Relativistic Laser Plasma Interactions at Short Wave Infrared Wavelengths

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Laser-Plasma Accelerator Workshop 2019 at Split, Croatia
Working Group 3: Secondary radiation generation & applications

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Contributors

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Graduate students

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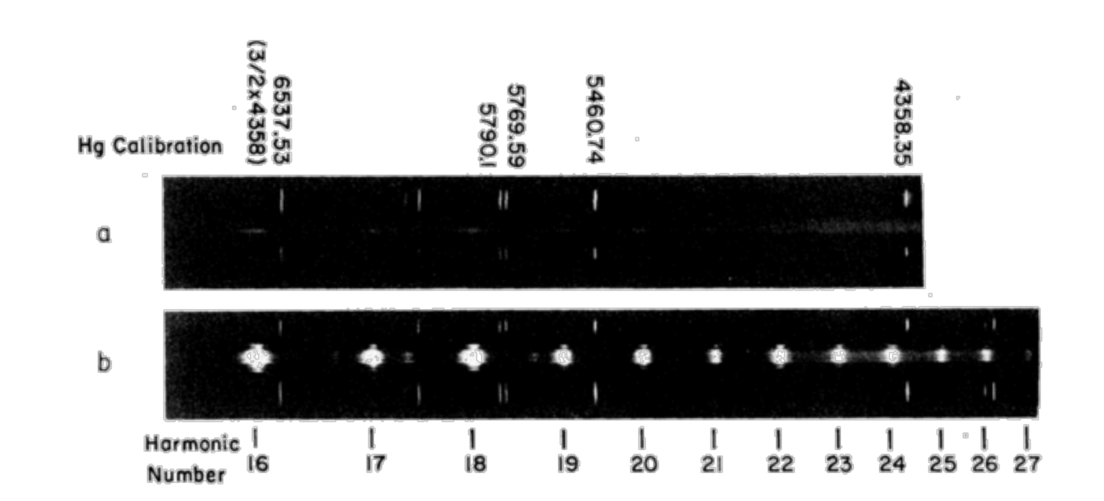
Early relativistic HHG experiments

- 1981 CO_2 laser experiment
  - 10^{16} Wcm^{-2} on target
  - 8 beams ~1 kJ
  - 0.6 ns FWHM envelope
- Since CPA all experiments at NIR
- Evidence of $I\lambda^2$ scaling



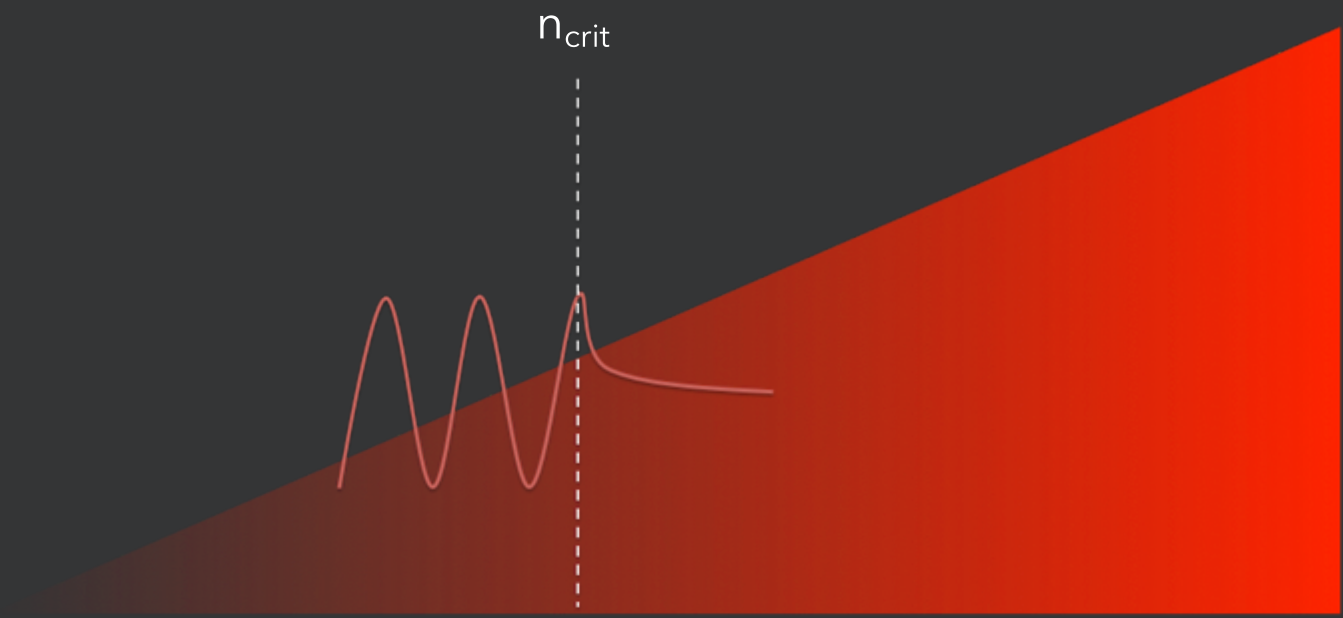
H. L. Carman, D. W. Forslund, and J. M. Kindel, PRL **46**, 29 (1981)

Plasma density

$$n_c = \frac{m_e \epsilon_0 \langle\gamma\rangle \omega^2}{e_c^2} = 1.12 \ldots \times 10^{21} \frac{\langle\gamma\rangle}{\lambda_{\mu m}^2} cm^{-3}$$

n_{crit} @ 800nm = 1.74 x 10^{21} cm^{-3}

n_{crit} @ 2100nm = 2.50 x 10^{20} cm^{-3}



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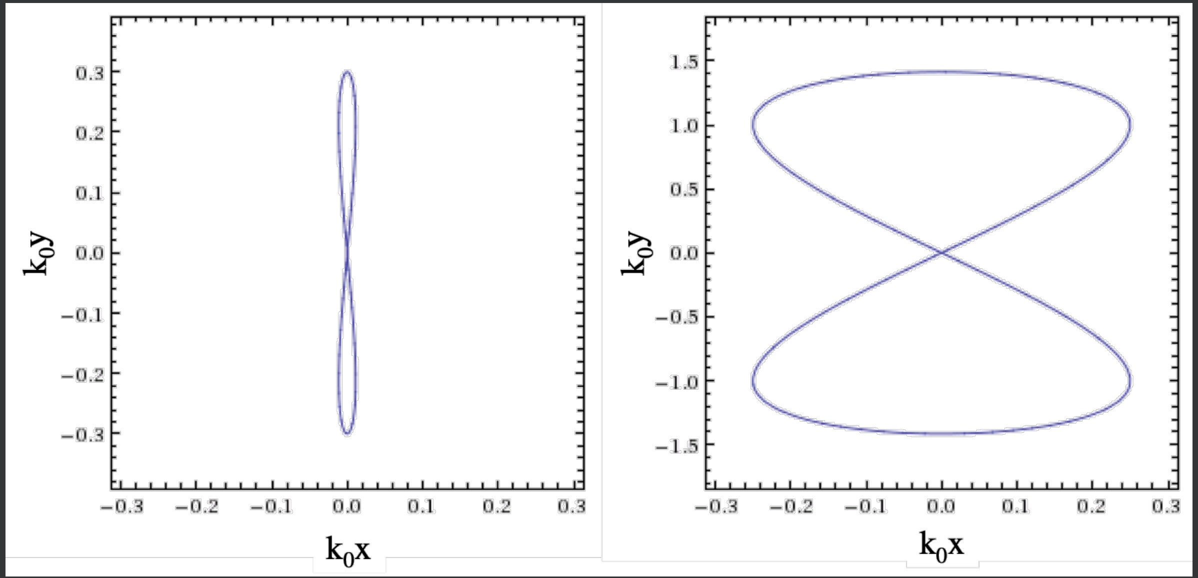
Scaling relationship

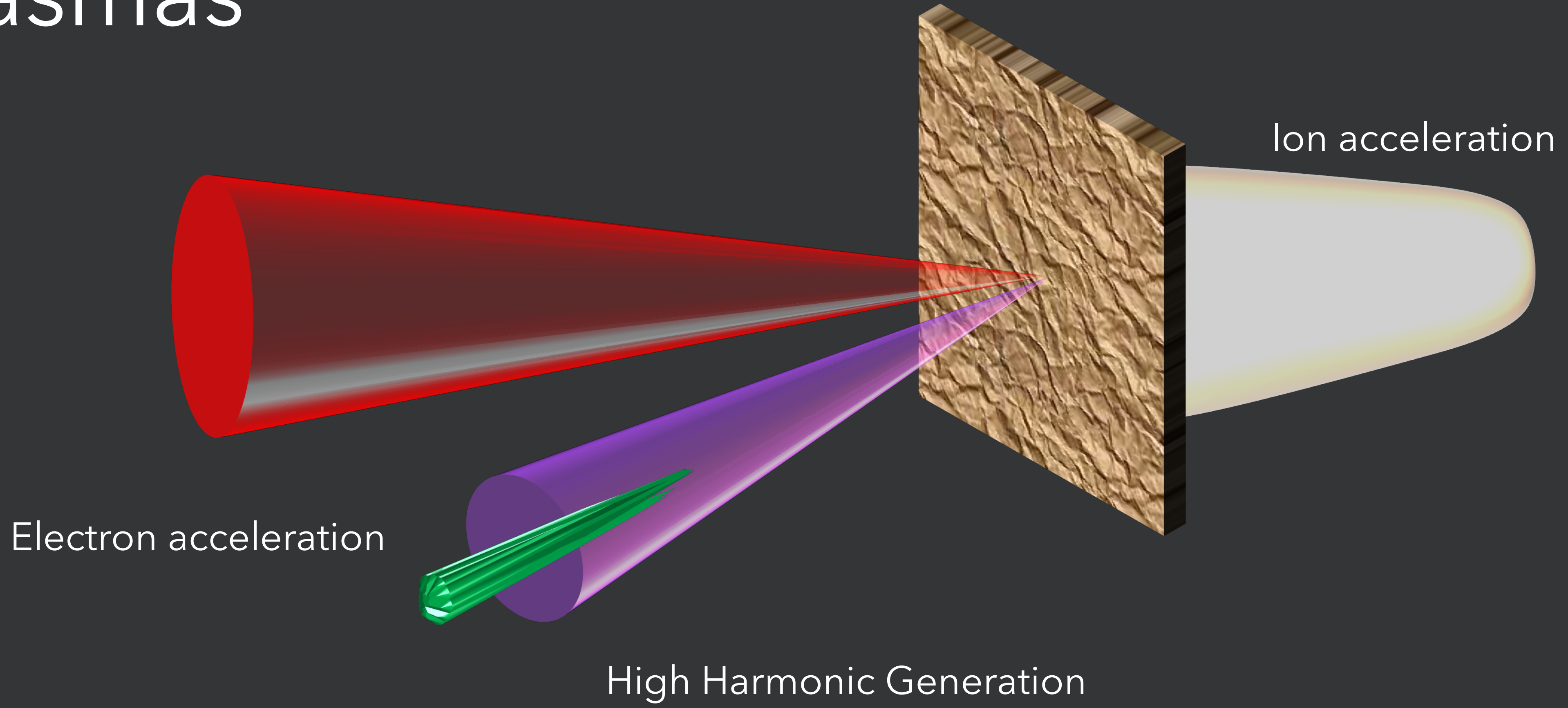
- Electron motion described with normalized vector potential
  - Ponderomotive force ∝ $\langle a_0 \rangle^2$
  - Lorentz force motion ∝ a_0^2 in longitudinal, ∝ a_0 in transverse
  - Relativistic Lorentz factor ∝ a_0



$$a_0 = \frac{p_0}{m_e c} = -\frac{e_c A_0}{m_e c} = -\frac{e_c E_0}{m_e c \omega_0}$$

$$a_0 = 0.85 \times 10^{-9} \lambda \sqrt{I}$$

Short pulse lasers and overdense plasmas



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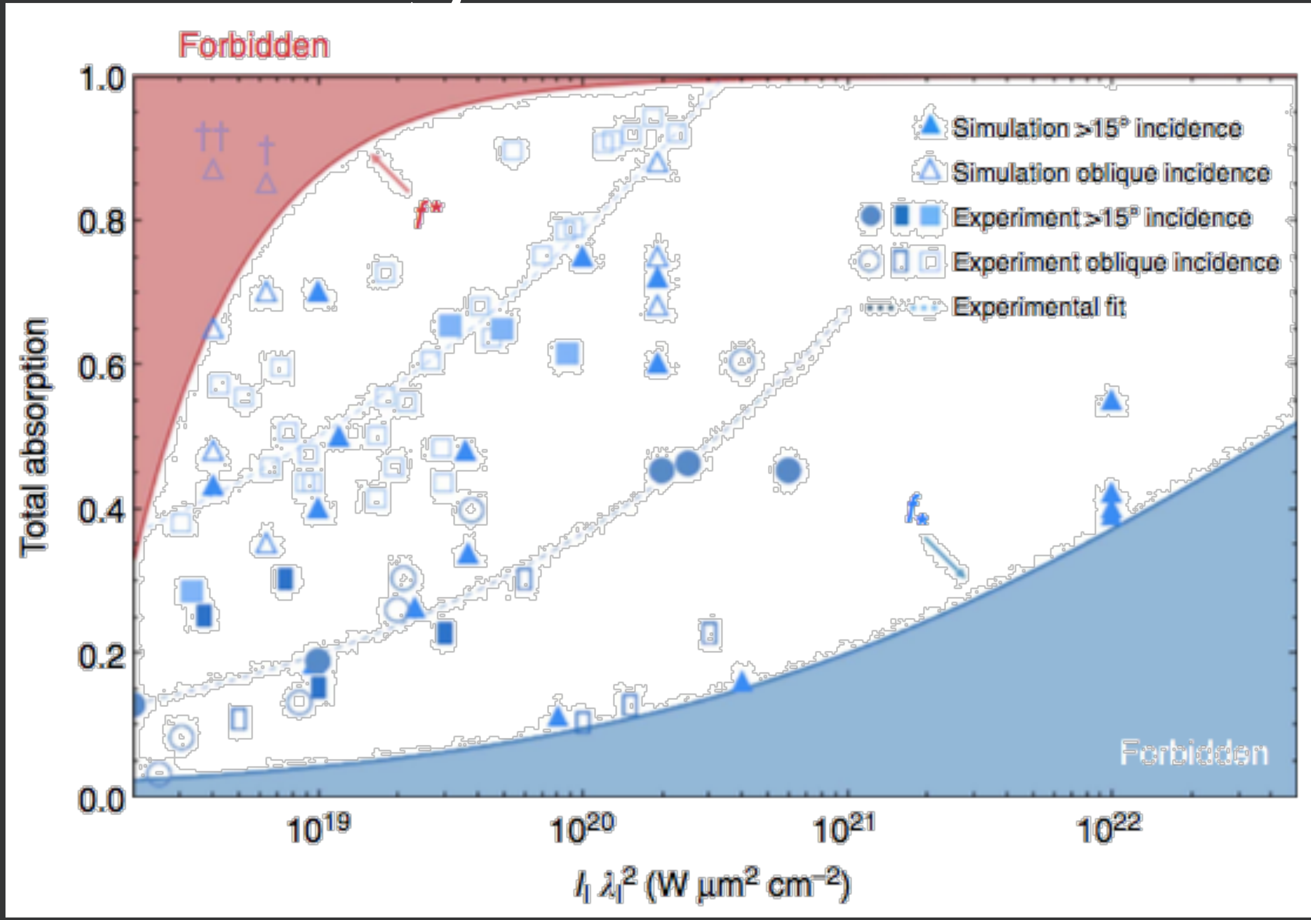
Absorption understanding

