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Dynamics of Plasma Heated by Electron Beam in Corrugated Magnetic Field

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Introduction

Multimirror traps with corrugated magnetic field are considered as an alternative concept of thermonuclear reactor. Experiments on plasma heating by electron beam, being carried out at the multimirror trap GOL-3, have discovered some new phenomena [1, 2], that are not considered by existing theory [3]. They have permitted to improve plasma parameters sufficiently making this approach more attractive. In particular, measurements have shown that ion temperature in the GOL-3 increases for a time much less than classical *e-i* energy exchange time. This fact has required an additional analysis of behaviour of the plasma heated by an electron beam in the multimirror trap.

In the present paper a numerical simulation is used for study of a plasma dynamics. Hydrodynamic code ISW is based on experimentally found scalings for beam-plasma interaction. It permits to describe properly the initial stage of electron heating and accompanied acceleration of ions. An optimization of parameters is done for increasing the energy of ions. Hybrid model combined kinetic and hydrodynamic descriptions of plasma, is proposed for numerical simulation of plasma dynamic in conditions of experiment.

Experiment on plasma heating at the GOL-3 facility

Conditions of experiment are the following. Deuterium plasma of density $n \sim 10^{21}\ m^{-3}$ and 12 m length is generated by linear discharge along the magnetic field in metallic chamber of 10 cm diameter (Fig.1, 2). A magnetic field consists of one central section of uniform field (B = 4.8 T) and two multimirror sections (B = 4.8/3.4 T) of 4 m length each, entrance and exit mirrors ($B \sim 9\ T$). The plasma is heated by relativistic electron beam (REB) of energy up

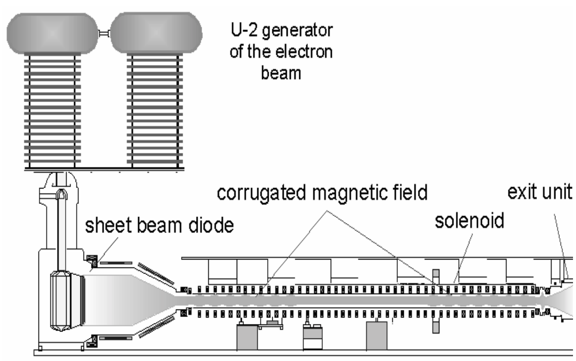

Fig.1 Layout of the GOL-3 facility.

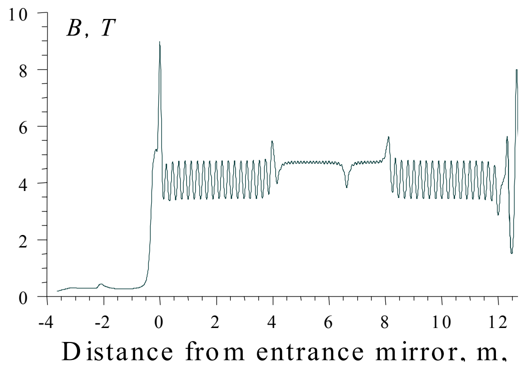

Fig.2. Configuration of magnetic field.

to ~ 1 *MeV*, current up to 30 *kA* (current density is ~ 1 kA/cm^2), duration $\tau_b \sim 6\ \mu s$ and energy content ~ 120 - 150 *kJ.*

As a result of beam-plasma interaction the temperature of plasma electrons rises to $T_e \sim$ 2 *keV* and of ions to $T_i \sim 1$ *keV* during beam pulse. An energy confinement time is ~ 0.3 *ms* [2], that is essentially higher than in the case of plasma heating in a simple mirror trap [4]. A time of ion heating is much less than electron-ion energy exchange time. Below a new mechanism of fast collective heating of ions by electrons is discussed.

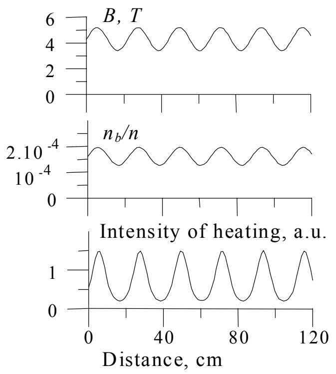

Fig.3. Nonuniformity of plasma heating in a corrugated magnetic field.

