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Pin-hole array production and detailed data analysis for advanced single-shot X-ray imaging of laboratory plasmas

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ABSTRACT

Laser produced plasmas offer the unique opportunity to investigate physical mechanisms working at extremely high field in pulsed regime [1] (Gizzi et al., 2009). Future large scale infrastructure like HiPER and ELI may open new frontiers of knowledge in this way. Technologies needed for improving diagnostic in this field have a strong impact on a wide range of multi-disciplinary applications as for compact plasma-based accelerators [1,2] (Gizzi et al., 2009; Betti et al., 2009) laser fusion oriented experiments, three-dimensional microscopy and lithography. As an example the X-ray imaging, being a powerful diagnostic tool for deep investigation on different variety of laser produced plasma, has obtained a grooving effort in recent years. Large scale facilities working in single-pulse regime for laser fusion oriented experiments have evidenced the necessity to obtain spectrally resolved X-ray images of produced plasmas in a single shot. By combining the charge coupled devices (CCD) based single-photon detection technique with a pin-hole array (PHA) a new diagnostic technique was developed, as shown in recent experiments related to the European HiPER project [3] (Labate et al., 2009). Here we qualitatively describe the PHA production process on a heavy metal substrate by means of SEM images that show an internal diameter on the micrometer scale and an aspect ratio of about 20. The characterization of the X-ray contrast up to 90 keV is presented. The data analysis of the X-ray photons interaction on CCD, for spectrum reconstruction up to high energy, is described [4] (Levato et al., 2008).

1. Introduction

Pin-holes for X-ray imaging are routinely used in different fields of research, including laser plasma physics [1,2,5] where they can be employed for the imaging for study of fast electron generation and transport in dense matter [6,7]. For the reconstruction of the electron propagation path, a diagnostic capable of both spatial (2D) and spectral resolution is essential. In recent experiments [8] such diagnostic was demonstrated using an X-ray pin-hole coupled with a charge coupled device (CCD) working in single photon detection regime (i.e. low flux) as described in Section 5.

Basically the idea is to acquire many low flux images of the X-ray source: the low flux combined with the linear response of the CCD, offers the energy of the impinging X-ray photons, to be measured even at high energy [4]. The collection of many images of the same source is then necessary, so that using custom developed algorithms, the reconstruction of the source images at a specific X-ray energy becomes possible [5,8]. The main limitation of such a technique is required to collect many hundreds of low photons flux images for a complete reconstruction of the source. This limitation makes this approach troublesome for single-shot experiments (e.g. Vulcan, Pals).

Recently a novel X-ray imaging technique has been proposed within the high power laser energy research (HiPER) facility to obtain spectrally resolved X-ray imaging in single-hit regime: the energy encoded pin-hole camera (EEPHC) [3]. Basically the idea is to collect many hundreds of images in a single hit by using a pin-hole array and a large area CCD camera. An important issue in high intensity experiments is the high flux of hard X-ray that typically generates noise on the detector making imaging in the keV range very difficult. These conditions require that thick substrates are used for pin-hole to ensure to enhance the contrast of the image.

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2. PHA fabrication

For the fabrication of such PHAs we used the 10 Hz secondary femtosecond beam of the *ILIL laser facility* [9] *suited in Pisa—Italy at the National Research Council*. The 10 mJ-level femtosecond Ti:Sa laser pulse of 67 fs FWHM time duration, was frequency doubled at 400 nm by means of KDP doubling crystal. The laser beam, propagating air, was focused onto the W target by using an aspherical lens. The focal spot was estimated to be about 2.7 μm (FWHM). After many (hundred) shots a hole was completely drilled and the laser beam was visible on a white screen placed on the back of the target. When a hole was drilled, using a micrometer motorized stages, the target was moved to another position to drill another hole. Fig. 1 shows a scheme reproducing the utilized experimental setup. Using this experimental setup different PHAs were fabricated with many hundreds of holes. The holes are shaped as a cone for the first few microns from the entrance surface, after this zone are like a long hollow cylinder. The total thickness of the W substrate was 70 μm, with an aspect ratio of 22.8 for the entire channel. The quality of the entrance surface is morphologically degraded (see Fig. 4) respect to the exit surface, this affect the entrance hole diameter (for not more than 3 μm in depth) to be larger (few μm) than the exit one, as can be see in Fig. 3. To drill a hole in this condition needed about 1 min time (i.e. 600 laser shot at 10 Hz repetition rate).

