Optimized ion acceleration and secondary radiation generation with liquid crystal targets

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CEA

THE OHIO STATE UNIVERSITY

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Outline

1) Motivation—ion acceleration
2) Liquid crystals – a new target medium
3) Linear Slide Target Inserter (LSTI)
4) Liquid crystal plasma mirrors
5) Conclusion

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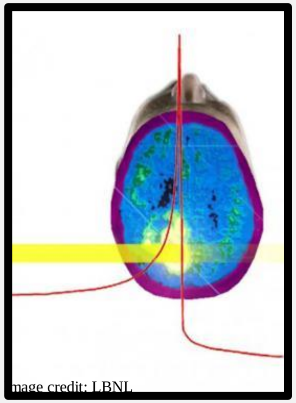
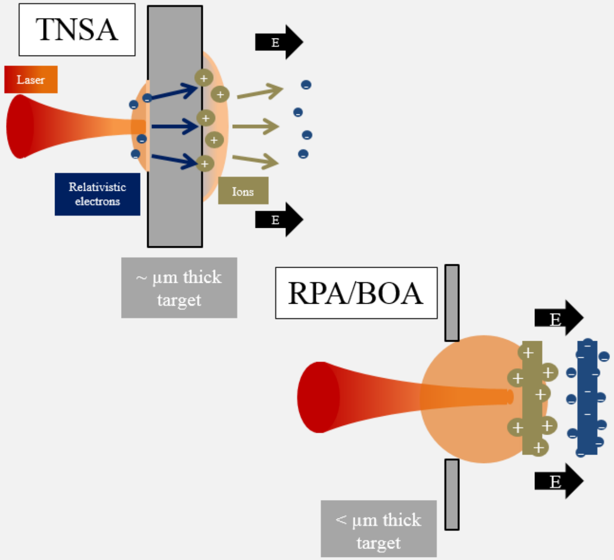
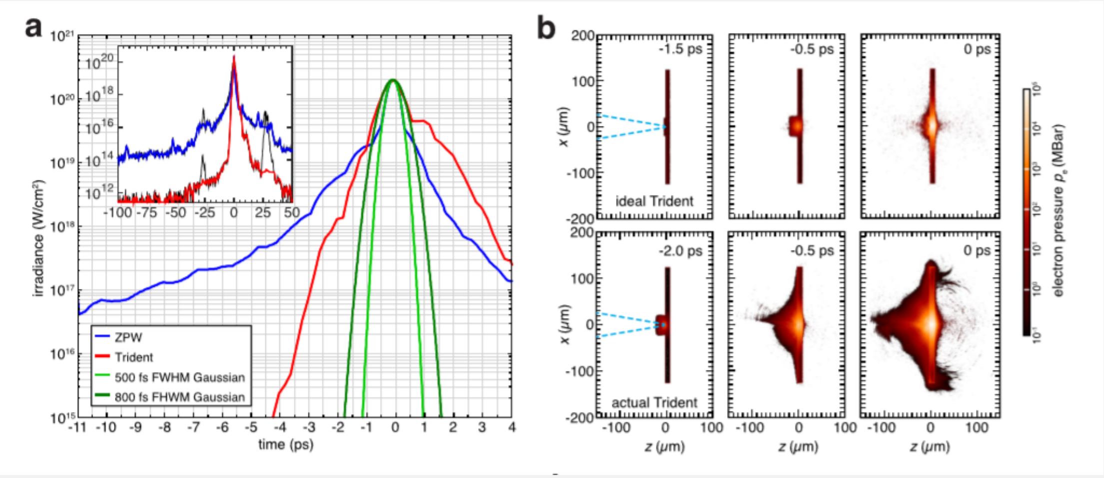
Laser-based ion acceleration: applications and challenges

- Applications: Ion cancer therapy, proton radiography, neutron imaging, *et al.*
- New acceleration mechanisms aren't yet well understood
- Proton energy scaling question—onset of instability?
- Onset and details of relativistic transparency
- Critical parameters:
  - Target thickness
  - Laser contrast







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

Current ion acceleration limitations

- Frontier of ion acceleration requires high quality laser
  - High intensity
  - Good focal spot
  - Proper alignment
  - **High contrast**
- Overall, need parameter scan:
  - Energy, pulse duration, spot size, contrast
  - **Target thickness**
    - Coarse thickness variability to choose acceleration mechanism
    - Fine thickness tuning to optimize acceleration for given laser parameters

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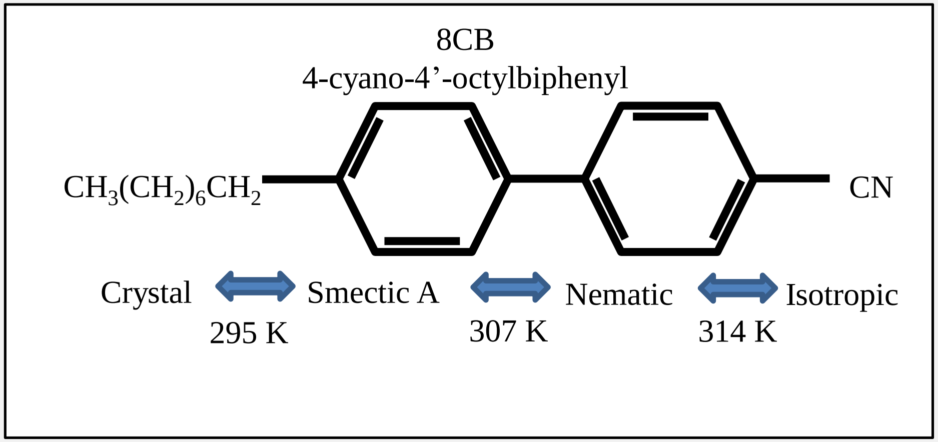
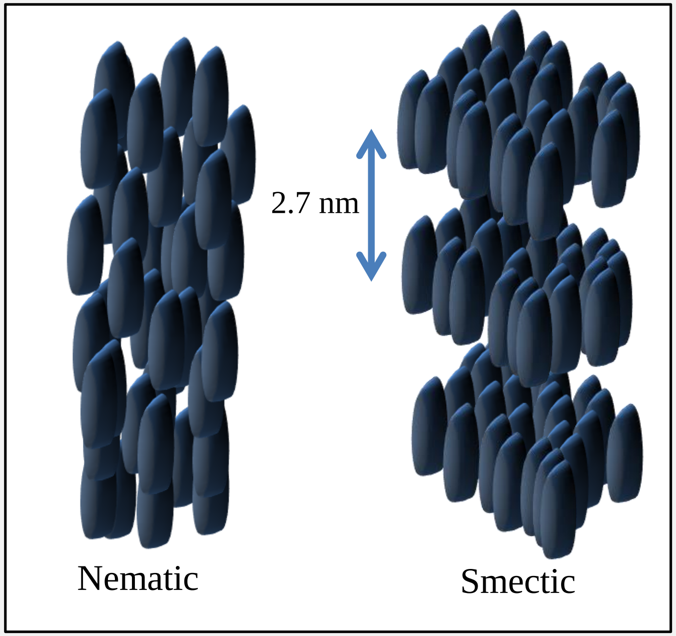
A new medium for HEDP: liquid crystals

