PLASMA CONFINEMENT IN SYSTEMS WITH HIGH β

I. K. Konkashbaev, L. B. Nikandrov,
T. V. Ryl'tseva, and F. R. Ulinich

UDC 533.95:537.84

The question of thermally insulating a hot dense plasma in systems with high $\beta = 8\pi p/H^2 \gg 1$ is considered. The major difficulty with such systems is that two problems must be considered simultaneously; that of equilibrium (maintaining the plasma pressure at 10^2 atm < p < 10^8 atm by means of the walls) and the problem of cooling across the magnetic field (thermal insulation) [1]. Among such systems are the θ-pinch, multitrap systems with high β [2], θ-pinch systems with a liner [3], etc. The problems of pressure maintenance and thermal insulation in such systems has been well studied. The basic parameter determining the character of pressure maintenance and insulation is the ratio of the gas pressure near the walls p_W (plasma pressure at wall) to the pressure of the plasma at the center p_0: $\xi = p_W/p_0$. Two separate cases may be distinguished: $\xi \ll 1$ and $\xi \approx 1$. For $\xi \approx 0$ the plasma is totally cut off from the walls (classical θ-pinch) and the problems of pressure maintenance and thermal insulation have been studied deeply in experiments with θ-pinch systems. The case $0 < \xi < 1$ ("gas insulation") has been studied in great detail, at least theoretically. The major part of the plasma pressure is transferred to the walls through a "magnetic interlayer" with $H \approx \sqrt{8\pi p_0}$, and the plasma is cooled by magnetized thermal conductivity across the magnetic field [2]. The case of purely "nonmagnetic confinement" ($\xi = 1$) was considered in [3].

1. Ideally Conductive Liner. Consideration of a system the liner of which possesses good conductivity is possible only at moderate plasma pressure and magnetic field values, e.g., in multibreakdown traps [4, 5] or in θ-pinches with a liner $n \approx 10^{17}$–10^{18} cm^{-3}, $H \approx 10^5$–10^6 G. Various modes of plasma cooling in systems with ideally conductive liners were considered in [2, 6, 7]. At present we are interested in the case of a plasma pinch of relatively small radius, where the system lifetime may be estimated from the thermal conductivity. As follows from [7], if the pressure of the plasma near the wall is maintained basically by the wall ($\beta(r \lessapprox R) > 1$) then

$$\tau_\varkappa = \frac{R^2}{\chi_0 \delta_0^{1/3}},$$

where R is the system radius, χ_0, δ_0 are the thermal diffusivity and degree of hot plasma ion magnetization in the center. If $\beta(r \lessapprox R) \ll 1$, i.e., when between the hot plasma with $\beta \gg 1$ and the wall there is a magnetic interlayer with $\beta \ll 1$, then

$$\tau_\varkappa = \frac{pR^2}{\varkappa_\perp T},$$

where p, T, $\varkappa_\perp$ are the pressure, temperature, and magnetic transverse thermal conductivity of the hot plasma.

We will consider the problem of the initial cooling stage: due to what processes and over what time period this magnetic confinement is formed. Cooling of a rapidly heated plasma located in contact with a cold wall has been studied many times, both theoretically [8-10] and experimentally [11]. However, it is desirable to consider this question again, since the theoretical studies [8-10] did not consider all phenomena simultaneously. Thus, [8, 10] ignored radiation; and [9], thermo-emf, while the results of the experimental [11] are ambiguous.

As was noted above, in order to determine the magnetic field distribution H it is necessary to consider the equations of heat transfer and pressure balance.

The equation for the magnetic field has the form (using the notation employed in [12])

$$\frac{\partial H}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rvH) = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\frac{c^2}{4\pi\sigma_\perp f_\sigma}\frac{\partial H}{\partial r} + \frac{ck}{e} f_T \frac{\partial T}{\partial r}\right)\right],$$

where the functions f_σ and f_T for conductivity and thermo-emf have the respective forms

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 3-11, March-April, 1980. Original article submitted March 4, 1979.

