Plasma Acceleration Group

CENTER FOR ACCELERATOR SCIENCE AND EDUCATION

# Optimizing Laser Parameters For Blowout Regime: From Petawatt NIR to LWIR Wakefield Drivers

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# The Collaboration


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**SEAWULF** @ Stony Brook University

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# What laser parameters underly the blowout formation and wakefield strength?

Consider two realistic laser systems

| | LWIR @ ATF | Ti:Sapph @ ZEUS |
|---|---|---|
| $P\ [TW]$ | 15 | 2500 |
| $\lambda_0\ [\mu m]$ | 9.2 | 0.8 |
| $\tau_0$ [fs] | 500 | 25 |
| $\boldsymbol{k_p c \tau_0}$ | **3.98** | **0.199** |
| $w_0\ [\mu m]$ | 75 | 75 |
| $\boldsymbol{k_p w_0}$ | **1.99** | **1.99** |
| $\boldsymbol{a_0}$ | **3.26** | **3.66** |
| $a_0/k_p w_0$ | 1.64 | 1.84 |

Similar
Different

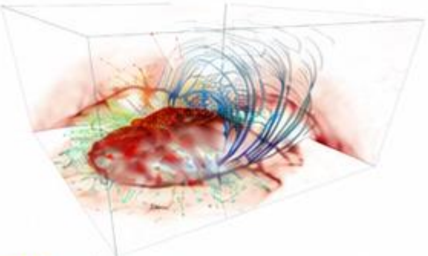
$$n = 2 \times 10^{16}; \frac{1}{k_p} = 37.6\ \mu m$$

# OSIRIS and FBPIC codes are used throughout this work

Osiris 4.0

osiris framework

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
- ⇒ UCLA + IST



code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU support
- Xeon Phi Support

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http://epp.tecnico.ulisboa.pt/

http://plasmasim.physics.ucla.edu/


https://fbpic.github.io/

FBPIC

0.13.0

Search docs

⊟ Overview of the code

⊟ FBPIC algorithm & features

Introduction to the PIC cycle

The distinctive features of FBPIC

Parallelization of FBPIC

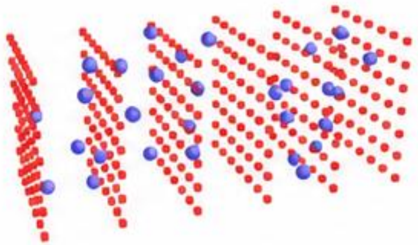
Installation

How to run the code

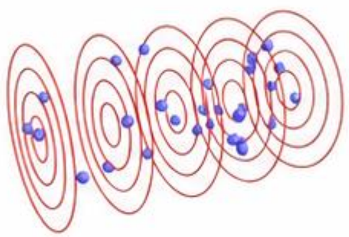
API reference

Advanced use

**FBPIC (Fourier-Bessel Particle-In-Cell) code:**

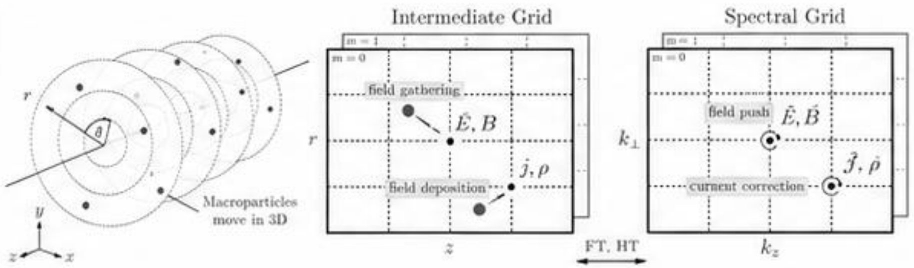


**3D Cartesian grid**



**Cylindrical grid (schematic)**

The above image is only a schematic view. In fact, instead of using a **3D Cartesian grid**, FBPIC (and other PIC codes such as Calder Circ) use a **set of 2D radial grids**, as represented below. Each 2D radial grid represents an **azimuthal mode** (labeled by an integer $m$):




- The grid for $m = 0$ represents the fields that are **independent of $\theta$**. (In idealized laser-wakefield acceleration, this is for instance the case for the wakefield.)
- The grid for $m = 1$ represents the fields that **vary proportionally to** $\cos(\theta)$ and $\sin(\theta)$. (In idealized laser-wakefield acceleration, this is the case of a linearly-polarized laser field, when expressed in cylindrical coordinates, as $E_r$ and $E_\theta$.)
- The grids for higher values of $m$ represent the fields that **vary proportionally to** $\cos(m\theta)$ and $\sin(m\theta)$. These modes take into account further departures from the cylindrical symmetry.

For more details on the cylindrical representation with azimuthal decomposition, see the original paper of the PIC code Calder Circ.

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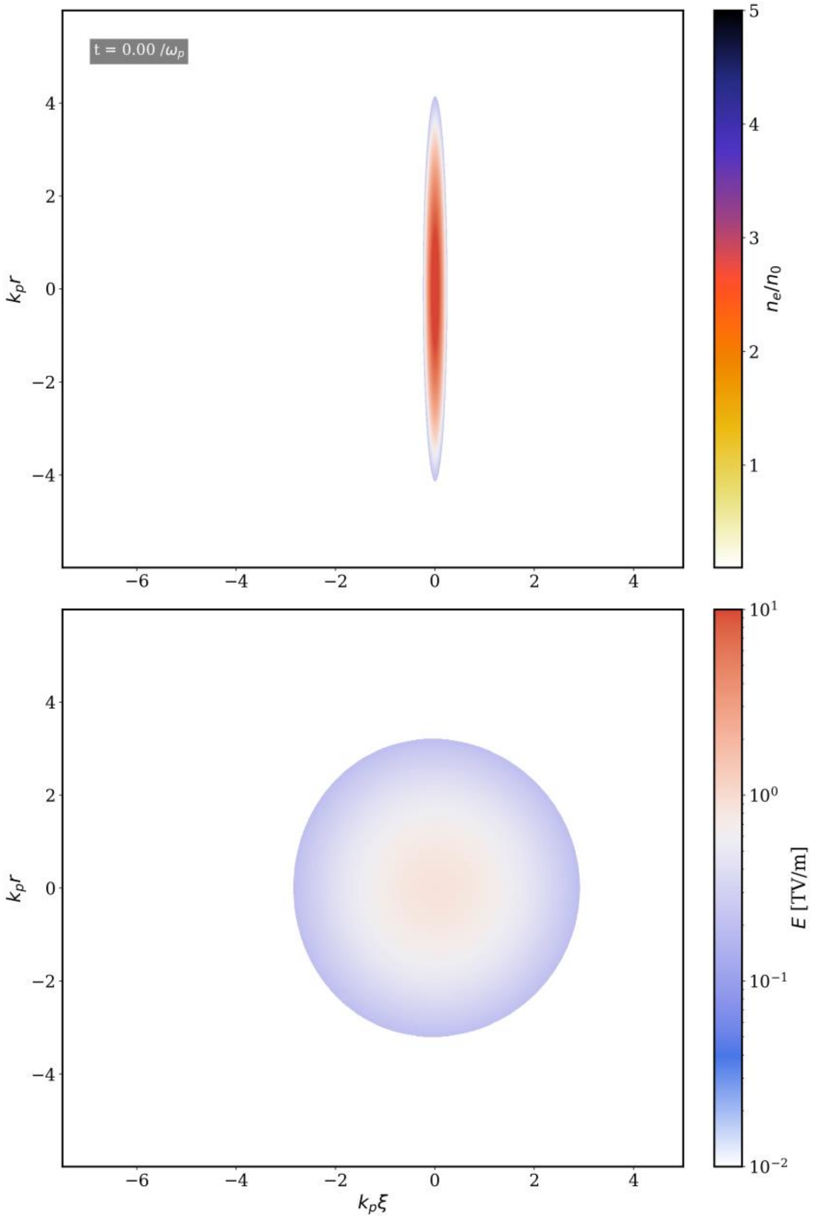
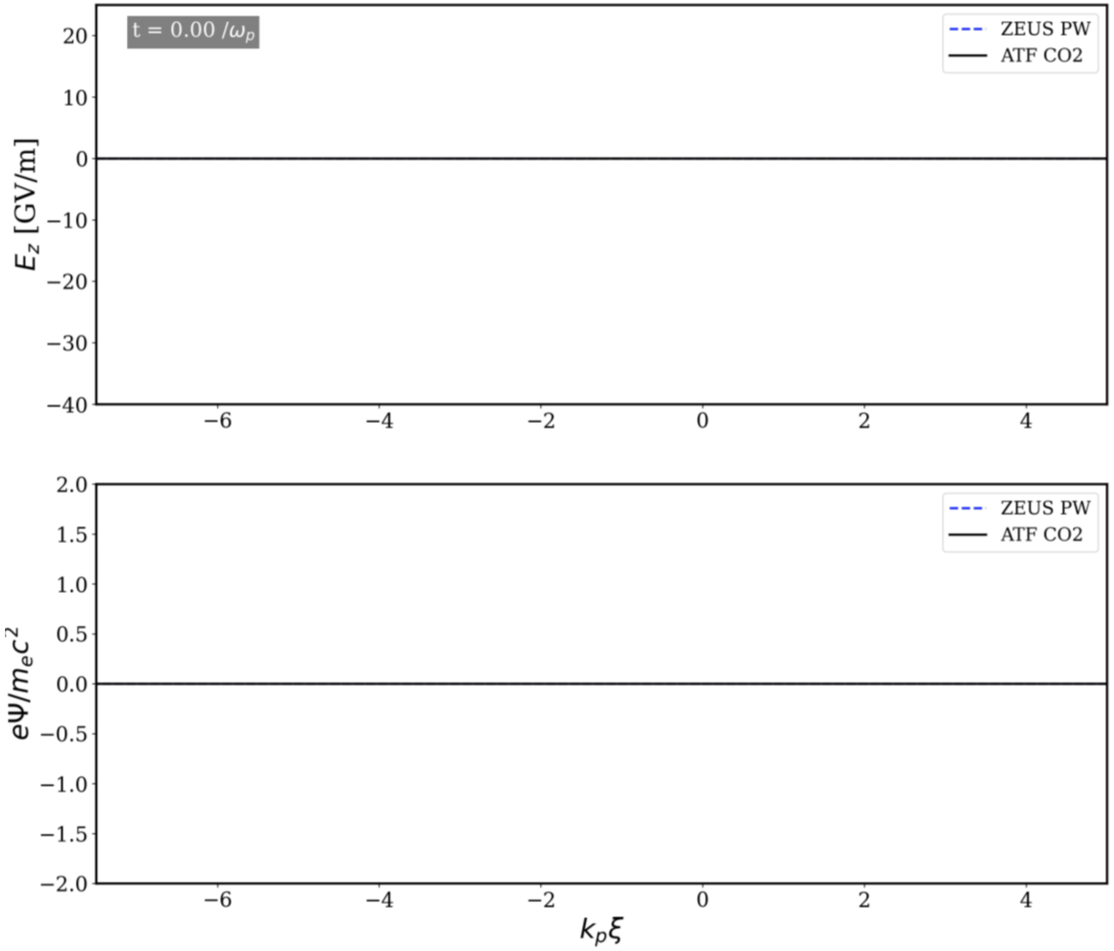
ZEUS
Ti:Sapph

