Talbot-Lau X-ray Deflectometer Electron Density Diagnostic for Laser and Pulsed Power High Energy Density Plasma Experiments[a)]

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Talbot-Lau X-ray Deflectometry has been developed as an electron density diagnostic for High Energy Density plasmas. The technique can deliver x-ray refraction, attenuation, elemental composition, and scatter information from a single Moiré image. An 8 keV Talbot-Lau interferometer was deployed using laser and x-pinch backlighters. Grating survival and electron density mapping was demonstrated for 25-29 J, 8-30 ps laser pulses using copper foil targets. Moiré pattern formation and grating survival was also observed using a copper x-pinch driven at 400 kA, ~1 kA/ns. These results demonstrate the potential of TXD as an electron density diagnostic for HED plasmas.

I. INTRODUCTION

A. Talbot-Lau X-ray Deflectometry (TXD)

The refraction-based Talbot-Lau X-ray interferometer is able to measure angular deviations caused by electron density gradients in matter. The interferometer has been adapted from a standard medical[1,2] setup to a High Energy Density (HED) compatible configuration[3]. The Moiré configuration allows for electron density retrieval using the Talbot-Lau X-ray Deflectometry (TXD) technique[4]. Moreover, simultaneous information about the probed object can be obtained through Fourier decomposition such as attenuation signal and elemental composition[5]. Additionally, the TXD technique can also detect microstructure presence through scatter imaging[6].

The Talbot-Lau Interferometer (shown in Figure 1) is an ideal electron density diagnostic offering high contrast imaging capabilities, in particular when low-Z matter is probed with energies between 1-100 keV. In this spectral range, the refraction signatures are much higher than attenuation signatures due to the large ratio between the real and imaginary index of refraction components[7]. Furthermore, the Talbot-Lau interferometer can achieve high refraction angle sensitivities through Talbot order and magnification adjustment, in addition to grating placement (relative to the probed object) and period. High magnification Talbot-Lau systems of 8 and 17 keV design energy have been developed using conventional x-ray tubes as sources[3,4,5].

The steps from operation with conventional x-ray sources to operation with HED compatible backlighters are reported. The specific modifications required for TXD illumination with laser driven backlighters as well as a pulsed power driven x-pinch backlighters will be discussed along with the efforts required to benchmark the TXD technique in the HED environment using the aforementioned x-ray backlighters.

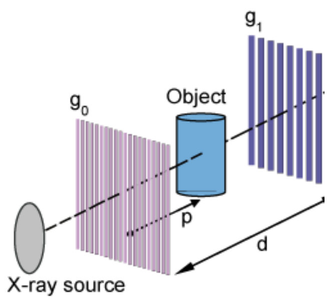

FIG. 1. (Color online). Talbot-Lau interferometer setup.

B. TXD Adaptation to HED Environment

X-ray refraction measurements can provide a wealth of information in HED laser-driven experiments, in particular for extremely high electron densities, such as those encountered in Inertial Confinement Fusion (ICF) experiments. The TXD technique can deliver important electron density, mixing, and scatter images, which are nowadays either technically difficult to obtain using present diagnostics or highly dependent on assumptions about the probed plasma[8]. A suitable X-ray source for a laser-driven experimental environment is a laser-driven x-ray backlighter, where a thin foil is irradiated to typically obtain a K-shell emission source. These laser-produced backlighters can range from a few to tens of keV and are standard in laser-driven experiments[9]. This type of x-ray backlighter is compatible with the Talbot-Lau interferometer and TXD method, due to their small duration and compact source size. This motivates the adaptation of the Talbot-Lau Interferometer and TXD technique to be used as a standard diagnostic for HED laser-driven experiments using laser-driven x-ray backlighters.

In many cases, HED plasmas with high enough densities cannot be probed using visible light. In these cases, in order to properly diagnose them, they require probing with x-ray sources instead. Ideally, this source has a sufficiently short duration and small size to resolve µm-scale details. In particular, magnetized liner inertial fusion experiments in large pulsed power facilities[10] could benefit from an accurate and reliable electron density diagnostic that can also provide mixing and micro-instability information, in particular, liners themselves would be penetrated by the x-ray backlighter, thus delivering more detailed information not available from typical visible laser interferometry. With this environment in mind, an x-pinch could potentially deliver detailed imaging from a single x-ray exposure in a compact, easy-to-use devices emitting a ~1 ns-long, micron-size pulse of x-rays with enough intensity for single-shot exposures.[11] Therefore, the x-pinch was also explored as x-ray source for the Talbot-Lau interferometer in order to demonstrate its capabilities as electron density diagnostic for HED pulsed power driven experiments.

