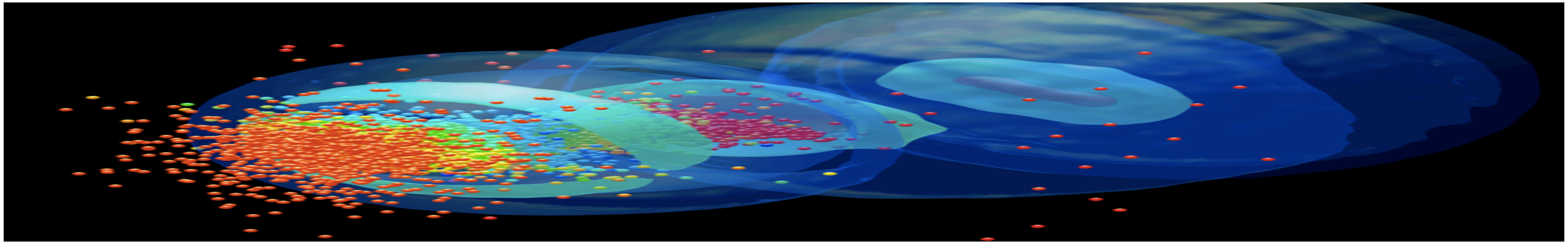


Future Perspectives on High Quality Ionization Based Injection Methods in Wakefield Accelerators at ATFII

Wei Lu

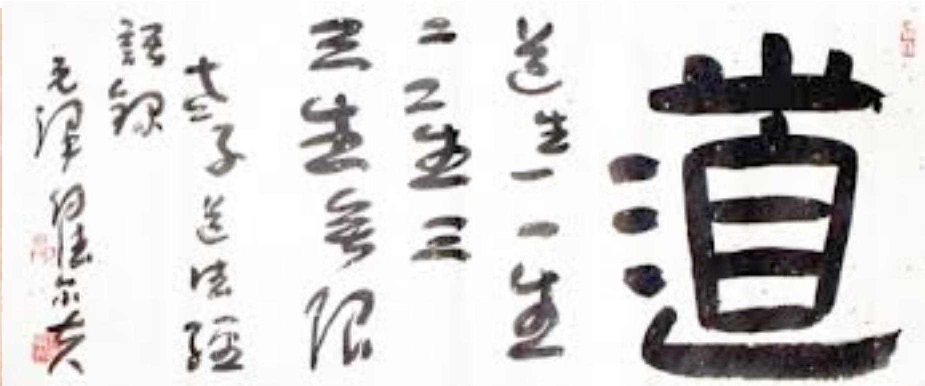
Tsinghua University

The ATF User Workshop

Oct 1-2 2015

Outline

- Some general thoughts on ATFII
- Ionization based Injection： basics
- Phase space dynamics in ionization injection
- A few possible schemes for ATFII



In the Universe

……

One *give* birth to two

Two *give* birth to three

and

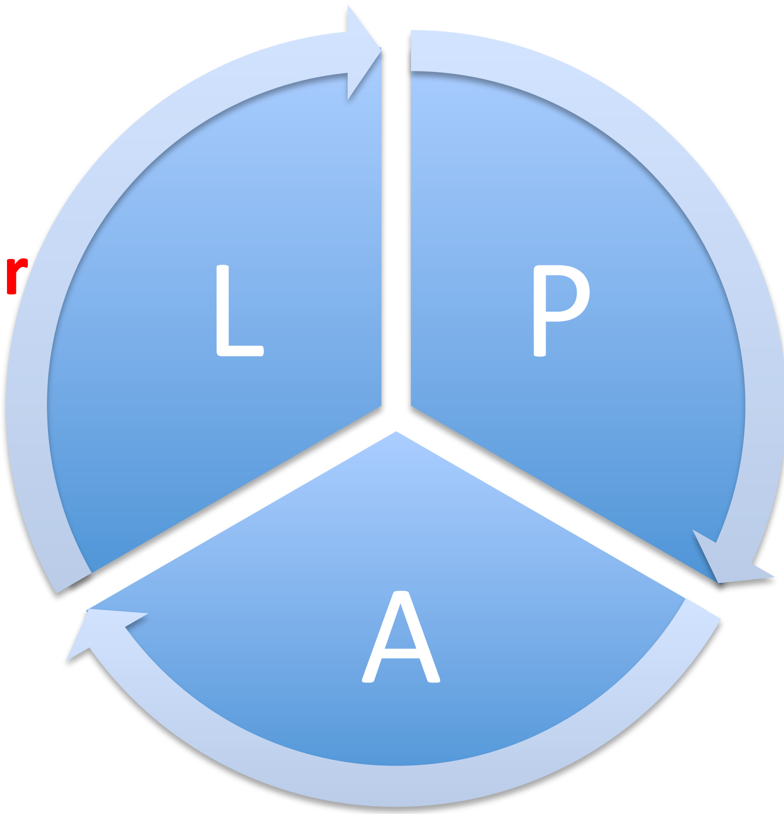
Three *give* birth to everything ……

See W. Lu's talk at 2014 ATFII upgrade workshop

Future Perspectives on Ultrafast CO2 Laser Driven LWFA and LPI

In the Universe of "Laser and Plasma Acceleration"

