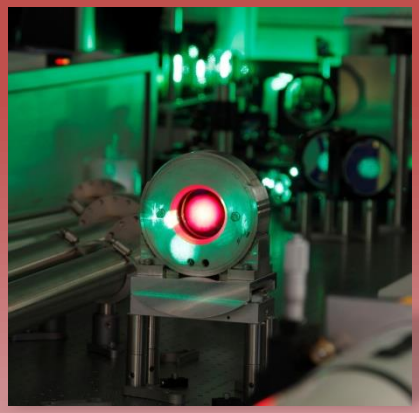
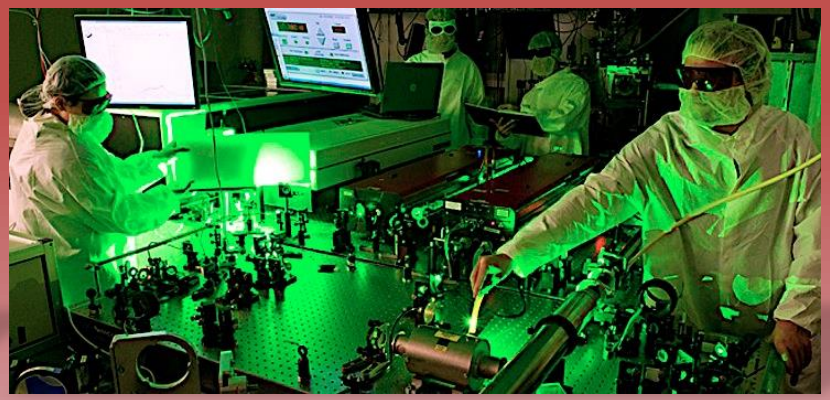
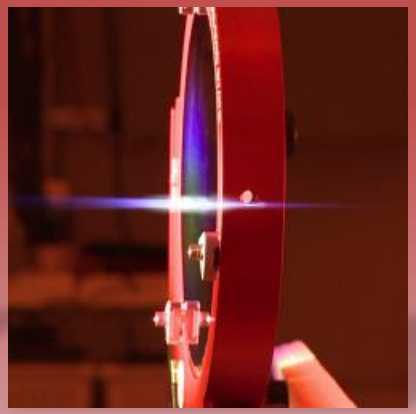
High Energy Density Physics Program At The Scarlet Laser Facility

Douglass Schumacher

Richard Freeman (PI)







Stewardship Science Academic Programs Symposium

February 17-18, 2016

National Nuclear Security Administration

Outline

1) Motivation and
   Review liquid crystal technology
2) Plasma mirrors - experiment
3) Plasma mirrors - simulation
4) Conclusion

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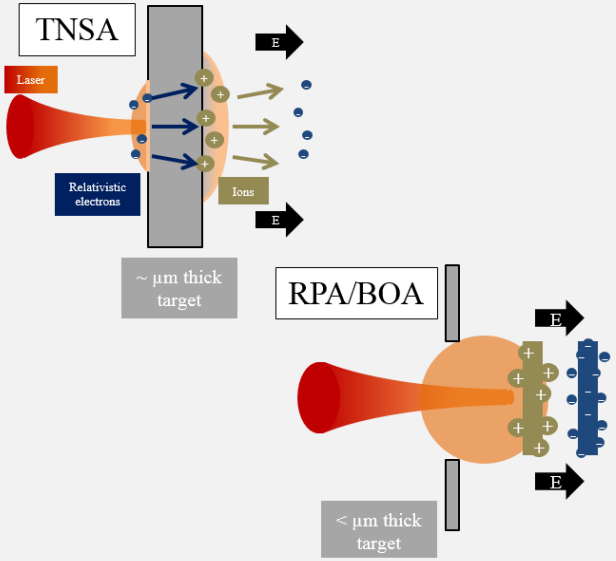
Patrick Poole

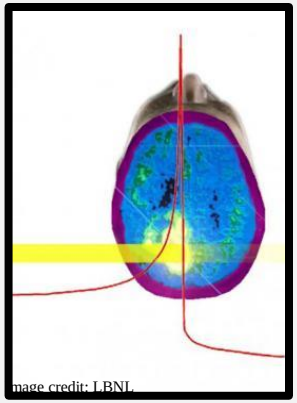
Chris Willis

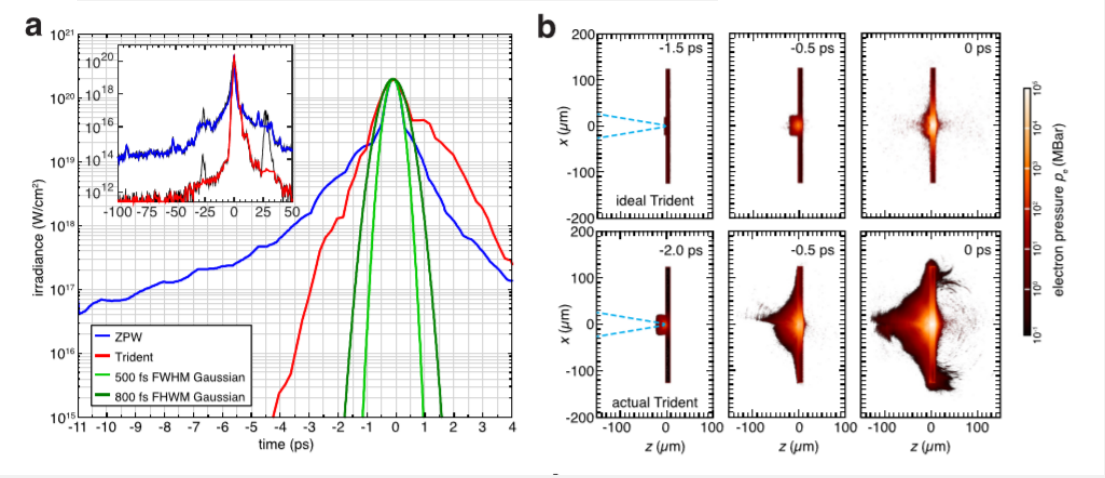
Ginevra Cochran

Fundamental laser-plasma interaction in dense targets

- Onset and effect of relativistic transparency
- Particle acceleration mechanisms still unfolding story for solid targets
- Applications: Proton radiography, ion cancer therapy, neutron imaging.
- Critical parameters:
  - Target thickness
  - Laser contrast



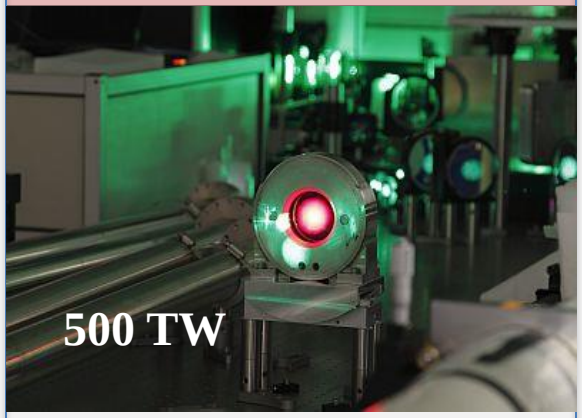




M. Schollmeier *et al.*, Physics of Plasmas **22**, 043116 (2015)

Laser facilities keep improving

Scarlet Laser



<u>Specifications</u>

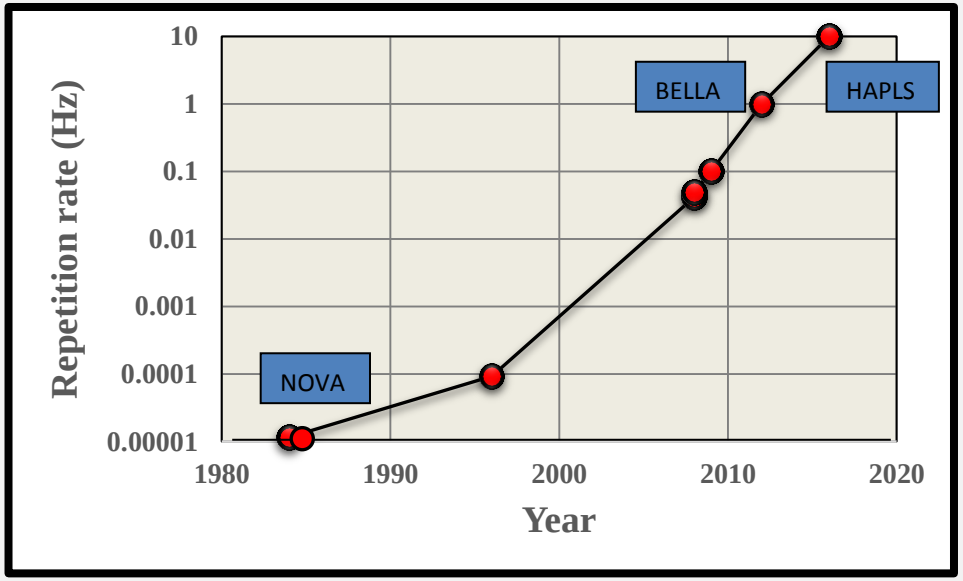
15 J energy per pulse

30 fs pulse duration

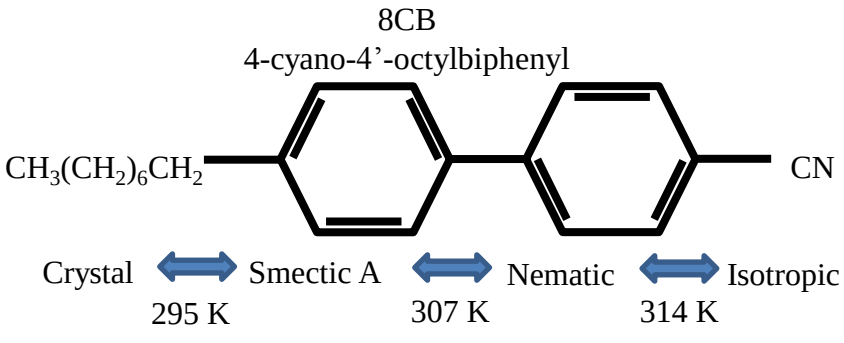
Center wavelength at 815 nm

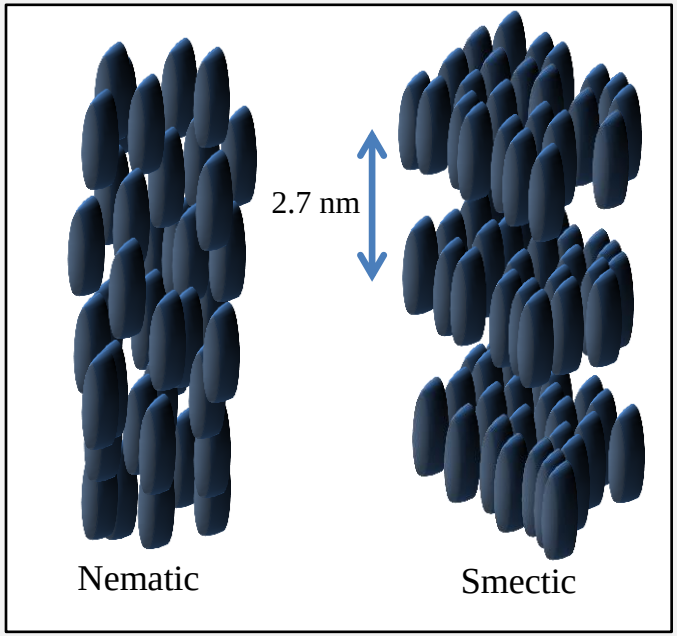
1 shot per minute

Intensity of >5 x 10^{21} W/cm^2

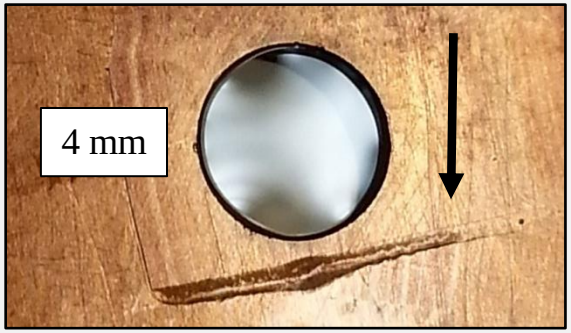


A new medium for HEDP: liquid crystals

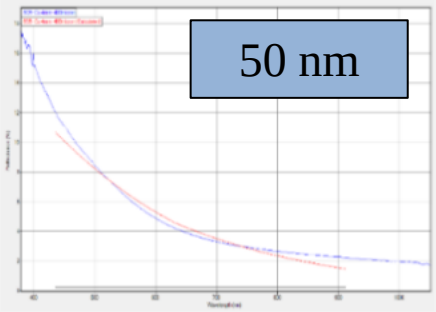


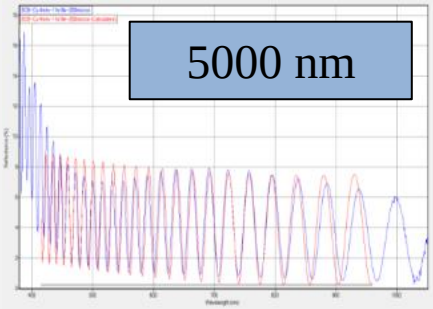


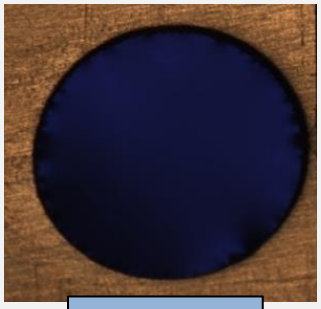
- Characterized by additional phases between solid and liquid
- Phases distinguished by molecular orientation and ordering
- Smectic phase forms films in stacked sheets **~3 nm per layer**
- Vapor pressure well below **10^{-6} Torr**
- Surface tension in smectic phase forms freely suspended film
- Films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



