U.S. NAVAL
RESEARCH
LABORATORY

Plasma Lenses for Laser Beams

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Outline

NRL PPD

- Relevance to ALIC
- Plasma Mirrors
- Plasma Lenses
  - Passive and Active
  - Aberrations and Corrections
  - Experimental Development

Spot size is a sensitive control parameter for laser plasma acceleration

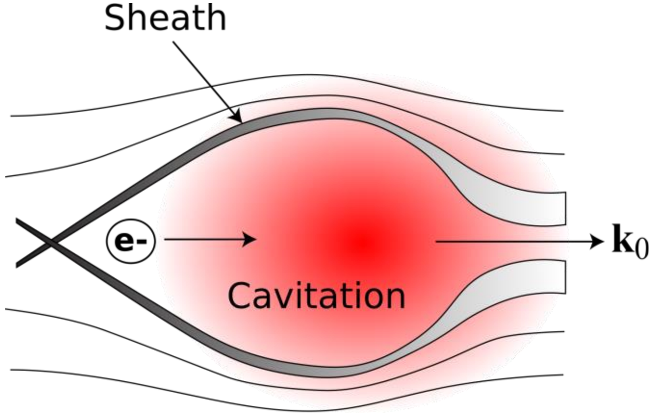
NRL PPD

$$k_pR \approx k_p r_0 \approx 2\sqrt{a_0}$$

Guiding condition

$$L \approx \min\left\{\frac{2}{3}\frac{\omega_0^2}{\omega_p^2} r_0, \frac{\omega_0^2}{\omega_p^2} c\tau_L\right\}$$

Dephasing and depletion lengths



Combining equations gives dephasing length as $$L_d \approx \frac{1}{24}\sqrt{\frac{m}{r_e c^3 P_0}}\omega_0^3 r_0^4$$

(depletion length scales similarly if we suppose pulse duration matched to bubble)

- **Conclude that focusing is a sensitive control parameter**
- **Typically long focal lengths are preferred**

* W. Lu et al., Phys. Rev. ST/AB 10, 061301 (2007)

Laser pulse energy is important for high energy stages

Energy gain in a quasilinear channel guided configuration is

$$\Delta E \approx 1.07 \mathcal{E}_L \frac{r_e}{\lambda_p}$$

Roughly this is laser energy divided by classical electrons in a bucket.
All other parameters are constrained by:

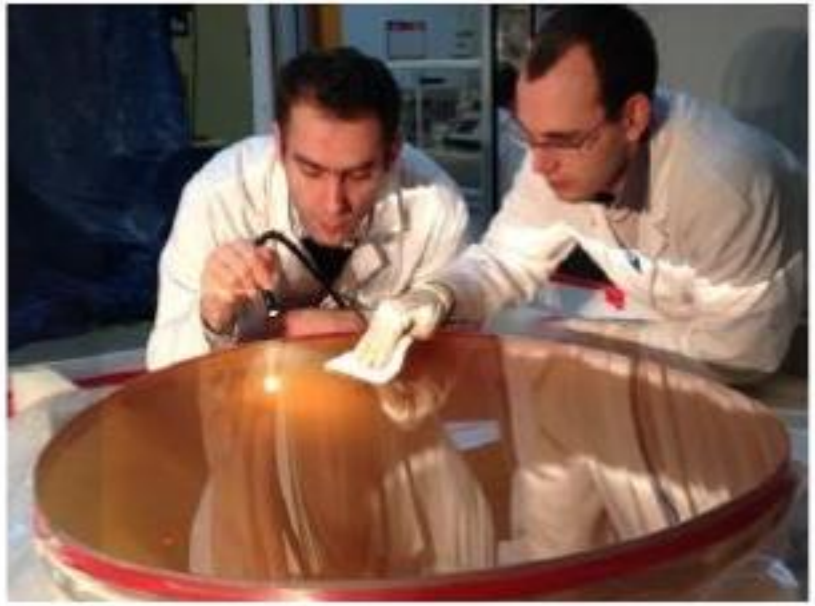
$a_0 \sim 1$	Weak to moderate nonlinearity
$\omega_p \tau_L \sim \pi$	Resonance condition
$k_p r_0 \sim 4$	Simultaneously suppress blowout and self focusing
$r_0 = \left(r_{\mathrm{ch}}^2 / \pi r_e \Delta n\right)^{1/4}$	Guiding condition

Need high energy and therefore large optics

Petawatt scale conventional optics are large and expensive

Example from ELI-NP (10 PW Thales laser)

1 m diameter, F/2.5 $\lambda/40$ OAP by REOSC-SAFRAN

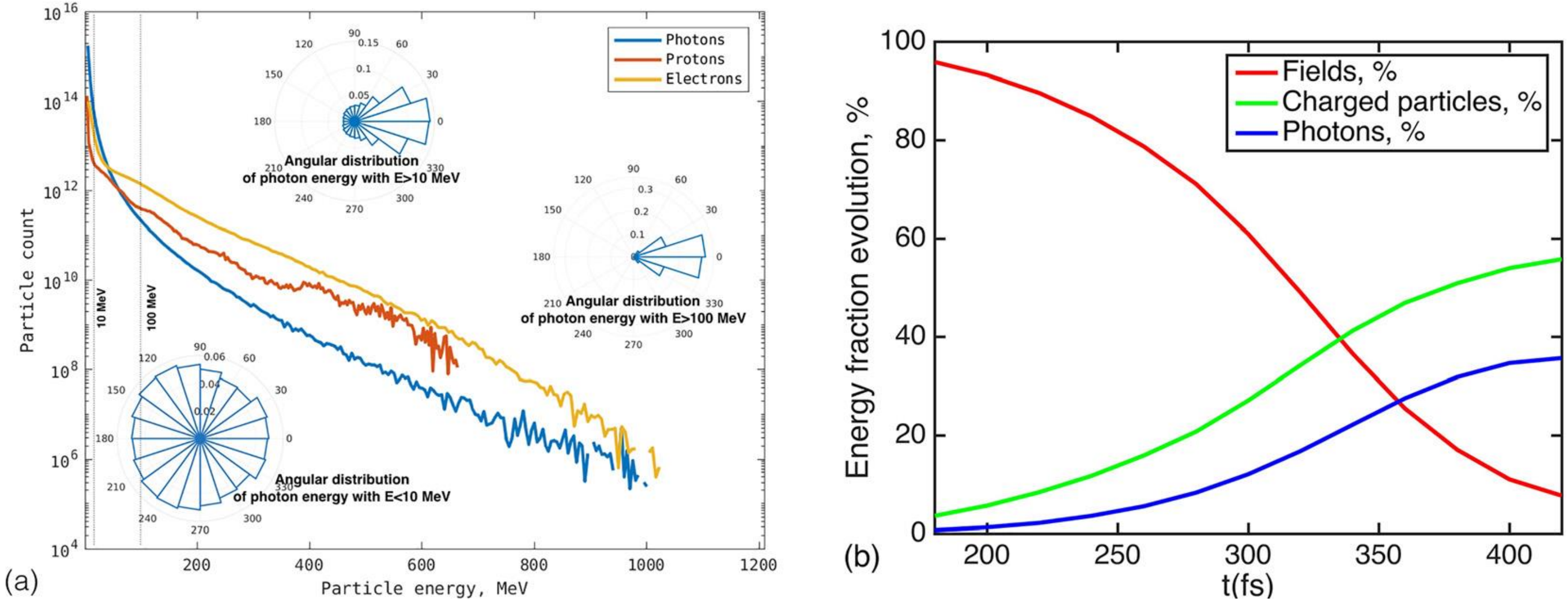


Hervy et al 2015

- Damage threshold ~0.3 J/cm^2 forces meter scale diameter
- Typical cost of a single optic is in the range of 1 million euros
- Beam transport becomes costly in terms of space and money

Strong focusing configurations may also be of interest

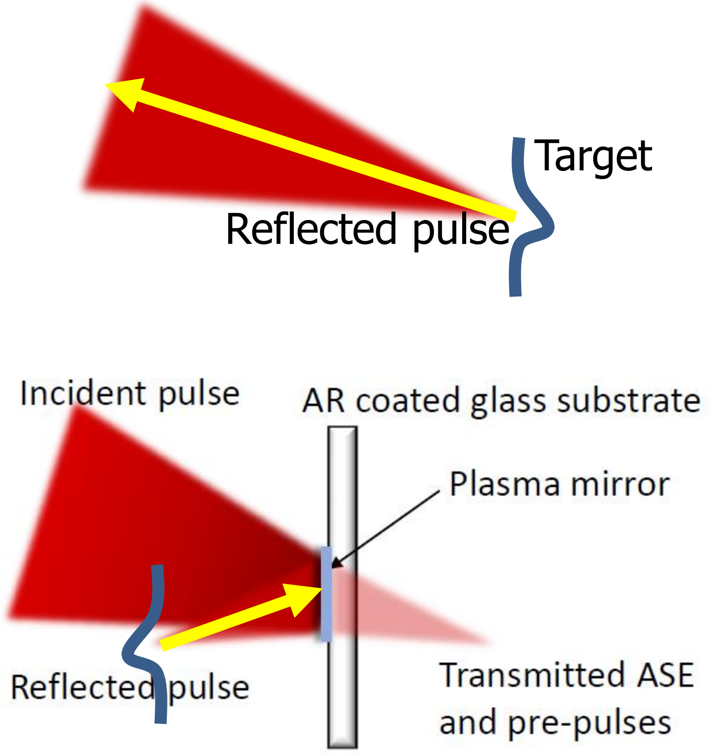
- Strong focusing useful for nonlinear QED, but do we need this for ALIC?
- Perhaps application to positron sources, consider, e.g., gamma flash*

