Collision of fast, dense plasma flux in an open trap

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The parameters of a plasma produced as a result of collision of fast, dense plasma jets in a trap with a "theta pinch geometry with acute-angled fields at its ends" were evaluated.

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A fast, dense plasma jet can displace a longitudinal magnetic field when it flows into it. A large fraction of an open magnetic trap can be filled by a plasma by colliding plasma jets in it at $\beta = 1$.

We shall assume that the drag due to such a collision is determined solely by Coulomb collisions.[1] The trap, therefore, must have a sufficiently extended section of a slightly inhomogeneous field. In addition, the plasma boundary must be stable at $\beta = 1$. A trap with a field geometry of the type "direct theta pinch with acute-angled fields at its ends" satisfies these requirements.[2] The region with acute-angled fields is assumed to be small compared with the length of the system. The magnetohydrodynamic stability of an axially symmetric trap cannot be affected significantly by changing its length, and the jets can be injected through the ends. If the plasma is compressed by the liners (one cylindrical liner compresses the longitudinal field and two ring-shaped liners compress the acute-angled fields[3]) after the collision of the jets, then the parameters of the system for electromagnetic acceleration can be easily calculated, since the energy is transferred primarily to the long, central liner. Since the liners are stationary during injection, the unperturbed magnetic field is directed longitudinally everywhere in the liner.

The existing compression coaxial injectors can produce a plasma flux with an energy content $Q \sim (0.1-1.0)$MJ and translational ion energy $W > 1$ keV.[4] This type of injectors allows the energy W and the number N of ions to vary in a broad range at $Q = NW =$ const while retaining a high efficiency of energy transfer (up to 50%) from a storage battery to the plasma flux. Two independent parameters, for example, the Q (of both jets) and W uniquely determine the plasma state in the trap after the collision: the temperature T, the density n, the radius r of the plasma column in the region with a uniform field B, and the length l of the system. These dependences can be found easily if we assume that the following parameters are defined: $f = \Delta r/r \ll 1$ and $g = \Delta r/r_i \gg 1$, where Δr is the width of the gap between the linear and the plasma, and $r_i = M\langle v\rangle/eB$ is the Larmor radius of the ion, which is determined by the average ion velocity in the transverse direction to the longitudinal field $\langle v\rangle = (\pi kT/2M)^{1/2}$. Therefore, we can write

$$f r = g\left(\frac{\pi k T M}{2}\right)^{1/2} \frac{1}{eB} \quad . \tag{1}$$

As a result of Coulomb retardation,

$$l = \frac{F\epsilon_0^2 (kT)^2}{e^4 n}. \tag{2}$$

$F \approx 20$ if the retardation of the flux induced by ions and electrons[1] is taken into account. We introduce the injection efficiency of particles η_N and of the energy η_T (because of electron cooling[5] $\eta_T < \eta_N$). By definition,

$$\pi r^2 l n = \eta_N Q/W, \tag{3}$$

$$Q_p + \Delta Q_B = \eta_T Q, \tag{4}$$

where Q_p and ΔQ_B is the plasma energy and the variation of the magnetic-field energy of the trap after the collision. If the magnetic flux in the gap between the plasma and the central liner is conserved, then

$$\Delta Q_B = (2/3)\, Q_p [1 - 1/(1+f)^2]$$

and at $Q_p = 3\eta_N kTQ/W$ we can see from (4) that

$$kT = \frac{\eta_T}{\eta_N}\;\frac{W}{5 - 2/(1+f)^2}, \tag{5}$$

and we obtain the following from (1)–(3) and from the equilibrium condition $B^2 = 4\mu_0 nKT$:

$$r = \frac{1}{(\pi F)^{1/2}}\left(\frac{\eta_N Q}{W}\right)^{1/2} \frac{W}{kT}\;\frac{e^2}{e_0 W},$$

$$B = \pi\left(\frac{F}{2}\right)^{1/2} \frac{g}{f}\left(\frac{W}{\eta_N Q}\right)^{1/2}\left(\frac{kT}{W}\right)^{3/2}\left(\frac{\epsilon_0^2 M W^3}{e^6}\right)^{1/2},$$

$$n = \frac{\pi^2 F}{8}\left(\frac{g}{f}\right)^2 \frac{W}{\eta_N Q}\left(\frac{kT}{W}\right)^2 \frac{\epsilon_0^2 M W^2}{\mu_0 e^6}, \tag{6}$$

$$l = \frac{8}{\pi^2}\left(\frac{f}{g}\right)^2 \frac{\eta_N Q}{W}\;\frac{\mu_0 e^2}{M}.$$

