Talbot-Lau X-Ray Deflectometry for Dynamic Density Profile Measurements[a)]

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(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)

X-ray phase contrast imaging with transmission gratings for density profile measurements is being developed for dynamic experimental applications. Talbot-Lau deflectometry is a new method of measuring x-ray refraction in addition to attenuation and ultra-small angle scattering that has recently been developed for static imaging, primarily for medical and industrial applications. A flash x-ray source, with a spot size much larger than the continuous microfocus sources of static imaging systems, must be used to obtain density profiles from fast-evolving systems, and only a single exposure can be obtained. These new challenges are addressed by introducing an asymmetric setup and developing a forward modeling technique to infer an electron density profile from a single-image, low spatial–resolution system.

I. TALBOT-LAU DEFLECTOMETRY

In experiments with dynamically evolving solids, liquids, or high-density plasmas, densities are typically probed with x-ray radiation. This usually takes the form of x-ray radiography, in which x-ray attenuation by a sample is measured and used to infer material density. Alternatively, x-ray phase contrast imaging (PCI), in which the phase shift of x-rays passing through a sample is analyzed, may also be used to infer density, as the index of refraction of x-rays through a sample depends on the density of the material. X-ray PCI has several advantages over traditional radiography, including a linear dependence on density, rather than an exponential dependence, that increases the range of densities over which the technique is applicable for a given x-ray source with a particular spectrum. Also, x-ray attenuation scales more strongly with atomic number Z than PCI, thus PCI is a more sensitive density diagnostic for low-Z materials. X-ray PCI can thus be used to image low-Z samples using high-energy x-rays that can penetrate high-Z material surrounding the samples.

One potential disadvantage of x-ray phase contrast imaging is the requirement for a coherent, monochromatic light source, historically only available at facilities such as x-ray synchrotrons. Recent advances in the manufacture of x-ray transmission gratings led to the development of Talbot-Lau x-ray deflectometry PCI diagnostics, which use compact, incoherent x-rays sources. A Talbot-Lau deflectometer consists of three transmission gratings with equal, micron-scale slit spacing[1]. The basic principle of the instrument is that coherent, monochromatic light passing through a diffraction grating forms images of the grating at periodic distances. This is referred to as the Talbot effect, and the images are formed at multiples of the Talbot length $z_0 = 2g^2/\lambda$, where g is the slit spacing and λ is the x-ray wavelength. When a sample is placed in front of (or behind) the grating, x-rays deflected by the changing index of refraction create fringe shifts in the image. We refer to this phase grating as the beam splitter, or G1, as shown in Fig. 1.

[a)]Contributed paper published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2016) in Madison, Wisconsin, USA.

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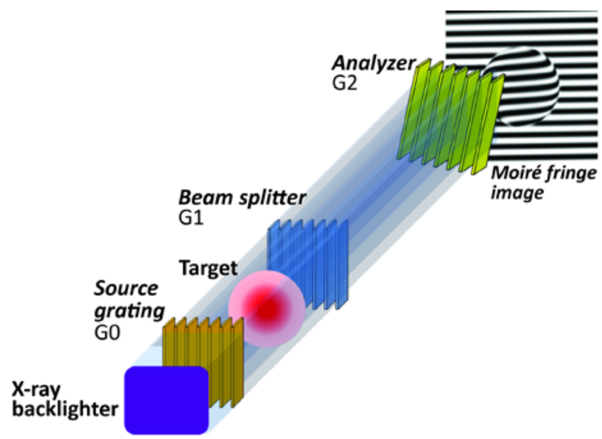

FIG. 1. A Talbot-Lau deflectometer with three transmission gratings. G0 and G2 are x-ray amplitude gratings, and G1 is an x-ray phase grating.

In the absence of a monochromatic coherent light source, the Lau effect can be relied upon to simulate such a source while using a polychromatic incoherent source.[2] An amplitude grating with the same slit spacing as G1, referred to as the source grating or G0, is placed in front of the x-ray source. Each slit of G1 can be thought of as an individual coherent light source. As shown in Fig. 2, when placed a Talbot length $z_0(\lambda)$ in front of G1, each slit of G1 sees a coherent source of wavelength λ due to constructive interference. With the source grating, it is thus possible to do dynamic x-ray phase contrast imaging in a small lab setting using a compact flash x-ray tube.