Ultrafast High Power CO2 Laser



Programmable Plasma Structure

High Brightness Linear Accelerator

See W. Lu's talk at 2014 ATFII upgrade workshop

Future Perspectives on Ultrafast CO2 Laser Driven LWFA and LPI

The Menu

- " A Physics Simulator"
  from "LWFA" to "RPA" to "SWA" to ……

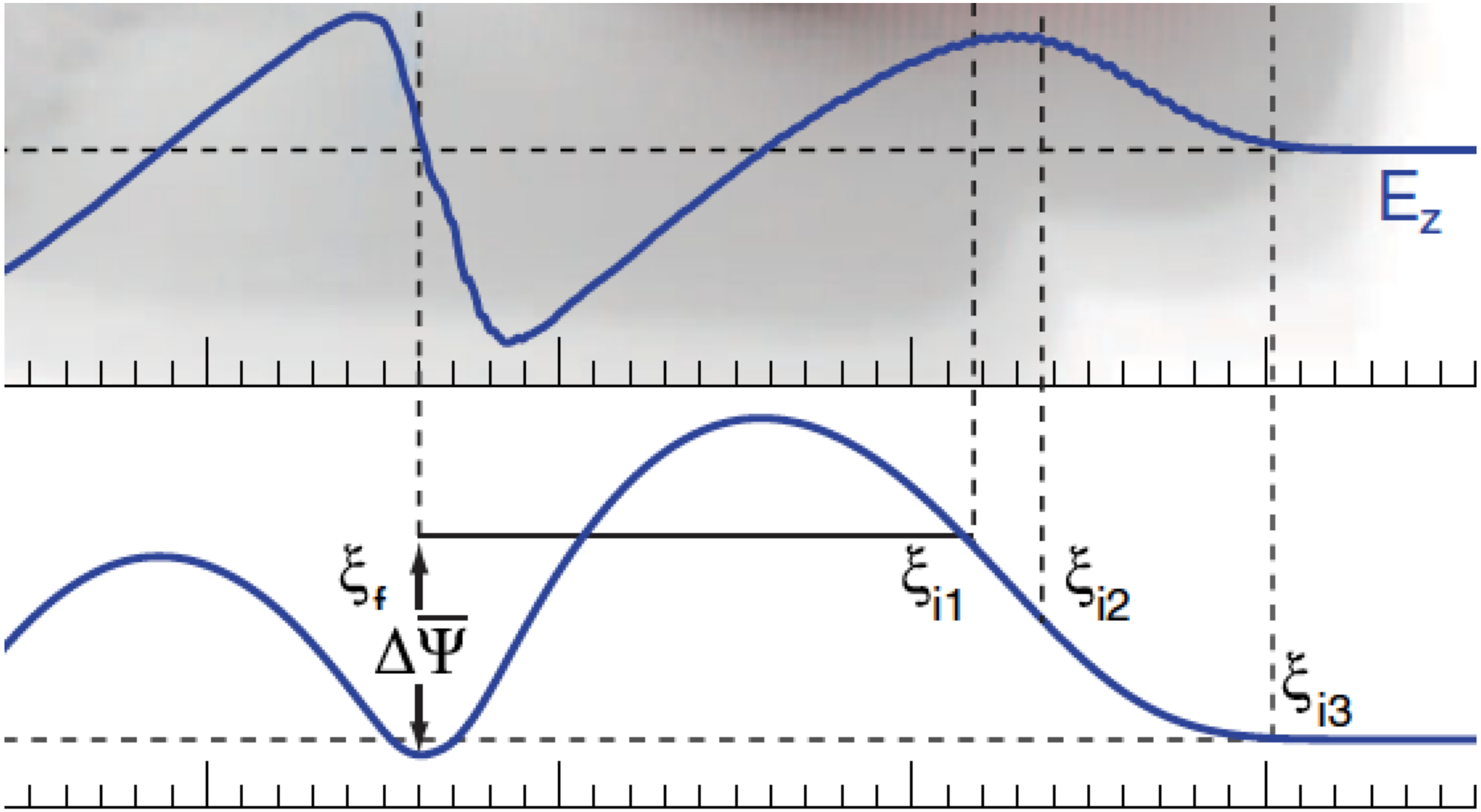
- "A Super Brightness Booster"
  Plasma Cathode: ionization injection in PWFA and two color LWFA, and others ……

- A Practical High Quality Accelerator Tech
  External Injection for Multi-GeV Acceleration, Self and Channel Guiding, Plasma Beam Optics……

See W. Lu's talk at 2014 ATFII upgrade workshop
Future Perspectives on Ultrafast CO2 Laser Driven LWFA and LPI

Ionization based Injection: A simple picture

easier trapping for electrons born inside the wake



Early hints using two crossing laser pulses

VOLUME 76, NUMBER 12 PHYSICAL REVIEW LETTERS 18 MARCH 1996

Laser Injection of Ultrashort Electron Pulses into Wakefield Plasma Waves

D. Umstadter, J. K. Kim, and E. Dodd
Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109
(Received 11 December 1995)

A novel laser-plasma-based source of relativistic electrons is described. It involves a combination of orthogonally directed laser beams, which are focused in a plasma. One beam excites a wakefield electron plasma wave. Another locally alters the trajectory of some of the electrons in such a way that they can be accelerated and trapped by the wave. With currently available table-top terawatt lasers, a single ultrashort-duration electron bunch can be accelerated to multi-MeV energies in a fraction of a millimeter, with femtosecond synchronization between the light pulse, the electron bunch, and the plasma wave. Both analytical and numerical-simulation results are presented.

the number of trapped electrons. This number can be increased by injecting electrons that are derived not just from the background, as discussed above, but also from the process of photoionization. Instead of using a fully ionized plasma (as above), one would use a medium with deeply bound inner shell electrons, which have an appearance intensity for tunneling ionization [12] below that of the injection pulse but above that of the pump pulse, a topic of a future publication.