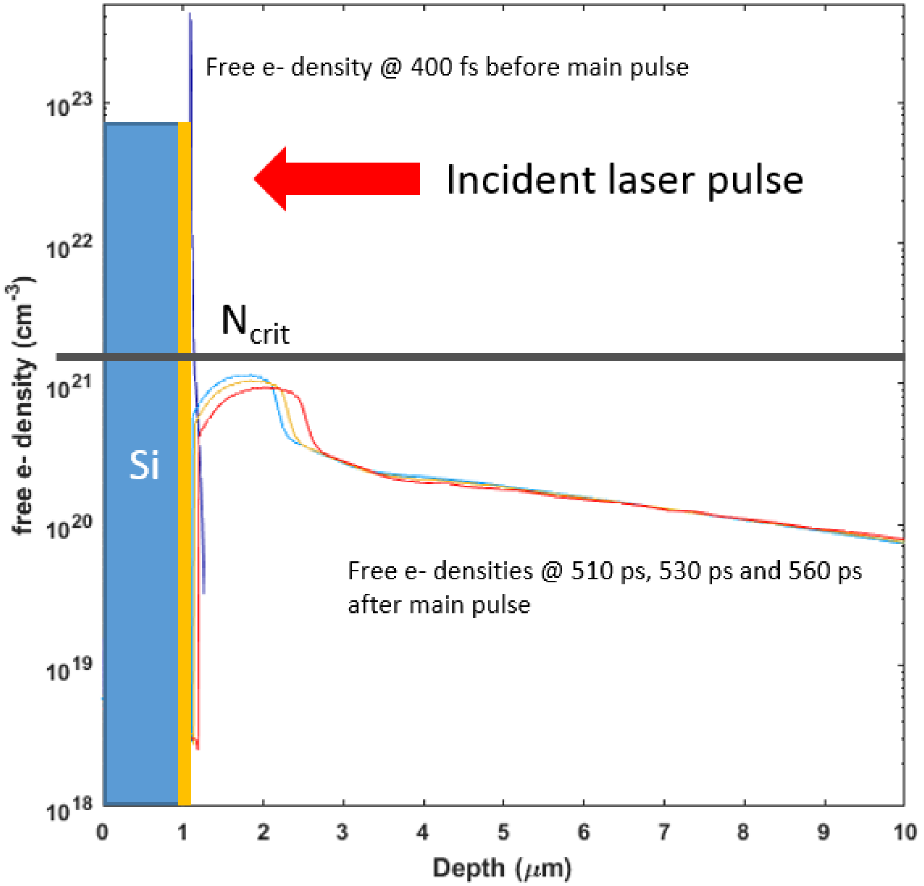


30% Conversion

* Copied from K.V. Lezhnin et al., Phys. Plasmas 25, 123105 (2018)

Plasma mirrors for contrast enhancement and protection

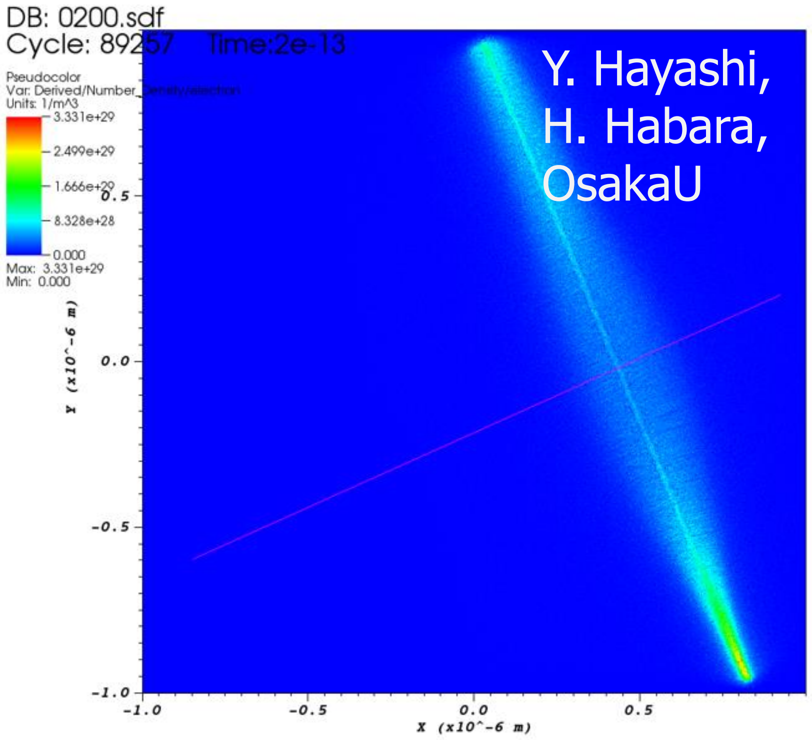


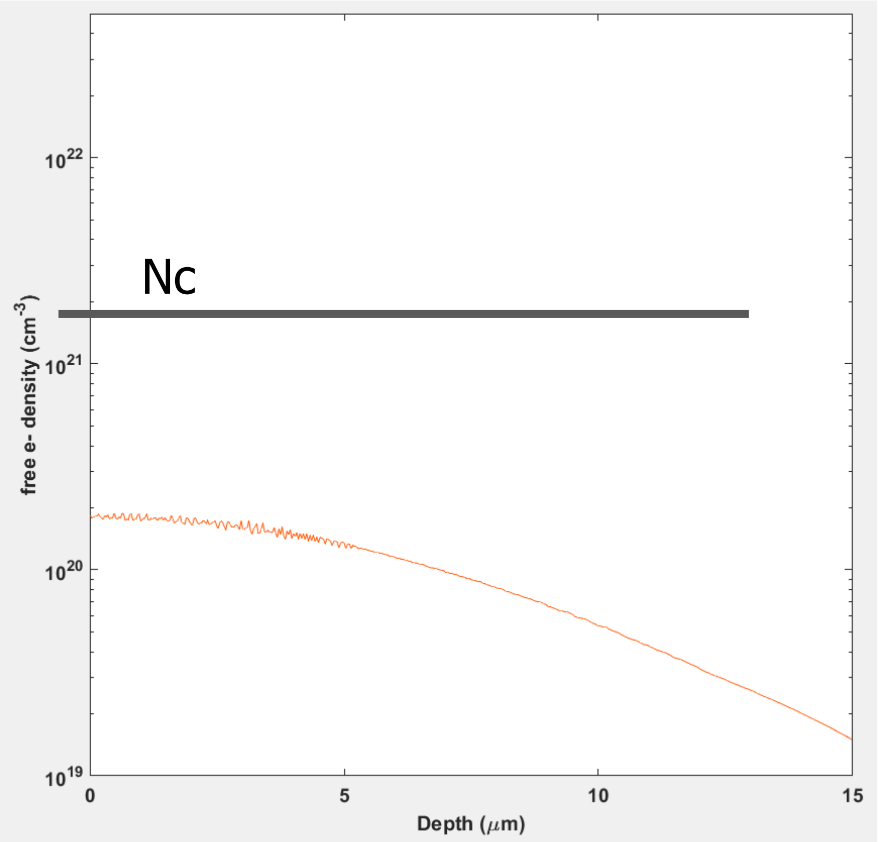


Computed plasma density profile at the sacrificial mirror surface at ~560 ps after the main laser pulse.
(Gales et al, Rep. Prog. Phys, 2018)

- High contrast lasers cannot trigger plasma as far from the target as low contrast lasers
- Reflectivity of plasma/sacrificial mirror on thick substrate predicted to decay slowly and also back-reflected pulse may regenerate it
- Back-reflection protection not 100% guaranteed

Ultrathin Film Plasma Mirror





Computed plasma density profile of the ultrathin film at ~90 ps after the main laser pulse. **(M. Cernaianu, ELI-NP)**

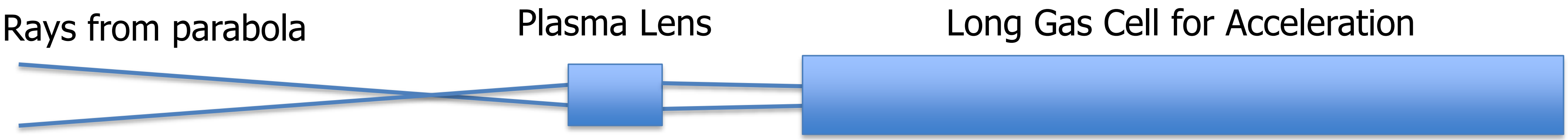
- Ultrathin (50 nm) free-standing film electrostatically explodes after laser pulse
- Solution with ultrathin plastic film being explored
- Novel regenerative ultrathin liquid crystal plasma mirror developed by OSU