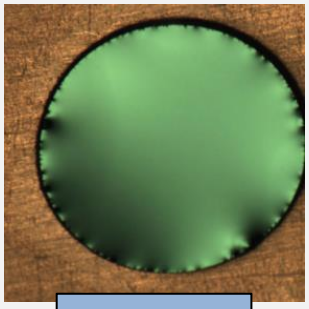
On demand film thickness control (with care)



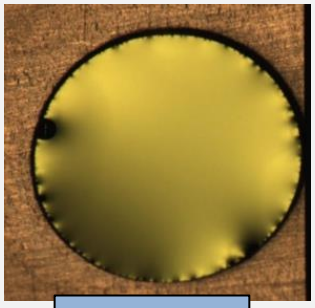




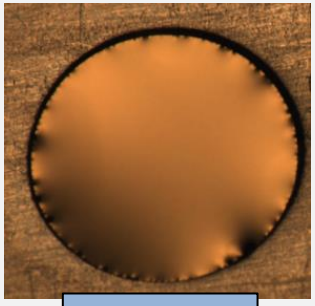
190 nm



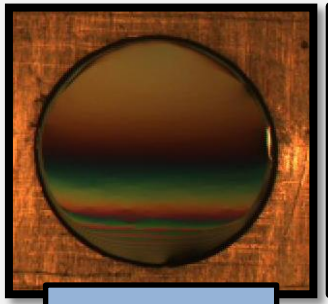
260 nm



300 nm



330 nm



Vertical film

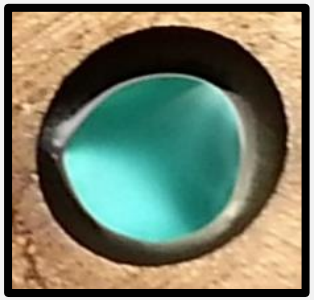
Meniscus shift

Mobile island

Control

Temperature
Volume

Surface polish
Wiper speed

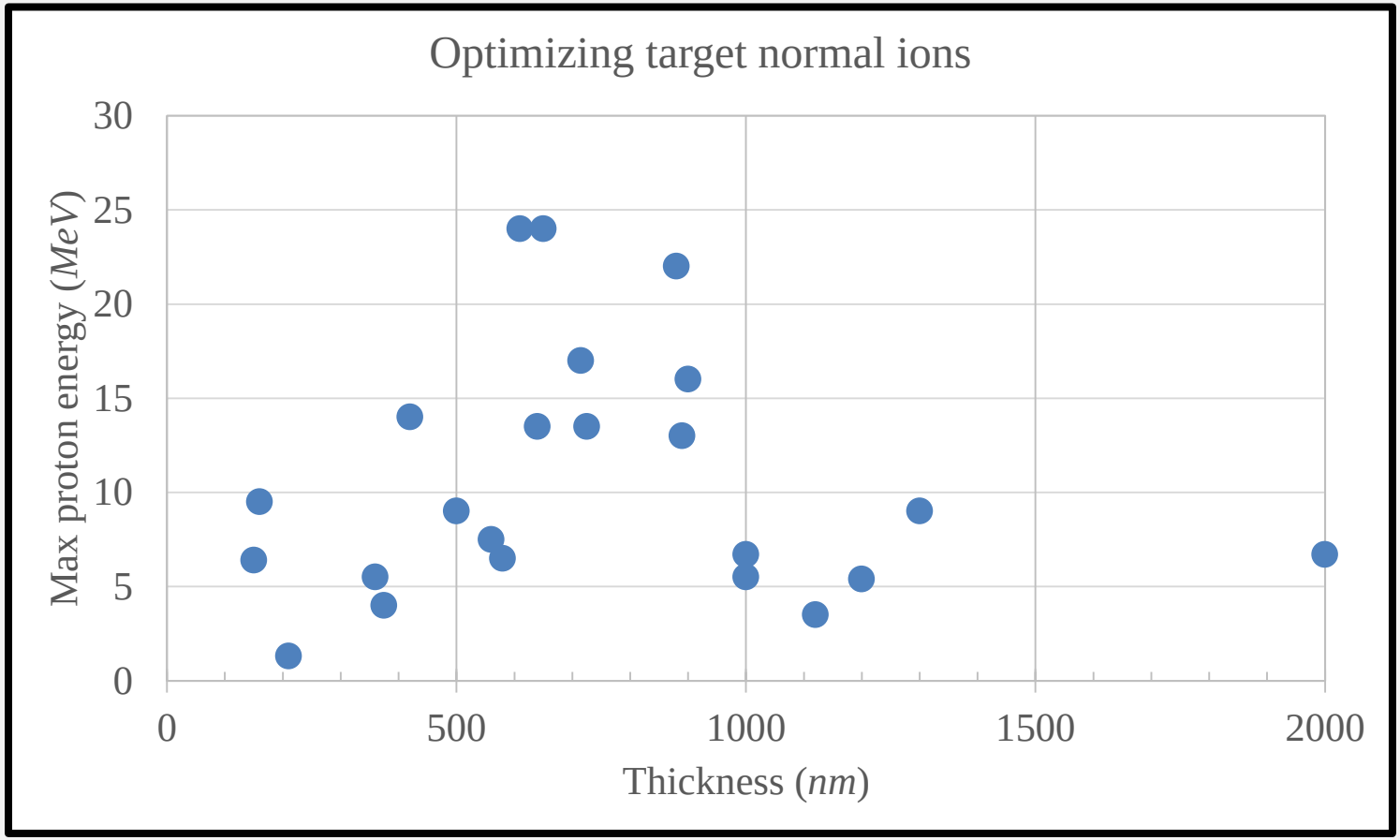


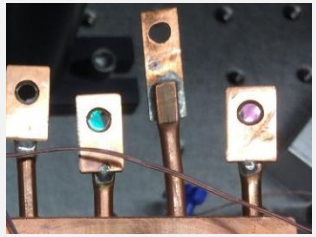
P. L. Poole, et al., Physics of Plasmas 21, 063109 (2014).

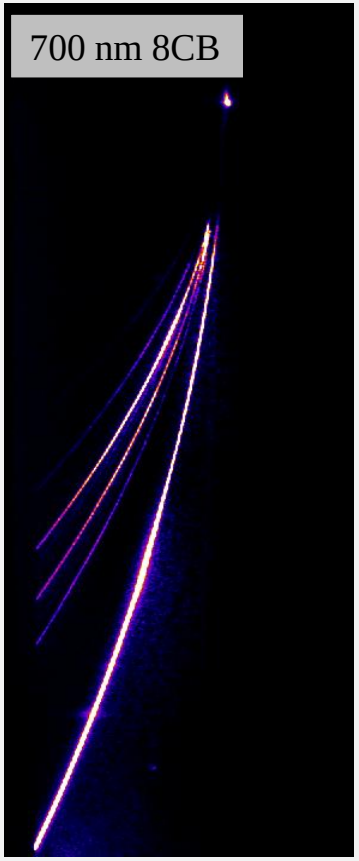
Ion acceleration thickness scan using Scarlet

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

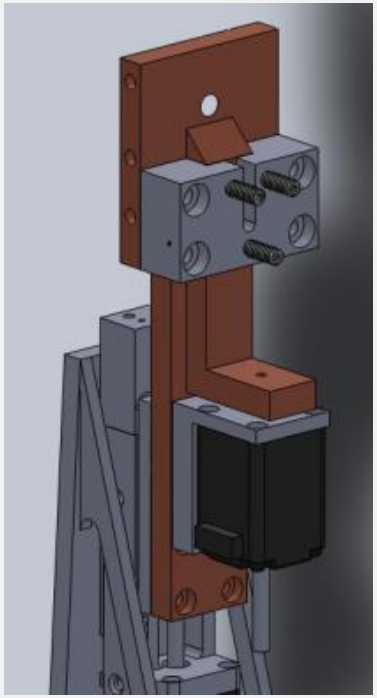
5 J on target, ~5x10^{19} W/cm^2

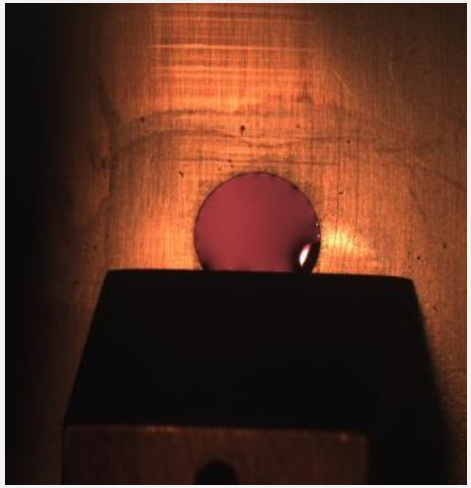


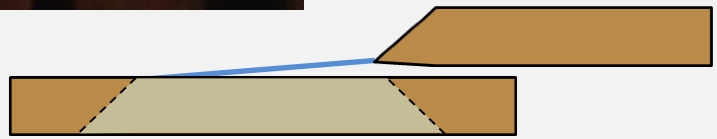




LSTI: linear sliding target inserter







- **10 nm to >40 µm**
- **Better than 2 µm RMS positioning repeatability**
- **$15 = 1 mL = well over 1000 films**
- **seconds/film for thinnest films**
- **BUT poor thickness reproducibility**

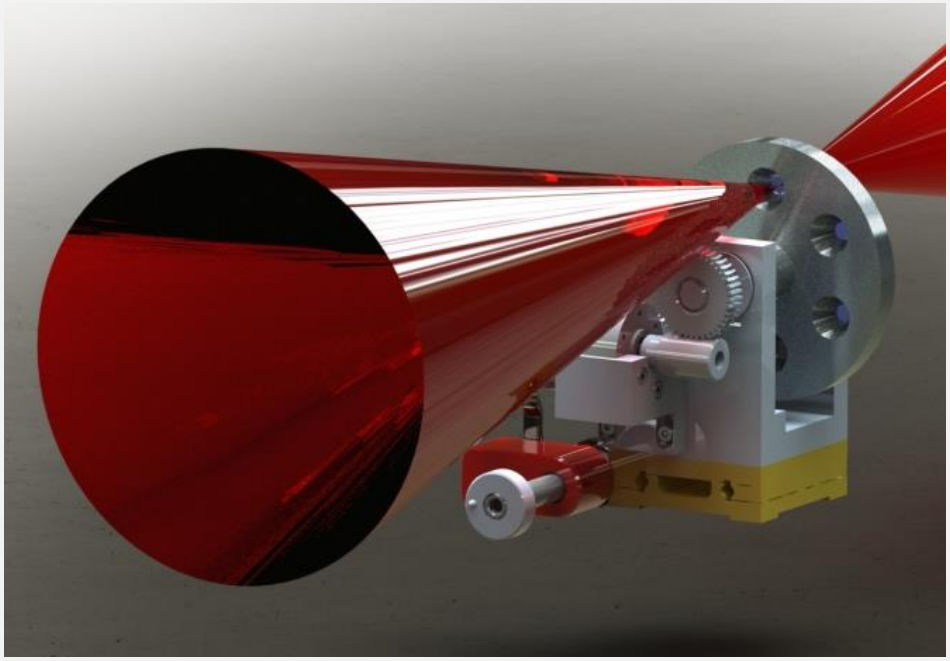
P. L. Poole, et al., Physics of Plasmas 21, 063109 (2014).

