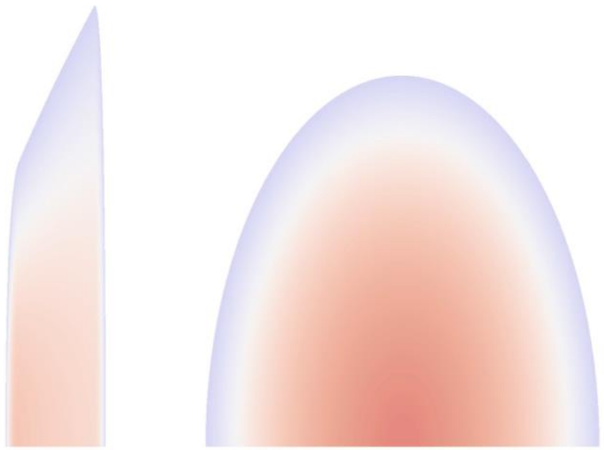
Self-loading LWFAs using two-color ionization injection with flying-focus lasers



July 27, 2026

Evan Trommer, Arohi Jain, Navid Vafaei-Najafabadi

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Synthesis

- An important area of focus with LWFAs is the acceleration of high charge (>100 pC) beams with sub-1% energy spreads and low transverse emittances (100 nm-rad) for future collider applications
- A "flying-focus plasma photoinjector" can utilize spatiotemporal coupling of a laser's fields to generate an e- beam with a trapezoidal shape, ideal for beam loading, with high amounts of charge
- Applying this concept with experimentally-relevant laser parameters can generate an asymmetric e- beam with nearly 200pC of charge and 100s of nm-rad emittance

FAR BEYOND

Bulanov, S. S., *et al.*, Journal of Instrumentation 19.01 (2024): T01010.
Schroeder, C. B., *et al.*, Journal of Instrumentation 18.06 (2023): T06001.

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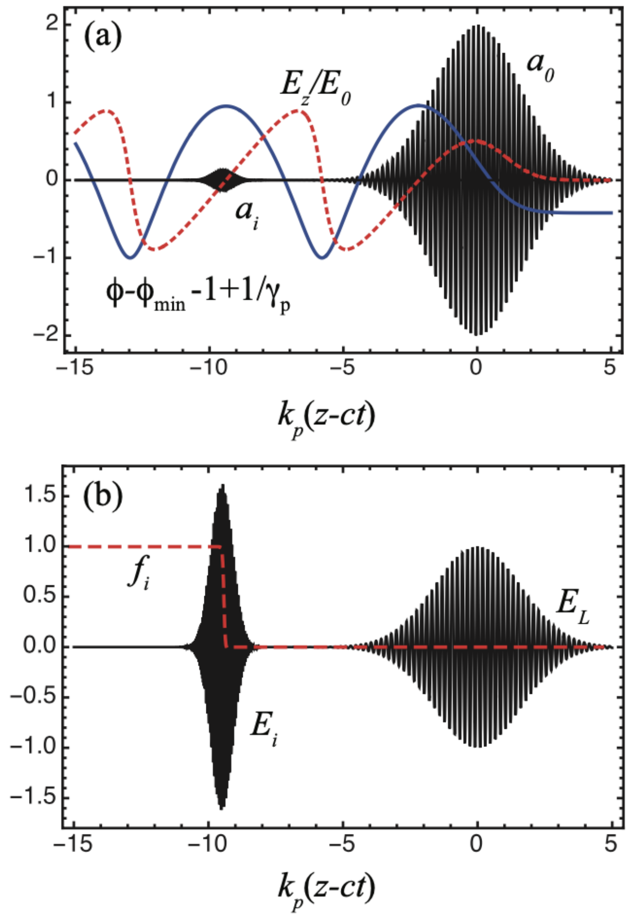
Two-color ionization injection uses a second laser to generate the electron beam inside the wake

- A high-intensity drive laser ($a_0 \gtrsim 2$) drives a nonlinear plasma wake
- A co-propagating laser with a **shorter wavelength** and **lower a_0** can be focused inside the wake as it is formed
- The focused injector further ionizes the gas; electrons with low transverse momenta can be trapped with low emittance
- The range of ionization is very short, so only a small amount of charge is injected

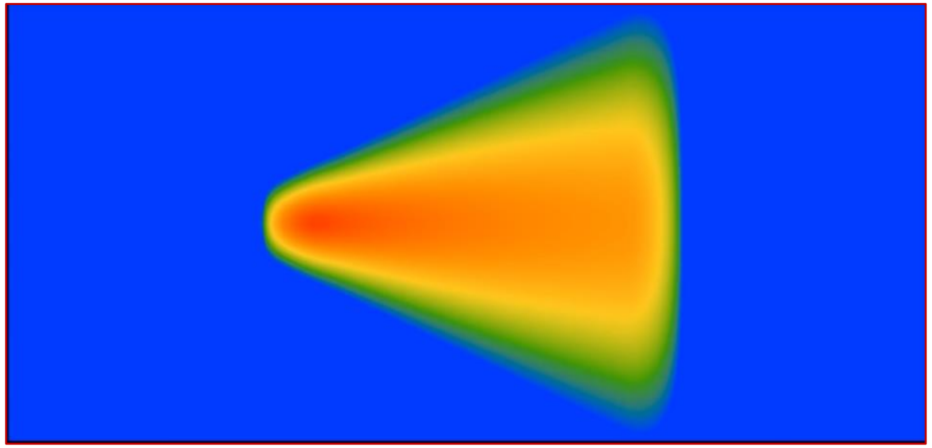


FAR BEYOND

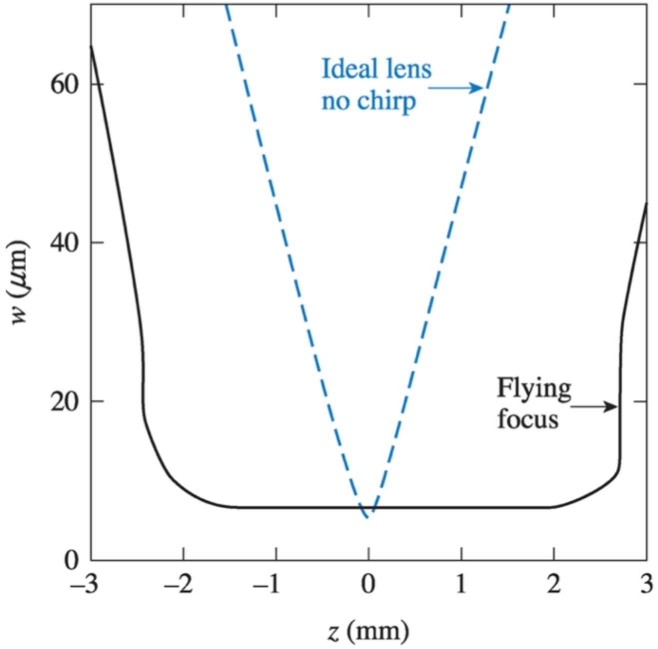
L. L . Yu *et al.,* Phys. Rev. Lett. **112**, 125001
C. B. Schroeder *et al.,* Optica Publishing Group paper JSIII_1_3. (2015)

Flying focus produces lasers with long intensity ranges

- Flying focus can be used to create intensity profile with a traveling focus spot. This acts as a dynamic ionization front for our usage
- The minimum spot size can be tuned to lengths $L \gg z_R$, allowing us control the amount of charge injected



Simulated FF laser intensity profile in a vacuum with $v_f > c$

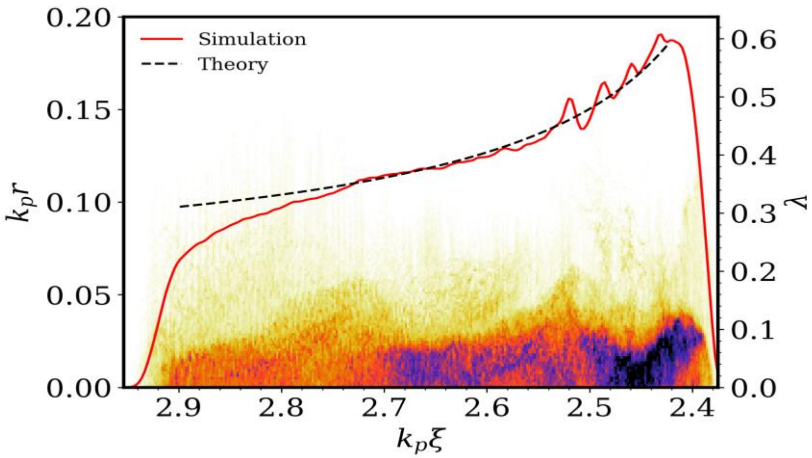


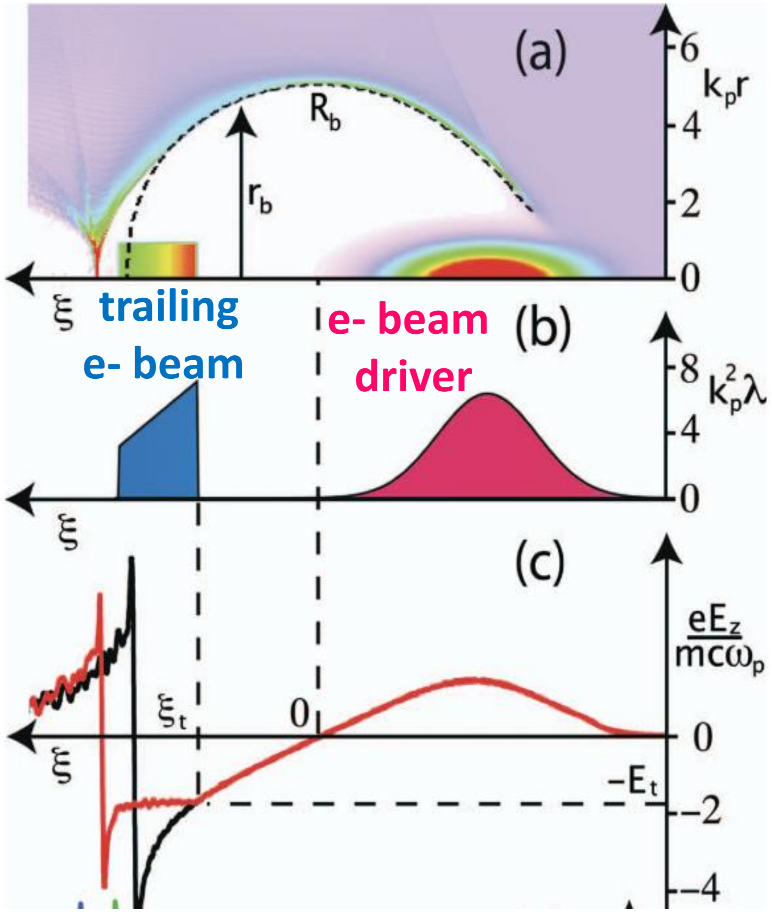
D. Froula *et al.,* Phys. Plasmas 1 March 2019; 26 (3): 032109.