Finally, another amplitude grating, referred to as the analyzer or G2 grating, allows micron-scale fringes to be imaged with a standard camera system. The G2 grating also has the same slit spacing as the G0 and G1 gratings and is placed a Talbot length after G1. The grating is rotated about the optical axis by a small angle θ, creating a moiré pattern on the detector. These moiré fringes have a period $p_M \sim g/\theta \gg g$. The angle θ can thus be chosen to optimize spatial resolution on the detector.

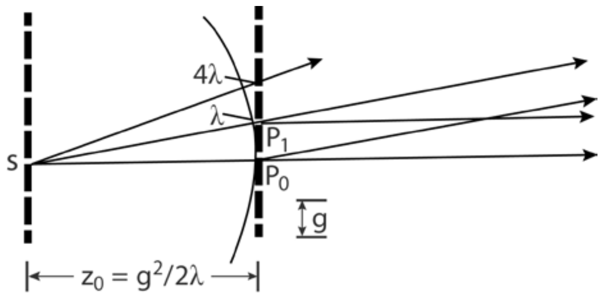

FIG. 2. A depiction of the Lau effect, where for a given wavelength λ, coherent light from slits along G0 constructively interfere at the slits along G1, which is placed a Talbot length z_0 away. Image from Ref. 2.

Despite using modern manufacturing techniques to produce micron-scale gratings up to about 100 microns thick, the amplitude gratings are still not thick enough to attenuate hard x-rays above a few tens of keV. Recently, this problem was solved by tilting the gratings to a glancing angle such that they are no longer normal to the optical axis[3]. In this geometry, the effective thickness of the amplitude gratings is increased enough that the diagnostic can then be used in the hard x-ray range around 100 keV.

II. MEASURING MATERIAL MIXING

One major advantage of Talbot-Lau x-ray deflectometry is that it provides three separate measurements in a single image: x-ray attenuation and ultra-small-angle x-ray scattering (USAXS) are measured in addition to refraction[4]. Refraction and attenuation both depend on the line-integrated density of the sample, but with different Z dependencies. The two measurements together can deconvolve the density profiles of a mix of elements. USAXS, caused by micron-scale variations in density, results in a loss of fringe contrast. The effects of all three phenomena on a background fringe pattern are shown in Fig. 3.

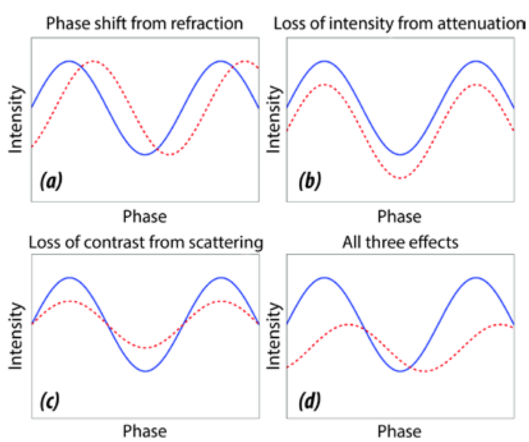

FIG. 3. The effects on the background fringe pattern from (a) refraction due to a differential phase shift, (b) attenuation, (c) USAXS, and (d) some combination of the three. The solid blue lines represent the unperturbed background fringe pattern and the dashed red lines represent changes due to the sample being measured.

Simulations with the X-ray WaveFront Propagation (XWFP) code[5] show how the densities of two elements can be deconvolved. For this simulation, the x-ray source was a 150 kV tungsten tube filtered with 0.25 mm of uranium for optimal imaging at 100 keV. The sample was a 1.5 mm diameter cylinder of mixed material. The resulting Talbot-Lau images were simulated, and the ratios of attenuation to phase shift for the middle 50% of the cylinders were computed and plotted as a function of elemental fractions. Both the simulated images and resulting ratio curves are shown in Fig. 4. These ratio curves, or those obtained from measurements of known samples, can then be used to determine the densities of two elements in an unknown mix independently.

