

# Laser-plasma-induced extreme-ultraviolet radiation from liquid mercury

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Extreme ultraviolet (XUV) radiation from 100 to less than 30 nm is emitted from a laser-induced plasma generated on a liquid-mercury surface. This surface does not degrade even after tens of thousands of laser pulses. The 532-nm laser light focused on the mercury forms a bright plasma core and a plume extending several millimeters above the liquid level. The plasma core produces primarily continuum radiation, whereas the plume emits lines at wavelengths above 77 nm. The mercury plasma was generated at the entrance port of a normal incidence vacuum monochromator, and the dispersed XUV radiation was monitored with a photomultiplier tube.

The recent discovery of continuum emission from laser-generated plasmas on rare-earth foils has created renewed interest in the use of laser-generated plasmas as sources of extreme ultraviolet (XUV) radiation.<sup>1-3</sup> A typical apparatus uses a pulsed laser of moderate power, a foil mounted on a translation stage in a vacuum, and a device to measure the output. Provision must be made for translation or replacement of the foil since the laser shots degrade the target and each shot sees a different surface. This limits the repetition rate of the shots and adds complexity to the target chamber. In this work, we show that XUV radiation from 100 to less than 30 nm is emitted from plasmas generated on a liquid-mercury surface. This surface does not degrade even after tens of thousands of shots with a repetition rate of 10 Hz. By eliminating the need for translation of the target, we can make the target chamber simple. In our case, the mercury plasma was generated at the entrance port of a vacuum monochromator.

Figure 1 shows the target chamber. A 25-mm-diameter Pyrex tube with a quartz input window is mounted at an angle of 45° on the input port of a vacuum monochromator. The lower end of the tube is partially blocked by a razor blade to contain the pool of liquid mercury and is otherwise open to the monochromator. The monochromator is tilted slightly from the horizontal so that the grating views the surface of the pool of mercury. In order to examine line structure in the XUV radiation, a 1-m normal-incidence monochromator with a magnesium fluoride-coated aluminum grating was used. A 0.2-m monochromator containing an osmium grating was used to record continuum emission below 70 nm. A sodium salicylate-coated EMI 9635 photomultiplier tube is mounted on the exit port. A thin-film filter (0.1 μm) is placed in front of the photomultiplier tube to shield it from scattered light.

An aluminum filter (10% transmission at 58 nm) is used in the 40–75-nm range, and an indium filter (12% transmission at 85 nm) is used in the 75–110-nm range.

Before operation, the entire apparatus was purged with high-purity helium gas and pumped with a diffusion pump to  $<10^{-5}$  Torr. Output intensities measured by the photomultiplier tube increased after several purges. The apparatus was then filled with helium at pressures of 2–50 Torr in order to contain the mercury vapor within the glass tube and prevent contamination of the grating when the laser light is applied. A commercial Q-switched Nd:YAG laser doubled to 532 nm is used to create the laser plasma at 10 pulses per sec. Laser light having energies from 40 to 220 mJ and pulse durations of 5 nsec was focused using a 200-mm lens to a 60-μm-diameter spot on the mercury surface. At 42 mJ, we estimate the intensity in the focus to be  $3 \times 10^{11}$  W/cm<sup>2</sup>.

A bright hot spot is readily visible on the mercury

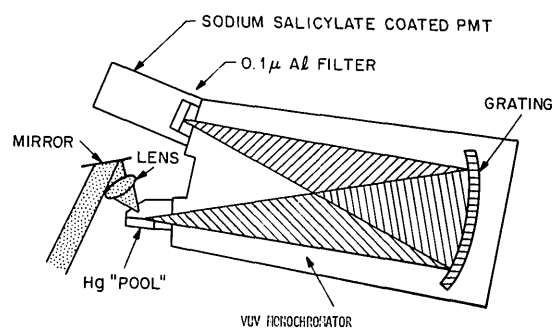


Fig. 1. Apparatus used to examine the spectrum of the mercury plasma. A pool of liquid mercury is placed at the input port of a vacuum monochromator. The monochromator is filled with 5 Torr of helium.

surface where the laser beam is focused. A plume can be seen rising several millimeters above the hot spot when observed through a filter, which eliminates the 532-nm laser light. The height of this plume is dependent on the pressure of the helium: the lower the pressure, the more extended the plume.

Between 77 and 100 nm, the XUV emission spectra exhibit both lines and a continuum, whereas, below 77 nm, the spectrum is a continuum. Figure 2 shows the XUV radiation transmitted through the 1-m monochromator from 70 to 95 nm. Apertures were set so that the detector saw only emission from the plume. The spectrum is dominated by line emission from Hg II and Hg III. We have found that emission lines from mercury atoms and ions emanate from the plume, whereas emission from the hot spot is primarily a continuum. The continuum emission coincides with the laser pulse (within the  $\sim 20$ -nsec resolution of the photomultiplier tube), whereas the line emission decays with a 20–90-

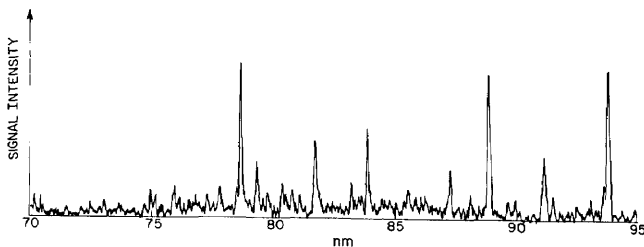


Fig. 2. Spectrum of line emission from a laser-induced mercury plasma in the range 70–95 nm. Continuum was eliminated by blocking emission from the plasma hot spot so that the detector saw only emission from the plasma plume. For this measurement, 50 Torr of helium buffer gas was present in the monochromator. The pronounced emission lines are all due to Hg II and Hg III recombination.

