Expansion of a laser plasma in a transverse magnetic field

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A study of the expansion of a laser plasma in a transverse magnetic field under conditions corresponding to the region where $\beta > 1$ (β is the ratio of the gaskinetic plasma pressure to the magnetic pressure) revealed a selective interaction of the field with the ions depending on their charge, which could result in the displacement of ions with higher charges from the head of a plasma to the central region. Expansion under conditions beyond the region where $\beta \sim 1$ reduced strongly the kinetic energy of the ion component because of a redistribution of the energy when the plasma became polarized and the plasma itself could propagate in the form of several bunches when $\beta \ll 1$.

The work reported by Bostick[1] was the pioneering experimental study of the interaction of plasma bunches with transverse magnetic fields. At present such investigations are used in connection with thermonuclear fusion, when plasma fills magnetic traps, and as ion sources.[2–4]

A plasma expands freely in a magnetic field, i.e., it expands in the same way as in the absence of a magnetic field for a time after the formation so long as the gaskinetic plasma pressure p_{pl} exceeds the magnetic pressure P_e exerted by an external magnetic field (i.e., until the ratio of these pressures becomes $\beta = P_{pl}/P_e \gg 1$). The ratio β decreases during expansion of a plasma because of a rapid reduction in the plasma density and temperature in the course of adiabatic expansion. When the ratio reaches $\beta \sim 1$ the plasma boundary comes to rest if the plasma has a spherically symmetric shape.[2,5,6] However, if the plasma expands preferentially in one direction and has a sufficient kinetic energy, it may go over to a region characterized by $\beta \ll 1$ as a result of polarization by a transverse magnetic field.[7] The plasma drift occurs in an external transverse magnetic field $\mathbf{B}$ crossed by a matched electric polarization field $\mathbf{E}$ at a velocity $\mathbf{V}_{dr} = [\mathbf{E}\times\mathbf{B}/\mathbf{B}^2]$ (Refs. 1, 8, and 9). In the case of a plasma formed by laser radiation incident on a plane thick target of dimensions exceeding the size of the spot formed by the laser radiation focused on the target we can expect typically such a spatial anisotropy of the expansion process.[10–12]

In the case of a laser plasma there are thermalization processes which occur directly after the formation and ensure that a major part of the plasma energy is concentrated in the kinetic energy of the component ions. We therefore have

$$\beta = (n_i m_i \langle V_i \rangle^2)/(B^2/2\mu_0),$$

where n_i is the concentration of ions in the plasma; m_i is the ion mass; $\langle V_i \rangle$ is the average velocity of ions in the plasma; μ_0 is the magnetic permeability. The characteristics of a laser plasma drifting in a transverse magnetic field under conditions $\beta \ll 1$ differ considerably from the characteristics of the expansion process in the absence of a magnetic field. A plasma expands in the form of a bunch at a velocity which is less than in the absence of a magnetic field.[4,13] It is shown in Refs. 14–16 that a plasma expanding in a transverse magnetic field is decelerated and the strongest slowing down (compared with free expansion) is experienced by the high-energy part of the plasma containing multiply charged ions.

A laser plasma traveling across a magnetic field passes through regions with different values of the parameter β so that the nature of the interaction of the plasma with the magnetic field varies. For this reason we can identify the influence of a magnetic field on the main plasma characteristics (spatial and energy distributions, charge spectrum) by investigating the expansion in the three characteristic regions with the corresponding values of the parameter β. The published information can only be used to compare the characteristics of a laser plasma in a transverse magnetic field when $\beta \ll 1$ with the characteristics of a freely expanding plasma.

Laser plasma used as a source of ions for a cyclotron[4,17] expands to the emission slit of a source in all the regions of β mentioned above. The process of expansion in a region with $\beta \gg 1$, crossing a region with $\beta \sim 1$, and the resultant drift motion are largely determined by the characteristics of the plasma used in such a source. Our aim was to investigate the conditions of formation of the spatial structure of the ion component of the plasma, and of the energy and charge distributions of the laser plasma ions in the process of transformation from free expansion to drift.

1. APPARATUS

In our experiments we formed a plasma using a CO_2 laser pumped by a transverse discharge. The laser radiation was in the form of 6-J pulses exhibiting two spikes of ~ 60 and ~ 500 ns durations (Fig. 1). This radiation was focused by a planoconvex sodium chloride lens of focal length 5.6 cm. The target was plane and thick. The target material was carbon, silicon, tantalum, or bismuth. The angle between the laser beam and the normal to the target was $\approx 40°$. The area

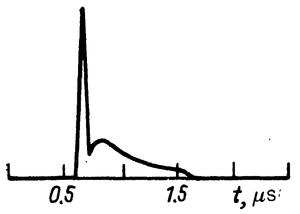

FIG. 1. Oscillogram of a CO_2 radiation pulse.