Mechanism of fast collective heating of ions

It was found in earlier experiments [5] that efficiency of plasma heating with REB of density n_b depends on plasma density *n.* In a region $n_b/n \le 1.5\cdot10^{-4}$ the Langmuir turbulence and electron heating are damped by electron collisions in plasma. On the contrary, a strong electron heating and suppression of longitudinal electron heat conductivity occurs in a region of developed turbulence $n_b/n > 1.5\cdot10^{-4}$ [1,5]. So as initial plasma density is uniform and the beam density follows the magnetic field magnitude, this dependence in the corrugated magnetic field results to longitudinal periodicity of electron pressure as shown on Fig.3. Gradients of electron pressure accelerate ions by ambipolar electric fields toward middles of magnetic cells. This mechanism of acceleration of ions is similar to one in an ion sound wave. A maximal ion velocity in ion sound wave is of order $V_{max} \sim C_s(\tilde{n}/n) \sim \sqrt{T_e/M}$ for large amplitude of density fluctuation $\tilde{n} \sim n$. Here C_s is a phase velocity of wave and *M* is mass of ion. In our case an electron temperature is varied along the system, and we use this expression with some mean electron temperature T^*_e only as estimate. Then, effectiveness of expected ion acceleration might be described as $\eta = W_{max}/T_e^* \sim 1/2$, where $W_{max} = MV_{max}^2/2\cdot$

Then accelerated counter-current ion flows are thermalized due to binary ion-ion collisions (and due to some another mechanism) that is much faster than ion-electron energy exchange time.

Modified numerical code ISW

Numerical simulation of collective plasma acceleration was performed with modified code ISW [6]. A plasma dynamics is described by usual hydrodynamic equations of motion and continuity for magnetised plasma:

$$\frac{\partial n}{\partial t}+B\frac{\partial}{\partial z}\left(\frac{nV}{B}\right)=0,\qquad \frac{\partial V}{\partial t}+V\frac{\partial V}{\partial z}+\frac{1}{Mn}\frac{\partial(nT+\mu)}{\partial z}=0,$$

where $T = T_e + T_i$; z is coordinate along magnetic force line; μ is artificial viscosity introduced for numerical stability. Heat balance equations for electrons and ions ($\alpha = e, i$) are

$$\frac{3}{2}\frac{\partial nT_\alpha}{\partial t}+B\frac{\partial}{\partial z}\left(\frac{3}{2}\frac{nT_\alpha V}{B}\right)+nT_\alpha B\frac{\partial}{\partial z}\left(\frac{V}{B}\right)=B\frac{\partial}{\partial z}\left(\frac{\kappa_\alpha}{B}\frac{\partial T_\alpha}{\partial z}\right)+Q_\alpha,$$

where $\kappa_e = F_e(Z_{eff})nT_e\tau_e/m\varsigma$, $\kappa_i = F_i(Z_{eff})nT_i\tau_i/M$ are thermal conductivities, $\zeta(P,z,n_b/n)$ is empirical coefficient of suppression for longitudinal electron thermal conductivity [1, 6]; $Q_{e,i}$ describes heating of electrons by REB and ions by electron-ion binary collisions [6]. Evidently, a hydrodynamic description may be valid only till colliding of counter-current ion flows in the magnetic cell.

Numerical simulation of real experiment

ISW code was used for simulation of plasma dynamic in multimirror magnetic field shown in Fig.2. Results are shown in Fig.4 for left multimirror section of solenoid for a time interval corresponded to initial stage of beam-plasma interaction up to $T_e \sim 0.2$ *keV*. As one can see in Fig.4, a plasma dynamics follows the mechanism of ion heating discussed above. An efficiency of ion acceleration is maximal for $t \sim 1.4$ μ*s* and it is low: $\eta \sim 0.1$. A reasons of smallness are clear: i) this is only beginning of plasma acceleration, and ii) time of acceleration is less than optimal one, i.e. two ion streams are collided earlier than a peak