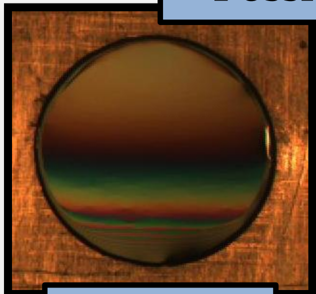




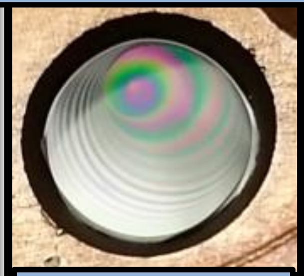
- Characterized by additional phases between solid and liquid
- Phases distinguished by molecular orientation and ordering
- Smectic phase forms films in stacked sheets **~3 nm per layer**
- Vapor pressure well below **10^{-6} Torr**
- Surface tension in smectic phase forms freely suspended film
- Films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

Tuning thickness requires controlling multiple parameters

Possible non-uniform films



Vertical film



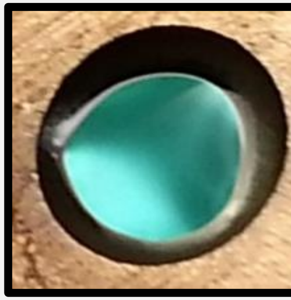
Meniscus shift

Mobile island

Control

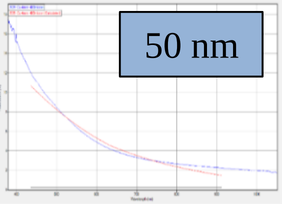
Temperature
Volume

Surface polish
Wiper speed

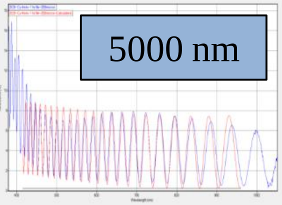


Coarse control: temperature, volume

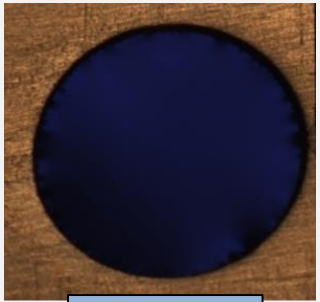
- Copper frame with resistive heaters
- Volume between 0.1 – 2 μL



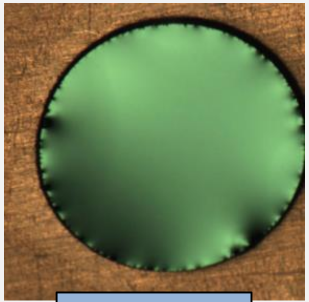
50 nm



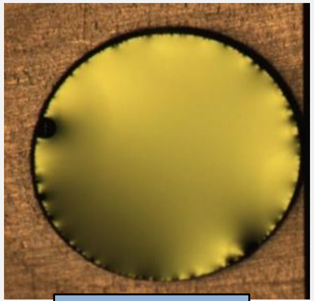
5000 nm



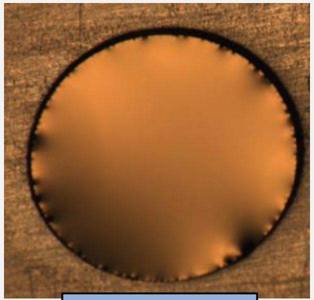
190 nm



260 nm



300 nm



330 nm

Fine control:

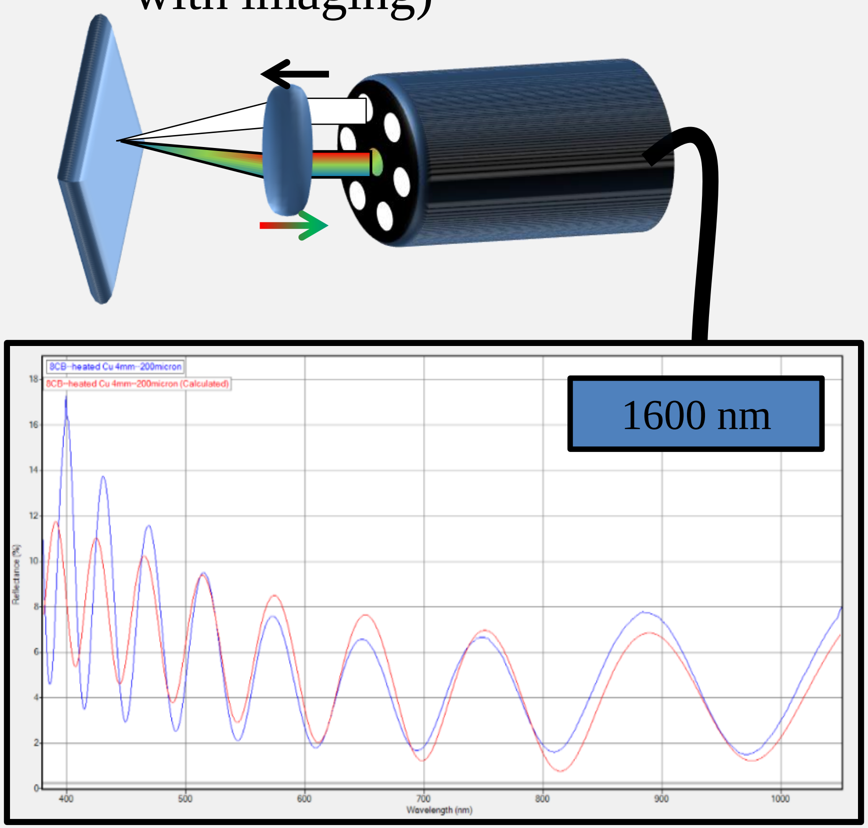
- Frame and wiper polish to mirror finish
- Wiper speed