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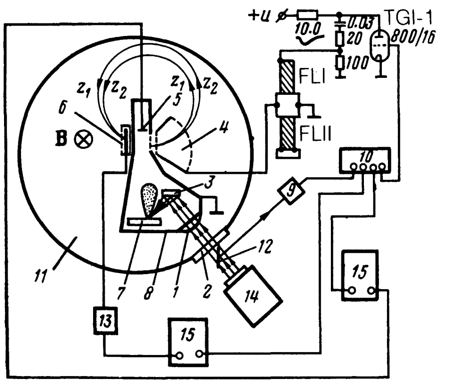

FIG. 2. Principal components of the apparatus: 1) lens; 2) entry window; 3) mirror; 4) electrode; 5), 6) collectors; 7) target; 8) casing; 9) triggering unit; 10) delay and synchronization unit; 11) vacuum chamber; 12) beam splitter; 13) fast amplifier; 14) CO_2 laser; 15) S8-2 oscilloscope.

of the focused spot of the laser radiation reaching the target was $\sim 10^{-3}$ cm^2. The first spike in a laser pulse carried about half the energy of the pulse. The flux density Φ established by this spike on the target surface was $\sim 3\times 10^{10}$ W/cm^2, which was deduced after allowance for the losses in the system used to transport and focus the radiation. In the course of our experiments the laser radiation flux density was varied by calibrated filters.

We used ion sources at the Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research in Dubna[18] subjected to a homogeneous transverse magnetic field $B \leqslant 0.5$ T. The vacuum in the apparatus employed was maintained at 2×10^{-6} Torr.

The apparatus was assembled as shown in Fig. 2. Radiation from a CO_2 laser passed through an entry window 2 and reached the vacuum chamber where it was focused by a lens 1 on a target 7. The target was oriented so that the normal to its surface was perpendicular to the magnetic lines of force of the field **B**.

In a mass-spectroscopic investigation of the ion component the ions were extracted from the boundary of a plasma traveling past an emission slit of 4×20 mm dimensions when an electrode 4 was subjected to a negative rectangular pulse of ~ 100 ns duration and of $\leqslant 16$ kV amplitude formed by a generator with ferrite lines FLI and FLII (Ref. 19). The plasma boundary was confined to the emission slit by a metal grid of 150×150 μm mesh. The distance between the emission slit and the target was varied from 5 to 6.5 cm. A collector 5 subjected to a voltage $U \leqslant -200$ V was placed in the path of the expanding plasma directly behind the emission slit. The high-voltage electrode 4 was made of stainless steel and was a hollow body bounded by two parallel surfaces. The shape and the dimensions of these surfaces were determined by the paths of motion of the ions extracted from the plasma and by their flight time across the space between the two parallel surfaces of the electrode, which should be longer than the duration of the high-voltage pulses. The electric field did not penetrate the internal space of the electrode because metal grids were placed at the entry and exit from the electrode. The ions extracted from the plasma in a homogeneous and transverse magnetic field followed a circular path and reached a screened collector 6.

The rotation period T_i of ions of charge z and mass m_i in a transverse magnetic field B was proportional to the ratio m_i/z, i.e., $T_i = 2\pi m_i/zeB$. The characteristic features of the operation of a mass spectrometer using the same principle of analysis were described by us earlier in Ref. 17. The resolution of this mass spectrometer in a magnetic field B depended both on the duration $\Delta\tau$ of a packet of ions (in the present case it was $\Delta\tau \sim 100$ ns) and on the flight time t_i until the collector was reached, i.e., it depended on the actual geometrical configuration of the apparatus. The ratio of ion motion time t_i after extraction from the plasma and traveling to the collector 6 during one revolution period T_i in a transverse magnetic field was (under experimental conditions) $t_i/T_i \approx 0.9$ for ions with the $A/z = 2$ ratio, where A is the atomic weight of the ions. The difference between t_i and T_i decreased for ions with large values of the ration A/z. The background reaching the collector 6 was reduced by ensuring that the processes of plasma formation and expansion occurred within a case 8, the cover and base of which were made of an insulator in order to avoid the influence of metallic surfaces on electrically charged regions in the plasma.[8,9,20] To determine the ion composition of the plasma at different angles φ from the normal to the target we used a unit composed of an emission slit, the electrode 4, and the collector 6 located in a plane perpendicular to the magnetic lines of force along an arc with its center at the focusing point of the laser radiation. A time delay and synchronization unit 10 triggered a generator of high-voltage pulses of the delay time t_d after the laser pulse and it synchronized the operation of the recording apparatus.

