Liquid Crystal Targets and Plasma Mirrors For Laser Based Ion Acceleration

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3rd ELIMED Workshop
7-9 September, 2016
Catania, Italy
Acknowledgments

- The Ohio State University
  - P. Poole, G. E. Cochran, C. Willis
  - Jordan Purcell, Richard Heery
  - C. D. Andereck, R. R. Freemam

- University Pierre et Marie Curie
  - A. Krygier

- Rutherford Appleton Laboratory
  - P. S. Foster, G. G. Scott, L. Wilson, N. Bourgeois, J. Bailey
  - D. Neely, R. Pattathil

- Helmholtz Zentrum Dresden Rossendorf

- DARPA PULSE program
  - Through AMRDEC
  - National Energetics

- Department of Energy NNSA SSAP
  - Contract DE-NA0001976
A great team

Dr. Patrick Poole
lead developer,
now at LLNL

Ginevra Cochran
experiment,
PIC modeling

Dr. Chris Willis
experiment,
diagnostics
development
Motivation: target thickness, laser contrast, rep-rate

Multiple ion accel. mechanisms identified. Intensity and target thickness are key “knobs”…

… but not the only ones. Pre-pulse has a dramatic effect on outcomes.

How do we best take advantage of high rep-rate PW lasers?


See talks by Bulanov, Macchi which include reviews.


Described in multiple talks by Korn, Margarone, Qing, Schillaci, Steinke, …
Summary

- Liquid crystals are a new medium for HED science with many helpful properties
- Demonstrated a target device, the LSTI, that forms targets on-demand (1 at a time)
  - Target thicknesses from 10 nm to >70 μm; ~ 1/3 Hz rate for thinnest films
  - 1000’s targets from 1 mL of liquid crystal costing ~10 EUR
  - Up to 24 MeV protons using 2-5 J short pulse
- Demonstrated pulse cleaning plasma mirrors – propose a debris handling strategy
- 1 Hz prototype operational for thinnest films
- Significant limitations remain – considerable development still required
Outline

1) Liquid crystals – a new target medium
2) Proton acceleration experiments
3) Liquid crystal plasma mirrors
4) Conclusion
A new medium for HEDP: liquid crystals

- Characterized by additional phases between solid and liquid
- Phases distinguished by molecular orientation and ordering
- Smectic phase forms films in stacked sheets \( \sim3 \text{ nm per layer} \)
- Vapor pressure well below \( 10^{-6} \text{ mbar} \)
- Surface tension in smectic phase forms freely suspended film
- Films contain \( \sim100 \text{ nL of } 8\text{CB} \), so hundreds can be made for 1 EUR

\[
\begin{align*}
8\text{CB} & \quad \text{4-cyano-4\textsuperscript{'}}\text{-octylbiphenyl} \\
\text{CH}_3(\text{CH}_2)\text{CH}_2 & \quad \text{CN}
\end{align*}
\]

Crystal \( 295 \text{ K} \) \hspace{1cm} Smectic A \( 307 \text{ K} \) \hspace{1cm} Nematic \( 314 \text{ K} \) \hspace{1cm} Isotropic

Nematic \hspace{2cm} Smectic

2.7 nm

4 mm
Careful control required to avoid defects

Typical non-uniform films

- Vertical film
- Meniscus shift
- Mobile island
Thickness control from 10 nm to >70 µm

150 nm  230 nm  370 nm  640 nm  5000 nm

Film characterization—thickness and position

Filmetrics commercial unit
• 2 nm measurement accuracy.
• 50 ms acquisition time.
• 48” standoff distance (or more with imaging)

Confocal positioner for ~ 1 µm alignment
• Establish TCC using traditional techniques
• Draw a spot on the film using scatter from a low power cw laser
• Measure relative position using confocal microscopy
• Works regardless of target surface morphology

C. Willis, P. Poole et al., Review of Scientific Instruments 86, 053303 (2015)
LSTI: linear sliding target inserter

- Apply charge with syringe pump
- Down stroke forms film
- Hundreds of films per charge
- 10 nm to >70 µm thickness
- <2 µm RMS positioning repeatability

Kraft – Wednesday talk
In these views, non-horizontal surfaces appear dark.

Film is present, but still at an angle.

Film detached from wiper.

Imperfections in polish will deform the film surface.

