Grazing-incidence ellipsoidal reflector for longitudinally pumping short-wavelength lasers

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We propose using a prolate ellipsoid for collecting and focusing soft-x-ray radiation from a laser-produced plasma to longitudinally pump short-wavelength lasers. Total collection efficiencies greater than 20% at 10 nm into gain regions with aspect ratios of 25 are possible. This geometry offers several advantages with respect to present transverse multiple-spot geometries.

In 1975 Duguay[1] suggested the use of laser-produced plasmas to pump short-wavelength lasers, and recent work[2] has shown that such plasmas can be practical and efficient sources of incoherent soft-x-ray radiation. Caro *et al.*[3] used a laser-produced plasma to produce large populations of excited metastable ions. That study used a geometry in which the plasma-generating laser beam propagates through a vapor of the active species to hit a heavy-metal target in the cell and the emitted soft x rays excite atoms in the surrounding vapor. Population is measured and fluorescence observed along an axis parallel to the target surface and perpendicular to the plasma-producing laser beam. Silfvast *et al.* have used a similar geometry to construct visible and ultraviolet lasers in Cd and Zn.[4]

Although it is appealingly simple, the direct pumping geometry has two major problems. First, amplified spontaneous emission (ASE) within the pumped hemispherical region can significantly shorten the upper-level lifetime and/or lead to self-termination by filling the lower laser level.[5] Second, the high vapor density required to absorb the pumping x rays efficiently within the narrow transverse region of interest can result in high electron densities, fast collisional deexcitation, and large Stark-broadened linewidths. In this Letter we describe a longitudinal pumping technique that significantly reduces these problems. The basic geometry is shown in Fig. 1; a section of a prolate ellipsoid is used to reflect, at grazing incidence, the soft-x-ray radiation from a laser-produced plasma located at one focus to the active atomic species located along the axis in the region of the second focus. The resulting high aspect ratio—the ratio of the length to the diameter of the pumped region—significantly reduces ASE effects, and pumping along the axis lowers the pressure required. In addition, removal of the plasma target from the active medium simplifies spectral filtering of the pumping radiation and prevents the active medium from affecting plasma generation or radiation processes.

Surfaces of revolution have been used to construct x-ray microscopes and telescopes. In those applications the primary requirement is accurate point-to-point imaging in a single plane, and usually this can be achieved only by using very short sections of the reflecting surface, resulting in typical collection efficiencies of 0.01%. Pearlman and Benjamin[6] used the long central section of an eccentric ellipsoid to collect radiation from a laser-produced plasma with an efficiency of 0.34%. They showed that the optic could focus the energy into a small spot in the focal plane suitable for nonimaging diagnostics such as calorimetry. Our analysis shows that a judicious choice of the ellipsoidal reflector can improve this collection efficiency significantly.

We use a numerical ray-tracing program to calculate the collection and concentration properties of ellipsoidal reflectors along the axis near the second focus for various values of the ellipsoid semiminor axis b and half-focal spacing c. The radiation emitted from the laser plasma target is assumed to have an angular distribution function proportional to the cosine of the angle from the target normal.[7] The reflectivity of the ellipsoid surface is modeled by a simple straight-line approximation to the data of Malina and Cash[8] for a gold surface at 10.4 nm. The reflectivity is taken as 1.0 for grazing angles of incidence less than 3 deg and 0.0 for angles greater than 25 deg, and a linear interpolation is used for angles between those limits. The ray-tracing program calculates the fraction F of the total source radiation relayed to an output plane and

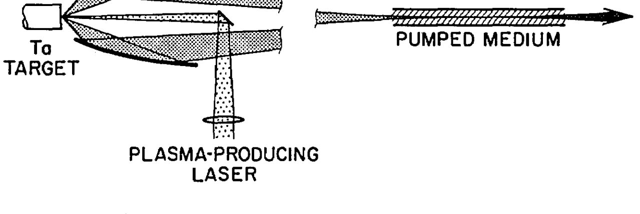

Fig. 1. Schematic of longitudinal pumping using a prolate ellipsoidal reflector.

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the spatial distribution of the radiation in that plane. Both ideal point sources and extended disk-shaped sources were considered.

Figure 2(a) shows the fraction of the source energy delivered to the focal plane as a function of the ellipsoid shape; this fraction is independent of the source size. Achievement of collection efficiencies greater than 25% is possible by using highly eccentric ellipsoids, $b/c \leq 0.1$. These results are for a section of the ellipsoid extending from the source to the midplane, but it is important to note that most of the energy is collected by a small length of the optic close to the focus. This is illustrated in Fig. 2(b), which plots the collected fraction as a function of distance along the optic measured from the source. The surface near the source subtends a large solid angle of the emitted radiation, and this more than compensates for the reduced reflectivity that is due to large angles of incidence until, close to the source, the angle becomes so large that the reflectivity falls to zero. (It is the rapidly varying angle of incidence that makes this portion of the reflector particularly unsuitable for true imaging applications.) Thus for eccentric ellipsoids it is important to use a section that starts as close to the source as practical, and little is gained by using sections longer than $c/3$.