ATF
LWIR



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# Value of the laser $a_0$ is not a sufficient predictor of the blowout strength

This conclusion is contrary to the conventional view of this interaction

"… for sufficiently intense and ultrashort lasers, $a_0 > 4$, the resulting electron density structure will resemble a spherical cavity and it was shown that the laser spot size needed to be matched to the maximum blowout (bubble) radius in order to achieve the most ideal wakes. It is worth noting for $2 < a_0 < 4$ electron blowout still occurs with the cavity slightly deviating from a spherical shape."

W. Lu, et al., "Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime," *Phys. Rev. ST Accel. Beams* **10**, 061301 (2007).

# Synthesis

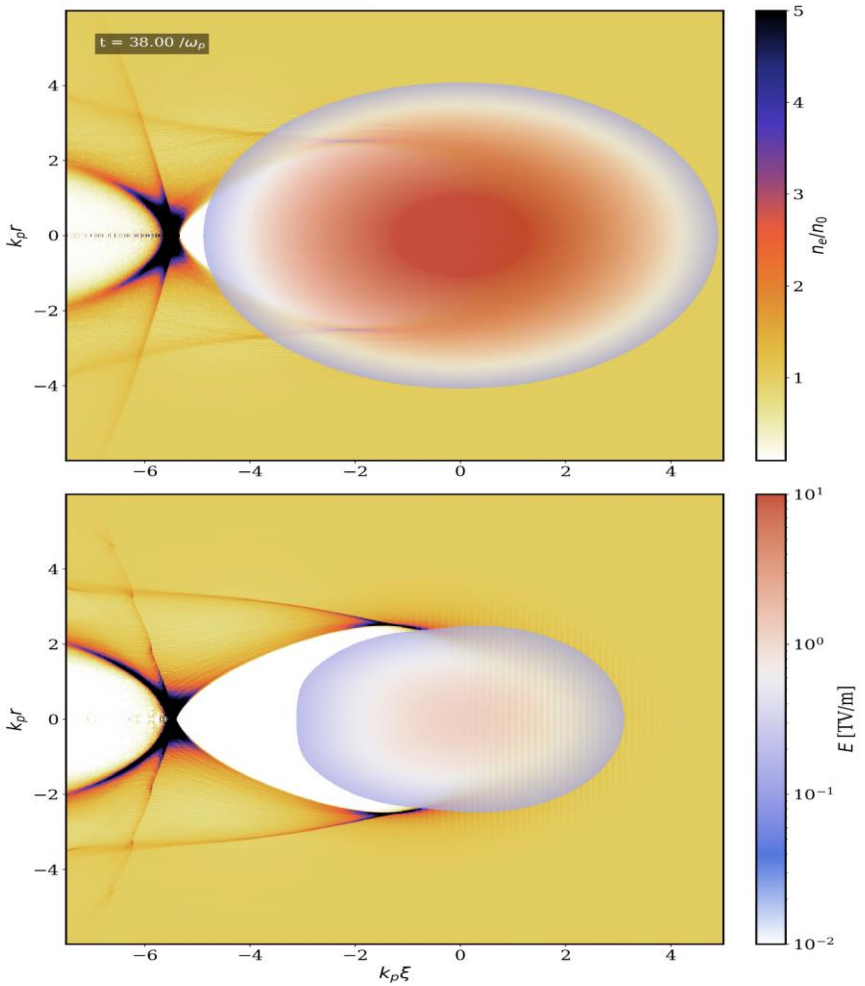
- Large blowout radius is important for a number of applications, including staging, multi-beam experiments like seeding ionization injection, or colliding beam experiments such as inverse Compton scattering.
- Both spot size and pulse length play essential roles in reaching blowout. Laser wavelength has no independent effect when normalized strength, size, and duration are matched.
- Across simulations, the onset of blowout is described by an integrated-force criterion
- LWIR lasers are naturally well suited to driving ‘petawatt-class’ plasma wakefields

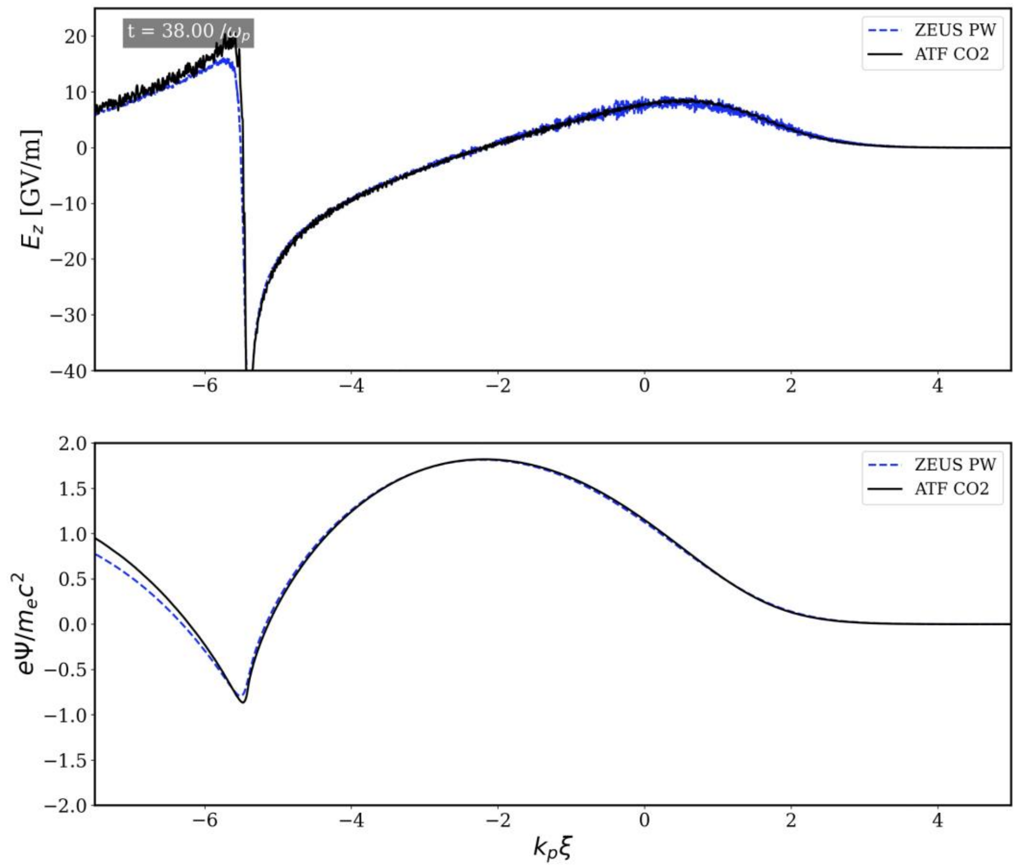
# Laser wavelength does not control blowout when normalized size and strength are equal

