Liquid Crystal Targets and Plasma Mirrors For Laser Based Ion Acceleration

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

THE OHIO STATE UNIVERSITY

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
  - L. Obst, J. Metzkes, K. Zeil, T. Kluge, H-P Schlenvoigt, S. Kraft, I. Prencipe, M. Rehwald, U. Schramm
- DARPA PULSE program
  - Through AMRDEC
  - National Energetics
- Department of Energy NNSA SSAP
  - Contract DE-NA0001976

A great team

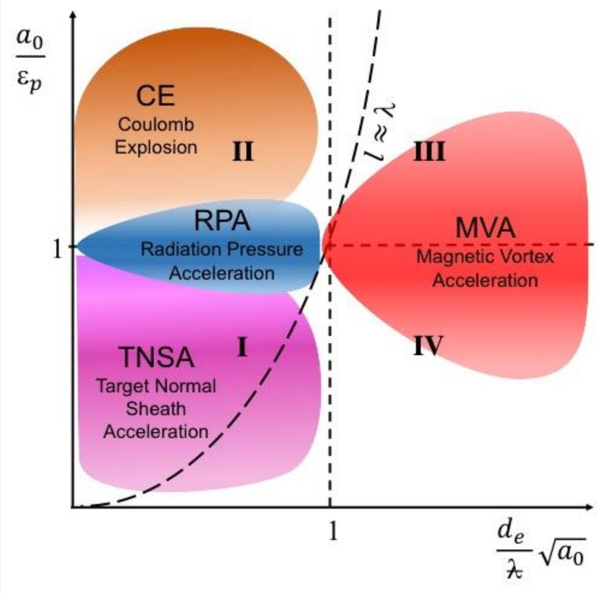
Dr. Patrick Poole
lead developer,
now at LLNL

Ginevra Cochran
experiment,
PIC modeling

Dr. Chris Willis
experiment,
diagnostics
development

Motivation: target thickness, laser contrast, rep-rate

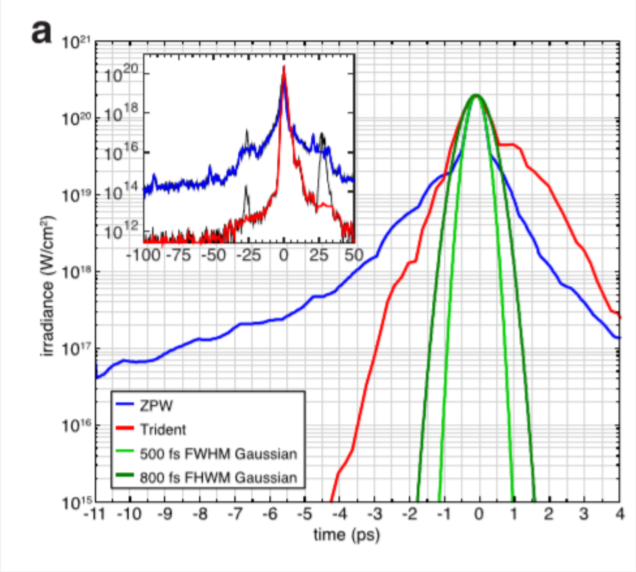
Multiple ion accel. mechanisms identified. Intensity and target thickness are key “knobs”…



Bulanov, *et al.*, Physics of Plasmas **23**, 056703 (2016)

See talks by Bulanov, Macchi which include reviews.

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



M. Schollmeier *et al.*, Physics of Plasmas **22**, 043116 (2015)

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

BELLA

>1 PW @ **1 Hz** – running!

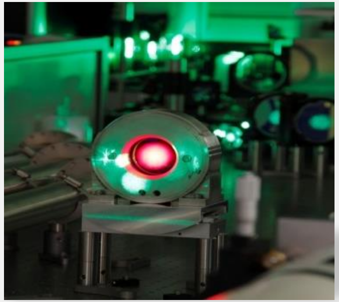
eli
eXtreme light infrastructure

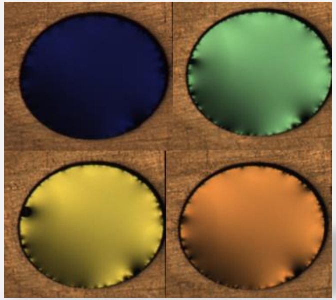
Beamlines, NP, ALPS
> 1 PW @ **10 Hz**, 10 PW

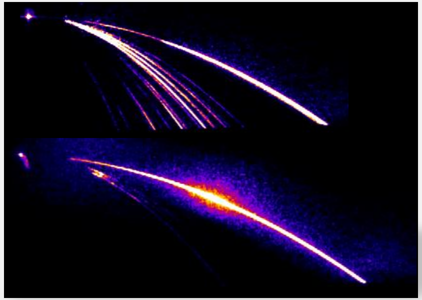
Described in multiple talks by Korn, Margarone, Qing, Schillaci, Steinke, …

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



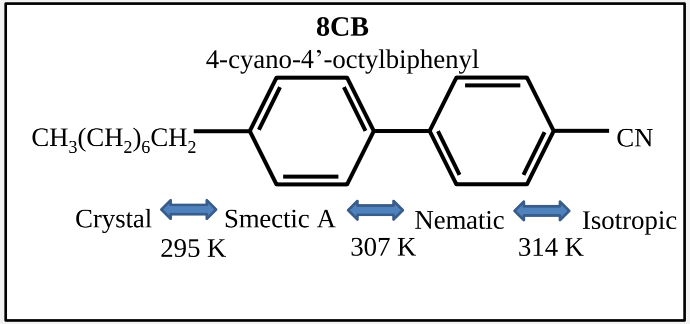


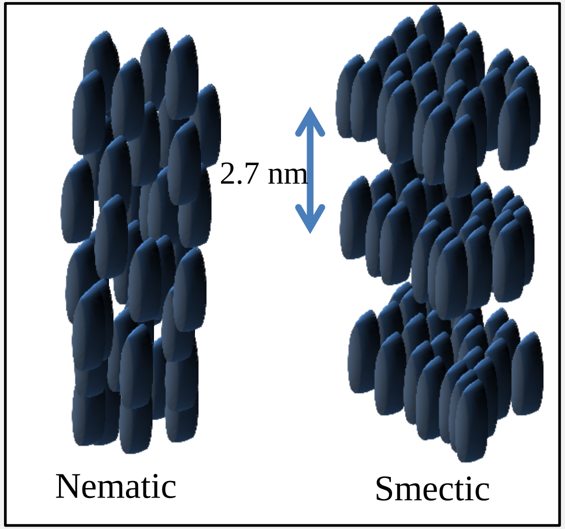


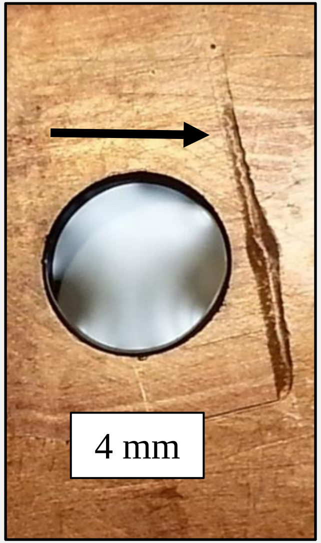
Outline

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



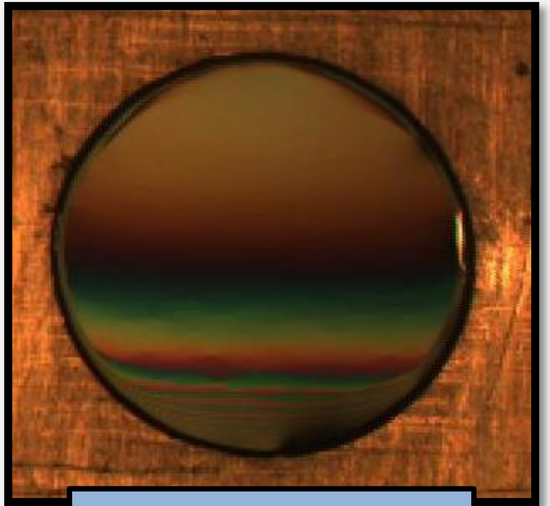




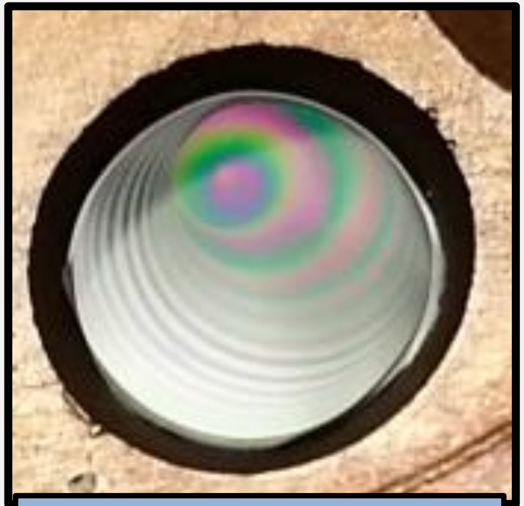
- Characterized by additional phases between solid and liquid
- Phases distinguished by molecular orientation and ordering
- Smectic phase forms films in stacked sheets **~3 nm per layer**
- Vapor pressure well below **10^{-6} mbar**
- Surface tension in smectic phase forms freely suspended film
- Films contain ~ 100 nL of 8CB, so hundreds can be made for 1 EUR

