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MATHEMATICAL MODEL OF PLASMA ACCUMULATION, HEATING AND CONFINEMENT IN A MULTISLIT ELECTROMAGNETIC TRAP.*

O.A.Lavrent'ev
Institute of Plasma Physics National Science Center Kharkiv Institute of Physics and Technology, 310108, Kharkiv, Ukraine, <lavr@ipp.kharkov.ua>, tel 0572 35 64 38

INTRODUCTION

The modern computer technologies play the important role in researches on controlled thermonuclear synthesis. The designing and structure of new experimental devices requires large material expenditures and it lasts 5-10 years. Each following step represents an extrapolation of obtained knowledge on conditions, which can not be executed experimentally on devices of the previous generation. The detail information about plasma behaviour in such conditions can be given only by numerical experiment. It essentially changes requests to works on numerical modeling. Development and analysis of mathematical models of processes in concrete devices with allowance of their geometries, magnetic field configuration and other design features come out on the first place instead of study general plasma properties in the idealized conditions. This purpose takes a main place in development of the concept of the thermonuclear reactor on the basis of a multislit electromagnetic trap.

The mathematical model is created for study of physical processes of plasma accumulation, heating and confinement in a concrete multislit electromagnetic trap "Jupiter 2M". The equations of material and power balance of charged particles in plasma with allowance of the multislit electromagnetic traps features are placed in a basis of a model. These features are : availability of large volume of unmagnetized plasma, strong electrical fields influence on plasma heating and confinement, absence of instabilities and close to classical transfer coefficients.

The nearest purpose is comparison and coordination of a mathematical model with actual experimental results on "Jupiter 2M" device. It achievement will allow to receive the developed picture of physical processes which take place in plasma of a multislit electromagnetic trap, to receive initial data for experiments on plasma accumulation in an increasing magnetic field with use of over barrier electrons injection.

The adjustment of a mathematical model with reference to modeling of plasma processes in the thermonuclear reactor "Elemag" and with reference to receiving of initial data for designing experimental device of the following generation will be made after fulfillment of theoretical works on plasma interaction with electrical and magnetic fields of electromagnetic trap.

A MULTISLIT ELECTROMAGNETIC TRAP "JUPITER 2M"

The mathematical model of plasma accumulation, heating and confinement is developed for concrete experimental device - multislit electromagnetic trap "Jupiter 2M". The trap has axisymmetrical magnetic field geometry formed by coaxial coils of counter inclusion, seven ring magnetic slits by a diameter 0.43 m and two axial holes on extremities. A distance between axial holes (length of a trap) - 1.3 m. Strength of a magnetic field in ring slits $B_A \le 10$ кGs, in axial holes $B_0 = 2B_A$. The configuration of a magnetic field is characterized by a deep magnetic well, so that in central area of a trap r≤0.1 м,|z| ≤0.25 м the strength of magnetic field $B \le 0.05\ B_A$. The ring magnetic slits and axial holes are closed by electrostatic fuses - electrodes with a high negative potential imposed on them. The plasma is created by ionization of neutral gas by electrons injected through axial holes. In ring magnetic slits it is limited by anode electrodes located on a distance of 2à=0.4 cm from each other, and in axial holes by diaphragms by a diameter 2.6 cm. Plasma increases area of a zero magnetic field displacing a weak magnetic field from a central part of a trap. Full volume of plasma on a boundary magnetic surface Vp = 50 l. Square of a boundary surface Sp =1.7 104 cm^2.

THE EQUATIONS OF MATERIAL BALANCE.

The equations of material balance describe dependences of a full amount of electrons Ne and full amount of ions Ni in a trap from time of plasma accumulation.

$$dN_e/dt = I_e/e + \Gamma - N_e/\tau_e \qquad (1)$$

$$dN_i/dt = \Gamma - N_i/\tau_i \qquad (2)$$

Where: **Ie** - current of injection of electrons in a trap; $\Gamma = \langle\sigma_e v_e\rangle n_{ap} N_e$ - amount of full electrons and full amount of ions, arriving in a trap in consequence of neutral gas ionization; $\langle\sigma_e v_e\rangle = 10^{-5}(T_e/E^z_\infty)^{1/2} \exp(-E^z_\infty/T_e)/(E^z_\infty)^{3/2}(6 + T_e/E)$ - velocity of ionization; n_a - density of neutral gas in plasma; τ_e - life time of electrons; τ_i - life time of ions;

