SUPPRESSION OF GASDYNAMIC TRAP LOSSES BY COMBINED ELECTRIC AND MAGNETIC FIELDS

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In the article the methods of significant reduction of end losses from the gasdynamic trap based on application of combined electrical and magnetic fields are described: with the help of one-slit electromagnetic traps located on the ends of the central solenoid and with the help of a magnetic grid, placed in area end expanders. Expected reduction of the tritium consumption with $2.16*10^{-3}$ up to 10^{-5} g/s.

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INTRODUCTION

Large losses of particles and energy occur in a gasdynamic trap (GDT)[1]. The plasma flow through the axial holes cannot be small. It executes the important function of hydrodynamic instability stabilization in the trap. Though creation of a thermonuclear reactor based on a GDT is in principle possible, its length must be several km because of end losses, and the required neutral beam injection power amounts to several GW [2].

The option of using a GDT as the target plasma of a two-component source of thermonuclear neutrons is most attractive [3]. A neutron source does not have to provide positive energy gain ($Q > 1$). The more important characteristics are the neutron flux, the expenditure of tritium in relative to the neutron yield, and engineering simplicity. The GDT has unique properties from this point of view.

In the GDT-NS project [4] a relatively cold deuterium target with density $n_D = 2*10^{14}$ cm^{-3}, electron temperature $T_e = 1.1$ keV and ion temperature $T_i = 0.3$ keV is confined by a longitudinal magnetic field $B_0 = 1.8$ T with mirror magnetic field $B_m = 26$ T (the mirror ratio $R = B_m/B_0 = 14.44$) with a gasdynamic trap regime in an axially symmetric mirror cell with length L_0 =10m and diameter 0.4 m. Beams of 94 keV neutral tritium atoms (T°) with equivalent current 69 A are injected into the plasma target at an angle of 45° relative to the axis. The fast triton pathlength is hundreds of times larger than the mirror cell length. The ions are confined adiabatically, oscillating between reflection points and gradually slowing down. Neutrons are generated by collisions of tritons and plasma target deuterons. With a significant excess of triton energy E_T over T_e the slowing down of fast tritons by electrons occurs much faster than scattering on deuterons, so the angular width of the triton distribution remains small down to low energies. Owing to small angular width of the distribution function the triton density near their turning points is considerably higher than their density in the homogeneous part of magnetic field, so the neutron flux is much higher near the turning points. A beam of 80 keV deuterium atoms (D°) with equivalent current 10^6 A is injected into the plasma to maintain the particle and energy balance. The neutron source strength would be 10^{18} n/s and the neutron flux would be 10^{14} n/cm^{2}s with an expenditure of tritium $2.16*10^{-3}$ g/s. The disadvantages of this GDT neutron source are the comparatively high energy input per neutron $\varepsilon_n=1.5*10^{-11}$ J/n (without taking into account a capacity of magnetic field source) and the low efficiency of tritium utilization: $\eta_T = M_{(DT)}/M_{inj} = 0.23\%$. These defects are caused by the large end losses. The longitudinal plasma losses from a GDT could be reduced approximately factor two by the addition of an additional mirror cell on each end of the facility. The length of mirror trap must satisfy the condition of hydrodynamic plasma confinement [5]. However the additional mirror cells complicate the design and could reduce the β limit in the central solenoid.

A method for significant reduction of end losses of particles and energy from a GDT, based on plasma confinement by combined electric and magnetic fields [6], is described below. To make this confinement effective it is necessary to expand the magnetic flux emerging from the end holes of the GDT into thin flat layers or ring layers, using appropriate magnetic field shaping coils. Such configuration can be formed by coils with counter-flowing currents. The magnetic slits would be plugged by external electrodes at high negative voltages, which would retard the flow of electrons emerging from the plasma. The transverse electron flow would be impeded by the magnetic field, and their longitudinal flow, by the electric field. The ion component of the plasma could be confined by placing the magnetic grid at a positive voltage relative to the axial holes.