Careful control required to avoid defects

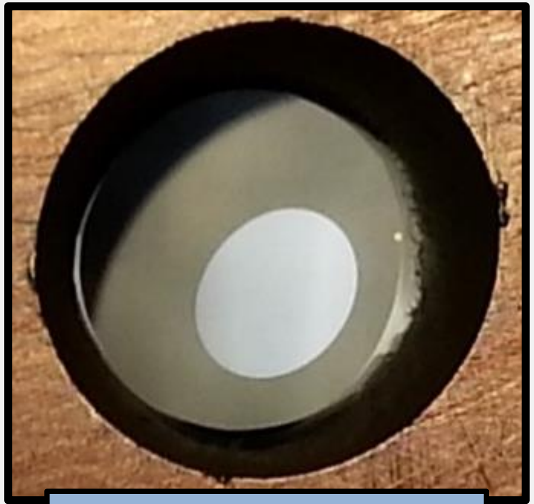
Typical non-uniform films



Vertical film

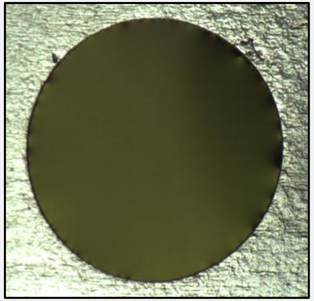


Meniscus shift

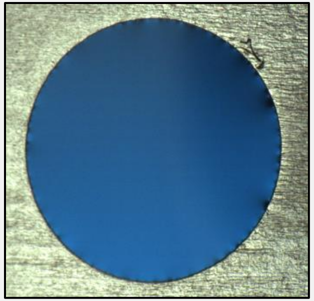


Mobile island

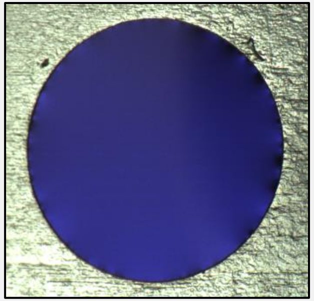
Thickness control from 10 nm to >70 µm



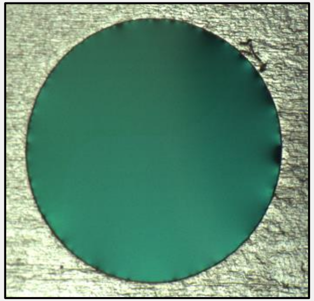
150 nm



230 nm

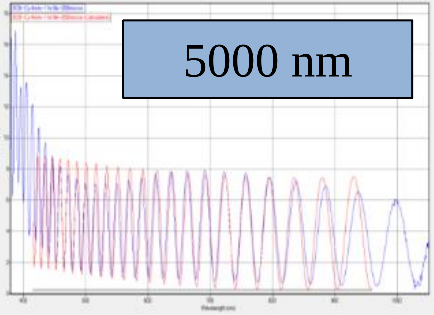


370 nm



640 nm

4 mm

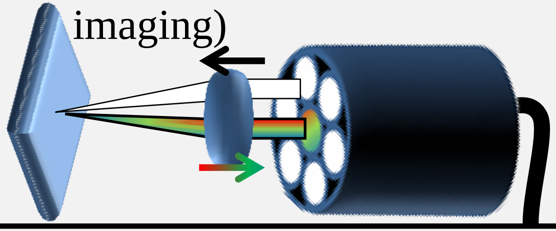


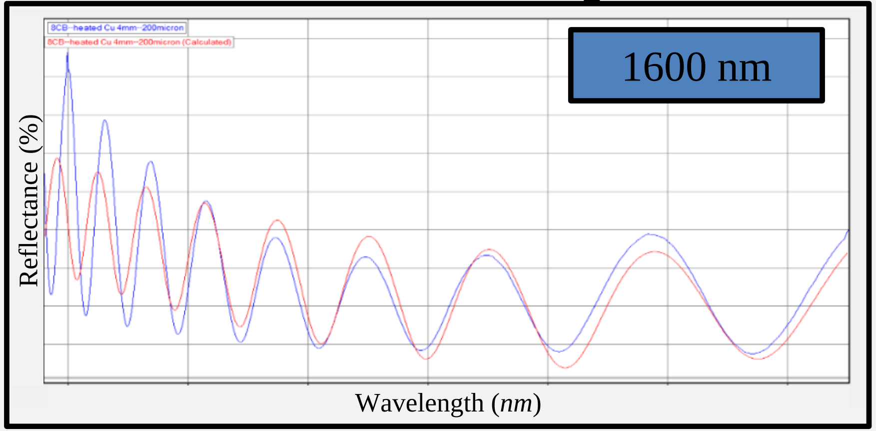
P. L. Poole, et al., Physics of Plasmas 21, 063109 (2014).

Film characterization—thickness and position

Filmetrics commercial unit

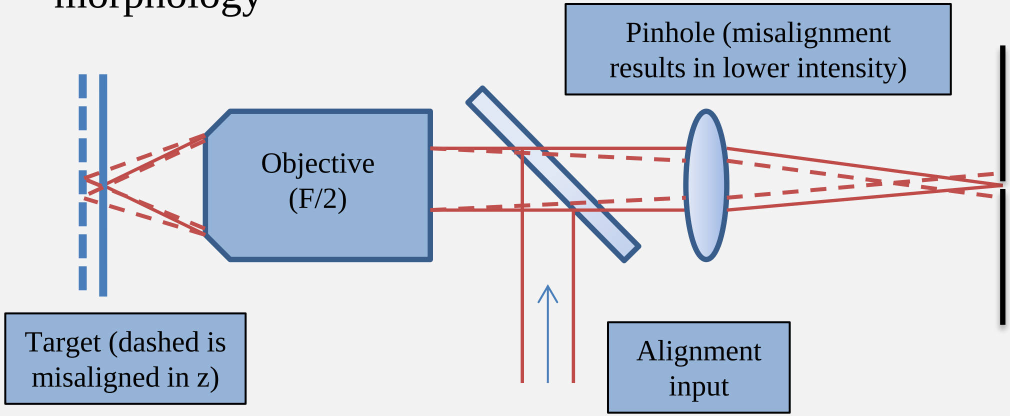
- 2 nm measurement accuracy.
- 50 ms acquisition time.
- 48” standoff distance (or more with imaging)





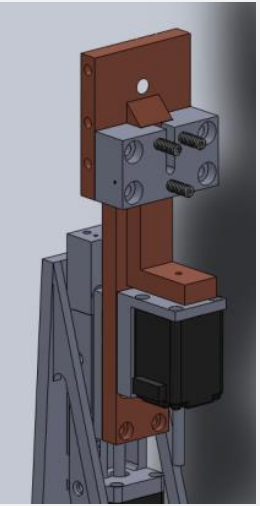
Confocal positioner for ~ 1 μm alignment

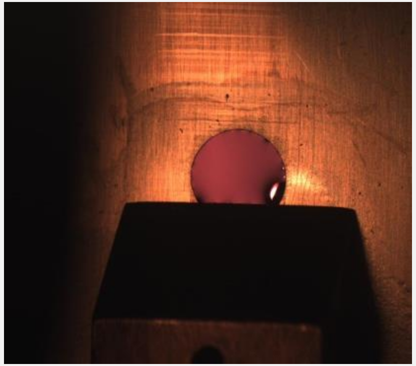
- Establish TCC using traditional techniques
- Draw a spot on the film using scatter from a low power cw laser
- Measure relative position using confocal microscopy
- Works regardless of target surface morphology



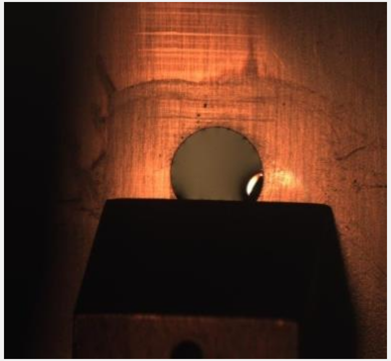
C. Willis, P. Poole et al., *Review of Scientific Instruments* **86**, 053303 (2015)

