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

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Workshop on High Energy Density Physics with BELLA-i
20-22 January, 2016
Lawrence Berkeley National Laboratory

The Ohio State University

Acknowledgments

- The Ohio State University
  - C. Willis, G. E. Cochran
  - C. D. Andereck, R. R. Freeman, D. W. Schumacher
- University Pierre et Marie Curie
  - A. Krygier
- Rutherford Appleton Laboratory
  - P. S. Foster, G. G. Scott, L. Wilson, N. Bourgeois, J. Bailey
  - D. Symes, D. Neely, R. Pattathil
- DARPA PULSE program
  - Through AMRDEC
  - National Energetics
- Department of Energy NNSA SSAP
  - Contract DE-NA0001976

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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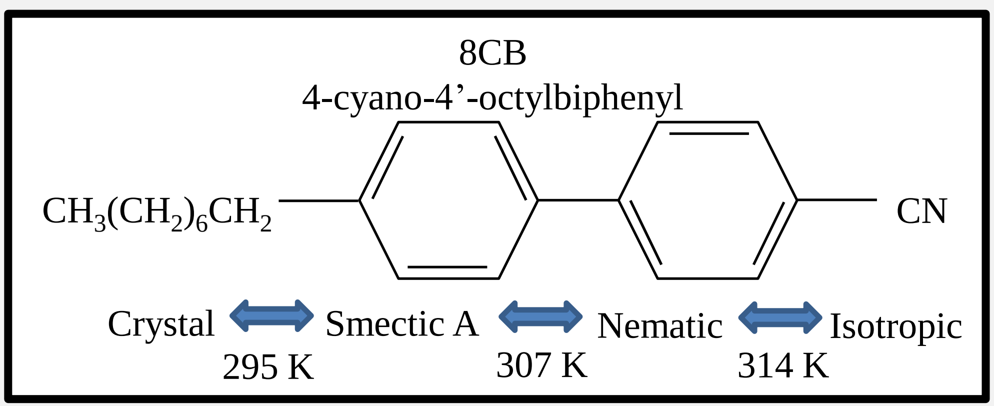
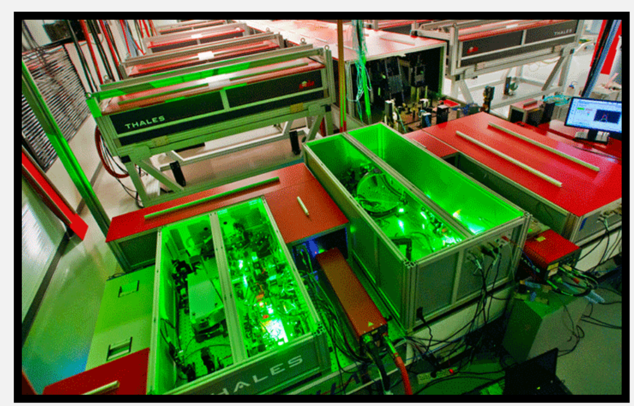
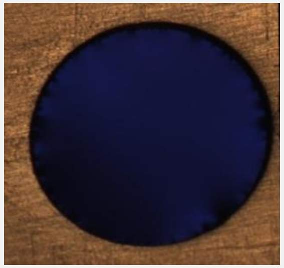
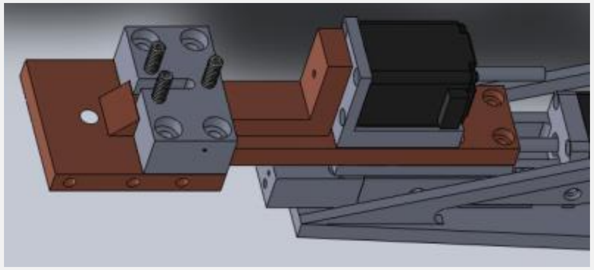




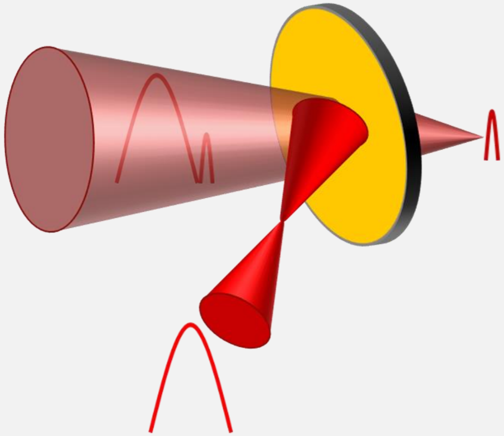
Brief synopsis: liquid crystal technology




- 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

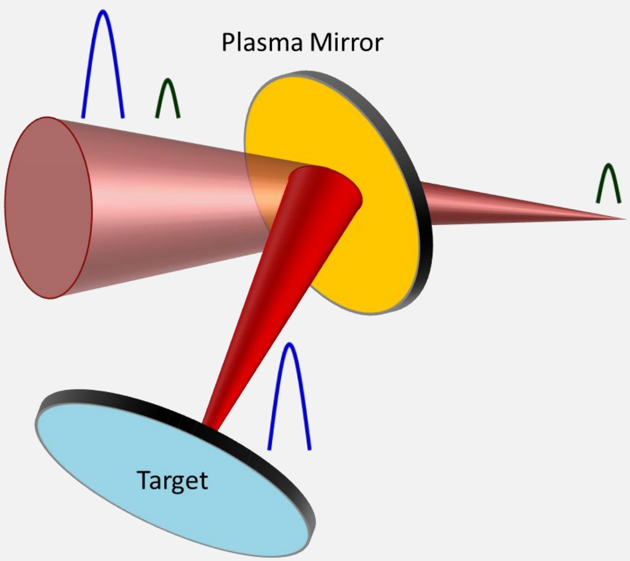


- Prototypes
  - 1 Hz prototype film formation device demonstrated
  - Large aperture prototype device demonstrated
  - Zero-order waveplates demonstrated

BELLA-I requirements and liquid crystals

Stage 1 (2017-2018)

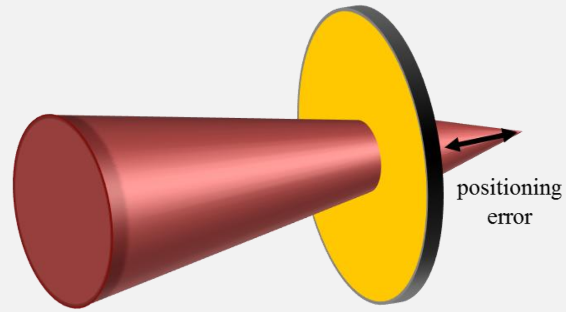
- Targets
  - Thin targets necessary for many experiments (e.g. Workshop #1):
    down to nm scale
  - Surveys and surprises:
    real-time thickness tuning (just like you'd want for intensity, pulse width)
  - $10/target would cost >$250,000 for an 8-hour day:
    low cost essential for a broad community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



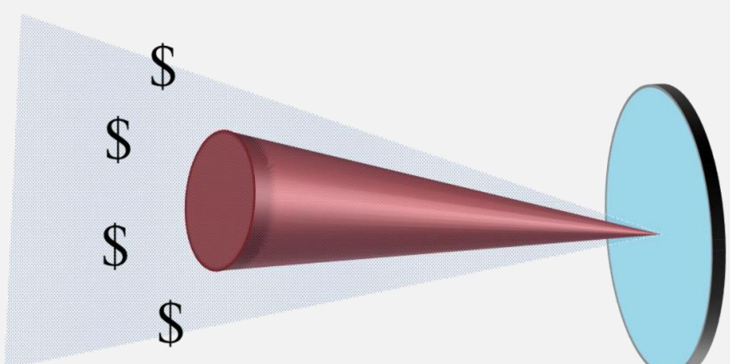
- Plasma mirrors for pulse cleaning
  - Not called for by facility **but**
  - Pre-pulse even at 100 ps problematic **and**
  - Long focus beamline permits **in-line** plasma mirror
  - Double plasma mirror also possible
  - Rep-rated plasma mirrors for hours-long runs

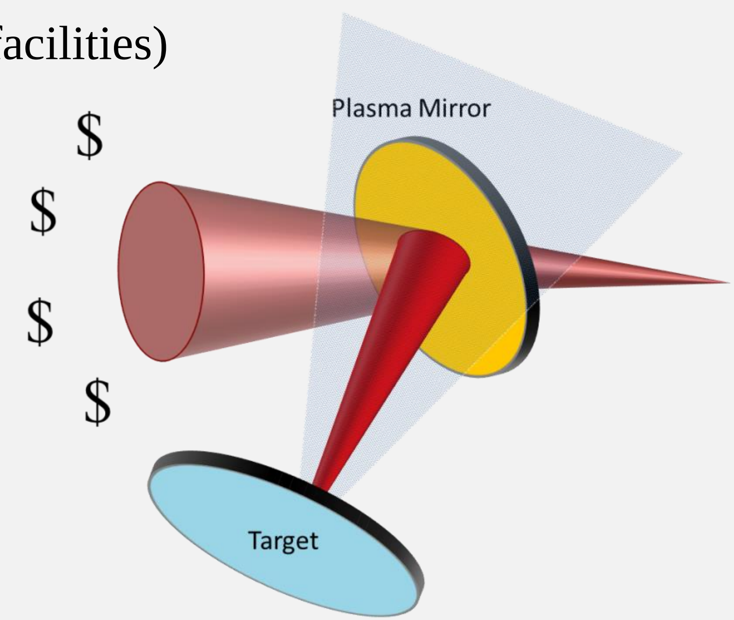
BELLA-I requirements and liquid crystals