3. PHA characterization

The produced PHA were characterized by means of scanning electron microscope (SEM) facility of the *BIONEM Laboratory at the Campus of Magna Graecia University of Catanzaro* [10]. This makes possible to have control on the quality of the produced holes depending on the interaction regime. Fig. 2 shows a SEM overview of a 3 × 2 PHA. Here the reproducibility of the drilling process is evident. Fig. 3 shows the inner part of a hole drilled without air breakdown, showing an inner diameter of approximately 3 μm and the cylindrical shape of the entire channel. Fig. 4 shows a SEM image of the external part of a hole drilled in the same conditions. Here different morphological micro and nano-structures near the holes edge are visible. The inset shows a magnified view of a periodic (period from 245 to 270 nm) structure indicated in literature as laser induced periodic surface structure (LIPSS) [11–13]. The presence of LIPSS is a residual effect of the ultrafast ablation process and is indicative of specific interaction regime in which thermal effect is negligible. In our case the presence of LIPSS was an indication of good conditions for hole drilling.

According to our measurements, we observe that the re-deposited material after the ultrafast ablation strongly affects the laser absorption and consequently the quality and diameter of the drilling process.

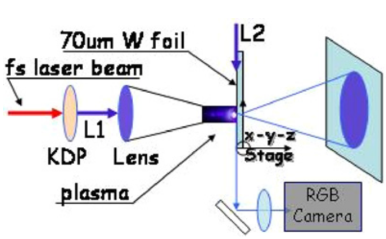

Fig. 1. Scheme reproducing the utilized experimental set-up.

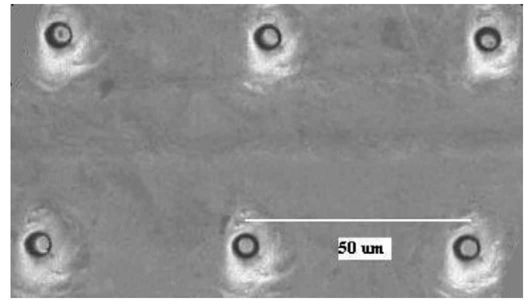

Fig. 2. SEM overview of some holes drilled in a 2 × 3 PHA.

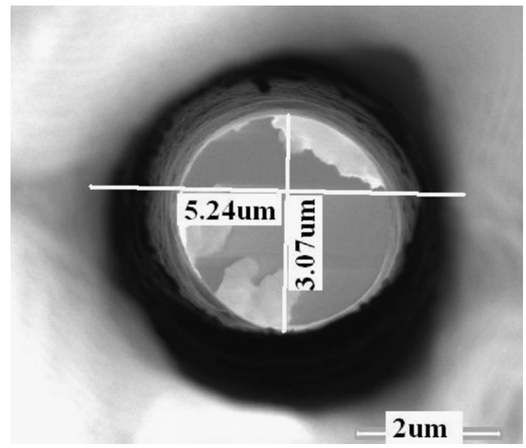

Fig. 3. Inner part of a hole drilled without air breakdown.

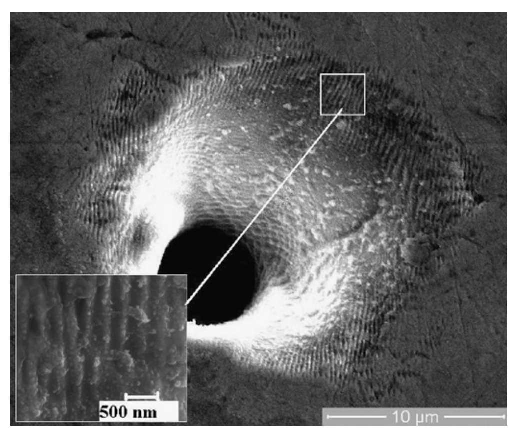

Fig. 4. SEM image of a hole and the external zone in the sketch a magnified view of the LIPSS.

4. PHA X-ray contrast

PHAs are intended to be used for advanced X-ray imaging purpose in laser-fusion oriented experiments. Therefore, it is useful to have a quantitative analysis of the contrast between the hole and W substrate.

PHA was placed in between a μ- sized X-ray source (a μ focus X-ray W tube) and a front illuminated CCD (in this case a Kodak-KAF0261). Fig. 5 shows different sub-images (each CCD image contains hundreds of such sub-images) obtained at different applied potential with corresponding outlines.

