THE THEORY OF PLASMA HEATING AND CONFINEMENT IN A MULTISLIT ELECTROMAGNETIC TRAP

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In the article the circle of questions connected to plasma heating and confinement in a multislit electromagnetic trap with axisymmetric geometry of a magnetic field is considered: plasma formation and heated by electrons injection, electrons cross transfer in a space of coordinates and in a space of speeds, ions losses through ring magnetic slits and axial holes, recuperation and direct transformation of α - particles kinetic energy in electrical one. The accounts of the basic characteristics thermonuclear reactor "Elemag" are offered.

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ELECTRONS INJECTION

Plasma in an electromagnetic trap is created and heated by the most simple way - with the help of electron injection. Electrons are injected in a trap through magnetic slits (in traps with axisymmetric magnetic field geometry - through axial holes). They ionize neutral gas directly in volume of a trap. The heating of the formed plasma by energy transfer from high-energy electrons of injection to plasma particles is carried out.

The current of electron injection cannot be arbitrary large. It is limited by a volumetric charge of electrons already accumulated in a trap. This current is equal to a flow of electrons, leaving a trap as a result of cross transfer through a magnetic field minus a ion flow which are carrying away a positive charge from a trap through magnetic slits

$$I_e = I_{e\perp} - I_i \qquad (1)$$

The maintenance of "fulfilled" electrons exit on the channel of classical difusion is indispensable condition of successful plasma accumulation and heating in electromagnetic trap by electron injection is

$$I_{e\perp} \leq I_{e\perp}^{cl} \qquad (2)$$

At default of this condition the quantity of electrons acting in plasma exceeds throughput of the Coulomb diffusion channel. Therefore plasma searches for an exit from the created situation: by interruption of electrons injection by volumetric charge potential with the subsequent downturn of electrons temperature and reduction of ionization speed, or by swing of HF-fluctuations with formation of the abnormal electrons transfer channel. Attempts to increase speed of plasma accumulation by increase of neutral gas submission have not crowned by success - in this mode smooth monotonous plasma accumulation interrupts by failures of density. The forced density accumulation in an electromagnetic trap ATOLL (IAE) has resulted in abnormal large electrons losses through a magnetic field exceeding classical on two orders.

Electrons are injected in a trap with energy Φ_a, and leave a trap with average energy $(3/2)T_e$. The capacity which will be entered into plasma

$$W_e = (I_{ek}/e)(\Phi_a - 1.5T_e) \leq (I_{e\perp}^{cl} - I_i)(\Phi_a - 1.5T_e)/e \qquad (3)$$

This capacity is spent on neutral gas excitation and ionization, plasma heating, losses of the energy which is carried away by charged particles from a trap, on radiation, on recharge etc.

COLLISIONAL ENERGY TRANSFER FROM ELECTRONS TO IONS

Electrons injected in a trap with energy $E_1 = \Phi_a$ transfer kinetic energy to plasma particles in result of Coulomb collisions. According to [1] efficiency of this process for plasma electrons

$$dE_1/dt = 4\pi e^4 L n_e/(2m_e)^{1/2} E_1^{1/2} \qquad (4)$$

for ions

$$dE_1/dt = 4\pi z_i^2 e^4 L n_e (m_e/m_i)\,/(2m_e)^{1/2} E_1^{1/2} \qquad (5)$$

It is in m_e/m_i times less, therefore collisional ions heating passes two stages: heating of an electron plasma component by a primary beam of injected electrons and temperatures alignment of plasma electrons and ions. From the equation (4), carrying out integration, we shall find time of energy transfer from electrons of injection to plasma electrons

$$\tau = E_1^{3/2}(2m_e)^{1/2}/6\pi e^4 L n_e \qquad (6)$$

The estimation shows, that this time is much less than time of plasma accumulation in a trap, i.e. all electrons injected in a trap have time to transfer the energy to plasma electrons during process of plasma accumulation.

Further heated electrons exchange energy with ions. Time of temperature alignment

$$\tau_{eq} = 3m_i T_e^{3/2}/8(2\pi n_e)^{1/2} e^4 L n_e \qquad (7)$$

exceeds 0.1 sec. for plasma parameters of an electromagnetic trap "Jupiter 2M", i.e. is much greater then duration of a magnetic field plateau. Collisional heating of plasma ions at electron injection is possible only in installations with long plasma accumulation, such, as "Jupiter 2T", "Elemag".

