Plasma and Gas Optics for Ultra-Intense Lasers

Matthew R. Edwards

Department of Mechanical Engineering

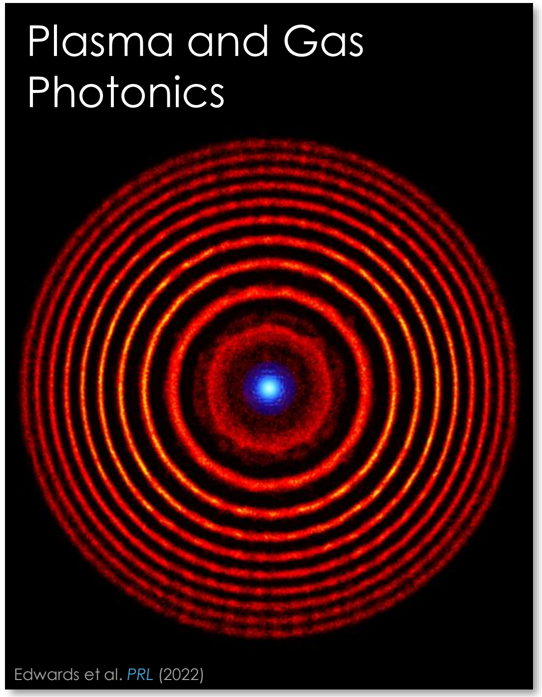
Stanford University

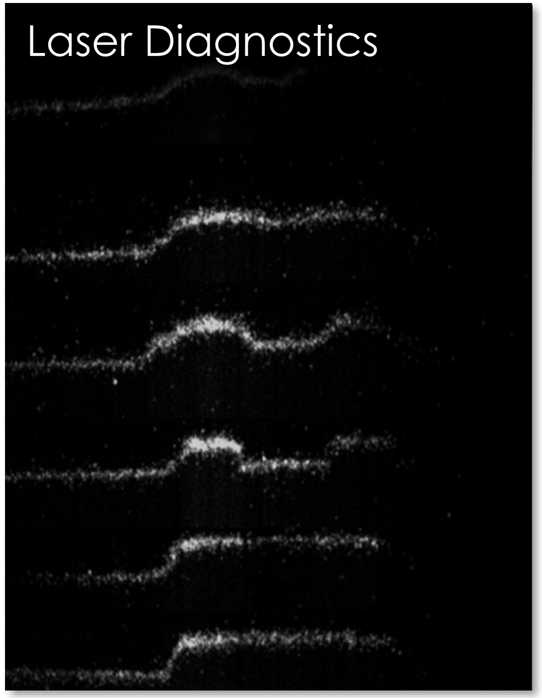
SAPPHIRE | Stanford Applied Plasma Physics & High-Intensity Radiation Engineering

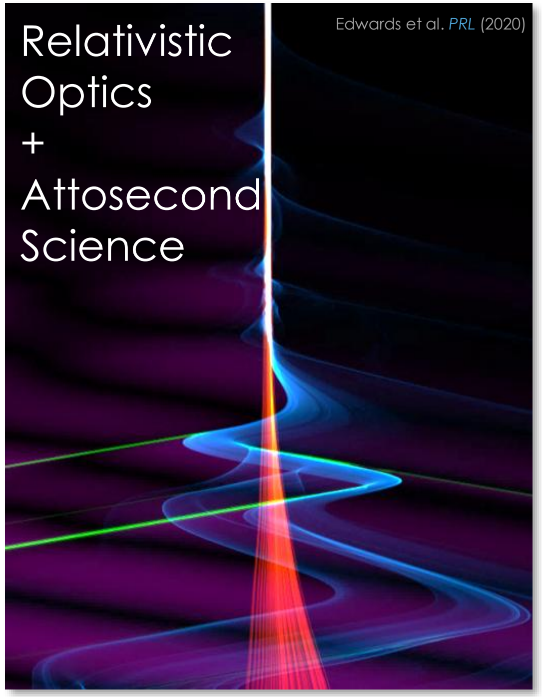
Research Areas:

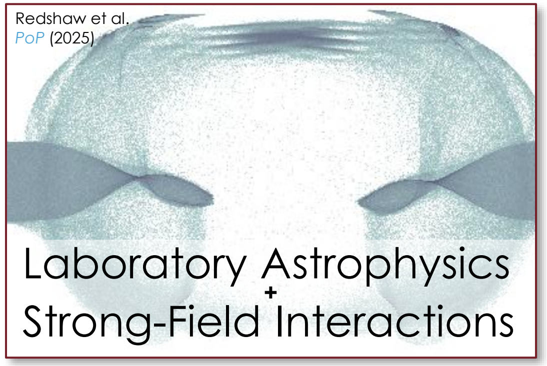
SAPPHIRE | Stanford Applied Plasma Physics & High-Intensity Radiation Engineering

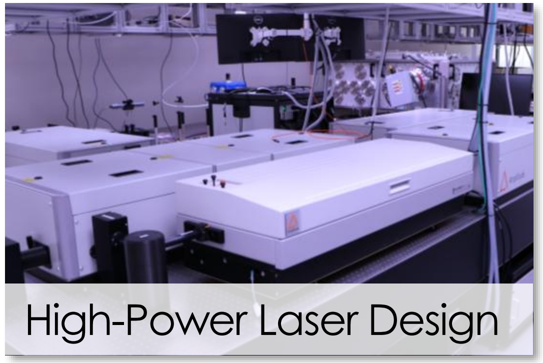
Applications of extreme light in science and technology

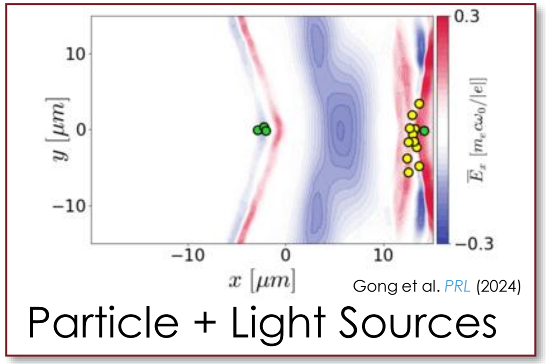






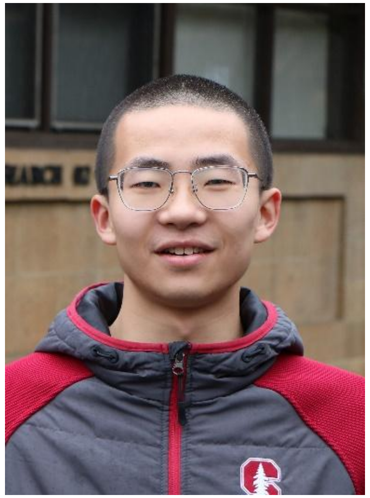




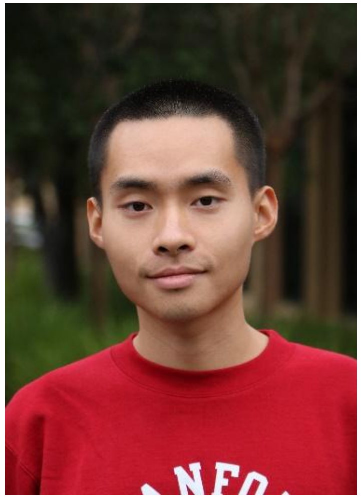


Lab Members

Victor Perez-Ramirez
PhD Candidate



Sida Cao
PhD Candidate



Ke Ou
PhD Candidate

Caleb Redshaw
PhD Candidate

Elaine Koh
PhD Candidate

Dave Singh
PhD Student

Debolina Chakraborty
PhD Student

Harsha Rajesh
PhD Student

Pelin Dedeler
Undergraduate

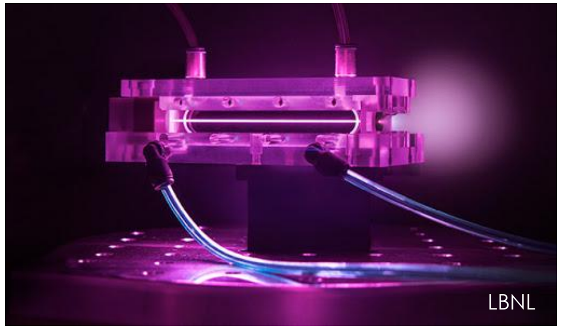
Outline

1. Introduction
   - Extreme Lasers • Plasma Optics • Diffractive Optics
2. Gas Gratings
   - Formation • Optical Properties • Applications
3. Plasma Gratings
   - Contrast Improvement • Plasma Chirped Pulse Amplification
4. Holographic Lenses
   - Focusing High-Power Beams • Generalized Diffractive Plasma Optics

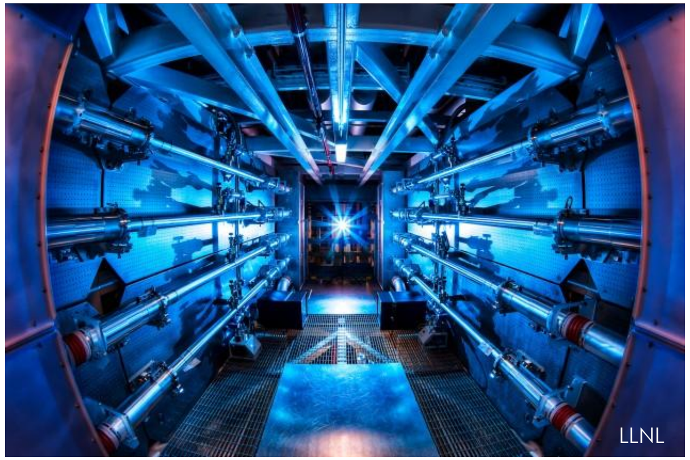
Extreme Lasers

High-Power

Short-pulse (fs) lasers with multi-petawatt peak power.

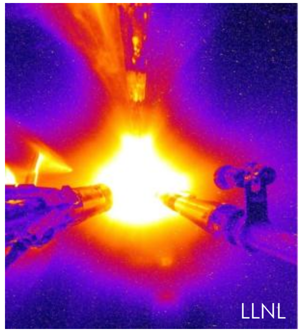


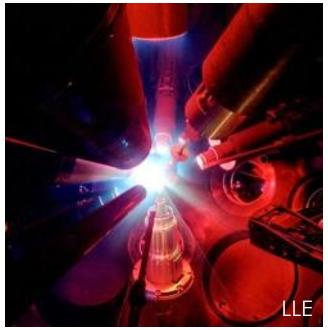
Laser Particle Acceleration
Schwinger Limit Physics
Secondary Radiation



High-Energy

Long-pulse (ps-ns) lasers with up to megajoule energy.

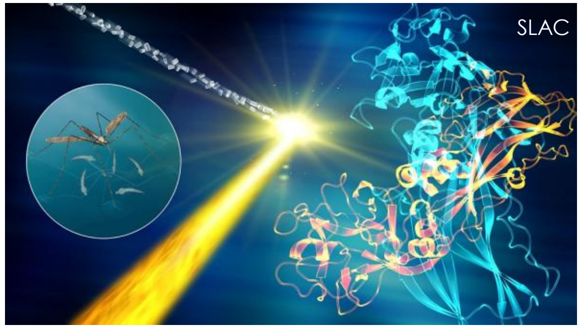




Inertial Confinement Fusion
High Energy Density Science
Laboratory Astrophysics

X-ray

Free-electron lasers produce short (fs) intense x rays.

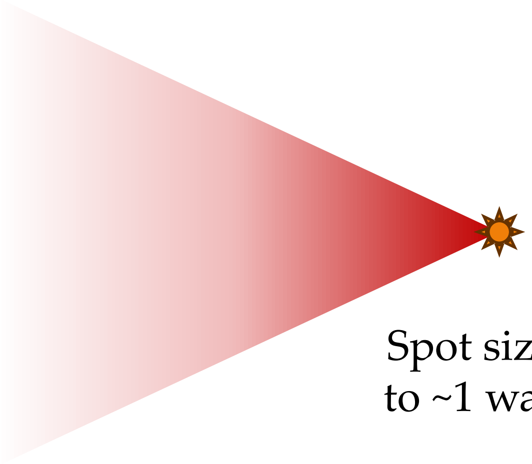


Ultrafast Science
Material Structure
Protein Crystallography

High-Intensity Lasers: Energy, Power, and Intensity

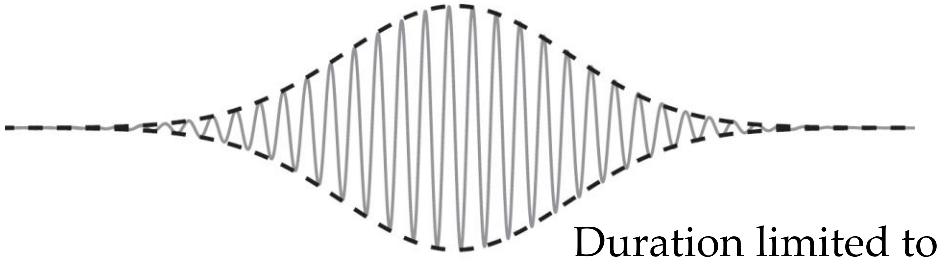
High-intensity lasers deliver moderate energy (~ 10 J) in very short times (10^{-14} s) to very small areas (10^{-7} cm^2), giving extreme intensity (> 10^{22} W/cm^2)

Focusing
(Compression in space)



Spot size limited to ~1 wavelength

Short Pulses
(Compression in time)

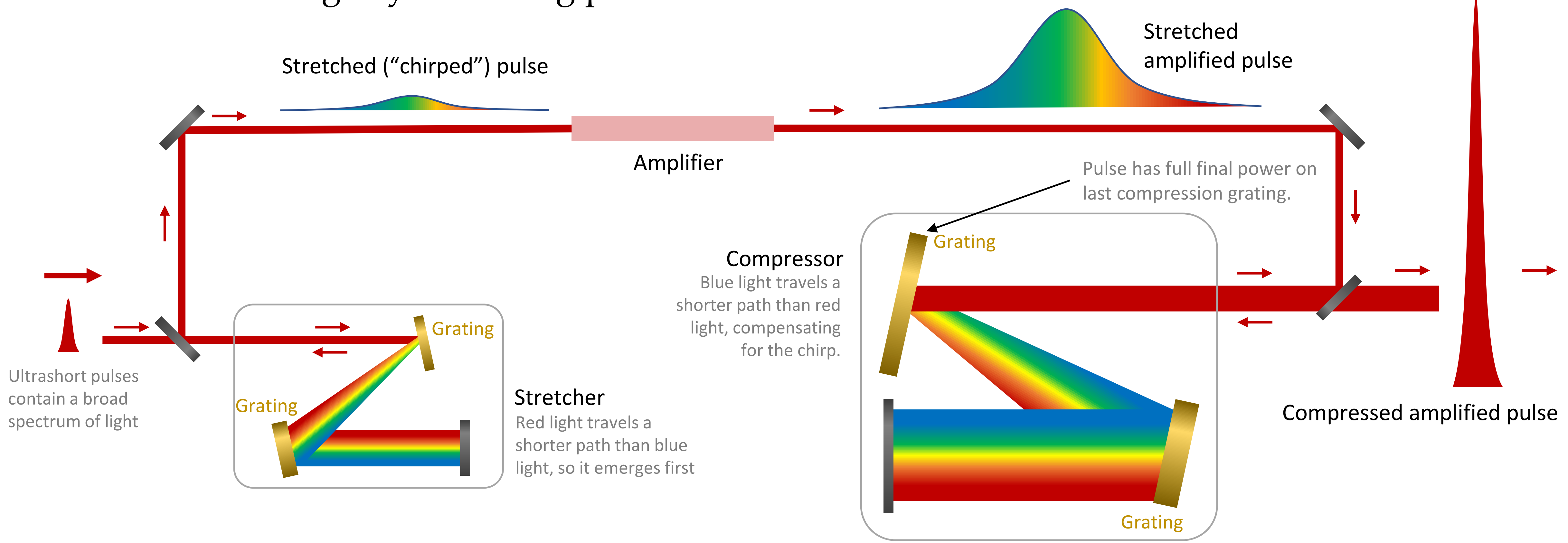


Duration limited to ~1 period (~10 periods more common for high-power systems)

Chirped Pulse Amplification (CPA)

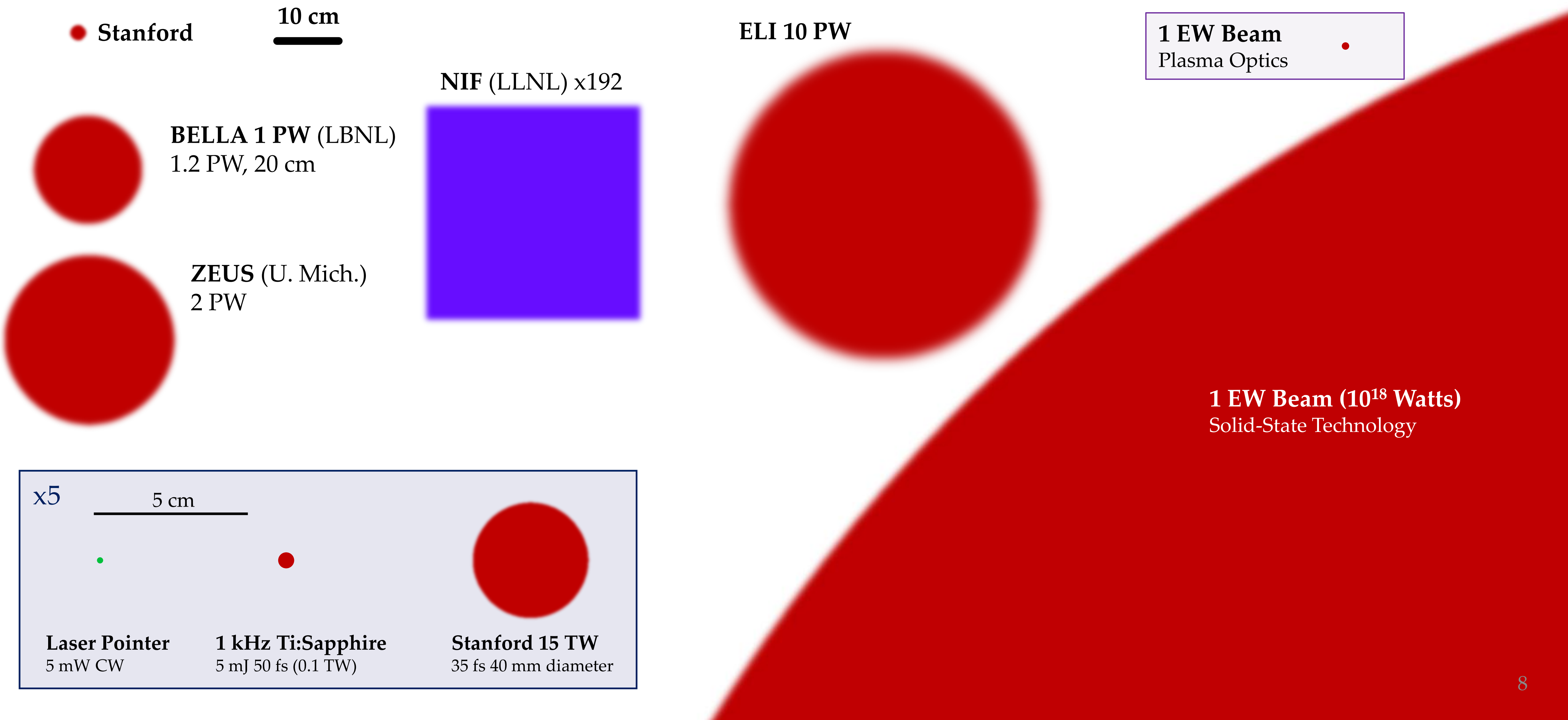
Avoids damage by stretching pulses in time

½ the 2018 Nobel Prize in Physics was awarded to Donna Strickland and Gérard Mourou for the invention of CPA.



To improve overall system performance, we can start by replacing final grating with a high-damage-threshold optic.

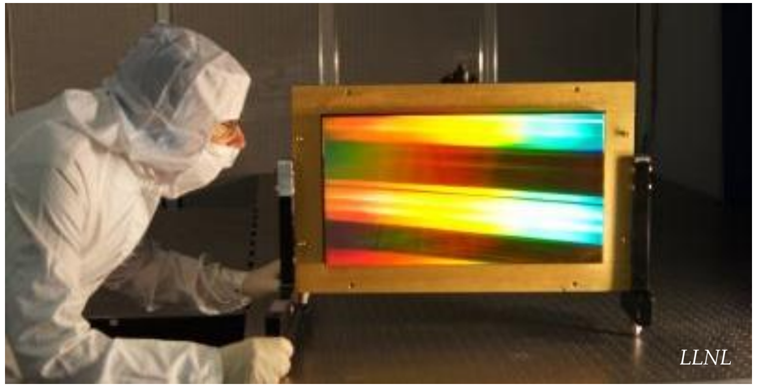
The Challenge of Building High-Peak-Power Lasers



How would <u>you</u> build an exawatt laser?

+ high-repetition-rate (>> kHz) high-peak-power (> 1 PW) systems?

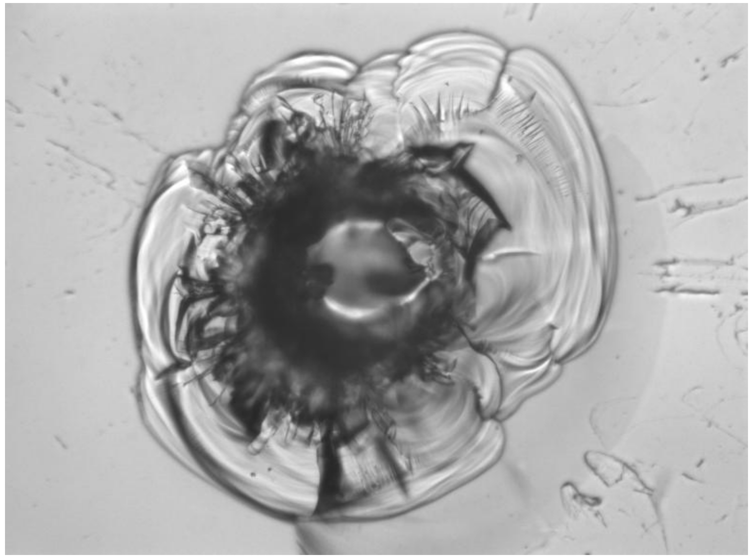
Solid-state limited to **<10^{12} W/cm^2**



Optical damage sets a minimum size on compression gratings and post-compression optics.

At 10^{18} W (1 EW), a threshold of 10^{12} W/cm^2 requires 100 m^2

For intensities significantly above 10^{13} W/cm^2, we must use plasma.

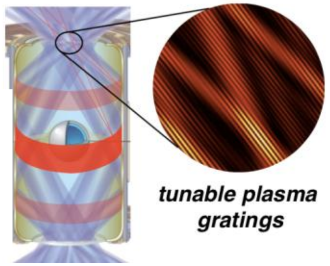


Plasmas support far higher light intensities than solids ($10^3 - 10^6\ \times$), so optics built from plasmas *could* allow compact ultra-high-power lasers.