0021-8944/80/2102-0161 $07.50

$$f_\sigma^{-1}(x) = 1 - \frac{6.416x^2 + 1.837}{\Delta}, \quad f_T(x) = x(1.5x^2 + 3.053)/\Delta,$$
$$\Delta = x^4 + 14.79x^2 + 3.77, \; x = (\omega\tau)_e.$$

We will estimate the characteristic times: $\tau_\varkappa$, cooling time; τ_σ, magnetic field diffusion time; τ_T, magnetic field thermo-emf generation time; τ_R, radiant cooling time. The time $\tau_\varkappa$ must naturally exceed the Lawson time -

$$\tau_\pi = \langle n\tau\rangle/n, \; \langle n\tau\rangle = 10^{14}\ \text{cm}\cdot\text{sec}.$$

The dependence of f_T on $x = (\omega\tau)_e$ for purposes of estimation may be approximated by:

$$f_T(x) = \begin{cases} 0.8x, & x < 0.3, \\ 0.23, & 0.3 < x < 10, \\ 1.5/x, & x > 10. \end{cases}$$

As was noted in [10], in the hot region with $(\omega\tau)_e \gg 1$,

$$\tau_T^0/\tau_\sigma^0 = 4/\beta_0 \ll 1.$$

Since now $\tau_T^0/\tau_\varkappa^0 \approx \sqrt{\frac{M}{m_e}} \gg 1$, in the region with $(\omega\tau)_e \gg 1$ diffusion and thermo-emf may be neglected, and it may be assumed that the magnetic field is frozen in the plasma. The effect of thermo-emf must be considered at $(\omega\tau)_e \approx 1$. In this region $f_T \approx 0.23$ and

$$\tau_T \approx \frac{\Lambda^2}{f_T}\frac{2}{c}\left(\frac{\omega_p}{v_{Te}\beta^{1/2}}\right)_0, \quad \beta_0 = \sqrt{8\pi p_0/H_0^2}$$

(the index 0 indicates values at the center), so that the time for increase of the magnetic field to $H = \sqrt{8\pi p_0}$ may be estimated as

$$\tau_T^* = \sqrt{\beta_0}\,\tau_T \approx \frac{\Lambda^2}{f_T}\frac{2}{c}\left(\frac{\omega_p}{v_{Te}}\right)_0,$$

where Λ is the characteristic size of the region with $(\omega\tau)_e \approx 1$. For characteristic parameters $n_0 \approx 10^{18}$-10^{19} cm^{-3}, $\beta_0 \approx 10^2$, τ_T^* is greater than $\tau_S = R/v_{Ti}$, the pressure equalization time, so we may take

$$p + \frac{H^2}{8\pi} = \text{const}\ (r).$$

The ratio of the field generation time τ_T^* to the system lifetime $\tau_\varkappa$ is small

$$\frac{\tau_T^*}{\tau_\varkappa} \approx 3\frac{\Lambda^2}{R^2}\frac{1}{(\omega\tau)_{i0}} \ll 1,$$

so that after the short time τ_T^* in the region with $(\omega\tau)_e \approx 1$ a magnetic field $H \approx \sqrt{8\pi p_0}$ is generated and forms a thin magnetic interlayer (magnetic confinement). The magnetic field flux Φ in an ideally conductive liner is conserved

$$\frac{d\Phi}{dt} = \left(\frac{c^2}{4\pi\sigma_\perp f_\sigma}\frac{\partial H}{\partial r} + \frac{ck}{e}f_T\frac{\partial T}{\partial r}\right)\Bigg|_{r=0}^{r=R} = 0,$$

$\frac{\partial T}{\partial r} = \frac{\partial H}{\partial r} = 0$ at $r = 0$ because of cylindrical symmetry.

Thus, magnetic field thermo-emf generation causes a redistribution of the field flux Φ. If conventional diffusion were absent, this would mean that the field in the region with

$$\psi = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{ck}{e}f_T\frac{\partial T}{\partial r}\right) < 0$$

would decrease, while in the region with $\psi > 0$ it would increase. Of course in reality upon increase of the field in the wall region, reverse diffusion begins into the hot plasma region, so that equilibrium is established between magnetic field thermo-emf generation, diffusion, and convective field transfer.

