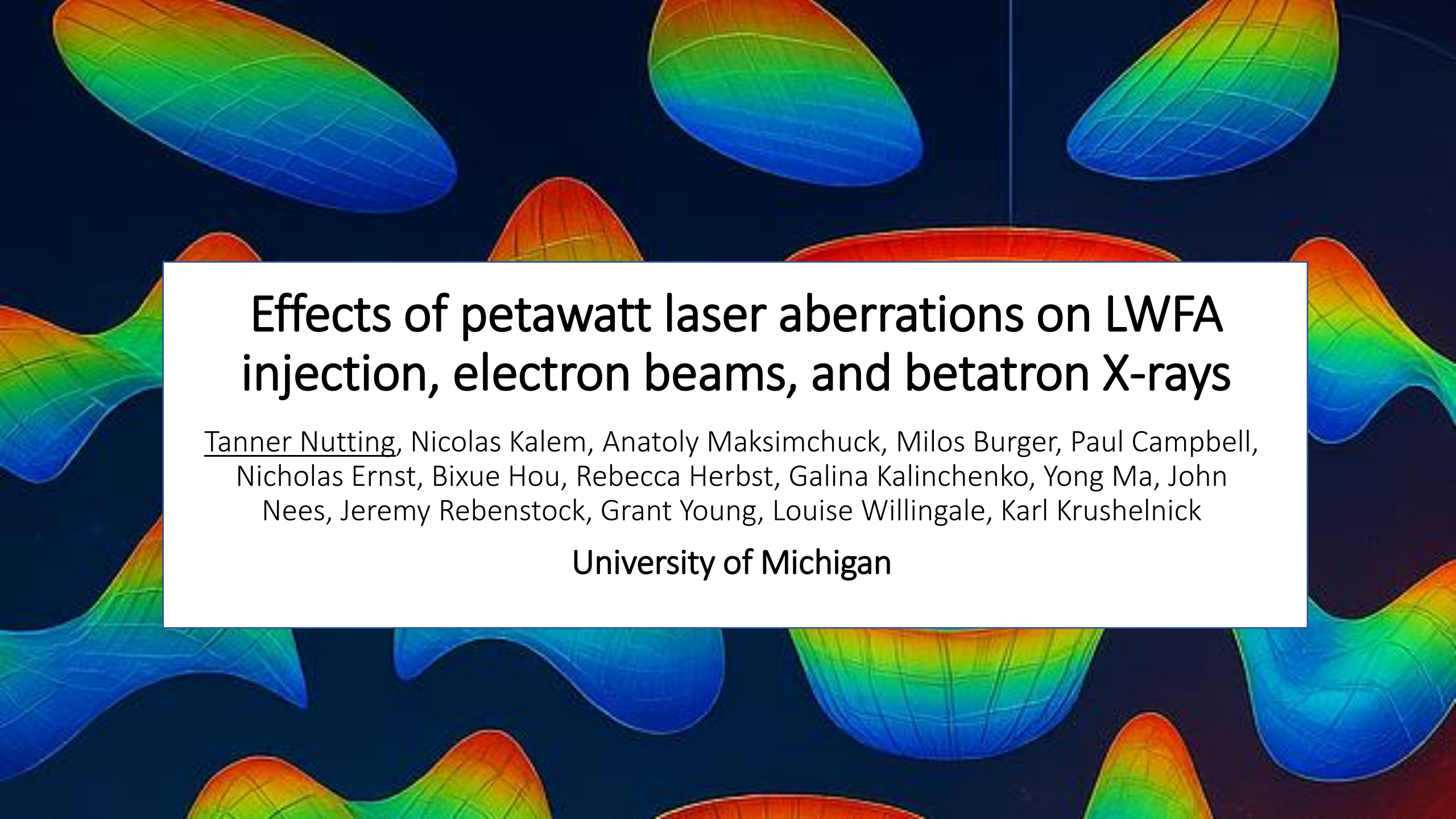


Effects of petawatt laser aberrations on LWFA injection, electron beams, and betatron X-rays

Tanner Nutting, Nicolas Kalem, Anatoly Maksimchuck, Milos Burger, Paul Campbell, Nicholas Ernst, Bixue Hou, Rebecca Herbst, Galina Kalinchenko, Yong Ma, John Nees, Jeremy Rebenstock, Grant Young, Louise Willingale, Karl Krushelnick

University of Michigan

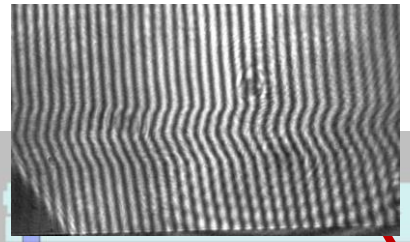
Presentation Overview

1. LWFA on the ZEUS Facility with controlled wavefront modification
2. Experimental Setup and Results
3. Coma's effect on betatron critical energy
4. Astigmatism's effects on injection and electron energies

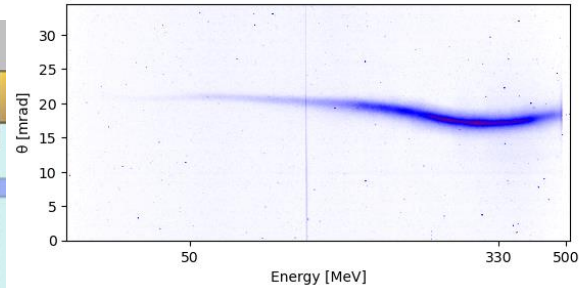
LWFA setup at the ZEUS facility- TA1

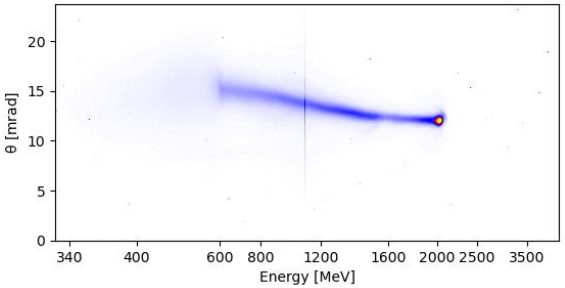
<u>Laser Parameters:</u>

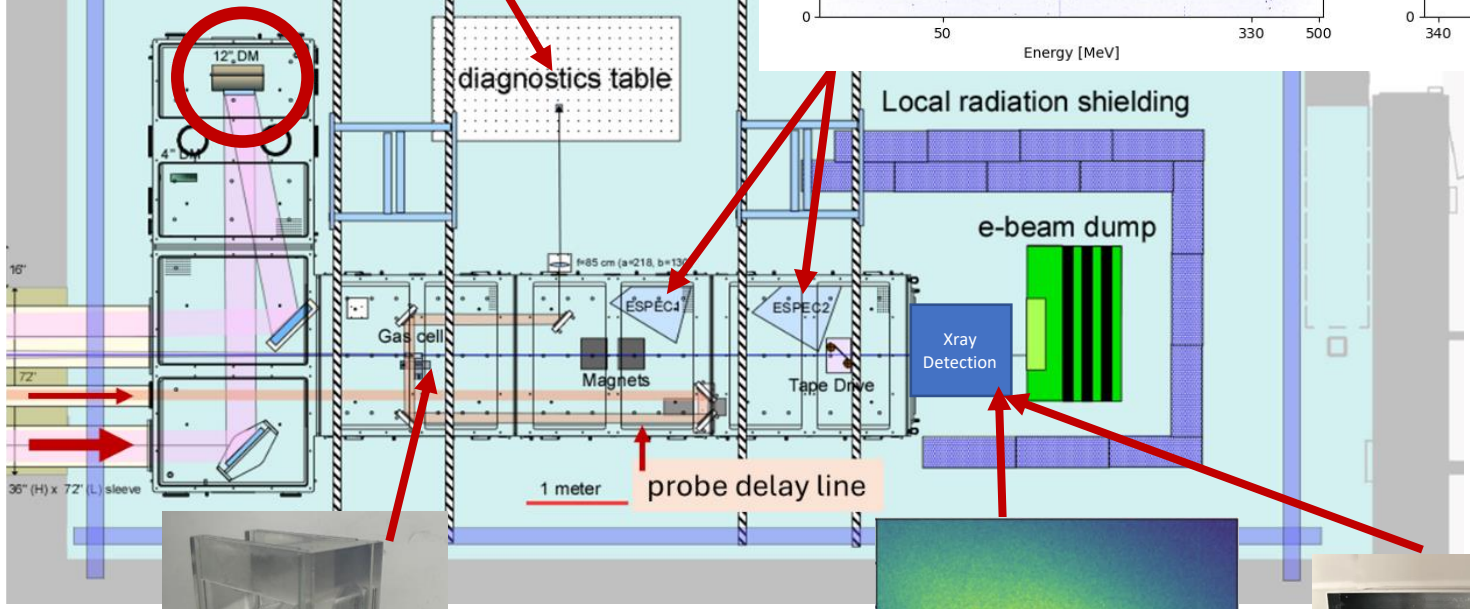
- 28 J on target
- 25 fs pulse duration
- f/# = 61
- 31 cm beam diameter
- 19 m focal length
- 70 µm FWHM focal spot



<u>Michaelson Interferometer:</u>
Source plasma density set to 5×10^{17} cm^{-3}







<u>Electron spectrometer:</u>
Resolves electron energies between 30 MeV and 4.2 GeV

