Development and Demonstration of Talbot-Lau X-ray Deflectometry Electron Density Diagnostic for HEDLP

D. Stutman, M. P. Valdivia
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218

NNSA Grants: DE-NA0001835, DE-NA0002955
NLUF Grant: DE-NA0003526
Collaborators

C. Stoeckl, C. Mileham, I. A. Begishev, W. Theobald, J. Bromage, S. P. Regan
Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623

S. R. Klein, H. Lefevre, P. A. Keiter
Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48105

D. J. Clayton, M. Berninger, A. Meidinger
National Security Technologies, LLC, 182 East Gate Drive, Los Alamos, NM 87544

M. Vescovi, G. Muñoz-Cordovez, V. Valenzuela-Villaseca, F. Villanueva,
E. S. Wyndham, F. Veloso
Instituto de Física, Pontificia Universidad Católica de Chile, Casilla 306, Santiago, Chile

Alexis Casner¹, Michel Koenig², B. Albertazzi², P. Mabey², T. Michel², G. Rigon²
¹CEA, DAM, DIF, F-91297, Arpajon / CELIA, University of Bordeaux, France,
²LULI, École Polytechnique, CNRS, CEA, UPMC, route de Saclay, F-91128 Palaiseau, France
Goals of Talbot-Lau project

- Demonstrate $n_e$, elemental composition ($Z_{avg}$), and micro-instability diagnostic capabilities of Talbot-Lau X-ray Deflectometry (TXD)
- Further develop techniques to align and obtain reference Moiré interferograms
- Develop improved algorithms for TXD processing

**NNSA (initial grant + renewal) + NLUF:**

* Support for one undergraduate student, two graduate students, two postdocs, three research scientists
* Total students involved in research: 3 undergraduate, 7 graduate
* 10 peer reviewed publications (2 in preparation)
Refraction based $n_e$ diagnostic

Expected density ($\rho R$) $>1$ g/cm$^2$

For low-Z matter probed at 1-100 keV:
*Refraction* signatures much larger than attenuation


HEDP diagnostics:
- Resolve high $n_e$ gradients
- High spatial resolution (<10 µm)
- High densities (well above $n_c$)
- Time resolved (ps-ns)
Talbot-Lau X-ray Interferometry

Phase shift $\sim$ ref. angle

Talbot effect -> self-images: $d_T = 2mg^2/\lambda$

TL for HEDP: Valdivia et al., *Journal Appl. Phys.* 144 (2013); *RSI* 85 (2014)

Direct $n_e$ gradient measurement
Talbot-Lau X-ray Deflectometry (TXD)

- Small rotation between gratings -> Moiré fringes with period: \( P_M \approx g/\theta \).
- Fringe shift proportional to phase shift:

\[
\alpha(x,y) = \frac{r_e \lambda^2}{2\pi} \frac{\partial}{\partial x} \left[ \int N_e(x,y,z) \, dz \right]
\]

Simulation of CH shell probed @8 keV.
Talbot-Lau order \((m)\): Contrast

Talbot distance: \(d_T = \frac{2m g^2}{\lambda}\)

<table>
<thead>
<tr>
<th>(g_0-g_1) (cm)</th>
<th>(g_1-g_2) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m=1)</td>
<td>1.56</td>
</tr>
<tr>
<td>(m=3)</td>
<td>4.67</td>
</tr>
<tr>
<td>(m=5)</td>
<td>7.78</td>
</tr>
<tr>
<td>(m=7)</td>
<td>10.89</td>
</tr>
</tbody>
</table>

Grating period

XR wavelength

\(G_0 = 2.4\, \mu m\)
\(G_1 = 3.85\, \mu m\)
\(G_2 = 12.0\, \mu m\)

Over 30% contrast
Measurements of $n_e$ gradient

- Strong signature of $n_e$ gradients and interfaces
- Spatial resolution
  - Horizontal: Source-size
  - Vertical: ~ Period

Accurate detection of interfaces and (sharp and mild) $n_e$ gradients in low-Z matter.

Talbot-Lau: Valdivia et al., RSI (2014)
TXD $n_e$ measurement dynamic range

\[
\frac{\Delta(N_e L)}{\Delta x} \approx \frac{2.2 \times 10^{29}}{\lambda^2_{\text{Angs}}} \cdot \alpha \approx \frac{2.2 \times 10^{29}}{\lambda^2_{\text{Angs}}} \cdot \frac{g_0}{P} \cdot F
\]

\(\alpha\) from ratio of \(g_0\) period and \(g_0\)-plasma distance \(P\), scaled by fringe shift \(F\).

