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研究課題名（和文）Development of X-ray phase contrast imaging platforms for investigations dynamic evolution of matter in extreme conditions

研究課題名（英文）Development of X-ray phase contrast imaging platforms for investigations dynamic evolution of matter in extreme conditions

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研究成果の概要（和文）：X線イメージングはフェムト秒スケールで高速に変化する現象を観察できる計測手法であり、高エネルギー密度科学の分野で広く用いられているが、これまでのX線イメージング技術は空間分解能が限定的であった。私たちは高輝度X線源とLiF結晶を組み合わせることで、サブミクロンの高空間分解能とミリメートルサイズの広視野、1e6を超える極めて高いダイナミックレンジを同時に実現する位相コントラストイメージングのプラットフォームを開発した。これによりプラズマ不安定性による乱流相の観察や、衝撃圧縮されたダイヤモンド試料を伝搬する連続的な弾性波と塑性波の観察、XFELビームの詳細な特性評価といった結果を得られた。

研究成果の学術的意義や社会的意義
This work provides a new insides for better understanding miscellaneous phenomena of instabilities in liquid and plasma flows, in engineering and nature, and for study compression dynamics of a matter important in astrophysics, inertial confinement fusion, and advanced material creation

研究成果の概要（英文）：X-ray imaging is a fundamental diagnostic in the high energy density physics including laboratory astrophysics, inertial confinement fusion research, and materials science, which enable the study of phenomena evolving on time scales down to the femtosecond level. Until recently, these diagnostics were limited to spatial resolution. By the combination of XFEL (or high-power laser-produced) sources with novel LiF crystal detector we have succeeded in developing the new phase-contrast imaging platform allowing simultaneously sub-micron resolution, mms-square field of view and ultra-high dynamic range > 1e6. The new approach provided pioneering results on the study of the turbulent phase of plasma instabilities in the micron-scale of energy dissipation, on dynamics of a mutual elastic-plastic shock evolution in plastics and diamond, and on advanced characterization of XFEL beams.

研究分野：High energy density physics

キーワード：Phase contrast imaging　High resolution Imaging　Pump-probe experiment　LiF detector　XFEL probe beam　Plasma instabilities　Shock compressed matter

１．研究開始当初の背景

Investigation of properties of the matter under extreme conditions is a hot topic of high energy density physics and technological applications. During the past decade, several physical fundamental problems have been pointed out in this field. Particular significant problems arise for shock physics, which are of prime importance for various domains such as astrophysics, inertial confinement fusion, planetology and technological and advanced material creation. X-ray micro-imaging of such conditions is fundamental method of study because only radiography gives 2D picture of state of mater over whole volume of investigated object at the time of snapshot. Particular, such diagnostics is crucial in the problem of the Rayleigh-Taylor instabilities (RTI) seeding in laser-matter interaction, which cause growth of any initial perturbation. Another problem to be studied is developing of instabilities in the solid phase in shock compression experiment in order to evaluate the impact of the inhomogeneity of the shock wave propagating inside a sample.

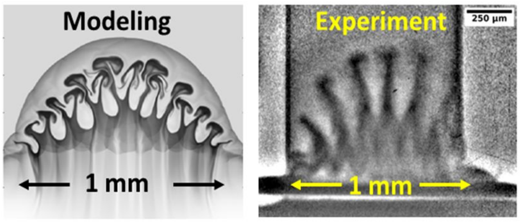

Fig. 1. Mixing phase of RTI: comparison modeling with experiment (LULI200 laser facility)

In fact, conventional X-ray radiography technique (pinhole, point projection technique) is restricted to a resolution of 10-20 μm with time resolution of ~ 1 ps. These values are largely above the expected spatial extension of the shock that is a few crystalline layers. Also it cannot satisfy RTI experiments because the nowadays theory allows to model picture of plasma flows with much high resolution (fig. 1). In traditional schemes any efforts to improve a spatial resolution causes undesired decrease of field of view and decrease of luminosity. Additionally, hard X-ray radiation has a low absorption in such ultrathin objects as shock waves or instabilities. This causes serious limitations for X-ray imaging applications for such and similar objects study. Fairly recently X-ray phase contrast techniques was proposed to solve this problem. A free space propagation of waves is using at particular setup to enhance phase changes, induced by low absorb sample, to obtain invisible in absorption structures (Fig.2). Nevertheless there are major drawbacks, which complicates practical application: namely, all of these techniques require sources, which produce both spatial or temporal coherent radiation, and use of high-performance X-ray imaging detectors.

The developing of new imaging platform using hard X-ray radiation (objects under interest are opaque to the optical and XUV radiation), which allow radiography with micron scale resolution, high contrast, large field of view and large dynamic range is a state-of-the-art of today investigations.