JOURNAL OF APPLIED PHYSICS 99, 056109 (2006)

1D simulation
+1D analysis

Electron injection and trapping in a laser wakefield by field ionization to high-charge states of gases

Min Chen, Zheng-Ming Sheng, Yan-Yun Ma,[a] and Jie Zhang[b]
Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China

(Received 12 January 2006; accepted 27 January 2006; published online 15 March 2006)

A scheme for electron injection into a laser wakefield is presented, which makes use of two orthogonally directed laser pulses and a gaseous medium with a moderate or high atomic number such as neon. A pump laser pulse ionizes the medium to its midcharge states to form underdense plasma and meanwhile excites a high amplitude wakefield firstly. Another ultrashort laser pulse with higher intensity is then injected transversely, which further ionizes the medium to high-charge states to produce new free electrons with certain energy. Part of these new-born electrons can be trapped and accelerated by the laser wakefield to high energies. Numerical simulations using a particle-in-cell code with field ionization included are conducted to verify the scheme. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2179194]

Ionization injection in beam driven wake:

experiment + quasi-3D PIC simulation + 1D threshold

PRL **98**, 084801 (2007) PHYSICAL REVIEW LETTERS week ending 23 FEBRUARY 2007

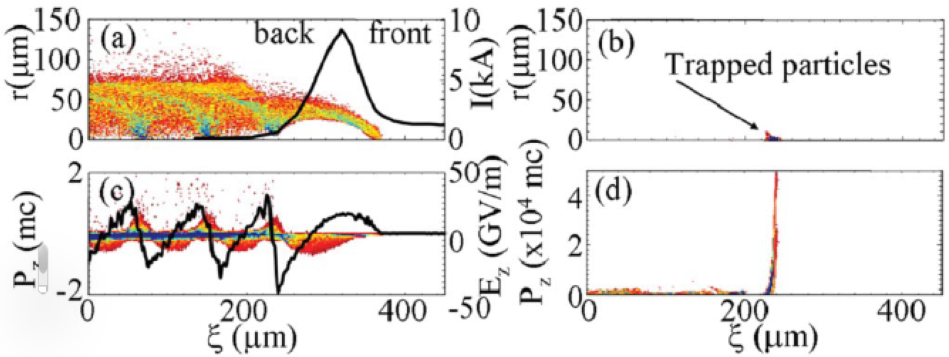
Ionization-Induced Electron Trapping in Ultrarelativistic Plasma Wakes

E. Oz,[1] S. Deng,[1] T. Katsouleas,[1] P. Muggli,[1] C. D. Barnes,[2] I. Blumenfeld,[2] F. J. Decker,[2] P. Emma,[2] M. J. Hogan,[2] R. Ischebeck,[2] R. H. Iverson,[2] N. Kirby,[2] P. Krejcik,[2] C. O'Connell,[2] R. H. Siemann,[2] D. Walz,[2] D. Auerbach,[3] C. E. Clayton,[3] C. Huang,[3] D. K. Johnson,[3] C. Joshi,[3] W. Lu,[3] K. A. Marsh,[3] W. B. Mori,[3] and M. Zhou[3]

[1]*Department of Electrophysics and Electrical Engineering, USC, Los Angeles, California 90089, USA*
[2]*Stanford Linear Accelerator Center, SLAC, Menlo Park, California 94025, USA*
[3]*Department of Electrical Engineering, UCLA, Los Angeles, California 90095, USA*

(Received 23 October 2006; published 23 February 2007)

The onset of trapping of electrons born inside a highly relativistic, 3D beam-driven plasma wake is investigated. Trapping occurs in the transition regions of a Li plasma confined by He gas. Li plasma electrons support the wake, and higher ionization potential He atoms are ionized as the beam is focused by Li ions and can be trapped. As the wake amplitude is increased, the onset of trapping is observed. Some electrons gain up to 7.6 GeV in a 30.5 cm plasma. The experimentally inferred trapping threshold is at a wake amplitude of 36 GV/m, in good agreement with an analytical model and PIC simulations.



$$mc^2\left(1 - \frac{1}{\gamma_\phi}\right) \leq q(\Psi_{\max} - \Psi_i).$$

Ionization injection in single laser pulse driven wake:

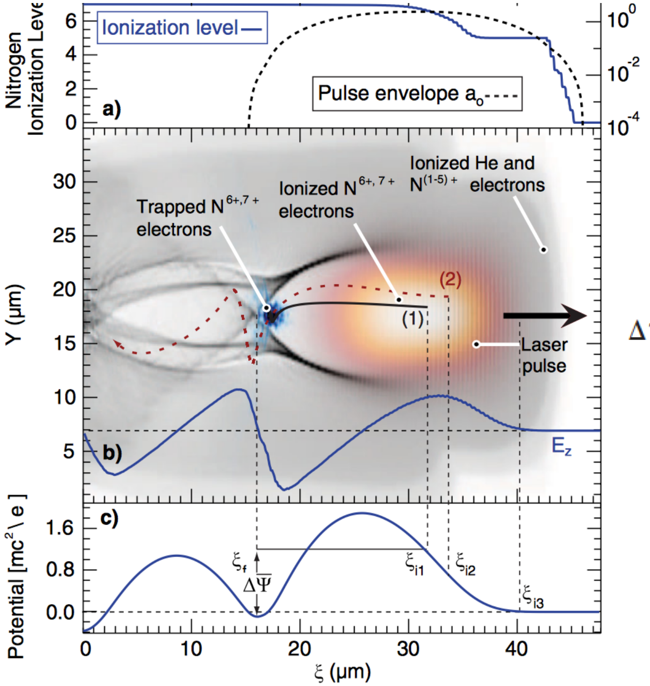
experiments + 2D/3D PIC simulation + 3D threshold