Consequently, as a result of magnetic field generation near the wall, there develops a magnetic field H_R, the pressure of which compensates the plasma pressure

$$H_R^2 \approx 8\pi p_0.$$

Two cases are possible here: The plasma is almost completely cut off from the wall ($n_w \ll n_0$, $(\omega\tau)_e|_R \gg 1$); or between the hot plasma and wall there is a dense cold wall plasma with pressure $p \ll \frac{H_R^2}{8\pi}$ and $(\omega\tau)_e|_R \ll 1$. Realization of one or the other case depends on the prehistory of the cooling process. In the situation considered here the state with the cold dense wall plasma near the wall is realized, with the magnetic field $H \approx$ const (due to the absence of thermo-emf, $(\omega\tau)_e \ll 1$ and low conductivity σ of the wall plasma), and consequently, $nT \approx$ const. Thus, it can be expected that the density n falls off as T^{-1} from the wall to the region with $(\omega\tau)_e \lessapprox 1$, while

$$\frac{n_w}{n((\omega\tau)_e \approx 1)} = \frac{T((\omega\tau)_e \approx 1)}{T_R} \approx 30,$$

since in the case considered $T((\omega\tau)_e \approx 1) \approx 300$ eV, while the wall temperature was taken equal to 10 eV (T_R = 10 eV).

Consequently, upon sudden contact between plasma and wall or rapid heating of the plasma to thermonuclear temperatures $T \approx 10^4$ eV over a time $\tau_T^* \ll \tau_\varkappa$ a magnetic confinement is formed, and over the time $\tau_\varkappa$ the plasma is cooled by magnetic thermal conductivity. This apparently explains the agreement of the calculations of [2, 13] with the experiment of [11] after $t > \omega_{Hi}^{-1}$ (for $t < \omega_{Hi}^{-1}$ the thermal flux on the wall is determined by "leakage" of ions with a thermal flux $q \approx nkT_i v_{Ti}$ [13]).

To verify the validity of these approximations numerical calculations were performed for cooling of a hot magnetized plasma located in contact with a cold wall in cylindrical geometry, in a manner similar to [2]:

$$\begin{gathered}
Mn\frac{dv}{dt} = -\frac{\partial}{\partial r}\left(2nkT + \frac{H^2}{8\pi}\right), \quad \frac{\partial n}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rvn) = 0, \\
3nk\frac{dT}{dt} + 2nkT\frac{1}{r}\frac{\partial}{\partial r}(rv) = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\varkappa_\perp^e + \varkappa_\perp^i\right)\frac{\partial T}{\partial r}\right] \\
+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\beta_\wedge}{n}\frac{ck}{4\pi e}\frac{\partial H}{\partial r}\right) + \frac{\beta_\wedge}{n}\frac{ck}{4\pi e}\frac{\partial T}{\partial r}\frac{\partial H}{\partial r} + \frac{j^2}{\sigma_\perp} - Q_R, \\
\frac{\partial H}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rvH) = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\frac{c^2}{4\pi\sigma_\perp}\frac{\partial H}{\partial r} + \frac{ck}{e}\frac{\beta_\wedge}{n}\frac{\partial T}{\partial r}\right)\right].
\end{gathered} \tag{1.1}$$

The boundary conditions for system (1.1) have the form

$$\frac{\partial T}{\partial r} = \frac{\partial H}{\partial r} = 0, \ v = 0 \ \text{for} \ r = 0, \ T = T_R, \ v = 0 \ \text{for} \ r = R,$$

$$\left.\frac{c}{4\pi\sigma_\perp}\frac{\partial H}{\partial r} + \frac{k}{e}\frac{\beta_\wedge}{n}\frac{\partial T}{\partial r}\right|_{r=R-0} = \left.\frac{c}{4\pi\sigma_l}\frac{\partial H}{\partial r}\right|_{r=R+0}.$$