LSTI: linear sliding target inserter



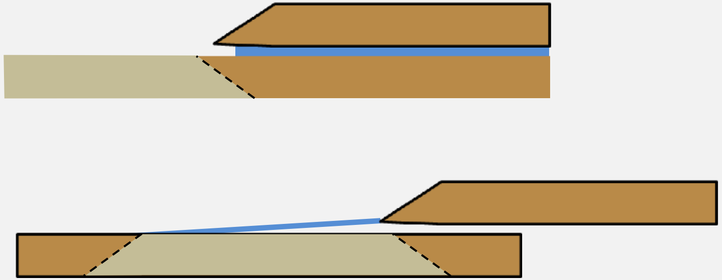


810 nm



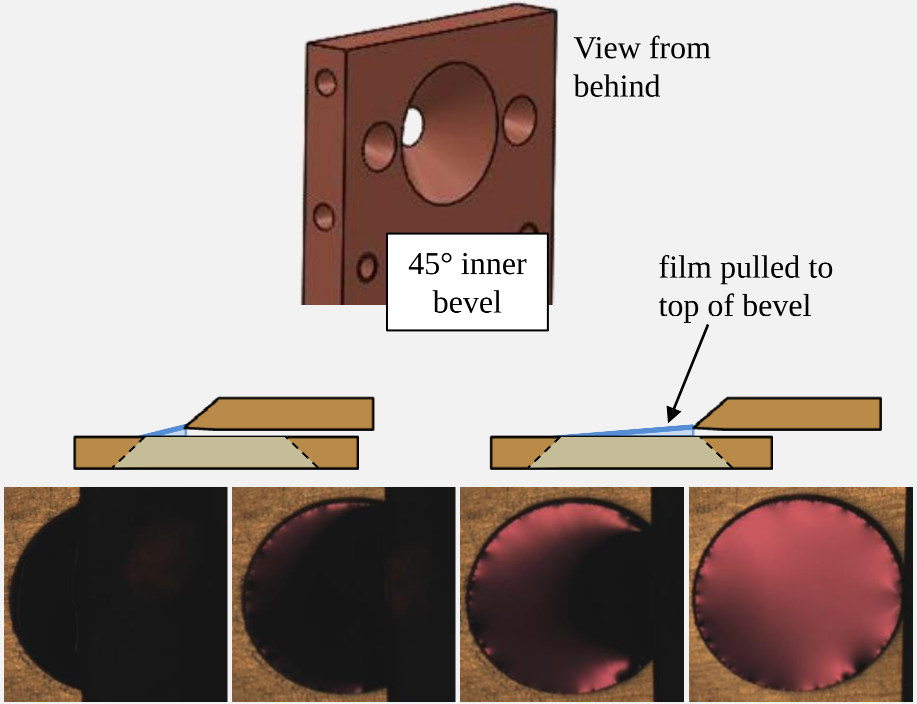
2200 nm

- 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**



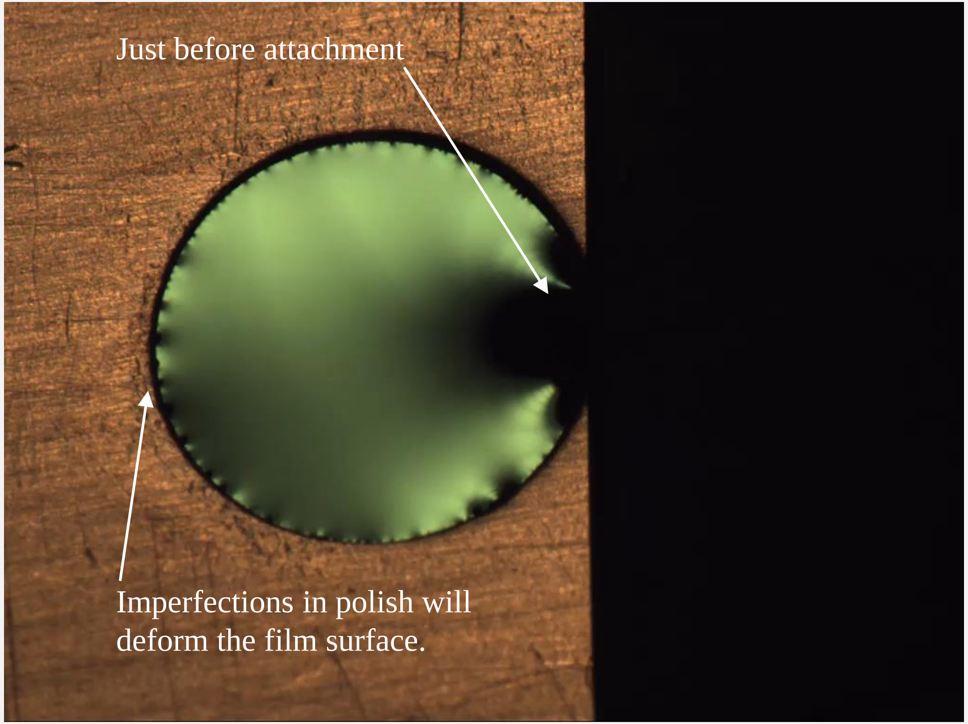
Kraft – Wednesday talk

LSTI film formation



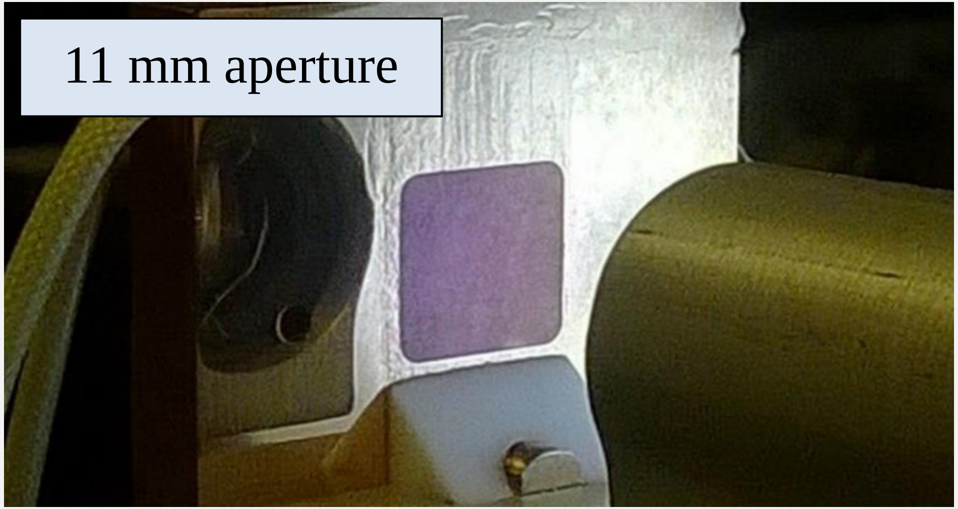
Film is present,
but still at an angle.

Film detached from
wiper.

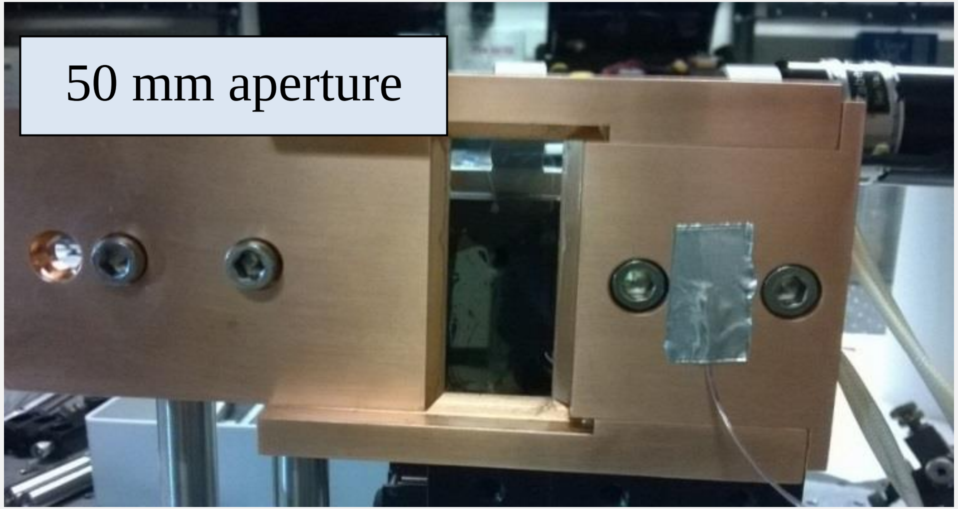


In these views, non-horizontal surfaces appear dark.

