Control of electron injection in laser wakefield acceleration with external DC magnetic fields*

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1. Introduction

External magnetic fields (B_0) at tens of tesla can provide additional control of electron injection in laser wakefield acceleration (LWFA). In the first case, we consider ionization injection assisted by a transverse magnetic field [1]. Both the electron trapping condition and the wakefield structure are changed significantly by the magnetic field such that injection occurs over a shorter distance and at an enhanced rate. Furthermore, beam loading is compensated for as a result of the trapezoidal-shaped longitudinal charge density profile of injected electrons. These lead to a reduction in the energy spread and an enhancement in the charge of the electron beam.

In the second case, we consider density down ramp injection assisted by a longitudinal magnetic field [2]. The magnetic field dynamically induces an expanding hole in the electron density distribution at the rear of the wake bubble, which reduces the peak electron velocity in its vicinity. Electron injection is suppressed when the electron velocity drops below the phase velocity. This enables the start and end of electron injection to be independently controlled, allowing the generation of sub-femtosecond electron bunches with peak currents of a few kilo-Ampere.

2. Magnetic controlled ionization injection in LWFA

2.1 Magnetic trapping threshold in modified wakefield

❅External magnetic field induces the asymmetric distribution of wakefield, which causes the modified transverse trapping condition and injection delay.

❅The evolution of self-generated magnetic field at bottom of wake restore the injection occurrence as the minimum value reaches the magnetic trapping threshold.

❅ The critical magnetic field required for transverse trapping is

$$b \geq b_{crit} = 2R_m(U_0 + b_0 R_m - b_0 x_\phi)/(R_m^2 - x_\phi^2)$$

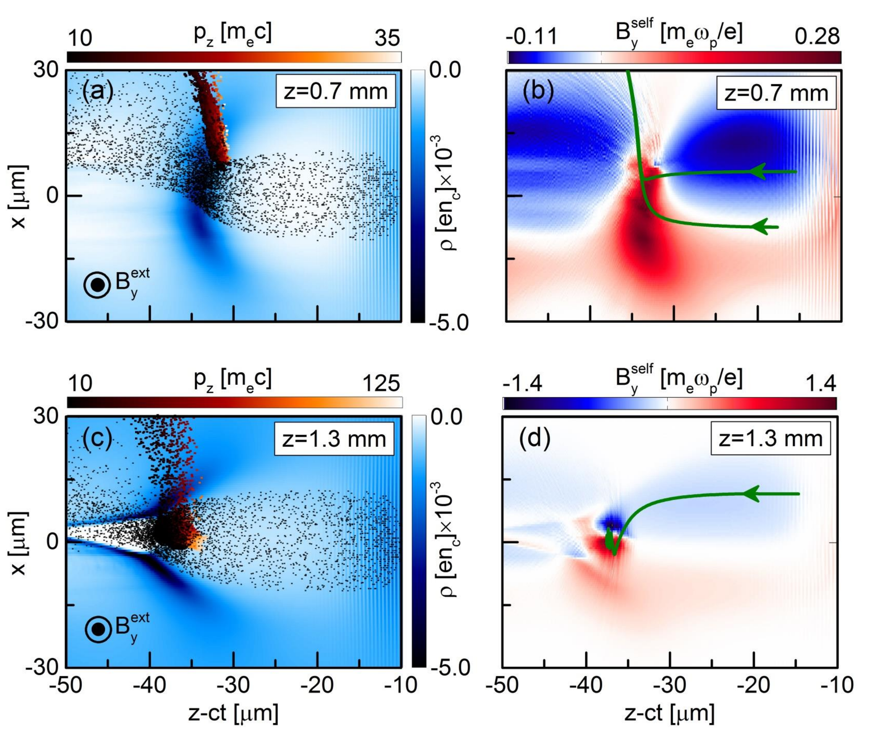

Fig. 1: (a) and (c) Laser induced wake at different propagation distances, superimposed with energetic electrons (color dots) with $\gamma > 10$ and low energy electrons (black dots) with $\gamma < 10$. (b) and (d) The distributions of azimuthal magnetic field component of wakefield at different propagation distances, the olive curves indicate the typical orbits of energetic. The imposed magnetic field is 50T in +y direction.