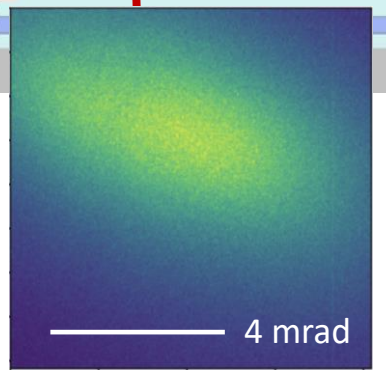
<u>Xray Diagnostics:</u>

- Spectrum
- Divergence
- Flux

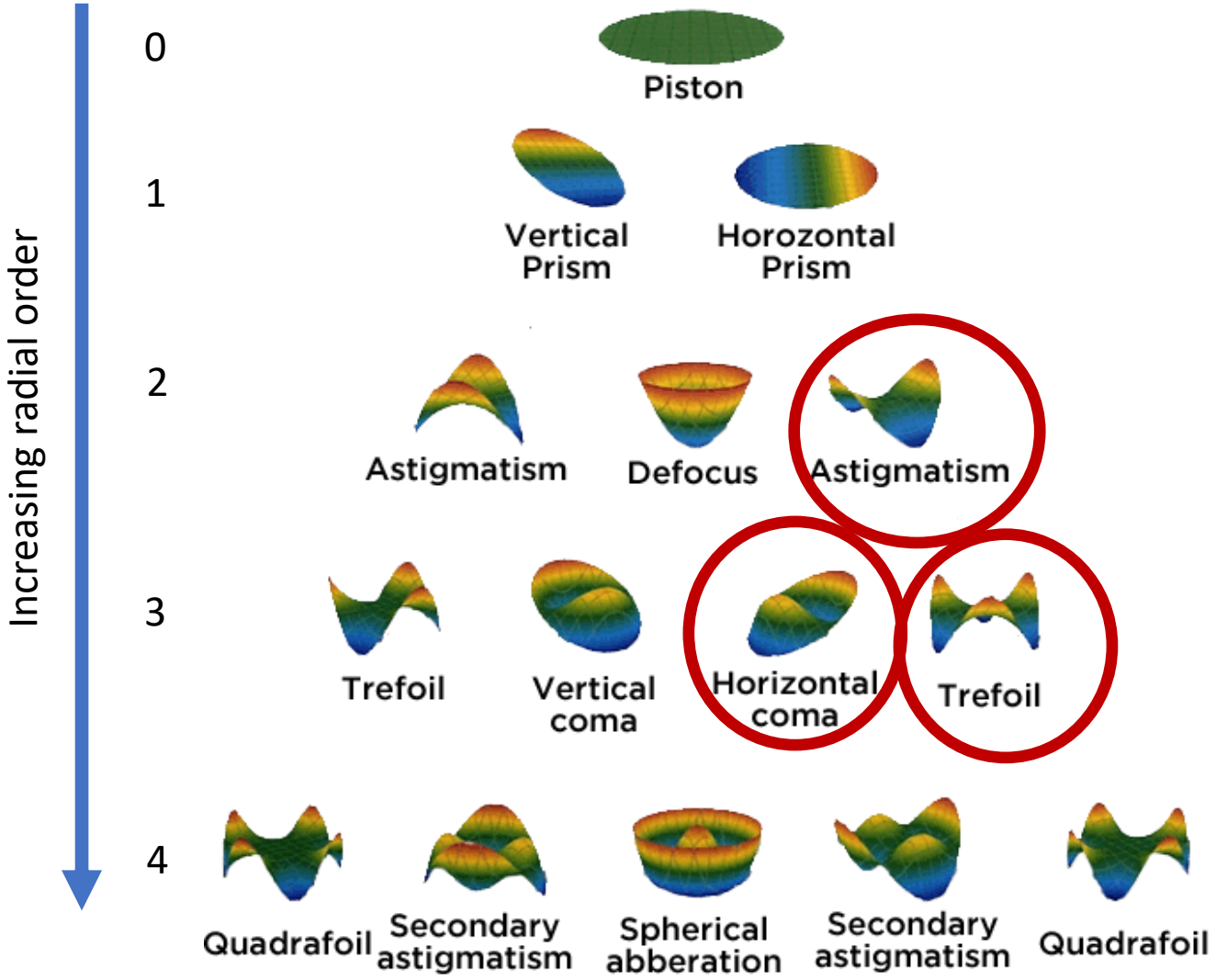
<u>Variable length gas cell target:</u>

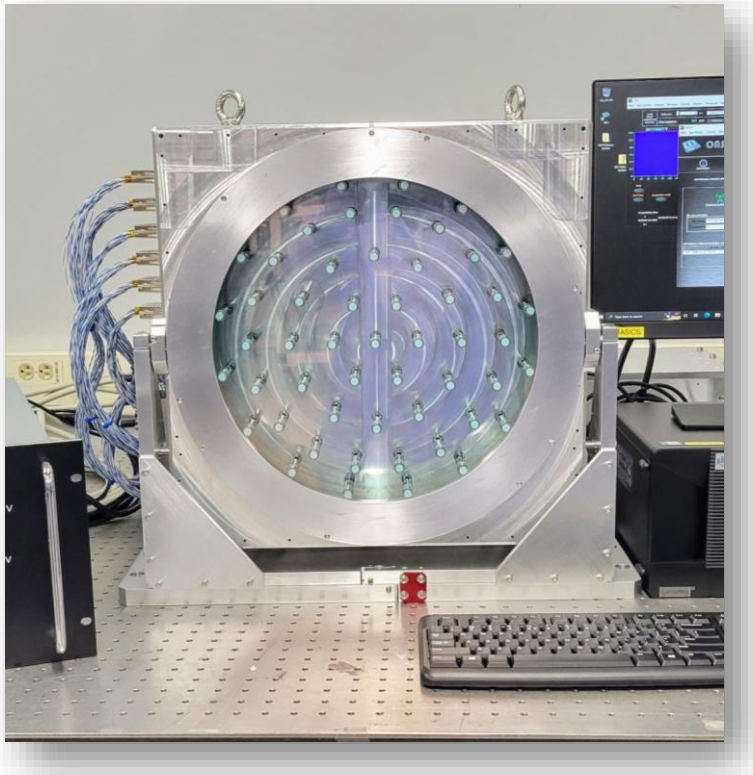
- 5 – 10 cm
- 97% He, 3% N gas mixture

Xray profile



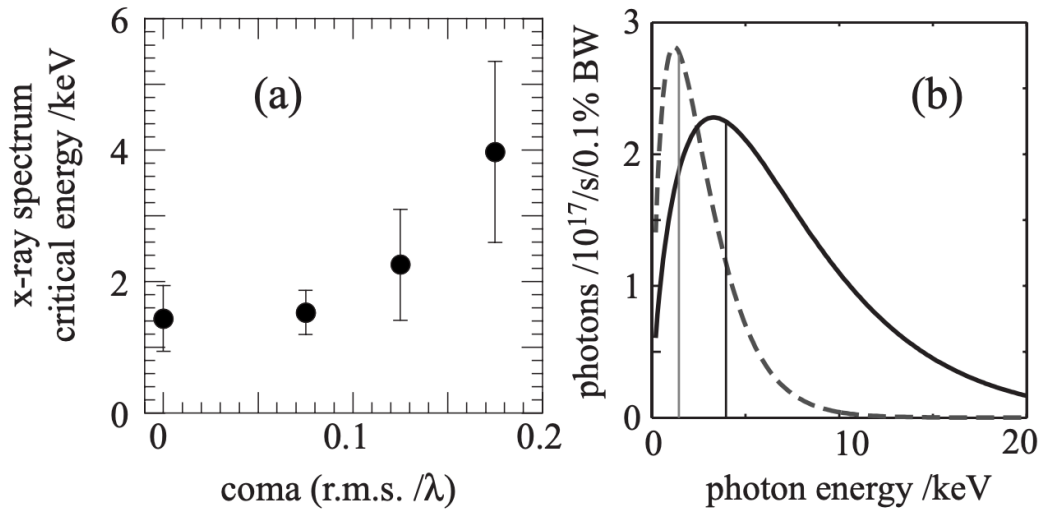
Wavefront modification with adaptive optics





- Adaptive optics allow for fast and precise control of laser wavefront (ideal for inputs to machine learning algorithms)
- Aberrations can be applied as knobs to adjust electron and X-ray properties

What effect do these aberrations have on LWFA?

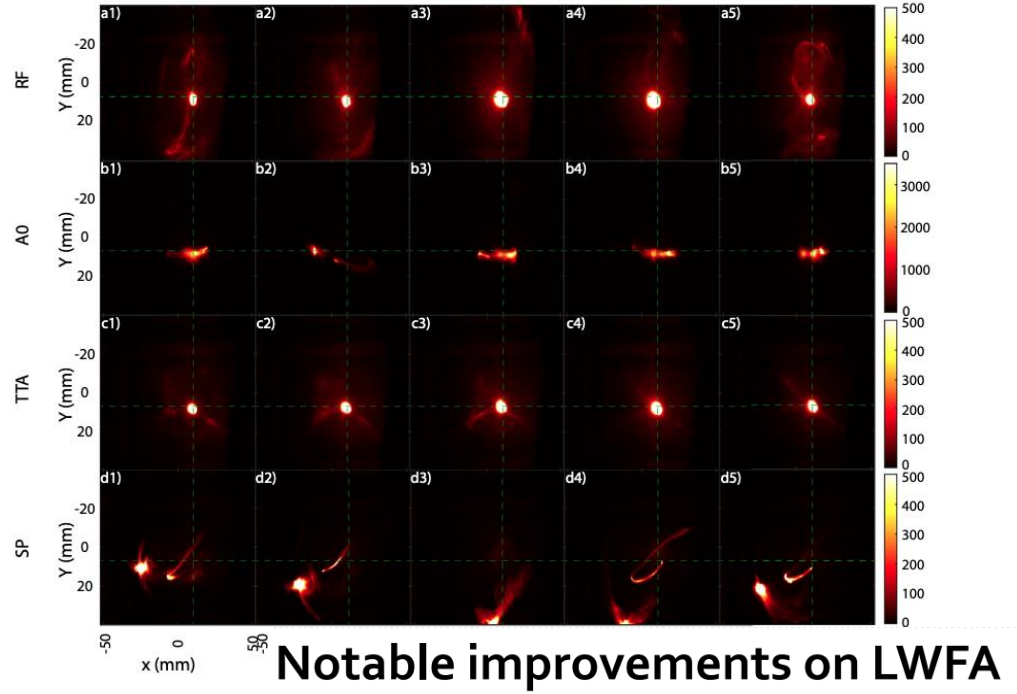


RESEARCH ARTICLE | NOVEMBER 04 2009

Controlling the spectrum of x-rays generated in a laser-plasma accelerator by tailoring the laser wavefront

S. P. D. Mangles; G. Genoud; S. Kneip; M. Burza; K. Cassou; B. Cros; N. P. Dover; C. Kamperidis; Z. Najmudin; A. Persson; J. Schreiber; F. Wojda; C.-G. Wahlström

13 TW, f/9



30 TW, f/20

Notable improvements on LWFA through precise laser wavefront tuning

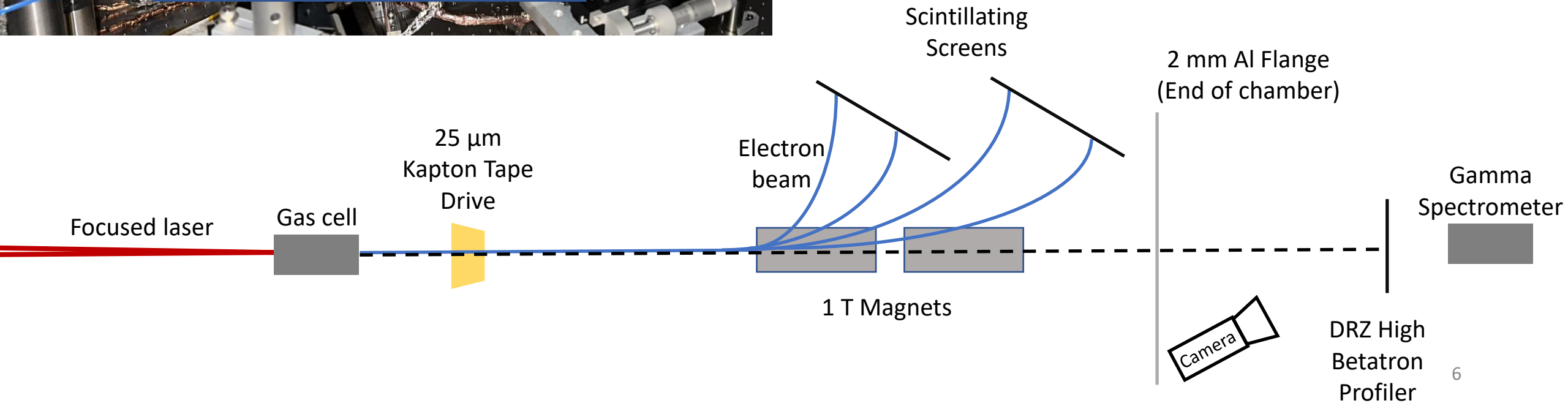
Driss Oumbarek Espinos[1,2,4]✉, Alexandre Rondepierre[1,2,4], Alexei Zhidkov[1,2], Naveen Pathak[1,2], Zhan Jin[1,2], Kai Huang[2,3], Nobuhiko Nakanii[2,3], Izuru Daito[3], Masaki Kando[2,3] & Tomonao Hosokai[1,2]

What can we learn via a systematic scan of induced aberrations with a petawatt laser/GeV electron beam?

