Advanced high resolution x-ray diagnostic for HEDP experiments

A. Y. Faenov1,2, T. A. Pikuz1,2, P. Mabey3, B. Albertazzi3, Th. Michel3, G. Rigon3, S. A. Pikuz2,10, A. Buzmakov5, S. Makarov2, N. Ozaki6,7, T. Matsuoka3, K. Katagiri5, K. Miyaniishi5, K. Takahashi6, K. A. Tanaka6,11, Y. Inubushi8, T. Togashi9, T. Yabuuchi9, M. Yabashi6,9, A. Casner5, R. Kodama4,6,7 & M. Koenig3,6

High resolution X-ray imaging is crucial for many high energy density physics (HEDP) experiments. Recently developed techniques to improve resolution have, however, come at the cost of a decreased field of view. In this paper, an innovative experimental detector for X-ray imaging in the context of HEDP experiments with high spatial resolution, as well as a large field of view, is presented. The platform is based on coupling an X-ray backlighter source with a Lithium Fluoride detector, characterized by its large dynamic range. A spatial resolution of 2 μm over a field of view greater than 2 mm² is reported. The platform was benchmarked with both an X-ray free electron laser (XFEL) and an X-ray source produced by a short pulse laser. First, using a non-coherent short pulse laser-produced backlighter, reduced penumbra blurring, as a result of the large size of the X-ray source, is shown. Secondly, we demonstrate phase contrast imaging with a fully coherent monochromatic XFEL beam. Modeling of the absorption and phase contrast transmission of X-ray radiation passing through various targets is presented.

X-ray imaging is a fundamental diagnostic in the high energy density physics (HEDP) community, finding use in a wide range of fields including laboratory astrophysics1,2 and inertial confinement fusion research3-4. It enables the study of the temporal evolution of fast evolving phenomena such as shock compression of matter5-7 or plasma jets8, blast waves9, or hydrodynamic instabilities which are often opaque to visible light10. The recent development of very high-energy laser systems such as the NIF or LMJ11 opens new opportunities for experimental investigations of HEDP, necessitating both high spatial and temporal resolution X-ray imaging techniques to follow the microscale dynamics of these extreme states of matter. X-ray radiography has previously been used to image density distributions, instabilities12 and plasma shapes13. In all of these cases, the precision of the measurements is limited by the resolution of the platform. High temporal resolution is required for many processes and hence X-ray sources created by the interaction of a short-pulse laser with a metal target as well as X-ray Free Electron Lasers (XFELs) are often used. This has allowed processes evolving over several picoseconds or even femtoseconds to be studied14,15. On the other hand, measurements are currently limited by the spatial precision of X-ray detectors and methods16. The simplest and most often used schemes consist of a pinhole or point projection coupled with an image plate (IP) detector17 or X-ray CCD. One of the advantages of this technique is its large field of view, limited only by the size of image plate used, often on the order of centimeters or more. However, this setup can achieve, at best, a 15–25 μm spatial resolution18, which, for a great number of applications, is not sufficient to draw meaningful conclusions. For example, one of the biggest challenges, in HEDP at the current time, is turbulence, as it plays a vital role in star formation and the evolution of our galaxy. Ideally, the measure of the plasma density in this scenario should be performed from the spatial scale at which the laser energy is injected into the system (δ, the characteristic scale of the experiment) down to the Kolmogorov microscale λₖ where dissipation occurs19. Also of much interest, is the Rayleigh-Taylor instability (RTI), observed in