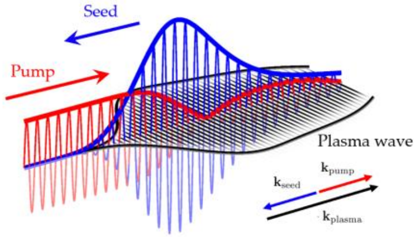
Plasma and Gas Optics

CBET for ICF

Michel et al. *Phys. Rev. Lett.* (2009).
Glenzer et al. *Science* (2010).
Moody et al. *Nat. Phys.* (2012).



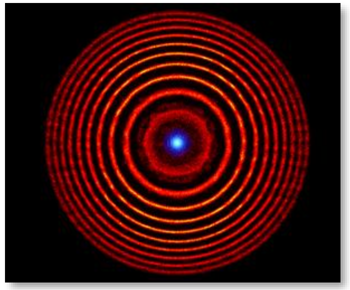
Raman and Brillouin Amplifiers



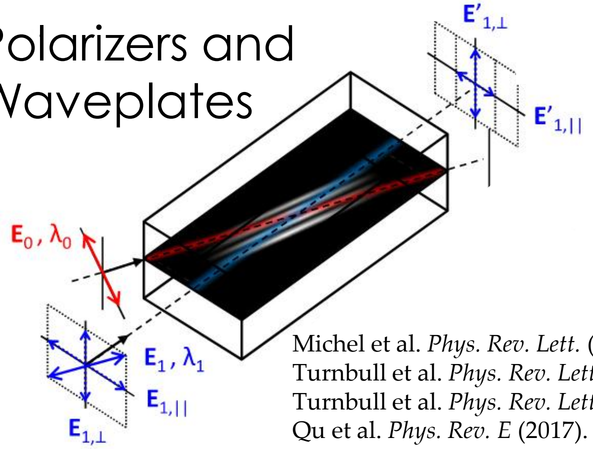
Trines et al. *Nat. Phys.* (2011).
Malkin et al. *Phys. Rev. Lett.* (1999).
Ping et al. *Phys. Rev. Lett.* (2004).
Andreev et al. *Phys Plasmas* (2006).
Edwards et al. *Phys. Plasmas* (2016).
Turnbull et al. *Phys. Rev. Lett* (2018).
Marques et al. *Phys. Rev. X* (2019).
Alves et al. *Plasma Phys. Control. F.* (2021).

Plasma Lenses

Palastro et al. *Phys. Plasmas* (2015).
Gordon et al. *Phys. Plasmas* (2018).
Lehmann et al. *Phys. Rev. E* (2019).
Edwards et al. *Phys. Rev. Lett.* (2022).

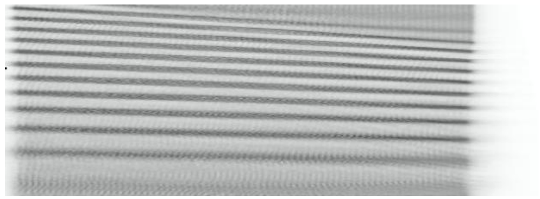


Polarizers and Waveplates



Michel et al. *Phys. Rev. Lett.* (2014).
Turnbull et al. *Phys. Rev. Lett.* (2016).
Turnbull et al. *Phys. Rev. Lett.* (2017).
Qu et al. *Phys. Rev. E* (2017).

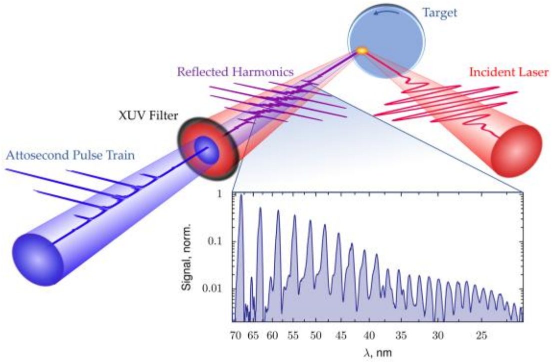
Plasma Gratings and Photonic Crystals



Lehmann et al. *Phys. Rev. Lett.* (2016).
Suntsov et al. *Appl. Phys. Lett.* (2009).
Peng et al. *Phys. Rev. E* (2019).
Edwards et al. *Optica* (2023).

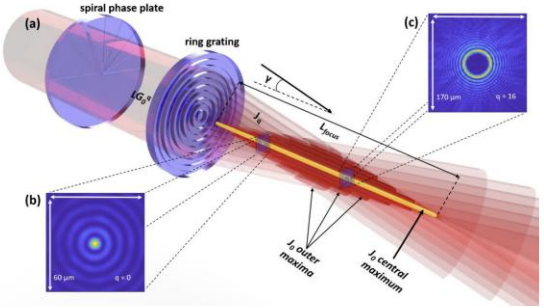
Plasma Mirrors

Murnane et al. *Phys. Rev. Lett.* (1989).
Thaury et al., *Nat. Phys.* (2007).
Mikhailova et al., *Opt. Lett.* (2011).
Edwards and Mikhailova, *Sci. Rep.* (2020).



Plasma Waveguides

Lemos et al. *Sci. Rep.* (2018)
Miao et al. *Phys. Rev. Lett* (2020).
Schrock et al. *Phys. Plasmas* (2022).



Plasma optics must be robust to plasma inhomogeneity, non-ideality, and kinetic effects.

Plasma and Gas Optics: Requirements

High damage tolerance: If the damage threshold is low, we might as well use a standard optic

High repetition rate: → Gas (or liquid) targets

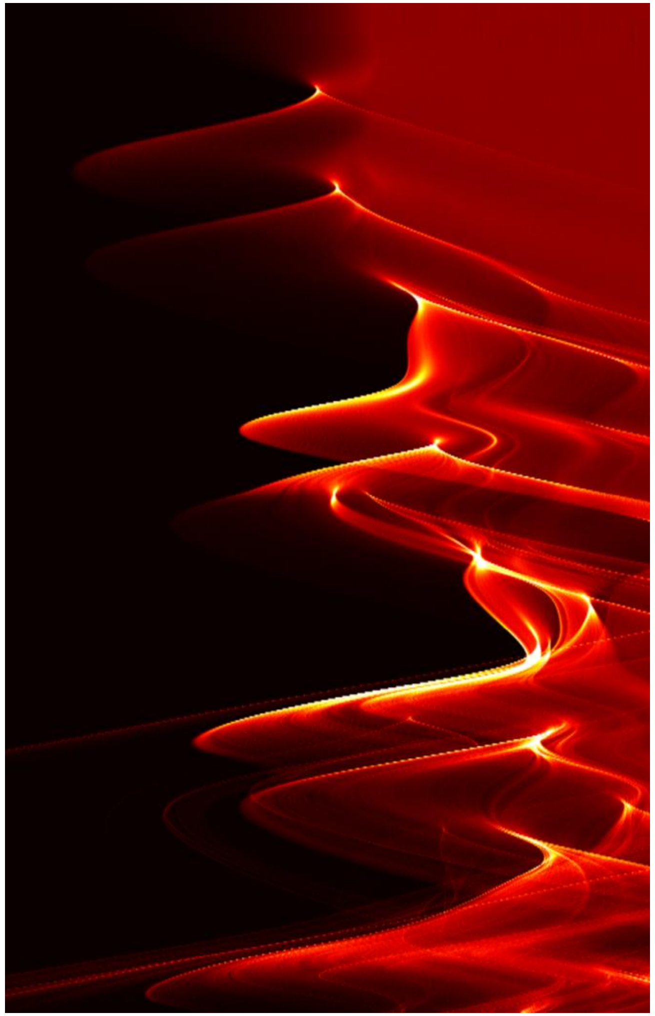
Optical quality: → laser shaped plasmas

'Cheap' to form: We are not going to get anywhere if we need a 10 PW laser to make an optic for a 1 PW laser.

Minimized nonlinearity and distortion: The beam leaving a plasma optic still needs to be usable.

Broad spectrum: Compatible with femtosecond pulses.

Robust and stable: Especially important for pulse pointing and duration. A challenge for plasmas.



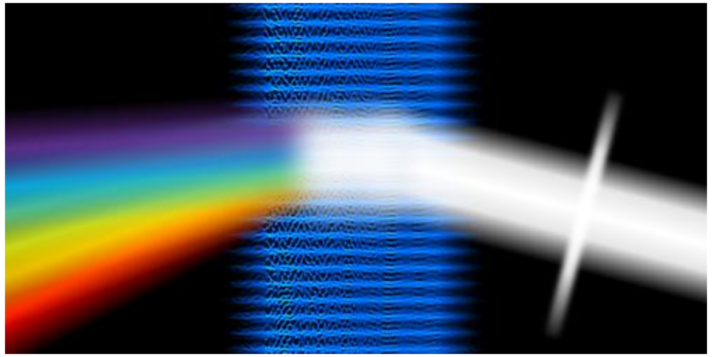
Today's Approach

Volumetric diffractive plasma optics:
Periodic patterns of plasma act as optical elements

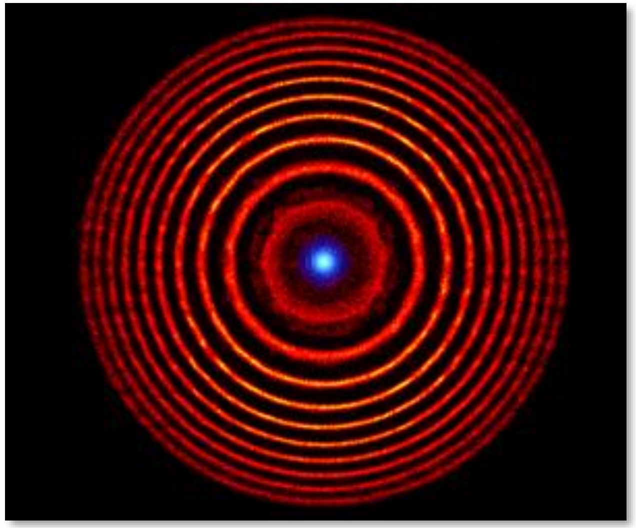
"Plasma gratings" or "Photonic crystals"

Advantages:

- Linear optics (minimal instabilities)
- Optical properties depend on location of plasma more strongly than density
- Transmissive optics require only gas density plasma



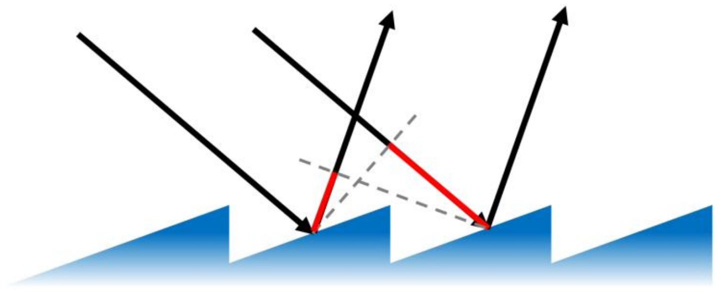
Plasma Transmission Grating

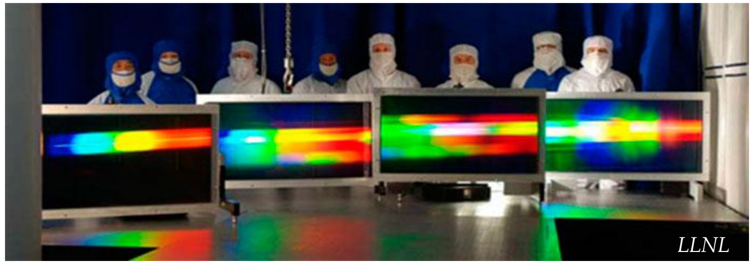


Plasma Diffractive Lens

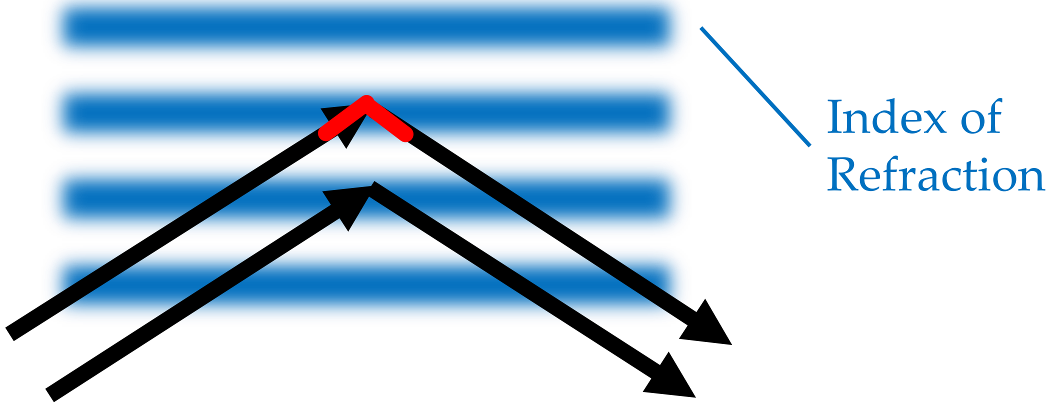
Diffractive Optics

Surface gratings





Volume grating: periodic variation of refractive index diffracts light with specific angle and wavelength.



Light incident at the **Bragg angle** will be efficiently diffracted:

$$\sin \boldsymbol{\theta_B} = \frac{\lambda_1}{2n_0\Lambda}$$

Probe wavelength

Grating period (wavelength)

Bragg Transmission Grating Efficiency

A Bragg transmission grating can diffract to one order with up to 100% efficiency

Efficiency

Coupling coefficient

Grating thickness

$$\eta_1 = \frac{\sin^2(\kappa D B)}{B^2}$$

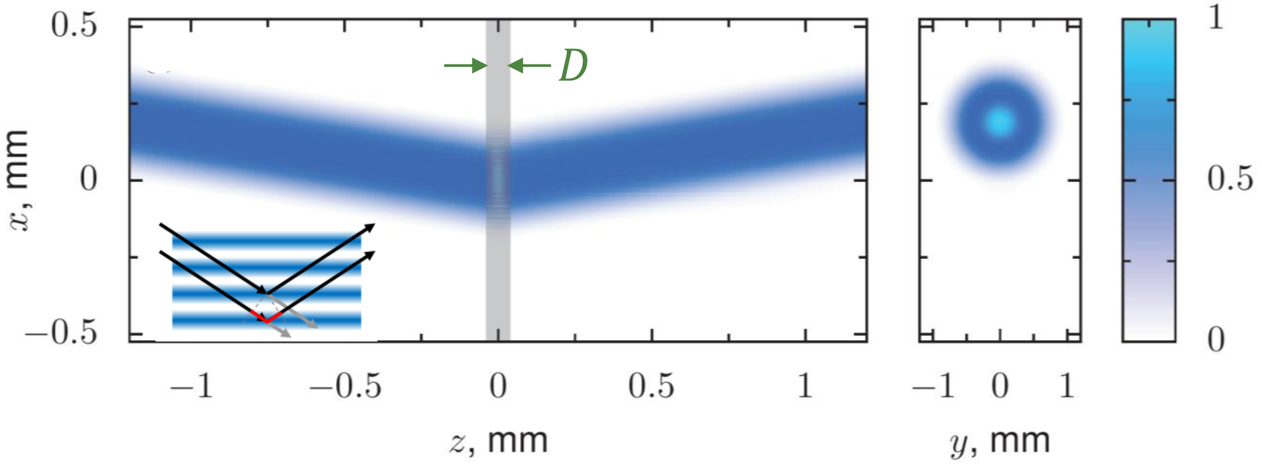
Measure of phase mismatch
($B = 1$ for no mismatch)

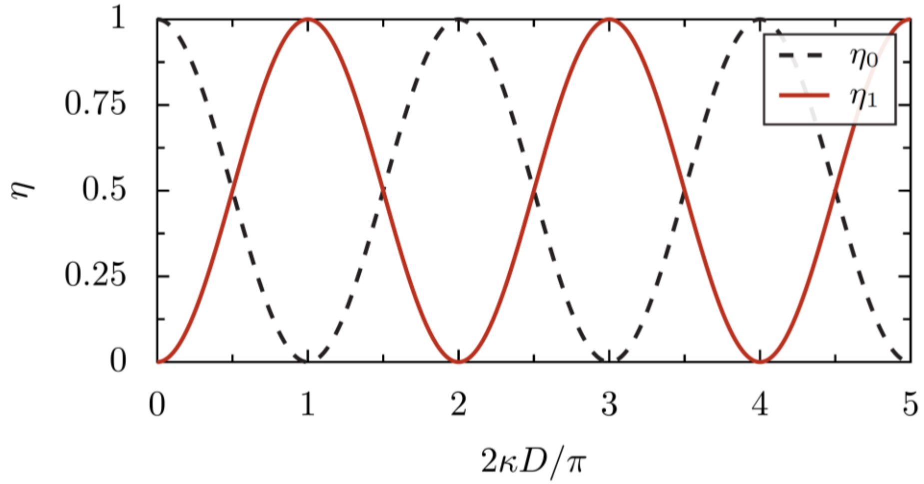
Index modulation

$$\kappa = \frac{\pi n_1}{\lambda_1 \cos\theta_B}$$

Grating Bragg angle

Probe wavelength

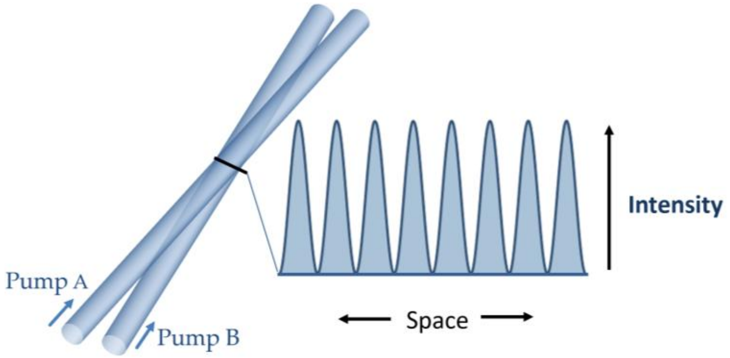




Creating a Laser-Driven Transmission Grating

The interference pattern of two crossed beams has period:

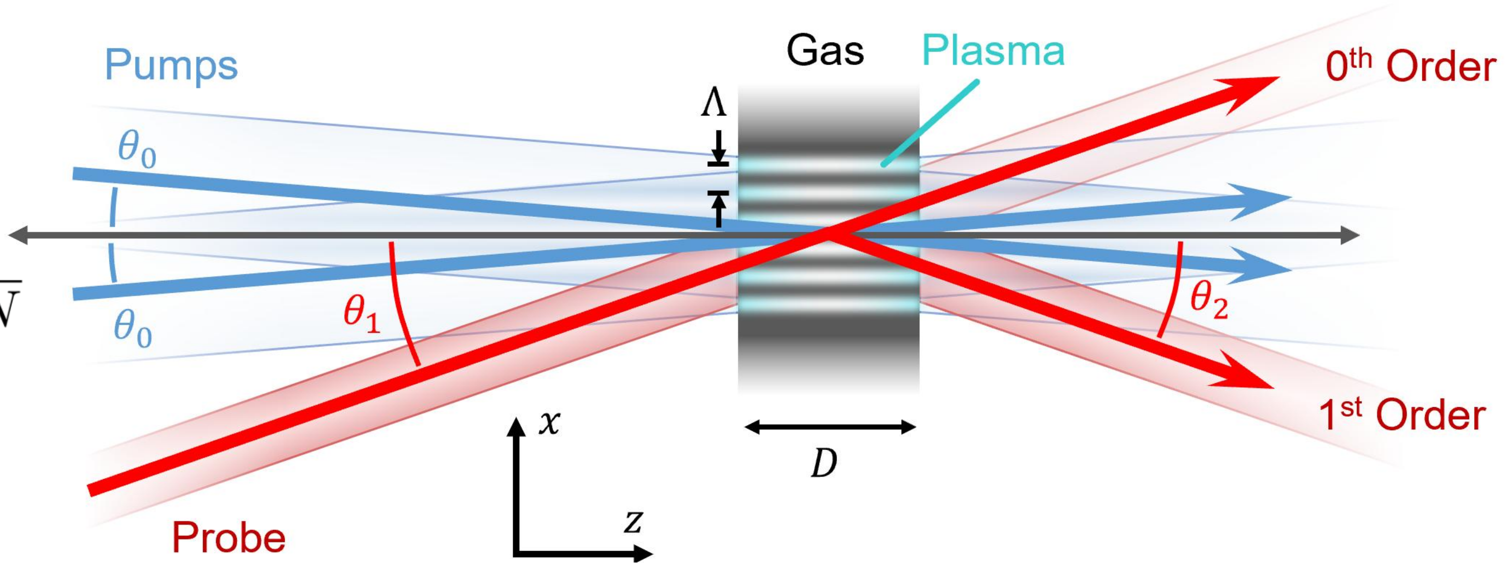
$$\Lambda = \frac{\lambda_0}{2\sin\theta_0}$$



If we can **map intensity to refractive index** in a plasma, we can create a plasma diffractive optic:

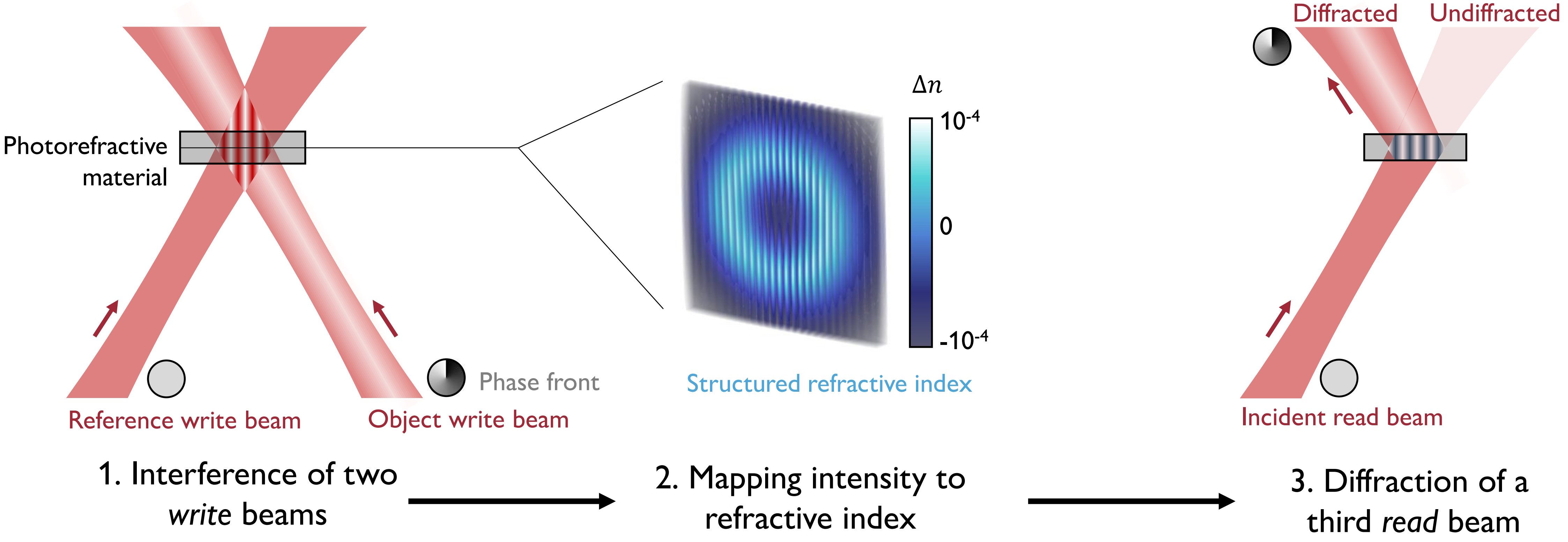
$$n = \sqrt{1-\omega_p^2/\omega^2} = \sqrt{1-N}$$

