Section 3
ADVANCED TECHNOLOGY DEVELOPMENTS

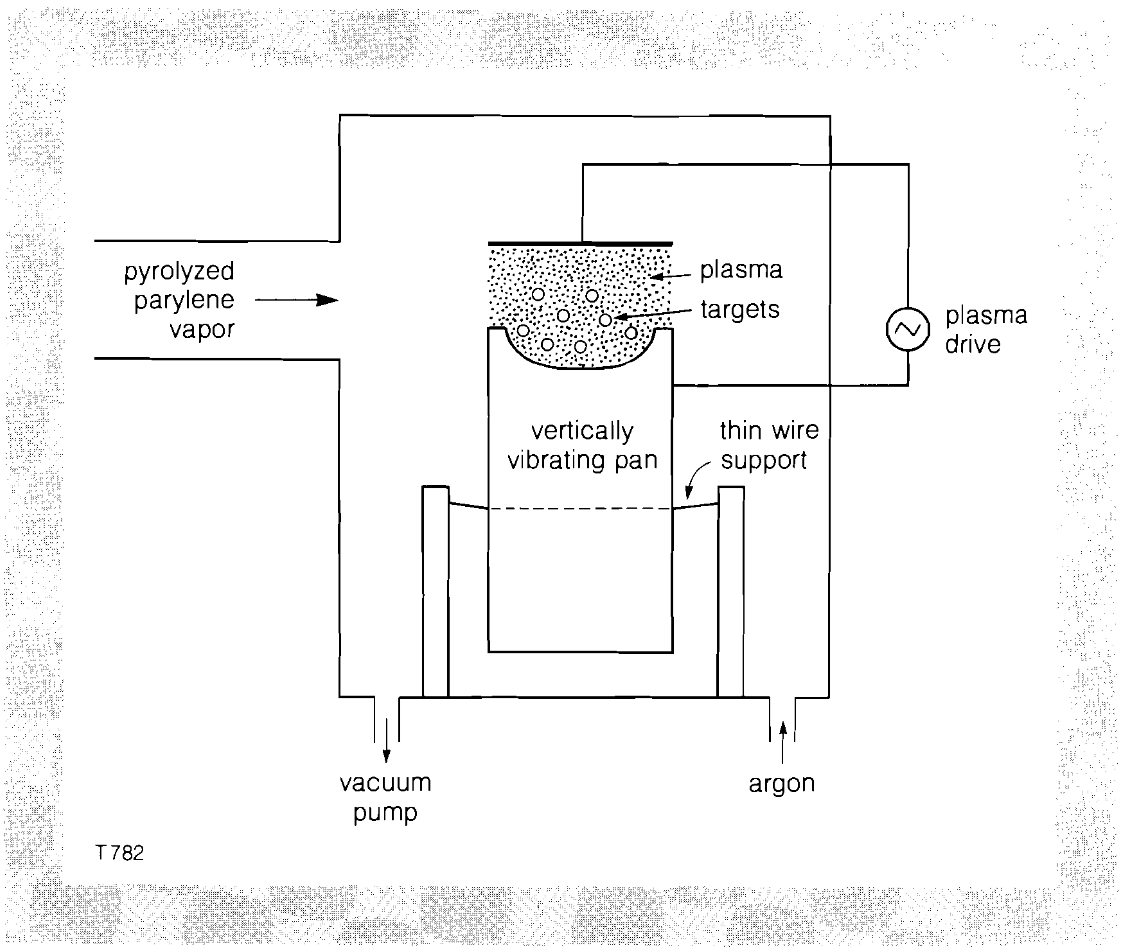
3.A Ablation-Layer Coating of Mechanically Unsupported Inertial Fusion Targets

A high degree of target perfection is required to achieve optimum performance for inertial fusion implosions. Target design calculations indicate that nonuniformities in sphericity, concentricity, and layer thickness should be less than ~5% and that rms surface roughness should be less than ~1000 Å.[1] Typically, targets are supported using glass fibers or films, which constitute a significant departure from spherical symmetry and can contribute to hydrodynamic instability growth during implosion. Alternative target support schemes have been developed, e.g., spider webs or drawn glass fibers, to minimize the target mass perturbation.[2] Compared to conventional glass fiber stalks of 10-μm diameter, these mounts produce a thousandfold reduction in the effective target support mass and significantly improve target symmetry.[2] This improvement is defeated, however, if a target with a low-mass support is coated with an additional material that also coats and thickens the diameter of the support stalk. It is desirable to coat targets which are not mechanically supported, and afterwards to mount the low-mass support.