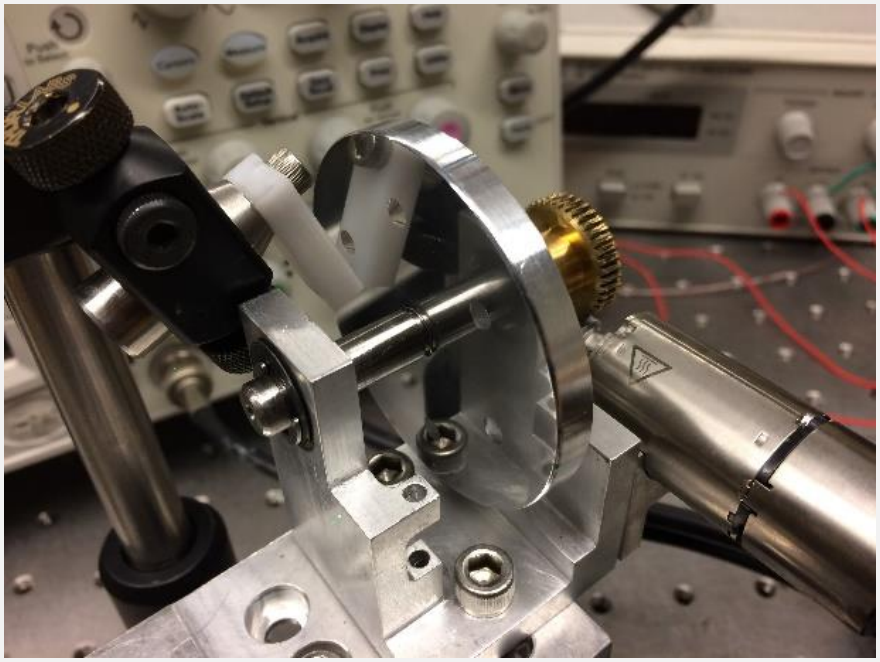
C. Willis et al., Review of Scientific Instruments **86**, 053303 (2015)

LSTI paper submitted, http://arxiv.org/abs/1507.08259

Patents pending

Rotary geometry – the Spinning Disk Inserter





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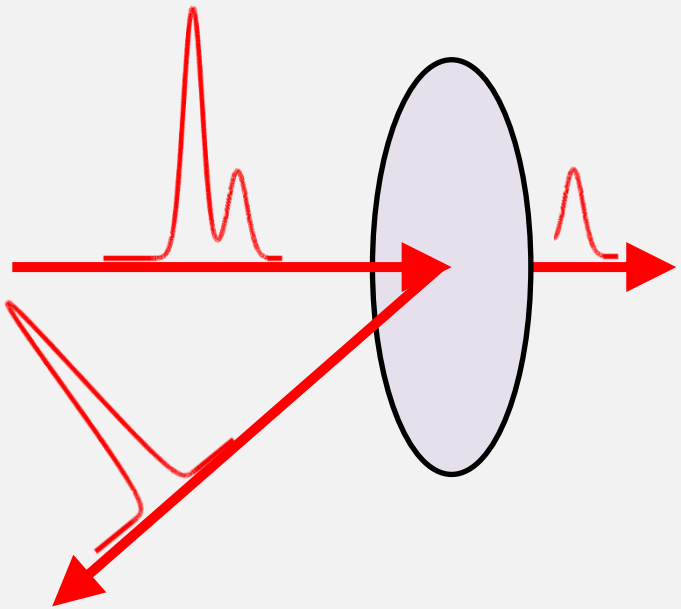
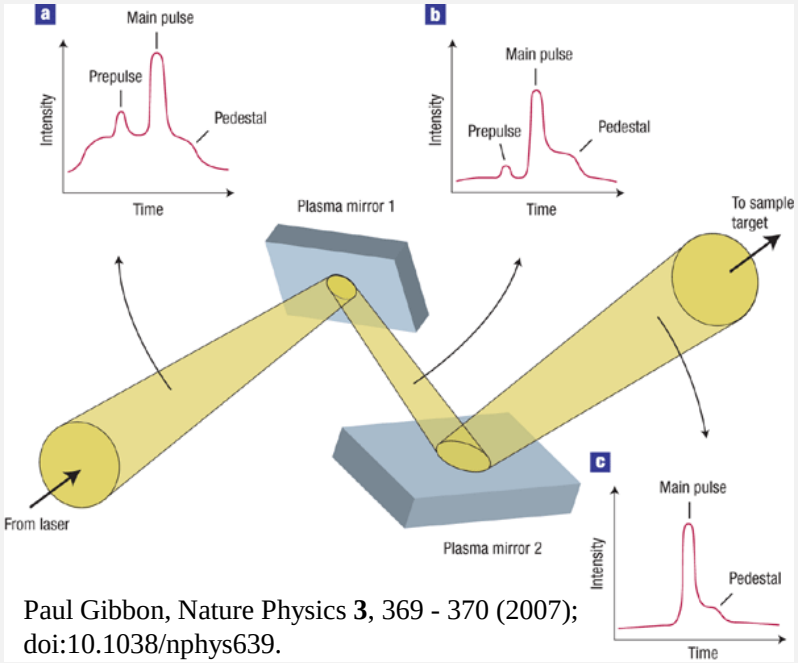
Patrick Poole

Plasma mirrors for pulse cleaning



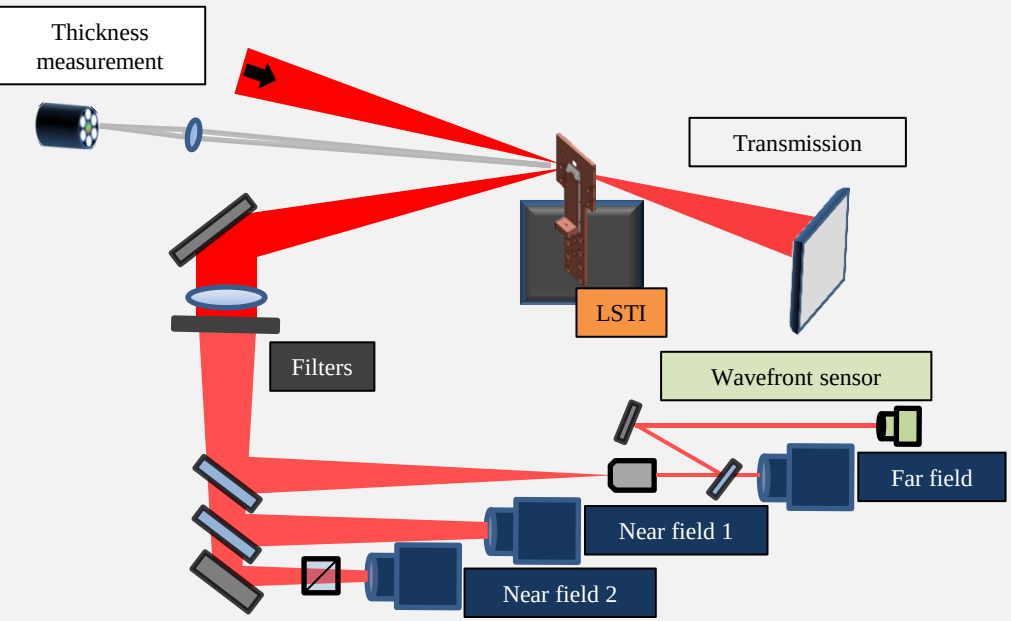


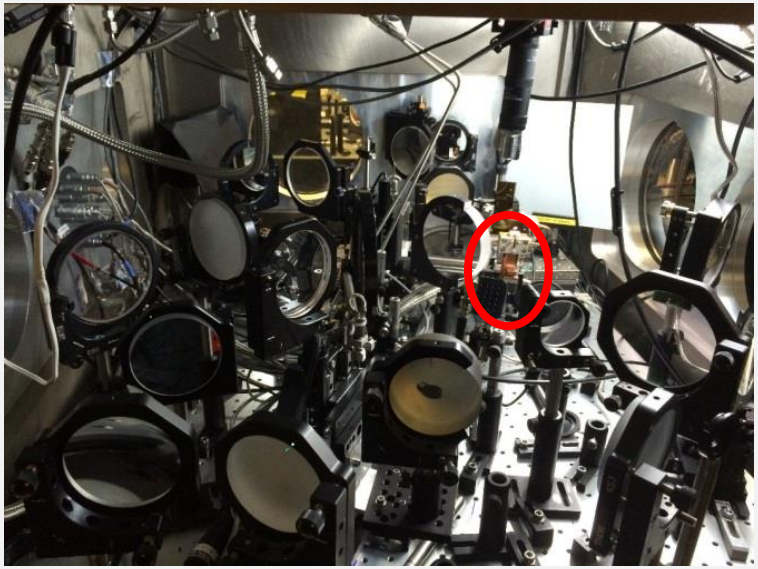
Paul Gibbon, Nature Physics **3**, 369 - 370 (2007); doi:10.1038/nphys639.

Plasma mirror requirements, issues:

- Low weak field reflectivity (usually AR coating)
- High strong field reflectivity
- Flat over wide area
- Vacuum compatible
- Available at laser rep rate
- For high rep rate systems: low cost

Experimental run



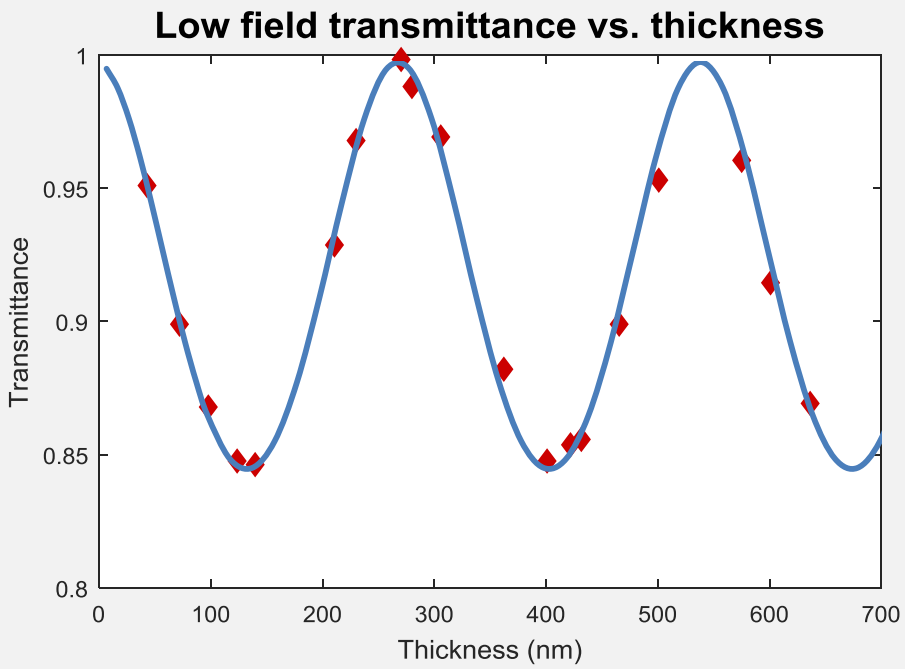


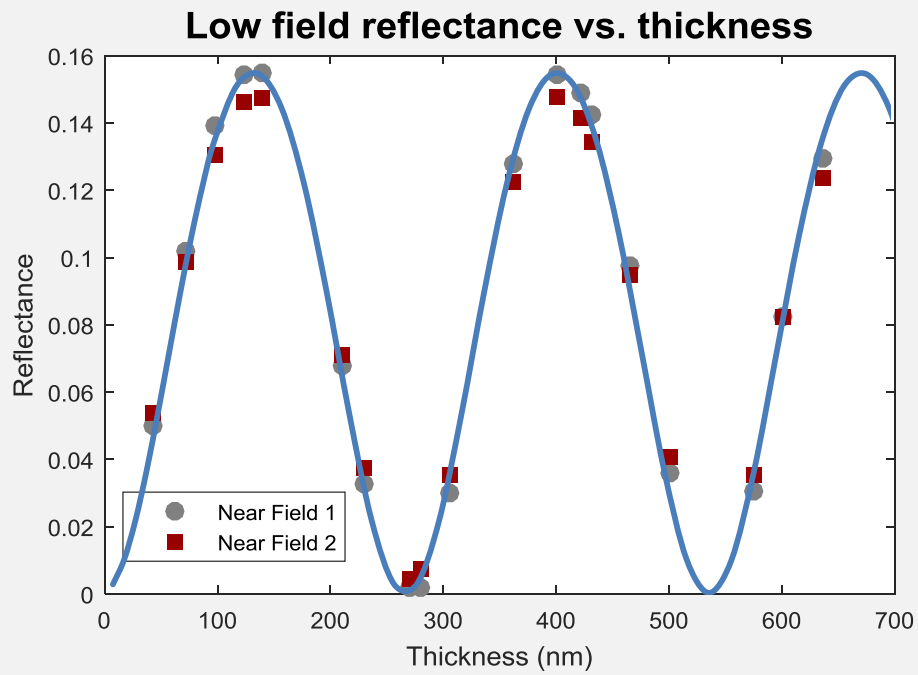
Run on Astra at RAL to test liquid crystal plasma mirrors
0.6 *J* input to chamber
40 *fs* pulse width
F/7 focus onto plasma mirror
S and P polarizations on target
Reflection and transmission diagnostics

- **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

Using LSTI, tune thickness to etalon minimum

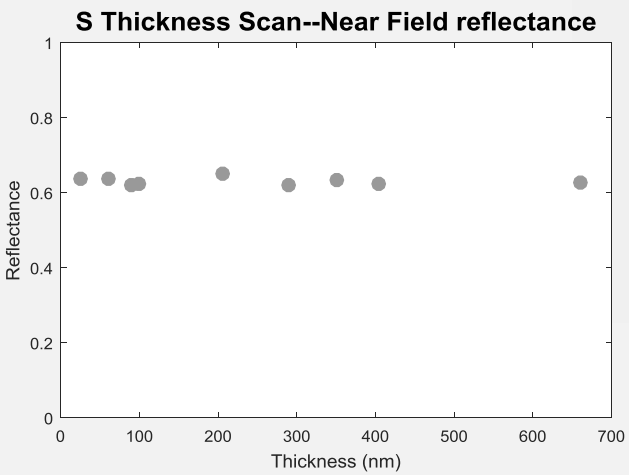
- Low intensity: ~5x10^{11} W/cm^2
- S polarization
- ~15° incident angle, 800 nm light
- First reflectance minimum is ~270 nm with R < 0.2%