Refractive index

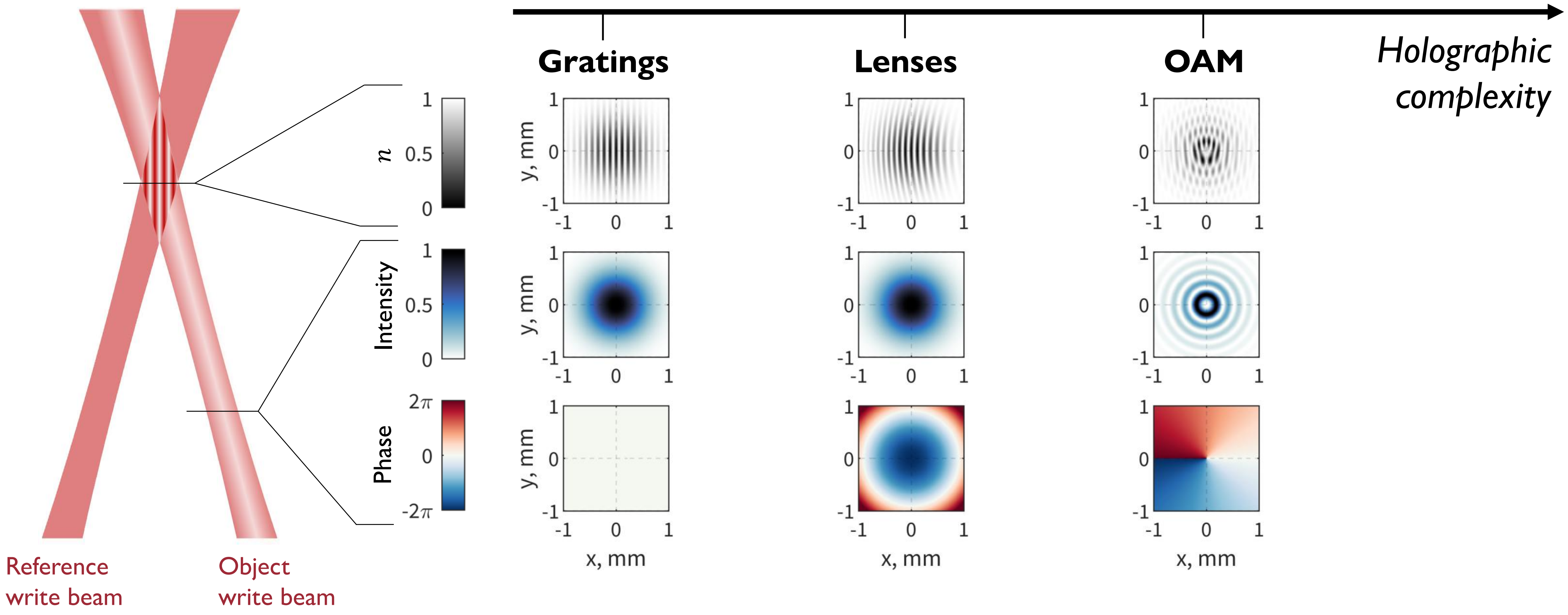


Generalizing to Holographic Optics

Holograms encode a three-dimensional light field of two *write* beams



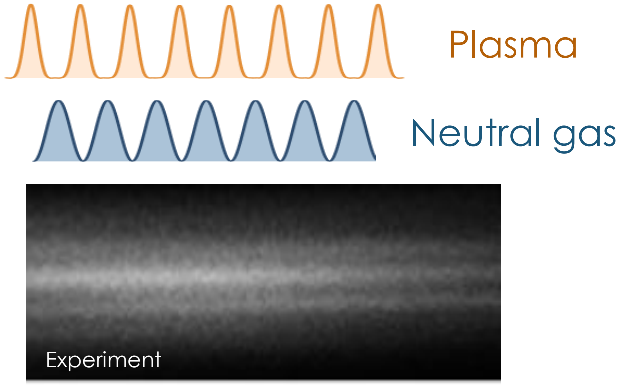
Holographic Optics



Mechanisms for Plasma and Gas Optics

Ionization

Alternating plasma and neutral gas

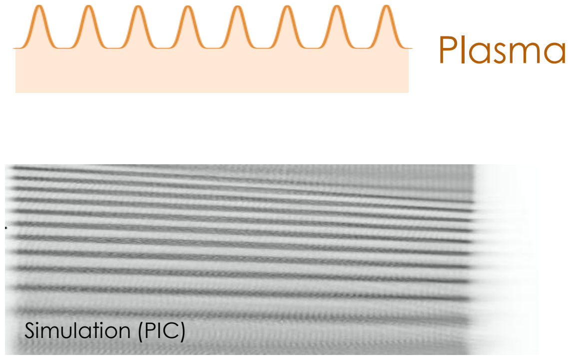


Ionization occurs in constructive interference fringes of pumps

Formation: **fs-ps**
Lifetime: **10-100 ps**
Index Modulation: $\mathbf{10^{-2}}$

Ponderomotive

Ion + electron density fluctuations



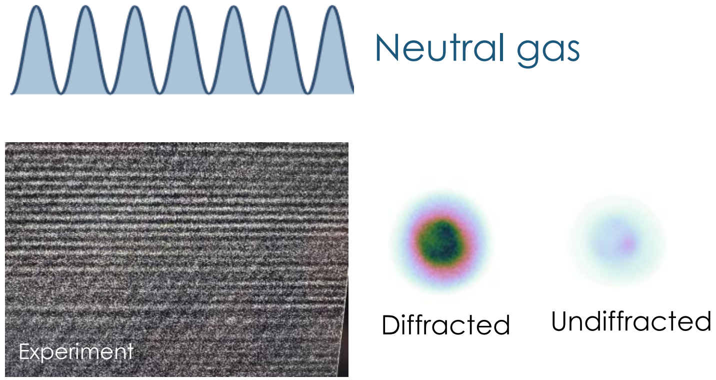
Ponderomotively driven electrons create ion density modulations

Formation: **1-100 ps**
Lifetime: **10-100 ps**
Index Modulation: $\mathbf{10^{-2}}$

Best performance for high-power femtosecond lasers

Gas Heating

Neutral gas density modulations



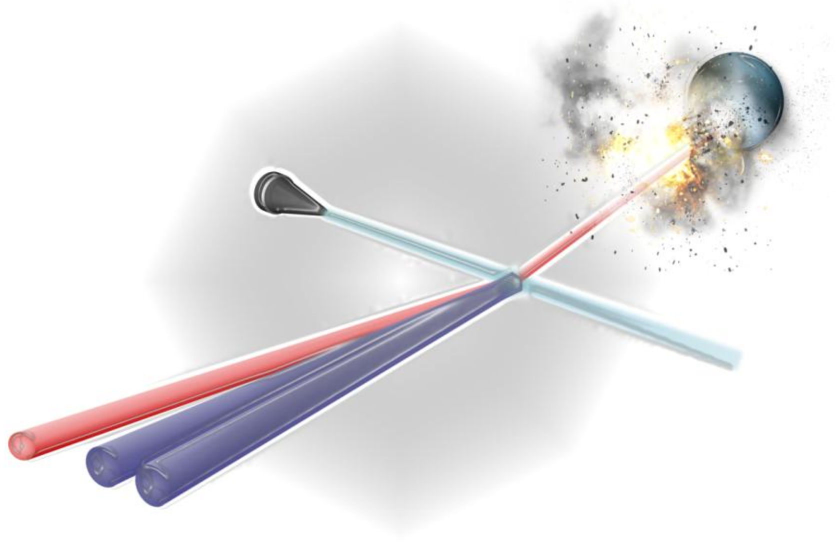
Absorption of UV light by ozone leads to heating and entropy waves

Formation: **1-10 ns**
Lifetime: **10-100 ns**
Index Modulation: $\mathbf{10^{-5}}$

Best performance for high-energy nanosecond lasers

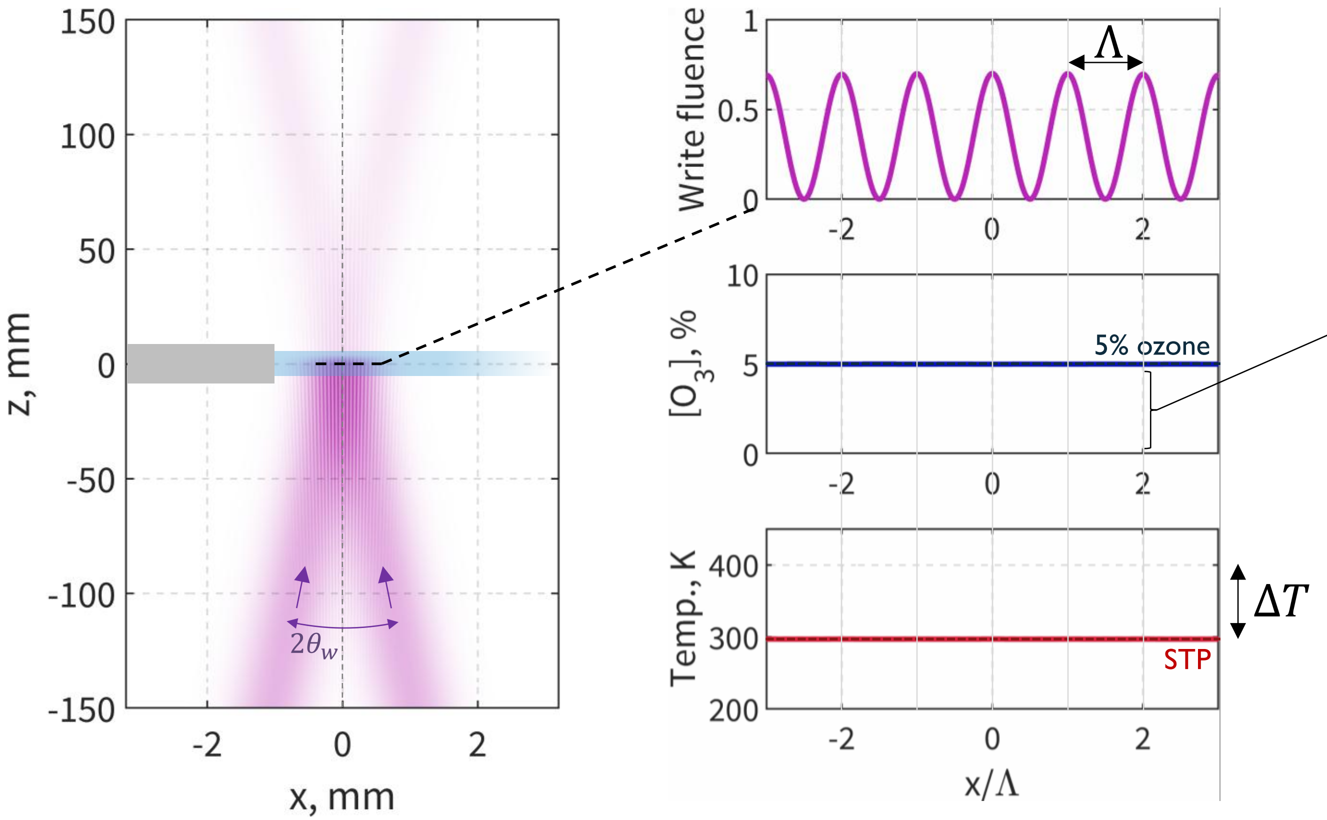
Suntsov et al. *Appl. Phys. Lett.* (2009).
Durand et al. *Phys. Rev. E* (2012).
Jarnac et al. *Opt. Commun.* (2014).
Edwards et al. *Optica* (2023).
Edwards et al. *Phys. Rev. Lett.* (2024).
Lehmann et al. *Phys. Rev. Lett.* (2016).
Peng et al. *Phys. Rev. E* (2019).
Edwards and Michel *Phys. Rev. Appl.* (2022).
Michine and Yoneda, *Comm. Phys.* (2020).
Michel et al., *Phys. Rev. Appl.* (2024).
Ou et al., *Opt. Lett.* (2025).

Gas Gratings



Diffraction Gratings in Ozone Gas

Ultraviolet beams can imprint a periodic temperature modulation in ozone gas.



Write wavelength

$$\Lambda = \frac{\lambda_w}{2 \sin \theta_w}$$

UV-induced photodissociation of ozone

$$h\nu + O_3 \rightarrow O_2 + O$$

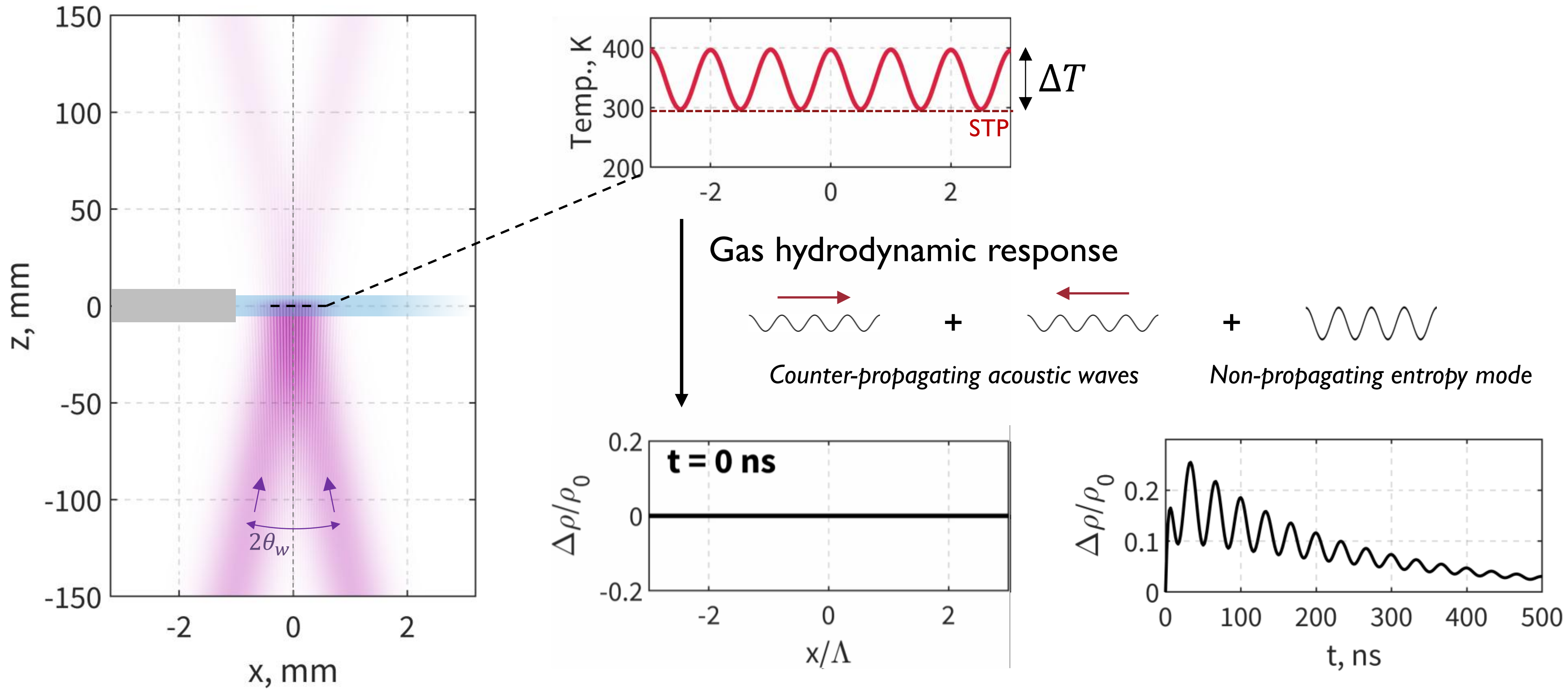
Products are translationally hot

Interference pattern maps to a temperature modulation

Y. Michine & H. Yoneda, *Commun. Phys.* (2020).
P. Michel et al., *Phys. Rev. Applied* (2024).
P. Michel et al., *Phys. Rev. Applied* (2026).
K. Ou et al. "Near-Unity-Efficiency Gas Gratings for Ultraviolet, Visible, and Infrared High-Power Lasers," *arXiv:2601.09963* (2026).

Diffraction Gratings in Ozone Gas

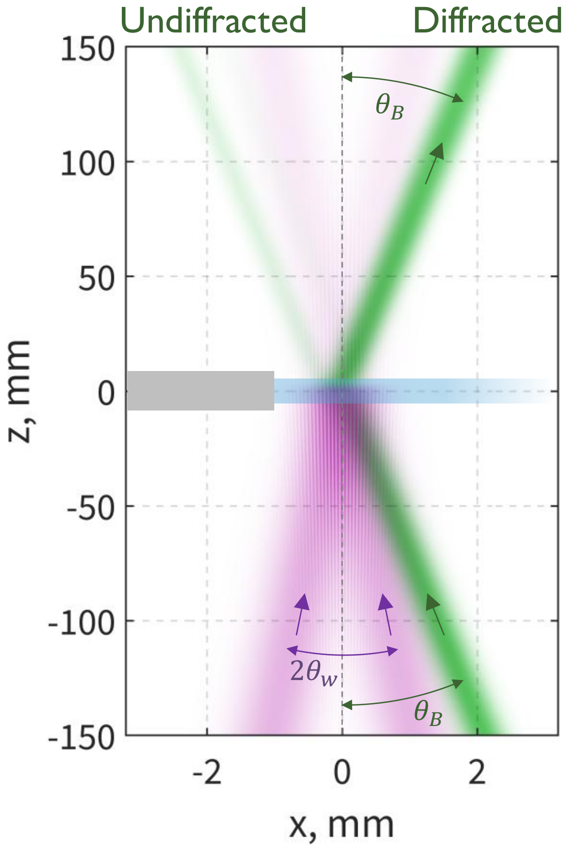
The local heating of gas drives a periodic density modulation.



Y. Michine & H. Yoneda, *Commun. Phys.* (2020)
P. Michel et al., *Phys. Rev. Applied* (2024)
K. Ou et al. "Near-Unity-Efficiency Gas Gratings for Ultraviolet, Visible, and Infrared High-Power Lasers," *arXiv:2601.09963* (2026)..

Diffraction Gratings in Ozone Gas

A third *read* beam incident at the Bragg angle will diffract off the acousto-optic structure.



Bragg angle

Read wavelength

$$\theta_B = \sin^{-1}\left(\frac{\lambda_0}{2n_0\Lambda}\right)$$

Background refractive index

Efficient diffraction occurs when:

First-order Fourier amplitude

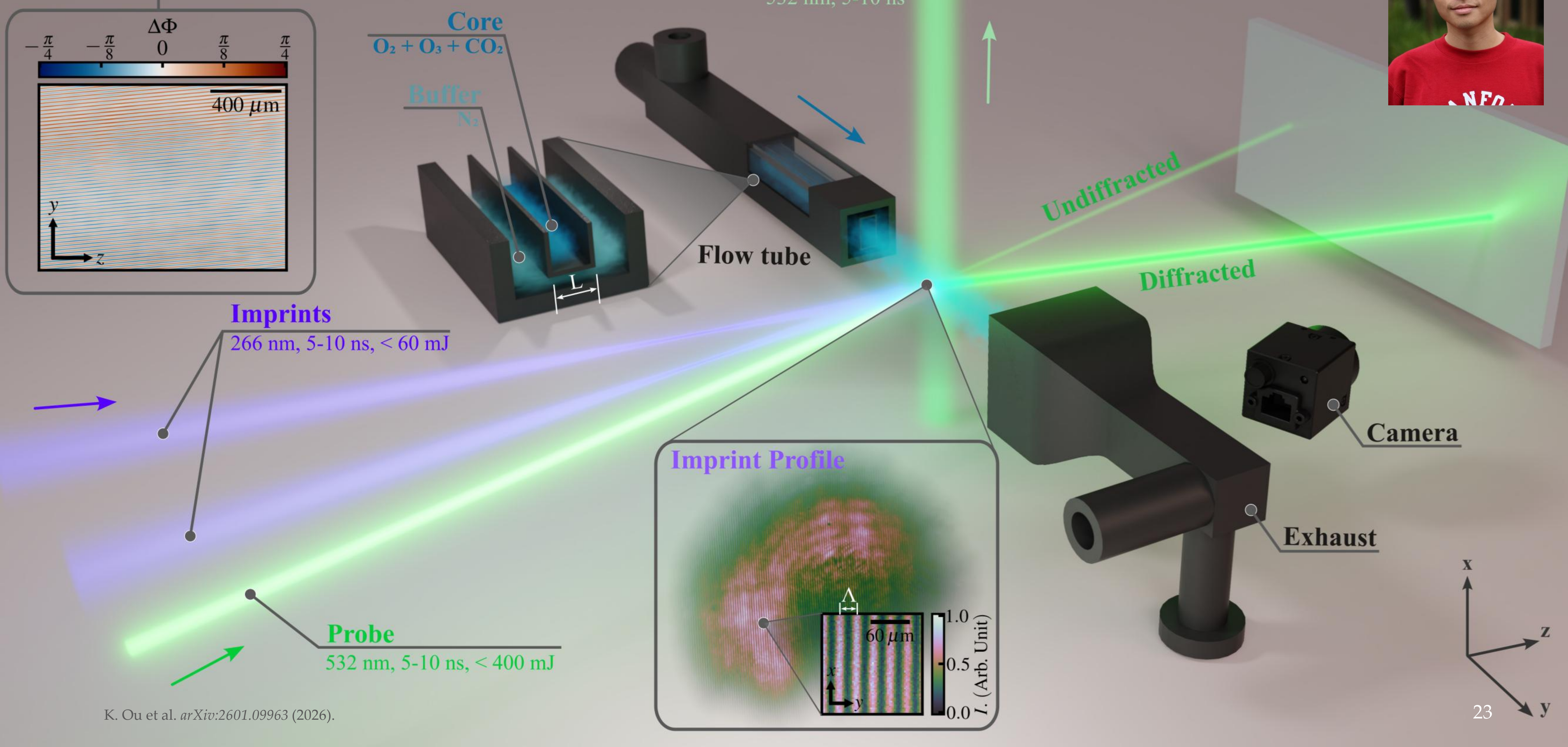
Length of optic

$$\frac{2n_1L}{\lambda_0} \approx 1$$

Y. Michine & H. Yoneda, *Commun. Phys.* (2020)
P. Michel et al., *Phys. Rev. Applied* (2024)
K. Ou et al. "Near-Unity-Efficiency Gas Gratings for Ultraviolet, Visible, and Infrared High-Power Lasers," *arXiv:2601.09963* (2026).