A flying focus laser can generate a near-trapezoidal beam inside a blown-out wake

- The linear charge density of a beam generated by a flying focus laser:

$$\Lambda(\xi) = \frac{w_f^2}{4} e n_g \frac{v_f}{|v_f - 1|} \frac{\xi}{\sqrt{\xi^2 - \frac{4}{\chi}}}$$





Ideal beam loading

$$\Lambda(\xi) = \Lambda_0 - \Lambda_1(\xi - \xi_t)$$

$$\Lambda_0 = \sqrt{\left(\frac{E_t}{\chi}\right)^4 + \left(\frac{R_b}{2}\right)^4}$$

$$\Lambda_1 = E_t/\chi$$

$E_t = E_z(\xi_t)$ = load field value

R_b = maximum wake radius

$\frac{\chi}{2}$ = slope of electric field

A. Jain, *et al.*, Phys. Rev. Research 8.2 (2026): 023213.

M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)
Jiayang Yan, PhD Thesis (2024)

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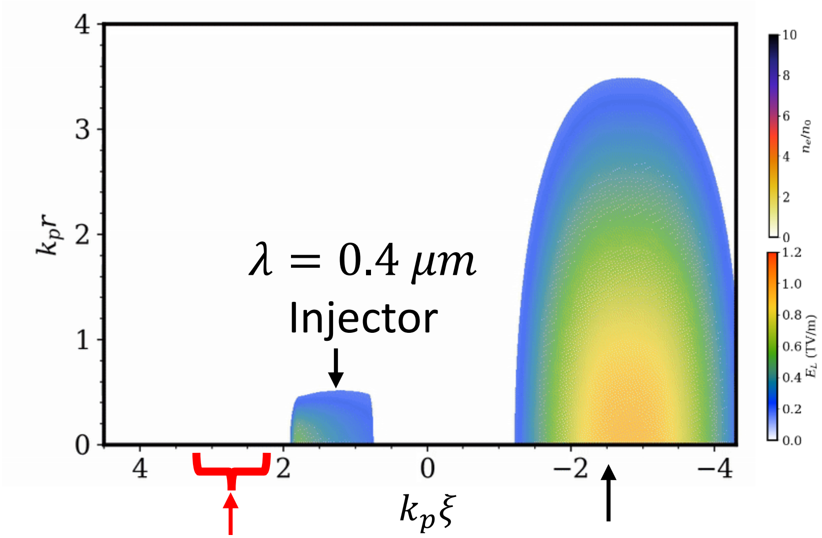
The e-beam could be produced in an LWFA stage, then accelerated in a PWFA stage

Injection stage

$n_0 = 2 \times 10^{16}\ cm^{-3}$



$\lambda = 0.4\ \mu m$
Injector

Injected beam

$\lambda = 9.2\ \mu m$
Driver

Injected beam

$Q = 220\ pC$

Before acceleration

$\epsilon_x = 170\ nm \cdot rad$

$\epsilon_y = 76\ nm \cdot rad$

$\Delta\mathcal{E}/\mathcal{E} = 6\%$

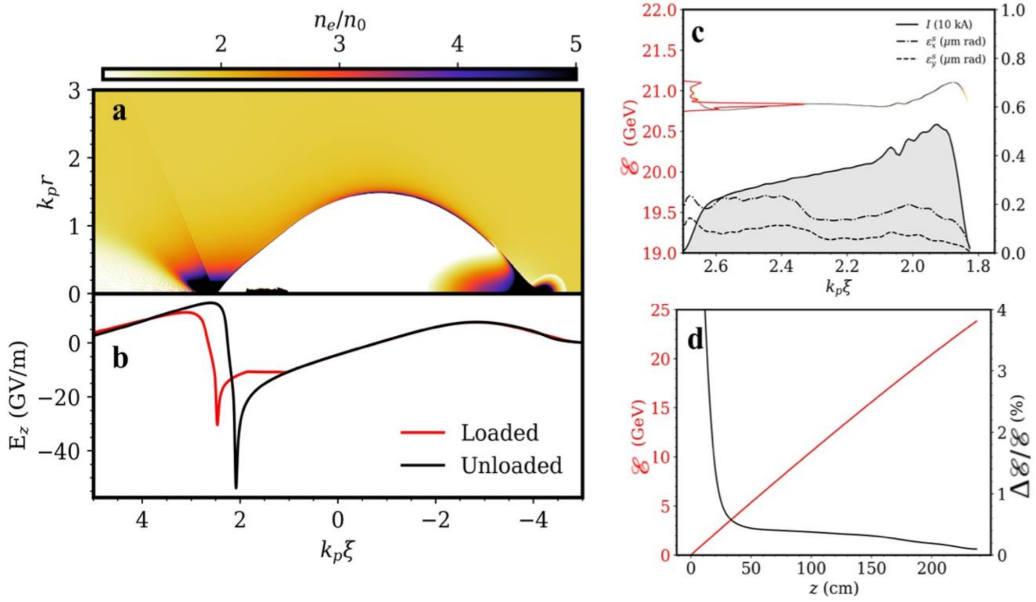
After acceleration

$\epsilon_x = 189\ nm \cdot rad$

$\epsilon_y = 80\ nm \cdot rad$

$\Delta\mathcal{E}/\mathcal{E} < 1\%$

Acceleration stage (20 GeV)



Instead of staging this process, can we inject and ideally load a beam in one stage?

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A. Jain, *et al.*, Phys. Rev. Research 8.2 (2026): 023213.

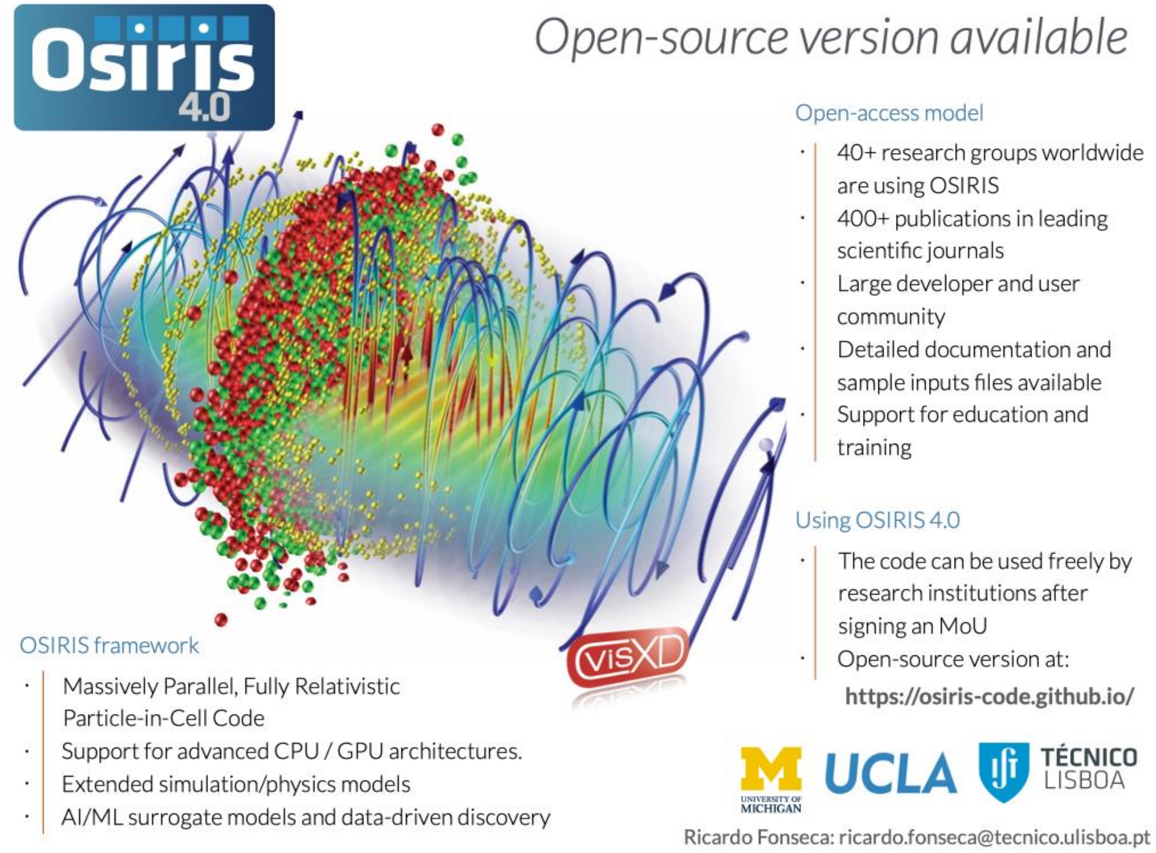
We want to verify this method with an experiment

- ATF @ BNL, the only lab with a TW-class CO_2 laser, requires upgrades to enable sub-ps pulse (ongoing)
- BELLA at LBNL could be well-suited for pursuing an experiment based on this method, before upgrades at BNL complete
- Two systems: hundred-terawatt (HTW) and petawatt (PW) with $\boldsymbol{\lambda_0 = 800\ nm}$ laser. The injector would need to be frequency-tripled ($\boldsymbol{\lambda_i = 267\ nm}$)

