MODELING OF PLASMA ACCUMULATION, HEATING AND CONFINEMENT IN A SOURCE OF THERMONUCLEAR NEUTRONS

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The mathematical model and computer program were prepared for modeling of physical processes in a source of thermonuclear neutrons. As a result of modeling, the time dependences on characteristics of system were obtained for plasma parameters in starting conditions, for the conditions to approach to a stationary mode, for the plasma parameters in stationary mode and for neutron yield.

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MATHEMATICAL PROGRAM FOR NUMERICAL MODELING OF PLASMA PROCESSES IN A SOURCE OF THERMONUCLEAR NEUTRONS

The equations of material and power balance are a basis of a model in view of specific features of electromagnetic traps. These are: the presence of a large volume of nonmagnetized plasma with fixed basic parameters, the absence of the most dangerous instabilities, the classical character of particles transfer and energy transfer, influence of an electrical field of a space charge on plasma heating and confinement. The calculations were carried out for an axisymmetric multislit electromagnetic trap with a magnetic field configuration similar to "Jupiter 2".

The equations describe the dependences of the complete electron N_e and ion N_i quantity, complete power content in electronic component $W_e = 1.5T_eN_e$ and ion component $W_i = 1.5T_iN_i$ in the trap on the time of plasma accumulation:

$$dN_e/dt = I_e/e + \Gamma - I_{e\perp} - I_{e||} \qquad (1)$$

$$dN_i/dt = \Gamma - I_i - I_\alpha \qquad (2)$$

$$dW_e/dt = P_{eh} - P_{ek} \qquad (3)$$

$$dW_i/dt = P_{ih} - P_{ik}, \qquad (4)$$

where I_e is the current of electronic injection. At an initial stage of plasma accumulation this current is limited by formation of a virtual cathode at the center of a trap. The special function is introduced in the program which limits the current of electronic injection to the level of electronic loses at approaching the potential of a space charge near the center to the cathode potential. The amount of electron and ion pairs formed in plasma volume in the time units because of neutral gas ionization:

$$\Gamma = \langle\sigma_e v_e\rangle n_{ap} N_e, \qquad (5)$$

where $\langle\sigma_e v_e\rangle$ - is the rate of ionization and n_{ap} – the neutral gas density in plasma. The neutral gas "burns out" and its density in the plasma is less than that in the vacuum chamber:

$$n_{ap} = n_{am}/(1 + \langle\sigma_e v_e\rangle N_e/v_a S_p), \qquad (6)$$

where $v_a = (8kT_a/\pi m_a)^{1/2}$ – is a velocity of neutral gas molecules, S_p - area of the surface which limits plasma.

Electron are lost from the trap as a result of cross transfer through the magnetic field with an exit on anode diaphragms, limiting plasma in magnetic slits and also due to longitudinal diffusion in the velocity space with overcoming of an electrostatic barrier Φ_e and exit onto electrodes of electrostatic system locking magnetic slits.

The flow of cross electron transfer through a magnetic field in view of electron mobility in a strong electrostatic field in electromagnetic traps with cross magnetic fields [1,2]:

$$I_{e\perp} = N[D_{ea}(1+\Phi_p/2T_{e0}) + D_{ei}]\, n_{e0}FR^2, \qquad (7)$$

where N – is the number of magnetic slits in a trap, $D_{ea} = T_e\nu_e/m_e\omega_{ce}^2$, $D_{ei} = T_e\nu_{ei}/m_e\omega_{ce}^2$ - factors of electron diffusion in a magnetic field on neutral gas and ions of plasma, Φ_p - plasma potential (in power units), n_{e0}, T_{e0} - density and temperature of plasma electron in the central volume of the trap, F - factor which is taking into account the geometry of magnetic field, R - radius of the trap on a ring magnetic slit.

Longitudinal losses, according to [3], are determined by velocity of particle maxwellization in plasma. At small rate of maxwellization, all particle achieving the energy of a potential barrier, do leave the plasma volume:

$$I_{||} = 4(2\pi)^{1/2} e^4 \lambda n^2 V_p m^{-1/2} T^{-3/2} \exp^{-\gamma}. \qquad (8)$$

At a large rate of maxwellization the exit of particles through the barrier is limited by throughput of magnetic slits:

$$I_{||} = 2(\pi)^{1/2} c r_p nkT(B_0/B_A)^{1/2} \exp^{-\gamma} / eB_A\gamma^{1/2}. \qquad (9)$$

Here V_p - plasma volume, $\gamma = \Phi/T$, r_p - radius of plasma, B_A - magnetic field in a ring slit, $B_0 = B(r_p)$, $\Phi_e = \Phi_A + \Phi_p$, $\Phi_i = \Phi_p - \Delta\Phi$, Φ_A - electrostatic potential locking out magnetic slits.