In the interest of establishing the Talbot-Lau interferometer as a standard HED diagnostic, some considerations must be taken into account. First, the instrument itself must be compatible with the experimental environment, that is, its footprint, as well as its vacuum compatibility, among others, must be evaluated. The first requirement can be achieved by changing the Talbot order and/or the Talbot magnification,[13] where higher Talbot orders and magnifications call for larger inter-grating distances, as mentioned previously.

Likewise, the interferometer X-ray illumination must be suitable for the HED experiment. These sources must have high spatial (<10 µm) and temporal resolution (ps-ns) and they should be reliable and reproducible. The emission must provide a sufficiently high photon count so that the Moiré images obtained with TXD provide reliable information of the probed plasma object. In addition, good image contrast is necessary, which for Talbot-Lau interferometry systems depends on spectral characteristics, where the spectral bandwidth of the Talbot-Lau interferometer

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is inversely proportional to the Talbot order, that is: ΔE/E ~ 1/m, with *m* the Talbot order. Regardless of the nature of TXD x-ray illumination used, the interferometer design energy[7] must match the x-ray backlighter emission. Specific details will be addressed in the following subsection.

1. X-ray Backlighters

If a laser produced plasma is to be probed, such as shock and ICF experiments, x-ray emission from laser-foil interaction is an ideal backlighter, whereas in the case of a pulsed power experiment, such as wire arrays or liner experiments, x-ray emission from an x-pinch is an ideal candidate. Both backlighters rely on K-shell emission and are compatible with HED environments. Figure 2 shows copper K-shell emission lines together with interferometer contrast for the Talbot orders used in a laser experiment (m=3), in an x-pinch experiment (m=1), and a the next Talbot order (m=5), obtained with the XWFP code.[14]

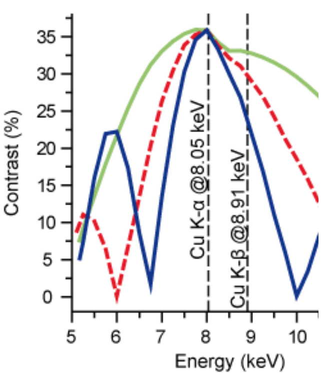

FIG. 2. (Color online). Cu K-alpha at 8.05 keV and Cu K-beta emission at 8.91 keV plotted along Talbot-Lau interferometer contrast for first (m=1), third (m=3), and fifth (m=5) Talbot order.

Considering the characteristic electron density ranges expected in HED experiments, x-ray backlighter energies under 10 keV are ideal. Given that refraction angles scale with energy as $\sim 1/E^2$, these lower x-ray energies will deliver large refraction angles, thus providing better interferometer sensitivity. A copper backlighter is suitable due to its emission in the 8 keV range and availability as a standard x-ray backlighter. It should be noted that backlighter emission at 8 keV does not overlap with expected plasma self-emission energies[15] and thus, accurate density profiles can be obtained even in the presence of background plasma radiation.

2. Grating survival

Due to X-ray transmission, a Talbot-Lau interferometer of 8 keV design energy requires micrometer thickness gratings, therefore, gold free-standing membranes were used in the experiments described below. Given that small grating periods (2.4 - 12 µm) are required in an HED compatible Talbot-Lau interferometer adaptation[4] an important factor to assess is grating survival. Since both the backlighter source and the plasma experiment itself produce high thermal and x-ray radiation, in addition to plasma debris, the thin membrane gratings can potentially expand and/or ablate, which could potentially modify the Talbot pattern. Therefore, grating survival should be assessed. In particular, the source grating is the most vulnerable on account of its proximity to the plasma acting as x-ray source and its small period. Nevertheless, it should be noted that gratings only need to survival long enough to deliver useful Moiré images[4]. The first task in TXD adaptation to the HED environment is to assess source grating survival, to then demonstrate fringe formation under X-ray HED backlighter illumination.