Various techniques have been employed for this purpose, including gas-jet levitation,[3] acoustic levitation,[4] and bouncing,[5] all with varying degrees of success. Most of the techniques have been discarded in favor of the bounce-coating method for a variety of reasons, one being that it is a batch process. The method has been mainly applied to ablation-layer coating using glow discharge polymerization schemes[5] that are not well understood. Another scheme, vapor-phase polymerization of parylene, is a well established process for forming conformal thin films on any substrate,[6] and it is the process exclusively used for ablation-layer coating at LLE. This article describes the adaptation of the bouncing-pan scheme to ablation-layer coating by the parylene process.

Incorporation of the bounce-coating scheme to the parylene process is schematically illustrated in Fig. 24.15. The pyrolyzed 2,2-paracyclopane molecules are introduced to the region above the vertically vibrating pan, where targets are bouncing in a weak plasma (sustained with a power of ~10 mW). The primary purpose of the plasma is to neutralize the surface charge formed on the targets and thus prevent sticking and agglomeration of the targets. The plasma has an additional effect. Parylene monomers in the plasma can be changed into ions, radicals, and other energetic species, so that plasma polymerization may also proceed in addition to the parylene process. The polymerization suppresses crystallization and yields a smooth layer of deposited material. Before the coating process begins, Ar gas is introduced at a pressure of 0.1 Torr to allow the glow discharge to be started. As the pressure of parylene monomers increases, the Ar pressure is reduced to keep the total pressure constant. The pressure is adjusted to achieve a coating rate of 1 to 2 μm per hour, determined by an interferometric technique.[7]

Fig. 24.15
Schematic of the bounce-coating process. Apparatus for sublimation and pyrolysis of the parylene is not shown.



To bounce targets successfully in a pan, it is important to be able to characterize the motion of all parts of the pan. If a pan of arbitrary shape is driven with a piezoelectric transducer, the system—consisting of pan, transducer, and connecting elements—responds with a unique set of vibrational modes. Each mode of vibration has regions of maximum and minimum motion, with amplitudes that are not readily predictable. In such a pan, the bouncing targets tend to stick at points of minimum motion. To overcome this problem, a system with predictable vibrational modes is needed.

A right circular cylinder has well characterized vibrational modes,[8-10] several of which are useful for bouncing targets. We employ a cylindrical resonator with a shallow pan shape machined into one end. The cylinder is suspended on thin wires, with its axis oriented vertically. A small piezoelectric strain transducer glued to the side of the cylinder excites a longitudinal mode of vibration. Modes with wavelengths larger than both the cylinder diameter and the pan depth have amplitudes that are reasonably uniform over the surface of the pan. In coating runs, we use the first longitudinal mode at a frequency of 16 to 20 kHz. There is no significance to this choice of frequency except that it is much higher than the bounce frequency of the targets, but much lower than the lowest mechanical resonant frequency of a target.[11] (25 Hz is used if the bounce height is 2 mm.)

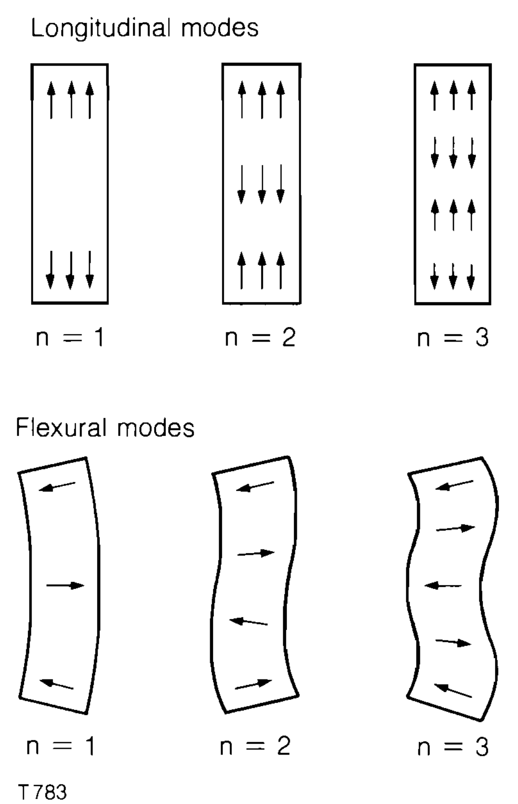


Fig. 24.16
Illustration of vibrational modes of a cylinder useful for bouncing targets or dislodging stuck targets. Arrows indicate the directions of motion of mass elements during half of a cycle.