Larger apertures demonstrated



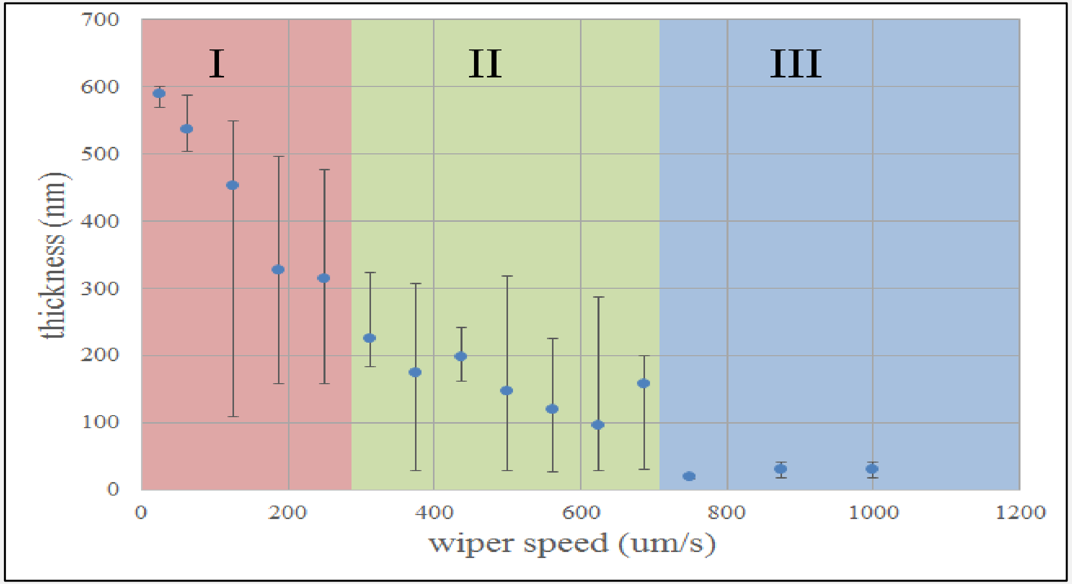
LSTI configuration



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

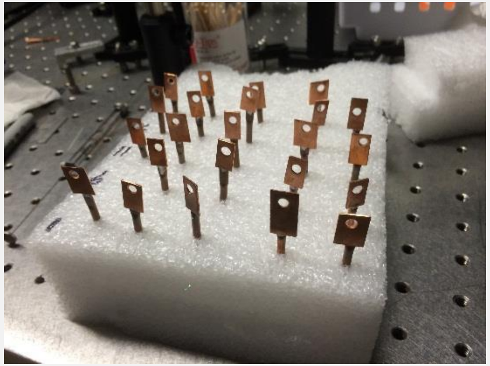


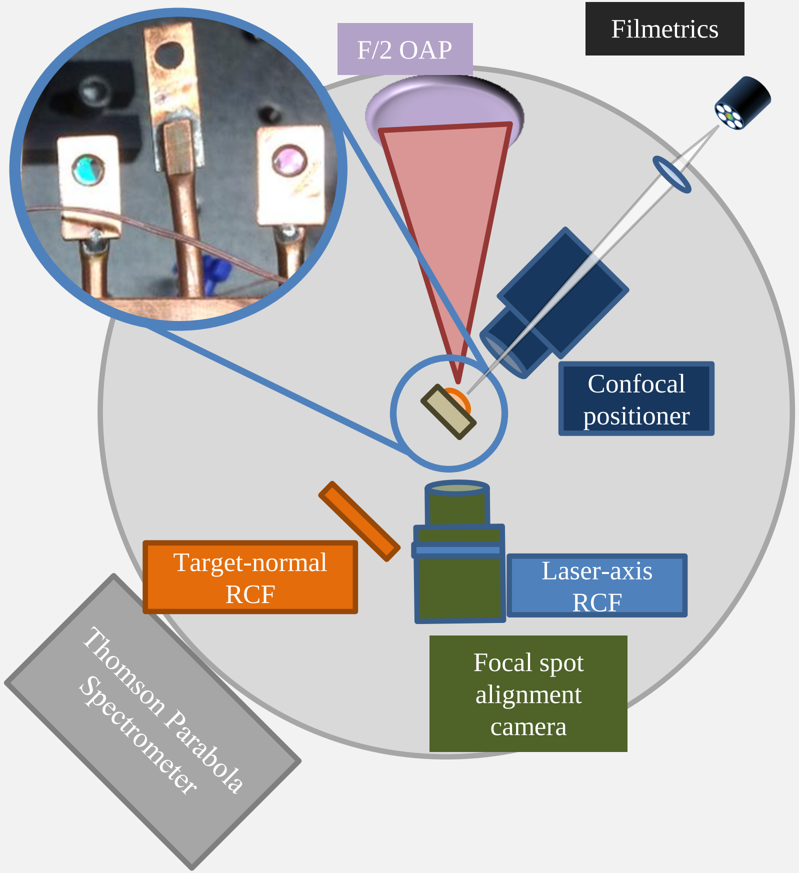
Current LSTI capbility

Parameter	Requirement
Thickness	10 nm to >70 µm
Positioning – longitudinal	<2 µm
Target area	4 mm typical 50 mm demonstrated
Pressure	<10^{-6} Torr
Temperature	Slightly above room temp
Cost	>100 films per 1 EUR
Repetition rate	> 0.1 Hz for thinnest films

First liquid crystal experiments

- Single-shot liquid crystals in flag targets
- Made to desired thickness at air, can be stored indefinitely

