Liquid crystal films as plasma mirrors and targets for high repetition rate secondary beams and experiments

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Outline

1) Overview: liquid crystal tech and BELLA-i
2) Liquid crystals – a new target medium
3) Linear Slide Target Inserter (LSTI)
4) Liquid crystal plasma mirrors
5) Newest prototypes
6) Conclusion
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Brief synopsis: liquid crystal technology

- Liquid crystals - unique properties for HED experiments
  - Readily forms very thin films on demand
  - Low vapor pressure
  - Low cost (hundreds of films per $)

- Demonstrated low rep-rate target machine
  - 10 nm to >40 μm thickness formed in situ
  - Max rep-rate 0.3 Hz for the thinnest films

- Demonstrated basic plasma mirror operation
  - 75% high-field reflectivity
  - <0.2% low-field reflectivity without AR coatings

- Prototypes
  - 1 Hz prototype film formation device demonstrated
  - Large aperture prototype device demonstrated
  - Zero-order waveplates demonstrated
Stage 1 (2017-2018)

- **Targets**
  - Thin targets necessary for many experiments (e.g. Workshop #1):
    - down to nm scale
  - Surveys and surprises:
    - real-time thickness tuning (just like you’d want for intensity, pulse width)
  - $10/target would cost >$250,000 for an 8-hour day:
    - low cost essential for a broad community of users
  - Laser propagation:
    - low vapor pressure
  - Destructive plasma environment:
    - low-cost, easy replacement

- **Plasma mirrors for pulse cleaning**
  - Not called for by facility **but**
  - Pre-pulse even at 100 ps problematic **and**
  - Long focus beamline permits **in-line** plasma mirror
  - Double plasma mirror also possible
  - Rep-rated plasma mirrors for hours-long runs
BELLA-I requirements and liquid crystals

Stage 2 (2018-2019)

- **Targets**
  - Same as Stage 1 **plus**
  - Rapid alignment to ~1µm needed to facilitate fast optics

- **Plasma mirrors for pulse cleaning**
  - Same as Stage 1 (except only one in-line PM possible)

- **Debris Management (short focal length geometry)**
  - New problem at this scale (being explored by many facilities)
  - Expensive OAP close to solid density targets
  - Standard pellicle shield might get coated quickly
  - **Renewable plasma mirror redirects debris**
  - Mass limited targets preferred
BELLA-i requirements and liquid crystals

Stage 3 (2019-2020)

- Targets
  - Same as Stage 2

- Plasma mirrors for pulse cleaning
  - Facility capability now with double plasma mirrors
  - Housed in dedicated chamber with optimized optics
  - Low cost / rep-rate requirement same as for targets

- Debris Management (short focal length geometry)
  - Same as Stage 2 but harder in constrained geometry
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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 ~3 nm per layer
- Vapor pressure well below $10^{-6}$ Torr
Free standing films by hand

- Surface tension of smectic phase favors freely-suspended membranes
- Membranes form readily by drawing liquid crystal across a rigid gap using a sharp wiper
- Films contain ~ 100 nL of liquid crystal
- Thousands of films can be made from 1 mL ($15) of 8CB
Thickness tuning requires multiple parameters

**Temperature Control**
- Modifying 8CB phase via temperature control is crucial—facilitated by copper frame with resistive heaters/PID control

**Volume Control**
- Vertical film formation leads to liquid crystal flow and non-uniform thickness due to gravity
- Meniscus region at frame edge results in uneven thickness, island formation

**Wiper**
- Shape, material, polish, angle, speed

![Vertical film](image1)
![Meniscus shift](image2)
![Mobile island](image3)

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Range of film thicknesses demonstrated

**Coarse Control**

- Liquid crystal volumes between 0.1 and 2 µL
- Temperature variation over several degrees

**Fine Control**

- Wiper speed

Characterizing the films - thickness

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

1600 nm
Films are very hard to see using cameras, so:
• 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

Ion acceleration thickness scan using Scarlet

Max proton energy along target normal direction (22.5° laser AoI)

5 J on target, ~5x10^{19} W/cm^2

![Graph showing max proton energy vs thickness (nm)]
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LSTI: linear sliding target inserter

- Applied a charge with syringe pump
- Down stroke forms film
- Control: volume, temperature, draw speed
- Hundreds of films per charge
- **Forms films with thicknesses varying from 10 nm to >40 µm**
- **Under 2 µm RMS positioning repeatability**

The yin and yang of liquid crystal films
Film thickness reproducibility

- Three regions of film formation
- Region III: consistent sub-100-nm film formation at high rep rate
- Regions I and II: wider range of possible thicknesses (indicated by vertical bars)
- Can close in on desired thickness within a few draws
LSTI – Current specifications, BELLA-i

- **Thickness:** 10 nm to > 40 µm
  - in 2-3 ranges, e.g. 10 nm to ~2 µm or 10 µm to >40 µm,
- **Diameter:** 4 mm (not critical)
- **Self-aligning:** <2 µm rms precision
- **Target change-out:** hundreds of films per charge
- **High repetition rate:** 0.3 Hz for thinnest films, < minute for 10’s of microns
- **Material cost:** 100’s target for $1 of 8CB
- **Environment:** vapor pressure < 10\(^{-6}\) Torr, disable motors and controllers on shot

**Suitability for BELLA-i**
- Continuous feed to reservoir should permit operation all day at 1 Hz
- *Higher rep-rate needed*
  - New prototype using different geometry has reached 1 Hz (more later)
- Successful implementation of above would meet requirements listed at beginning
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Plasma mirrors for pulse cleaning

**Requirements, issues:**
- low weak field reflectivity
- high strong field reflectivity
- area
- flat
- vacuum compatible
- low cost
- rep rate

Main pulse

Prepulse (ps)

Pedestal (ns)

log(Intensity)

log(Time)

Usually via an AR coating.
Liquid crystal film – use etalon minimum?

Depends on plasma excitation
Run on TA2 (RAL)


**Laser parameters**

**RAL TA2**

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

**Diagnostics**

- Liquid crystal thickness measurement
- Near field cameras
- Far field and wavefront sensor
Experimental set-up
Using LSTI, tune thickness to etalon minimum

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

- Initial results: reflectance of ~75%
- Implied contrast enhancement >350
- P-polarization results lower by ~10%
Good mode preservation in weak field limit

- Running at $I \sim 5 \times 10^{11}$ W/cm$^2$ and spot size $\sim 0.5$ mm
- Little change to laser mode

Far field

Near field

Input laser

Au slide reflection

Liquid crystal reflection
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Rotary geometry – the Spinning Disk Inserter

10 Hz water

0.1 Hz 8cb

1 Hz 8cb
Larger area films are easily made

11 mm aperture

50 mm aperture
Zero-order waveplates are possible

- 8CB film between crossed polarizers
- p-polarization, 632 nm
- Film at ~45° angle (ideal for protecting laser)
- Large area films would needed in practice
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Conclusion

Liquid crystals
- Liquid crystals provide ready access to the otherwise difficult thin film regime; thin films are easier than thick!
- We have developed a complete solution (formation and characterization) that works well for shot/minute type experiments.
- Development is required for 1 Hz rep-rate, but initial work indicates this is possible.

A rep-rated liquid crystal system with LSTI-like specifications would
- Provide excellent targets for study of ion acceleration, relativistic transparency, etc.
- Provide plasma mirrors for interim pulse cleaning for 1,2 BELLA-i.
- Provide plasma mirrors for pulse cleaning 3 BELLA-i
- Provide a plasma mirror for debris control