1Open and Transdisciplinary Research Initiatives, Osaka University, Suita, 565-0871, Japan. 2Joint Institute for High Temperature RAS, Moscow, 125412, Russia. 3LULI - CNRS, Ecole Polytechnique, CEA: Université Paris-Saclay; UPMC Univ Paris 06; Sorbonne Universités, F-91128, Palaiseau cedex, France. 4FSRC “Crystallography and Photonics” RAS, Moscow, 119333, Russia. 5Université de Bordeaux-CNRS-CEA, CELIA, UMR 5107, F-33405, Talence, France. 6Graduate School of Engineering, Osaka University, Suita, Osaka, 565-0871, Japan. 7Institute of Laser Engineering, Osaka University, Suita, Osaka, 565-0871, Japan. 8Japan Synchrotron Radiation Research Institute, Sayo, Hyogo, 679-5198, Japan. 9RIKEN SPring-8 Center, Sayo, Hyogo, 679-5148, Japan. 10MEPhI, Moscow, 115409, Russia. 11ELI-NP/IFIN-HH, Maquarele-Bucharest, 077125, Romania. Correspondence and requests for materials should be addressed to T.A.P. (email: pikuz.tatiana@gmail.com)
astrophysics, electro-hydrodynamics and notably in inertial confinement fusion (ICF) at the ablation front. Theory and computational methods describe the development of the RTI with high accuracy for different materials and different initial conditions. Existing X-ray imaging methods, however, are not yet able to compete with theory because of their poor spatial resolution and therefore computational models cannot yet be validated or improved upon. Improved spatial resolution has been achieved recently, but always with the cost of a severely diminished field of view. Fresnel zone plates have been used to measure the spots of XFELs to a precision of 10\(\text{s}\) of nm, as well as the X-rays produced in laser target interactions, yet their field of view is only several \(\mu\text{m}\) and hence are not compatible with HEDP experiments. Other methods, such as, Kirkpatrick-Baez systems are employed at XFELs or in ICF experiments to achieve a resolution of up to 8 \(\mu\text{m}\), and a field of view on the order of tens of \(\mu\text{m}\), yet for the latter case, this is still not sufficient to provide quality imaging for the capsule implosion. Talbot-Lau interferometers can give access to density gradients in a particular direction, but are still limited to \(\mu\text{m}\) using a conventional fluorescent microscope. In theory, the spatial resolution of an LiF detector corresponds to the size of the CCs, that is on the order of nanometres. However, in practice, for very hard X-ray radiation, photoelectron blurring is observed. This is because the energy of the incident photons is enough to generate secondary electrons, which in turn create CCs throughout the detector. For example, a spatial resolution of 1 \(\mu\text{m}\) has been reported for 10 keV radiation. Moreover, since LiF is a passive detector and can be readily produced in any required quantity, its possible field of view is not limited as is the case for other X-ray detection techniques. LiF also has a large (at least 10\(^6\)) dynamic range, is not sensitive to visible light and does not require electronic circuits.

Results

Radiography with laser-produced X-ray source. The experiment was carried out at the LULI2000 facility using the setup shown in Fig. 1(a). Detailed descriptions of the laser beams, diagnostics and sample setup are given in the methods section. In Fig. 1(b), the formation of a shadow image of an opaque element, with a size much smaller than the size of the backlighter, is shown schematically. The maximum spatial resolution theoretically possible, \(\delta x\), is defined by the distance over which the umbra (full shadow) disappears and the penumbra (blurring) becomes 100%. It is linked to the geometry of the setup by the relation: \(P = \delta x \cdot S / D\), where \(S\) is the size of the backlighter source and distances \(P\) and \(D\) are defined in Fig. 1(b). Assuming that the source has the same size as the wire itself, \(S = 25 \mu\text{m}\), then \(\delta x = 5 \mu\text{m}\). In Fig. 2(a), the image of the 300 lpi, 600 lpi and 1000 lpi meshes obtained on the LiF detector in one shot of the PICO2000 laser beam, is shown. As LiF is not sensitive to visible light, no filtering was required; therefore, all radiation from the backlighter above the threshold energy of 14 eV was recorded by the detector. All three meshes are well resolved and the whole image exhibits a qualitatively good contrast. Traces of intensity taken through the crop of the 1000 lpi mesh image demonstrate a spatial resolution of 3.3 \(\mu\text{m}\) (Fig. 2(b)). This value is in agreement with our prediction based on a very simple geometric calculation.

The same setup was then used to perform radiography on a real target, designed for use in a typical RTI experiment. A complete description of these targets may be found in the methods section. We compared the transmission image of an RTI target obtained on the LiF and on a common detector used in this type of experiment, an image plate (IP) (see Fig. 3(a)). In order to obtain the IP image, the LiF detector is removed and the IP is placed at a distance of 700 mm from the target (see Fig. 1(a)). Traces of intensity profiles taken along the white lines clearly show that the interface is resolved significantly better with the LiF (trace in Fig. 3(b)) compared to with the IP (Fig. 3(c)): 7.5 \(\mu\text{m}\) and 30 \(\mu\text{m}\) respectively. It must be noted however, that the IP does show a higher contrast image because of the difference in response of the two detectors in the 4–5 keV spectral range. This indicates that although the spatial resolution is five times higher with the LiF detector, a comparatively higher X-ray flux is nevertheless required. The quality of the results displayed here, however, show that the laser energy provided by the LULI facility does indeed meet these requirements. We estimate that, using this configuration there are on the order of 5 \(\times\) 10\(^7\) photons/mm\(^2\) according to previous papers, incident on the LiF. Our preliminary...
Figure 1. LULI2000 experimental setup: (a) The X-ray radiography scheme. (b) Schematic showing the geometrical limit on spatial resolution and the positioning of the detector.

