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# Nanoscale Electron Bunching and Spiraling in Laser-Triggered Ionization Injection in Plasma Accelerator


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PICKSC

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Aug 2th, 2016

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# Ionization Injection

- 2007, E. Oz: an electron beam
- 2010, A. Pak: a laser pulse

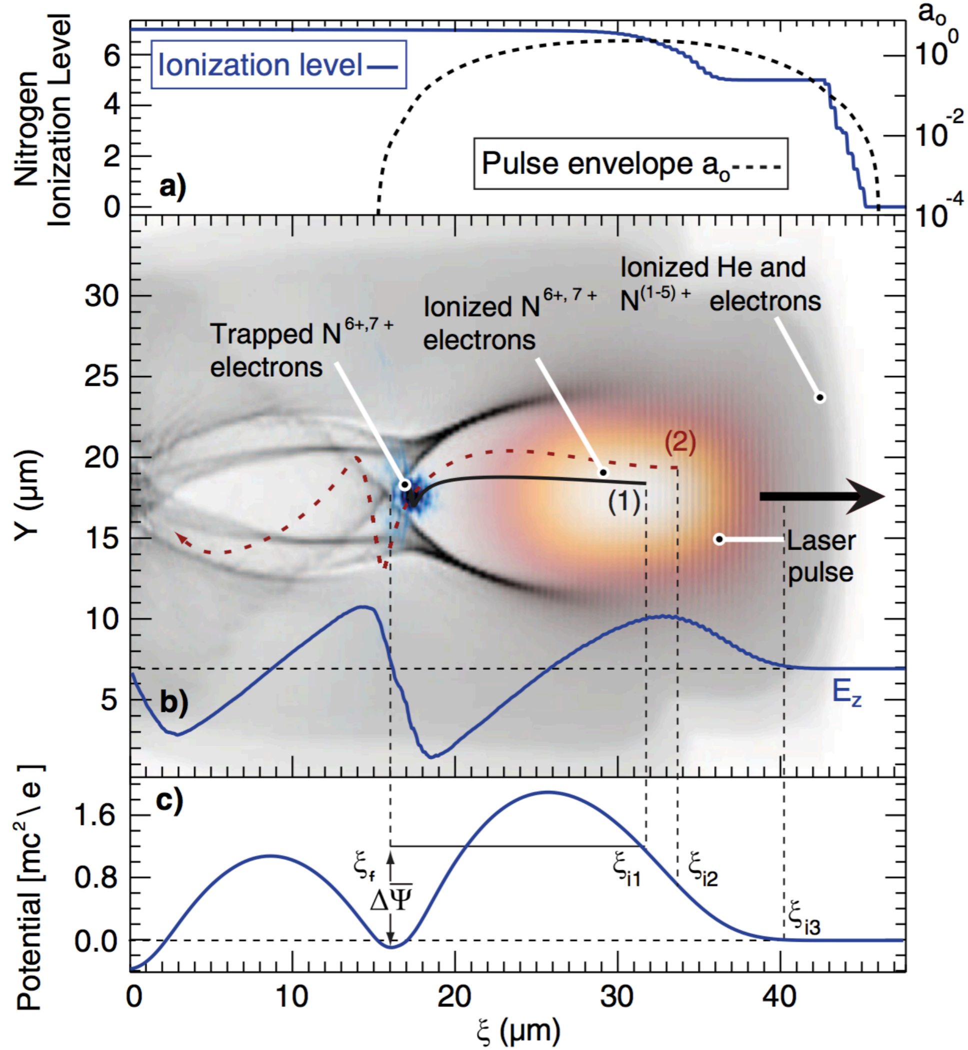
Quasi-static approximation:

$$\gamma - \frac{v_\phi}{c} p_z - \psi = \mathrm{Const}$$

Injection condition:

$$\psi - \psi_i = -1 + \sqrt{1 + p_x^2 + p_y^2}/\gamma_\phi$$

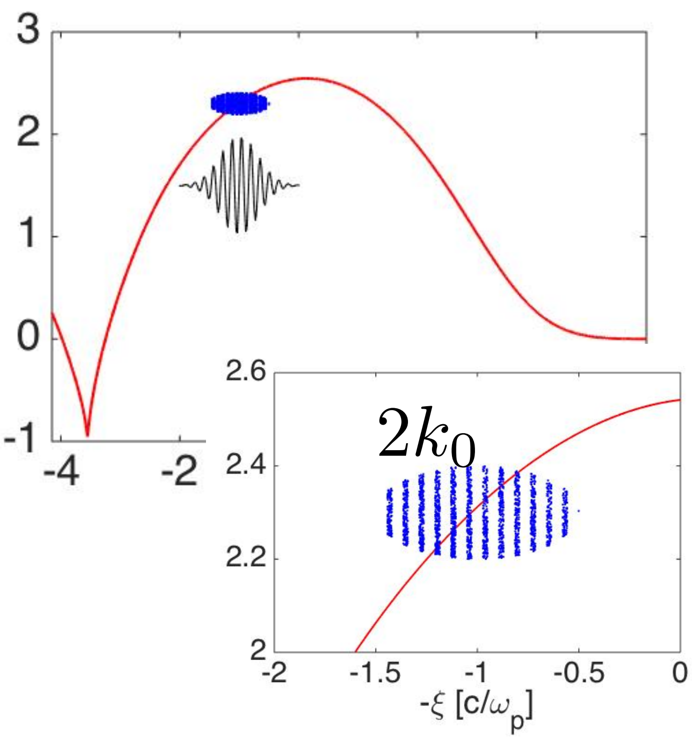
$$\text{where } \psi \equiv (e/mc^2)[\phi - (v_\phi/c) A_z]$$




E. Oz et al., PRL 98, 084801 (2007); A. Pak, et al., PRL 104, 025003 (2010)

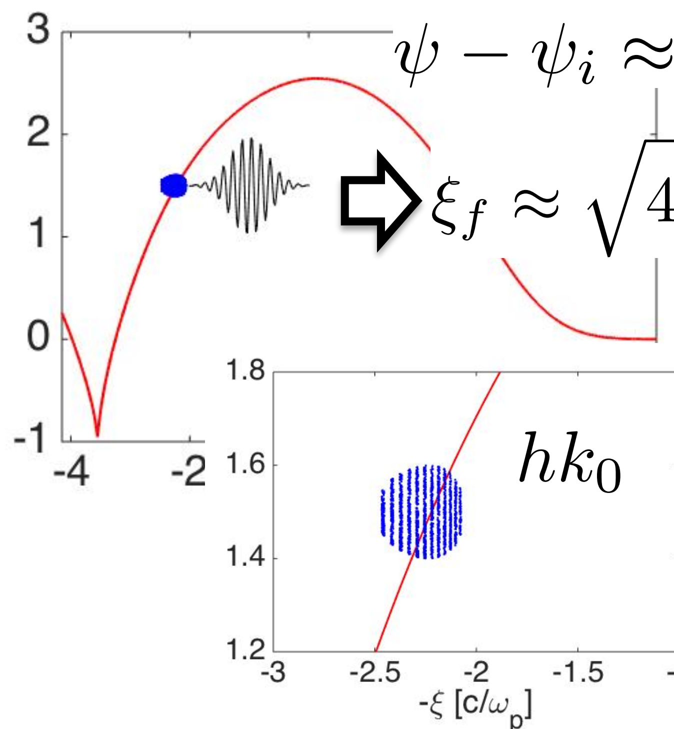
# Intrinsic discretization of charge in laser-triggered ionization injection