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

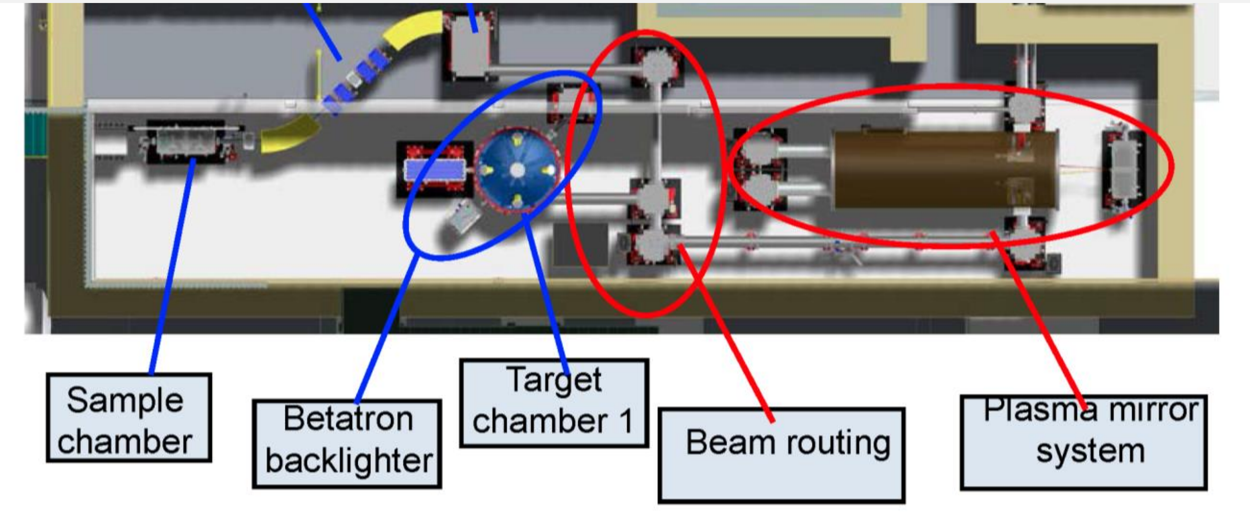




BELLA-i requirements and liquid crystals

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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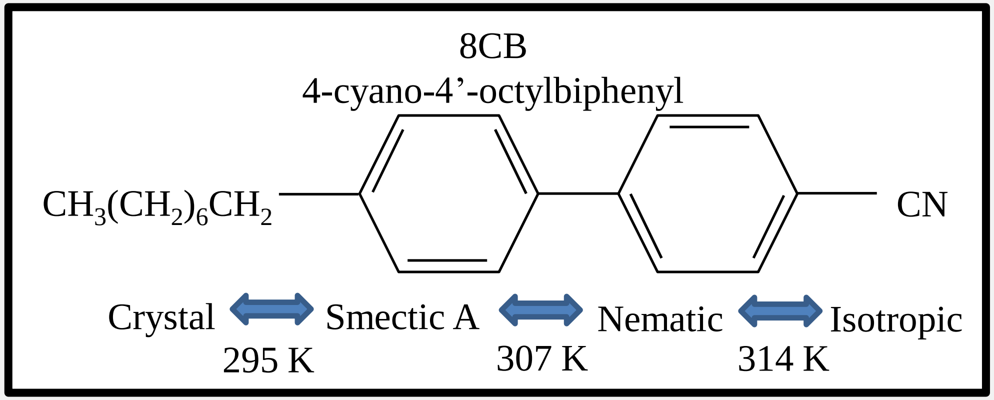
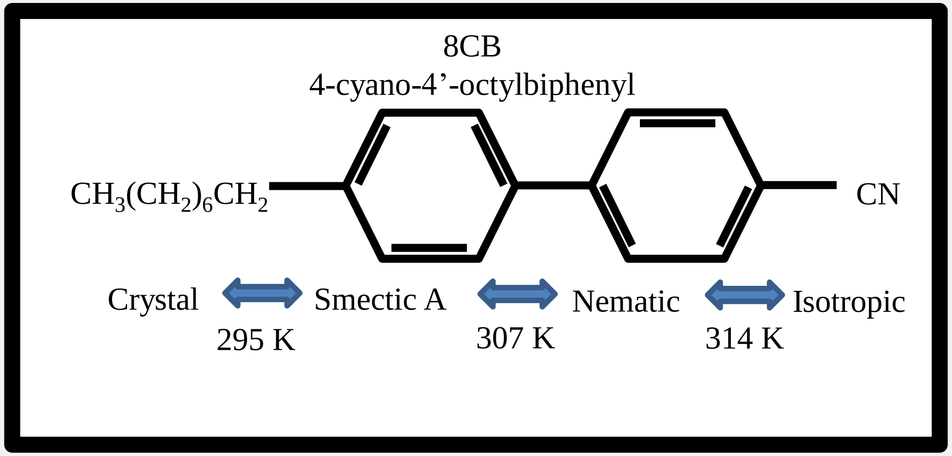
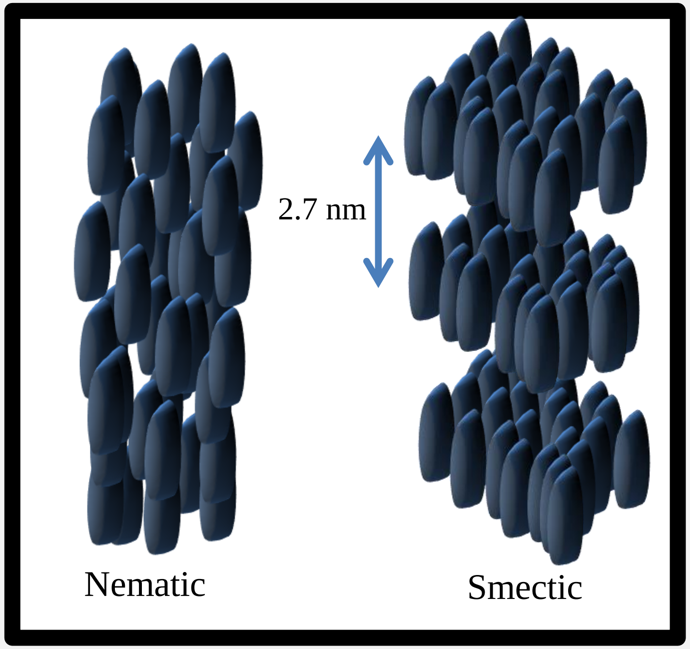


A new medium for HEDP: liquid crystals



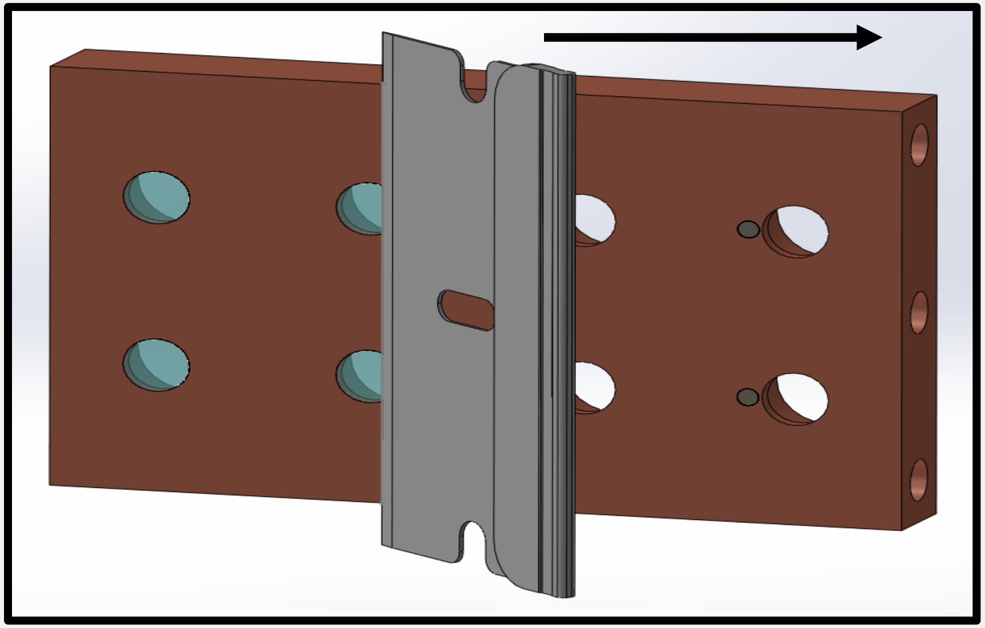


- Characterized by additional phases between solid and liquid
- Phases distinguished by molecular orientation and ordering

- 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

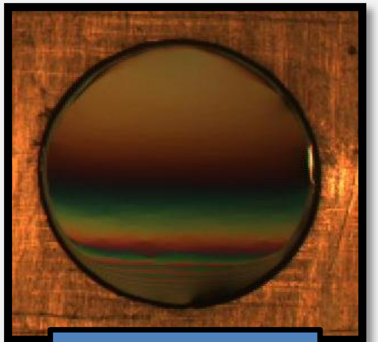
- Modifying 8CB phase via temperature control is crucial—facilitated by copper frame with resistive heaters/PID control

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

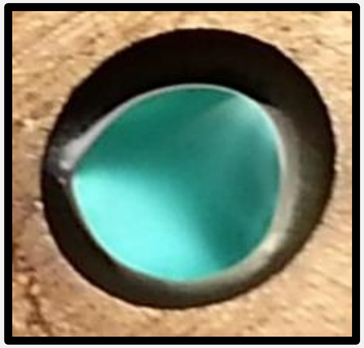


Vertical film

Meniscus shift

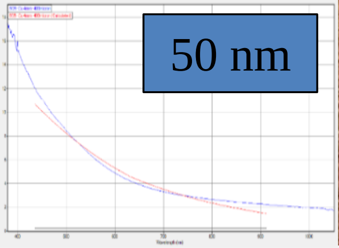
Mobile island

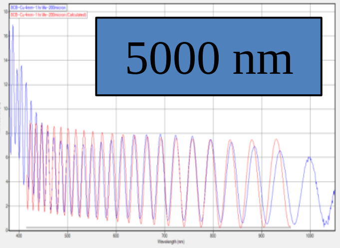
Control



Range of film thicknesses demonstrated

Coarse Control

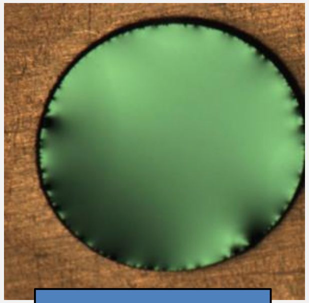




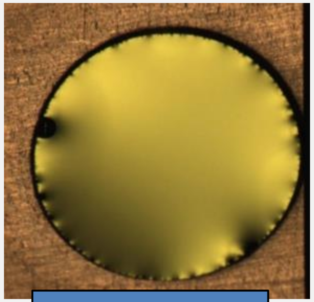
- Liquid crystal volumes between 0.1 and 2 μL
- Temperature variation over several degrees