In addition to employing the longitudinal mode for bouncing, we have investigated the use of flexural and torsional modes. Flexural modes were found to be particularly useful in unsticking targets before coating begins. After the targets are placed in the pan and a glow discharge is established, it is frequently observed that nearly all the targets are stuck to the pan with sufficient force that exciting the longitudinal mode to high amplitude fails to dislodge them. At this point, driving a flexural mode can dislodge them within seconds or minutes. Once dislodged, they can be bounced in the plasma, using longitudinal vibrations with little or no further sticking. Alternately, the targets may be left in the longitudinally vibrating pan with a glow discharge for several hours, after which most (though not necessarily all) will be bouncing.

The shapes of the vibrational modes are shown schematically in Fig. 24.16. The frequencies of these modes may be accurately predicted. Figure 24.17 shows how the frequencies of the modes vary with the ratio of diameter to length. This figure applies to materials with a Poisson's ratio of 0.333, characteristic of aluminum and its alloys. Cutting a pan shape into the end of the cylinder renders these predicted frequencies less accurate. Nevertheless, the predictions are

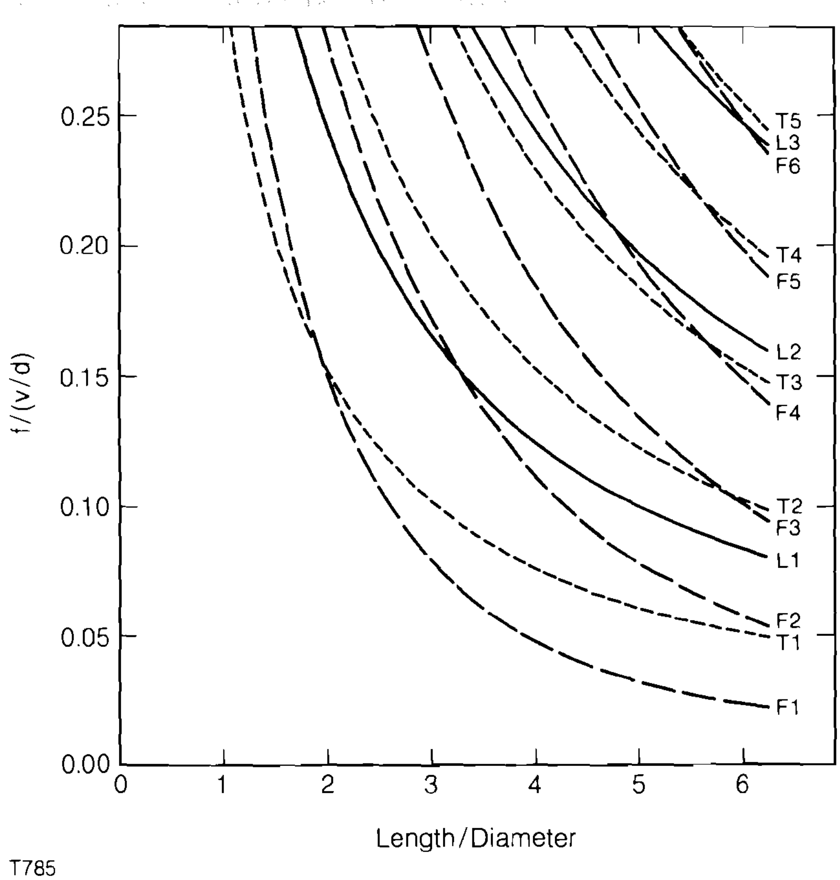


Fig. 24.17
Vibrational frequencies of a cylinder with Poisson's ratio = 0.333 as a function of its diameter-to-length ratio. The frequency f is expressed in units of v/d, where v = velocity of sound and d = diameter. The type of mode is denoted by L for longitudinal, F for flexural, or T for torsional, followed by the mode number.

still quite useful as approximations for helping to specify dimensions. Cylindrical dimensions are chosen so that no vibrational mode used for bouncing is close in frequency to another vibrational mode.

