中国科学院高能物理研究所

Studies of beam quality control in plasma accelerators at IHEP

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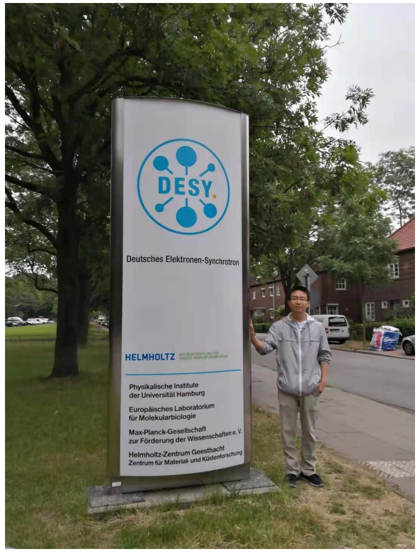
Contents

Introduction to myself

- 2015 PhD. at Shanghai Jiao Tong Univ.
- 2015-2017 post-doc
 at ELI-NP

- 2017-2020 DESY Fellow



- 2020- Associate professor at IHEP

Acknowledge to my group

- Plasma Acceleration group at IHEP
  - Prof. Jie Gao, Prof. Dazhang Li, and myself
  - 5 students

- Collaborations
  - Prof. Wei Lu at Tsinghua Univ.
  - Prof. Weiming An at Beijing Normal Univ.
  - Prof. Min Chen at Shanghai Jiao Tong Univ.

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Contents

Review of Plasma Acceleration

- In 1979, Tajima & Dawson proposed laser-plasma acceleration, which has 1000 higher gradient compared with RF accelerators
- In 1985, P. Chen et al. proposed similar acceleration mechanism driven by charged particles
- In 2004, three groups obtained mono-energetic beams from laser driven plasma wakefield accelerators (LWFA)
- In 2019, LWFA has reached the energy gain of ~8 GeV
- In 2021, the low energy spread record has reached ~0.3%
- Now, plasma acceleration studies are mainly aiming for real applications

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[(a)]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024

PHYSICAL REVIEW LETTERS **122,** 084801 (2019)

Editors' Suggestion | Featured in Physics

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

A. J. Gonsalves,[1,*] K. Nakamura,[1] J. Daniels,[1] C. Benedetti,[1] C. Pieronek,[1,2] T. C. H. de Raadt,[1] S. Steinke,[1] J. H. Bin,[1] S. S. Bulanov,[1] J. van Tilborg,[1] C. G. R. Geddes,[1] C. B. Schroeder,[1,2] Cs. Tóth,[1] E. Esarey,[1] K. Swanson,[1,2] L. Fan-Chiang,[1,2] G. Bagdasarov,[3,4] N. Bobrova,[3,5] V. Gasilov,[3,4] G. Korn,[6] P. Sasorov,[3,6] and W. P. Leemans[1,2,†]
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[2]*University of California, Berkeley, California 94720, USA*
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[5]*Faculty of Nuclear Science and Physical Engineering, CTU in Prague, Brehova 7, Prague 1, Czech Republic*
[6]*Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, 182 21 Prague, Czech Republic*

PHYSICAL REVIEW LETTERS **126,** 214801 (2021)

Near-GeV Electron Beams at a Few Per-Mille Level from a Laser Wakefield Accelerator via Density-Tailored Plasma

L. T. Ke,[1,2] K. Feng,[1] W. T. Wang,[1,*] Z. Y. Qin,[3,†] C. H. Yu,[3] Y. Wu,[1] Y. Chen,[1] R. Qi,[1] Z. J. Zhang,[3] Y. Xu,[1] X. J. Yang,[1] Y. X. Leng,[1,4] J. S. Liu,[1,3,‡] R. X. Li,[1,2,4,§] and Z. Z. Xu[1,2,4]
[1]*State Key Laboratory of High Field Laser Physics and CAS Center for Excellence in Ultra-intense Laser Science, Shanghai Institute of Optics and Fine Mechanics (SIOM), Chinese Academy of Sciences (CAS), Shanghai 201800, China*
[2]*Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[3]*Department of Physics, Shanghai Normal University, Shanghai 200234, People's Republic of China*
[4]*School of Physical Science and Technology, Shanghai Tech University, Shanghai 200031, People's Republic of China*

High quality injection: a key issue for the optimization

- Optimization of multiple parameters is required in plasma accelerators
- Energy spread and charge mainly depend on the injection process
- Energy spread and charge are contradictory parameters
- Optimized injection mechanism is required to alleviate the contradiction

	RF accelerators	Plasma accelerators
Acceleration gradient (MeV/m)	10 ~ 50	10^3 ~ 10^5
Maximum energy (GeV)	~ 6000	~ 10
Energy spread	<0.1%	10% ~ 0.3%
Bunch charge (nC)	10	<1
Normalized emittance (mm mrad)	<100	<10

To be optimized

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1D injection theory

- Constant of motion in wakefield

$$H = \gamma - v_\phi p_z - \psi = \text{const.}$$

where the pseudo-potential is defined as

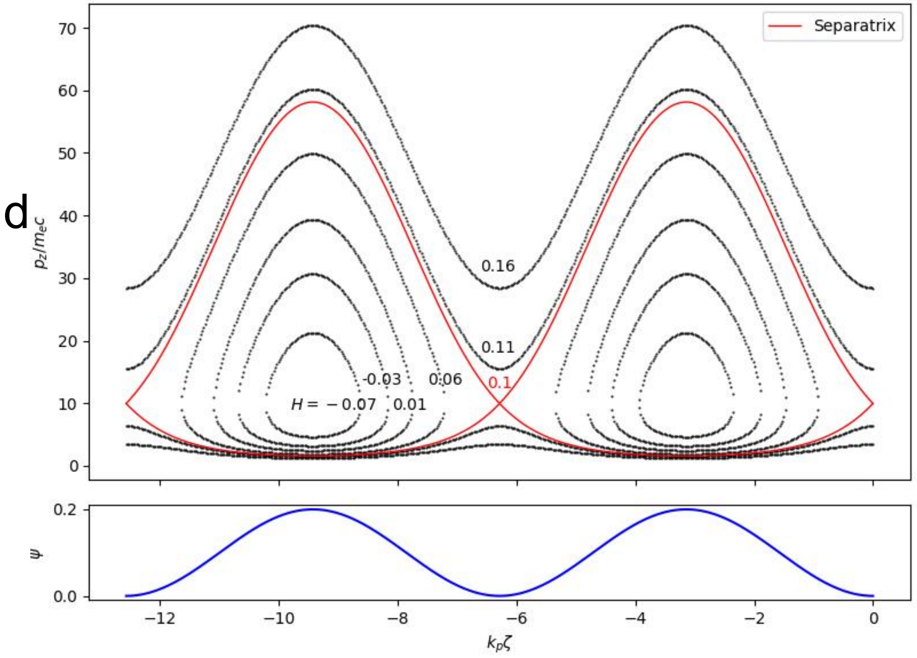
$$\psi \equiv \varphi - v_\phi A_z$$

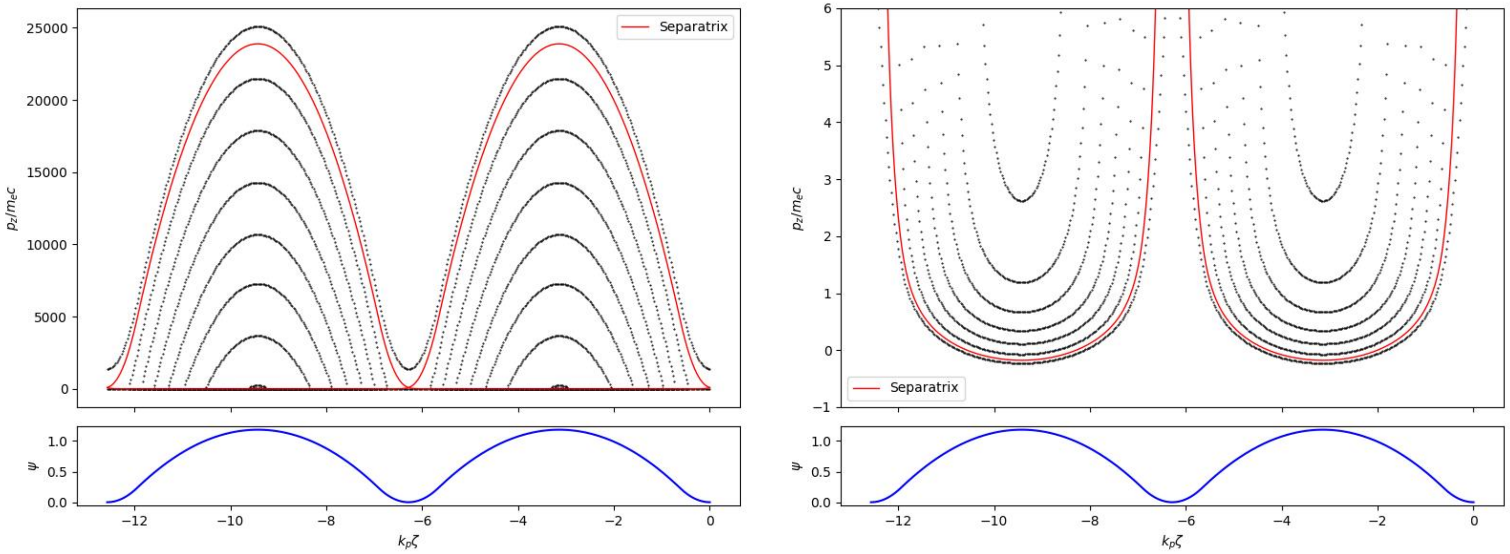
- For 1D cases, $p = p_z$, $\gamma = \sqrt{1+p^2}$
- The solution is one branch of the hyperbola