The length l turned out to be independent of F in the approximation under consideration, and the radius r is independent of f and g. If $f \ll 1$, then the field $B_0 \approx 2fB$ before the injection is also independent of f. Since $kT/W \sim \eta_T/\eta_N$, consistent with (5), we have

$$r \sim \eta_N^{3/2}/\eta_T, \quad B \sim \eta_T^{3/2}/\eta_N^2, \quad n \sim \eta_T^2/\eta_N^3, \quad l \sim \eta_N.$$

At $f = 0.1$, $g = 10$, $Q = 300$ kJ, $W = 1.5$ keV, and $\eta_T = \eta_N = 1/2$ the deuterium plasma has the following parameters: $r = 0.12$ m, $l = 0.5$ m, $B = 3.3$ Tesla, $n = 3 \times 10^{22}$ m^{-3}, and $kT = 0.5$ keV.

If the energy $W \approx 12$ keV can be reached, then the trap will be filled immediately with the plasma with temperature $kT \approx 4$ keV after the collision of such jets. In this case Δr should be larger than the maximum Larmor radius of the charged reaction products. Suppose that their energy, mass, and charge are equal to W_r, M_r, and Ze, respectively. Thus,

$$f r = g_r \frac{(2 W_r M_r)^{1/2}}{Z e B} ,$$

where $g_r > 1$ and (1) holds. The expressions for T and r remain the same [T is determined from the energy balance and r from Eqs. (2) and (3), which do not change] and for the remaining parameters they acquire the following form:

$$B = (2\pi F)^{1/2} \frac{g_r}{f} \left(\frac{W}{\eta_N Q} \right)^{1/2} \frac{kT}{W} \left(\frac{\epsilon_0^2 M_r W_r W^2}{Z^2 e^6} \right)^{1/2} ,$$

$$n = \frac{\pi F}{2} \left(\frac{g_r}{f} \right)^2 \frac{W}{\eta_N Q} \frac{kT}{W} \frac{\epsilon_0^2 M_r W_r W}{\mu_0 Z^2 e^6} , \qquad (7)$$

$$l = \frac{2}{\pi} \left(\frac{f}{g_r} \right)^2 \frac{\eta_N Q}{W} \frac{kT}{W} \frac{W}{W_r} \frac{\mu_0 (Z e^2)^2}{M_r} .$$

The dependence on η_N and η_T changes as compared with (6). In accordance with (5) and (7),

$$B \sim \eta_T / \eta_N^{3/2} , \quad n \sim \eta_T / \eta_N^2 , \quad l \sim \eta_T .$$

If, however, $\eta_N = \eta_T = \eta$, then

$$B \sim 1/\eta^{1/2} , \quad n \sim 1/\eta , \quad l \sim \eta .$$

in both cases (for the foreplasma and the thermonuclear plasma). At $Q = 10$ MJ, $W = 12$ keV, $g_r = 1.5$, $f = 0.2$, and $\eta_N = \eta_T = 0.5$ the deuterium-tritium plasma with equal components has the following parameters: $r = 35$ mm, $l = 0.55$ m, $B = 62$ Tesla, $n = 1.4 \times 10^{24}$ m^{-3}, and $kT = 4$ keV. It is possible to achieve a temperature $kT \approx 10$ keV and $n\tau > 10^{19}$ s/m^{-3} by radially compressing (conventional theta pinch) such palsma by a factor of two by the increasing magnetic field when the total energy content of the system is about 30 MJ.

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