# JOINT WAKEFIELD ACCELERATION BY LASER PULSE AND BY SELF-INJECTED ELECTRON BUNCHES

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The multi-bunches self-injection, observed in laser-plasma accelerators in the bubble regime, may be challenging. Namely, it affects the energy gain of electrons accelerated by laser wakefield. With time the first witness bunches turn into drivers and contribute to acceleration of the last witness bunches. Thus, the combined joint acceleration occurs of last self-injected bunches by laser pulse and by first self-injected bunches which have become drivers. It is shown that the charges of originally self-injected bunches equal more pC, the charges of additionally self-injected and accelerated bunches with the greatest energy are much less. It is also shown that the energies of additionally self-injected and accelerated bunches are more than the energies of originally self-injected bunches which have become drivers. It is demonstrated that originally self-injected bunch in the second wake bubble in the case of injection of a single laser pulse and in the third wake bubble in the case of injection of short chain of laser pulses after deceleration is self-cleaned as a result of radial defocusing by transversal fields.

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## INTRODUCTION

At the laser acceleration of self-injected electron bunches by plasma wakefield field (LPWA) it is important to accelerate bunches up to the high energy. In [1-5] it has shown that at certain conditions in blowout regime the laser wakefield acceleration of self-injected electron multi-bunches by plasma wakefield with time is replaced by a combined joint LPWA acceleration and beam-plasma wakefield acceleration by first self-injected electron bunch in each bubble of their short chain. The purpose of this paper is to study some properties and dynamics of self-injected electron bunches, which are accelerated by wakefield electron bubbles of their short chain, excited by a short laser pulse. It is shown that in the first and second wake bubbles of the plasma electrons, excited by the laser pulse, first on one electron bunches are self-injected and accelerated under certain conditions, and then after these bunches the additional electron bunches are self-injected and accelerated. It has been shown that over time, initially self-injected bunches become driver-bunches, while additionally self-injected electron bunches are accelerated. Initially self-injected electron bunch in the second wake bubble after deceleration is self-cleaned due to defocusing by radial fields. Charges of initially self-injected electron bunches are several pC, and the charges of additionally self-injected and accelerated electron bunches with the largest energy are much less. It is shown that the energies of additionally self-injected and accelerated electron bunches in the first and second wake electron bubbles are larger than the energies of the bunches, originally self-injected and accelerated in the first and second wake electron bubbles.

Radial dynamics of driver-bunches is important. In [6, 7] it has been shown that certain radial dynamics of electron driver-bunches can increase the intensity of the wakefield excitation. In this paper it is demonstrated in the case of injection of a single laser pulse and in the case of injection of short chain of laser pulses that originally self-injected bunch in the second wake bubble after deceleration is self-cleaned as a result of defocusing by radial fields.

## 1. PARAMETERS OF THE NUMERICAL SIMULATION

Results of fully relativistic electromagnetic PIC simulation by the UMKA 2d3v code [8] are presented. The short laser pulse or short chain of two short laser pulses with a wavelength $\lambda = 0.8$ μm is injected into a homogeneous semi-infinite plasma. The plasma density is chosen to be equal to $n_0 = 1.8 \cdot 10^{19}$ cm$^{-3}$=0.01016 nc. $n_c=m_e\omega_0^2/4\pi e^2$ is the critical plasma density, $\omega_0$ is the frequency of the laser pulse. The pulse has a Gaussian profile in the transverse direction. The laser pulse is defined with a "cos$^2$" distribution in its spatial longitudinal direction. The longitudinal and transverse dimensions of the laser pulse are selected to be smaller the wavelength. The length of the laser pulse at half-maximum equals to $2\lambda$, and the width at half-maximum equals $8\lambda$. The intensity of the laser pulse is equal to $I = 5.3 \cdot 10^{19}$ W/cm$^2$.

Also the case of injection of short chain of two laser pulses is considered. The distance between the first and second laser pulses equals to two lengths of wake bubble.

The coordinates, time t, amplitudes of electric and magnetic fields, momentum of electrons, electron plasma density $n_e$ are presented in dimensionless form in units of $\lambda$, $t_0=2\pi/\omega_0$, $E_0=m_ec\omega_0/2\pi e$, $m_ec$, $n_a=m_e\omega_0^2/16\pi^3e^2$.

## 2. RESULTS AND DISCUSSION

The s-polarized laser pulse is injected from the left boundary normally on the plasma. A short chain of wake bubbles is formed by a laser pulse.