## Tunneling Ionization




$$\theta = k_0(ct - z) = k_0\xi$$

## Injection




$$\psi - \psi_i \approx -1$$

$$\Rightarrow \xi_f \approx \sqrt{4 + \xi_i^2}$$

$$h = \frac{2\sqrt{4 + \xi_i^2}}{|\xi_i|}$$

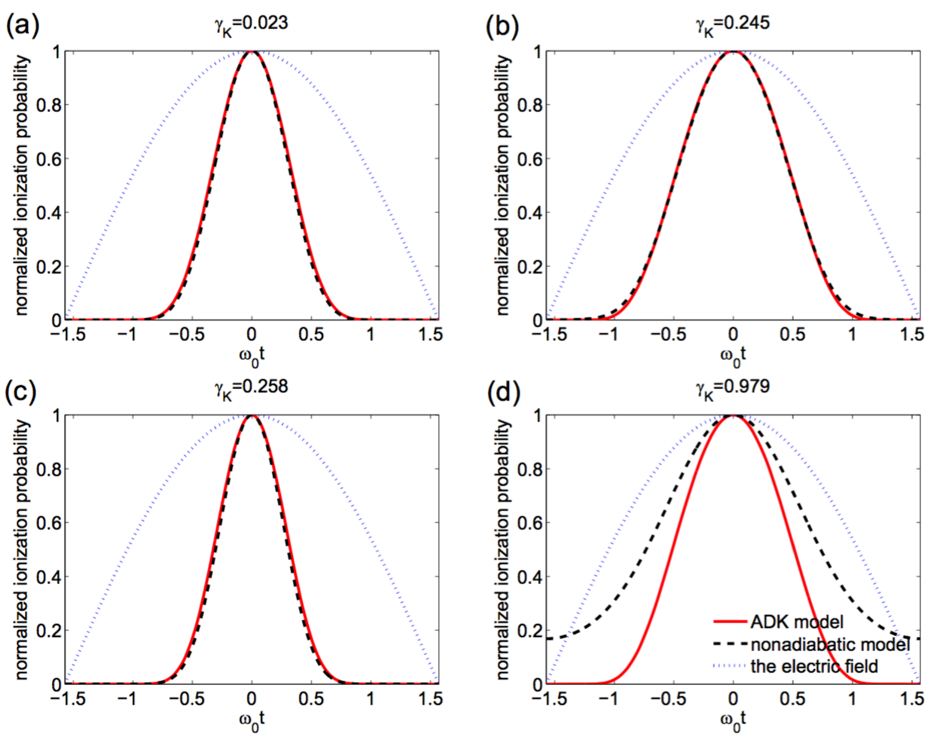
E. Oz et al., PRL 98, 084801 (2007); A. Pak, et al., PRL 104, 025003 (2010);…

# The photoionization process

- The Keldysh parameter $\gamma_K = \sqrt{I_p/2U_p}$,

➢ $\Upsilon_K$ << 1, tunneling ionization, ADK model, $w \propto \exp\left[-\frac{2(2I_p)^{3/2}}{3E_0}\right]$

➢ $\Upsilon_K$ >> 1, multiphoton process, $w \propto E_0^{2K}$




| Parameters | Case A | Case B | Case C | Case D |
|---|---|---|---|---|
| Laser wavelength $\lambda_0$ [nm] | 800 | 800 | 400 | 200 |
| Normalized laser vector potential $a_0$ | 2.0 | 0.04 | 0.09 | 0.01 |
| The atoms or ions | $N^{5+}$ | He | $O^{5+}$ | He |
| IP (eV) | 552 | 24.6 | 138 | 24.6 |
| $\gamma_K$ | 0.023 | 0.245 | 0.258 | 0.979 |

$$\theta = k_0(ct - z)$$

N B Delone, V P Krainov, Physics-Uspekhi, 41 (5) 469-485 (1998); V S Popov, Physics-Uspekhi 47 (9) 855-885 (2004); L V Keldysh, Zh. Eksp. Teor. Fiz 47, 1964 (1945); M V Ammosov, N B Delone, V P Krainov, Sov. Phys. JETP, 64, 1191 (1986); G L Yudin, M Y Ivanov, Phys. Rev. A, 64, 013409 (2001).

# The injection process in ionization injection

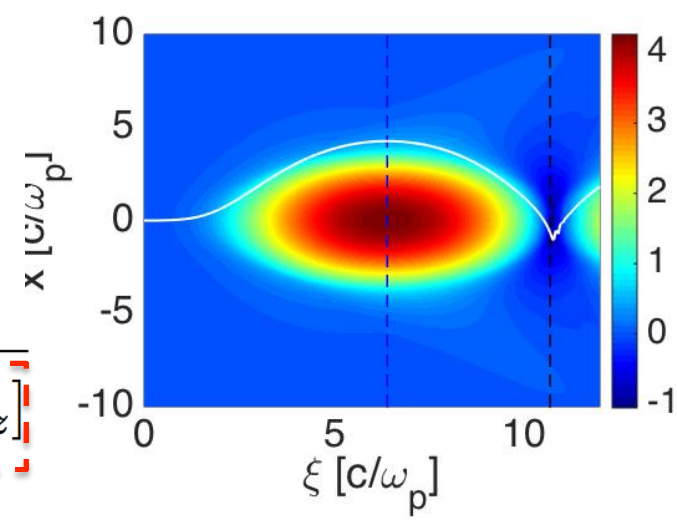
- With the quasi-static approximation ( $\xi \equiv v_\phi t - z$ ),

$$\gamma - \frac{v_\phi}{c} p_z - \psi = \text{Const} \quad \text{where } \psi \equiv (e/mc^2)[\phi - (v_\phi/c)A_z]$$

- Inside the nonlinear blowout wake,

$$\psi(\xi, r) = \frac{r_b^2(\xi) - r^2}{4}$$

$$r_b(\xi) = \sqrt{r_m^2 - \xi^2}$$




$$\xi = \sqrt{4 + \xi_i^2 + \boxed{r_i^2 - r^2} - \boxed{4\left[\gamma - (v_\phi/c)p_z\right]}}$$

$$\xi \approx \sqrt{4 + \xi_i^2}$$

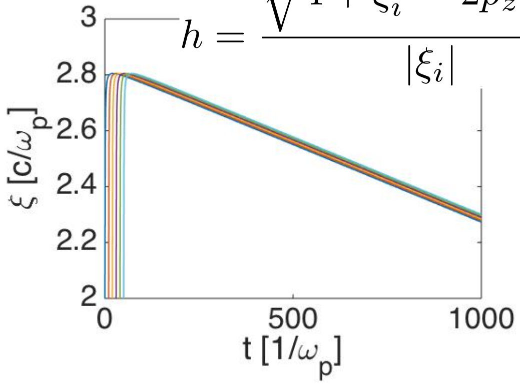
# Intrinsic discretization of charge: 1D analysis

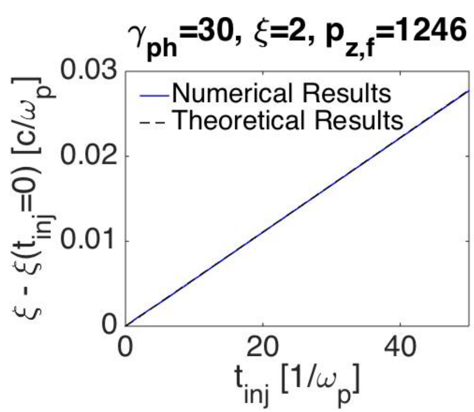
- 1D analysis: $\xi = \sqrt{4 + \xi_i^2 - 4\left(\gamma - \beta_{ph} p_z\right)}$

$$\approx \sqrt{4 + \xi_i^2 - 2p_z \left(\frac{1}{\gamma_{ph}^2} + \frac{1}{p_z^2}\right)}$$