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

Film characterization—thickness and position

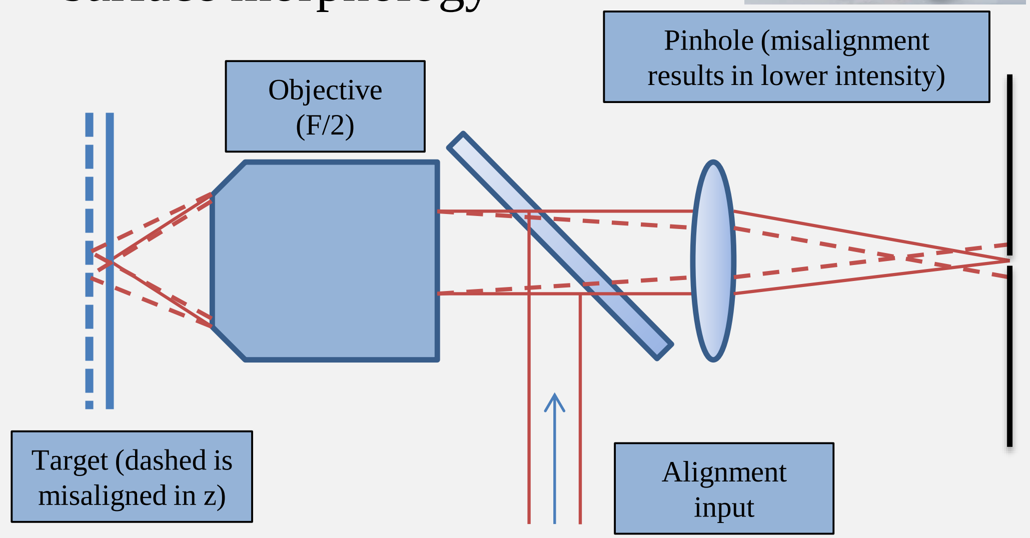
Filmetrics commercial unit

- 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

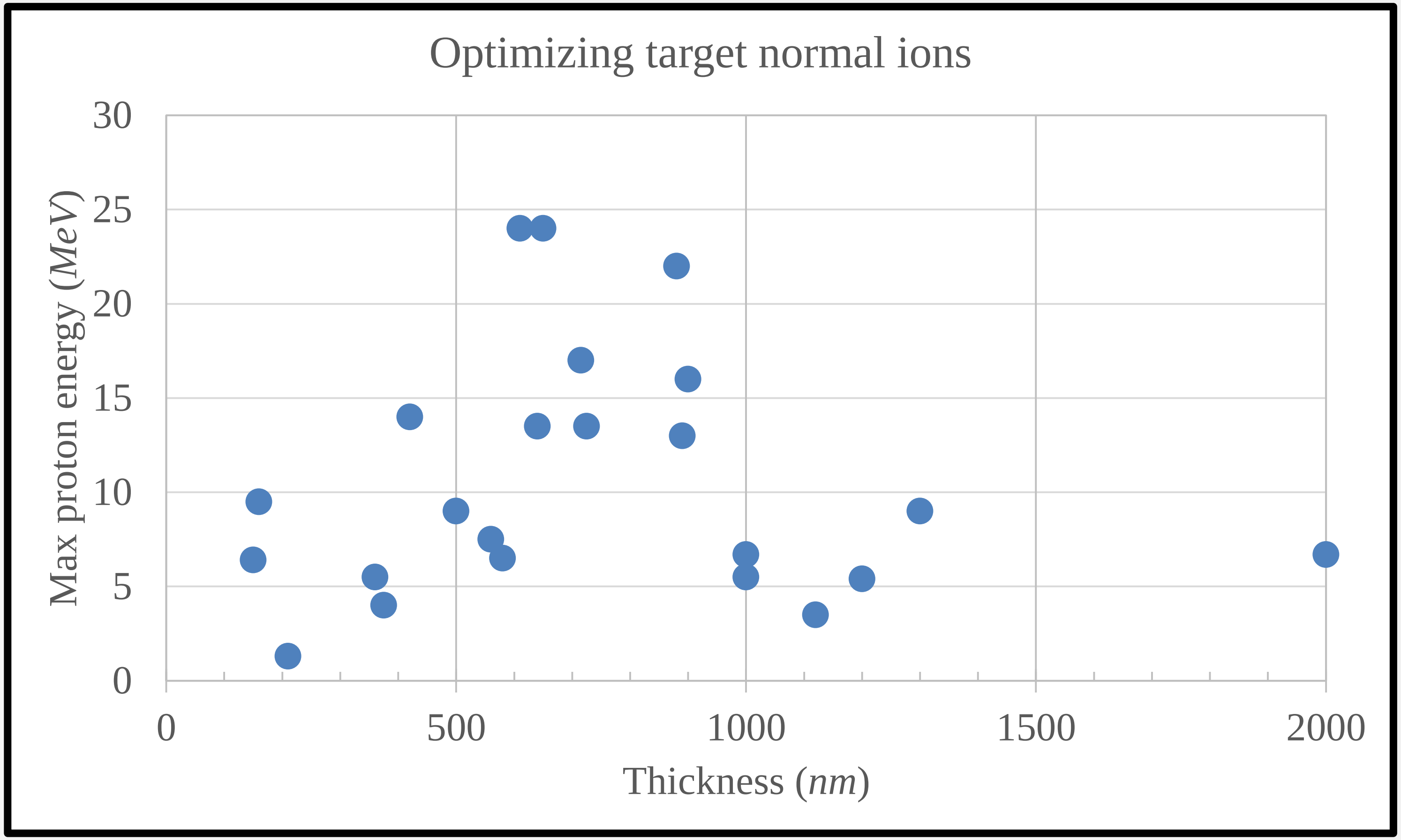


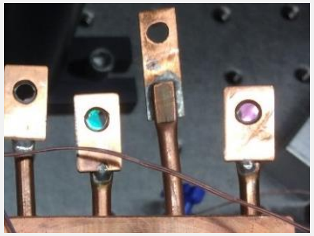
C. Willis et al., Review of Scientific Instruments **86**, 053303 (2015)

