

EXPANSION AND DIFFUSION OF A LASER PLASMA IN A MAGNETIC FIELD

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Results are presented of an experimental investigation of the radiation a plasma produced by irradiation, with Nd^{3+} laser pulses, of separate LiH particles injected into the focal region. The expansion rate of the plasma boundary and the total number of ions produced are measured and data are obtained regarding the crowding-out of the magnetic field at the initial stage. The technique of microwave radiation cutoff is used to study the nature of plasma decay in mirror and opposing magnetic fields.

INTRODUCTION

One of the interesting aspects in the study of a laser plasma is the investigation of the possibility of filling magnetic traps with hot plasma produced by laser irradiation of individual solid particles in vacuum. That relatively few experiments have been performed in this field is apparently due to a number of specific difficulties that arise when experiments of this type are undertaken. Some of them are connected with the main requirement that a sufficiently large number of target atoms must be heated and ionized in order to fill a trap of considerable volume. For example, to fill a volume of 10^4 cm^3 with plasma of density 10^{14} cm^{-3} with complete combustion of the irradiated particle, the diameter of the latter must be $\sim 0.35 \text{ mm}$ at a solid-body density 5×10^{22} atoms per cm^3 . This means the diameter of the laser beam should be $\sim 0.5 \text{ mm}$, whereas in ordinary experiments with a plasma of the laser-flare type this dimension can be made smaller by one order of magnitude, and consequently the radiation flux density can be increased by two orders of magnitude, making it possible to obtain a much higher plasma temperature at a given laser power. (Theoretical estimates and data from a number of experiments give for the plasma temperature T_e a dependence on the laser radiation flux density q at the focus of the lens in the form $T_e \propto q^\alpha$, where $\alpha = 1/3 - 2/3$). This circumstance, together with allowance for the adiabatic cooling of the expanding plasma, leads to the conclusion that it is necessary to aim, from the very outset, towards additional heating, by an independent method, of the plasma captured in the trap.

A substantial obstacle in experiments on filling magnetic traps with a laser plasma is the asymmetric structure of the plasma cloud produced at target dimensions on the order of tenths of a millimeter^[2,3] This leads to the development of convective instability^[4] and to rapid escape of the plasma from the volume of the magnetic trap. This difficulty can be overcome in part by simultaneous irradiation of the target with several laser beams from different directions, something that can be realized by a method analogous to that used by the authors in experiments with an immobile target^[3].

There is also the purely technical difficulty of injecting individual particles into the focal region with

sufficient accuracy, for when working with traps of large dimensions the travel distances will amount to tens of centimeters. The methods that have proved themselves by now are the injection of solid hydrogen particles by a shock wave^[2] and by mechanical means^[5] and injection of LiH particles with the aid of an electrostatic injector^[6].

We report here the results of an investigation of plasma produced by irradiating individual LiH particles with radiation from an Nd^{3+} laser in magnetic traps with mirror and opposing fields.

EXPERIMENT

The device for throwing the LiH particles into the focal region has been described in^[6]. The experimental setup is shown in Fig. 1. The light from a helium-neon laser 1 is scattered by the moving particle and is registered by photomultiplier 5, the signal from which is fed to the synchronization block 4, which triggers the main laser system 3, consisting of an Nd^{3+} generator with a single amplification stage. The laser is Q-switched with a Kerr cell; the half-width of the laser pulse is $\sim 30 \text{ nsec}$ and the peak power $2 \times 10^8 \text{ W}$. The laser-beam diameter at the focus of the lens was 0.6 mm , and the helium-neon laser beam diameter at

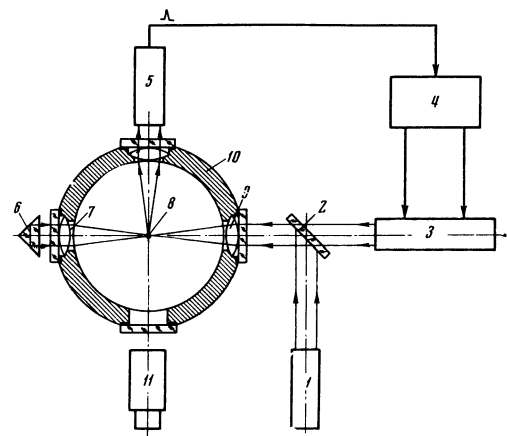


FIG. 1. Experimental setup. 1—helium-neon laser, 2—glass plate, 3— Nd^{3+} laser, 4—synchronization block, 5—photomultiplier, 6—total internal reflection prism, 7,9—lenses, 8—target, 10—vacuum chamber, 11—image converter.

the center of the chamber was 0.4 mm; the dimensions of the injected particles were 0.1–0.3 mm, and the travel distance was 20 cm.