  - For the laser driver case, when $p_z \gg \gamma_{ph}$ $\quad \xi \approx \sqrt{4 + \xi_i^2 - \frac{2p_z}{\gamma_{ph}^2}} - \frac{\Delta p_z}{\gamma_{ph}^2 \sqrt{4 + \xi_i^2 - 2p_z/\gamma_{ph}^2}}$

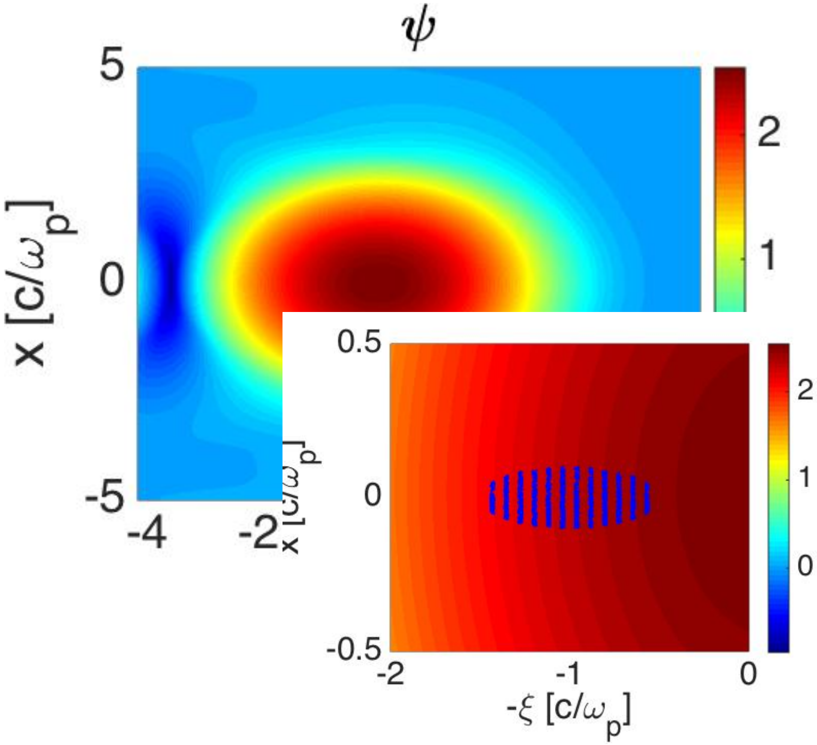
$$h = \frac{\sqrt{4 + \xi_i^2 - 2p_z/\gamma_{ph}^2}}{|\xi_i|}$$



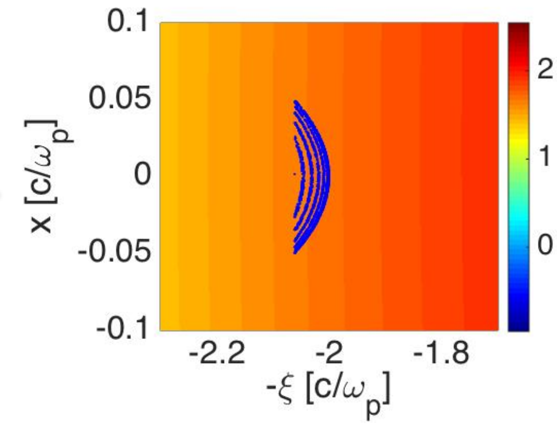

  - For the beam driver case with $\gamma_{ph} \gg 1$, the effects of the energy spread is very small as the energy is high enough.

# Intrinsic discretization of charge: 3D effect




$$\psi(\xi, r) = \frac{r_b^2(\xi) - \boxed{r^2}}{4}$$

$$\Rightarrow \xi_f \approx \sqrt{4 + \xi_i^2 + \boxed{r_i^2}}$$



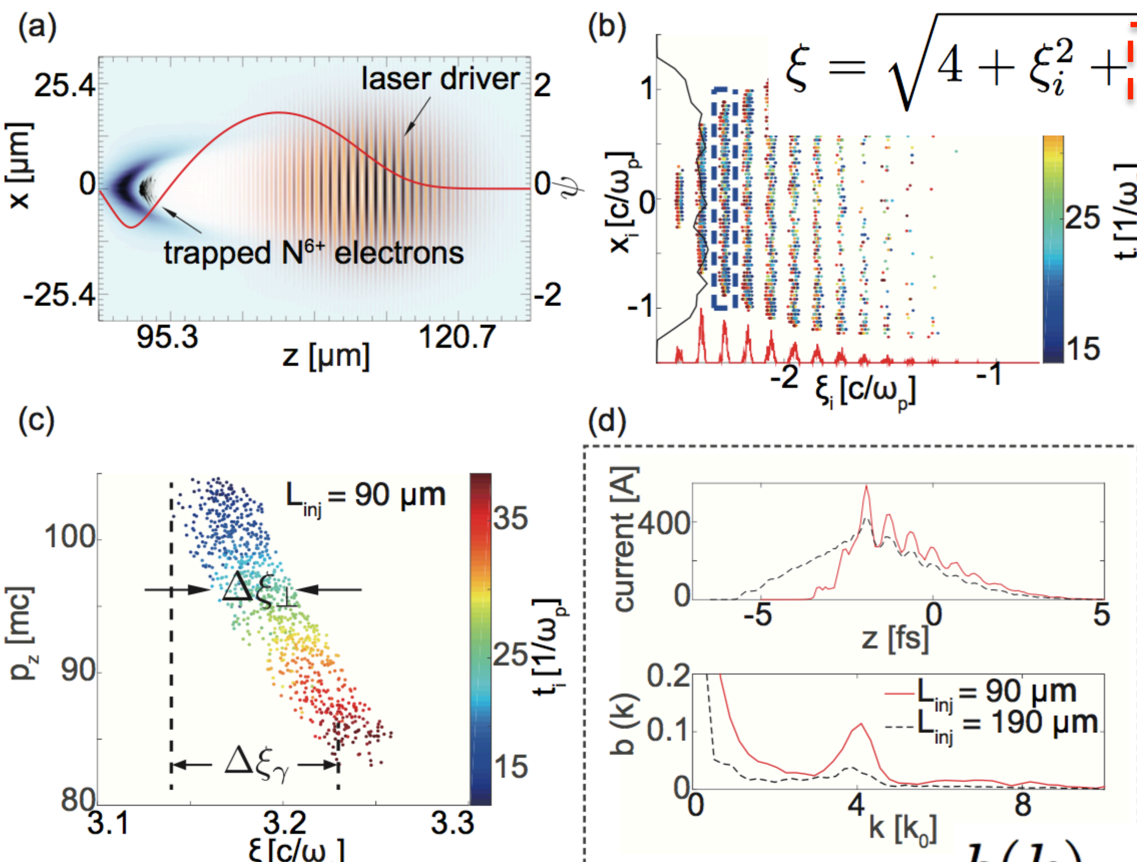

$$b(k) = \sum_{n=-\infty}^{+\infty} |F_n| \, R(\hat{\sigma}_r, \hat{\sigma}_e) \mathrm{e}^{-\frac{(k - 2nh_m k_0)^2 \sigma_e^2}{2h_m^2 (1+\hat{\sigma}_e^4)}}$$

3D Reduction Factor: $R = \left[(1+\hat{\sigma}_r^4)(1+\hat{\sigma}_e^4)\right]^{-1/4}$