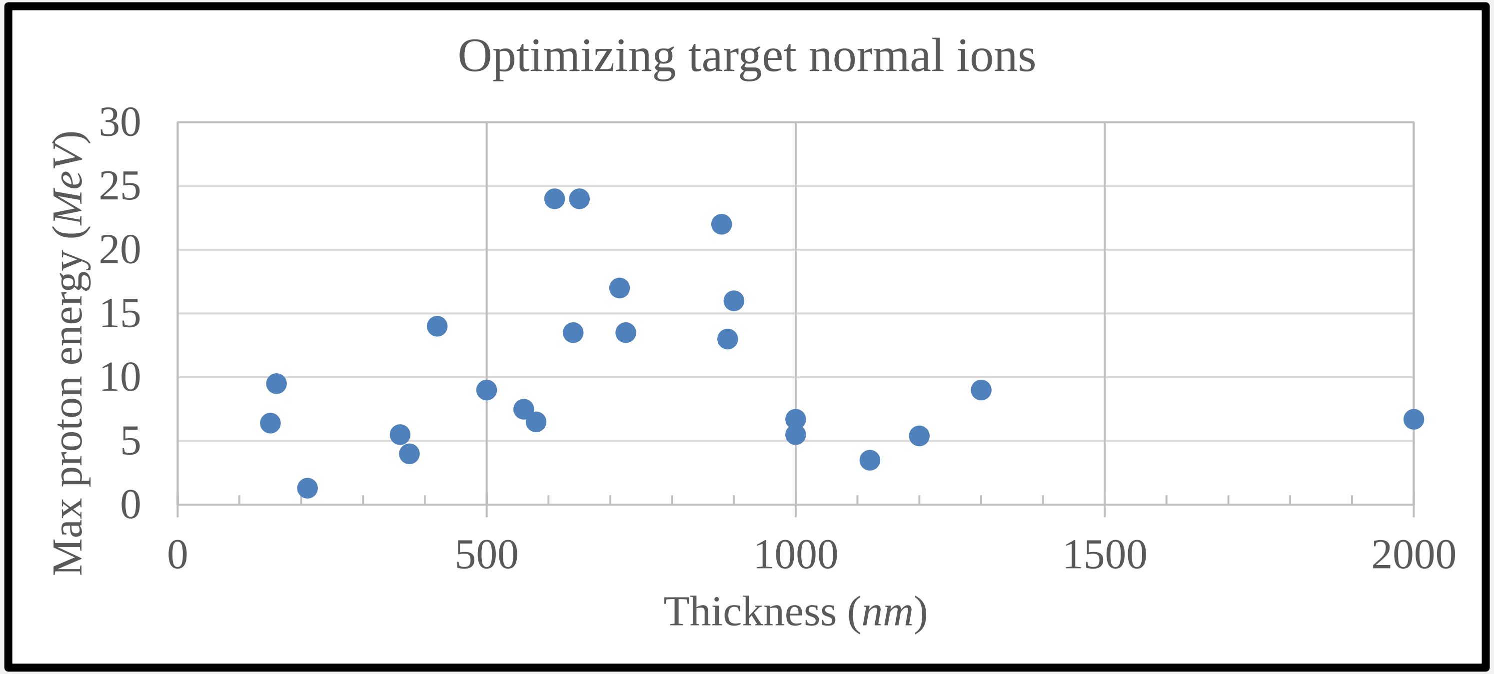


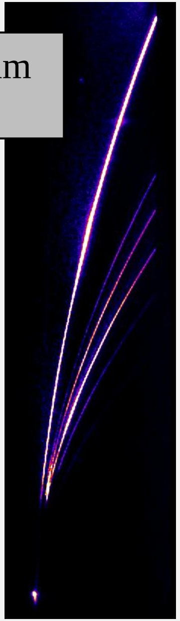


Ion acceleration thickness scan using Scarlet

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

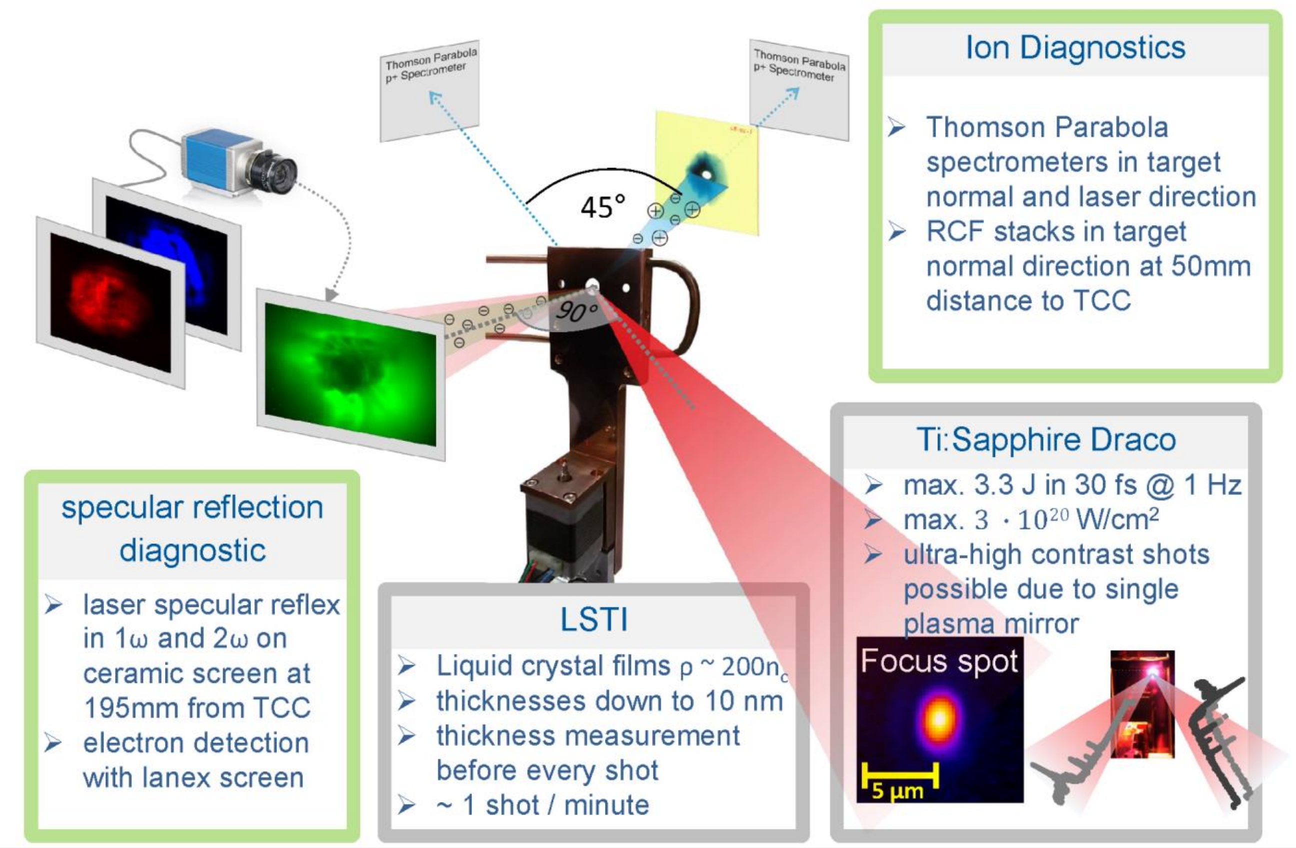
5 J on target, ~5x10^{19} W/cm^2





700 nm
8CB

DRACO Laser Ion Acceleration Study Recently Completed



HZDR

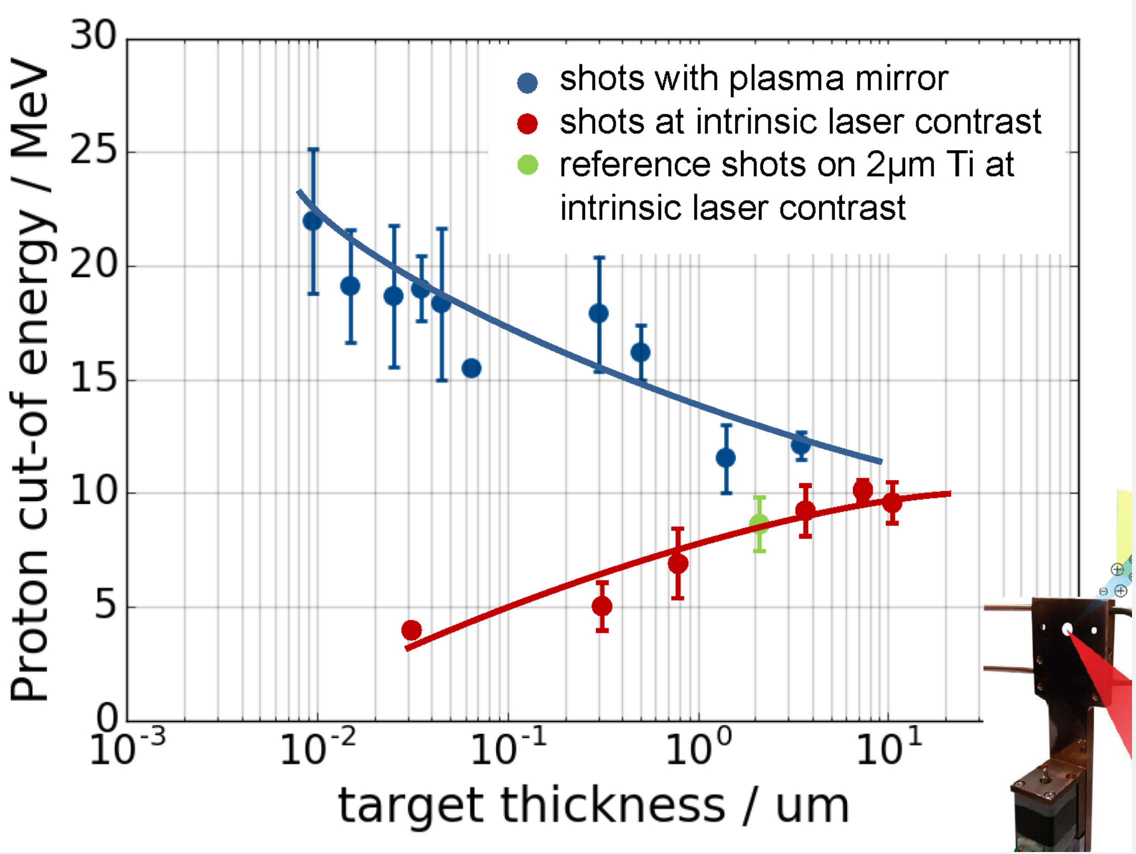
L. Obst, J. Metzkes, K. Zeil, T. Kluge, H-P Schlenvoigt, S. Kraft, I. Prencipe, M. Rehwald, U. Schramm

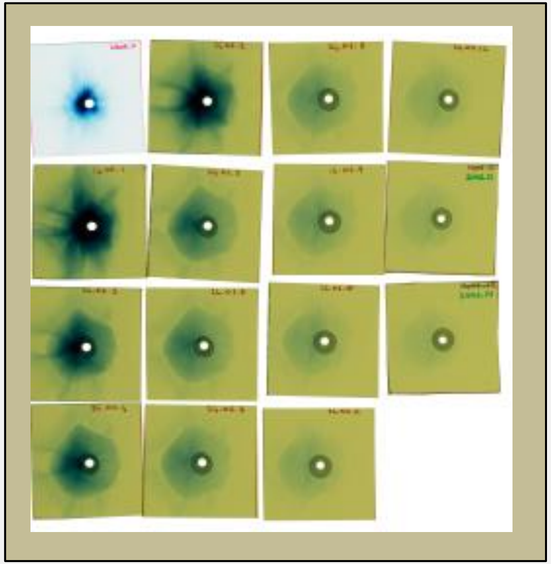
Kraft – Wednesday talk

Prencipe – Friday talk

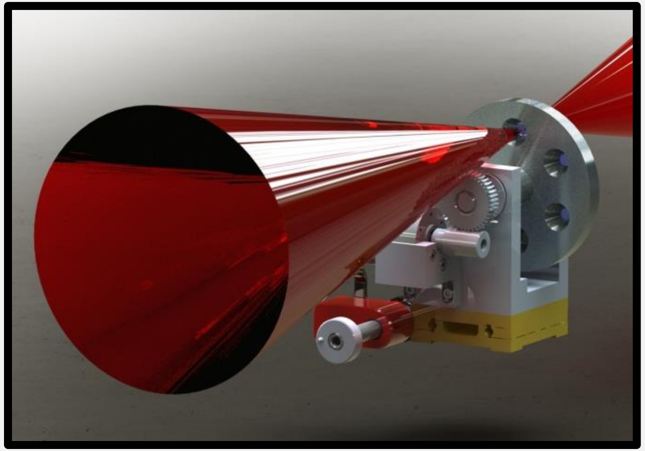
~450 shots over 5 days

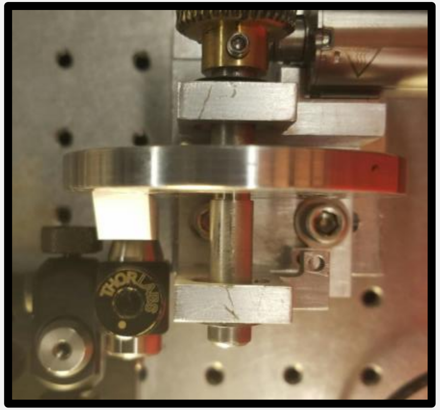
Max-proton energy vs. thickness



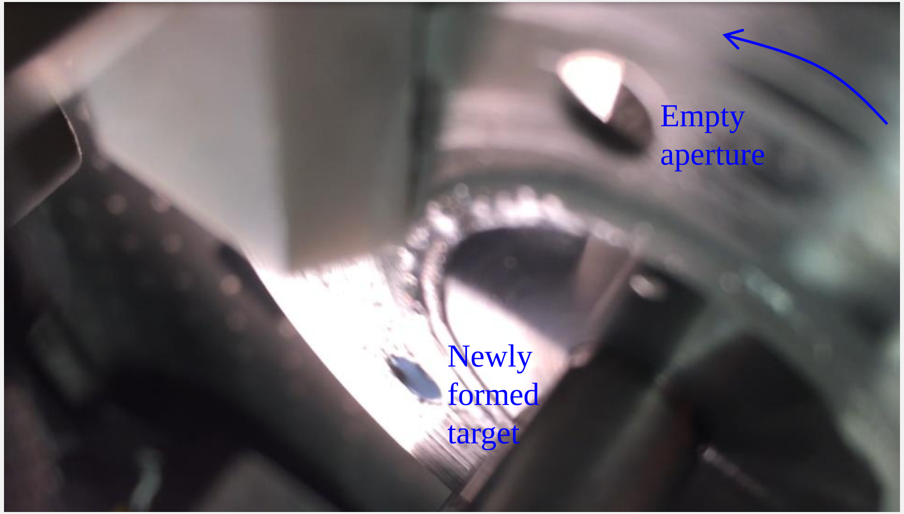


Prototype: Spinning disk for > **1 Hz**



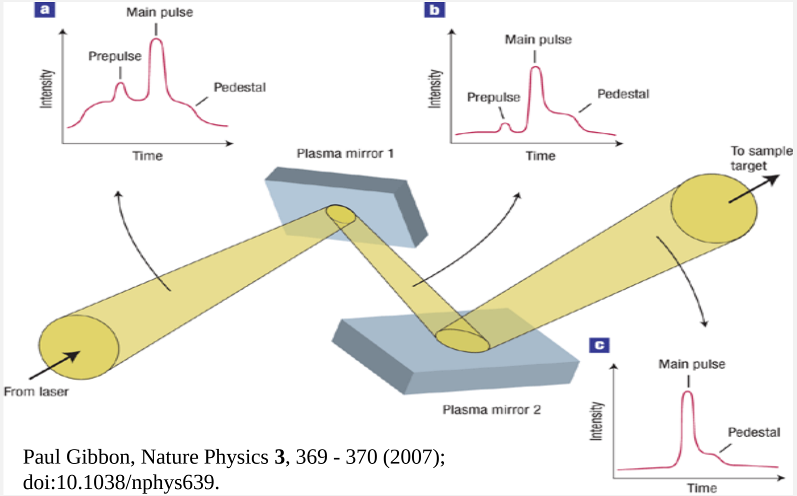


- Forms thin films reliably at 1 Hz
- 2 Hz with 90% success rate
- Sub-100 nm films depending on settings.