- Experiment and simulation shows large variation in absorption measurement
- Variables include:
  - Pulse duration
  - Polarization
  - Plasma density profile
  - Focal conditions



M. C. Levy, et al., Nat. Comm. 5, 4149 (2014)

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Attaining relativistic intensities

Solstice ACE

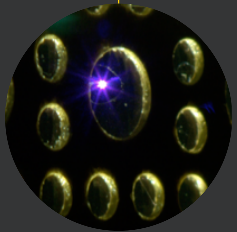
800 nm

1 kHz, 7 mJ, 35 fs

Mid-Infrared Beam

1300/2100 nm

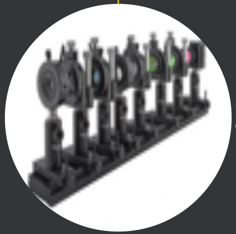
1 kHz, 1.3/0.7 mJ, 40 fs



Probe Beams

2 x 800 nm

1 kHz, 1 mJ, 35 fs



Femtokit

267-400 nm

1 kHz, 2 mJ, 35 fs

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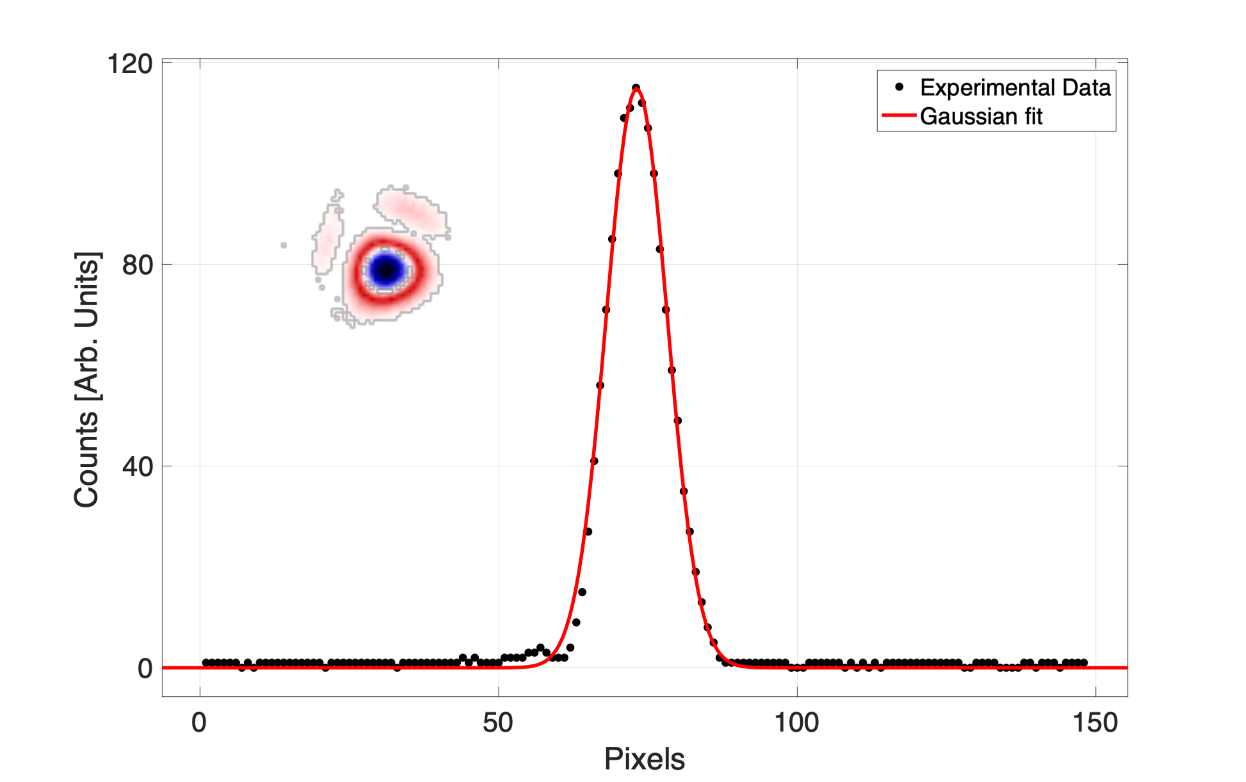
High quality focusing

- 1300 nm (1 mJ, 30 fs)
  - F/2: 5×10^{17} Wcm^{-2} (a_0 = 0.5)
  - F/1: 2×10^{18} Wcm^{-2} (a_0 = 1)
- 2100 nm (0.6 mJ, 40 fs)
  - F/2: 8×10^{16} Wcm^{-2} (a_0 = 0.4)
  - F/1: 3×10^{17} Wcm^{-2} (a_0 = 0.7)

2.01 μm FWHM measured
1.73 μm diffraction limit



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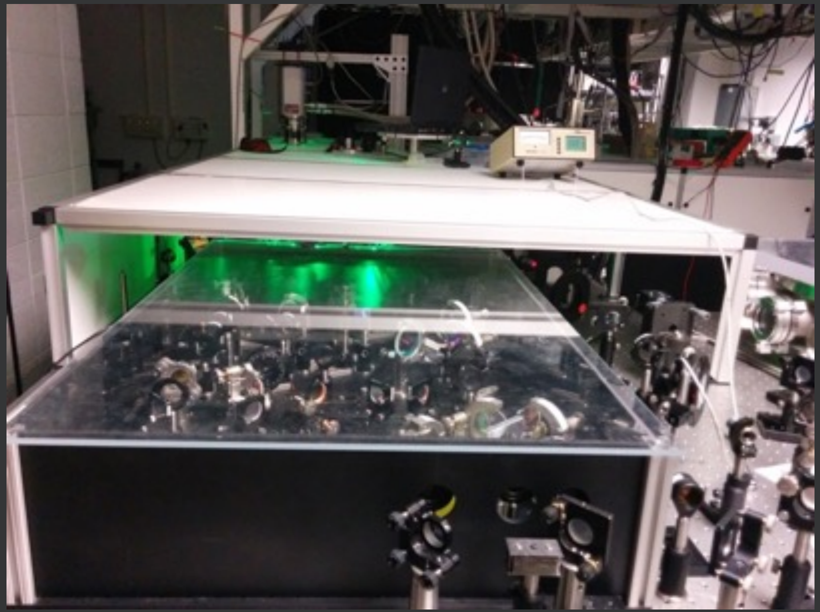
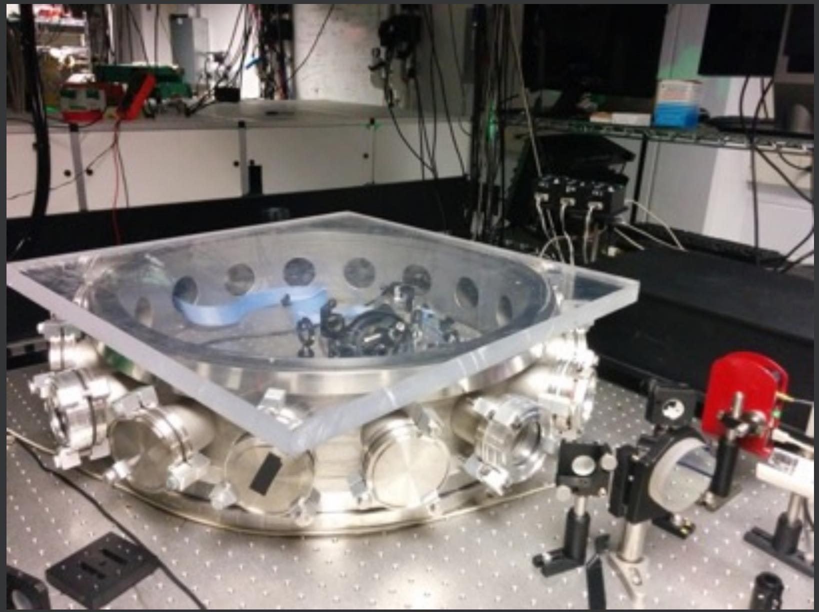
Experimental setup at Michigan

- Lambda Cubed
  - 800 nm, 0.5 kHz
  - 30 fs
  - 20 mJ
- 2 micron OPA
  - 35 fs
  - 2 mJ





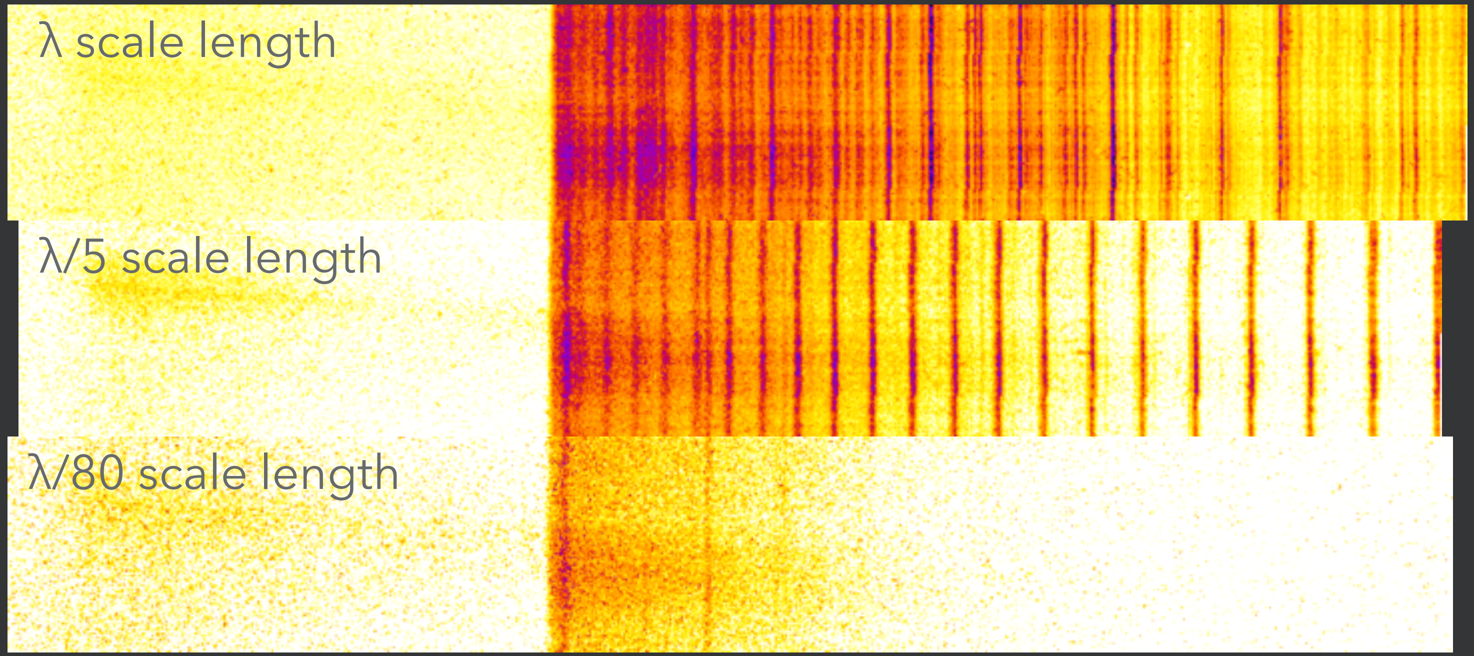
F/2: 3×10^{17} Wcm^{-2} ($a_0 = 0.7$)

F/1: 1×10^{18} Wcm^{-2} ($a_0 = 1.4$)