COLLISIONLESS ENERGY TRANSFER FROM ELECTRONS TO IONS

Collisionless plasma heating by the way of acceleration of electrons and ions, formed at neutral gas ionization,by electrical field of a volumetric charge is realized in electromagnetic trap. The efficiency of ions heating will depend on a location of a point on a slope of a potential well, where there was an ionization. The location of a point is determined by the relation of depth of electrical field penetration into plasma

$$\lambda_d = (\Phi_p/6\pi e^2 n_e)^{1/2} \qquad (8)$$

to length of neutral atoms run in plasma before ionization

$$\lambda = v_a/<\sigma_e v_e>n_e \qquad (9)$$

$v_a = (8kT_a/\pi m_a)^{1/2}$ - speed of neutral atoms. With growth of plasma density this relation is increased as $n^{1/2}$. Energy inserted in ion plasma component at the bottom of a potential well

$$W_{ei} = \Phi_p/(1 + \lambda/\lambda_d) \qquad (10)$$

achieves value $W_{ei} \sim 0.4\Phi_p$ at plasma density $n_e = 1*10^{14}$ cm^{-3}, other 60 % of energy is inserted in an electron component. Capacity of collisionless ions heating

$$P_{ei} = \alpha\Phi_p\Gamma \qquad (11)$$

where $\alpha = 1/(1 + \lambda/\lambda_d)$ - factor of collisionless energy transfer, which is determined from structures of volumetric charge potential and neutral gas density in plasma, $\Gamma = <\sigma_e v_e>n_{ap}N_e$ - amount of the ionization acts per second, N_e - complete quantity of electrons. For parameters of electromagnetic trap "Jupiter 2M" $\alpha = 0.1$.

CHARGED PARTICLES LOSSES FROM A TRAP WITH ACUT ANGLED MAGNETIC FIELD GEOMETRY

The electromagnetic traps have acut angled magnetic field geometry formed by conductors or coils with alternating polarity of a current inclusion. The magnetic slits are closed by electrostatic fuses - electrodes with high negative potential, imposed on them. Electrons injected through magnetic slits create a negative volumetric charge and potential well for ions confinement in a trap. The electrodes of electrostatic system, situated at the external part, do not hamper to free moving of electrons in magnetic slits - electrons flow from plasma into magnetic slit of an electromagnetic trap has the same value, as in a acut angled trap, only, being reflected by an external electrical field, it comes back in a trap practically without losses. It allows to use results of theoretical accounts of charged particles losses in magnetic slits executed for acut-angled traps.

The most complete theoretical account of charged particles losses in a trap with acut-angled magnetic field geometry is executed in A. Kaye article [2]. He used the Vlasov equations for collisionless neutral plasma with density n and temperature T. The Vlasov equation is satisfied with any function of integrals of movement. Energy of particle were chosen to be the one of such function(without the calculation of an electrical field)

$$H = m/2(v_r^2 + v_\theta^2 + v_z^2)$$

The moment of movement quantity

$$P_\theta = mrv_\theta + erA_\theta/c$$

And adiabatic invariant, offered by Grossman [3]

$$\mu = \oint P_r dr$$

Flow of any quantity $Q(H,P_\theta, \mu)$ through any r - θ plane can be found from the equation

$$F(Q) = 2\pi\int_0^\infty rdr\iiint Qfdv_r dv_\theta dv_z$$

The limits of integration are determined by area of phase space, accessible to particles.

Losses of the charged particles in a ring magnetic slit

$$F_1 = 2\pi cnRkT(B_0/B_A)^{1/2}/eB_A \qquad (12)$$

and axial hole

$$F_2 = \pi cnRkT(B_0/B_{A0})^{1/2}/eB_{A0} \qquad (13)$$

Where R - radius of a trap on a ring magnetic slit, B_A - magnetic field in a ring magnetic slit, B_{A0} - magnetic field in an axial hole, B/B_0 - the mirror relation.

The formulas A. Kaye allow determine value of electrons flows, circulating in magnetic slits and axial holes of an electromagnetic trap and very important characteristic - potential depth of a volumetric charge (potentials of electrons volumetric charge in a ring magnetic slit and axial hole).

