Wakefield Excitation in Plasma of Metallic Density by a Laser Pulse*

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INTRODUCTION

The maximal accelerating field can be obtained in conventional accelerators approximately equals 100 MV per meter [2], because of very high probability of break-down at higher amplitudes. For accelerators where plasma is used, this limit is several orders greater up to 100 GV per meter [2, 3]. It is so complex for us to excite wakefield resonantly by the long sequences of electron bunches, to focus them, and to obtain large transformer ratio because of heterogeneity and nonstationarity of the laboratory plasma [4-5].

Scientists found [5] and study [6] the mechanism of resonant sequence focusing by nonresonant sequence of short electron bunches.

Laser technology and Plasma-Based Accelerators are actual and fast-developed technologies now [7-8]. The importance of Laser Plasma-Based Accelerators approved by a lot of number of experiments on wakefield acceleration [7-10]. Great accelerating gradients help to diminish geometrical parameters of the accelerators and the estimated cost.

INTRODUCTION

Scientists studied electron self-injection generated by intense laser pulse in the wake bubble (plasma is under-dense) by numerical simulation [11].

In [12] the researches have been considered and experimentally studied phenomena of electron acceleration and self-injection.

The occurrence of the slingshot effect at the impact of a very short and intense laser pulse onto a diluted plasma has been studied in [13].

In some cases, one can see a transition from laser wake-field acceleration to plasma wakefield acceleration [14]. It is known that modern laser technologies sustain pro-ducing of 100 PW laser pulses with a single-cycle dura-tion in order of several femtoseconds. Professor T. Tajima proposed use intense coherent X-Ray pulses (produced by new laser technologies) for particles acceleration. This X-Rays are focusing so distant from the diffraction limit of the original laser wavelength. The X-Rays injected into a metallic-density electron plasma are ideal for wake-field acceleration by laser [1].

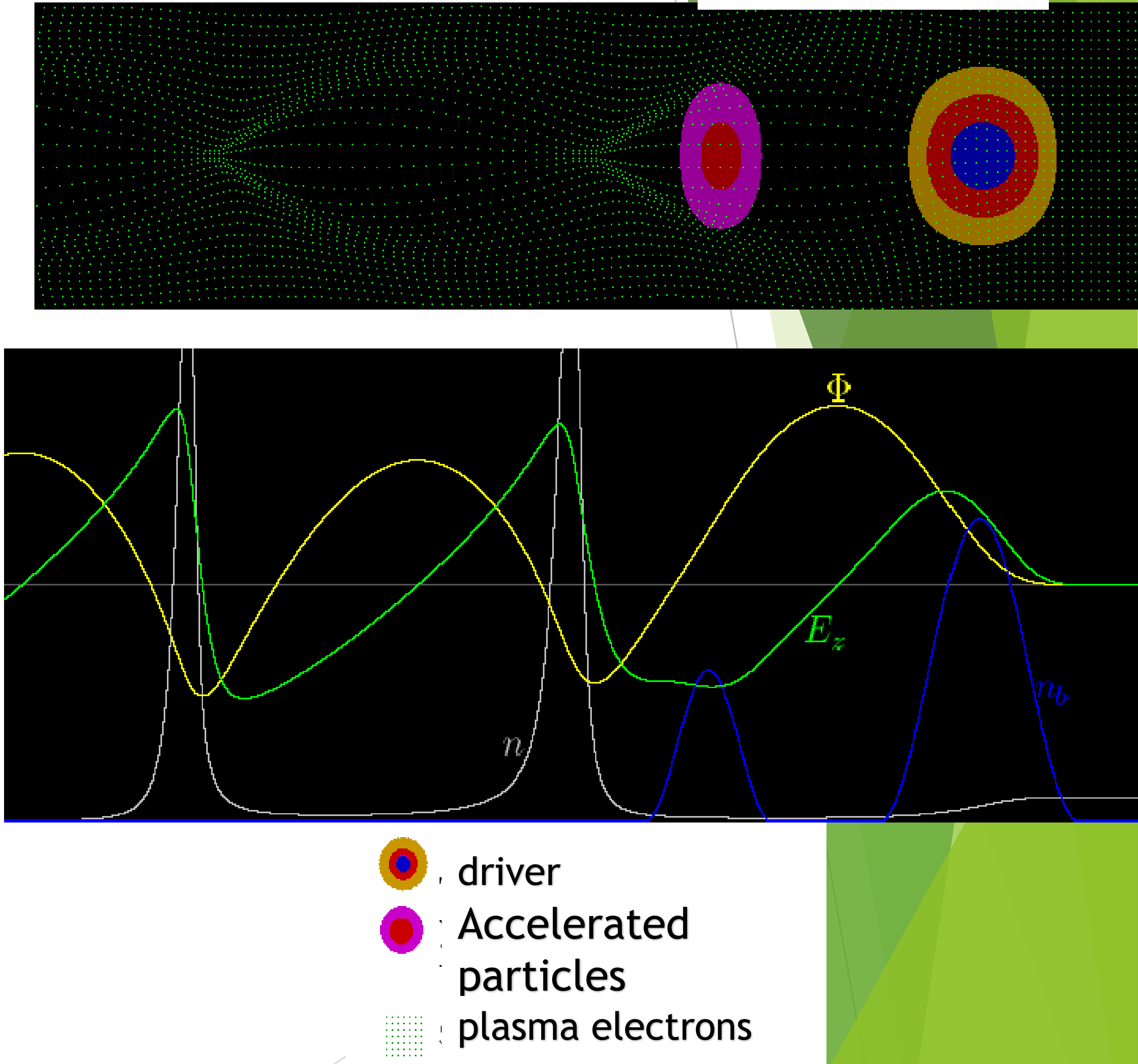
Wakefield acceleration

I.Yu.Kostyukov

In the right Figure one can see the wakefield principle illustration. Driver (in our case) - a laser pulse moving through the plasma pushes electrons apart.

This is due to the action on the electrons of the so-called pondemotor i.e. Millar force. As a result, it is possible to separate the charges, creating an excess of negative electrons in one region. Heavy ions remain inactive.

