中国科学院高能物理研究所

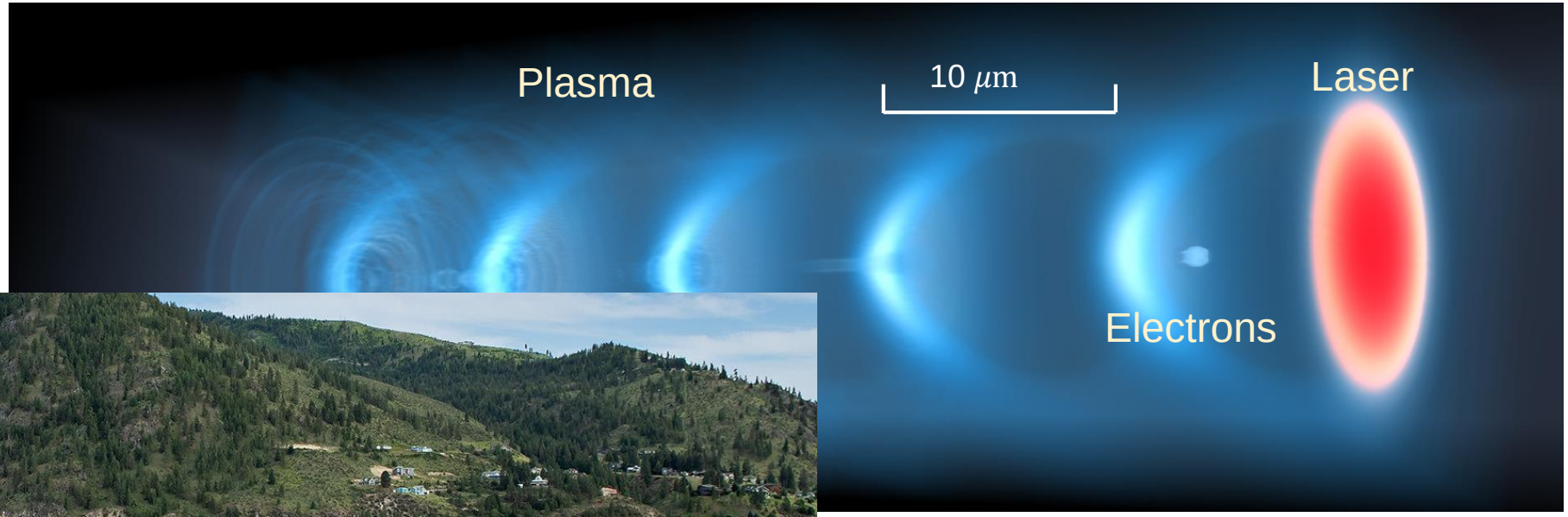
Improved injection mechanisms and the production of simultaneous high-charge small-energy-spread electron beams in laser wakefield accelerators

Ming Zeng

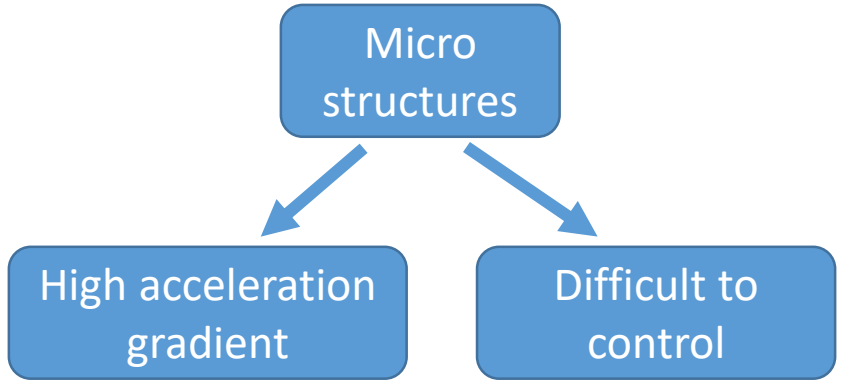
Institute of High Energy Physics, Chinese Academy of Sciences

CEPC International Workshop, 2026

What is laser wakefield acceleration?







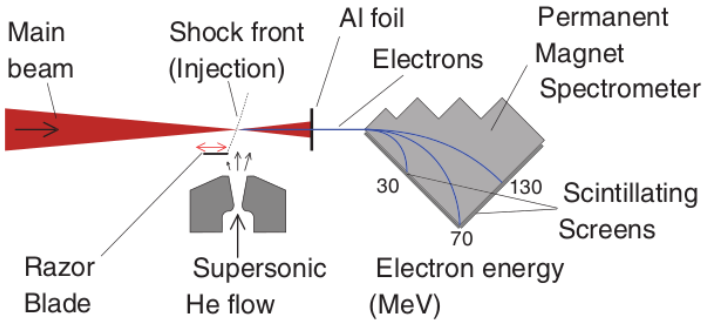
Injection mechanisms

- Self-injection



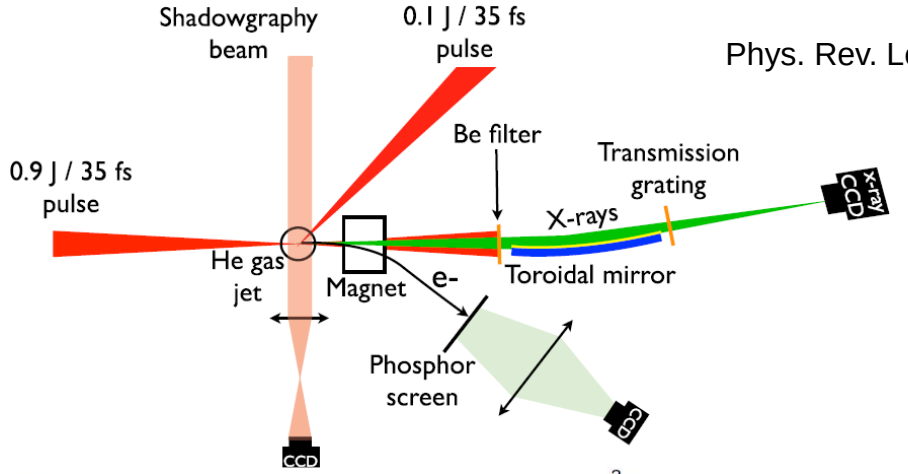


- Shock (density gradient) injection

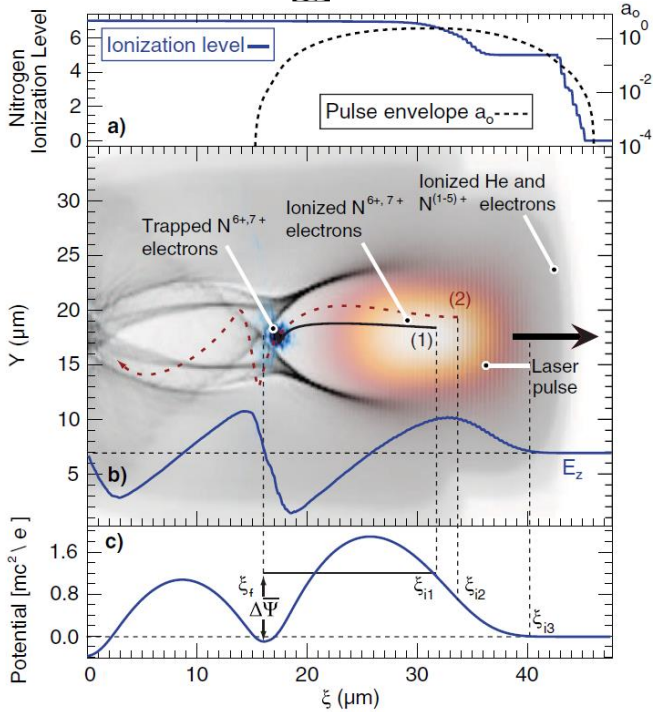


Phys. Rev. Lett. 110, 185006 (2013)

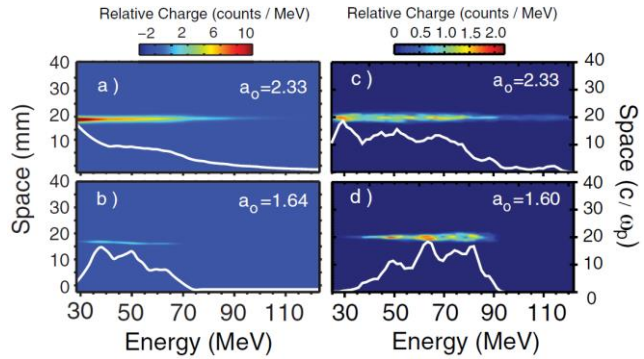
- Optical (colliding laser) injection



Phys. Rev. Lett. 107, 255003 (2011)



- Ionization injection



Phys. Rev. Lett. 104, 025003 (2010)