The last boundary condition implies continuity of the tangential electric field component on the plasma–liner boundary, with σ_l being the liner conductivity. The initial conditions are that at t = 0, $H = H_0$,

$$v = 0, \quad 2nkT + \frac{H^2}{8\pi} = 2n_0kT_0 + \frac{H_0^2}{8\pi}.$$

The initial temperature distribution has the form

$$T = T_R + (T_0 - T_R)\left[1 - \exp\left(-\left(\frac{r-R}{\Delta}\right)^2\right)\right],$$

where the characteristic dimension Δ at which the temperature increases from T_R to $T \approx T_0$ is much less than R, $\Delta/R \approx 10^{-2}$. The quantity T_R, the wall temperature (temperature of plasma near the wall), was varied from 1 to 10 eV, but since T_1 (the temperature corresponding to $(\omega\tau)_e \approx 1$) is of the order of 100 eV, the solution depended only slightly on variation of T_R over this range. The initial magnetic field was taken constant along the radius

$$H(t = 0) = H_0 = \sqrt{8\pi p_0/\beta_0}.$$

Figures 1-4 present results of calculations for the typical case:

$$T_0 = 10^4 \text{ eV}, \ n_0 = 10^{18}\,\text{cm}^{-3}, \ H_0 = 10^5\text{G}, \quad \beta_0 = 80, \ R = 5 \text{ cm}, \ \Delta = 5\cdot10^{-2} R.$$

Characteristic times are:

$$\tau_\varkappa \approx 10^{-4}R^2, \text{ sec}, \quad \tau_\sigma^0 \approx 0.1R^2, \text{ sec}, \quad \tau_T^0 \approx 2\cdot10^{-3}R^2, \text{ sec}, \quad \tau_T^* \approx 4\cdot10^{-8} \text{ sec}.$$

In the calculation the magnetic confinement is formed after $t \approx 7\cdot10^{-8}$ sec, which agrees approximately with the estimate.

Figure 1 shows the temperature distribution T and plasma density n at various times, with temperature measured in units of 100 eV; density, in units of 10^{18} cm^{-3}; and magnetic field, in units of 10^3 G. Numbers

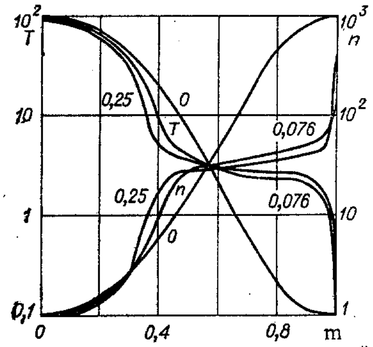

Fig. 1

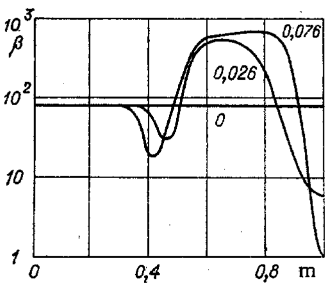

Fig. 2

above the curves correspond to times t, measured in units of 10^{-6} sec. Figures 2-4 show $\beta = 8\pi p/H^2$, magnetic field H, and $(\omega\tau)_e$ as functions of the mass coordinate m for various times.

It is evident that by the time $t \approx 0.076$ μsec the β value at the wall becomes equal to unity, and the magnetic field in this region has increased intensely. The magnetic interlayer appears not only because of field generation, but also due to radiation, since the scintillation time of a layer with $T \approx 300$ eV ($(\omega\tau)_e \approx 1$) $\tau_R \approx 0.1$ μsec is comparable to τ_T^*. However the influence of this effect is attenuated to a significant degree by the quite large conductive heat flux in the region. It is clear from Fig. 4 that the plasma tends to leave the cooling regime with $(\omega\tau)_e$ greater than unity everywhere. In the center the temperature, magnetic field, and plasma density change insignificantly over this time period.