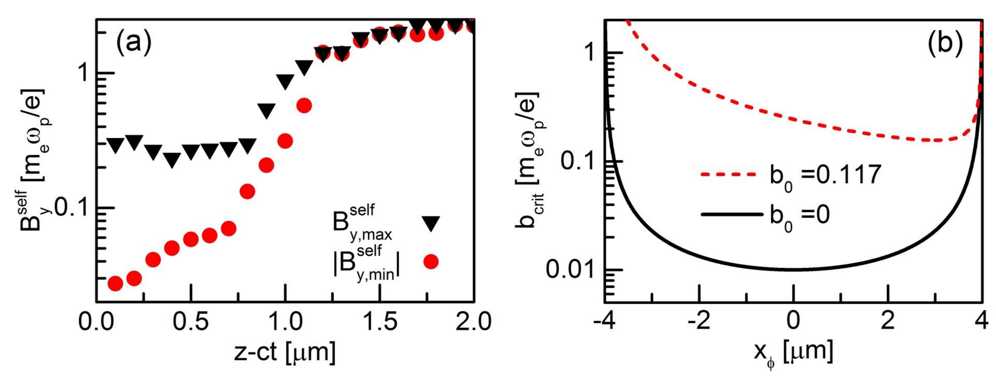

Fig. 2: (a) The evolution of magnitude of azimuthal magnetic field in injection region. (b) b_{crit} in the cases b_0=0 and 0.117(50T).

2.2 Optimized beam charge profile produced by magnetic controlled ionization injection

❅ Magnetic controlled ionization injection produces the optimized charge profile, which can modify the accelerating field to be uniform and produces the high-charge and low energy spread electron beam.

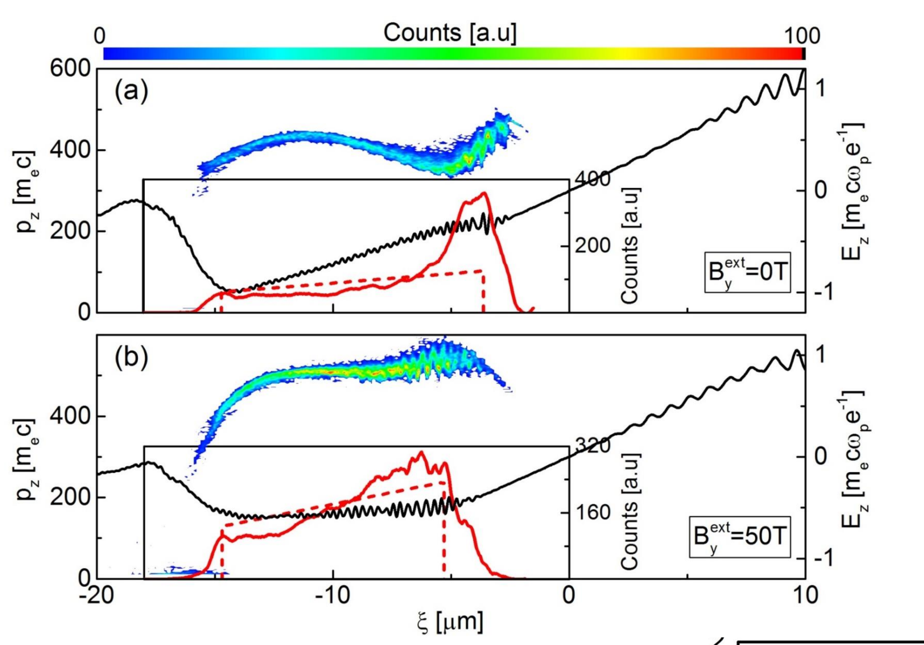

Fig. 3: (a) - (b) Phase-space of injected electrons and the accelerating field E_z (black curve) for B_0 =0, 50 T. Insets compare the charge profiles from the simulations (red solid curve) with the predicted trapezoidal-shaped profiles (red dash curve).