	BELLA HTW System	BELLA PW System
P	$\sim$ 50 TW	$\sim$ 1PW
λ_0	800 nm	800 nm
τ_{FWHM}	$\sim$ 40 fs	$\sim$ 40 fs

- In this presentation, we will show preliminary results with some idealized scenarios based on these parameters

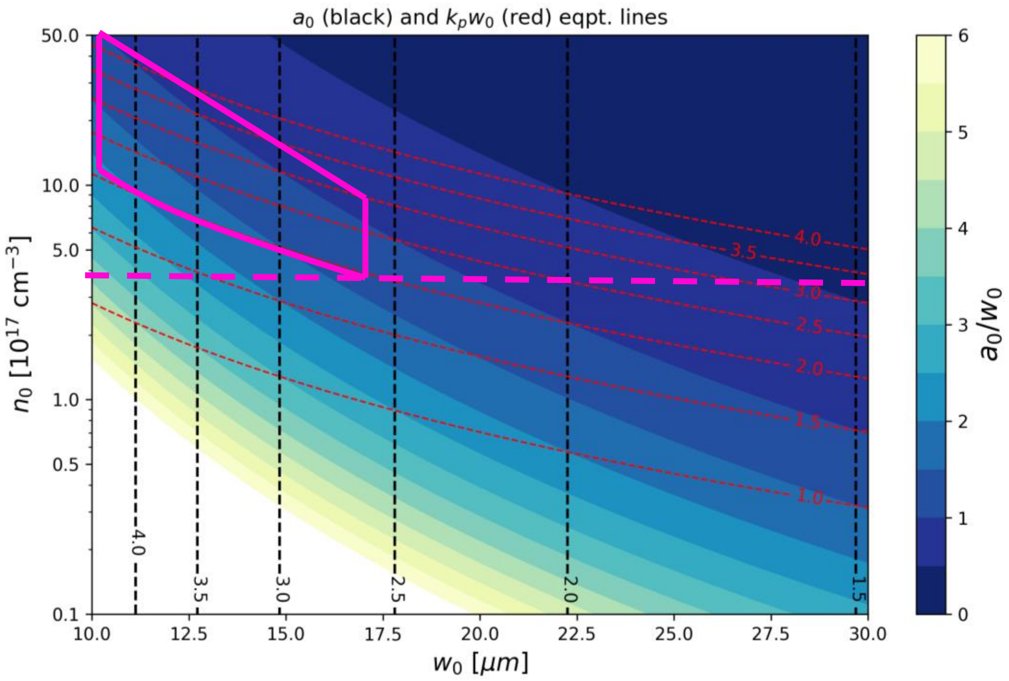
Particle-in-cell simulations drive our studies



- OSIRIS is our primary PIC code for studying flying focus lasers with ionization physics
- Using Quasi-3D geometry with $m = 0, 1$ azimuthal modes

This material is based resources of NERSC facility, operated under Contract No. DE-AC02-5CH11231.

Choosing optimal driver parameters



- To drive a nonlinear wake while not ionizing some chosen gas

$$2 \leq a_0 < 3$$

- Trapping mechanics are optimized for large potentials

$$\psi(\xi, r) \approx \psi_{max} - \frac{\chi}{4}\xi^2 - \frac{r^2}{4}$$
$$\psi_{max} \propto R_b^2$$

Since the size of the wake scales with the laser spot size, we want

$$2 \leq k_p w_0$$

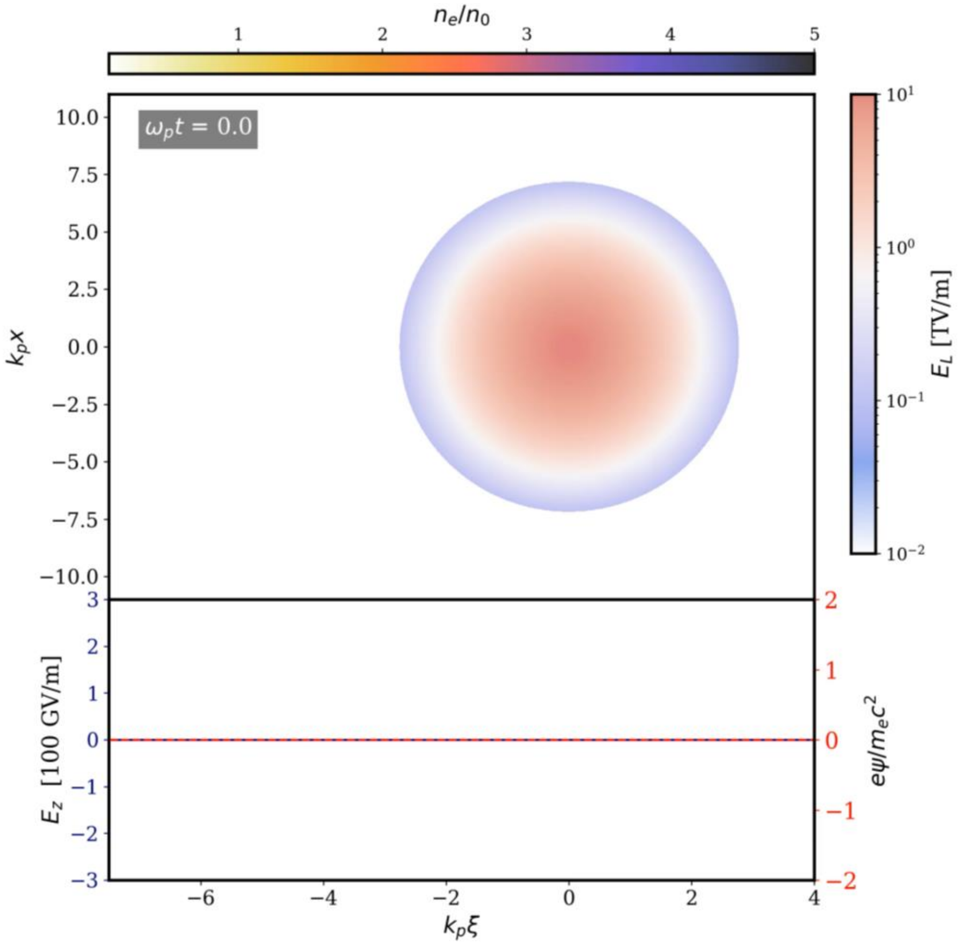
- To keep the blown out structure of the wake, we require sufficient ponderomotive force and pulse length:

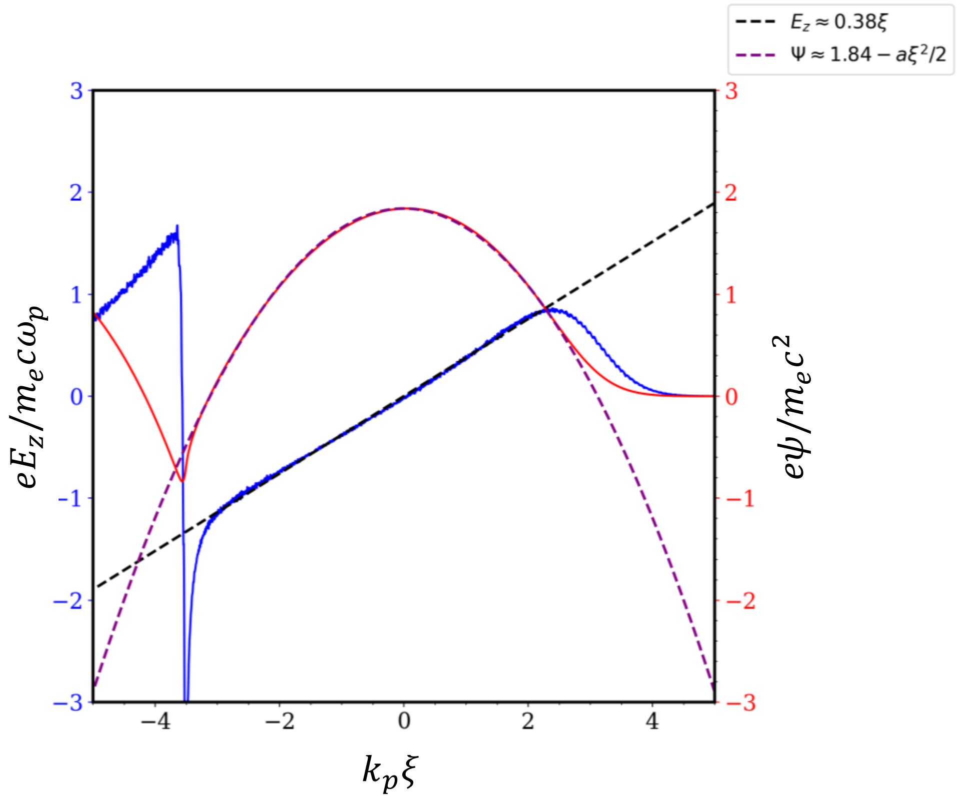
$$F_p \propto (a_0/k_p w_0)^2 \Rightarrow (a_0/k_p w_0) > 1$$
$$1 < k_p c\tau < k_p w_0$$

See: Navid Vafaei-Najafabadi WG1 Tue 5:20!