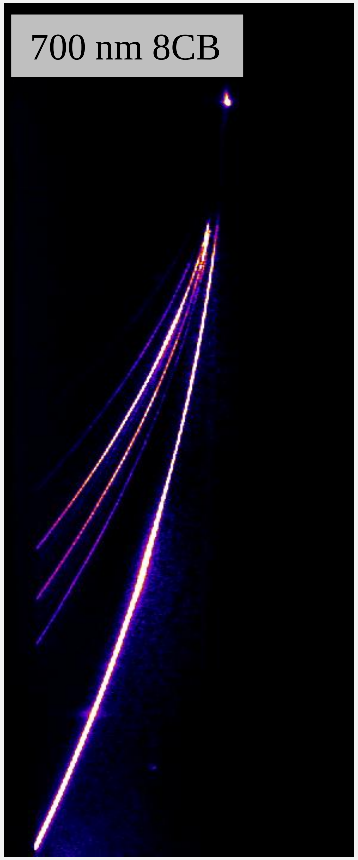
Ion acceleration thickness scan using Scarlet

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

5 J on target, ~5×10^{19} W/cm^2







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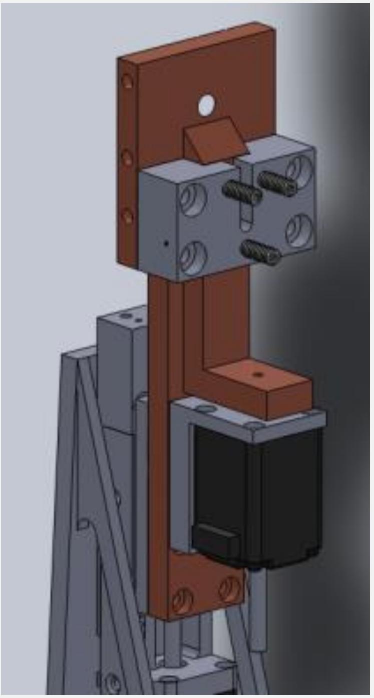
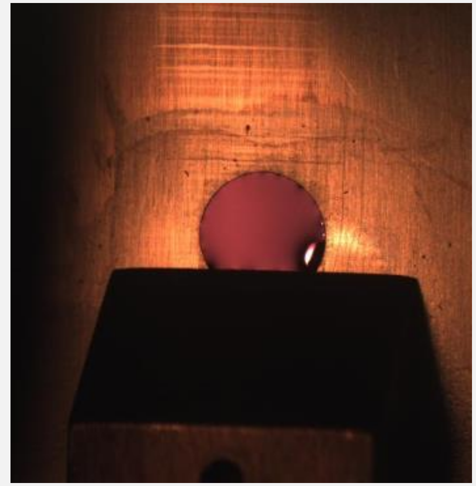
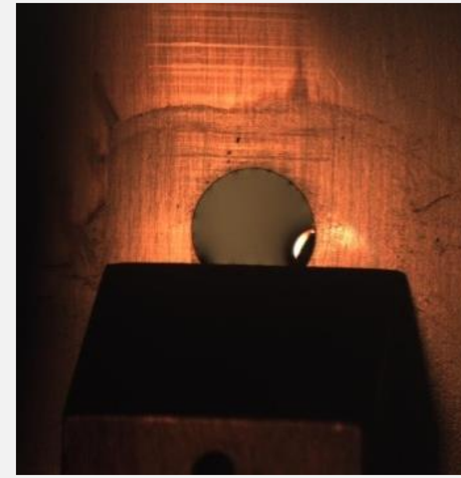
LSTI: linear sliding target inserter