A precise measure of the high energy contrast requires to take under consideration the contribution of high energy spurious

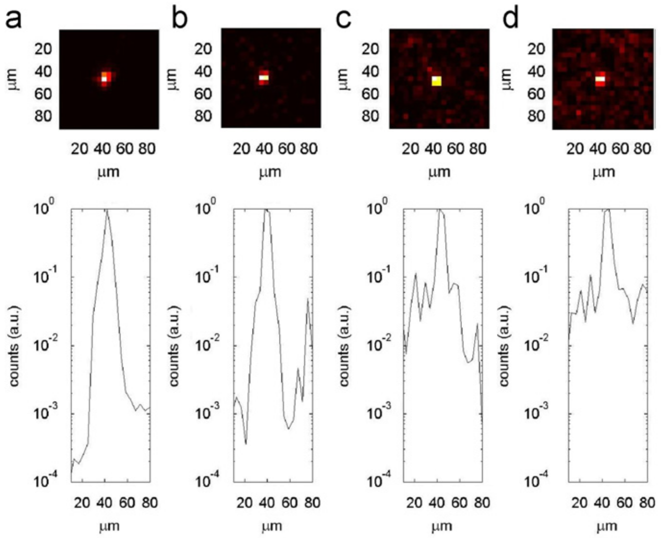

Fig. 5. (Upper) X-ray images of a μ focus X-ray W tube working at 30 kV (a), 50 kV (b), 70 kV (c), 90 kV (d). (Lower) Outline intensity of respective X-ray images.

X-ray photons coming from the neighbours holes (visible as spike in the outline of Fig. 5—lower), the X-ray fluorescence coming from the substrate itself (it can be controlled by changing the CCD to PHA distance), the CCD quantum efficiency and charge transfer efficiency (that actually affect the measured contrast), these points are out of the scope of this work. These images show that PHA transmission contrast ratio changes with the presence of the high energy photons in the spectra and was estimated to be of the order of 10^{-2} at 90 kV. The estimated value of 10^{-2} for the high energy contrast have to be considered as a raw indication for the contrast order of magnitude, more details on the determination of the contrast at different applied potentials will be the subject of the future work, for the scope of this work it is important to note that the high energy contrast remain well under 10^{-1}.

This is a very encouraging result for laser plasma experiments where X-ray are usually a strong component of the scattered radiation. Our measurements show that a high contrast (≈ 100) can be obtained with our custom made pin-holes. This is a fundamental pre-requisite for pin-hole imaging in high intensity laser plasma experiments.

5. Data analysis

The analysis of CCD data in the case of X-ray detections is often effectuated by the adoption of a *threshold* to trigger the identification of an X-ray event from the background. In all these analysis methods, the *threshold* sets the conditions for the identification of events with a different number of pixel. Even with a monochromatic X-ray source the events distribution, on the number of involved pixel, is wide and changes from sensor to sensor. The energy conversion factor, i.e. the detector energy calibration, can depend on the number of the involved pixels and thus on the *threshold*. For this reason a large fraction of the events is rejected and lost. Moreover, the higher energy part of the spectra is lost because of the higher number of pixels involved in an event for increased X-ray photon energy. A new analysis method, in which the use of a *threshold* is overcome, is described in detail in Ref. [4]. In this way all the detected events are collected in the spectra and the energetic range is extended up to 100 keV. This method is shown to work for a front illuminated CCD but can be easily adopted for any kind of "pixelized" detector. We stress here that with this new analysis method it is possible to obtain information on the energetic content and the shape of the detected events. Therefore we can also use this method for the identification of different interacting particles like electrons and protons. This capability is actually under development and will not be presented in this context.

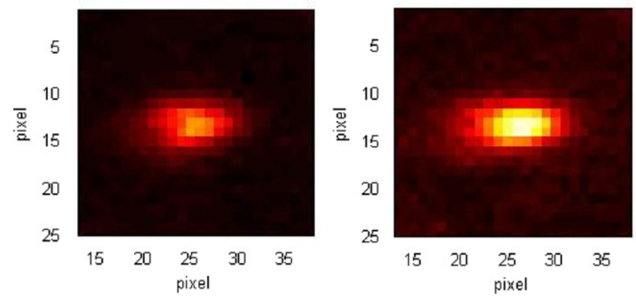

Fig. 6. Reconstructed X-ray source on two energetic range (left) $E<9$ keV and (right) $E>9$ keV.

A PHA makes possible to acquire many hundreds of single-photon images of the same X-ray source, working in low flux regime. In this section we illustrate the basic use of the energy encoded X-ray images reconstruction. Using the centroid of each sub-images it is possible to superimpose all the photons in order to build up a single image. In this way, by selecting the desired energy range, the source can be reconstructed with energy resolution. Fig. 6 shows the reconstructed X-ray source (the same μ- focus source described in the previous section) on two energy ranges $E<9$ keV (left) and $E>9$ keV (right). The image reconstruction is possible with apposite custom developed software capable to obtain, for each detected X-ray photon, the energy and landing position (i.e. the pixel in which the photon was detected). These are integer positions (i.e. the pixel row and column) and there is no information between them. We recall that the new analysis method described in Ref. [4], based on the fitting over many pixel about the X-ray photon landing position, gives higher resolution on the photon's positions offering an improved sub-pixel resolution.

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