Section 3
ADVANCED TECHNOLOGY DEVELOPMENTS

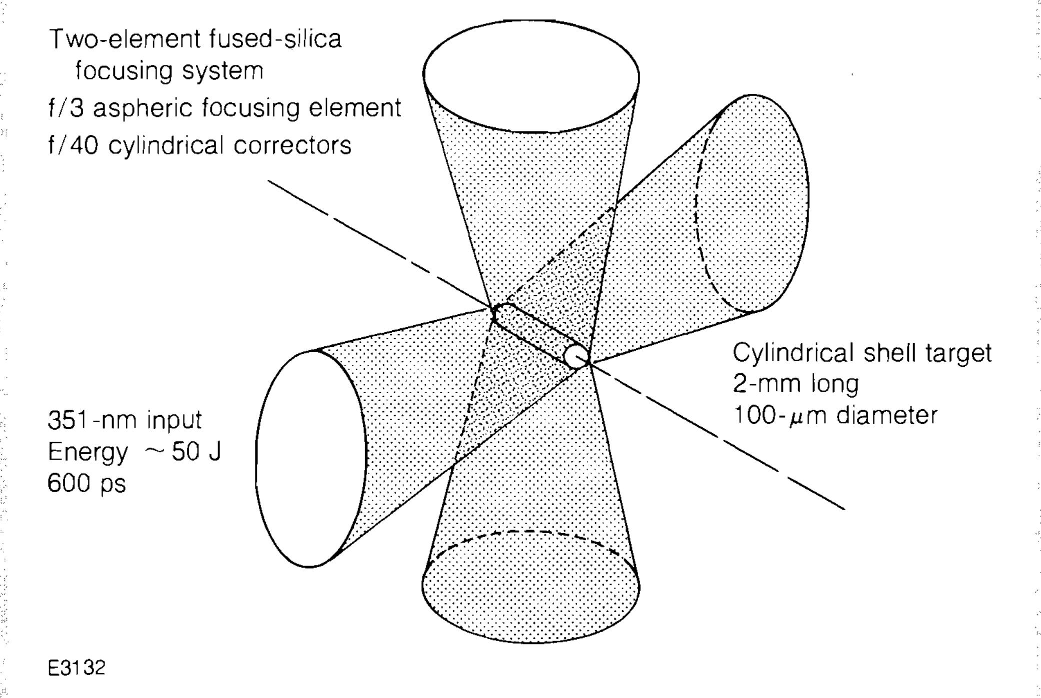
3.A Multibeam, Laser-Imploded Cylindrical Plasmas

Many proposed x-ray laser schemes incorporate a linear, high-density, high-temperature plasma generated by a cylindrically focused beam, or by multiple spherically focused beams from a high-intensity laser.[1] For the plasma to be optimum as an x-ray laser medium, it should not only have density and temperature conditions appropriate for maximum population of the x-ray laser ion states, but also a geometric shape and uniformity of plasma conditions conducive to providing high x-ray gain along the axis of the plasma. Most experimental studies of collisionally excited or recombination x-ray laser schemes have so far used expanding plasmas created by focusing a laser on a solid target. The characteristics of such plasmas produced by spherically focused laser beams have been investigated in great detail because of their application to laser-fusion studies; plasmas created by cylindrically focused laser beams have not been examined so thoroughly.[2] In many respects, plasmas produced by short, intense laser pulses focused on solid massive targets are not ideal for x-ray laser schemes. These plasmas have steep density and temperature gradients across which ion state populations are rapidly varying, making the conditions for x-ray gain highly transient. Moreover, refraction of x rays on the plasma density profile can contribute to a reduction in gain. These detrimental factors are compounded by the microscopic variations produced in the plasma profile by the small-scale variations in the intensity profile of most focused laser beams. These limitations can be alleviated with simple changes to the target design.

One approach to producing a more uniform plasma in which the effects of nonuniformities in the irradiating beam are smoothed out is to form the plasma from an exploding thin foil. This may be achieved effectively by suprathermal electrons generated by resonance-absorption in interaction with a short-pulse ($\lesssim$ 100 μm), intense ($>10^{14}$ W/cm^2), long-wavelength (>1-μm) laser. Similar conditions may be achieved with intense, short-wavelength radiation where rapid decompression of the foil results from shock and radiational heating. Alternatively, targets consisting of low-density material ($n < n_{solid}$) may also be good candidates for x-ray laser media, although the effects of self-induced, whole-beam self-focusing may have to be taken into account.