Experimental Setup

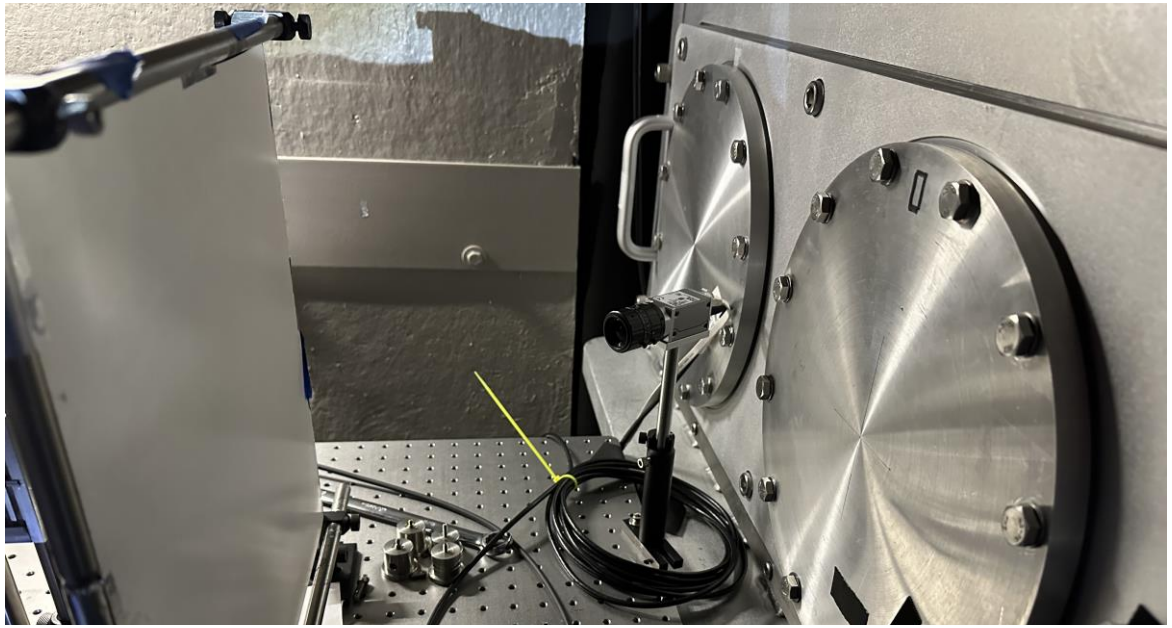
Diagnostics:
- Electron spectrometer
- Betatron X-ray profiler
- Gamma Spectrometer

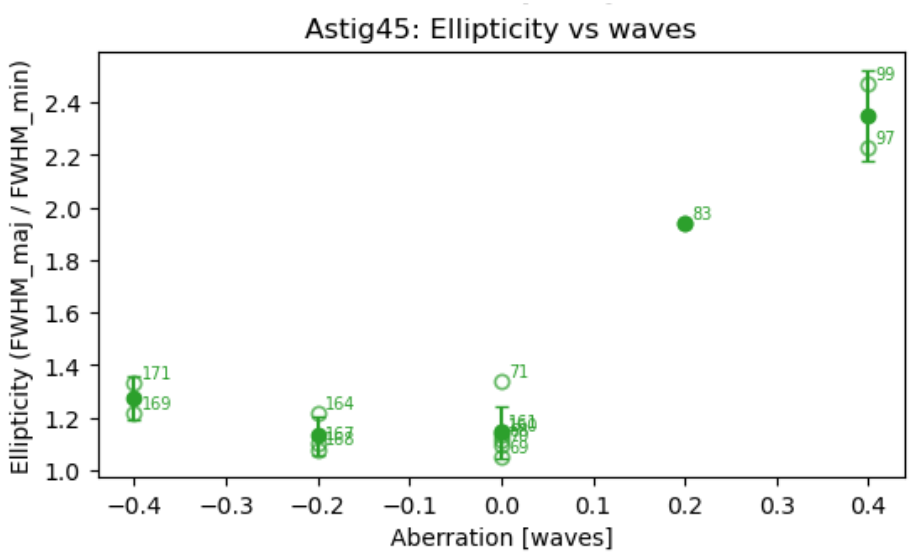
Parameters:
- Plasma density = 5e17 cm^-3
- 6 cm Gas Cell
- Ionization injection (3% N)

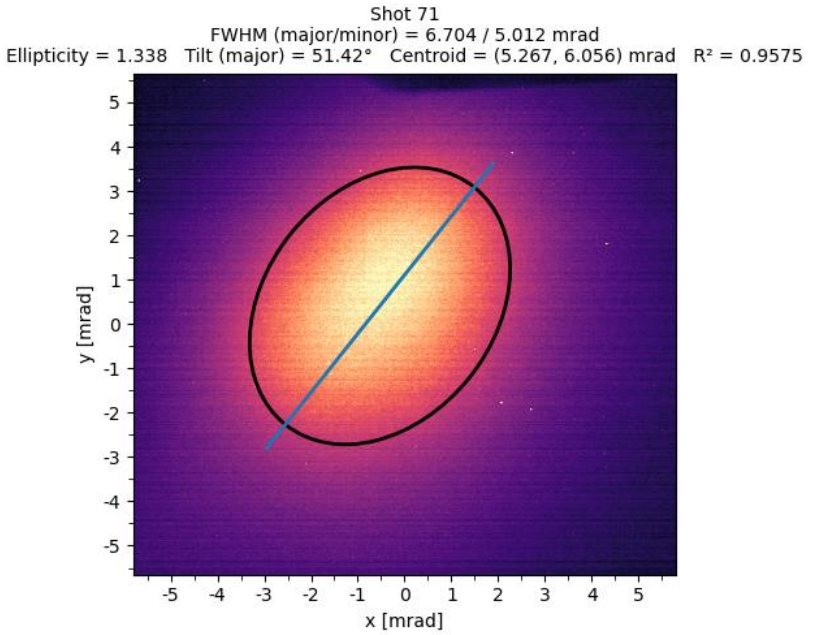


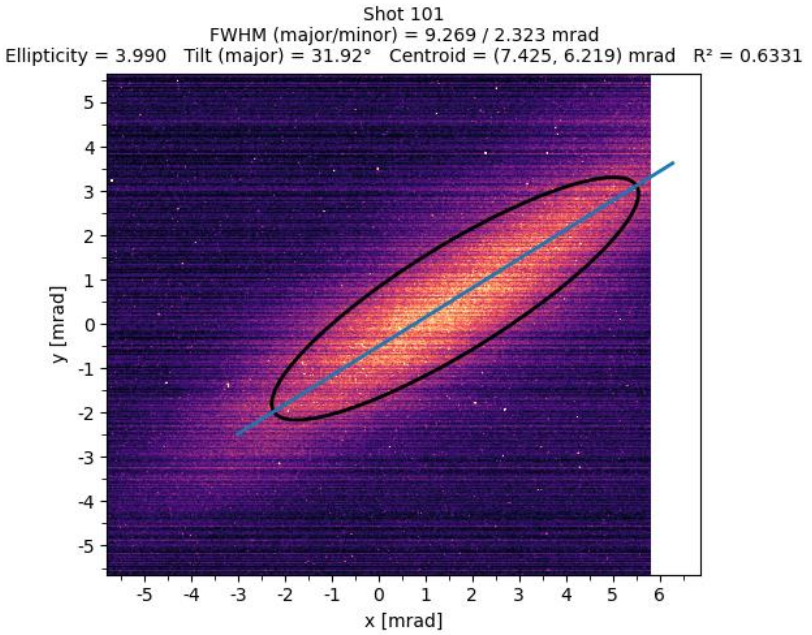
Betatron X-ray beam profiles

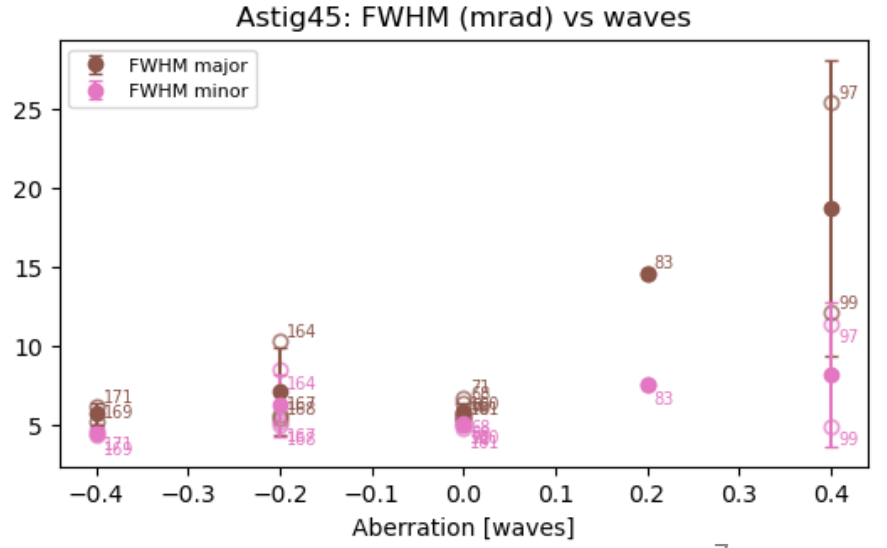
Open circle = one shot
Full circle = Average