Figure 2. A radiography image of three Au meshes (300, 600 and 1000 lpi respectively), obtained with an LiF detector on one shot of the PICO2000 laser. An intensity profile taken from the lineout of the 1000 lpi mesh is also displayed.

Figure 3. (a) A comparison of the transmission images of the RTI target, obtained with both LiF and IP detectors (thick arrows show relevant peaks of ripple surface). Panels (b) and (c) indicate intensity the profile along thin arrows in the LiF image and IP image respectively.
measurements with synchrotron sources show that an LiF colorization threshold is of $(1–5) \times 10^7$ photons/mm² for photon energy range around 5 keV. Therefore in our experiments the X-ray flux had to be at an upper bound on the minimum flux needed for this detector. Since X-ray photon numbers scale with laser energy, facilities such as LMJ PETAL or NIF ARC, which have over 10 times more available laser energy, as well as XFELs, with a single shot flux in excess of $10^{11}$ photons/mm², therefore comfortably meet these flux requirements. Additionally, in the experiment described here, the source-to-detector distance was 50 mm because of experimental constraints, but could readily be lowered in cases of low photon flux. A more detailed study on the response of LiF would be required to assess the feasibility of using this detector at smaller facilities, but is beyond the scope of this work.

**X-ray imaging with monochromatic fully coherent XFEL source.** In addition to the large increase in brightness of XFEL radiation, the beam is also coherent and well collimated, thus allowing the possibility to perform phase contrast imaging (PCI) rather than simple absorption radiography. This technique is based on the propagation of phase-shifted X-ray photons induced by a density gradient; spatially coherent radiation is deflected from regions of higher density to regions of lower density. Due to the lack of coherence, and relatively modest numbers of divergent photons, laser-produced X-ray sources are not well suited to PCI. XFEL and synchrotron radiation, however, does not have these drawbacks.

To that end, an experiment at the SACLA XFEL was performed in order to characterize the new experimental scheme using a higher photon count and employing PCI rather than simple radiography. The experiment was carried out at beam line BL3, experimental hutch EH5 and a full description of the X-ray beam parameters used can be found in the methods section. Initially a 1500 lpi mesh was attached to the front surface of the RTI target and the LiF detector placed at a distance of 120 mm from the target chamber center. The target was illuminated with one shot of the XFEL beam at full energy, with the resulting LiF images shown in Fig. 4. Panel (a) contains a large field of view photoluminescent image, observed with a 4X microscope objective. Panel (b) shows part of the full image with different elements of target, observed with objective 40X, while panel (c) shows an enlarged crop of this image, in which the diffraction pattern in open areas of the mesh is clearly seen. Panel (d) contains an intensity profile taken from the cropped image.

![Figure 4](image)

**Figure 4.** The image of 1500 lpi mesh obtained on LiF for the evaluation of an instrumental spatial resolution: Panel (a) contains a large field of view photoluminescent image, observed with a 4X microscope objective. Panel (b) shows part of the full image with different elements of target, observed with objective 40X, while panel (c) shows an enlarged crop of this image, in which the diffraction pattern in open areas of the mesh is clearly seen. Panel (d) contains an intensity profile taken from the cropped image.
rather than a laser-produced X-ray source is of course expected, however, and should not be seen as unique to the LiF detector. Rather, these results illustrate the full potential of this type of detector under optimal conditions.

The experimental results are also compared to a model of the idealized case of the radiography of the RTI target using a hard X-ray backlighter (monochromatic – spectral bandwidth is $\delta$-function, fully coherent) with the results shown also in Fig. 6. The details of the model employed can be found in the methods section. One of its primary capabilities is the ability to determine whether PCI is expected for a given set of X-ray source and geometrical parameters. PCI is indeed predicted by the model for the experiment described here, although one notes a higher phase contrast enhancement than that measured experimentally on the LiF detector. This is inevitable however, due to the idealized approximations included for both the X-ray beam and the target. Aside from this, the model recreates the experimental image very well with the relative absorptions of the different sections of the target, well taken into account. Planning future X-ray imaging experiments will therefore be aided greatly by this tool. Not only will one have the ability to predict whether PCI will be possible with the given probe beam parameters, the contrast of the radiographic image may also be well predicted and therefore optimized by considering the design of the target.