Gas Grating Experiments

Ke Ou
PhD Candidate
Stanford



K. Ou et al. *arXiv:2601.09963* (2026).

Temporal evolution of gas gratings

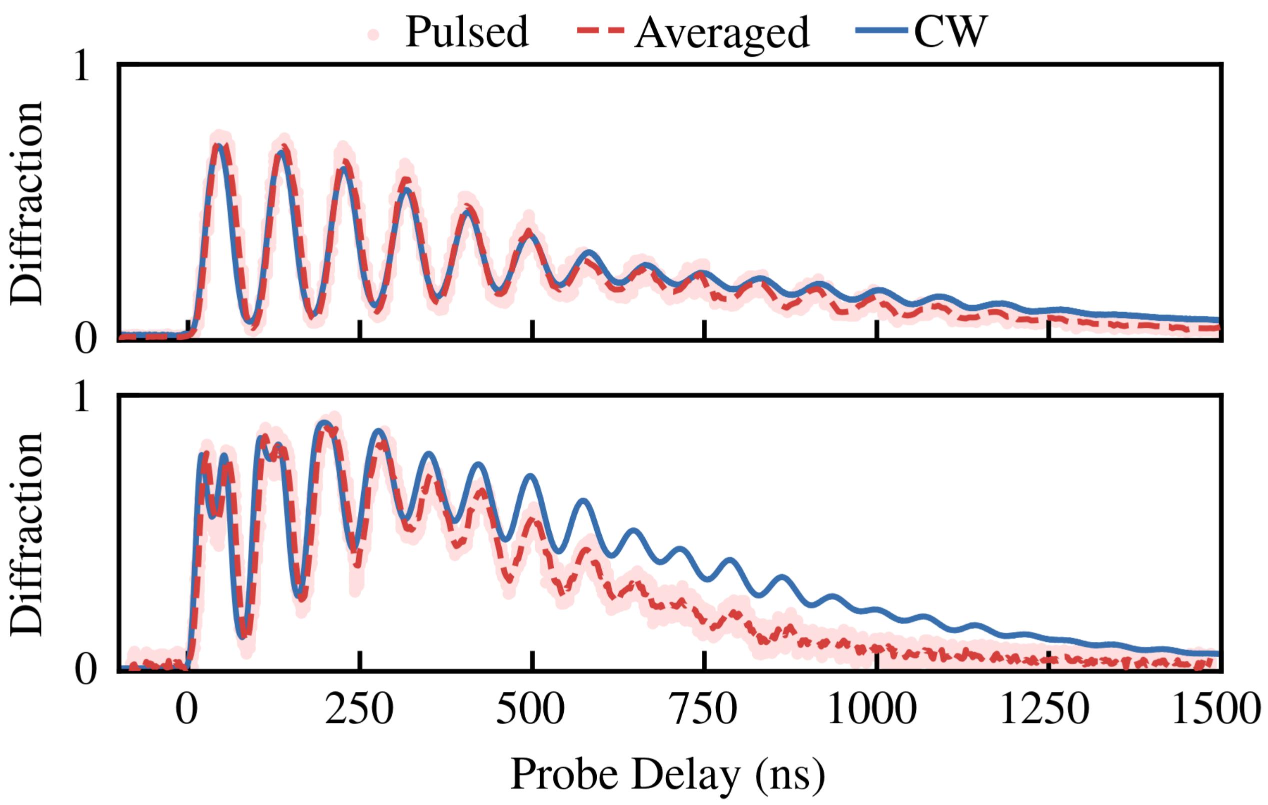
Diffraction efficiency oscillates with respect to probe delay.

Grating stays ‘on’ during each peak for tens of nanoseconds

Period controllable with wavelength and gas properties

Oscillation period:

$$\tau_s = \Lambda / c_s$$



K. Ou et al. *arXiv:2601.09963* (2026).

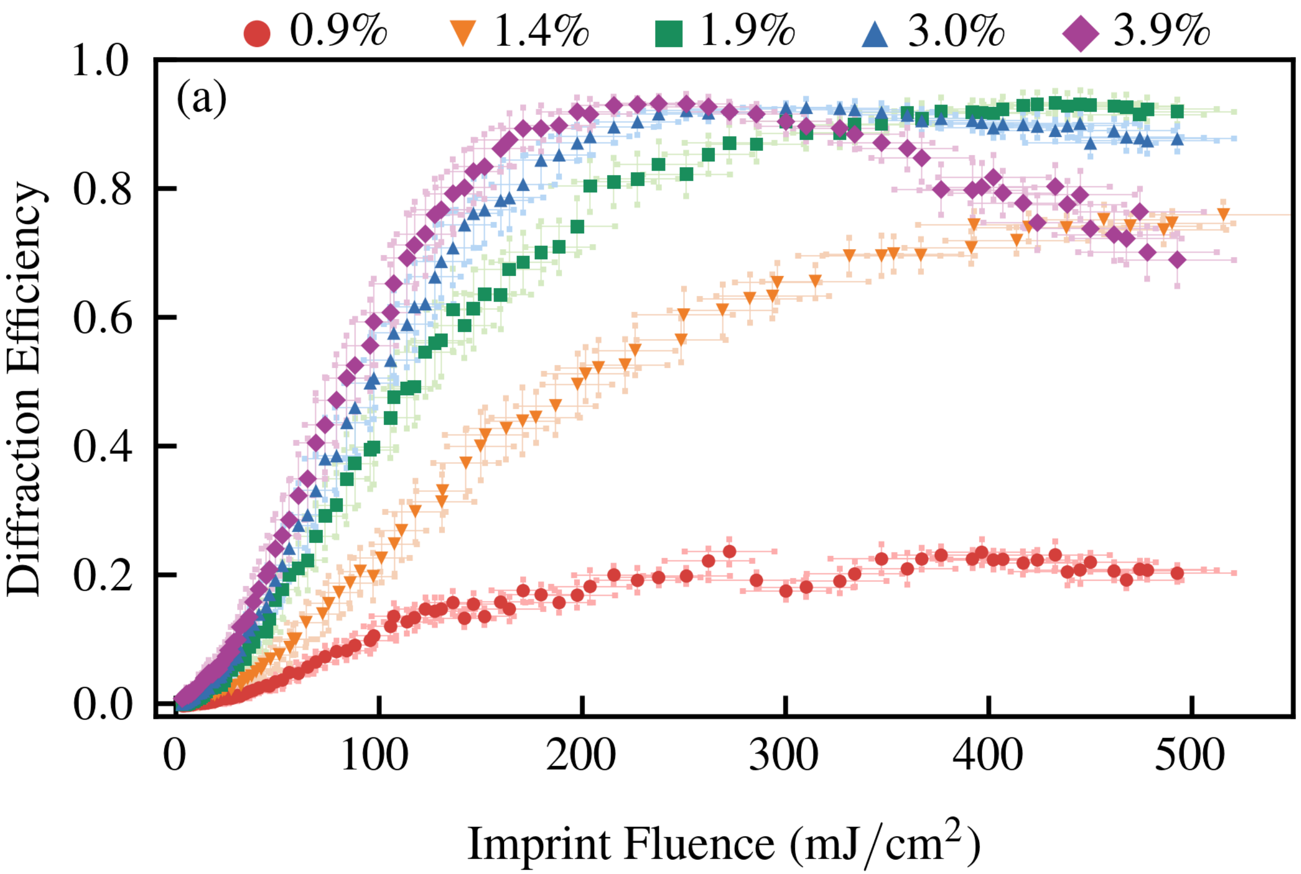
Imprint Laser Fluence Requirements

Diffraction efficiency measured when index modulation peaks.

At low fluences, imprint beams deplete in ozone.

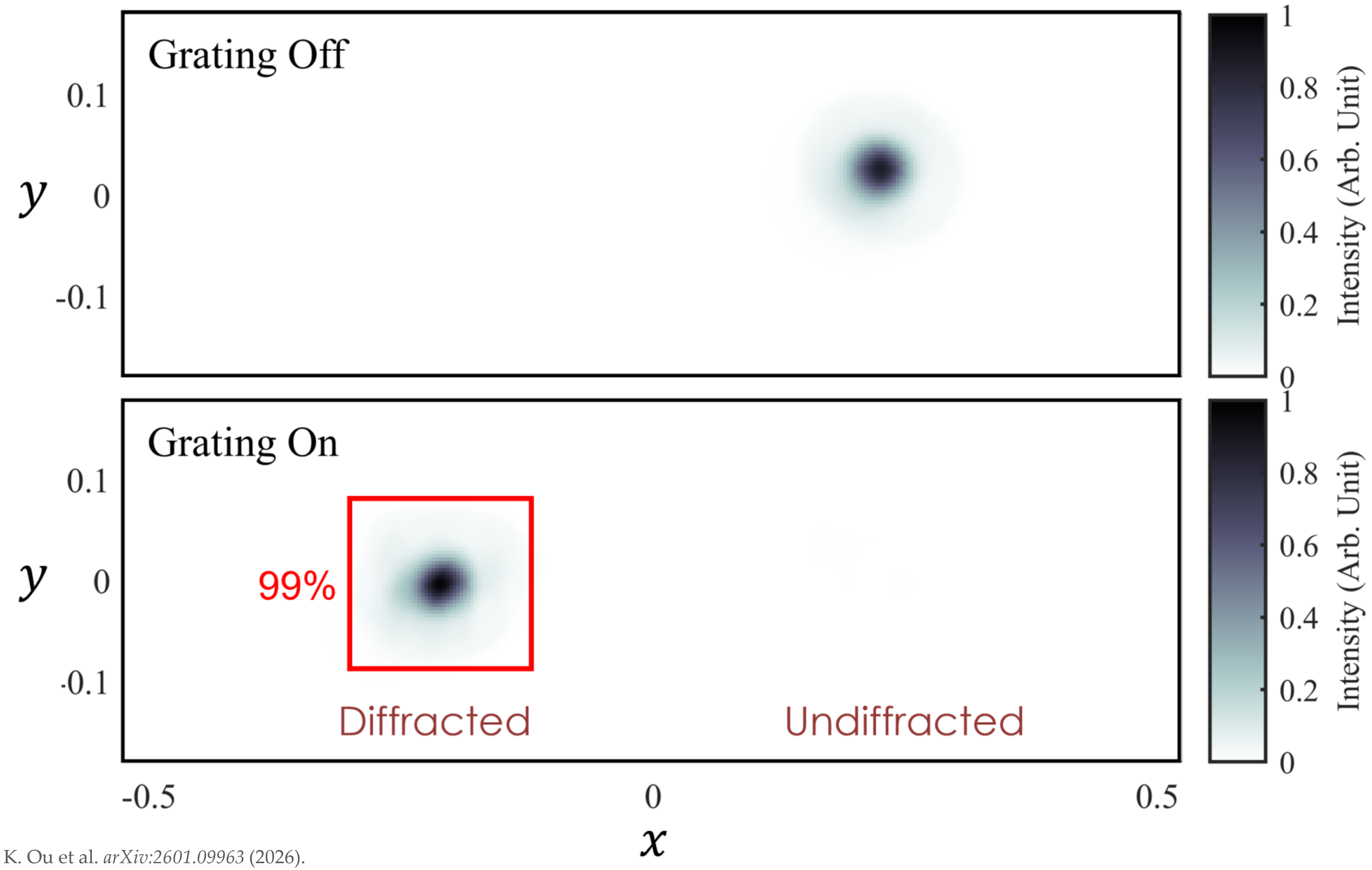
At high fluences, ozone depletes.

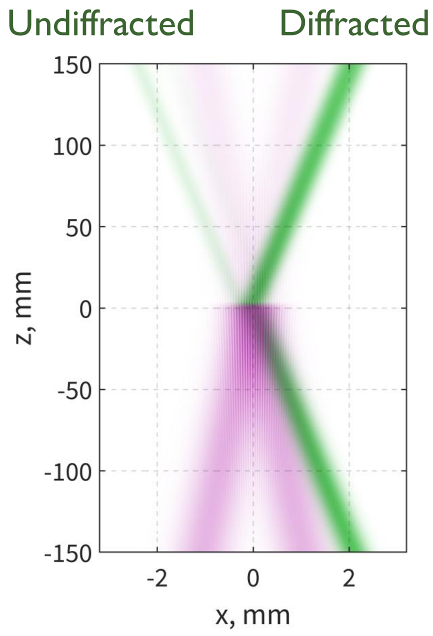
At high fluence and high O_3 concentration, beam begins to diffract back to zeroth order



K. Ou et al. *arXiv:2601.09963* (2026).

Gas Grating Diffraction Efficiency

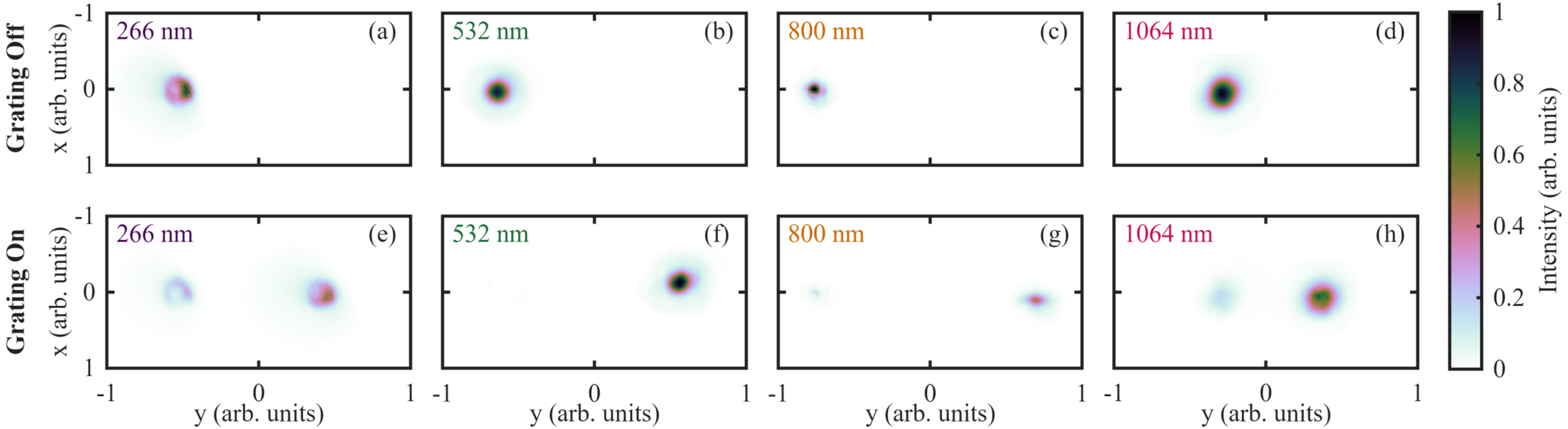




Grating Properties:
$D = 5$ mm
$\Lambda = 30$ μm
2% O_3

K. Ou et al. *arXiv:2601.09963* (2026).

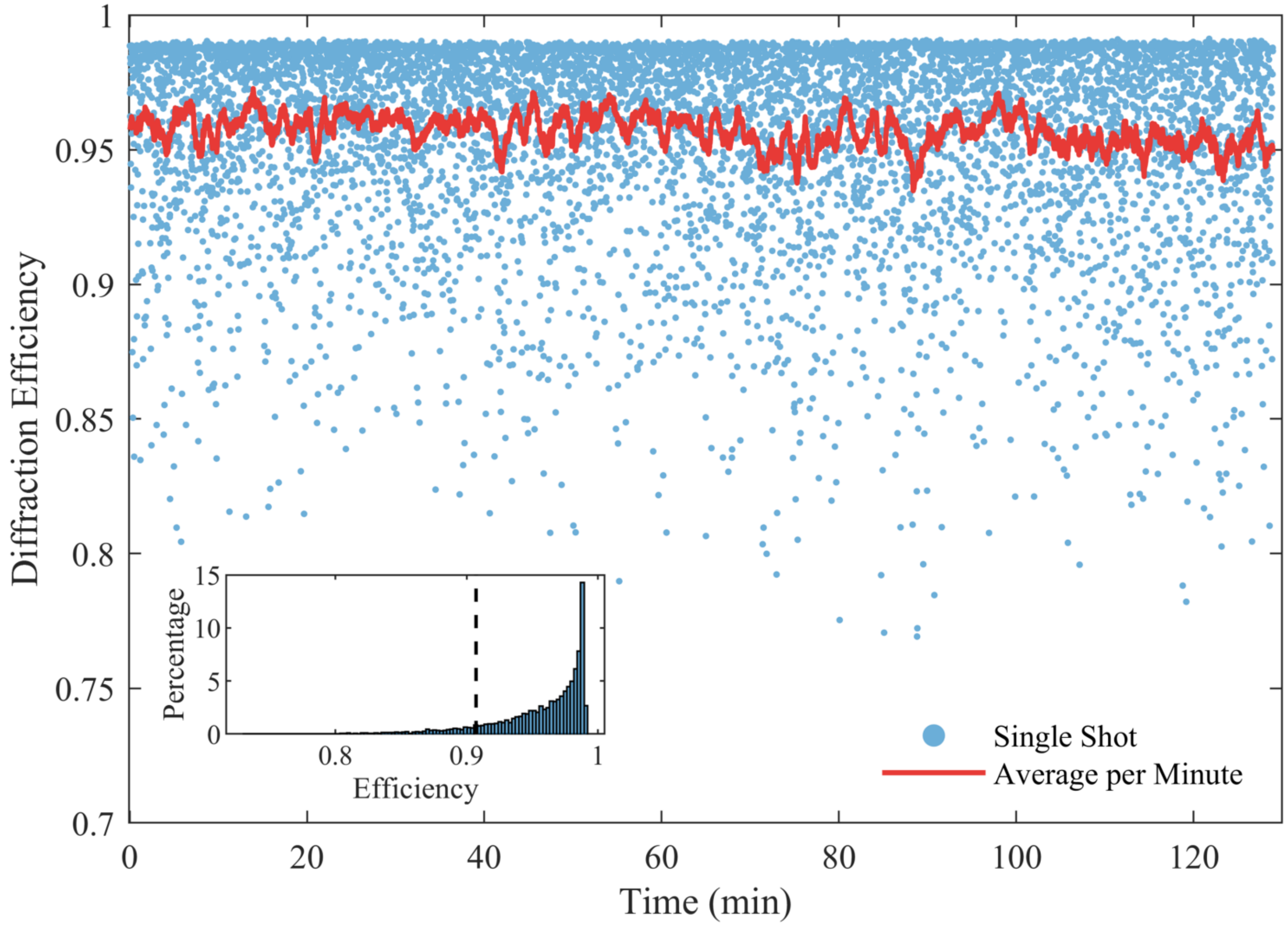
Grating Wavelength Insensitivity



Gratings operate efficiently across wide range of read beam wavelengths.

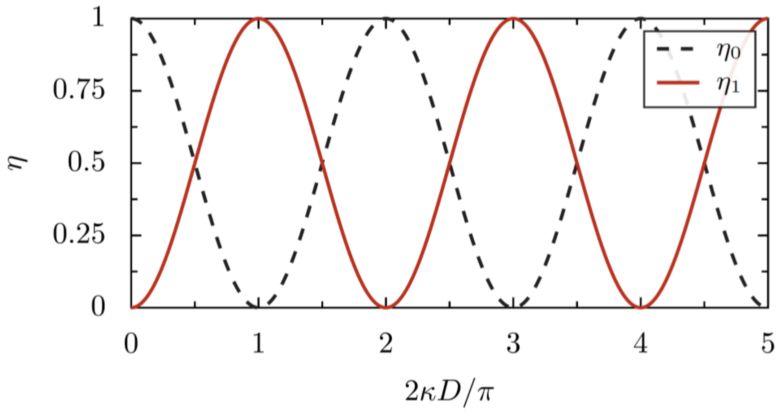
K. Ou et al. *arXiv:2601.09963* (2026).

Gas Grating Stability



10 Hz operation for hours is possible.

Operating at efficiency peak reduces impact of fluctuating parameters

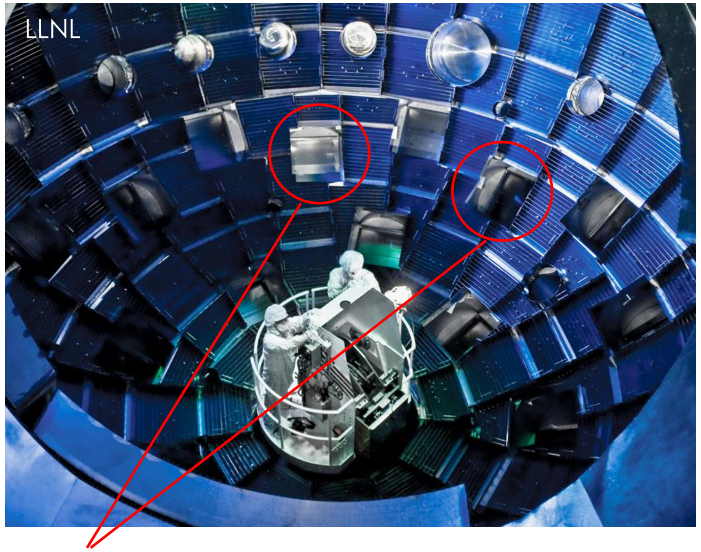


K. Ou et al. *arXiv:2601.09963* (2026).

Applications to Inertial Fusion Energy

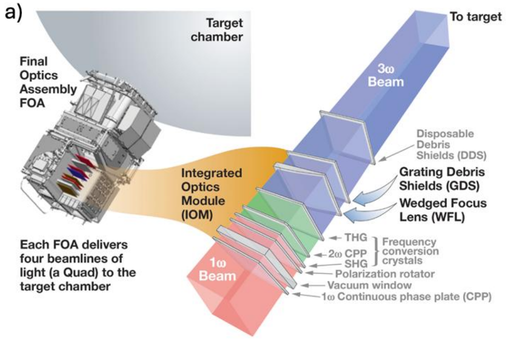
What would an IFE plant look like?