Two variants of combined plasma confinement in the GDT are considered:

* with the help of single-slit (ring cusp) electromagnetic traps (EMT) located at the ends of the central solenoid.
* with the help of magnetic grids placed in the expansion regions

EXPANDER WITH A MAGNETIC GRID

In the GDT-NS installation a plasma target of diameter $2r_0 = 0.4$m is confined by the central solenoid longitudinal magnetic field Bo = 1.8 T. The magnetic flux

$$\Phi = \pi r_0^2 B_0 = 0.226 \text{ T m}^2 \quad (1)$$

is compressed in the axial holes up to a diameter $2r_m = 0.1052$ m, and then diverges in the expander to a diameter $2r_{ex} = 4$ m, so that the magnetic field $B_{ex} = 1.78*10^{-2}$ T at the outer wall surface. Flows of plasma electrons and ions from the axial holes and their energy losses can be determined using the results of calculations [7]:

$$I_i = q_i S_m = \pi r_m^2 n_0 (T_i/2\pi m_i)^{1/2} F_1(T_e/T_i) \quad (2)$$

$$I_e = q_e S_m = \pi r_m^2 n_0 (T_e/2\pi m_e)^{1/2} \exp(-U_w)\, F_2 (T_e/T_i) \quad (3)$$

$$P_i = Q_i S_m = \pi r_m^2\ \text{æ}_i\ q_i T_i \qquad (4)$$

$$P_e = Q_e S_m = \pi r_m^2\ \text{æ}_e\ q_e T_e \qquad (5)$$

Here $U_w = e\Phi_w/T_e$ - electrical potential. Its difference between edge of the mirror and the end wall of expander is arranged to ensure on equality of electron and ion flows onto the wall, $q_e = q_i$. For $T_e/T_i = 3.67$ $F_1(T_e/T_i) = 2.62$, $\text{æ}_i = 1.47$, $\text{æ}_e = 6.86$, $q_e = q_i = 2.5*10^{21}$ $1/cm^2s$, $eq_iS_m = 34.9$ kA, $Q_iS_m = 15.4$ MW, $Q_eS_m = 263$ MW, $\tau_p = 5.75*10^{-4}$ s, $\tau_E = 10^{-4}$ s *.

Excitation of Langmuir fluctuations by an electron beam instability in the expander and scattering of flying electrons on these fluctuations can lead to some reduction of electron energy losses [8]. But even reduction of these losses up to the level of the ion losses doesn't solve the problem with end walls in the GDT. In the GDT - NS project the power input from the T° and D° beams will reach 15 MW.

The scheme of the expander with a magnetic grid is indicated in fig. 1. The magnetic grid represents a system of co-axial coils with alternating directions of current flow. The surface of coils is covered by anode diaphragms, isolated from the coil casings. The diaphragms are biased to a positive potential, which creates a potential barrier to reflect the ions flowing out from axial aperture. The electrons flowing out through the slits between the magnetic grid coils are reflected by electrostatic electrodes based at high negative potentials.

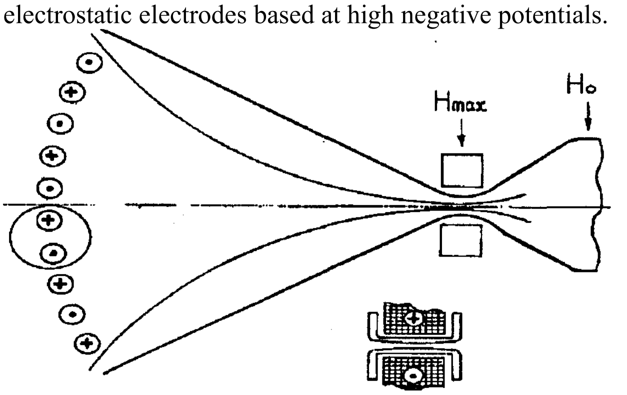

Fig.1. Scheme of the expander with a magnetic grid

The electrostatic system of magnetic slit consists of three electrodes: a central electrode, reflecting the flow of electrons, and two lateral ones, located in shadow of anode diaphragms. A higher negative potential is imposed on them for suppression of the secondary electron emission from central electrode. The magnetic field direction in the magnetic grid alternates from one slit to the next, as shown in Figure 2. In some slits (designated "even") the direction is the same as that in the expander, and in the other slits (designated "odd") the direction is opposite to that in the expander. The magnetic grid coil current is chosen to match the magnetic flux Φ from the axial hole with the total flux through the "even" magnetic slits. The total area occupied by the even slits is