$$(H + \psi + v_\phi p)^2 - p^2 = 1$$

with $H + \psi + v_\phi p > 0$

Linear wakefield





Nonlinear wakefield

3D injection theory

- The constant of motion is the same, but $\gamma = \sqrt{1 + |\mathbf{p}_\perp|^2 + p_z^2}$
- Subscript 0 stands for the initial value, and subscript 1 stands for the instant value
- When injection occurs, $v_{z1} = v_\phi$, so that

$$\gamma_1 - v_\phi p_{z1} = \gamma_\phi^{-1}\sqrt{1 + |\mathbf{p}_{\perp 1}|^2}$$

where $\gamma_\phi = 1/\sqrt{1 - v_\phi^2}$

- Use the constant of motion we obtain

$$\gamma_0 - p_{z0} = -\Delta\psi + \frac{\sqrt{1 + |\mathbf{p}_{\perp 1}|^2}}{\gamma_\phi} - \frac{p_{z0}}{2\gamma_\phi^2} = -\Delta\psi + \mathcal{O}\left(\gamma_\phi^{-1}\right)$$

where $-\Delta\psi \equiv \psi_0 - \psi_1$

- So the injection can be discriminated by the initial state of the particle and the property of the wakefield

M. Zeng et al., New J. Phys. 22, 123003 (2020)

Main injection categories

$$\gamma_0 - p_{z0} = -\Delta\psi + \frac{\sqrt{1 + |\mathbf{p}_{\perp 1}|^2}}{\gamma_\phi} - \frac{p_{z0}}{2\gamma_\phi^2} = -\Delta\psi + \mathcal{O}\left(\gamma_\phi^{-1}\right)$$

- Ionization injection
  - In the wakefield $-\Delta\psi \geq 1$ exists, so we can release electrons (with 0 initial momentum) in there wakefield where $-\Delta\psi = 1$ is satisfied
- Optical injection
  - No need to have $-\Delta\psi \geq 1$. Use laser colliding or beating to pre-accelerate the electrons so that $\gamma_0 - p_{z0} < 1$
- Injection with reduced phase velocity
  - Reduce the phase velocity of the wakefield (reduce γ_ϕ), so that there can be RHS ≥ 1

Ponderomotive injections

- Pre-accelerate the electrons by a transverse colliding laser pulse
- Initially proposed by using a laser from 90° direction
- Recently mostly realized by 90° to 180° collision angle (commonly accompanied by other injection mechanisms)

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.

PHYSICAL REVIEW LETTERS **121,** 104801 (2018)

Electron Trapping from Interactions between Laser-Driven Relativistic Plasma Waves

Grigory Golovin,[1] Wenchao Yan,[1] Ji Luo,[2,3] Colton Fruhling,[1] Dan Haden,[1] Baozhen Zhao,[1] Cheng Liu,[1] Min Chen,[2,3] Shouyuan Chen,[1] Ping Zhang,[1] Sudeep Banerjee,[1] and Donald Umstadter[1,*]
[1]*Department of Physics and Astronomy, University of Nebraska-Lincoln, Lincoln, Nebraska 68588, USA*
[2]*Key Laboratory for Laser Plasmas (Ministry of Education) and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
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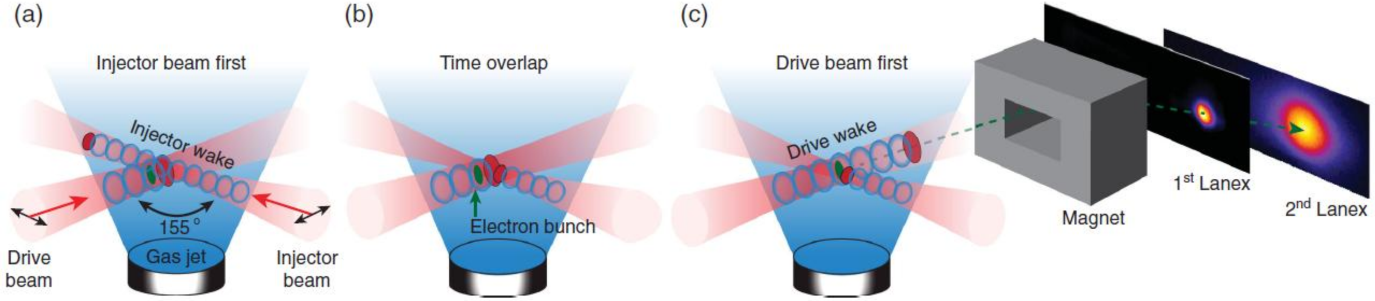
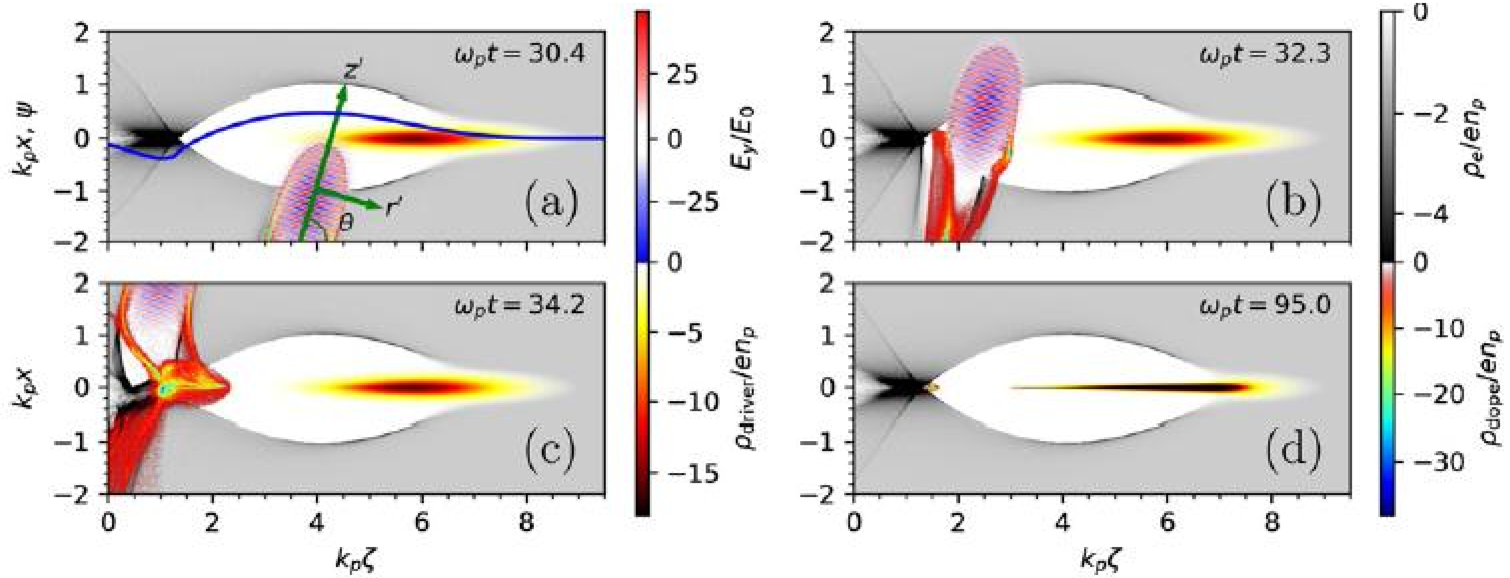
(Received 15 December 2017; published 7 September 2018)