We investigated the ion component of the plasma by placing collectors at various angles φ from the normal to the target. The collectors were located at a distance of 5 or 6.5 cm from the target. The spatial resolution was $\sim 1°$.

2. EXPERIMENTAL RESULTS

2.1. Spatial distribution

Figure 3 shows the results of determination of the ion current by the collectors at various moments in time from the formation of a plasma in a region with low pressure ratio ($\beta \lesssim 0.1$), whereas Fig. 4 gives the ion current along different directions recorded at $t_d \approx 0.2$ μs after a giant laser radiation pulse (corresponding to $\beta \approx 0.6$). In the range $t_d > 0.2$ μs the ion current reaching the collectors had an angular distribution of the kind shown in Fig. 4. The positive angles were measured from the normal since this matched the di-

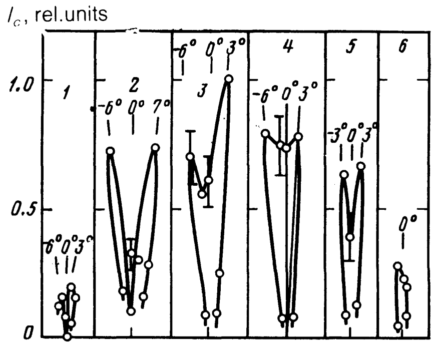

FIG. 3. Ion current reaching the collectors at various moments in time after a giant laser radiation pulse: 1) $t = 0.6\,\mu$s; 2) $0.9\,\mu$s; 3) $1.1\,\mu$s; 4) $1.2\,\mu$s; 5) $1.9\,\mu$s; 6) $2.7\,\mu$s. These results were obtained for a carbon target; $B = 0.2$ T, $L = 5$ cm, $\Phi \sim 6\times 10^9$ W/cm^2.

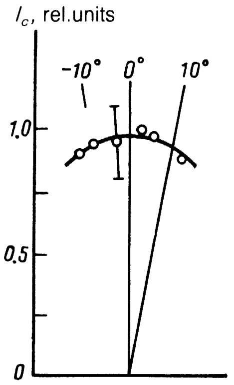

FIG. 4. Ion current reaching the collectors from the head part of a plasma in the region characterized by $\beta \sim 1$. The results were obtained for a carbon target; $B = 0.2$ T, $\Phi \sim 3\times 10^{10}$ W/cm^2, $L = 5$ cm.

rection of revolution of the ions in a transverse magnetic field. The precision of the experimental results was estimated in terms of the rms error. The ratio β was calculated for the maximum value of the ion saturation current reaching the collector. The concentration of the ions needed to determine β was found from the expression describing the density of the ion current j_i reaching the collector $j_i = n_i e V_i$.

The ion current to the collectors in the region characterized by $\beta \ll 1$ (Fig. 3) varied with time and in space. The plasma occupied the region characterized by $-10 \lesssim \varphi \lesssim 10°$. We observed clearly the spatially separate regions, particularly at the head and rear parts of a bunch, where the ion concentration was higher. The plasma consisted of two bunches. In the middle part either the plasma was more homogeneous due to expansion of the bunches or their approach, or the spatial resolution in our measurements was insufficient.

In a region with $\beta \sim 1$ the spatial distribution of the plasma was homogeneous (Fig. 4) and the plasma expanded freely. For example, it was found[5] that a plasma boundary stopped moving in a transverse magnetic field such that $\beta = 0.15$.