HTW laser can drive a nonlinear wake at $n = 1e18\ cm^{-3}$

$$n = 1e18\ cm^{-3}, w_0 = 17.2\ \mu m, k_p w_0 = 3.2, a_0 = 2.6, \tau_{FWHM} = 38fs, k_p c\tau = 2.1$$





<u>wake properties</u>

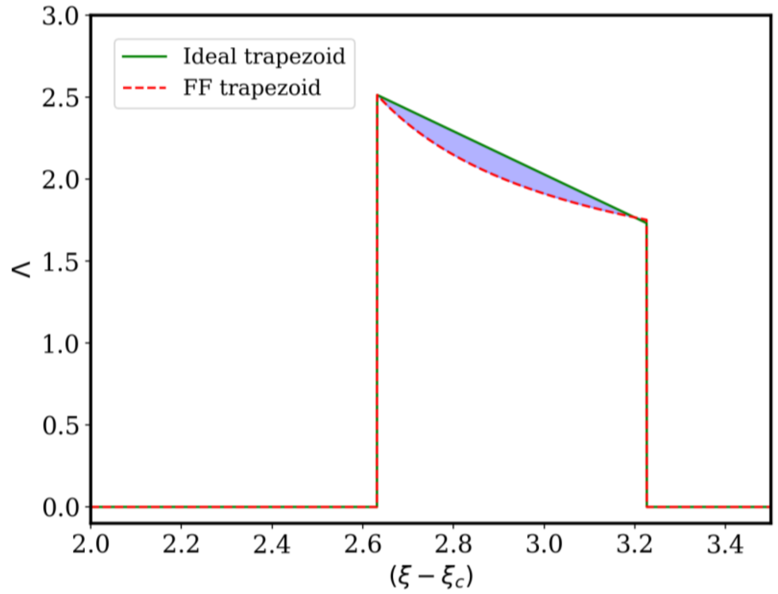
$$\frac{\chi}{2} \approx 0.38$$
$$\psi_{max} \approx 1.85$$
$$k_p R_b \approx 2.7$$

Designing the FF injector for the HTW bubble

Ionization levels	$a_0(\lambda_0 = 800\ nm)$	$a_0(\lambda_0 = 267\ nm)$
O^{5+} -> O^{6+}	0.171	0.063
O^{6+} -> O^{7+}	3.051	1.141
O^{7+} -> O^{8+}	3.742	1.385

- Loading the beam where $E_z \approx 96\ GV/m$
- To achieve ideal beam loading, we match the initial linear charge density Λ_0 and choose a viable combination of w_f, v_f

$$\Lambda_0 = \sqrt{\left(\frac{E_t}{\chi}\right)^4 + \left(\frac{R_b}{2}\right)^4} = \frac{w_f^2}{4} e n_g \frac{v_f}{|v_f - 1|} \frac{\xi_t}{\sqrt{\xi_t^2 - 4/\chi}}$$



Injector

a_0	1.2
L_f	$483\mu m \approx 5 z_R$
w_f	$3\ \mu m$
v_f/c	1.011

Expected beam

Q	$182\ pC$
Δz	$3.2\ \mu m$
ϵ_x	$1215\ nm \cdot rad$
ϵ_y	$86\ nm \cdot rad$

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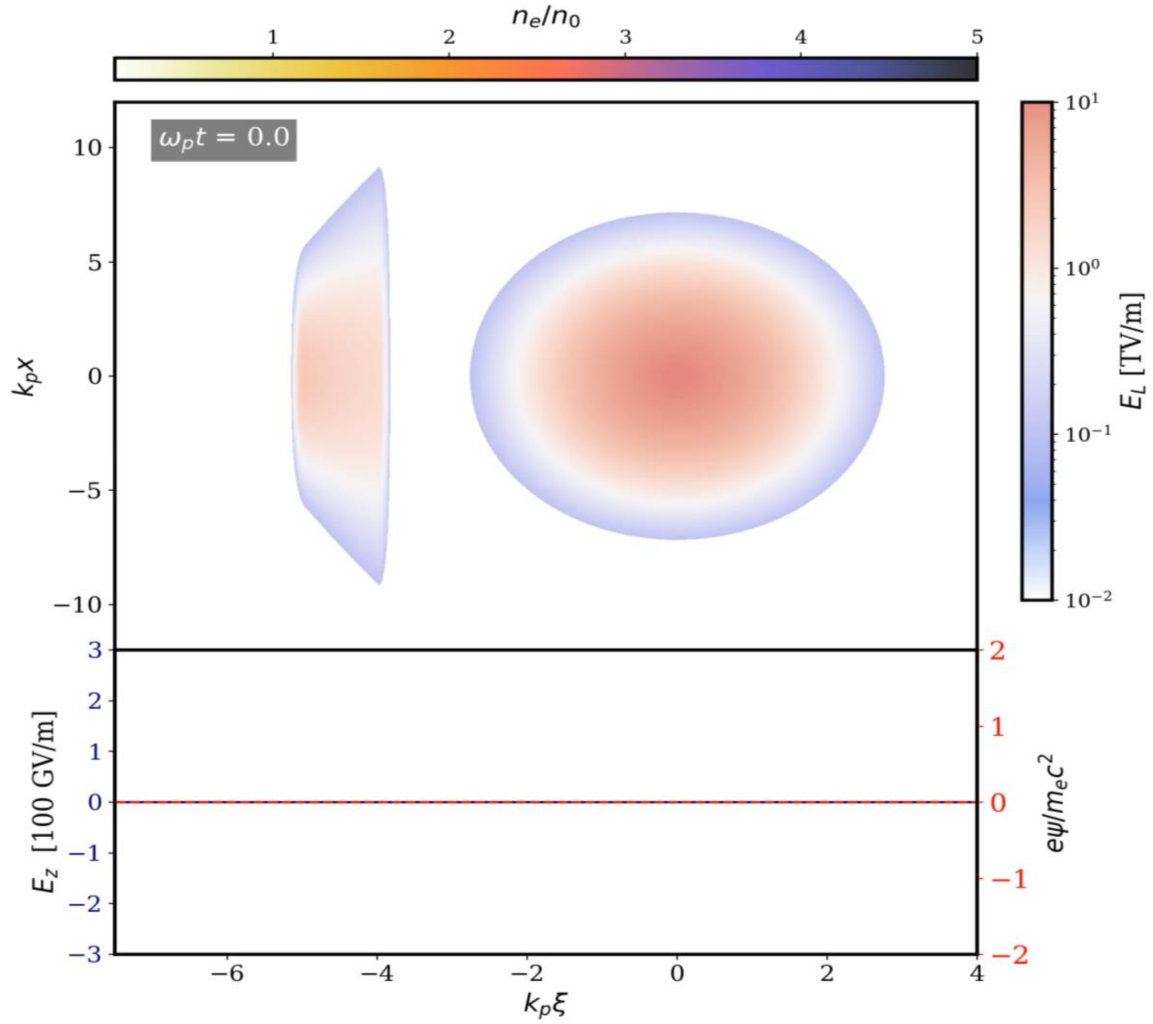
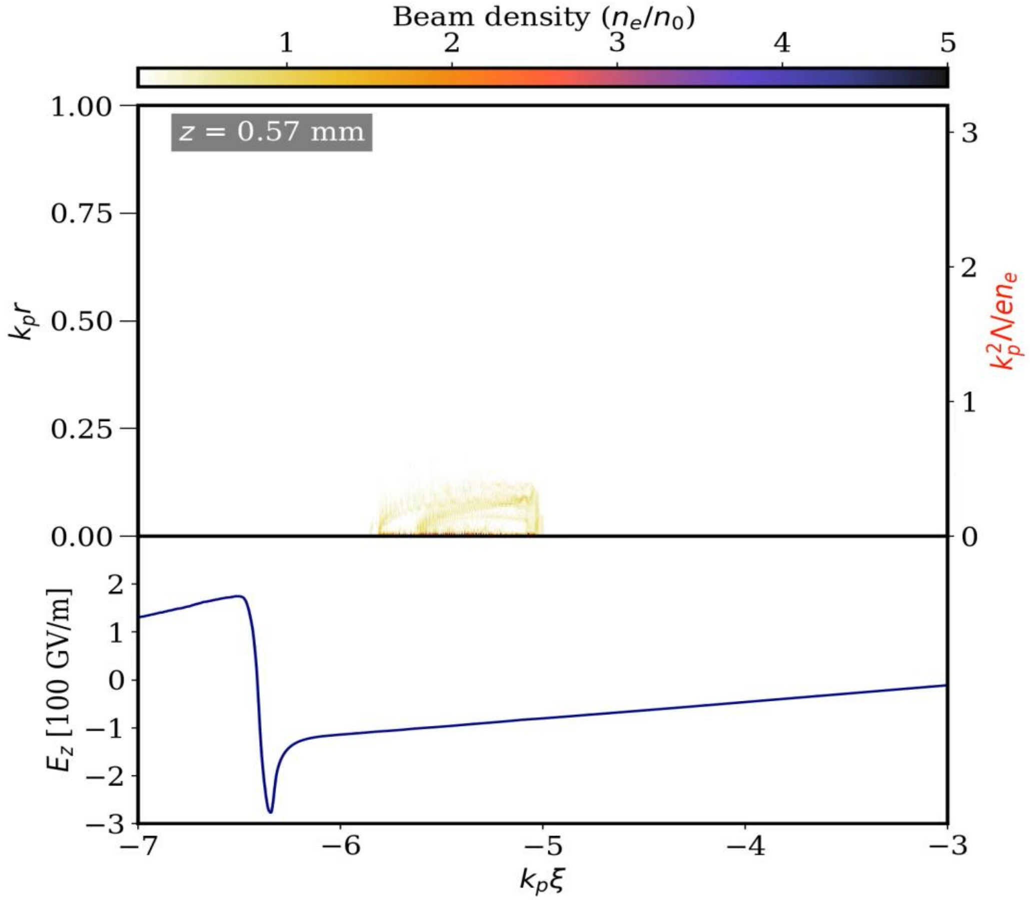
The beam generated has trouble flattening the field





We are observing an overloading effect, which will harm the energy spread!