Scale length influence on HHG

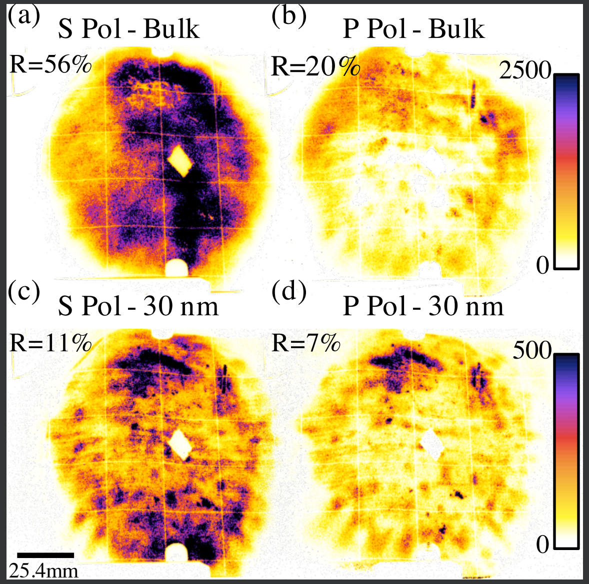
- 800 nm experiments
- 10^{17} – 10^{21} Wcm^{-2}

- Preplasma controlled with heating beam

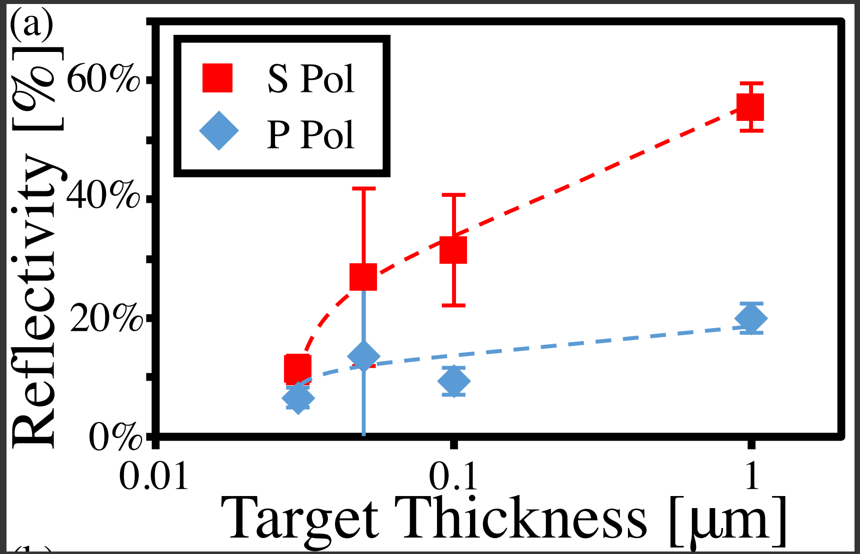


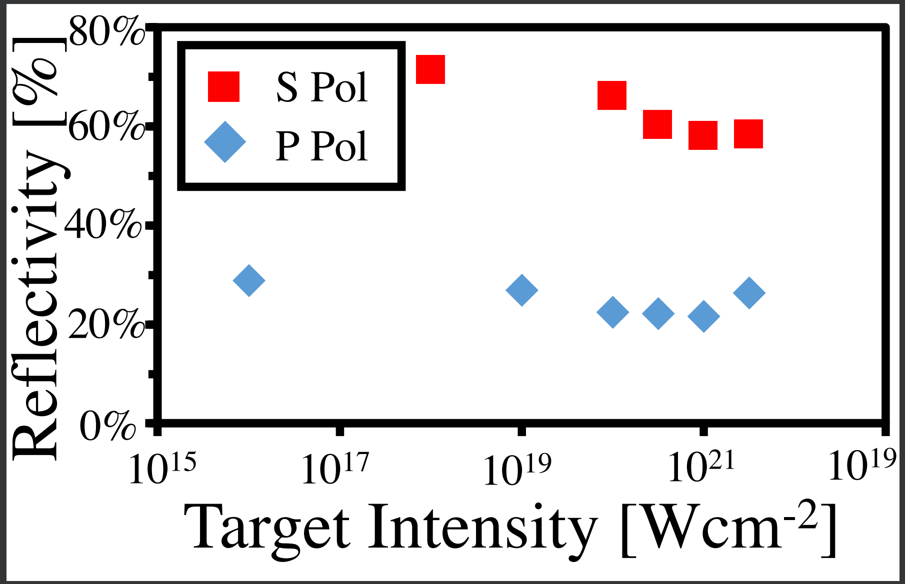
F. Dollar, et al., PRL **110**, 175002 (2013)

Imaging fundamental reflections



Ion motion/plasma pressure also strong influence





F. Dollar, et al., New J. Phys. 19, 063014 (2017)

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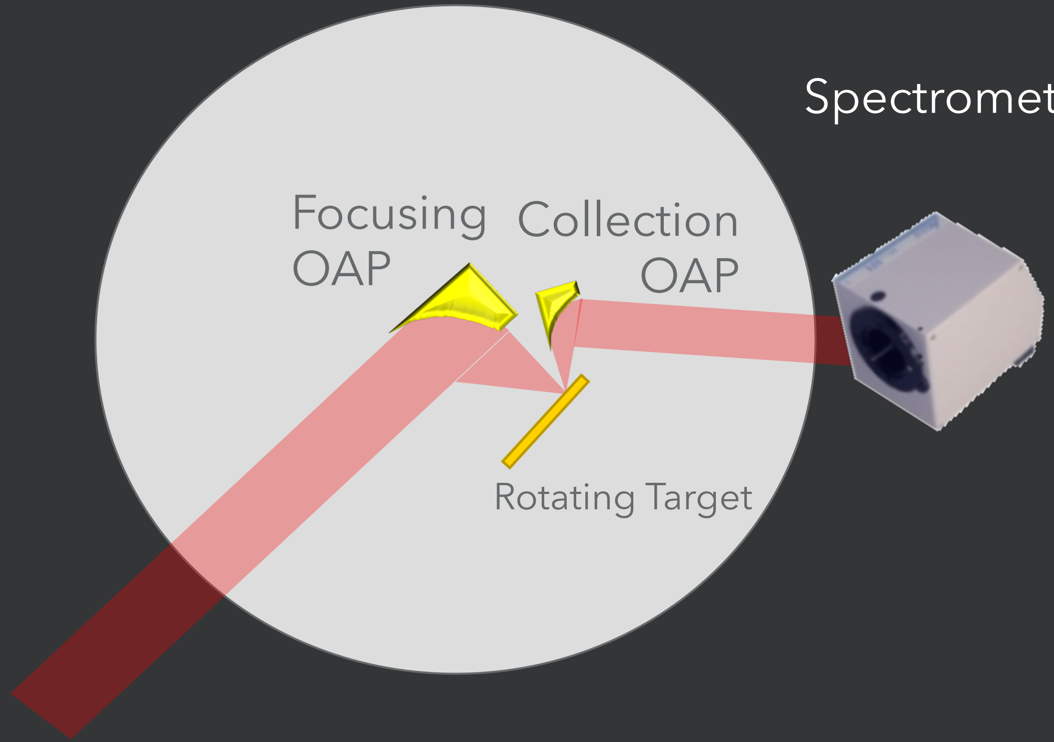
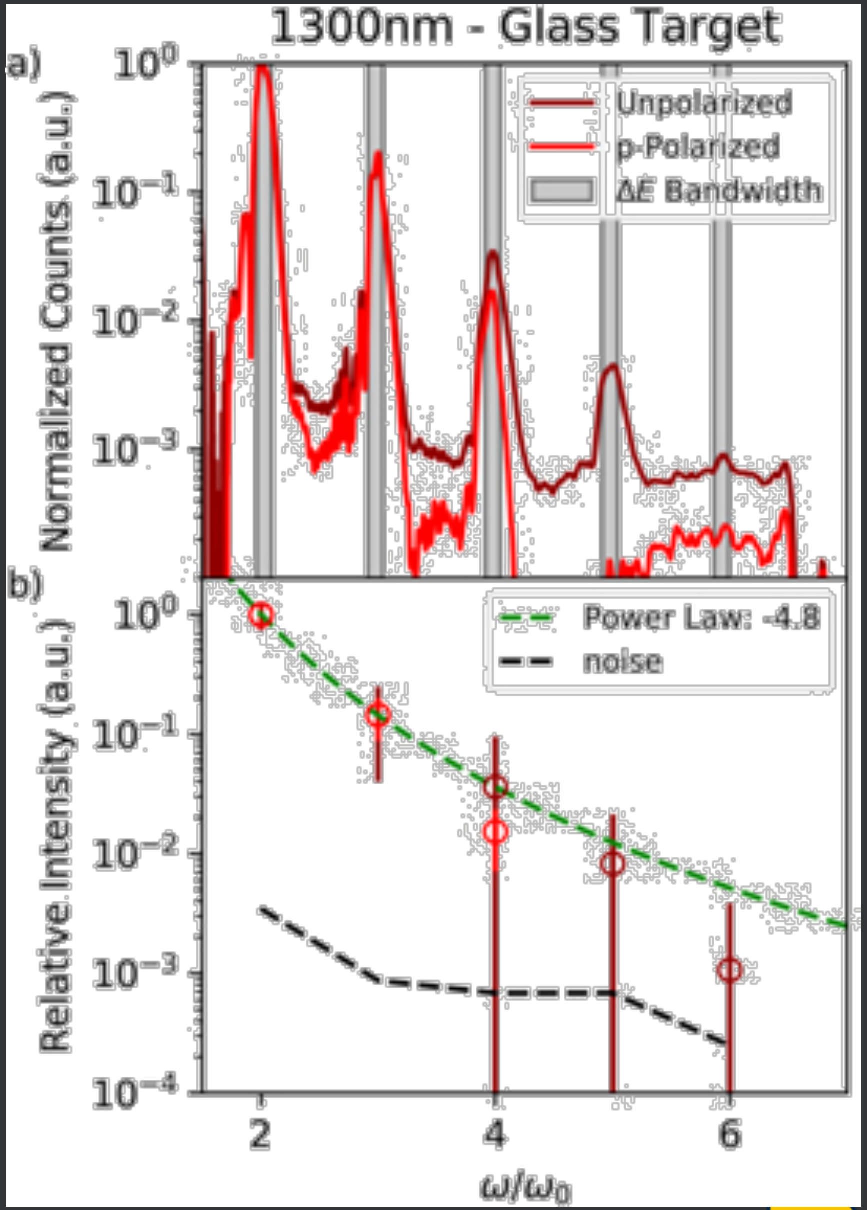
Relativistic HHG

- Fundamental questions remain
  - What is the relation between hot electron generation and HHG?
  - How do plasma conditions affect surface plasma waves?
  - Do single atom scalings hold for collective effects?
- Mid infrared provides unique experimental opportunities
  - Visible harmonics
  - Overdense targets
  - Higher a_0 for a given intensity