< 10 MJ (yield) @ 1 shot/day (current at NIF) → > 100 MJ @ ~10 Hz (required)

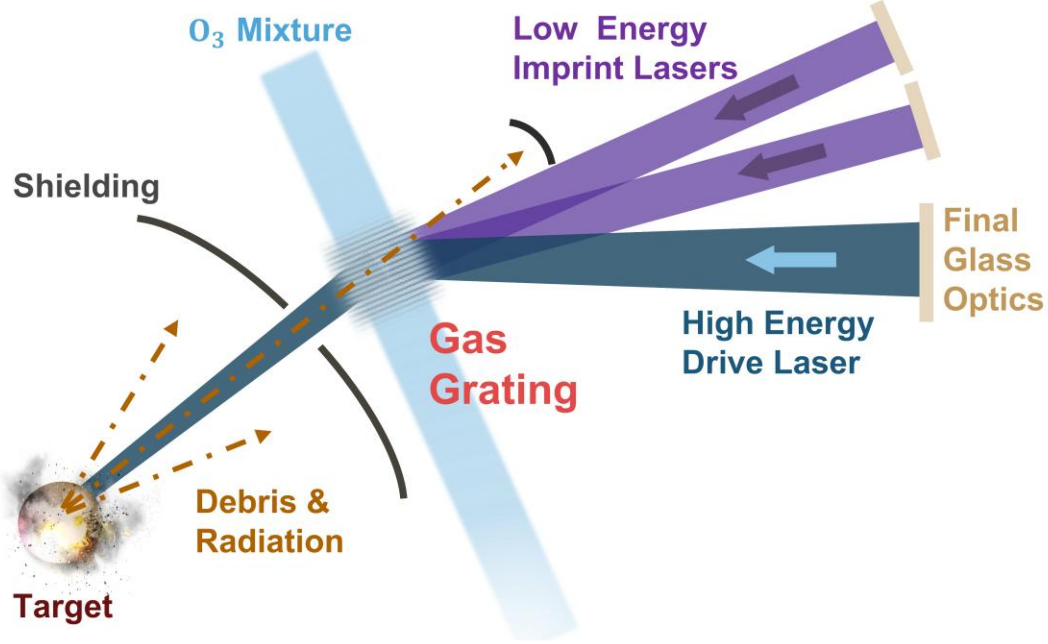


Laser entry

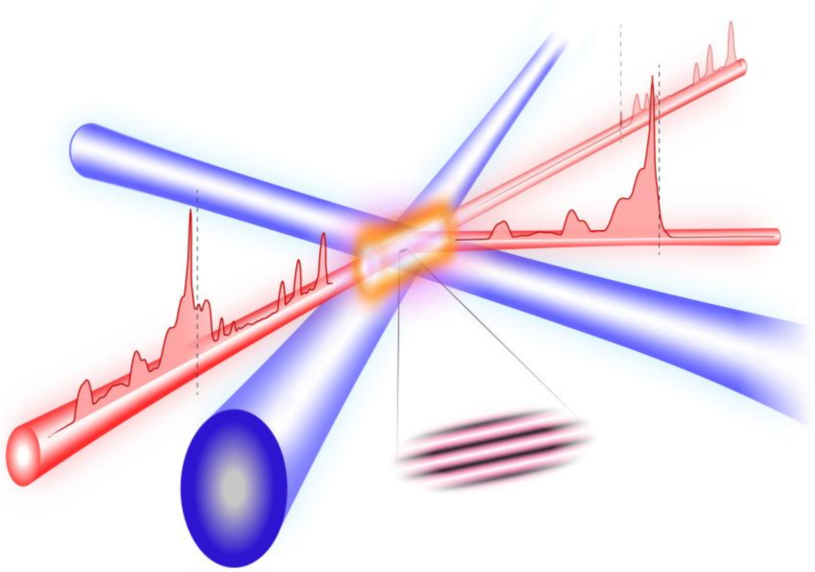
Final lenses protected with frequently replaced debris shields



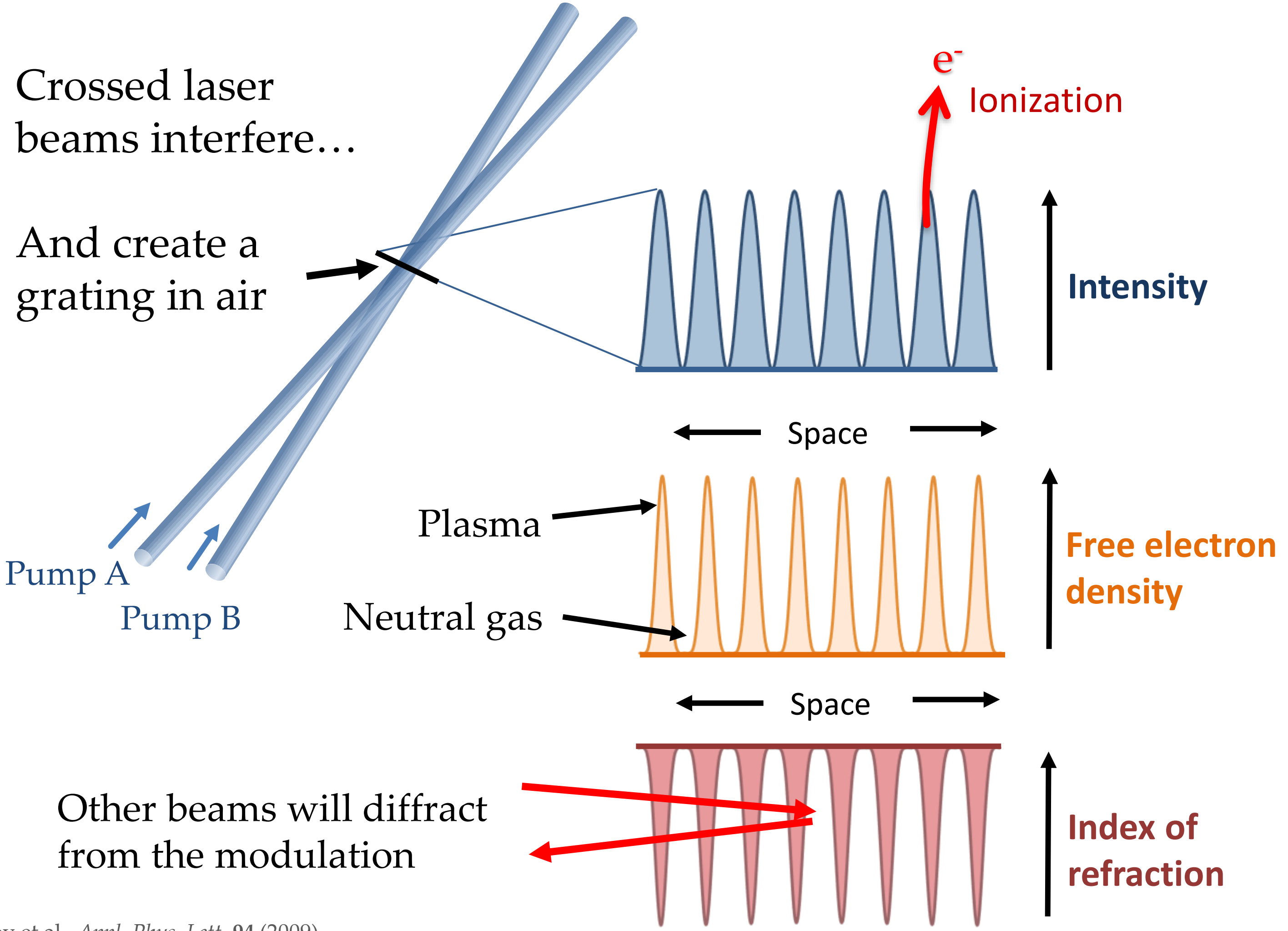
<u>The final optic problem:</u>
Can any optic focus lasers on target and withstand enormous debris, x-ray, neutron, and light fluxes?



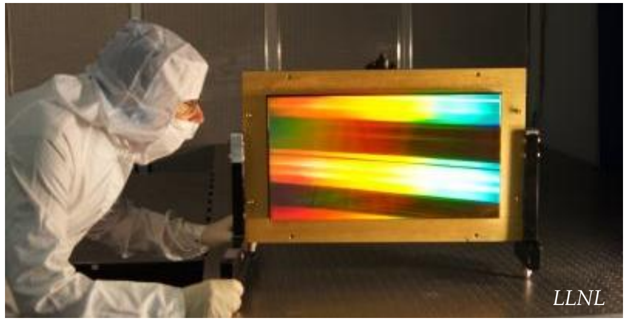
Plasma Gratings



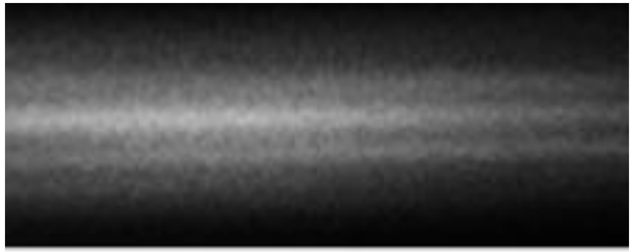
Diffractive Plasma Optics via Controlled Ionization



Solid-state limited to $<10^{12}$ W/cm^2

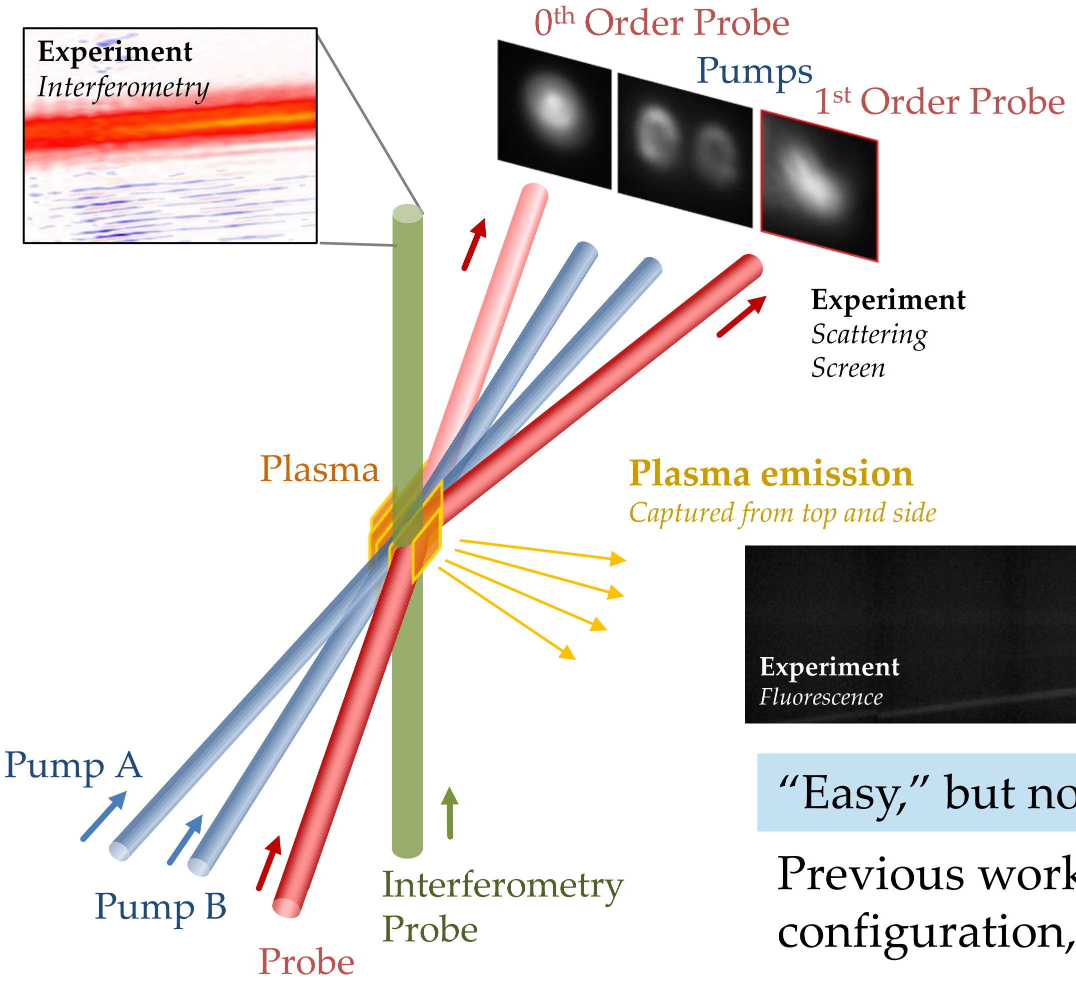


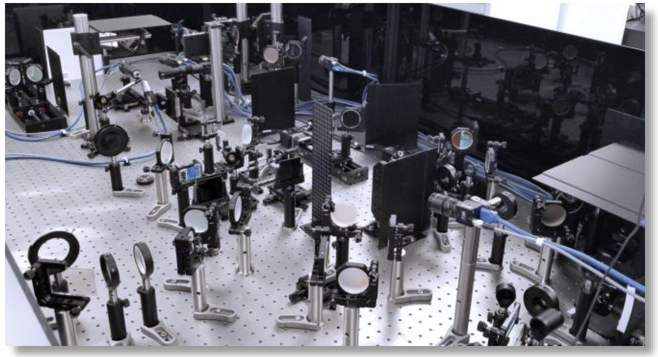
Ionization grating at $>10^{14}$ W/cm^2

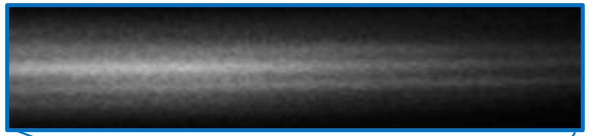


Suntsov et al., *Appl. Phys. Lett.* **94** (2009).
Yang et al., *Appl. Phys. Lett.* **97** (2010).
Shi et al., *Phys. Rev. Lett.* **107** (2011).
Durand et al., *Phys. Rev. E* **86** (2012).
Jarnac et al., *Opt. Commun.* **312** (2014).
Edwards et al., *Optica* **10** (2023).
Edwards et al., *Phys. Rev. Lett.* **133** (2024).

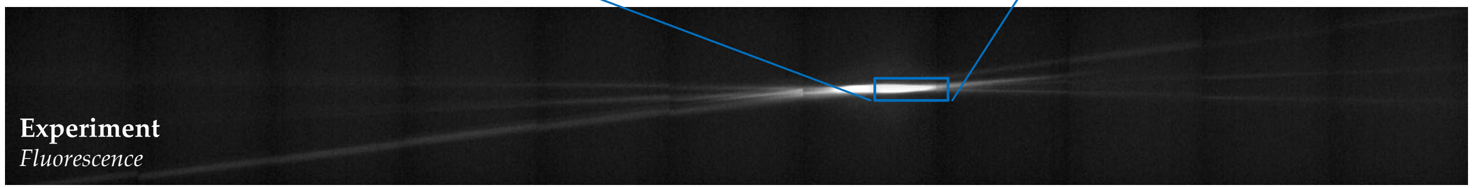
Creating an Ionization Grating in Air







Ionization grating at
>10^{14} W/cm^2

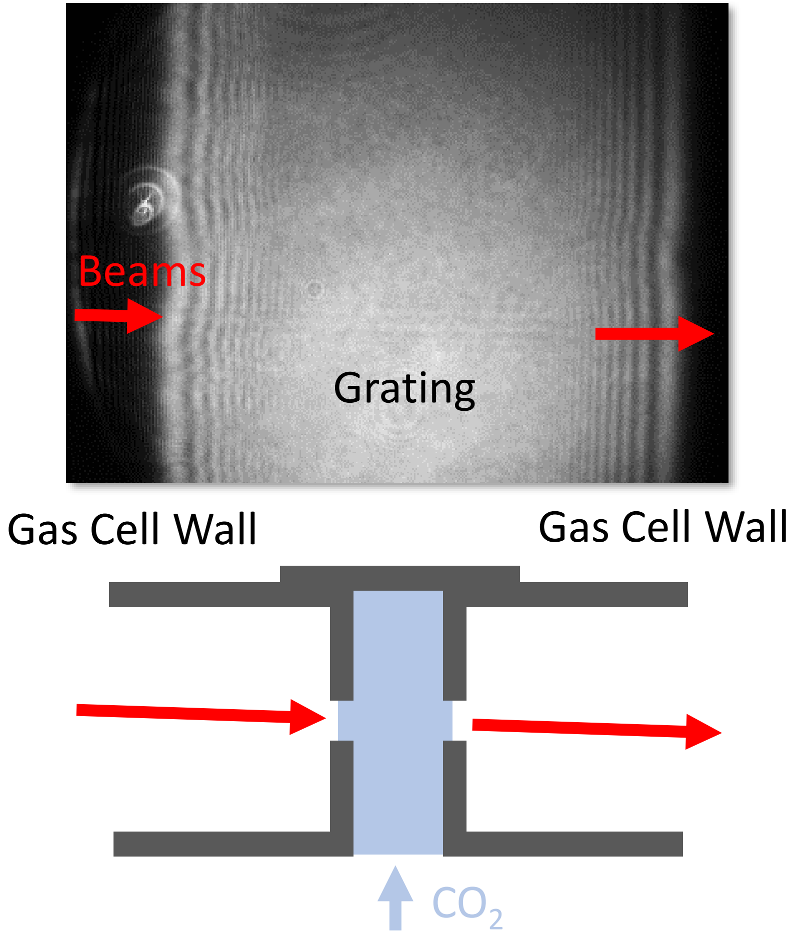


"Easy," but no ability to control grating thickness

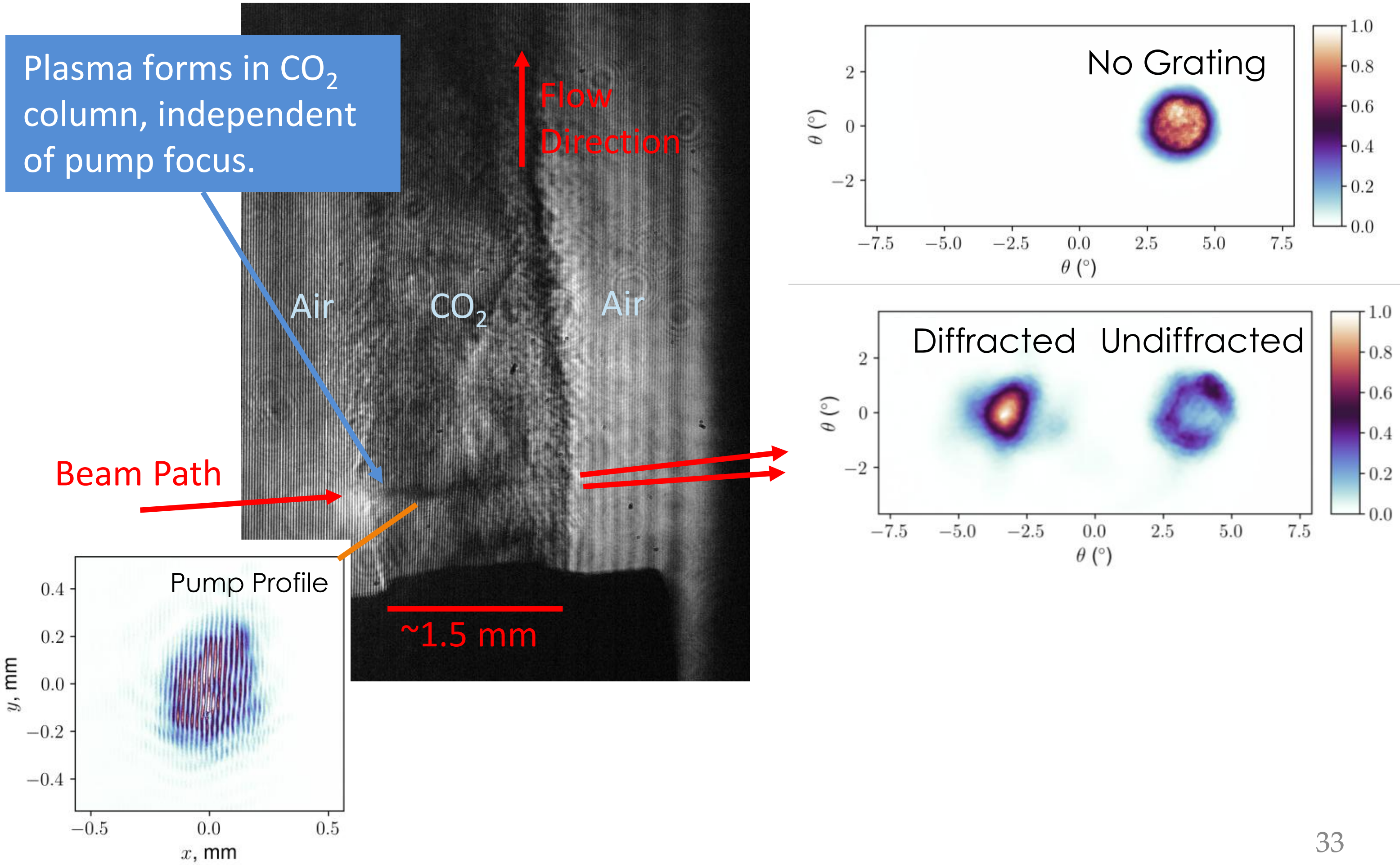
Previous work on ionization gratings was done in this configuration, with up to 18% efficiency (usually ~1%).