CH shell of 200 \(\mu\)m:

i) 0.1X solid density (few keV)
ii) >100X solid density (~20 keV)

Fringe shifts: few percent to several periods detected. At 5 keV and 25 keV, the dynamic ranges are \(\sim 10^{23}-10^{25}\) and \(\sim 5 \times 10^{24}-5 \times 10^{26}\) cm\(^{-3}\), respectively.
TXD: simultaneous information

\[ I(x,y) = a_0 + a_1 \cos\left(\frac{2\pi}{P_M} + \psi\right) \]
Z-average: composition and mixing

\[ \beta(x, y, z) = r\delta(x, y, z). \]
\[ \delta = (r_0/2\pi)\lambda^2n_a(Z + f'). \]
\[ \beta = (r_0/2\pi)\lambda^2n_a f'', \]
\[ \mu = -\ln(I/I_0)/L, \]
\[ \Delta\Phi(x, y) = 2\pi\delta L/\lambda, \]
\[ r = -\ln(I/I_0)/(2\Delta\Phi). \]

‘r’ \sim third degree polynomial of \( Z_{\text{avg}} \)

Fluorocarbon fiber

\[ <Z_{\text{avg}}> \approx (f_C Z_C^3 + f_{\text{Be}} Z_{\text{Be}}^3)^{1/3}; \]
\[ f_i \equiv L_i / \sum L_i \]

\[ Z_{\text{avg}} \]

Attenuation Refraction Attn./ Refr.
Adaptation to HED environment

Demonstrate $n_e$ diagnostic capabilities in a HEDP experiment:

- A high power laser produced x-ray backlighter (LLE)
- A pulsed power driven x-ray backlighter (PUC)
- A flash x-ray tube (LANL)

Grating survival, Talbot pattern formation, and refraction measurement for electron density retrieval.

Multi-TeraWatt experiment

Laser produced 8 keV backlighter

- 25-29 J, 8-30 ps laser
- 500 x 500 x 20 μm³ Cu target
  - 500 x 500 x 12.5 μm³ Polymide backed:
    - 20 μm diameter Cu wire
    - ~10-30 μm diameter Cu grain

TL laser backlighter: Valdivia et al., *RSI* 87 023505 (2016)
MTW: laser-driven backlighter

- K-shell + He-like emission within contrast curve.
- High energy photons from micro-backlighters decrease contrast from 27% to 22%.

Source size FWHM:
- \(~70\) µm for Cu foil
- \(~40\) µm for Cu wire
- \(~25\) µm Cu spheroid

Areal density: \(0.050\) g/cm\(^2\)
Density: \(1.66\) g/cm\(^3\)
\((\sim10\%\) error\)

Source gratings survive: \(~30\) J / 8-21 ps laser pulse \(~1\) cm away

Limitations: Grating quality

As backlighter source size decreases, grating quality becomes relevant.


8 keV Talbot-Lau: Valdivia et al., *RSI* 85 (2013)
Limitations: Reference images

Phase image retrieval requires a matching reference fringe pattern.

Simple ex-situ method using a phase-scan procedure to generate synthetic Moiré images developed.

Objective:

- Obtain $n_e$ profile from a laser-irradiated planar foil ($>n_c$)
- Gain better understanding of thermal electron transport in laser produced plasmas. Use measurements to help benchmark radiation hydrodynamic codes

Specific deliverables:

- Grating survival demonstration
  X-ray backlighter
  Irradiated foil target
- Moiré imaging: areal $n_e$ profiles
Simulations of ablation front

Simulations of ablation front:
- Electron density profiles
- Refraction angle (8 keV)

TXD detects electron density gradients
OMEGA EP implementation

- Interferometers pre-aligned
- \( g_0 \sim 1 \times 1 \text{ mm}^2 \) effective area
- Talbot order \( m=7 \)

- BL
- UV
- CH foil (3x3 mm\(^2\) x 120 \(\mu\text{m}\))

100-1250 J

1700-2000 kJ/beam

554 mm

109 mm

1.0 mm
Objective:
- Test grating survival
- Demonstrate Moiré fringe formation

7% contrast with imaging plates
(>27% with XR tube)
High-Z materials @60 keV: DARHT

TXD @60 keV with 150 kV x-ray flash tube for DARHT facility at LANL:

- Dense plasma plumes ejected from beam-target interactions -> $n_e$ gradient measurements
- TXD will provide the first experimental constraints to models.