The conflict of charge against energy spread

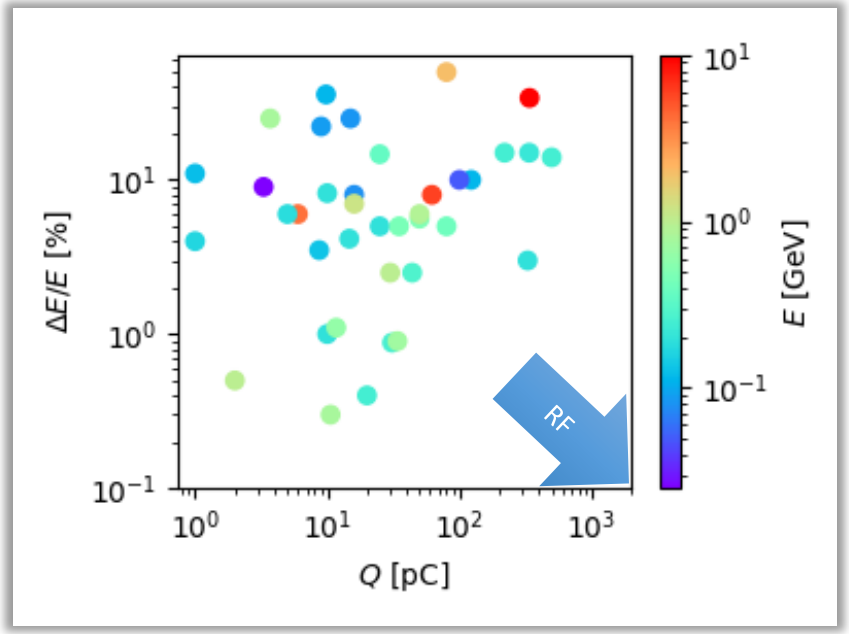
- Radio-frequency (RF) accelerators has simultaneously

$$\frac{\Delta E}{E} \lesssim 0.1\%, Q \gtrsim 1\ \mathrm{nC}$$

- Laser wakefield accelerator (LWFA) can hardly reach

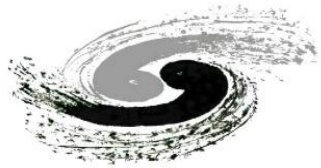
$$\frac{Q}{\Delta E/E} > 10\ \mathrm{nC}$$

- Energy efficiency (laser to monoenergetic electron beam) is extremely low ($\lesssim 1\%$)



Contents

1. Wakefield potential and injection theory
2. Scissor-cross ionization injection
3. Coaxial interference injection
4. Plasma telescope injection
5. Experiment at CoReLS



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1D injection theory

- Wakefield transition $\xi = v_\phi t - z, s = z$
- QSA $\frac{\partial}{\partial s} \approx 0$ (translational symmetry)
- Constant of motion in wakefield

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

The pseudo-potential is defined as

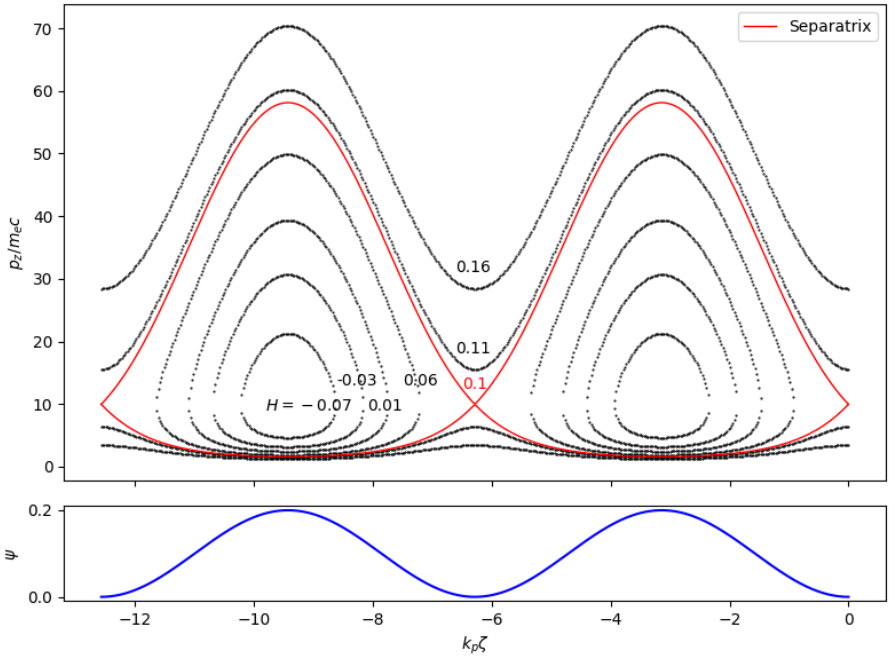
$$\psi \equiv \varphi - v_\phi A_z$$

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

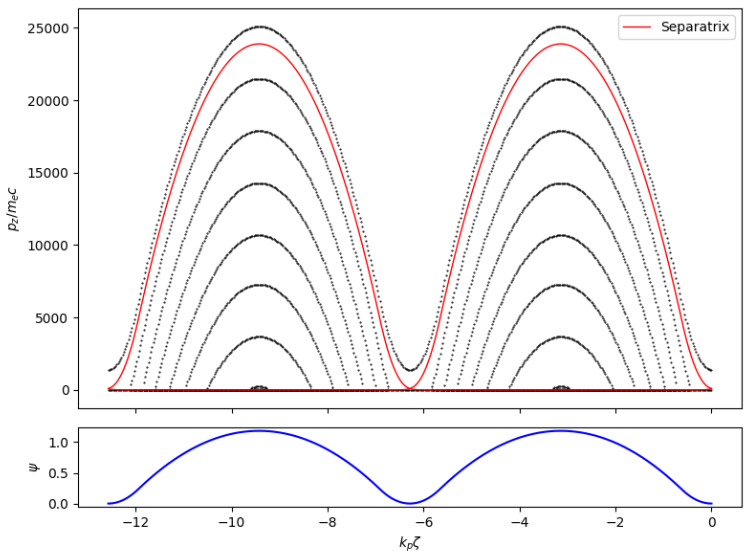
$$(H + \psi + v_\phi p)^2 - p^2 = 1$$

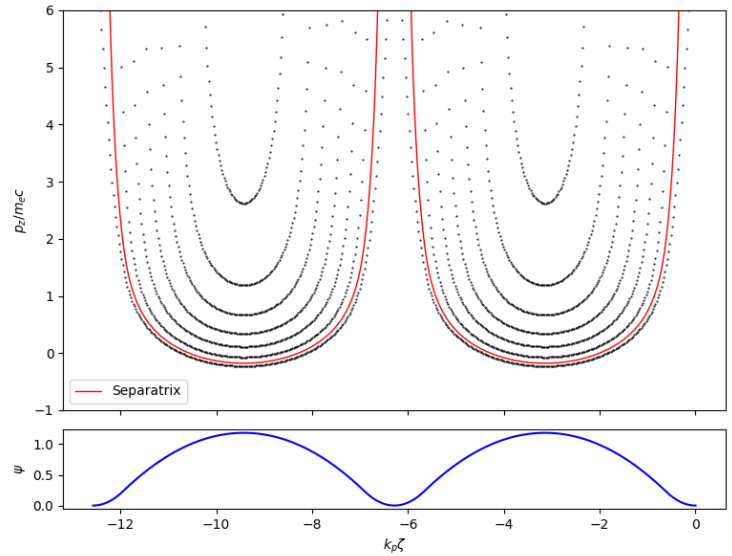
where $H + \psi + v_\phi p > 0$

Linear wakefield (small amplitude)



Non-linear wakefield (large amplitude)





3D injection theory

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

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

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

- Use the constant of motion to 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 $-\Delta\psi = \psi_0 - \psi_1$

- The injection threshold is determined by the property of the wakefield and the initial status of the electron!

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

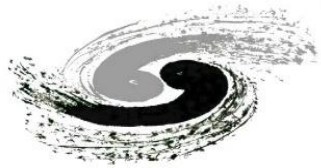
Major categories of injection schemes

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

- Ionization injection
  - Delayed ionization of electrons at $\psi_0 > 0$, so that $-\Delta\psi \geq 1$ can be satisfied
- Optical injection
  - Even though $-\Delta\psi < 1$, pre-accelerate electrons with another laser so that $\gamma_0 - p_{z0} < 1$
- Injection due to slow down of phase velocity (such as density down-ramp injection)
  - Reduce γ_ϕ, so that $\mathcal{O}\left(\gamma_\phi^{-1}\right)$ increases the RHS

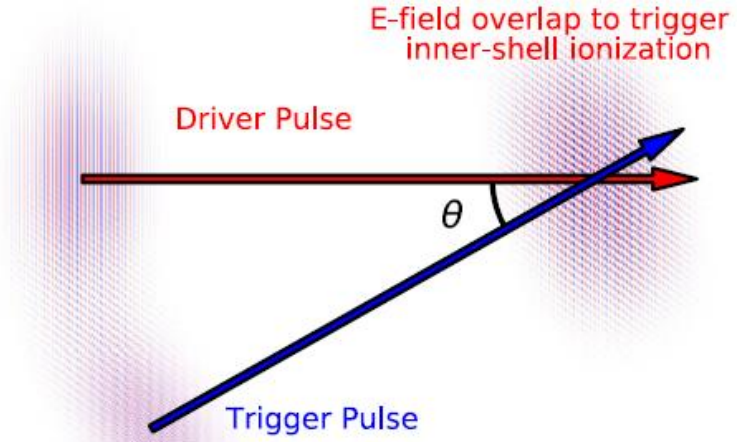
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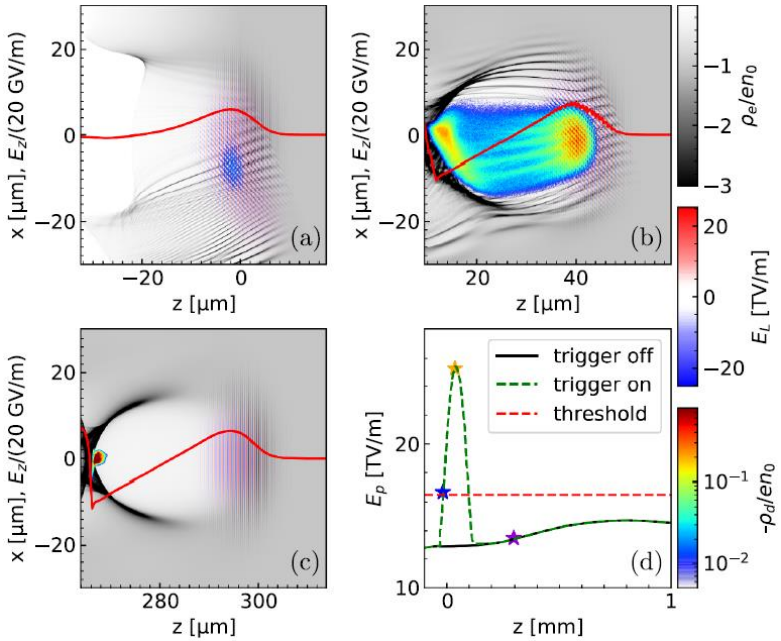
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Scissor-cross ionization injection