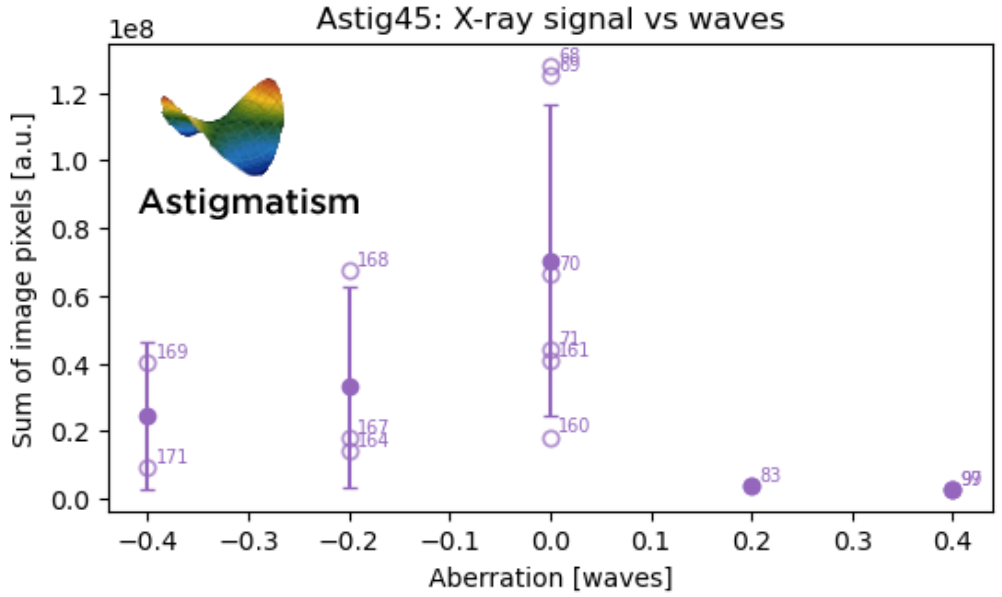


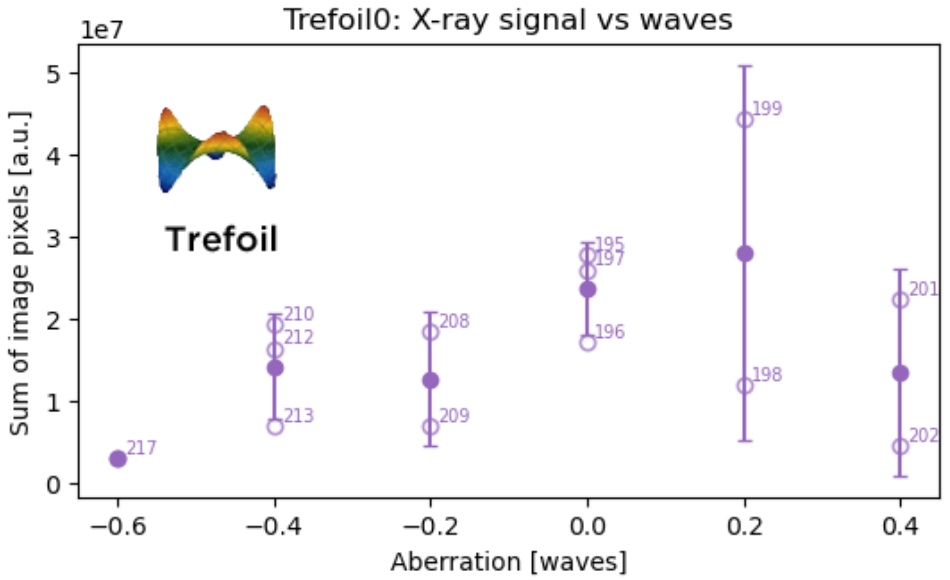


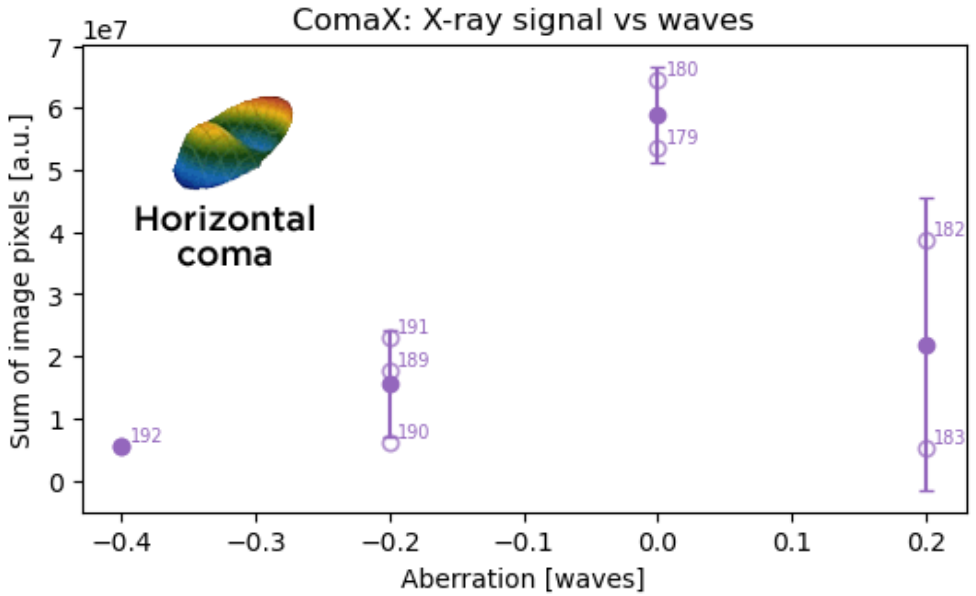




Effect on X-ray flux



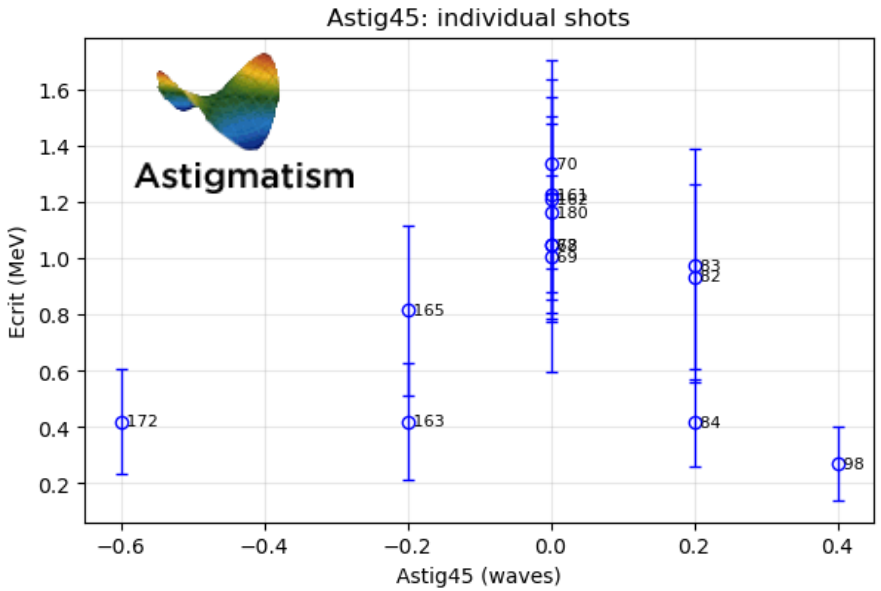


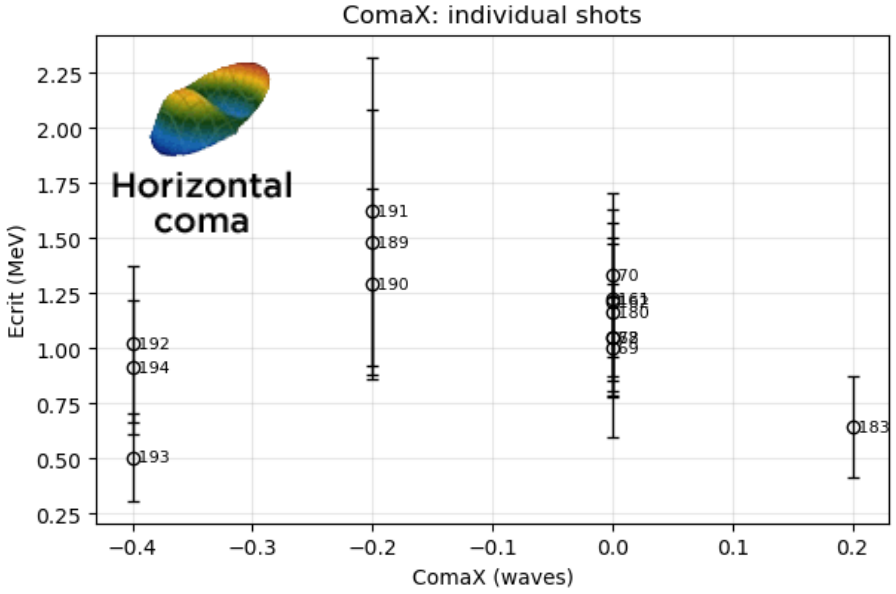


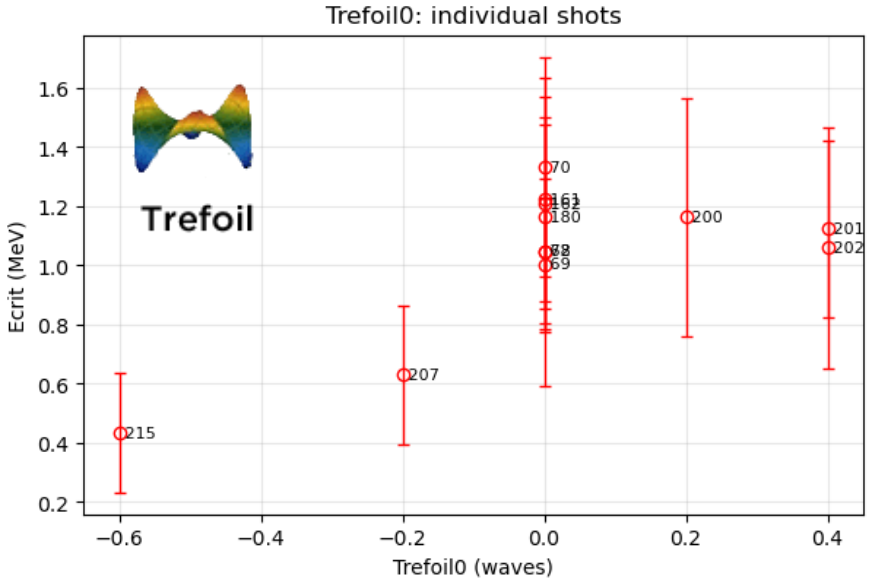
- X-ray flux reduced with increased aberrations

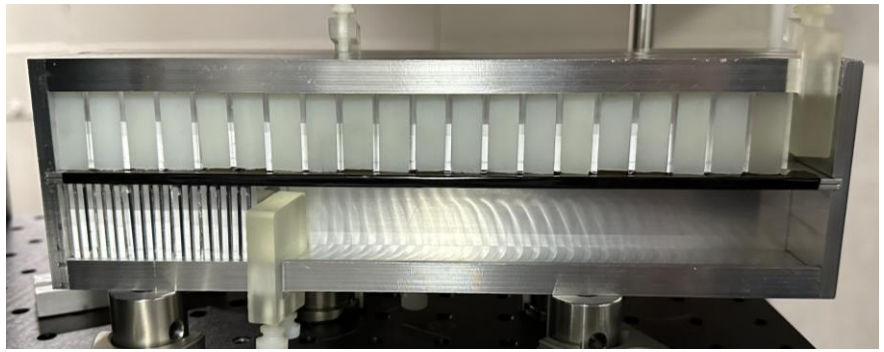
Effect on X-ray Spectrum

$$S \propto \left(\frac{E}{E_{cr}}\right)^2 K_{2/3}\left(\frac{E}{E_{cr}}\right)$$