Four bunches are self-injected, but at different times. First, the evolution is developed, studied in [5]. Namely, firstly 1-st bunch is self-injected into the 1-st bubble, as

well as 1-st and 2-nd bunches − in 2-nd bubble (Fig. 1) [5] in case of single laser pulse injection.

In the case of injection of two laser pulses at first 1-st bunch is self-injected in 1-st bubble, also 1-st and 2-nd bunches − in 3-rd bubble (Fig. 2).

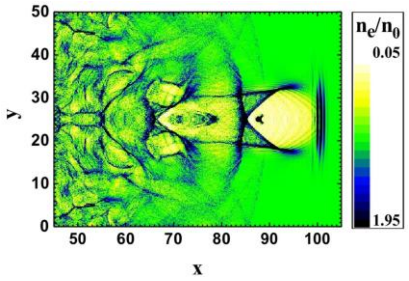


*Fig. 1. Wake perturbation of plasma electron density, excited by one laser pulse at the time $t=105t_0$*

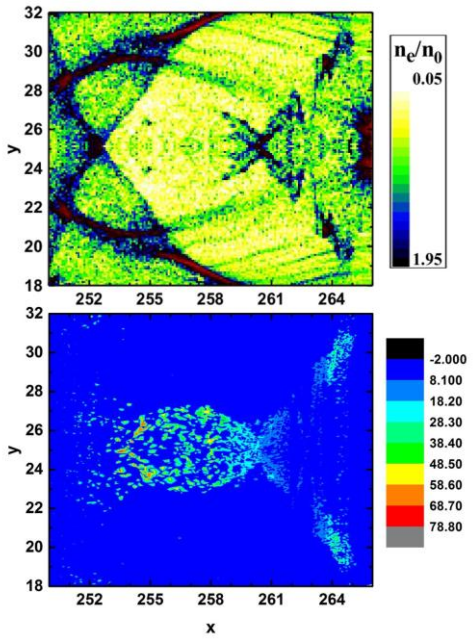


*Fig. 2. Longitudinal momentum of electrons $P_x$ (bottom figure) and wake perturbation of plasma electron density (top figure), excited by two laser pulses*

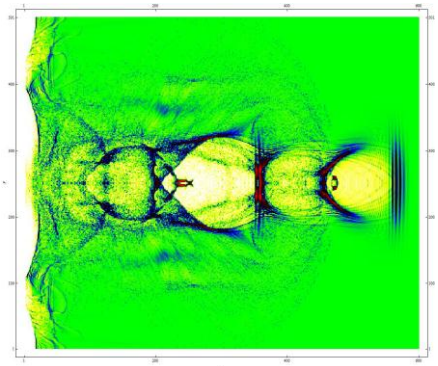

*Fig. 3. Wake perturbation of plasma electron density, excited by two laser pulses*

The charge of 1-st bunch in 1-st bubble approximately equals 3pC. The charge of 1-st bunch in 3-rd bubble in the case of injection of two laser pulses (Fig. 3) approximately equals 2.4pC.

After acceleration the 1-st bunches in 1-st and 2-nd bubbles are decelerated, keeping together with the laser pulse the bubbles for acceleration of the 2-nd bunch in 2-nd bubble.

Last accelerated bunch in the 2nd bubble is in larger average accelerating field, compared with the average accelerating field for the 1st bunch in the 2nd bubble at the stage of its acceleration. As a result of comparing Fig. 4 and Fig. 5 one can see that the energy of the last accelerated bunch is in 2 times more than the maximum energy of the 1st bunch in the 2nd bubble until its transformation into the driver.

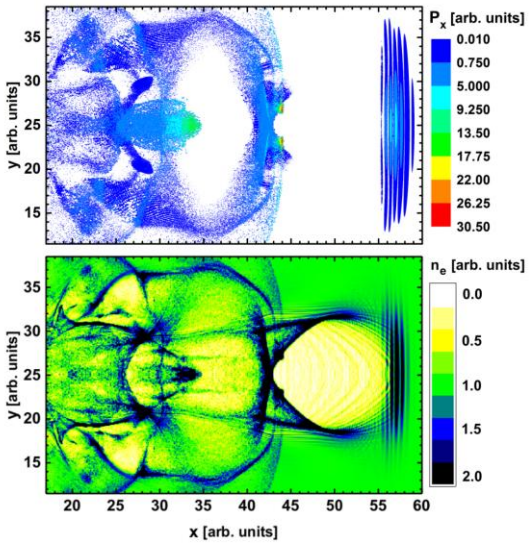


*Fig. 4. Longitudinal momentum of electrons $P_x$ (top figure) and wake perturbation of plasma electron density (bottom figure) at the time $t=60t_0$*