Limiting the extent of a grating (in z) dramatically increases efficiency

Gas Cell Configuration



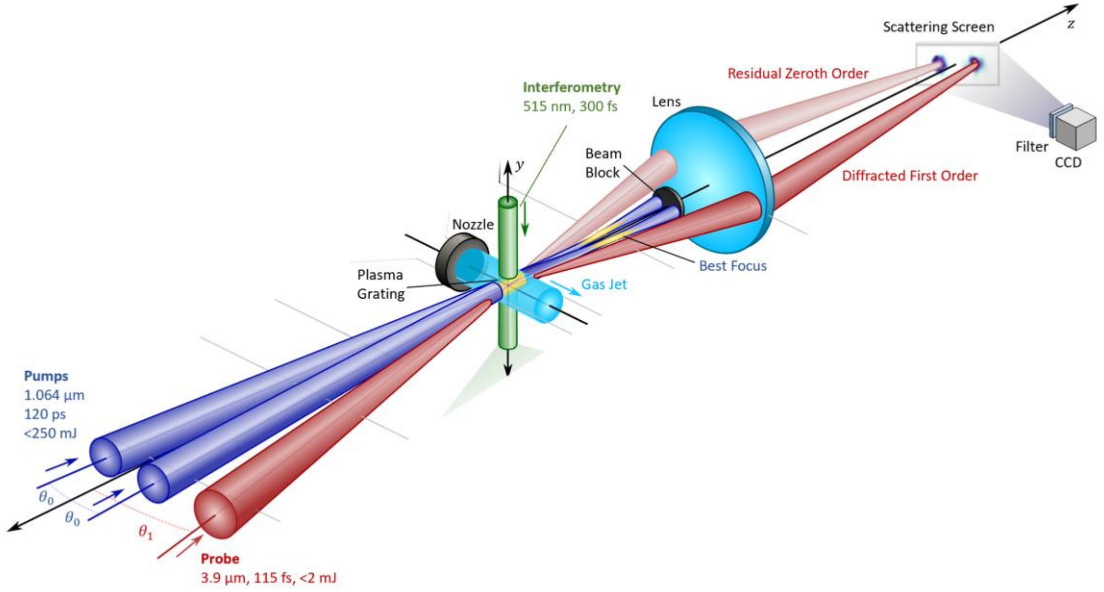
Gas Jet Configuration

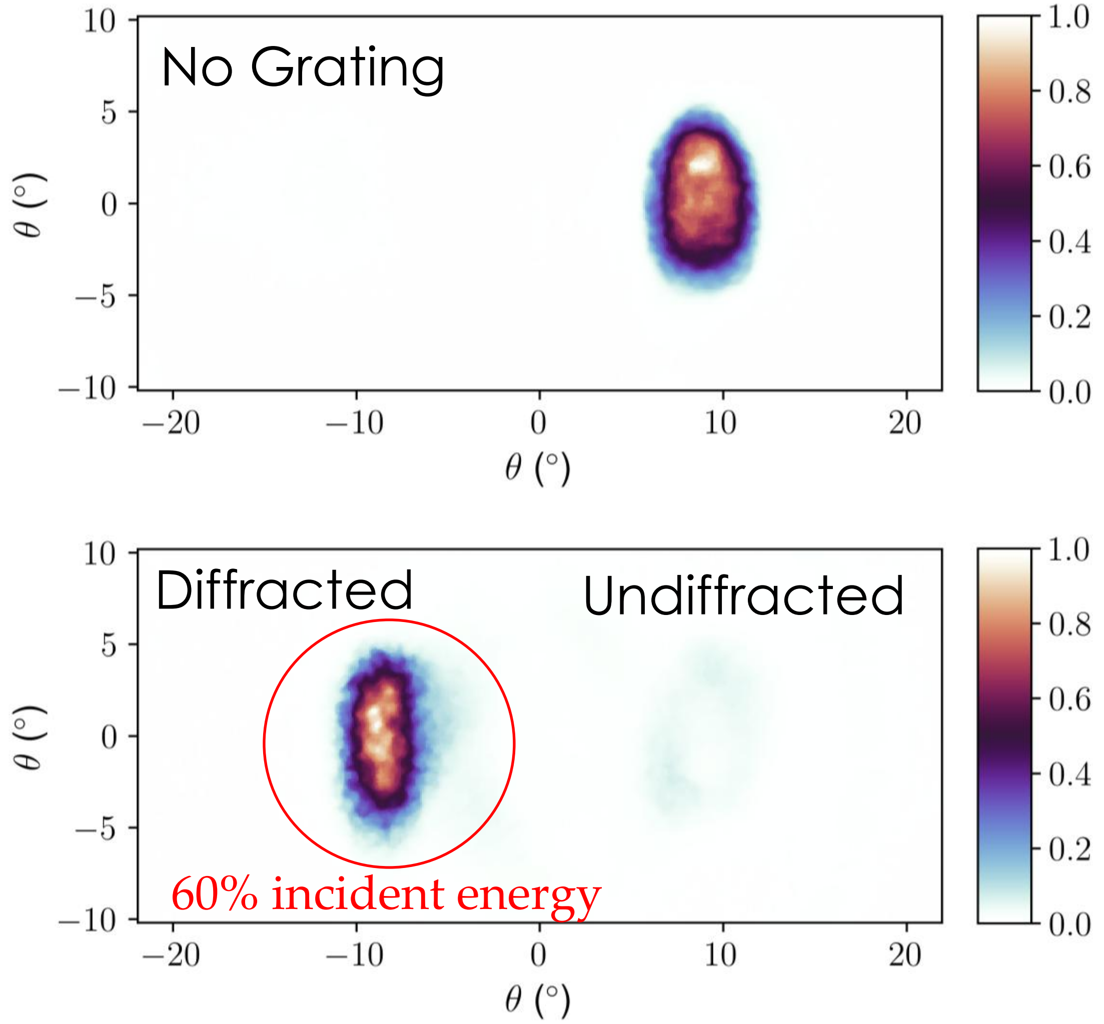


High-efficiency diffraction of mid-infrared light

Up to 60% of incident energy diffracted into a beam (losses mostly absorption)

Ratio of diffracted to undiffracted energy is **8.7**:1





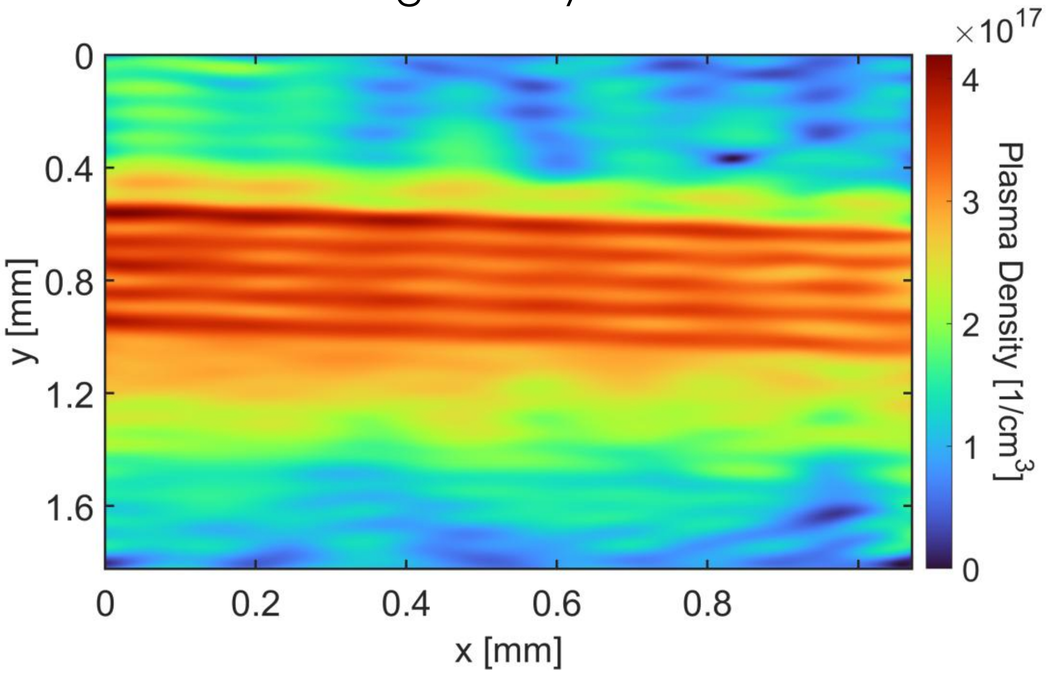
Edwards et al., *Optica* **10** (2023).

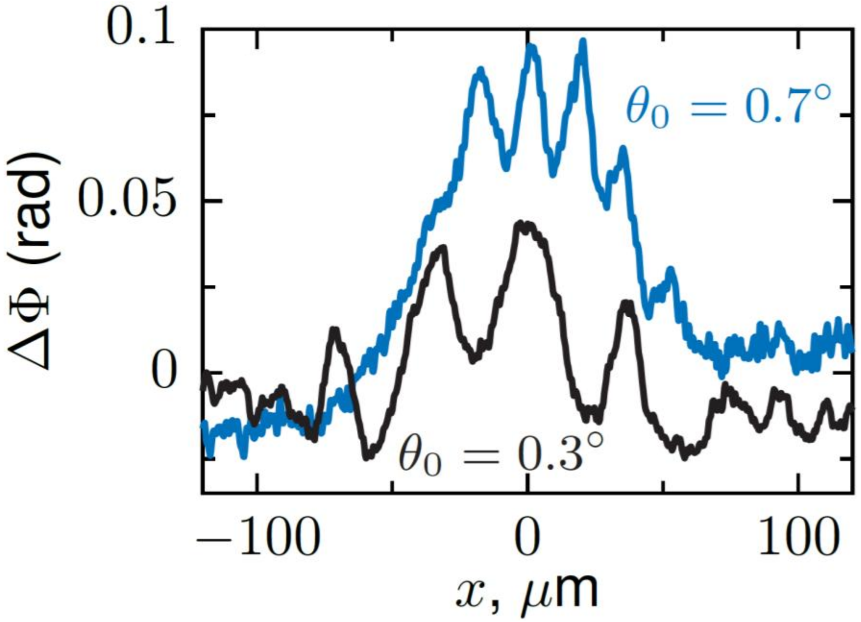
Creating Gratings for 800 nm Light


Michelle Wang
PhD Candidate
Princeton

Victor Perez-Ramirez
PhD Candidate
Stanford

Plasma Grating Density





We can produce (and measure) plasma gratings in a gas cell under vacuum – length and density are (reasonably) controllable.

Fringe spacing follows analytic dependence on pump crossing angle: $\Lambda = \frac{\lambda_0}{2 \sin \theta_0}$

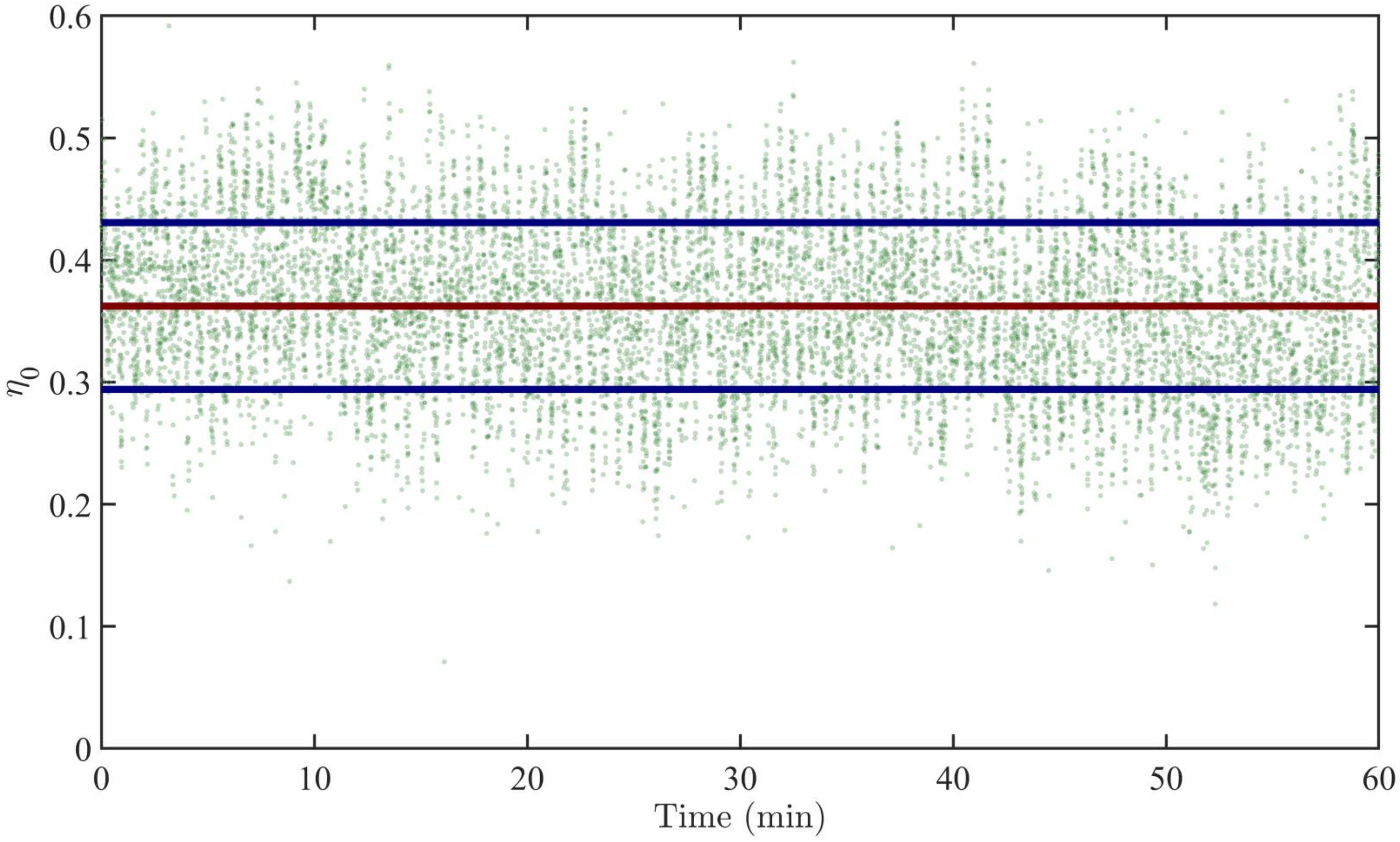
Plasma Grating Stability

Average efficiencies above 35% achieved at 800 nm.

Single-shot efficiencies above 50%

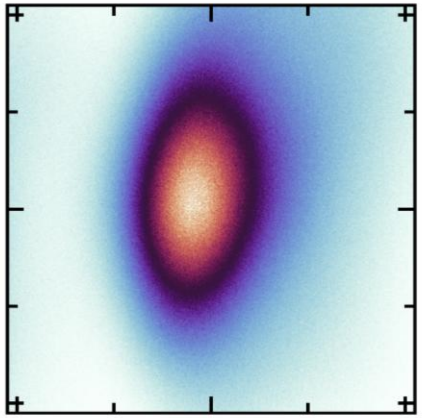
10 Hz operation can be maintained for hours or more.

Well-suited for high-repetition-rate operation

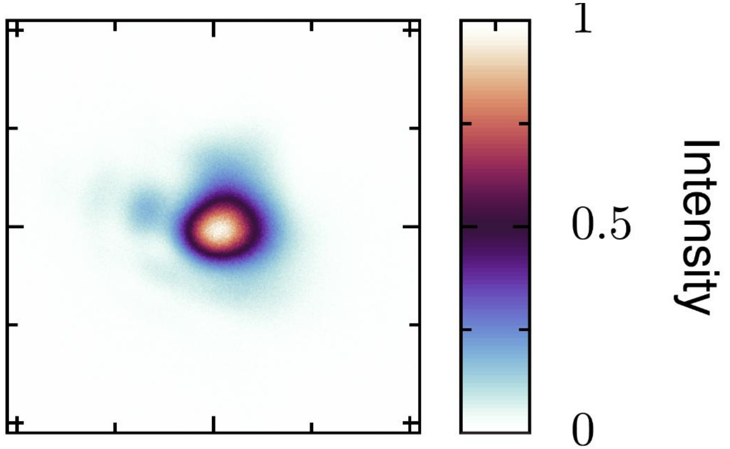


Optical Properties of Diffracted Beams

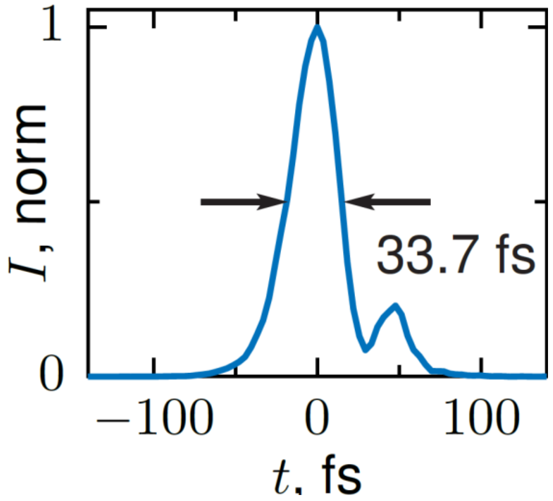
Near-field beam profile



Far-field (at focus)



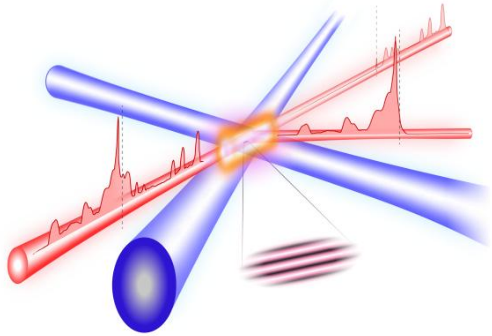
Pulse Duration



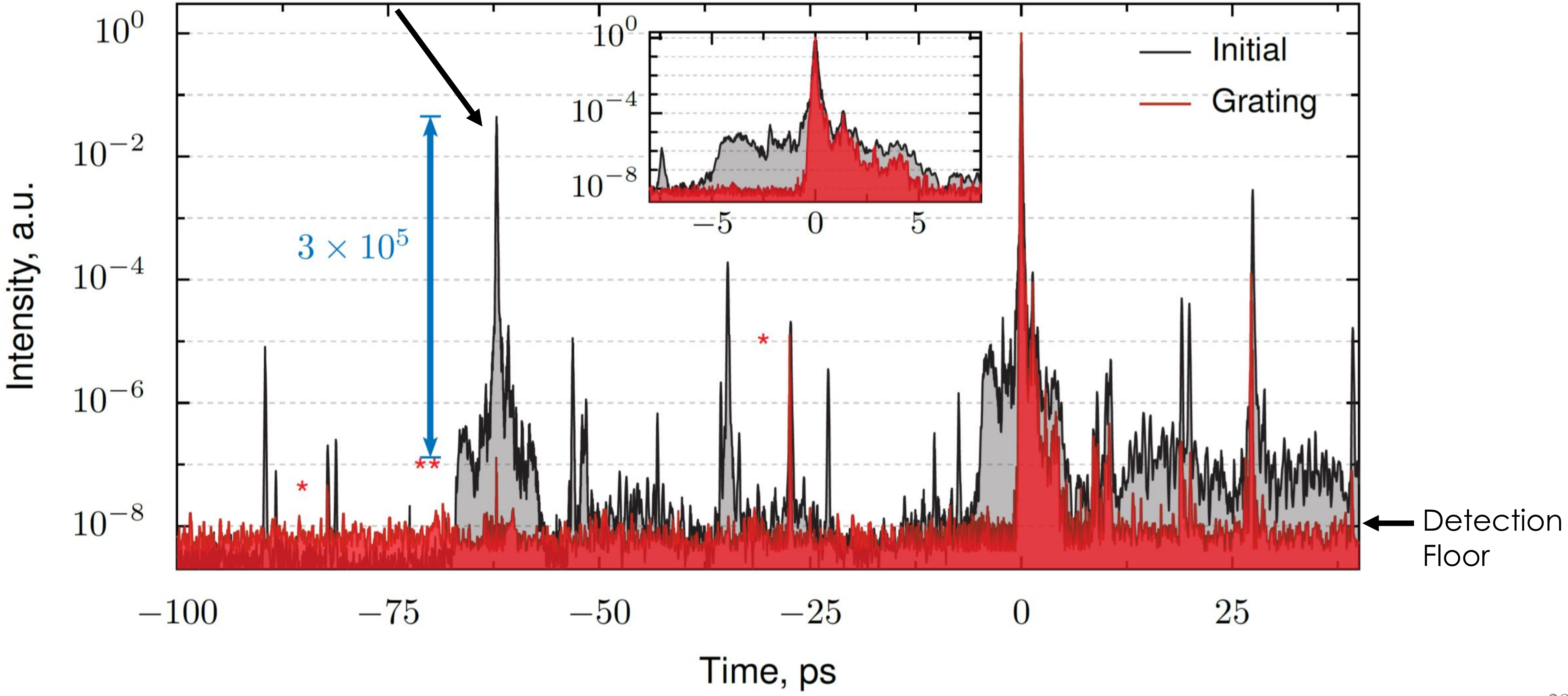
Diffracted beams have good spatial and temporal quality and diffraction angles follow analytic predictions

M.R. Edwards et al., *Phys. Rev. Lett.* (2024).

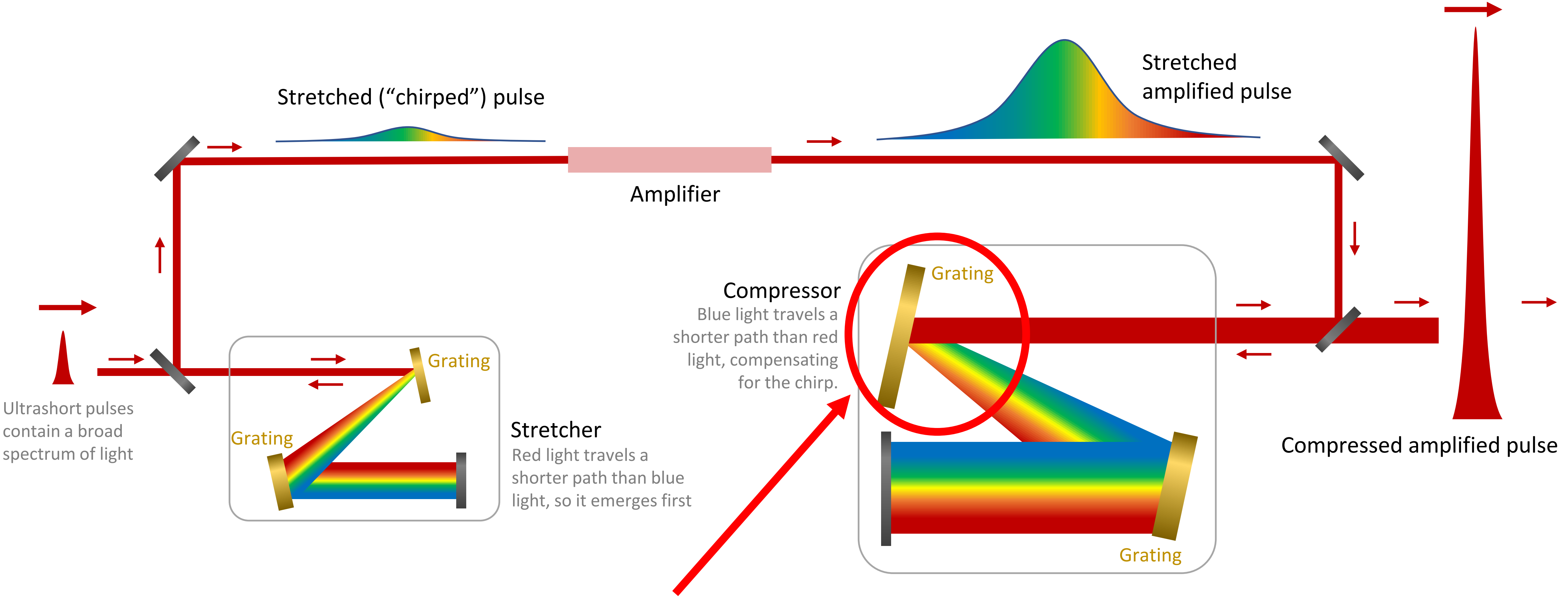
Contrast Improvement



Deliberately spoiled initial beam



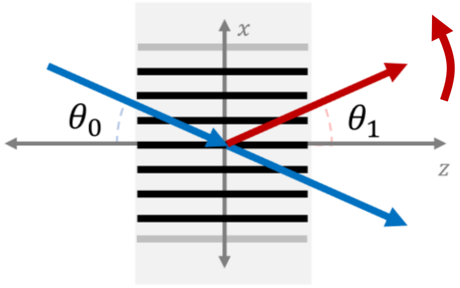
Chirped Pulse Amplification

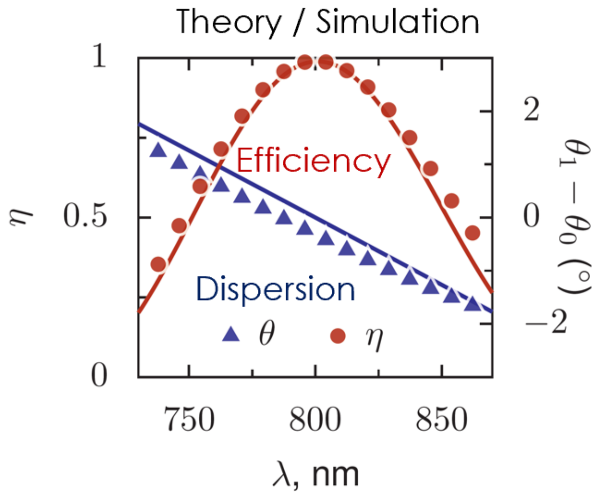


We want to replace this grating – we need a dispersive optic

Volume transmission gratings are dispersive

Can we build a compressor?