**Discussion**

The results demonstrate that the LiF detector, coupled with an X-ray backlighter source, represents an improvement on the experimental X-ray radiography platform, boasting a sufficiently large field of view (several mm) to image an entire HEDP experiment, with a high spatial resolution. First applied for imaging with non-coherent quasi-monochromatic laser-produced plasma X-rays, the platform reduces the amount of penumbra blurring. Experiments on imaging test-meshes and RTI targets in static conditions show that a spatial resolution of $\sim 3.3 \mu m$ can be obtained with a backlighter size of $\sim 25 \mu m$. A second experiment employing phase contrast imaging with a coherent monochromatic XFEL beam significantly increases the visibility of inhomogeneities in low absorption objects. Coupling with the LiF detector allows the imaging of objects with spatial resolution better than $2 \mu m$ across the full aperture of the XFEL beam. These results have important consequences for future experiments across a wide range of areas in HEDP. LiF detectors could be used on ICF experiments at large laser facilities, such as the NIF or LMJ-PETAL, in order to vastly increase the resolution available for imaging the small-scale structures and instabilities with the imploding fusion core, thus paving the way to better understand the dynamics of the system and enabling the validation of various models. Additionally, experiments investigating RTI instabilities in order to understand crucial astrophysical phenomena, such as supernovae remnants, would benefit greatly from the higher resolution and field of view enabled by this experimental platform. Moreover, the combination of spatial and temporal resolution, could be used for a range of applications in the field of shock physics. With a

![Figure 5](a) Photoluminescence image of the RTI target interface obtained on a single shot of the SACLA XFEL using an LiF detector. The effect of the phase contrast enhancement is clearly seen. Two parts of the image are enlarged to better see the structural details of the target and multiple small inhomogeneities. The left hand panel shows schematically a measurement of the angular misalignment of the RTI target. Z is the axis of the XFEL beam, $\alpha$ and $\beta$ are the angles of rotation around horizontal X and vertical Y axis, respectively. Panel (b) shows a view of the target indicating the part which is irradiated by the XFEL.
resolution smaller than typical grain sizes in most polycrystalline samples, LiF detectors open up the possibility of observing the effect of grain boundaries and orientations on shock propagation through samples. In general, coupled with their low cost, and ease of use, LiF detectors represent a vast improvement on the image plate detectors that are in widespread use in the field today.

**Methods**

**RTI Targets.** The targets used in this work consist of a layer of brominated plastic, attached to a thin (~1 µm) gold foil used as a radiation shield, a plastic ablator and a thin cylindrical shock tube, filled with low density plastic foam. Ripples with sinusoidal profile are pre-imposed on the entire surface of the brominated plastic layer. A sketch of the target is shown in Fig. 7(a). The shock tube is made from polyamide, with a diameter of ~1 mm,

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**Figure 6.** Comparison of experimental image obtained on the LiF crystal with modelling with lineout taken across rippled target edge. Phase contrast enhancement is observed in both cases.

**Figure 7.** (a) A sketch of the RTI target, used to test the radiography platform. The material composition and the dimensions of the targets are shown. (b) The parameters of the pre-imposed ripples on the surface.
modeling, one can build a 3D numerical model of the object and integrate it to obtain the 2D transmission function:

\[ T(x, y, z) = \int T(x, y, z, \omega)dz. \]

where, the z - axis is perpendicular to the observation plane.
Using this formula and the optical constants calculated with the xraylib software library\(^\text{99}\) we can build the transmission plane of our modeling object. The RTI target was considered as consisting of four different elements: a cylinder with thin walls, foam, an air cupola and a disk with a rippled surface. For each element, a 3D model and a complex 2D transmission plane, including absorption and phase shift, was built. The SACLA XFEL beam was modeled as a Gaussian beam object in WPG. After building the incident beam and the transmission plane, we propagate the wavefront using a free space propagator over a distance of 120 mm to the observation plane. This procedure was repeated for each element of the target.

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Author Contributions
A.Y.F., T.A.P., B.A., N.O., R.K. and M.K. conceived the project. A.Y.F., T.A.P., P.M., B.A., Th.M., G.R., N.O., S.A.P., A.C. and M.K. conducted the experiments at LULI. A.Y.F., T.A.P., B.A., N.O., T.M., K.K., K.M., K.A.T., M.Y., K.T., Y.I., T.T. and T.Y. conducted the experiments at SACLA. A.Y.F., T.A.P., S.M., S.A.P. and G.R. analyzed the results. A.B. performed the WPG modelling. A.Y.F., T.A.P., P.M., A.B. and S.M., wrote the paper. All authors discussed and reviewed the manuscript.

Additional Information
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