The transverse and longitudinal spatial profile of the focused radiation depends on the source size and the ellipsoid shape. For a point source and a perfectly accurate surface, the radiation is focused into an annular cone, which converges to a point at the second focus. The convergence half-angle θ_F is determined by the maximum radius of the optic and its distance from the focus. For the short sections of eccentric ellipsoids considered here $\theta_F \approx (1/2)(b/c)$. Finite source sizes blur this pattern, filling in the central hole and eliminating the focal singularity. The qualitative nature of the focal pattern can be determined by applying conservation of optical êntendue[9] between the source and the focal plane, i.e., $A_S \Omega_S = A_F \Omega_F$, where A and Ω are the area and the solid angle, respectively. The source area A_S is determined by the power density required to produce a plasma with the desired blackbody temperature[1] and/or by the plasma-producing laser characteristics; the solid angle Ω_S intercepted by short ellipsoid sections is typically $\sim\pi/3$ sr. The solid angle at the focus is $\pi \theta_F^2$, and the focal area is given by $A_F \approx A_S/(b/c)^2$. The area remains within a factor of $A_F/2$ over a length of $L_F \approx 4\sqrt{A_S}/(b/c)^2$, and the aspect ratio of the pumped region is $2\sqrt{2}/(b/c)$. Thus, for $b/c = 0.1$, the optic will produce a linear magnification of the source of 10 with an aspect ratio of about 25. We note that the aspect ratio might be further increased by placing a tube of area $\sim A_F$ at the second focus. Because of the small convergence angle of the radiation, grazing-incidence reflection inside the tube should be effective in confining the radiation for several times L_F.

For the simple case of an optically thin active medium, laser gain along the axis is proportional to the product of atomic number density, length, and pumping power density. We define a normalized integrated pumping $\propto$density as $P \equiv FL_F/A_F \propto F/\sqrt{A_S}$. Thus small source sizes are advantagous; eccentric ellipsoids are also desirable since F is larger for small values of b/c. If, however, laser power density on target is limited by the desired plasma blackbody temperature, then the available pumping power will be proportional to A_S, and $P \propto F\sqrt{A_S}$.

These general results are borne out by detailed ray tracing. We calculate an average pumping density for a particular output plane by finding the diameter d that encompasses 50% of F and dividing $F/2$ by the area $\pi d^2/4$. The integral of the pumping density along the axis in the region of the focus, P, is plotted in Fig. 3 for a 100-μm-diameter source and three el-