Plasma Lens as a Compact Magnification Section

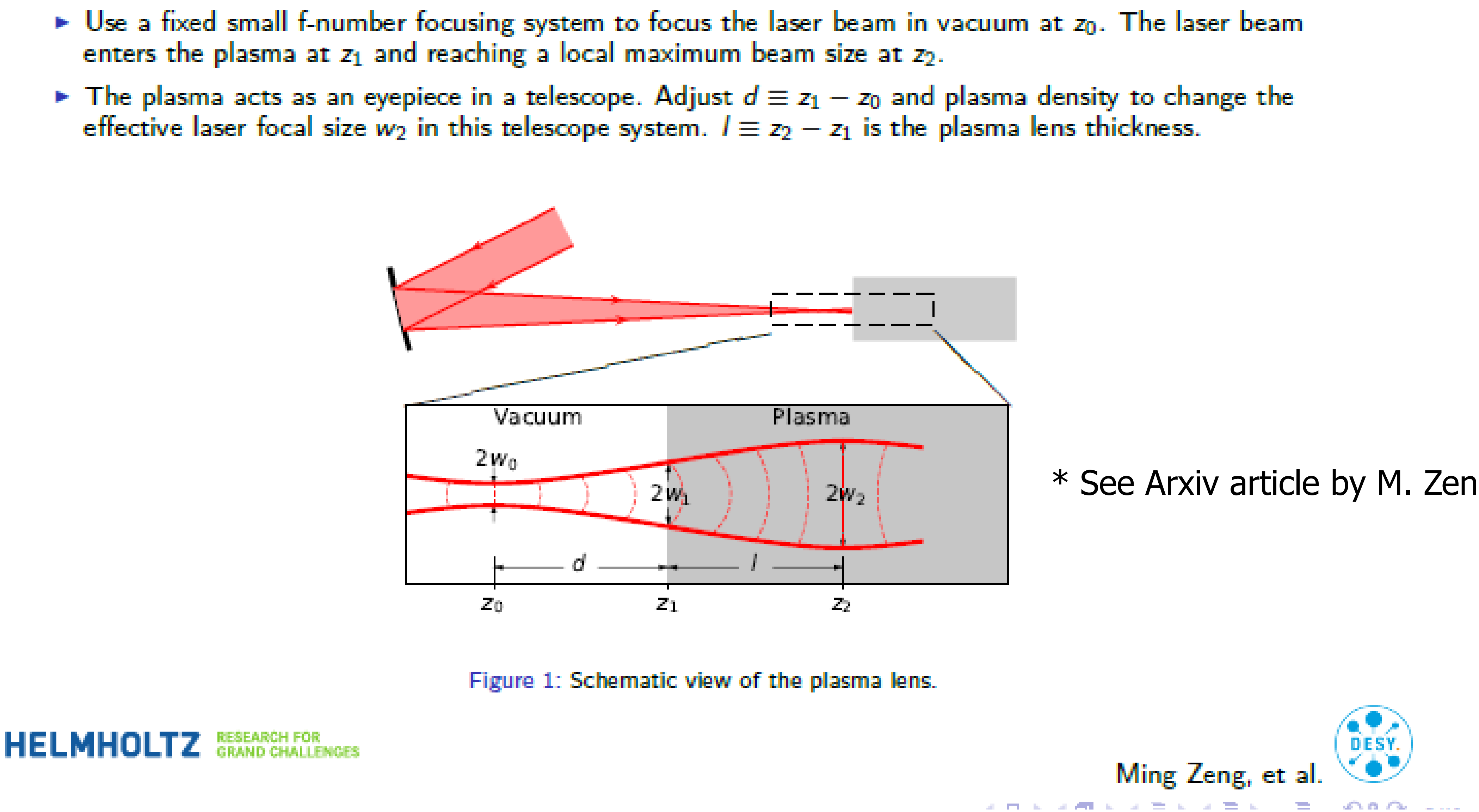
- Fixing the final focusing optic has consequences for energy gain
- Plasma optics can be used to adjust the focusing over a small path length
- Consider 2.5 PW laser pulse as an example

Focal spot	**eA/mc^2**	**Energy (GeV)**	**Pulse Length (fs)**	**Plasma Length (cm)**	**Plasma Density (cm^{-3})**
25 um	10	3.4	100	1.6	1.87×10^{18}
50 um	5	10.2	100	20	0.23×10^{18}

Requires only a weak plasma lens to transform large f-numbers. Moreover for this application stretching of the pulse is actually desirable.



Passive Approach : “plasma eyepiece” concept*



- Use a fixed small f-number focusing system to focus the laser beam in vacuum at z_0. The laser beam enters the plasma at z_1 and reaching a local maximum beam size at z_2.
- The plasma acts as an eyepiece in a telescope. Adjust $d \equiv z_1 - z_0$ and plasma density to change the effective laser focal size w_2 in this telescope system. $l \equiv z_2 - z_1$ is the plasma lens thickness.

Figure 1: Schematic view of the plasma lens.

Ming Zeng, et al.

* See Arxiv article by M. Zeng et al., 2019

Basic Principle of an "Active" Optical Plasma Lens*

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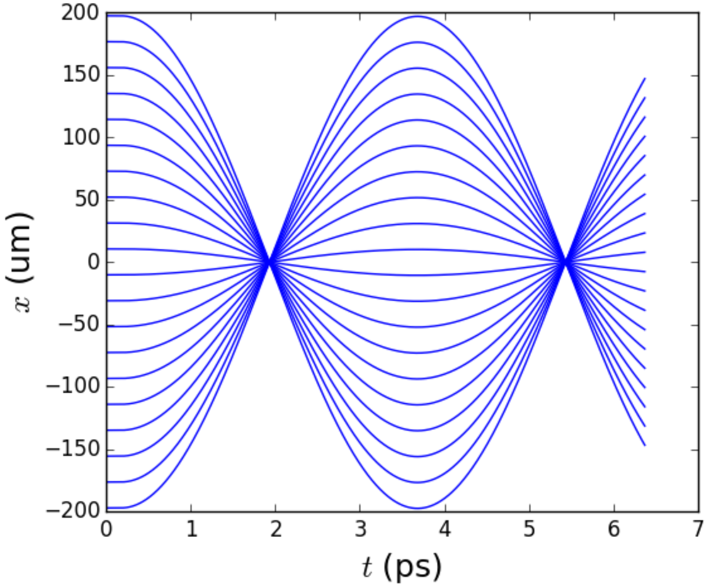
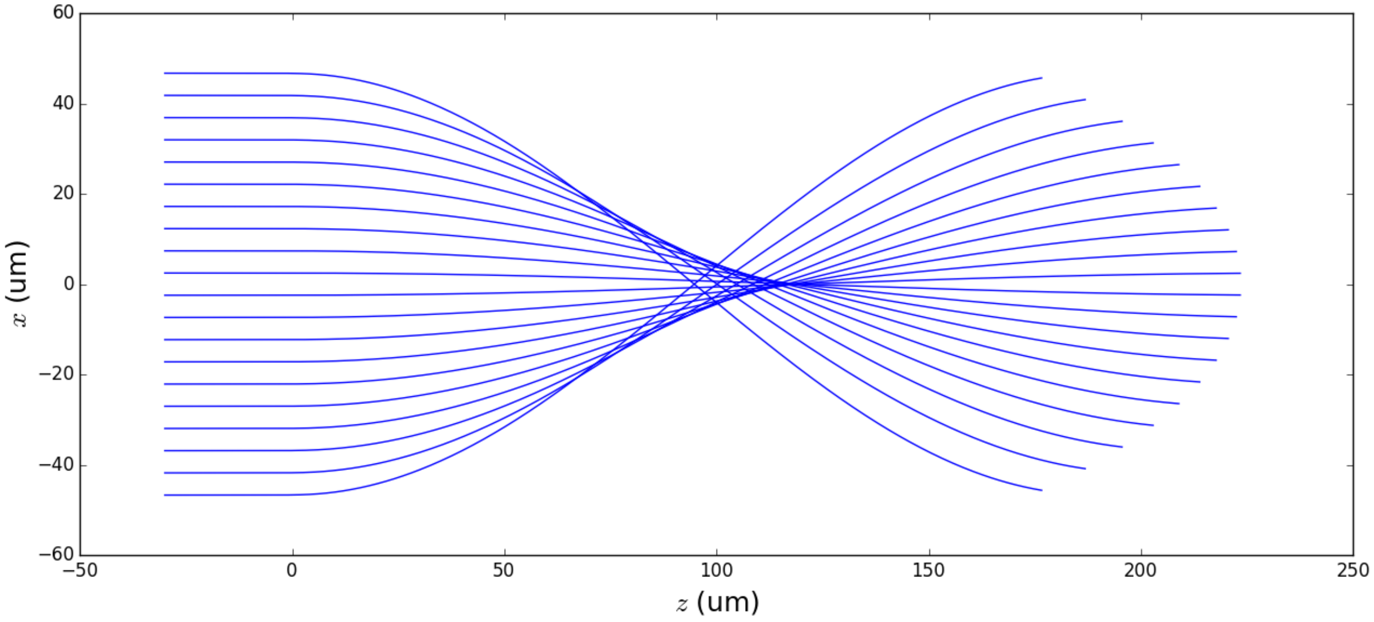
Parabolic channel $n(r) = n_0 + \frac{\Omega^2}{c^2} r^2$ leads to ray equation $\frac{d^2 r}{dt^2} + \Omega^2 r = 0$ $\Omega^2 = \frac{c^2}{r_{\mathrm{ch}}^2} \frac{\Delta n}{n_0} \frac{\omega_p^2}{\omega^2}$

Focusing is synchronous in ray time



However marginal rays are over-focused



* R. Hubbard et al., Phys. Plasmas 9, 1431 (2002)

Eikonal Treatment of Plasma Lens Problem

- Ray tracing with eikonal field reconstruction is a natural ”glue” that can be used to stitch together varying solutions in different regions
- Amplitude and phase can be reconstructed from rays