3. Interferometry Reference Image

When adapting the TXD technique to HED experiments, an important consideration is the Moiré imaging electron density retrieval method itself. Interferometry usually compares an image where fringes have been shifted due to the presence of a refractive object, known as object image, and an image with unperturbed images, known as the reference or background image. Considering the grating survival expectations mentioned above, a method to obtain reliable reference images must be implemented since the source grating might not survive the reference/background shot. Even if the grating were to survive the reference shot, it is experimentally convenient to acquire object images for all available laser shots or pulsed power discharges, rather than exclusively dedicating a fraction of them to reference imaging. Thus, a reference ex-situ imaging method has been developed[16] to obtain reliable reference images. The method uses a phase scan procedure to generate synthetic reference images. Electron density retrieval from HED x-ray backlit Talbot-Lau interferometers using the synthetic Moiré reference imaging method will be reported elsewhere.

II. MULTI-TERA WATT LASER

The first test of the TXD method in an HED environment was performed using an 8 keV design energy Talbot-Lau interferometer. The test experiments were performed at the Laboratory for Laser Energetics using the Multi-Tera Watt (MTW) laser[17]. The laser is a single laser beam system often used as a test bed for the OMEGA EP laser as well as a backlighter development platform. The X-ray illumination for the Talbot-Lau interferometer was achieved using laser pulses of 25-29 J, 8-30 ps, focused (~132 µm) on a copper foil target.

A. Experimental setup

The technical details of the 8 keV Talbot-Lau interferometer adaptation to the MTW chamber have been discussed in detail elsewhere[18]. The Talbot-Lau interferometer has shown to be robust under mechanical vibrations, which allowed for the interferometer to be assembled on a common rail and to be previously calibrated under X-ray illumination in the laboratory. Once in the MTW chamber, the rail was aligned on-axis to the backlighter target.

B. Backlighter performance, Grating survival, and Density retrieval

As mentioned previously, the backlighter X-ray emission was obtained from copper foil laser targets of 500 x 500 x

20 µm^3. These foils, when irradiated with laser pulses of 25-29 J, 8-30 ps at a 45 degree angle of incidence, delivered ~8-9 keV K-shell emission with source size of ~80 µm.[18] In light of these results, new target configurations were explored aiming to achieve higher spatial resolutions through source size reduction. Therefore, copper objects were tested in a follow-up experiment and irradiated at normal incidence. The objects were either a 20 µm diameter wire or a 14-35 µm diameter grain, which were glued on polyimide foils of 500 x 500 x 12.5 µm^3, as shown in Figure 3.

The survival of the source grating, which was protected by either a 25-µm aluminum or a 50-µm aluminized Mylar foil, was demonstrated for a 29 J, 8 ps laser pulse ~1 cm away from the foil target. Taking into account the adaptation of the TXD method for standard laser-driven HED experiments, additional grating survival tests should be performed using higher laser intensities (>100 J), such as those characteristic from OMEGA EP backlighter beams. Moreover, the survival of the phase grating in the presence of a plasma object still remains to be confirmed.

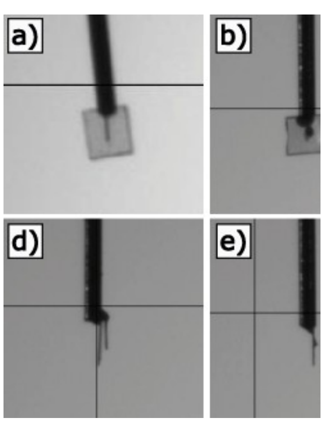

FIG. 3. Polymide backed copper wire (a, d) and grain (b, c, e, f) targets.

Moiré fringe formation was observed for all three backlighter copper targets. Moiré fringe images also provided an additional source size assessment. Figure 4 shows images obtained with the copper foils. The Moiré image was compared to computer simulations, which agree with edge measurements of source FWHM of ~80 µm for copper foils. Furthermore, electron density retrieval was demonstrated for CH cylinders and fluoro-carbon fibers.[18]

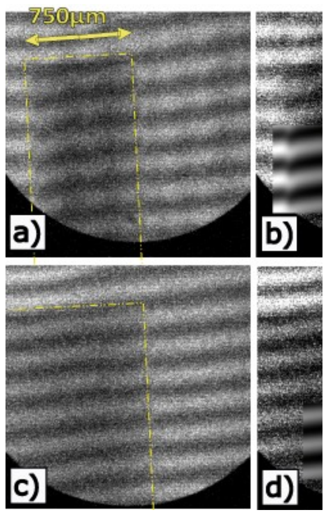

FIG. 4. Moiré images of a,b) 750 µm and c,d) 1.0 mm diameter CH rods obtained with Cu foil backlighter and laser pulse of 29 J, 8 ps. Simulations of ~80 µm FWHM 8 keV source shown as insets in b) and d).