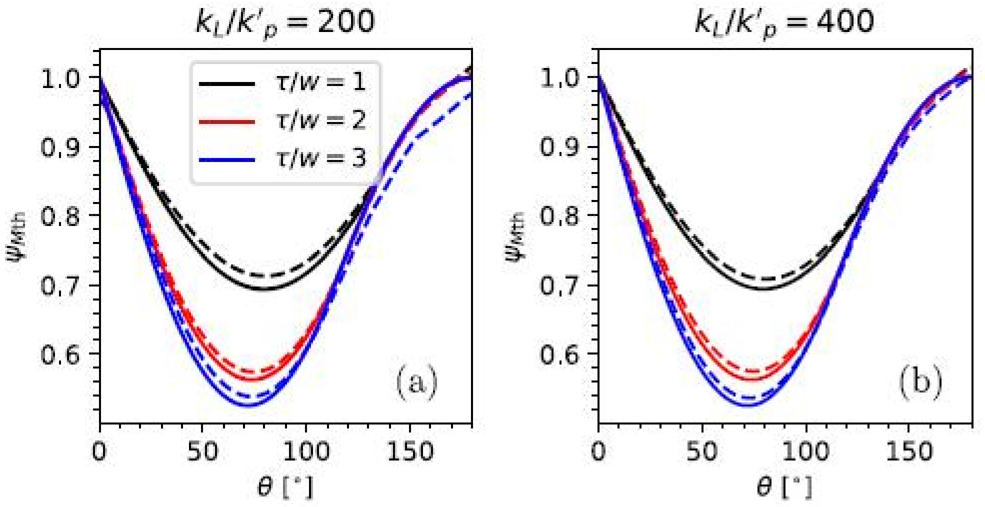
Interactions of large-amplitude relativistic plasma waves were investigated experimentally by propagating two synchronized ultraintense femtosecond laser pulses in plasma at oblique crossing angles to each other. The electrostatic and electromagnetic fields of the colliding waves acted to preaccelerate and trap electrons via previously predicted, but untested injection mechanisms of ponderomotive drift and wake-wake interference. High-quality energetic electron beams were produced, also revealing valuable new information about plasma-wave dynamics.



Optimized ponderomotive injection: acute angle collision

- An acute angle collision provides more forward momentum
- Use high-Z gas to provide electron in the blowout wakefield
- Our study shows that the optimal angle is mostly between 70º-80º, and is not significantly depends on the aspect ratio of the laser pulse
- With the laser parameter $a_0{\sim}1$, the injection threshold can already be largely reduced

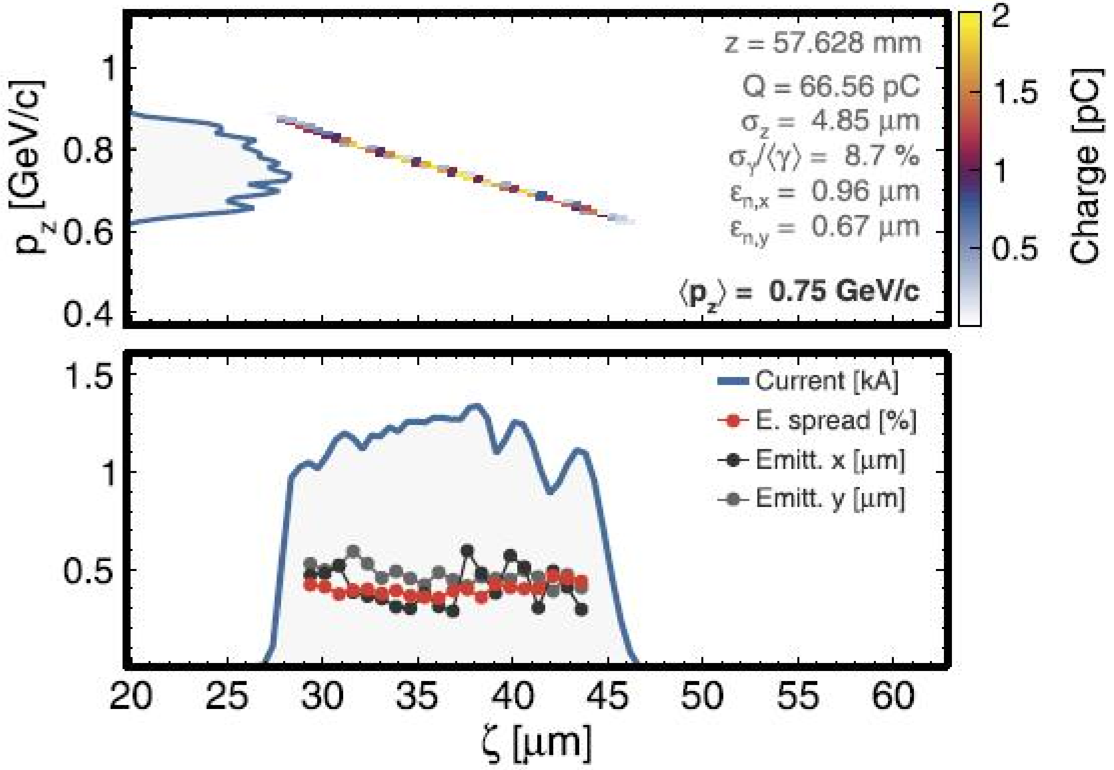




M. Zeng et al., New J. Phys. 22, 123003 (2020)

Optimized ponderomotive injection: acute angle collision

- Even if the driver is not strong enough, e.g. $-\Delta\psi < 1$ with 3 kA beam driver, this scheme can produce high quality injection
- The injection threshold is a filter, and only high-quality part of the injected beam remains in the wakefield



Ionization injection

- For strong enough drivers, $-\Delta\psi \geq 1$ exists
- Plasma is doped with high-Z gas element such as N and O, which releases inner-shell electrons inside the wakefield
- These electrons are trapped at $-\Delta\psi \approx 1$

-M. Chen et al., J. Appl. Phys. 99, 056109 (2006);

-C. McGuffey et al., Phys. Rev. Lett. 104, 025004 (2010);

-A. Pak et al., Phys. Rev. Lett. 104, 025003 (2010);

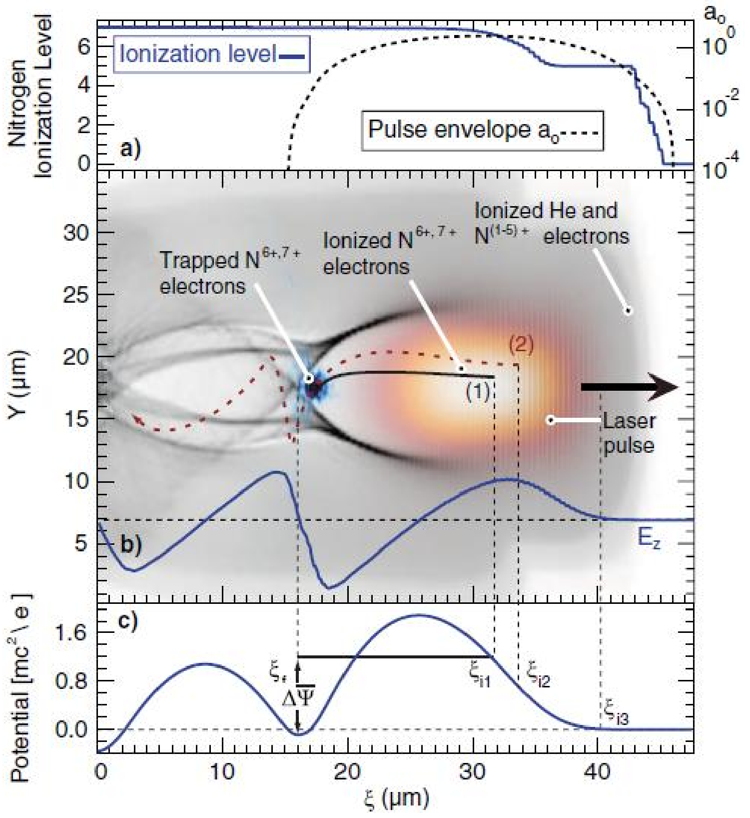
-C. E. Clayton et al., Phys. Rev. Lett. 105, 105003 (2010);

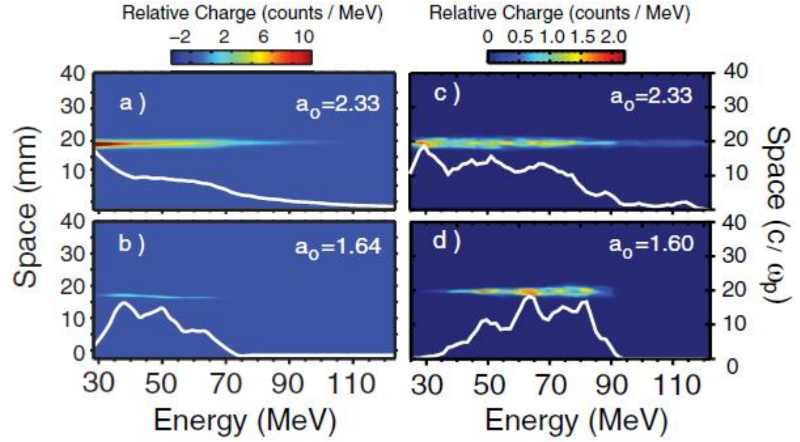
-B. Hiddinget al., Phys. Rev. Lett. 108, 035001 (2012);

-B. B. Pollock et al., Phys. Rev. Lett. 107, 045001 (2011);

-J. S. Liu et al., Phys. Rev. Lett. 107, 035001 (2011).

