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Propagation-based imaging phase-contrast enhanced imaging setup for single shot acquisition using laser-generated X-ray sources

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ABSTRACT

The development of new diagnostics is crucial to improve the interpretation of experiments. Often well known physical processes and techniques origibally developed in a certain field of physics can be applied to a different area with a significant impact on the quality of the produced data. X-ray phase-contrast imaging (XPCI) is certainly one of these techniques found many applications in biology and medicine due to its capability to evidence the presence of strong density variation normally oriented with respect to the X-ray propagation direction. However the availability of short energetic X-ray pulses allows extending the use of XPCI to experiments on laser-matter interaction where strong density gradient are also present. In this work we present the setup for a x-ray phase-contrast imaging realized and tested at the laser PHELiX at GSI in Germany.

Keywords: X-ray radiography and digital radiography (DR), X-ray detectors, Lasers, Plasma generation (laser-produced, RF, x ray-produced)

1 INTRODUCTION

The development of diagnostic techniques has a crucial impact in different scientific areas. In particular, X-ray imaging has applications in different fields, from biology to medicine and physics. X-rays allow to look inside materials without compromising the internal structure, with a negligible effects on the ongoing physical (or biological) processes (according to the dose deposited). They are commonly used as a medical diagnostic (1), and also for the assessment of material properties (e.g. target to be used in experiments) (2). In physics, X-ray radiography was proved to be a valid tool to investigate matter in extreme conditions generated by laser irradiation (3; 4; 5; 6; 7). Standard X-ray absorption radiography is based on the capability of the sample under analysis to absorb part of the incident X-ray flux. The transmitted flux will eventually form the image on the detector. The absorption is a function of the photon energy and material density.

However, under particular conditions, it is possible obtain phase-contrast enhancement. In this case the final image will contain two different contributions, one due to X-ray absorption, and a second one, due to X-ray phase-shift. The phase-shift is induce by the object illuminated, which results in a deflection of the X-rays. The measurable result is an intensity redistribution on the detector plane. The consequence is an enhancement of the contrast at interfaces, where rays with different deflection start to interfere each other.

The amount of the flux deflected depends on several parameters which concurs to the final result. This technique is well established in medicine and biology, where phase-contrast enhancement allow to image properly tumors where the absorption-contrast is not adequate (8).

In this work we will show how to implement X-ray phase contrast imaging (XPCI) in the warm dense matter (WDM) and high energy density physics (HED) studies using a laser-induced X-ray plasma source. Our description will be supported with experimental data acquired at the laser PHELiX at GSI (9) in Germany. Some details about the experiment can be found in (10).

2 XPCI

2.1 Theoretical principles

We consider a point-projection radiography set up known as propagation-based imaging (PBI). In this set up an object to investigate is placed between the source and the detector, without any optics. This is indeed the simplest experimental set up one can think of, in order to realize XPCI and absorption radiography. Let us now consider the general definition of refractive index n:

$$n = 1 - \delta - i\beta, \tag{1}$$

where the imaginary part β is related to absorption while the real part δ is related to phase-shift. Attenuation is described by the linear attenuation k which is defined as

$$k = \frac{4\pi\beta}{\lambda}. \tag{2}$$

In particular, given an incident intensity I_0, the transmitted intensity will be described by:

$$I = I_0 \exp\left(\int_{z_1}^{z_2} k(E,x,y,z)dz\right), \tag{3}$$

where z_1 and z_2 represent the entrance and exit points in the object and E represents the incident X-ray photon energy. The linear attenuation coefficient can be written as:

$$k(E,x,y,z) = \mu(E,x,y,z)\rho(x,y,z), \tag{4}$$

where $\mu = \frac{4\pi}{\lambda}\beta$ is the mass attenuation coefficient which is a property of the specific material, while ρ is the density of the object. The mass attenuation coefficient depends also on the material temperature, but in typical WDM experiment this dependence can be neglected (6). If the object is cylindrical symmetric the density can be directly recovered applying Abel inversion as detailed shown in (4).

Under specific conditions, the rays propagating from the object to the detector can interfere with each other generating phase-contrast. this effect is mainly related to the source size and the distance object-detector. The source size should be small enough to provide sufficient coherence to the X-ray radiation. The precise degree of coherence is related to the object observed, the smaller is the object the higher is the needed coherence.