Longitudinal modes are characterized by displacement along the cylinder axis by an amount Δz given by

$$\Delta z \simeq \Delta z_o \sin(2\pi f_{Ln} t) \begin{cases} \sin \dfrac{n\pi z}{\ell}, & \text{odd } n \\ \cos \dfrac{n\pi z}{\ell}, & \text{even } n \end{cases} , \tag{1}$$

where z is the distance along the axis from the center of the cylinder, ℓ = length of the cylinder, and Δz_o is the peak amplitude. The frequency is given by

$$f_{Ln} \simeq \frac{nv}{2\ell}, \; n = 1, 2, 3, \ldots, \tag{2}$$

where v is the velocity of sound. Equations (1) and (2) apply to long, thin cylinders. Corrections that depend on diameter and Poisson's ratio have been calculated.[8] Equation (1) is useful for choosing the positions of the support wires and the strain transducers. The cylinder is best supported where $\Delta z = 0$. The strain transducers are best placed at a region where the strain (the derivative of Δz with respect to z) is maximum. These principles are used to enhance some modes of vibration and to suppress others.

The flexural modes cannot be described with simple functions. Numerical solutions for their frequencies of motion are given in Refs. 9 and 10. It should be mentioned that each flexural mode is split into a pair of modes with perpendicular directions of motion and slightly different frequencies. We make use of both components, using a separate strain transducer for each.

Although torsional modes of vibration are potentially useful for moving targets, we have not yet coupled a strain transducer to these modes strongly enough to obtain more than slight target motion. These modes remain worthy of study, however, because unlike bending modes they produce pan motion perpendicular to the axis with no component along the axis.

The resonant pan is machined from a single piece of solid material with a high mechanical quality factor Q. By keeping the Q high, the drive transducer can be kept small and the driving signal can be kept at a low level. In addition, achieving a high value of Q minimizes the coupling between vibrational modes that happen to be close in frequency. Materials with an intrinsic $Q > 10^5$ at room temperature include several aluminum alloys such as 6061 and 5056 and some single crystals such as Si and Al_2O_3. In all of these materials, the value of Q increases as the temperature is reduced to cryogenic values, suggesting the possibility of doing coatings at cryogenic temperatures.

Because of the high value of Q, a vibrational mode cannot be maintained at a constant amplitude with an external oscillator. The temperature dependence of Young's modulus produces a fractional frequency change of -2×10^{-4} per °C in aluminum alloys, and a change in temperature of 0.1°C shifts the frequency by an amount greater than the width of the resonance. This problem is easily overcome by adopting a feedback scheme in which the resonant cylinder becomes the frequency control element of an oscillator. The feedback scheme, shown in Fig. 24.18, amplifies the signal from a detector strain transducer (which is identical to the drive transducer), filters out the signals associated with any unwanted modes, shifts the phase appropriately for driving the mode of interest, and provides some means of limiting the amplitude. Using this means to drive the first longitudinal mode, we have kept targets bouncing during coating runs that last many hours.