View from behind

45° inner bevel

film pulled to top of bevel

Just before attachment

LSTI film formation
Larger apertures demonstrated

11 mm aperture

LSTI configuration

50 mm aperture

Alternate configuration
Issues – more development needed

- Poor reproducibility for films above 50-100 nm thickness (depending on the specific design and operation of the LSTI)
- Can close in on desired thickness using several draws, however
- Polish and operating parameters critical leading to quirky behavior
## Current LSTI capability

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>10 nm to &gt;70 µm</td>
</tr>
<tr>
<td>Positioning – longitudinal</td>
<td>&lt;2 µm</td>
</tr>
<tr>
<td>Target area</td>
<td>4 mm typical&lt;br&gt;50 mm demonstrated</td>
</tr>
<tr>
<td>Pressure</td>
<td>&lt;10^{-6} Torr</td>
</tr>
<tr>
<td>Temperature</td>
<td>Slightly above room temp</td>
</tr>
<tr>
<td>Cost</td>
<td>&gt;100 films per 1 EUR</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>&gt; 0.1 Hz for thinnest films</td>
</tr>
</tbody>
</table>
First liquid crystal experiments

- Single-shot liquid crystals in flag targets
- Made to desired thickness at air, can be stored indefinitely
Max proton energy along target normal direction (22.5° laser AoI)

5 J on target, \(\sim 5 \times 10^{19} \text{ W/cm}^2\)

### Optimizing target normal ions

<table>
<thead>
<tr>
<th>Thickness (nm)</th>
<th>Max proton energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>1500</td>
<td>15</td>
</tr>
<tr>
<td>2000</td>
<td>20</td>
</tr>
</tbody>
</table>

700 nm
8CB
DRACO Laser Ion Acceleration Study Recently Completed

Ion Diagnostics
- Thomson Parabola spectrometers in target normal and laser direction
- RCF stacks in target normal direction at 50mm distance to TCC

HZDR

Kraft – Wednesday talk
Prencipe – Friday talk

~450 shots over 5 days

specular reflection diagnostic
- laser specular reflex in $1\omega$ and $2\omega$ on ceramic screen at 195mm from TCC
- electron detection with lanex screen

LSTI
- Liquid crystal films $d \sim 200\text{nm}$
- thicknesses down to 10 nm
- thickness measurement before every shot
- ~ 1 shot / minute

Ti:Sapphire Draco
- max. 3.3 J in 30 fs @ 1 Hz
- max. $3 \cdot 10^{20} \text{W/cm}^2$
- ultra-high contrast shots possible due to single plasma mirror

Focus spot
- 5 µm
Max-proton energy vs. thickness

- shots with plasma mirror
- shots at intrinsic laser contrast
- reference shots on 2μm Ti at intrinsic laser contrast
Prototype: Spinning disk for > 1 Hz

- Forms thin films reliably at 1 Hz
- 2 Hz with 90% success rate
- Sub-100 nm films depending on settings.

Still from a video of 1 Hz operation.
A lamp was placed below illuminating the apertures at grazing incidence. Note reflection from lower aperture.
Only one target is intended to be present at a time so collateral damage is less of an issue.
Plasma mirrors for pulse cleaning


Run on Astra at RAL to test liquid crystal plasma mirrors

- 0.6 J input to chamber, 40 fs pulse width
- F/7 focus onto plasma mirror
- S and P polarizations on target
- Reflection and transmission diagnostics

Plasma mirror requirements, issues:
- Low weak field reflectivity (usually AR coating)
- High strong field reflectivity
- Flat over wide area
- Vacuum compatible
- Low cost
- Available at laser rep rate

Using LSTI, tune thickness to etalon minimum

- Low intensity: $\sim 5 \times 10^{11}$ W/cm$^2$
- S polarization shown here
- $\sim 15^\circ$ incident angle, 800 nm light
- First reflectance minimum is $\sim 270$ nm with $R < 0.2\%$
High field reflectance measurement

- High field reflectance of ~75%
- Implied contrast enhancement >350
- Similar or better than AR-coated slides, but good for prolonged, moderate repetition rates

Poole, et al., Scientific Reports 6, 32041 (2016).
PIC modeling: weak field response

Dielectric (low field)

270 nm target
PIC modeling: strong field response

Plasma (high field)
High field reflectance measurement

- LSP PIC simulation
- Target starts cold with neutral atoms
- Dielectric model
- MPI and collisionality included

Poole, et al., Scientific Reports 6, 32041 (2016).

Ginevra Cochran
Reformable plasma mirrors for debris control

Membrane

Plasma Mirror

Target
• 1 meter focal length allows plasma mirror installation just before target
• While enhancing contrast, turning beam away from OAP protects it as well
• Key: liquid crystal plasma mirror is renewed on each shot, so prolonged debris-free operation is possible

Bonus: separate beam can tailor preplasma scale length to optimize reflection

In-line plasma mirror for contrast enhancement and debris control
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