When compared to the foil copper targets, the polymide backed wire and grain emission was more intense overall, while also showing He-like line at 8.35 keV. As expected, source size was improved reaching FWHM of ~40 µm for copper wires and ~25 µm for copper grains.

Fringe formation was observed for all three types of copper backlighters tested with a contrast of 20-27%. The laser driven x-ray backlighter images match the laboratory data acquired with a standard x-ray tube source, as well as simulation predictions, both in contrast and angular resolution (if spatial resolution is taken into account). Thus, the TXD technique potential has been demonstrated in the HED environment using a laser-driven x-ray backlighter. In order to benchmark the TXD technique further studies need to be performed to qualify the technique in the presence of a plasma target, by demonstrating grating survival and plasma probing through electron density retrieval.

III. LLAMPUDKEN PULSED POWER GENERATOR

The TXD technique was tested in the pulsed power generator Llampudkeñ,[19,20,21] using 8 keV illumination from an x-pinch backlighter driven at ~400 kA, ~1 kA/ns. The generator consists of two Marx capacitor banks of 0.25 µF, chargeable up to 480 kV, and up to 28.8 kJ energy. The equivalent impedance of the driver at the load is 0.8 Ω. Single (2 x 64 µm) and double (4 x 25 µm) copper x-pinches were driven in order to obtain K-shell emission at ~8 keV.

A. Experimental setup

The Talbot-Lau interferometer was setup in the first (m=1) Talbot order and Talbot magnification of ~5. Source grating (2.4 µm period) to phase grating (4.0 µm period) distance was 1.6 cm, while the distance between phase grating and analyzer grating (12 µm period) was 7.7 cm. In this configuration, the source grating was protected by a 25 µm aluminum foil and placed ~6.5 cm away from the x-pinch cross-point. The beryllium object imaged (3 mm diameter rod or 1 mm thickness beryllium sheet) was placed ~0.5 cm behind the phase grating rotation stage, which lead to an angular sensitivity of ~240 µrad. A Carestream D-Speed x-ray film (Bio-MAX equivalent) was used for imaging and placed behind the analyzer grating rotation stage, thus achieving an object magnification of ~2.

B. Backlighter performance, Grating survival, and Fringe formation

X-pinch discharge emission time and spectral information was obtained from AXUV diodes. Figure 5 shows traces from the double x-pinch configuration of 4x25 µm copper wires. It can be observed that the Al+Ni filter signal shows a second peak that is lower than the Al+Fe filter signal which, considering the filter x-ray transmission curves, indicates that copper K-shell emission takes place ~50ns before peak current. Additionally, self emission images show the characteristic diode gap produced in this configuration after the separation in the crossing point of the anode and cathode sides of the x-pinch plasma. The spatial location of the most intense, well defined, and temporally resolved x-ray source from these configurations is the hotspot produced at this crossing point.

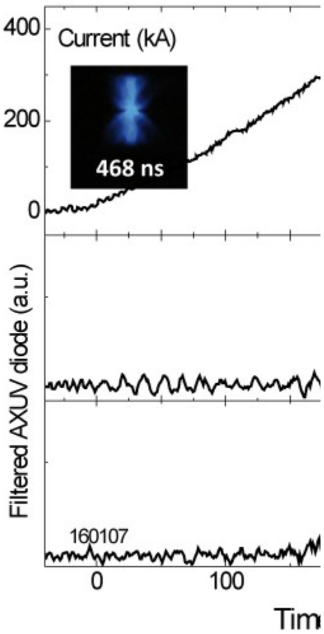

FIG. 5. Diode signals show 8 keV emission for a double x-pinch configuration of 4x25 μm copper wires in Llampudken. A self emission (MCP) image is shown as an inset.