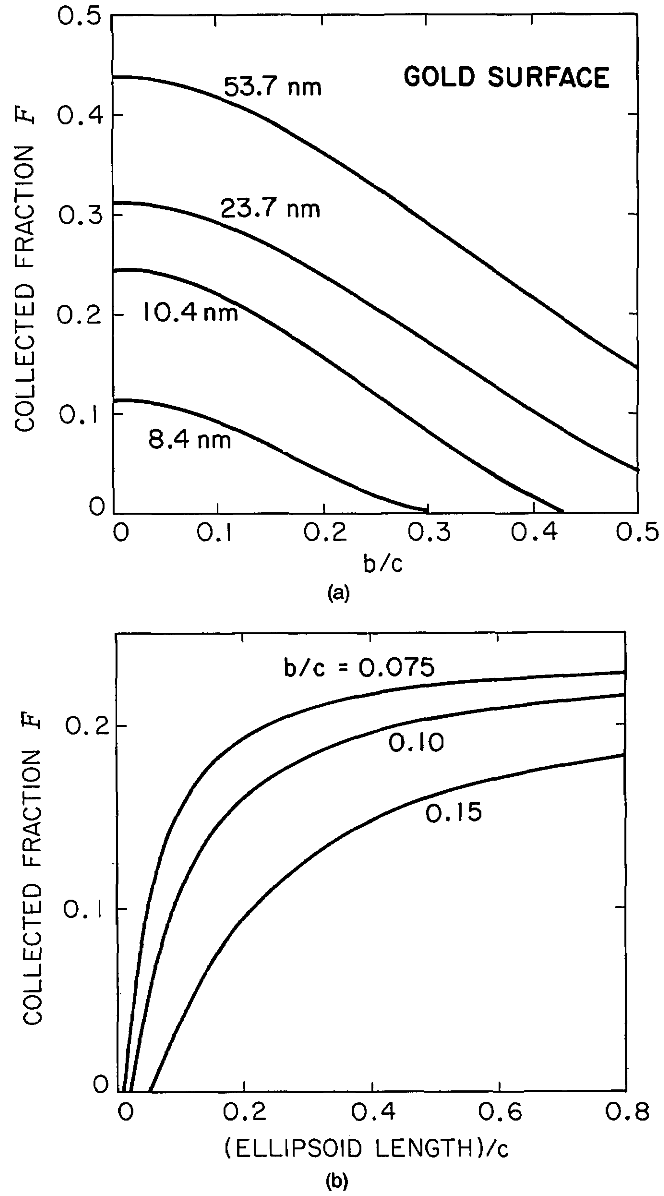

Fig. 2. (a) Fraction F of the source energy delivered to the focal plane versus ellipsoid shape for several wavelengths, based on the reflectivity data of Ref. 8; b/c is the ratio of the semiminor axis to the half-focal separation. (b) Collected fraction F versus ellipsoid length for three values of b/c. Length is measured from the source point and normalized to $c \equiv 50$ cm.

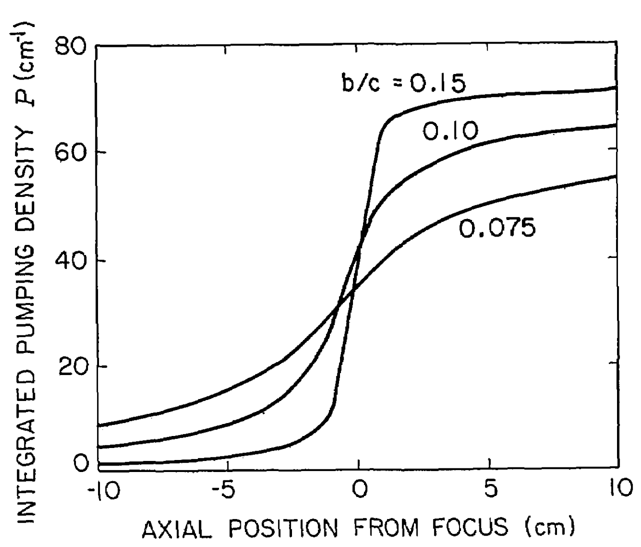

Fig. 3. Integrated pumping density P in the region of the focus as a function of ellipsoid shape. The focal plane is located at 0, and the integration is started at −50 cm. The source diameter is 100 μm, and $c = 50$ cm for all three cases.

lipsoids of different shape. The focal plane is located at 0, and the lower limit of the integral is −50 cm. The least eccentric ellipsoid has a large convergence angle, which produces a high pumping density concentrated at the focus and a low aspect ratio. In contrast, the most eccentric ellipsoid distributes the collected energy over a long region with high aspect ratio. Such a reflector eliminates regions of high power density but provides lower incremental gain per unit length.

Clearly, choices of ellipsoid shape, source size, and zone length are interrelated and dependent on the specific parameters of the system being pumped. Nevertheless, it is possible to compare the gain expected using the longitudinal geometry described in this Letter with that using a multispot direct-pumping geometry. We assume an identical total laser power focused to a single spot of area A_S in the first case, and distributed equally among q spots in the second case, each focused tighter so that the plasma blackbody temperature is the same. The number of spots q and the perpendicular distance from the targets to the gain axis $d_\perp$ are determined by the maximum pumping flux desired. If the ellipsoid shape is chosen to provide the same flux, then the ratio of the integrated pumping density for the longitudinal to the multispot case is $R \approx 3Fd_\perp/\sqrt{A_S}$. For the typical values $F = 0.20$, $d_\perp = 1$ cm, and $\sqrt{A_S} = 200$ μm, $R = 30$. If, however, the source area must be larger in order to obtain a lower plasma blackbody temperature, longitudinal pumping would be less favorable; alternatively, if the peak pumping flux is limited by system properties, then $d_\perp$ or q must be increased and longitudinal pumping becomes even more attractive.

In summary, we have described a longitudinal pumping geometry for soft-x-ray lasers that uses grazing-incidence ellipsoidal reflectors. Its advantages include a high aspect ratio, lower pressures, spectral filtering, removal of the plasma from the active medium, and potentially higher gains. For this low-resolution, nonimaging application, the surface accuracy and finish requirements of the optic appear to be quite moderate. For example, for $c = 50$ cm and a focal spot diameter of 4 mm, the surface slope error can be as large as 2 mr and scattering will not be important unless surface roughness exceeds ~2-nm rms amplitude at spatial frequencies above 0.05 μm^{-1}.[10] These requirements can be met by standard diamond-turned surfaces with light polishing.[11] Debris ejected from the target, however, can degrade the quality of the surface in time. Our initial experiments indicate that this problem is greatly reduced when free-standing thin-film (250-nm) targets are used. In addition, an electroformed[12] or lacquer-coated[13] reflector could be used; the first is disposable, and the second is easily stripped and recoated.

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