Apart from the usual Hamiltonian equations of motion we have:

$$\frac{d}{dt}\log\left(a\Lambda^{1/2}\right)=0$$

Amplitude equation, Λ = ray volume

$$\frac{d\psi}{dt}=\frac{d\mathbf{r}}{dt}\cdot\mathbf{k}$$

Phase evolution

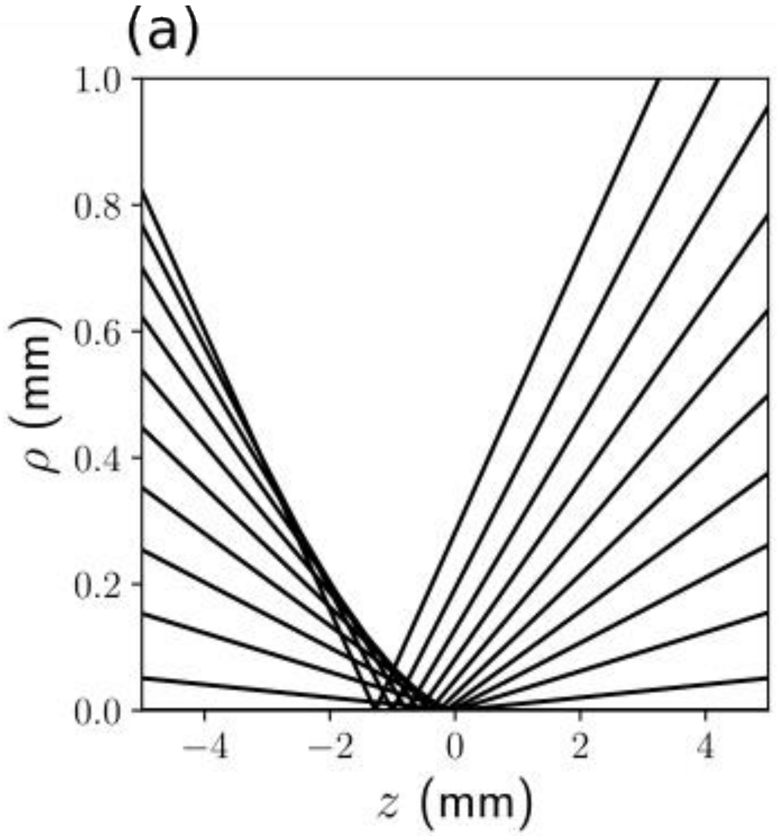
$$\frac{d\mathbf{e}_1}{dt}=\left(\mathbf{n}\times\frac{d\mathbf{n}}{dt}\right)\times\mathbf{e}_1$$

Polarization evolution (degenerate medium)

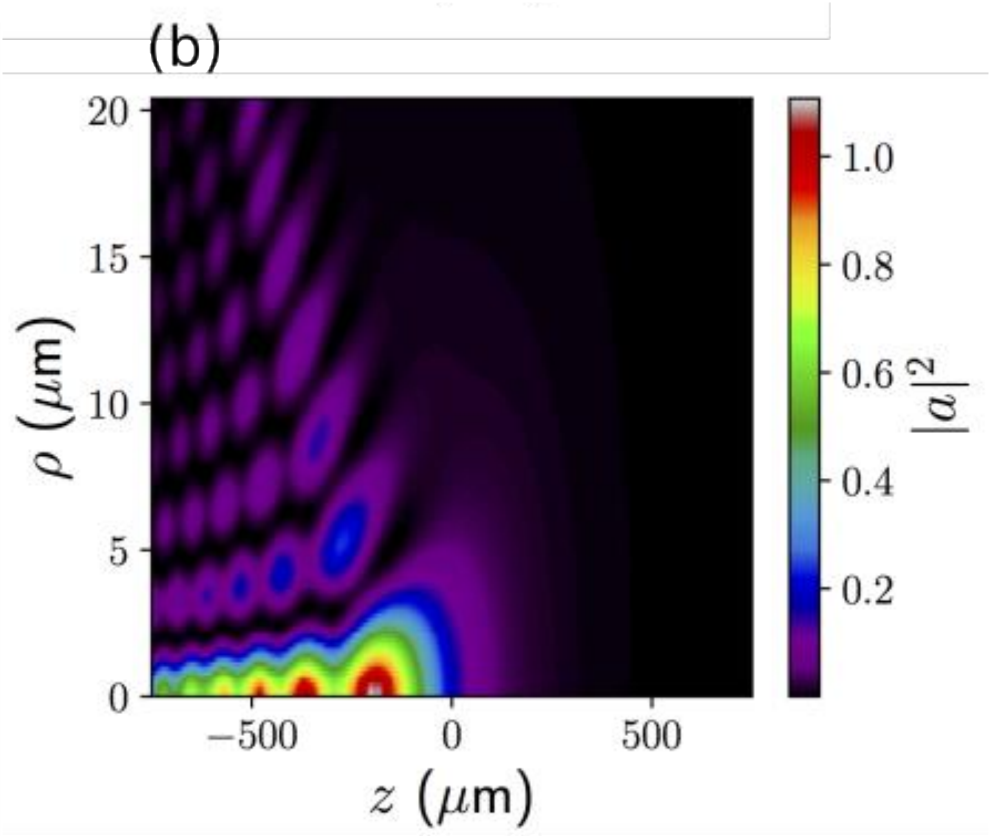
See, e.g., E. Tracy et al., *Ray Tracing and Beyond*

Example of Spherical Aberration with f/3 Lens

Ray tracing through a parabolic plasma channel lens



Projection of eikonal fields into the wave zone



Can be greatly improved by adding quartic term, but we will go right to the ideal forms.

Ideal Form Plasma Lenses from Eikonal Analysis

The eikonal equation is a nonlinear equation in the phase:

$$\nabla\psi \cdot \nabla\psi = k^2(\omega, \mathbf{r})$$

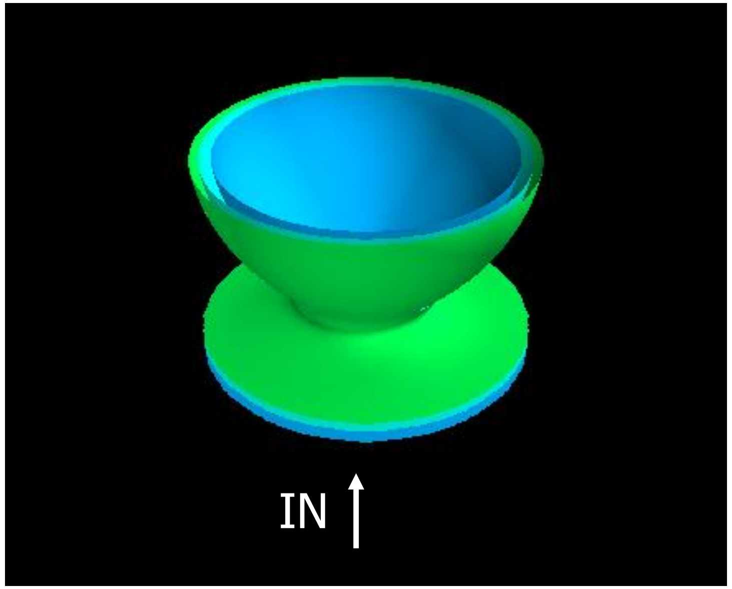
Seems to be worse than the linear wave equation. But turn it around, and we get something useful:

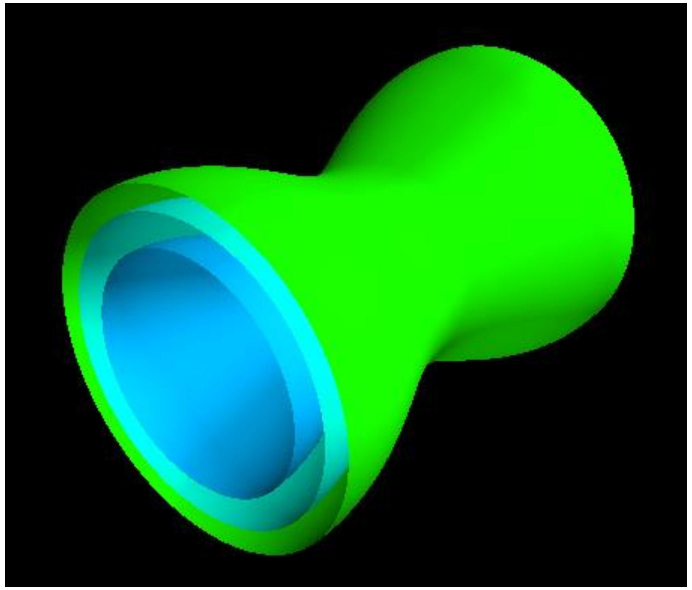
$$\frac{n}{n_c} = 1 - \frac{c^2 \nabla\psi \cdot \nabla\psi}{\omega^2}$$

If we know the phase we want, the required plasma density is determined immediately.

In case of a lens, we want the outgoing phase fronts to be spherical.

