\partial \theta} = \frac{s_a(\theta)}{4\pi v_{0a}^2}\delta(v - v_{0a}) - L_a . \quad (1)$$

Here f_a is the velocity distribution function of particles of kind a; D_{vv}^C, $D_{\theta\theta}^C$, A_v^C are the coefficients of Coulomb diffusion and Coulomb dynamical friction [13]; A_v^N is the coefficient of dynamical friction due to nuclear elastic scattering; $s_a(\theta)$ is the angular distribution of the particle source ; L_a is the operator of the particle losses.

In steady-state regimes $\partial f_a / \partial t = 0$. To simulate the formation of thermal population of the injected particles we consider temporal evolution of the velocity distribution. The dependence of the source on the velocity is assumed to be a δ-function. As thermal populations are assumed to be Maxwellian the coefficients of Coulomb diffusion and friction are used in corresponding form [9, 13]. The coefficient of dynamic friction due to nuclear elastic scattering A_v^N can be calculated using experimental data on cross-section and energy transfer rate [12].

Particle losses are described by perpendicular and parallel to magnetic field lines components: $L_{a\perp} = f_a / \tau_\perp(v,\theta)$ and $L_{a\|} = f_a / \tau_\|(v,\theta)$. Perpendicular loss time $\tau_\perp$ is determined by turbulent transport of particles across magnetic field force lines. Its value is assumed to be a constant for the presented modeling. Parallel loss time $\tau_\|$ from the loss region in the velocity space is about the time of the passing through the trap. Outside the loss region $L_{a\|} = 0$.

Loss region in the velocity space is determined by the condition

$$\frac{m_a v_\|^2}{2} > \frac{m_a v_\perp^2}{2}\left(\frac{B_m}{B_0} - 1\right) + Z_a e \Delta\varphi , \quad (2)$$

where $\Delta\varphi$ is electrostatic barrier for considered particles which is equal to the corresponding difference of the electric potential values between central sell and mirror regions; B_0 is the magnetic induction in the central sell; B_m is the induction in the mirrors.

For rough estimates and qualitative testing (not for numerical modeling) the approximation for high-energy distribution function is used [14]. It can be used in the following velocity range: $v_{Ti} < v < v_{Te}$, where v_{Ti} and v_{Te} are thermal velocities of Maxwellian ions and electrons. Besides, this approximation neglects the losses due to the scattering into the loss region, i.e. injected particles heat Maxwellian components with no energy losses during slow down to velocity $v \sim v_{Ti}$.

To calculate total efficiency and consistent values of plasma parameters the consideration of the plasma power balance taking into account the kinetics of each plasma components is needed. Here we consider power balance on the basis of the model developed in Ref. 5. A simplified scheme of the power balance is shown in Fig. 1 where energy sources are placed on the left side and energy losses are placed on the right side of the scheme.

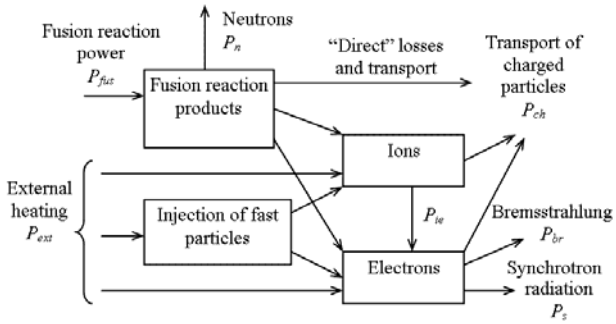

Fig. 1. Plasma power balance scheme

Sources are the following: heating by injected fast particles, heating by the products of D–T reaction (alpha-particles), some additional heating of ions and electrons (if needed). The heating by injection is dominant energy source for the neutron generator under consideration.

Major losses of fast particles are connected with the angular scattering into the loss region in the velocity space during the slow-down. These losses can be as high as 40..50 % of injected power. Fast alpha-particles losses are about 25 % of their initial energy. Radiation losses include bremsstrahlung and synchrotron radiation. But the part of radiation in total balance is few percents at T_e = 10..20 keV. Convective energy losses are presented by the energy loss time τ_E which is connected with particle loss time τ_p. Value of τ_p includes both parallel and perpendicular losses: $1/\tau_p = 1/\tau_\| + 1/\tau_\perp$. Parallel loss time $\tau_\|$ is calculated taking into account the potential $\Delta\varphi$ [15].