- Driver laser and trigger laser intersect with an acute angle
- The inner-shell electrons are only ionized when the two lasers overlap
- Injection length and charge are controllable by adjusting the angle
  - Small angle (<20°), long injection length, larger charge and larger energy spread
  - Moderate angle (~30°), small energy spread and moderate charge
  - Large angle (>60°), large charge and large energy spread, accompanied with other injection schemes
- This injection scheme has been experimentally demonstrated using the 200 TW laser at SJTU

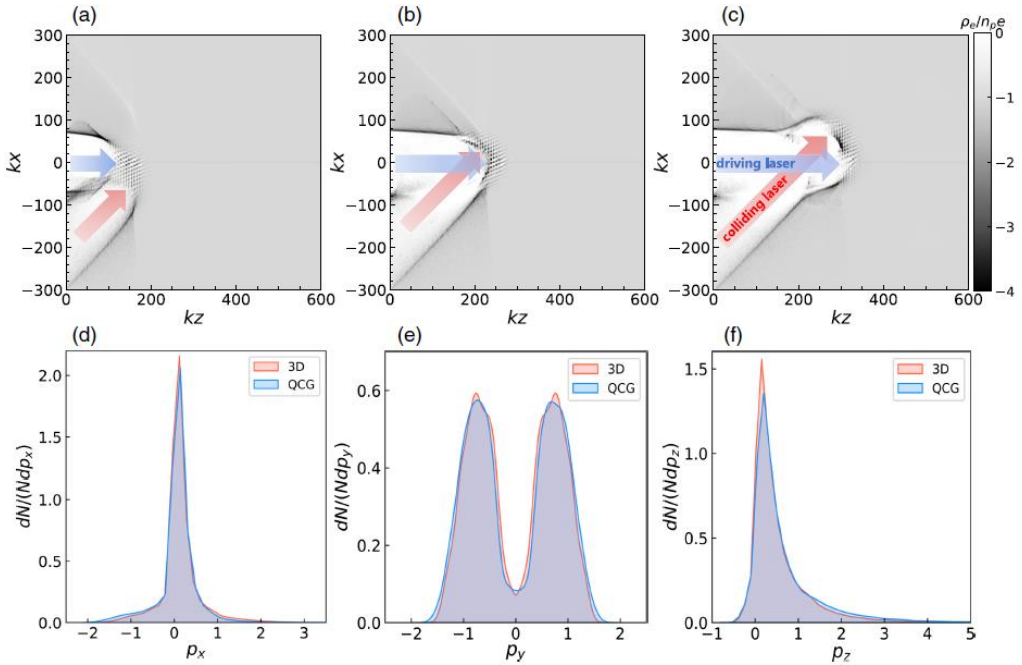


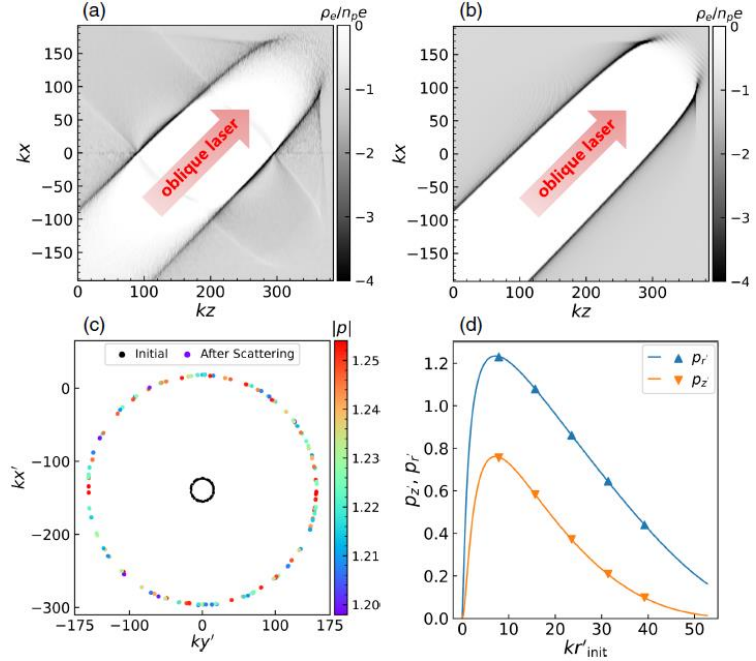


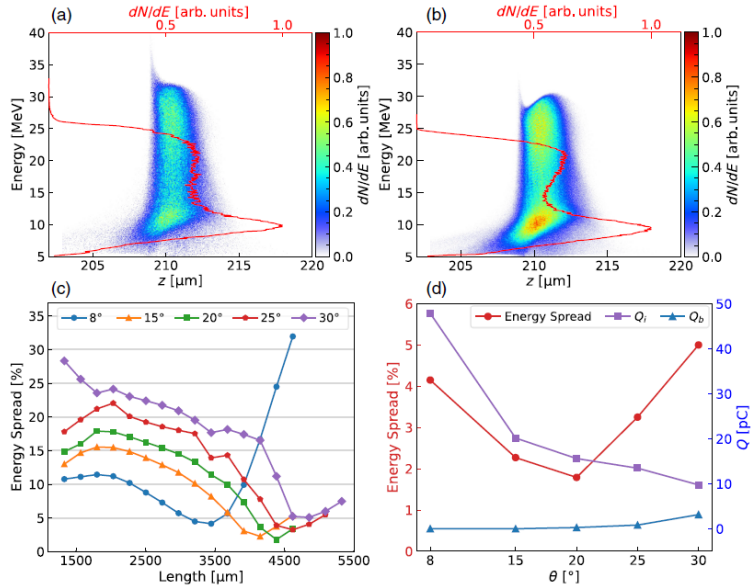
Jia Wang, Ming Zeng et al., Plasma Phys. Control. Fusion 64 (2022) 045012

Oblique laser in quasi-cylindrical geometry

- Quasi-cylindrical (or quasi-3D) geometry largely reduces computation time
- Oblique laser does not fit in this geometry, and needs very consuming 3D simulations
- We found oblique laser can be realized in quasi-cylindrical geometry using the external EM field module
- Oblique laser is defined by expressions of E and B fields