Fine Control

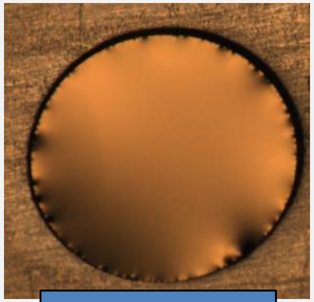
190 nm



260 nm



300 nm



330 nm

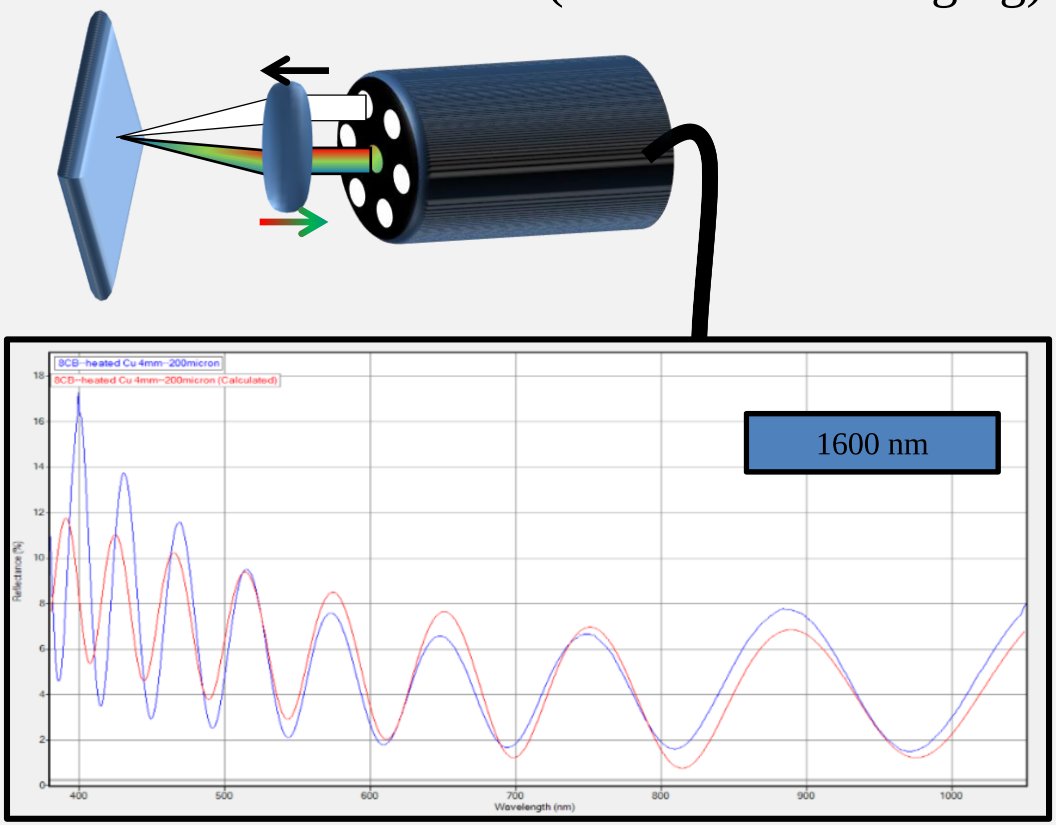
- Wiper speed

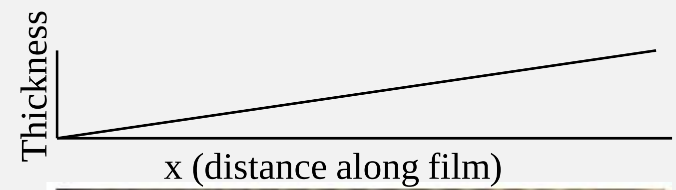
P. L. Poole, et al., Physics of Plasmas 21, 063109 (2014).