- Cons: injection is continuous, which leads to broad energy spread, unless extra methods are applied





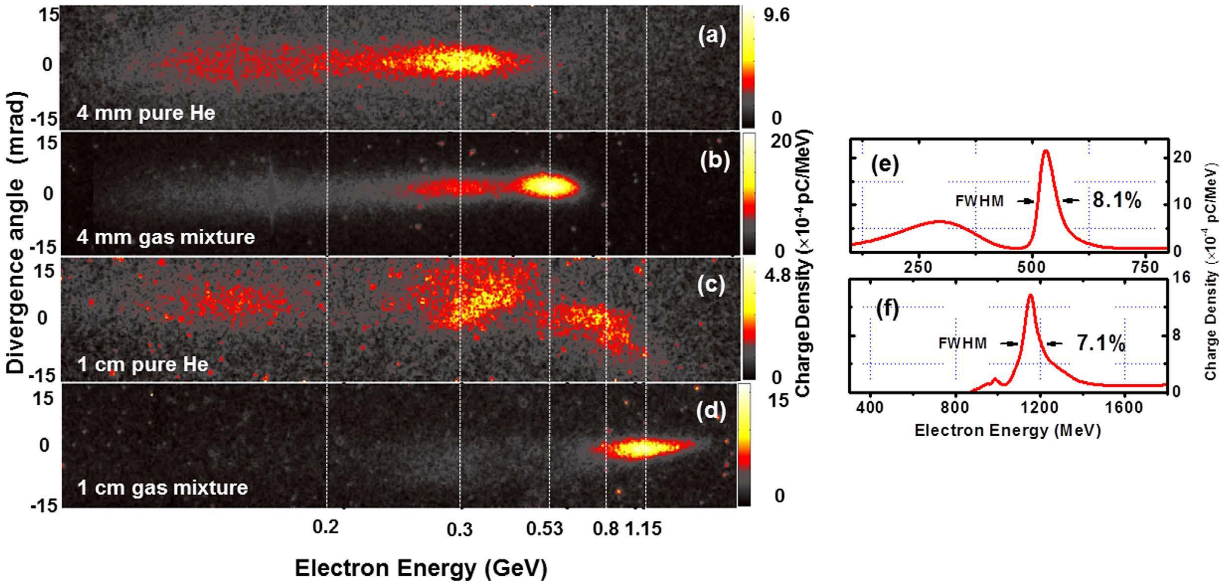
A. Pak et al., Phys. Rev. Lett. 104, 025003 (2010)

My early work 1: self-truncated ionization injection

- Use laser spot size relatively larger than the matched size, so that the ionization injection is automatically stopped during the propagation

-M. Zeng et al., Phys. Plasmas **21**, 030701 (2014)

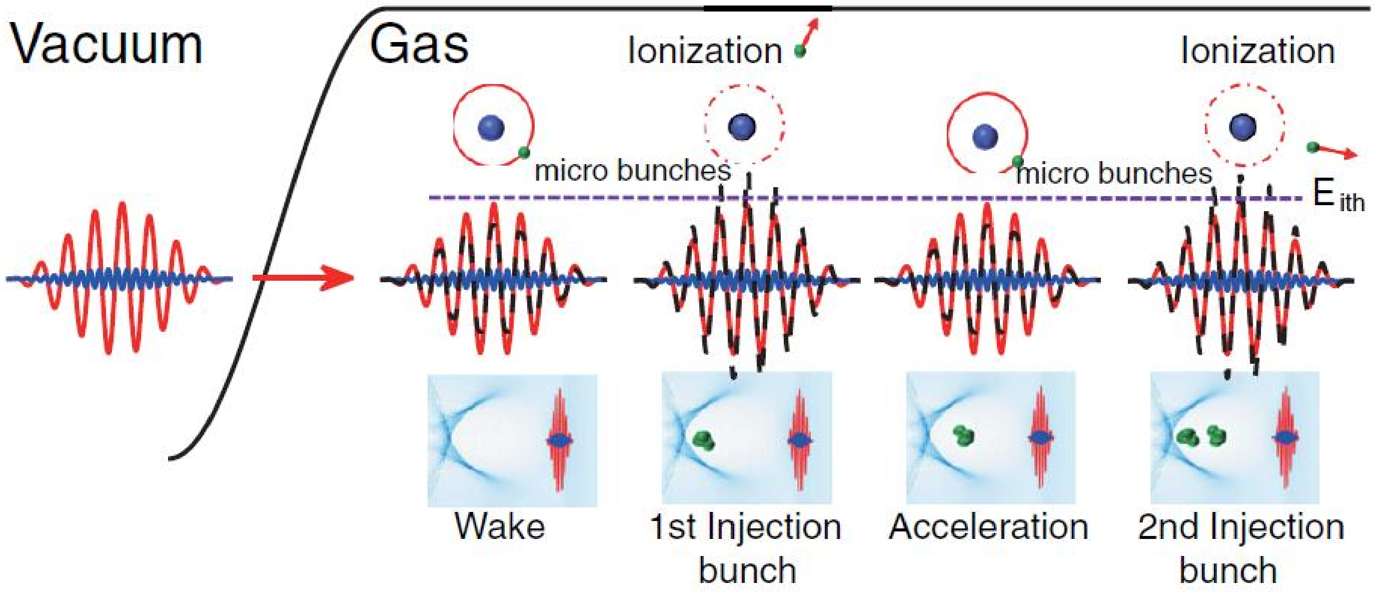
-M. Mirzaie, S. Li, M. Zeng et al., Sci. Rep. 5:14659 (2015)



- This optimization has been widely used worldwide

My early work 2: ionization injection by beating of dual-color lasers

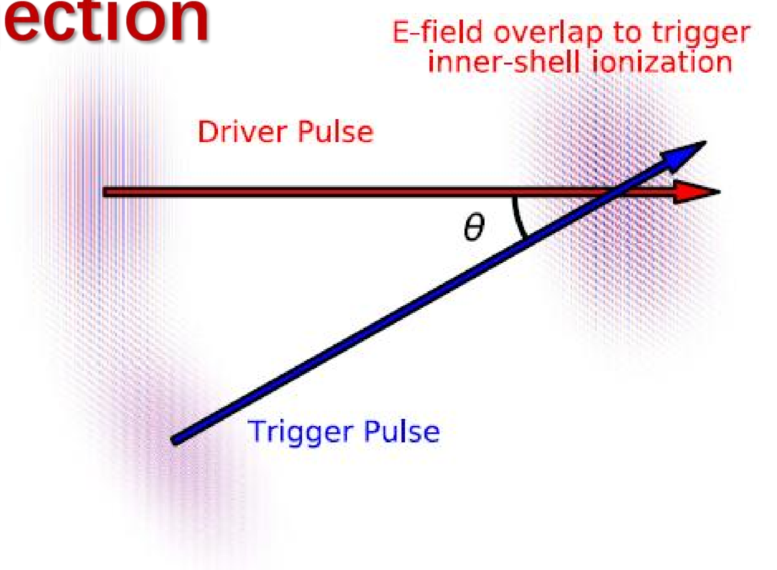
- Use dual-color laser with wavelength ratio of 3:1 and intensity ratio of 9:1, the ionization threshold is reached in separated regions
- Multiple high-quality bunches can be produced
  - -M. Zeng et al., Phys. Rev. Lett. 114, 084801 (2015)
  - -M. Zeng et al., Phys. Plasmas 23, 063113 (2016)