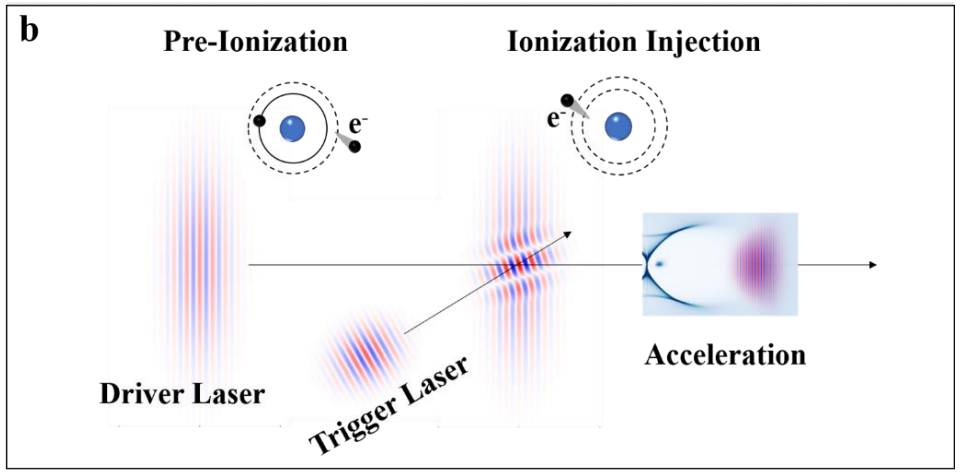


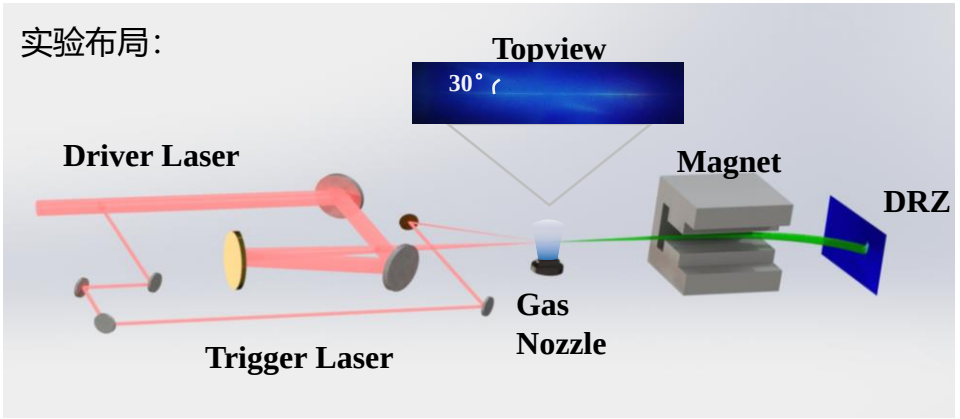


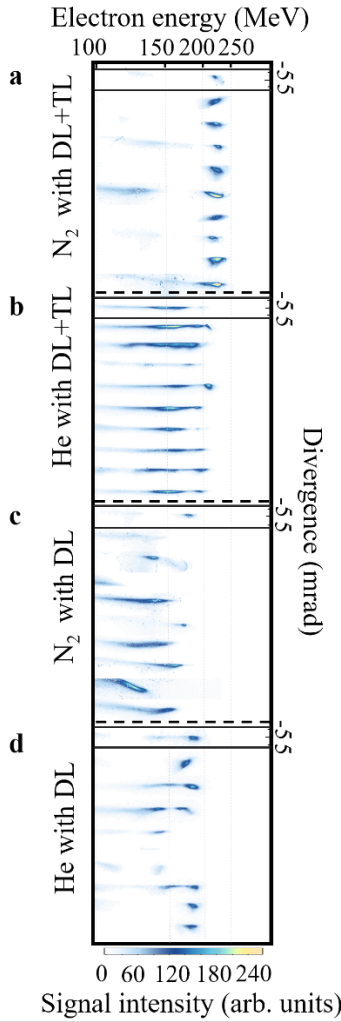


Experiment at Shanghai Jiao Tong University

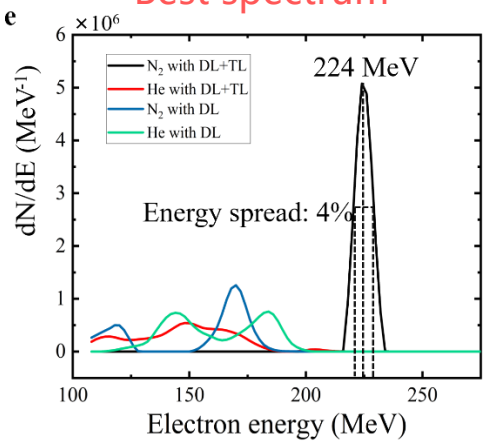
Siyu Chen, ..., Ming Zeng, ..., Wenchao Yan et al., *Communications Physics* **volume 9**, Article number: 9 (2026)



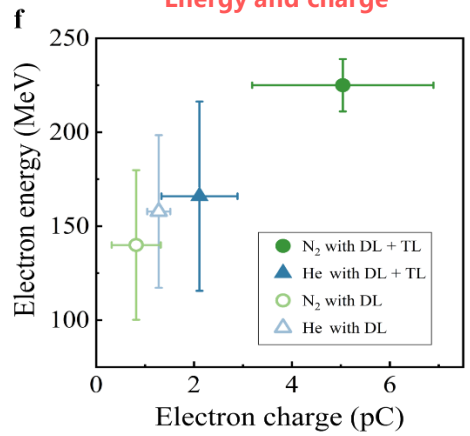




Best spectrum



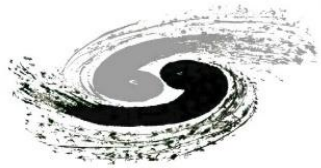
Energy and charge



a. Scissor-cross ionization injection
b. Colliding laser injection
c. Ionization injection
d. Self-injection

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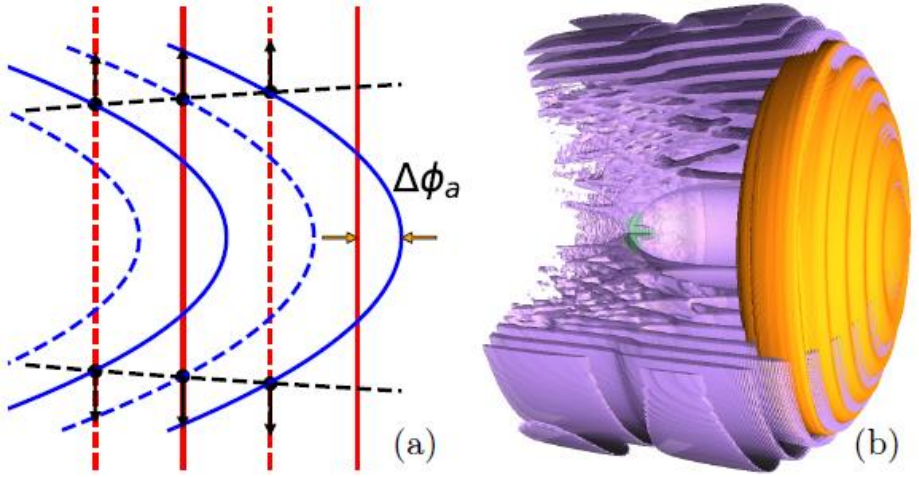


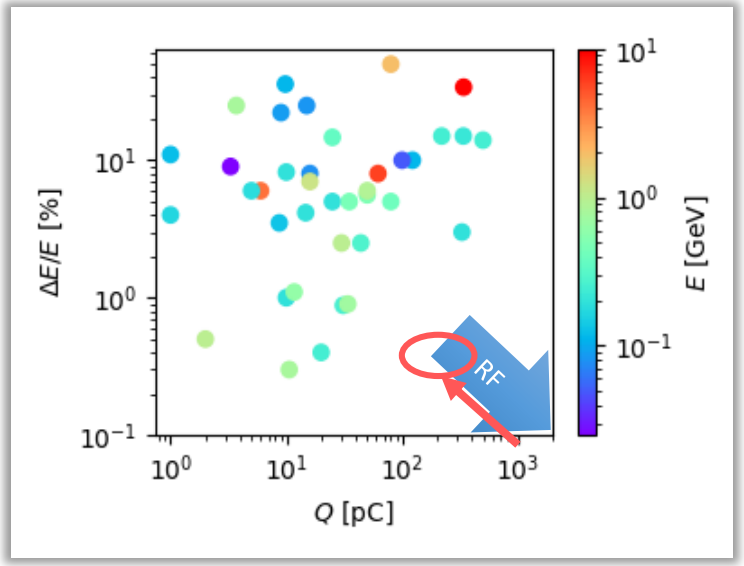
Interference injection of coaxial lasers

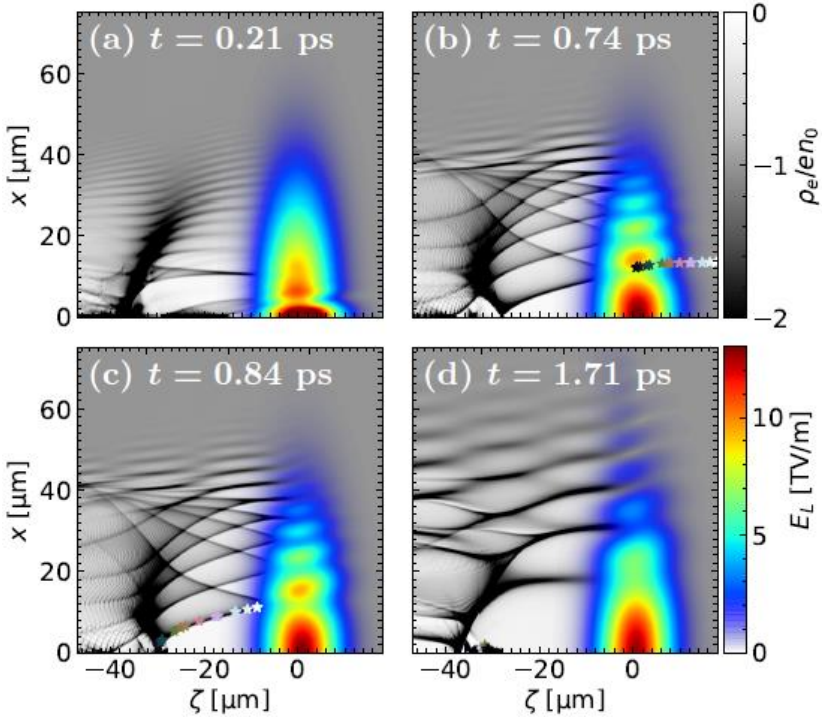
- Drive laser has relative larger spot size
- Trigger laser is tightly focused, forming interference ring with the drive laser
- The wakefield has an onion shape, and the inner shell expand, which reduces phase velocity