For a direct comparison, Ti:Sapphire parameters are adjusted so that $a_0$, $k_p w_0$, and $\mathrm{k_p} c\tau$ match the LWIR case

ZEUS - modified Ti:Sapph

ATF $CO_2$



# Let's return to basics…

- The normalized ponderomotive force (in linear limit)

$$F_p = -\nabla(a^2/2)$$

- Consider vector potential envelope of a form

$$a = a_0 \exp\left(-\frac{r^2}{w_0^2}\right)\exp\left(-\frac{\xi^2}{(c\tau)^2}\right)$$

- The role of transverse spot size is clear:

$$F_\perp \propto a_0^2/w_0^2$$

- The role of pulse length is more ambiguous

(1) It can act like a plow (smaller $\tau$ is better)

$$F_\parallel \propto a_0^2/(c\tau)^2$$

(2) It can reinforce transverse push (larger $\tau$ is better)

$$p_\perp = \int F_\perp d\tau$$

# Performed a pulse length scan to isolate its role

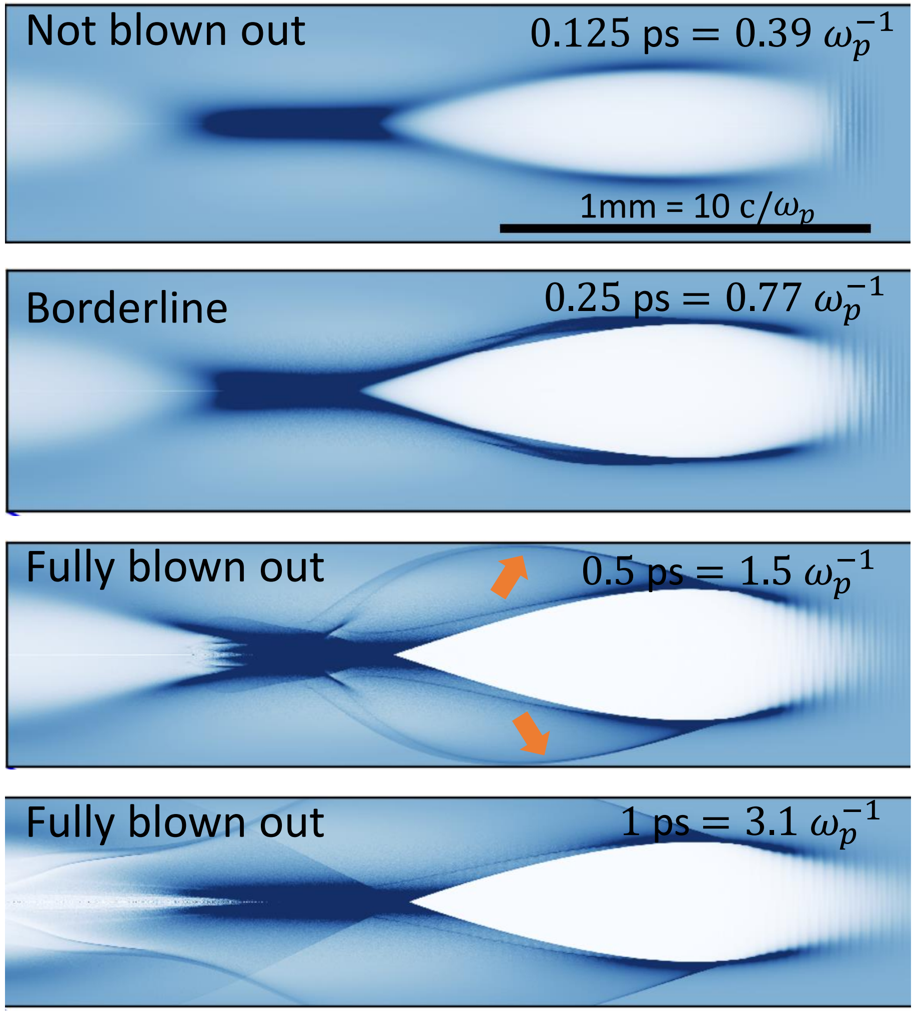
## Fixed Conditions

| | Physical Input | Normalized Parameters |
|---|---|---|
| Plasma density | $3 \times 10^{15}$ cm$^{-3}$ | $c/\omega_p = 97\mu$m |
| Laser strength ($a_0$) | 1.0 | |
| Spot size | 40 $\mu$m | $k_p w_0 = 0.41$ |
| Laser wavelength | 9.2 $\mu$m | |
| Focus position | 3.7 mm | $k_p z_f = 38$ |

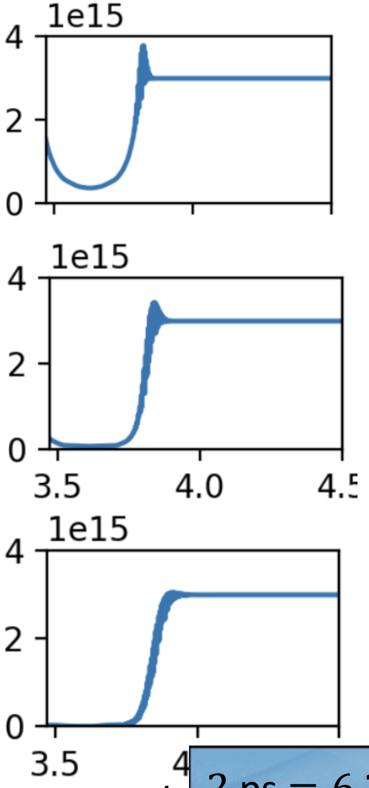
## Pulse Length Scan

| $\boldsymbol{\tau_{FWHM}}$ | 2 ps | 1 ps | 0.5 ps | 0.25 ps | 0.125 ps |
|---|---|---|---|---|---|
| $\mathbf{k_p c \tau}$ | 6.2 | 3.1 | 1.5 | 0.77 | 0.39 |