$$S_{sl} = 2\pi a l_{ex}[\sin(3b/2l_{ex}) + \sum_{k=1}^{2m-1} \sin(2kb/l_{ex})] \qquad (6)$$

with a concentric arrangement of 2m magnetic slits of width 2a on the surface of the back wall of the expander, with distance b between neighboring slits. Choosing 2m = 20, a = 0.005 m, b = 0.1 m we obtain $S_{sl} = 0.34$ m^2. The magnetic field in the even magnetic slits will be increased by $\Delta B = \Phi/Ssl = 0.648$ T, however it will be decreased in odd slits from the value of a magnetic field in expander $B_{ex} = 0.0178$ T. The results of calculation of magnetic field geometry in the expander with a magnetic grid for a current in the coils I_e=500kA are indicated in fig. 2. With this current the magnetic flux of the expander is inscribed into the sizes of magnetic anode slits. The magnetic field in the even slits is B_{ev}= 3.6T and in the odd slits: B_{od} = 3.0T.

The flow of electrons from the axial hole of the GDT is numerically equal to the flow of ions. The electron density in the area of the even magnetic slits is

$$n_A = 2I_e/\ S_{sl} v_{Te} = 9*10^{10}\ cm^{-3} \qquad (7)$$

and the resulting space charge potential is

$$\Delta U = 2\pi e n_A a^2 = 5.09\ kV \qquad (8)$$

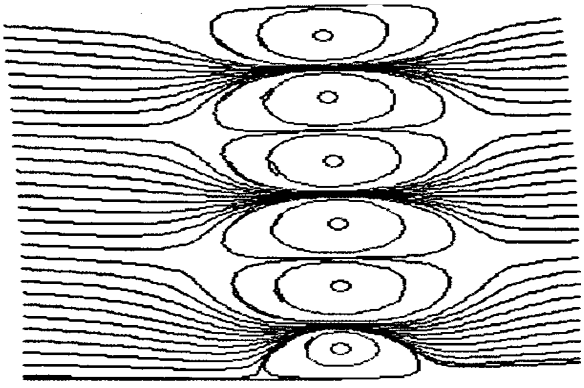

Fig. 2. Magnetic field geometry of the expander with a magnetic grid

Taking into account the maxwellian particle distributions, the potential barriers for their reflection should exceed the temperatures by 5-7 times. From here we obtain the required potentials: $U_A = U_i + \Delta U \approx 8$ kV - positive potential, enclosed to anode diaphragms and reflecting ions; $U_k = -U_A + U_e \approx -15$ kV - negative potential on electrodes, reflecting electrons. Certainly, these values should be accordingly increased with increasing electron and ion temperature of the plasma target. The magnetic grid reflects flows of electrons and ions, returning them back to the central cell, and thus reducing the end losses of particles and energy. This reflection does not violate the conditions for stabilization of hydrodynamic instabilities, because the positive contribution of plasma in the expander is kept in the Rosenbluth - Longmire stability integral.

As to stabilization of plasma instabilities by the conducting end walls of the expander, the experiments with sectioning of the end faces have not revealed any

[The plasma radius in the central solenoid is chosen proceeding from the geometrical size of the chamber. If the plasma cross section is limited by diaphragms in the axial apertures, the longitudinal losses will be reduced, but cross-field losses on the axial diaphragms will increase.]*

influence of sectioning on the plasma loss processes [9]. Besides that, the magnetic grid does not completely close the ends of the plasma. The plasma flowing from the target plasma boundary layer onto the conducting diaphragm may be adjusted for "pumping" the plasma target. This diaphragm is located outside the magnetic grid.

An increase of target plasma temperature at constant magnetic field increases the value of β, and consequently it increases the danger of the ballooning mode instability. However, magnetic field of 1.8 T keeps $\beta = 0.5$ (which is less than $\beta_{er} = 0{,}7 - 0.8$) even for target plasma parameters of $n_{e,i} = 2*10^{14}$ cm^{-3}, $T_{e,i} = 10$ keV.

