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Soft X-ray imaging with multilayer optics in laser fusion experiments

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1. Introduction.

Before describing the different applications of V-UV and X-ray imaging of laser produced plasmas, the interaction of laser with matter will be described.

When a powerful laser is focused on a solid target it rapidly produces spatial, temperature and density profiles along the laser axis. Typical profiles are presented in figure 1. The hot plasma (1 keV) expands toward the vacuum, the temperature being approximatively constant. Inside the target, together with a large density gradient, there is a steep temperature decrease from 1 keV to the cold material temperature. Along these profiles, different species of ions having different ionization states are located, each ionization state depending on the local temperature. One can define typical values for the electron density: the critical density corresponding to the cut off for the laser wavelength and the density at the ablation point where the electron density begin to decrease from solid density value. This zone located between these two typical values is called ablation front and is where energy transport occurs. Inside this zone the different ionic species radiate from the X-ray to the V-UV range of photon energy depending on their temperature and on their ionization state.

This paper is organized as follows:

In part 2 we present imaging of laser created plasmas to study the thermal front zone where transport occurs. The lateral transport and the effect

![Fig. 1. — Typical profiles of density and temperature in a laser created plasma.](http://dx.doi.org/10.1051/rphysap:0198800230100173300)
of the atomic number of the target material is also illustrated by V-UV imaging. In part 3 we show how to image plasmas using multilayer mirrors in grazing incidence. In part 4 a diagnosis of the overdense region of laser created plasmas using the refraction of light in the V-UV range is described. Finally, in part 5, a diagnosis of preheat of a thin foil target using imaging in the V-UV with a Schwartchild microscope is shown.

Except for X-ray Laser development, the main use of multilayer optics in laser fusion experiments has been done in our laboratory; only part 3 shows an application from another laboratory.

2. Pinhole camera in the V-UV range.

In order to record images of plasmas in the V-UV range, we have developed a pinhole camera containing a planar multilayered mirror [1] which works at an angle of incidence of 45°. The mirror plays the role of an interference filter and selects a narrow bandwidth in photon energy. The pinhole camera is schematised in figure 2. Due to the camera working in the soft X-ray range (100 eV) the pinhole size has to be relatively wide in order to prevent diffraction.

A diameter size greater than or equal to 20 μm is acceptable. The camera used has a 25 μm hole size. The spatial resolution is therefore limited by the hole size. Nevertheless, it has been possible to do very interesting studies of laser created plasmas with such a camera.

2.1 EFFECT OF THE LASER WAVELENGTH ON THE STRUCTURE OF THE V-UV IMAGES.

In laser fusion research, one studies the effect of laser wavelength on absorption efficiency. The ablation layer is always located at the same place but the critical density layer's position varies according to the laser wavelength \((n_c \sim 1/\lambda^2)\). Figure 3 shows how the density and temperature profiles evolve as a function of time for laser interactions at 1.06, 0.53, and 0.26 μm given by a hydrocode simulation done with FILM [2].

![Fig. 2. — Arrangement of the pinhole camera including a multilayered mirror.](image)

![Fig. 4. — Images at 154 Å for an aluminium plasma created at 1.06, 0.53 and 0.26 μm.](image)

Fig. 3. — Temporal evolution of density and temperature profiles for interactions at different laser wavelengths. The different curves are given, from the left to the right, at times 500, 1 000, 1 500, 2 000 ps with respect to the beginning of the laser pulse.

Figure 4 shows 3 images at 154 Å, recorded from a plasma created on a flat massive target at the three laser wavelengths of 1.06, 0.53 and 0.26 μm. The incident laser intensity of \(5 \times 10^{14} \text{ W/cm}^2\) was the
same for the three images. The V-UV radiation selected was that of the Al$^{10+}$ line 4f$^2$3d$^3$3/2 ionic species playing the role of tracer because its emission depends on its temperature. We have previously shown [3] that the 154 Å emission inside the plasma comes from the thermal front. The densitograms in figure 4 show the axial expansion of the three images. The slowly decreasing part represents the expanding plasma. The emissivity is due to the recombination radiation from the corona late in time. The sharply decreasing part comes from the inner part of the plasma. The 154 Å emissivity scale lengths were 150 µm at 1.06 µm, 80 µm at 0.53 µm and 52 µm at 0.26 µm, showing that the emissivity scale length inside the plasma decreases with laser wavelength. These steeply decreasing parts of the emissivity curves show the moving zone of the 155 Å emissive species inside the thermal front during the laser pulse. They can be related to the thickness of the ablation front (distance between the ablation and the critical layer) at each laser wavelength.