The magnetic field was produced by two coils with inside diameter 25 mm, placed horizontally at a distance 40 mm (between centers) from each other. The laser radiation was focused at the center of the gap between the coils. The particles were injected from above through an opening in the upper coil. The magnetic field was produced by discharging a capacitor bank and had the form of a damped sinusoid with a half-period 130 μsec.

The change from the mirror-type spatial field configuration to an anti-probkotron configuration was effected by reversing the current in one of the coils. Typical values of the magnetic field were 30 kG at the center of each coil and 13 kG at the center of the chamber for a mirror configuration. The laser pulse was synchronized in time with the first maximum of the magnetic field. The total-internal-reflection prism 6 was used for additional irradiation of the target on the reverse side by part of the laser radiation not absorbed during the forward passage through the focusing region. The initial pressure in the chamber was 5×10^{-6} Torr.

To investigate the initial state of the plasma expansion, sweep photographs were obtained of the plasma glow by using a single-stage image converter camera as well as magnetic-probe and interferometer measurements. The pictures of the glow of the plasma without a magnetic field, obtained at 0.5 m distances, reveal two external weakly-glowing zones that expand at rates $(1-2) \times 10^7$ and $(2-3) \times 10^6$ cm/sec. The glow of the external fast zone is noticeable only during the time for which the target is irradiated by the laser, and is apparently connected with the formation of a hot plasma by absorption of the laser radiation in the peripheral regions of the central zone of the colder dense plasma. The second zone of weakly-glowing plasma corresponds, in all probability, to the onset of free expansion into the vacuum in the boundary regions of the central plasmoid after termination of the laser pulse. In the experiments with a magnetic field, the glows were photographed only at large distances (~ 2 m) owing to the strong induced signals in the image-converter camera. Owing to the small aperture, only the glow of the bright central zone, which expands at a rate of $\sim 10^6$ cm/sec, was registered, and the photographs obtained are analogous to those produced under the same conditions without a magnetic field.

More accurate data on the rate of expansion of the plasma boundary in the absence of a magnetic field were obtained by time-of-flight measurements with the aid of a charge collector consisting of three consecutively placed pairs of electrodes and a limiting diaphragm of 1 mm diameter (Fig. 2). The detector was installed in the horizontal plane at angles $\alpha = 45^\circ$ and $\alpha = 135^\circ$ to the laser-beam axis, at a distance 13 cm from the center of the chamber. In the obtained oscillograms (Fig. 2), the electron current for each pair of electrodes is 6–10 times larger than the ion current, this apparently being due to the larger thermal velocity of the electrons at the entrance into the detector and their larger mobility in the electric field of the collec-

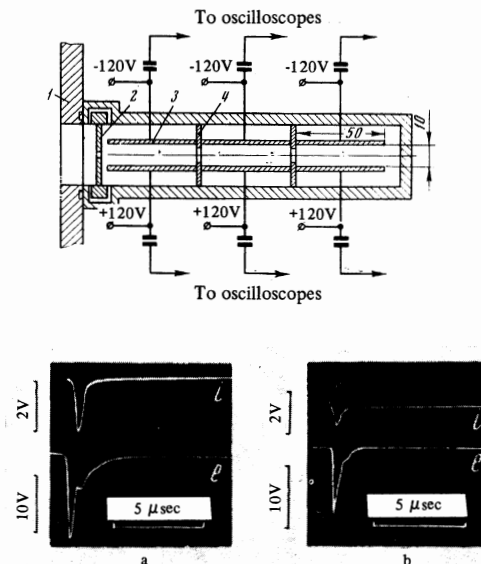


FIG. 2. Diagram of the Collector (top): 1—chamber wall, 2—diaphragm, 3—electrode, 4—insulator. Bottom half of figure—oscillograms of ion (i) and electron (e) signals at the first (a) and second (b) pairs of electrodes.