# For a fixed $a_0/w_0$, reducing pulse length only reduces the degree of nonlinearity

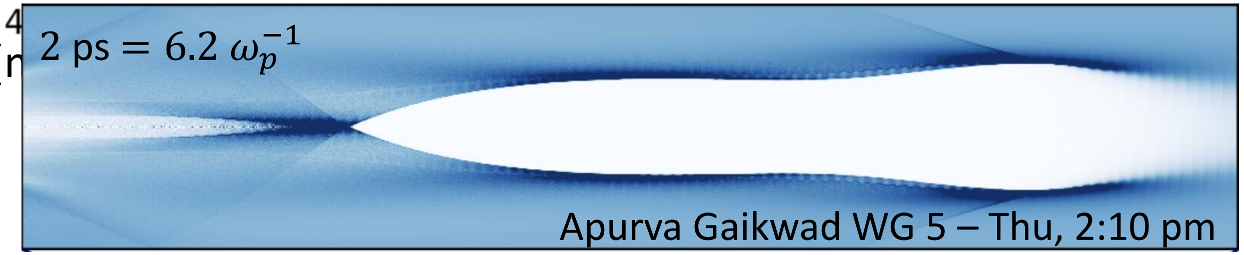



On-axis density

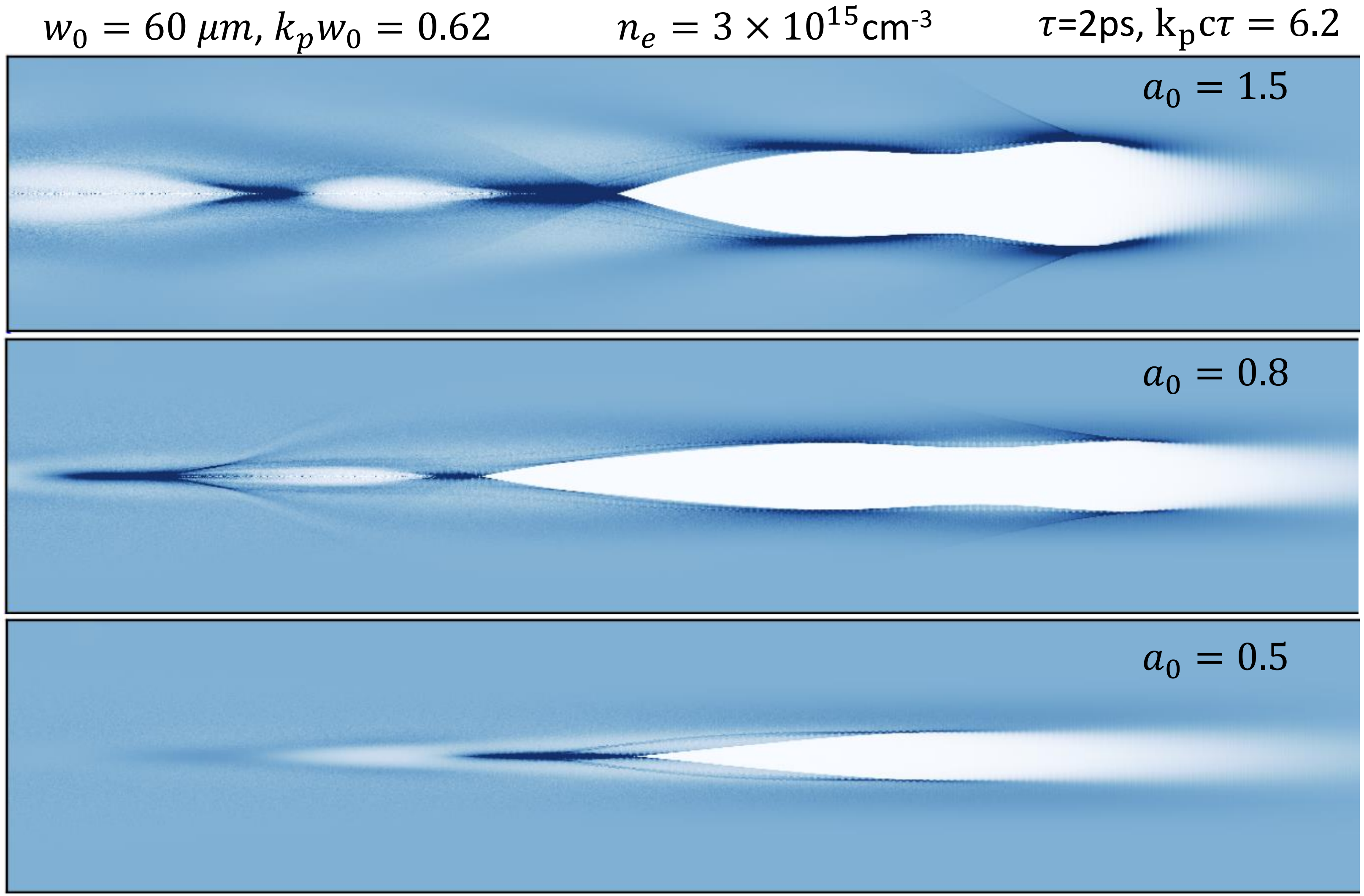



- Increasing pulse length primarily manifests in the transverse momentum of electrons in "outer sheath" defining wakefield boundary
- The "inner sheath" is formed by a population of electrons starting from laser edge and are only modestly affected by laser fields
- Therefore, past a threshold, increasing pulse length does not affect the blowout region

This case is the exception!