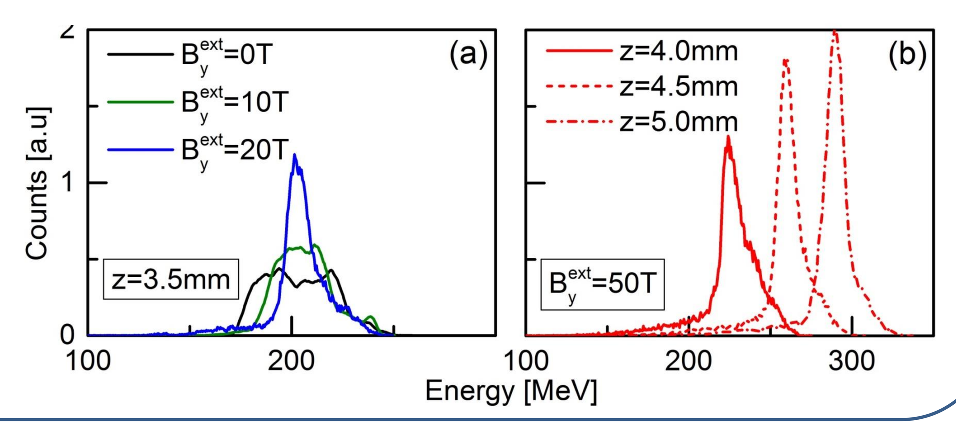

Fig. 4: Energy spectra of electron beams (a) with different B_0 (b) with B_0 =50 T for different propagation distances.

3. Injection suppression along density down-ramp via magnetic field in LWFA

3.1 Magnetic induced density hole and its effect on density down-ramp injection

❅The response of sheath currents to B_0 results in azimuthal velocities v_φ at bottom of bubble and thus the centrifugal force $m_e\gamma_e v_\varphi^2/r$, causing the formation of density hole structure at bottom of plasma bubble.

❅The increase of $\gamma_{\rm rms}$ causes the increase of $r_{\rm rms}$ because of the centrifugal force $p_\varphi v_\varphi/r \propto r_{\rm rms}$. As a result, the increase of $r_{\rm rms}$ inhibits the acceleration of sheath electron and causes the quick decrease of $v_{z,\rm rms}$ and thus the quick termination of injection.

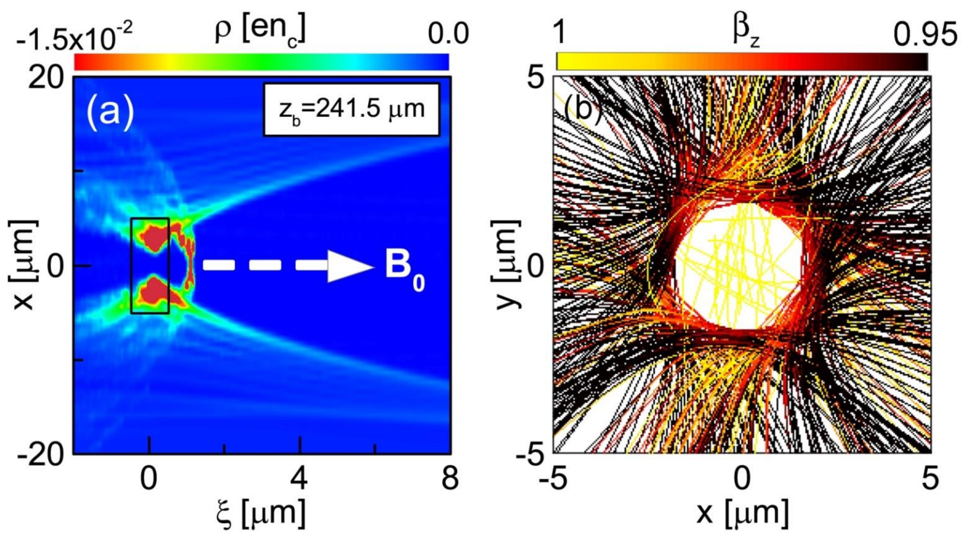

Fig. 4: (a) B_0 induced density hole at bottom of plasma bubble with the injected electron bunch. (b) Transverse trajectories of electrons shown in rectangle region of figure (a).

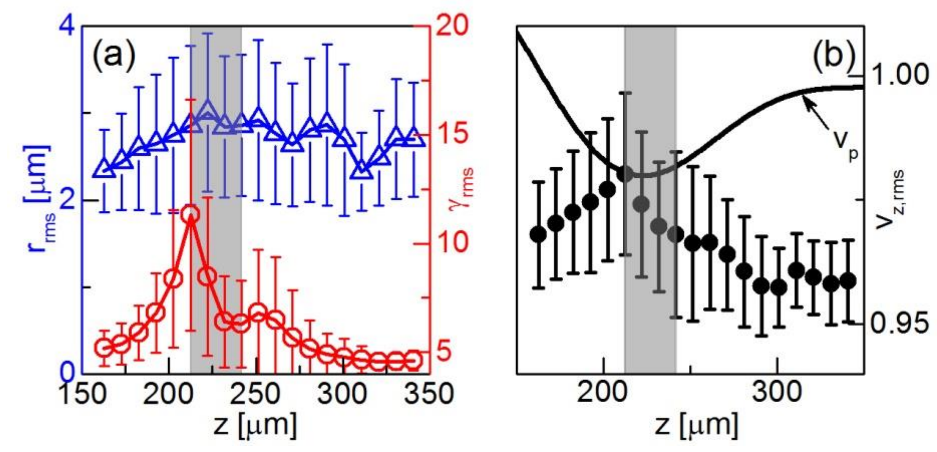

Fig. 5: (a) Evolution of the r.m.s. radius and Lorentz factor of energetic electrons around the density hole. (b) r.m.s longitudinal velocity of energetic electrons around the density hole versus the bubble velocity along density down-ramp.