tor. The rates of expansion obtained from the time of flight to the collector and from the time shift of the signals from different pairs of electrodes amount to $\sim 1.5 \times 10^7$ cm/sec for $\alpha = 45^\circ$ and $\sim 10^7$ cm/sec for $\alpha = 135^\circ$, corresponding to ion energies ~ 50 eV for hydrogen and 350 eV for lithium. The total number of ions with the indicated energies, obtained by reducing the ion signals, is $\sim 5 \times 10^{16}$ if we assume an ion charge $Z = 1$. A comparison with the total number of atoms in a target of 0.2 mm diameter ($N \approx 4 \times 10^{17}$) shows that an appreciable fraction of the target material will apparently not succeed in becoming heated to high temperatures within the time of the laser pulse, owing to the absorption of the radiation in the boundary layers, and that recombination processes lead to a rapid annihilation of the central cold dense plasmoids after the end of the laser pulse.

The electron density in the produced plasma was measured with a Mach-Zender interferometer and a

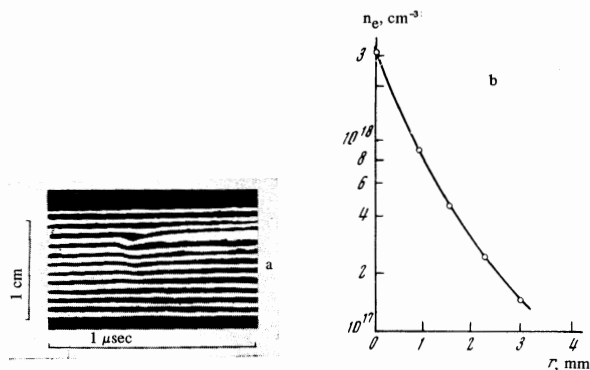


FIG. 3. Interference pattern of plasma expansion along the laser beam and profile of the electron density, plotted for the instant $t = 50$ nsec from the start of the laser pulse.

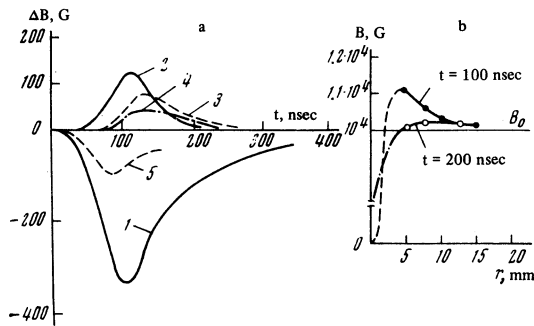


FIG. 4. Magnetic-probe measurements: a—curves 1–4 were obtained at distances 0, 5, 10, and 15 mm, respectively, from the center of the probe to the chamber axis; curve 5—variation of the average flux for a probe of 2 cm diameter; b—plots of spatial variation of the magnetic field.

ruby laser with noninstantaneous loss elimination as an illumination source. The fringe shifts were registered with the image-converter camera. Typical interference patterns and the electron-density contour obtained assuming cylindrical symmetry are shown in Fig. 3 for the instant $t = 50$ nsec after the start of the laser pulse. The general character of the interference patterns is the same with and without external magnetic fields.

The results give an estimated electron density $n_e \gtrsim (3-5) \times 10^{18} \text{ cm}^{-3}$ at the center of the plasma formation, and point to the existence of considerable plasma-concentration gradients in this region. The total number of plasma electrons, according to the interferometer measurements, is $(4-6) \times 10^{16}$, in good agreement with collector measurements of the ion charge.

The plasma temperature was estimated by measuring the absorption of the soft x-radiation of the plasma. The measurement procedure is described in^[7]. The obtained value of the temperature of the hottest regions of the produced plasmoid is ~ 20 eV.

The presented values of the temperature and density of the plasma show that during the initial stage, the gasdynamic pressure of the plasma is $nkT \gg B^2/8\pi$ and that the expanding plasma crowds out the magnetic field. The character of the crowding-out of the magnetic field was investigated with the aid of magnetic probes. The results are shown in Fig. 4 and can be summarized as follows:

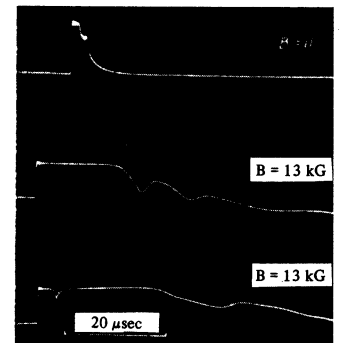
1) The deceleration and stopping of the boundary of the outer zone of a rapidly expanding plasma occurs at distances $\lesssim 5$ mm from the center.