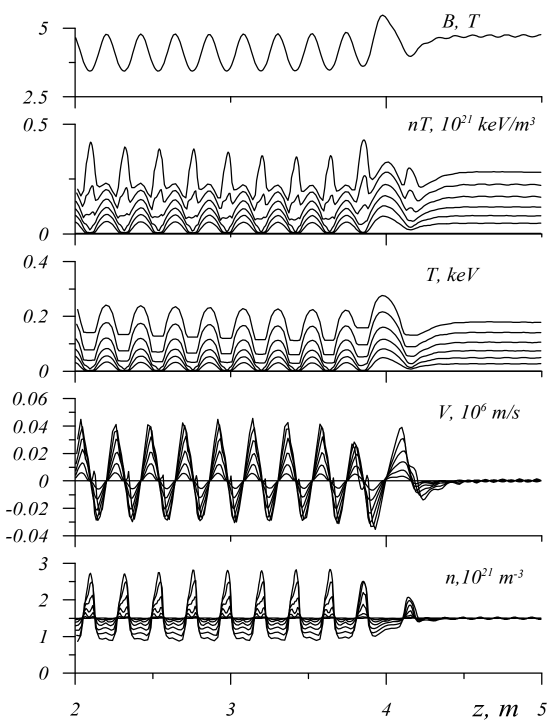

Fig.4. Existing magnetic system. Dependencies are shown in interval 0.6-1.6 μs through 0.2 μs.

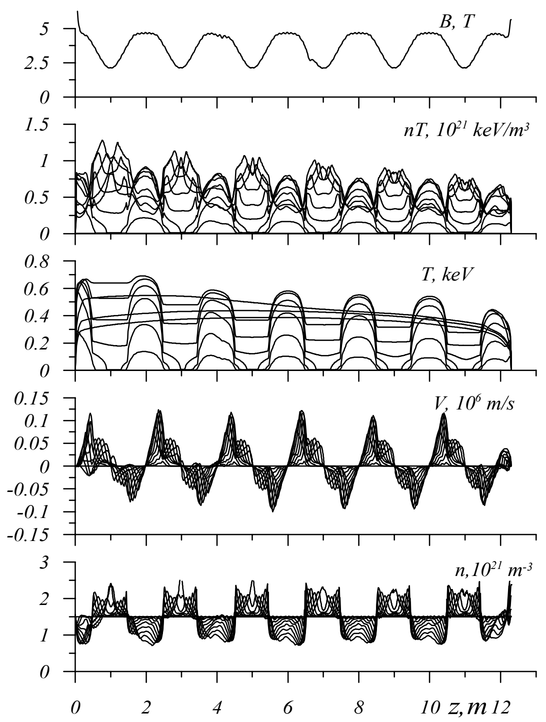

Fig.5. Optimized magnetic system. Dependencies are shown in interval 1-5 μs through 0.5 μs.

electron temperature is achieved. For maximum efficiency of ions acceleration the magnetic field configuration was optimized for existing design of magnetic coils.

Numerical simulation of optimized system

Fig.5 shows that, as earlier, electron heating begins from areas of maximal magnetic field. It determines shape of pressure and following acceleration of plasma toward centers of magnetic cells. So as numerical code doesn't take into account a specific multimirror decreasing of energy loss due to trapping a part of particles, a maximal electron temperature in modelling run is less than in a real experiment. An efficiency of ion heating reaches value $\eta \sim 0.3$-0.5, that is much higher than for existing system.

Such a way, a high efficiency of described mechanism of collective ion acceleration is confirmed by results of numerical simulation. As in the experiment, the energy of ions in the stream is of order of electron temperature. A further development of the code has to take kinetic phenomena into account.

Hybrid model for description of plasma dynamics in multimirror trap

During the plasma heating a mean free path of ions and electrons is less than length of trap, generally. It becomes greater than the cell length at $T > 0.15$ *keV*. A time of *e-e* binary collisions is less than times of other main processes in plasma. As for ions, they aren't in equilibrium at $W_i > 0.1$ *keV*. So, the following hybrid plasma model for numerical simulation is suggested. Electrons are described by condition of quasi-neutrality in non-inertial approximation, providing a longitudinal electric field in the system. The energy balance equation for them is similar to one in ISW code. As for ions, they are described by kinetic collisional Boltzmann equation.

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