2.2 LATERAL EXPANSION. — With the same arrangement as in paragraph 1, we have recorded images of an aluminium plasma created at 0.53 micron on a flat target. A multilayered mirror [1], reflecting at 45 degrees of incidence, radiation at 154 angströms, is located inside a pinhole camera of 25 µm hole size. We first recorded an image for a laser intensity of $5 \times 10^{14}$ W/cm$^2$. Next, we recorded several images at the same wavelength lowering the laser intensity until the photographic film 101-01 is not blackened. This happens for a laser intensity of $6 \times 10^{12}$ W/cm$^2$.

In order to determine the intensity distribution inside the focal spot, we record the image of the focal spot on Kodak film Royal X-Pan of $\gamma = 0.3$.

Figure 5 shows the laser intensity distribution in the focal spot and the lateral distribution on the 80 eV image, taking into account the responses of the two films [4] used for the record (curves a). The dashed line (b) represents a curve of same area as the triangular curve but, here, we take into account the value of the laser threshold flux giving a blackening on the 101-01 film. The laser conditions for this record are: 0.53 µm wavelength, 1 ns pulse duration and $5 \times 10^{14}$ W/cm$^2$ laser peak intensity in the local spot.

From figure 5, one can see that the blackening of the film for distances greater than 120 µm from the center of the image comes from lateral spreading of the plasma. Indeed, the laser intensity in these places is lower than the threshold value of $6 \times 10^{12}$ W/cm$^2$. This lateral spreading could be generated by the existence in this zone of a cold and diluted plasma created by either the laser energy in the wings of the focal spot or other processes such as fast electrons or radiation.

2.3 EFFECT OF THE ATOMIC NUMBER OF THE TARGET MATERIAL AT DIFFERENT LASER WAVELENGTHS. — Using the GRECO ILM laser facilities at Ecole Polytechnique we have recorded using the same pinhole camera previously described, the 80 eV images of laser created plasmas on flat targets made of different materials.

The laser was working successively at 1.06 µm, 0.53 µm and 0.26 µm in a pulse duration of about 500 picoseconds.

At the same time, we record the 1 keV images with a 10 µm size pinhole camera filtered by 25 µm thickness aluminium, in order to control for each shot the best focus and the laser spot size.

Figure 6 shows the images taken with 80 eV light, for plasmas created at 1.06 µm on aluminium targets (a), copper targets (b) and gold targets (c). The laser absorbed intensity was approximatively $2 \times 10^{14}$ W/cm$^2$.

Figure 7 shows the 80 eV images of plasmas created at 0.26 µm on the same targets for the same absorbed laser intensity.

The images of figures 6 and 7 show that:

1. the lateral expansion increases with the atomic number of the target material for a same laser frequency;
2. the lateral expansion decreases when one increases the laser frequency for a given atomic number;
3. the 80 eV emissivity towards the target decreases more rapidly for the images of plasmas created at 0.26 µm when one increases the atomic number of the target material (Fig. 7);
4. the 80 eV emissivity of the corona towards vacuum decreases more slowly for the images of plasmas created at 0.26 µm when one increases the atomic number of the target material (Fig. 7);
5. the emission of the corona is very weak for the 80 eV images of 0.53 µm created plasmas;
Fig. 6. — 80 eV images of plasmas created at 1.05 μm laser wavelength. (a) aluminium, (b) copper, (c) gold. The laser comes from the right.

Fig. 7. — 80 eV images of plasmas created at 0.26 μm laser wavelength. (a) aluminium, (b) copper, (c) gold. The laser comes from the right.

(6) as shown previously, the emissivity scale length towards the target decreases when the frequency of the laser creating the plasma is increased for a given target material [3];

We shall try to explain all these observations on the different 80 eV images recorded.

The point 2 is a consequence of the effect of the suprathermal electrons created in the 1.06 μm interaction [5]. Indeed, in this case and for the incident laser intensity of $5 \times 10^{14}$ W/cm², a tail of hard electrons is generated (several tens of keV in energy). These hard electrons escape from the focal spot and due to their high energy penetrate the target far from the region where the laser energy is deposited. In the region of hot electron deposition, a cold and dilute plasma is created permitting the hot plasma to spread to a greater distance from where it was created at this laser wavelength.

Point 4 and 1 are a consequence of radiative heating increasing with the atomic number of the target material [6], [7]. Images of figure 6 recorded at 1.06 μm show more lateral spreading for gold than for aluminium. One can consider that this difference in lateral size is due to radiation heating. 80 eV images of gold taken at 0.26 μm laser wavelength show less spread than the corresponding images taken at 1.06 μm, due to the combined effect of hard electrons and radiation at 1.06 μm. At 0.26 μm for gold, only the effects of radiation are important, but this effect is more efficient for this laser wavelength. Consequently, we observe a 80 eV gold image which is more homogeneous towards vacuum; the hot plasma of the corona reradiates in all directions and due to the less rapid expansion for a high Z plasma, the emissivity of the corona at 80 eV is greater and decreases more slowly towards vacuum. The difference between the aluminium and gold images for laser created plasmas at 0.26 μm is due to a combined effect of a slower hydrodynamic expansion and a more intense transport of energy by
radiation as the atomic number of the target material is increased.