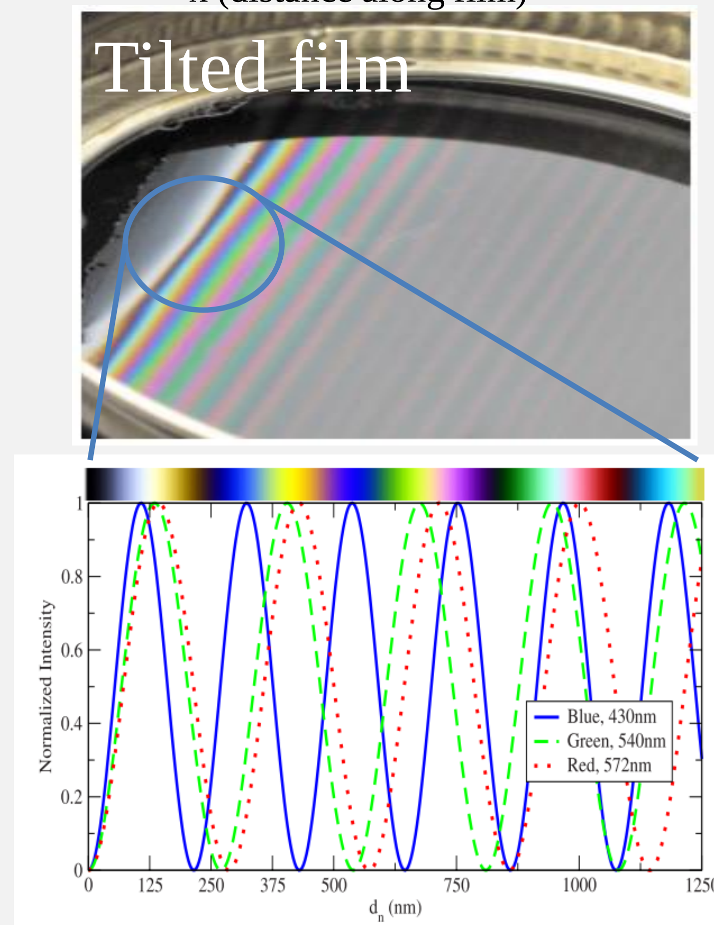
Characterizing the films - thickness

Filmetrics commerical unit

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



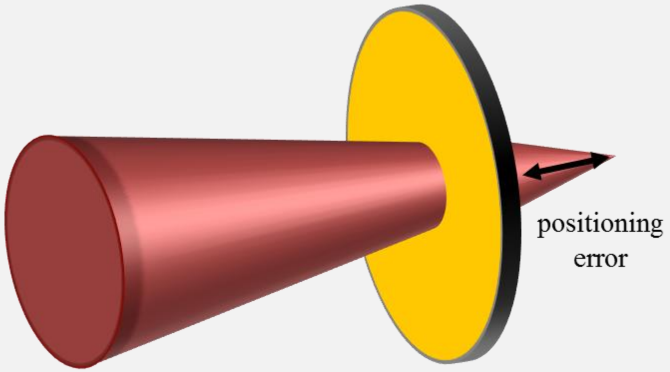


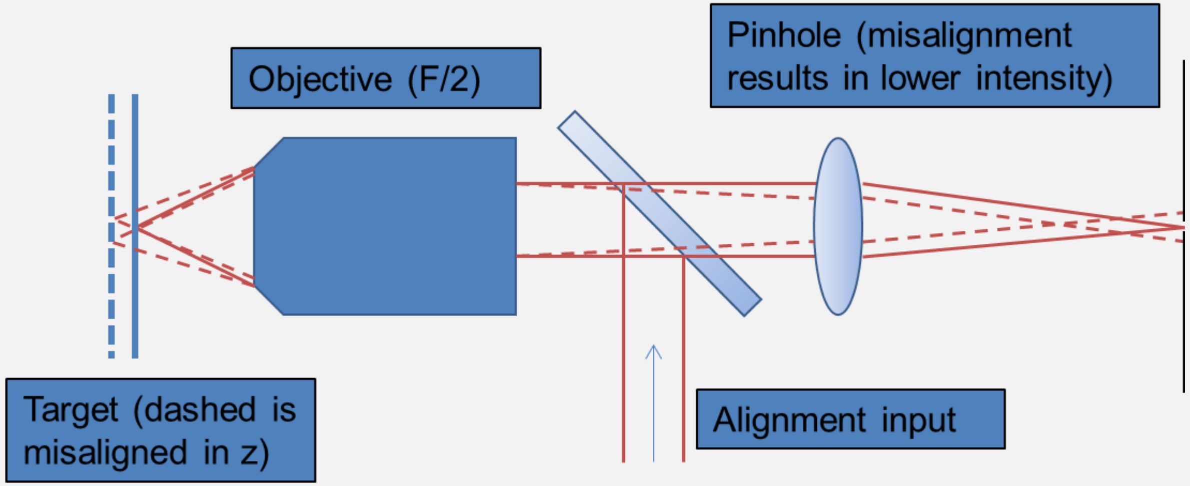


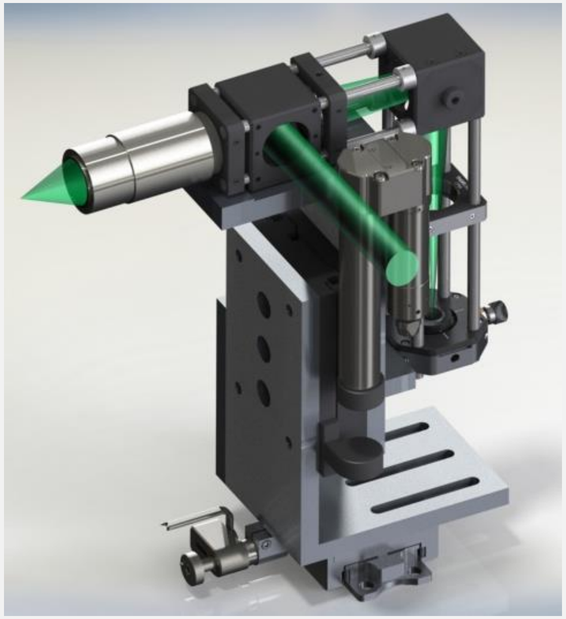
Characterizing the films – z-position

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





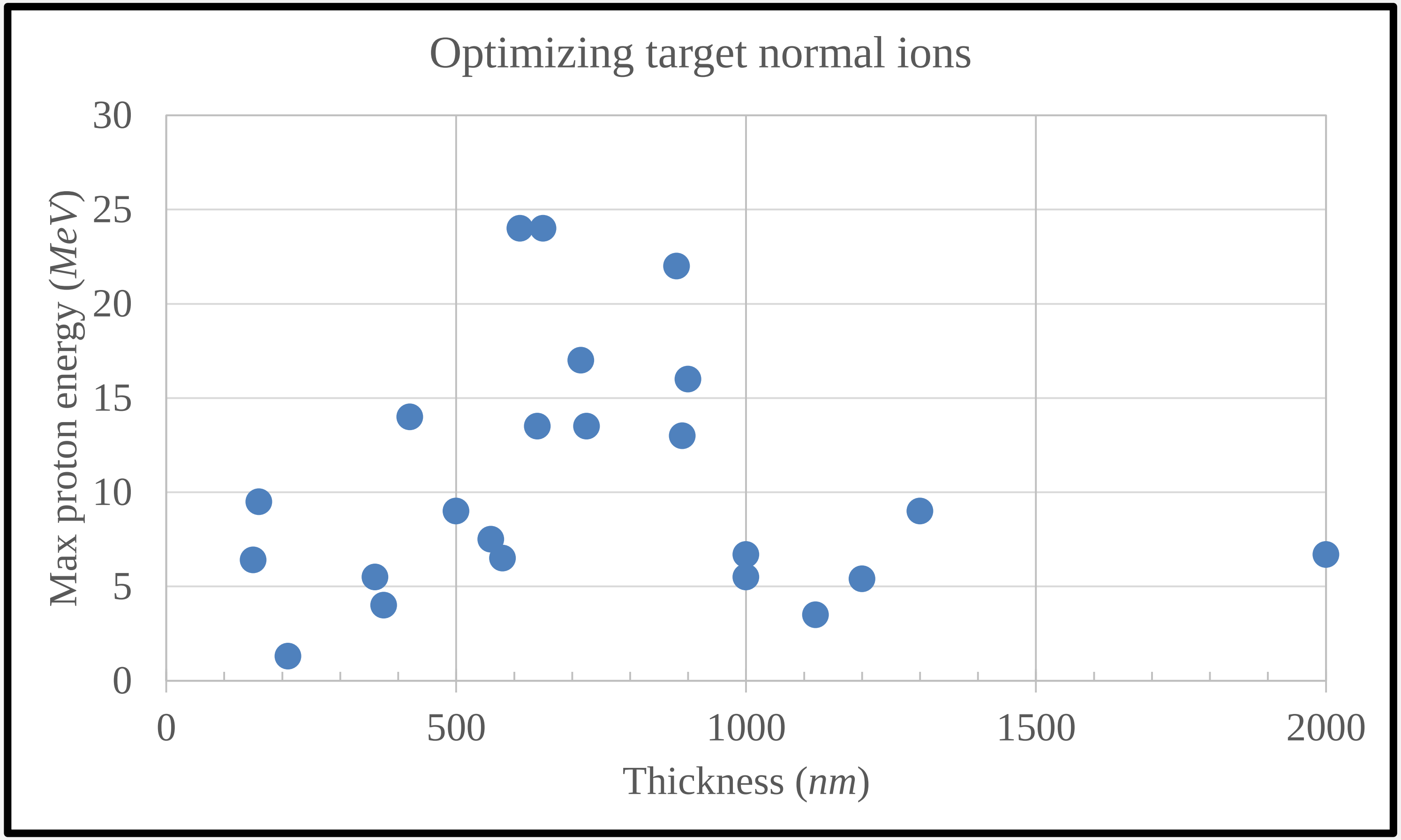


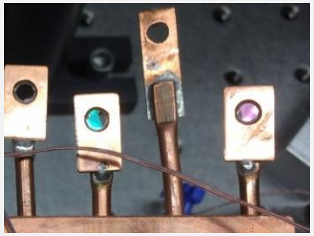
C. Willis et al., Review of Scientific Instruments **86**, 053303 (2015)

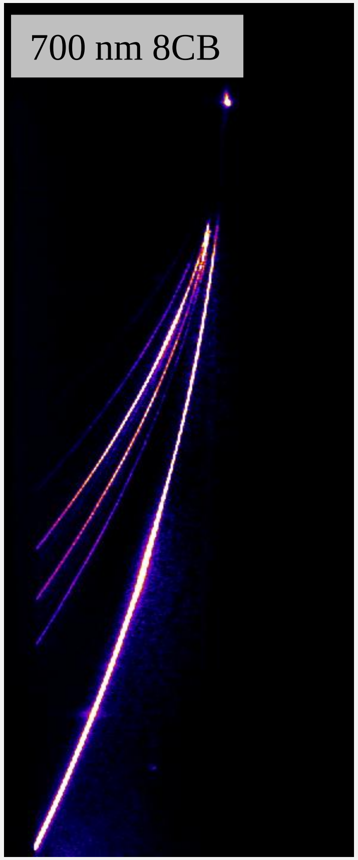
Ion acceleration thickness scan using Scarlet

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

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







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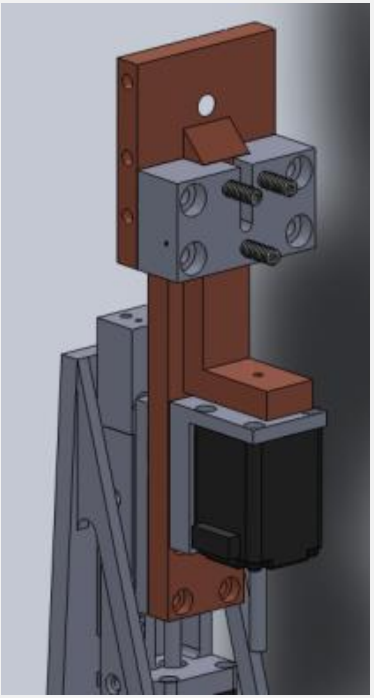
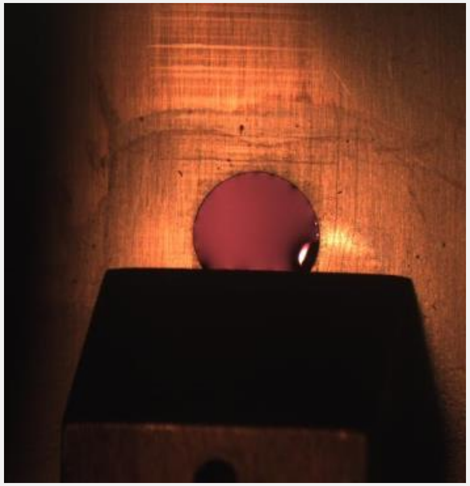
LSTI: linear sliding target inserter