We describe here two novel approaches to the development of a linear uniform medium suitable for x-ray gain conditions. Both these approaches depend upon the ability to uniformly compress cylindrical targets with multiple, line-focused laser beams. Here, we present some initial investigations of these approaches performed with four line-focused beams of the upconverted 351-nm OMEGA facility.[3] The four beams, each producing ~50 J in ~600 ps, were focused orthogonally onto the cylindrical target (Fig. 21.17) by an f/3.7 fused silica lens combination comprising a high-power aspheric singlet lens and a close-coupled spherical cylindrical corrector plate. The focused beams produced a line focus of length 1700 μm and width $\gtrsim$50 μm. Average irradiation intensities of ~10^{14} W/cm^2 were produced when the beams were focused onto 100-μm-diameter targets with the four orthogonal beams tangentially overlapping the target. The four beams were co-aligned with aid of a reflective solid cylindrical surrogate target, from

Fig. 21.17
Four-beam compression of cylindrical targets with 351-nm, four orthogonal line-focused beams of OMEGA.



which fiducials were transposed to fixed high-resolution viewing systems for positioning the irradiated targets. Individual beams were aligned in position to an accuracy of ~20 μm and were oriented parallel to one another within $\sim 10^{-2}$ radians. The axis of the cylindrical target could be set to an axis fixed to the enclosing vacuum chamber to an accuracy of 3×10^{-3} rad.

Two types of imploding targets were investigated, and they were compared to a solid Al cylinder target (see Fig. 21.18). The first, shown in Fig. 21.18(a), comprised a 100-μm-diameter CH cylindrical shell, 3- to 5-μm thick, and the inside of the shell was coated with a 0.3-μm-thick layer of Al. The CH in this target serves as an ablator, and its thickness was chosen to equal the ablation depth for an intensity of $\sim 10^{14}$ W/cm^2. Thus, the Al layer is subjected to minimal heating until it stagnates at the center of the target. Cylindrical, 1-D (*LILAC*) Lagrangian hydrodynamic code calculations indicate the Al reaches final density and temperature of 10^{22} cm^{-3} and ~500 eV, respectively, over an extent of ~40 μm. Being ablatively driven by short-wavelength radiation, this target is sensitive to irradiation nonuniformities resulting from the use of only four beams. The final core density is higher than optimum for most soft x-ray laser schemes. This can be reduced by coating a thin (~0.015-μm), high-Z (Au) material on the outside of the CH shell. The initial burst of x-ray emission from the Au shell penetrates the CH and preheats the Al before it is compressed. The resulting in-flight decompression of the Al should reduce the final core density without leading to a reduced core temperature.

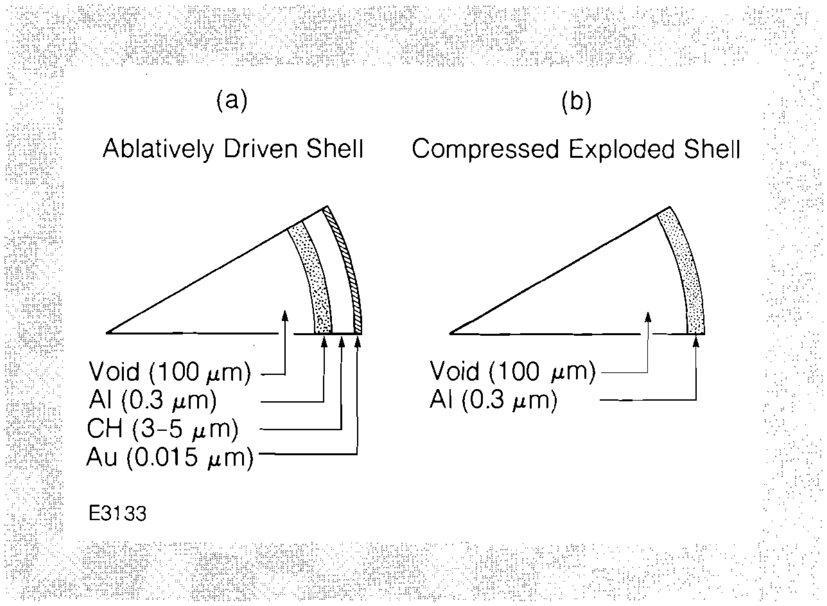


Fig. 21.18
Cylindrical shell targets investigated for the production of linear high-density, high-temperature plasma conditions.

