Laser-driven proton sources and their applications: Femtosecond Intense Laser Plasma Driven Simultaneous Proton and X-ray Imaging

M Nishiuchi, H Daido, AYogo, A Sagisaka, K Ogura, S Orimo, M Mori, J Ma, A S Pirozhkov, H Kiriyama, S Kanazawa, S Kondo, Y Yamamoto, T Shimoura, M Tanoue, Y Nakai, A Akutsu, A Nagashima, S V Bulanov, T Zh Esirkepov, T Kimura, T Tajima, K Nemoto, Y Oishi, T Nayuki, T Fujii, A Noda, Y Iwashita, T Shirai, S Nakamura, I W Choi, T J.Yu, J H Sung, H T Kim, T M Jeong, K -H Hong, Y -C Noh, D -K Ko, J Lee

1 Advanced Photon Research Center, JAEA, Kizugawa-shi, Kyoto, Japan
2 Central Research Institute of Electric Power Industry (CRIEPI), Yokosuka, Japan
3 Institute for Chemical Research, Kyoto University, Uji, Kyoto, Japan
4 Femto Science Laboratory, Advanced Photonics Research Institute, GIST, Gwangju, Korea

E-mail: nishiuchi.mamiko@jaea.go.jp

Abstract. We have performed simultaneous proton and X-ray imaging with an ultra-short and high-intensity Ti: Sap laser system. More than $10^{10}$ protons, whose maximum energy reaches 2.5 MeV, were delivered within a ~ps bunch. At the same time, keV X-ray is generated at almost the same place where protons are emitted. We have performed the simultaneous imaging of the copper mesh by using proton and x-ray beams, in practical use of the characteristics of the laser produced plasma that it can provide those beams simultaneously without any serious problems on synchronization.

1. Introduction
Recent years have seen remarkable advancements in the laser-driven proton accelerators [1]. Researches on laser-driven proton accelerators and their applications have been intensively performed [2–10]. The laser-plasma driven proton beam has significant and peculiar characteristics. The protons are emitted into vacuum within short pulse duration of ~ps. The proton beam has an effective source size of ~10 μm in diameter and a small transverse emittance [4,9-10]. The maximum proton energy is controllable from a few hundred keV to ~10MeV with the wide energy spread (a chirped proton pulse). The proton beam is a diverging beam with an angle of ~10°. Because of these peculiar characteristics, many applications are proposed. For example, it is applicable for table-top accelerators of charged particles [11-12], construction of injectors for conventional accelerators [13], material science [14], and the production of short-lived isotopes for medical diagnostics [15, 16]. The proton beam is also applicable to the time-resolved proton microscopy for imaging electric field profiles in laser-produced plasmas [5] as well as static samples for feasibility demonstration [4,10].
It is well known that proton and X-ray emissions occur simultaneously at a laser-irradiated target. X-ray having duration of a few ps and a source size of 10 µm diameter is produced by a high-intensity fs laser. By generating a proton image of a sample simultaneously with an X-ray image, we can obtain precious information on a sample if the sample responds to each beam with specific features. Laser produced plasma can inherently provide us easily an X-ray source and a proton source simultaneously within a very small space. Adding to that, we should not take into account any device for precise synchronization between proton and X-ray beam.

2. Experimental setup
The experiment is performed at the Advanced Photonic Research Institute (APRI), Gwangju Institute of Science and Technology (GIST) in Korea at the Advanced Photon Research Center (APRC). The wavelength and the pulse energy of the pumping laser are 800 nm and 670 mJ on target. A prepulse that comes from the leakage from the regenerative amplifier is at 4.7 ns prior to the main pulse. The contrast ratio of a prepulse to the main pulse is $10^{-6} \sim 10^{-4}$. The ratio of an amplified spontaneous emission (ASE) followed by the ~ns prepulse to that of the main pulse is $10^{-6}$. The ASE duration, which is controlled by the Pockel’s cell switch, lasts from a few ns prior to the main pulse up to 4 ps before the main pulse. A p-polarized laser pulse with 70mm diameter is irradiated onto a 5-µm-thick, 20-mm-wide copper tape target at an incidence angle of 45°. The focal length of an off axis parabolic mirror is 238mm (F/3.4). The tape target driver supplies a fresh surface to the focus spot at every shot. The measured focal spot size is 16x13 µm^2 in horizontal and vertical directions (full width at half maximum: FWHM), respectively. The main pulse duration was changed from 35 to 190 fs by adjusting the grating separation in the pulse compressor, providing intensities of $\sim 4.4 \times 10^{18}$ W/cm^2 for the minimum pulse duration and $\sim 1 \times 10^{18}$ W/cm^2 for the longest duration at the focal spot.

3. Proton beam characteristics
We obtain the maximum proton energy of 2.4MeV with $8 \times 10^{10}$ protons in the entire spectrum per laser pulse at 100 fs pulse duration, as is shown in Fig. 1(a). We measure the angular distribution of the proton beams with the energy ranges of >0.8, >1.2, and >1.8MeV. We place the CR-39 nuclear track detector (Nagase-Landauer BARYOTRAK) with mylar range filters whose thicknesses are determined for detecting protons in each energy range. In Fig. 1(b), the darker region corresponds to the higher-intensity region. The beam divergence of the proton beam is recorded shot by shot on the CR-39 nuclear track detector covered with range filters. The divergence angles are 10°(horizontal) and 14.5°(vertical) for protons with energies of >1.8 MeV, 17.8°(horizontal) and 20.6°(vertical) for >1.2 MeV, and >25.3°(horizontal) for >0.8 MeV. We cannot determined the vertical divergence axis of protons with energies of >0.8 MeV, because the proton beam spreads over a larger area than that of the detector. The pulse duration of the accelerated protons is expected to be in picoseconds at the source.