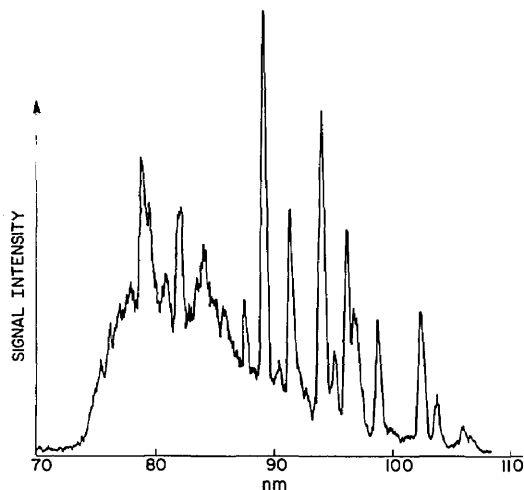


Fig. 3. 70–110-nm XUV radiation from plasma hot spot and plume exhibiting both continuum and line emission. The rapid rise followed by a gradual decrease in the continuum resulted from the transmission profile of an In filter. Continuum emission primarily originates in the plasma hot spot, whereas the plume emits lines.

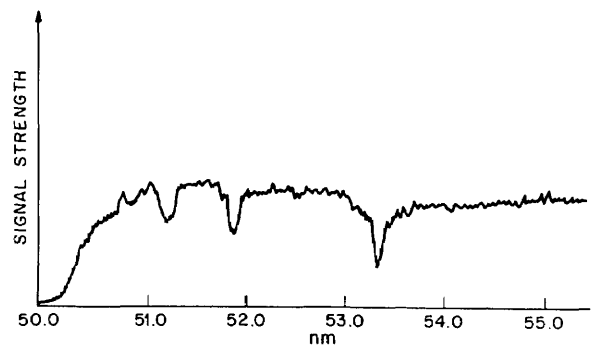


Fig. 4. 50–55-nm continuum emission from a laser-induced plasma in mercury. The dips are the absorptions arising from the 5 Torr of helium in the monochromator. The abrupt cutoff at 50.5 nm is due to the onset of continuum absorption by the helium.

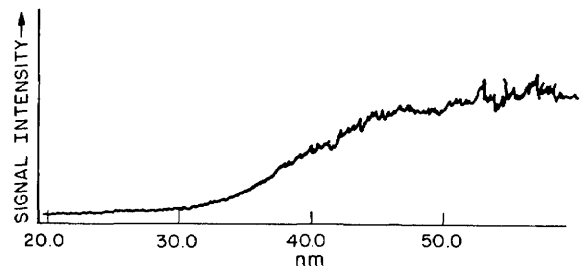


Fig. 5. Signal from a laser-induced plasma in mercury from 20–60 nm when no helium is used in the monochromator. The fall off below 40 nm is due to loss of reflectivity of the normal-incidence monochromator.

nsec time constant. The helium pressure was 50 Torr for this measurement. Decreasing the helium pressure to 5 Torr reduces the line emission peaks. Figure 3 shows 70–110-nm XUV radiation exhibiting both continuum from the hot spot and lines from the plume. The 1-m monochromator was filled with 50 Torr of helium as a buffer gas. The rapid rise to a maximum followed by a gradual decrease in the continuum was caused by an In filter placed in front of the detector.

An examination of the 50–70-nm spectrum using the 1-m monochromator, which has a resolution of 0.05 nm, showed the emission to be continuous except for weak absorption that is due to the Lyman lines of helium. A portion of the recorded output with 5 Torr of helium in the monochromator is shown in Fig. 4. The cutoff seen below 50.5 nm is due to continuum absorption by the helium gas. When the helium is removed from the chamber, emission below 50 nm can be observed. This is illustrated in Fig. 5. The decrease in intensity below 40 nm is due to loss of reflectivity of the normal incidence grating. Work has begun on a grazing-incidence monochromator to record this region of the emission.

In conclusion, liquid mercury provides a convenient laser target for the production of XUV radiation by using laser-induced plasmas without the need to change

the target surface even at 10 pulses per sec. Using the 0.2-m monochromator at 58 nm, we conservatively estimate the output flux before the Al filter to be  $4 \times 10^7$  photons/sec/10% bandwidth. The detection sensitivity was measured at 266 nm by using a calibrated detector, and appropriate corrections were made to estimate the sensitivity at 58 nm. Strong continuum radiation is produced when the emission is limited to the core of the hot plasma. Line emission is radiated by the plume at wavelengths above 77 nm. This method can provide a good alternative to more-costly and limited sources

of XUV radiation. We suspect that it can provide useful radiation to wavelengths shorter than 10 nm.

### References

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2. G. O'Sullivan, P. K. Carroll, T. J. McIlrath, and M. L. Ginter, *Appl. Opt.* **20**, 3043 (1981).
3. See T. J. McIlrath and R. R. Freeman, eds., *AIP Conf. Proc.* **90** (1982), Chap. 3.