PRL 104, 025003 (2010) PHYSICAL REVIEW LETTERS week ending 15 JANUARY 2010

Injection and Trapping of Tunnel-Ionized Electrons into Laser-Produced Wakes

A. Pak,[1] K. A. Marsh,[1] S. F. Martins,[3,2] W. Lu,[2] W. B. Mori,[2] and C. Joshi[1]
[1]*Department of Electrical Engineering, UCLA, Los Angeles, California 90095, USA*
[2]*Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA*
[3]*GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Lisbon, Portugal*
(Received 3 August 2009; published 15 January 2010)

A method, which utilizes the large difference in ionization potentials between successive ionization states of trace atoms, for injecting electrons into a laser-driven wakefield is presented. Here a mixture of helium and trace amounts of nitrogen gas was used. Electrons from the *K* shell of nitrogen were tunnel ionized near the peak of the laser pulse and were injected into and trapped by the wake created by electrons from majority helium atoms and the *L* shell of nitrogen. The spectrum of the accelerated electrons, the threshold intensity at which trapping occurs, the forward transmitted laser spectrum, and the beam divergence are all consistent with this injection process. The experimental measurements are supported by theory and 3D OSIRIS simulations.



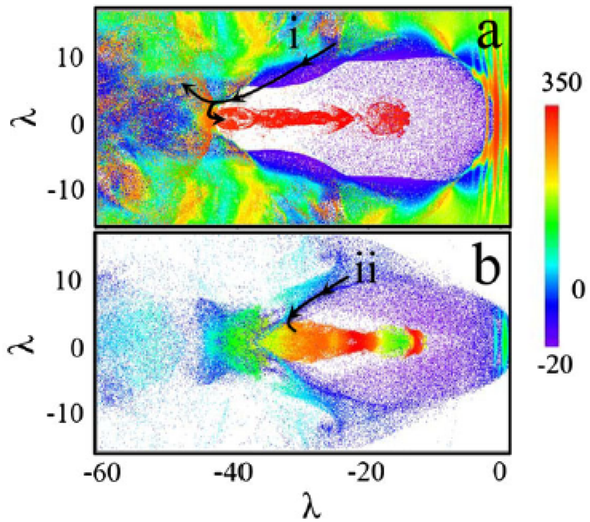
PRL 104, 025004 (2010) PHYSICAL REVIEW LETTERS week ending 15 JANUARY 2010

Ionization Induced Trapping in a Laser Wakefield Accelerator

C. McGuffey, A. G. R. Thomas, W. Schumaker, T. Matsuoka, V. Chvykov, F. J. Dollar, G. Kalintchenko, V. Yanovsky, A. Maksimchuk, and K. Krushelnick
Center for Ultrafast Optical Science, The University of Michigan, Ann Arbor, Michigan 48109, USA
V. Yu. Bychenkov
P. N. Lebedev Physics Institute, Russian Academy of Science, Leninskii Prospect 53, Moscow 119991, Russia
I. V. Glazyrin and A. V. Karpeev
RFNC-VNIITF, Snezhinsk 456770, Chelyabinsk region, Russia
(Received 3 August 2009; published 15 January 2010)

Experimental studies of electrons produced in a laser wakefield accelerator indicate trapping initiated by ionization of target gas atoms. Targets composed of helium and controlled amounts of various gases were found to increase the beam charge by as much as an order of magnitude compared to pure helium at the same electron density and decrease the beam divergence from 5.1 ± 1.0 to 2.9 ± 0.8 mrad. The measurements are supported by particle-in-cell modeling including ionization. This mechanism should allow generation of electron beams with lower emittance and higher charge than in preionized gas.

$$\Delta\bar{\Psi} + 1 = \frac{\gamma}{\gamma_\phi^2} = \frac{\sqrt{1 + (P_\perp/mc)^2}}{\gamma_\phi},$$



also seeing some evidence in **T. P. Rowlands-Rees et al., Phys. Rev. Lett. 100, 105005 (2008)**

3D injection threshold derived in W. Lu Ph.D dissertation (2006)

Different Scenarios

- **Beam Driven Wake+ Beam or Wake field ionization**

➢ E. Oz et al., PRL 2007 (exp+sim+1D theory)

➢ A. Martinez et al., PRL 111, 245003 (2013) (3D sim)

- **Laser Driven Wake + Laser ionization**

Single pulse:

➢ A. Pak et al., PRL 2010 (exp+3D theory+sim) , C. McGuffey et al., PRL 2010 (exp+2D sim)

➢ C. Clayton et al., PRL 2010 (exp)

➢ B. Pollock et al., PRL 2011 (exp), J.S. Liu et al., PRL 2011 (exp)

Multiple pulses:

➢ Intense transverse colliding pulses: M. Chen et al., AIP 2012 (sim)

Two color schemes:

Yu et al., SPIE Conf. Proc. (2013) 1D, PRL 2014 (2D) collinear injection

Xu et al., PRSTAB, 2014 collinear and transverse colliding injection

Y. Wan et al., arXiv：1509.09091 colliding injection

- **Beam Driven Wake + Laser ionization**

Collinear injection:

B. Hidding et al., PRL 2012 and LPAW 11; Lu et al., LPAW11 (sim)

Transverse colliding pulses injection:

F. Li et al., PRL 2013 (sim)

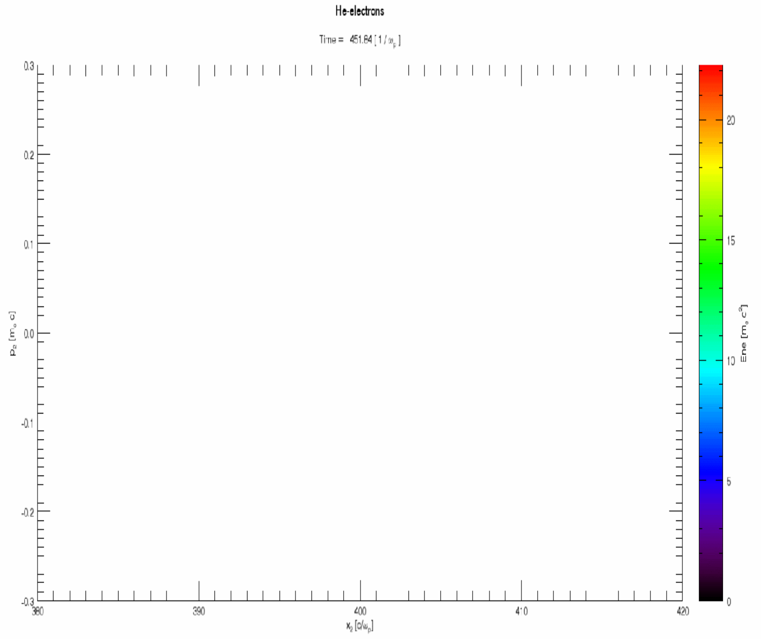
Collinear colliding injection:

Y. Wan et al., arXiv：1509.09091

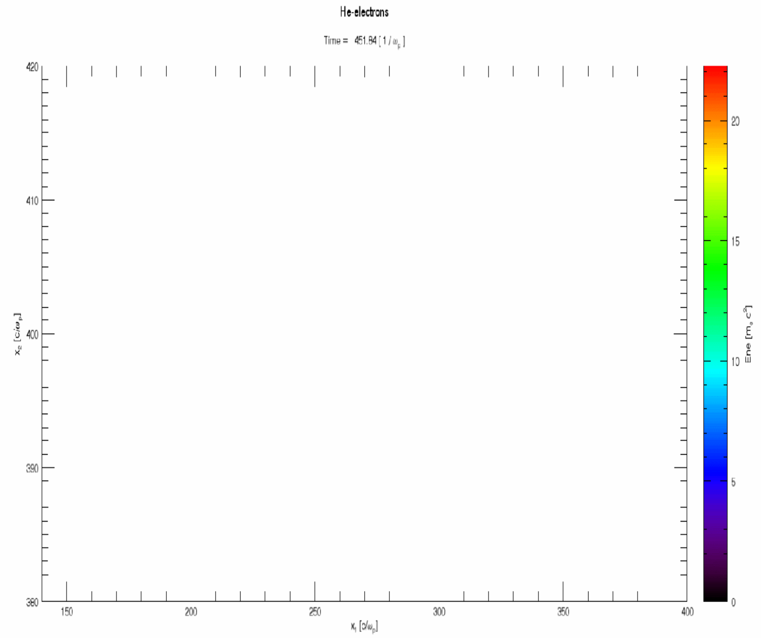
The Key Physics:

Transverse and Longitudinal Phase Mixing

Transverse Phase Mixing



Longitudinal Phase Mixing

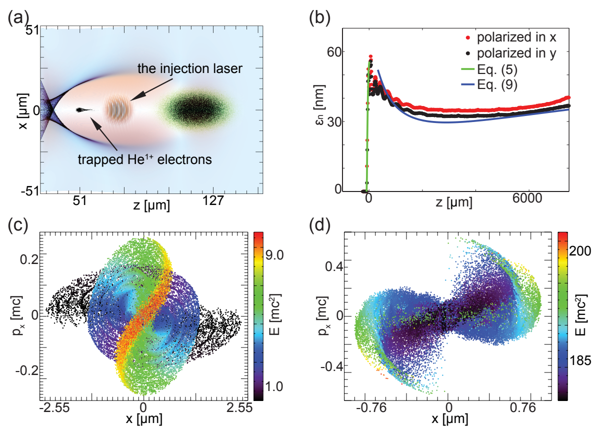


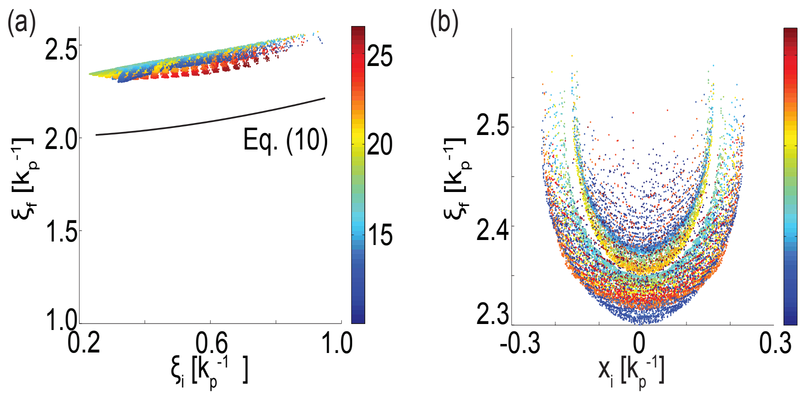
The phase space evolution determines the beam quality: emittance , energy spread

X.L. Xu et al., Phys. Rev. Lett. 112, 035003 2014

Theoretical Model for Phase Space Dynamics of Mixing

The model can explain quantitatively the induced emittance dynamics, such as the initial anomalous growth, oscillation, decay and saturation.