1300 Driven HHG (UCI)





N. Beier, et al., NJP **21**, 043052 (2019)

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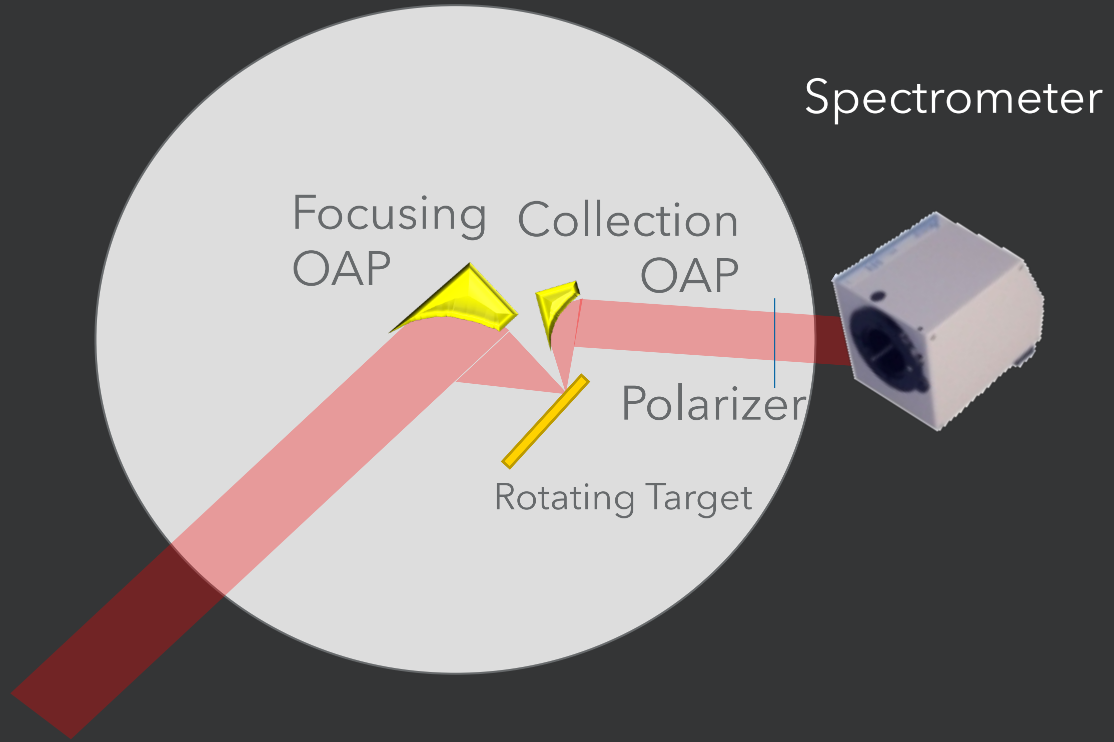
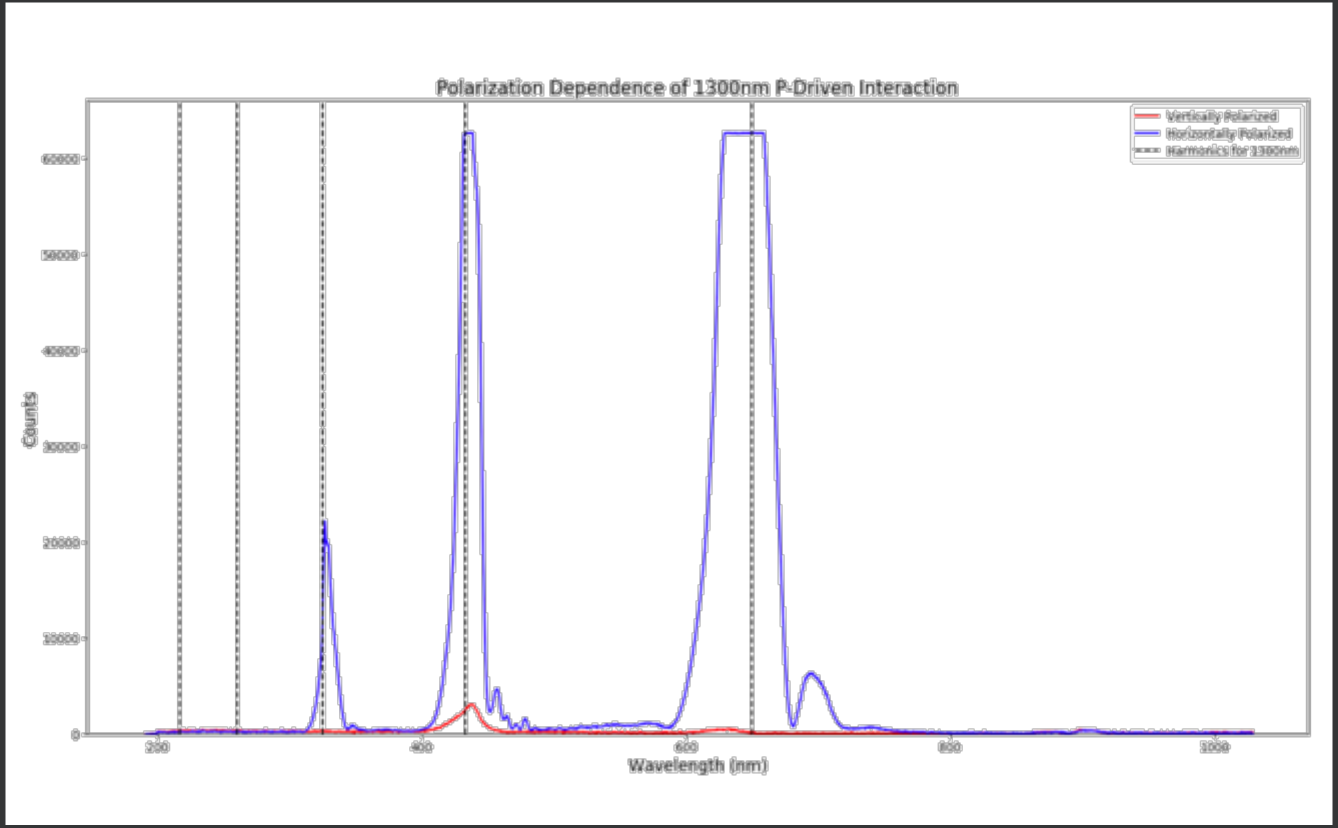
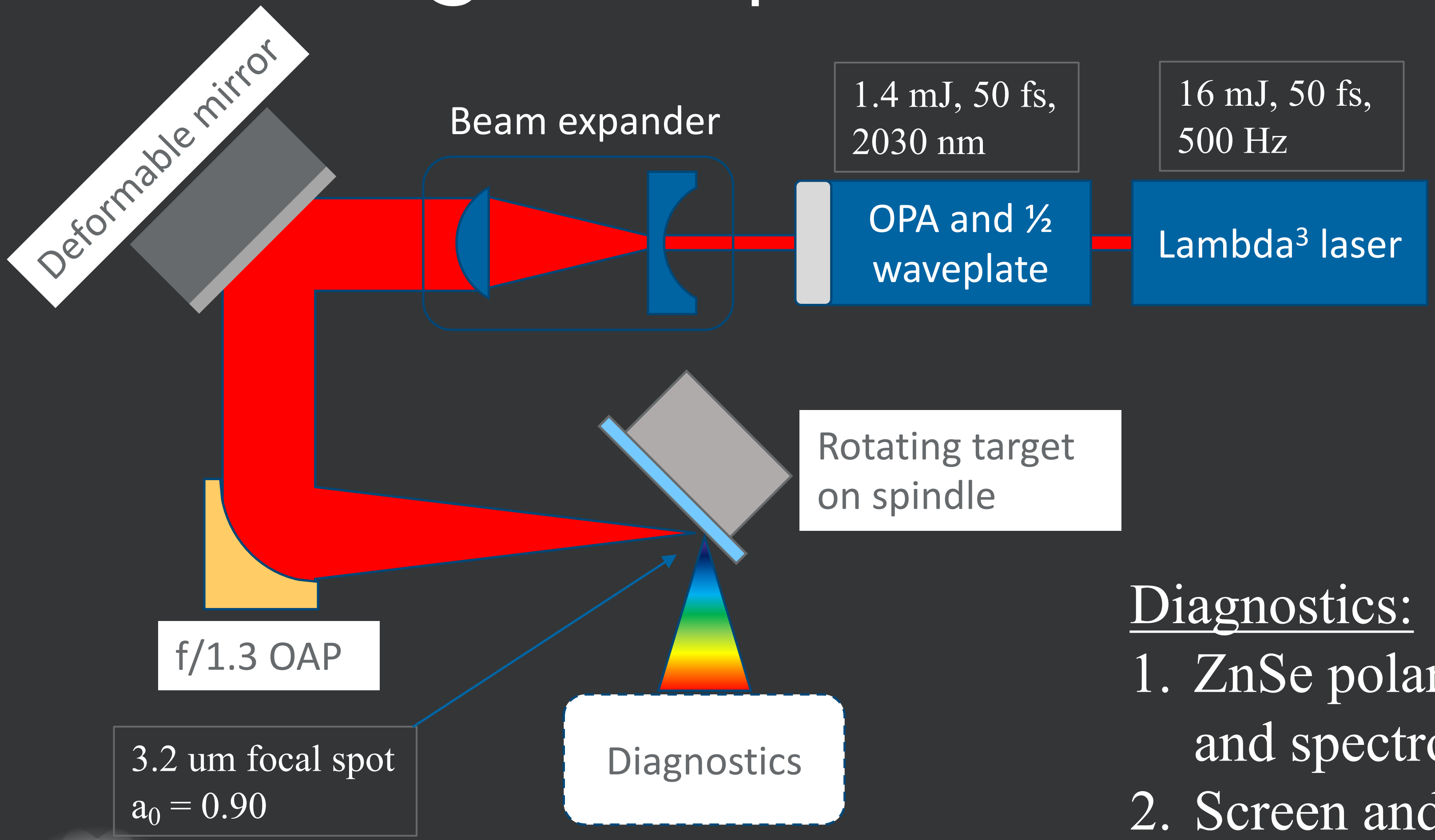
Polarization dependence of harmonics

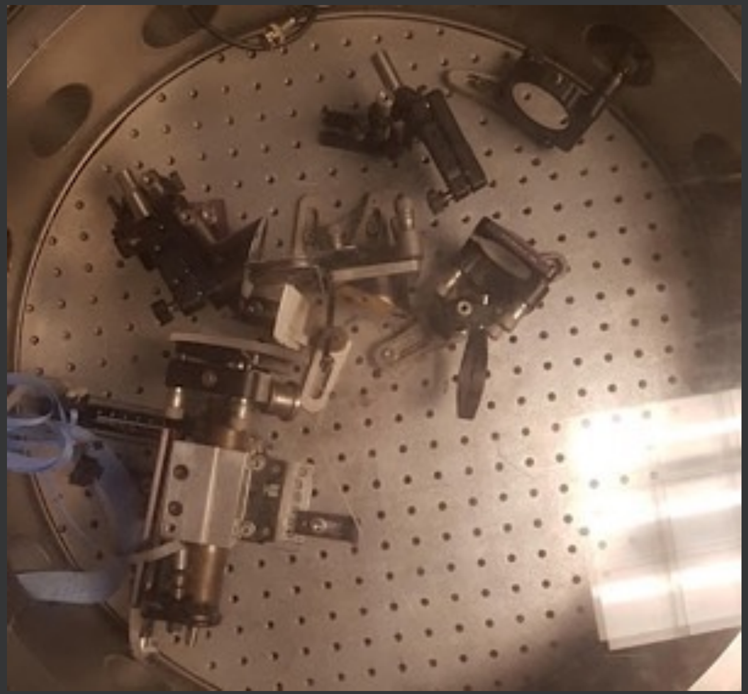




N. Beier, et al., NJP **21**, 043052 (2019)

Michigan Experiments





Diagnostics:

1. ZnSe polarizer and spectrometer
2. Screen and CCD

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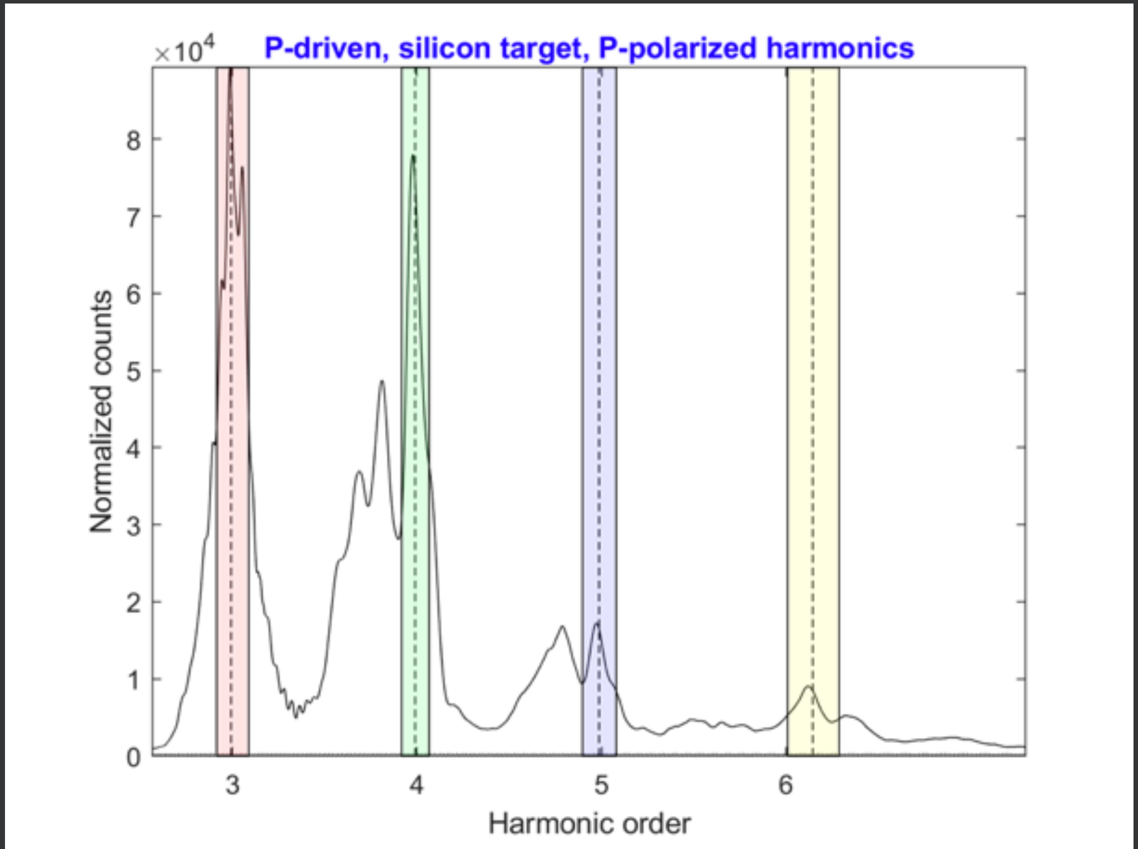
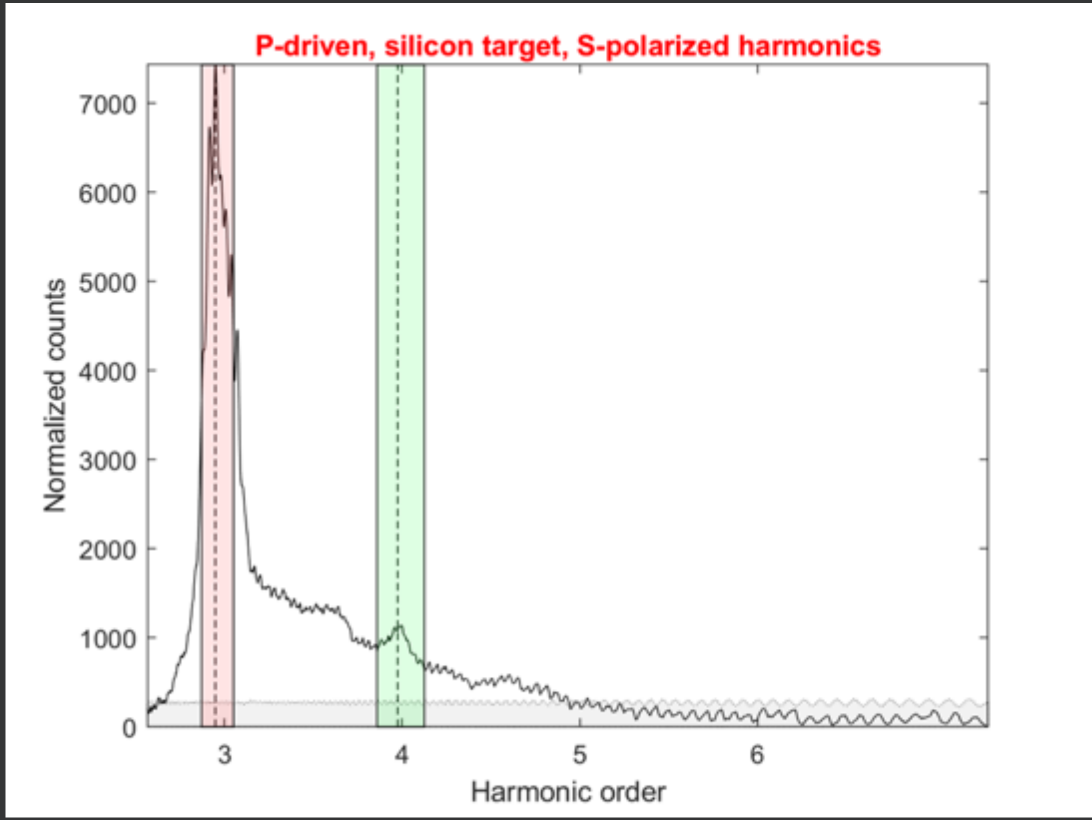
2100 Driven HHG (Michigan)