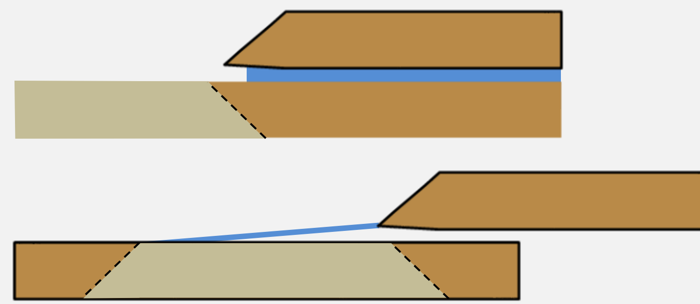






810 nm **2200 nm**

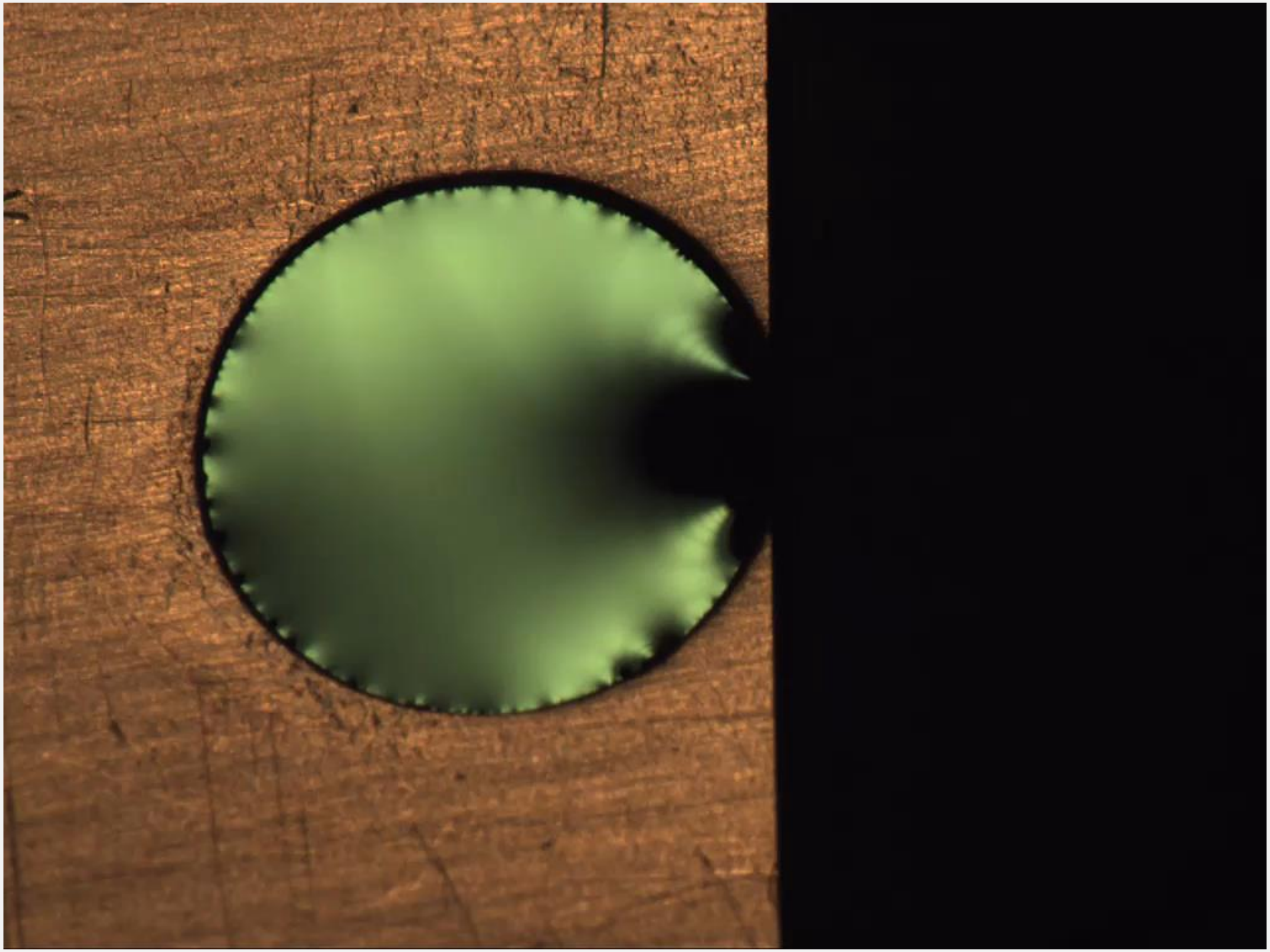
repetitive formation in vacuum



- 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**

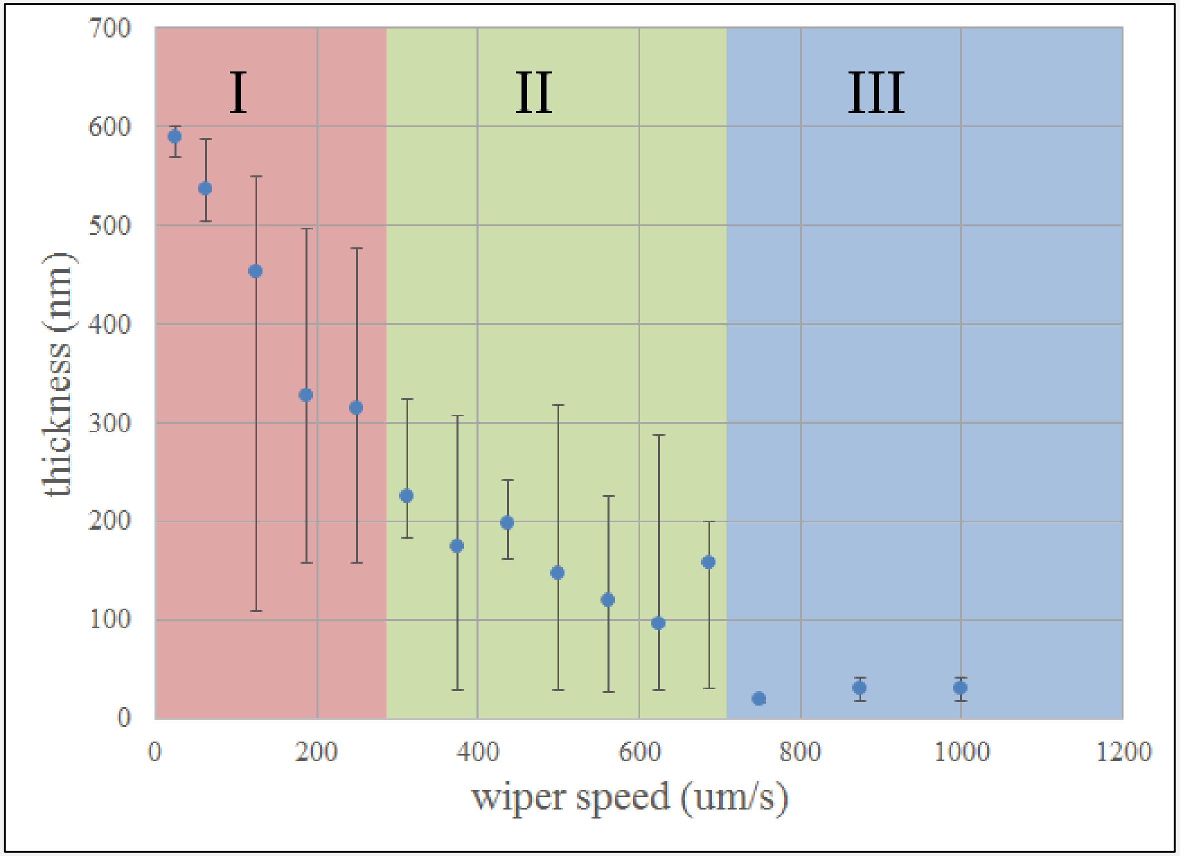
Submitted, http://arxiv.org/abs/1507.08259

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—**ideal for 1/min shot rate**