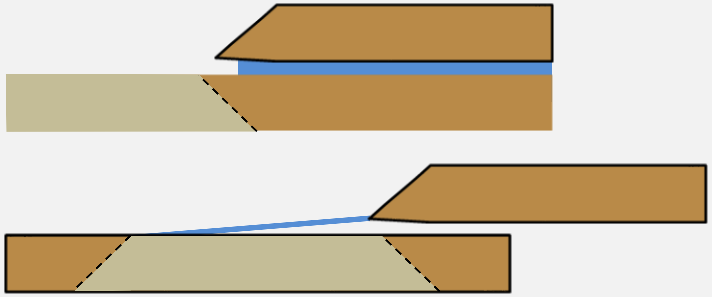




810 nm

2200 nm

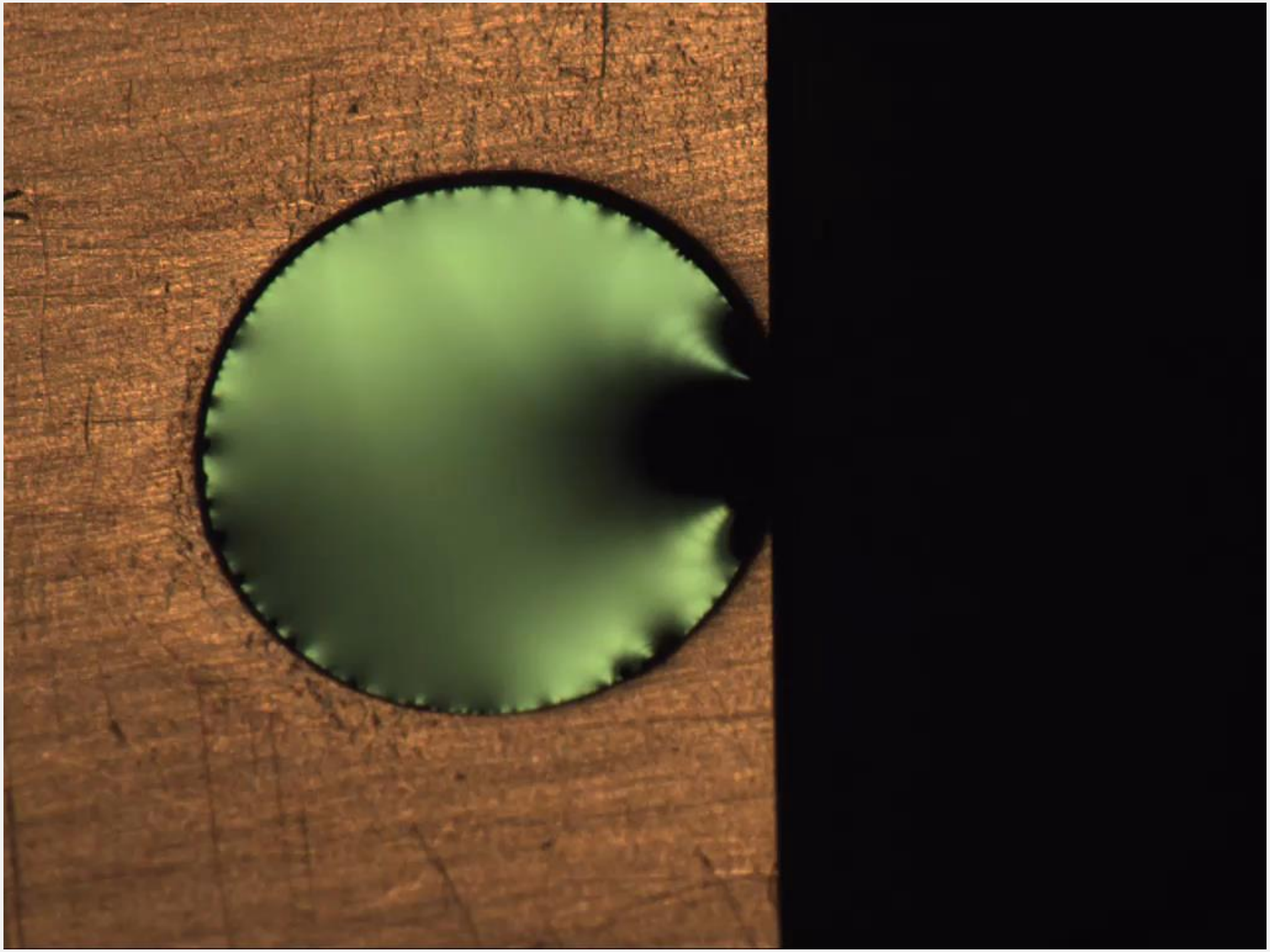
repetitive formation in vacuum



- 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**

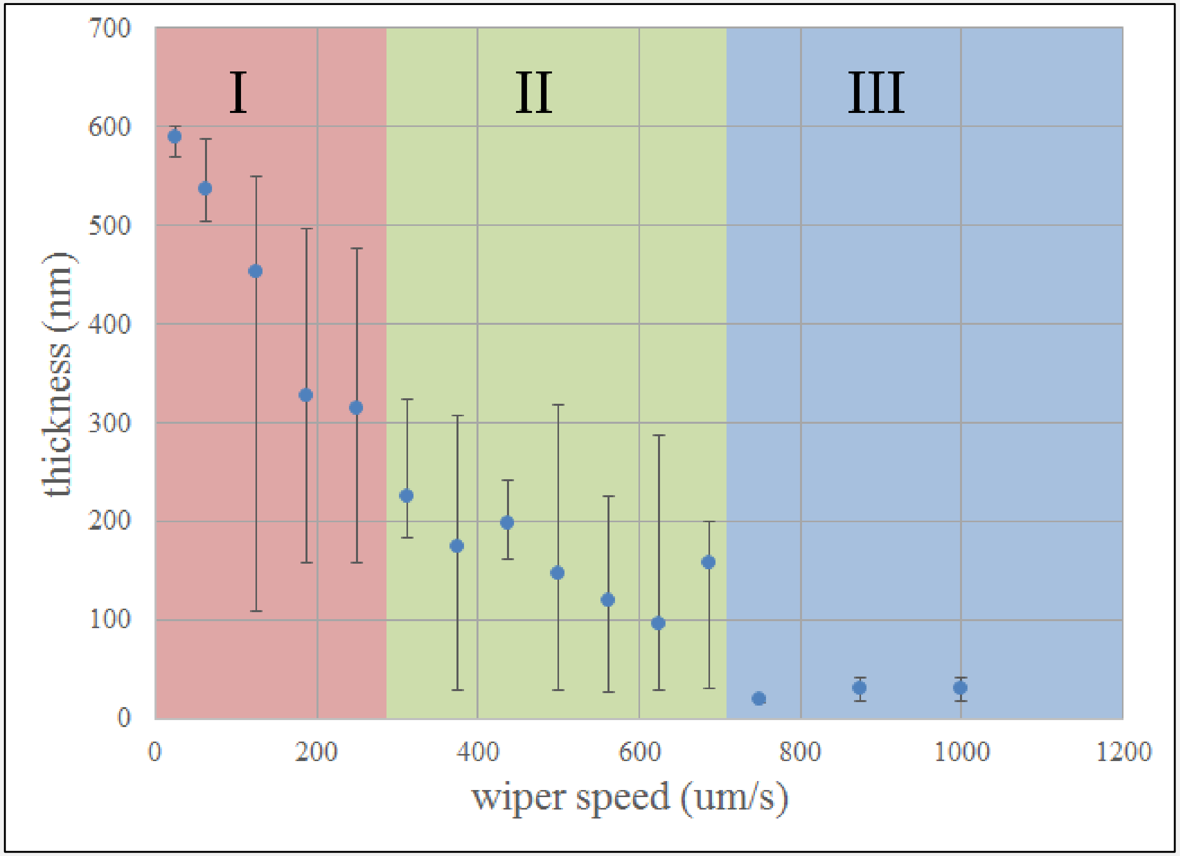
Submitted, http://arxiv.org/abs/1507.08259

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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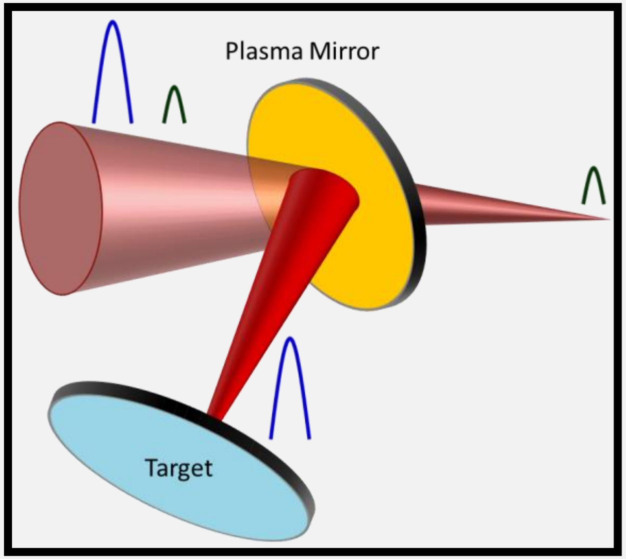
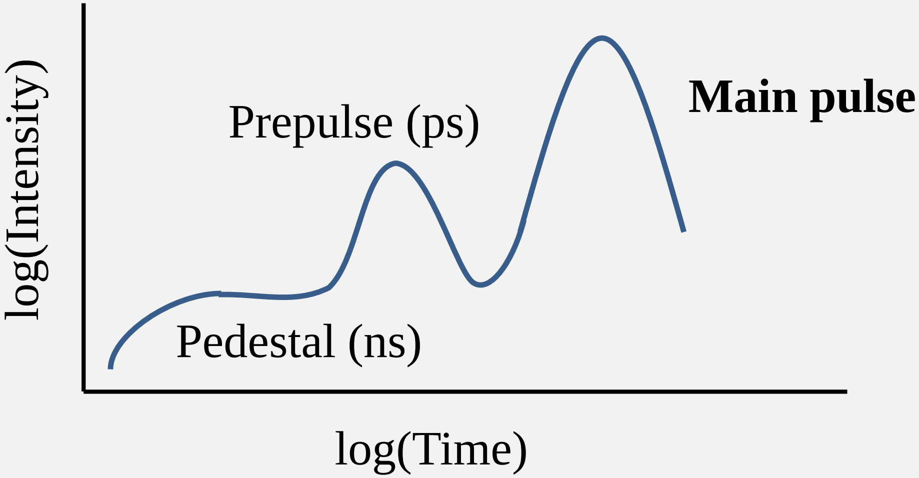
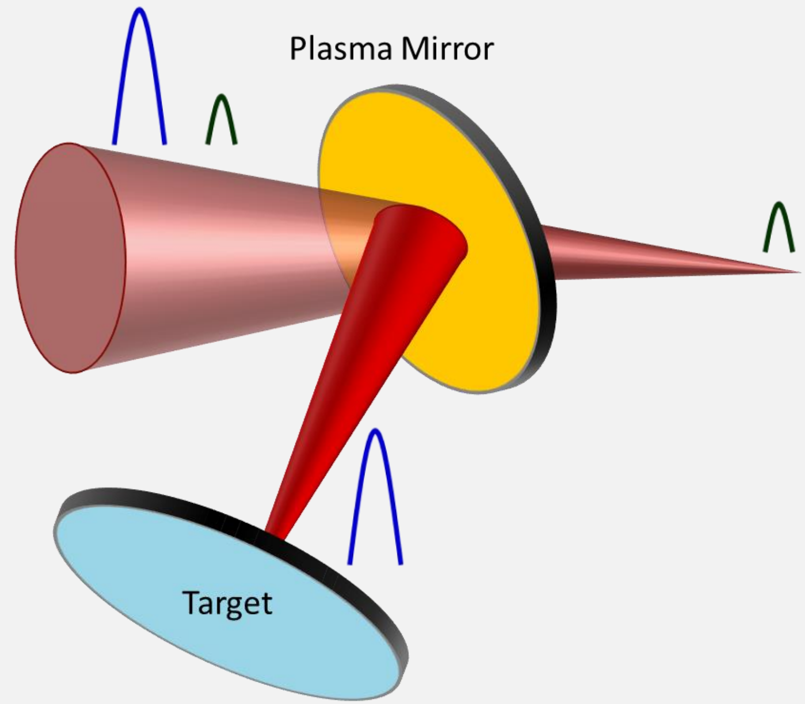


Plasma mirrors for pulse cleaning





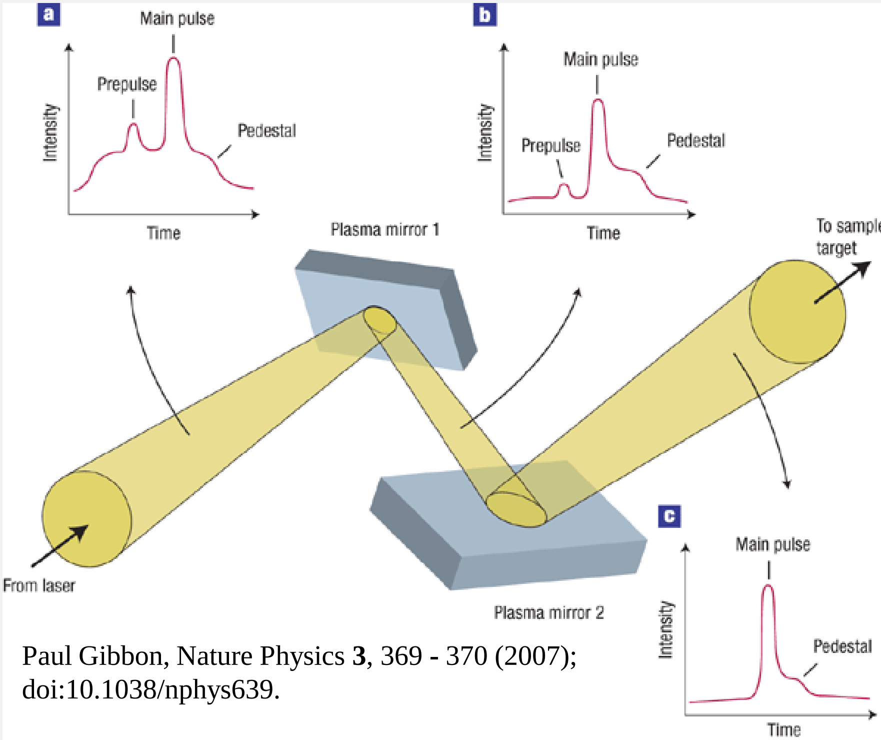
Requirements, issues:

- low weak field reflectivity
- high strong field reflectivity
- area
- flat
- vacuum compatible
- low cost
- rep rate