W. Lu et al., PRL 96, 165002 (2006)

# Bunching in ionization injection using a single laser pulse

- A laser pulse ($a_0$=2), pre-plasma($n_p$=2×$10^{18}$ cm$^{-3}$) + $N^{5+}$




$$\xi = \sqrt{4 + \xi_i^2 + \boxed{r_i^2 - r^2} - \boxed{4\left[\gamma - (v_\phi/c)p_z\right]}}$$

1. due to the spread of transverse motion:

$$\Delta\xi_\perp \approx 0.05$$

2. due to the spread of energy:

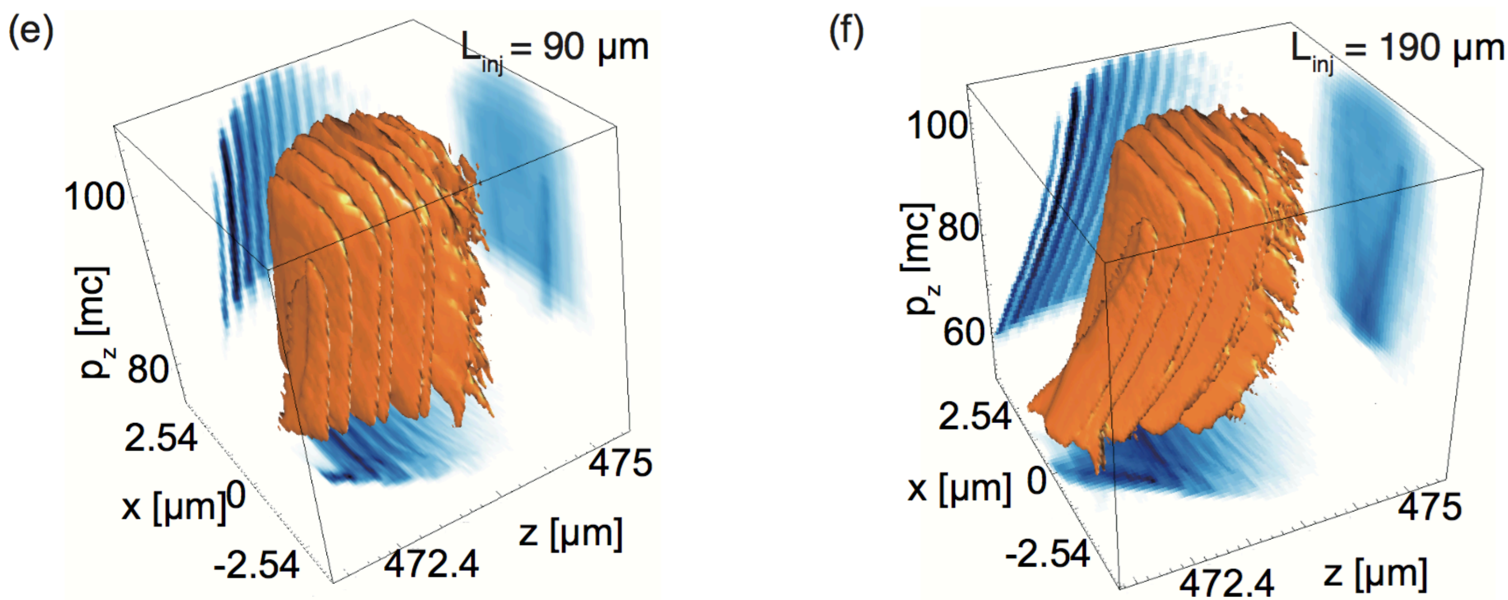
$$\gamma - (v_\phi/c)p_z \approx \omega_p^2/(2\omega_0^2)\gamma$$

$$\Delta\xi_\gamma \approx 0.1$$

$$b(k) = \left|\int dz g(z) \exp(ikz)\right|$$

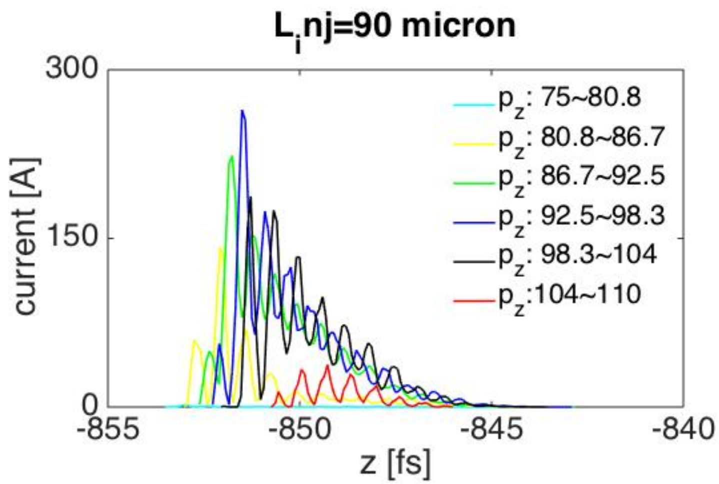
# Bunching in ionization injection using a single laser pulse

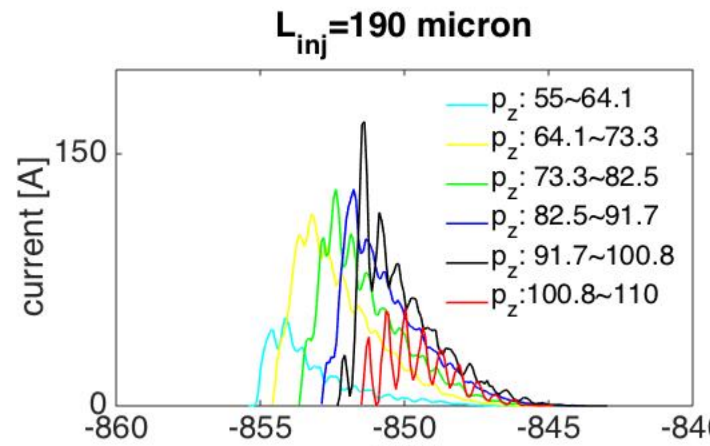
- The sliced structure in $(z, x, p_z)$ space

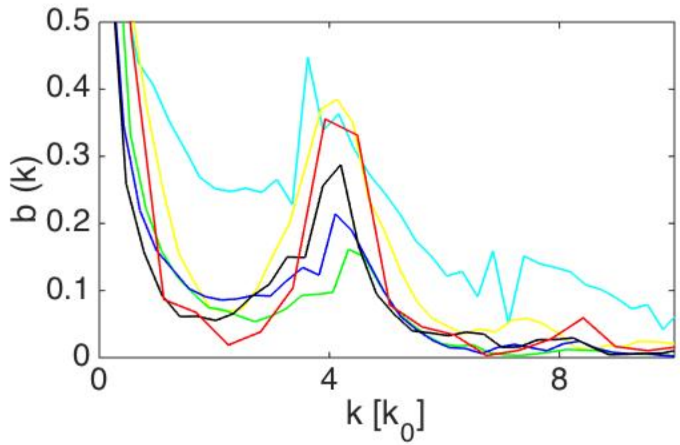


# Bunching in ionization injection using a single laser pulse

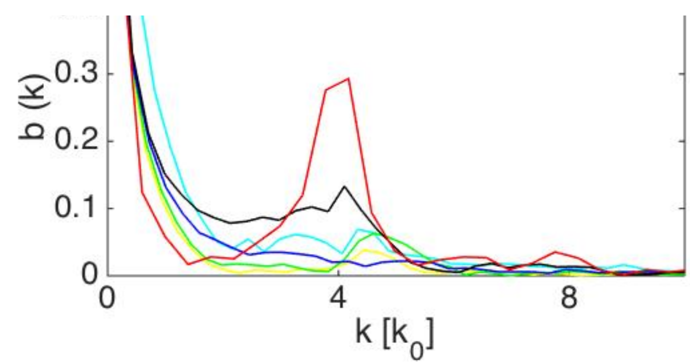
- Bunching for electrons with different energy