Thus, it is possible to create fields of the order of 100GV/m in plasma and TV/m in plasma of metal density with the possibility of their subsequent use to accelerate charged particles.



The problem at laser wakefield acceleration is that laser pulse quickly destroyed because of its expansion.

Ways to solve:

- **using of a capillary as a waveguide for laser pulse**
- **to transfer laser energy to the electron bunches which as drivers accelerate witness.**

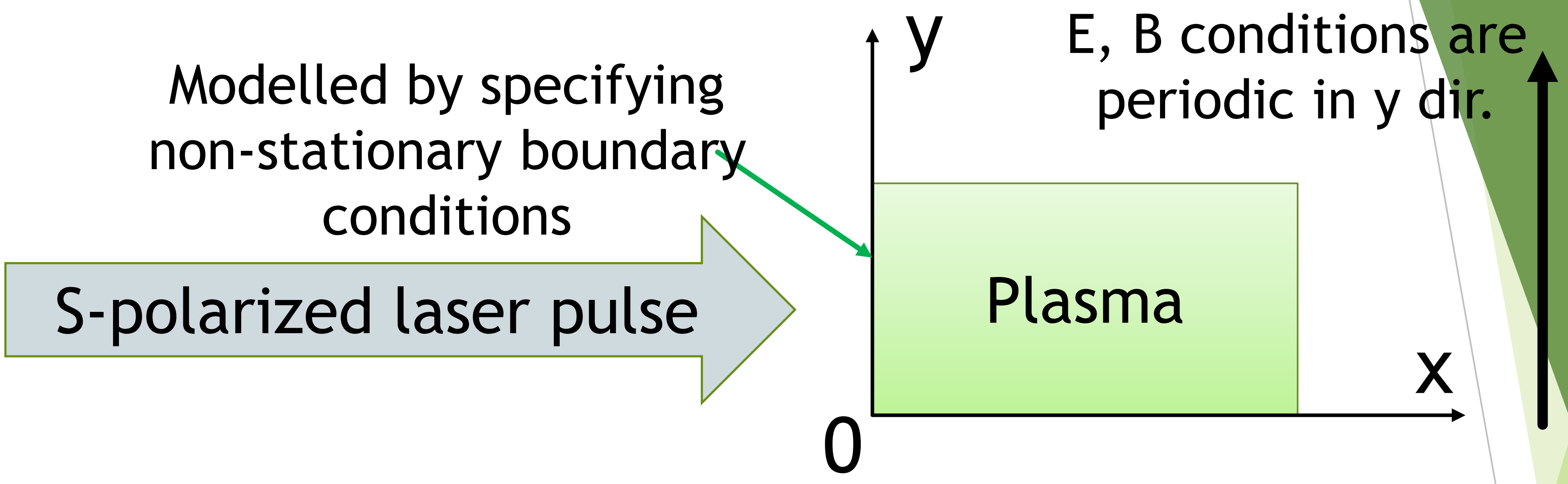
A transition from a laser wakefield accelerator to plasma wakefield accelerator can be occurred in some cases at laser-plasma interaction.

The subject of the study: accelerating gradient in high density plasma and dynamics of self-injected and accelerated electron bunches (combined mode of plasma-wakefield acceleration)

In this paper are numerically simulated:

- laser wakefield acceleration in a plasma of metallic-density,
- the maximum accelerating gradient in such a new medium,
- the transition to the regime of joint laser wakefield acceleration and beam-plasma wakefield acceleration.

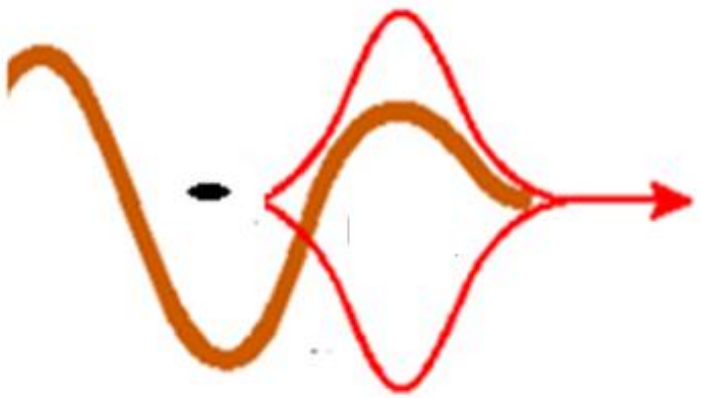
UMKA 2.5D Code Parameters of numerical simulation



Longitudinal and transverse dimensions of the laser pulse shorter than the plasma wavelength.

Pulse $\cos^2 A$ in longitudinal direction

and Gaussian in transverse direction



Parameters of numerical simulation

UMKA 2.5D Code [15]

Plasma density $n_e = 1.8 \cdot 10^{22}\ cm^{-3}$

(homogeneous plasma)

Plasma frequency $\omega_{pe} = 7.51 \cdot 10^{17}\ {}^{rad}/_{s}$

Laser wavelength λ= 25 nm

$$^{\omega_{pe}}/_{\omega_{laser}} = 0.1008$$

$$1a_0 = 20.6\frac{TV}{m}$$

First laser: length = 2λ, width = 8λ, amplitude = $3a_0$

Second laser: length = 4λ, width = 4λ, amplitude = $3a_0$

Simulation window: 800λ (length), 50λ $(width)$

Normalizations of numerical simulation

UMKA 2.5D Code [15]

Plasma density n normalized on $n_c = m_e\omega_0^2(4\pi e^2)^{-1}$

All length normalized on λ

Electric, magnetic field, focusing force normalized on

$$E = a_0 e(m_e c\omega_0)^{-1}$$

time t normalized on $2\pi\omega_0^{-1}$

First laser: length = 2λ, width = 8λ, amplitude = $3a_0$

Second laser: length = 4λ, width = 4λ, amplitude = $3a_0$

Simulation window: 800λ (length), 50λ ($width$)