After formation of the magnetic confinement the solutions are similar to those obtained in [2], where the width of the magnetic interlayer is quite large. Plasma cooling is also described by the estimate $\tau_\varkappa \approx pR^2/\varkappa_\perp T$, which, as has been indicated, is completely natural, since the hot plasma is in essence cut off from the walls. For comparison, calculations were performed with a liner having poor conductivity, the conductivity of the liner material corresponding to the conductivity of the plasma near the wall at a temperature of the order of 10 eV. As would be expected, the magnetic field rapidly penetrates through the liner, magnetic confinement is not established, and the plasma cools rapidly.

2. Systems with Nonmagnetic Confinement. In systems where the plasma pressure is maintained not by inertia, but directly by the walls, the achievement of high plasma densities required for reduction of total system energy is possible only with nonmagnetic confinement, where the magnetic field serves only to reduce thermal conductivity, since megagauss fields cannot be maintained for long periods. The possibility of achieving such a variant was considered in detail in [3], where the possibility of existence of a stationary cooling wave was demonstrated. For applicable systems with rapid energy introduction and $Q \approx 10$ MJ a solution is possible only at very high pressures ($p \approx 10^8$–10^9 atm). In propagation of a stationary cooling wave it is necessary that the magnetic field carried off from the center by the plasma flux which generates the thermo-emf not accumulate along the wall, but pass freely through a "dielectric" liner.

We will now consider the possibility of modeling such a system, i.e., achieving nonmagnetic confinement with a quasistationary cooling wave in a device with moderate parameters: $p \approx 10^6$–10^7 atm, $T \approx 1$ keV. Such temperatures can be reached in θ-pinches with a liner with a liner velocity $V_l \approx 10^6$ cm/sec, length $L \approx 10$ cm,

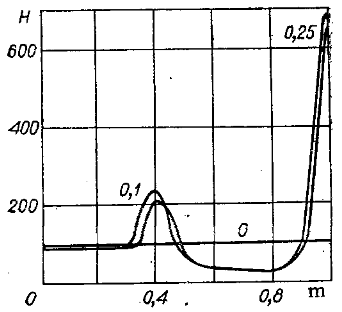

Fig. 3

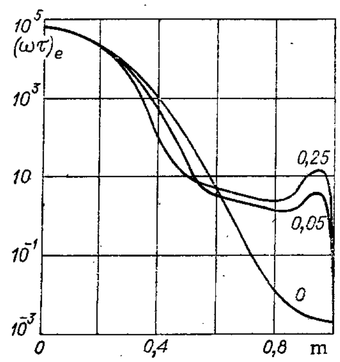

Fig. 4

and energy level Q ≈ 1 MJ. We will estimate the required parameters, using the quasistationary equation

$$(5/2)p \operatorname{div} \mathbf{v} = \operatorname{div}(\varkappa \nabla T) - Q_R,$$

where Q_R is the volume radiation power.

Since the width of the cooling wave l_w is small in comparison to the system radius R, the planar problem may be solved. For the estimates we will assume that the magnetic field H is constant along the radius, since H changes significantly only at $(\omega\tau)_e \leq 1$. System energy losses are determined by the region with $(\omega\tau)_e \approx 1$, where demagnetization of the plasma commences. Since heat is supplied to this region mainly by thermal conductivity, by neglecting the work of compression in comparison to the conductive thermal flux, we obtain

$$\frac{d}{dx}\left(\varkappa \frac{dT}{dx}\right) = Q_R. \tag{2.1}$$

Considering that in this region braking radiation is more significant than recombination radiation, we take $Q_R = \alpha n^2\sqrt{T}$. We multiply both sides of Eq. (2.1) by $\varkappa dT/dx$, and integrating over from R to ξ (where R is the wall coordinate where the flux $q(R) = \varkappa dT/dx \approx 0$, and ξ corresponds to the region with $(\omega\tau)_e \approx 1$), we obtain

$$q^2(\xi) = \int_R^{\xi} \alpha n^2 \sqrt{T}\, \varkappa \frac{dT}{dx}\, dx.$$

Considering that $\varkappa = \varkappa_{e0}\Theta^{5/2}$ and $\rho\Theta = 1$, where $\Theta = T/T_0$, $\rho = n/n_0$ (where $\varkappa_{e0}$, T_0, n_0 are the nonmagnetized electron thermal conductivity, temperature, and density of the plasma in the hot region), we obtain an estimate of the thermal conductivity flux into this region necessary for maintaining the quasistationary state