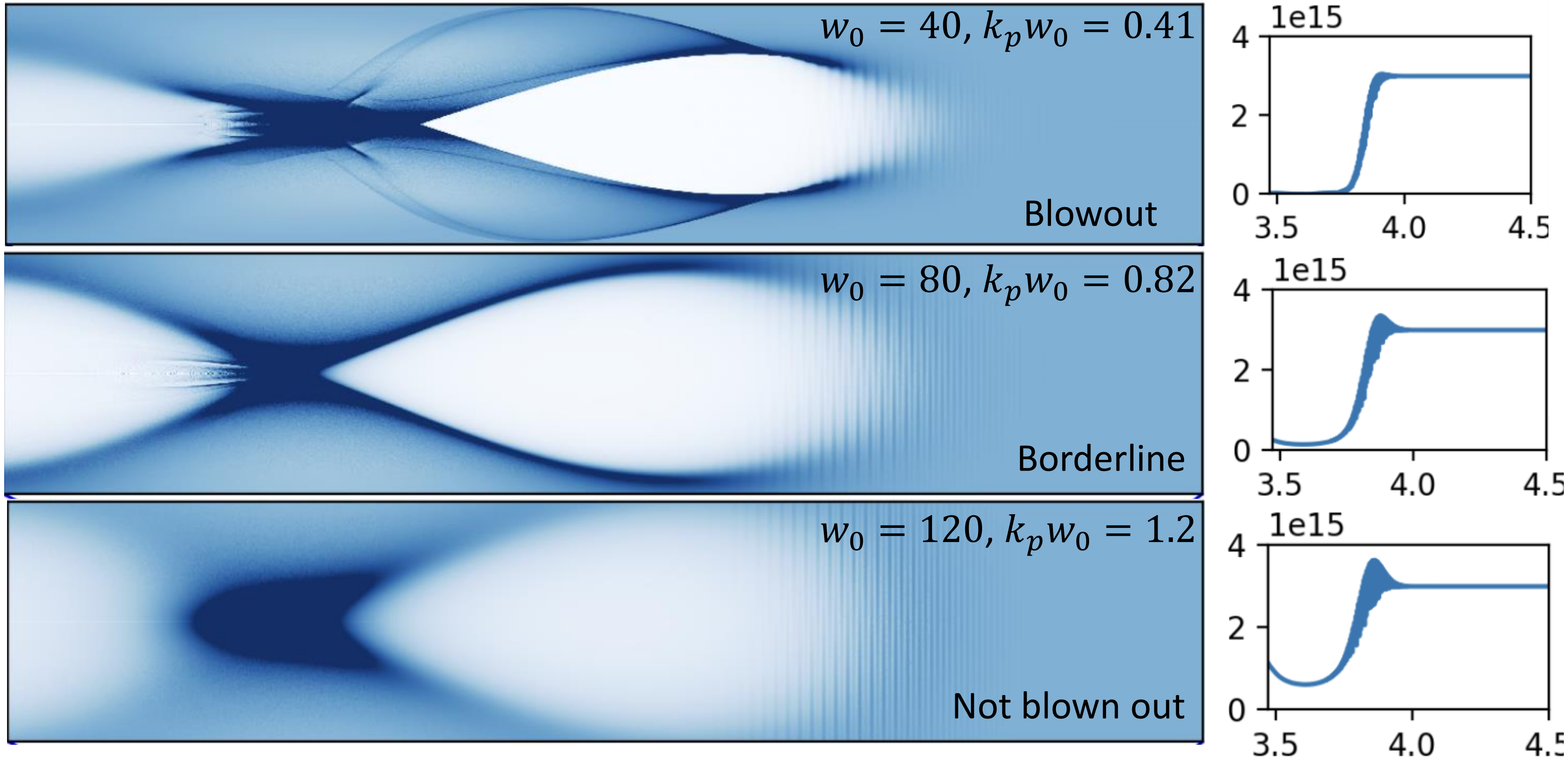


# Conversely, full blowout persists at low $a_0$ if the pulse is long enough



# Spot size governs the strength and the size of the wake

$a_0 = 1$ $n_e = 3 \times 10^{15}$cm-3 $\tau$=0.5 ps, $k_p c\tau = 1.5$

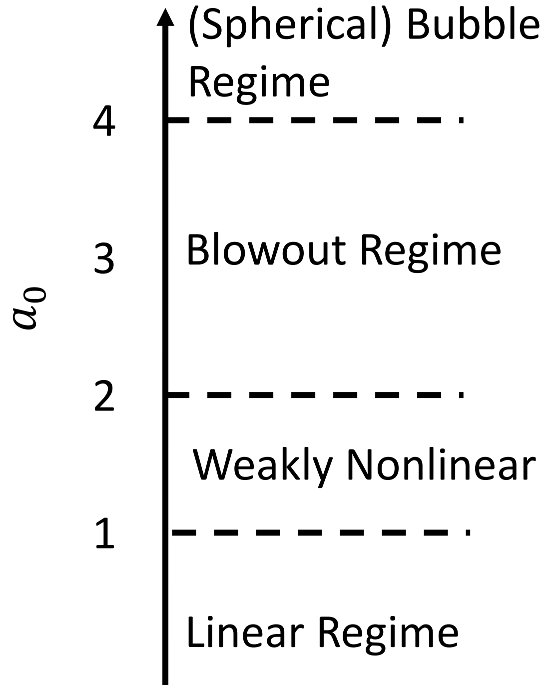



(1) $F_\perp \propto a_0^2/w_0^2$

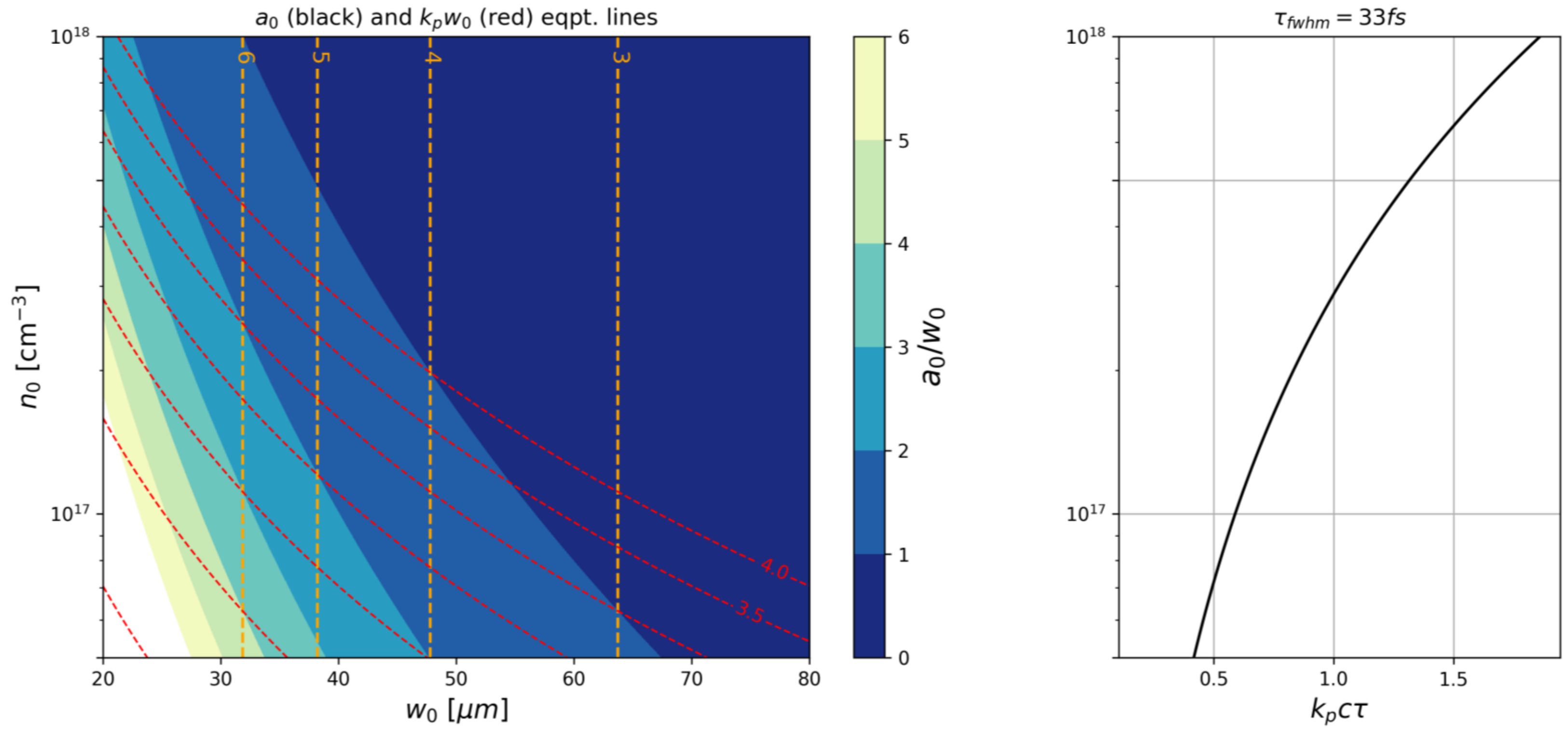
(2) Electrons forming the “inner sheath” comes from the outer edge of laser

# A multi-dimensional view is needed for optimizing wake strength towards blowout

Conventional view

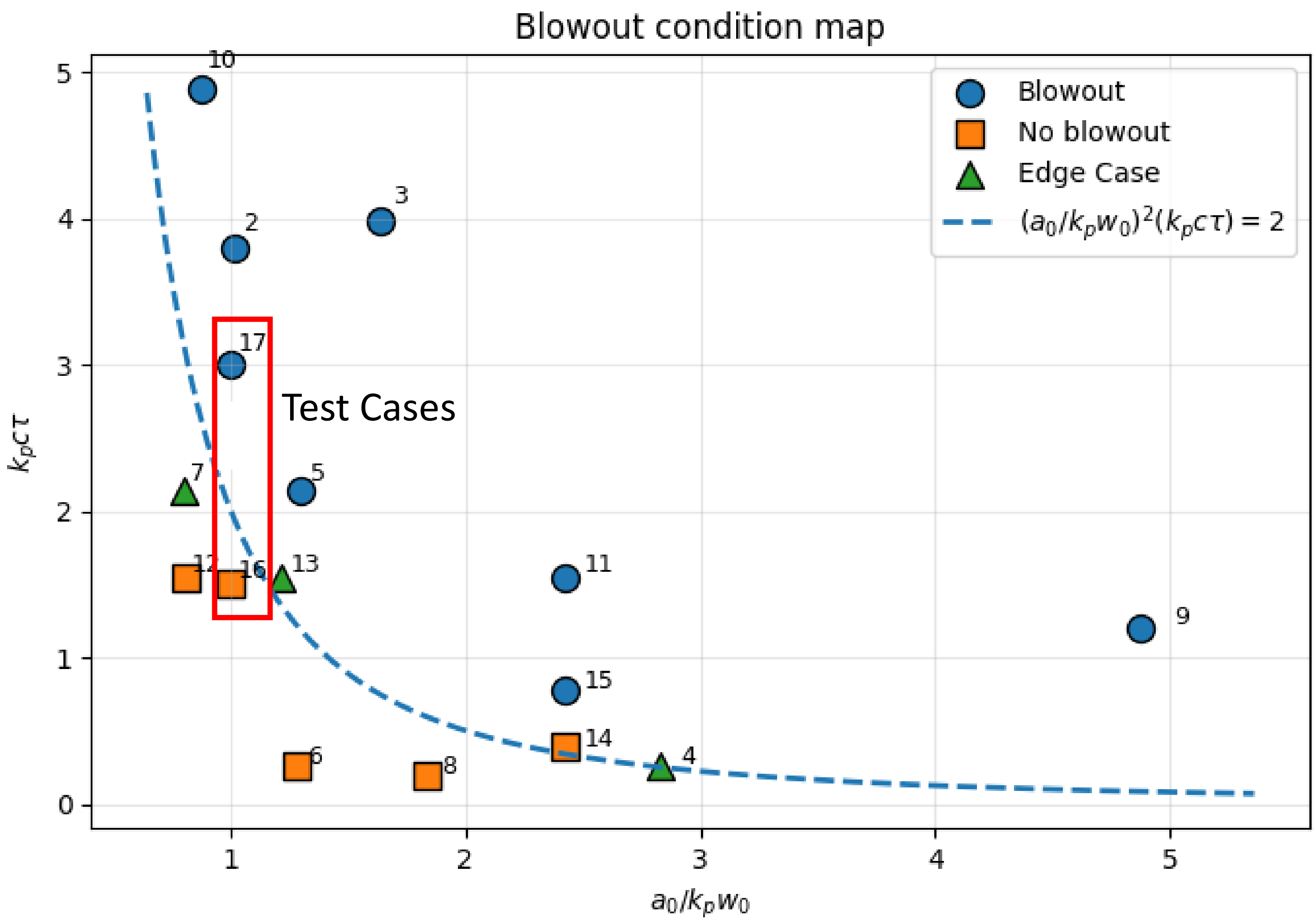



Multi-dimensional view – 1 PW example (~40J, 33fs)