Solid target $n_e$ at a) t=0 ns, b) t=500 ns, c) 500 ns (log), and d) target material T at t=500 ns.

X-pincher backlighter

Single and double x-pincher (64, 40, and 25 µm) driven @350kA, 350 ns

- He-like and K-shell emission (~8keV) around peak current
- Source grating structure survives discharge at ~6.5 cm
- X-ray backlighter FWHM: <27 µm
- Fringe contrast: ~13% with x-ray film vs. 30% in the laboratory.

\[ n_e = 8.1 \pm 0.5 \times 10^{23} \text{ cm}^{-3} \]
\[ \rho = 1.97 \text{ g/cm}^{-3} \]

Scaling assessment for larger pulsed power adaptations.
Future work

- **OMEGA EP demonstration of TXD:**
  - Moiré fringe formation: backlighter $G_0$ survival
  - Plasma target grating survival ($G_0$ and $G_1$)
  - Electron density retrieval

- **X-ray backlighter development:**
  - Spatial resolution: micro-backlighters
  - Monochromatic spectra through reflective optics

- **TXD technique**
  - Moiré reference image through phase-stepping
  - In-situ laser alignment
  - Gratings: better Moiré pattern
  - Algorithms

- **Extension of TXD technique:**
  - Lower energies to enable measurements closer to $n_{crit}$
  - 2D and radial gratings
Summary

**TXD capabilities:**

- Areal $n_e$ gradients detection through Refraction (and Attenuation)
- Micro-turbulence and material mixing through (Z-average)
- Hydrodynamic instability through scatter

**TXD tested in HED environment:**

- Grating survival:
  - 1.5 cm from 60J laser pulse
  - 6.5 cm from 350kA/350ns pulsed power generator

- Moiré fringe formation:
  - High-power laser: MTW, LULI, ECLIPSE
  - Pulsed power generator: Llampudkeñ
Refraction $n_e$ diagnostic

$N_e < N_{\text{crit}}$ ($\sim 10^{21}\text{ cm}^{-3}$)

$N_e > N_{\text{crit}}$

$N_e < N_{\text{crit}}$


Measures angular deviations due to refraction index gradients.
No spatial/temporal coherence required. Mechanically robust with a large FOV.
Refraction and Attenuation

Refraction diagnostics (x-rays):
- Talbot-Lau Deflectometry
  (Valdivia et al., J. Appl. Phys, 2013; RSI 2016)
- ‘Refraction enhanced’ radiography
  (Koch et al., AO, 2013; Ping et al., J Inst, 2011)
- Hartmann sensors
  (K. Baker Optical Engineering, 2013)

Index of refraction:
\[ n = 1 - \delta - i\beta \]
Fringe shift proportional to refraction angle $\alpha$

$$\alpha(x,y) = \frac{e \lambda^2}{2\pi} \frac{\partial}{\partial x} \left[ \int N_e(x,y,z) \, dz \right]$$

- Works with line or continuum backlighters from 5 to 50 keV

Stutman and Finkenthal RSI 2011

Talbot-Lau deflectometer (TXD)
Talbot-Lau X-ray Interferometry

• Source grating: Polychromatic incoherent -> coherent monochromatic

• Phase grating: fringe patterns, due to the Talbot Effect, which are shifted by an object with density changes

• Analyzer grating: microscopic pattern from phase grating -> macroscopic pattern

• Talbot effect with self images: 
\[ d_T = 2mg^2 \frac{\theta}{\lambda} \]

• Phase-stepping technique used in medical and materials science applications. Samples are static and resolution of >100µm

• Moiré configuration: refraction, attenuation, elemental composition, and scatter information through Fourier analysis

• Refraction enhanced configuration: analysis is more involved
Talbot-Lau: x-ray energy response

X-ray backlighter energy modifies range of $n_e$ detected:

- Medical applications: $>30$ keV
- Materials science (NDT): $>60$ keV
- HED systems developed using 8 and 17 keV x-ray tubes.