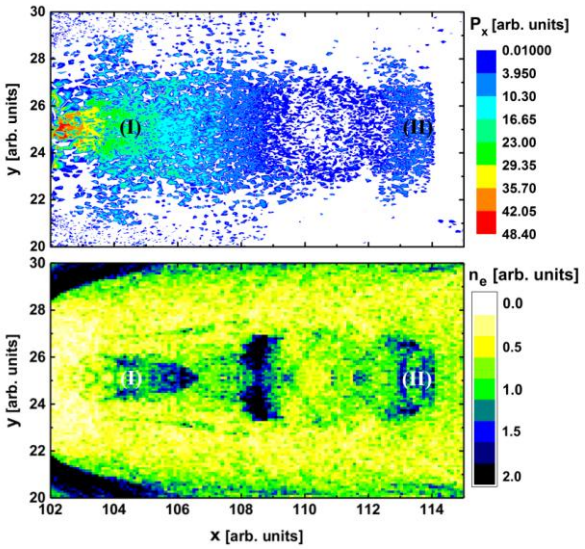


*Fig. 5. Longitudinal momentum of electrons $P_x$ (top figure) and wake perturbation of plasma electron density (bottom figure) at the time $t=140t_0$*

After deceleration the 1-st bunch in the 2-nd bubble is self-cleaned in the radial direction due to defocusing by transverse fields (Fig. 6 for the case of injection of short chain of two laser pulses).

Later the 2-nd bunch is self-injected in the 1-st bubble (Fig. 7).

1-st bunch in the 1-st bubble continues to support, together with the laser pulse, bubbles for acceleration of

the 2-nd bunches in 1-st and 2-nd bubbles. The maximum electron energy of 2-nd bunch in the 1-st bubble (Fig. 8) is larger than the maximum energy of 1-st bunch in the 1-st bubble $\gamma_w \approx 170 > \gamma_{dr} = 140.5$.

In the case of injection of short chain of two laser pulses the dynamics of self-injected and accelerated electron bunches, similar to considered in the case of the injection single laser pulse, is realized in the 1-st and 3-rd wake bubbles. In the case of injection of short chain of two laser pulses the electron bunch is self-injected in the second wake bubble after defocusing of 2-nd laser pulse (see Fig. 6).

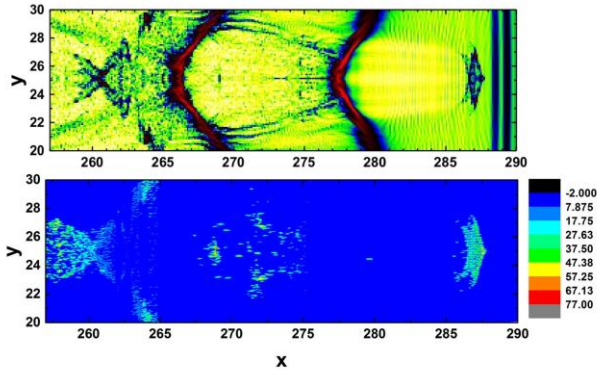


*Fig. 6. Longitudinal momentum of electrons $P_x$ (bottom figure) and wake perturbation of plasma electron density (top figure), excited by two laser pulses*

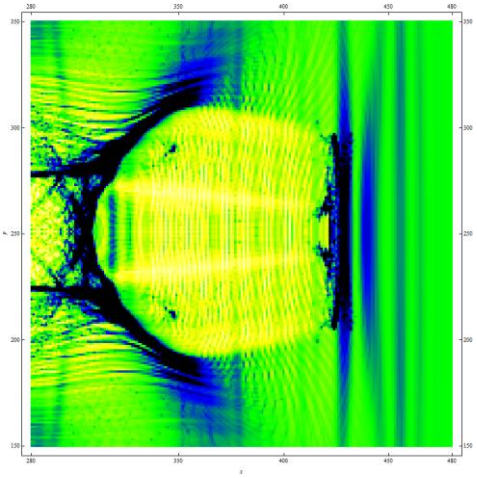

*Fig. 7. Wake perturbation of plasma electron density, excited by one laser pulse at the time $t=470t_0$*