The second type of cylindrical target is shown in Fig.21.18(b). This consists of an ultrathin (0.3-μm) Al cylinder of 100-μm diameter.[4] Upon irradiation, this shell quickly explodes and, according to *LILAC* calculations, the decompressed shell is rapidly imploded. Following stagnation of the implosion, the high-temperature core unloads radially, producing a cylindrical, high-temperature plasma (Fig. 21.19). From Fig. 21.19, it can be seen that two regions of the plasma possess parameters suitable as an x-ray laser medium. The narrow central region reaches densities

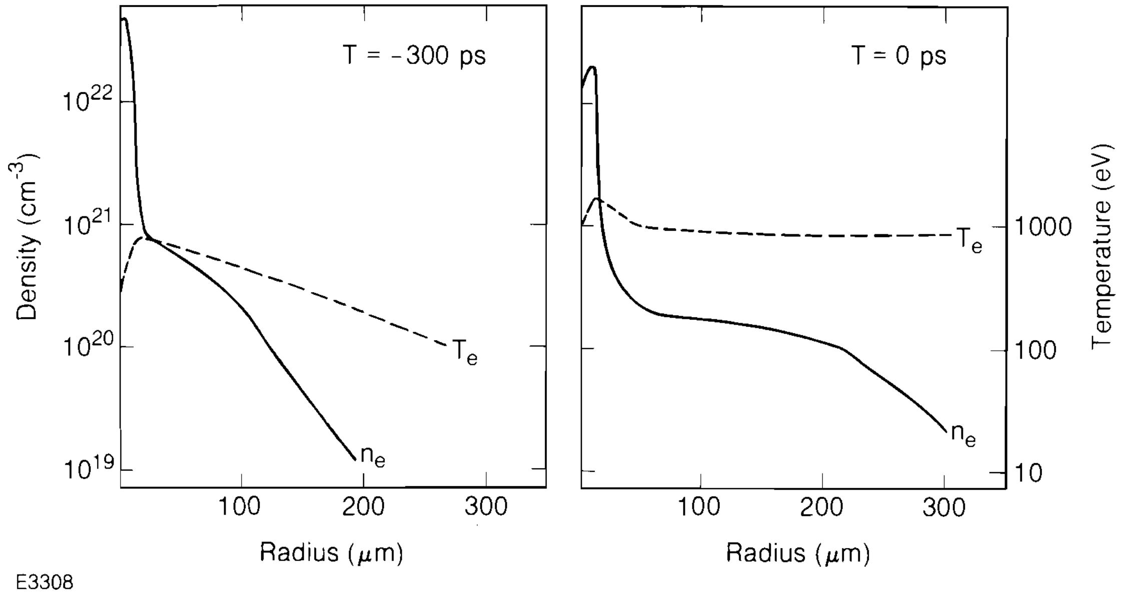


Fig. 21.19
Density and temperature profiles predicted by the 1-D code LILAC *for the thin Al cylindrical target shown in Fig. 21.18(b).*

higher than 10^{22} cm^{-3} over a radial extent of 10–20 μm with a temperature of several hundred electron volts. Although the code predicts a minimum in the electron temperature on axis, it is likely that the temperature in this region would be smoothed by small-scale inhomogeneities. This high-density, high-temperature region persists for some time (~ 100 ps) following the implosion, and, therefore, offers a potentially optimum medium for x-ray amplification. The underdense region of the plasma is maintained by flow of plasma from the dense core. Under the influence of continuing absorption during the remainder of the laser pulse, a long, radially expanding plateau of plasma having an electron density larger than 10^{20} cm^{-3} is produced. Almost stationary in profile, and with an electron temperature approaching 1 keV, this plasma provides conditions generally considered optimum for collisional excitation or recombination-pumped laser schemes.