Spectral Bandwidth:

$$\frac{\Delta\lambda_{\mathrm{FWHM}}}{\lambda_0} \approx \frac{n_1}{2\sin^2\theta_B}$$

Larger Bragg angle reduces bandwidth

Larger plasma density increases bandwidth (but is harder to make)

Dispersion:

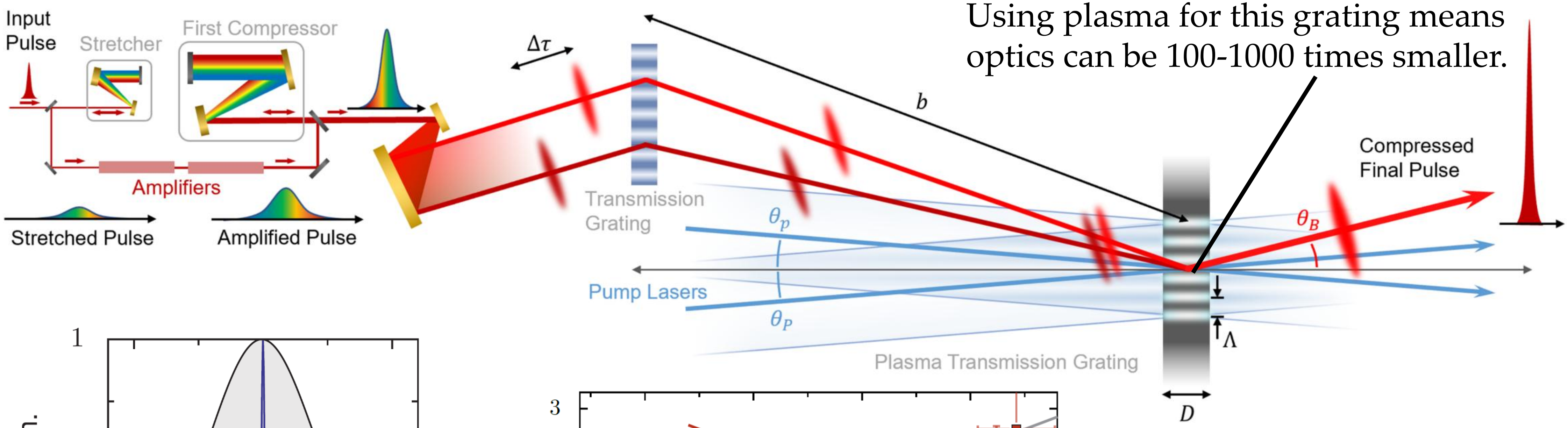
$$\frac{\lambda}{\Lambda} = \frac{2\lambda\sin\theta_B}{\lambda_0} = \sin\theta_0 + \sin\theta_1$$

Larger Bragg angle increases angular dispersion

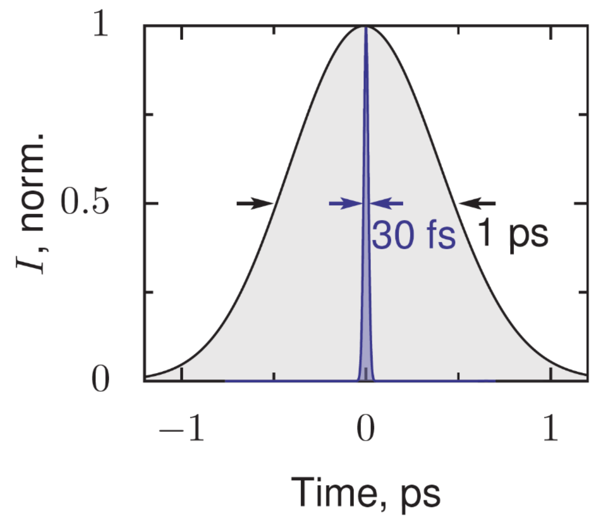
A CPA compressor requires large angular dispersion: performance set by tradeoff between bandwidth and dispersion

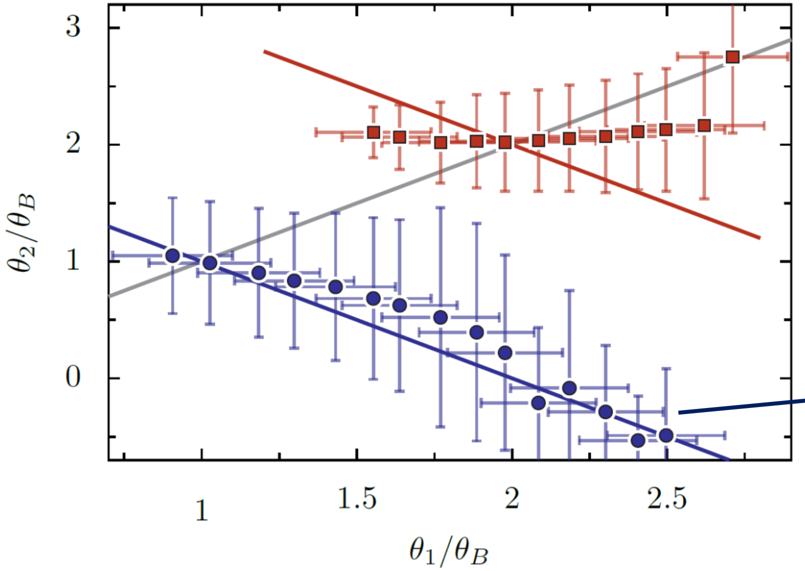
Edwards and Michel, *Phys. Rev. Appl.* **18** (2022).

Designing a plasma grating compressor



Using plasma for this grating means optics can be 100-1000 times smaller.





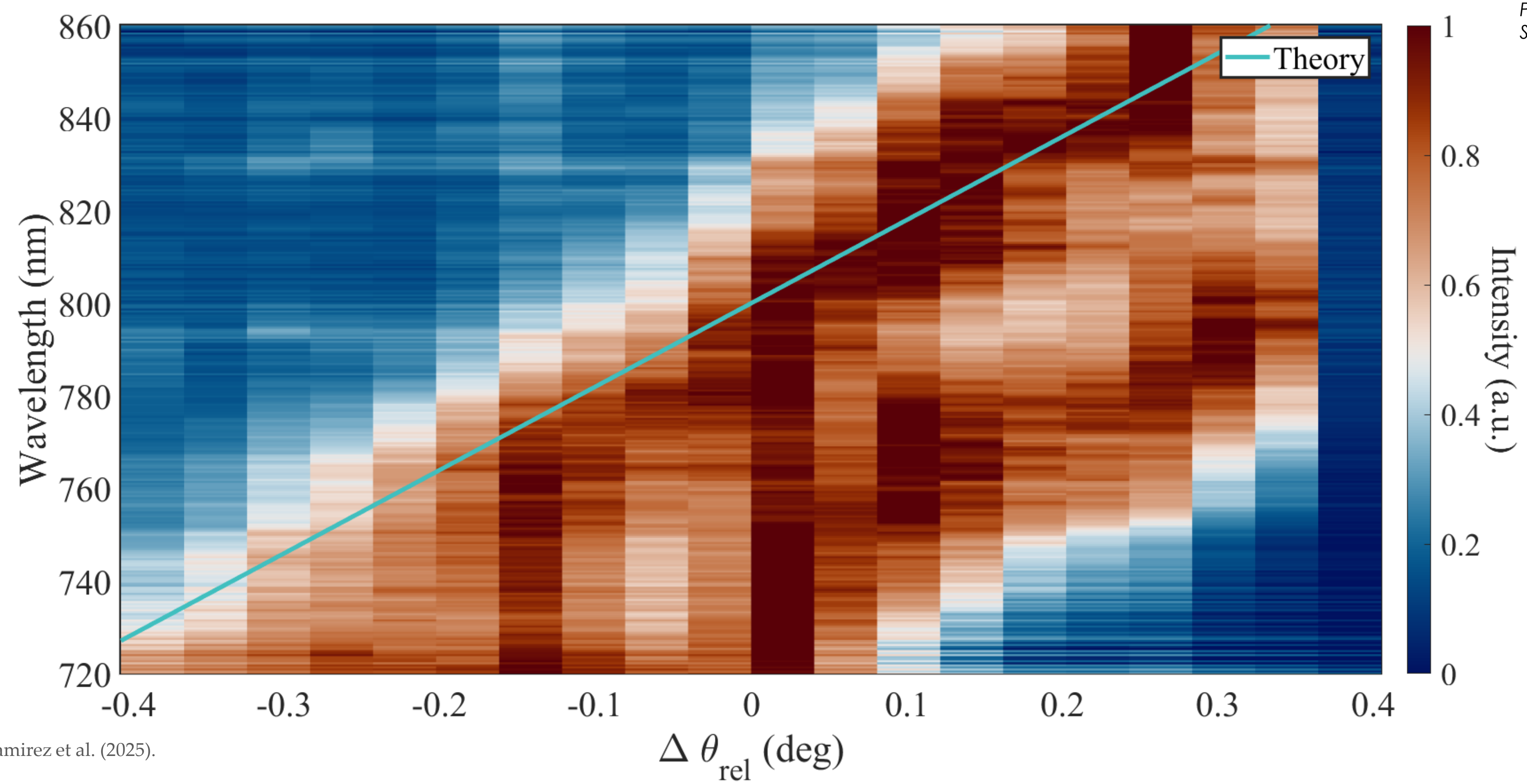
Experiments agree with predicted first-order dispersion

Edwards and Michel, *Phys. Rev. Appl.* **18** (2022).

Angular Dispersion of Femtosecond Pulses from an Ionization Grating

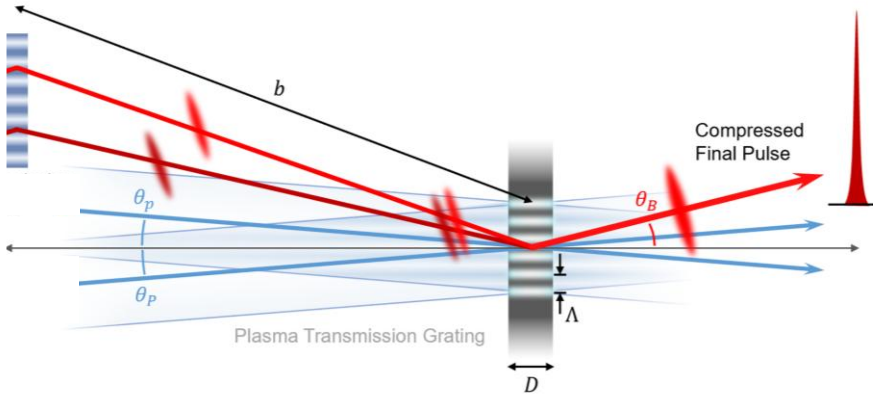
Victor Perez-Ramirez
PhD Candidate
Stanford

Measured dispersion of plasma gratings close to analytic predictions.



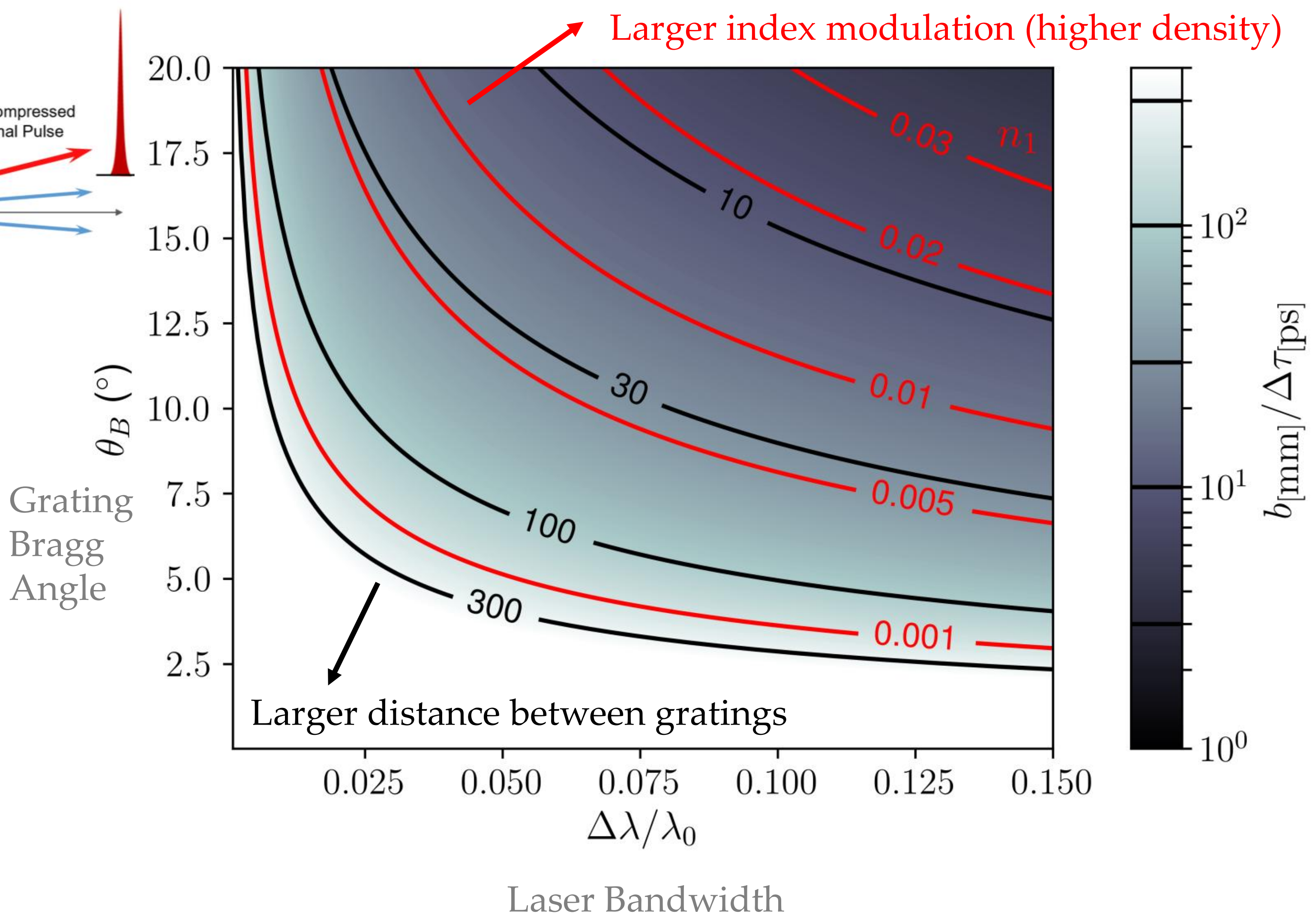
V. M. Perez-Ramirez et al. (2025).

Design envelope for a plasma grating compressor

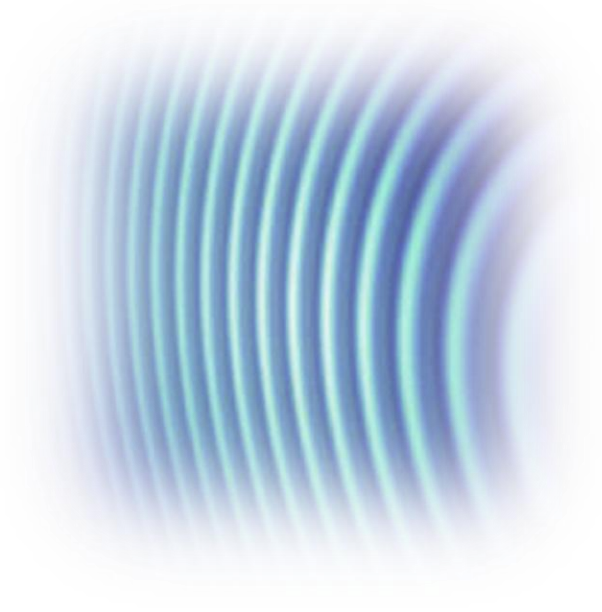


Compressor design is constrained by **plasma density** and **distance between gratings.**

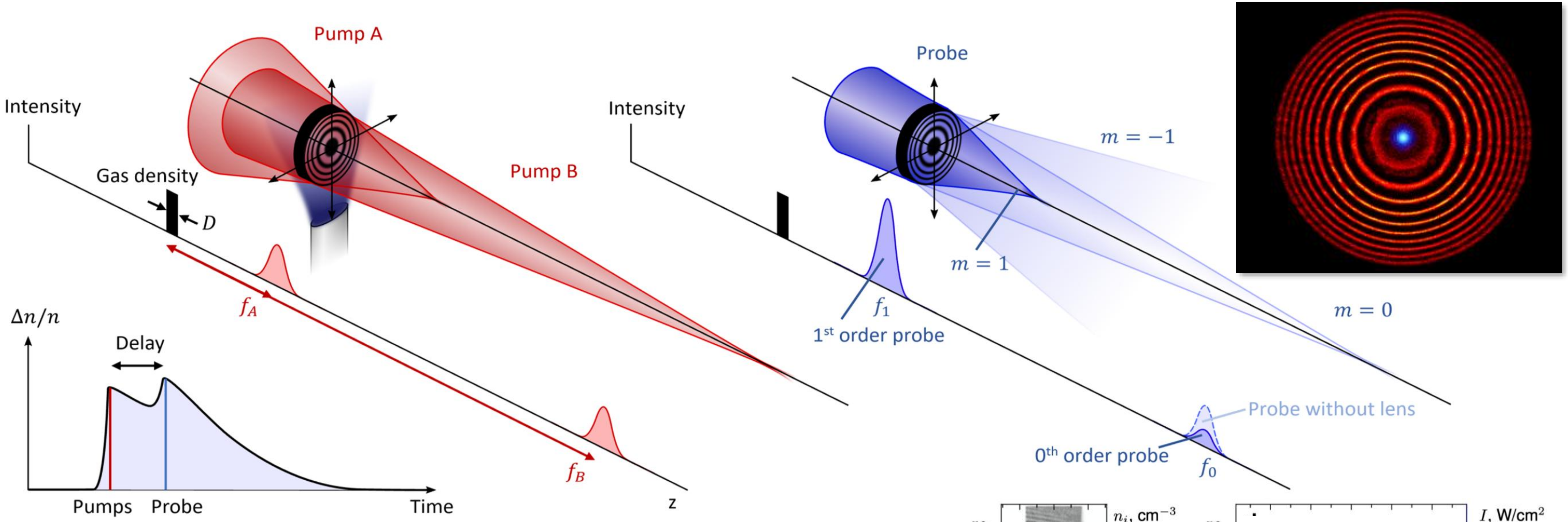
$$\frac{b_{[mm]}}{\Delta\tau_{[ps]}} \approx \frac{0.075}{\tan^2\theta_B}\left(\frac{\Delta\lambda}{\lambda_0}\right)^{-1}$$

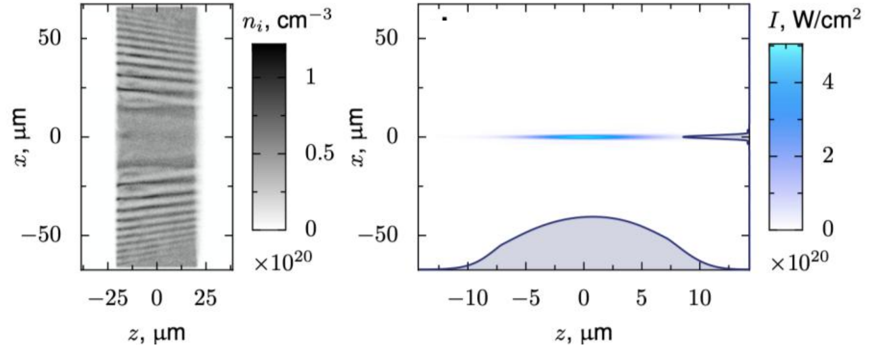


Holographic Lenses



Holographic Lenses

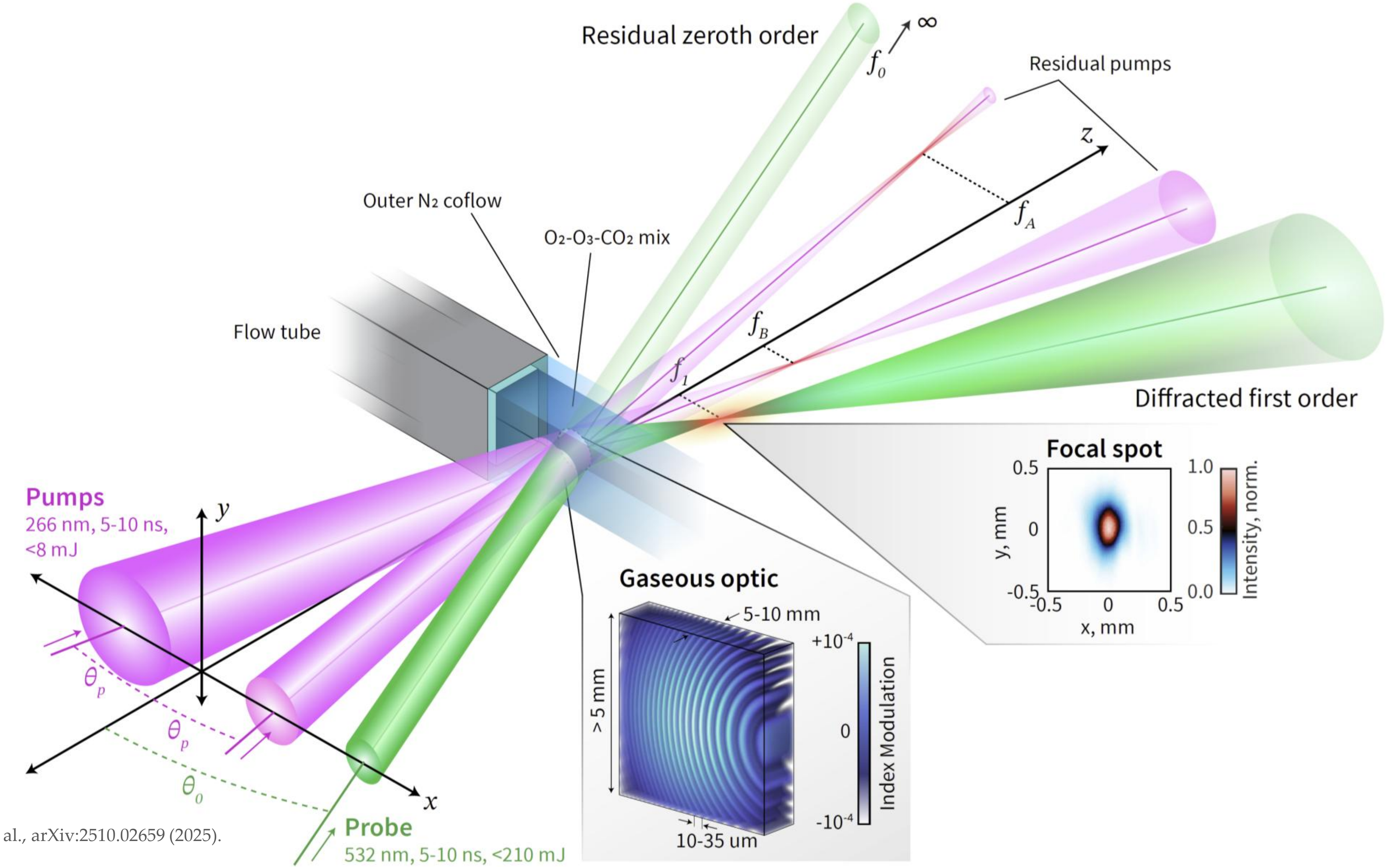




Changing pump beam focusing produces diffractive lenses instead of gratings.

M.R. Edwards et al. *Phys. Rev. Lett.* **128**, 065003 (2022).