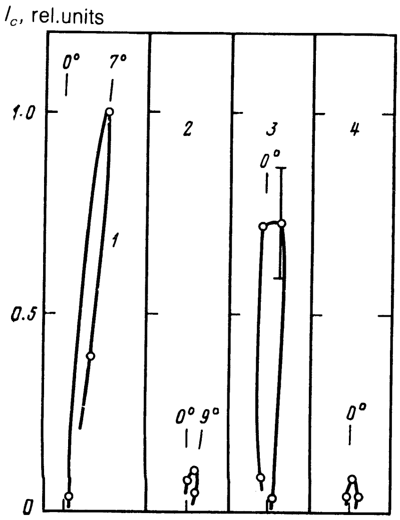

FIG. 5. Ion current reaching the collectors recorded at different moments after the formation of a plasma: 1) $t = 1.1$ μs; 2) 2.0 μs; 3) 2.3 μs; 4) 3.0 μs. The target was carbon; $B = 0.5$ T; $L = 6.5$ cm; $\Phi \sim 4\times 10^9$ W/cm^2.

Figure 5 shows the results of our determination of the ion current to the collectors for an even lower value of β_i: $\beta \lesssim 0.003$. The arrival time of the front boundary of the plasma at the collector was ≈ 1 μs from the plasma formation time. The two-bunch structure was retained but the bunches were separated in space not only in the transverse direction but also in the longitudinal direction. The size of the region (characterized by $\beta \ll 1$) occupied by the plasma in the transverse direction did not exceed 1.5 cm in a magnetic field of 0.2 T, whereas the size of each of the bunches was half that. In a magnetic field 0.5 T after longitudinal separation of the bunches the width of each did not exceed 5–6 mm. The exact transverse dimensions of the bunches were difficult to determine because of some "wandering" of the direction of expansion of each bunch within 2–3° from one laser pulse to the next. The existence of a spatial inhomogeneity in the form of two bunches in the region $\beta \ll 1$ was confirmed also by mass-spectrometric investigations.

2.2. Charge separation of ions

Figure 6a shows mass-spectrometric measurements of the total ion component of the plasma in the range with $\beta = 2$–0.5. Indeterminacy of the parameter β was related to the error in the determination of the time intervals between the laser pulse and the arrival of the plasma at the emission slit. Figure 6a gives also the integral ion current $i(t)$ found by summing the partial ion currents characterized by different degrees of ionization $i_z(t)$. Figure 7 shows an oscillogram of the ion current to the collector determined in the region where $\beta \lesssim 0.01$. The results plotted in the two figures were obtained for the same direction of expansion. The average velocity of the fast maximum of the ion current over a distance of $L_1 = 5$ cm was $(1$–$2.5)\times 10^5$ m/s. After traveling a distance $L_3 = L_2 - L_1$ between the points located at $L_2 = 6.5$ cm and L_1 from the target, the average velocity of this maximum was $(3$–$5)\times 10^4$ m/s. The average velocity of the ions in the region L_3 decreased by a factor of 3–5 compared with the average velocity of the ions in the region L_1. Therefore, a strong deceleration of the plasma was observed as it "leaked out" from the region where $\beta \sim 1$. Not only the central part of the plasma was decelerated, but also the front (head) and rear parts of the plasma bunch.

The kinetic energy W_f of a freely expanding plasma of mass M (in the region $\beta \gg 1$) became redistributed on passing through a region where $\beta \sim 1$ between the energy W_E of a plasma "capacitor" of volume Ω, the kinetic energy of expansion of a polarized plasma bunch W_p, and an increase in the internal energy of the bunch W, i.e., $W_f = W_E + W_p + \Delta W$. In the case of the experimental conditions corresponding to Fig. 6a, we deduced that $W_f \approx M\langle V_i\rangle^2/2 \approx 0.8$–$0.9$ J and $W_E \approx \varepsilon\varepsilon_0 E^2\Omega/2 \approx 0.6$–$0.7$ J, where $M \sim 10^{-10}$ kg, $\langle V_i\rangle \approx 1.3\times 10^5$ m/s, $\Omega \approx 2\times 10^{-4}$ m^3, $\varepsilon \approx 7.5\cdot 10^6$, and the value of E is deduced from the drift velocity in a transverse magnetic field using the expression $E = VB$. Hence, we found that $W_p + \Delta W \sim 0.2$ J, i.e., on going across the region of equality of the pressures there was a considerable change in the energy (and time) characteristics of a plasma bunch.