Several experiments were performed with the four orthogonally oriented, line-focused, 351-nm beams of the OMEGA system using the targets depicted in Fig. 21.18, and the results were compared with those of the experiments using uniformly irradiated, solid Al cylindrical targets of the same diameter. Diagnostics included plasma calorimetry, x-ray photography, time-integrated x-ray spectroscopy, and time-resolved x-ray spectroscopy.

Absorption was measured with an approximately isotropic array of 20 plasma-calorimeters. These registered a uniform plasma blow-off distribution, with overall absorption of ~ 50% for the solid and ablatively driven cylinders, and typically ~ 44% for the thin Al cylinders. This is about a factor of 2 less than that measured for spherical targets at this intensity. Excluding the possibility that there is a higher plasma blow-off along the axis, which was not measured, this implies that a considerable fraction of the beam energy was missing the target. Apart from x-ray photography studies of the extent of the line focus, no optical measurements of the focal distribution have been made. From previous studies of line focus distributions,[2] an intensity distribution in which about half of the energy is in a broad, low-intensity component is not unexpected.

X-ray image data of these types of targets irradiated are shown in Fig. 21.20. The x-ray image of the solid Al target [Fig. 21.20(a)] qualitatively indicates the apparent uniform illumination of the target in cylindrical geometry. Figure 21.20(b) shows the x-ray image of an ablatively driven Al shell. Weak x-ray emission from the core of the imploded shell can be observed. However, its uniformity along the 2-mm length of the target is poor, as is the linearity of the compressed core. Figure 21.20(c) shows the x-ray image of a compressed, thin (0.3-μm) Al shell. The resulting x-ray emission (0.8–1.2 keV) is uniform and collinear with the original cylinder axis, and its radial extent (~ 25-μm diameter) is in good agreement with the *LILAC* predictions.

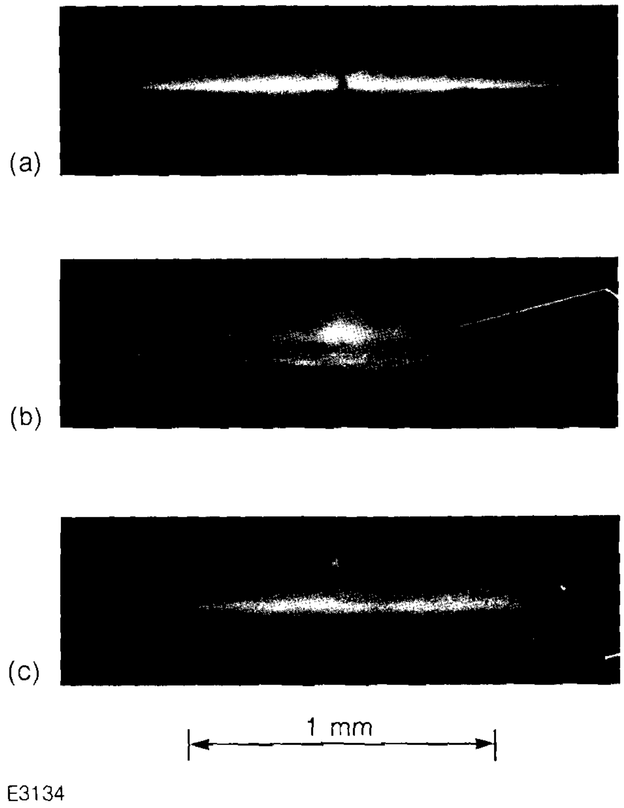


Fig. 21.20
X-ray photographs of three types of cylindrical targets irradiated by four orthogonal beams of OMEGA.
(a) a solid Al cylinder of 100-μm diameter,
(b) an ablatively driven plastic shell having a thin, linear Al shell, and
(c) a 3000-Å, thin Al shell of 70-μm diameter.