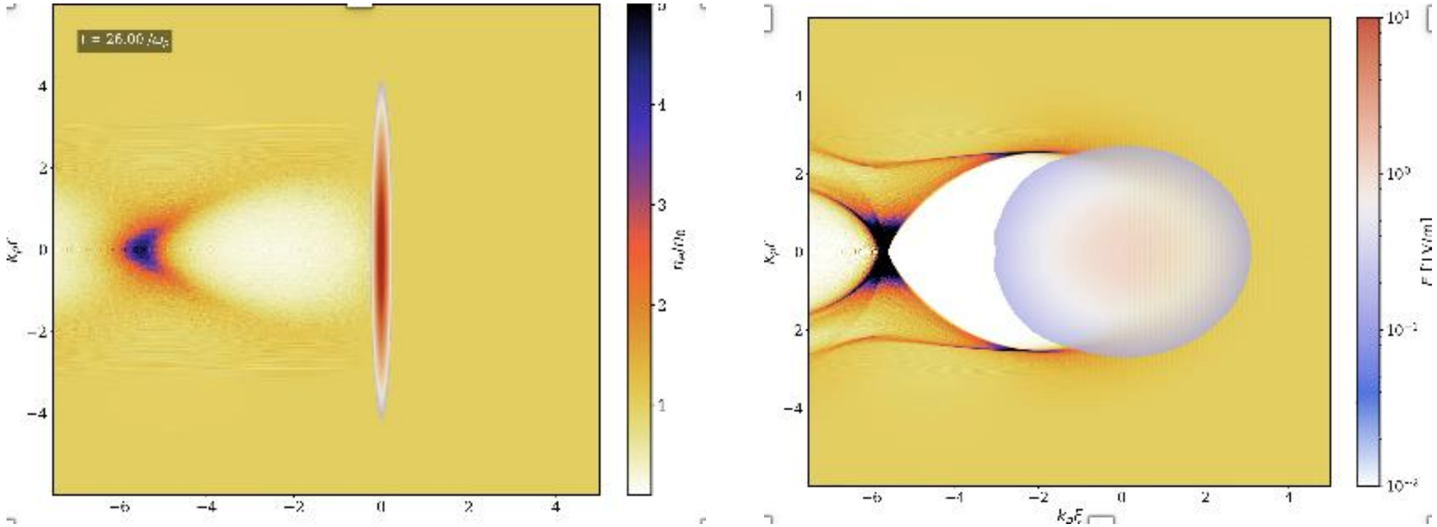



The smaller $a_0/w_0$, the longer $k_p c\tau$ is needed to reach blowout

# Looking across simulations, we can come to a (preliminary) criteria for ‘integrated ponderomotive force’



# Long-wave-infrared lasers ($\lambda \sim 10\mu m$) have a natural advantage in generating large, high-amplitude wakes



(1) $a_0 = 0.86 \times 10^{-9}\sqrt{I[Wcm^{-2}]\lambda_0^2[\mu m]}$ makes a 15 TW LWIR laser equivalent to > 1 PW near IR

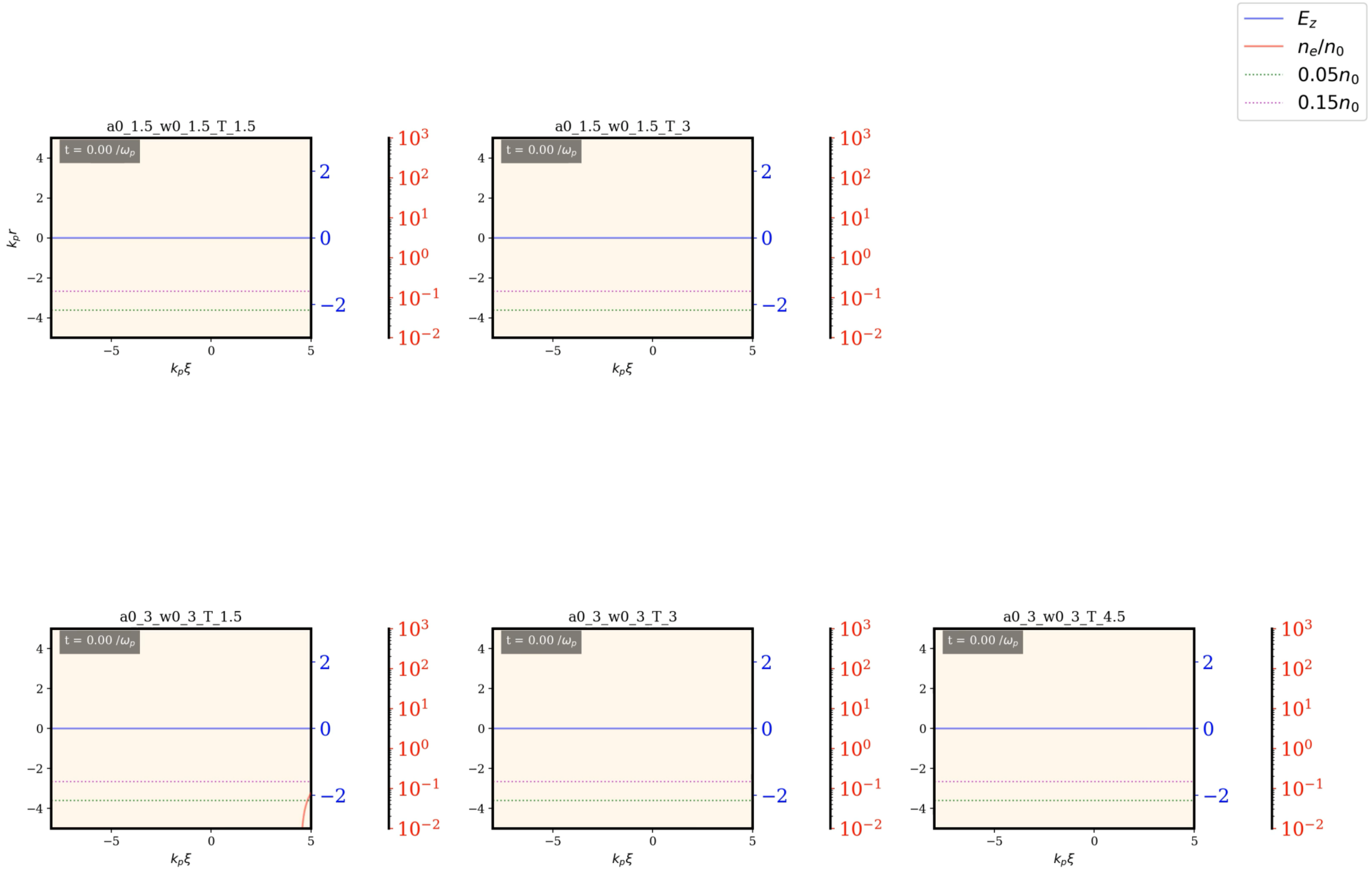
(2) Small bandwidth of amplifying medium (such as $CO_2$) produces a naturally long pulse

(3) $w_0 \propto F_{\#}\lambda$ allows LWIR lasers to make a naturally large wakefield at small $F_{\#}$