Rotation of plasma around axis of symmetry, caused by radial electrical field, exerts an unfavorable influence on hydrodynamic stability. The electric field arising in the trap as a consequence of the faster electron escape has a value $\approx T_e/er_0$. The velocity of the electric drift in this field is $v_d = cT_e/er_0B_0$. For a plasma density decreasing with radius the centrifugal acceleration v_d^2/r_0 makes the "floating up" of heavier flutes from internal areas of a plasma energetically profitable. Therefore the plasma rotation is important destabilizing effect and it requires a significant increase of the safety factor provided by the expander. In a GDT with a magnetic grid, one can control the plasma potential by varying the potentials on the anode diaphragms and retarding electrodes. The applied potentials can be varied experimentally to maintain stability and optimize the plasma parameters.

EXPANDER WITH SINGLE-SLIT ELECTROMAGNETIC TRAP

There are also proposals to use ring cusps at the ends of a GDT [10,11]. The cusps would provide a large margin of stability. If the ring cusp gap and point cusp hole on the axis were plugged by electrostatic mirrors, then MHD stability could be ensured and the end losses of particles and energy could also be reduced. The scheme of a ring-cusp electromagnetic trap (EMT) at the end of a GDT is shown in Figure 3.

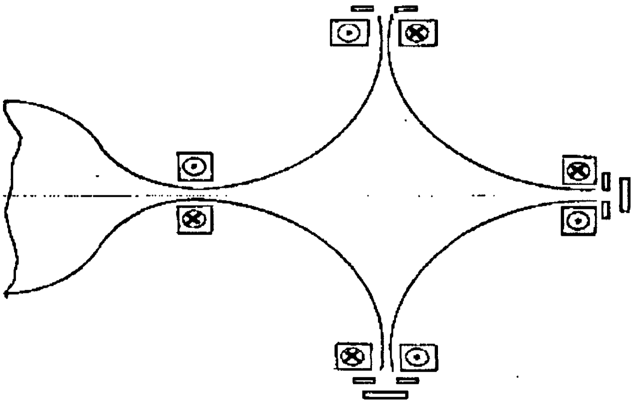

Fig. 3. A ring cusp electromagnetic trap at the end of a GDT

The GDT mirror coil also serves as a mirror of the EMT, and it connects the GDT target plasma target with the EMT plasma. The magnetic flux Φ emerging from the GDT axial hole passes through the left half of the ring cusp, and only part of this flux enters the anode diaphragm. The rest of the flux, coming from the plasma target surface layer, is removed by a special plasma receiver (not shown). Thus impurities, fusion reaction products, and unused deuterons and tritons can be removed by this "pumping" effect, similar to a scrape-off layer and divertor. The width of the diverted plasma layer can be adjusted by changing the magnetic field in the ring cusp (or with the help of additional coils, which divert the outer plasma layer into a receiver). For a ring cusp radius R = 2m and magnetic field $B_A = 4$T the magnetic flux Φ passes through an anode slit in a layer with thickness:

$$a = \Phi/2\pi RB_A = 0.45 \text{ cm} \qquad (9)$$

The same parameters of plasma as in the plasma target (i.e. $n = 2*10^{14}$ cm^{-3}, $T_e = 1.1$keV, $T_i = 0.3$ keV) are established by the plasma flowing from the GDT plasma target into the EMT and back. The problem of GDT end-loss reduction is thus linked to confinement of the plasma in a single-slit EMT.

The main channel of electron losses is their diffusion across magnetic field in the EMT. According to theoretical calculations [12] (confirmed by experiments on a single-slit EMT):

$$I_{e\perp} = \pi R^2 D_{ei} n_{e0} a = 2.82*10^{19} \text{ 1/s } (=4.5 \text{ A}) \qquad (10)$$

that is many times less than diffusion losses of electrons from the plasma target in the GDT. The efficiency of ion confinement in the trap depends on height of potential barrier U_i. It is determined by the potential difference between the main plasma in the EMT and the space-charge potential in the cusp gap, $U_p - \Delta U$. We can find the flow of electrons into the ring cusp slit using theoretical calculation [13].