RING MAGNETIC SLIT

The flow of electrons $F = 2F_1$, circulating in a ring magnetic slit, creates average on section density

$$n_A = F_1/2\pi Ra_0v_e \qquad (14)$$

and potential of a volumetric charge at the centre of a slit

$$(\Delta\Phi)_m = kea_0F_1/Rv_e \qquad (15)$$

Here R - radius of a trap on a ring magnetic slit, $2a_0$ – width of anode diaphragm, limiting plasma in a ring magnetic slit, v_e- electrons speed, which is determined by electron temperature in plasma and additional acceleration of electrons by an electrical field of a potential ion barrier Φ_i. Factor k takes into account geometry of electrons flow. Limits of its change are from k = 1 for uniform distribution of electrons flow on section of a slit up to k = 2, if width of electrons flow is much less than width of anode diaphragm.

Potential depth

$$\Delta\Phi = [1-(\Delta\Phi)_m a^2/a_0] \qquad (16)$$

has maximum value at the center of a magnetic slit at a = 0 and falls down up to 0 at edges of anode diaphragm at a = a_0. The ions flow in a ring magnetic slit is determined by the A. Kaye formula with taking into account electrostatic confinement of ions by a potential barrier

$$\Phi_i = \Phi_p - \Delta\Phi \qquad (17)$$

On the initial stage of plasma accumulation in an electromagnetic trap, when plasma density is still small, $\Delta\Phi \ll \Phi_p$, ions flow in a ring magnetic slit

$$I_i = F_1\exp(-\Phi_p/T_i) \qquad (18)$$

There is an additional multiplier in formula (18) which is taking into account increase of ions losses as a result of potential barrier Φ_i reduction at increase of plasma density and potential depth of volumetric charge. If $(\Delta\Phi)_m < \Phi_p$, fig. 1a,

$$I_i = F_1\exp(-\Phi_p/T_i)\frac{1}{a_0}\int_0^{a_0}\exp(\Delta\Phi/T_i)da \qquad (19)$$

At $(\Delta\Phi)_m > \Phi_p$, the fig. 1b, the neutral channel with width $2a_1$ is formed in the middle of a slit, where $\Phi_i \equiv 0$ and the ions leave a trap, not feeling influence of a detaining electrical field,

$$I_i = F_1\exp(-\Phi_p/T_i)\frac{1}{a_0}[a_1 + \int_{a_1}^{a_0}\exp(\Delta\Phi/T_i)da] \qquad (20)$$

Where a_1 is from the equation

$$a_1 = \{1-\Phi_p/(\Delta\Phi)_m\}^{1/2}a_0 \qquad (21)$$

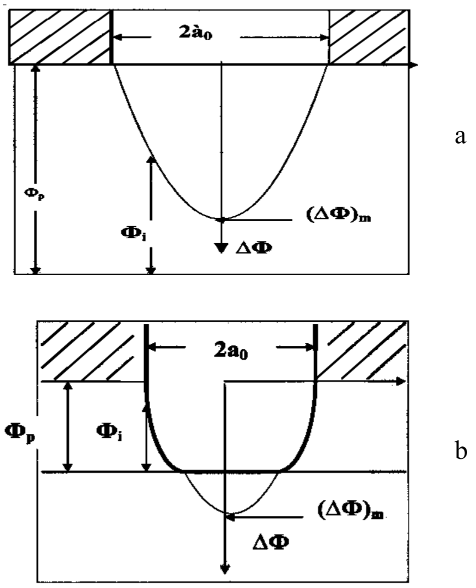

Fig.1.

For parameters of a multislit electromagnetic trap "Jupiter 2M" $n_e = 1*10^{12}$ cm^{-3}, T_e = 100 eV, T_i = 30 eV, B_A = 5000 Gs, Φ_p =180 V, potential depth in a ring magnetic slit Φ = 83.5 V (к=1.5), ions flow through a slit I_i = 82 ma, that is close to experimentally observable values.