The life time of electrons τ_e is determined by transversal (in space of coordinates) and longitudinal (in space of velocities) losses of electrons from a trap.

$$1/\tau_e = 1/\tau_{e\perp} + 1/\tau_{e\parallel}^{(1)} + 1/\tau_{e\parallel}^{(2)} \qquad (3)$$

The stream of a transversal electrons diffusion in a multislit electromagnetic trap with axisymmetrical magnetic field geometry and with allowance of electrons mobility in strong electrical field was calculated in works [1,2]

$N_e/\tau_{e\perp} = [D_{ea}(1+\Phi_p/2T_{e0}) + D_{ei}]\, n_{e0}FR^2$ **(4)**

Where: $D_{ea} = T_e \nu_{ea} / m_e \omega_{ce}^2$, $D_{ei} = T_e \nu_{ei} / m_e \omega_{ce}^2$ - coefficients of electrons diffusions on neutral atoms and plasma ions; Φ_p - potential of plasma (in power units); n_{e0}, T_{e0} - plasma density and temperature of electrons in central area of a trap; **F** - shape factor which is taking into account magnetic field geometry; **R** – radius of a trap on a ring magnetic slit.

The longitudinal losses consist of two parts: electrons leaving central area of unmagnetized plasma, and electrons leaving a diffusion layer, surrounding central area. They leave a trap through magnetic slits, overcoming an external electrostatic barrier. In the first case the adiabatic invariant for charged particles is not saved and calculations of slit losses of electrons were conducted with use of the theory A. Kaye [3]. In the second case the adiabatic invariant is saved, and the electrons are in a magnetic field of mirror geometry, their losses were calculated with use of the theory V. Pastukhov [4].

The value and functional dependence of a longitudinal diffusion stream from area of unmagnetized plasma depends on its density. For low density the value of a stream is limited by a velocity of particles maxwellization in plasma volume and

$N_e/\tau_{e\|}^{(1)}=4(2\pi)^{1/2}e^4\lambda n_{e0}^2V_pm_e^{-1/2}T_{e0}^{-3/2}\exp(-\Phi_e/T_e)$ **(5)**

Where: **Vp** - volume of unmagnetized plasma; Φ_e - height of an electrostatic barrier holding electrons in magnetic slits.

For a high plasma density the value of a stream is determined by ability to handle of ring magnetic slits and axial holes

$N_e/\tau_{e\|}^{(1)} =N4(\pi)^{1/2}cr_pn_{e0}(T_{e0})^{3/2}(B_0/B_A)^{1/2}(eB_A\Phi_{eA}^{1/2})^{-1}\exp(-\Phi_{eA}/T_{e0}) +2(\pi)^{1/2}cr_pn_{e0}(T_{e0})^{3/2} (B_0/B_{A0})^{1/2}(eB_{A0}\Phi_{ec}^{1/2})^{-1}\exp(-\Phi_{ec} /T_{e0})$ **(6)**

Where: **N** - amount of ring magnetic slits; r_p - radius of unmagnetized plasma area; B_A - magnetic field in a ring magnetic slit; B_{A0} - magnetic field in an axial hole $B_0 = [8\pi n_{e0}(T_e + T_i)]^{1/2}$ - magnetic field on a surface dividing plasma and vacuum magnetic field; Φ_e - height of an electrostatic barrier holding electrons of plasma in ring magnetic slits; Φ_{e0} - height of an electrostatic barrier holding electrons of plasma in axial holes (potential - in power units - on cathodes).

From two values of a stream the smaller one is selected. A longitudinal stream from a diffusion layer is calculated under the formula of Pastukhov for mirror magnetic traps.

$N_e/\tau_{e\|}^{(2)} = 4(2\pi)^{1/2}e^4\lambda n_e^2(m_eT_e)^{1/2}\{V_{Dc}[\Phi_{ec}\ln(4B_{A0}/B+2)]^{-1}\exp(-\Phi_{ec}/T_e) +V_{DA}[\Phi_{eA}\ln(4B_{A0}/B+2)]^{-1}\exp(-\Phi_{eA}/T_e)\}$ **(7)**

Where: V_{Dc} - volume of a diffusion layer of a face part of a trap; V_{DA} - volume of a diffusion layer (total) of a central part of a trap.