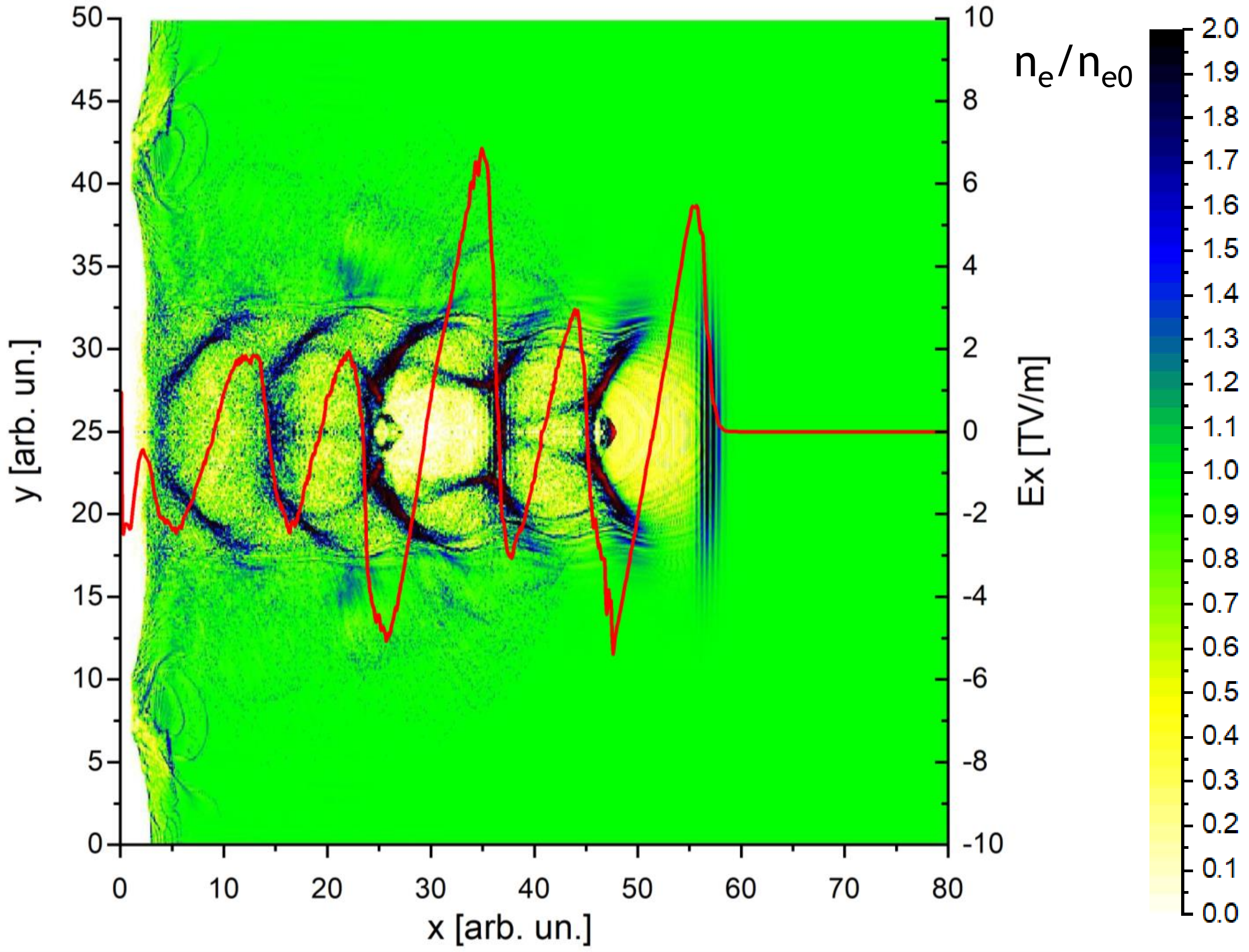
RESULTS OF SIMULATION

Figures in slides 11-16 illustrate the three main stages of wake-field excitation by a sequence of laser pulses in a plasma. Slides 11-12 show that as a result of the wake process, two self-injected bunches are formed: both after the first and after the second laser pulses. Self-injected bunches move into the accelerating phase of the wakefield. They have a small spatial spread. At the same time, they have relatively low energy.

Slides 13,14 show that after the self-injected bunch passed the accelerating phase and begin to enter the wakefield deceleration phase, its spatial spread in-creases, the energy spread is almost saved and the electron energy of the bunches increases

Combined mode of PWA and LWA

We consider the wakefield excitation by a train of two laser pulses. One can see that wakefield bubbles was formed.



Wake perturbation of plasma electron density n_e and longitudinal component of the wakefield E_x (red line) excited by two laser pulses of identical amplitude at the time $t = 60t_0$