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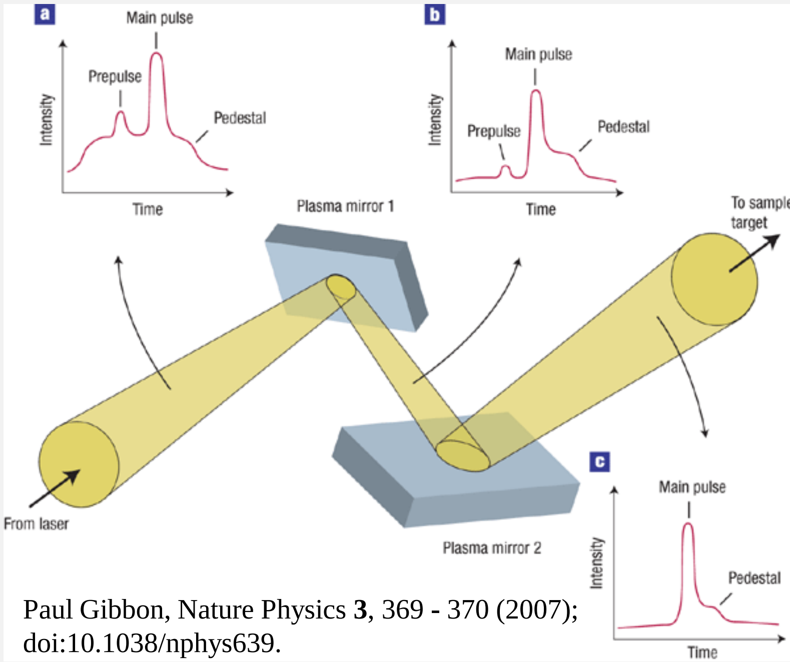
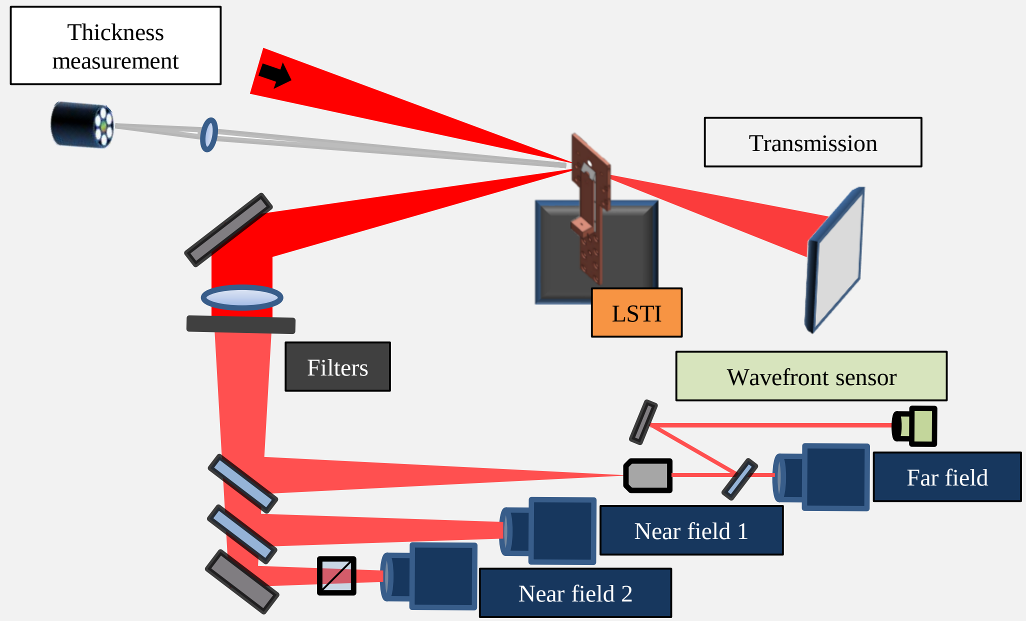
Plasma mirrors for pulse cleaning