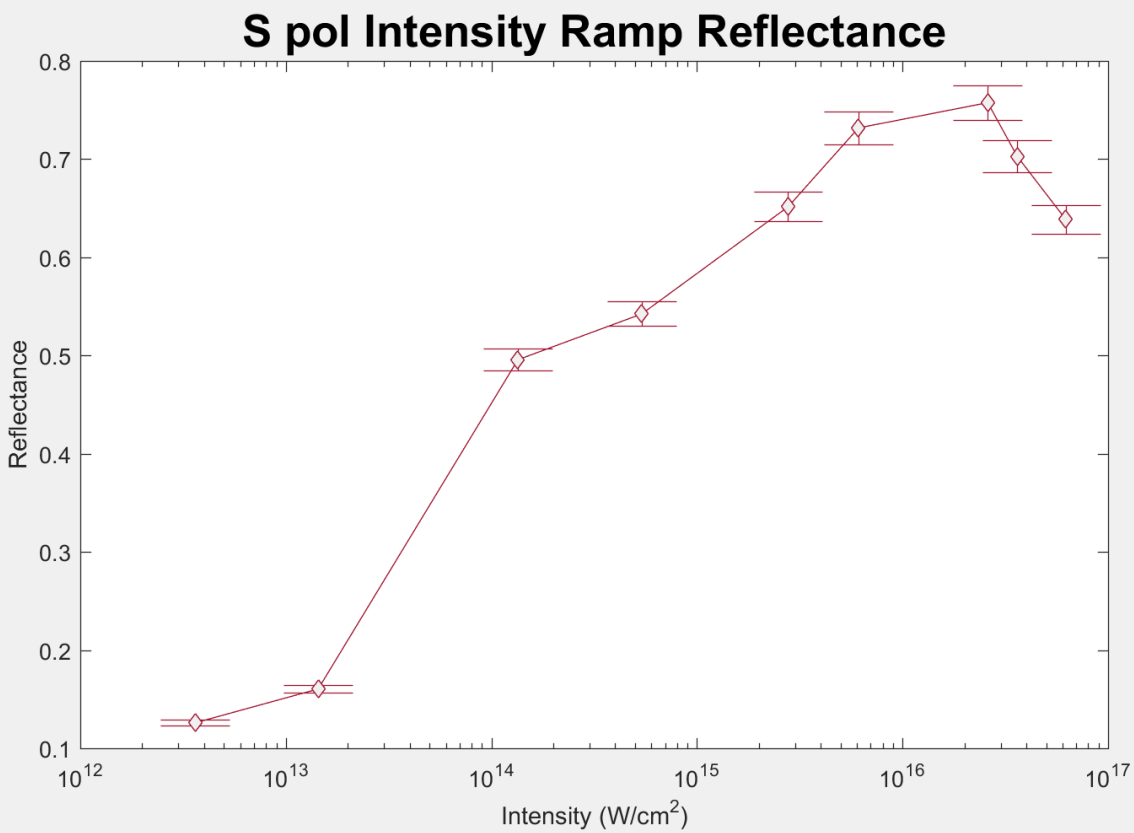




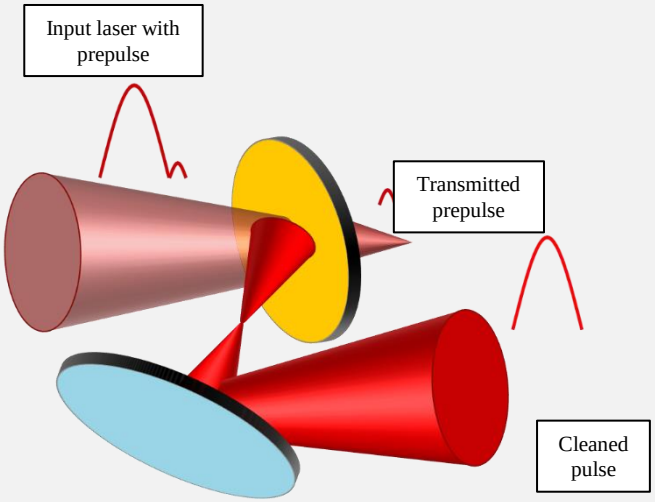
Intensity ramp

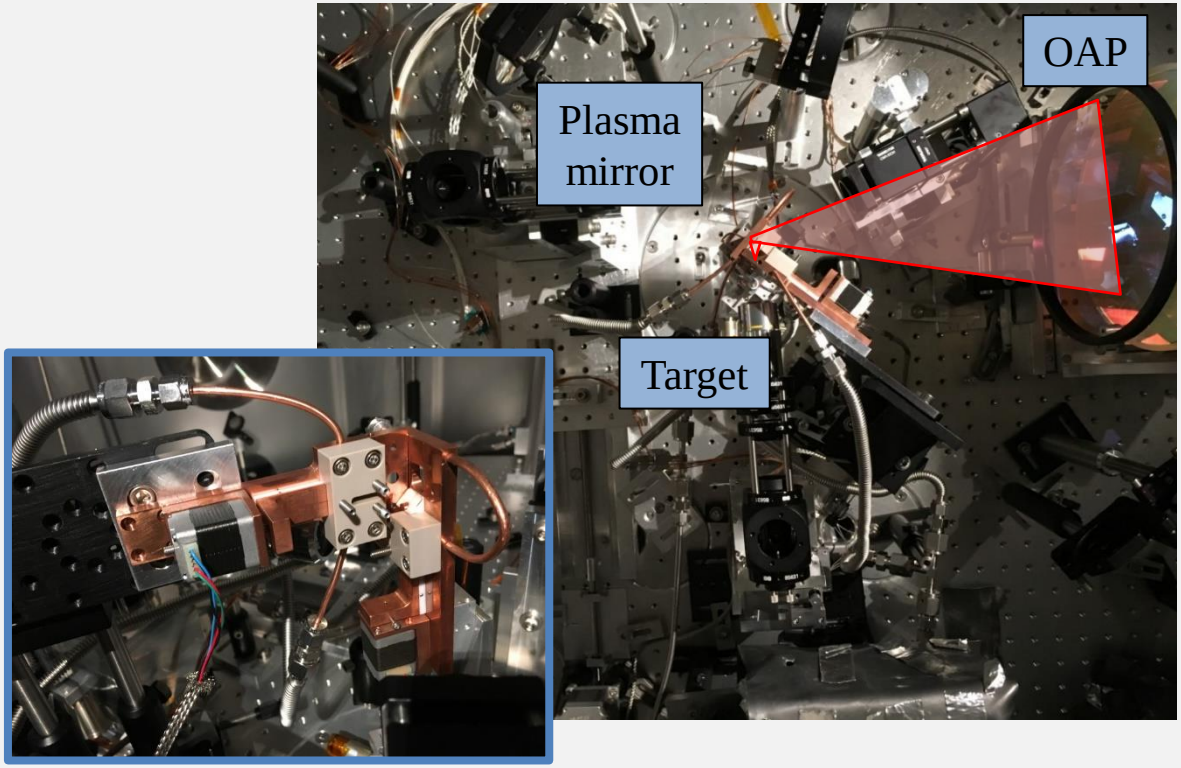
- Initial results: reflectance of ~ 75%
- Implied contrast enhancement >350
- P-polarization results lower by ~10%





In-line plasma mirror for contrast enhancement and debris control

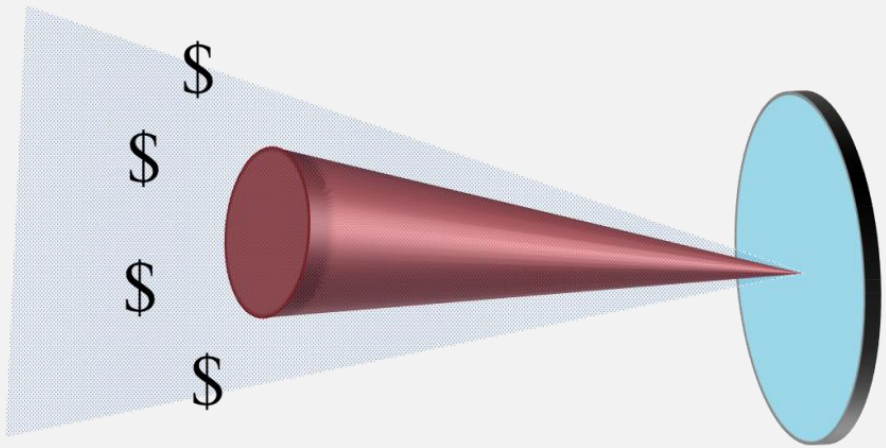


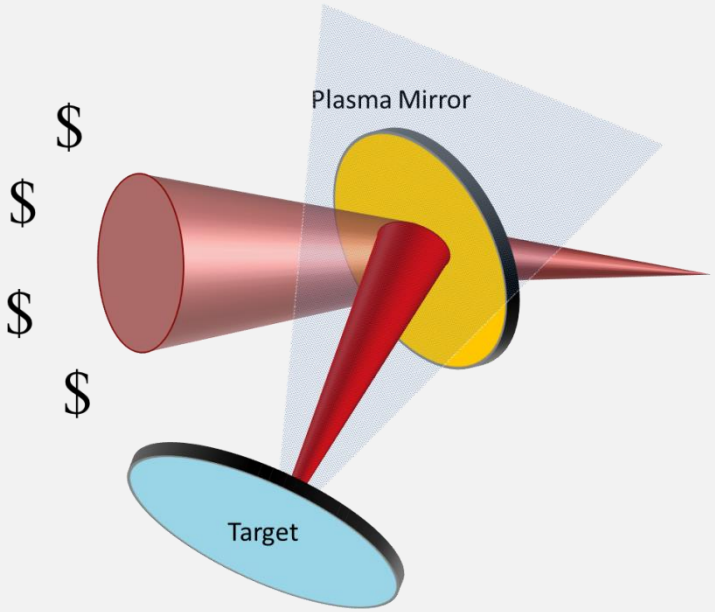


14 MeV from 167 nm target (not optimized)

- 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

Debris control





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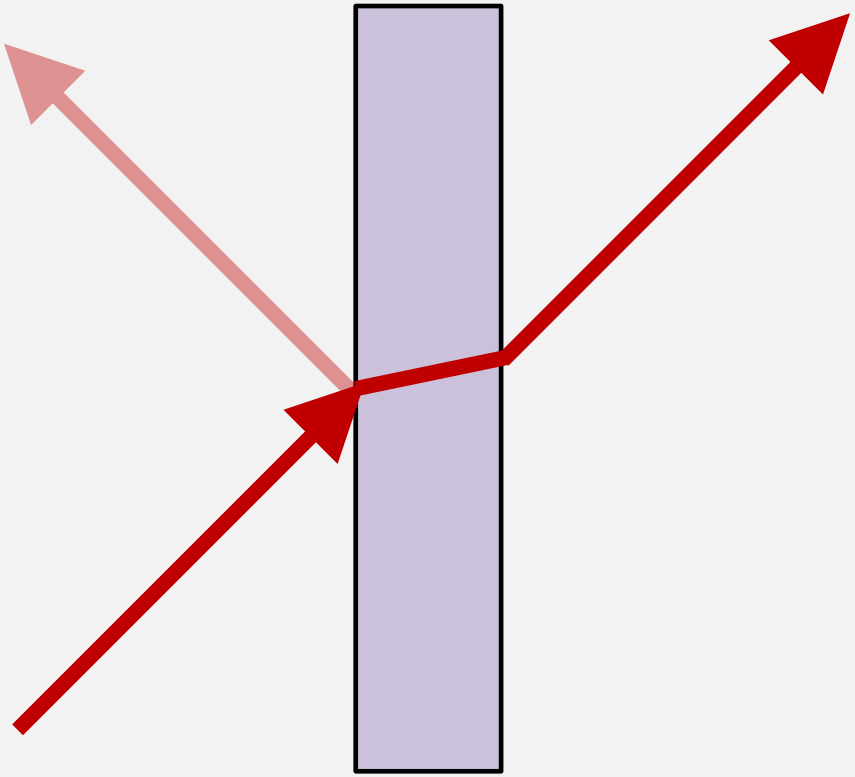
Ginevra Cochran

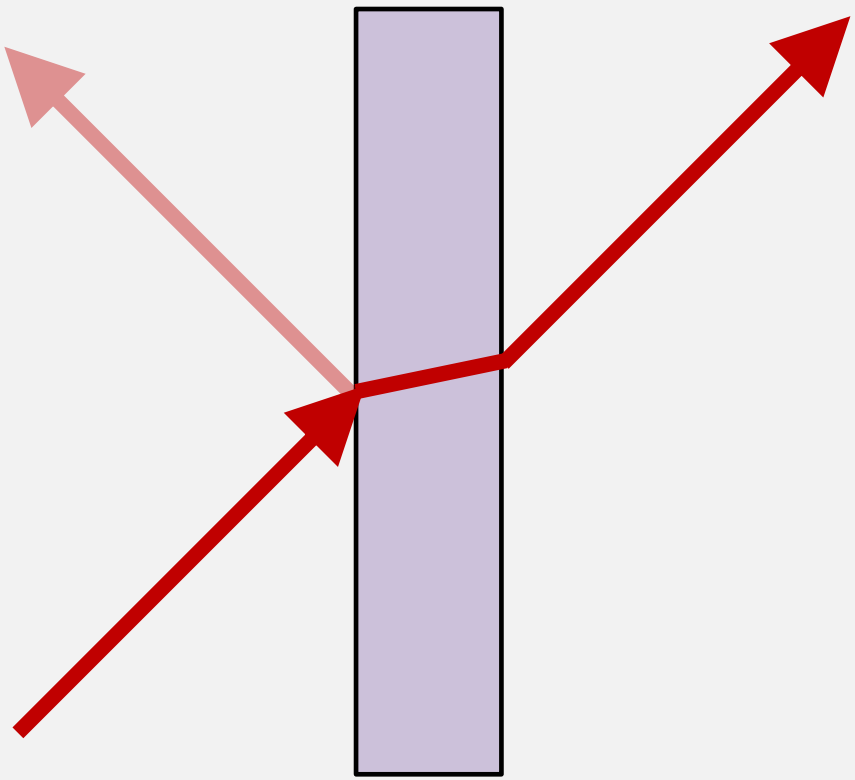
Modeling plasma mirrors

Dielectric (low field)