$$n_e = 1.8 \cdot 10^{23}\ cm^{-3}$$

$$\lambda = 10.65\ nm$$

$$first\ laser: half - length = 1,$$

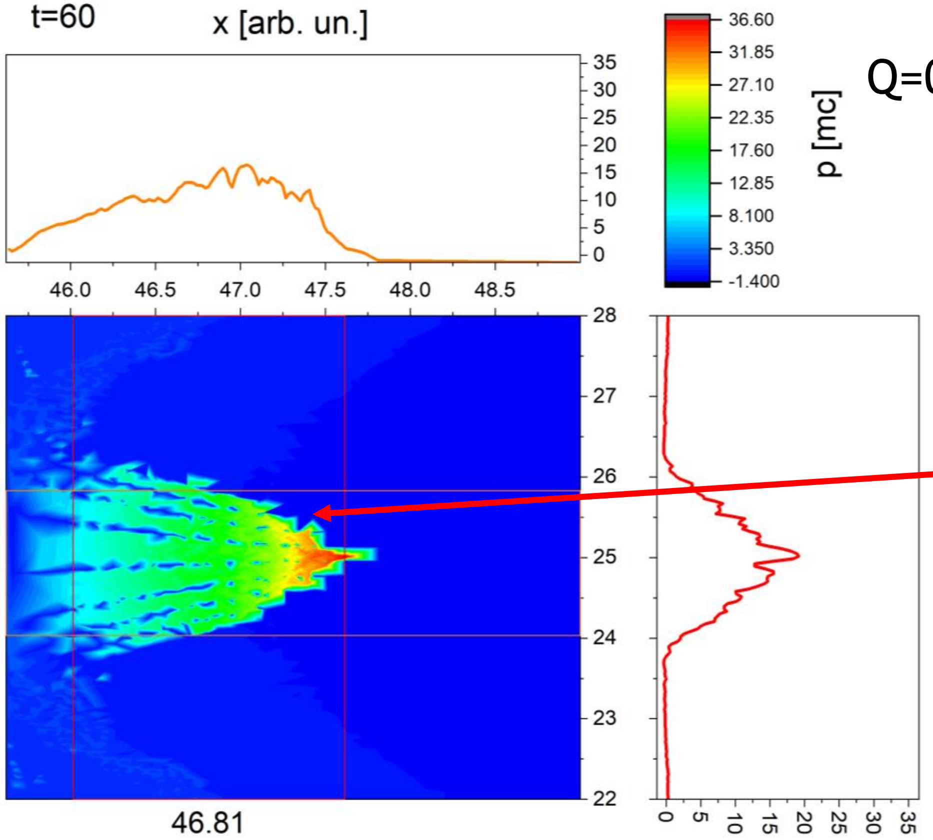
$$half - width = 5$$

$$second\ laser: half - length = 2$$

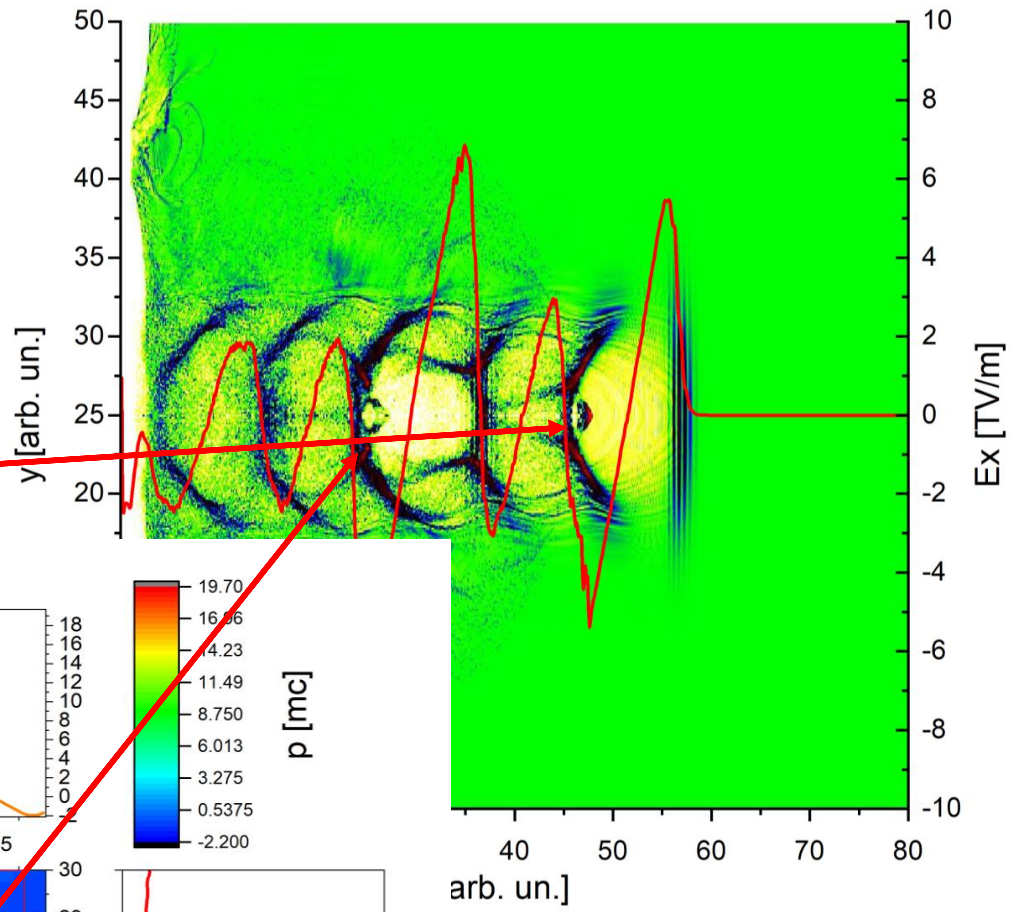
$$half - width = 3$$

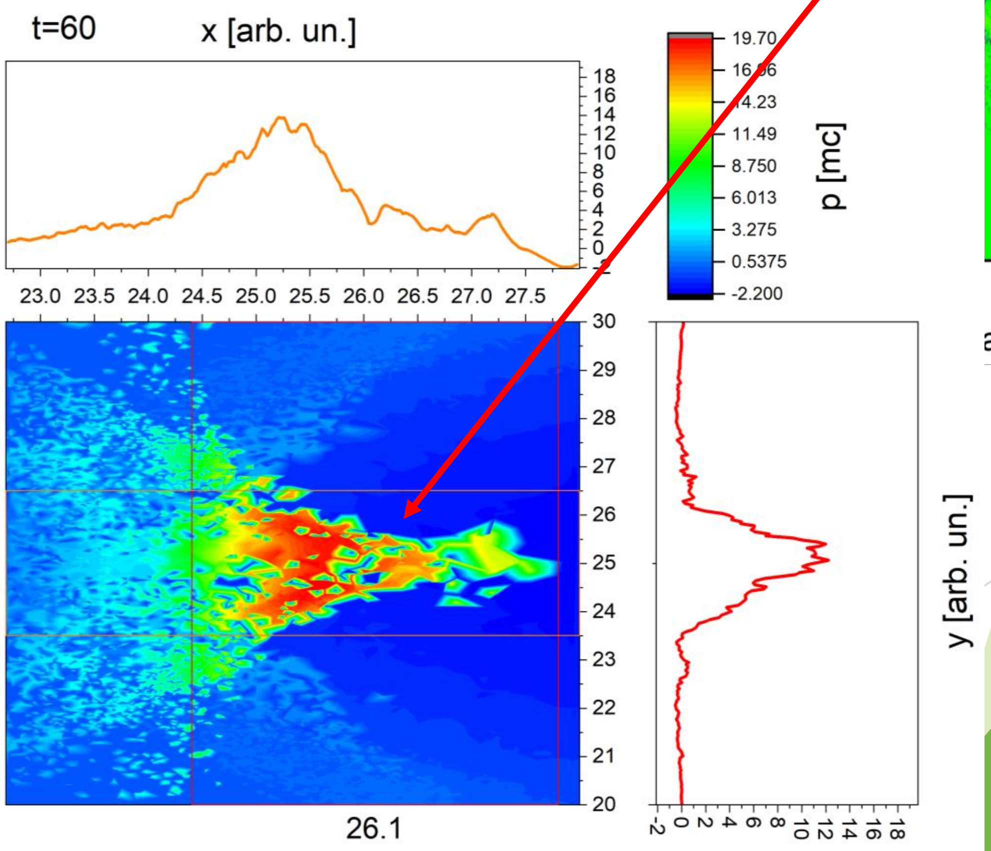
$$first\ laser:\ amplitude = 3$$

$$second\ laser:\ amplitude = 3$$



Q=0.16 pC