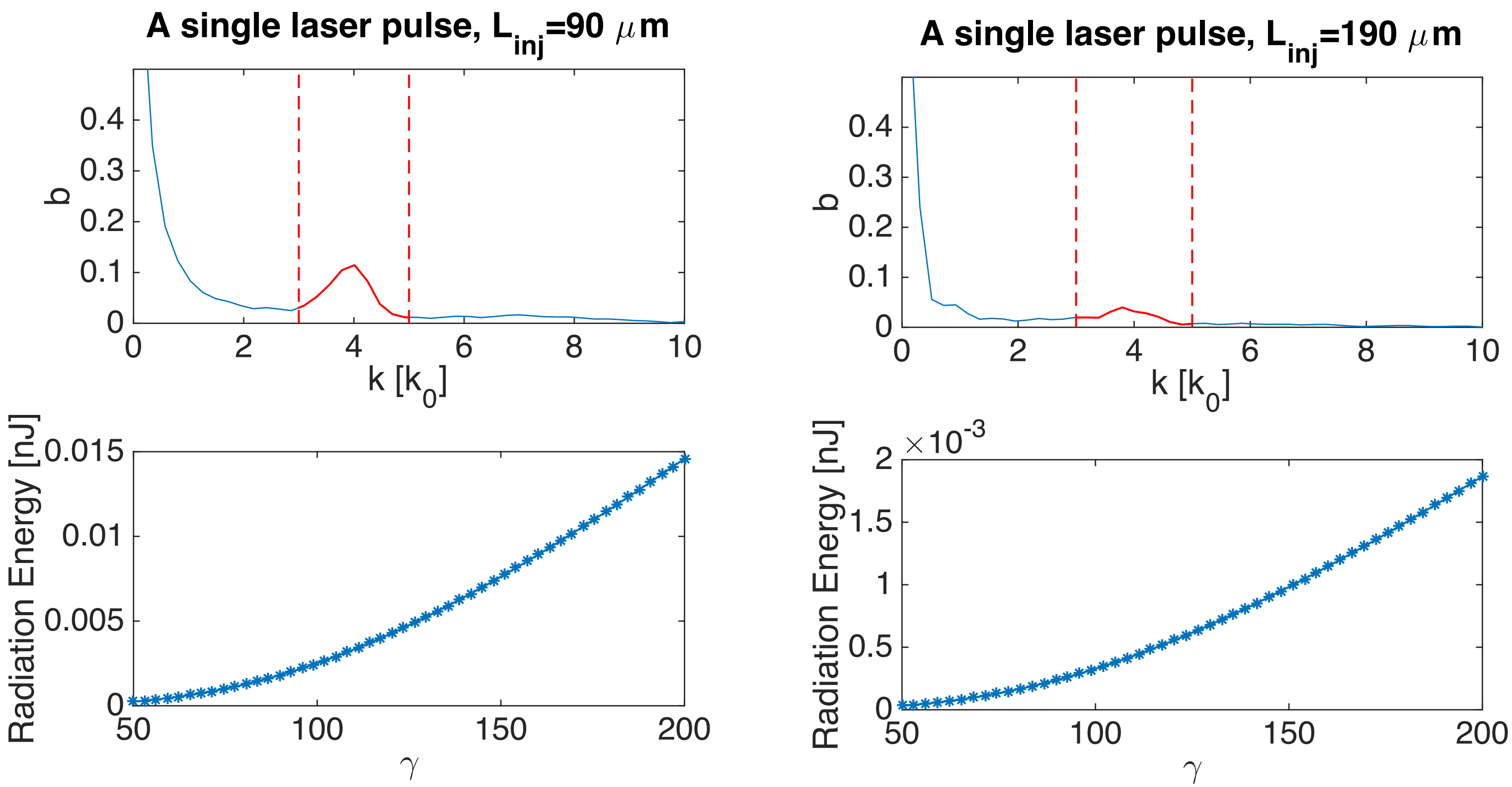




$$\xi = \sqrt{4 + \xi_i^2 + r_i^2 - r^2 - \boxed{4\left[\gamma - (v_\phi/c)p_z\right]}}$$



# How to diagnosis this phenomenon in experiments?

- Coherent transition radiation: from plasma to vacuum

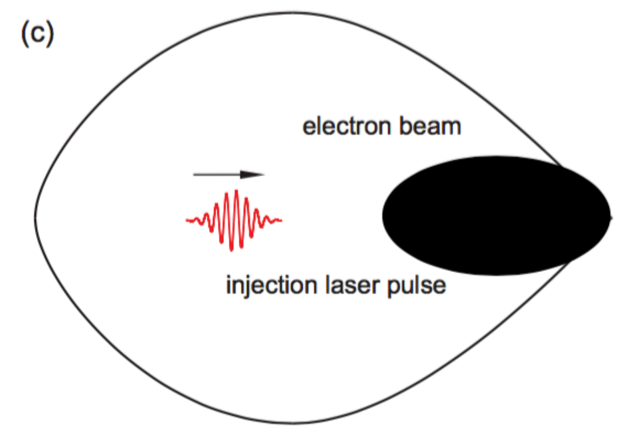



P. 412, Electrodynamics of Continuous Media, 2rd Edition, L. D. Landau et al.
W. Leemans, et al., Phys. Rev. Lett. 91, 074802 (2003).