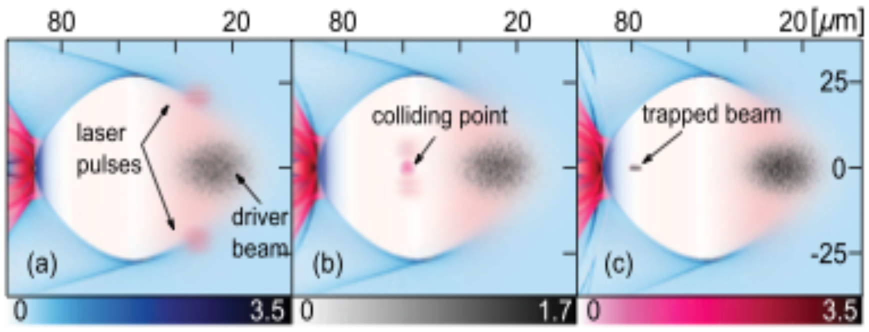


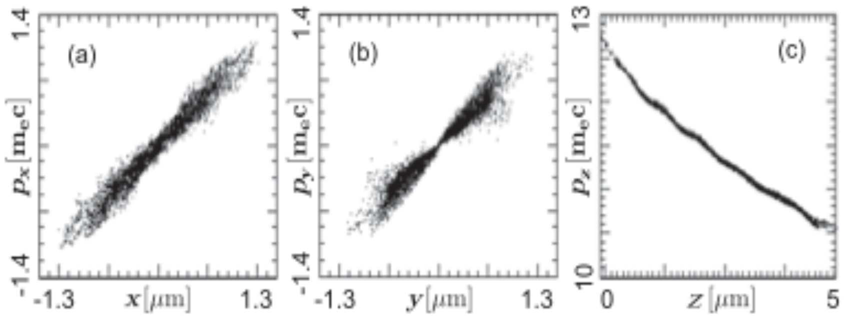
X.L. Xu et al., Phys. Rev. Lett. 112, 035003 2014

Ionization Injection by Transverse Colliding Pulses in PWFA

F. Li et al., PRL 111,015003 (2013)

Key factors:

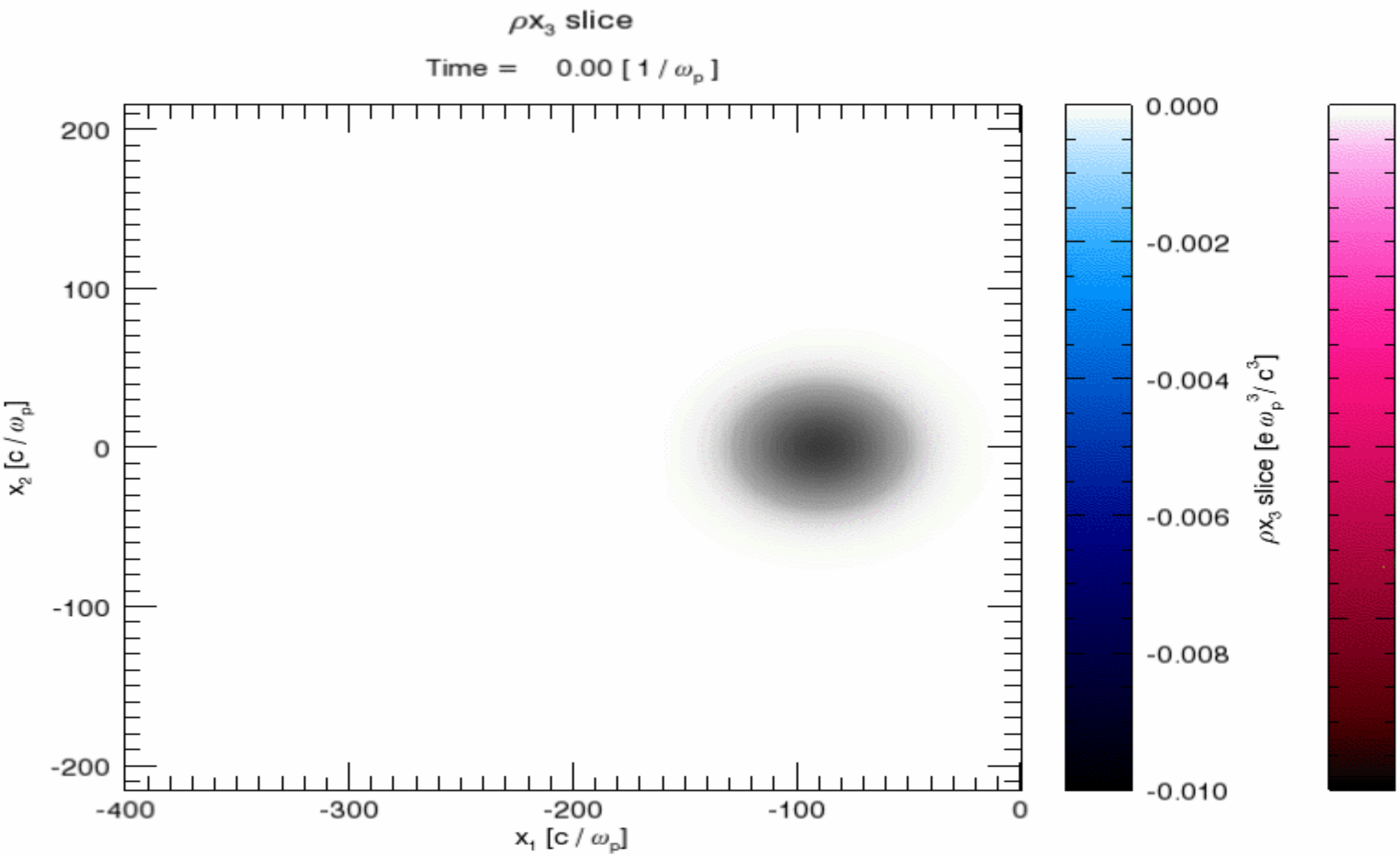




- Laser polarization (z, beam path)
  - ➢ reducing thermal emittance
- Laser intensity (weak)
  - ➢ nearly no perturbation of wake
  - ➢ No random heating by colliding pulses
- Very short overlapping time
  - ➢ Much less phase mixing