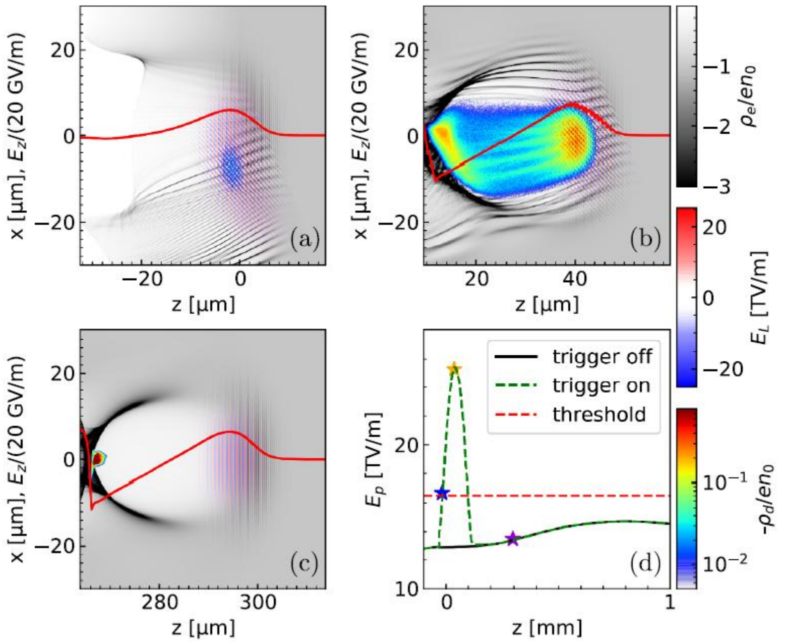


- Experimental verification is pending

Our recent optimization: Scissor-cross ionization injection

- The trigger laser collide with the drive laser with an acute angle
- The instant E-field exceeds the ionization threshold when the two lasers overlap
- The injection length and beam quality can be controlled by the collision angle
  - Very small angle (<20°), long injection length, large energy spread and large charge
  - Moderate angle (~30°), small energy spread and moderate charge
  - large angle (>60°), large energy spread and large charge, gradually turns to optical injection, and ionization injection is suppressed
- 40 pC, 1.6% energy spread beam can be produced





Jia Wang, Ming Zeng et al., Plasma Phys. Control. Fusion 64 (2022) 045012

Injection with reduced phase velocity

- Phase velocity can be changed commonly by plasma density gradient

-S. Bulanov et al., Phys. Rev. E 58, 5257 (1998);

-A. Buck et al., Phys. Rev. Lett. 110, 185006 (2013);

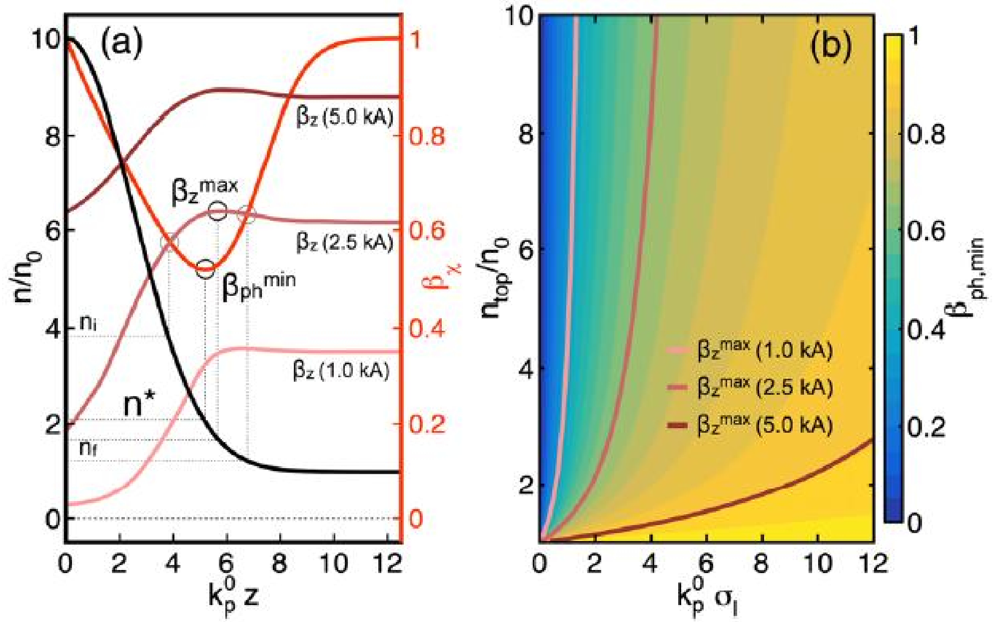
-W. T. Wang et al., Phys. Rev. Lett. 117, 124801 (2016);
-X. L. Xu et al., Phys. Rev. Accel. Beams 20, 111303 (2017);

-A. Martinez de la Ossa et al., Phys. Rev. Accel. Beams 20, 091301 (2017);

-L. T. Ke et al., Phys. Rev. Lett. 126, 214801 (2021);

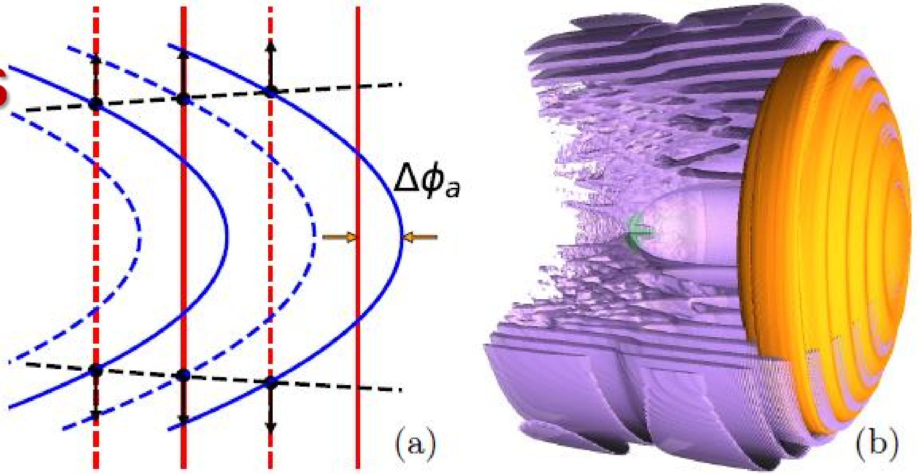
- Also possible by drivers with flying-focus

-F. Li et al., Phys. Rev. Lett. 128, 174803 (2022)



A. Martinez de la Ossa et al., Phys. Rev. Accel. Beams 20, 091301 (2017)

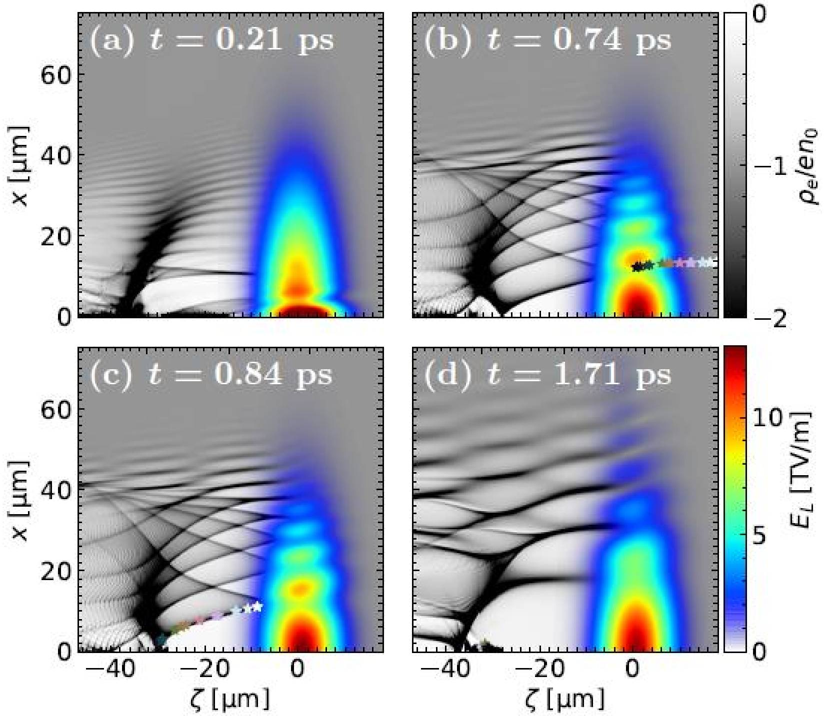
Our optimization: interference by coaxial lasers



- Drive laser is relatively loosely focused
- Trigger laser is tightly focused and coaxially propagates, forming Onion-like wakefield structure
- The inner bubble expands during the propagation because of the defocusing of the trigger laser
- The innermost bubble radius is

$$r_c^* \approx \sqrt{\frac{3\pi + 2\Delta\phi_{-\infty}}{k}}\sqrt{z - z_{f1}}$$

- The innermost bubble length is also elongated, so that the phase velocity is reduced



Jia Wang et al., Matter Radiat. Extremes 7, 054001 (2022)