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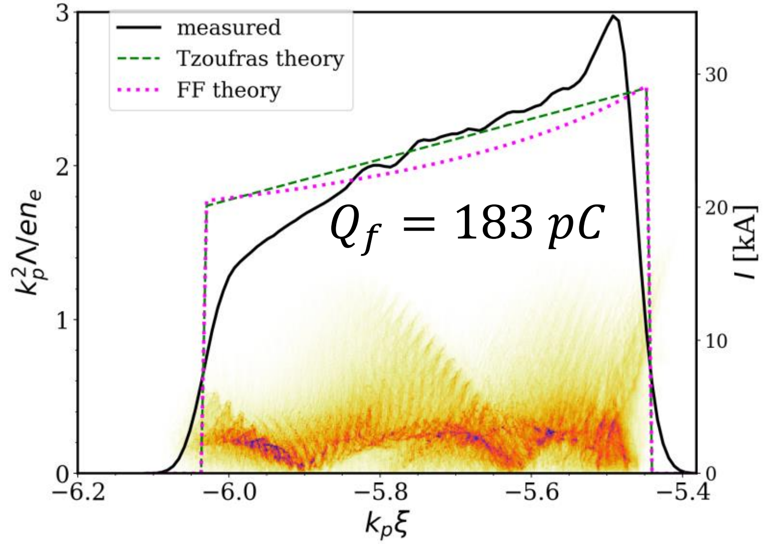
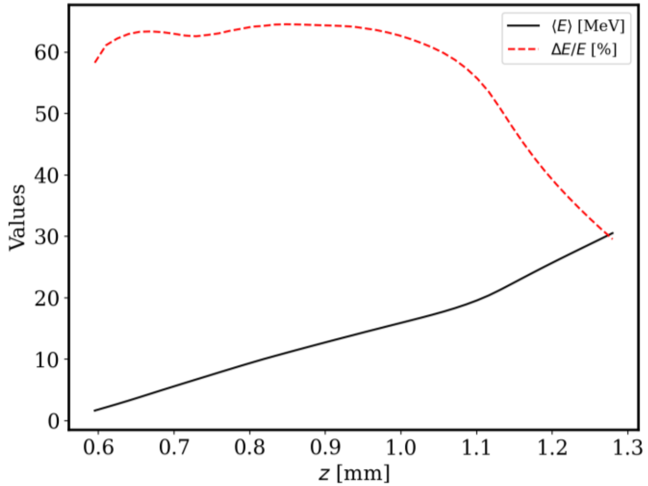
The beam has good shape and emittances but poor energy spread



The injector creates a nice trapezoid which has reasonable agreement with theory. The total charge is consistent with calculations.

Energy spread evolution

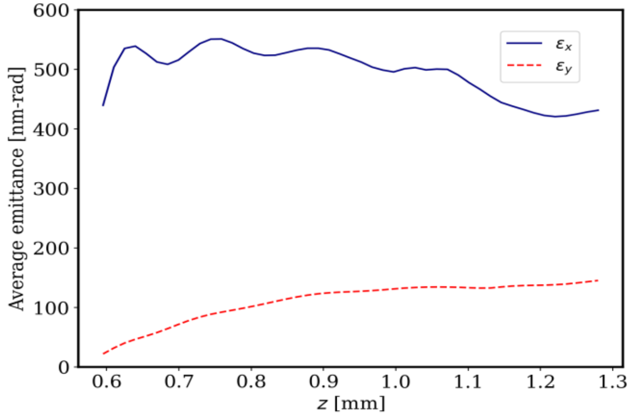


Average energy and energy spread once beam is fully injected:

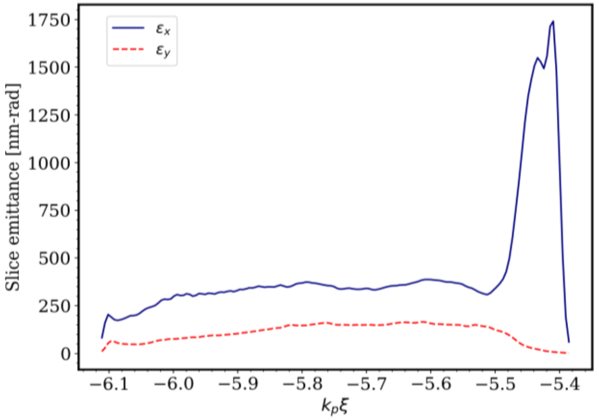
$$\langle E \rangle = 30.5\ MeV$$

$$\frac{\Delta E}{E} = 29.6\%$$

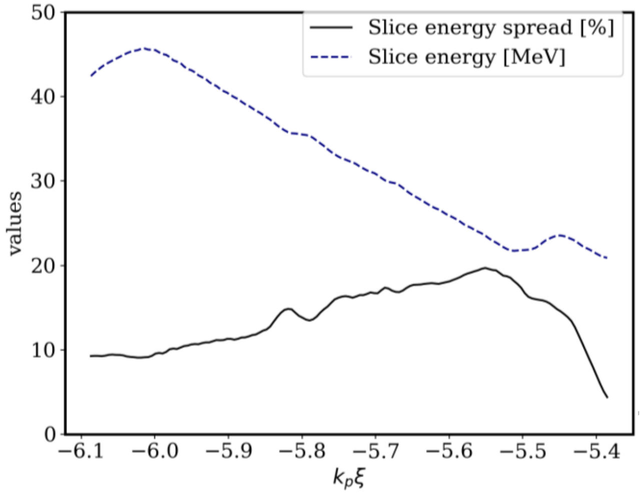
Emittance evolution



Last slice emittance



Last slice energy spread



Average emittances once beam is fully injected:

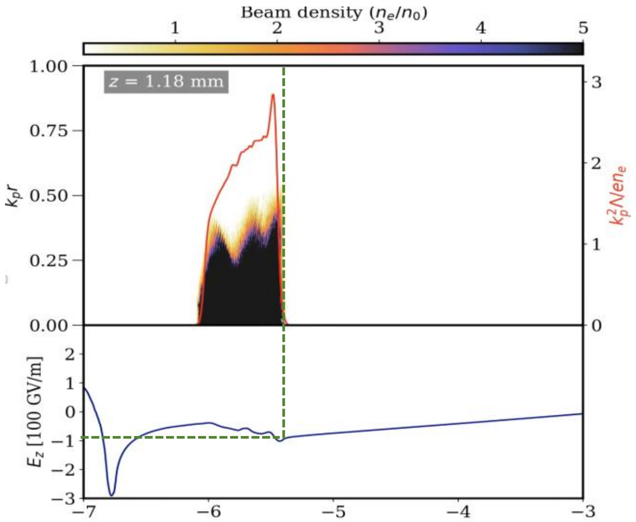
$$\epsilon_x = 431\ nm \cdot rad, \epsilon_y = 145\ nm \cdot rad$$

Why is our beam not ideally loading?

(1) our estimated wake properties are incorrect

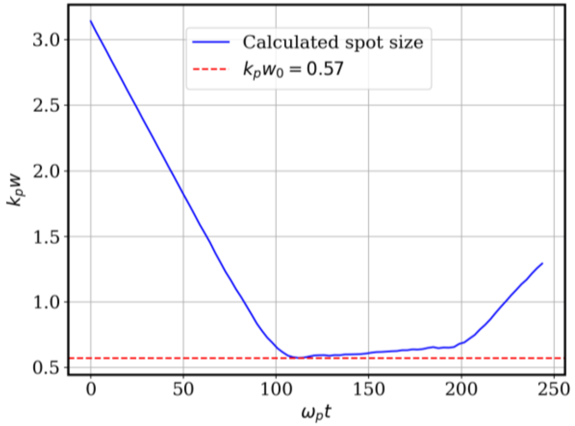
$$\Lambda_0 = \sqrt{\left(\frac{E_t}{\chi}\right)^4 + \left(\frac{R_b}{2}\right)^4}\, , Q_{max} = \frac{\chi \pi R_b^4}{16 E_t}$$

Our R_b may be over-estimated, meaning we designed the beam with too much charge



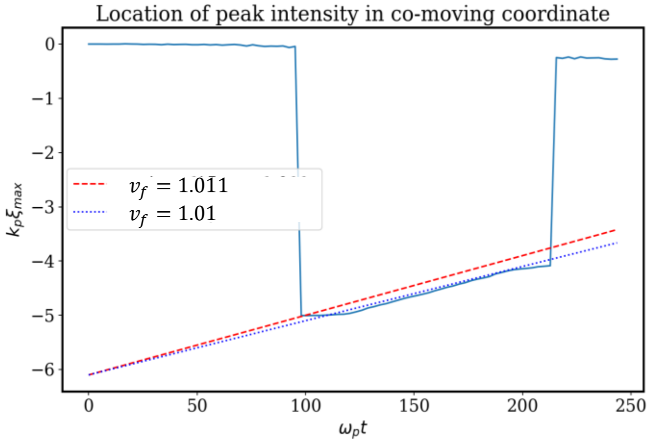
Our load field E_t and position ξ_t appear correct with our inputs and model

(2) The injector properties in simulations do not match expected values



w_0 is not constant over the focus range

Measured v_f doesn't exactly match simulation input



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Potential parameters for using a PW driver

- Using the PW system would allow us to operate at higher densities with laser bubbles, though higher emittances are expected

$n_0 = 1.6e17\ cm^{-3}$

Driver parameters

$\lambda_0 = 800\ nm$

$w_0 = 36\ \mu m$

$a_0 = 2.7$

$\tau_{fwhm} > 40\ fs$

Injector parameters

$\boldsymbol{a_0}$	1.2
$\boldsymbol{L_f}$	$860\ \mu m$
$\boldsymbol{w_f}$	$7.5\ \mu m$
$\boldsymbol{v_f/c}$	1.01

Expected beam parameters

$\boldsymbol{Q}$	$350\ pC$
$\boldsymbol{\Delta z}$	$6.1\ \mu m$
$\boldsymbol{\epsilon_x}$	$\sim 2800\ nm \cdot rad$
$\boldsymbol{\epsilon_y}$	$\sim 220\ nm \cdot rad$

Summary of results

- Identified possible experimentally-relevant parameters to perform a flying-focus ionization injection experiment at a facility with high-power NIR lasers

- Identified main limitations with the 1st/3rd harmonic setup
  - Need relatively high a_0 to ionize gas with the injector pulse
  - Still able to achieve high charge and near-trapezoidal profile with moderate transverse emittances