Figure 6b shows the results of a determination of the

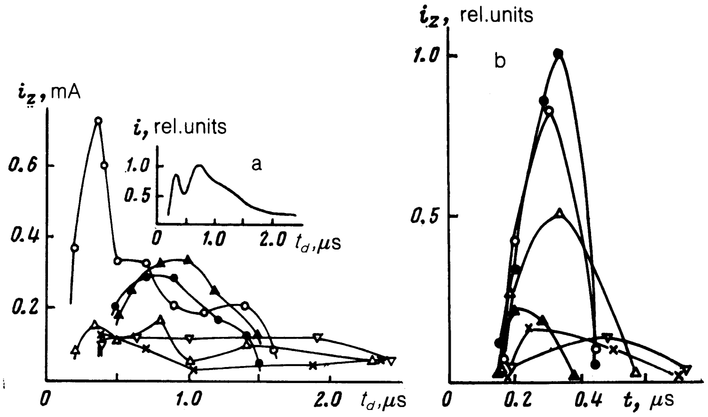

FIG. 6. Charge spectrum of the carbon ions represented by $i_z(t)$ for $L = 5$ cm: a) $B = 0.2$ T, $\Phi \sim 3\times10^{10}$ W/cm^2, $\varphi = -3°$, high-voltage pulse amplitude -3 kV, $i(t) = \Sigma i_z(t)$ is the sum of the partial currents $i_z(t)$ under the same experimental conditions; b) $B = 0$, $\Phi \sim 2\times10^{10}$ W/cm^2, $\varphi = 0°$. The experimental results are plotted for $z = 1$ (▽), $z = 2$ (×), $z = 3$ (△), $z = 4$ (○), $z = 5$ (●), and $z = 6$ (▲).

charge spectrum of carbon ions in the absence of a magnetic field, carried out using a time-of-flight mass spectrometer.[21] It is clear from a comparison of Figs. 6a and 6b that the time of arrival of the ion maximum was the same in both cases, indicating that a transverse magnetic field had little influence on the middle part of the plasma expanding up to the region of equality of the pressures, determined by us specifically for the middle part of a plasma bunch. Electrons and ions in the front and rear parts of the plasma experienced the transverse magnetic field over all the expansion paths. This was manifested by broadening of the ion distribution and a displacement of the highly charged carbon ions with $z \geqslant 5$ from the front (head) to the middle part of the plasma. The appearance of a "tail" of low-velocity ions could be due to a transverse magnetic field acting on the rear part of the plasma and by setting in motion, across the magnetic field, low-energy ions traveling at large angles from the normal to the target in the absence of a magnetic field. Some of the ions could also move along a circular orbit without crossing the magnetic field. A low-velocity tail was observed right up to delay times $t_d \sim 10\,\mu$m and it consisted of ions with $z = 1$ and 2.

Figure 8 shows the dependences of the expansion time up to the region of analysis of the ion current maxima, obtained for different values of the charge z and allowing for changes in the laser radiation flux density from $\Phi \sim 3\times10^{10}$ W/cm^2 (corresponding to $\beta \sim 1$) to $\Phi \sim 10^9$ W/cm^2 (corresponding to $\beta \lesssim 0.005$). The following characteristic features of the change in $\tau_{\max}$ were noted.

1. The expansion time decreased monotonically as z increased within the range $z \leqslant 4$, and it then increased for ions of higher charges $z \geqslant 5$.

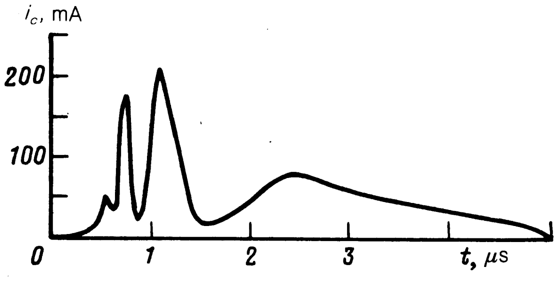

FIG. 7. Oscillograms of the ion current to the collectors. $B = 0.2$ T, $L = 6.5$ cm, $\Phi \sim 3\times10^{10}$ W/cm^2, $\varphi = -3°$.

2. The time of flight of ions with the same value of z was approximately the same when the laser radiation flux densities were $(1–6)\times10^9$ W/cm^2, provided $\beta \ll 1$.

3. There was a strong reduction in $\tau_{\max}$ for $\beta \sim 1$ for all the charged ions.

The influence of a transverse magnetic field on the higher charges $z_{\max} = 4$ was investigated for $\Phi \sim 1–2$ W/cm^2 (Fig. 9). This influence was manifested by broadening of the distribution of ions compared with the experiments in the absence of a magnetic field[22] and the appearance in $i_z(t)$ of maxima which, because of the low laser radiation flux density, could not be explained by the recombination processes occurring in the plasma. For the sake of comparison, we plotted in Fig. 9 the dependence of the current $i(t)$ for ions with the charge $z = 4$ in the absence of a magnetic field for $L = 5$ cm when $\Phi \sim 2\times10^9$ W/cm^2, in accordance with the calculations reported in Ref. 22 (this dependence is shown in Fig. 9 by a dashed curve). Our calculations were carried out using the expression

$$i(t) = (\Delta N/\Delta E)\,(8E^3)^{1/2} ze/m_i^{1/2} L,$$

whereas the dependence $\Delta N/\Delta E(E)$ was taken from Ref. 22.