$$q(\xi) = \sqrt{\varkappa_{e0} T_0 \alpha n_0^2 \sqrt{T_0}}\, \Theta_1,$$

where $\Theta_1 = T_1/T_0$ is the temperature of the plasma in the region with $(\omega\tau)_e \approx 1$. Since $q(\xi)$ must compensate the work of plasma compression in the wall region by the hot plasma flux, the expansion velocity V_e of the hot region can be determined from the condition

$$\int_0^{\xi} \frac{5}{2} p_0 \frac{dv}{dx}\, dx = \int_0^{\xi} \frac{d}{dx} q \approx q(\xi).$$

Estimating $dv/dx \sim V_i/\xi$, we obtain

$$V_i = \frac{3}{5} \frac{L_0}{\tau_R} \Theta_1,$$

where

$$\tau_R = \frac{3p_0}{2\alpha n_0^2 \sqrt{T_0}}; \quad L_0^2 = \frac{\varkappa_{e0} T}{\alpha n_0^2 \sqrt{T_0}}.$$

The hot plasma cooling (flow-out) time is then

$$\tau_i = \frac{\frac{3}{2} p_0 R^2}{\frac{5}{2} p_0 V_i R} \approx \frac{R}{V_i}.$$

As was noted in [3], such an estimate agrees well with numerical calculations. The attainable plasma pressure in a θ-pinch with liner is equal to

$$p = A \rho_l V_l^2,$$

where ρ_l is the liner density, A ≈ 1 (a simple determination of the efficiency of energy transfer from the liner to the plasma η with consideration of liner compressibility was performed in [14]). From these estimates we obtain the following parameters for the system modeling that of [3]: initial parameters: T = 30 eV, $n = 5 \cdot 10^{18}$ cm^{-3}, R = 5 cm, H = 5 kG, $\beta = 6 \cdot 10^2$, $V_l = (0.5\text{–}1.0) \cdot 10^6$ cm/sec, $\rho_l = 3$ g/cm^3; final parameters: $T = 10^3$ eV, $n = 10^{21}$ cm^{-3}, R = 0.3 cm, $H = 10^3$ kG, $\beta = 10^2$. The final parameters were obtained with the assumption of adiabatic compression of the plasma by the liner, but with consideration of magnetic flux losses, which comprise ≈ 30%. The plasma energy Q_p = 0.25 MJ, which with an actual efficiency $\eta \approx 0.2$ corresponds to Q ≈ 1–1.5 MJ.

Thus, in θ-pinches with a liner with the technologically achievable parameters Q ≈ 1 MJ, $V_l \approx 10^6$ cm/sec, one can conduct experiments simulating a system with nonmagnetic confinement [3] if the plasma cooling time (or time for flow to the walls) is of the order of or larger than the inertial time $\tau_i \gtrsim R/V_l$.

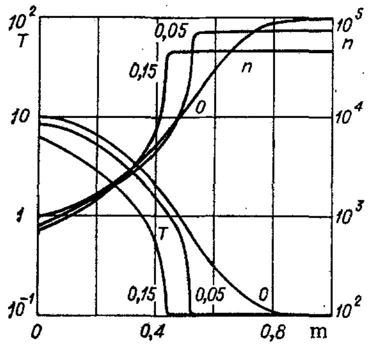

Fig. 5

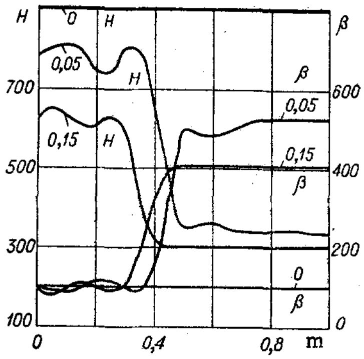

Fig. 6

To verify these considerations numerical calculations were performed for cooling of a θ-pinch plasma with initial parameters corresponding to the final ones for a liner conductivity $\sigma_l = \sigma_m$ and $\sigma_l \gg \sigma_m$. The minimum conductivity σ_m was taken equal to the conductivity of the near-wall plasma with T = 10 eV. The character of distribution over mass of temperature, plasma density, and magnetic field were the same as in Sec. 1.