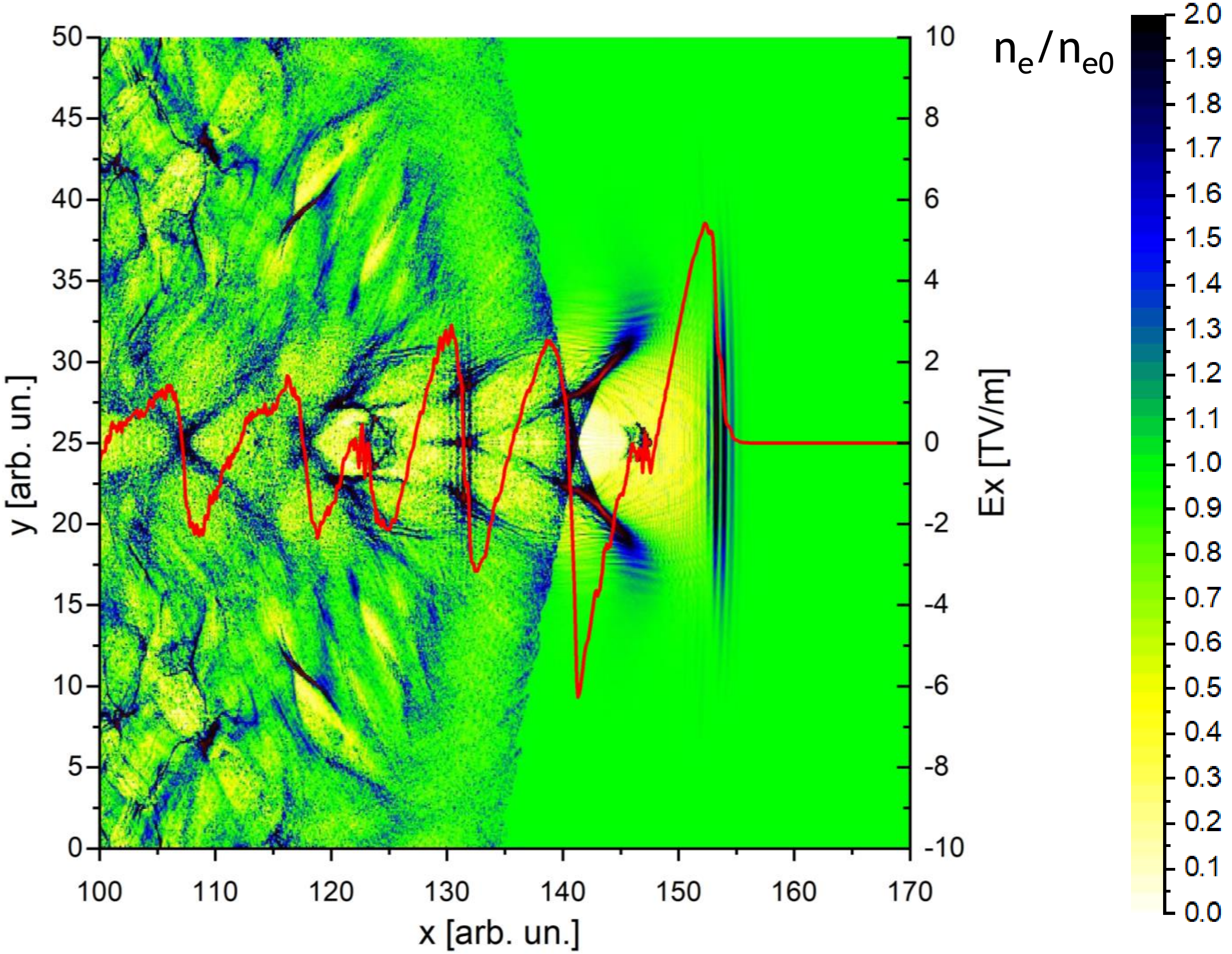
Q=0.87 pC

Wake perturbation of plasma electron density n_e and focusing force of the wakefield F_r (red line) excited by the laser pulse at the time $t = 60t_0$

Longitudinal (Px) pulse distribution (from x and y)

Combined mode of PWA and LWA

We consider the wakefield excitation by a train of two laser pulses. One can see that self-injected bunches move through wakefield bubble.