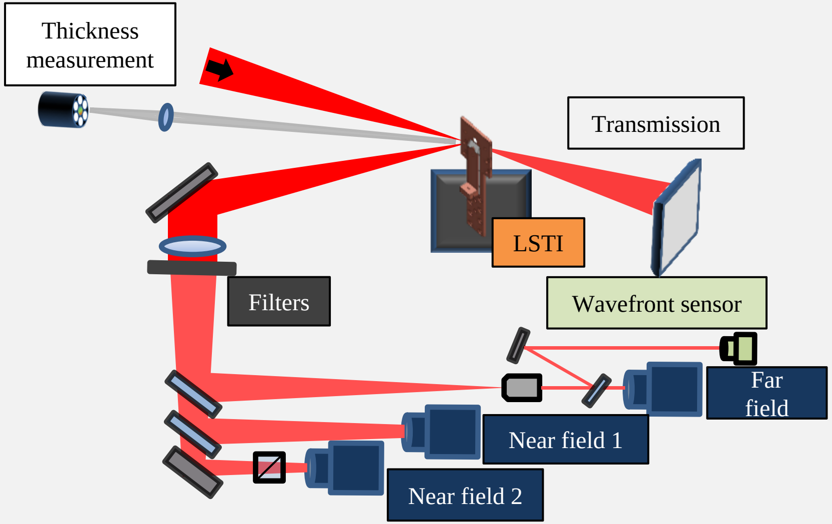


Still from a video of 1 Hz operation.
A lamp was placed below illuminating the apertures at grazing incidence. Note reflection from lower aperture.
Only one target is intended to be present at a time so collateral damage is less of an issue.

Plasma mirrors for pulse cleaning



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



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

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

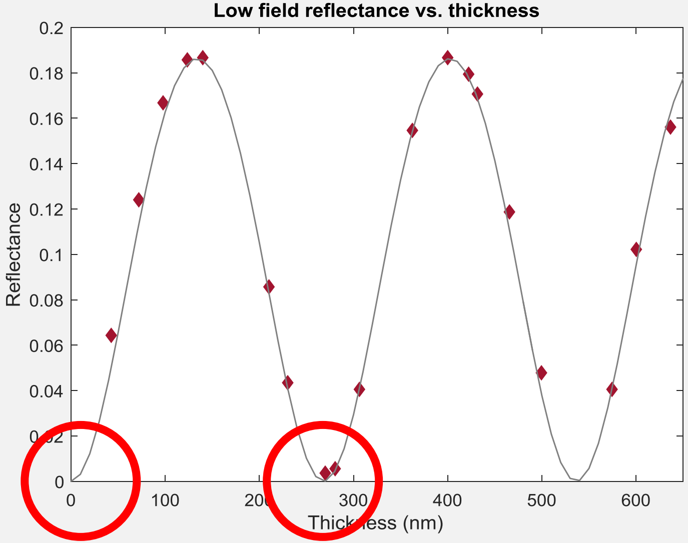
S and P polarizations on target

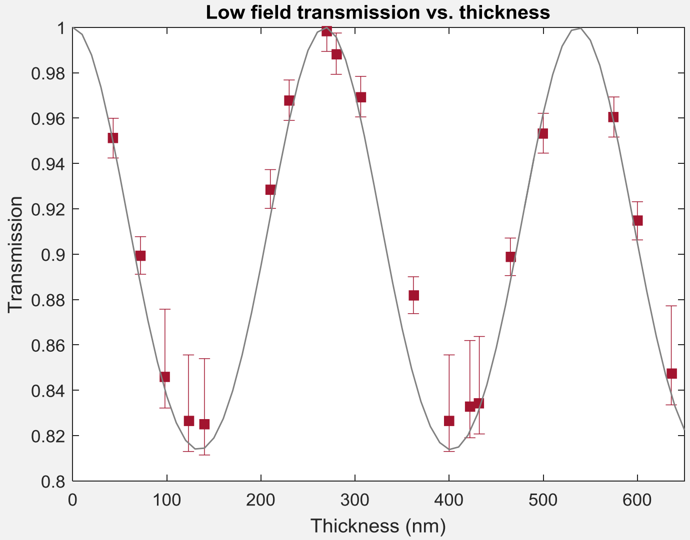
Reflection and transmission diagnostics

UPMC - A. Krygier, CLF - P. S. Foster, G. G. Scott, L. Wilson, N. Bourgeois, J. Bailey, D. Neely, R. Pattathil

Using LSTI, tune thickness to etalon minimum

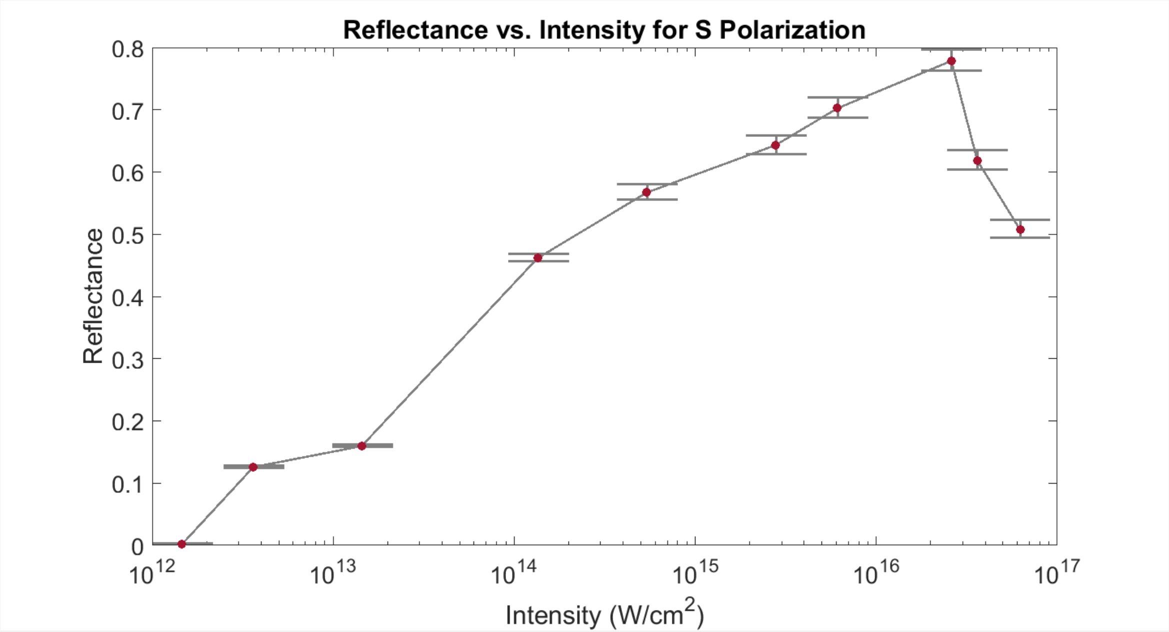
- Low intensity: ~5x10^{11} W/cm^2
- S polarization shown here
- ~15° incident angle, 800 nm light
- First reflectance minimum is ~270 nm with R < 0.2%





High field reflectance measurement

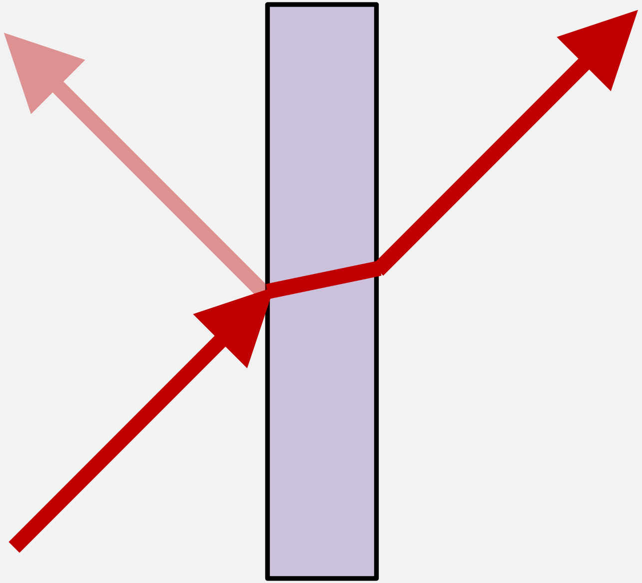
- High field reflectance of ~ 75%
- Implied contrast enhancement >350
- Similar or better than AR-coated slides, but good for prolonged, moderate repetition rates