Types of Ideal Form Plasma Lenses





“Teacup” focusing lens:
Plane wave in
Converging wave out

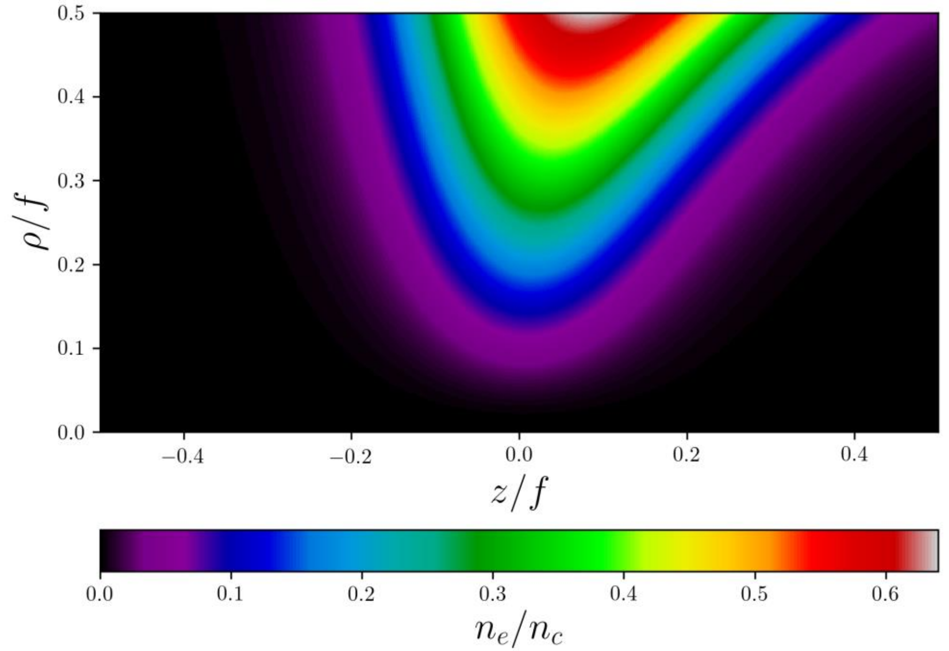
“Hourglass” imaging lens:
Plane wave in
Converging wave out

Cf. plano-convex conventional lens

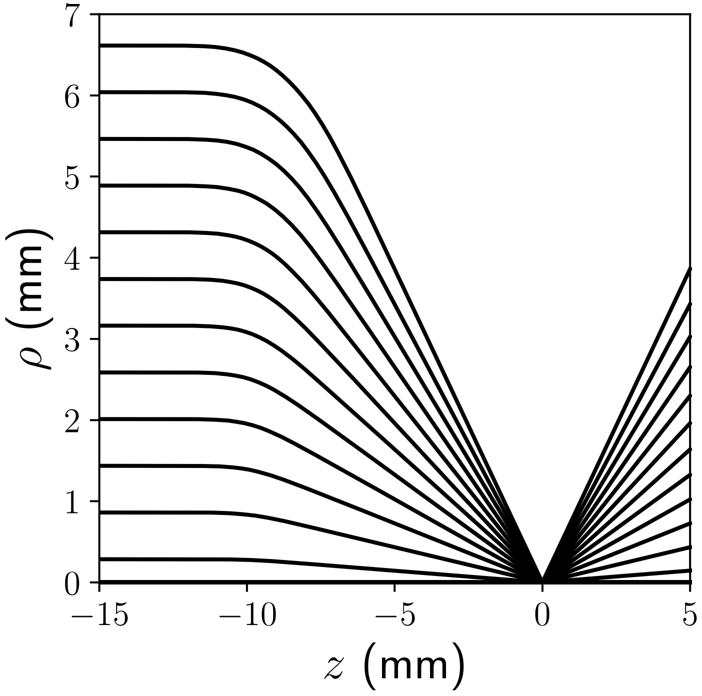
Cf. bi-convex conventional lens

Ideal Form Focusing Lens Ray Tracing

Density structure of F/1 ideal lens



Ray tracing through ideal plasma lens



Plasma Lenses : Chromatic aberration for a 25 fs pulse

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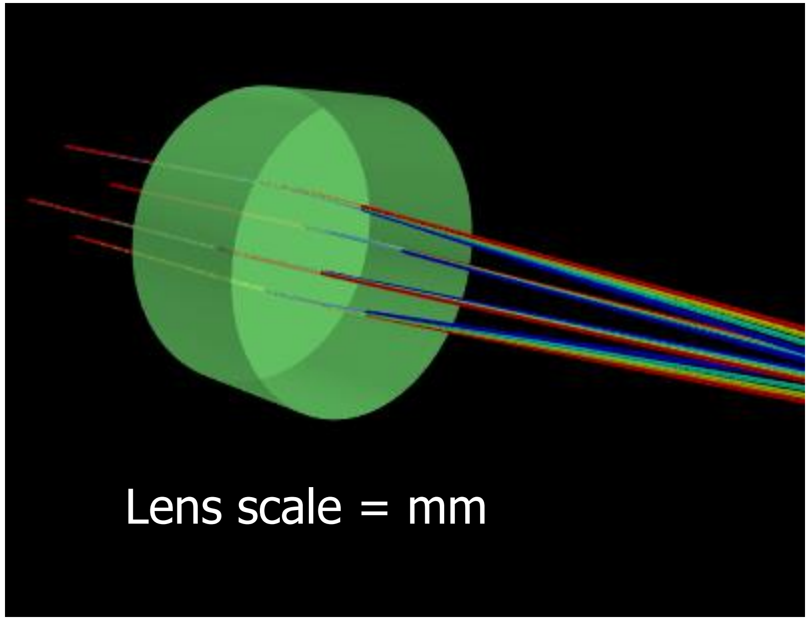
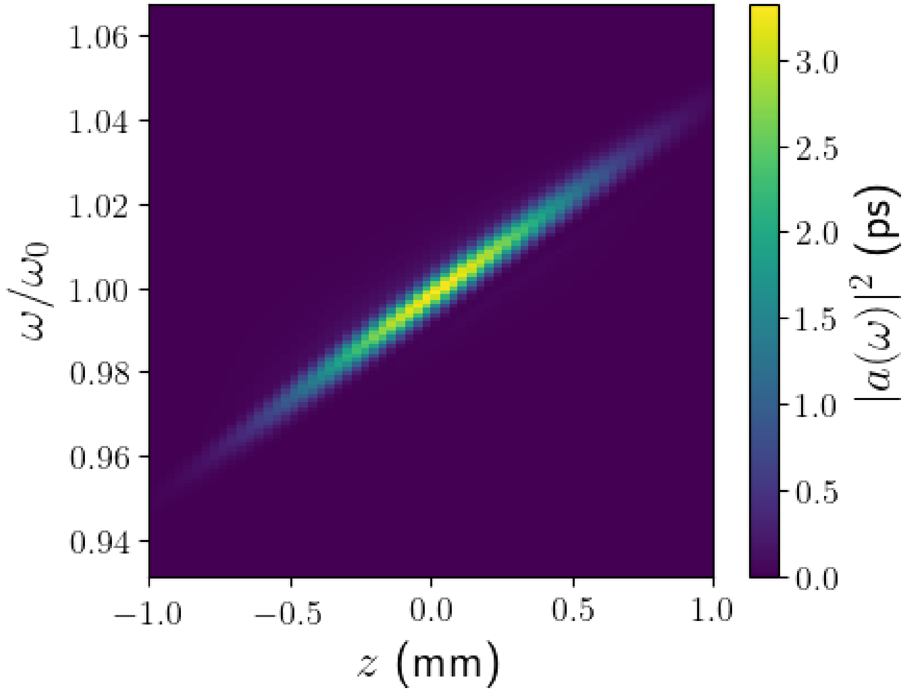
- We showed that in principle all spherical aberration can be eliminated*
- Dispersive effects are much more challenging, especially for strong focusing
- For the shortest pulses the effect is large

f/5 quartic plasma lens showing frequency resolved rays.



Chromatic aberration of f/5 quartic plasma lens (spectral intensity vs. z)



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* D.F. Gordon et al., Phys. Plasmas 25, 063101 (2018)

Plasma Lenses : Temporal distortion for a 25 fs pulse

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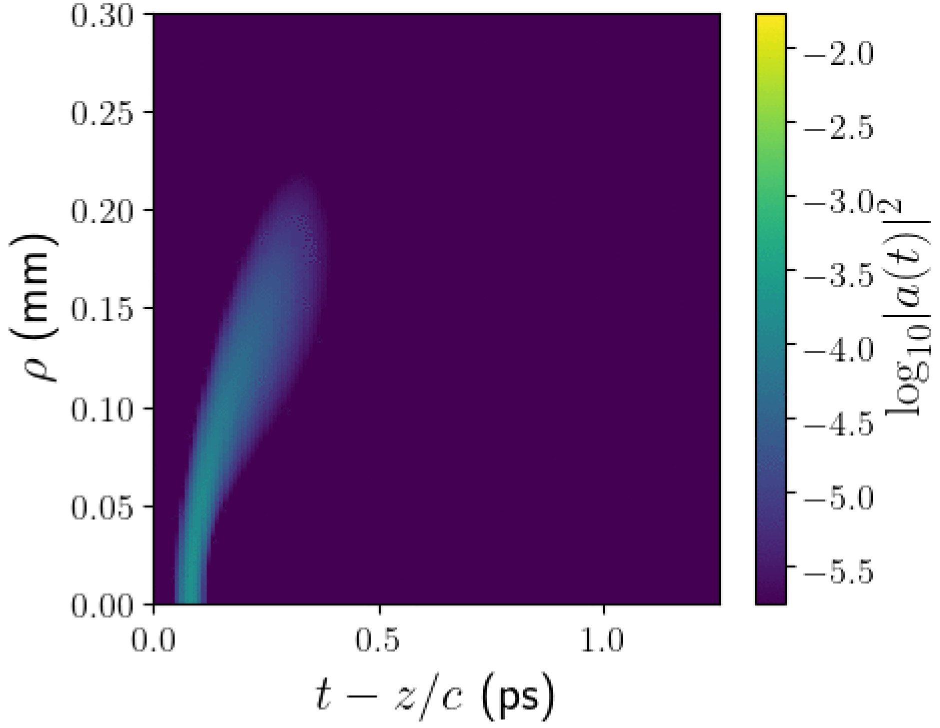
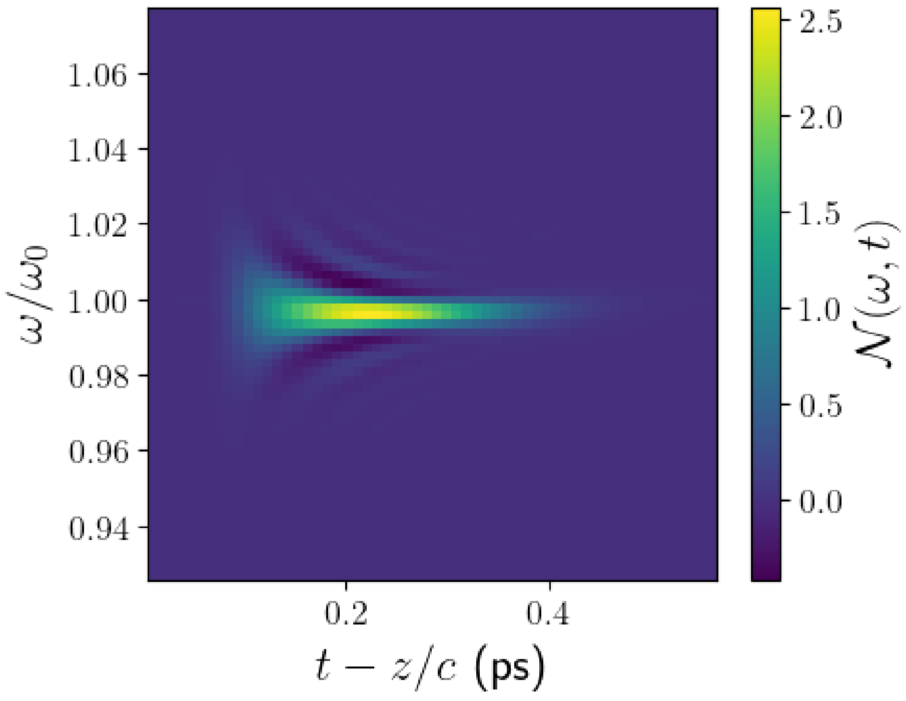
- Unlike a conventional lens, pulse stretching does not become manifest until focal point is reached. The stretched pulse does not have a simple chirp.