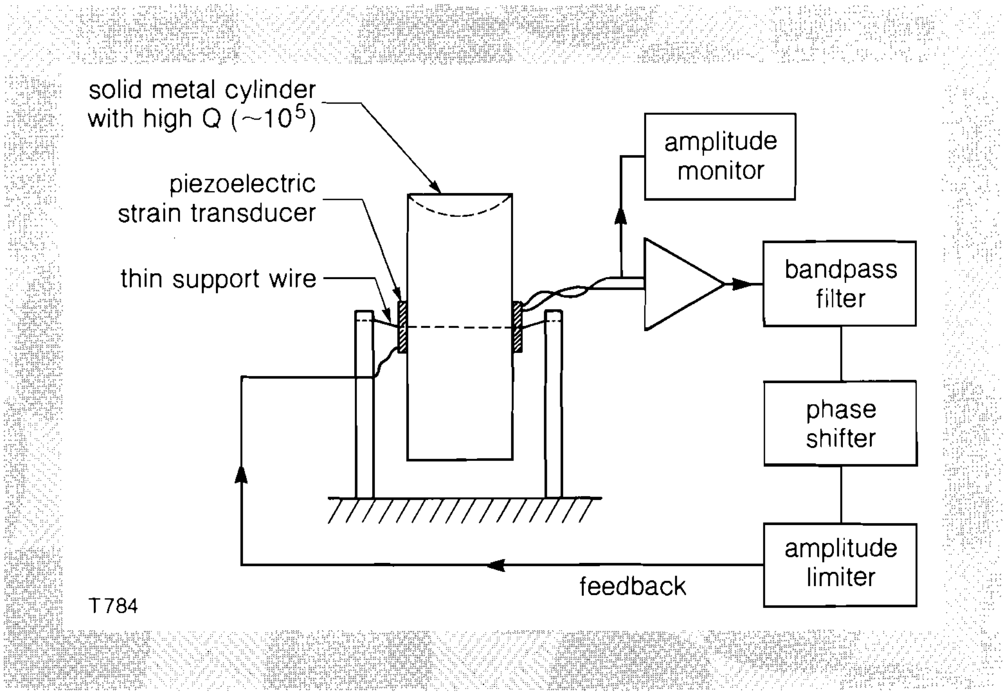
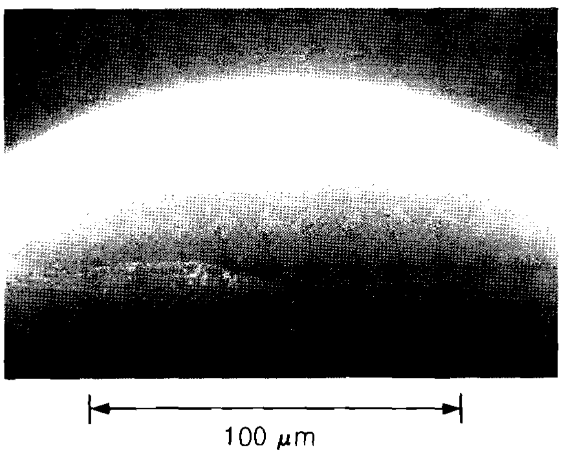


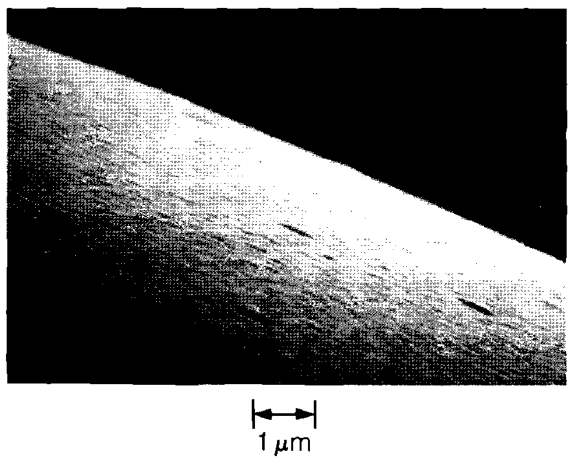
Fig. 24.18
Feedback circuit for maintaining a vibrational mode of a cylinder at constant amplitude.

A useful feature of the feedback scheme is the opportunity to constantly monitor the amplitude of pan motion and to calibrate the monitoring signal. The monitor is calibrated for a longitudinal mode by rigidly attaching a small, calibrated accelerometer to the bottom of the cylinder. The mode is excited by applying a signal to the drive transducer while comparing the resulting signals from the accelerometer and the detector transducer (both linear devices). The resulting calibration is expressed in volts at the strain transducer per unit acceleration of an end. One can then convert to velocity or amplitude by dividing acceleration by one or two powers of the angular frequency.

The pan velocity is chosen to try to maintain vigorous bouncing while not losing targets by bouncing them too high. A peak vertical pan velocity of ~34 mm/s is found to be suitable for bouncing glass microballoon targets of 400-μm diameter with a 1- to 2-μm wall. Under these conditions, a wide distribution of bounce heights is seen, with the apparent average being several mm. After several microns of parylene are deposited, the targets bounce much higher and the peak pan velocity must be reduced by half to keep the average bounce height constant. We presume this phenomenon is related to the increased mass of the targets and to mechanical properties of the coating.

The quality of the ablation layer of targets coated by the present method has been investigated with a scanning electron microscope (SEM), and the results are shown in Figs. 24.19(a), 24.19(b), and 24.19(c). The surface smoothness is similar to that observed in the parylene coating of stalk-mounted targets.[12] Two methods can be applied to further improve the surface smoothness. The use of ethyl-substituted 2,2-paracyclopane instead of the nonsubstituted type has been shown to improve the surface smoothness.[12] No complications are expected in using ethyl 2,2-paracyclopane in the present experiment. The use of the low-power glow discharge should improve the surface quality of the coating, as mentioned previously. The plasma power is kept low, however, because—among other effects—film embrittlement occurs at higher plasma power and the film develops an amber color. The exact nature of the discoloring process is not known but it appears that the plasma may induce formation of color centers in the plastic.