In the case of heavy tantalum and bismuth ions we observed no displacement of the ions with $z_{\max}$ from the head

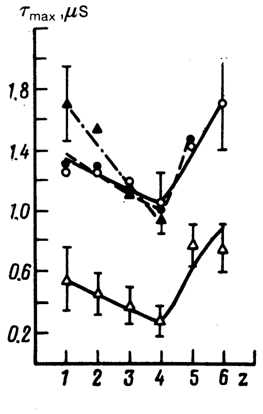

FIG. 8. Expansion time from the target to the region of analysis of the maxima of the current representing ions with different charges. $B = 0.2$ T, $L = 5$ cm, $\varphi = -3°$; △) $\Phi \sim 3\times10^{10}$ W/cm^2; ○) $\Phi \sim 6\times10^9$ W/cm^2; ●) $\Phi \sim 4\times10^9$ W/cm^2; ▲) $\Phi \sim 10^9$ W/cm^2.

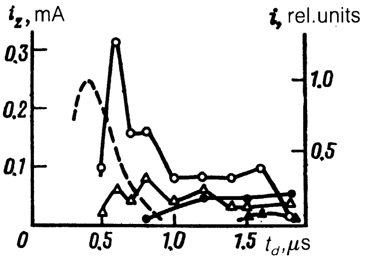

FIG. 9. Charge spectrum of carbon ions represented by $i_z(t)$ for $z = 1$ (▲), $z = 2$ (●), $z = 3$ (△), and $z = 4$ (○). $B = 0.2$ T, $L = 5$ cm, $\Phi \sim 10^9$ W/cm^2, $\varphi = +3°$, and amplitude of high-voltage pulses -3.9 kV.

part of a plasma bunch in a magnetic field, at least within the limits of the experimental error. This could also be due to a wider energy distribution of these ions, compared with the distribution of carbon in Ref. 23. Silicon and niobium ions with the maximum charge, like carbon ions, were displaced out of the head part of a bunch to the middle part.

3. DISCUSSION OF RESULTS

Our investigation, carried out at the maximum possible (in our experiments) laser radiation flux densities, showed that both the spatial distribution of ions with different charges in a plasma bunch as well as the energy spectrum of ions experienced major changes on application of a transverse magnetic field. For example, carbon ions with higher charges ($Z = 5, 6$), traveling at the maximum expansion velocity and located at the front boundary of the plasma in the absence of a field, were displaced in a magnetic field to the middle part of a plasma bunch during the time of expansion to the pressure-balance region $\beta \sim 1$ and this happened because of the shift of the energy spectrum of these ions toward lower energies. Since the ions characterized by $z = 1$–4 experienced no significant influence of a magnetic field under the same conditions, we concluded that the magnetic field interacted selectively with the ions, depending on the value of z during expansion up to the region where $\beta \sim 1$.

The observed effect can be explained by splitting the whole space traversed by a plasma into two regions characterized by $\beta \gg 1$ and $\beta \sim 1$. In the region where the condition $\beta \gg 1$ was satisfied (corresponding to the early stage of the plasma expansion) the influence of the magnetic field on the plasma characteristics could be ignored so that in this region one would expect the usual "sequencing" of the plasma ions depending on z, resulting in the concentration of the ions with the maximum value of z at the head of a plasma bunch.[24–26] Expansion of the plasma to $\beta \sim 1$ resulted in effective expulsion of the magnetic field from the inner part of the plasma because of induction currents flowing at the boundary with the magnetic field.[27,28] This decelerated the front boundary of the plasma, which was traveling at a velocity governed by the velocity of the ions with the maximum value of z. The mechanism of deceleration of the ions located at the front boundary of the plasma was described in sufficient detail in Ref. 6. Ions and electrons located at the front and rear boundaries of the plasma were magnetized. In view of the large Larmor radius, the ions were driven forward out of a plasma bunch, giving rise to an electric field which decelerated the ions. Since the leading group of the ions in a laser plasma during the initial stages of the expansion process should consist primarily of the ions with the maximum charge, these ions were decelerated most strongly and were extracted from the head part of the plasma during expansion in a transverse magnetic field. In the case of a carbon plasma with $z_{\max} \leqslant 4$, a wider energy distribution of the ions resulted in a change of the ion velocities on application of a magnetic field, which was manifested primarily by the appearance of low-velocity tails in the distribution of the ions. The mechanism of the formation of such low-velocity ions was clearly similar to that described above.