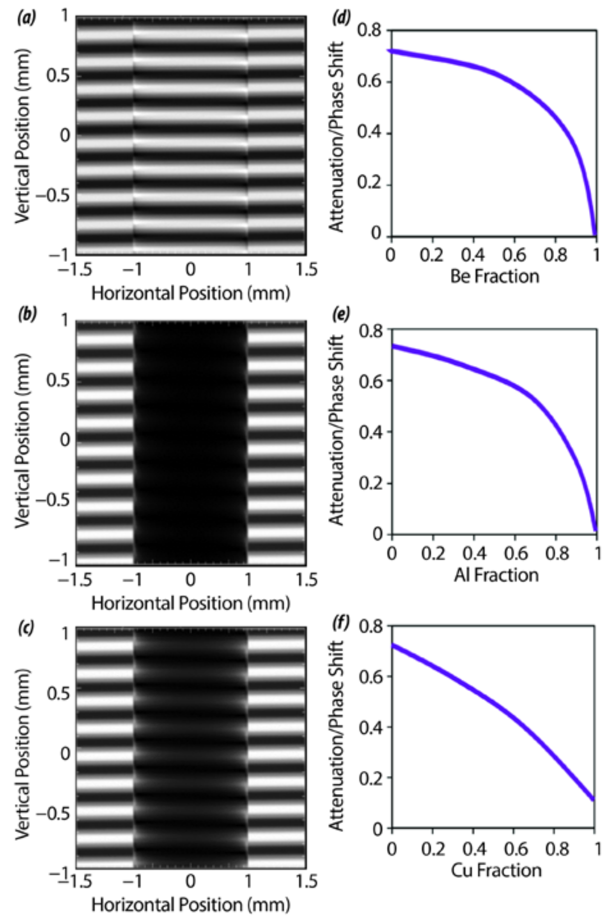

FIG. 4. Simulated deflectometry images of (a) pure beryllium, (b) pure uranium, and (c) a mix of 60% Be and 40% U; ratio curves for (d) Be+U, (e) Al+U, and (f) Cu+U.

III. CHALLENGES FOR DYNAMIC EXPERIMENTS

While Talbot-Lau x-ray deflectometry has been used for static imaging, except in a few unique cases[6], dynamic PCI is still performed at synchrotrons. Dynamic experiments introduce new challenges to x-ray deflectometry. Typically, these systems achieve high spatial resolution by using continuous, microfocus x-ray sources with spot sizes less than 10 µm. By comparison, commercially available flash x-ray sources typically have a spot size greater than 1 mm. Previous Talbot-Lau diagnostic systems have used phase scanning[4] or fringe scanning[7] to obtain separate images of refraction, attenuation, and USAXS. These methods require at least three exposures of the same static object, precluding their use for dynamic experiments. Also a single exposure limits photon statistics, limiting the usefulness of single-image fringe-fitting routines.

In addition to the challenges all dynamic experiments face, many of these experiments, including most plasma physics applications, generate their own x-rays that produce a background on the measured signal. Possible solutions to this problem include spectral filtering with multi-layer x-ray mirrors to reduce background, and will be tested if the background indeed proves bright enough to prohibit accurate density measurements in future experiments.

A. Low-Magnification Asymmetric Deflectometry

Preliminary studies have been performed to address these challenges associated with dynamic experiments. With a large x-ray source spot size, the spatial resolution of the system can be maximized by building a low-magnification, asymmetric deflectometer in which $L > D$, where L is the distance between G0 and G1 and D is the distance between G1 and G2. In this case, the grating slit spacings differ: $g_0 \neq g_1 \neq g_2$. While asymmetric systems have previously been tested in standard grating configurations, this had not been tried before in a glancing angle configuration. A static bench-top test of an asymmetric, glancing-angle deflectometer was performed using 10 keV x-rays and a glancing angle of $\alpha = 51°$, where α is the angle between the plane of the grating and the optical axis of the system. The system was asymmetric, with $L = z_0 = 9.7$ cm, $D = 5z_0 = 48.4$ cm, $g_0 = 2.4$ µm, $g_1 = 4.0$ µm, and $g_2 = 12$ µm, as shown in the sketch in Fig. 5(a). The Talbot order of the system, defined as the number of Talbot lengths between G1 and G2, was $m = 5$. A sample image taken with this system is shown in Fig. 5(b).