Animation of pulse envelope
(f/5 quartic plasma lens)



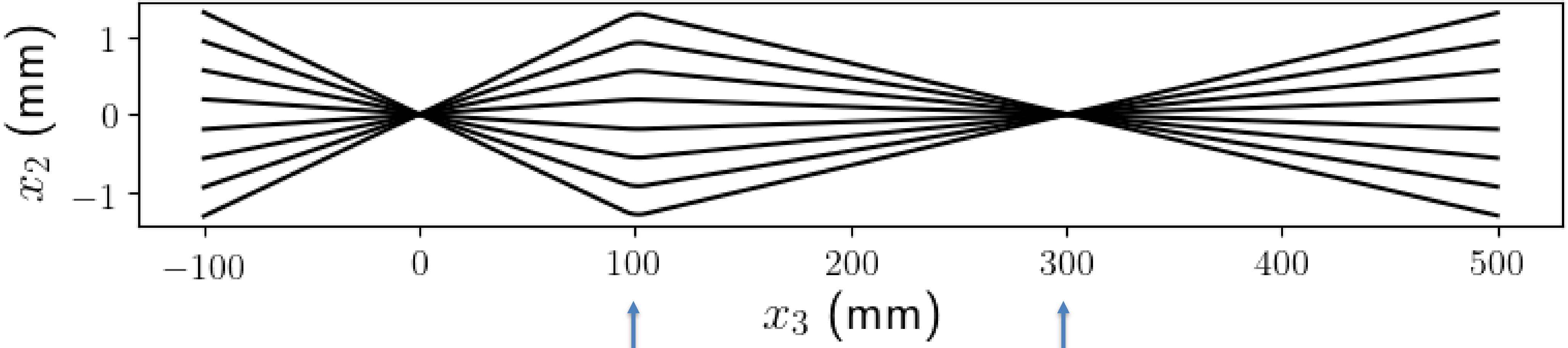
Wigner phase space at best focus.
Stretched, but no chirp in time.
Instead there is transverse structure.



Plasma lens in 2X magnification configuration (f/50 to f/100)

NRL PPD

- To reduce nonlinearity in lens, forced to go to substantial scales
  - Plasma lens dimensions ~ 1 cm, magnification system dimensions ~ ½ meter
  - Even so, eA/mc^2 ~ 0.5 at a few PW, will ionize and drive significant wakes



Plasma lens

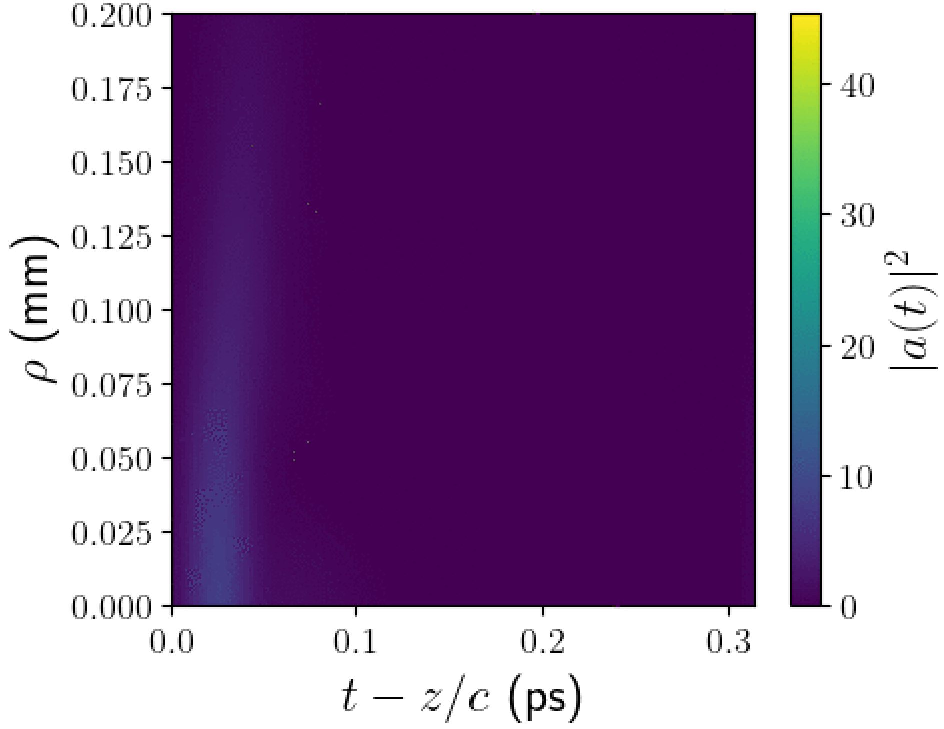
Gas cell starts here

Plasma lens in 2X magnification configuration (f/50 to f/100)

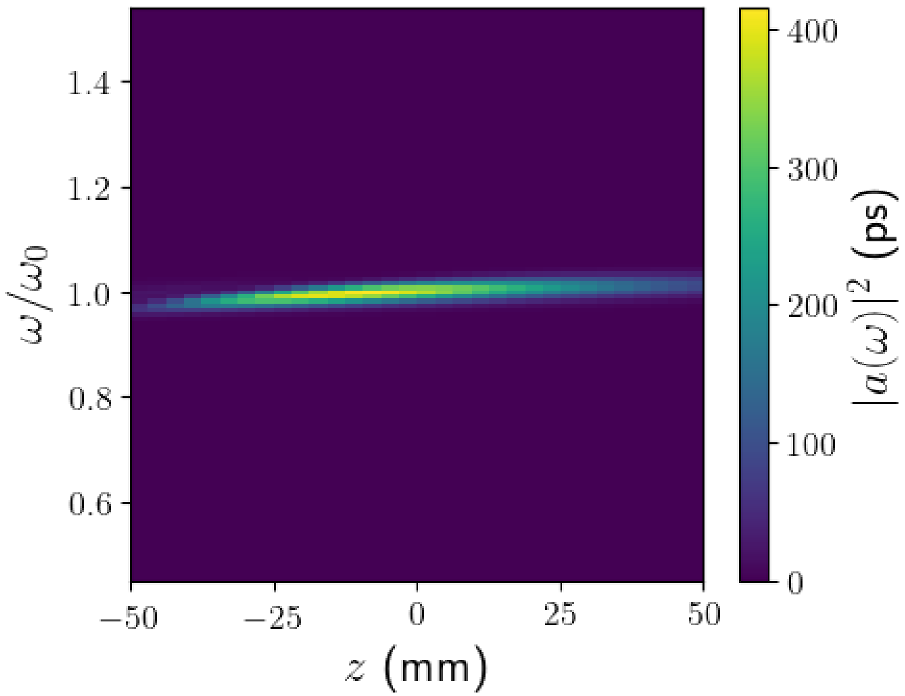
NRL PPD

- Investigate dispersion of a 25 fs pulse
- Expect stretching and transverse mode distortion