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

- 170 pC，3‰ beam can be produced







Two self-dechirping processes

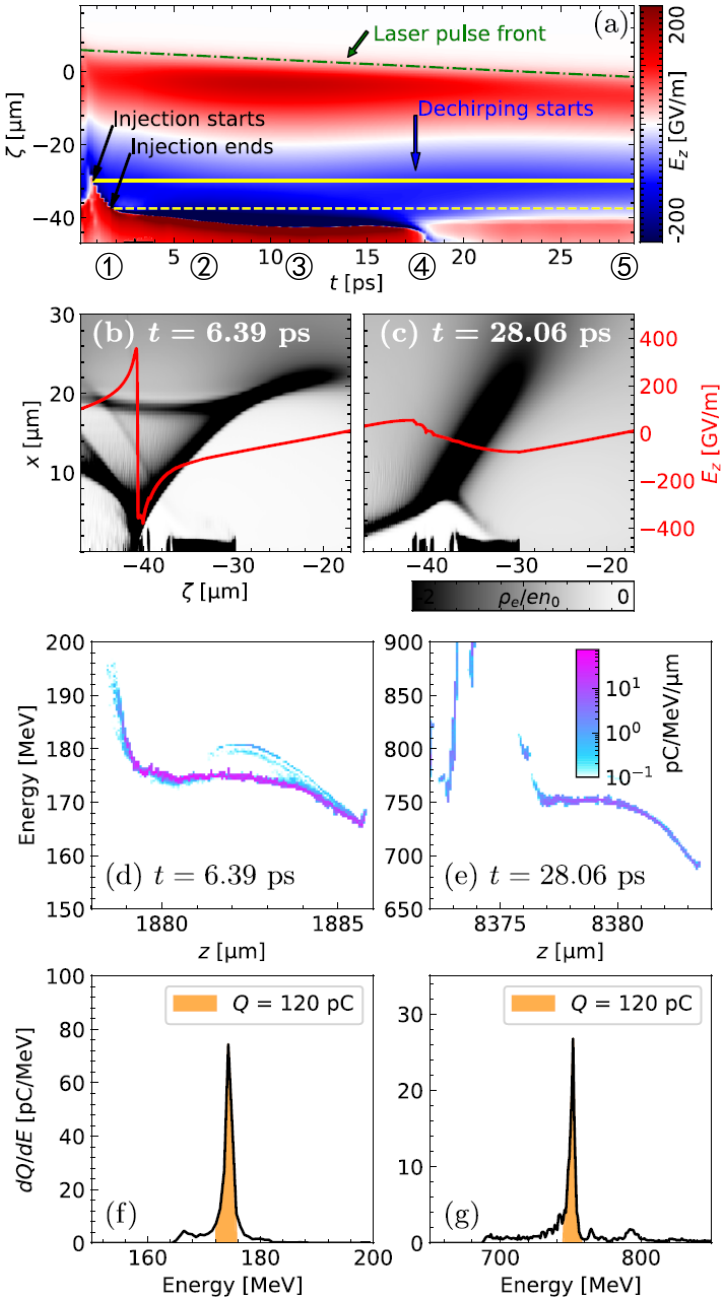
① Injection due to coaxial interference, small slice energy spread

② E-z phase space distribution of the rotates clockwise, until chirp is mitigated (1st dechirping)

③ Clockwise rotation overshoots

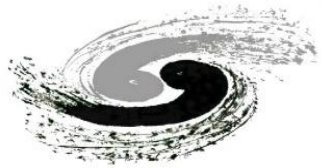
④ Laser becomes weak and the chirping direction is reversed, phase space rotation turns to counterclockwise

⑤ Chirp is mitigated again at an higher energy (2nd dechirping)



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Laser self-focusing and self guiding in plasmas

- Self-focusing: a phenomenon when laser propagates in a nonlinear media (plasma), if laser power exceeds the critical power

$$P_c \approx 17 \frac{\omega_0^2}{\omega_p^2} \ (\mathrm{GW})$$

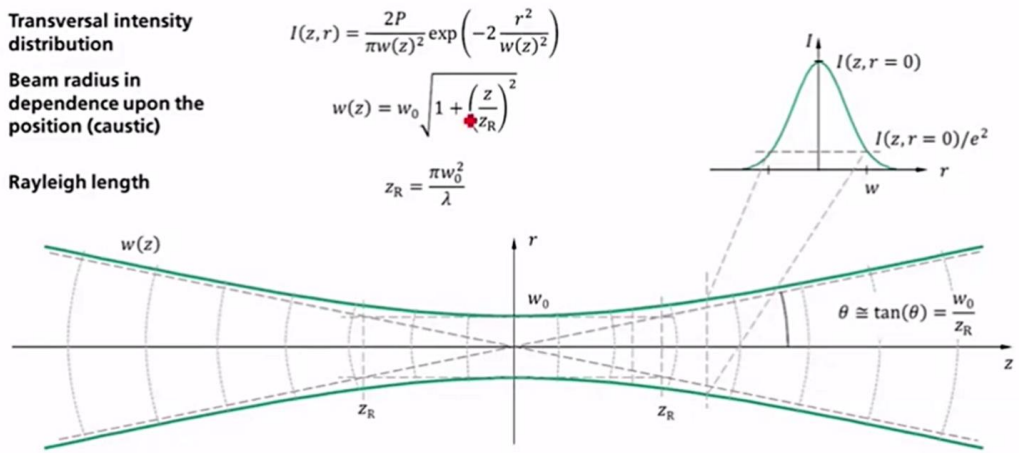
- Self-guiding: laser does not diverge in a distance longer than the Rayleigh length due to the self-focusing effect
- Matched spot size of laser: the laser focal size that allows stable propagation in multiple Rayleigh lengths

$$k_p w_0 \approx 2\sqrt{a_0}$$

- Laser peak power: $P = 21.5 \left(\frac{a_0 w_0}{\lambda_0}\right)^2 \ (\mathrm{GW})$
- Example: for 800 nm laser in $n_p = 1 \times 10^{18}\ \mathrm{cm}^{-3}$ plasma, $P_c \approx 30\ \mathrm{TW}$. If $a_0 = 4$, the matched spot size is $w_0 \approx 20\ \mu\mathrm{m}$, and the corresponding power is $P = 215\ \mathrm{TW}$.

LWFA with petawatt lasers

- Efficient LWFA requires moderate (constant) a_0
  - $P\uparrow$ $\quad w_0 \propto \frac{\sqrt{P}}{a_0} \propto \sqrt{P}\uparrow$
- Consider mirror breakdown, beam diameter $D \propto \sqrt{P}$
- F/# scales with focal spot size $\frac{f}{D} = \frac{z_R}{2w_0} \propto w_0$



- Finally, $f \propto P$
- Example: A. J. Gonsalves et al., Phys. Rev. Lett. 122, 084801(2019)

$P = 0.85\ \mathrm{PW}, \quad f = 13.5\ \mathrm{m}$

For 10~100 PW lasers, focal length has to be extremely long

LWFA with petawatt lasers

- If pulse duration is optimized so that the dephasing length equals to the pump-depletion length [W. Lu et al., PRSTAB 10, 061301 (2007)]

$$\tau \propto w_0$$

- Laser energy

$$\varepsilon \propto a_0^2 w_0^2 \tau \propto a_0^2 w_0^3$$

- Mirror break down limit requires

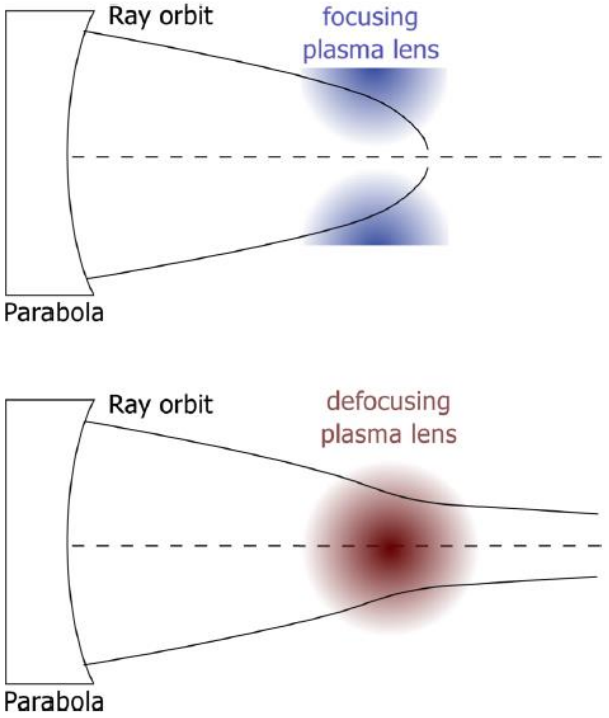
$$D \propto \sqrt{\varepsilon} \propto a_0 w_0^{\frac{3}{2}}$$

- The scaling (with a fixed a_0) is modified as

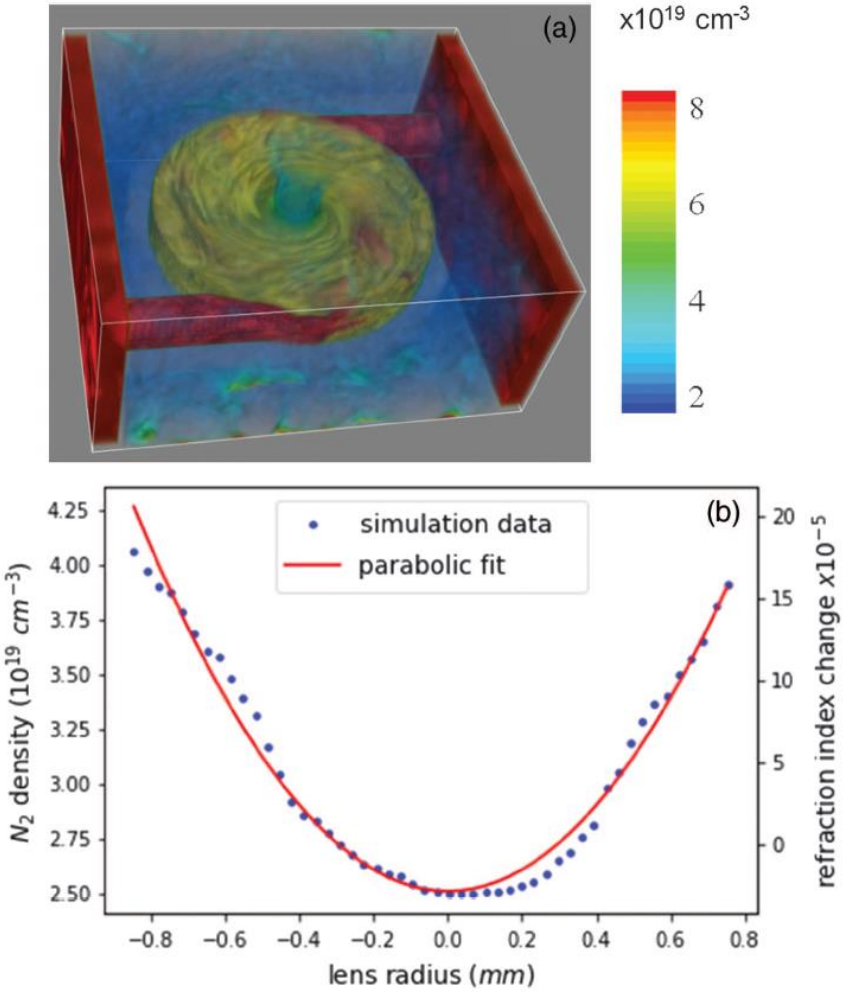
$$f \propto D w_0 \propto w_0^{\frac{5}{2}} \propto \varepsilon^{\frac{5}{6}}$$