Moreover, a transverse magnetic field could affect the charge spectra of ions in a laser plasma at the early stages of formation of the velocity distributions in a plasma jet. The mass-spectrometric method used in the present study did not allow us to determine at what stage of expansion in the region $\beta \gg 1$ did multiply charged ions become displaced to the middle part of a plasma bunch.

When the boundary of the plasma reached the pressure balance region, the appearance of a magnetohydrodynamic instability at this boundary resulted in rapid diffusion of the magnetic field into the inner layer.[27] The plasma became polarized and its further motion across the magnetic field was in the form of a drift in crossed electric polarization and magnetic fields.[13]

The kinetic energy of a plasma bunch (not only in the head part but also in the inner layers) decreased because of the energy lost in the formation of the polarization layers.[13]

The two-bunch spatial structure of the plasma could be due to the two spikes in the laser radiation pulses. Laser pulses consisting of two spikes were known to create two groups of ions differing in respect of their energy[11,29] and spatial[10,11] characteristics. We did not investigate the influence of the laser pulse profile on plasma expansion in a transverse magnetic field.

The spatial structure of the plasma could also depend on the energy characteristics of the ions. When a plasma bunch crossed a region with $\beta \sim 1$ the potential energy of the ions in the charged layer could not exceed the initial kinetic energy, i.e., $qEd < m_i V_0^2/2$, was obeyed; here, q is the ion charge, d is the width of the bunch, and V_0 is the initial velocity of the bunch. This condition led[30,31] to the restriction on the width of the bunch $d < r_i/2$, where r_i is the Larmor radius of the ions. In the case of a plasma of considerable width this could result[31] in splitting of bunches of smaller width not exceeding $d' < r_i/2$ in each case. Each bunch should then drift independently across the magnetic field. In the case of carbon ions under the experimental conditions of the kind used in Ref. 32 and in our study the average degree of ionization was $\bar{z} \approx 3$ and the velocity was $V_0 \sim 10^5$ m/s. This gave an estimate $d < 0.8$ cm for a magnetic field $B = 0.2$ T. In fact, under these experimental conditions we observed the formation of two plasma bunches traveling at different angles in a transverse magnetic field and the size of each bunch did not exceed 0.8 cm.

In the case of larger masses of the ions the Larmor radius of the ions is $r_i \propto m_i V_i \propto (E_i A)^{1/2} \propto A^{2/3}$ because $E_i \propto A^{1/3}$ (Ref. 24). For this reason we did not observe the formation of two bunches for silicon targets (as in the case of carbon) under our experimental conditions. A bunch consisting of the silicon ions was spatially inhomogeneous and this was manifested by changes in the profile, duration, and amplitude of the ion current pulses recorded by collectors from one laser pulse to another. However, the time of arrival of the front of the plasma at the collectors located at various angles φ was the same for the collectors located at the same distance from the target.

In the case of heavy niobium, tantalum, and bismuth ions the Larmor radii in magnetic fields used in our experiments were considerably longer than for carbon and silicon. In the case of plasma of these elements we observed formation of just one plasma bunch traveling across a magnetic field beyond the pressure balance region.

