# Formation of directed intense vacuum ultraviolet radiation from a laser plasma

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A method is proposed for producing intense, directed VUV radiation from a laser plasma by means of multilayer normal-incidence mirrors. This method has been implemented. A radiant energy flux density of $1\times10^{7}$ W/cm$^{2}$ has been achieved in the spectral region $\lambda$ 182 Å.

The hot laser plasma produced at a target with a large atomic number $Z$ is an intense source of radiation in the vacuum-ultraviolet (VUV) part of the spectrum.[1–4] Definite progress has recently been achieved in the fabrication of highly reflecting multilayer mirrors in this part of the spectrum.[5–7] A laser plasma, with its high brightness and small emitting region, can therefore be regarded as the most efficient source for producing highly intense collimated beams of VUV radiation. Such beams might then be used as "lamps" for pumping short-wavelength lasers, in x-ray lithography, in applications in atomic physics, etc.

Our purpose in the present study was to learn about the possibility of using spherical multilayer mirrors to form intense directed VUV radiation from a hot laser plasma produced at the surface of a massive solid target with a high $Z$.

The plasma was produced by radiation at the second harmonic ($\lambda = 0.53\ \mu$m) of a Nd-glass laser with a pulse energy up to 20 J and a pulse length of 3 ns. The radiation was focused by a lens with $f = 300$ mm into a spot $\sim 30\ \mu$m in diameter on the surface of a rhenium target (atomic number 75) in a vacuum chamber (pressure of $10^{-3}$ torr).

In the experiments we used two identical Mo-Si multilayer mirrors, fabricated by

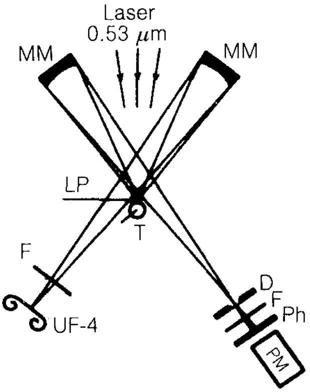

FIG. 1. Experimental layout. LP—Laser plasma; T—target; MM—multilayer mirror; F—aluminum filter; D—diaphragm; Ph—phosphor.

electron-beam evaporation[7] on a concave quartz substrate (radius of curvature of 150 mm; diameter of 27 mm). The period of the multilayer mirrors was $2d = 182$ Å; the peak reflection coefficient at normal incidence was 20%; and the spectral resolution was $\lambda/\Delta\lambda = 14$. The mirrors were positioned symmetrically, at an angle of 30° with respect to the axis of the laser beam and to the normal to the target. They produced a $2\times$ image of the laser plasma on UF-4 photographic film and in a luminescence detector (Fig. 1). This detector consisted of an FÉU-51 photomultiplier and a glass plate coated with a layer of sodium salicylate, 3–7 mg/cm$^2$ thick. Since the quantum yield of sodium salicylate in the wavelength interval 100–3400 Å is constant,[8,9] an absolute calibration of the quantum yield of the detector was carried out at the wavelength $\lambda = 3080$ Å (the output from a XeCl excimer laser). Using the detector calibrated in this way, we also carried out an absolute calibration of the UF-4 film at the wavelength $\lambda = 182$ Å.

As filters for the visible light in the experiments we used pieces of aluminum foil 0.6 and 1.2 $\mu$m thick. The transmission of the filters at the wavelength 182 Å was measured independently and found to be 15% and 1.9%, respectively. Control experiments showed that the signal from the visible emission of the plasma which passed through microscopic holes in the foils amounted to no more than 1% of the VUV-radiation. To estimate the contribution of long-wavelength radiation, which is determined by the passband of the aluminum filter ($\lambda = 170$–700 Å; Ref. 10) and by the reflection coefficient of the multilayer mirror outside the selective region, we replaced the multilayer mirror by a mirror with a tungsten coating. The measured signal decreased by a factor of no more than five as a result. Consequently, the contribution to the plasma emission signal outside the selected region of the multilayer mirror, $\lambda$ 182 Å, is no more than 20%.