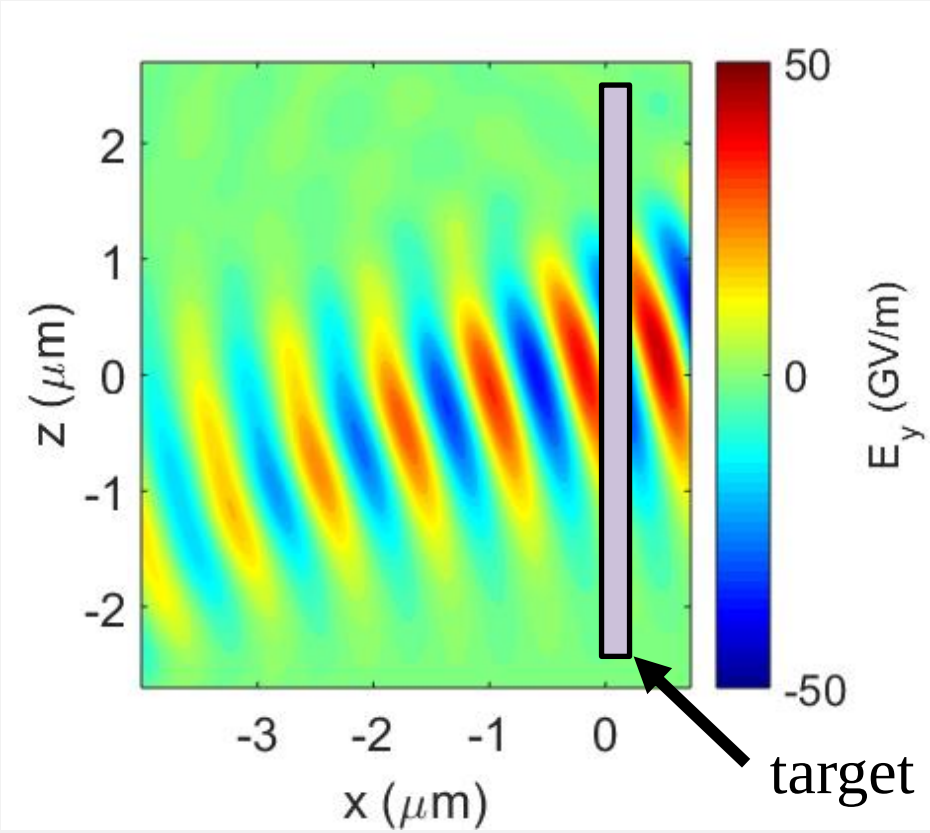


Modeling plasma mirrors

Dielectric (low field)

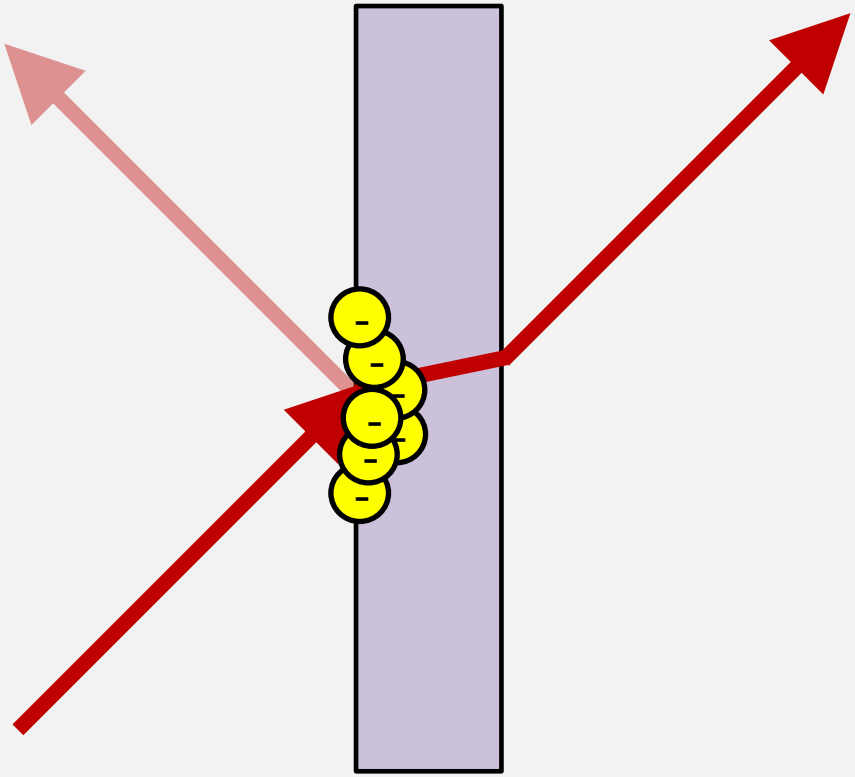


270 nm target



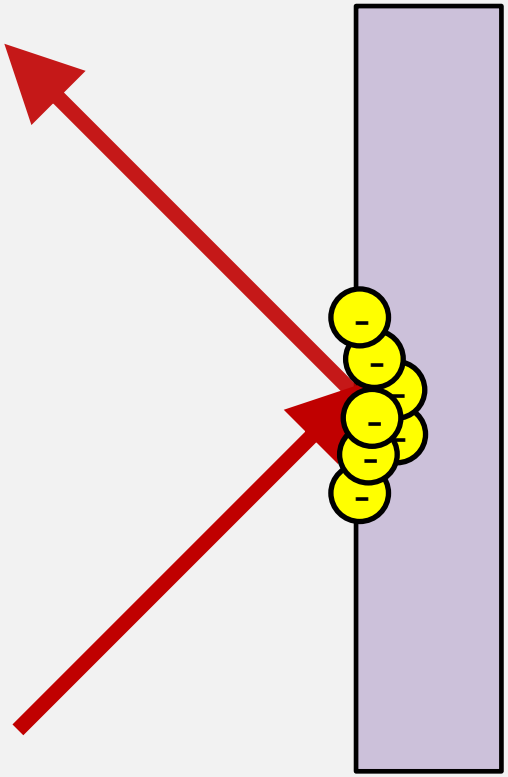
Modeling plasma mirrors

Dielectric ionization



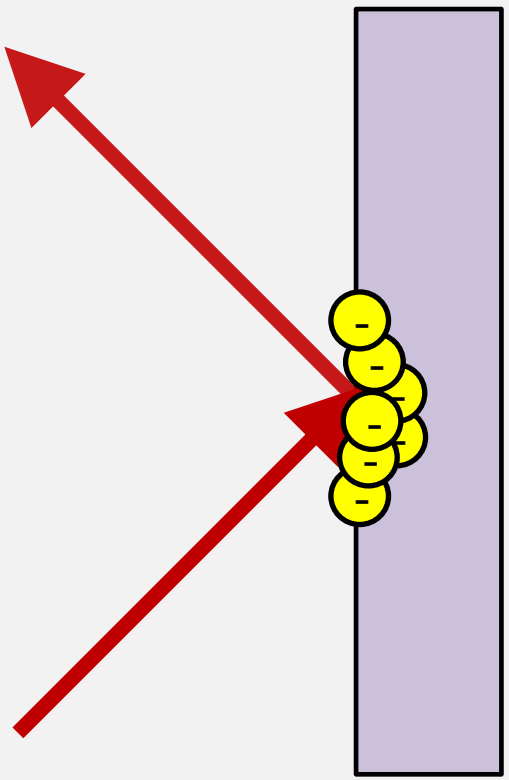
Modeling plasma mirrors

Plasma (high field)

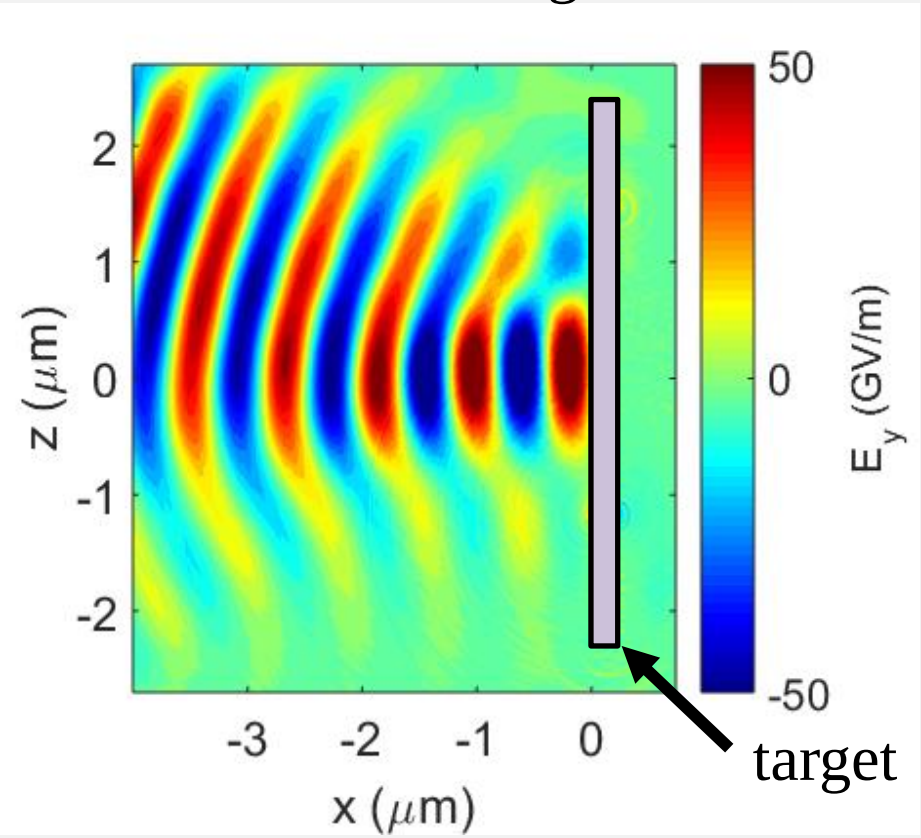


Modeling plasma mirrors

Plasma (high field)



270 nm target



PIC Simulations

2D3V (x-z) LSP [1] simulations

Laser

- 60 fs FWHM pulse duration
- 800 nm, $I_o = 5 \times 10^{12\text{-}16}$ W/cm^2
- 1.2 µm FWHM spot
- 16º angle of incidence
- s-polarized

Numerics

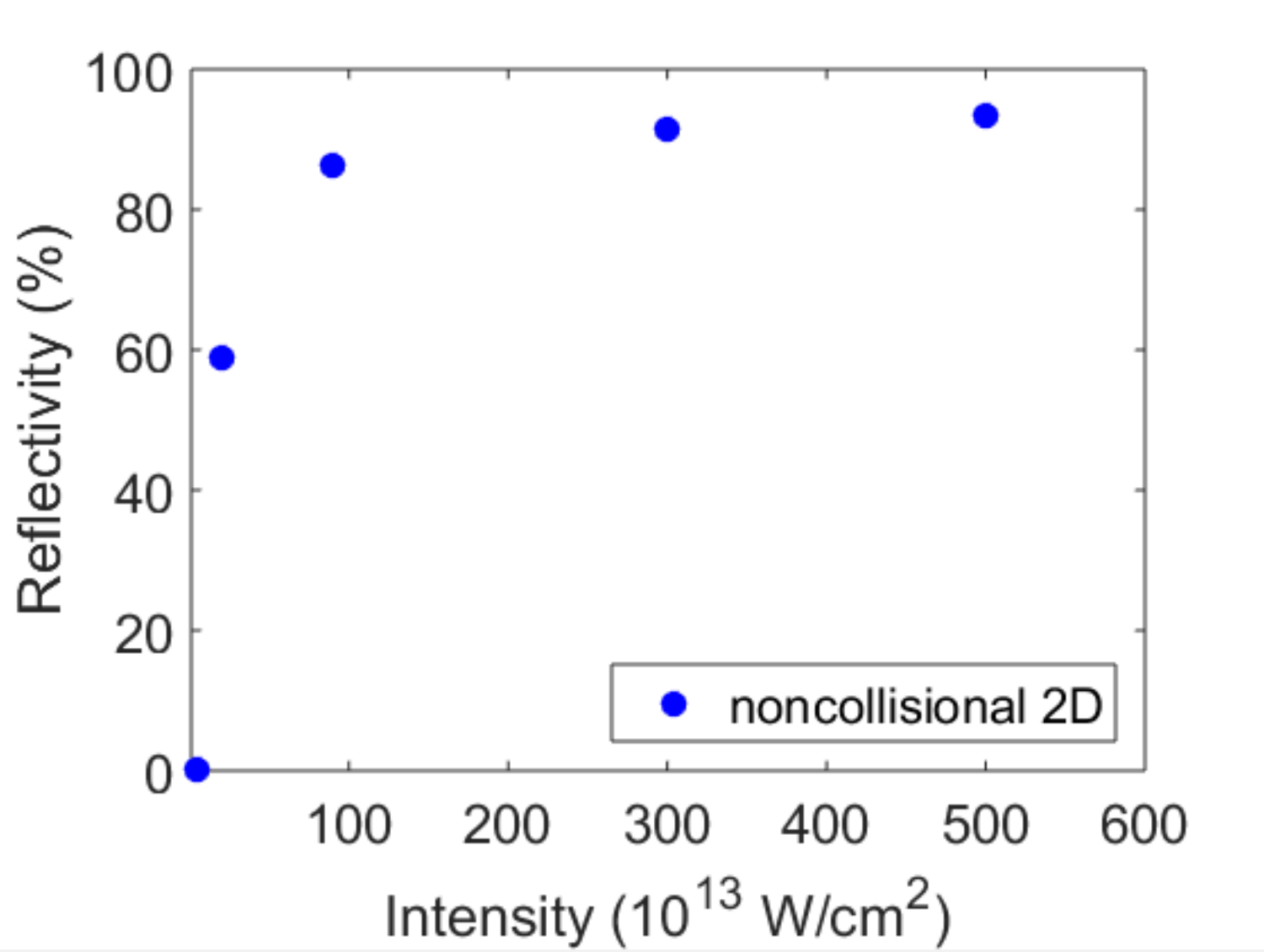
- 10 particles per species per cell
- 2.5 by 3 nm cells
- Fully explicit
- $\Delta t = 0.75$ Courant limit
- 4 µm vacuum gap