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[1]W. H. Bostick, Phys. Rev. **104**, 292 (1956).
[2]S. Kogoshi, K. N. Sato, and T. Sekiguchi, J. Phys. D **11**, 1057 (1978).
[3]B. B. Kadomtsev (ed.), *Laser and the Thermonuclear Problem* [in Russian], Atomizdat, Moscow (1973).
[4]O. B. Anan'in, Yu. A. Bykovskiĭ, V. P. Gusev *et al.*, Preprint No. R9-80-832 [in Russian], Joint Institute for Nuclear Research, Dubna (1980).
[5]S. Sudo, T. Sekiguchi, and K. N. Sato, J. Phys. D **11**, 389 (1978).
[6]Yu. P. Raĭzer, Zh. Prikl. Mekh. Tekh. Fiz. No. 6, 19 (1963).
[7]K. D. Sinel'nikov and B. N. Rutkevich, Zh. Tekh. Fiz. **37**, 56 (1967) [Sov. Phys. Tech. Phys. **12**, 37 (1967)].
[8]D. A. Baker and J. E. Hammel, Phys. Fluids **8**, 713 (1965).
[9]C. R. Parsons and G. Jellison, J. Appl. Phys. **54**, 1631 (1983).
[10]S. V. Gaponov and M. D. Strikovskiĭ, Zh. Tekh. Fiz. **52**, 1838 (1982) [Sov. Phys. Tech. Phys. **27**, 1127 (1982)].
[11]S. V. Gaponov, V. I. Luchin, and M. D. Strikovskiĭ, Pis'ma Zh. Tekh. Fiz. **6**, 1409 (1980) [Sov. Tech. Phys. Lett. **6**, 607 (1980)].
[12]J. F. Ready, *Effects of High Power Laser Radiation*, Academic Press, New York (1971).
[13]T. Matoba and S. Ariga, J. Phys. Soc. Jpn. **30**, 1477 (1971).
[14]B. N. Gikal, I. V. Kolesov, V. B. Kutner *et al.*, Proc. Eighth All-Union Conf. on Charged-Particle Accelerators, Protvino, 1982 [in Russian], Vol. 1, Dubna (1983), p. 116.
[15]Yu. A. Bykovskiĭ, S. M. Sil'nov, and G. A. Sheroziya, Fiz. Plazmy **12**, 237 (1986) [Sov. J. Plasma Phys. **12**, 140 (1986)].
[16]O. B. Anan'in, Yu. A. Bykovskiĭ, E. D. Vorob'ev *et al.*, Preprint No. R7-7368 [in Russian], Joint Institute for Nuclear Research, Dubna (1973).
[17]O. B. Anan'in, Yu. A. Bykovskiĭ, V. P. Gusev *et al.*, Zh. Tekh. Fiz. **53**, 94 (1983) [Sov. Phys. Tech. Phys. **28**, 54 (1983)].
[18]A. S. Pasyuk, Kuo Ch'i Ts'en, Preprint No. 1523 [in Russian], Joint Institute for Nuclear Research, Dubna (1964).
[19]G. A. Mesyats, *Generation of High-Power Nanosecond Pulses* [in Russian], Sovet-skoe Radio, Moscow (1974), p. 256.
[20]I. I. Demidenko, N. S. Lomino, V. G. Padalka *et al.*, Zh. Tekh. Fiz. **35**, 823 (1965) [Sov. Phys. Tech. Phys. **10**, 640 (1965)].
[21]Yu. A. Bykovskiĭ, V. I. Dorofeev, V. I. Dymovich *et al.*, Zh. Tekh. Fiz. **38**, 1194 (1968) [Sov. Phys. Tech. Phys. **13**, 986 (1969)].
[22]S. M. Sil'nov and A. I. Suslov, Deposited Paper No. 2010-78 (Fizika) [in Russian], VINITI, Moscow (1978).
[23]G. F. Tonon, IEEE Trans. Nucl. Sci. **NS-19**, 172 (1972).
[24]Yu. A. Bykovskiĭ, N. K. Degtyarenko, V. F. Elesin *et al.*, Zh. Eksp. Teor. Fiz. **60**, 1306 (1971) [Sov. Phys. JETP **33**, 706 (1971)].
[25]W. Demtroder and W. Jantz, Plasma Phys. **12**, 691 (1970).
[26]V. V. Berezovskiĭ, Yu. A. Bykovskiĭ, S. M. Sil'nov *et al.*, Pis'ma Zh. Tekh. Fiz. **3**, 310 (1977) [Sov. Tech. Phys. Lett. **3**, 126 (1977)].
[27]D. W. Koopman, Phys. Fluids **19**, 670 (1976).
[28]L. P. Gorbachev, Magn. Gidrodin. No. 4, 81 (1984).
[29]P. E. Dyer, S. A. Ramsden, J. A. Sayers, and M. A. Skipper, J. Phys. D **9**, 373 (1976).
[30]W. Peter and N. Rostoker, Phys. Fluids **25**, 730 (1982).
[31]W. Peter and A. Ron, Phys. Fluids **26**, 2276 (1983).
[32]I. Apostol, E. Cojocaru, I. N. Mihailescu *et al.*, Rev. Roum. Phys. **21**, 1009 (1976).

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