3.2 Generation of ultrashort electron bunch

❅Plasma density profile: $n_e/n_0 = 1 + \alpha\exp(-(z - z_i)^2/2\sigma_z{}^2)$

❅The length of injected electron bunch with 10 T is significantly shortened.

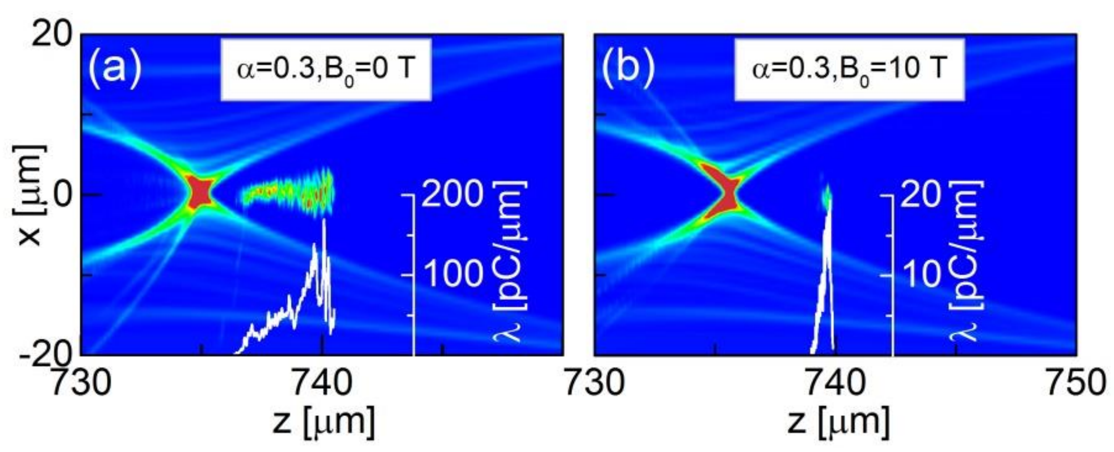

Fig. 6: Bubble structures and injected electron bunches in density profile-tailored plasma with $n_0 = 0.0002n_c$, $\sigma_z = 100\ \mu m$ and (a) $B_0 = 0$, (b) $B_0 = 10$ T .

Table 1: Parameters of electron bunches associated with α and B_0, including charge Q, pulse duration $\tau_{\rm rms}$, emittance $\epsilon_{n,x(y)}$ and energy spread ΔE.

α	B_0 (T)	Q (pC)	$\tau_{\rm rms}$ (fs)	$\epsilon_{n,x(y)}$ (μm)	ΔE (MeV)
0.3	0	52.9	3.3	0.8(0.8)	3.8
	10	7	0.6	0.8(1.1)	1.3
	20	0	—	—	—
0.5	0	119.4	6.2	0.8(1)	5.6
	10	73.3	3.7	1.2(1.1)	4
	20	35	1.3	1.2(1.3)	2.4

Summary

- External transverse magnetic field induces the asymmetric distribution of the laser wakefield, which results in the modified transverse trapping condition, leading to the asymmetric and higher magnetic trapping threshold. The magnetic controlled ionization injection is beneficial to produce electron beam with high-charge and low energy spread.
- The imposed external longitudinal magnetic field on density down-ramp causes the evolved density hole structure, which results in the 3D manipulation of plasma bubble. This control of injection enables realization of sub-femtosecond electron bunches with readily accessible parameters both for density profiles and magnetic field strength.

References

[1] Zhao Q, Weng S M, Sheng Z M, Chen M, Zhang G B, Mori W B, Hidding B, Jaroszynski D A and Zhang J. New Journal of Physics, 2018, 20:063031.

[2] Zhao Q, Weng S M, Chen M, Zeng M, Hidding B, Jaroszynski D A, Assmann R and Sheng ZM. Plasma Physics and Controlled Fusion, 2019, 61:085015.