Wake perturbation of plasma electron density n_e and longitudinal component of the wakefield E_x (red line) excited by two laser pulses of identical amplitude at the time $t = 160t_0$

$$n_e = 1.8 \cdot 10^{23}\ cm^{-3}$$

$$\lambda = 10.65\ nm$$

$$first\ laser: half - length = 1,$$

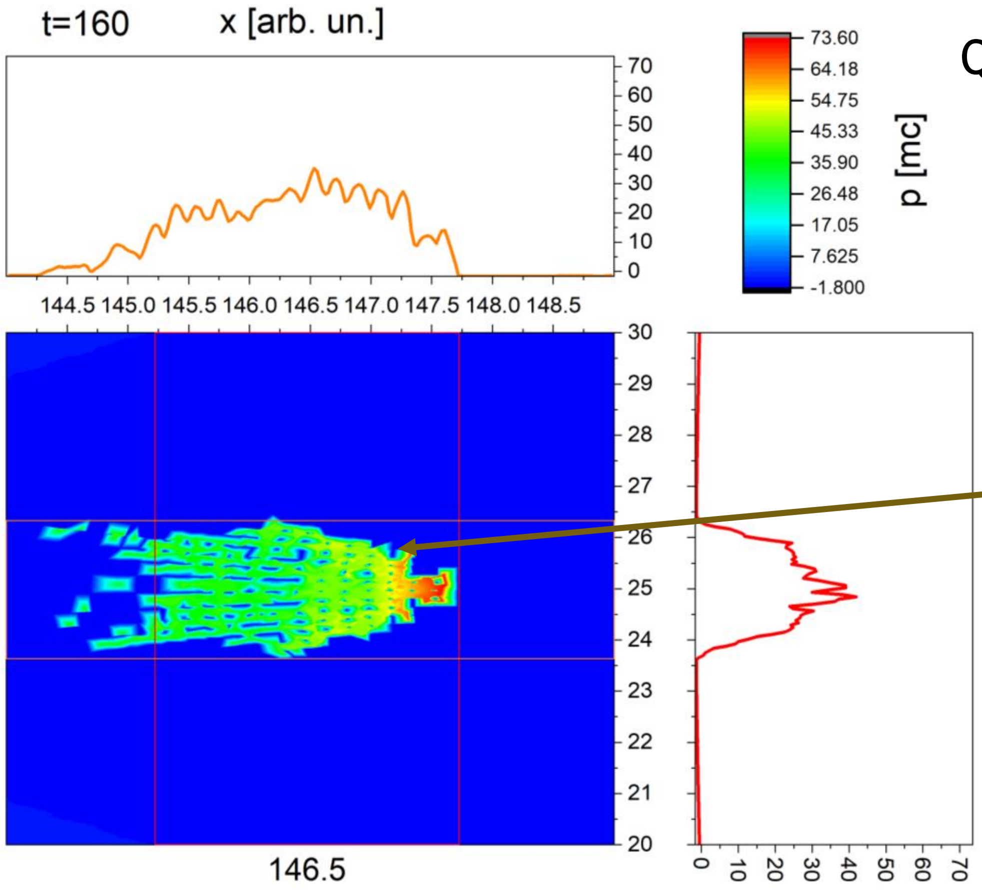
$$half - width = 5$$

$$second\ laser: half - length = 2$$

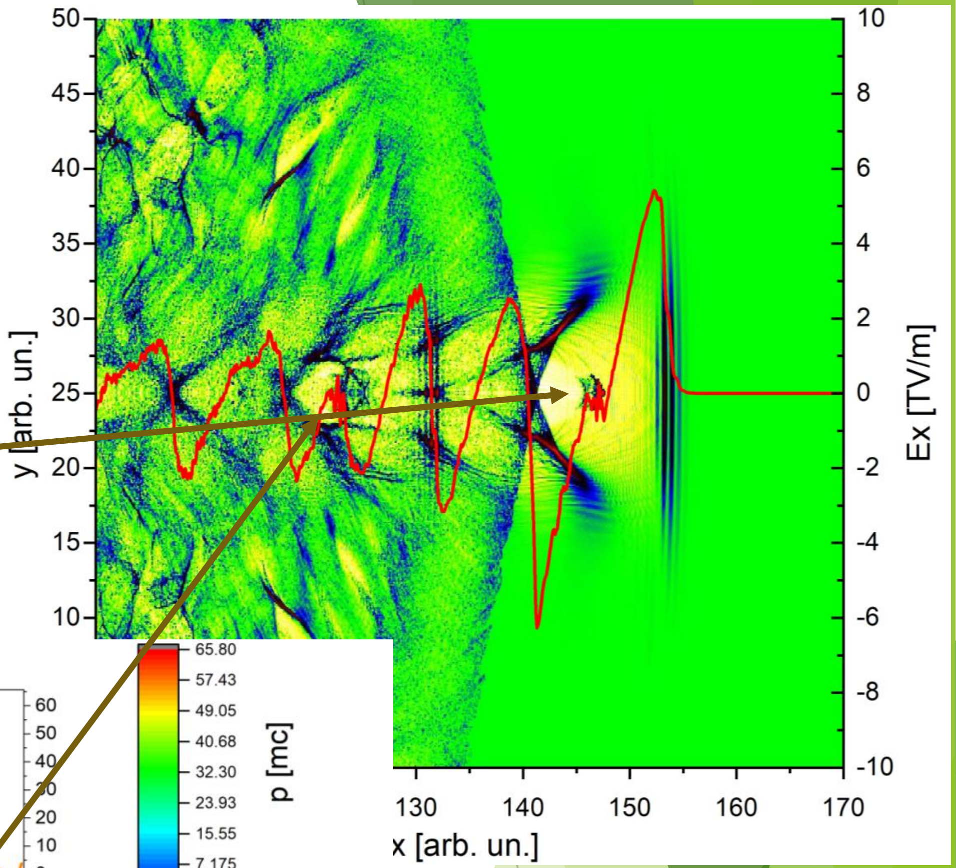
$$half - width = 3$$

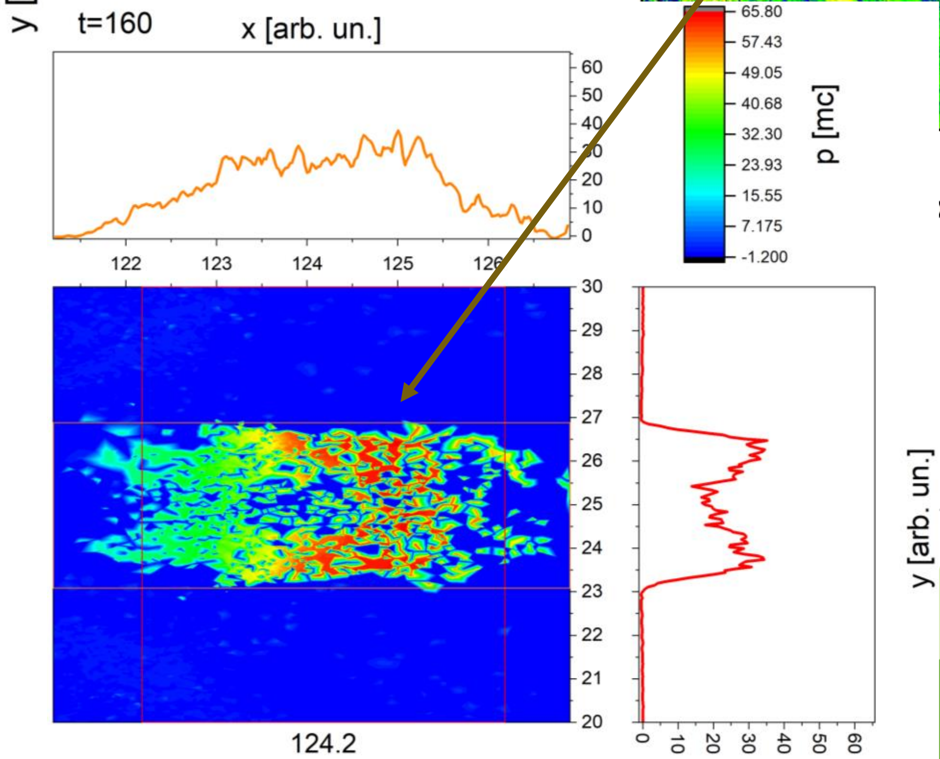
$$first\ laser:\ amplitude = 3$$

$$second\ laser:\ amplitude = 3$$



Q=0.49 pC





Q=2.07 pC

Wake perturbation of plasma electron density n_e and focusing force of the wakefield F_r (red line) excited by the laser pulse at the time $t = 160t_0$