The overall relative x-ray conversion was measured with the low-energy channels ($E < 3$ keV) of a 15-channel, K-edge-filter pin diode/photomultiplier-scintillator x-ray continuum spectrometer. Assuming isotropy of x-ray emission, the x rays from the CH ablative target, the Al-coated ablative target, the thin Al target, and the solid Al target were in the ratio 0.02:0.1:1.3:1.0. Time-resolved x-ray spectroscopic studies of the x ray emitted from the line plasma were made with two streak spectrographs.

A streak transmission-grating spectrograph[5] comprising a freestanding Au bar grating (period 3000 Å, and thickness ~1 μm) displayed first-order spectral emission in the range 1–30 Å across the Au on CH soft x-ray photocathode of a streak camera. The second time-resolved spectrograph is sensitive in the 5- to 7-Å region and consists of an elliptical crystal dispersive element in conjunction with a CsI-on-Be photocathode-streak camera. The time resolution of both units is <20 ps.[6] Figure 21.21 shows typical spectra from the latter instrument for two types of cylindrical targets: a solid Al cylinder target and a thin Al shell cylinder. The He-like and H-like resonance line emission is evident in both spectra. The emission from the solid cylinder results from coronal plasma ablating from the target, and its duration is consequently of the same order as the laser pulse duration. The duration of the x-ray line emission from the imploding Al cylindrical target is significantly shorter (~150 ps). The major part of the x-ray emission occurs before the peak of the laser pulse, the implosion of the shell occurring on the rising edge of the pulse. Detailed analysis of these spectra is planned to obtain greater characterization of the plasma conditions.

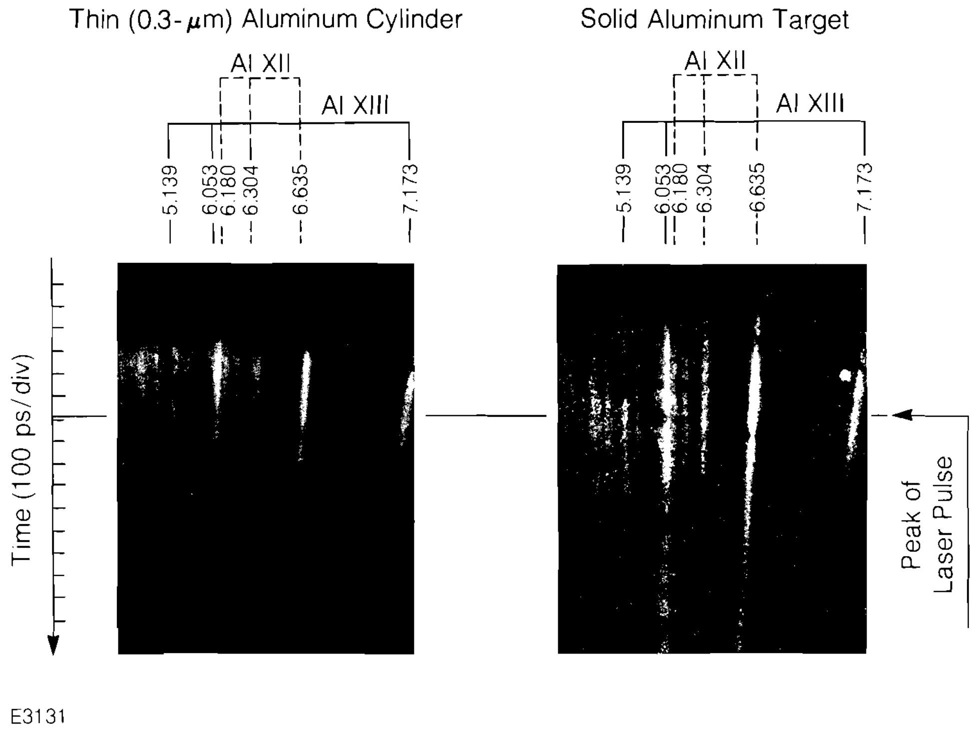


Fig. 21.21
Time-resolved x-ray line spectra recorded from cylindrical targets.

This initial investigation of the plasma created by imploding cylindrical targets has provided some interesting data from which future studies can optimize the production of linear plasmas suitable as x-ray laser media. From the present studies it is clear that thick, ablatively driven cylindrical shells will only implode symmetrically under illumination conditions more uniform than those used in these investigations.