Figures 5, 6 present the results of calculations for $n_0 = 10^{21}$ cm^{-3}, $T_0 = 10^3$ eV, $(\omega\tau)_{e0} \approx 17$, $T_R = 10$ eV, $H_0 = 0.9$ MG, $\beta_0 = 100$ for a poorly conducting liner. The scales of the quantities in Figs. 5, 6 are the same as in Figs. 1-4. Figure 5 shows the distribution of temperature T and plasma density n over mass at various times. For $t \approx 0.15$ µsec the temperature at the center of the system decreases to $0.7T_0$. A cooling wave moves through the plasma from the wall to the center. The rate of plasma flow to the wall is 10^5 cm/sec $\leq V_p \leq 10^6$ cm/sec. Since the liner is a poor conductor, as shown in Fig. 6, the magnetic field carried off from the center and generating a thermo-emf is strongly diffused in the liner $H_R \approx 0.2H_0$, and correspondingly $\beta_R \approx 5\beta_0$, with growth in β retarded by the pressure drop upon cooling. The characteristic magnetic field peak is formed in the region where $(\omega\tau)_e \approx 1$, where a balance is established between field generation and field diffusion into the cold wall layer of plasma and liner.

In the case of a high-conductivity liner, where σ_l is equal to the conductivity of copper under normal conditions, numerical calculations show that after the time in which the temperature at the center drops to $0.7T_0$ for a plasma with initial conditions similar to those of Figs. 5, 6 the magnetic field at the wall increases intensely and reaches $\approx 2H_0$, while β falls. Although magnetic confinement is not achieved in this regime, nevertheless the appropriate "poor" conductance liner must be provided in model experiment and in the thermonuclear system of [3].

LITERATURE CITED

1. S. G. Alikhanov, I. K. Konkashbaev, and P. Z. Chebotaev, "The energy balance in a dense fusion plasma contained by walls," Nucl. Fusion, 10, No. 1 (1970).
2. G. E. Vekshtein, D. D. Ryutov, M. D. Spektor, and P. Z. Chebotaev, "Nonmagnetic confinement of a dense plasma," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1974).
3. S. G. Alikhanov and I. S. Glushkov, "Stationary cooling wave in a magnetized plasma," Dokl. Akad. Nauk SSSR, 226, No. 3 (1976).
4. G. I. Budker, "Thermonuclear fusion in installations with a dense plasma," in: Proc. VI European Conference on Plasma Physics and Controlled Fusion, Vol. 2, Moscow (1973).
5. B. Grant Logan, A. J. Lichtenberg, M. A. Lieberman, and A. Makhijani, "Multiple-mirror confinement of plasmas," Phys. Rev. Lett., 28, 144-147 (1972).
6. G. E. Vekshtein, "Peculiarities in radiant cooling of a dense plasma with high β," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1976).
7. G. E. Vekshtein, "Dimensional estimates of cooling time for a plasma with $\beta \gg 1$," Dokl. Akad. Nauk SSSR, 237, No. 2 (1977).
8. M. S. Chu, "Hot plasma in contact with a cold wall," Phys. Fluids, 16, No. 9 (1973).
9. R. A. Gross, "A shock-heated wall-confined fusion cycle," Nucl. Fusion, 13, 293-296 (1973); "Physics of a wall-confined fusion system," Nucl. Fusion, 15, 729-735 (1975).
10. C. Jablon, "Magnetic field evolution in a very-high-β plasma," Nucl. Fusion Lett., 16, No. 4 (1976).
11. B. Feinberg, "An experimental study of a hot plasma in contact with a cold wall," Plasma Phys., 18, 265-275 (1976).