$$\alpha(x,y) = \frac{r_e \lambda^2}{2\pi} \frac{\partial}{\partial x} \left[ \int N_e(x,y,z) \, dz \right]$$
Areal electron density retrieval

Accurate density retrieval even with object attenuation of >90%

PMMA sphere:
M.P. Valdivia et al., RSI 85 (2014)
Resolution equivalent to radiography (better if $g_0 \ll \text{FWHM}$)
Vertical resolution: Spheres

Direct refraction/density gradient

Attenuation map
Attenuation measurements

Attenuation and refraction components, separated in the Fourier space, deliver simultaneous independent information.

\[ l(x,y) = a_0 + a_1 \cos\left(\frac{2\pi}{P_M} + \psi\right) \]

a) Moiré. b) Refraction angle. Attenuation from c) Moiré and d) Radiography.
Scatter imaging for micro-instability diagnostic

- A third image is also obtained in TXD corresponding to the fringe contrast loss due to scattering on microscopic (sub-resolution) density gradients.
- Potential for a μ-turbulence region diagnostic in ICF, which does not require μm radiographic resolution.

XWFP TXD simulation:
- H filaments
- $\rho = 2 \text{ g/cm}^3$
- 8 keV
- 15 μm FWHM backlighter

Marinak et al EPJ 2013
A line-of-sight average of the mean atomic number, $<Z_{eff}>$, can be mapped by combining refraction with attenuation.

Potential for a simple diagnostic for material mixing in ICF.
Laser driven backlighter: Copper foils

TXD with laser x-ray backlighting at the Multi-TeraWatt (MTW):

- 25-29 J, 8-30 ps laser focused on
- 500 x 500 x 20 µm³ Cu target.

Grating survival and $n_e$ retrieval demonstrated with 30 J, 8 ps laser pulses, K-shell emission from Cu foil targets (500 x 500 x 25 µm³), and CH backed wire (20 µm diameter) and microsphere (~10-30 µm diameter) targets.
MTW: micro-backlighter targets

To improve source size:
- 20 µm diameter Cu wire
- ~10-30 µm diameter Cu grain (spheroid)

Polymide backing:
~500x500x12.5 µm³

TL laser and x-pinch backlighters: Valdivia et al., RS/87 (2016)
X-ray backlighter source size

Moiré image of acrylic rod (1mm diameter):

- Free space propagation simulation comparison
- Edge method

X-ray backlighter FWHM of ~80 µm

TXD limited by source size -> A smaller source (<10 µm) is necessary
At the edge: 8 µrad expected. Effective angular sensitivity = 82.8 µrad -> Angular resolution ± 0.8 µrad (± 1% fringe shift)

Spatial resolution limited by x-ray backlighter FWHM of ~80 µm
Micro-backlighter performance

Cu foil: full chip

Cu grain: 4x4 bin.

- K-shell AND He-like emission lines within interferometer optimum contrast curve. High energy photons decrease contrast.
- Laser defocusing (132 μm) and longer pulse length (29 J, 21 ps) deliver 22% contrast.
- Source size decreases notably.

Source size FWHM:
~70 μm for Cu foil, ~40 μm for Cu wire, ~25 μm Cu spheroid.
Source gratings survive a 20-30 J and 8 ps pulse at ~1 cm distance using AlMy, Al, and no filters
G0 survival: Ablation induced closure

Pinhole closure experiments suggest G0 will survive long enough to produce data.

A. B. Bullock et al, JAP 2006

Transmission

Time (ns)

1.0

0.5

0.0

0.0

0.5

1.0

10 µm

5 µm
Source grating estimated to survive for at least tens of ps

**Soft X-ray heating lifetime estimate**
- **Backlighter laser**
  - 100 J/10 ps
- **Target laser**
  - 2.5 kJ/2.5 ns
- 2 µm period
- Au grating
- 3 mm 15 mm

**Tamped pinhole estimate**

- **Reighard et al RSI 2008**
- Aperture (µm)
- Resolution (µm)

**Source grating main challenge**
- **Grating expansion Δx** must be < 0.1 µm
- Assuming expansion at the sound velocity $C_s \approx 0.0036 T^{1/2}$ µm/ps → Au bar heating of $\Delta T=5$ eV needed for $\Delta x=0.1$ µm in 10 ps
- Estimated soft X-ray heating for above setup is $\approx 0.6$ J/mm²
  → $\Delta T\leq 2$ eV in 10 ps → Ok
- Longer lifetime with grating substrate, shield