# Bunching in ionization injection using two pulses

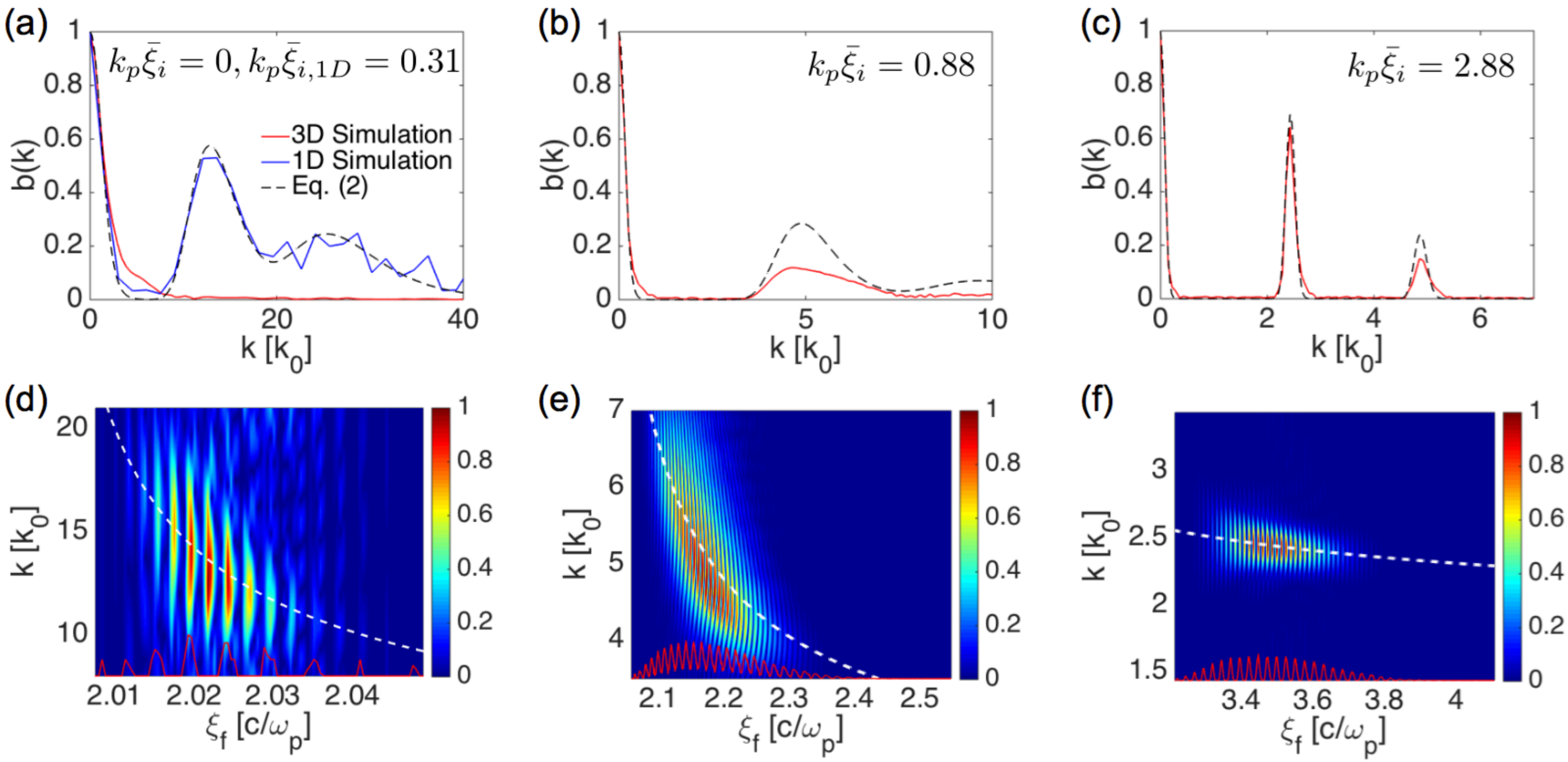
$$\xi = \sqrt{4 + \xi_i^2 + \boxed{r_i^2 - r^2} - \boxed{4\left[\gamma - (v_\phi/c)p_z\right]}}$$

- Using two pulses
  - Reduce the initial transverse radius
  - Reduce the injection distance
  - Improve the phase velocity of the wake




$$\xi = \sqrt{4 + \xi_i^2 + r_i^2}$$

# Bunching in ionization injection using two pulses: external field model

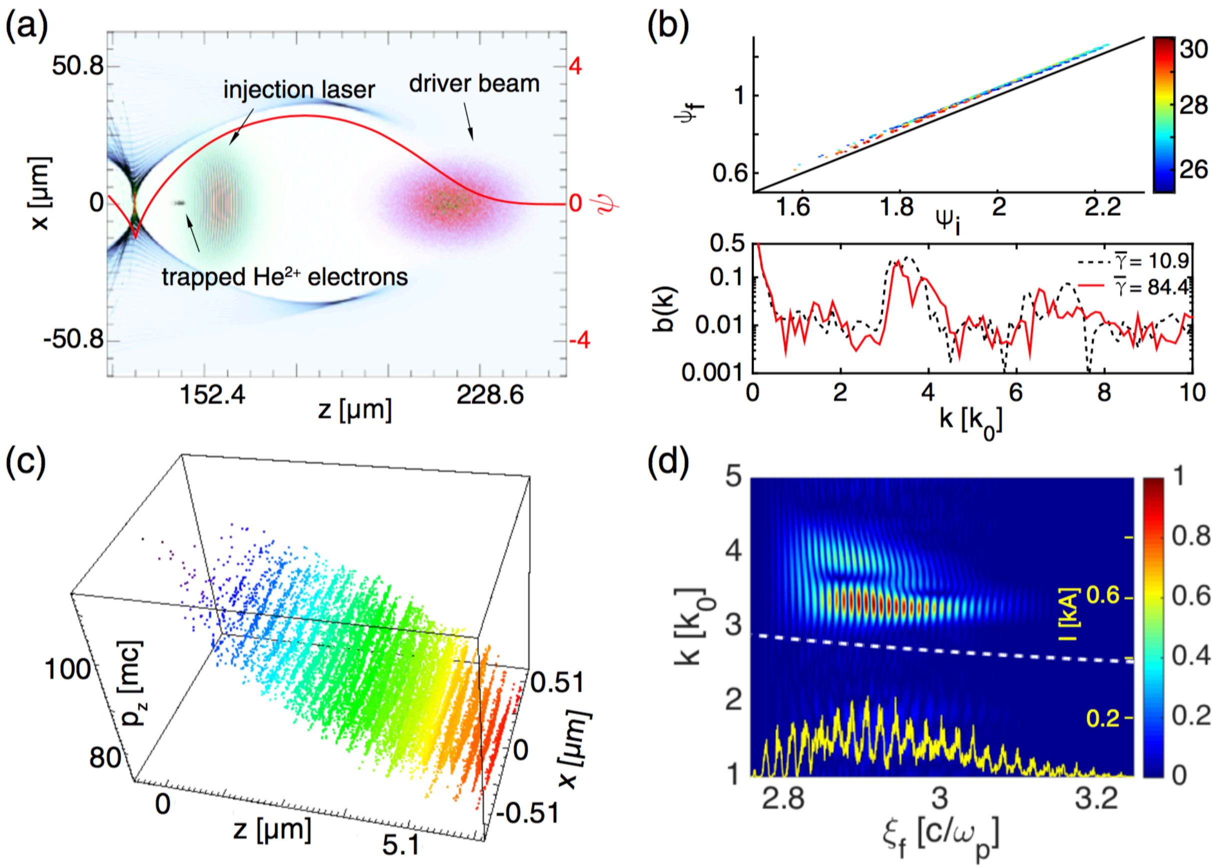



$$h = 2h_m = 2\sqrt{4 + \bar{\xi}_i^2}/|\bar{\xi}_i|$$

- Control the beam length.
- Control the beam longitudinal profile.

# Bunching in ionization injection using two pulses

- Beam Driver + 800 nm injection laser ($a_0$=0.12)