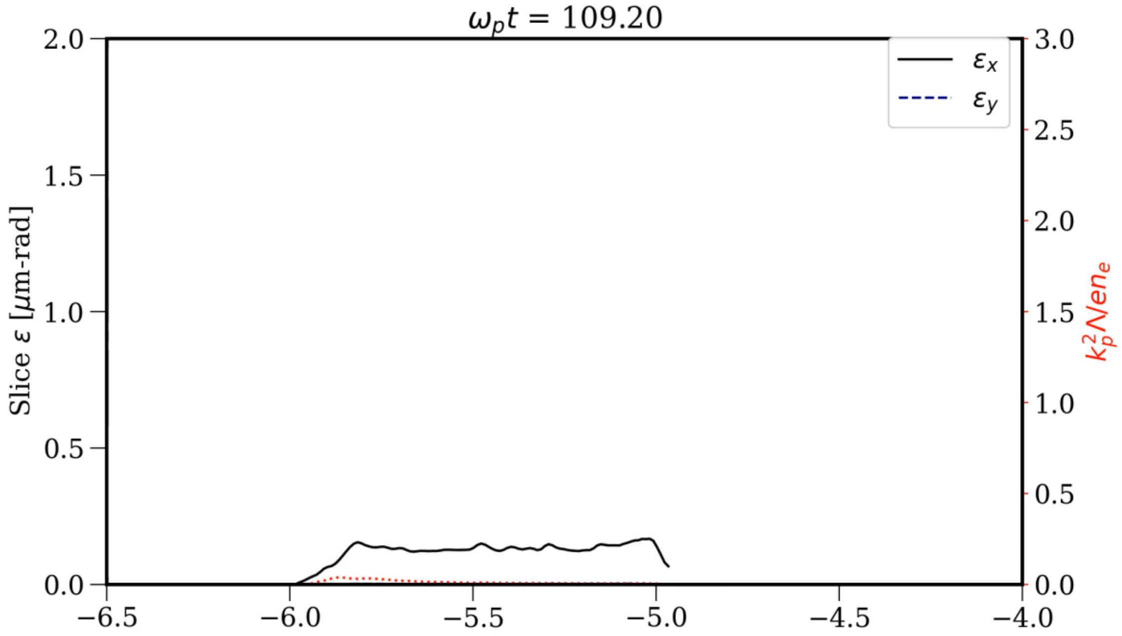
- Work is continuing on revising the setup for a HTW injection stage and simulating a PW injection stage

Thank you for listening!

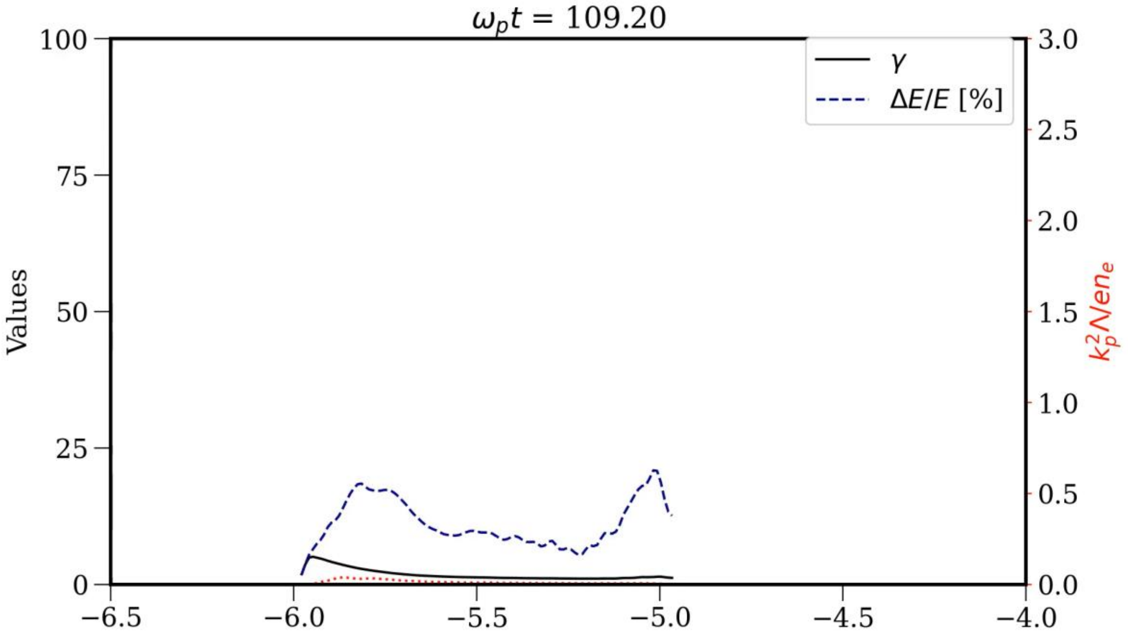
Backup slides

Backup plots

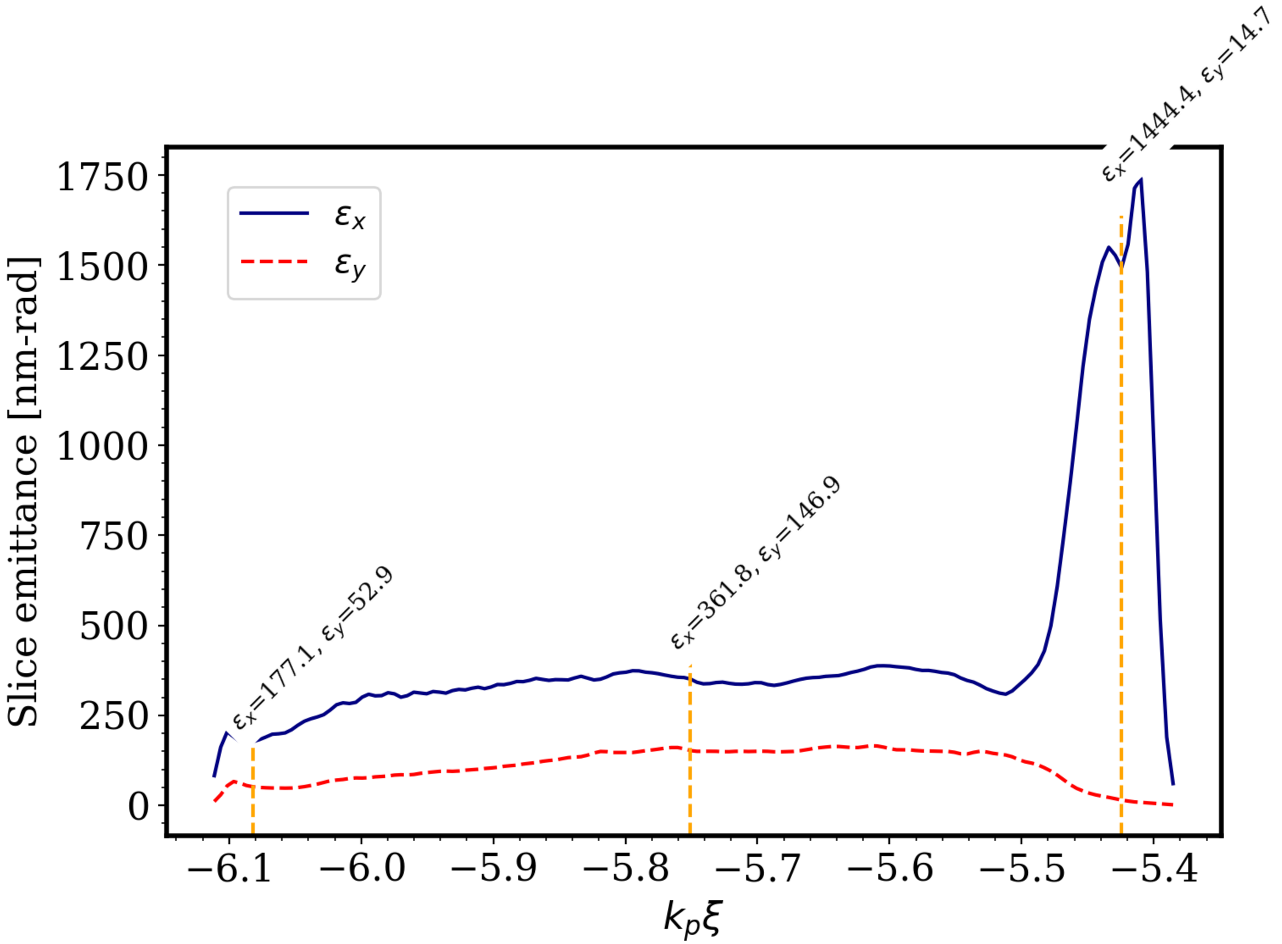
Slice emittance over time



Slice energy spread over time



Backup plots



Requirements for electron trapping with ionization injection

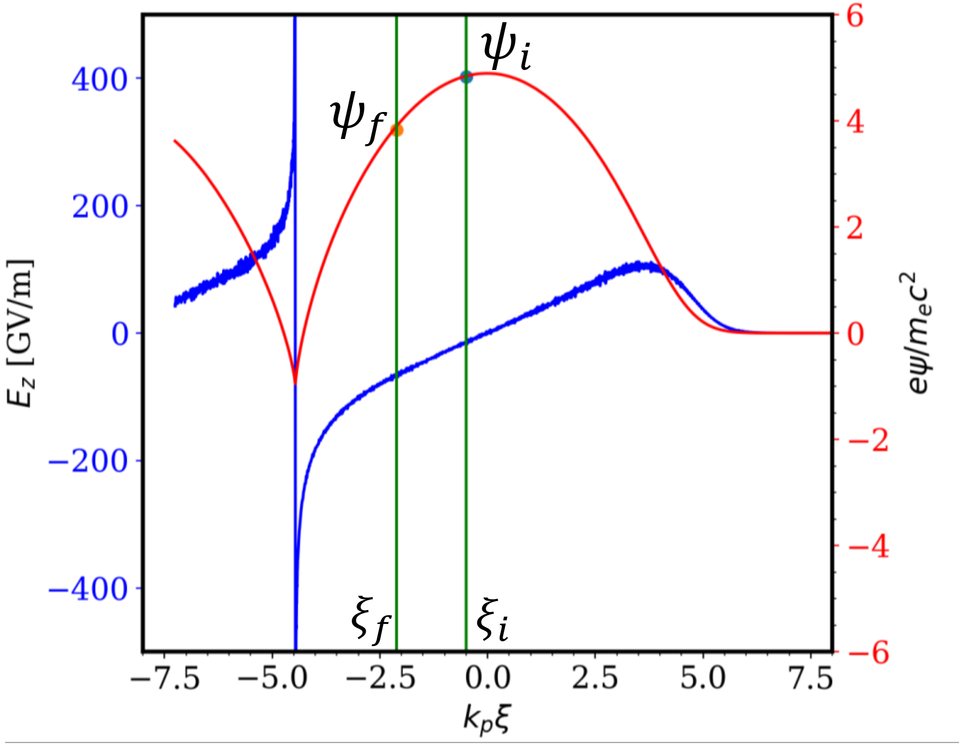
- For a particle ionized inside the bubble, it is “trapped” if:

$$\psi_f - \psi_i \lesssim -1 - \frac{\gamma_\perp}{\gamma_\phi}$$

- If $\gamma_\perp$ is small, which is determined by the injector's a_0, then the condition relaxes:

$$\psi_f - \psi_i \lesssim -1$$

- **Small a_0 for the injector is important for the trapping condition and for emittance (discussed later on)**



$$\psi_i = \psi(\xi_i)$$
$$\psi_f = \psi(\xi_f)$$

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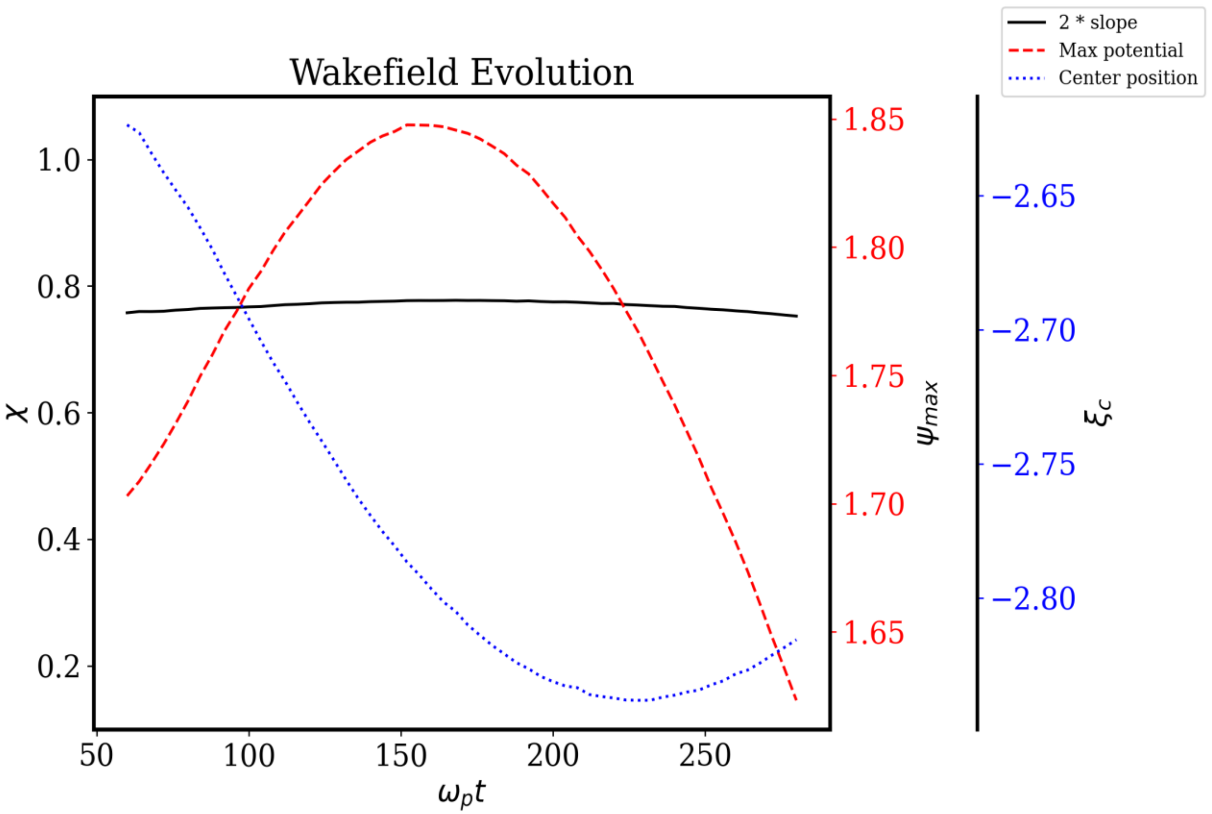
Wake evolution and trapping may affect beam profile



Trapping dynamics may impact the shape of the beam

$$-1 = \psi_f - \psi_i$$

$$\psi_f = \psi_0 - \frac{\chi}{4}\xi_f^2 - \frac{r_f^2}{4}$$

$$\psi_i = \psi_0 - \frac{\chi}{4}\xi_i^2 - \frac{r_i^2}{4}$$

Electrons are born off-axis:

$$r_i \approx 0.4, \frac{r_i^2}{4} \approx 0.04$$

FAR BEYOND

A flying-focus laser can generate a near-trapezoidal beam inside a blown-out wake

- The linear charge density of a beam generated by a flying focus laser:

$$\Lambda(\xi_f) = \frac{1}{2\pi}\frac{dQ}{dz}\frac{dz}{d\xi_i}\frac{d\xi_i}{d\xi_f}$$

$$\frac{dQ}{dz} = \frac{\pi}{2} w_i^2 (e n_g)$$

$$\frac{dz}{d\xi_i} = \frac{v_f}{|v_f - 1|}$$

(1) Amount of charge ejected from the ions by the moving focused laser. Note that $n_g \approx n_0/Z$, Z is the ion level before ionization

(2) Encompasses motion of the focus spot in the co-moving coordinate with constant v_f

- For a wake with a parabolic potential,

$$\psi(\xi_f) - \psi(\xi_i) = \frac{\chi}{4}(\xi_i^2 - \xi_f^2) = -1$$

$$\Rightarrow \frac{d\xi_i}{d\xi_f} = \frac{\xi_f}{\xi_i} = \frac{\xi_f}{\sqrt{\xi_f^2 - \frac{4}{\chi}}}$$

(3) "Compression factor" describes compression of electrons as they are trapped in an accelerating phase

FAR BEYOND

A. Jain *et al.*, Phys. Rev. Research https://doi.org/10.1103/q36y-6jqn (2026)

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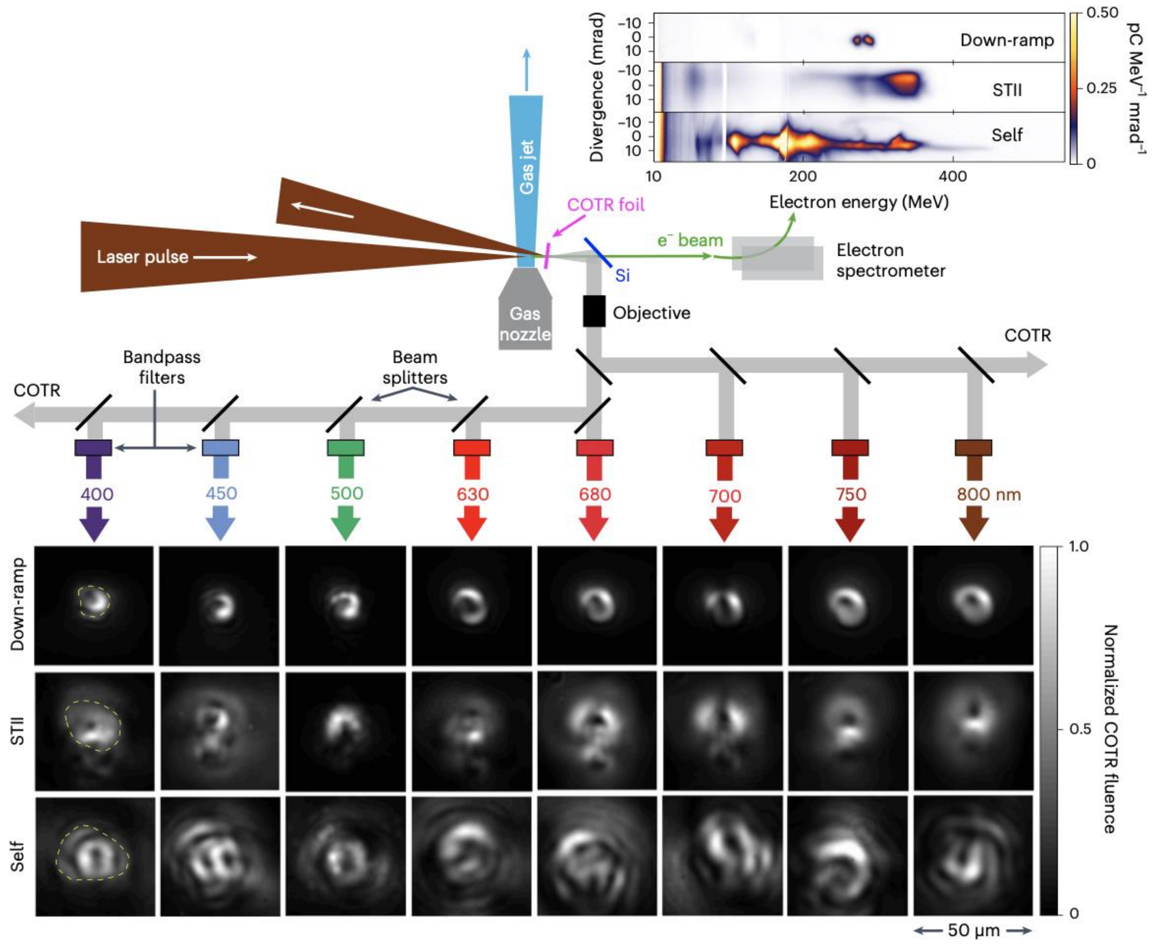
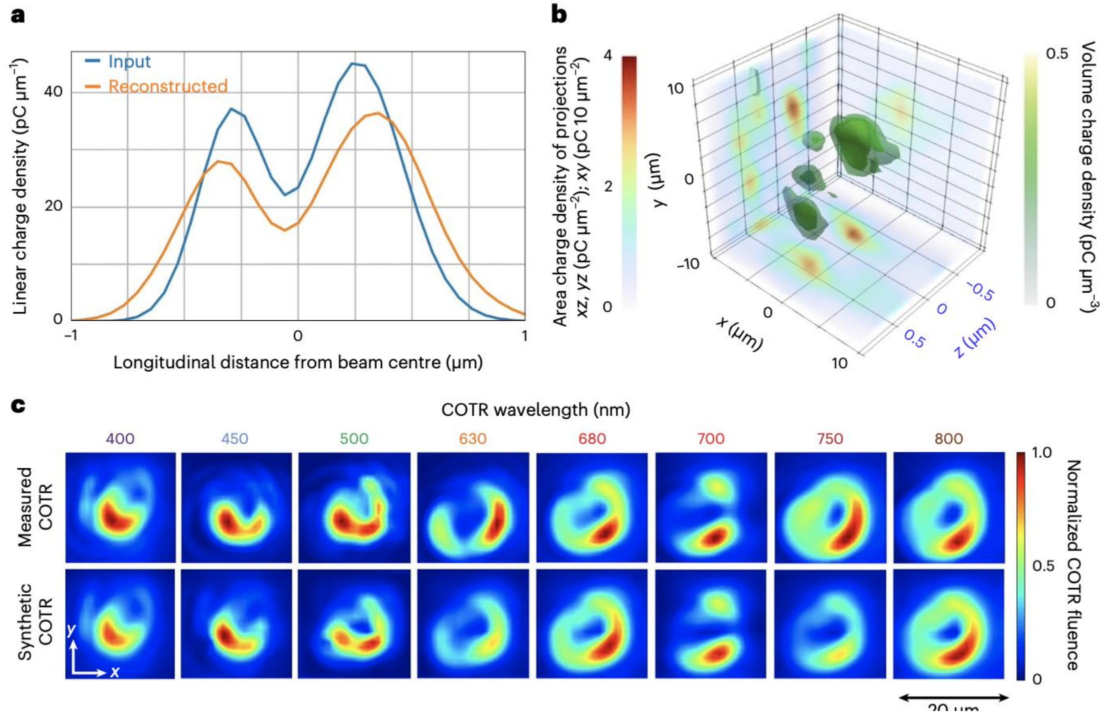
Extra Slides: Threshold Ionization a_0 calculations