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

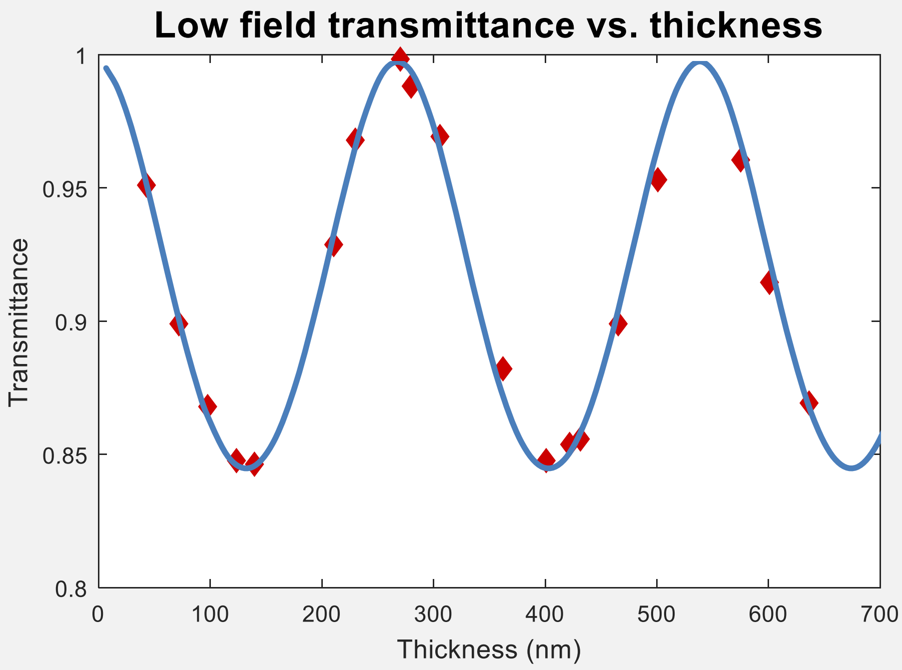
F/7 focus onto plasma mirror

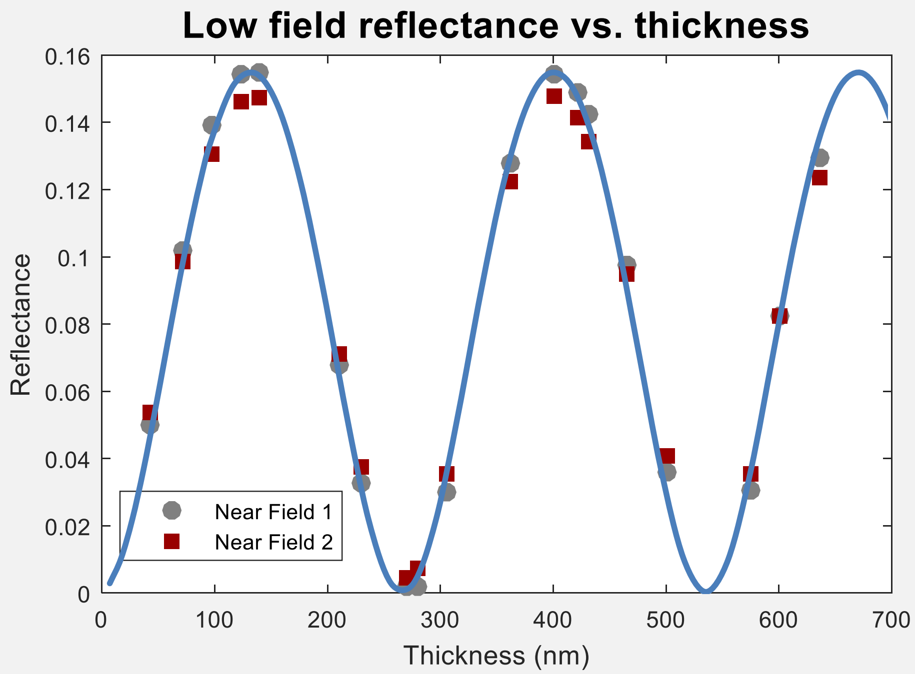
S and P polarizations on target

Reflection and transmission diagnostics

Using LSTI, tune thickness to etalon minimum

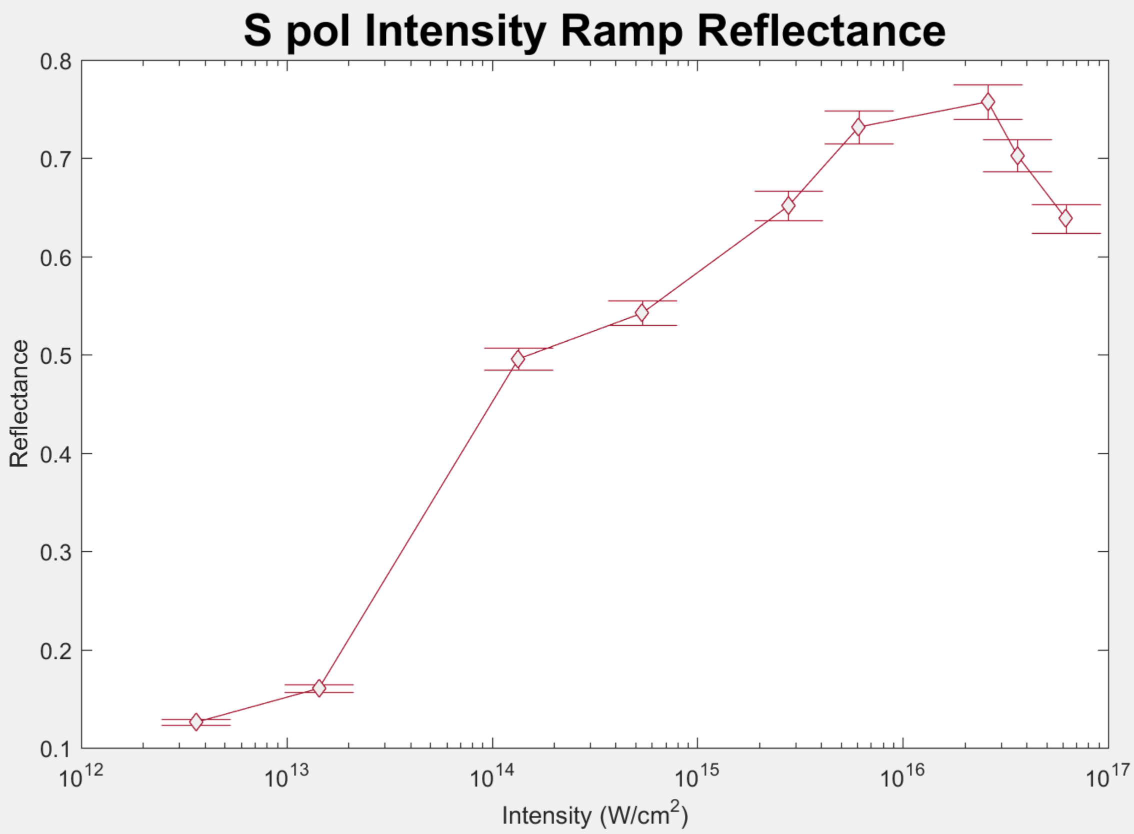
- Low intensity: ~5x10^{11} W/cm^2
- S polarization
- ~15° incident angle, 800 nm light
- First reflectance minimum is ~270 nm with R < 0.2%

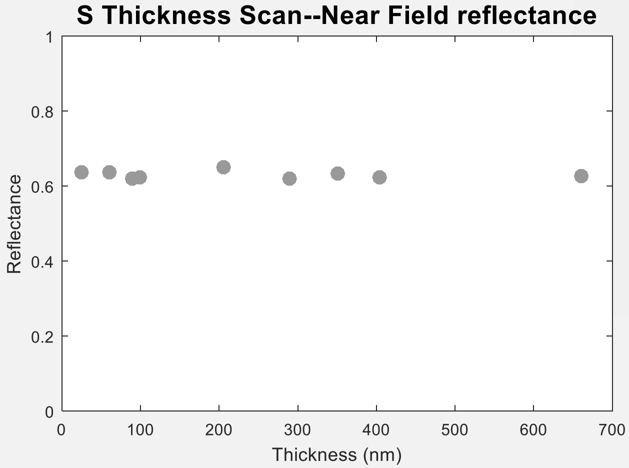




Intensity ramp

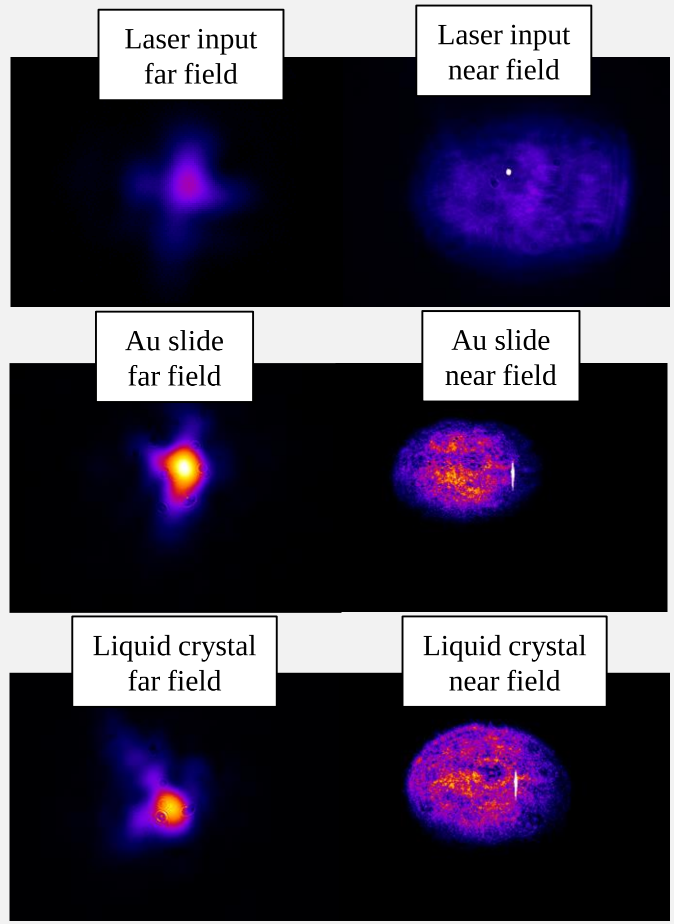
- Initial results: reflectance of ~ 75%
- Implied contrast enhancement >350
- P-polarization results lower by ~10%