N. Beier, et al., NJP **21**, 043052 (2019)

25 shots integrated

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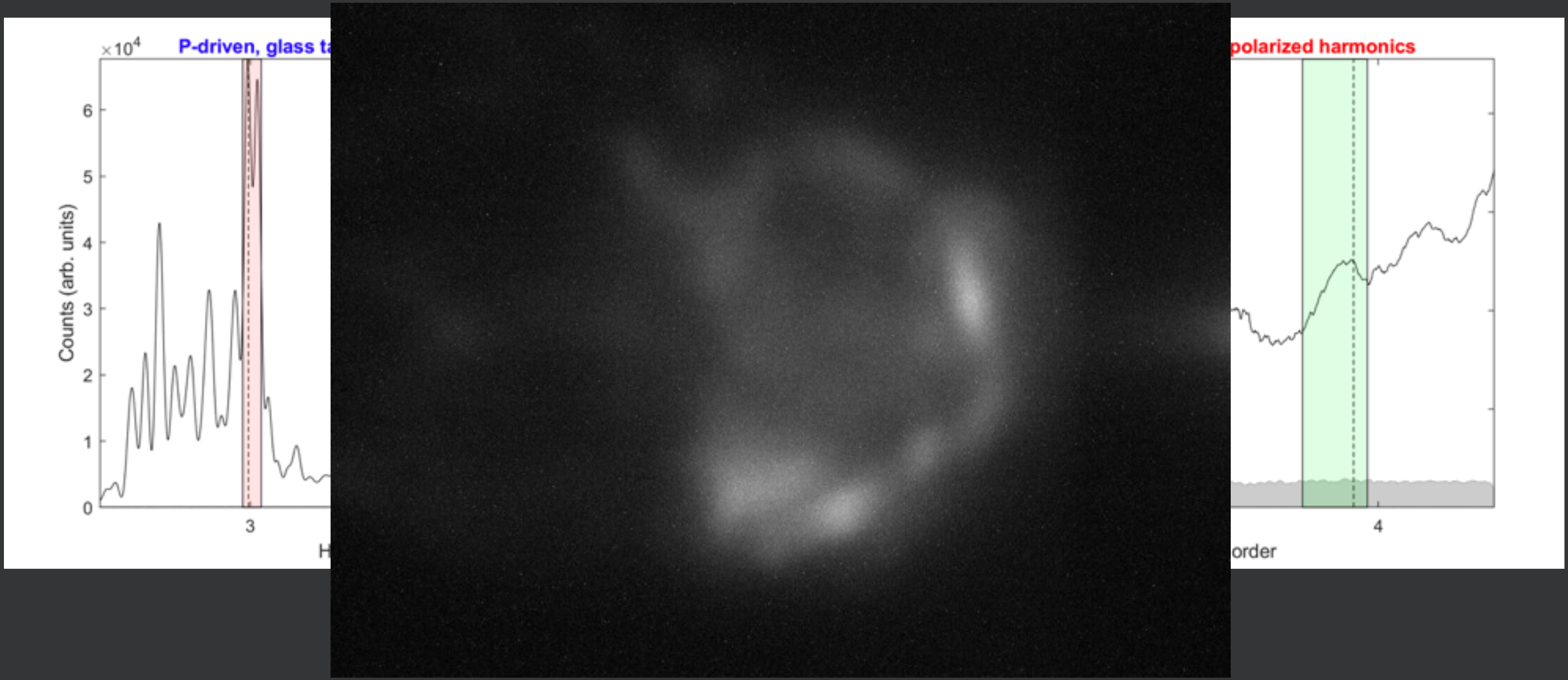
Polarized harmonics



25 shots integrated

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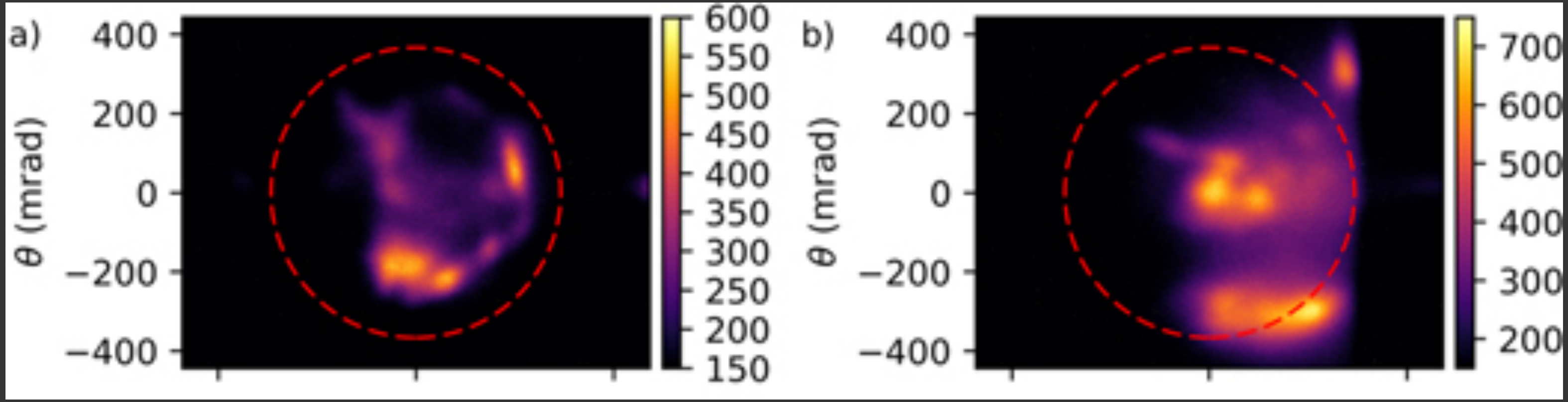
High order wavefronts

3ω Profile (Silicon) 3ω Profile (Glass)



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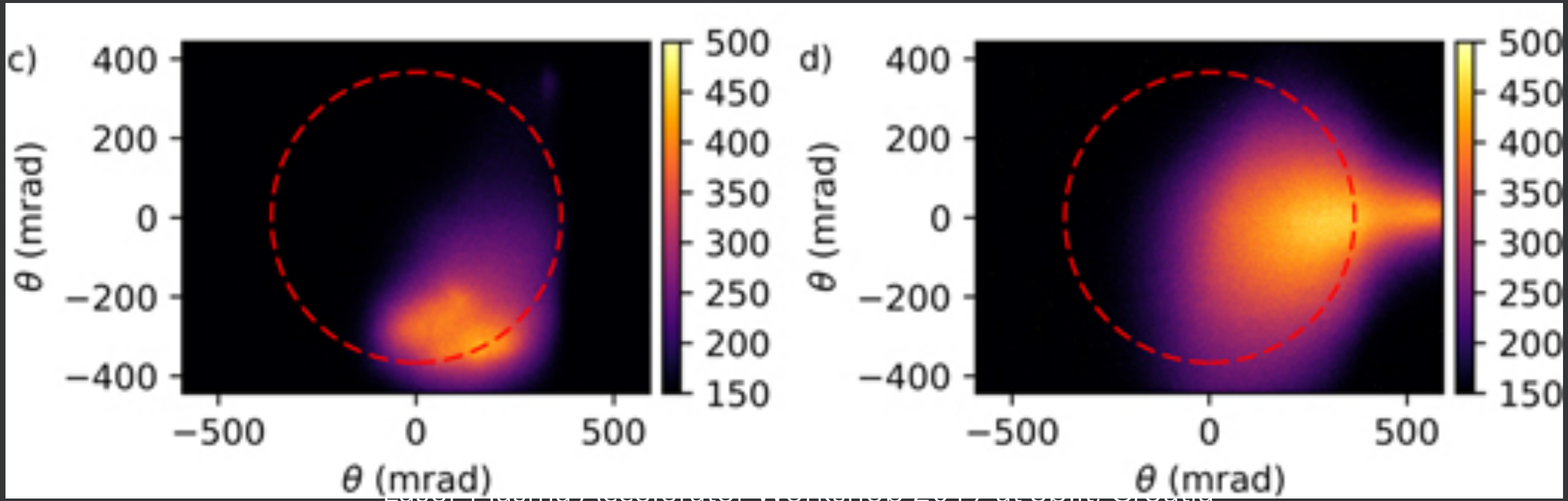
4ω Profile (UVFS) 5ω Profile (UVFS)



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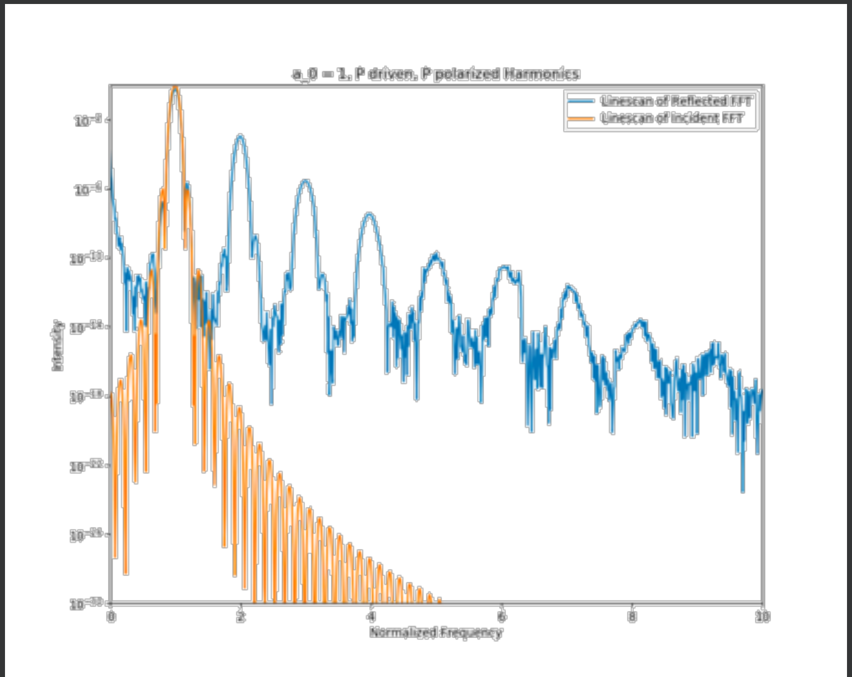
PIC Simulation capabilities

- GreenPlanet Computing cluster @UCI
- 592 Intel Xeon E5 cores
- 6 GB/core
- OSIRIS particle-in-cell



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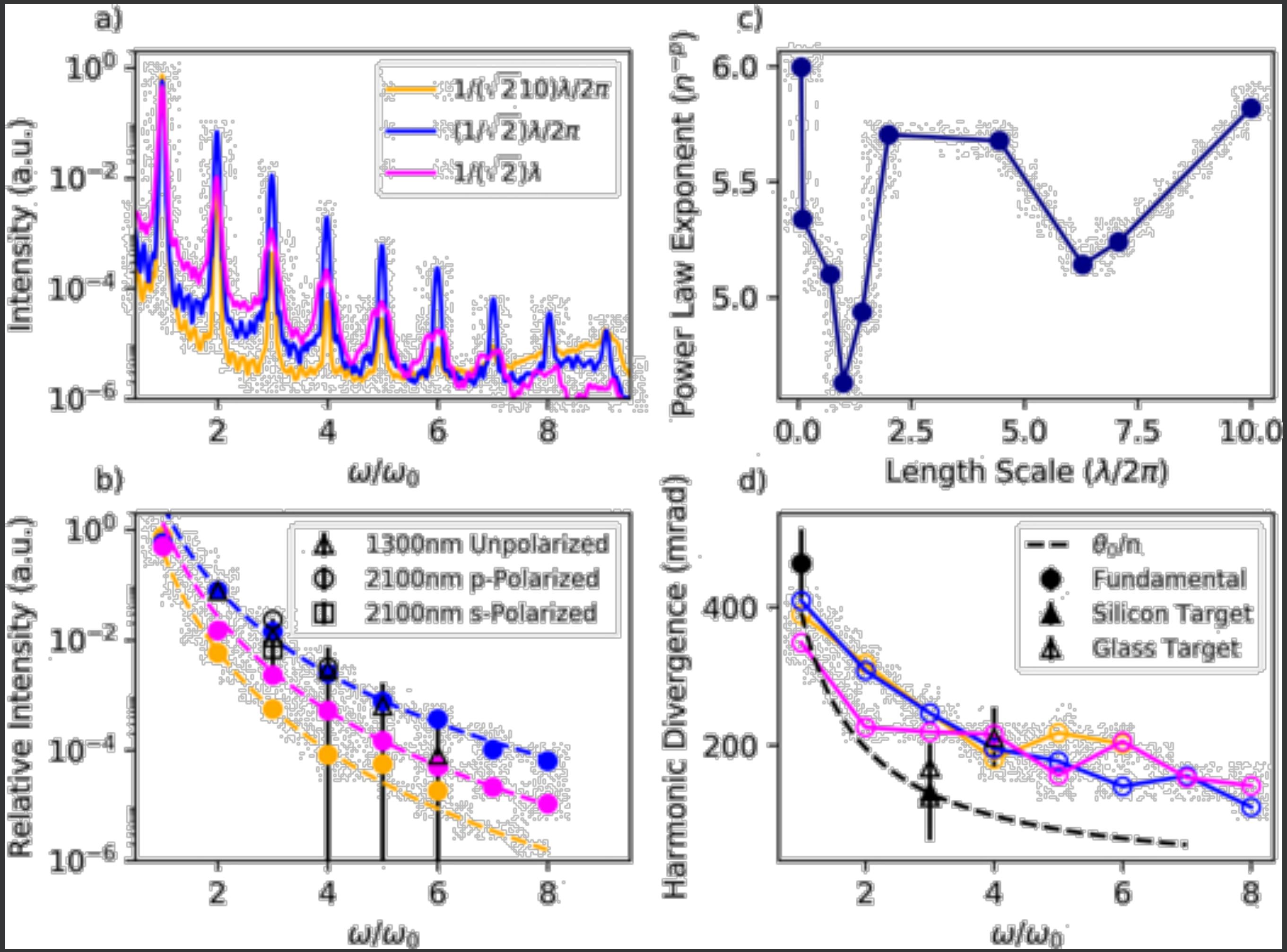
We acknowledge the OSIRIS Consortium (UCLA/IST Portugal) for use of OSIRIS.