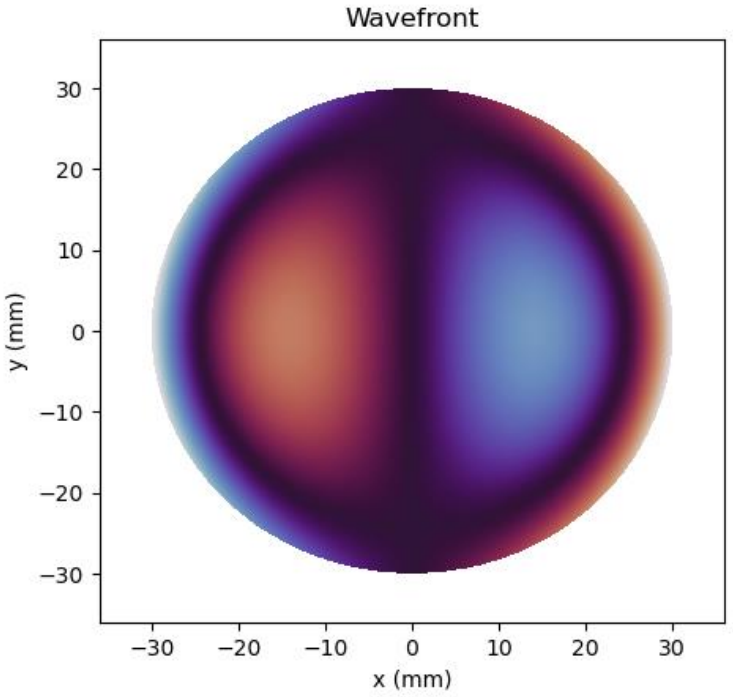


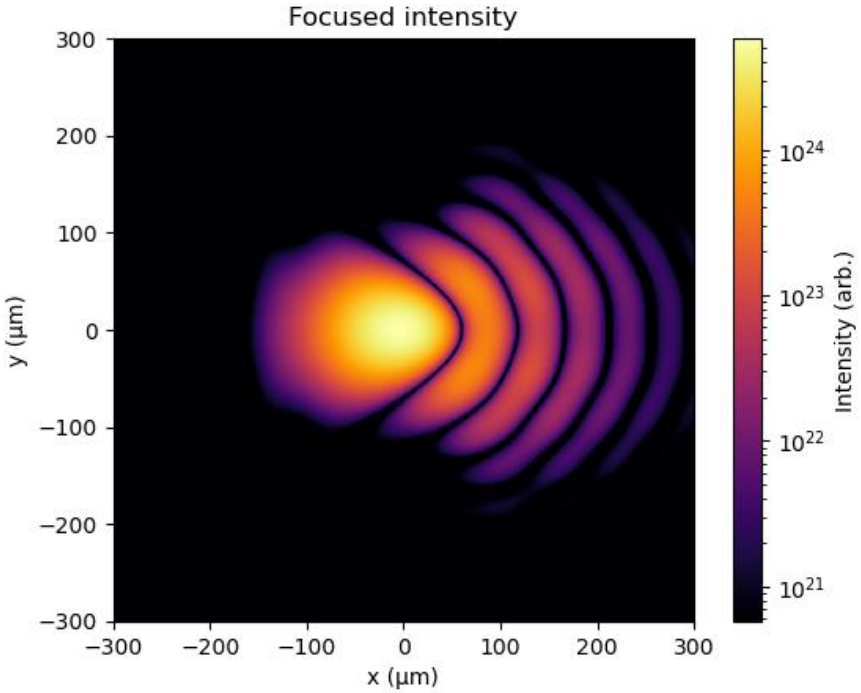


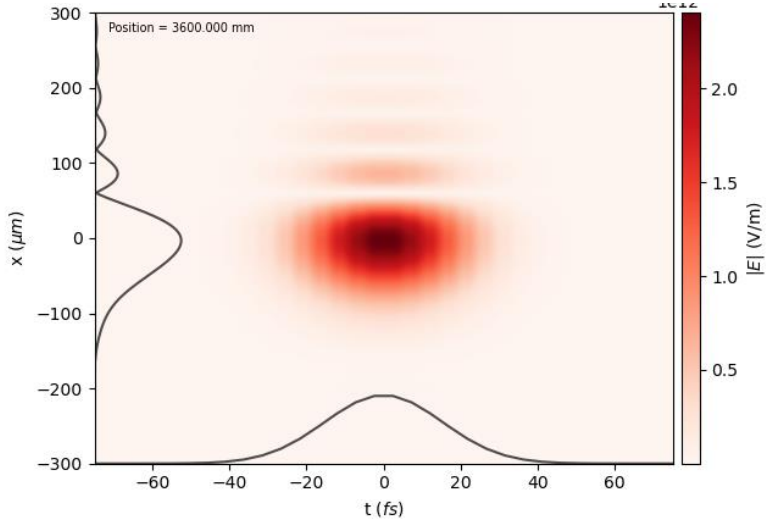


- Apart from coma, aberrations soften the X-ray spectrum

Modeling coma with LASY





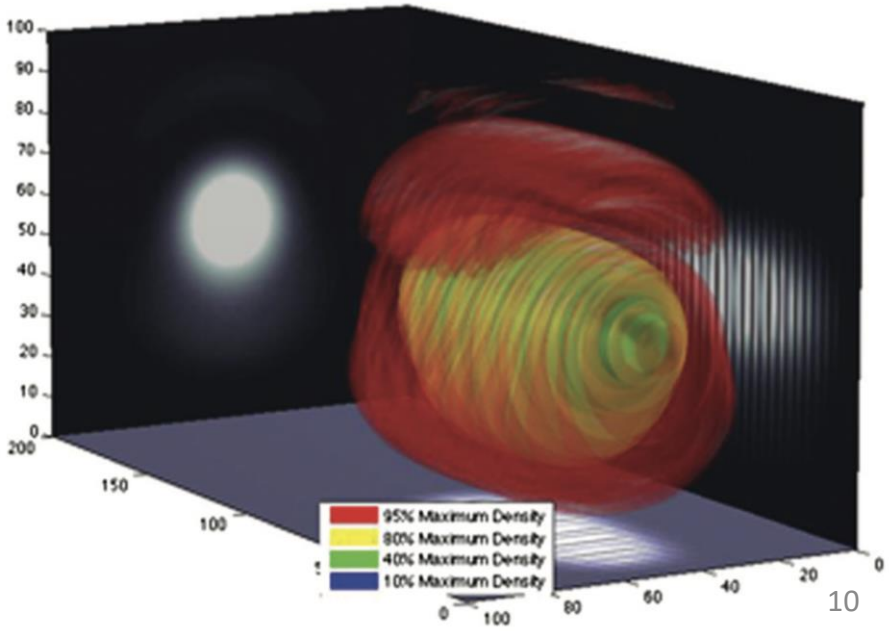


- Apply comatic phase and focusing phase in the nearfield
- Use Fresnel Chirp-Z Transform Propagator to view focus

Previous method:

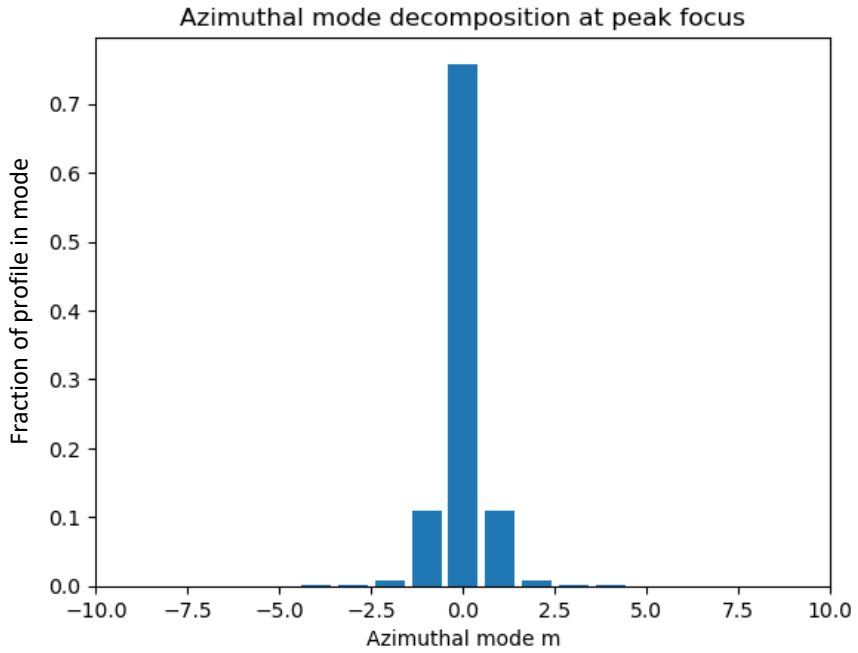
P. Cummings, A.G.R.T P.o.P. (2011)

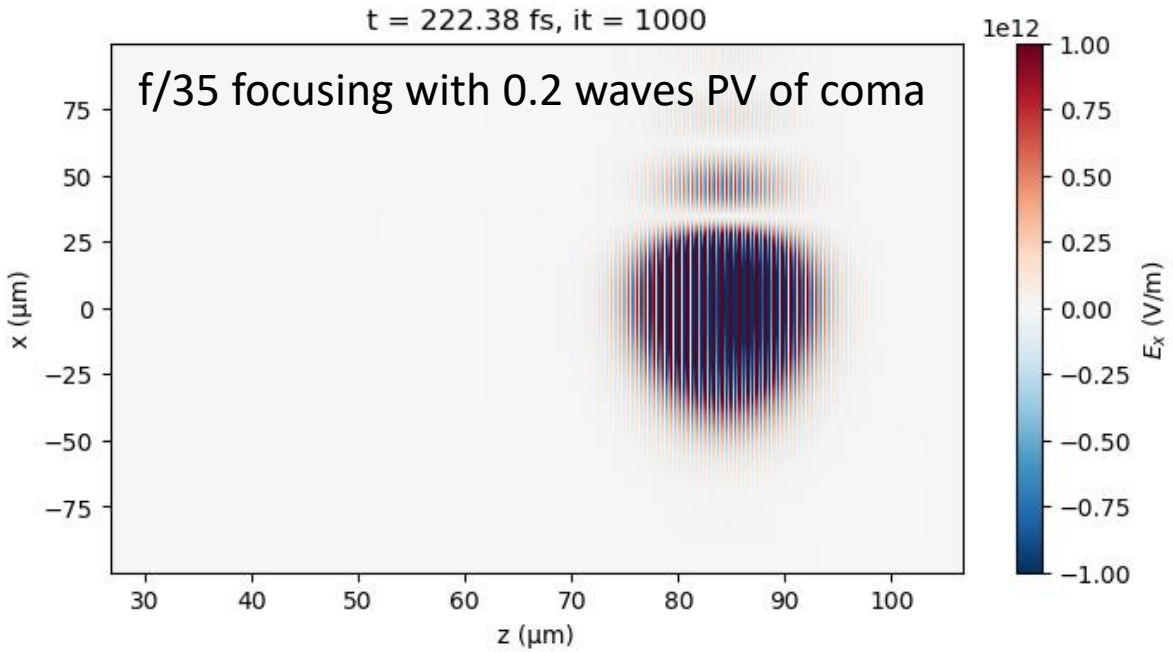
Combines TEM_{00} and TEM_{10} modes to model coma