$$F = 2\pi c n_e r_p k T_e (B_0/B_A)^{1/2} / eB_A = 1.68*10^{22} \text{ 1/s} \qquad (11)$$

where $B_b = [8\pi n(T_e + T_i)]^{1/2} = 0.34$ T, $r_p = 0.17$ m is the radius, where $B = B_b$. The flowing electron density in the ring cusp slit is

$$n_A = 2F/\, 4\pi aRv_e = 9.14*10^9 \text{ cm}^{-3} \qquad (12)$$

The space charge potential depression in the slit is $\Delta U = 2\pi ena^2 = 1.67$ kV. The ion flow into the ring cusp slit $I_i = F\exp(-eUi/Ti)$ is determined by the balance of charged particles entering into the trap and leaving it. If electron injection is increased, then the potential well depth and potential barrier confining ions are increased also, and the ion outflow decreases, restoring the balance. If the potential well depth decreased, then the flow of ions could increase. The balance is reached via redistribution of the potential difference applied to the retarding electrodes, between the electron and ion potential barriers: $U_{AC} = U_e + U_i + \Delta U$. The suppression of velocity-space diffusion losses of electrons and ions becomes effective at: $U_{AK} \geq 15$ kV for the target plasma parameters mentioned above. An increase of plasma target temperature to $T_{e,i} = 10$ keV would require an increase of magnetic field in the ring cusp slit to $B_A = 6$T and applied potential to $U_{AC} = 100$ kV.

The suppression of end faces losses could facilitate GDT neutron source operation with a 50% deuterium-tritium mixture. Initially the target plasma would be created via gas ionization by high energy electrons injected through the magnetic slits. Injection of spiral beams [14,15] appears to be rather effective when single-slit EMTs are used as the anchors of GDT.

Further increase of target plasma parameters would be accomplished by injection of equal component (T° -50%, D° -50%) neutral beams with equivalent currents 69.1 and 106.2 A. The neutron yield and flux would be increased by about 25% (at the same target parameters). Now the unreacted deuterons and tritons would be removed from the trap in a gas mixture with roughly equal deuterium and tritium components. This gas could be recycled into neutron source after removing fusion reaction products and impurities. Thus the tritium expenditure could be reduced from $2.1*10^{-3}$ g/s to 10^{-5} g/s.

CONCLUSION

As a neutron source for testing thermonuclear reactor materials the GDT has two clear advantages: suppression of MHD-instabilities with an axially symmetric magnetic field and increased plasma density near the turning points of the injected tritium beams, which provides a neutron flux in the sample irradiation region. The axial symmetry of the magnetic field facilitates electrostatic suppression of the end losses. The method of end loss suppression by combined electrical and magnetic fields considered in this article is not unique. Using methods, applied in ambipolar tandem mirror traps could also lead to a positive result. The main problem now consists in determination of the variant (or variants) which are the most suitable for solving this problem.

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ПРИДУШЕННЯ ВТРАТ В ГАЗОДИНАМІЧНІЙ ПАСТЦІ КОМБІНОВАНИМИ ЕЛЕКТРИЧНИМИ ТА МАГНІТНИМИ ПОЛЯМИ

О. О. Лаврентьєв

В роботі описуються методи значного зменшення втрат із газодинамічної пастки, засновані на застосуванні комбінованих електричного та магнітного полів: за допомогою однощільових електромагнітних пасток, розташованих на кінцях центрального соленоїду, та з допомогою магнітної сітки, що знаходиться в області кінцевих розширювачів. Очікується зменшення затрат тритію від $2.16*10^{-3}$ до 10^{-5} g/s.

ПОДАВЛЕНИЕ ПОТЕРЬ В ГАЗОДИНАМИЧЕСКОЙ ЛОВУШКЕ КОМБИНИРОВАННЫМИ ЭЛЕКТРИЧЕСКИМИ И МАГНИТНЫМИ ПОЛЯМИ

О. А. Лаврентьев

В работе описываются методы значительного уменьшения концевых потерь из газодинамической ловушки, основанные на применении комбинированных электрического и магнитного полей: с помощью однощелевых электромагнитных ловушек, расположенных на концах центрального соленоида, и с помощью магнитной сетки, расположенной в области концевых расширителей. Ожидается уменьшение расхода трития с $2.16*10^{-3}$ до 10^{-5} g/s.