Plasma focusing and defocusing devices

- Preformed (nonuniformed) plasma can be used for laser focusing or defocusing
- But high power laser may destroy the preformed distribution, and reduce the device efficiency



J. P. Palastro et al., Physics of Plasmas 22, 123101 (2015).



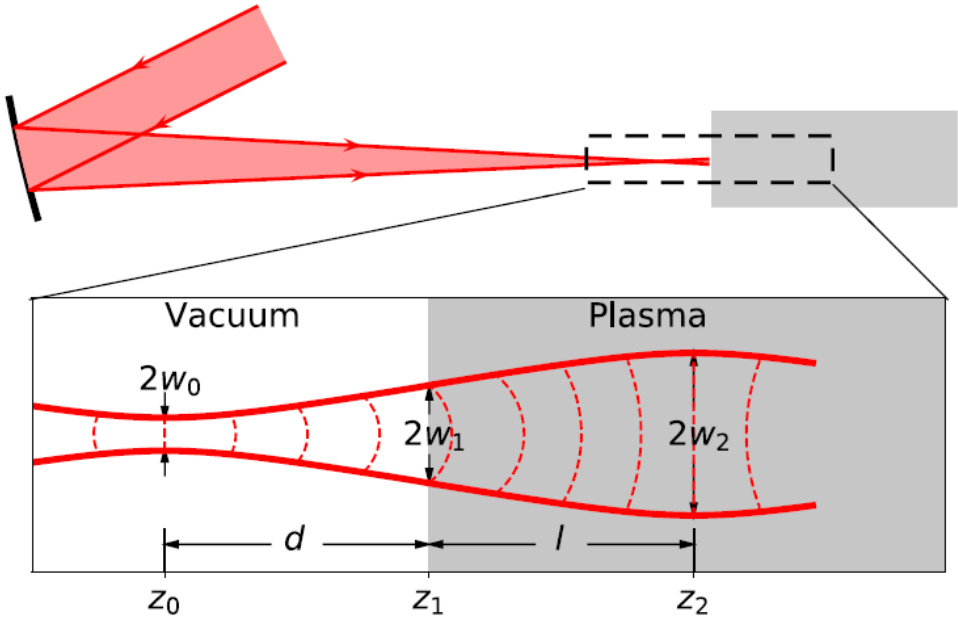
D. Kaganovich et al., Applied Optics 57, 9392 (2018).

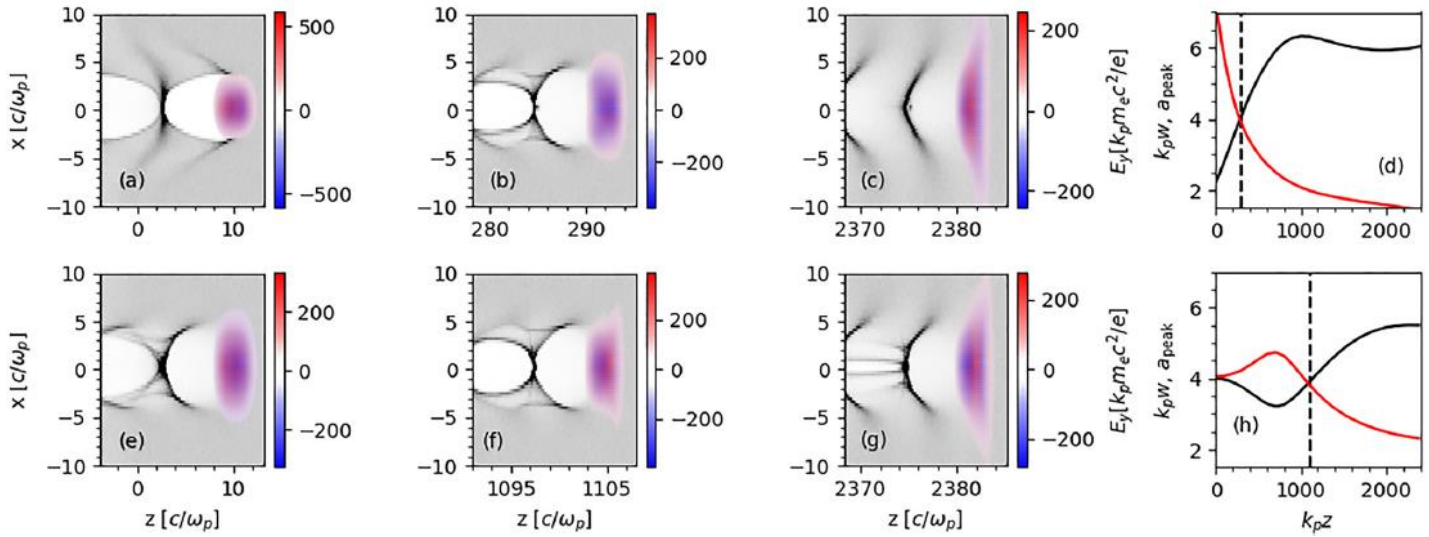
Plasma telescope mechanism

- Use short focal optics to focus laser to the waist radius of w_0 at d before plasma
- After laser enters plasma, it refocuses to the radius of w_2, and $w_2 > w_0$
- The wakefield acceleration afterwards is similar to a long focal LWFA

$$\frac{w_2}{w_0} = \sqrt{1 + \frac{d^2}{\zeta^2}}$$

$$k_p\zeta \approx 0.95 k_p z_R - 1.2\frac{k_0}{k_p} - 13$$

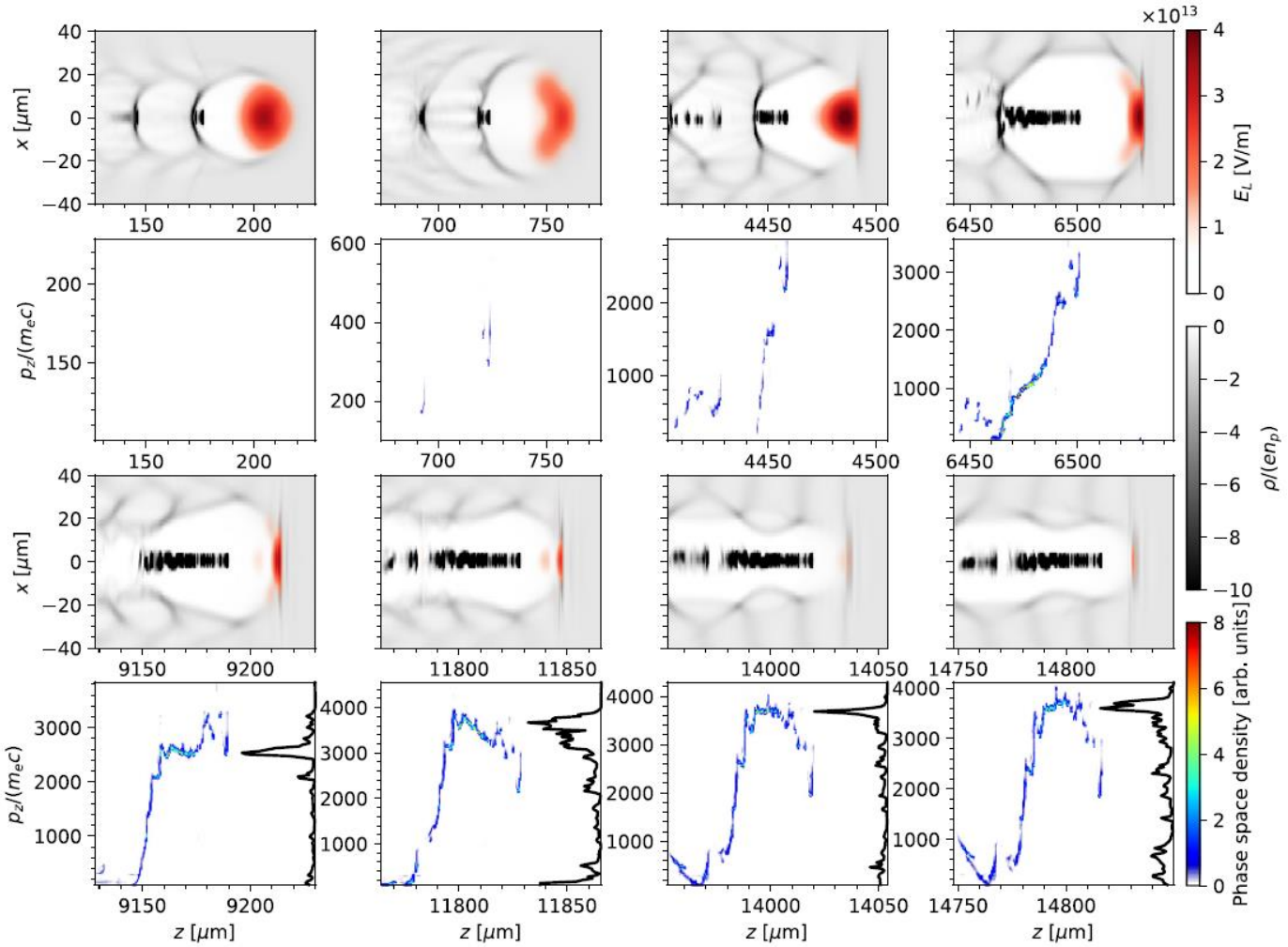




Ming Zeng et al., Phys. Plasmas 27, 023109 (2020)

Self-injection in the plasma telescope

- High-current (~100 kA) self-injection is triggered in the plasma telescope
- In a proper acceleration distance, energy spread can be down to ~1%
- Example: laser energy 30 J, pulse duration 47 fs, $w_0 = 8.5\ \mu\mathrm{m}$, $n_p = 2 \times 10^{18}\mathrm{cm}^{-3}$, $d = 230\ \mu\mathrm{m}$
- Electron beam 1.87 GeV, energy spread 0.05 GeV (2.7%), charge within the peak 2 nC



Ming Zeng, Phys. Plasmas 31, 080702 (2024).