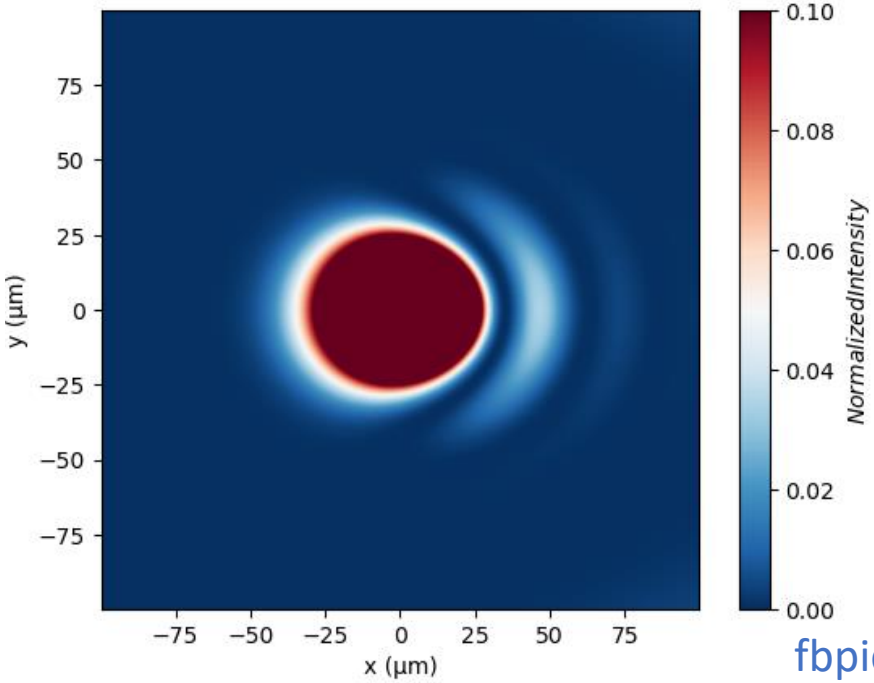
Import into FBPIC

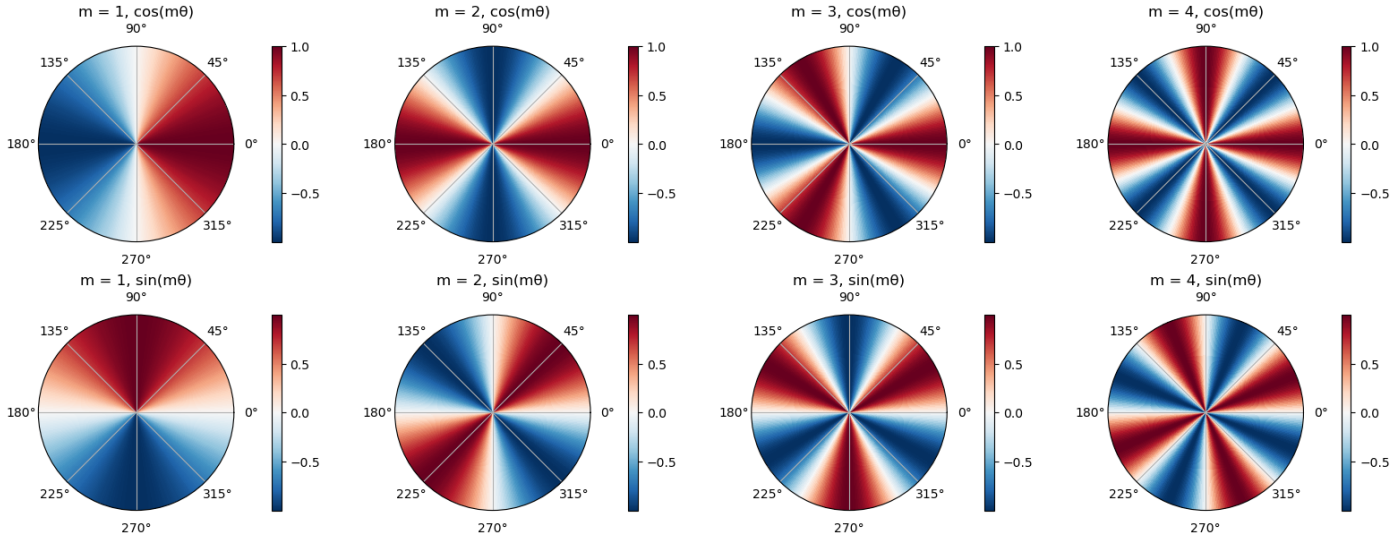
Using 5 modes (Nm = 5) in FBPIC





Saturated to show wings





fbpic.github.io

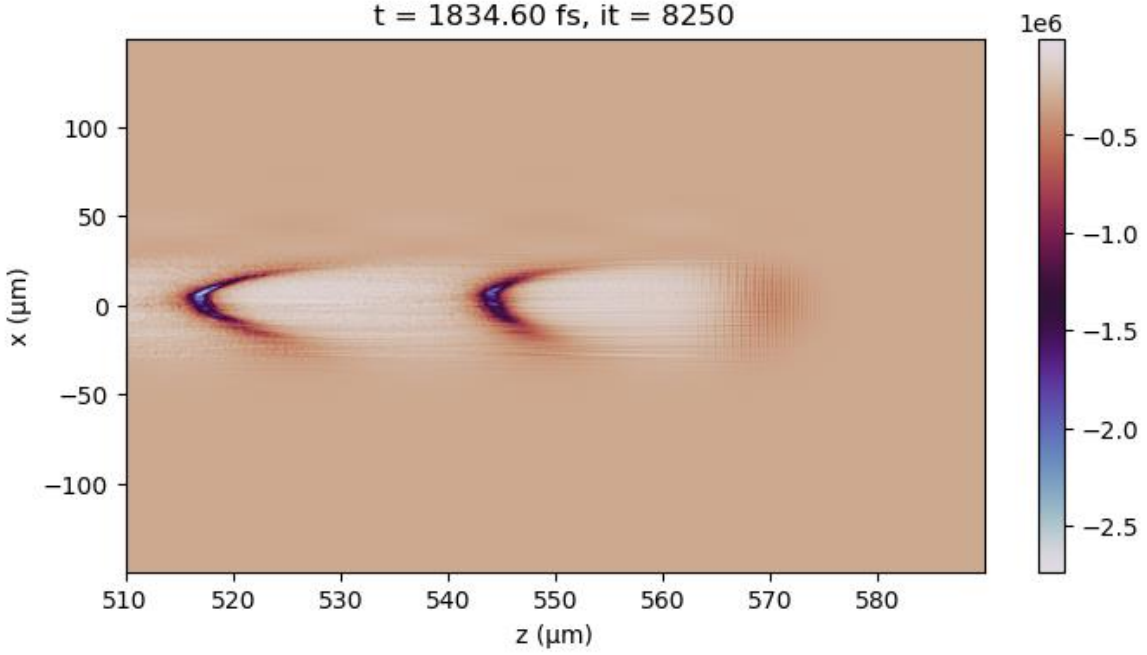
Coma increases electron oscillation amplitude

Simulation parameters:

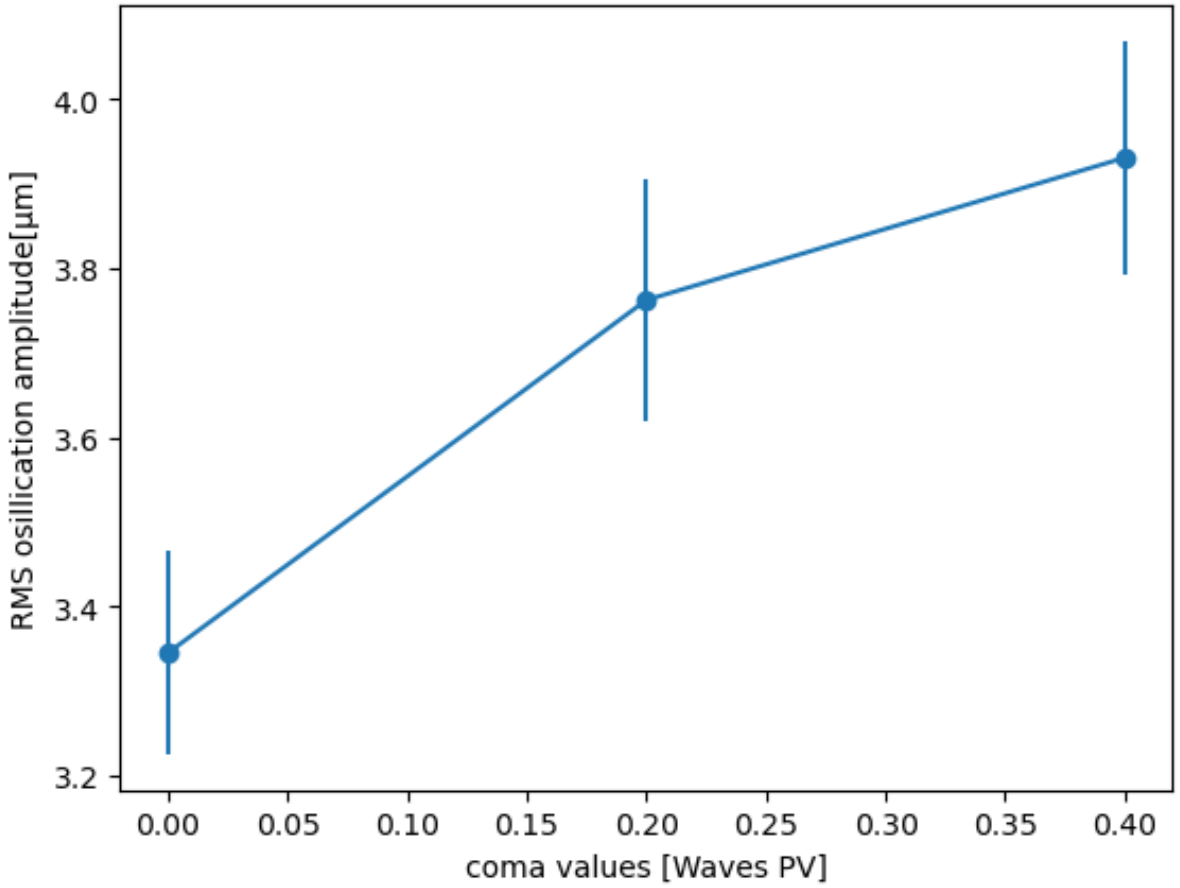
- Energy = 1.3 J
- w_0 = 17.5 µm (f/35)
- tau = 25 fs
- 800 nm central wavelength
- n_e = 2 x 10^{18} cm^{-3}
- 1% N, 99% He

$$k_{p,exp}w_{0,exp} = k_{p,sim}w_{0,sim}$$

Distorted wake

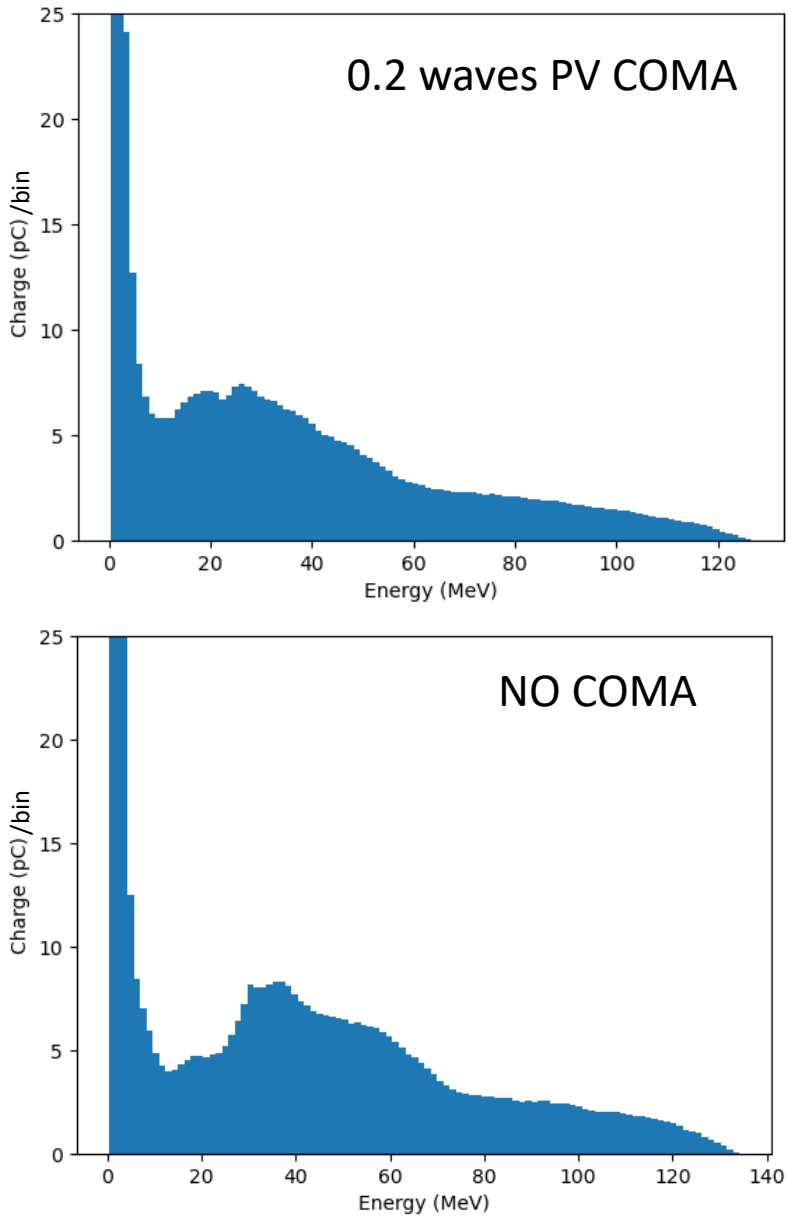


$$E_c[\mathrm{keV}] = 1.1 \times 10^{-23}\gamma^2 n_e[\mathrm{cm}^{-3}]r_\beta[\mu\mathrm{m}]$$