**Long-pulse ‘tamped’ pinhole closure experiments at OMEGA:**
- 20µm CH filled pinhole
- 0.4 mm C spacer
- 10 kJ/7 ns Zn backlighter
- Slow closure rate of 1-2 µm/ns
- TL gratings ‘tamped’ by photoresist
- 50-100 ps lifetime possible
Talbot-Lau Deflectometry
Measurements of Irradiated Foils

to TIM13 port
to TIM10 port
Considerations:

- G0 must be protected by an Al foil (~10-25 um)
  
  *Could G1 mount have the option of adding a protective foil? Not necessary, but it would be good*

- The bigger distance ‘p’, the better the angular resolution:
  - Because pointing distance is fixed at ~ 2cm, the backlighter foil is very close to G0
  - The closer that G0 is to the backlighter, G0 degradation risk is higher.

- Main goal of experiment: Achieve Moiré fringes (G0 degradation after delivering images)

- We want to test how close we can get G0 to the backlighter foil:
  - Systematically vary distance ‘p’ keeping Pointing distance at max.
# Talbot-Lau Deflectometry Measurements of Irradiated Foils

## Laser Configuration

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Beams</th>
<th>DPPs</th>
<th>Pulse</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics driver (Foil irradiation)</td>
<td>1,2,3</td>
<td>EP-SG8-0750</td>
<td>10 ps</td>
<td>Max energy on each beam (1700-2000 kJ/beam)</td>
</tr>
<tr>
<td>Cu Backlighter</td>
<td>Sidelighter</td>
<td></td>
<td></td>
<td>100 – 1250 J</td>
</tr>
</tbody>
</table>

## Diagnostic Configuration

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>TIM</th>
<th>Priority</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talbot-Lau Deflectometry</td>
<td>13</td>
<td>1</td>
<td>Image plasma gradients, holds gratings and camera</td>
</tr>
<tr>
<td>Spherical crystal imager assembly</td>
<td>10</td>
<td>1</td>
<td>Hold TXD grating and backlighter foil</td>
</tr>
<tr>
<td>Angular Filter Refractometry</td>
<td></td>
<td>1</td>
<td>Image plasma gradients at low densities</td>
</tr>
</tbody>
</table>
Preliminary experiments

- Grating survival:
  - 1 cm from target at MTW (90° from gratings)
  - 1.5 cm at LULI (normal)
  - 4 cm at ECLIPSE (100-1000 shots).

Eclipse (800 nm, 30 fs, 200 mJ, 10 Hz)
X-pinchn backlighter: Llampudkeñ

• Pulsed power driven x-pinchn (2x64 µm and 4x25 µm Cu wires). Llampudkeñ pulsed power generator, 400 kA peak current, 350 ns rise-time

• First Talbot order chosen due to vacuum chamber geometrical restrictions. Minimum detectable refraction angle ~3 µrad.

Grating survival and Moiré fringe formation using 4 x 25 µm Cu wire x-pinchn backlighter driven by pulsed power generator (350 kA, 1 kA/ns).
X-pinch backlighter

• Demonstrate $g_0$ survival and Moiré pattern formation with fringe shift from a static object

• Image plasma object:
  - Laser produced plasma
  - X-pinch
  - another wire array

L = 1.56 cm  d = 7.78 cm
Moiré deflectometry routine diagnostic at low $N_e$

Deflectometry of Z-pinch plasma with laser backlighter


- Strong refraction expected in HEDP (100 $\mu$rad)
- X-ray backlighter for penetration
- High magnification for $\geq 10 \, \mu$m resolution
Llampudkeñ: Grating survival/Contrast

Source grating survives 400 kA current x-pinch discharge at ~6.5 cm distance. Even when filters are destroyed, we obtain Moiré images of ~13% contrast.
XR source and X pinch evolution

4 x 25 µm better than 2 x 64 µm

107 ns, 2 x 64 µm
88 ns, 4 x 25 µm

Backlighter FWHM: <27 µm

Cu Kα 8.05 keV and Kβ 8.91 keV (Heα 8.35 keV, Lyα 8.69 keV)