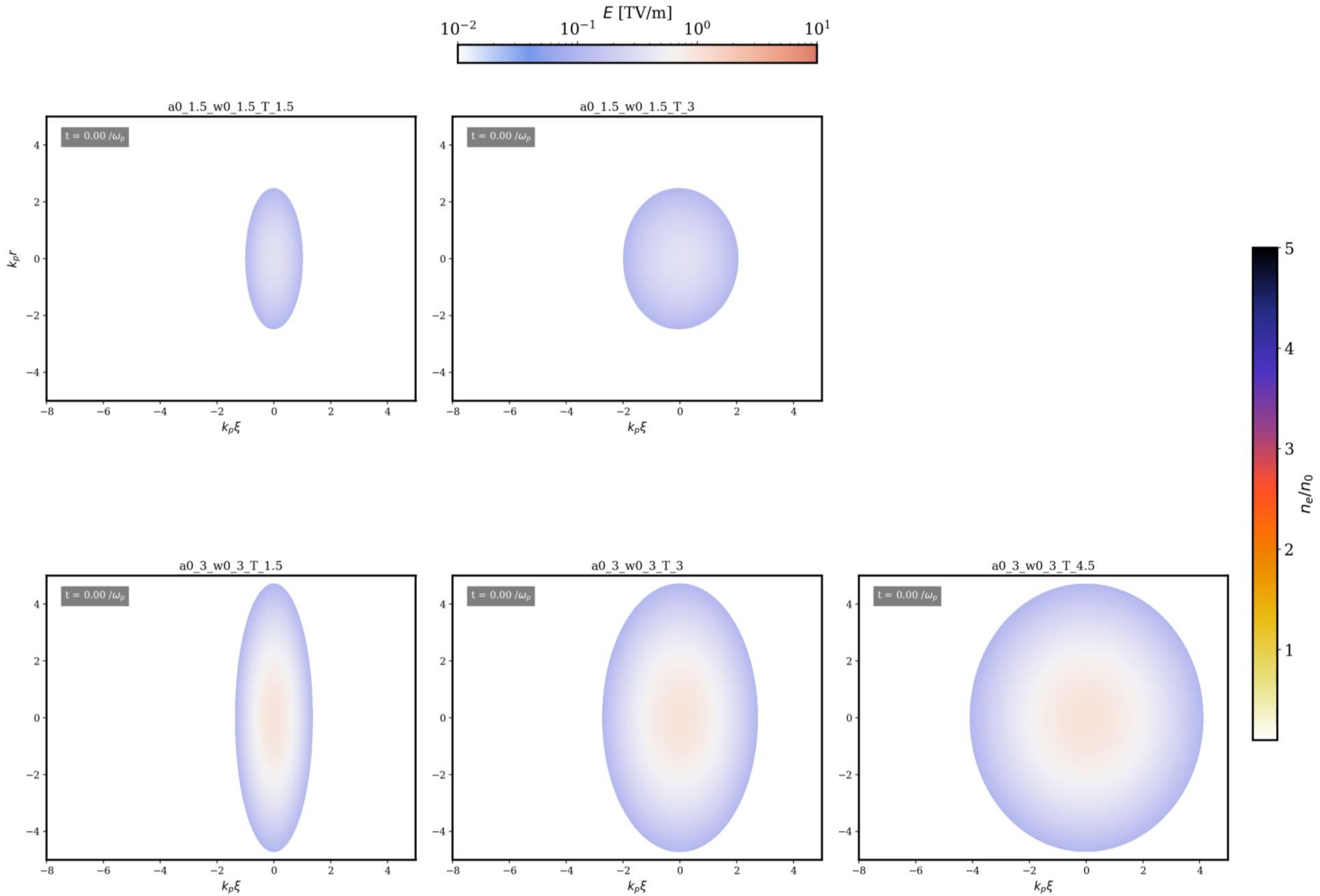
# Conclusions

- Both spot size and pulse length play essential roles in reaching blowout: spot size controls the wake size and transverse force, while pulse length determines the accumulated transverse momentum. A sufficiently long pulse can sustain full blowout even at low $a_0$.
- Across simulations, the onset of blowout is described by the integrated-force criterion $(a_0/k_\mathrm{p} w_0)^2 (k_\mathrm{p} c\tau) \gtrsim 2$ (preliminary ). Laser wavelength has no independent effect when normalized strength, size, and duration are matched.
- LWIR lasers are naturally well suited to this regime: their long wavelength provides high $a_0$ at modest power, $CO_2$ amplifiers produce naturally long pulses, and diffraction produces large spots—and therefore large wakes—at practical f-numbers.

# The End



$E_z$
$n_e/n_0$
$0.05n_0$
$0.15n_0$
a0_1.5_w0_1.5_T_1.5
a0_1.5_w0_1.5_T_3
a0_3_w0_3_T_1.5
a0_3_w0_3_T_3
a0_3_w0_3_T_4.5
t = 0.00 /$\omega_p$
$k_p r$
$k_p \xi$


E [TV/m]
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
a0_1.5_w0_1.5_T_1.5
a0_1.5_w0_1.5_T_3
a0_3_w0_3_T_1.5
a0_3_w0_3_T_3
a0_3_w0_3_T_4.5
t = 0.00 /$\omega_p$
$k_p r$
$k_p \xi$
$n_e/n_0$

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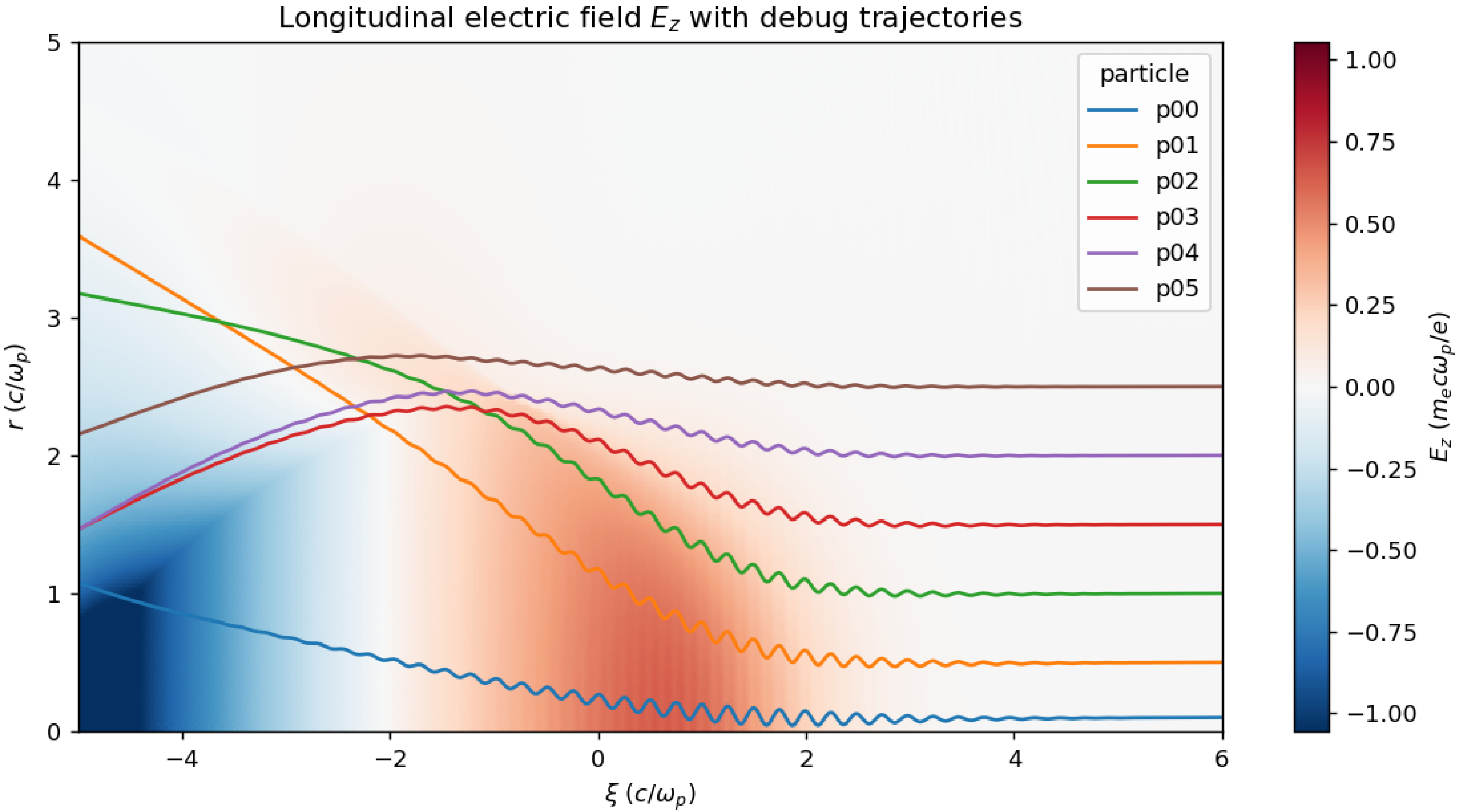
# Example single particle trajectory show the role of electrons at different points