(a)


(b)


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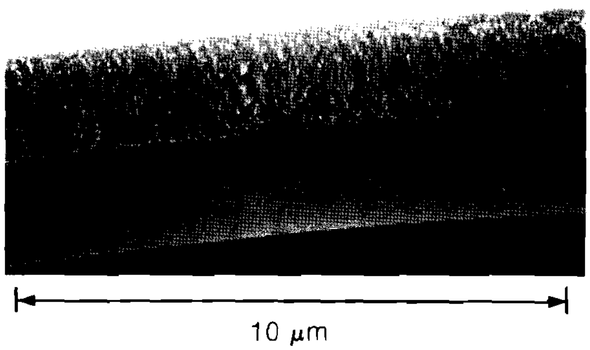
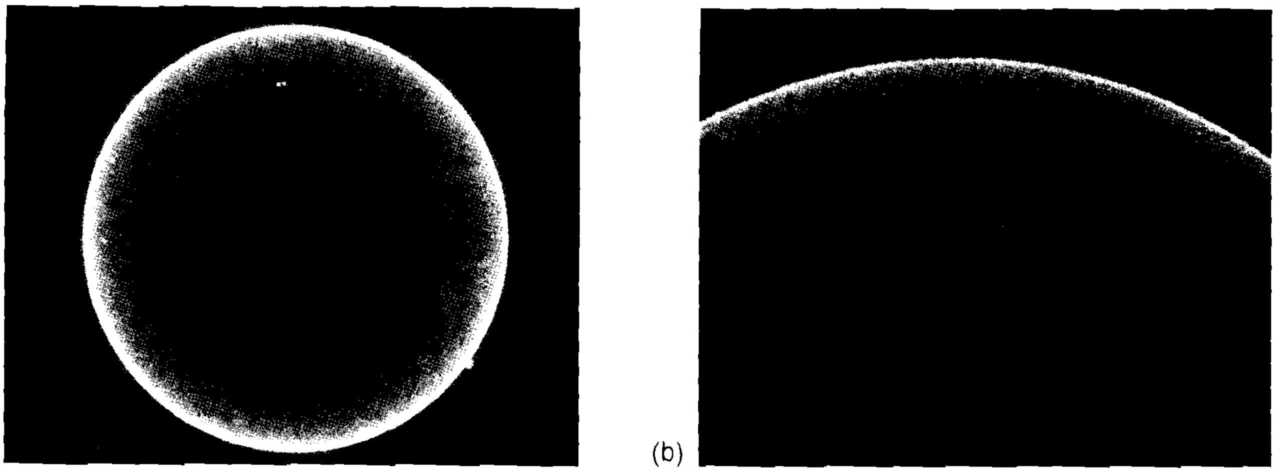
(c)


Fig. 24.19
SEM photographs of glass microballoon targets bounce coated with 2.5 μm of parylene. In photograph (c), the target has been broken to reveal the cross section of the coating and the glass.

It is seen in Fig. 24.19 that the application of the low-power plasma does not degrade the quality of the coating. The interior of the film shown in the fractured cross section [Fig. 24.19(c)] is of solid density, devoid of pores. This is similar to what is obtained with conventional parylene coating.[12] The thickness of the coating can also be estimated from Figure 24.19(c). However, x-ray radiography offers a more accurate means of determining film thickness and uniformity. The fact that radiography is nondestructive is also an advantage over the SEM measurements. Figure 24.20 shows an x-ray radiograph of a bounce-coated target. The 6.3-μm film thickness measured from Fig. 24.20 agrees with the interferometric measurements[7] within the 7% measurement uncertainty. Figure 24.20 also shows the film to be uniform within the measurement uncertainty. These initial results indicate that the optical interferometer can accurately measure and monitor the coating thickness during the bounce-coating process.

In conclusion, we have developed a cylindrical resonator for bouncing inertial fusion targets and used it for coating targets with parylene ablation layers. Several vibrational modes of the cylinder are found to be useful: longitudinal modes for bouncing and flexural modes for unsticking the targets. The cylinder has kept targets bouncing during coating runs that last many hours, producing ablation layers of high quality.



(a) 100 μm (b) 100 μm

Fig. 24.20
X-ray radiographs of a target coated with 6.3 μm of parylene.

ACKNOWLEDGMENT

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