12. S. I. Braginskii, "Transfer phenomena in plasma," in: Questions of Plasma Theory [in Russian], Atomizdat, Moscow (1963).
13. B. K. Jensen, "Physics of a fusion plasma boundary layer," Phys. Fluids, 20, No. 3 (1977).
14. S. G. Alikhanov and I. K. Konkashbaev, "Effectiveness of a thermonuclear system of the 'theta-pinch and liner' type," Nucl. Fusion Suppl., 123-126 (1975).

LASER COLLISIONAL PUMPING OF HF MOLECULES

G. K. Vasil'ev, E. F. Makarov,
Yu. A. Chernyshev, and V. G. Yakushev

UDC 539.196.5

The effect of IR laser radiation on molecules can result in the production of strongly nonequilibrium molecular gas states because of the selective "heating" of the vibrational degrees of freedom. Research to use vibrational–translational nonequilibrium occurring during the absorption of laser radiation for its effect on chemical processes has recently been performed. As a rule, the possibilities of stimulating and controlling reactions relate primarily to the high reactivity of vibrationally excited molecules, as well as to the formation of high-activity particle concentrations during nonequilibrium dissociation caused by "heating" the molecular vibrations. At this time a sufficiently large number of papers devoted to both the dissociation of molecular gases and to laser-induced chemical reactions (e.g., [1, 2], as well as the surveys [3, 4]), have been published. Let us note that the proof of the selective action of laser radiation on the progress of a process is not indisputable in many of the reported cases. Hence, further research in this area is expedient.

Various aspects of vibrational kinetics have been examined in a number of theoretical papers (cf. [5-10]), for systems of anharmonic oscillators under conditions of a strong deviation from equilibrium (finding the vibrational distribution function and the energy relaxation rate, determining of the energy dissipation of the vibrational degrees of freedom, estimating the nonequilibrium dissociation rates).

Because of the lack of quantitative data on the rate constants of all the possible relaxation processes for the majority of molecular systems, the theoretical comprehension necessarily remains at a qualitative level.

An analysis of the processes occurring during the insertion of significant quantities of energy during laser exposure, and the determination of the limit energy capacity of the vibrational degrees of freedom, the total energy capacity, as well as the comparison of theoretical and experimental results, are performed more conveniently on model systems. Small atoms and, especially, diatomic molecular gases, can be model systems since the relaxation processes (rotational–translational (R–T), vibrational–translational (V–T), vibrational–vibrational (V–V) exchanges) have been studied to greatest degree for small-atom molecules, and the structure of the energy levels of these molecules is simple.

At this time, an experimental investigation of the vibrational pumping of HF molecules because of resonance absorption of HF laser radiation by HF molecules in the low vibrational states and subsequent pumping in the high state in collisions of vibrationally excited molecules has been performed. For brevity, we will later denote such a process laser-induced collisional pumping (LCP). A pulsed HF laser with ~10-J radiation energy and a pulse duration of 2 μsec at the foundation [11] was used in the experiments. The spectrum consisted of 20 lines of the first four vibrational–rotational HF bands. About 10% of the laser pulse energy was concentrated in the 1–0 band, about 80% in the 2–1 band, while the rest of the energy was distributed between the 3–2 and 4–3 bands. The 1–0 band started with an intense P_8 line, and the most intense lines in the the 2–1 band were P_7 and P_8. Singularities associated with the spectral composition of the radiation result in the process of laser energy absorption being started by the HF molecules populating the rotational half-level J = 8 of the vibrational ground state. Consequently, a small fraction of the molecules being pumped are initially in resonance with the laser radiation (a fractional part of $\sim 10^{-3}$ of the total number of molecules is in the initial state at the J = 8 level). The total radiation intensity (the mean during a pulse) was $I \approx 0.5$ MW/cm^2 ($6.5 \cdot 10^{24}$ photons/cm$^2 \cdot$ sec) and could be increased by focusing to $I \sim 10$ MW/cm^2 ($1.3 \cdot 10^{26}$ photons/cm$^2 \cdot$ sec). Focusing was performed by a lens with a 50-cm focal length. A cylindrical zone of 6 mm diameter was exposed at

Chernogolovka. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 11-17, March-April, 1980. Original article submitted April 2, 1979.

0021-8944/80/2102-0167$07.50