2D simulation results

- OSIRIS 2D3V PIC Simulations
  - Reflected beam profiles
  - Incident beam $a_0=1$
  - Target density $500n_{crit}$

N. Beier, et al., NJP **21**, 043052 (2019)



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Higher intensities

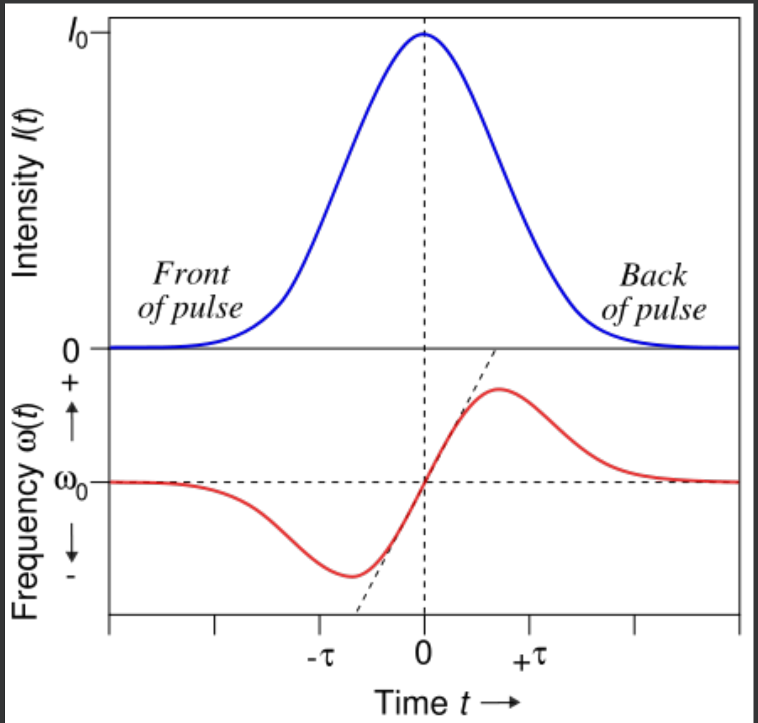
- How to increase intensity
  - Increase energy
  - Decrease pulse duration

- Thin Film Compression
  - Self Phase Modulation in solids

$$\Delta\omega_{inst}(t) \propto -\frac{dI}{dt}$$

$$\frac{d\phi}{dt} = \omega_{inst}(t) = \omega_0 - k_0 n_2 \frac{dI}{dt} z$$

$$B = \frac{2\pi}{\lambda} \int n_2 I(z) dz$$



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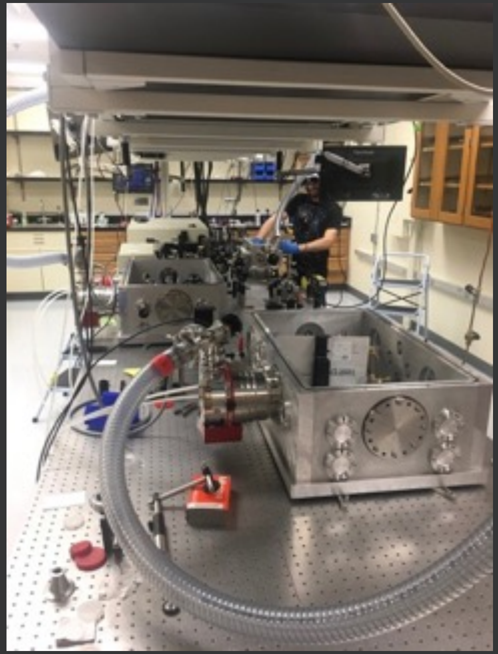
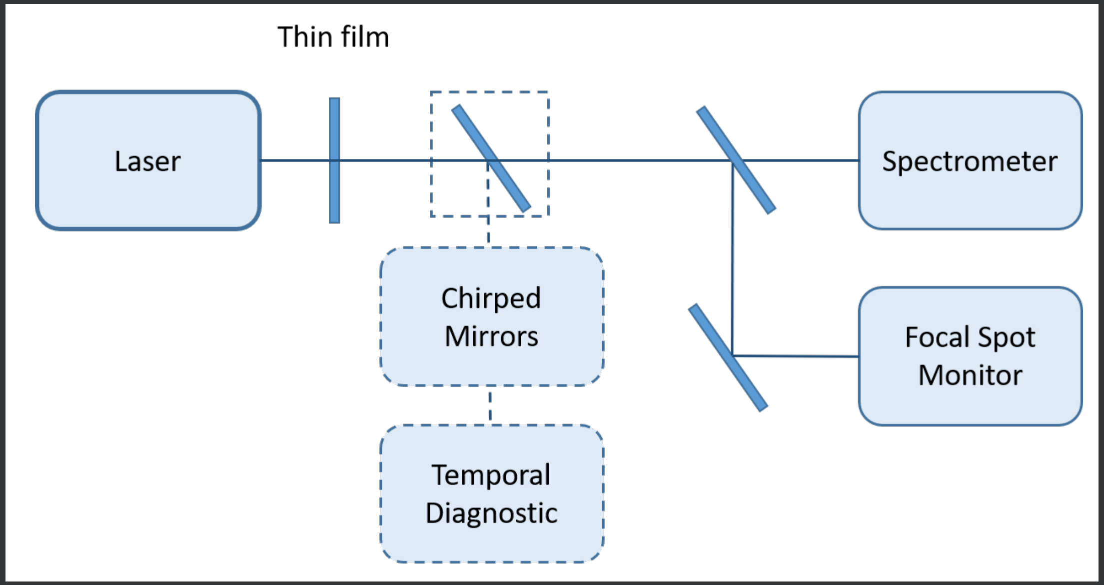
Scaling TFC

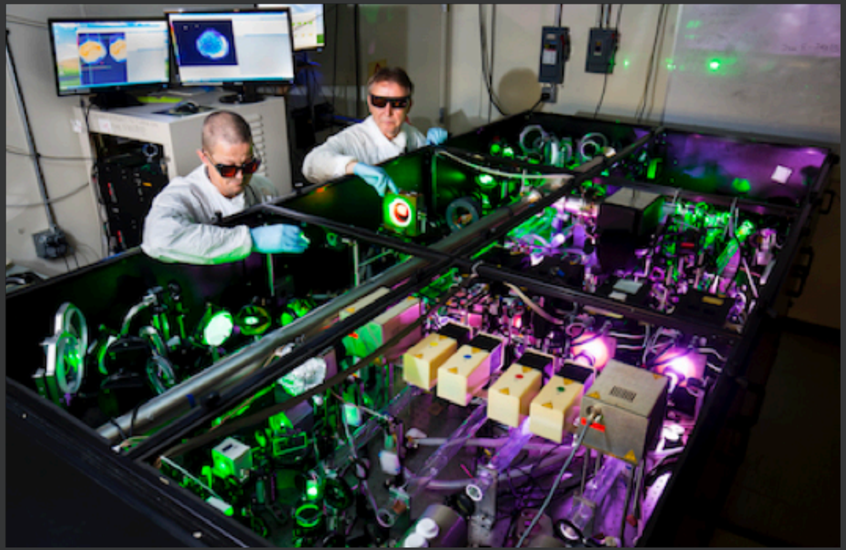
Gaussian (Terawatt)



UCI Solstice

Flat top (Petawatt)





HERCULES Laser & LASERIX

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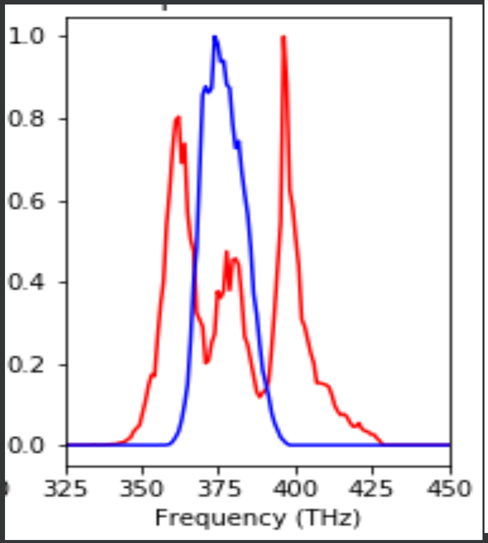
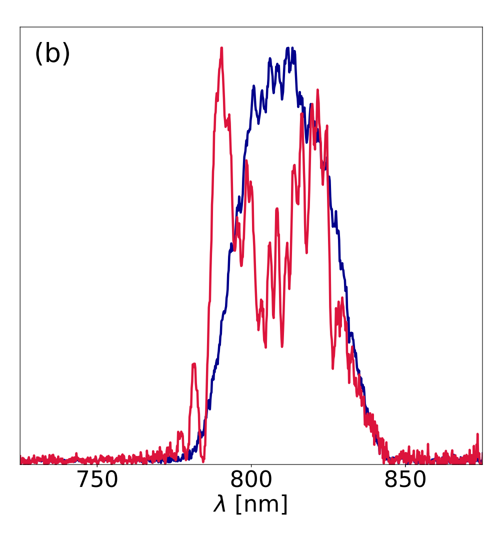
Bandwidth generation