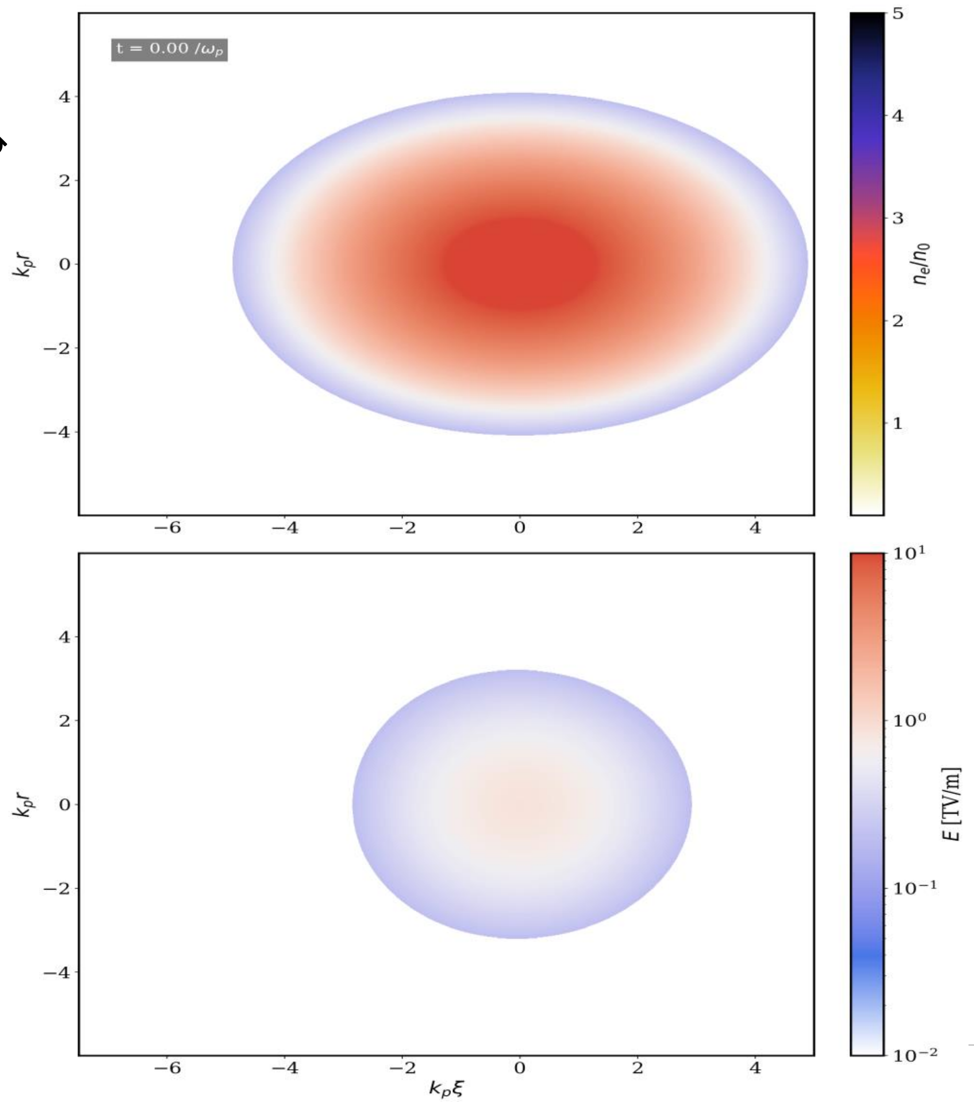
# Comparing TS vs CO2 with same properties

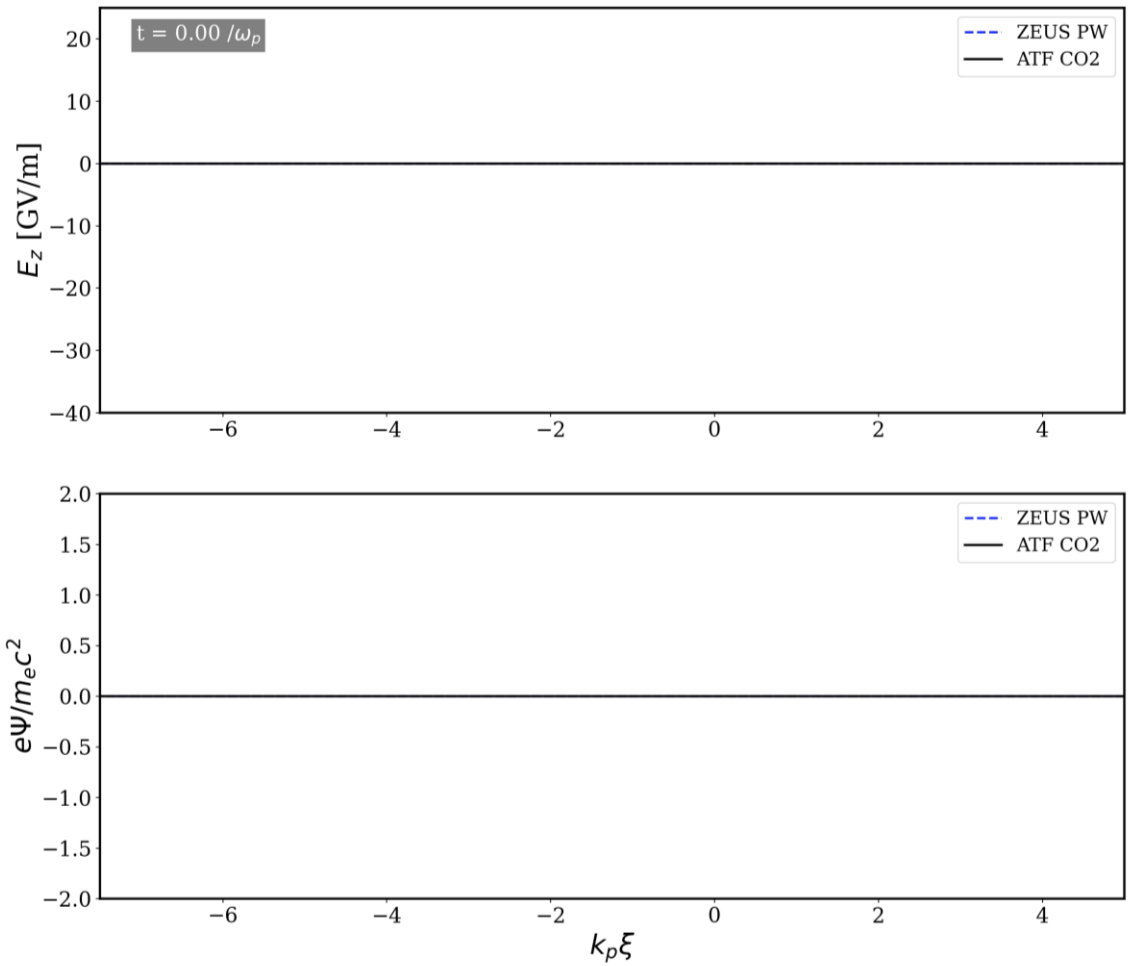
| | $CO_2$ @ ATF | (Fictional) Ti:Sapph@ ZEUS |
|---|---|---|
| $P\ [TW]$ | 15 | 1980 |
| $\mathcal{E}\ [J]$ | 7.5 | 992 |
| $\lambda_0\ [\mu m]$ | 9.2 | 0.8 |
| $\tau_0$ [fs] | 500 | 500 |
| $k_p c\tau_0$ | 3.98 | 3.98 |
| $w_0\ [\mu m]$ | 75 | 75 |
| $k_p w_0$ | 1.99 | 1.99 |
| $a_0$ | 3.26 | 3.26 |
| $a_0/k_p w_0$ | 1.64 | 1.64 |

$$n = 2\ \times\ 10^{16}; \frac{1}{k_p} = 37.6\ \mu m$$

ZEUS - modified Ti:Sapph

ATF $CO_2$



# Spot size directly impacts the blowout length

n_e=3e15 $\tau$=2ps $a_0 = 1.5$