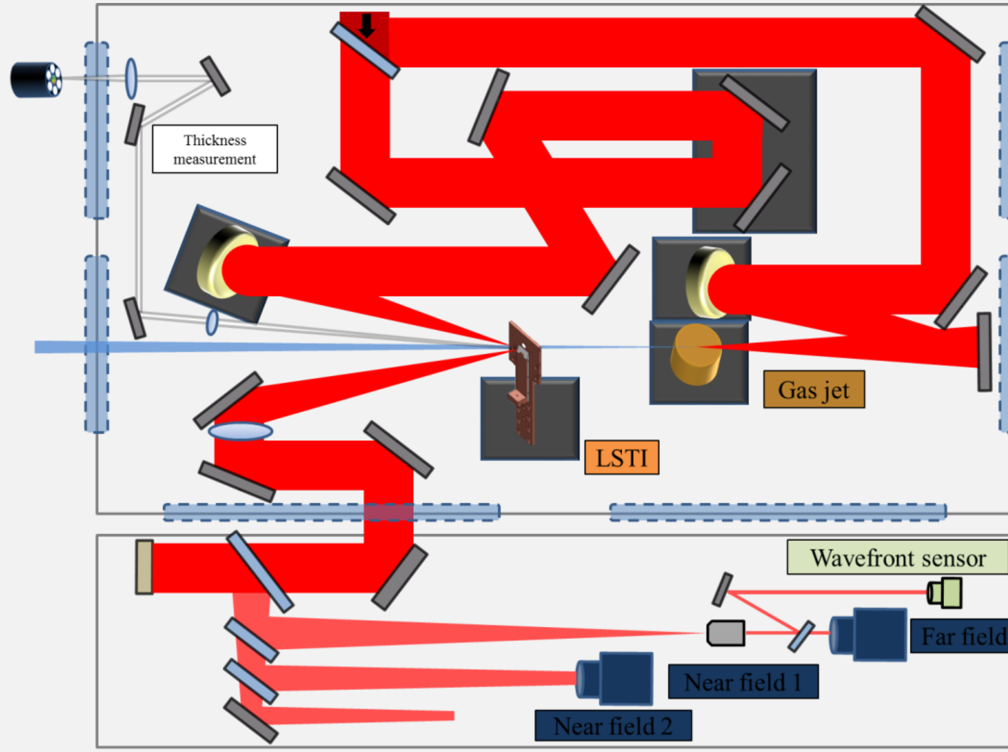
Usually via an AR coating.
Liquid crystal film – use etalon minimum?

Depends on plasma excitation

Run on TA2 (RAL)



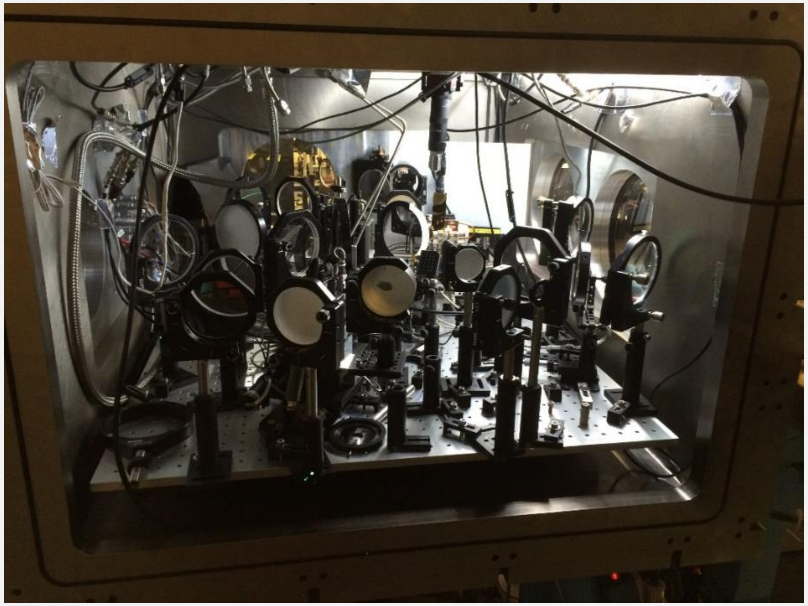
Paul Gibbon, Nature Physics **3**, 369 - 370 (2007); doi:10.1038/nphys639.

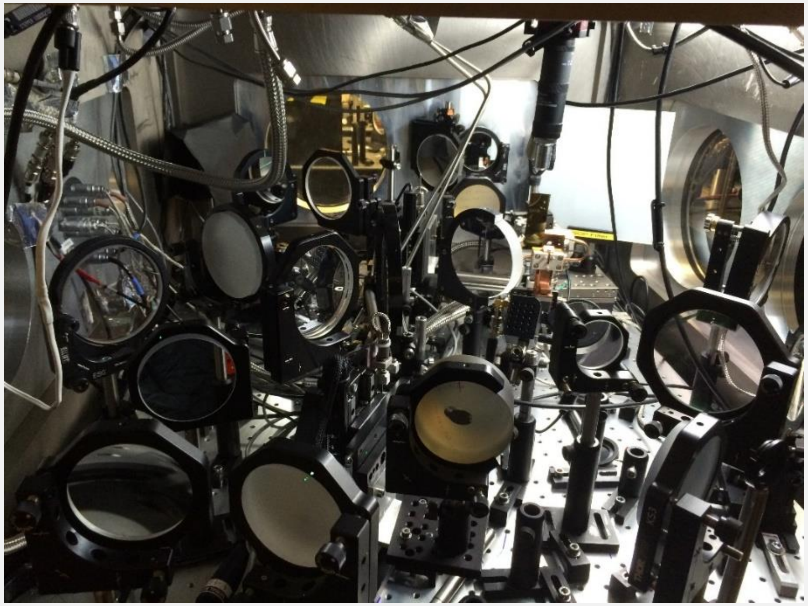


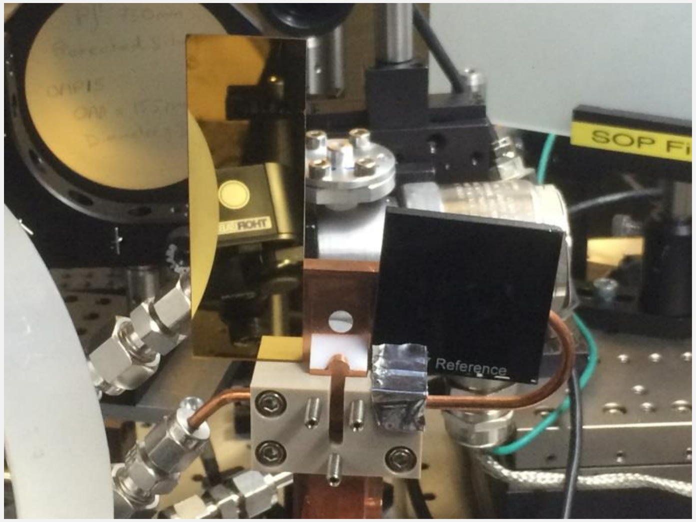
Laser parameters
RAL TA2
0.6 *J* input to chamber
40 *fs* pulse width
F/7 focus onto plasma mirror
S and P polarizations on target

Diagnostics
Liquid crystal thickness measurement
Near field cameras
Far field and wavefront sensor