Slit-wire measurements[22] were performed to qualify the source size and emission. A combination of a slit and a set of micron size wires placed across the slit provided one-dimensional imaging. Different filters provided information about the emitting source based on their characteristic transmission curves. An array of four slits of 4.7 mm width was placed 27.5 cm away from the x-pinch. Each slit-wire arrangement was composed of wires of different composition, so that they would be opaque to the x-ray emission. The wires chosen were tungsten 13 μm and 25 μm diameter, titanium 50 μm diamter, and copper 75 μm diameter. Each slit used a combination of Ross-pair filters (50 μm Al + 10 μm Fe, 50 μm Al + 7.5 μm Ni, 50 μm Al + 15 μm Ni, and 50 μm Al) in order to distinguish from K_α, K_β, and He-like emission at ~ 8-9 keV. Figure 6 shows the slit-wire X-ray images obtained with X-ray film. These results show that that K-shell energy emission has a source FWHM of <27 μm.

Source grating survival was observed for all x-pinch shots. Unlike the laser driven backlighter tests with a 29 J, 8 ps laser pulse, the protective aluminum filter can be severely damaged by the pulsed power discharge depending on the maximum current achieved. The post-shot images of the source grating rotation stages in combination with the source grating and protective filter configuration are shown in Figure 7 below. These images seem to indicate that thicker protective filters would be better suited to protect the source grating from the x-pinch discharge.

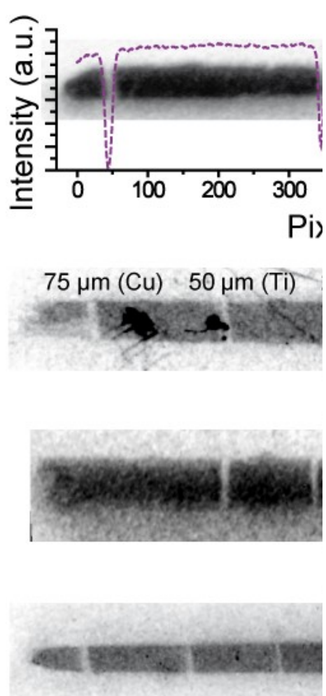

FIG. 6. Suit of filtered slit-wire images used to perform source size measurements. Sample line-out profile shown for the 50 μm aluminum filtered wire set.

FIG. 7. Source grating rotation stages (a, c) and protective filters post 400 kA, 350 ns discharge. The aluminum filters show signs of b) plasma deposit, indentation, and/or d) ablation.

Even in the most extreme case where the protective foil was completely destroyed, the source grating endured the x-ray pulse only showing small plasma deposition, as seen in Figure 6c. There was no evidence of any structural modification or relevant morphological damages experienced by the gratings, supported by X-ray tube imaging performed a posteriori, where source grating performance matched previous results. Even if the grating experienced any expansion during the x-ray pulse (not expected from theoretical calculations),[18] this did not affect Moiré image acquisition, which is the goal when performing TXD technique using x-pinches as x-ray backlighters. Moreover, currents of ~100 kA - 1 MA are needed to drive an x-pinch configuration in order to produce an appropriate x-ray backlighter for pulsed power HED experiments. Notably, at 400 kA, the experimental results shown provide good scaling comparison to asses grating survival for other pulsed power drivers of similar characteristics within the aforementioned current range.

In addition to source grating survival, Moiré fringe formation under x-pinch assisted x-ray illumination at 8 keV was observed, as shown in Figure 8. Moiré fringe contrast of 13% was obtained. This is lower than contrast measured using standard X-ray source imaging and laser-driven x-ray backlighters. This is thought to be due to a combination of factors. Mainly, intensity background is not constant throughout the film, which is a common issue when imaging with X-ray film instead of CCD cameras. Thus, X-ray film recording, and specially film development methods, need to be improved. Another factor affecting contrast is plasma self emission which produces non-uniform stray light and, as seen from Figure 1, it also impacts interferometer contrast as a result of low energy emission. This issue can be easily addressed though better filtration. Lastly, in this particular shot, at least two hotspots were observed. Since the X-ray film detection is time integrated, both X-ray sources produce a characteristic fringe pattern, displaced according to their spatial separation. In this regard, single sources of smaller size and shorter pulse length can be achieved through changing the wire diameters and/or the number of wires in the x-pinch load according to the pulsed power driver characteristics.[12]

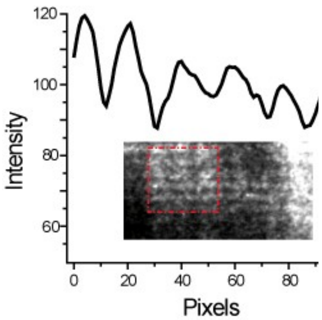

FIG. 8. Moiré fringe formation under x-pinch assisted x-ray illumination at 8 keV. Contrast of up to 13% calculated.

