Effect of magnetic field on soft x-ray radiation from laser plasma

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It is observed experimentally that in a magnetic field H ~ 200 kOe the total energy of soft x-rays from a laser plasma is reduced on the average by a factor 2.5. The explanation is that in a magnetic field the plasma shields the target from the laser radiation, owing to increase of the optical density of the luminous region. The plasma electron temperature is measured and found to be $T_e = 200$ eV.

Estimates show[1] that to raise the temperature of a laser plasma, besides increasing the light-flux power density it is expedient to employ a strong magnetic field. The magnetic field prevents gas-dynamic scattering of the produced plasma[2] and reduces the thermal conductivity, contributing to more efficient heating. It was shown in[3,4] that the brightness of a laser plasma is increased if it is produced in a magnetic field H ~ 200–300 kOe.

The purpose of this experiment was to study the effect of a strong magnetic field on the plasma parameters responsible for the intensity of soft x-radiation. A diagram of the apparatus is shown in Fig. 1. Radiation from the Q-switched laser 1 ($\lambda = 1.06\ \mu$) was focused by the lens 2 onto the surface of a copper target located in the working volume of a pulsed magnet setup[5,6]. The working volume was the cavity of solenoid coil 3 which was part of the vacuum chamber 4 in which a pressure of a few torr was maintained.

The main experiment was carried out in a field H = 200 kOe of duration ~100 μsec. The target was irradiated with laser pulses of energy from 3 to 6 J and half-width duration ~40 nsec.

The soft x-rays were recorded by two scintillation counters optically connected to photomultipliers by light pipes. Owing to the use of the light pipes, the photomultipliers were separated from the solenoid by a distance of 1 m. This prevented the stray magnetic field from affecting the operation of the photomultipliers. The recorded signal, proportional to the total energy of the x-rays, was observed on an oscillograph screen. The electron temperature was determined from the ratio of the signals produced by x-rays passing through beryllium filters of different thickness (120 μ and 270 μ), under the assumption that the separated wavelength band had bremsstrahlung and recombination continua. According to our measurements the electron temperature is $T_e \sim 200$–500 eV. The wave band separated by the beryllium filters used in this experiment was 3–10 Å at 120 μ and 3–7 Å at 270 μ.

To eliminate the effect of the fluctuations due to the non-reproducibility of the laser pulses, we determined the dependence of the x-ray intensity on the laser energy ε was determined. In the range of radiation energies used in the experiment, this dependence was approximated to a good degree by the formula $I \sim \epsilon^n$ with n ~ 8–10 (see Fig. 2).

We observed that in the presence of a magnetic field the total x-ray energy passing through each of the beryllium filters was reduced on the average by a factor 2.5 (Fig. 3). The presence of fluctuations due to the non-reproducibility of the experimental conditions precluded any quantative conclusion concerning the effect of the magnetic field on the x-ray spectrum. In most cases, however, an increase in the hardness of the spectrum was observed.

The result can be explained by resorting to the following model. The magnetic field, whose direction in our experiment coincided with that of the laser radiation, prevents radial spreading of the plasma. For this reason the plasma density in the presence of the magnetic field must be higher. Increasing the optical thick-

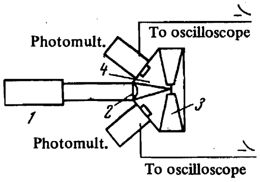

FIG. 1. Diagram of the apparatus. 1–Q-switched laser with λ = 1.06 μ; 2–focusing lens f = 7 cm; 3–solenoid producing the pulsed magnetic field; 4–vacuum chamber.

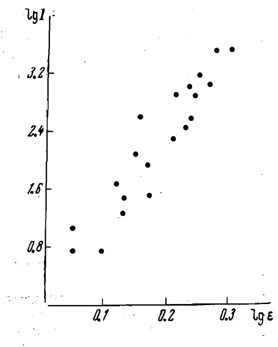

FIG. 2

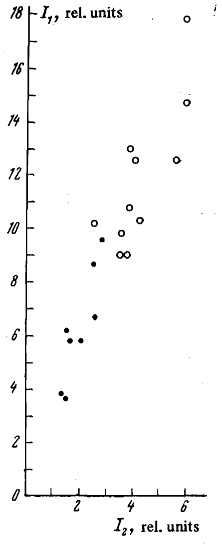

FIG. 3

FIG. 2. Experimental dependence of the x-ray intensity I on the laser energy ε ($I \sim \epsilon^n$ with n ~ 8-10).