Experimental set-up

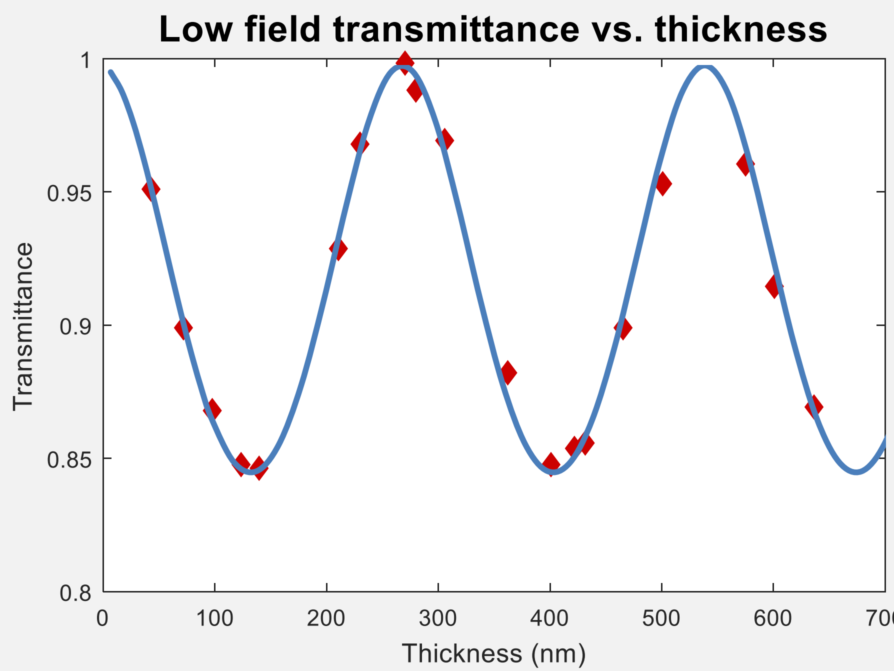


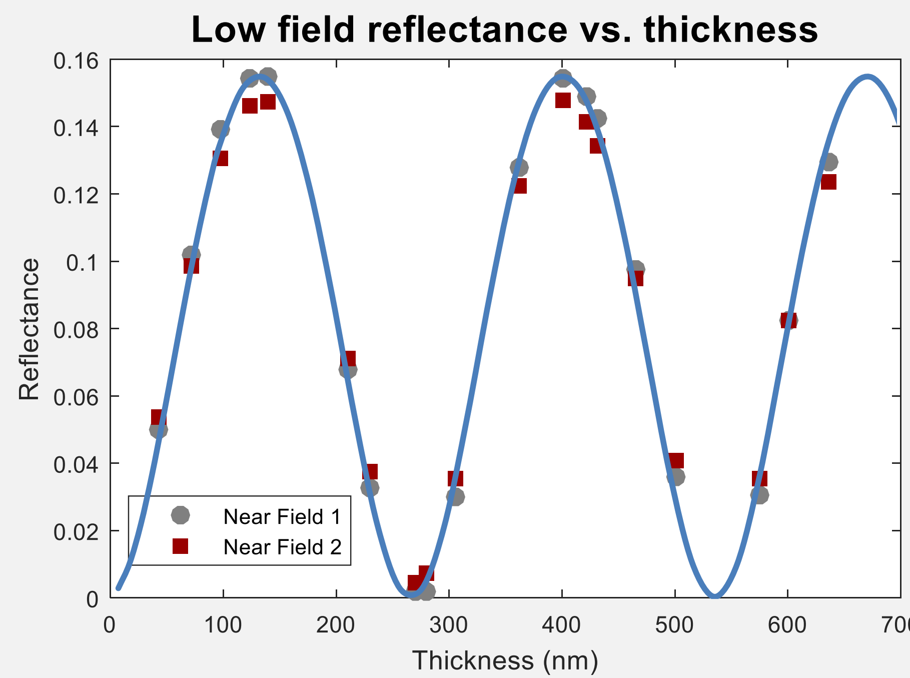




Using LSTI, tune thickness to etalon minimum

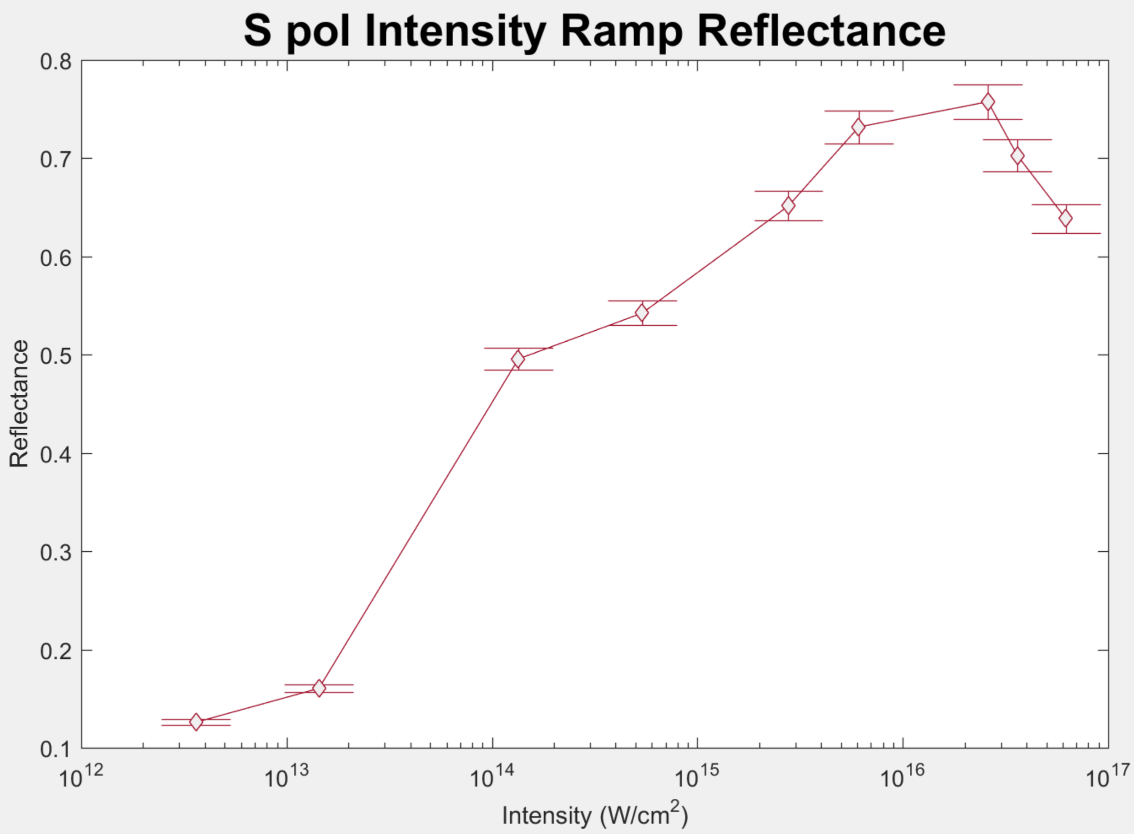
- Low intensity: ~$5\text{x}10^{11}$ W/cm^2
- S polarization
- ~15° incident angle, 800 nm light
- First reflectance minimum is ~270 nm with R < 0.2%

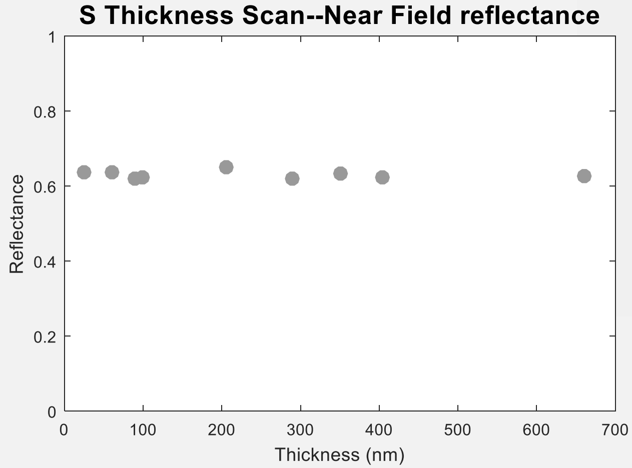




Intensity ramp

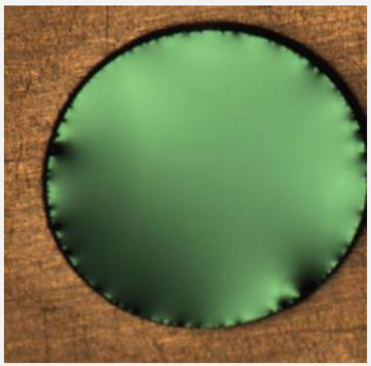
- Initial results: reflectance of ~ 75%
- Implied contrast enhancement >350
- P-polarization results lower by ~10%

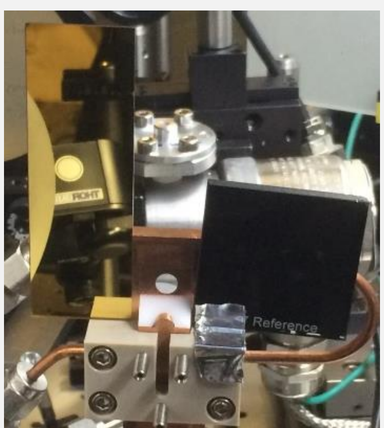




Good mode preservation in weak field limit

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



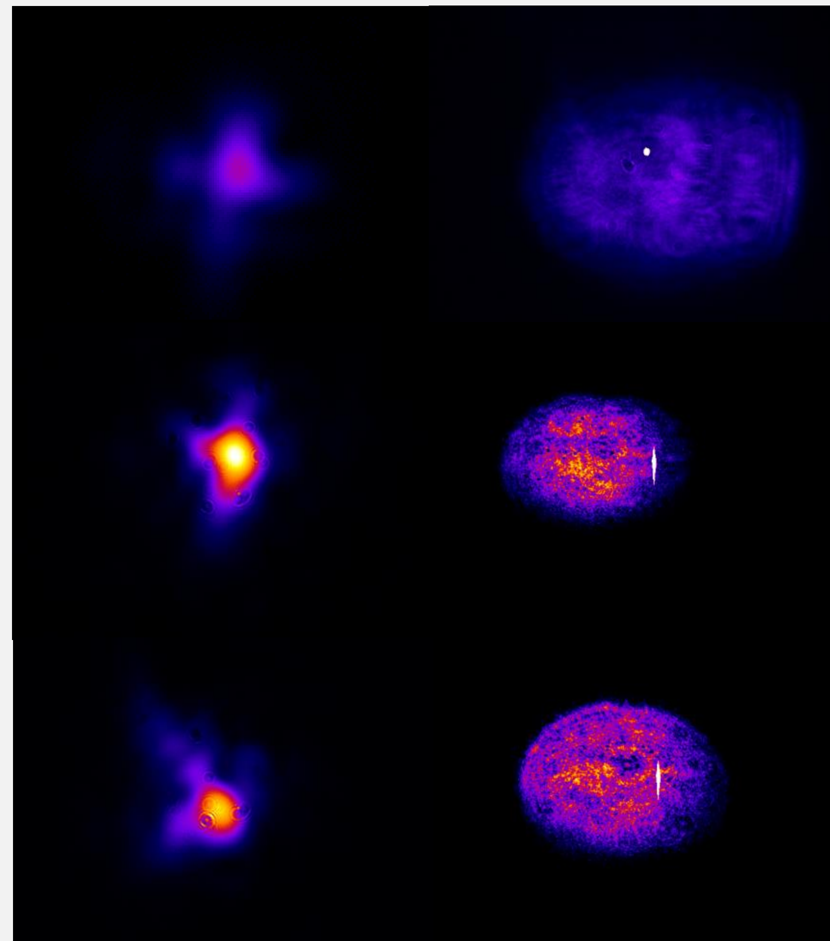


Far field | Near field

Input laser

Au slide reflection

Liquid crystal reflection



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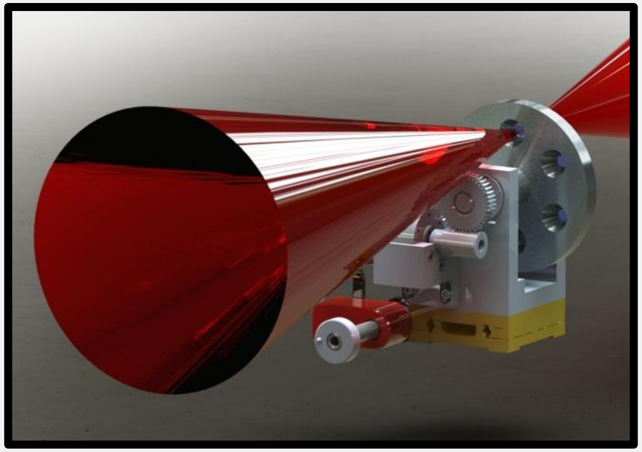
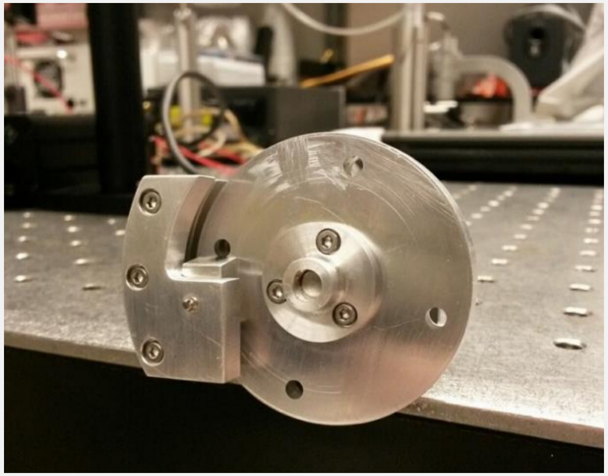