We have shown that the 80 eV images of laser created plasmas always spread out of the focal spot and that this spreading depends on the laser wavelength and on the kind of the target material. We discussed the mechanisms of spreading outside and far from the region where the laser energy is deposited, in a place where the laser intensity is below a threshold we determined experimentally. The possible mechanisms we consider are the effects of suprathermal electrons for plasmas created at 1.06 μm and the effect of radiation for plasmas created either on high Z material or at shorter laser wavelength.

3. X-ray pinhole camera in grazing incidence.

Another application of multilayered mirrors is the monochromatic X-ray imaging of laser created plasmas by Key et al. at the Rutherford Appleton Laboratory (England). The set-up is a pinhole camera including a mirror with multilayers. This camera is outline in figure 8. The photographic film receives direct photons as in a standard pinhole camera. It also receives photons from the mirror. The angle of incidence is calculated for radiations of energy higher than 2 keV. The accepted photon energy is varied by vertically moving the mirror, so the angle of incidence is varied. This arrangement was developed in order to study the uniformity of illumination of a microsphere illuminated by 6 laser beams at 2 μm. The monochromatic images were recorded by such a camera, the nature of the target material being chosen to radiate inside the reflectivity bandwidth of the mirror.

4. V-UV refraction through a laser created plasma.

In order to study the overdense parts of the laser created plasmas, we have developed a diagnostic of the refraction of V-UV radiation produced by an auxiliary laser created plasma. This radiation is selected and collimated by a spherical multilayered mirror. Simple calculations showed that to measure sufficient refraction through a plasma of electron density between 10^{22} and 10^{23} cm^{-3} one needs radiation of around 100 eV to pass through an optical length of one hundred microns.

Figure 9 shows the experimental arrangement. A powerful laser beam is divided into two parts. The first part is focused on a flat aluminium target. The plasma is used as an auxiliary source. It is located at the focus of a spherical multilayered mirror working close to normal incidence which selects and collimates the 155 Å radiation emitted by the Al^{10+} line. This collimated beam illuminates a second plasma created on the edge of a magnesium flat target which refracts the V-UV light [8]. A knife edge is also used to prevent direct light from the source reaching the photographic plate.
Fig. 11. — Image of a Mg edge with a created plasma: (a) knife edge at 2 mm; (b) knife edge at 1.2 mm.

the target edge. There is no evidence of refracted light. In figure 11c the knife edge is at 1.2 mm from the target edge. One can observe a bright spot inside the shadow of the knife edge. This is due to refraction by the plasma of the collimated radiation and corresponds to refraction angles varying through $1.5 \times 10^{-2}$ and $2 \times 10^{-2}$ radian. A comparison with a model of refraction of a probe beam through a spherical plasma exhibiting realistic profiles of density and temperature and taking into account the atomic bound states contributing to refraction showed the action of near resonance effects [8].

5. Schwartzchild microscopes for high resolution V-UV images.

The pinhole camera has a limited spatial resolution. It is an important step in V-UV imaging techniques of plasmas but to be able to resolve spatial evolution of the order of one micron, it has been necessary to use instruments of higher resolution. The laboratory of Institut d’Optique of Orsay University and CNRS developed and built high spatial resolution V-UV microscopes for different photon energies. This development allows us to begin a study of front and rear V-UV emission of thin foils illuminated by lasers [9]. Microscopes have been built for 40 and 80 eV. They are sketched in figure 13. They have a total reflectivity of 1% i.e. 10% per reflective surface. The experimental geometry is shown in figure 12. The measured spatial resolution for the 40 eV microscope is better than 5 μm. The aperture of $F/2.5$ of the objectives compensates the relatively weak reflectivity of the mirrors. We show in figure 13a and b images of plasmas created on a flat massive aluminium targets by a laser of moderate

Fig. 12. — Scheme of the Schwartzchild microscope.
power (1 GW) recorded by the two microscopes at 40 and 80 eV. This new optics in the V-UV allowed us to study the preheat of thin foil illuminated by a UV powerful laser [10].

In conclusion, we have shown the application of the powerful technique of V-UV imaging to laser fusion research. Multilayered mirrors will be even more interesting when specialists will be able to deposit thinner layers in order to reach reflectivity in a higher energy range. This technique also has applications in astrophysics [11].

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References
[1] Mirrors manufactured and tested by J. P. Chauvineau and the staff of Institut d’Optique of Orsay University, France.