Target

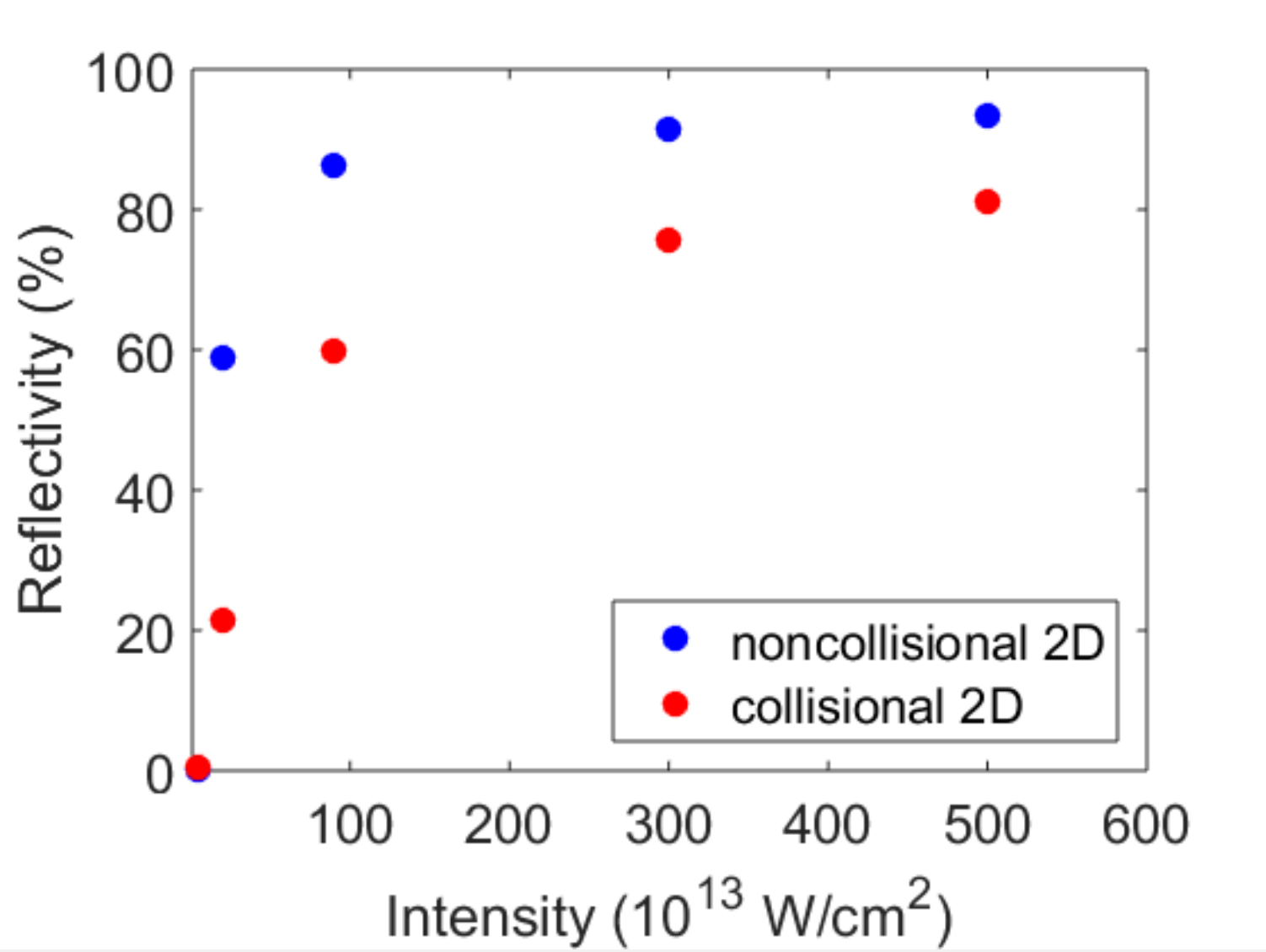
- 270 nm thick (reflection minimum)
- neutral atoms of 8CB ($C_{21}H_{25}N$) at 1 eV – 1 g/cc
- Index of refraction: n = 1.52 in target [2]
- Ionization model: $\Gamma(t) = I_p^{5/2} \frac{1}{F(t)} exp\left[-\frac{2}{3} I_p^{3/2} \frac{1}{F(t)}\right]$ [3]

[1] Welch & Rose, Comp. Phys. Comm. 164, 183-188 (2004)
[2] R.G. Horn. Journal de Physique 39, 1 (1978)
[3] P.B. Corkum. Phys. Rev. Lett. 71, 12 (1993)

Reflectivity vs intensity



Reflectivity vs intensity - collisional



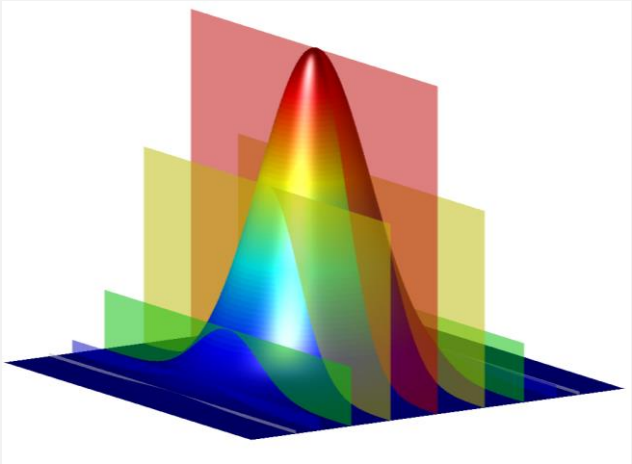
Estimated 2D correction

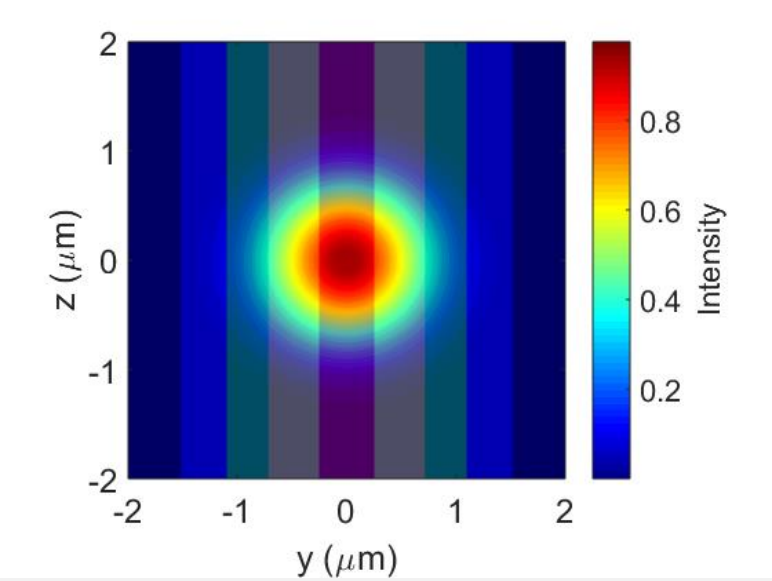
2D simulations can't capture a 3D experimental laser focus

Estimate 3D reflectivity by approximating intensity distribution as several line foci and using 2D sim reflectivities

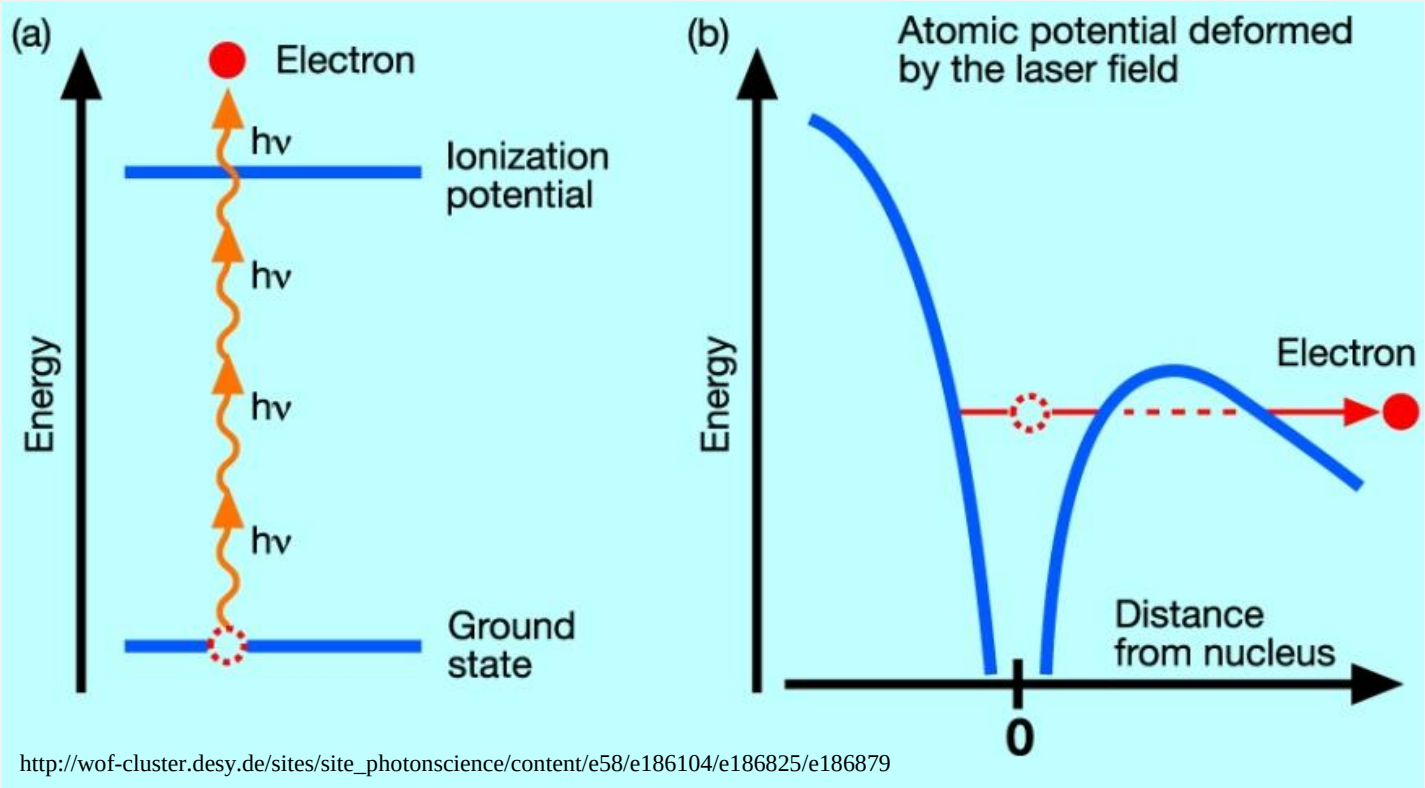
Define bins around 2D intensities and weight the energy in each by 2D reflectivity:

$$R_{3D} = \frac{\Sigma E_j R_{2D,j}}{\Sigma E_j}$$





Tunneling vs MPI



http://wof-cluster.desy.de/sites/site_photonscience/content/e58/e186104/e186825/e186879