Pre-plasma + $He^{1+}$

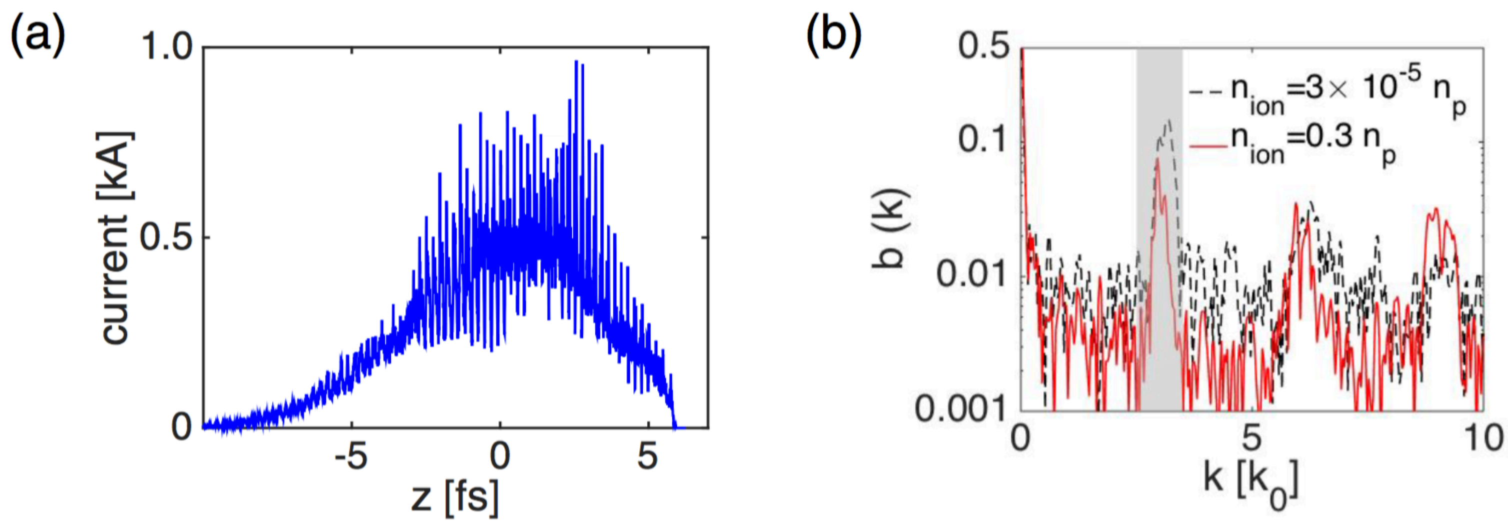
$$n_p = 1.74 \times 10^{17}\mathrm{cm}^{-3}$$

$$n_{\mathrm{He}^{1+}} = 0.1 n_p$$

$$h \approx 2.9$$

# Bunching in ionization injection using two pulses

- Beam driver + 200 nm injection laser ($a_0$=0.023)




➢Transition radiation: 0.02 nJ when the energy is ~0.5 GeV.

➢Seeded FEL: $\varepsilon_{nx}=\varepsilon_{ny}$=11nm, $\sigma_\gamma$=4, $\gamma$=1068.9

$\lambda_u$=3 cm, K=2 --> $\lambda_r$=65.6 nm

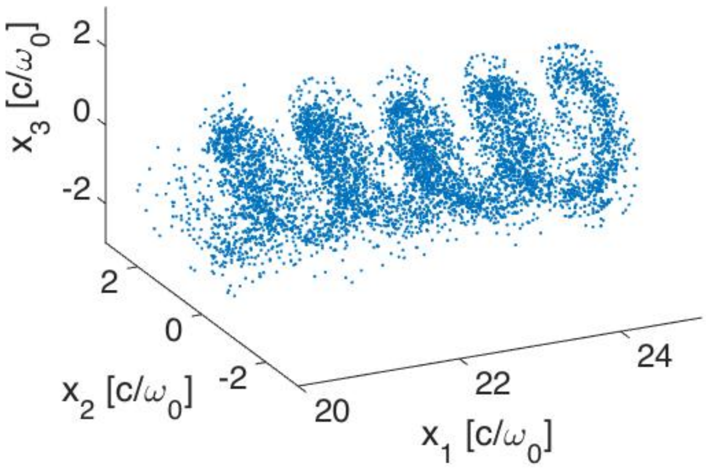
140 MW in a 3.5 m undulator

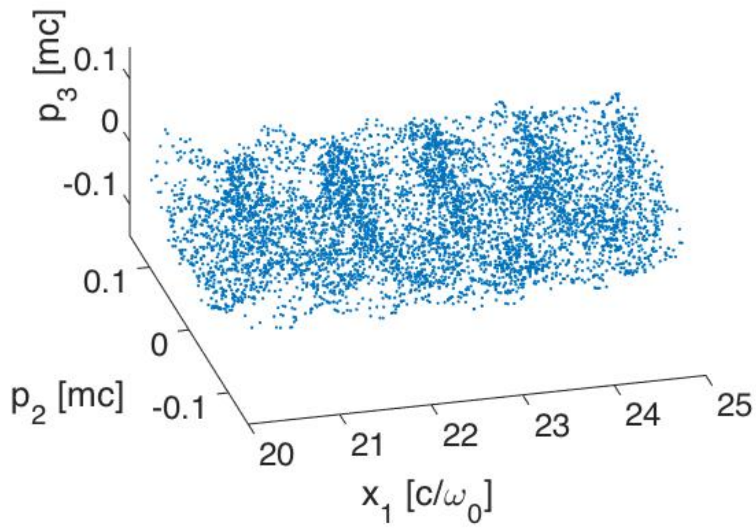
S. Reiche, Nucl. Instrum. Methods Phys. Res., Sect. A 429, 243 (1999).

# Spiral beam generation

- Using a Circularly Polarized injection laser

➢ Beam driver + 200 nm CP injection laser ($a_0$=0.023/√2)