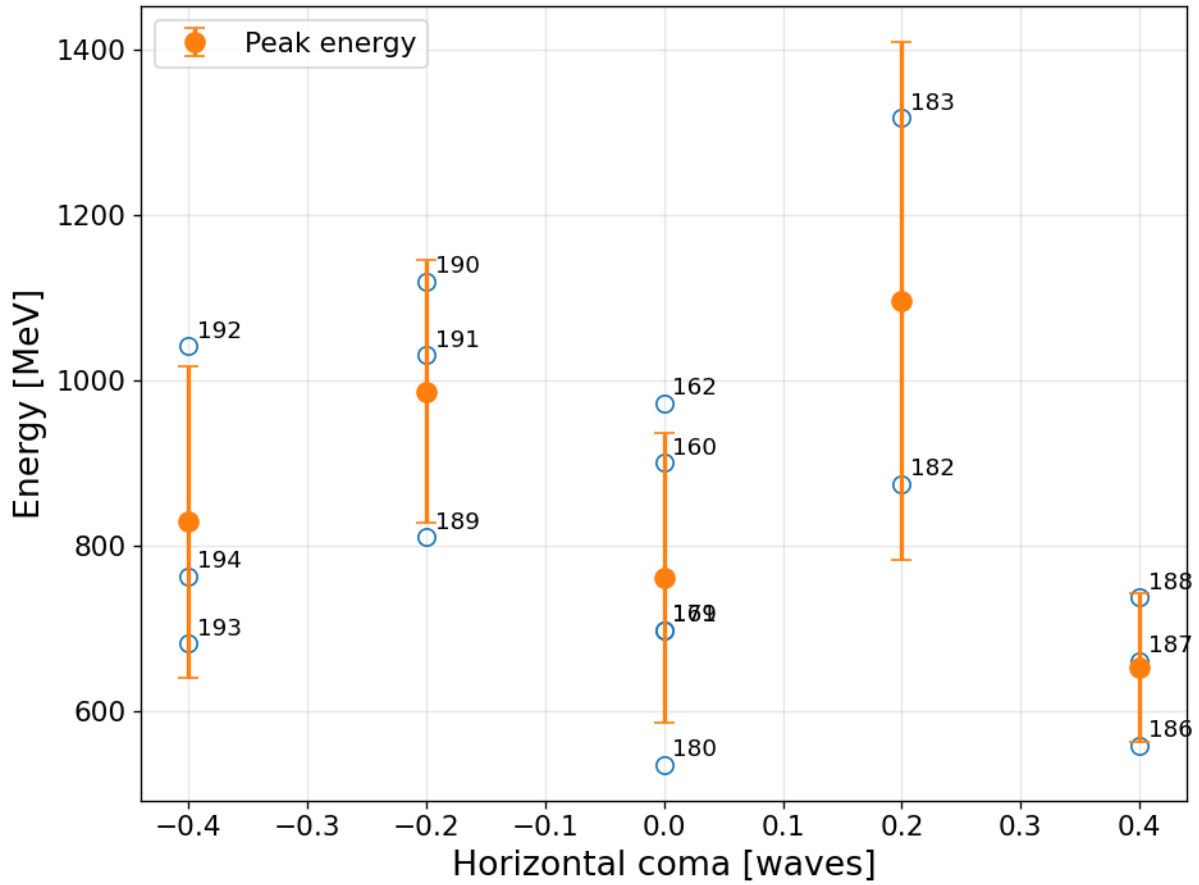


Electron spectra are comparable with coma

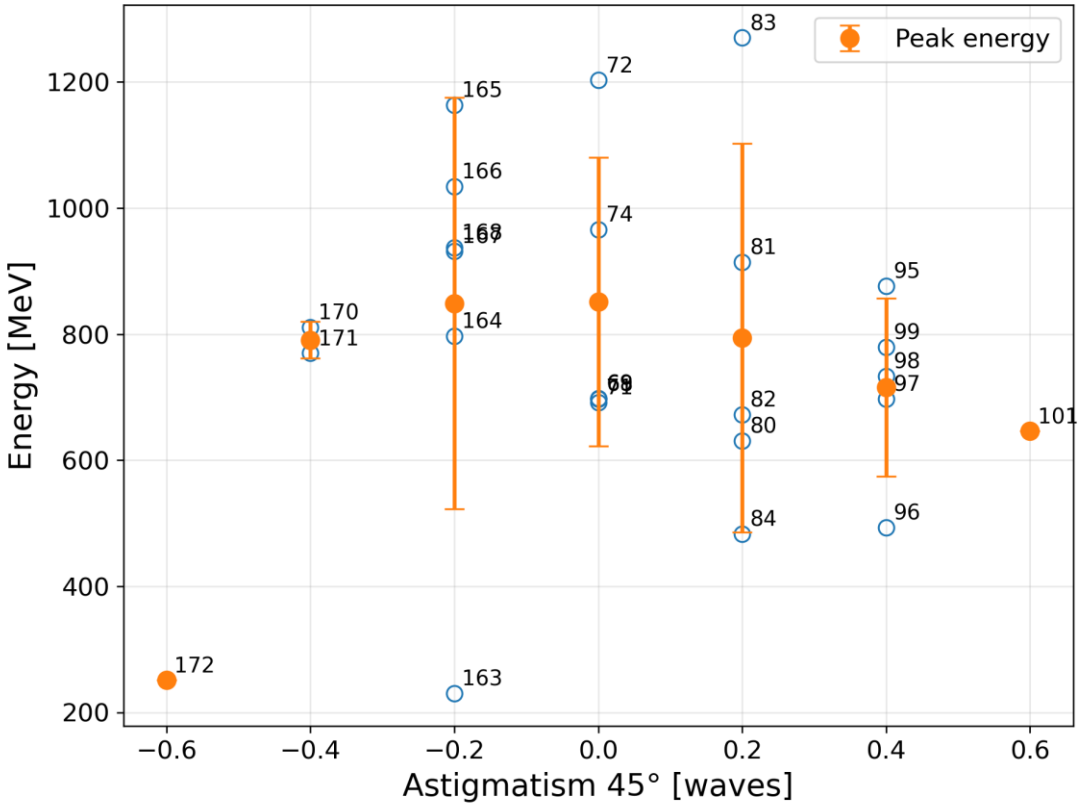
Simulations



Experiment



Astigmatism's effect on peak electron energies/injection

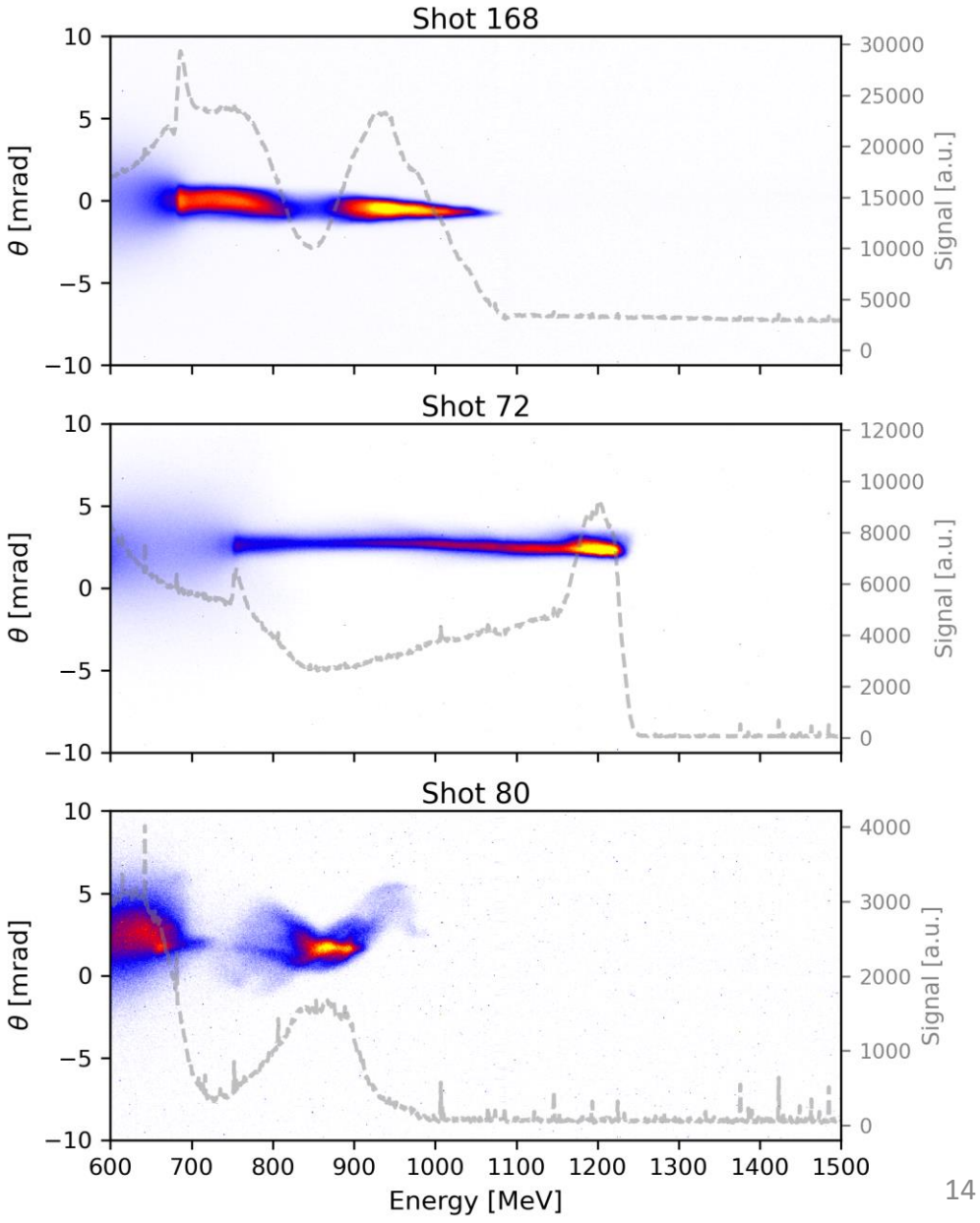


- Astigmatism tends to shift the peak electron energy lower

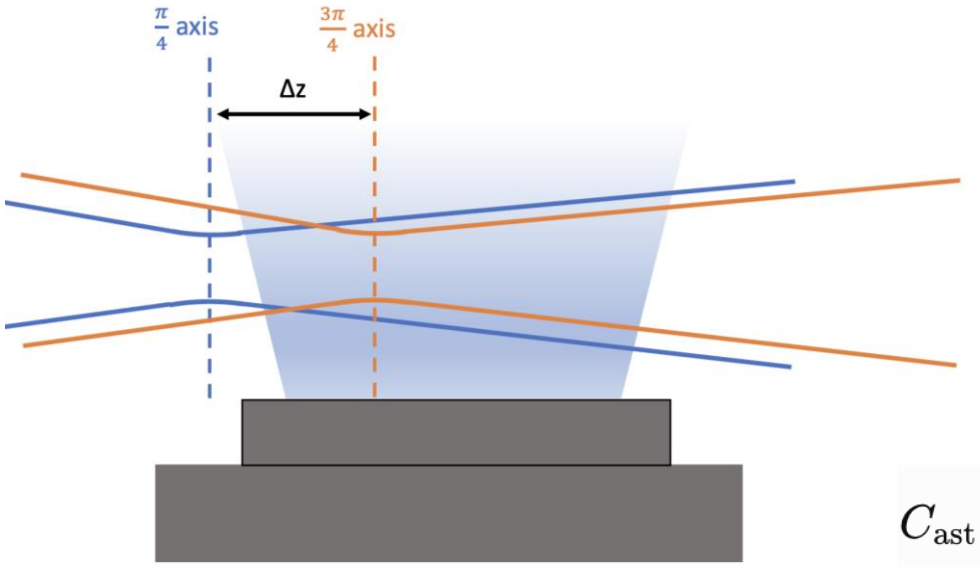
-0.2 waves

0 waves

0.2 waves



What contributes to this reduction of peak electron energy?



$$C_{\text{ast}} \approx -\frac{\Delta z_f}{16\lambda_0 N^2}$$

Principal axes are given by:

$$a = x\cos\phi + y\sin\phi, \qquad b = -x\sin\phi + y\cos\phi,$$

Custom transverse electric field profile:

$$T(a,b,z) = \frac{1}{\sqrt{Q_a(z)Q_b(z)}} \exp\left[-\frac{a^2}{w_0^2 Q_a(z)}\right] \exp\left[-\frac{b^2}{w_0^2 Q_b(z)}\right]$$

Dimensionless complex beam parameter:

$$Q_a(z) = 1 + i\frac{z - z_{f,a}}{z_R}, \qquad Q_b(z) = 1 + i\frac{z - z_{f,b}}{z_R}$$

<u>Laser parameters:</u>

Energy = 3 J
w_0 = 8 µm
tau = 25 fs
800 nm central wavelength
z_r = 350 µm
Δz = 100, 200, 300, 400, 500 µm

<u>Plasma:</u>

3% N, 97% He
Density = 1×10^{18} cm^{-3}
Ionization on

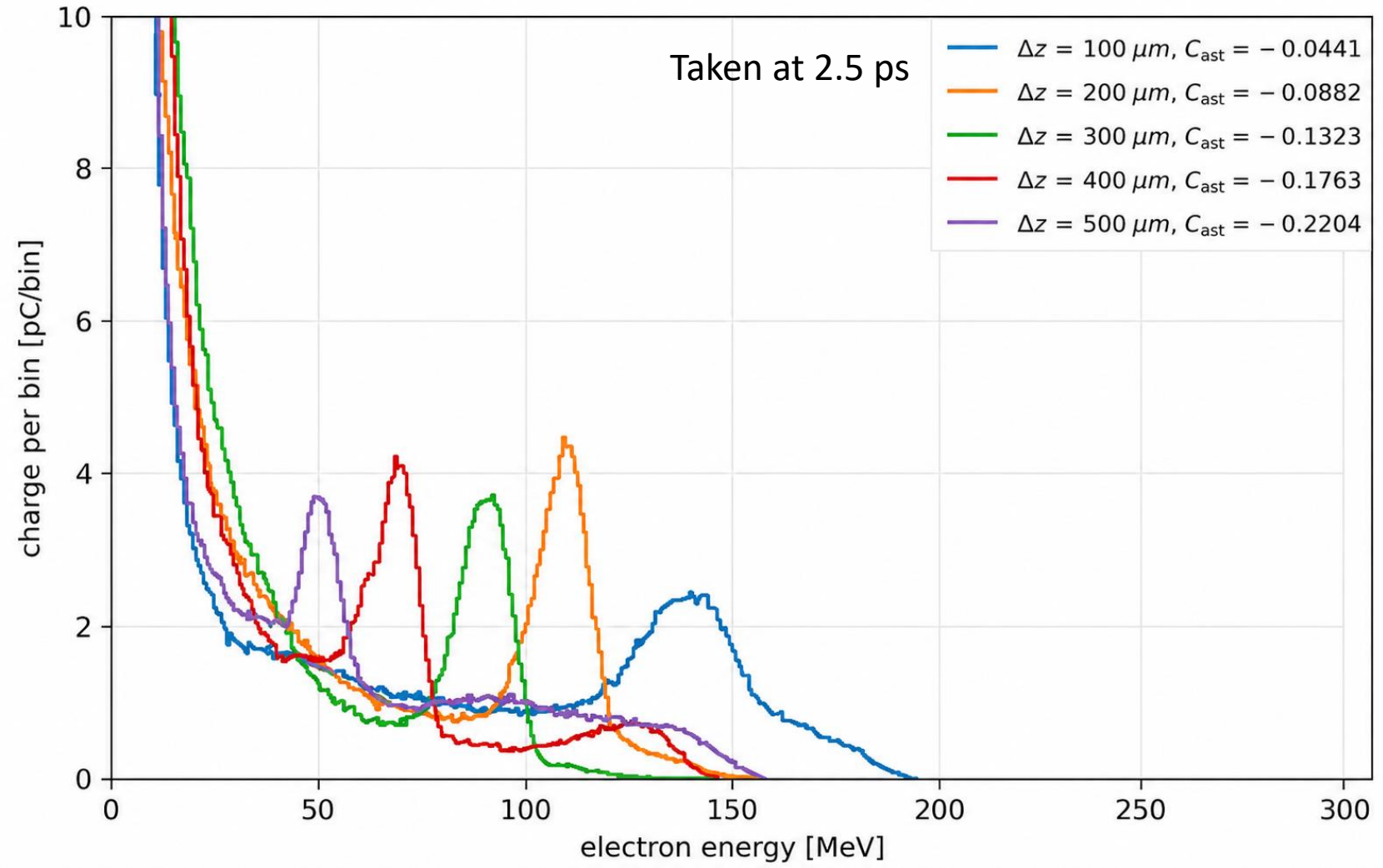
Simulations ran for 1 mm to investigate injection