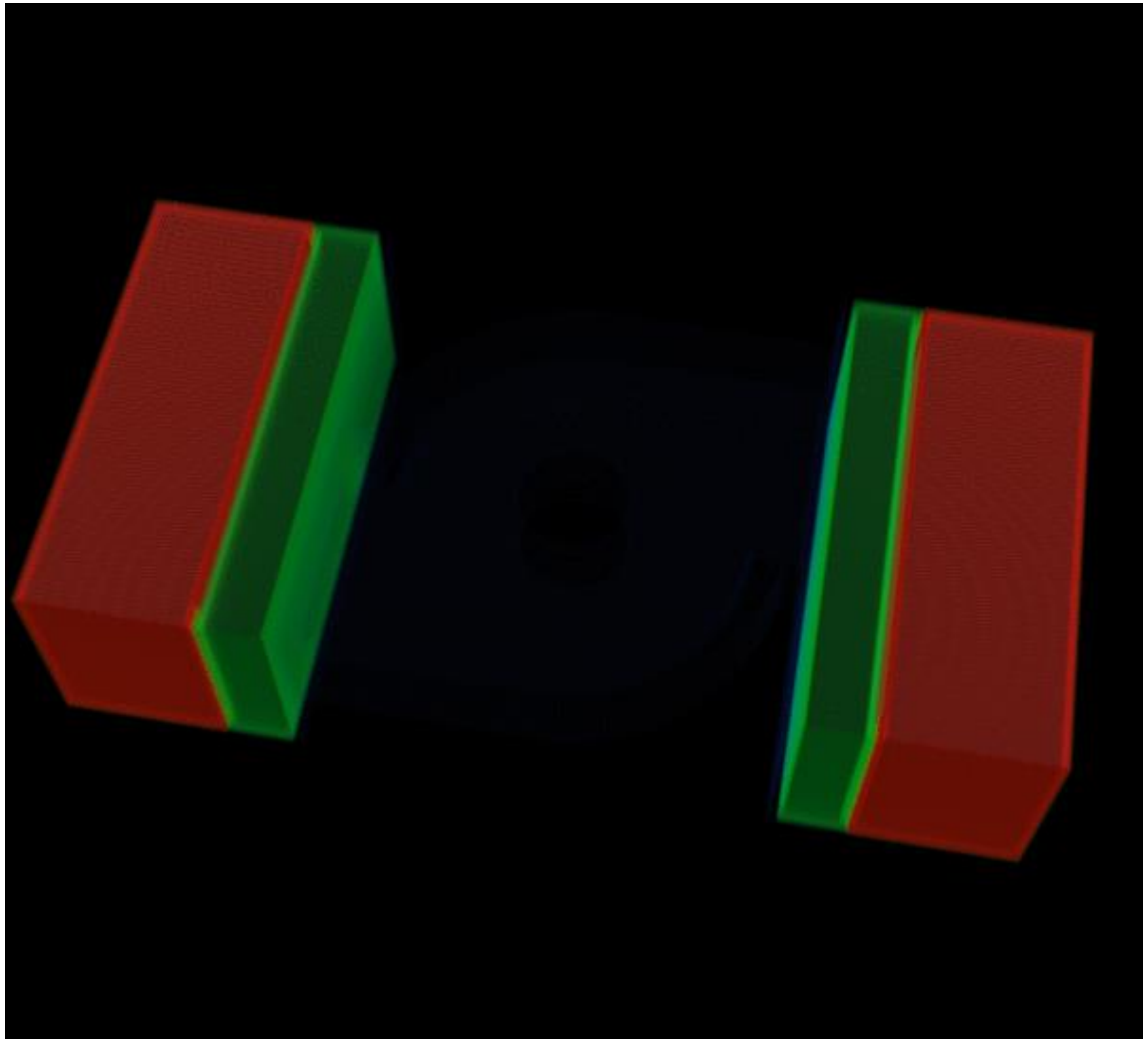
Animation of envelope: ideal focusing would give a^2=100



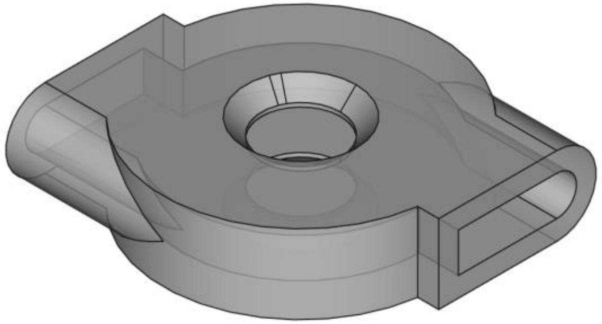
Chromatic aberration: not significant compared with z_R



Realization of Plasma Lens

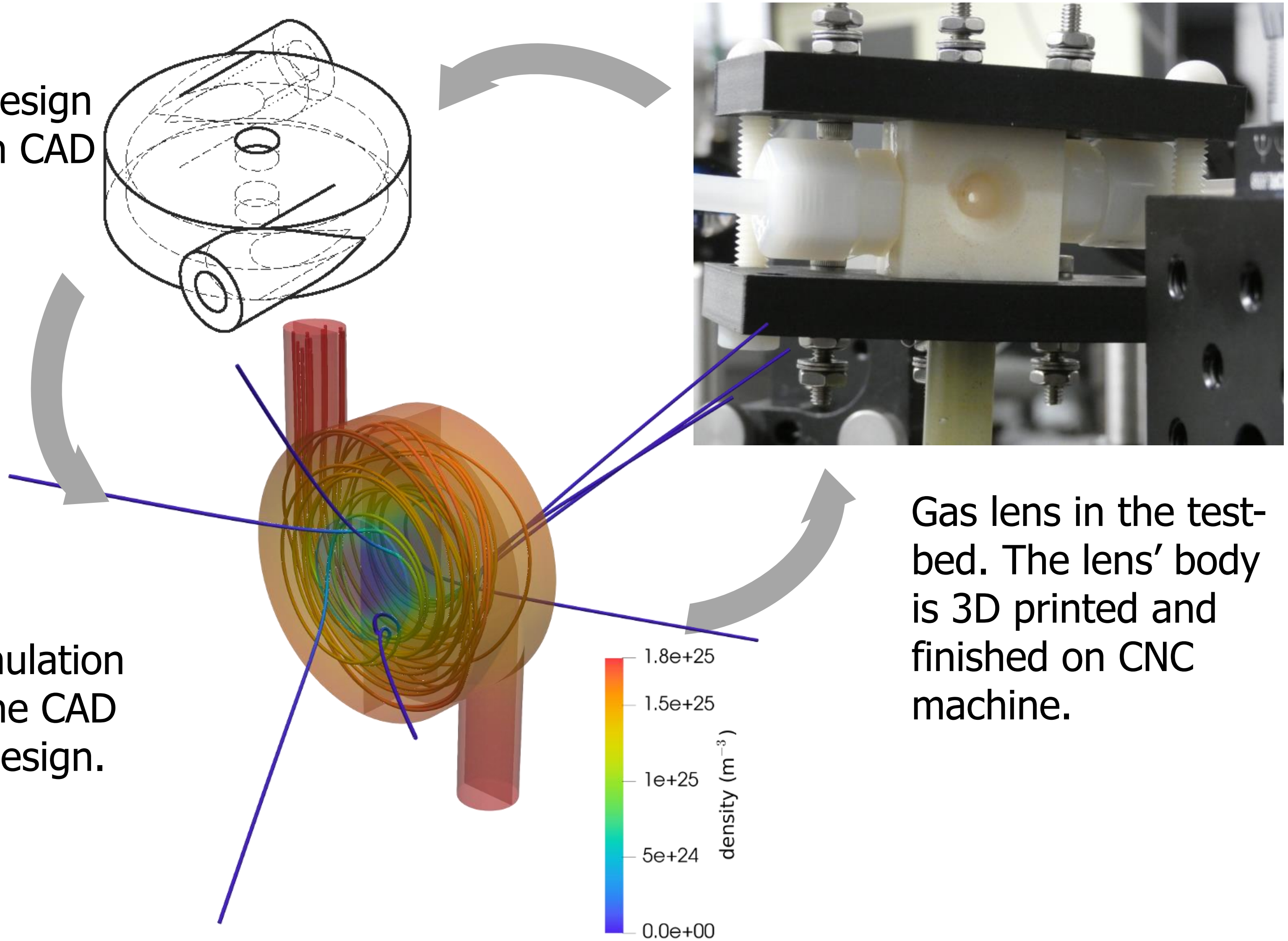


D. Kaganovich et al., Appl. Opt. 57, 9392 (2018)



The laser guiding structure employs colliding gas streams to generate a gas channel. It employ two or more gas jet nozzles with equal angular separation, ejecting gas toward a common axis. When the gas jets are synchronized and set to the same backing pressure, a symmetric rotational density profile is formed along the central axis.