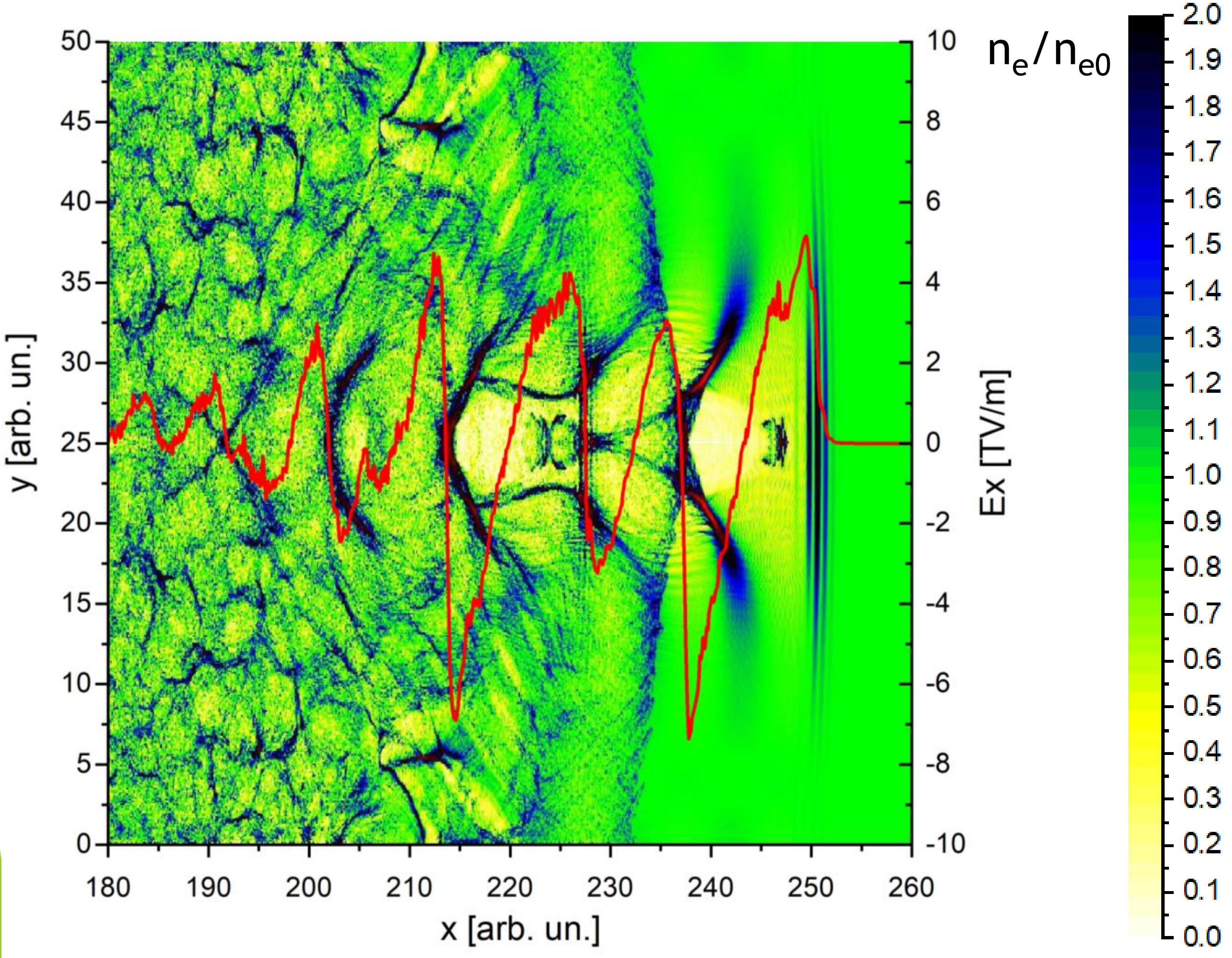
Longitudinal (Px) pulse distribution (from x and y)

RESULTS OF SIMULATION

This means that due to the action of the wakefield, self-injected bunches acquire additional energy without significant defocusing. This is an important stage in combined laser-plasma acceleration. Finally, Slides 16,17 show that self-injected bunches fall into the decelerating phase of the wake wave. This leads to an increase in their spatial size and energy dispersion and to a decrease of self-injected bunches energy. The bunches are substantially defocused and destroyed. The reason for this may be relativistic defocusing due to a decrease in the gamma factor of bunches electrons.