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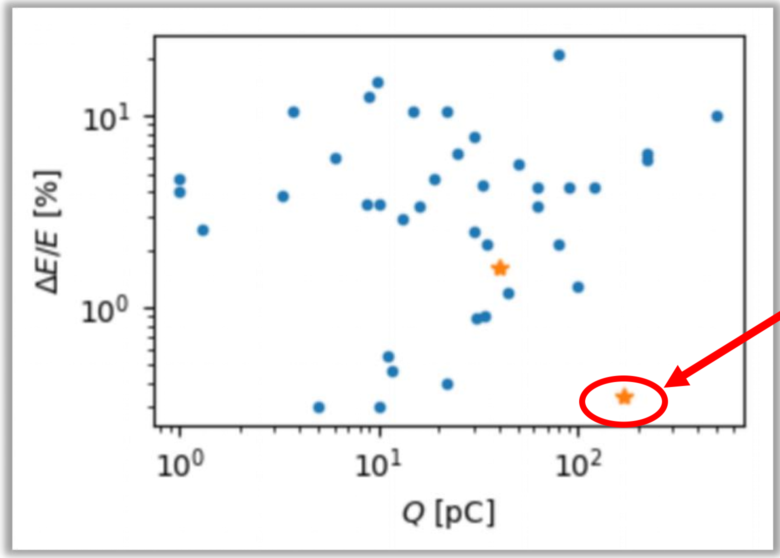
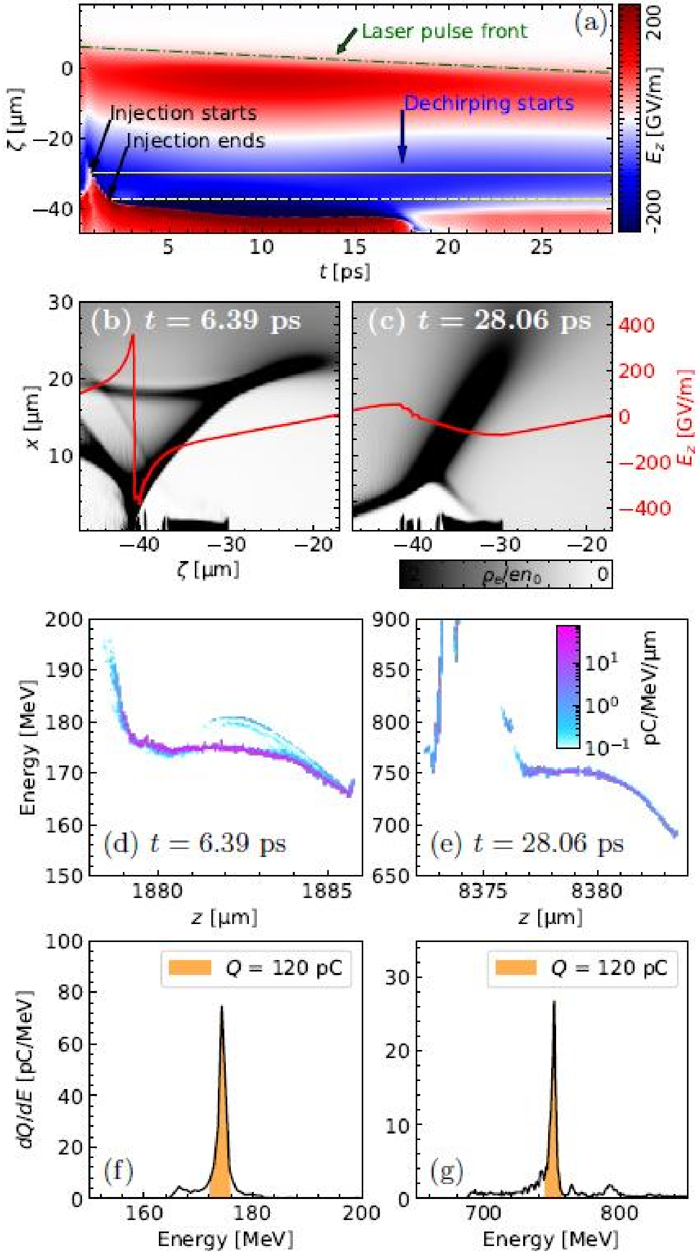
Interference by coaxial lasers

- Large charge due to long injection length, but low slice energy spread
- After self-dechirping, energy spread of the whole beam is reduced to the same level
- A breakthrough of simultaneous optimization of energy spread and charge



A collection of energy spread vs. charge from published results



Jia Wang et al., Matter Radiat. Extremes 7, 054001 (2022)

Contents

Betatron oscillation in plasma accelerators: long-term radiation reaction

- The restoring force

$$F_r \propto -\kappa^2 r$$

with the parameter $\kappa = 1/\sqrt{2}$ in blowout regime

- The transverse motion of single electron

$$\ddot{x} + \frac{\dot{\gamma}}{\gamma}\dot{x} + \frac{\kappa^2}{\gamma}x = 0$$

- In the limit $\dot{\gamma}/\gamma \ll 1$, betatron frequency is

$$\omega_\beta = \frac{\kappa}{\sqrt{\gamma}}$$

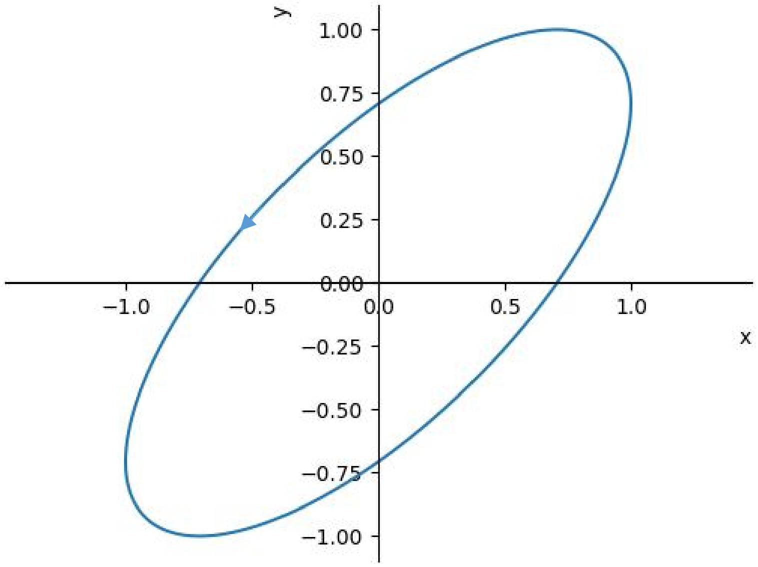
- Radiation reaction reduces the acceleration, and has transverse cooling effect
- There is asymptotic solution with extremely long acceleration and extremely high energy: longitudinal radiation reaction force=acceleration force×2/3

-A. Deng et al., Phys. Rev. ST Accel. Beams 15, 081303 (2012);

-I. Yu. Kostyukov et al., Phys. Rev. ST Accel. Beams 15, 111001 (2012)

- How about before reaching asymptotic solution? A important question for large scale plasma accelerator design.

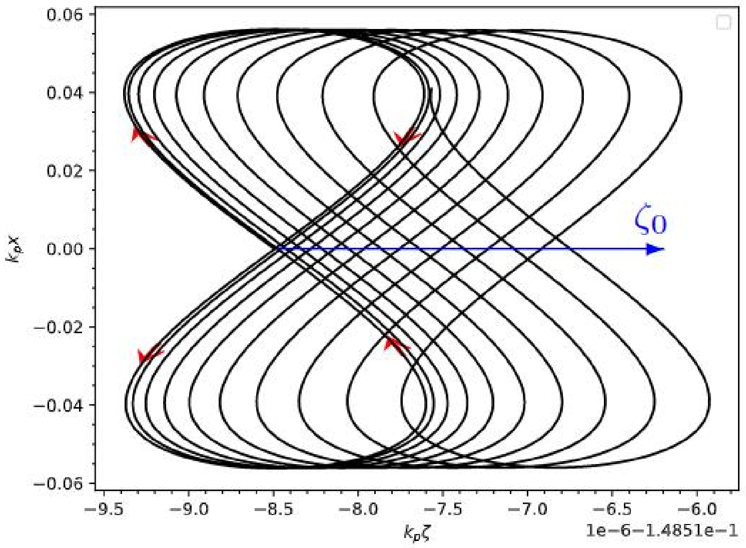
3D betatron oscillation model



- In transverse space, electron trajectory is an ellipse in general
- Consider the general form of E- and B-field in a blowout wakefield

$$
\begin{aligned}
E_z &= E_{z0} + \lambda\zeta_1, \\
\vec{E}_\perp &= \kappa^2 (1-\lambda)\,\vec{r}, \\
B_\theta &= -\kappa^2 \lambda r,
\end{aligned}
$$

where E_{z0} is the averaged longitudinal E-field, ζ_1 is the high-frequency component of the comoving coordinate, λ is the slop of longitudinal E-field



- The forces including the radiation reaction are

$$
\begin{aligned}
f_z &= -E_{z0} - \lambda\zeta_1 + \kappa^2\lambda(x\beta_x + y\beta_y) + f_z^{\mathrm{rad}}, \\
f_x &= -\kappa^2 (1-\lambda+\lambda\beta_z)\, x + f_x^{\mathrm{rad}}, \\
f_y &= -\kappa^2 (1-\lambda+\lambda\beta_z)\, y + f_y^{\mathrm{rad}},
\end{aligned}
$$