2) The boundary between the plasma and the magnetic field is essentially blurred.

3) The magnetic field of the currents in the expanding plasma can be approximated by a dipole field. An estimate of the value of the magnetic field at the center of the plasma cloud in such an approximation indicates that the magnetic field is completely crowded out in a region of radius ~ 2 mm (dashed curve in Fig. 4b).

To study the character of the plasma decay in magnetic fields, we used the method of cutting off the microwave radiation at a wavelength $\lambda = 3.9$ mm. The electric vector of the probing electromagnetic wave

FIG. 5. Oscillograms of cutoff signal in the case of a plasma without a field and in a mirror field.



is parallel to the force lines of the mirror-configuration magnetic field.

Typical oscillograms are shown in Figs. 5 and 6. A study of the resultant oscillograms leads to the following conclusions:

1. In the case of a mirror field, the plasma decay occurs in most cases in a strongly nonmonotonic manner and is accompanied by considerable collective motions in the plasma. This may be due to the development of the flute instability characteristic of magnetic fields of convex configuration, which occurs readily if the plasma cloud has an asymmetrical structure.

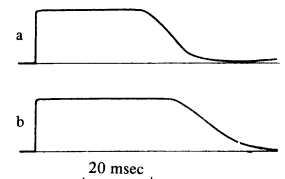
2. Decay in opposing fields appears without noticeable oscillations of the plasma density. The time during which the plasma decays to a level $\approx 10^{14} \text{ cm}^{-3}$ (the critical density for $\lambda = 3.9$ mm) is 30–40 μsec and is comparable with the time of existence of the magnetic field. This is evidence of sufficiently good filling and retention of a laser plasma in a magnetic trap of the anti-probokotron type.

3. The reduction of the smooth oscillograms (Fig. 6) obtained for the mirror field shows that in these cases the time during which the plasma density decreases from 10^{15} – 10^{16} cm^{-3} (the density value at which one can assume plasma capture by the field at a temperature of several electron volts) to the 10^{14} cm^{-3} level coincides approximately with the time of escape of the plasma through the ends of the trap, and is comparable with the time of existence of the magnetic field. The small fraction of such cases is apparently evidence that more stringent requirements must be satisfied with respect to the symmetry of the initial plasma configuration when a magnetic trap of mirror configuration is filled.

CONCLUSION

A comparison of the plasma parameters obtained by different methods indicates that the obtained values of the expansion rate, temperature, density, and total

FIG. 6. Smooth cutoff oscillogram for a plasma in a mirror field (a) and typical cutoff oscillogram in opposing fields (b).



number of particles are sufficiently reliable. The problem of the exact energy spectrum of the plasma particles, which is important from the point of view of filling magnetic traps, calls for the performance of more detailed experiments. However, even the obtained data make it possible to state with assurance that the use of lasers with quite easily realizable parameters makes it possible to produce $\gtrsim 10^{16}$ particles with energies of hundreds of electron volts by irradiating moving targets in vacuum. It should be noted that an increase of the power of the laser flux at a specified energy level (by reducing the pulse duration), for the purpose of obtaining higher temperatures, leads to a smaller total amount of evaporated mass^[8]. Therefore the most advantageous pulse for experiments on filling of magnetic traps is of "rectangular" form with a steep leading edge at an appreciable duration (several tens of nsec) and high power. The realization of these conditions encounters certain difficulties due to the shortening of the pulse when it is nonlinearly amplified in the optical-quantum-amplifier stages^[9]. The simplest way out of the situation is to irradiate the target simultaneously with several laser beams from different sides, which can be done on the basis of the described setup. Experiments of this type should be the second stage of the initiated research.

The data obtained on the plasma decay times in magnetic fields show that it is preferable to use mirrors with more complicated containing-field configurations, which ensure suppression of flute instabilities. The advantages of the developed method of plasma injection with the aid of lasers are in this case obvious.

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