FIG. 3. The result of one series of experiments, showing the effect of a magnetic field H ~ 200 kOe on the energy of the x-rays from the plasma at a constant average laser energy. ○–H = 0, ●–H = 200 kOe. The thicknesses of the beryllium filters are 120 and 270 μ. The scatter in each group of points is due to fluctuations in the experimental conditions.

ness in the path of a laser causes more laser energy to be absorbed (in the presence of a field). Consequently, the focused power light-flux power density responsible for the x-ray intensity decreases. For this effect to be significant, the following conditions must be satisfied: the optical density of the plasma must not be low, the magnetic pressure should be of the order of the gas-kinetic pressure, and the thickness of the plasma skin layer must be less than its transverse dimensions.

Let us make the necessary estimates. The extinction coefficient of a plasma made up of multiply charged ions can be assumed approximately equal to

$$\varkappa(\nu) = 1.45\cdot 10^{-8}\frac{n_e n_i Z_{\text{eff}}^2}{\nu^2 (kT_e)^{3/2}}, \qquad \frac{h\nu}{kT_e} \ll 1, \tag{1}$$

where kT_e is in electron volts, $\nu = 3\times 10^{14}$ sec^{-1} is the laser frequency and Z_{eff} is the effective charge of the plasma ions.

We assume an initial plasma temperature kT_e equal to 200 eV and an initial ionization corresponding to $Z_{\text{eff}} = 8$.

It was shown by Irons et al.[7] that since the surface temperature of a target irradiated by a laser pulse is at all times maintained high, the spatial distribution of ions of different multiplicity is such that the ion charge remains the same as at the focus up to a distance of ~1 mm from the target. We have taken this circumstance into account in our calculations. The length of the laser pulse in our experiment was 40 nsec. It is reasonable to estimate the extinction coefficient at an instant of time τ such that most of the pulse has not yet struck the target. For numerical estimates we have assumed $\tau = 10$ nsec. Starting with the dimensions of the crater formed on the surface of the target after the laser shot, we determined roughly the number of vaporized atoms along with the change in the plasma volume (owing to ion scattering) in the time $\tau = 10$ nsec.

The average electron temperature in the volume of the plasma at a time $\tau = 10$ nsec after the formation of the plasma turned out to be $kT_e \sim 10$ eV. Then $n_e \sim 10^{19}$ cm^{-3}, and $Z_{\text{eff}} = 10$, which when substituted in (1) yields $\kappa \sim 4$ cm^{-1}, i.e., there is sufficient absorption over the length of the flare.

For obtained plasma parameters at $H = 200$ kOe the depth of penetration of the magnetic field into the plasma at a time $\tau = 10$ nsec is $l = c\sqrt{\tau/4\pi\sigma} \sim 10^{-2}$ cm, which is less than the transverse dimensions of the plasma.

Thus, the reason for the decrease in the x-ray intensity is the additional laser-radiation absorption in the plasma because of the magnetic field. Owing to the strong dependence of the x-ray intensity on the laser energy, a 10% reduction in the laser energy reaching the target is sufficient to decrease the x-ray intensity by a factor 2–2.5. The above-mentioned increase in the hardness of the x-rays, along with the general decrease in their intensity, can be explained by assuming that besides the screening of the target in the magnetic field there is a decrease in the energy loss, through a decrease in the thermal conductivity across the field. The estimates have shown that the condition $\omega\tau_i > 1$, which is necessary for the change in the thermal-conductivity coefficient to be significant, is satisfied in the focusing region in our experiment.

Our experiment has shown that to heat a plasma efficiently in a magnetic field the recommended field geometry is one that impedes the spreading of the plasma in the direction of the laser beam. The plane of the target should then be at an angle to the direction of the optical axis. We are planning experiments with the field direction perpendicular to the optical axis and with the target at an angle to the direction of propagation of the laser radiation.

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