AXIAL HOLES

The axial holes occupy the special place in researches of electromagnetic traps with axialsymmetric magnetic field geometry. The magnetic flow from a ring magnetic slit passes an axial hole, being condensed in a beam of circular section

$$r_0=(a_0R)^{1/2} \qquad (22)$$

At such sizes potential depth in an axial hole

$$(\Delta\, \Phi)_{m_0} = 2eF_2/v_e \qquad (23)$$

exceeds plasma potential in many times and the electrostatic ions confinement by a longitudinal electrical field is absent. It seems, that axial holes should become the basic channel of ions losses from a trap under the given conditions. However experimental researches have shown, that the basic channel of ions losses are the ring magnetic slits, the losses in axial holes are lower almost on the order.

The reason of low ions losses into axial holes is the additional forces, arising at plasma interaction with crossed electrical and magnetic fields. Causing drift rotation of the charged particle around of an symmetry axis of a magnetic field, they result in occurrence of centrifugal force,which push a particle along a force line of a magnetic field in a direction from an axial hole to a ring slit. Besides that electrical field increases cross speed and magnetic moment of the charged particle. Additional force of braking, which is proportional to cross speed increase in an electrical field, arises as a result of interaction with magnetic field increasing along magnetic tube. Potential of these forces

$$\Phi_s = 8.18 m_i c^2 \rho^2 (\Delta\, \Phi)_{m_0}{}^2\, (B_{A0}/B_z - 1)/e\rho_0{}^4 B_{A0}{}^2 \qquad (24)$$

where ρ - current coordinate in an axial hole, ρ_0 - radius of an axial hole, B_z - magnetic field on an axis. Potential Φ_s acts only on ion plasma component. For electrons its action is in m_e/m_i times weaker. A flow of ions through an axial hole

$$I_{i0} = F_2 \frac{1}{\rho_0} \int_0^{\rho_0} \exp(-\Phi_s/T_i)d\rho \qquad (25)$$

The ions flow, calculated on this data, into axial hole I_i = 48 мA, that is less than ions losses through one ring slit.

CONCLUSIONS

Creation of the theory of plasma heating with the help of electrons injection, theoretical accounts and experimental measurements of ions losses in ring magnetic slits and axial holes are the main results of work. It is established, that collisional heating of plasma ions is possible only for installations with a stationary magnetic field. Collisionless ions heating as a result of their acceleration by electrical field of a volumetric electrons charge is carried out for installations with a pulse magnetic field. The efficiency of such heating grows with increase of plasma density and for parameters of the "Jupiter 2M" installation is about 10 % from plasma potential, i.e. on the average ions get such energy at the bottom of potential hole. The results of theoretical account and numerical modeling of ions losses in ring magnetic slits and axial holes of an electromagnetic trap "Jupiter 2M" will be satisfactorily coordinated with results of experimental measurements. The direct experiments confirm small ion losses in axial holes in comparison with losses in ring magnetic slits.

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ТЕОРІЯ НАГРІВУ ТА УТРИМАННЯ ПЛАЗМИ В БАГАТОЩІЛИННІЙ ЕЛЕКТРОМАГНІТНІЙ ПАСТЦІ

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В статті розглядається коло питаннь, пов’язаних з нагрівом та утриманням плазми в багатощілинній електромагнітній пастці з осесиметричною геометрією магнітного поля: створення і нагрів плазми з допомогою електронної інжекції; перенос електронів в просторі координат і просторі швидкостей; втрати іонів через кільцеві магнітні щілини та осьові отвори, рекуперація і безпосереднє перетворення кінетичної енергії α-часток в електричну. Приводяться розрахунки основних характеристик термоядерного реактору «Елемаг».

ТЕОРИЯ НАГРЕВА И УДЕРЖАНИЯ ПЛАЗМЫ В МНОГОЩЕЛЕВОЙ ЭЛЕКТРОМАГНИТНОЙ ЛОВУШКЕ

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В статье рассматривается круг вопросов, связанных с нагревом и удержанием плазмы в многощелевой электромагнитной ловушке с осесимметричной геометрией магнитного поля: образование и нагрев плазмы при помощи электронной инжекции; перенос электронов в пространстве координат и в пространстве скоростей; потери ионов через кольцевые магнитные щели и осевые отверстия; рекуперация и непосредственное преобразование кинетической энергии α-частиц в электрическую. Приводятся расчеты основных характеристик термоядерного реактора «Элемаг».