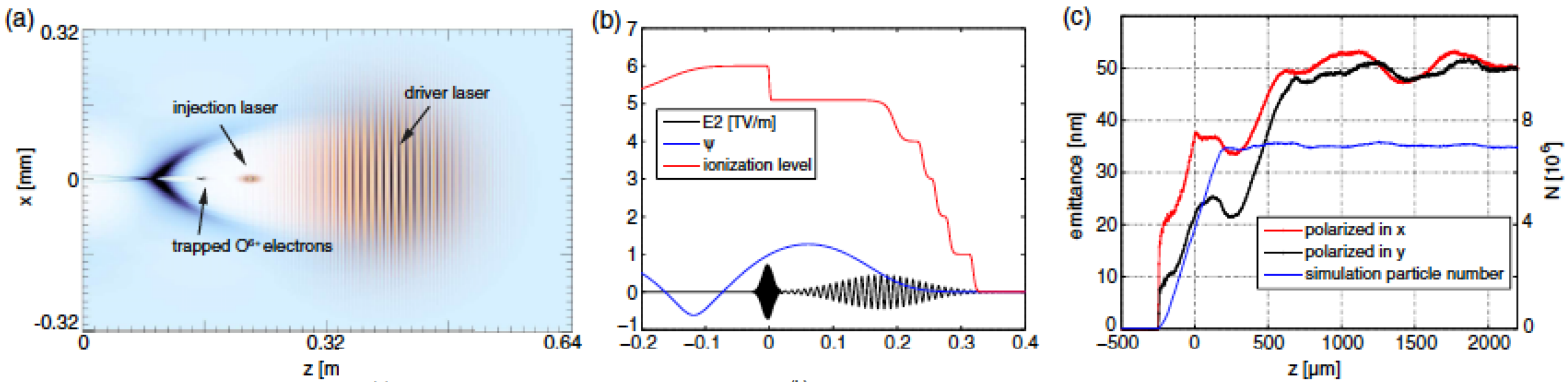
As a result, it could lead to very good beams through optimization:

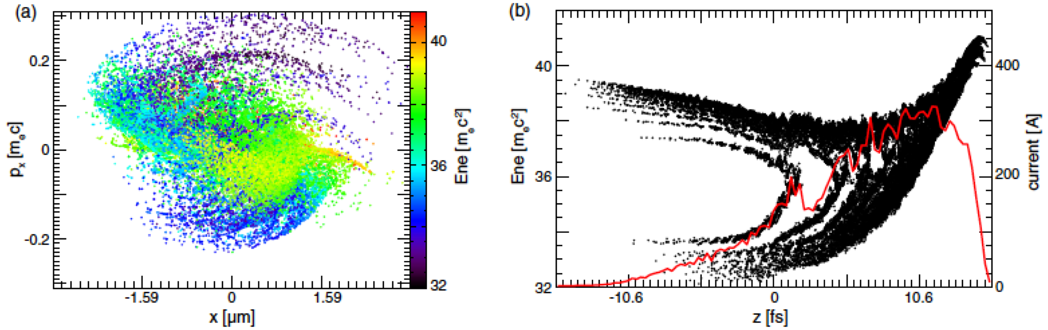
- ➢ **Low normalized emittances (~1-10 nm)**
- ➢ **High current, short pulse (~.1-1kA, ~fs, few pC)**
- ➢ **Low energy spread (~1-10keV for slice, ~.1% level for total)**



ρx3 slice
Time = 0.00 [1 / ωp]
200
100
0
-100
-200
x2 [c / ωp]
-400
-300
-200
-100
0
x1 [c / ωp]
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
ρx3 slice [e ωp3 / c3]

Two color： collinear injection





17 TW 350fs CO2 laser, Gas: O2, 4pC of injected charge (based on 2D estimation)

Xu et al., Phys. Rev. STAB 17,061301 2014 (**co-linear and transverse colliding two color**)

Yu et al., PRL 112, 125001 2014 (c**o-linear two color**)

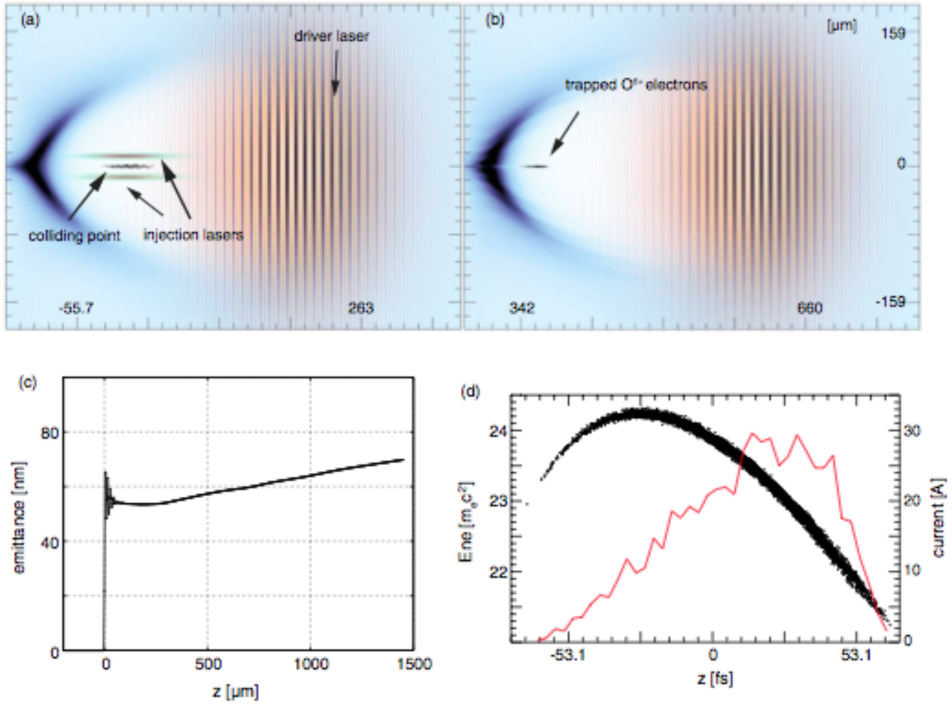
Two color: Transverse Colliding injection