4. X-ray beam characteristics
An example of the incident X-ray spectrum onto the imaging plate in the keV spectral region, which is
measured using an X-ray charge-coupled-device (CCD) camera using the photon-counting technique, is shown in Fig. 2. The incident spectrum is deconvolved from the spectrum detected using an X-ray CCD camera on the basis of the information on the spectral sensitivity of the X-ray CCD camera. By comparing the information on this incident X-ray spectrum with that of the spectral sensitivity of the imaging plate (FUJIFILM BAS-SR2025) [17], we can estimate the energy band of the majority of X-ray photons which form the X-ray image on the imaging plate. The dominant spectral component of the X-ray image is estimated to be approximately 8 keV (Cu Kα line). The number of X-ray photons at the energy of the Cu Kα line (8.05 keV) with an energy band of 0.4 keV is $1.9 \times 10^9$ photons/sr, after we take into account the transmittance of the filters used and the quantum efficiency of the CCD camera.

**Fig. 2 Typical X-ray spectrum in the keV region taken with the X-ray CCD camera by the single photon counting technique**

5. Results and Discussion

The geometry used is explained in Fig. 3(a). The magnification of the projection is 30. The proton and X-ray images are recorded on the CR-39 nuclear track detector and the imaging plate, respectively. The object for the imaging is 19µm-thickness copper mesh, having a smallest structure of ~10µm (Fig. 3(b)). Each projection image is taken by a single shot. The results of the simultaneous proton and X-ray shadow images are shown in Figs. 3(c) and 3(d), respectively.

In the proton image, the entire proton energy component contributes to the image configuration because we set no filters on the CR-39 to eliminate the lower-energy photons. In our case, the resolution is determined mainly by the source size rather than the resolution due to the detector. The resolution due to the detector can be estimated as a grain size of the CR-39 divided by magnification. The spatial structures with a scale of ~10 µm are clearly visible, as is shown in Fig. 3(c). However, we obtain a rather poor X-ray image because of the lack of photons, as is shown in Fig. 3(d). The dynamic range of an X-ray image is determined by the spectral sensitivity of the imaging plate and the incident X-ray spectrum onto the imaging plate. The X-ray photons which pass through the holes of the mesh, penetrate through the CR-39, and are detected on the imaging plate, correspond to the darker region shown in Fig. 3(d). For these photons, we have to take into account the X-ray transmittance of 1-mm-thick CR-39 and the absorption of the phosphor layer of the imaging plate. The percentage of the X-ray photons detected at the imaging plate near 8 keV is 0.4. The X-ray photons which penetrate through the 19-µm-thick copper of the mesh bar and the CR-39, and detected on the imaging plate, correspond to the brighter region shown in Fig. 3(d). For these photons, we have to take into account the X-ray transmittance of the 19-µm-thick copper as well as the 1-mm-thick CR-39 and the absorption of the phosphor layer of the imaging plate. The percentage of X-ray photons that reached and were detected on the imaging plate near 8 keV is 0.17. The number of X-ray photons that fall within 1 cm$^2$ of the imaging plate is $5.3 \times 10^6$ photons/cm$^2$. Because the size of one pixel in the imaging plate is 25x 25 µm$^2$, the numbers of X-ray photons that fall within one pixel on the dark and bright regions are 13.2 and 5.6 X-ray photons, respectively, after we take into account the spectral sensitivities for both components. The number of X-ray photons that determines the signal level is $13.2 - 5.6 = 7.6$ X-ray photons, corresponding only 2.7-fold the standard deviation.

In order to improve the quality of X-ray images, the combination of a target material, a sample, and filters should be optimized for each specific purpose. One of the useful methods is to use the monochromatic Kα line from the target material. It is one of our further endeavors to further improve the clarity of X-ray images by collecting the Kα X-ray photons using appropriate focusing X-ray
optics[18], simultaneously with proton images. The use of appropriate X-ray optics such as curved crystal reflectors also provides us the precise simultaneity between the X-ray and the proton beams. In our case, the distances between the target and the mesh, and the target and the detector are 6 and 180 mm, respectively. The difference between the traversal times of the protons and the X-ray from the source to the sample mesh causes the time delay of the exposure by protons from that by the X-ray. If the distance is 6mm and the proton energy for imaging is 1.5 MeV, the delay between the two images is 320 ps. In this simple configuration, we are able to guarantee a simultaneity of <1 ns, which is sufficiently small for observing a dynamic effect having a time constant of nanoseconds. The results show that the simultaneous generations of ultra-short intense beams such as energetic protons, X-ray and the laser itself are applicable to pump-probe measurements for transient phenomena in microstructures. In particular, a proton beam probing technique provides us information on electromagnetic field configurations inside a sample or local information on specific interactions between the beam and the materials.

Fig.3 (a) Experimental setup for the proton and X-ray simultaneous imaging. (b) Patterns in the copper mesh used. (c) Proton shadowgraph with the magnification of 30. (d) X-ray shadowgraph with the same magnification.

6. Summary
We have demonstrated the successful simultaneous generation of projection images of a test sample using protons and X-ray with a resolution of~10 µm placed close to the source. With simple configuration performed, the simultaneity between two images is a few 100 ps. The quality of X-ray images should be improved using the appropriate X-ray optics. The technique is applicable to the precise observation of microstructures.

7. References
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