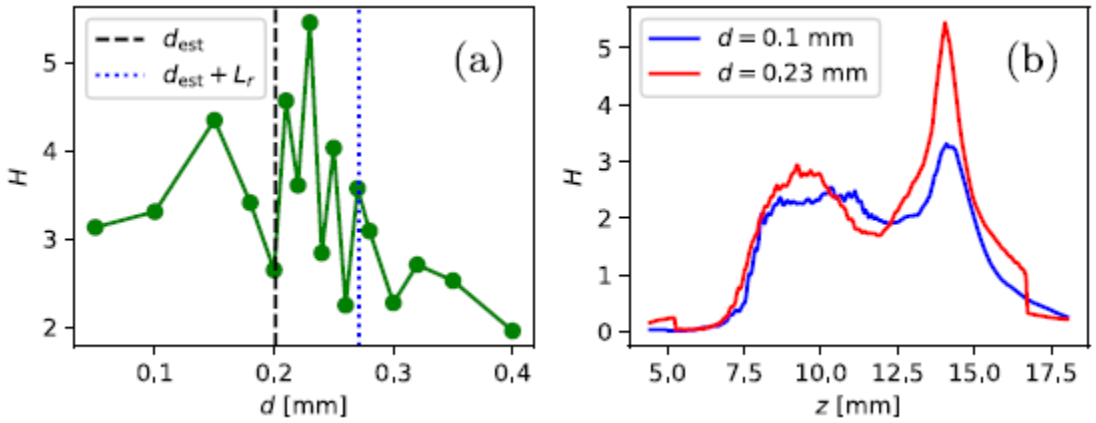
zengming@ihep.ac.cn

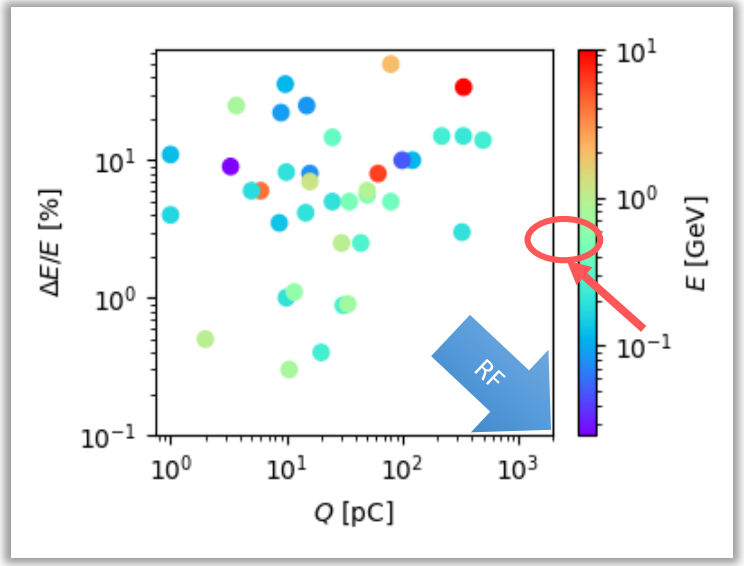
Effectiveness parameter H

- Energy transfer efficiency from laser to e-beam spectrum density

$$H = \frac{Q_{\mathrm{FWHM}}\bar{E}/\varepsilon_L}{\Delta E_{\mathrm{FWHM}}/\bar{E}}$$

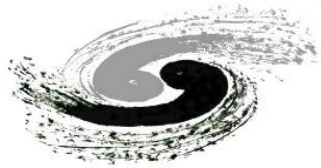
- Common LWFA has H<1, mostly H~0.1
- Simulations using plasma telescope can achieve H~5



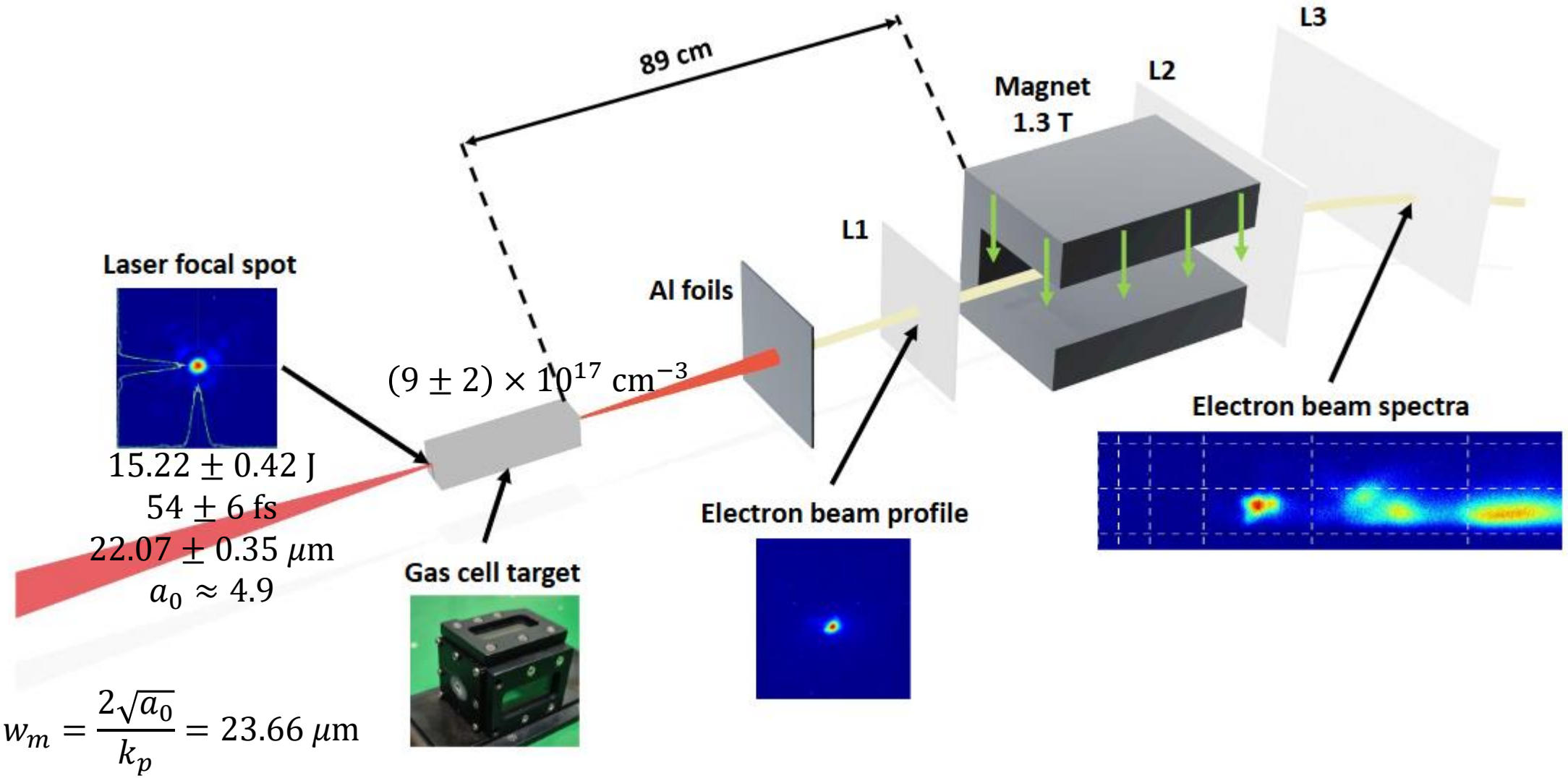


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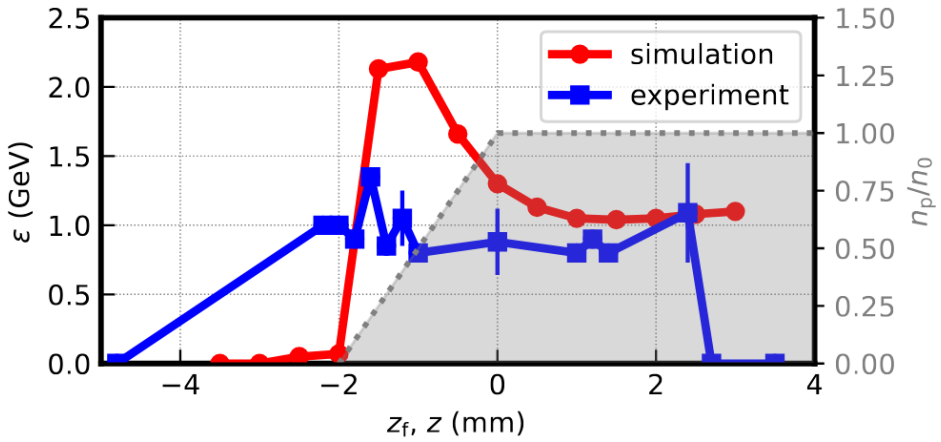
Experiment at CoReLS