In the adaptation of the Talbot-Lau system to the Llampudkeñ discharge chamber, geometrical constraints as a result of the reduced vacuum chamber size (~40 cm diameter) limited the angular sensibility. Due to the low geometrical magnification and film granularity, fringe shift measurement was not possible due to the lack of resolution needed to detect a 10% of fringe shift. Considering the small source size achieved, the variables to be optimized in order to achieve better spatial resolution are the effective angular sensitivity, object magnification, fringe period, and contrast.

Nevertheless, the preliminary results obtained in this first x-pinch experiment are significant. Even if fringe shift was not able to be measured due to low magnification and angular sensitivity, fringe formation, along with the measured x-ray backlighter source FWHM of 27 µm, show that TXD has a high potential to be a reliable diagnostic for pulsed power HED experiments. Moreover, standard electron density diagnostics used in pulsed power experiments are limited to critical electron density or below.[23]

Before main X-ray emission, the main characteristics of the x-pinch dynamics, such as plasma jets and wire ablation, were observed through Mach–Zehnder interferometry and Schlieren imaging, which were obtained using a 3 ns frequency doubled Nd:YAG laser (λ = 532nm). X-pinch backlit Talbot-Lau X-ray Deflectometry could provide additional and complementary information to these standard diagnostics in experiments where, even at early times, visible light probing does not provide sufficient electron density information as high densities are reached rapidly. Additionally, the fine wires and foils used in wire array[20,24] and magnetized liner[10,25] experiments, for example, are transparent to X-rays, TXD can also provide high resolution end-on and radial imaging and electron density mapping.

IV. SUMMARY

The Talbot-Lau interferometer has been adapted to be compatible with HED environments. These results show that the TXD technique can be a suitable standard diagnostic for both laser-driven and pulsed power plasma experiments. The general conditions and requirements for the adaptation have been discussed and addressed in detail. Source grating survival was demonstrated at ~1 cm from a 29 J, 8 ps laser pulse and at ~6.5 cm away from an x-pinch driven by a ~400 kA, ~350 ns pulsed power generator. In both cases source grating survival and Moiré fringe formation was demonstrated with good interferometer contrast. Electron density retrieval was achieved in the laser-driven x-ray backlighter experiment at MTW and geometrical constraints encountered in the pulsed power experiment did not allow for proper implementation of the TXD technique. X-ray backlighter quality was assessed in both experiments. Copper K-shell emission from both sources was measured at ~8 keV and He-like emission was observed for laser driven copper micro targets. For MTW experiments, X-ray source FWHM was found to be ~80 µm for copper foil targets and 25-40 µm for copper micro targets. In turn, copper x-pinches delivered well defined sources of <27 µm and ~5 ns duration.

In light of these encouraging results, further studies will be performed with the aim to benchmark the TXD electron density technique as a HED plasma diagnostic. When considering the requirements for electron density retrieval using laser-driven backlighters, a more stringent design is needed for larger facilities such as OMEGA EP. Likewise, grating survival must be assessed for higher intensity laser pulses as well as in the presence of the plasma object to be probed. Similarly, source size must be further reduced and spectral emission must be limited to the 8-9 keV region through filtration, laser defocusing and/or use of optics. In the case of pulsed power driven backlighters, electron density retrieval through TXD must be first demonstrated for solid objects towards a later experiment aiming to probe a plasma object. Correspondingly, grating survival needs to be further demonstrated in the presence of the plasma object to be probed. Additionally, the x-pinch backlighter might be improved by producing a single X-ray source of smaller size and shorter pulse duration, as demonstrated in previous experiments where the load and driver parameters were optimized properly.[12,19] In particular, the optimization of an 8 keV source from an x-pinch driven by the Llampudken generator will be subject for future studies.

V. ACKNOWLEDGMENTS

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