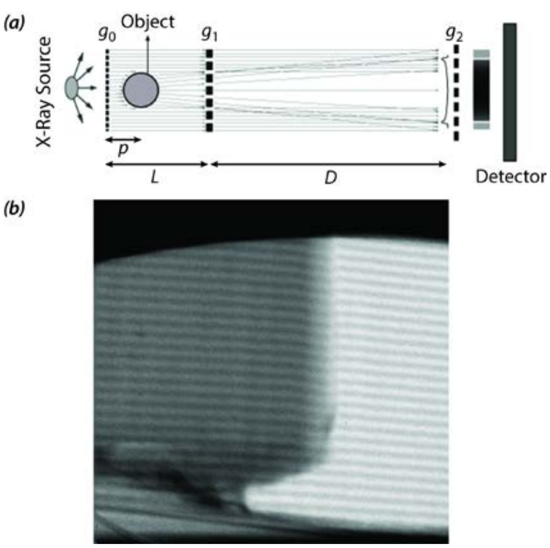

FIG. 5. (a) Asymmetric Talbot-Lau deflectometer setup. (b) Image of a solid beryllium sample.

B. Density Profiles from Forward Modeling

Obtaining density profiles of complex plasmas from a single exposure with limited spatial resolution and photon statistics is challenging or even impossible using standard fringe-shift codes. Preliminary tests have shown that forward modeling, in which deflectometer images are computed from given density profiles and then fit to the raw data, produce more reliable results. Furthermore, forward modeling has proven to be more robust when experimental images are first deconvolved into separate refraction, attenuation, and USAXS images using Fourier transforms. Both the refraction and attenuation images can then be fit. The experimental data is deconvolved by first applying a 2-D Fourier transform to the image. The attenuation image is simply taken from the absolute value of the Fourier transform over the interval $\pm 1/2p_M$, where again p_M is the moiré period. The refraction image is obtained by taking the argument, or phase shift, of the Fourier transform over the interval of $\pm 1/2p_M$ about the

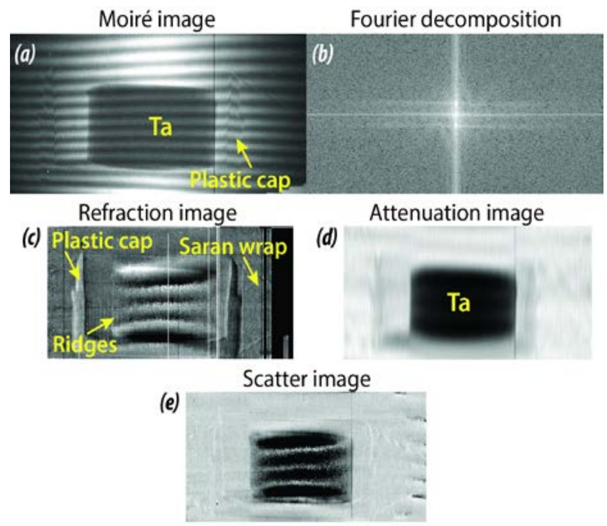

FIG. 6. Images of a tantalum aerogel sample: (a) raw data with moiré fringes, (b) Fourier decomposition of the raw image, (c) refraction, (d) attenuation, and (e) USAXS.

frequency p_M. While not used in density profile calculations, an USAXS image may be obtained by taking the ratio of the absolute values of the Fourier transforms over these two intervals. Results from a Fourier transform of an experimental image of a static object are shown in Fig. 6.

IV. FUTURE EXPERIMENTAL PLANS

The next step is to test a Talbot-Lau x-ray deflectometer in the lab with a dynamic sample. A deflectometer is being constructed with a flash x-ray source to measure the density profiles of dense plasma plumes generated when a high-current pulsed electron beam strikes a thin bremsstrahlung target at the DARHT facility at Los Alamos National Laboratory. The diagnostic will then be used to measure material mixing in a variety of dynamic experiments.

V. ACKNOWLEDGMENTS

This manuscript has been authored by National Security Technologies, LLC, under Contract No. DE-AC52-06NA25946 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published forms of the manuscript, or allow others to do so, for United States Government purposes. The U.S. Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan). DOE/NV/25946--2865.

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