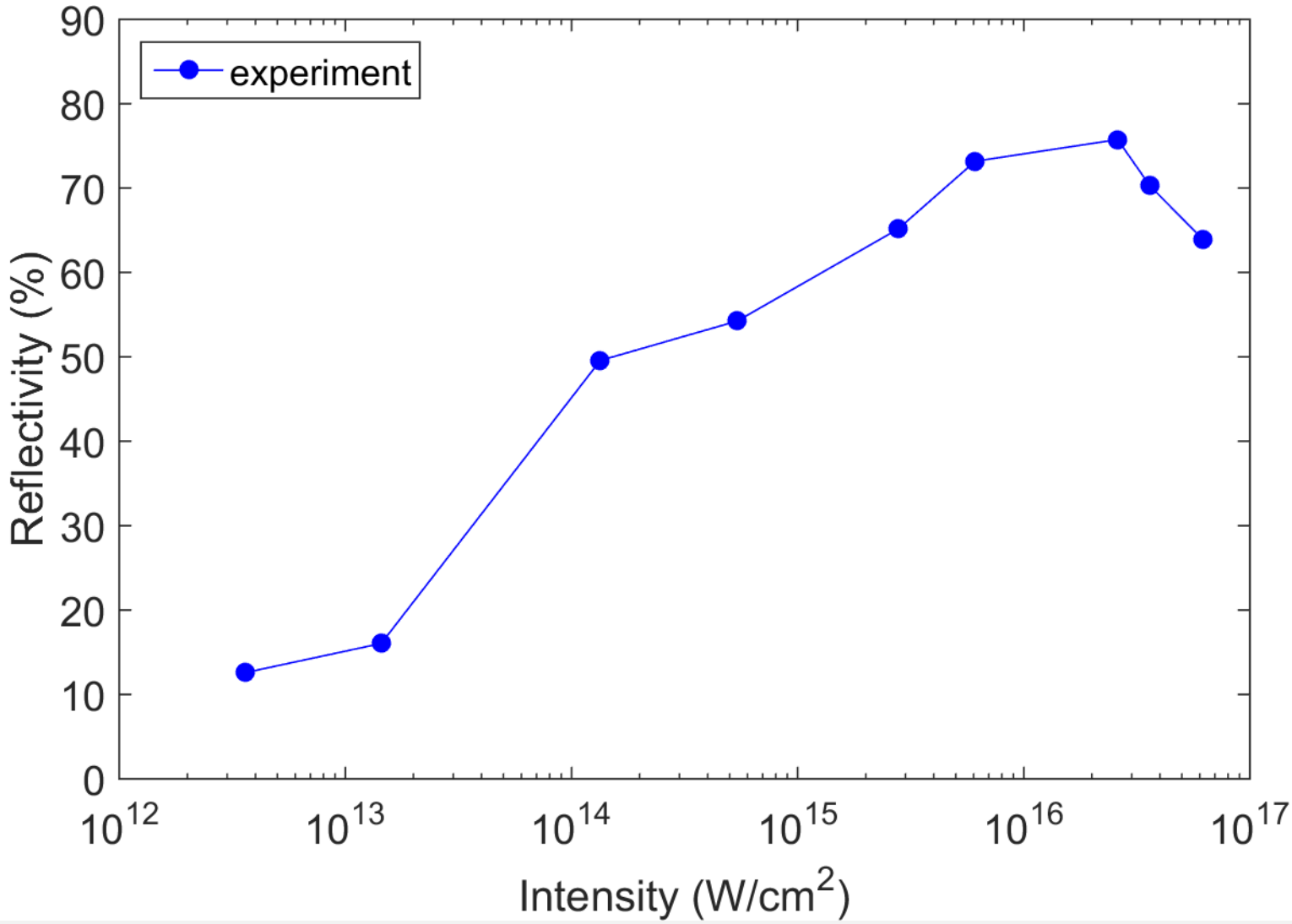
$$\gamma = \sqrt{\left(\frac{I_p}{2U_p}\right)}$$

$$U_p \propto I\lambda^2$$

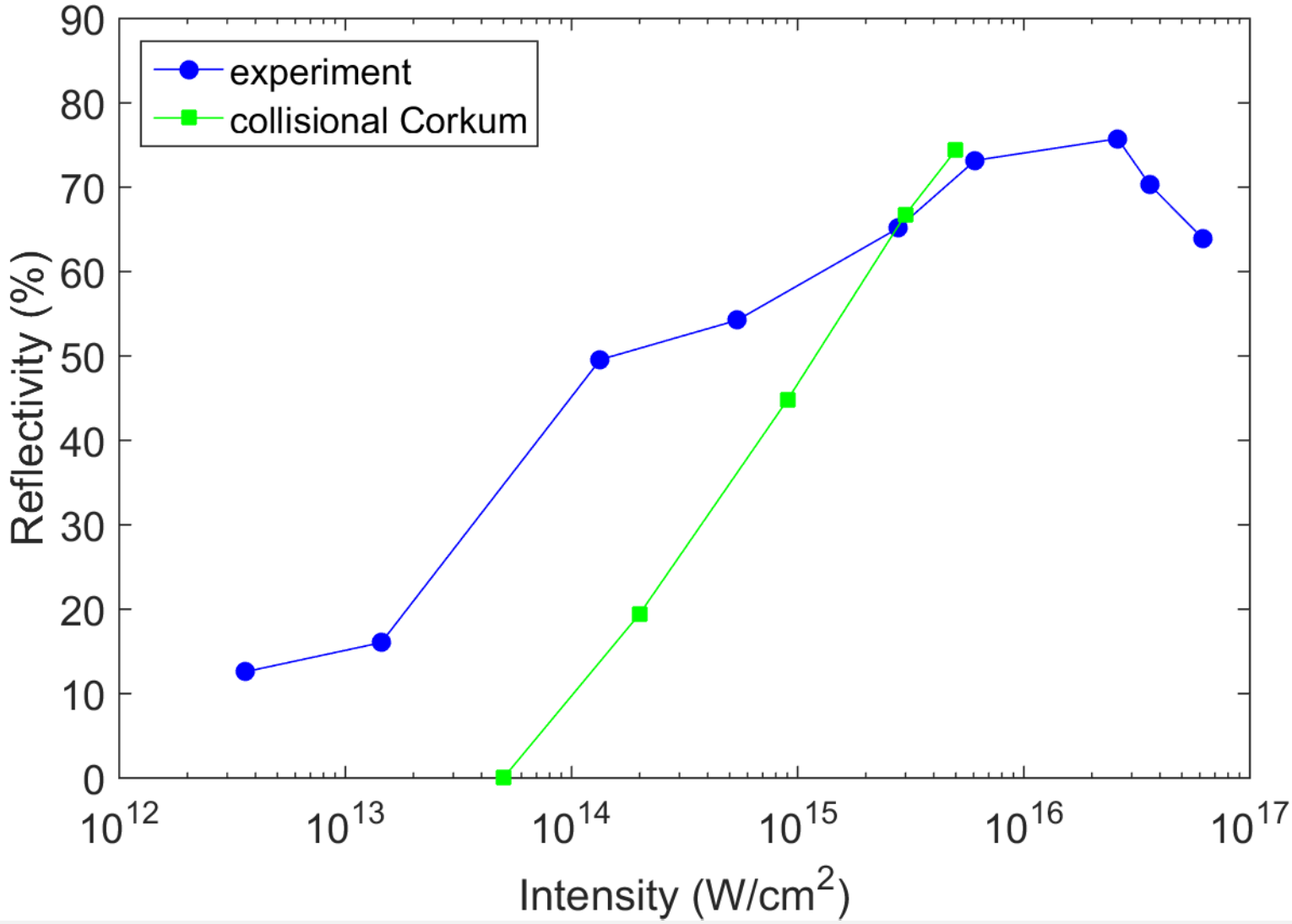
$$R = (C * E)^{2N_{MPI}}$$

$$N_{MPI} = ceil\left(\frac{I_p}{1.55\ eV}\right)$$

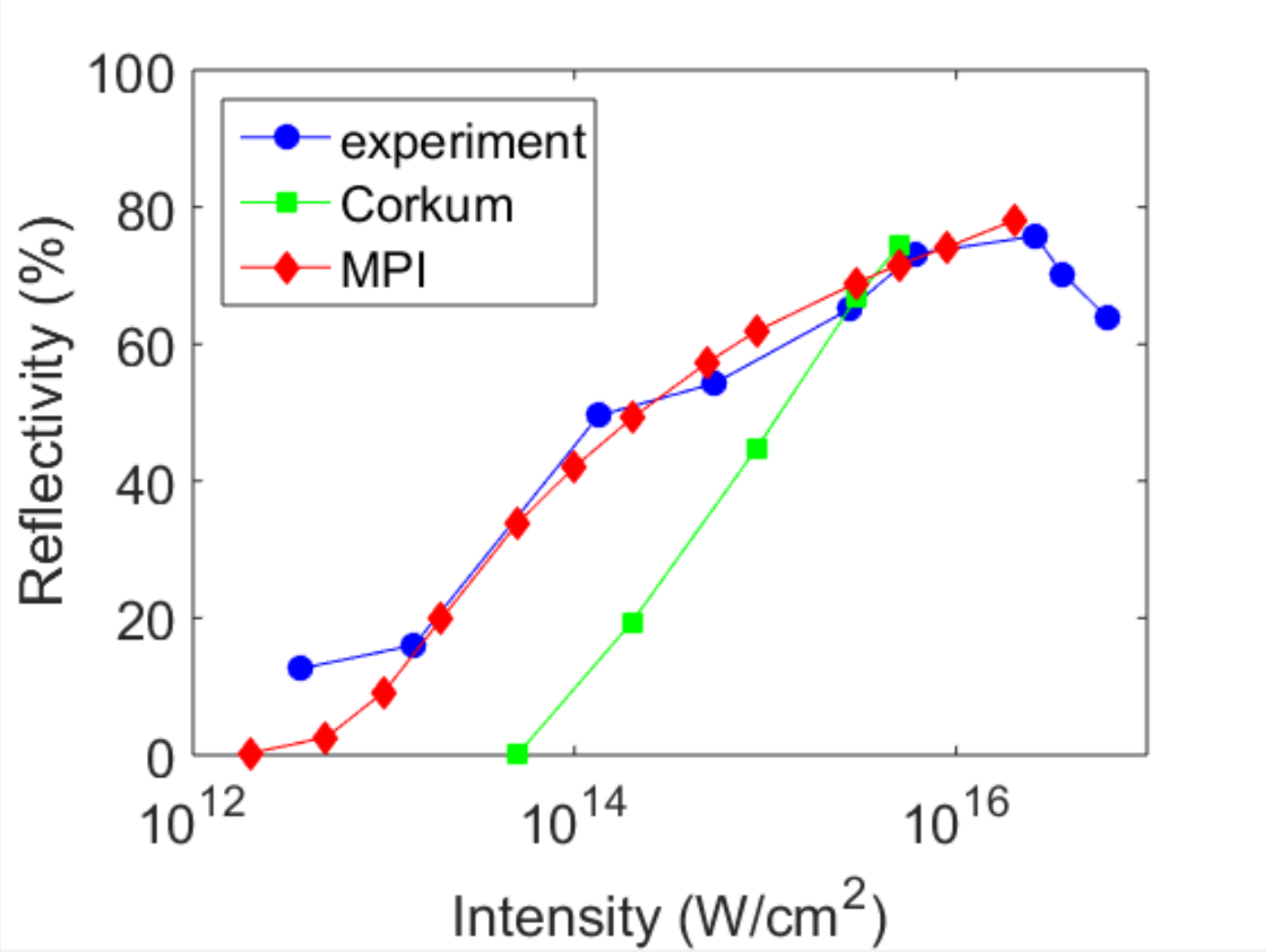
Comparison to experiment



Comparison to experiment



Comparison to experiment



Outline

1) Motivation and
   Review liquid crystal technology
2) Plasma mirrors - experiment
3) Plasma mirrors - simulation
4) **Conclusion**

Great people driving this work

Patrick Poole

Chris Willis

poster

Ginevra Cochran

poster

Recent graduates:

- Dr. Anthony Link
  Postdoc at LLNL 2011-2014
  Applied Physicist 2014

- Dr. Gregory Elijah Kemp
  Lawrence Fellow 2011
  Postdoc at LLNL 2013

- Dr. Sheng Jiang
  Postdoc at LLNL 2014

- Dr. Matthew McMahon
  Postdoc at LLNL 2015

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  - P.L. Poole G.E.Cochran, C. Willis
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THE OHIO STATE UNIVERSITY

- Ohio Supercomputer Center

Ohio Supercomputer Center
An OH·TECH Consortium Member

- Department of Energy NNSA SSAP
  - Contract DE-NA0001976
- DARPA PULSE program
  - Through AMRDEC
  - Contract from National Energetics