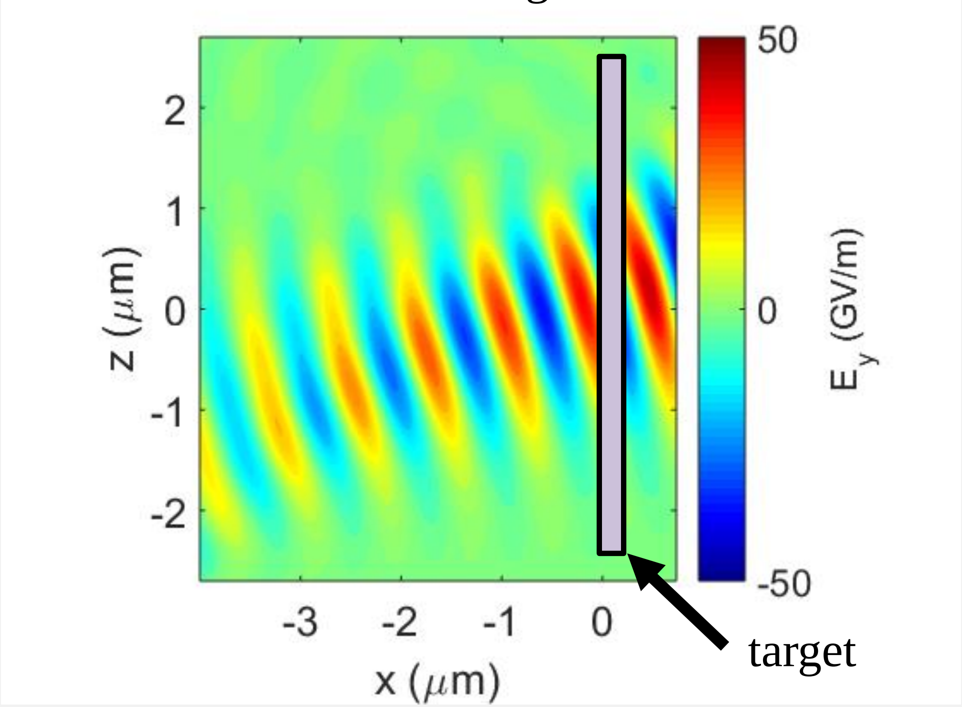
Poole, et al., Scientific Reports **6**, 32041 (2016).

PIC modeling: weak field response

Dielectric (low field)

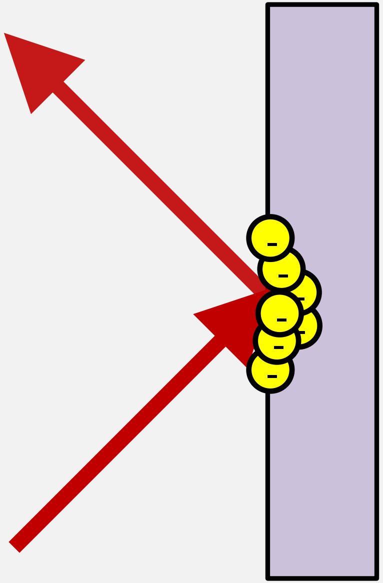


270 nm target

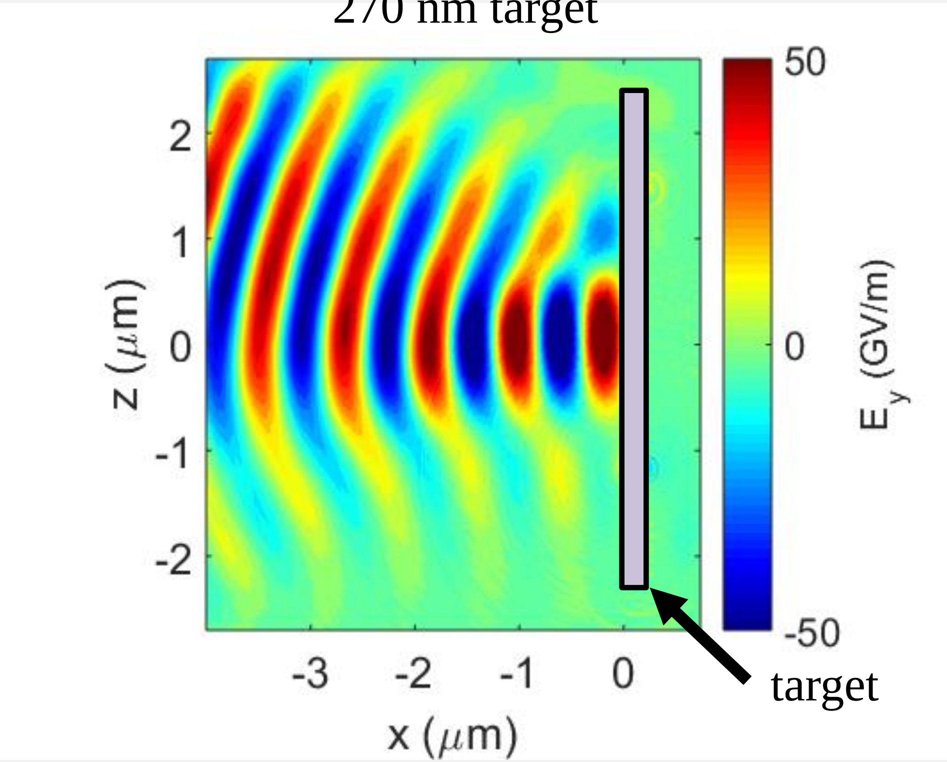


PIC modeling: strong field response

Plasma (high field)



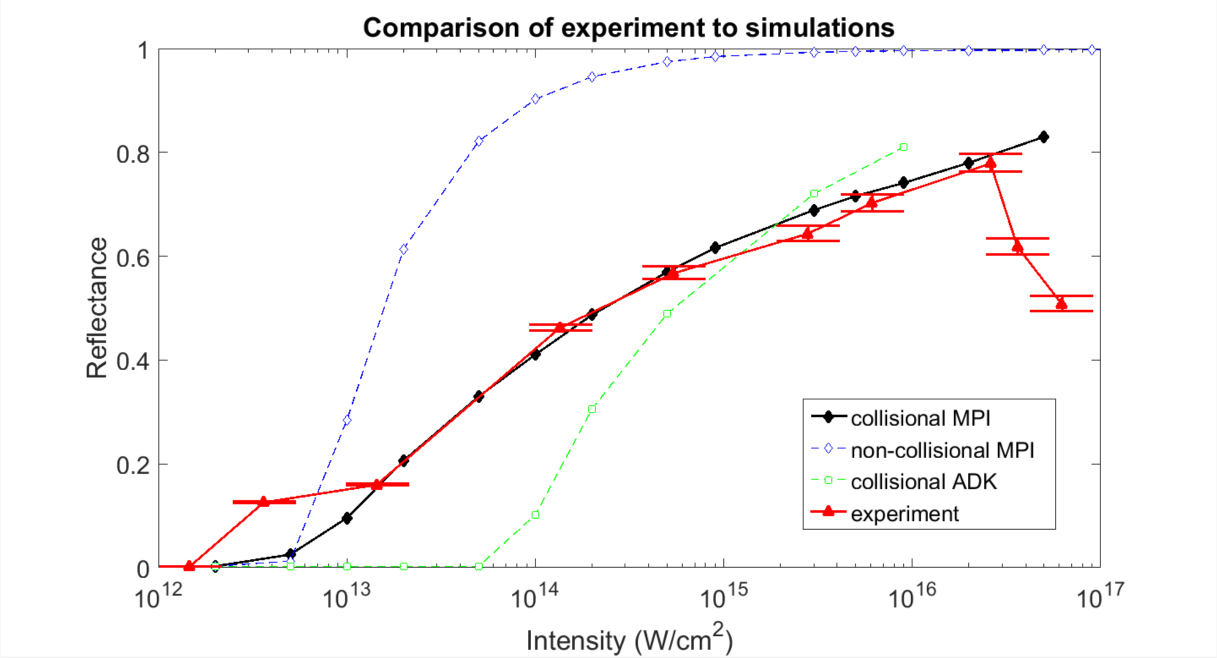
270 nm target



High field reflectance measurement

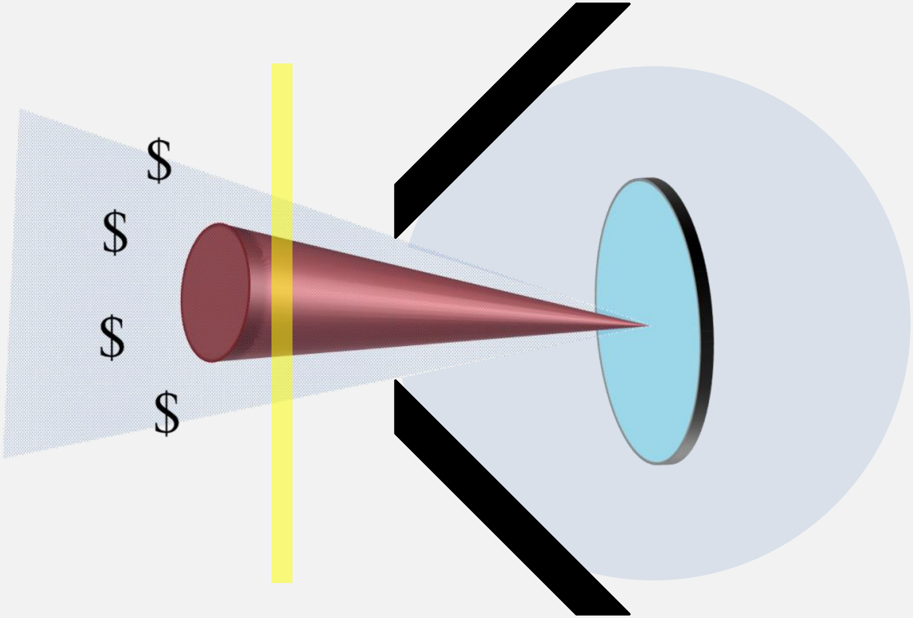
- LSP PIC simulation
- Target starts cold with neutral atoms
- Dielectric model
- MPI and collisionality included