The temperatures of Maxwellian components were assumed to be approximately equal: $T_i \approx T_e$. Note that balance estimations show the possible difference between ion and electron temperatures as low as 1..3 keV at $T_i \approx T_e$ = 10..20 keV. As the optimization criterion here we consider the ratio $Q_{inj} = P_{fus}/P_{inj}$, where P_{fus} is the power of nuclear fusion reaction in D–T plasma, P_{inj} is the injected power. This ratio characterizes the efficiency of utilization of the fast particle energy in the neutron generator regime. It should be as high as possible. For neutron generator reasonable value is $Q_{inj} \approx 0.5–1$.

III. RESULTS OF THE CALCULATIONS

The kinetic code FPC2 was used for the modeling of temporal evolution of velocity distribution function of injected particles. Initial values of the distribution function are zero. If the initial plasma contains some non-zero portions of particles of kind under consideration, they correspond to Maxwellian distribution. The calculation starts with the injection switch on. The injection power is constant during the calculation time. In this case the changing time of plasma parameters is about the Coulomb slow-down time. We use slow-down time $\tau_{s\infty}$ as time scale; the value of $\tau_{s\infty}$ is calculated with the steady-state plasma regime. Typical time of steady-state regime setting is about $(2..3)\tau_{s\infty}$.

We consider the magnetic system with the following parameters: magnetic induction inside the central solenoid B_0 = 1.5..2 T, induction in the mirrors B_m up to 20 T. The ratio of plasma pressure to magnetic pressure is β = 0.5.

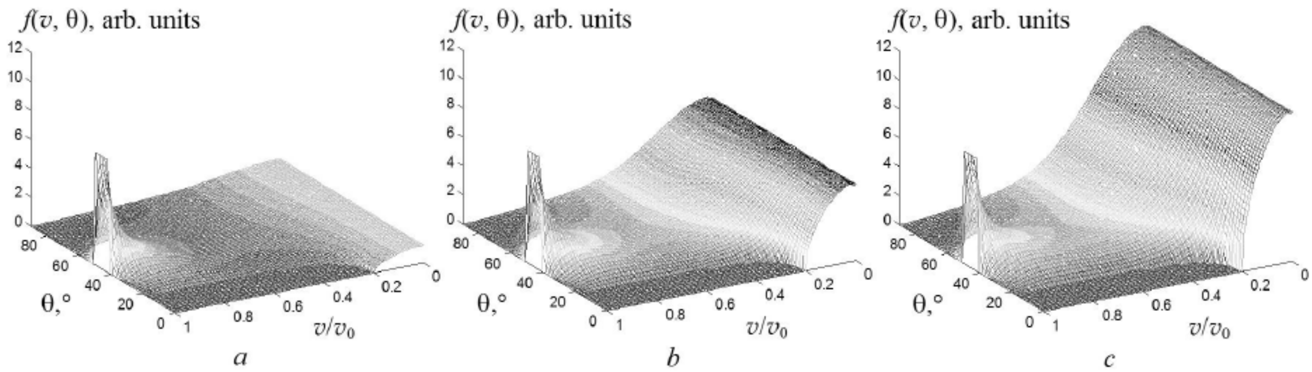

Fig. 2. Velocity distribution function of tritium injected into deuterium plasma at the different time moments: $0.1\tau_{s\infty}$ (*a*), $0.3\tau_{s\infty}$ (*b*), and $10\tau_{s\infty}$ (*c*). Deuterium density is $n_D = 3.3\cdot10^{19}$ m^{-3}; initial energy of injected particles is 250 keV; injection angle is 45°±5°; injection power is 2 MW/m^3; $T_i = T_e$ = 20 keV; $\Delta\varphi$ = 10 keV; $\tau_{s\infty}$ = 4.5 s; $\tau_\perp = \tau_{s\infty}$

Table: Parameters of the mirror-based fusion system with powerful neutral beam injections and tandem mirror reactors