Making a Holographic Gas Lens

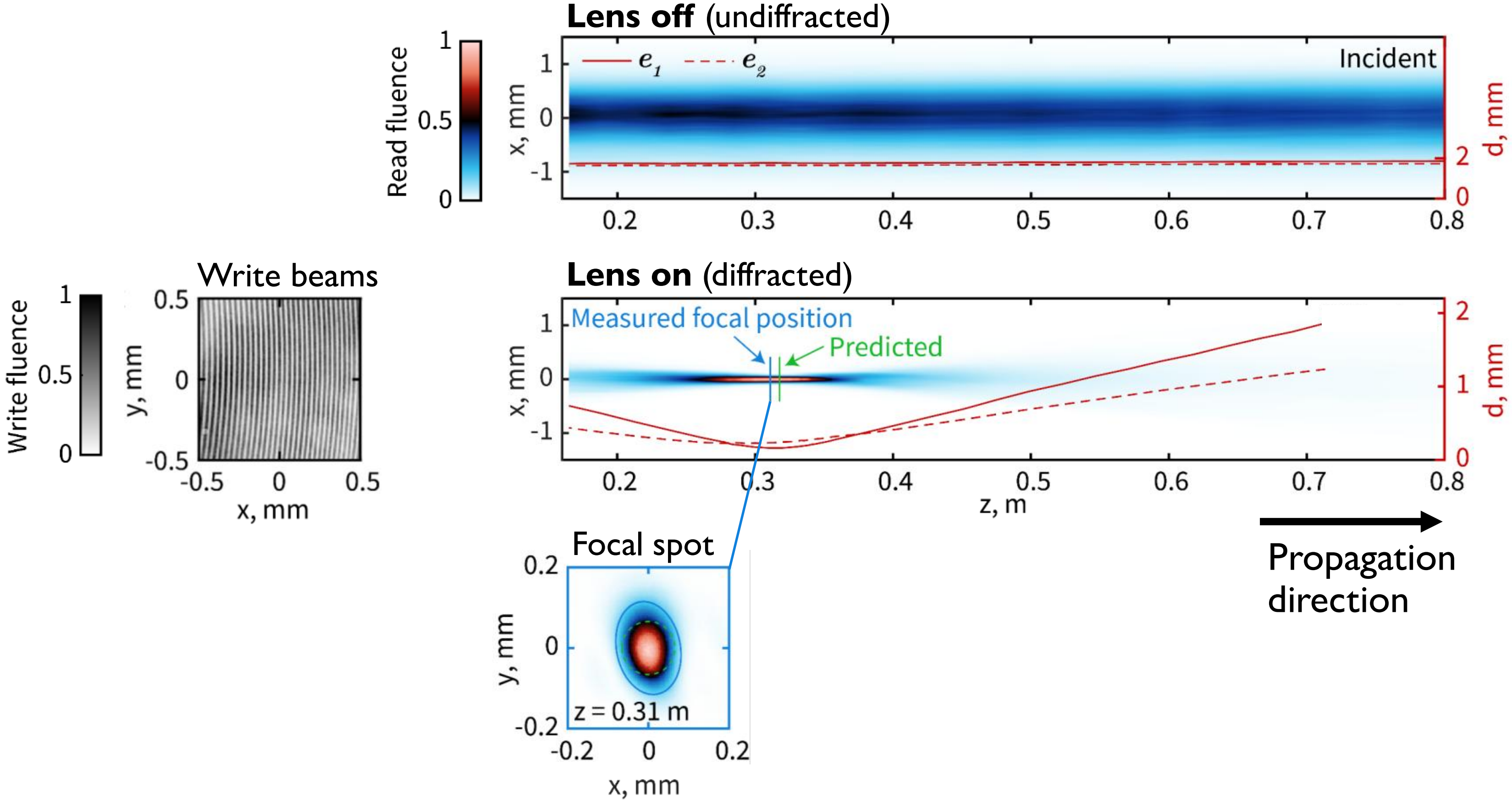


Dave Singh
PhD Student
Stanford

D. Singh et al., arXiv:2510.02659 (2025).

Gas Lens as a Focusing Optic

In experiments, >50% efficiency achieved for focusing a 532-nm 5-ns read beam.



Write: 266 nm, 5 ns, 5.5 mJ
Read: 532 nm, 5 ns
Gas: 5 mm, 4.3% O_3, 50% CO_2

D. Singh et al., "Holographic Gaseous Lenses for High-Power Lasers," arXiv:2510.02659 (2025).

Tuning the Focal Length of a Gas Lens

The gas lens focal length can be tuned by changing the focal plane of one write beam.

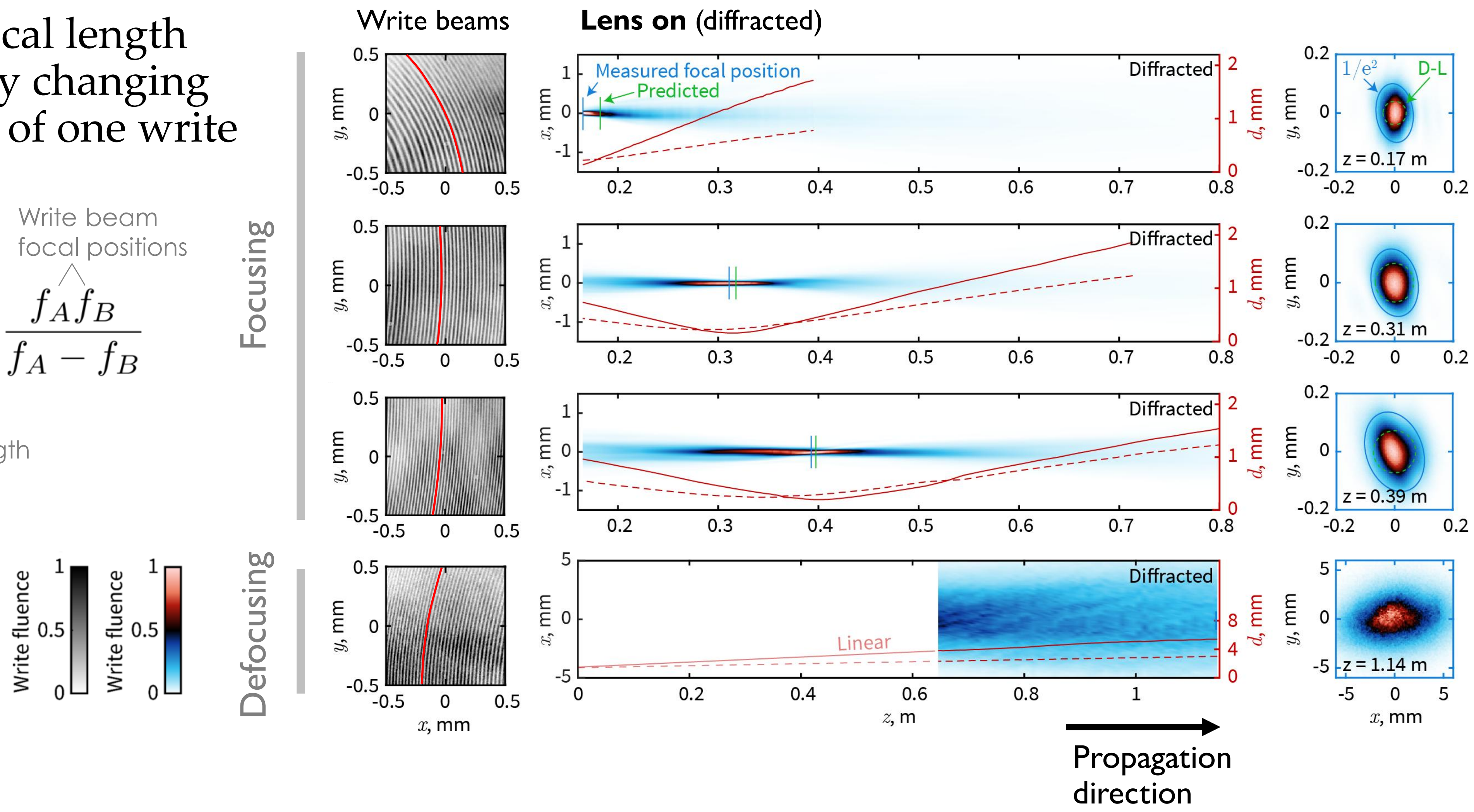
$$f = \frac{\lambda_w}{\lambda_0} \cdot \frac{f_A f_B}{f_A - f_B}$$

Write wavelength

Write beam focal positions

Gas lens focal length

Read wavelength

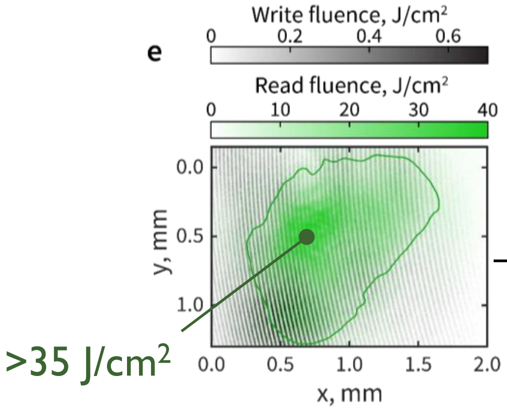


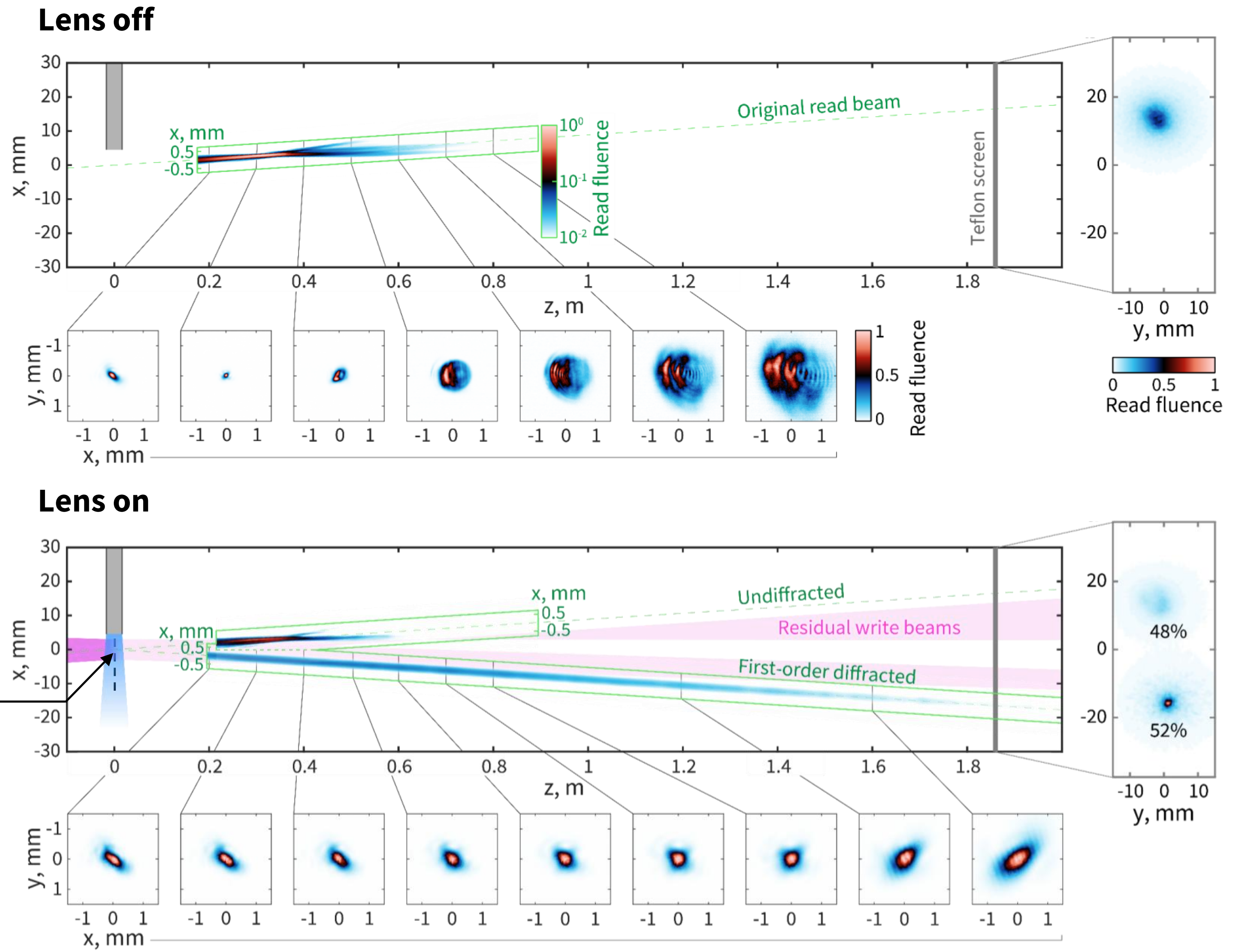
D. Singh et al., "Holographic Gaseous Lenses for High-Power Lasers," arXiv:2510.02659 (2025).

Collimating Gas Lens

For nanosecond beams, the laser-induced damage threshold is >1 kJ/cm².

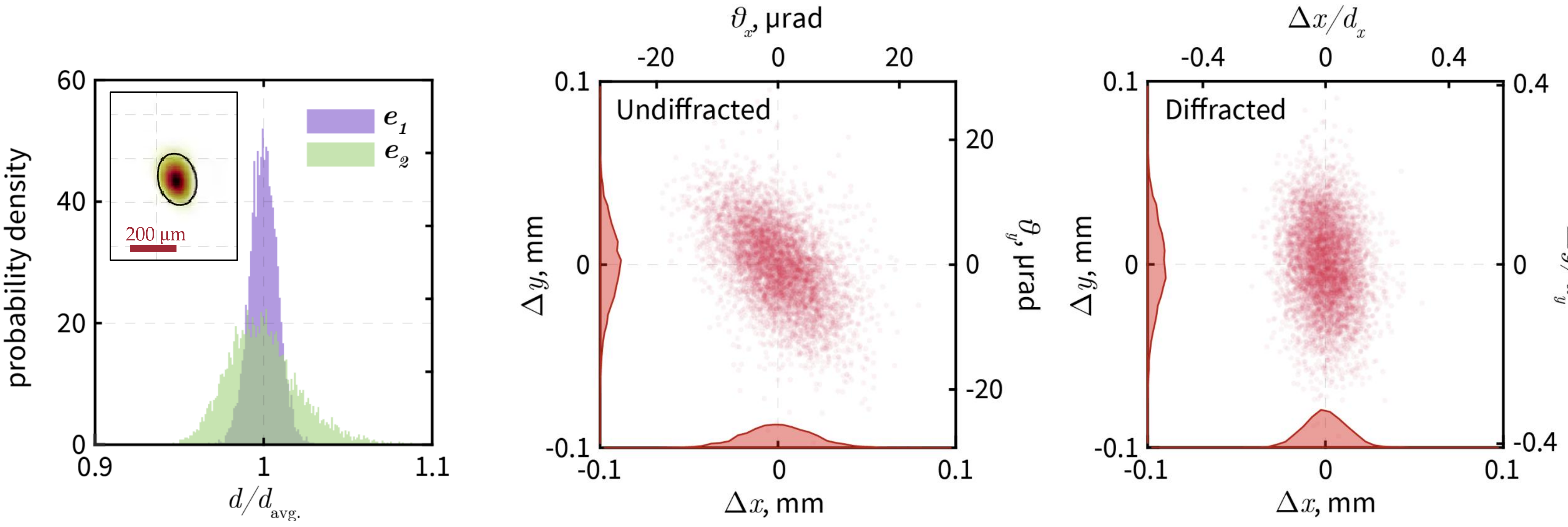
Write: 266 nm, 5 ns, 6.4 mJ
Read: 532 nm, 5 ns, 210 mJ
Gas: 10 mm, 1-5% O_3, 50% CO_2





Pointing Stability of a Gas Lens

Focal spot size in a focusing configuration is also stable.



Write: 266 nm, 5 ns, 5.5 mJ
Read: 532 nm, 5 ns
Gas: 5 mm, 4.3% O_3, 50% CO_2

Each data point is a single-shot beam centroid.

D. Singh et al., "Holographic Gaseous Lenses for High-Power Lasers," arXiv:2510.02659 (2025).

Focusing of Femtosecond Pulses with a Gas Lens

> 40% diffraction efficiency achieved with 800-nm 35-fs pulses in a collimating configuration.

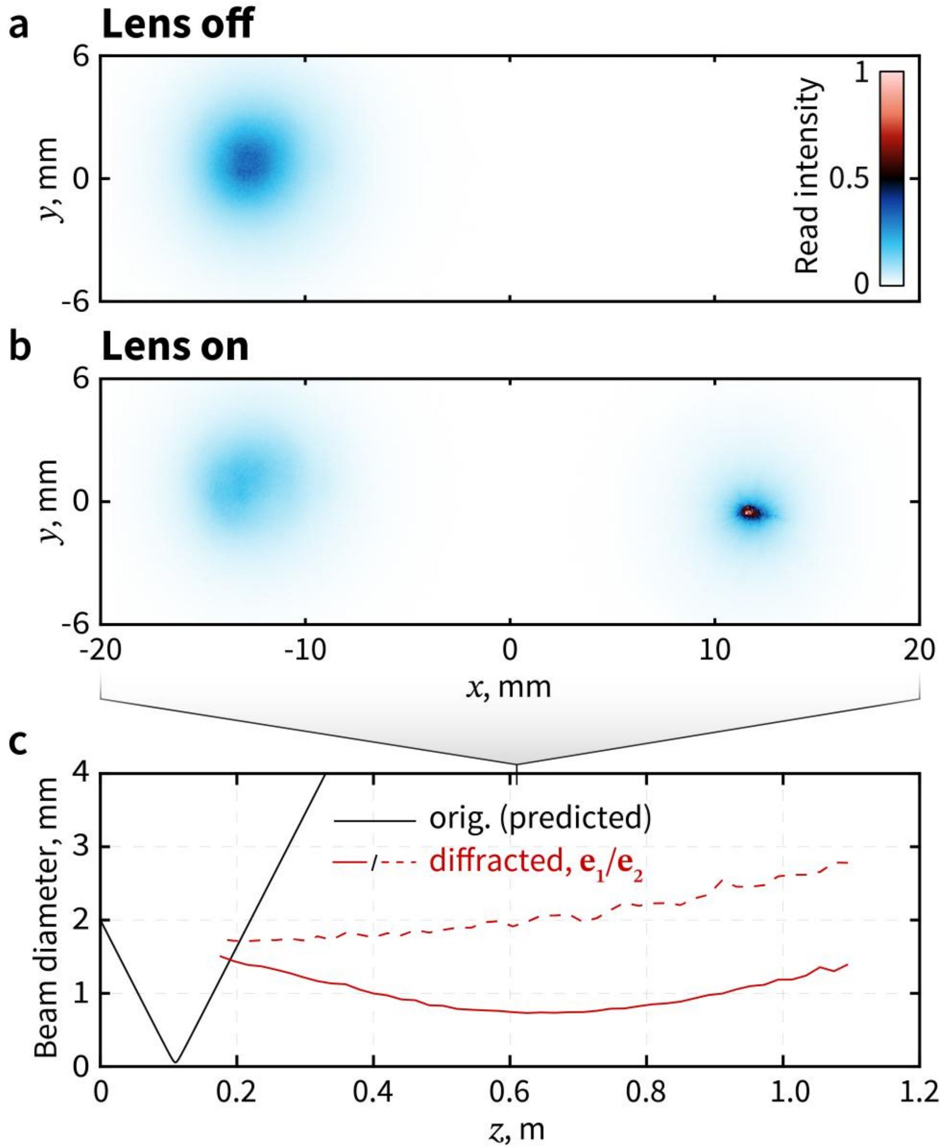
(no fundamental limit to higher efficiency)

FWHM bandwidth

Λ-period Fourier mode of refractive index modulation

$$\frac{\Delta\lambda}{\lambda_0} \approx 0.8 \frac{n_1}{\sin^2 \theta_B}$$

$\Delta\lambda \approx 60$ nm for $\theta_B = 1.2°, n_1 = 4 \cdot 10^{-5}$



D. Singh et al., "Holographic Gaseous Lenses for High-Power Lasers," arXiv:2510.02659 (2025).

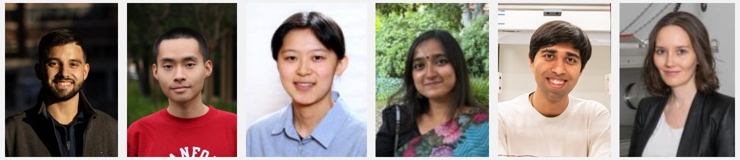
Acknowledgements

V.M Perez-Ramirez, S. Cao, K. Ou, D. Singh, C. Redshaw, H. Rajesh, D. Chakraborty, E. Koh, P. Dedeler
Stanford University

P. Michel, A. Oudin, N. Lemos, E. Kur
Lawrence Livermore National Laboratory

J. Wurtele, V. Munirov
University of California, Berkeley

J.M. Mikhailova, M.M. Wang, N.M. Fasano
Princeton University



Here at ZEUS through February

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J.P. Palastro, J. Pigeon, P. Estrela
Laboratory for Laser Energetics, University of Rochester

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University of Michigan

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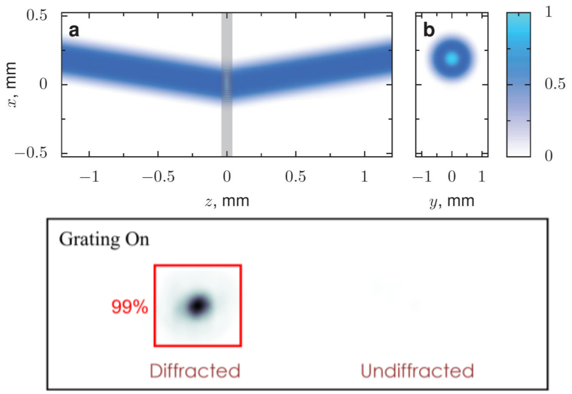
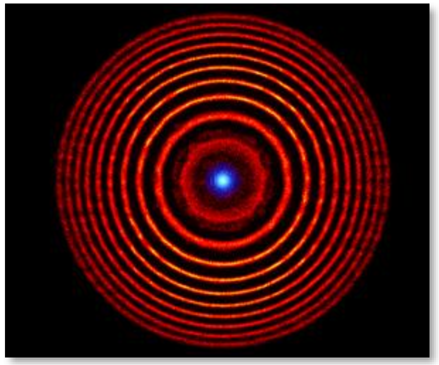
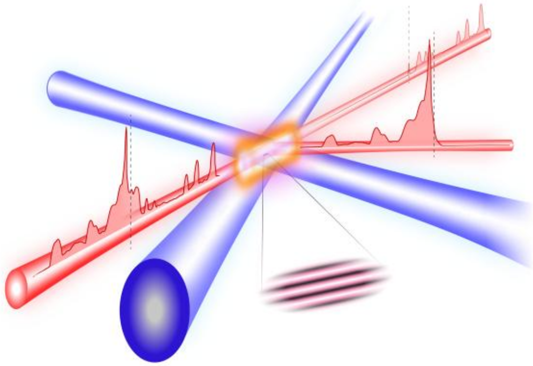
Summary

mredwards@stanford.edu

Diffractive plasma and gas optics offer higher damage thresholds than traditional optics and robustness compared to other plasma optics.







These optics can be used as components of high-power laser systems: pulse cleaning, pulse compression, and holographic lenses.