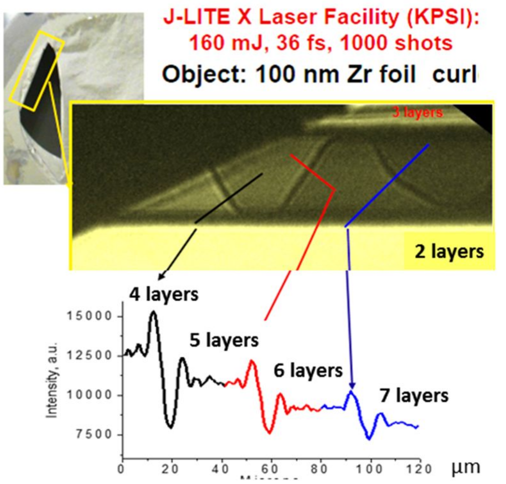

Fig.2. EUV phase-contrast enhancement in the image of thin multilayer curl from Zr foil

２．研究の目的

The goal of this research was the development of new x-ray imaging platform for investigation dynamic evolution of matter in extreme conditions with the following characteristics:

(1) spatial resolution < 2 microns; (2) field of view > 1 mm^2 ; (3) dynamic range ≥ 1e5; (4) spectral range of probe beam of 4 – 10 keV. Simultaneously such parameters have not been previously demonstrated.

For reaching the goal the phase-contrast imaging approach had to be realized on the base of coupling a high-power-laser pump and XFEL (and laser-produced plasma) probe with innovative

high-resolution, large-dynamic-range lithium fluoride (LiF) crystal imaging detector.
It was aimed to demonstrate experimentally the achievement of desired characteristics by carrying out at XFEL facility a pioneering radiography study of shock wave dynamics in solids and evolution of RTI in foam-solid targets from the early linear stage until the turbulent phase reaching the Kolmogorov micrometer-scale of energy dissipation.

３．研究の方法

Properties of LiF crystal detector in the hard x-ray spectral range

In this work the LiF detector was a LiF crystal plate with diameter of 20 mm and thickness of 2 mm. In LiF images created by F_2 and F_3^+ types color centers (CCs) generated under x-radiation. These CCs are stable at room temperature and store recorded image for years. The metrological characterization of LiF resulted on finding the photoluminescence response I_{PL} of LiF to monochromatic x-ray irradiation dose as $I_{PL} = kD^{0.45}$ (where k depends on readout system), determination of spatial resolution limit 0.8 micron and its weak dependence on the photon energy, and evaluation of dynamic range of $> 10^6$. Measurements have been done at the SOLEIL (France), PETRA III (Germany) synchrotron facilities and XFEL SACLA (Japan). In total LiF detector properties have been tested in the range of photon energies 0.5 – 10 keV and in the range of irradiation fluxes $10^{-5} – 10^3$ J/cm^2.

Modeling the propagation of XFEL radiation through investigated object

The modeling of the absorption and phase contrast images was provided using the software framework for coherent and partially coherent X-ray wavefront propagation simulations, WavePropaGator (WPG) [Samoylova et al., J. Appl. Cryst. 49 1347 (2016)]. This software package is the most relevant for FEL applications as well as being open access. The propagation of the beam through 3D multicomponent objects was described as a set of propagators corresponding to individual optical components, which numerically solved by means of a 2D FFT algorithm.

The RTI targets

The main targets used in this work for the study of RTI consist of a layer of brominated plastic, a plastic ablator and a thin cylindrical shock tube, filled with low density plastic foam. Ripples with sinusoidal profile were pre-imposed on the entire surface of the brominated plastic layer. The shock tube is made from polyamide, with a diameter of ~1 mm, a height is of ~3.5 mm, and a wall thickness of ~40 μm. The initial profile of the ripples on the brominated layer had a wavelength of ~40 μm (single mode) and 15 μm (bi-mode), with a peak-of-valley depth of ~10 and 8 μm correspondently. The density of the brominated layer (elemental composition C8H7Br) was 1.54 g/cc, while the density of the CH foam was of 100 mg/cc (Atwood number A = 0.88). The bromine, buried into the profiled layer, increases the absorption and enhances the contrast of the radiography.

X-ray imaging platform with monochromatic fully Coherent XFEL Probe (CXP)

The experiments were carried out at SACLA at beam line BL3, experimental hutch EH5 at the XFEL beam photon energy of 7 and 10 keV, a pulse energy at the exit of the undulator of ~ 490 J/pulse, a FWHM spot size on the target of ~1 mm. The distance between LiF detector and investigated object (RTI target or thin foil) was kept optimal for phase-contrast image enhancement according with modeling results and in the most cases was in the range of 100-107 mm (Fig. 3).