The transversal transfer of electrons through a magnetic field is the main channel of electrons losses from a trap . The longitudinal diffusion renders essential influence only on a initial stage of plasma accumulation, when the virtual cathode is formed in a trap and Φ_e is close to zero. Φ_e grows in accordance with plasma accumulation and longitudinal losses of electrons decrease exponentially with increasing of Φ_e/T_e .

The ions arrive in a trap in consequence of neutral gas ionization and leave a trap through magnetic ring slits and axial holes, overcoming a potential barrier Φ_i, formed by a negative volumetric charge of electrons. For a low plasma densities (also, as well as for electrons) the stream of ions is limited by velocity of particles maxwellization

$N_i/\tau_i = 4(2\pi)^{1/2} e^4\lambda n_{e0}^2m_i^{-1/2}T_{i0}^{-3/2}V_p\exp(-\Phi_i/T_{i0})$ **(8)**

For high plasma density the value of a stream is limited by ability to handle of magnetic slits. Experimentally installed, that the main channel of losses for ions are the ring magnetic slits. The losses in axial holes make no more than 10 % from total losses of ions. For N of ring magnetic slits

$N_i/\tau_i = \pi NRv_{iT}n_{i0} \int_0^a \exp(-\Phi_i/T_i)da$ **(9)**

The potential barrier for ions $\Phi_i = \Phi_p - \Delta\Phi$ has maximum significance $\Phi_i = \Phi_p$ on edges of ring anode diaphragms bounding a magnetic slit, and reduces to a middle of a magnetic slit because of potential sagging $\Delta\Phi$, caused by a volumetric charge of electrons circulating in a magnetic slot. A stream of electrons in a magnetic slit according to the theory A. Kaye

$F = 2\pi cn_{e0}r_pkT_e(B_0/B_A)^{1/2}/eB_A$ **(10)**

It creates a density of electrons in a magnetic slit

$n_A = 2F/4\pi aRv_e$ **(11)**

And potential

$\Delta\Phi = 2\pi en_Aa^2$ **(12)**

The losses of ions from a trap are agreed on a volumetric charge with losses of electrons. The modification of this equilibrium results in a modification of potential barriers for electrons and ions regenerating infringed equilibrium.

POWER BALANCE.

A power $P_e = I_eU_e$ is entered into a trap by electrons injection through axial holes. It is spent for creation of volumetric charge electrical field, neutral gas excitation and ionization, heating of electrons and ions, power losses connected with charged particles leaving from a trap, recharge, braking and betatron radiation. The equations of power balance describe dependences of full energy-keeping in an electronic component of plasma $W_e = 1.5\ T_eN_e$ and full energy-keeping in an ionic component of plasma $W_i = 1.5\ T_iN_i$ from time of plasma accumulation.

$dW_e/dt = P_e - \Sigma_k P_{ek}$ **(13)**

$$dW_i/dt = P_i - \Sigma_k P_{ik} \qquad (14)$$

Here P_e and P_i entered capacities in electronic and ionic components of plasma, P_{ek} and P_{ik} - channels of power losses.

The power losses by electrons on neutral gas excitation and ionization $P_{e1} = \varepsilon\Gamma$ are calculated from a condition, that each act of ionization is accompanied by excitation (with consequent highlighting) of neutral gas. In aggregate for one act of ionization E=70 eV is spent.

The part of energy from the electron channel is spent for heat of ions. A power $P_{e2} = 1.5(T_e - T_i)N_e/\tau_{eq}$, where $\tau_{eq} = 3m_iT_e^{3/2}/8(2\pi m_e)^{1/2}e^4\lambda n_e$ is transmitted by the Coulomb collisions. The collisionless transfer of energy from electrons to ions is carried out on slopes of a potential well of electrons volumetric charge. The ions, formed in consequence of neutral gas ionization, are accelerated by an electrical field to centre of a potential well. The analysis of ions trajectories has shown, that in conditions of a deep magnetic well the ion which has started from any point, achieves centre, acquiring energy $\Phi(x_{st}) - \Phi_p$. The averaging on plasma volume gives for a power of energy, transmitted to ions, $P_{e3} = \alpha\Phi_p\Gamma$, where α is determined from structures of a potential and neutral gas density in a trap.