National Nuclear Security Administration

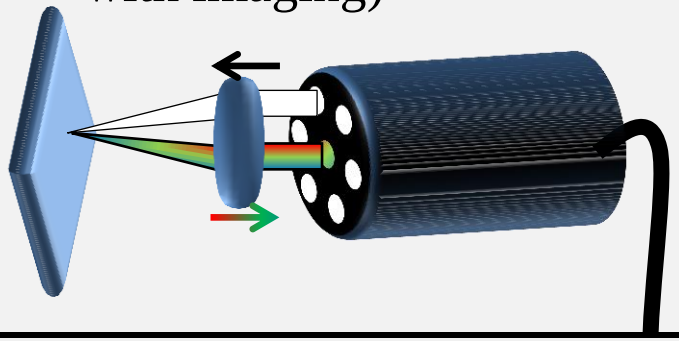
DARPA

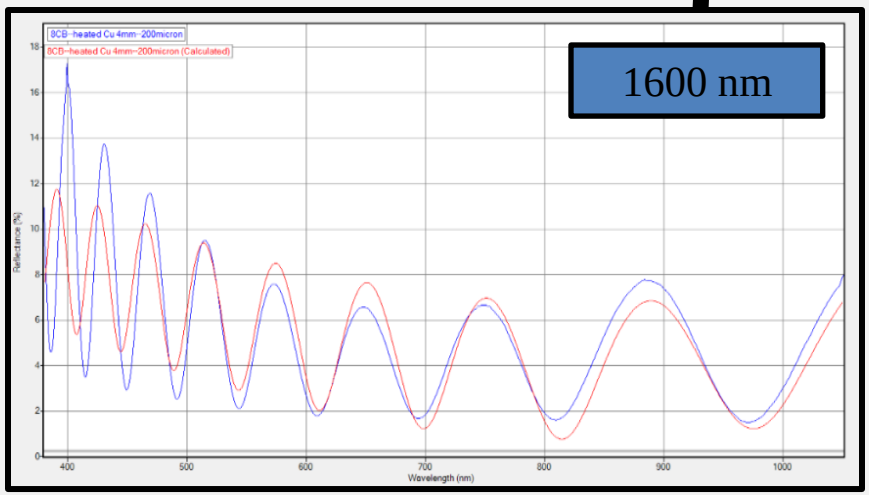
NATIONAL ENERGETICS

Film characterization—thickness and position

Filmetrics commercial unit

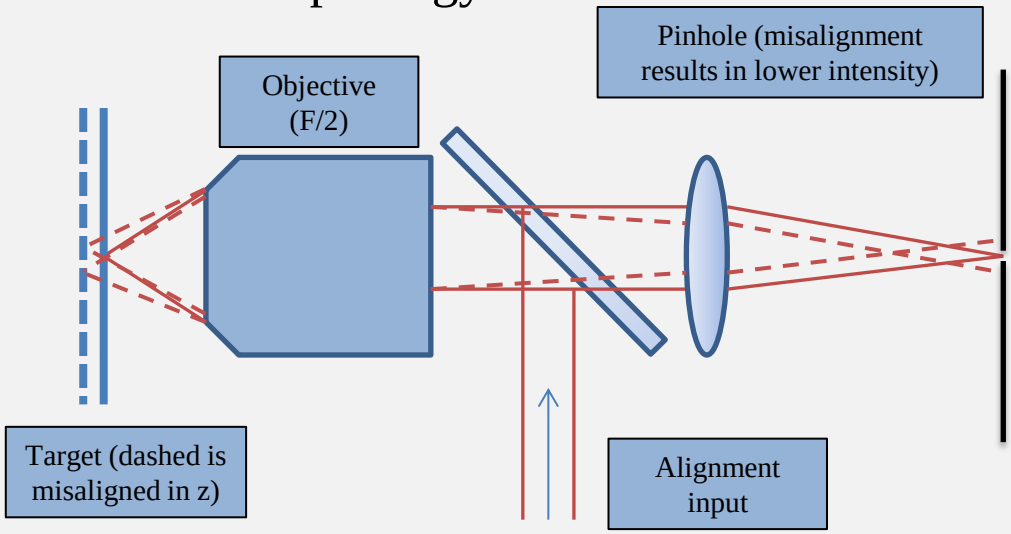
- 2 nm measurement accuracy.
- 50 ms acquisition time.
- 48” standoff distance (or more with imaging)





Confocal positioner for ~ 1 µm alignment

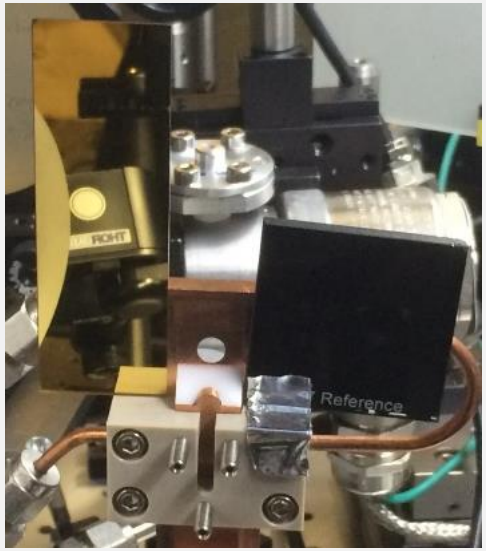
- Establish TCC using traditional techniques
- Draw a spot on the film using scatter from a low power cw laser
- Measure relative position using confocal microscopy
- Works regardless of target surface morphology

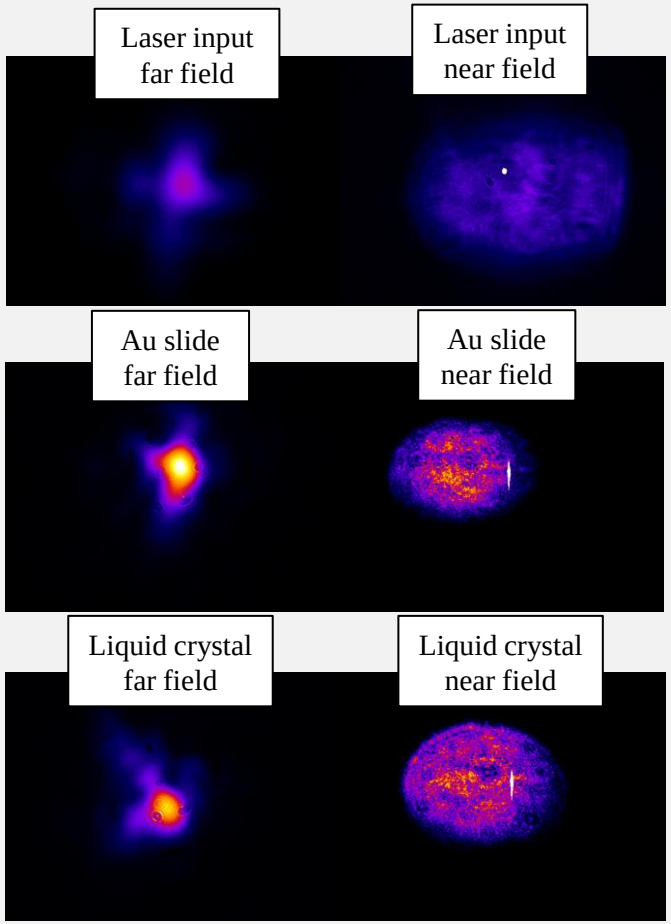


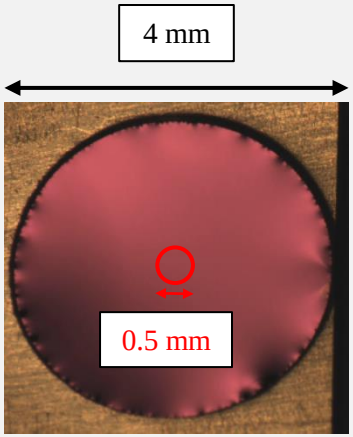
C. Willis et al., Review of Scientific Instruments **86**, 053303 (2015)

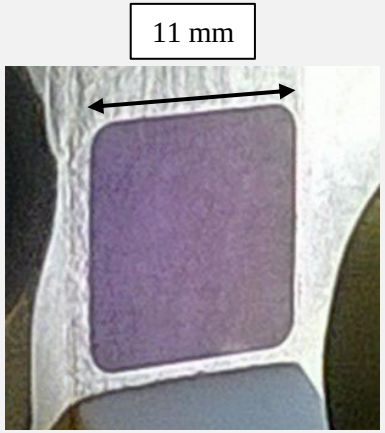
Good mode preservation in weak field limit

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

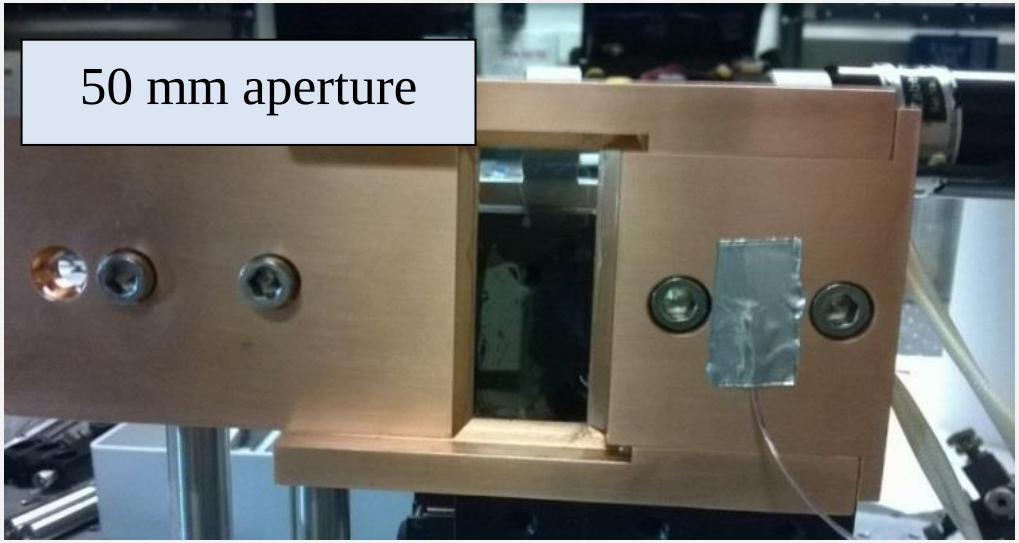


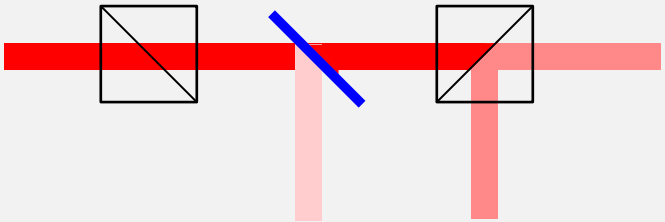
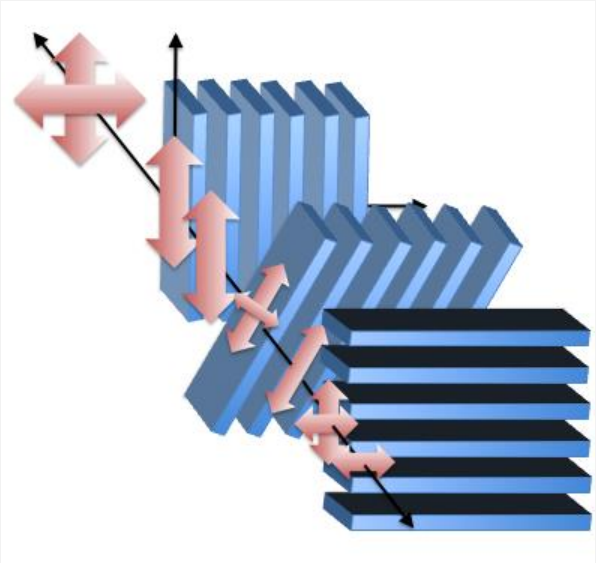
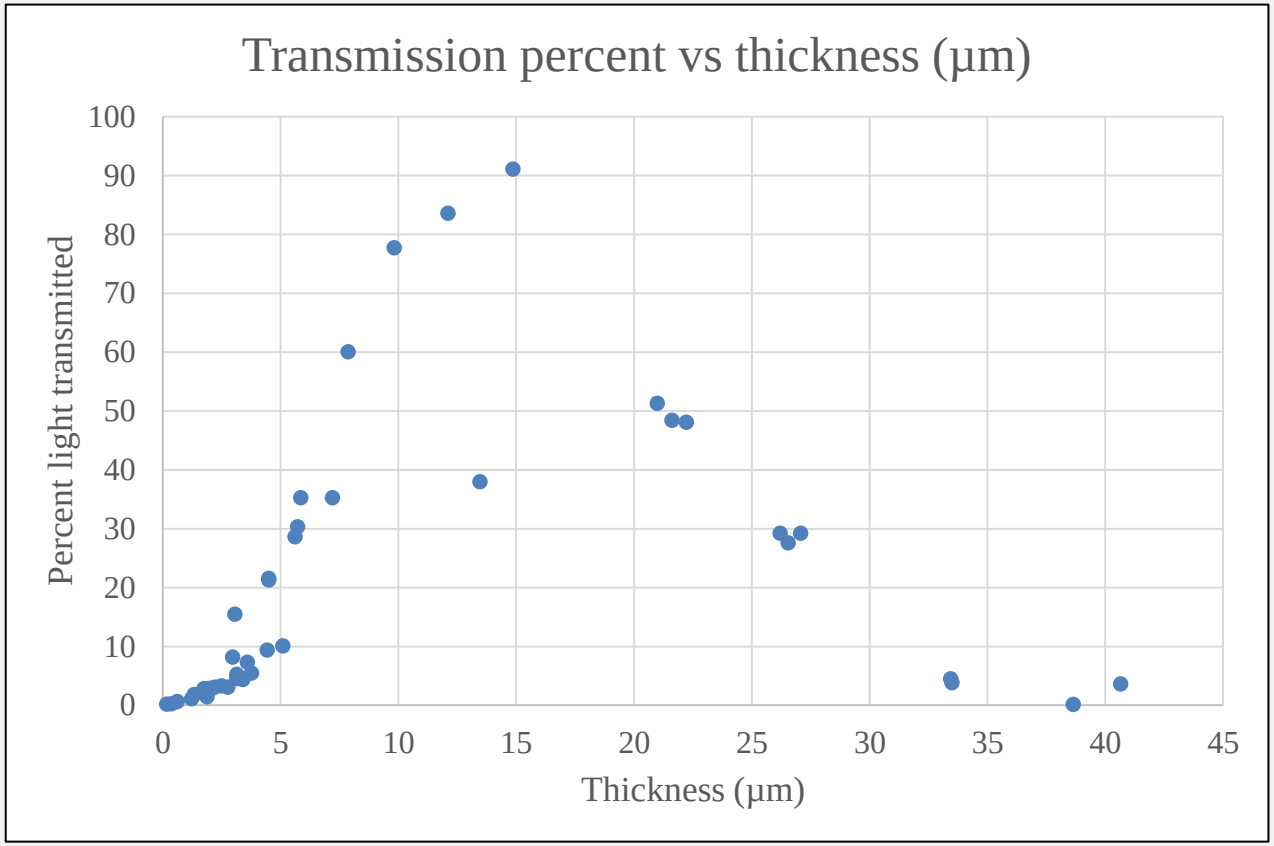






Larger area films are easily made



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