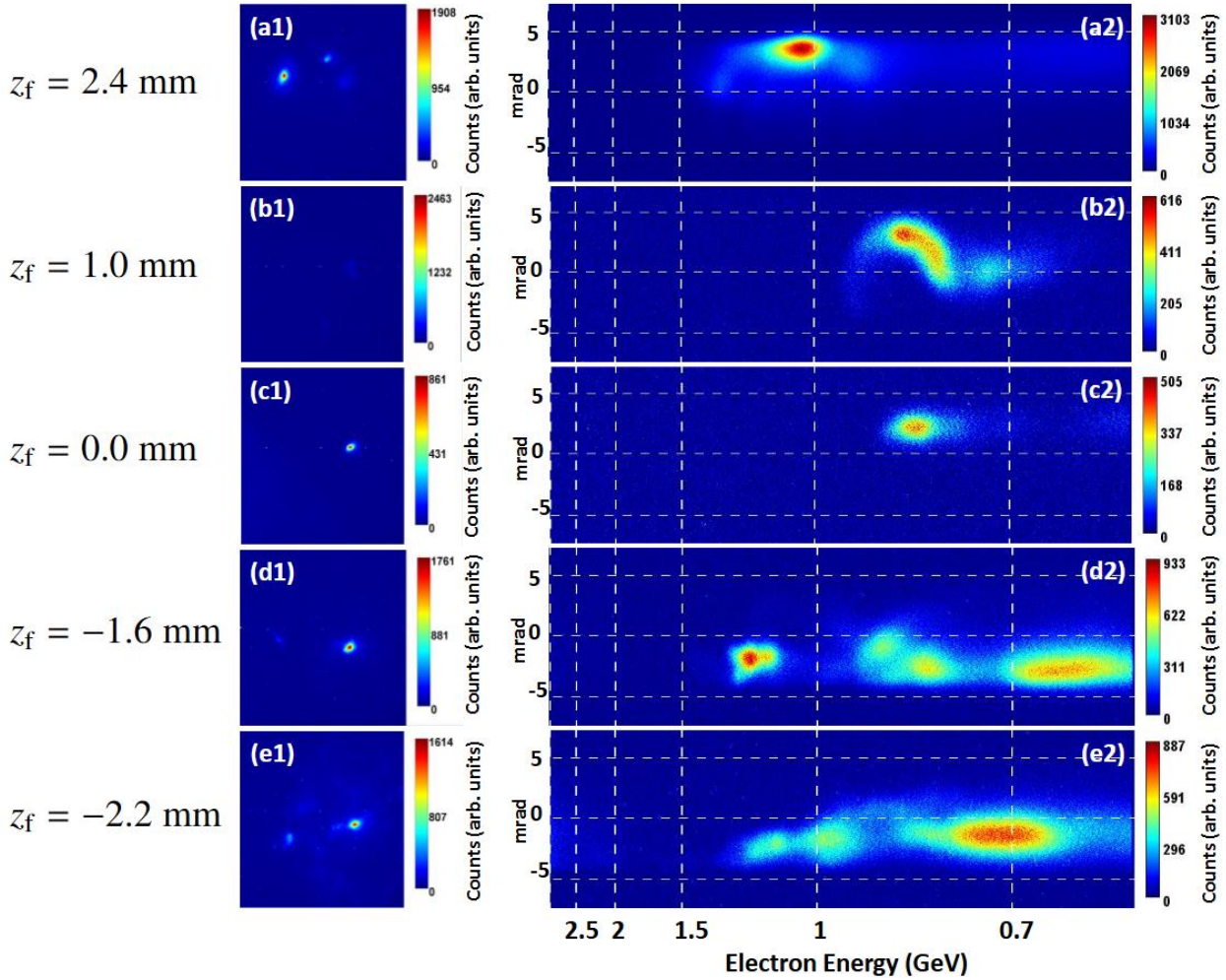


$$w_m = \frac{2\sqrt{a_0}}{k_p} = 23.66\ \mu\text{m}$$

Experiment at CoReLS

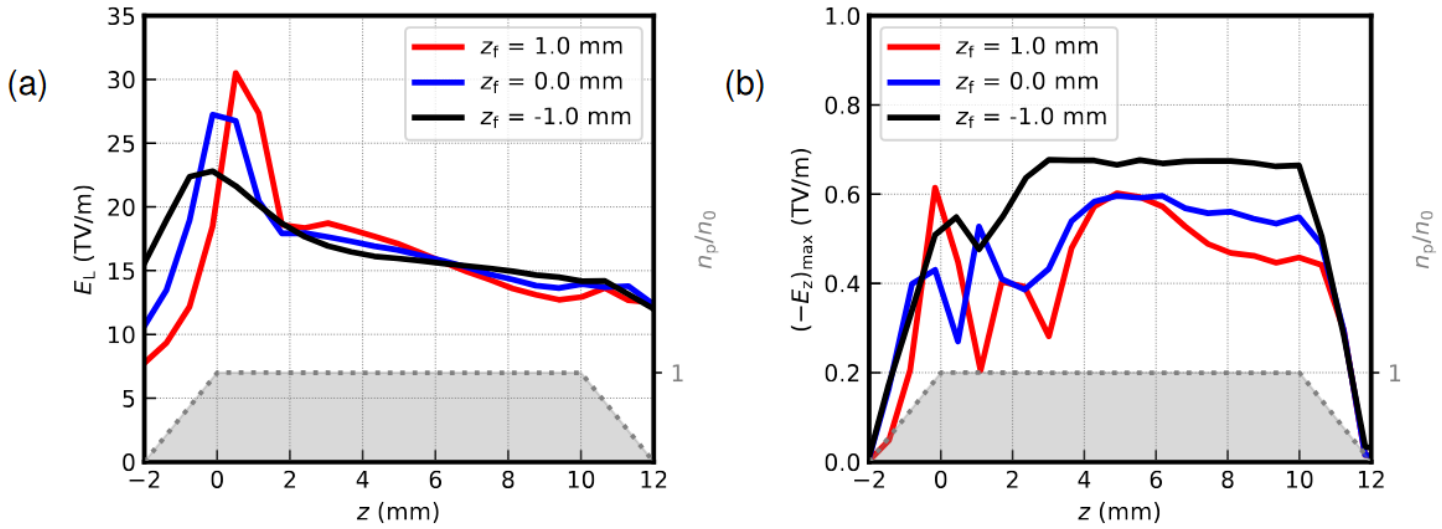
- Acceleration is maximized if laser is focused slightly before the plasma ($z_f = -1 \sim -2$ mm)

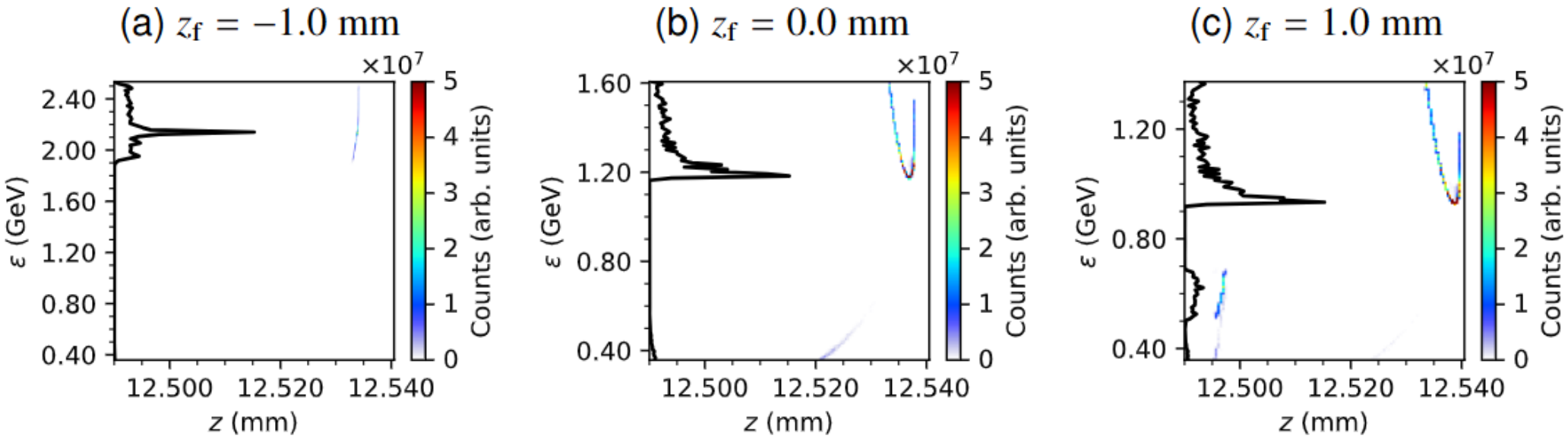




Experiment at CoReLS

- Simulations show, the laser E-field is more stable and the acceleration Ez-field is larger for $z_f = -1\ \mathrm{mm}$ (up-stream focus) compared with $z_f = 0\ \mathrm{mm}$ (on-edge focus) and $z_f = 1\ \mathrm{mm}$ (down-stream focus)





Xinyuan Chang, Ming Zeng, Mohammad Mirzaie, Calin Ioan Hojbota, Dazhang Li, Mohammad Rezaei-Pandari, Do Yeon Kim, Taegyu Pak, Hyung Taek Kim, Kiyong Kim, Plasma Science and Technology (2026 , accepted)

Conclusion

- LWFA needs simultaneous optimization of charge and energy spread
- We proposed a few injection mechanisms including scissor-cross ionization injection (demonstrated by experiment) and coaxial interference injection
- Plasma telescope mechanism use short focal length for long distance LWFA
- Simulations shows plasma telescope mechanism can produce e-beams with ~nC charge and ~1% energy spread
- Experiments showed the mechanism exist
- However, the high-quality e-beam has not yet been observed