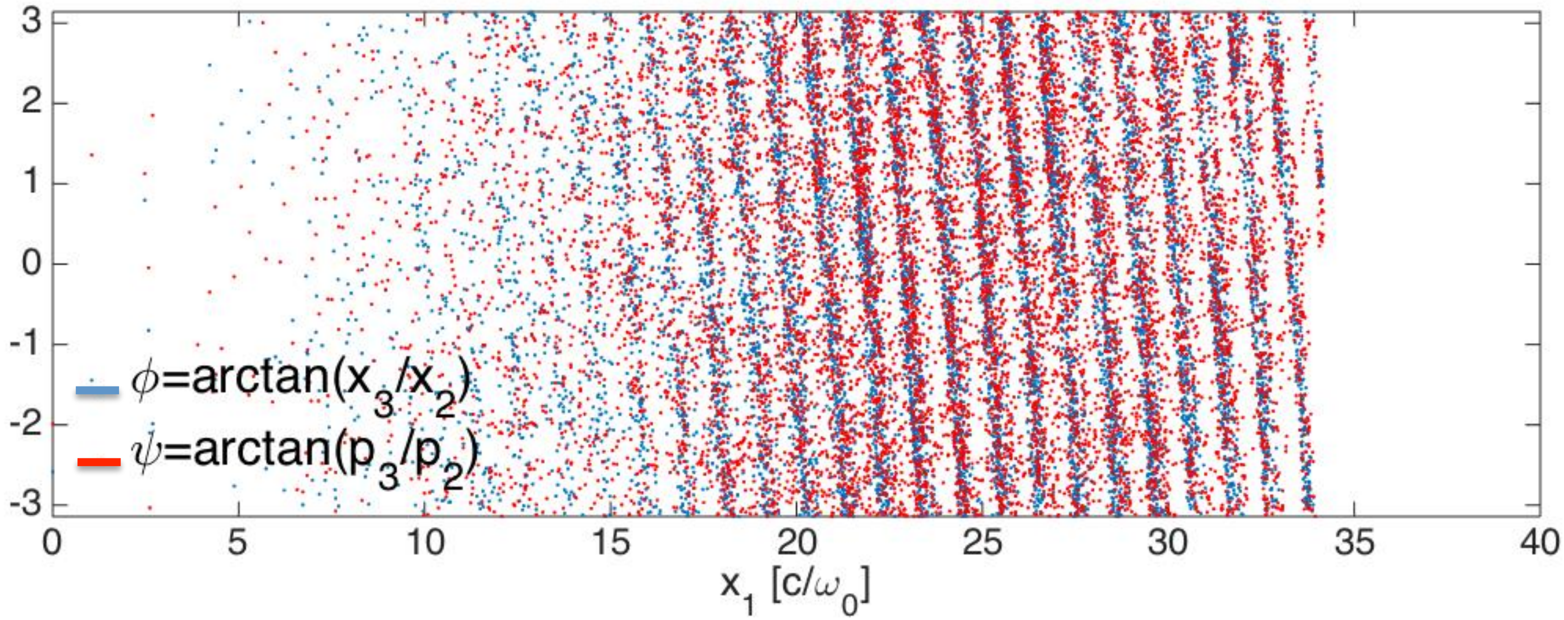


# Spiral beam generation

- Using a Circularly Polarized injection laser

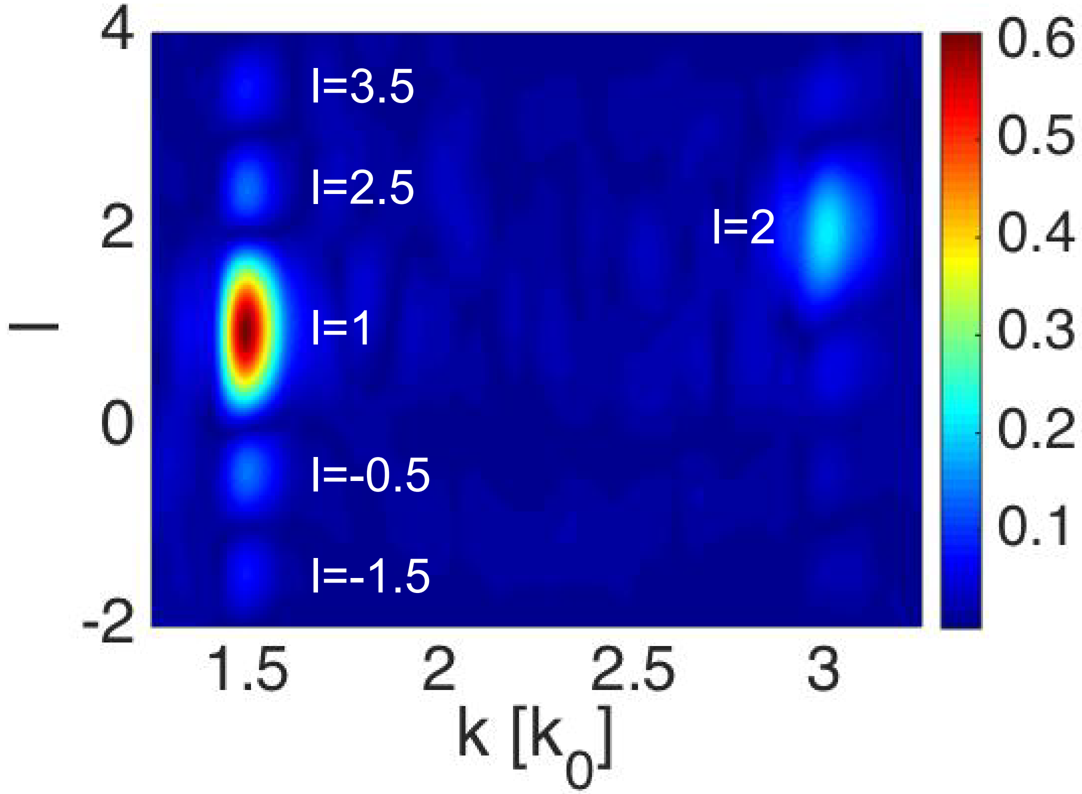
➢ Beam driver + 200 nm CP injection laser ($a_0$=0.023/√2)



# Spiral beam --> OAM light generation

- bunching factor:

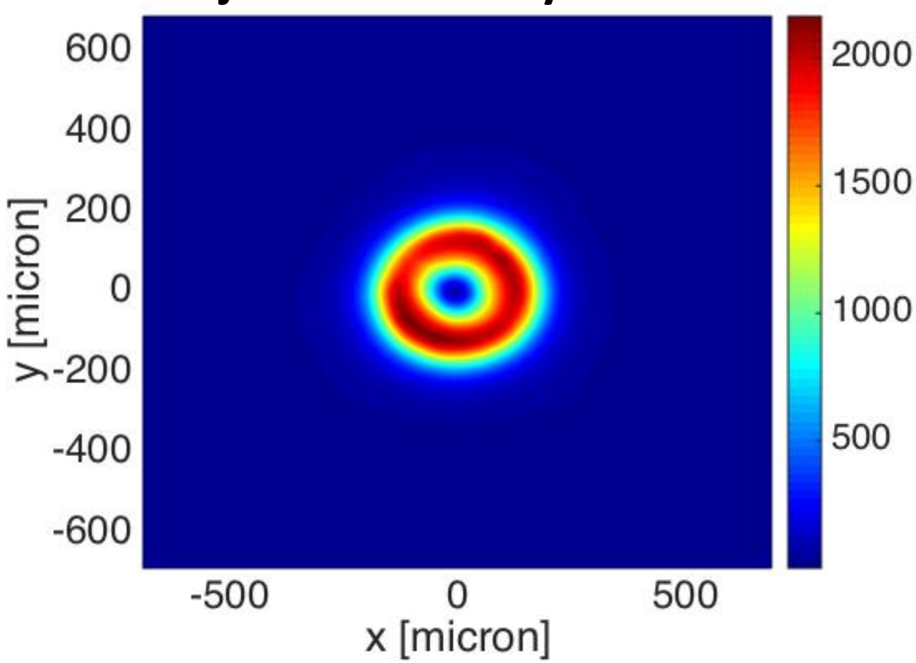
$$b = \left| \int dz d\phi f(z,\phi) \exp\left(ikz + il\phi\right) \right|, \text{ where } \phi = \arctan(y/x)$$

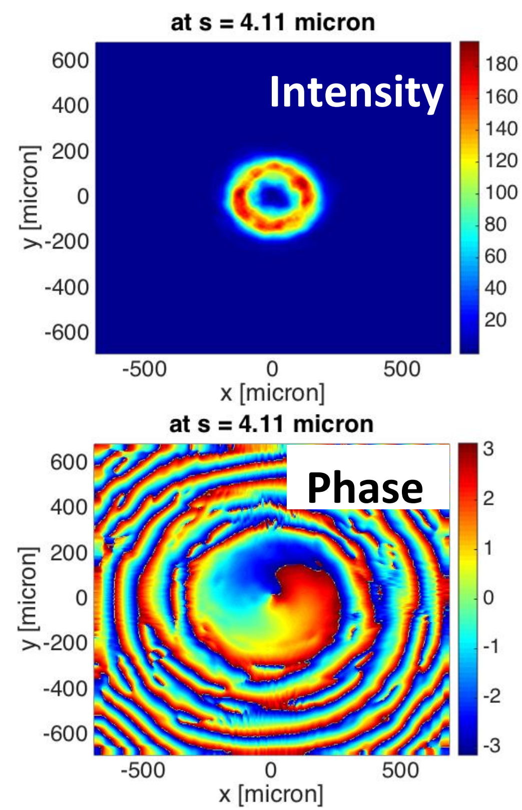


# Spiral beam --> OAM light generation

- Coherent transition radaition[1]
- Undulator: $\lambda_u$=3 cm, K=2 --> $\lambda_r$=137.0 nm

**Projected Intensity at screen**




E. Hemsing and J. B. Rosenzweig, J. Appl. Phys. 105, 093101 (2009); E. Hemsing, et al., Appl. Phys. Lett. 100, 091110 (2012).

# Conclusions

- We found bunched electron beams and spiral beams can be generated in laser-triggered ionization injection.
- Theoretical analysis and 3D PIC simulations are presented to understand these unique beam generation processes.
- These unique beams can be diagnosed through coherent transition radiation and may find use in generating high-power EUV radiation upon passage through a resonant undulator.

**X. L. Xu, et al., Phys. Rev. Lett. 117, 034801 (2016)**