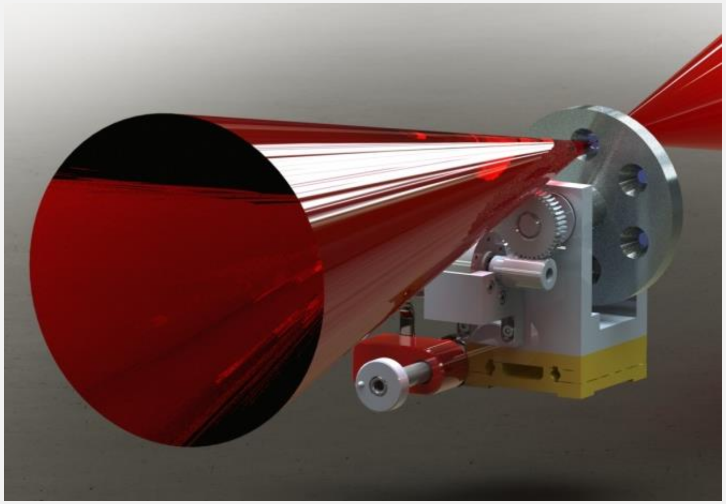
Rotary geometry – the Spinning Disk Inserter

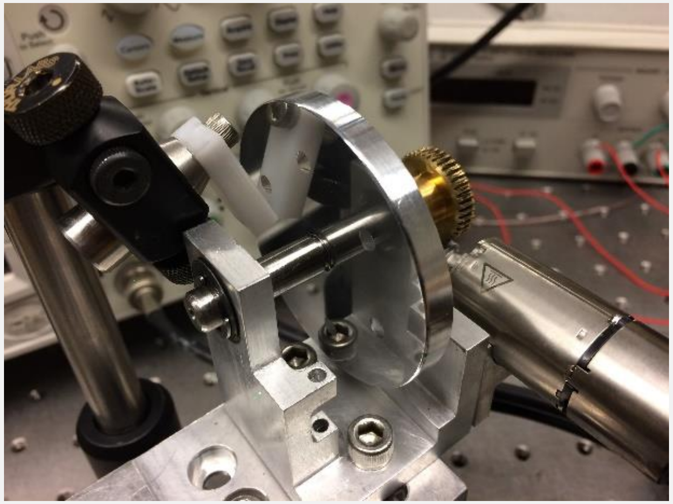
10 Hz water

0.1 Hz 8cb

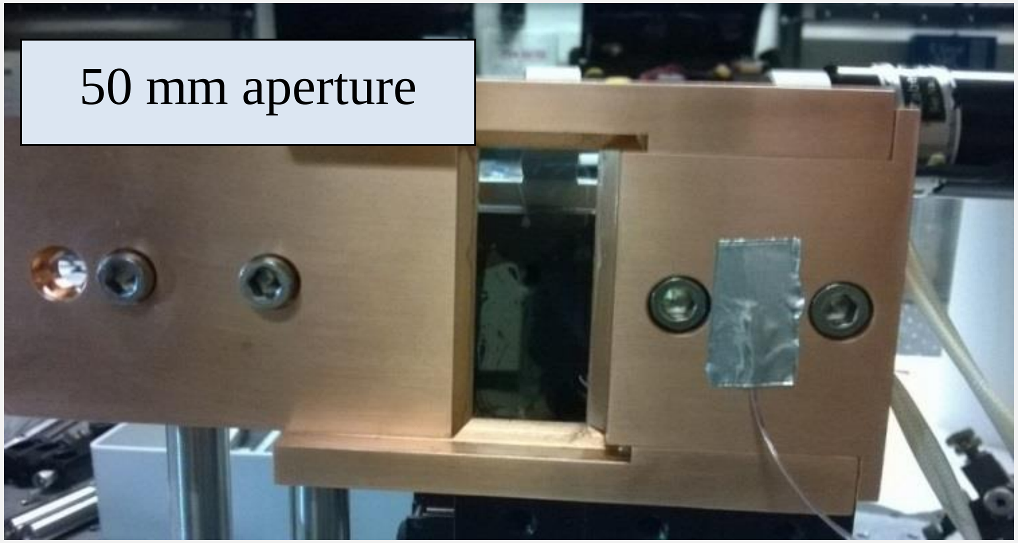


1 Hz 8cb



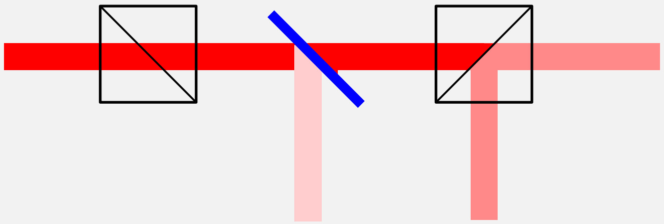


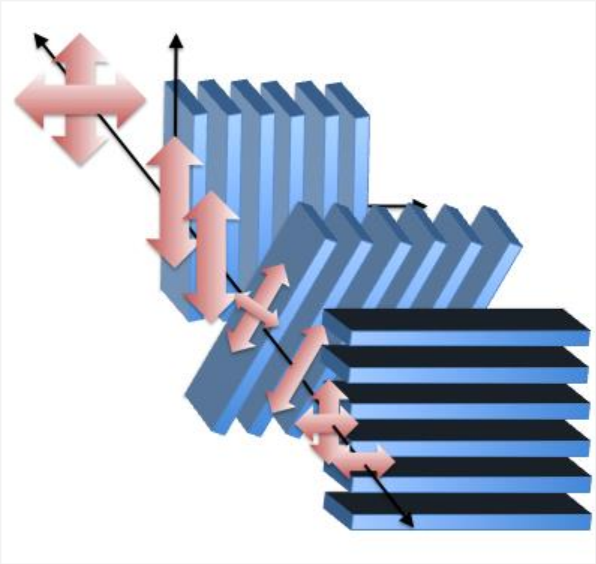
Larger area films are easily made

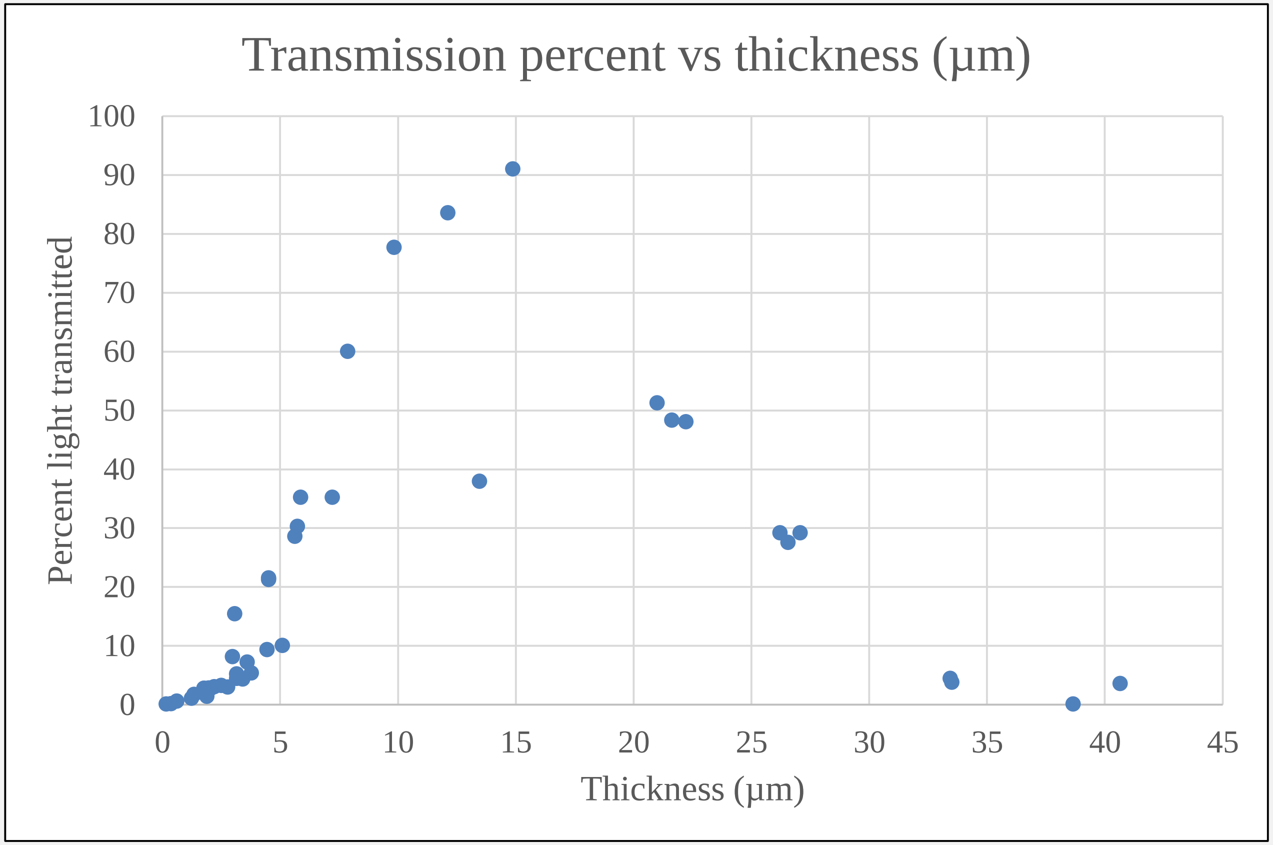


Zero-order waveplates are possible

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

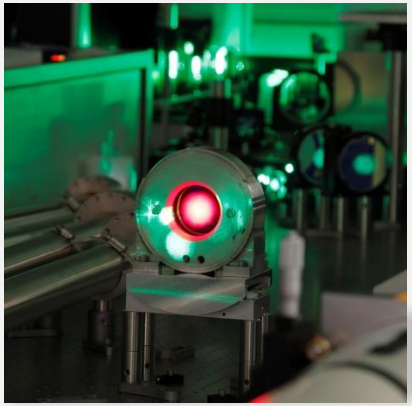


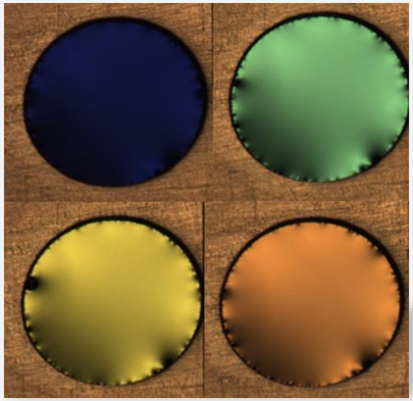


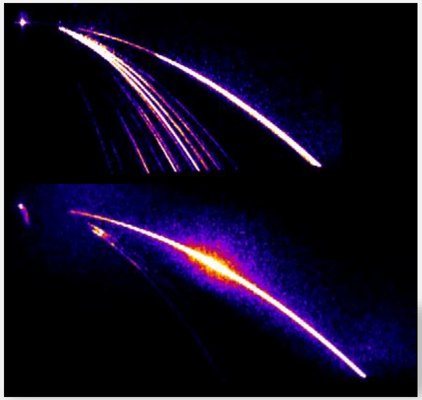


Outline

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**







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