Ionization levels	$\lambda_0 = 800\ nm$	$\lambda_0 = 267\ nm$
O^{5+} -> O^{6+}	0.171	0.063
O^{6+} -> O^{7+}	3.051	1.141
O^{7+} -> O^{8+}	3.742	1.385
N^{4+} -> N^{5+}	0.106	0.039
N^{5+} -> N^{6+}	2.0368	0.7649
N^{6+} -> N^{7+}	2.5577	0.9549
F^{6+} -> F^{7+}	0.258	0.094
F^{7+} -> F^{8+}	4.3476	1.6198
F^{8+} -> F^{9+}	5.1905	1.9258
Ne^{7+} -> Ne^{8+}	0.37	0.134
Ne^{8+} -> Ne^{9+}	5.9584	2.2128
Ne^{9+} -> Ne^{10+}	6.9893	2.5867

Ionization levels	$\lambda_0 = 800\ nm$	$\lambda_0 = 267\ nm$
Ar^{13+} -> Ar^{14+}	1.9428	0.6989
Ar^{14+} -> Ar^{15+}	2.3128	0.8309
Ar^{15+} -> Ar^{16+}	2.5027	0.8969
Ar^{16+} -> Ar^{17+}	>10	>10
Xe^{24+} -> Xe^{25+}	1.3839	0.485
Xe^{25+} -> Xe^{26+}	1.4609	0.5119
Xe^{26+} -> Xe^{27+}	4.0236	1.4209
Xe^{27+} -> Xe^{28+}	4.2926	1.5148
Kr^{23+} -> Kr^{24+}	2.2658	0.7989
Kr^{24+} -> Kr^{25+}	2.6557	0.9369
Kr^{25+} -> Kr^{26+}	2.7817	0.9799
Kr^{26+} -> Kr^{27+}	>10	4.9525
Kr^{27+} -> Kr^{28+}	>10	>5

Current profile monitor: COTR





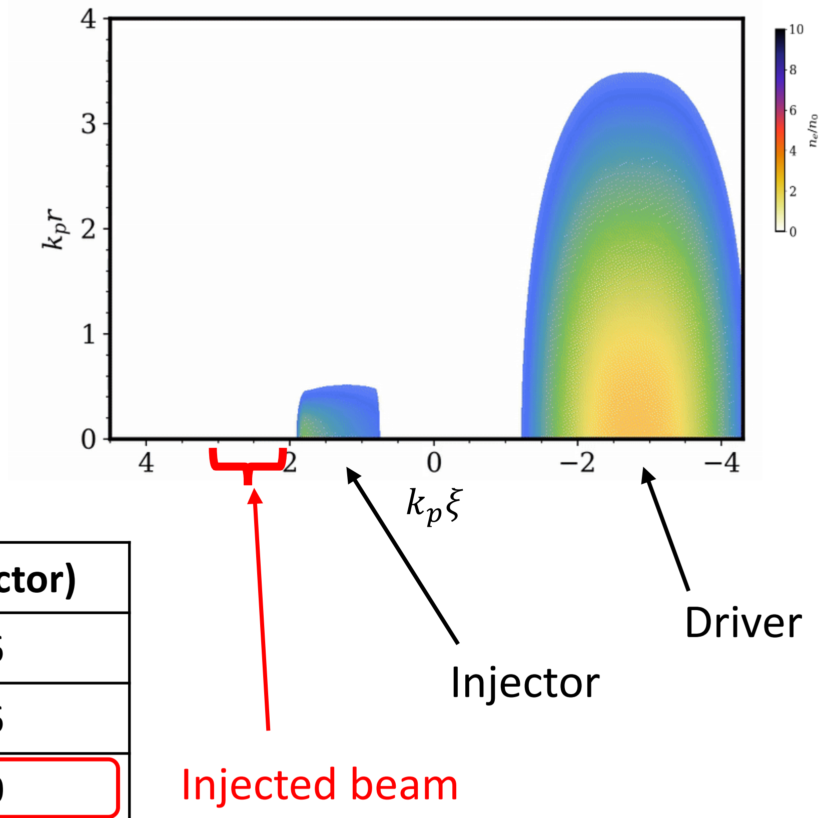
M. LaBerge *et al.,* Nat. Photon. 18, 952–959 (2024)

Backup: details of previous work

$n_0 = 2e16\ cm^{-3}$

Driver	**Injector**
$\lambda_0 = 9.2\ \mu m$	$\lambda_0 = 0.4\ \mu m$
$\tau = 250\ fs$	$\tau = 20\ fs$
$w_0 = 105\ \mu m$	$w_f = 8.6\ \mu m$
$a_0 = 2.7$	$a_0 = 0.17$
	$\beta_f = 1.04$

Ion. level	a_T (Driver)	a_T (Injector)
Kr^{7+} -> Kr^{8+}	1.87	0.06
Kr^{8+} -> Kr^{9+}	3.10	0.16
Kr^{9+} -> Kr^{10+}	3.78	0.20
Kr^{10+} -> Kr^{11+}	4.51	0.23



Generated beam

$Q = 220\ pC$

$\epsilon_x = 170\ nm \cdot rad$

$\epsilon_y = 76\ nm \cdot rad$

A. Jain, *et al.*, Phys.l Rev. Research 8.2 (2026): 023213.

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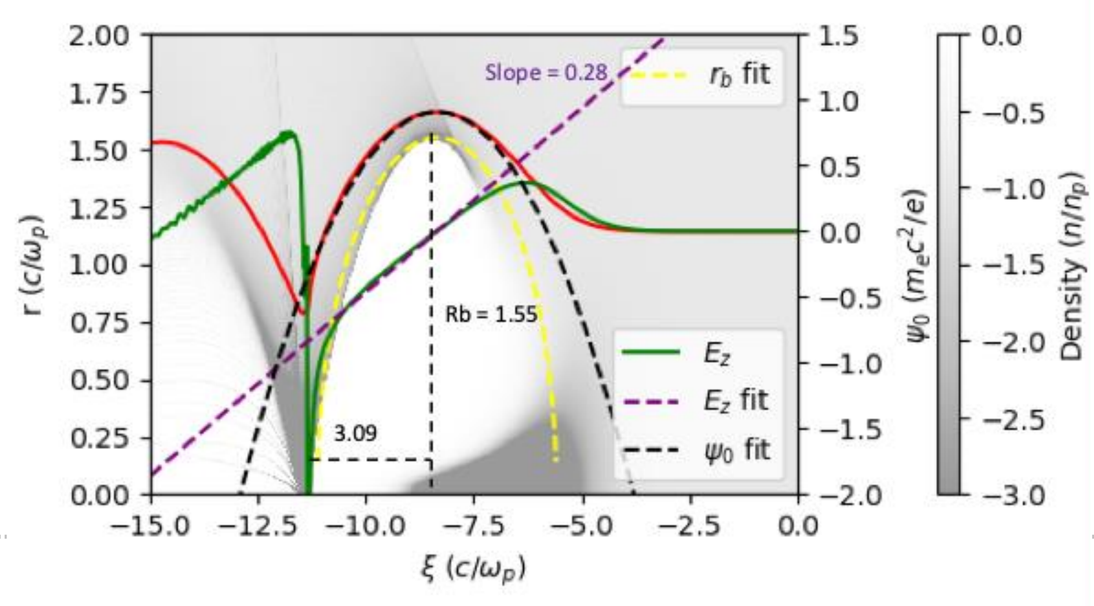
Extra Slides: 3D Nonlinear Theory

- In the "small bubble" regime,

$$R_b^2 \approx r_b(\xi)^2 + \chi^2\xi^2$$
$$E_z = -\frac{\chi}{2} r_b r_b' \approx -\frac{\chi}{2}\xi$$



Jiayang Yan, PhD Thesis (2024)