3D betatron oscillation model

- The radiation reaction force in LAD form

$$F_\mu^{\mathrm{rad}} = \frac{2}{3} k_p r_e \left[\frac{d^2 P_\mu}{d\tau^2} + \left(\frac{dP_\nu}{d\tau} \frac{dP^\nu}{d\tau} \right) P_\mu \right]$$

- The longitudinal oscillations can be expressed by the transverse terms
- The equations of motion become

$$\begin{aligned}
\dot{\gamma} &= -E_{z0}\beta_{z0} + \boxed{\left(\frac{\lambda\beta_{z0}}{4} + \kappa^2\lambda - \kappa^2 \right) (x\beta_x + y\beta_y)} - \frac{2}{3} k_p r_e \gamma^2 \kappa^4 \left(x^2 + y^2 \right), \\
\dot{p_z} &= -E_{z0} + \boxed{\lambda \left(\frac{1}{4} + \kappa^2 \right) (x\beta_x + y\beta_y)} - \frac{2}{3} k_p r_e \gamma^2 \kappa^4 \left(x^2 + y^2 \right), \\
\dot{p_x} &= -\kappa^2 x + \boxed{\frac{\kappa^2\lambda}{2} \left(\langle\gamma\rangle^{-2} + \beta_x^2 + \beta_y^2 \right) x} - \frac{2}{3} k_p r_e \gamma^2 \kappa^4 \left(x^2 + y^2 \right) \beta_x, \\
\dot{p_y} &= -\kappa^2 y + \boxed{\frac{\kappa^2\lambda}{2} \left(\langle\gamma\rangle^{-2} + \beta_x^2 + \beta_y^2 \right) y} - \frac{2}{3} k_p r_e \gamma^2 \kappa^4 \left(x^2 + y^2 \right) \beta_y,
\end{aligned}$$

The averaging of the 3D betatron oscillations

- We use the same averaging method as in I. Y. Kostyuk et al., PRAB **15**, 111001 (2012), and introduce two complex variables

$$U = \left(x - i\kappa^{-1}\gamma^{\frac{1}{2}}\beta_x\right)e^{-i\varphi},$$
$$V = \left(y - i\kappa^{-1}\gamma^{\frac{1}{2}}\beta_y\right)e^{-i\varphi},$$

where $\varphi = \int \omega_\beta dt = \kappa \int \gamma^{-\frac{1}{2}} dt$

- x, y, β_x, β_y, p_x, p_y can be expressed by U and V, and averaged equations can be obtained

$$\langle\dot{\gamma}\rangle = -E_{z0}\beta_{z0} - \frac{1}{3}k_p r_e \kappa^4 \langle\gamma\rangle^2 \left(|U|^2 + |V|^2\right),$$

Energy change

$$\langle\dot{\zeta}\rangle = \frac{1}{2}\gamma_w^{-2} - \frac{1}{2}\langle\gamma\rangle^{-2} - \frac{1}{4}\kappa^2\langle\gamma\rangle^{-1}\left(|U|^2 + |V|^2\right),$$

Longitudinal phase change

$$\dot{U} = \frac{1}{4}E_{z0}\beta_{z0}\langle\gamma\rangle^{-1}U - \frac{1}{24}k_p r_e \kappa^4 \langle\gamma\rangle \left(|U|^2 U + 2|V|^2 U - V^2 U^*\right) + i\frac{1}{64}\kappa\lambda\beta_{z0}\langle\gamma\rangle^{-\frac{3}{2}}\left(|U|^2 U + V^2 U^*\right)$$
$$- i\frac{1}{16}\kappa^3\langle\gamma\rangle^{-\frac{3}{2}}\left[\left(|U|^2 + 2\lambda|V|^2\right)U - (2\lambda - 1)V^2 U^*\right] - i\frac{1}{4}\kappa\lambda\langle\gamma\rangle^{-\frac{5}{2}}U.$$

betatron amplitude and phase change

Simplifying the averaged equations

- Decompose the complex variables

$$
\begin{aligned}
U &= |U|\, e^{i\Phi_x}, \\
V &= |V|\, e^{i\Phi_y}, \\
\Delta\Phi &= \Phi_y - \Phi_x.
\end{aligned}
$$

- Introduce new variables (areas in the transverse phase spaces x-p_x and y-p_y)

$$
\begin{aligned}
S_x &= \kappa \langle\gamma\rangle^{\frac{1}{2}} |U|^2, \\
S_y &= \kappa \langle\gamma\rangle^{\frac{1}{2}} |V|^2,
\end{aligned}
$$

- Simplified averaged equations are obtained

Simplified averaged equations (long-term equations)

$$\langle\dot{\gamma}\rangle = -E_{z0}\beta_{z0} - \frac{1}{3}k_p r_e \kappa^3 \langle\gamma\rangle^{\frac{3}{2}} (S_x + S_y)\,,$$

Energy change

$$\langle\dot{\zeta}\rangle = \frac{1}{2}\gamma_w^{-2} - \frac{1}{2}\langle\gamma\rangle^{-2} - \frac{1}{4}\kappa\langle\gamma\rangle^{-\frac{3}{2}} (S_x + S_y)\,,$$

Longitudinal phase change

$$\dot{S}_x = -\frac{1}{4}k_p r_e \kappa^3 \langle\gamma\rangle^{\frac{1}{2}} \left(S_x^2 + \frac{4-\cos 2\Delta\Phi}{3} S_x S_y\right) - \frac{1}{8}\left[\frac{1}{4}\lambda\beta_{z0} - \kappa^2(1-2\lambda)\right]\langle\gamma\rangle^{-2} S_x S_y \sin 2\Delta\Phi,$$

Phase space area change

$$\begin{aligned}\dot{\Phi}_x =& \frac{1}{24}k_p r_e \kappa^3 \langle\gamma\rangle^{\frac{1}{2}} S_y \sin 2\Delta\Phi + \frac{1}{64}\lambda\beta_{z0}\langle\gamma\rangle^{-2}(S_x + S_y\cos 2\Delta\Phi) \\ &- \frac{1}{16}\kappa^2\langle\gamma\rangle^{-2}\left[S_x + 2\lambda S_y + (1-2\lambda)S_y\cos 2\Delta\Phi\right] - \frac{1}{4}\kappa\lambda\langle\gamma\rangle^{-\frac{5}{2}}\,,\end{aligned}$$

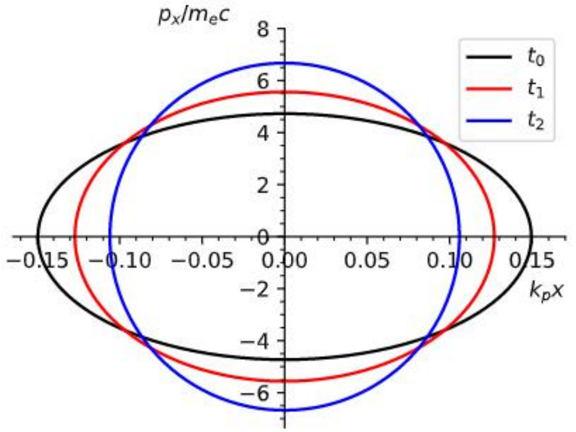
Betatron phase change

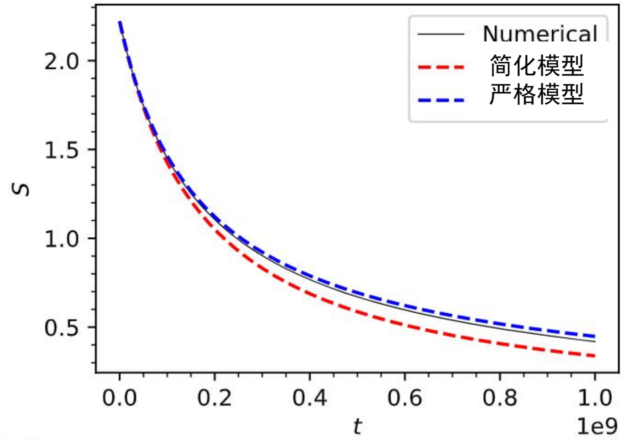
$$\frac{d\Delta\Phi}{dt} = -\frac{1}{24}k_p r_e \kappa^3 \langle\gamma\rangle^{\frac{1}{2}} (S_y + S_x)\sin 2\Delta\Phi + \frac{1}{8}\left[\frac{1}{4}\lambda\beta_{z0} - \kappa^2(1-2\lambda)\right]\langle\gamma\rangle^{-2}(S_y - S_x)\sin^2\Delta\Phi.$$