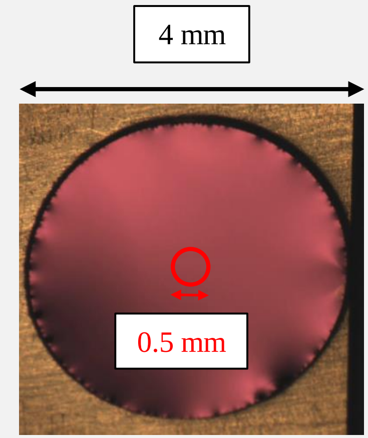


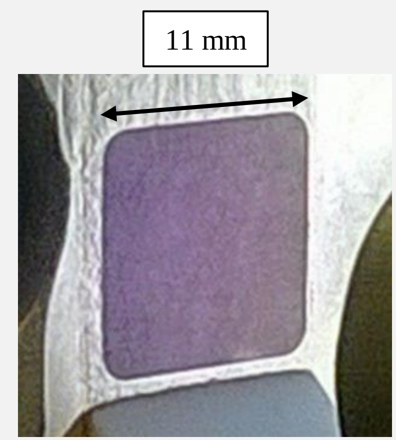


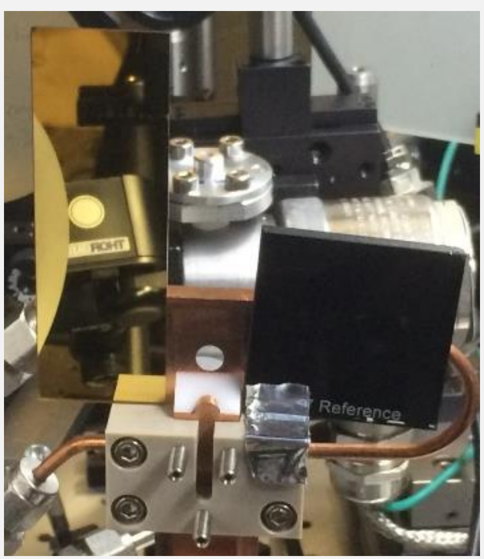
Good mode preservation in weak field limit

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

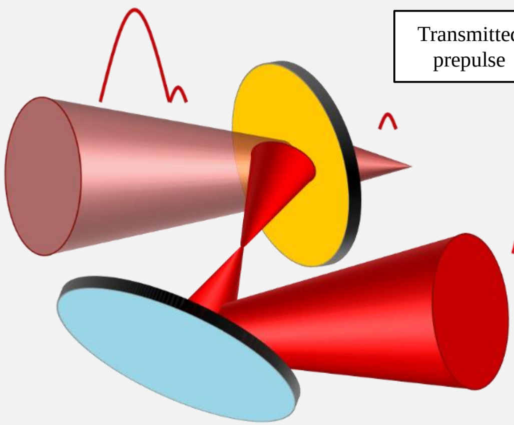


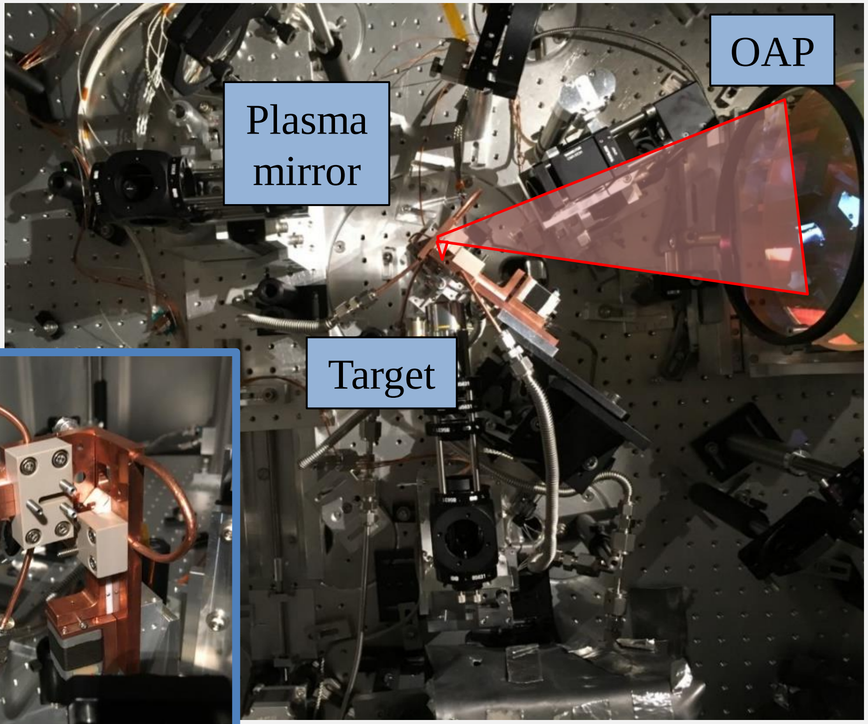


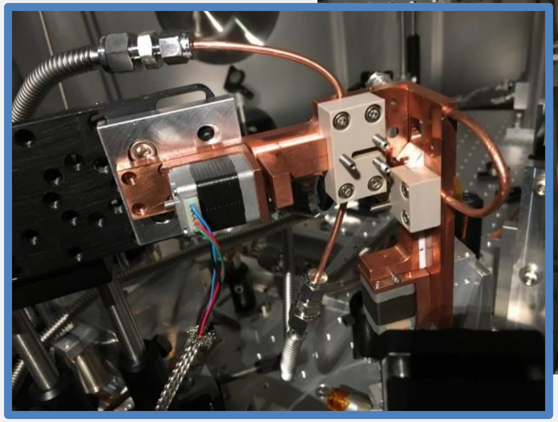




In-line plasma mirror for contrast enhancement and debris control







- 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)

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Conclusion

Ion acceleration studies need high quality, clean laser

- Parameter scan necessary to fully understand acceleration mechanisms, relativistic transparency, and optimization

Liquid crystals provide important thickness tunability

- Films formed between 10 nm and over 50 µm, allowing access to full range of ion acceleration mechanisms
- Fine thickness control allows optimization of acceleration, parameter scan investigation
- Liquid crystals function as low-cost plasma mirrors for contrast enhancement and debris control
- We have developed a complete solution (formation and characterization) that works well for shot/minute type experiments.