- Fused silica targets
  - 0.5 – 8 mm
- Bandwidth increased 10-100%

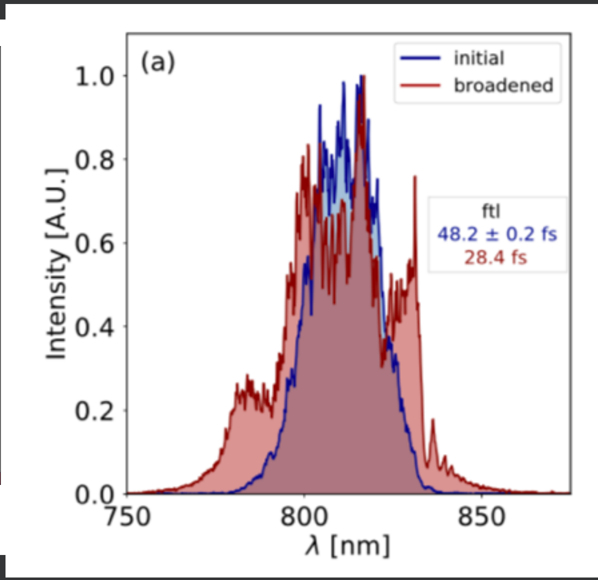
UCI



Michigan



LASERIX



D. Farinella, et al., JOSA B **36**, A28-A32 (2019)

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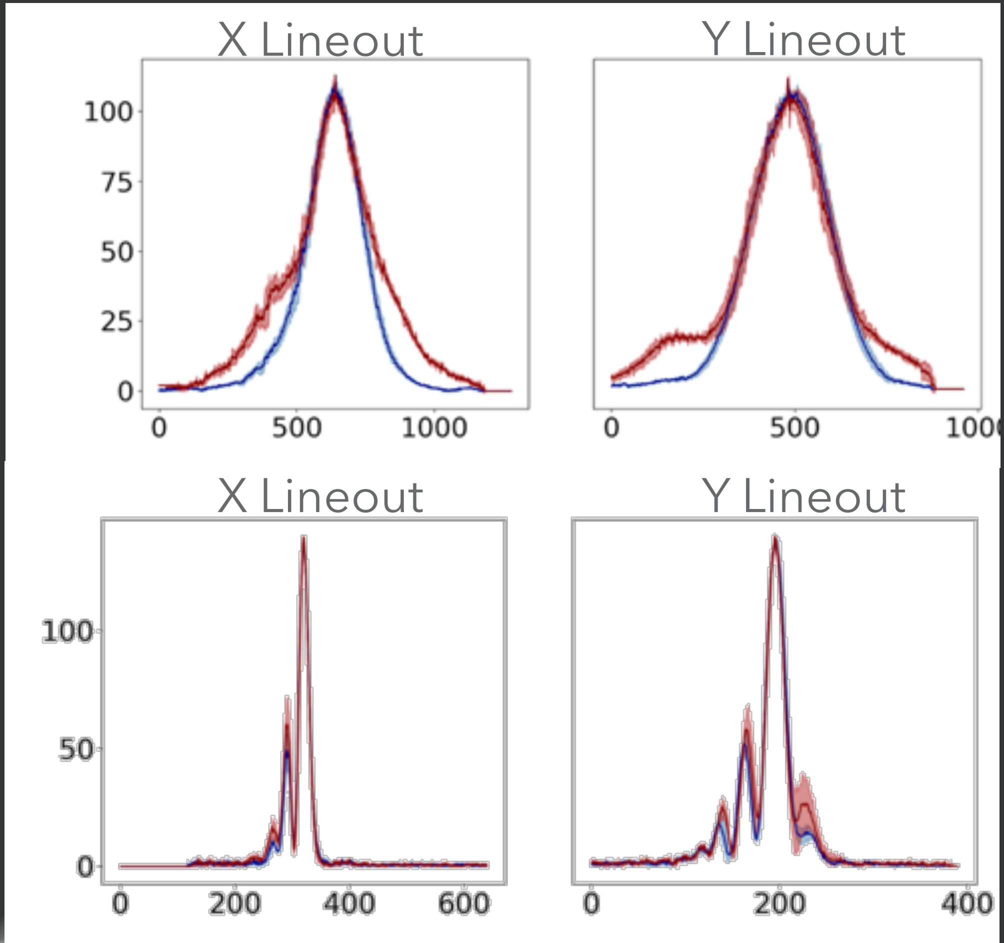
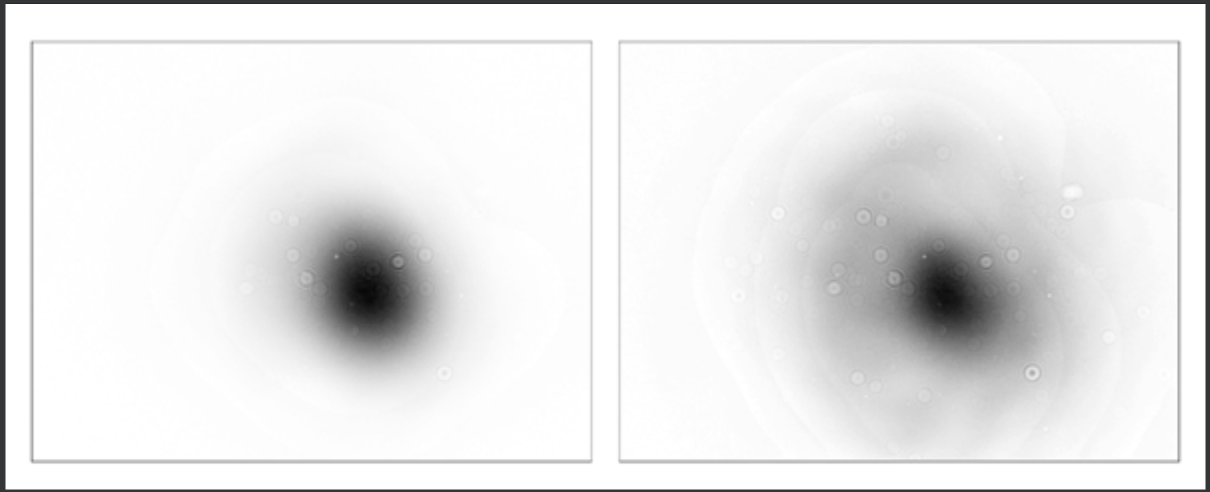
Focusability of broadened pulses



UCI



Michigan

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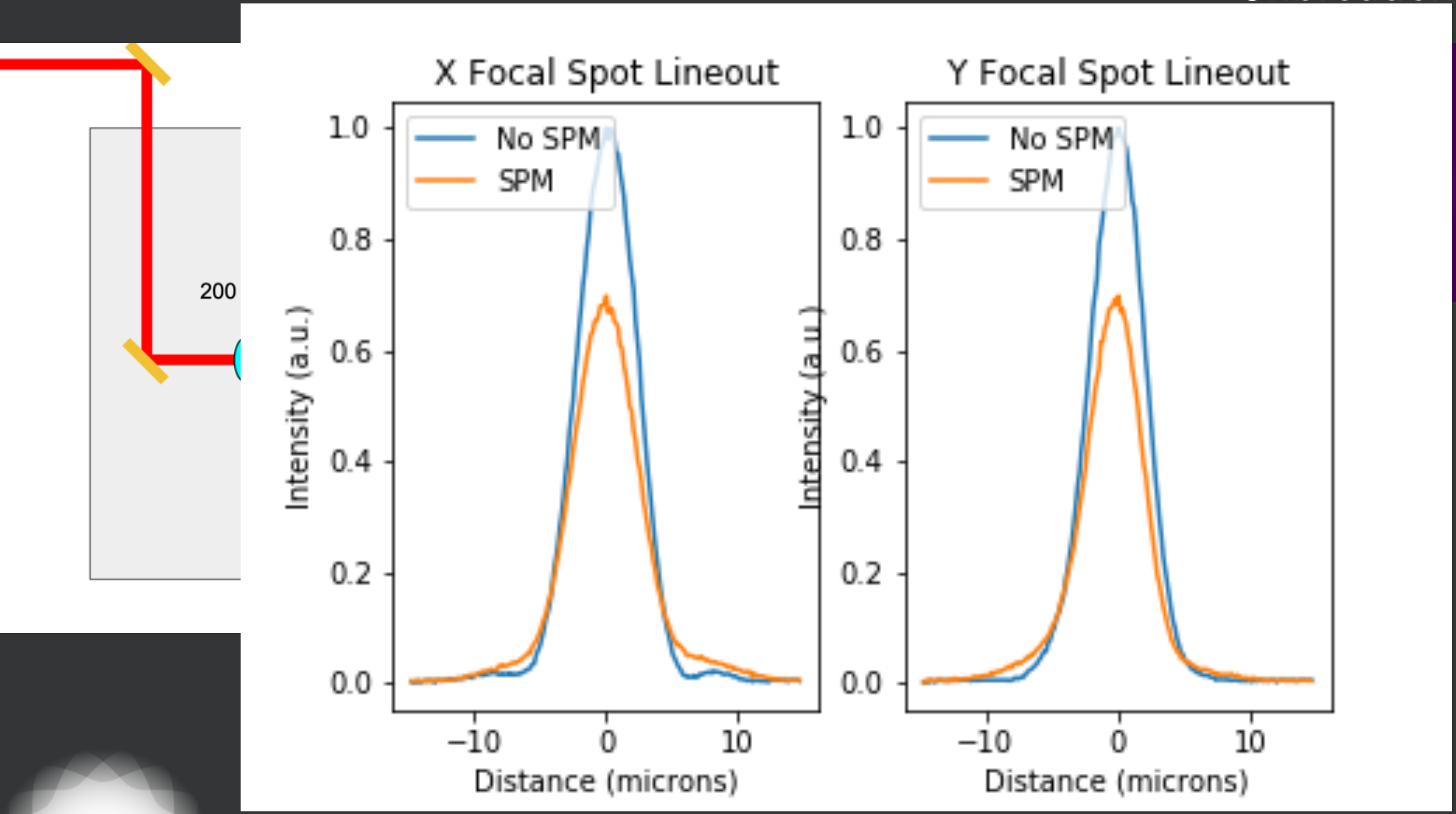
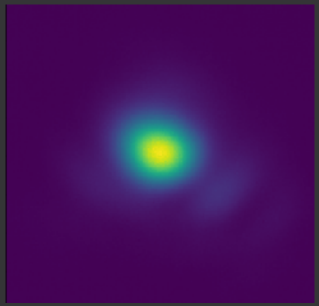
Focusability of Gaussian Pulses