When these conditions are fulfilled, the detected intensity is given by the formula (11)

$$I_{PBI} = M^{-2} I_0 T \left(1 - \frac{\lambda d}{2\pi} \nabla_\perp^2 \phi\right), \tag{5}$$

where M is the magnification, I_0 the incident intensity, T the transmission, λ the x-ray wavelength, d the defocusing distance defined as the ration between the source sample distance divided the magnification and ϕ (12)

$$\phi = \frac{2\pi}{\lambda} \int \delta(z) dz \tag{6}$$

is the phase-shift produced by the object.

2.2 Source characteristics

A variety of X-ray sources can be considered for XPCI. The most effective are are coherent radiation sources such as synchrotron and X-ray free electron laser (XFEL). In the work of Schropp et al. (13) a study of laser-induced shock-waves in diamond using a XFEL shows a remarkable level of details of the shock-wave.

Anyhow, to apply this technique in medium and large scale laser facilities, we need to consider other options. A successful method which generates intense and directional X-ray source is Betatron radiation emitted by a laser-wakefield cavity (15). However, this requires specific laser characteristics suitable for laser-walefield acceleration.

A simpler approach could be the laser-irradiation of solid targets, which produces X-ray radiation. Using short and intense laser pulses it is possible to transfer a significant fraction of laser energy to a suprathermal electron population (16). The propagation of these fast electron inside a solid target produces a strong continuum broadband emission which can be used as a backlighter. This approach requires a short (compared to the time scale to observe) and energetic laser pulse (to generate an enough bright source). Source dimensions can be reduced by suitable target design, as we did in our experiment at laser PHELiX in Germany (10). In particular we focused a short laser pulse beam onto 5 μm diameter tungsten wire. The wire diameter limits the source size in one direction. In the other direction the flow of hot electrons along the wire resulted in a larger source size. In our experiment we measured 5 μm in one direction and 30 μm in the orthogonal one. The lateral coherence assumes values from 1 up to 10 μm in our experiment.

2.3 Experimental set-up

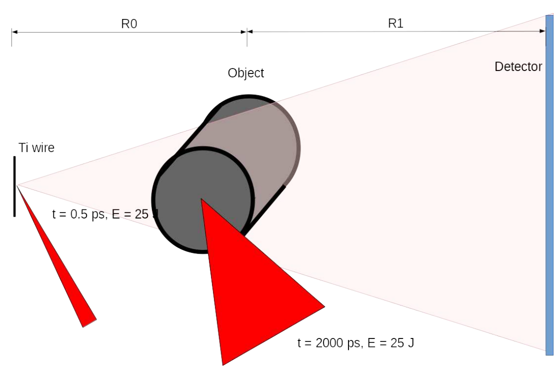

Figure 1. Experimental set-up.

Figure 1 shows our experimental set-up. A short pulse laser beam (τ = 0.5 ps, E = 25 J, λ = 1.06 μm) was used to irradiate 5 μm diameter tungsten wire while a second long laser pulse (τ = 2 ns, E = 25 J, λ = 1.06 μm) was used to lunch a shock inside a plastic cylinder. The distance $R0$ was set to 24.5 cm and $R1$ was 94 cm. The spatial properties of the source were evaluated using a knife edge placed opposite to the source compared to the object. The X-ray emission from the source was evaluated using a highly oriented pyrolytic graphite (HOPG) crystal spectrometer together with a bremsstrahlung cannon. As detectors for our experiment we tested X-ray CCD camera and image plates (IP). The X-ray CCD camera has a better spatial resolution, but is less sensitive than the IP. Also, it is sensitive to EM pulses, while the IP, being a passive detector is not affected.