Key factors:

- **Long wavelength CO2 Laser driven wakes**
  - ➢ large ponderomotive force at low intensity

- **Short wavelength injection Laser**
  - ➢ low ponderomotive force at high intensity
  - ➢ weak perturbation to the wake
  - ➢ weak random heating by colliding pulses

- **Very short overlapping (injection) time**
  - ➢ much less phase mixing
  - ➢ low slice energy spread (~30keV)

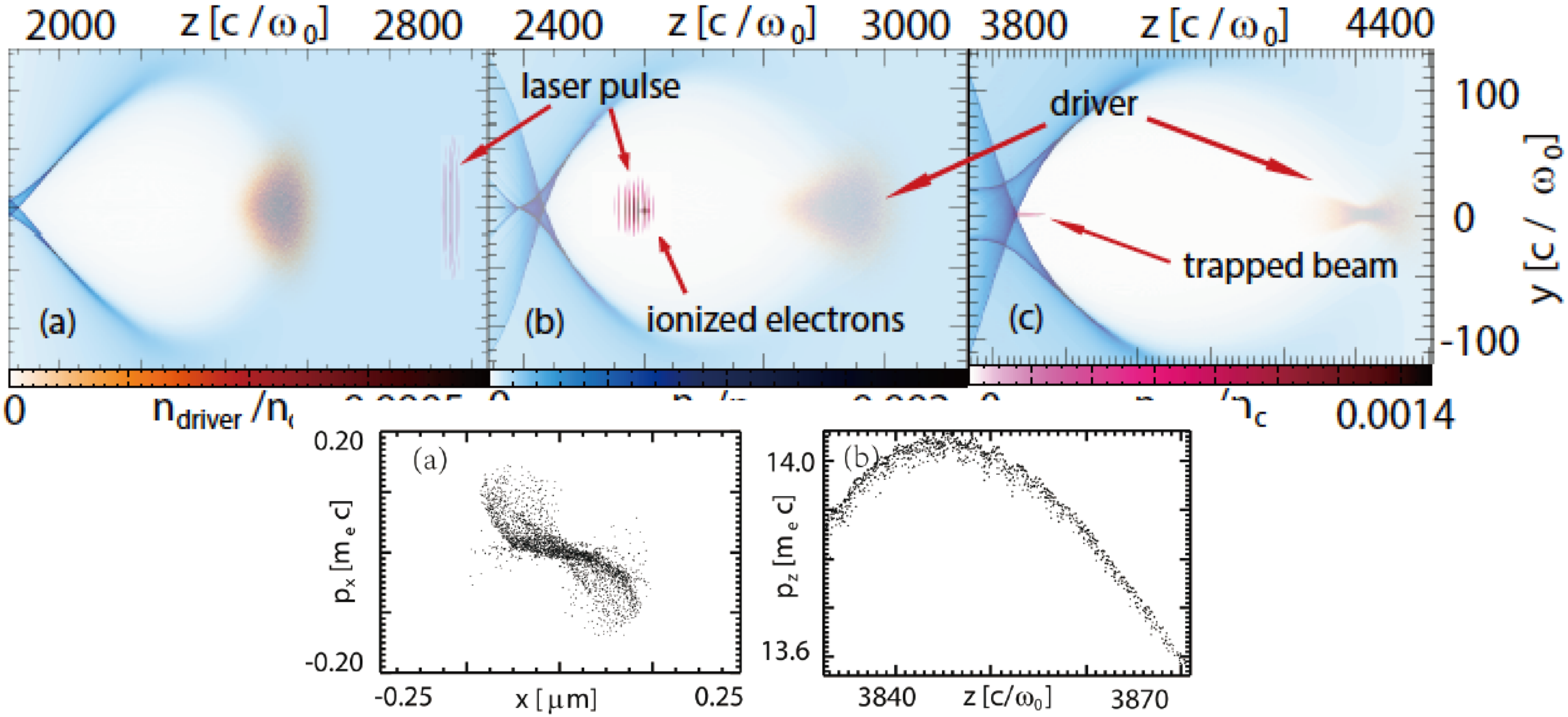


17TW 350fs CO2, 2pC of charge

Xu et al., Phys. Rev. STAB 17,061301 2014 (**co-linear and transverse colliding two color**)

Colliding ionization injection

Making the Injection time almost the same：



Very low emittance： **3nm**

Low slice energy spread: **30keV**

Relatively lower charge： **0.4pC (4.5fs)**

Y. Wan et al., arXiv：1509.09091

Summary

- ATFII will be an unique place for many interesting new research on plasma based acceleration

- many ionization based injection methods for generating high quality electron beams can be tested by using the Linac and the CO_2 laser at ATFII