Parameter	Ver. # 1	Ver. # 2	Ver. # 3	Ver. # 4	Tandem mirror reactors [5, 6]	
					D–T fuel	D–^{3}He fuel
Plasma radius a, m	1	1	1	1	1	1
Plasma length L, m	10	10	10	10	10	44
Magnetic field of the central solenoid B_0, T	1.5	1.5	2	2	3.3	5.4
Magnetic field in plugs (mirrors) B_m, T	11	11	14	14	14.8	14.8
Averaged β	0.5	0.5	0.5	0.5	0.2	0.7
Deuterium density n_D, 10^{20} m^{-3}	0.22	0.26	0.21	0.415	0.82	1.35
Tritium density n_T, 10^{20} m^{-3}	0.33	0.26	0.42	0.415	0.82	–
Density of α-particles n_α, 10^{20} m^{-3}	0.04	0.03	0.06	0.085	–	–
Ion temperature T_i, keV	11	10	22	22	15	65
Electron temperature T_e, keV	8.5	10.5	18	19	15	65
Ion electrostatic barrier $\Delta\varphi$, keV	16.5	15	33	44	60	260
Initial energy of injected particles ε_0, keV	250	250	250	250	–	–
Averaged energy of injected particles $<\varepsilon>$, keV	90	90	100	65	–	–
Injection power P_{inj}, MW	74	60	60	55	–	–
ECRH power P_{RH}, MW	0	18	0	0	–	–
Neutron power P_n, MW	30	24	43	59	–	–
Plasma amplification factor $Q_{pl} = P_{fus}/(P_{inj} + P_{RH})$	0.5	0.38	0.9	1.34	10	10
Total neutron output N, 10^{18} neutrons/s	13	11	19	26.5	–	–
Neutron energy flux out of plasma J_n, MW/m^2	0.4	0.4	0.7	1	2	0.04
Heat flux out of plasma J_H, MW/m^2	1.8	1.2	1.8	2.0	2.4	0.94

The electrostatic potential difference $\Delta\varphi$ between the plasma in the central solenoid and mirror regions corresponds the relationship $e\Delta\varphi \sim (0.1..1)k_BT$. For such values the warm Maxwellian plasma confinement regime takes intermediate place between the gas dynamic exhaust and ambipolar potential confinement.

Regimes with $e\Delta\varphi \sim (0.1..1)k_BT$ can be supported by neutral beam injection [2].

In Fig. 2, the example of calculation of the velocity distribution function is presented for the case of fast tritium injection into deuterium plasma. One can see the formation of the fast particle population as well as thermal particle population.

At $e\Delta\varphi \sim k_BT$ the total quantity of fast particles is comparable with the quantity of particles of thermal population. Increasing $\Delta\varphi$ results in the strong growing of thermal population. But the efficiency of heating remains close to the same level.

We used the high-energy approximation [14] for tentative estimations for the regimes with $Q_{\rm inj} \approx 1$. Corresponding optimal parameters are the following: Maxwellian plasma temperature $T \approx 10$ keV, initial energy of injected particles is about 100 keV. But numerical study shows essential difference of the optimal regime from this estimation. The numerical modeling indicates optimal plasma temperature about 20 keV and optimal initial energy of injected particles about 250 keV.

We assume perpendicular transport time $\tau_\perp = \tau_{s\infty}$. According to the balance calculation, the potential could satisfy the relation $e\Delta\varphi \approx k_BT$. In this regime, other parameters are close to values used in the example presented in Fig. 2. Loss times values are the following: $\tau_\perp = 4.5$ s, $\tau_E = 0.15$ s, $\tau_p = 0.7$ s. Consequently, parallel losses are dominant in the considered regime.

As it was mentioned the concept of the thermonuclear neutron generator based on the Axially Symmetrical Open Trap was formulated recently [4]. In the Table, calculated parameters are presented for possible regimes of this system. These regimes appear to be appropriate for the high efficiency neutron generator. Besides, parameters for the central section of the D–T, and D–^{3}He tandem mirror reactors [5, 6] are presented in the Table for comparison.

Further enhancements of the considered neutron generator scheme require the increase of electrostatic potential. But it is probably connected with the complications of the construction due to the necessity of additional elements for high potential formation.

In the considered system $e\Delta\varphi \approx k_BT$ is achieved by the injection of fast particles. The modeling of fast ion kinetics appears to be the key element of physical justification of such systems.

ACKNOWLEDGMENTS

Work was partially supported by Russian Foundation for Basic Research (grants 09-08-00137-a and 10-02-90734-mob_st) and the Ministry of Education and Science of Russian Federation in framework of Presidential Program (grant MK-1811.2010.8).

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