X-ray imaging platform with Laser-Produced X-ray Probe (LPP scheme)

The experiments were carried out at the LULI2000 (80 J, 10 ps) and LFEX (300 J, 1.5 ps) facility. The X-ray probe source was created by the interaction of laser pulse with the diameter 25 microns wire targets. The X-ray yield was optimized in the spectral range of 4.5 – 4.8 keV of the order of 10^{11} photons in a 4π solid angle. The LPS scheme was tested in the proposed geometry of reduced image blurring. Gold meshes (300, 600 and 1000 lines per inch) were used to test the resolution of the platform as well as RTI target. The spatial resolution of 3.3 microns in 7 times smaller than probe source was confirmed.

Readout of photoluminescence images recorded by LiF detector

Experimental images recorded on the LiF were observed by scanning a confocal fluorescent Nikon C2 microscope with a laser excitation wavelength of 445 nm and magnifications of 4X, 20X, 40X, and 100X.

４．研究成果

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 object with a high spatial resolution. Experimental employing phase contrast imaging with a coherent monochromatic XFEL beam significantly increases the visibility of inhomogeneities in objects with small gradients of density. 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 take place. Therefore the systematic study of achievable spatial resolution was done in the wide range of photon energies using XFEL and synchrotron radiation (see Methods). It was obtained that for photon energies of 0.5-10 keV a spatial resolution is changing, but it is better of 1.5 microns. 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. LiF detect is a simple crystal plate, while it combines unique imaging properties with very simple in use and low cost.

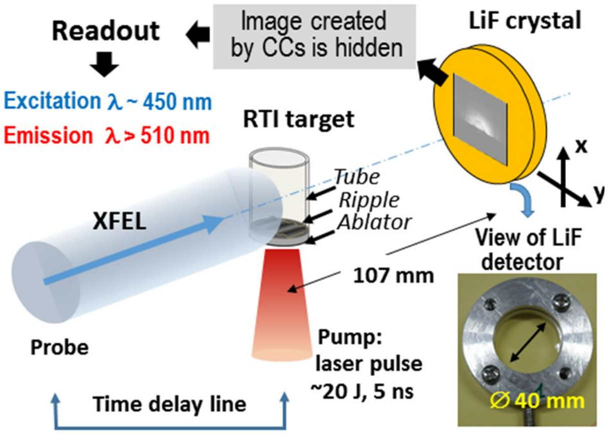

Fig. 3. Principles of imaging platform CXP based on coupling XFEL beam and LiF detector

The principals of CXR imaging platform are shown in Fig.3. Presented setup was applied at SACLA, BL3 for investigation RTI driven by high-power laser pulses in the conventional for such type experiment targets with pre-imposed ripple interface attached to low density foam (see description in Methods). Experiments carried out at photon energy 7 keV and 10 keV. In both cases the spatial resolution of 0.8 micron in the full aperture of direct XFEL beam about 2 mm (FWHM = 0.8 mm) have been confirmed in the single-shot diffraction image of Ni mesh placed as an object instead of RTI target (Fig. 4). We note that due to large dynamic range the high order diffraction fringes can be seen in the far periphery of the pattern.

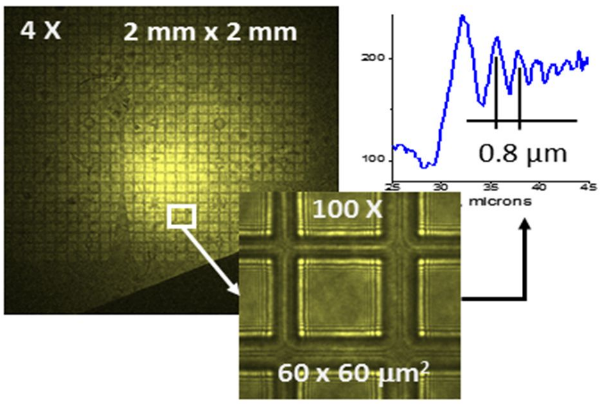

Fig. 4. PL image of 400 lpi Ni mesh obtained on LiF in full aperture of XFEL beam at photon energy 7 keV with resolution 0.8 μm