Plasma Lens Development Cycle

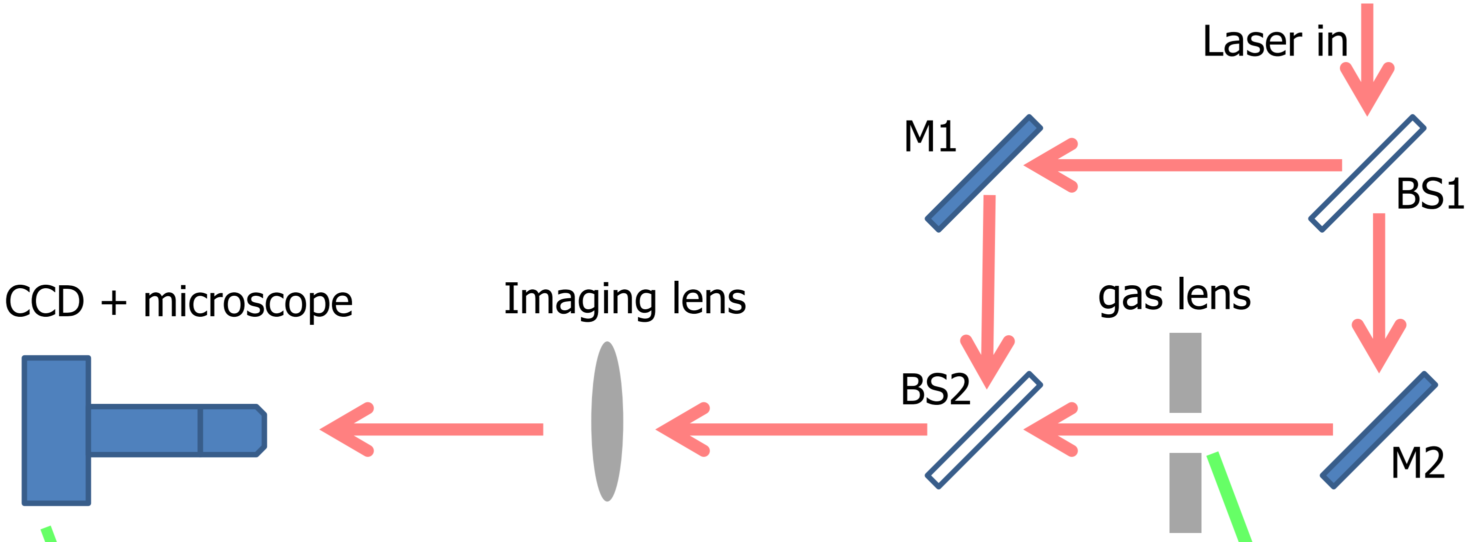


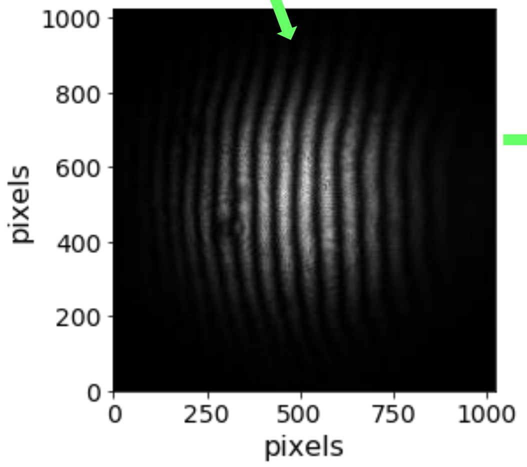
Lens body design generated in CAD software

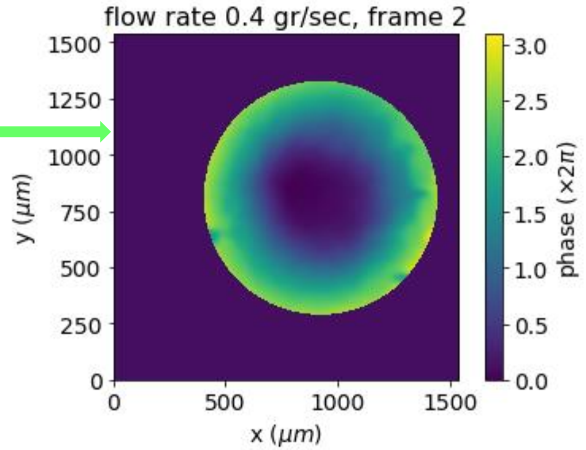
3D CFD simulation based on the CAD geometry design.

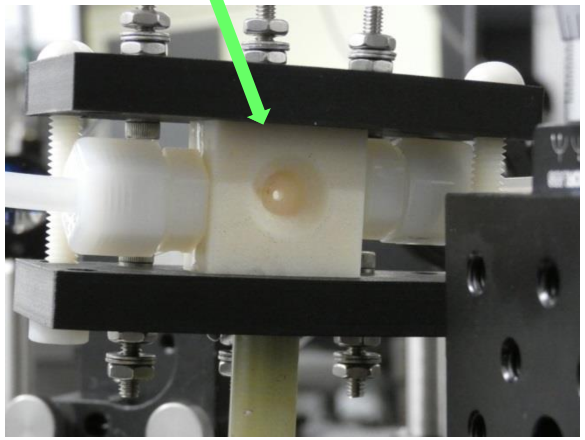
Gas lens in the test-bed. The lens' body is 3D printed and finished on CNC machine.

Interferometry Measurements







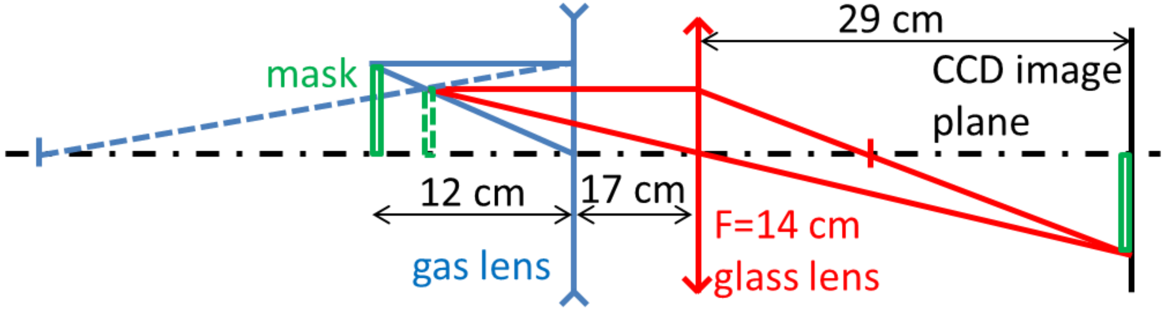


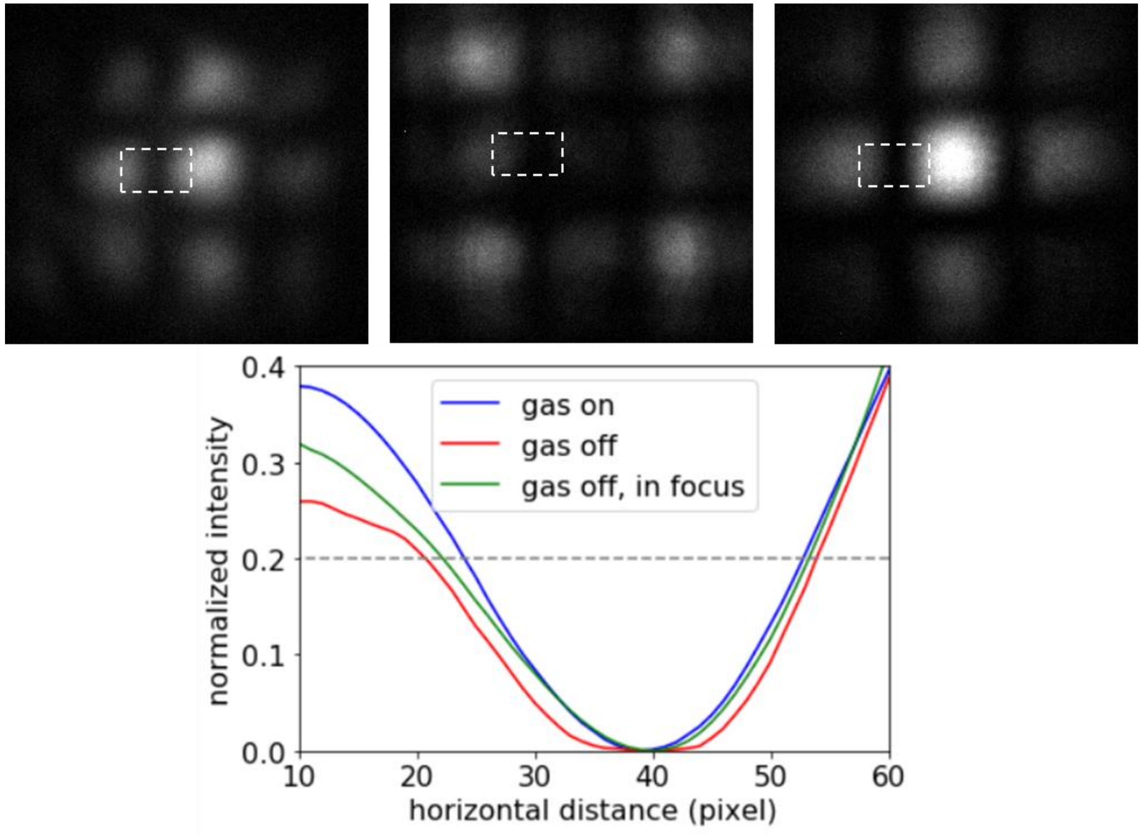
Variable mass flow rate, different geometries

Measurement of focal length of unionized gas

NRL PPD

0.4 g/s N_2 mass flow rate,
1.75 mm clear aperture





5% change in the transition width corresponds to a ±5 mm shift of the image plane

Focal length of the gas lens is calculated to be −67± 18 cm, where ±18 cm is the uncertainty due to the depth of focus

D. Kaganovich, L. A. Johnson, D. F. Gordon, A. Mamonau, B. Hafizi, "Lensing properties of rotational gas flow," Appl. Opt. 57, 9392 (2018).

Conclusions

- Focusing systems for high power lasers present unique challenges
- Not clear at present whether strong focusing is needed for ALIC
    - Presumably only would be needed for an injection concept or positron source
    - Plasma lenses appear to be ineffective for strong focusing of the shortest pulses
    - High rep rate capable plasma mirrors may be crucial
- Weak focusing configurations are needed for LWFA accelerator stages, and the performance depends sensitively on the focused spot size.
    - Passive solution would be to utilize nonlinear effects to match the beam at the plasma entrance
    - Active lenses may offer more control
    - Great deal of work to learn how to control gas flow to create quality lenses