Unbroadened

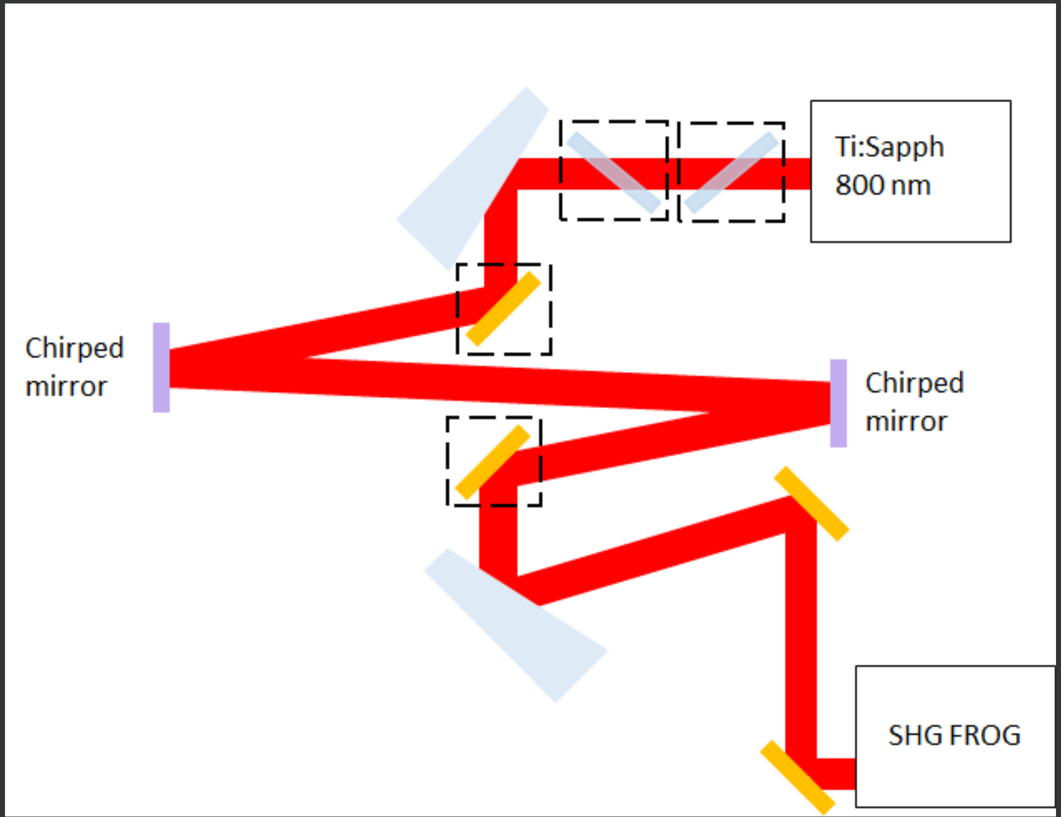
2.3 times
bandwidth growth

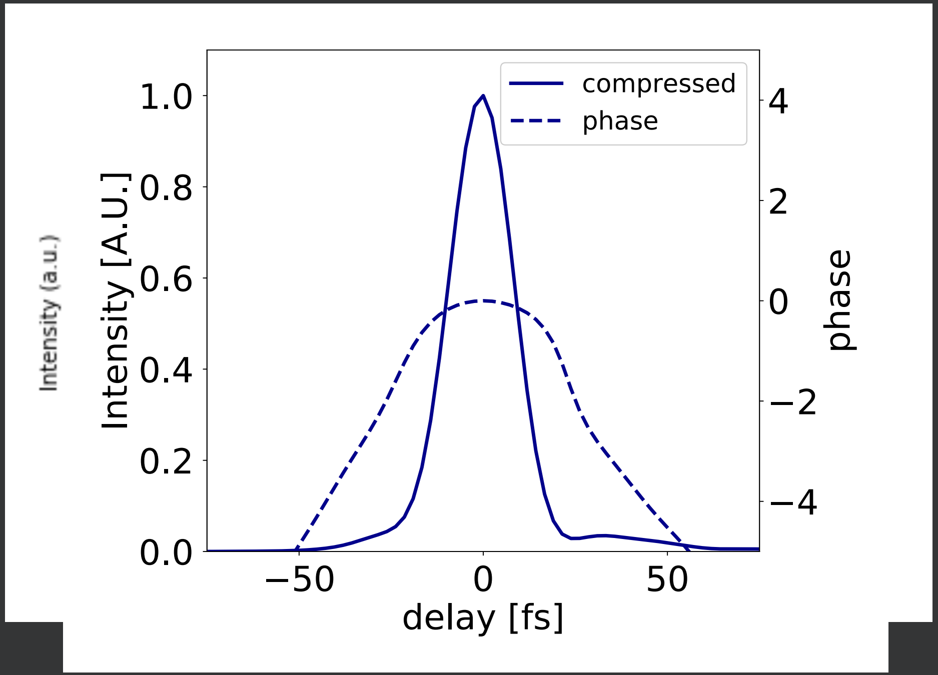
Broadened



Intensity Gain of >63%

Compression of broadened pulses





Pulse limited by diagnostic <15 fs measured

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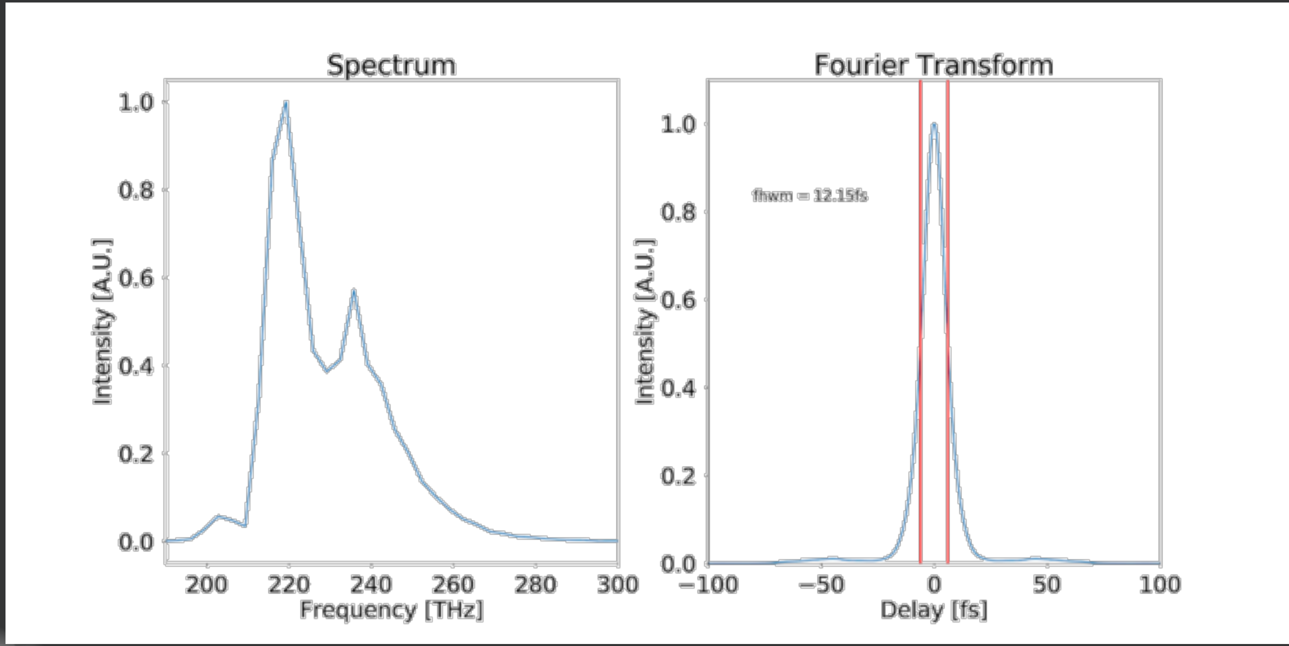
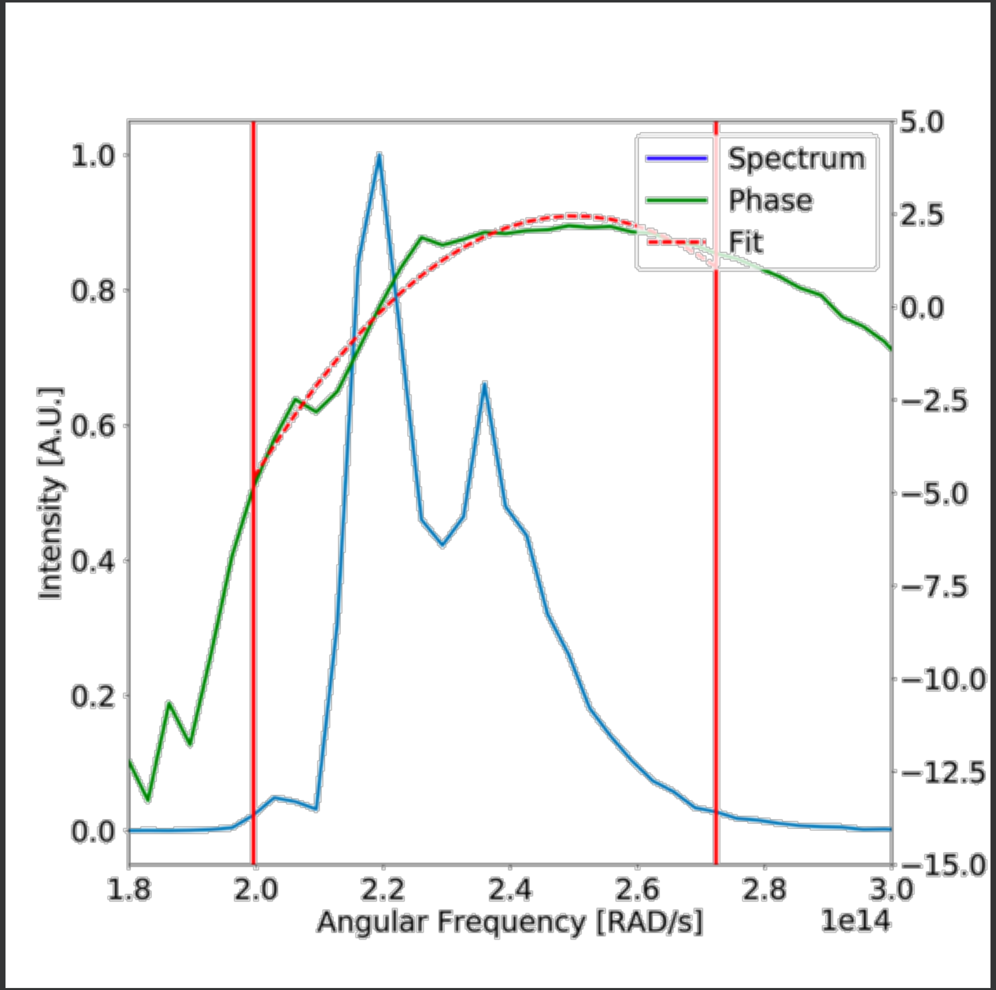
Extension to MIR

- 1300 nm TFC to FTL of 12 fs





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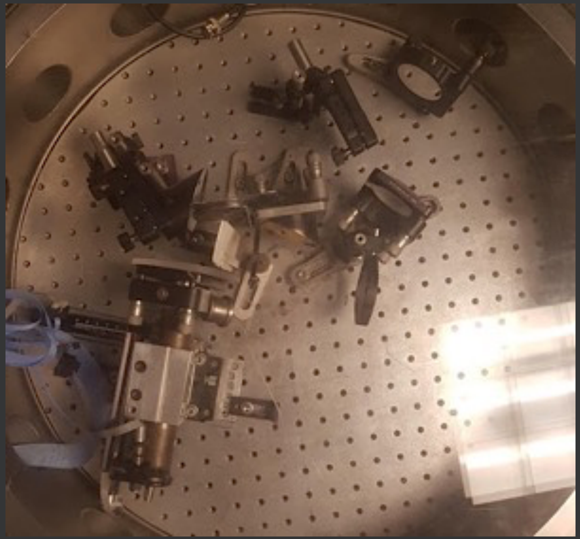
Example experiment

- Lambda cubed (Michigan) broadened to 1 cycle at 2100 nm
  - 2 mJ @ 2100 nm with duration of 8 fs
  - $5x10^{18}$ Wcm^{-2} peak intensity (a0 of ~3)

- Lambda cubed with increased laser power
  - OPA conversion of 10% assumed
  - Require increase of 400% to get similar intensity
  - Lambda cubed would require upgrade to 80 mJ

Future experiments

- UCI and Michigan joint experiments
  - Increase focusing capabilities
  - Can improve focal quality to >10^{17} Wcm^{-2}
  - Diagnostics for lower order harmonics
    - Divergence
    - Polarization
    - Phase
  - Correlation with x-rays
  - Subsurface probing



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Recent Refereed Publications

1. **N. Beier, T. Nguyen, J. Lin,** J. Nees, K. Krushelnick, F. Dollar, Relativistic short-pulse high harmonic generation at 1.3 and 2.1 μm wavelengths, **New J. Phys.** 21, 043052 (2019).
2. **D. M. Farinella**, J.Wheeler, **A. Hussein**, J. Nees, **N. Beier**, **M. Stanfield**, G. Cojocaru, G. Ungureanu, R. Fabbri, R. Secareanu, M. Masruri, **T. Nguyen**, **S. Hakimi**, **H. Allison**, A. Maksimchuk, K. Krushelnick, **G. Mourou**, **T. Tajima**, and **F. Dollar**, Focusability of high intensity laser pulses generated by Thin Film Compression, **JOSA B** 36, A28-A32 (2019).
3. L. Willingale, A. V. Arefiev, G. J. Williams, C. Zulick, **F. Dollar**, A. U. Hazi, A. Maksimchuk, M. J.-E. Manuel, E. Marley, W. Nazarov, Z. Zhao, and H. Chen, The Unexpected Role of Evolving Longitudinal Electric Fields in Generating Energetic Electrons in Relativistically Transparent Plasmas, **New J. Phys.** 20, 093024 (2018).
4. C. McGuffey, W. Schumaker, T. Matsuoka, V. Chvykov, **F. Dollar**, G. Kalintchenko, S. Kneip, Z. Najmudin, S.P.D. Mangles, M. Vargas, V. Yanovsky, A. Maksimchuk, A. G. R. Thomas, and K. Krushelnick, On the properties of synchrotron-like x-ray emission from laser wakefield accelerated electron beams, **Phys. Plasm.** 25, 043104 (2018).
5. **D. Popmintchev**, **B. R. Galloway**, M.-C. Chen, **F. Dollar**, **C. A. Mancuso**, A. Hankla, L. Miaja- Avila, G. O'Neil, J. M. Shaw, G. Fan, S. Ališauskas, G. Andriukaitis, T. Balcˇiunas, O. D. Mücke, A. Pugzlys, A. Baltuška, H. C. Kapteyn, T. Popmintchev, and M. M. Murnane, Near- and extended-edge x-ray-absorption fine-structure spectroscopy using ultrafast coherent high-order harmonic supercontinua, **Phys. Rev. Lett.** 120, 093002 (2017).
6. **S. Hakimi**, **T. Nguyen**, **D. Farinella**, **C. Lau**, H.-Y. Wang, **P. Taborek**, **F. Dollar**, and **T. Tajima**, Wakefield in solid state plasma with the ionic lattice force, **Phys. Plasm.** 25, 023112 (2018).
7. **F. Dollar**, C. Zulick, **A. Raymond**, V. Chvykov, L. Willingale, V. Yanovsky, A. Maksimchuk, A. G. R. Thomas, and K. Krushelnick, Enhanced laser absorption from radiation pressure in intense laser plasma interactions, **New J. Phys.** 19, 063014 (2017).
8. **J. L. Ellis**, **K. M. Dorney**, C. G. Durfee, C. Hernández-García, **F. Dollar**, **C. A. Mancuso**, **T. Fan**, D. Zusin, C. Gentry, P. Grychtol, H. C. Kapteyn, M. M. Murnane, and D. D. Hickstein, Phase matching of noncollinear sum and difference frequency high harmonic generation above and below the critical ionization level, **Opt. Exp.** 25, 10126 (2017).
9. X. Zhang, **T. Tajima**, **D. Farinella**, Y. Shin, **G. Mourou**, J. Wheeler, **P. Taborek**, P. Chen, **F. Dollar**, and B. Shen, Particle-in-cell simulation of x-ray wakefield acceleration and betatron radiation in nanotubes, **Phys. Rev. Acc. Beams** 19, 101004 (2016).
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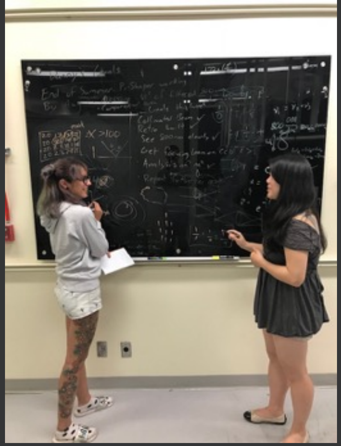
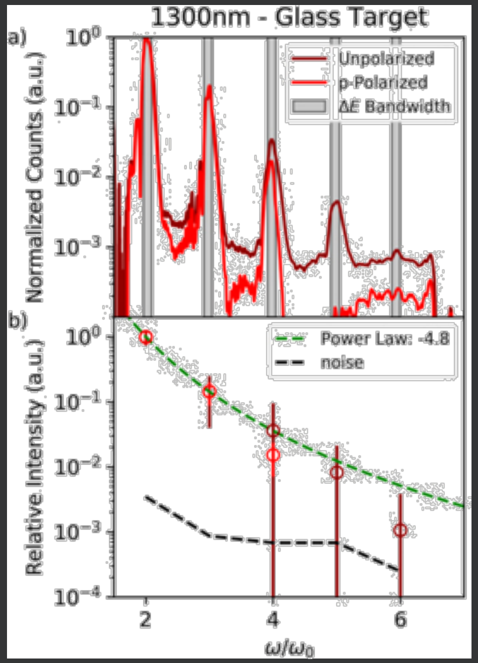
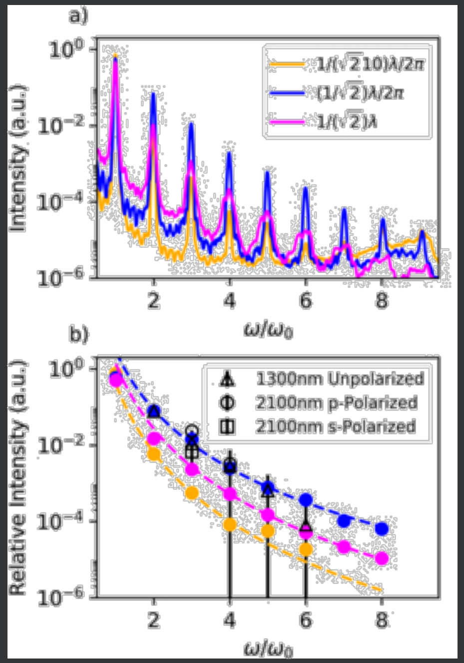


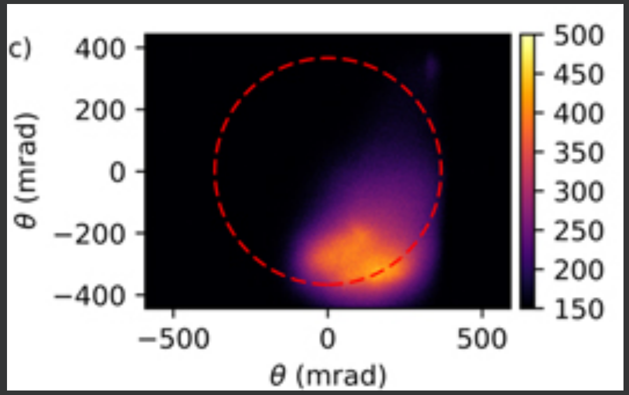
Relativistic Laser Plasma Interactions at Short Wave Infrared Wavelengths

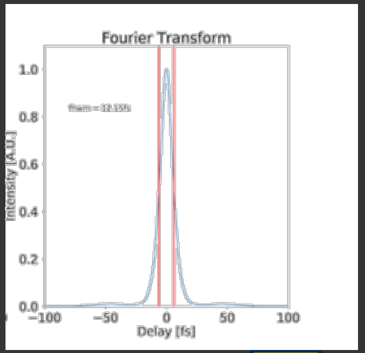
Franklin Dollar - University of California, Irvine

- Laser solid interactions at wavelength of 1300 and 2100 nm with intensities $a_0 \sim 1$
- Optical order harmonic spectrum and wavefront measured
- Thin Film Compression shows intensity gain for relativistic intensities
- Few cycle NIR pulses measured









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