"Depression" of the space charge potential in a magnetic slit $\Delta\Phi$ is calculated with the help of the A. Kaye theory [4], allowing to find an electron flow, circulating in a magnetic slit:

$$\Delta\Phi = 4\pi c n_{e0} kT_e (B_0/B_A)^{1/2} a_0/v_e B_A, \qquad (10)$$

$2a_0$ - width of a magnetic slit which is limited by anode diaphragms, v_e - velocity of electrons in a magnetic slit. The least value from expressions for longitudinal losses of particles (8) and (9) is chosen.

When plasma parameters are approaching the thermonuclear ones, the losses of ions due to thermonuclear reactions have to be taken into account. The α - particles with energy 3,5 MeV are not kept by a thin layer of a magnetic field and leave the trap carrying away from plasma the positive charge and leaving in it some part of their kinetic energy.

Flow of α - particles from plasma (in recalculation for singly ions):

$$I_\alpha = 0.5\langle\sigma_f v_i\rangle n_i^2 V_p. \qquad (11)$$

By electronic injection through magnetic slits into the trap the energy $P_e = \Phi_a I_e$ is introduced. It is spent for creation of the space charge, excitation and ionization of the neutral gas atoms, heating of electrons and ions, compensation of the energy losses connected with leaving of particles, the bremsstrahlung, and cyclotron emission from plasma. The additional contribution to the electronic channel gives a recuperation of thermonuclear α-particles $P_\alpha = \Phi_p I_\alpha$ and hot ions $P_i = \Phi_i I_i$ leaving the trap through magnetic slits, overcoming a potential barrier Φ_i. Thus, the total power introduced into the plasma through the electronic channel is:

$$P_{eh} = P_e + P_\alpha + P_i. \qquad (12)$$

Collisional and collisionless energy transfer from electrons to ions is the source of energy for ion heating. The energy which is transferred by collisional way is:

$$P_{eq} = 1.5(T_e - T_i)N_e/\tau_{eq}, \qquad (13)$$

where $\tau_{eq} = 3m_i T_e^{3/2}/8(2\pi m_e)^{1/2}e^4\lambda n_e$.

The collisionless energy transfer is carried out due to the acceleration of the ions formed by ionization of neutral gas in an electrical field of a space charge. The efficiency of heating depends on the place of neutral atom ionization on the slope of potential well, i.e., on the ratio of neutral atom mean free pass in the plasma before ionization, λ_l, to the depth of electrical field penetration into plasma, λ_d.

The energy, which is transferred by collisionless way is:

$$P_E = \alpha\Phi_p\Gamma , \qquad (14)$$

where $\alpha=1/(1+\lambda_l/\lambda_d)$, $\lambda_l=V_a/\langle\sigma_e v_e\rangle n_a$, $\lambda_d = (\Phi_p/6\pi e^2 n_e)^{1/2}$.

The energy spent for ion heating is:

$$P_{ih} = P_{eq} + P_E. \qquad (15)$$

The expense of energy through the electronic channel:

$$P_{ek} = P_\varepsilon + P_{eq} + P_E + P_{e\perp} + P_{e\|} + P_{br}, \qquad (16)$$

where: $P_\varepsilon = \varepsilon\Gamma$ - losses for neutral atom excitation and ionization, ε = 70 eV - the energy spent for atom ionization and accompanying this process excitation of neutral gas atoms, P_{eq} and P_E – the power expent for collisional and collisionles ion heating, $P_{e\perp} = 1.3T_e I_{e\perp}$, $P_{e\|} = \Phi_a I_{e\|}$ - losses connected with the transfer of electrons across magnetic field on anode diaphragms and along magnetic field on electrostatic system electrodes of locking-out of magnetic slits, P_{br} - bremsstrahlung losses from plasma.

The power losses through the ion channel are:

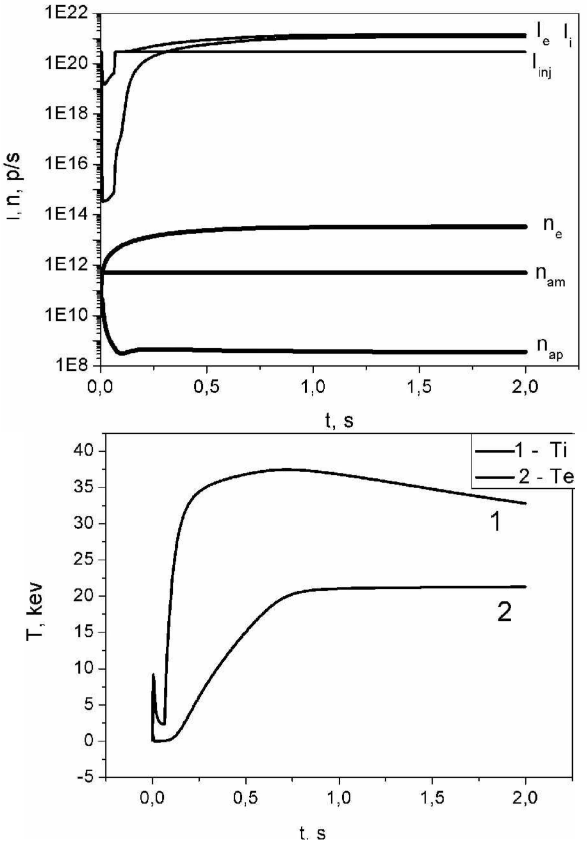
$$P_{ik} = P_i + P_p + P_r , \qquad (17)$$

where $P_i = \Phi_i I_i$ - losses connected with ions leaving the trap through magnetic slits, $P_p = 1.5T_i I_\alpha$ – ion losses connected with thermonuclear reaction, $P_r = T_i\langle\sigma_{i0}v_i\rangle n_{ap}$ – charge exchange losses.