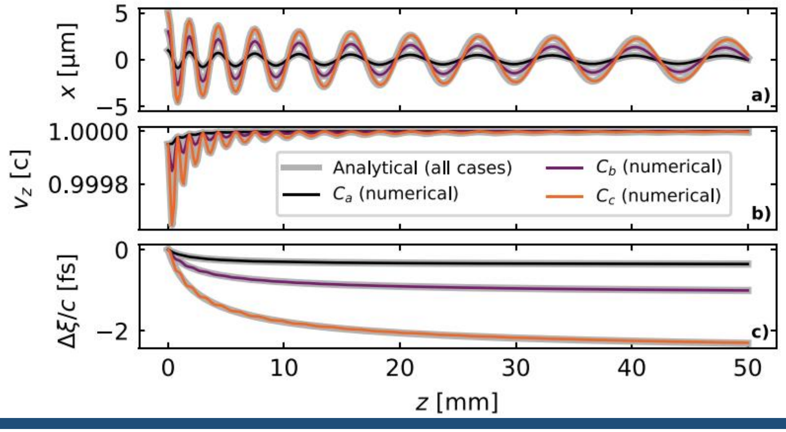
Betatron phase difference in x and y directions

Previously found phenomena

- betatron amplitude scale with $\gamma^{-\frac{1}{4}}$
- Longitudinal deceleration due to radiation reaction
  - P. Michel et al., Phys. Rev. E **74**, 026501 (2006)
- Transverse cooling
  - A. Deng et al., Phys. Rev. ST Accel. Beams **15**, 081303 (2012)
  - I. Y. Kostyuk et al., Phys. Rev. ST Accel. Beams **15**, 111001 (2012)
  - M. Zeng and K. Seto, New J. Phys. **23** 075008 (2021)
- Longitudinal phase drift
  - A. Ferran Pousa et al., Sci. Rep. 9, 10.1038/s41598-019-53887-8 (2019)







Typical values

Typical values of betatron amplitude damping

Case No.	n_p (cm^{-3})	k_p (m^{-1})	S	γ_{0max}	γ_0	L_S (m)	χ_{max}
1	10^{18}	1.88×10^5	2	5.4×10^6	1×10^5	563.2	1.9×10^{-4}
2					5×10^6	80.0	3.6×10^{-3}
3			8	2.1×10^6	1×10^5	140.8	3.9×10^{-4}
4					2×10^6	31.5	3.7×10^{-3}
5	10^{17}	5.95×10^4	2	1.2×10^7	1×10^5	5632	6.1×10^{-5}
6					1×10^7	563.2	1.9×10^{-3}
7			8	4.6×10^6	1×10^5	1408	1.2×10^{-4}
8					4×10^6	222.6	2.0×10^{-3}

M. Zeng and K. Seto, *New J. Phys.* **23** (2021) 075008

Newly found phenomena

- Longitudinal drift:
  - Electron velocity matches phase velocity
  - Electron drifts around $E_z = 0$ position with the frequency

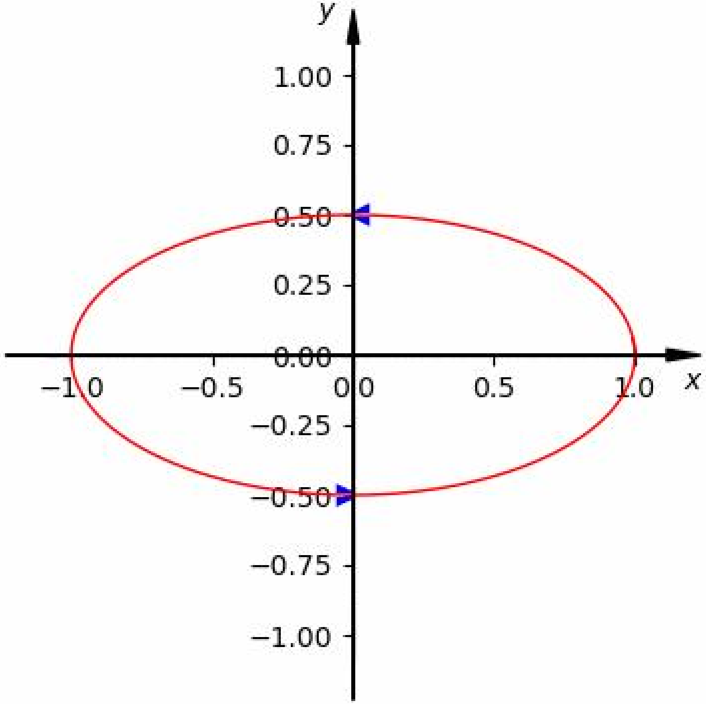
$$\omega_{\langle\zeta\rangle} = \sqrt{\lambda\beta_{z0}\left(1+\frac{3}{8}\kappa\left\langle\gamma\right\rangle^{\frac{1}{2}}S\right)\left\langle\gamma\right\rangle^{-3}}.$$

- Two regimes:
  - betatron phase shift dominate regime: $k_p r_e \gamma^{\frac{5}{2}} \ll 1$
  - betatron radiation reaction dominate regime: $k_p r_e \gamma^{\frac{5}{2}} \gg 1$

New phenomena

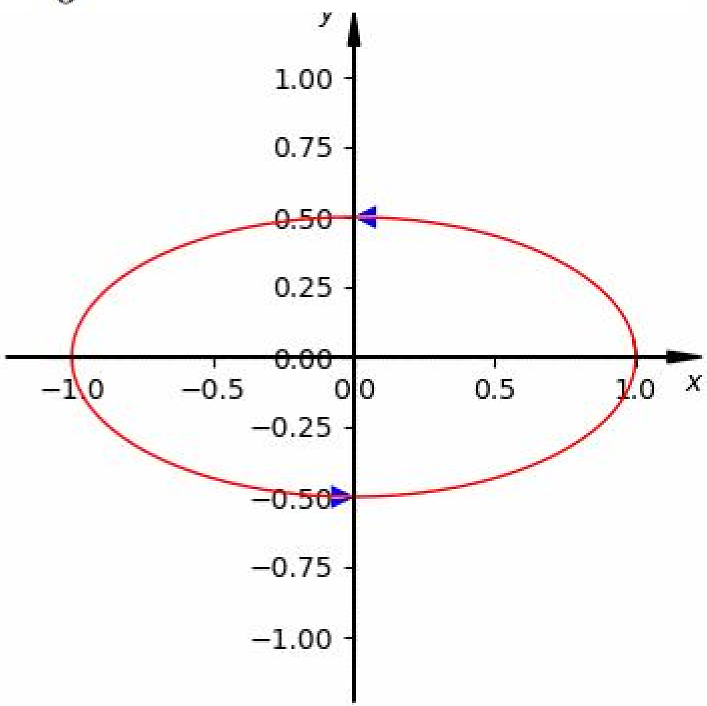
- $k_p r_e \gamma^{\frac{5}{2}} \ll 1$, elliptical betatron oscillation has precession

$$\Omega = -\frac{1}{8}\left[\frac{\lambda\beta_{z0}}{4} - \kappa^2(1-2\lambda)\right]\langle\gamma\rangle^{-2}\langle L_z\rangle$$



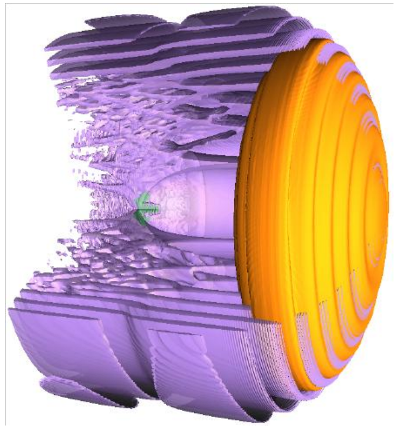
- $k_p r_e \gamma^{\frac{5}{2}} \gg 1$, elliptical betatron oscillation approaches linear polarization

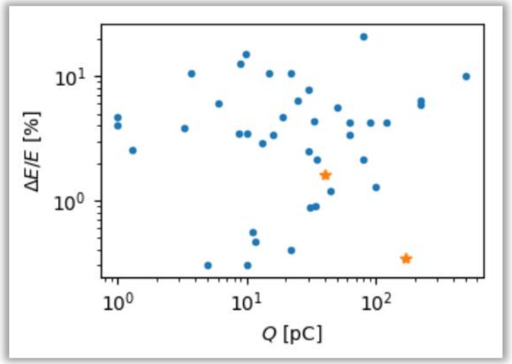
$$\dot{R} = -\frac{1}{6}k_p r_e \kappa^3 \langle\gamma\rangle^{\frac{1}{2}} R\left(S_x - S_y\right) < 0$$



Yulong Liu and Ming Zeng, Phys. Rev. Accel. Beams **26**, 031301 (2023)

Summary





- IHEP is doing several plasma acceleration researches
- High-quality injection in plasma accelerators
  - Ponderomotive injection
  - Scissor-cross ionization injection
  - Interference injection by coaxial lasers
- Betatron oscillation and radiation reaction
  - 3D betatron oscillation model
  - Averaged equations
  - Reproduce previous results
  - Find 3 new phenomena for long-distance plasma accelerators
  - Can be applied to optimization of future large-scale plasma accelerators