The solid confirmation that the challenging problem posed in this project successfully achieved was obtained on the observation the development of Richtmyer-Meshkov and Rayleigh-Taylor instabilities that evolve into turbulence. The evolution of the expanding plasma was diagnosed up to 80 ns after the main laser shot with the step of 10 ns. Selected radiographic images are presented in Fig. 5. The phase-contrast enhancement is clearly seen. The upper panels show images of single-mode (left) and bi-mode(right) interfaces in initial condition (parameters are described in the Methods). Below are the correspondent images obtained with time delay. Important to stress that for every delay a new target was used and LiF detector was shifted in (x,y) directions to be exposed on each shot to the fresh surface (for images taken with delays 60 and 50 ns initial profiles don't shown). At time of 30 ns the spike and bubble evolution is seen clearly. At later times of 60 ns, structures are losing and isotropy is attained, those features are consistent with a turbulent flow. The transition between those two phases occurs between 40 ns and 50 ns. That are the first direct experimental measurement of the turbulent spectrum over a large order of amplitude and down to the Kolmogorov scale in a laser produced plasma experiment. It shows numerous features, which could contribute to benchmark the models and simulations. Moreover, suitably designed experiments could solve outstanding problems in astrophysics, where turbulence is of central importance.

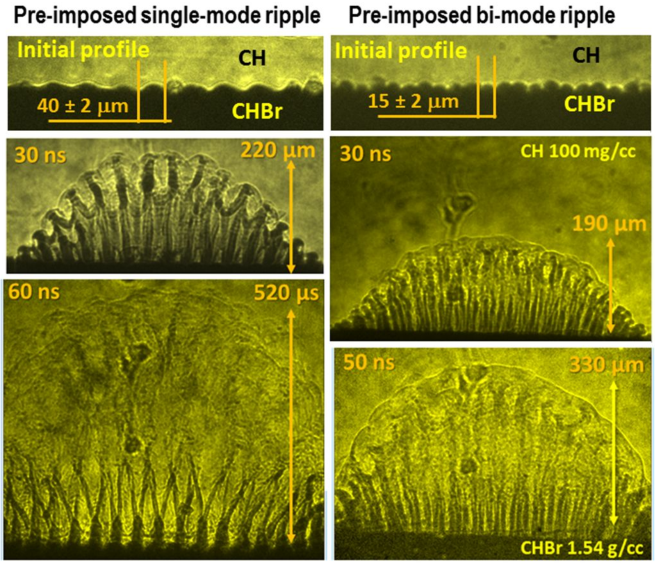

Fig. 5. Measured by LiF detector initial profile of ripple interface of RTI target and development of RTI at non-linear mixing and turbulent stages

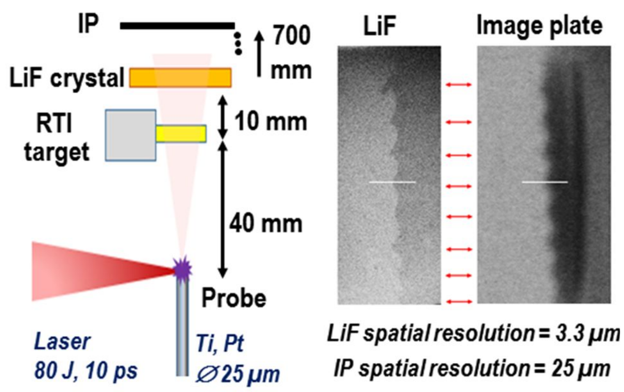

Fig. 6. LPP imaging platform. Images of RTI target ripple obtained on LiF and Image Plate (IP).

With the same setup impressive results have been obtained on observation dynamics of shock waves generated in diamond. The formation of elastic and plastic shock fronts and their relative motion was studied in the 240 micron thick diamond plate along the crystallographic direction [100] until the time of 12 ns when elastic front reached the back surface and energy dissipation in plastic wave occur. The feature of front's shape, speed have been measured with high accuracy.

The LPP experimental platform was tested at the LFEX and LULI2000 facility using the setup shown in Fig. 6. The absorption imaging of RTI target interface provided at photon energy ~ 4.5 keV. It is clearly seen that spatial resolution of LiF significantly better than size of probe source and the interface is resolved better with the LiF compared to with the IP. However, the IP shows a higher contrast image because of the difference in response of the two detectors in the 4–5 keV spectral range. This indicates that a comparatively higher X-ray flux is nevertheless required. The LPP scheme can be efficient if the laser produced probe allowed the irradiation flux > (1–5)·107 photons/mm^2 wich is the colorization threshold of liF.

The main experiments have been carried out supported wholly or in part by funding of this proposal. Additionally, equipment bought with the grant money continues to be used for x-ray radiography diagnostics supporting experiment at SACLA and LFEX in the frames of other beamtimes. One more proposal on the high resolution x-ray imaging of RTI using CXP platform at SACLA has been accepted and will be carried on the base of setup used during this project.

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

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