- The custom transverse profile defines the astigmatism.
- FBPIC's 'ParaxialApproximationLaser' takes a transverse and longitudinal field as input and is energy normalized

fbpic.github.io

Changing astigmatism can tune electron spectra

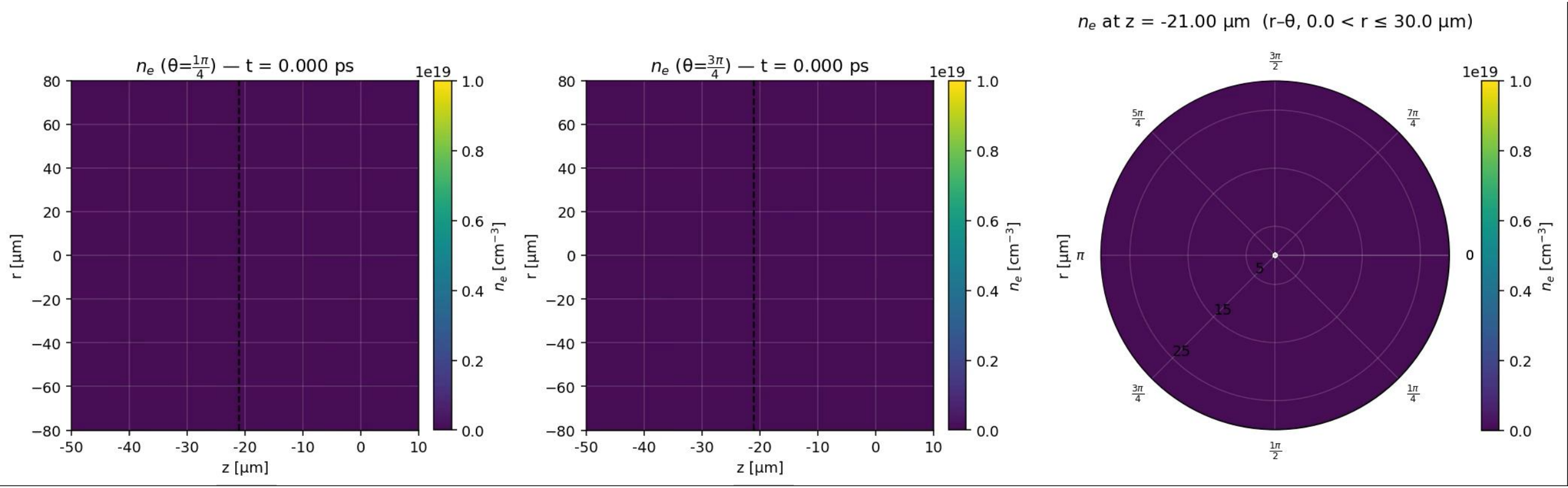
- Increasing astigmatism reduces peak energy as focal plane of axis is shifted into plasma
- Provides a means of tuning electron energies with simple alterations of phase



Reduction in peak energy with increasing astigmatism agrees with experimental data

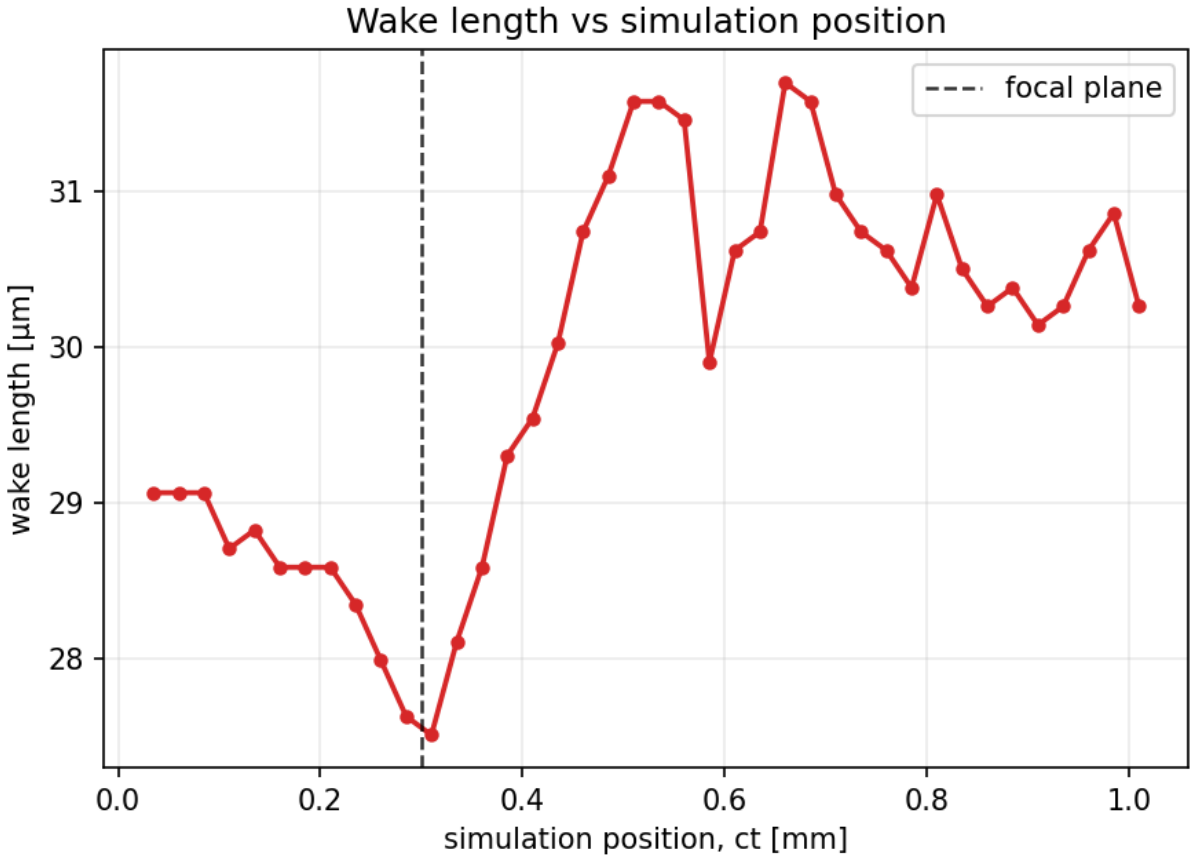
Delayed injection due to contraction of wake

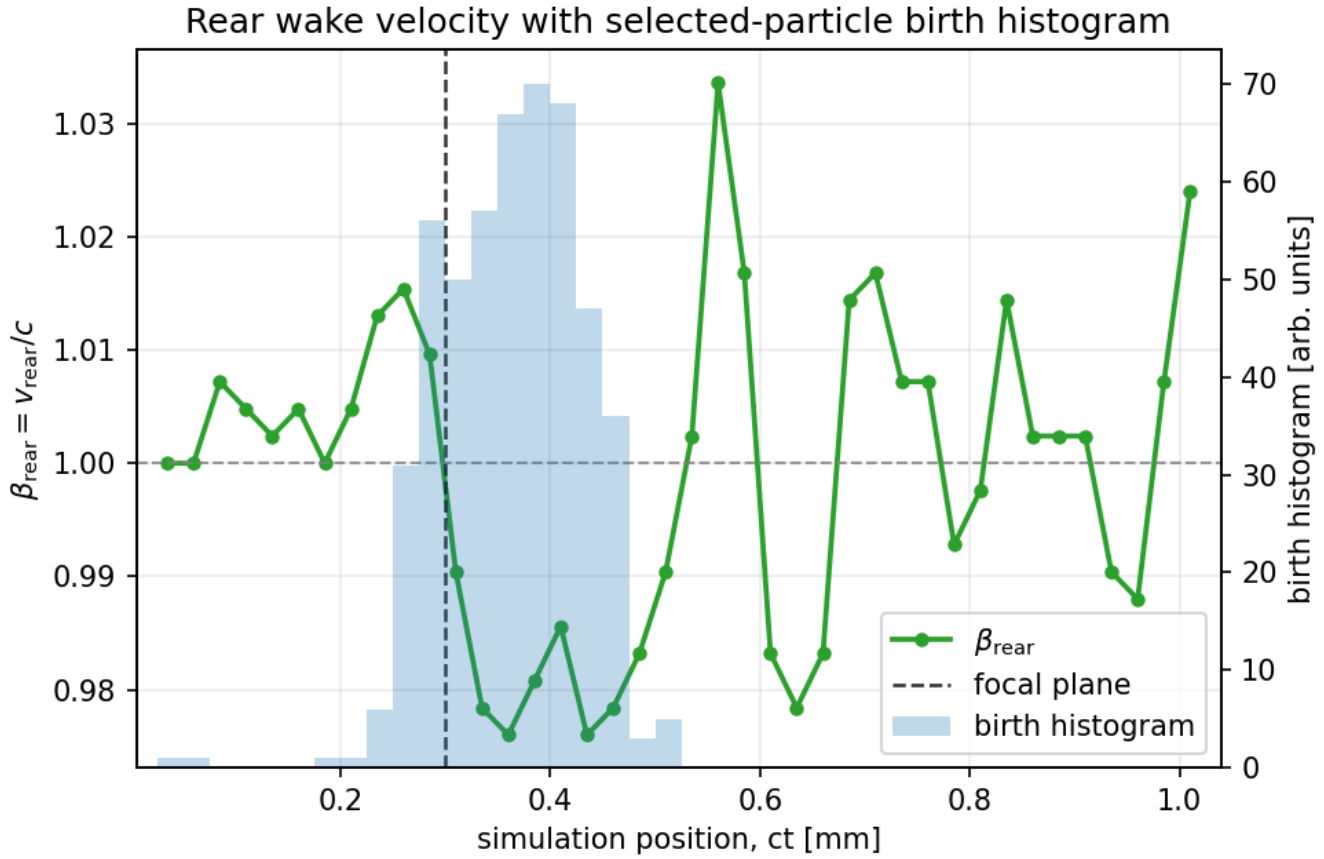
- Wake contraction when focusing one axis inside plasma produces a delayed injection event, reducing energy



Wake contraction delays injection

- Birth positions of electrons in the peak of the beam correspond to wake contraction caused by focal position of second axis





*Plots show wake data in plane of $3\pi/4$ axis

Conclusions

- Aberrations are easily applied to petawatt laser beams using deformable mirrors
- These aberrations have noticeable effects on LWFA electron beams and betatron X-rays
  - Coma can increase X-ray energy likely due to an increase in r_β
  - Astigmatism can delay injection due to wake contraction as the second principal axis comes to focus