Our basic purpose in these experiments was to measure the flux density of the radiant energy, $q$, in the region $\lambda$ 182 Å in the plane in which the laser plasma was imaged by the multilayer mirror. Measurements were carried out by two methods: from the intensity distribution in the spot on the UF-4 film and by inserting diaphragms of various diameters in front of the detector. Figure 2 shows the results of measurements of the flux density $q$ versus the energy of the laser pulse. The duration

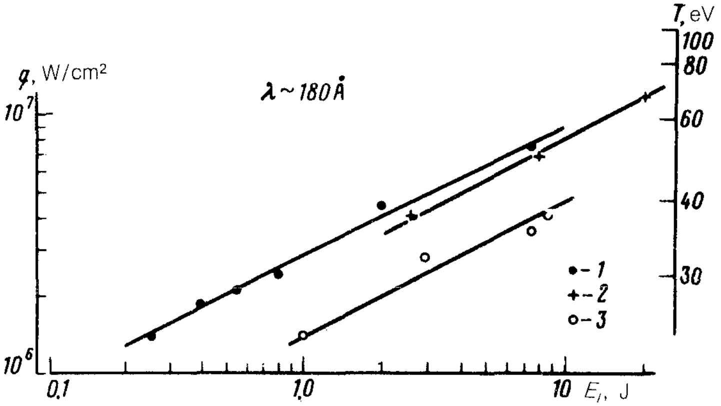

FIG. 2. The flux density ($q$) of the VUV radiation in the region $\lambda$ 180 Å and the corresponding plasma brightness temperature $T$ versus the energy of the laser pulse, $E_l$. 1—Peak value of $q$ found from the intensity distribution on the photographic film; 2—average value of $q$ found from measurements with a luminescence detector and a diaphragm 120 $\mu$m in diameter; 3—the same, 220 $\mu$m in diameter.

of the VUV radiation was assumed to be the duration of the laser pulse (see Ref. 3, for example). From these results we can determine the distribution of the brightness temperature $T$ in the laser plasma (Figs. 2 and 3). It can be seen from Figs. 2 and 3 that the maximum flux density in the region $\lambda$ 182 Å reaches $q = 1 \times 10^7$ W/cm$^2$, and the brightness temperature is $T \sim 70$ eV. We estimate the measurements of the energies to be accurate within a factor of two; we are reporting the lowest values here.

The length scale of the emitting region in the plasma, $\sim 100$ $\mu$m (Fig. 3), makes it possible to use multilayer mirrors to produce collimated beams of VUV radiation with a divergence no worse than $10^{-3}$ rad in the wavelength interval 100–600 Å.

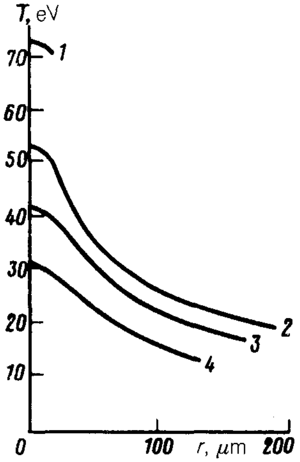

FIG. 3. Radial profile of the brightness temperature $T$ at a target surface for various energies of the laser pulse. 1—$E_l = 20$ J; 2—7.5 J; 3—3.0 J; 4—0.8 J.

Normal-incidence multilayer mirrors are presently available for this interval.[5-7] The monochromaticity of the VUV radiation in this study, $\lambda/\Delta\lambda = 14$, was set by the spectral selectivity of the multilayer mirrors. It is possible to choose a particular target material and particular illumination conditions such that the reflection band of the multilayer mirror contains a strong isolated line, so it becomes possible to achieve a monochromaticity $\sim\lambda/\Delta\lambda_{\text{Doppler}} = 10^3$–$10^4$. The efficiency at which the laser-beam energy ($E_l$) is converted into VUV radiation, $E_{\text{VUV}}$, produced by the multilayer mirror, was $\eta = E_{\text{VUV}}/E_l = 10^{-5}$–$10^{-6}$ in the present experiments. By optimizing the experimental geometry, by choosing a target material to maximize the radiation yield in the region $\lambda$ 182 Å, and by using a multilayer mirror with a larger aperture, one can increase the values of $q$ and $\eta$ by one or two orders of magnitude. There have been recent reports of the observation of an amplification of stimulated emission in the VUV part of the spectrum on transitions in multiply charged ions, SeXXV $\lambda$ 206–209 Å (Ref. 11) and CVI $\lambda$ 182 Å (Ref. 12), in laser plasmas. The conversion efficiency in these experiments has been $\eta = 10^{-10}$–$10^{-5}$.

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