MODELING OF THE OPERATION OF SOURCE OF THERMONUCLEAR NEUTRONS

The source of thermonuclear neutrons is represented a multislit electromagnetic trap with axisymmetric magnetic field geometry. The number of magnetic slits is N = 7. Radius of a ring magnetic slit 0.64 m, the length between axial apertures 4 m. The width of magnetic slit limited by anode diaphragms is $2a_0$ = 0.5 cm. A magnetic field in a ring magnetic slit – B_A = 25 kG, in axial apertures B_{A0} = 50 kG. The electrostatic potential locking-out the magnetic slits is 200 kV.

The modeling of plasma accumulation and heating was carried out in real time. Plasma density $n_{e,i}$ electron and ion temperatures T_e and T_i, plasma potential Φ_p and potential "depression" in a magnetic slit ΔΦ, neutral gas density in plasma n_{ap}, current of electron injection I_e, current of cross $I_{e\perp}$ and longitudinal $I_{e\|}$ electron transfer, ion current in magnetic slits I_i, current α - particles I_a and capacities which are introduced into reactor and spent there, were displayed on the screen of the monitor. The results of modeling are shown in the Figure.



The results of modeling

Plasma parameters achievable in a starting mode depend on the electron injection power and theirs growth rates are determined by amount of neutral gas letting-to. The electron temperature is less than the ion temperature, what is connected with continuing plasma accumulation and an expense of electron channel energy on neutral gas ionization and heating. Besides the electric channel spends some energy for bremsstrahlung and for indemnification of electron losses due to the cross and longitudinal transfer.

The source of thermonuclear neutrons achieves the stationary mode for ~2 seconds with parameters of plasma $n_e = 10^{13} \ldots 10^{14}$ cm^{-3}, $T_e \sim T_i \cong 10^4$ eV. The total neutron yield dependence on magnetic field in 10...50 kGs range is approximated by linear function, and the dependence on the injection current saturates when the current I_e exceeds 2 A. The latter is connected with longitudinal electron diffusion in the velocity space and outflow of them through the external electrostatic barrier with recovering the energy spent for ion acceleration into the external circuit. Actually, the amount of injected electrons intothea trap is determined by the difference between the injection current and the current of longitudinal diffusion.

A very strong dependence of the neutrons yield on the electron injection energy occurs: from ~10^{11} n/s at the energy 50 keV to ~10^{18} n/s with the energy 700 keV. The “power price” of a neutron is $\varepsilon = 10^{-11} \ldots 10^{-13}$ J/n and the expenditure of deuterium - tritium mixture is 5×10^{-4} g/s.

CONCLUSIONS

The modeling of plasma accumulation, heating and confinement in a source of thermonuclear neutrons on the base of multislit electromagnetic trap was provided. The dependences of neutron yield on the current of electronic injection and electrostatic potential locking out magnetic slits are found. In the optimum performance, with electron injection current 5A and with electrostatic potential 200 kV, the stationary state is achieved for the time 2 s from the injection with neutron yield 10^{18} n/s and neutron flux density 10^{14} n/cm^{2}s. The power price of a neutron is 10^{-12} J/s, expenses of the equicomponent gas mixture of deuterium and tritium 5×10^{-4} g/s.

The essential difference of this project from the other projects of neutron sources is the aggregation in one device of the plasma target and the source of high energy ions.

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МОДЕЛИРОВАНИЕ НАКОПЛЕНИЯ, НАГРЕВА И УДЕРЖАНИЯ ПЛАЗМЫ В ИСТОЧНИКЕ ТЕРМОЯДЕРНЫХ НЕЙТРОНОВ

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Подготовлена математическая модель и компьютерная программа для моделирования физических процессов в источнике термоядерных нейтронов. В результате моделирования получены временные зависимости параметров плазмы в пусковом режиме, определены условия выхода на стационар, параметры плазмы в стационарном режиме и выход нейтронов от параметров установки.

МОДЕЛЮВАННЯ НАКОПИЧУВАННЯ, НАГРІВ ТА УТРИМАННЯ ПЛАЗМИ В ДЖЕРЕЛІ ТЕРМОЯДЕРНИХ НЕЙТРОНІВ

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Підготовлена математична модель та комп’ютерна програма для моделювання фізичних процесів в джерелі термоядерних нейтронів. В результаті моделювання були отримані часові залежності параметрів плазми в пусковому режимі, визначені умови виходу на стаціонар, параметри плазми в стаціонарному режимі та вихід нейтронів від параметрів установки.