3 EXPERIMENTAL RESULTS

3.1 Static object

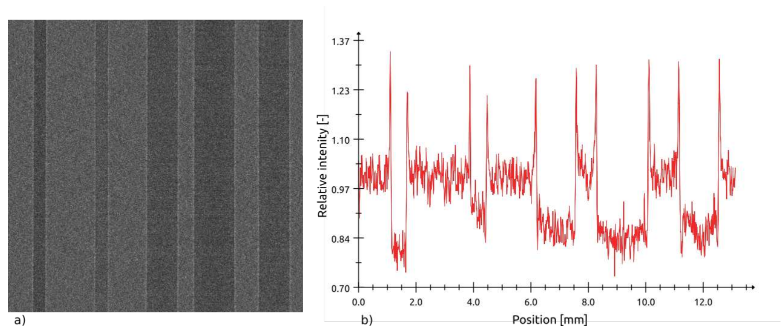

Figure 2. The image shows: a) the experimental radiograph of different wires, from left to right: fluorocarbon (diameter 120 μm), nylon (320, 420 and 320 μm); b) lineout along the horizontal axis of the image.

We first tested our XPCI set-up on a static object, composed by multiple wires with different diameters. A plastic wire is geometrically a simple cylinder and the XPCI pattern is quite straightforward to interpret. The experimental result is shown in fig.2. Both, the contribution of the absorption and the phase-shift are visible. Phase-enhancement is visible on the object-vacuum interface, where the density variation is maximum. In the center of the object the profile is mostly given by the absorption.

3.2 Shock-wave

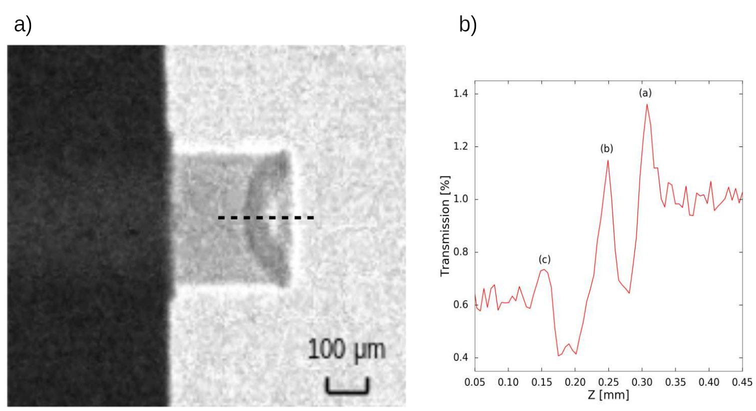

Figure 3. (a) the experimental radiograph, and (b) the lineout along the cylinder axis.

The capability of this technique to enhance the presence of density gradient makes it suitable to evidence the presence of material interface and density variation. This is visible in fig. 3a, which shows a laser-driven shock-wave traveling inside a plastic cylinder, while fig. 3b shows a lineout along the cylinder axis. The detector used in this case was an IP. The characteristic intensity edges produced by phase-shift are particularly visible on the cylinder-vacuum interface (a). Contrast-enhancement is also present on the shock wavefront (c), and in the internal region of the shock (b) (between the shock front and the interaction surface). This internal intensity peak (b) which is surely generated by the deflection of the X-rays (the intensity is higher than the source intensity in vacuum) reflects the presence of a strong density gradient, probably related to connected with the rarefaction wavefront. The image was taken 6 ns after the end of the laser pulse, so the rarefaction wave had time to propagate inside the shocked region. This important detail would not be spotted by a standard absorption radiography which, in similar case, would show a smooth density profile (4; 5). It is worth to notice that phase-enhancement is clearly visible also on the horizontal target-vacuum edges. In this direction the measured source size was 30 μm, which means that the expected lateral coherence was several times lower than in the perpendicular direction (along the cylinder axis).

4 CONCLUSION

In this work we presented a method to implement XPCI using a laser-induced X-ray source. Our data show that using a continuum broadband and incoherent radiation phase-enhancement can be obtained if source dimensions as well as the distances between source, object and detector are carefully controlled. XPCI has a potential impact in the study of low density materials in astrophysical contexts, where standard X-ray absorption radiography cannot be applied. The only requirement is the presence of strong density variations, such as occurring in shock-waves, plasma filaments, target impurities, etc... The proof-of-principle experiment described in this work opens the possibility to export this diagnostic to large scale laser facilities (such as NIF and LMJ) where short-pulse laser backlighters are available, and where relevant astrophysical conditions can be achieved.

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