Ginevra Cochran

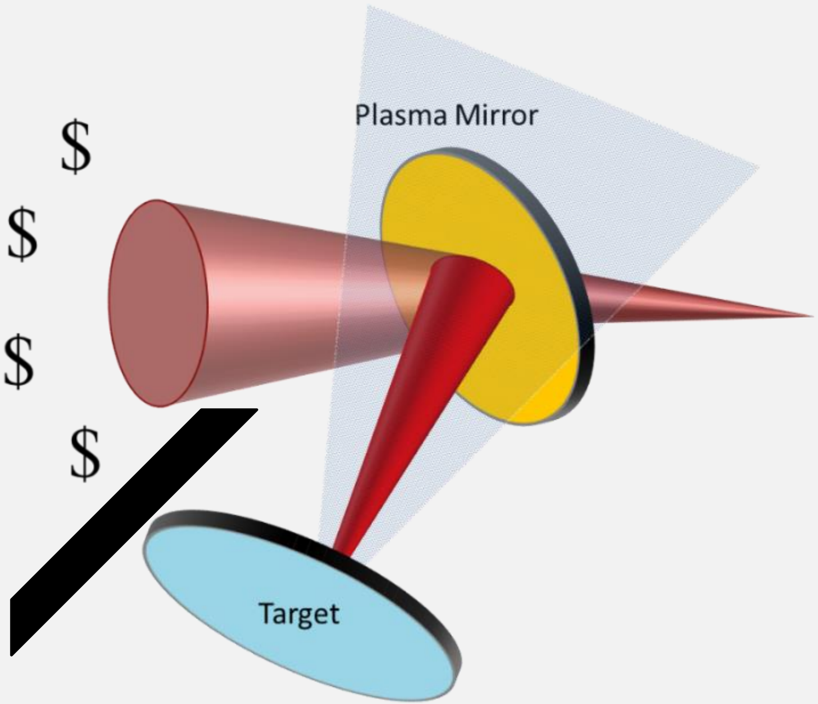


Poole, et al., Scientific Reports **6**, 32041 (2016).

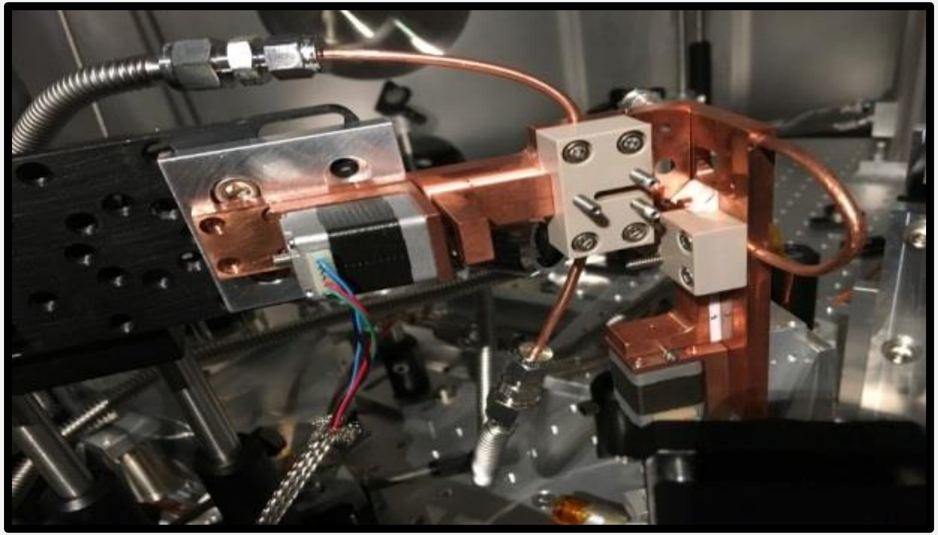
Reformable plasma mirrors for debris control

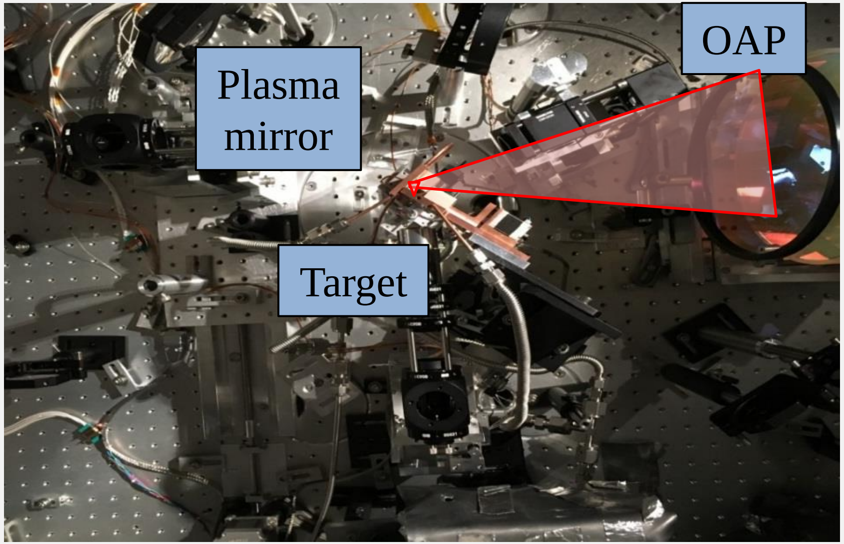


Membrane



In-line plasma mirror for contrast enhancement and debris control



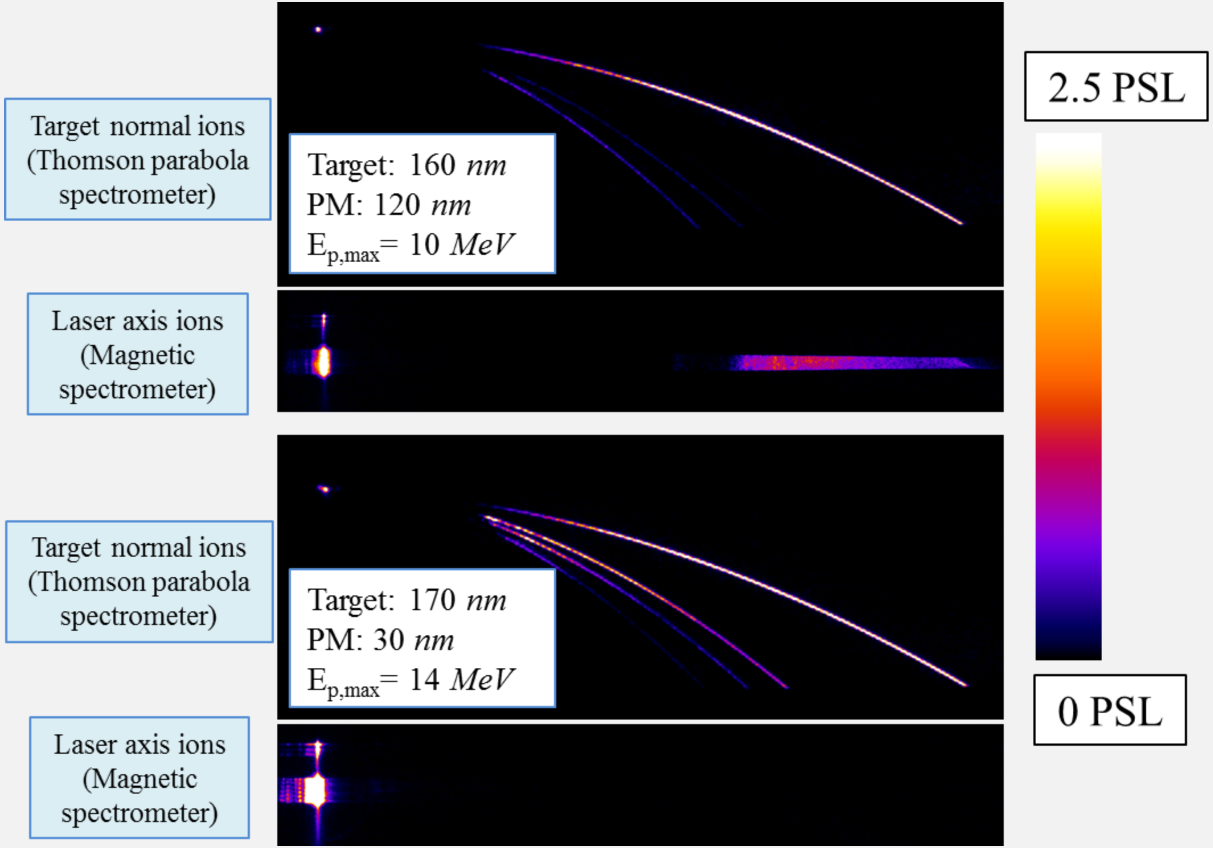


- 1 meter focal length allows plasma mirror installation just before target
- While enhancing contrast, turning beam away from OAP protects it as well
- Key: liquid crystal plasma mirror is renewed on each shot, so prolonged debris-free operation is possible

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

G. G. Scott *et al.*, New Journal of Physics **17**, 033027 (2015)

In-line plasma mirror for contrast enhancement and debris control



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
  - 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 25 MeV protons using 2-5 J short pulse
- Demonstrated LSTI plasma mirrors – propose a debris handling strategy
- 1 Hz prototype operational for thinnest films
- Significant limitations remain – considerable development still required