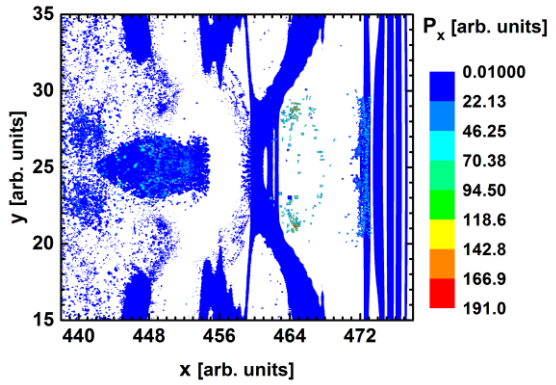


*Fig. 8. Longitudinal momentum of electrons $P_x$ at the time $t=470t_0$*

## CONCLUSIONS

Thus we have shown that at the multi-bunches self-injection, observed in laser–plasma accelerators in the bubble regime the charges of initially self-injected electron bunches are equal to several pC, the charges of additional self-injected and accelerated electron bunches with the largest energies, are much less. It has been also shown that the energies of additionally self-injected and accelerated electron bunches in the 1-st and 2-nd wake bubbles of electrons are larger than the maximum energies of initially self-injected in the 1-st and 2-nd wake bubbles electron bunches, which have become drivers. It has been demonstrated in the case of injection of a single laser pulse (two laser pulses) that originally self-injected electron bunch in the 2-nd (3-rd) wake bubble after deceleration is self-cleaned as a result of radial defocusing by transverse fields.

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## СОВМЕСТНОЕ КИЛЬВАТЕРНОЕ УСКОРЕНИЕ ЛАЗЕРНЫМ ИМПУЛЬСОМ И САМОИНЖЕКТИРУЕМЫМИ ЭЛЕКТРОННЫМИ СГУСТКАМИ

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Многосгустковая самоинжекция, наблюдающаяся в лазерно-плазменных ускорителях в нелинейном режиме, может оказаться многообещающей. А именно, она приводит к увеличению энергии электронов, ускоряемых лазерным кильватерным полем. Со временем первые самоинжектированные сгустки превращаются в драйверные и способствуют ускорению последующих ускоряемых сгустков. Таким образом, наступает комбинированное совместное ускорение последних самоинжектированных электронных сгустков лазерным импульсом и первыми самоинжектированными электронными сгустками, ставшими драйверами. Показано, что заряды первоначально самоинжектированных электронных сгустков равны нескольким пикокулонам, заряды же дополнительно самоинжектированных и ускоряемых электронных сгустков, имеющих самую большую энергию, гораздо меньше. Также показано, что энергии дополнительно самоинжектированных и ускоряемых электронных сгустков больше, чем энергии первоначально самоинжектированных сгустков электронов, ставших драйверами. Продемонстрировано, что как в случае инжекции одного лазерного импульса, так и в случае инжекции короткой цепочки лазерных импульсов, первоначально самоинжектированный электронный сгусток во второй кильватерной полости после торможения самоочищается в результате радиальной дефокусировки поперечными полями.

## СПІЛЬНЕ КІЛЬВАТЕРНЕ ПРИСКОРЕННЯ ЛАЗЕРНИМ ІМПУЛЬСОМ І САМОІНЖЕКТОВАНИМИ ЕЛЕКТРОННИМИ ЗГУСТКАМИ

***В.І. Маслов, О.М. Свистун, І.М. Онищенко, О.М. Єгоров***

Багатозгусткова самоінжекція, що спостерігається в лазерно-плазмових прискорювачах у нелінійному режимі, може виявитися багатообіцяючою. А саме, вона призводить до збільшення енергії електронів, прискорених лазерним кільватерним полем. Згодом перші самоінжектовані згустки перетворюються в драйверні і сприяють прискоренню наступних самоінжектованих згустків. Таким чином, настає комбіноване спільне прискорення останніх самоінжектованих згустків лазерним імпульсом і першими самоінжектованими згустками, що стали драйверами. Показано, що заряди спочатку самоінжектованих згустків рівні декільком пікокулонам, заряди ж додатково самоінжектованих і прискорених електронних згустків, що мають найбільшу енергію, набагато менше. Також показано, що енергії додатково самоінжектованих і прискорених згустків більше, ніж енергії спочатку самоінжектованих згустків, що стали драйверами. Продемонстровано, як в разі інжекції одного лазерного імпульсу, так і в разі інжекції короткого ланцюжка лазерних імпульсів, що спочатку самоінжектований електронний згусток в другій кільватерній порожнині після гальмування самоочищається в результаті радіального дефокусування поперечними полями.