Energy on the average T_e on one gone electron and $P_{e4} = W_e/\tau_{e\perp}$ is carried away from plasma in consequence of a transversal diffusion of electrons. During longitudinal diffusion the electrons carry away from plasma energy which is equal to energy of a potential barrier, holding them, Φ_e and so-called overbarrier addition, formed in consequence of electrons maxwellization up to a moment of their arriving into a magnetic slit. Energy Φ_e is carried away from plasma, but it remains in an electrostatic system and can be returned in plasma in consequence of electronic injection. Overbarrier addition of energy is lost irrevocably. The value of overbarrier addition is determined by an equilibrium of a velocity of electrons maxwellization to a velocity of their leaving from a trap through magnetic slits and can vary in limits from 0 to $2T_e$. For a low plasma density $P_{e5} = \Phi_eN_e/\tau_{e\|}^{(1)}$, $P_{e6} = \Phi_eN_e/\tau_{e\|}^{(2)}$. For a high plasma density $P_{e5} = (\Phi e + 3T_e)\, N_e/\tau_{e\|}^{(1)}$, $P_{e6} = (\Phi e + 3T_e)\, N_e/\tau_{e\|}^{(2)}$.

The heat of ions is carried out by collisional and collisionless energy transfer from an electronic component of plasma $P_i = P_{e2} + P_{e3}$. The main channel of losses is the exit of ions through ring magnetic slits and axial holes with overcoming of a potential barrier for ions Φ_i. For a low plasma density (8) a potential depression of a volumetric charge in magnetic slits are close to zero. Overcoming a potential barrier the ion carries away from plasma energy $\Phi i \approx \Phi_p$, but this energy is not lost, and passes in potential energy of an electrical field of a volumetric charge and can be again returned in plasma. The power $P_{i1} = \Phi_pN_i/\tau_i$ is lost from plasma. For a high plasma density (9) $\Phi_i = \Phi p - \Delta\Phi$ a power also is lost

$$P_{i1} = 2\pi NRv_{iT}n_{i0} \int_0^a (\Phi_i + 3T_i)\exp(-\Phi_i/T_i)da \qquad (15)$$

Power losses on recharge:

$$P_{i2} = T_i \langle \sigma_{10}\, v_{iT} \rangle n_{ap}N_i \qquad (16)$$

Here σ_{10}- recharge section of an ion of hydrogen in hydrogen, n_{0p} - density of hydrogen in plasma.

BALANCE OF NEUTRAL GAS

It is experimentally installed, that during plasma accumulation in a multislit electromagnetic trap "Jupiter 2M" up to 10^{18} particles of neutral gas are beaten out from walls of a magnetic system. These particles render essential influence on processes of plasma accumulation, heating and confinement in a trap. The equations considered below describe dependences of a neutral gas density n in plasma from time of it accumulation.

$$V_pdn_{ap}/dt = 0.25v_a\, S_p(n_{am} - n_{ap}) - \Gamma \qquad (17)$$

$$V_pdn_{am}/dt = 0.25v_a[S_m(n_{ac} - n_{am}) + S_p(n_{ap} - n_{am})] + q \qquad (18)$$

$$V_pdn_{ac}/dt = 0.25v_a\, S_m(n_{am} - n_{ac}) - vn_{ac} + \Gamma \qquad (19)$$

The first equation describes receipt of neutral gas from a cavity of a magnetic system V in plasma volume V and its cost for plasma formation. Plasma volume is separated from a cavity of a magnetic system by a boundary surface S, transparent for neutral gas, but not transparent for charged particles. The neutral gas, circulating through a boundary surface with a velocity $v_a = (8kT_a/\pi m_{H2})^{1/2}$ is ionized, being accumulated as plasma in plasma volume. The ions leave plasma only through magnetic slits, i.e. are removed for limits of a magnetic system.

The second equation describes receipt q of neutral molecules in consequence of it knocking out from walls of a magnetic system, its coming in the vacuum chamber through axial holes and slits in a magnetic system by total square S_m, receipt in plasma volume through a surface S_p with consequent ionization.

The third equation describes process of neutral gas evacuation from the vacuum chamber of device by pumps with productivity V.

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