Combined mode of PWA and LWA

We consider the wakefield excitation by a train of two laser pulses. One can see that self-injected bunches situate at the deceleration phase of wakefield.



Wake perturbation of plasma electron density n_e and longitudinal component of the wakefield E_x (red line) excited by two laser pulses of identical amplitude at the time $t = 260t_0$

$$n_e = 1.8 \cdot 10^{23}\ cm^{-3}$$

$$\lambda = 10.65\ nm$$

$$first\ laser\colon half - length = 1,$$

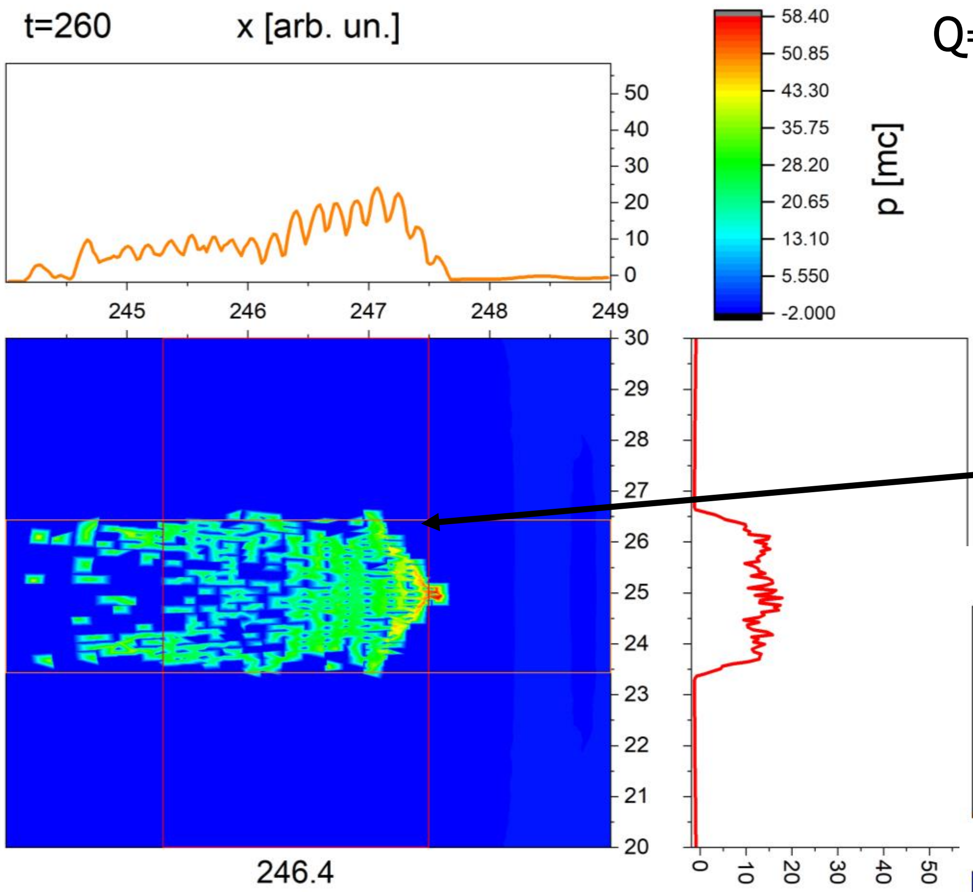
$$half - width = 5$$

$$second\ laser\colon half - length = 2$$

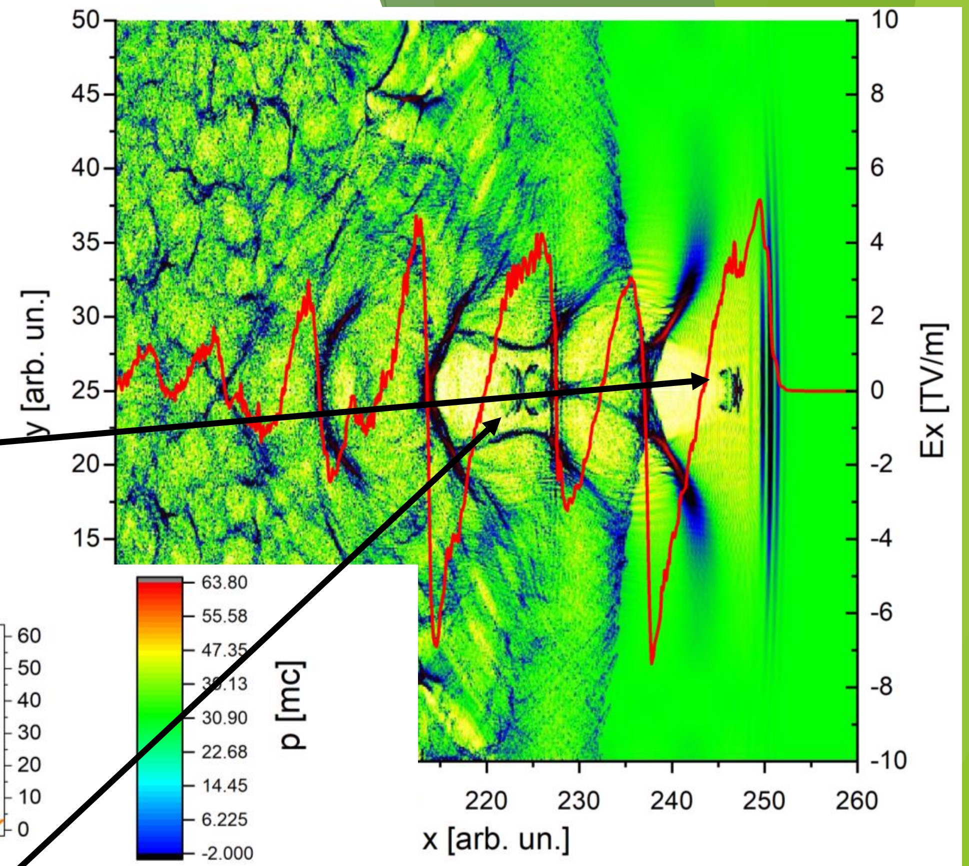
$$half - width = 3$$

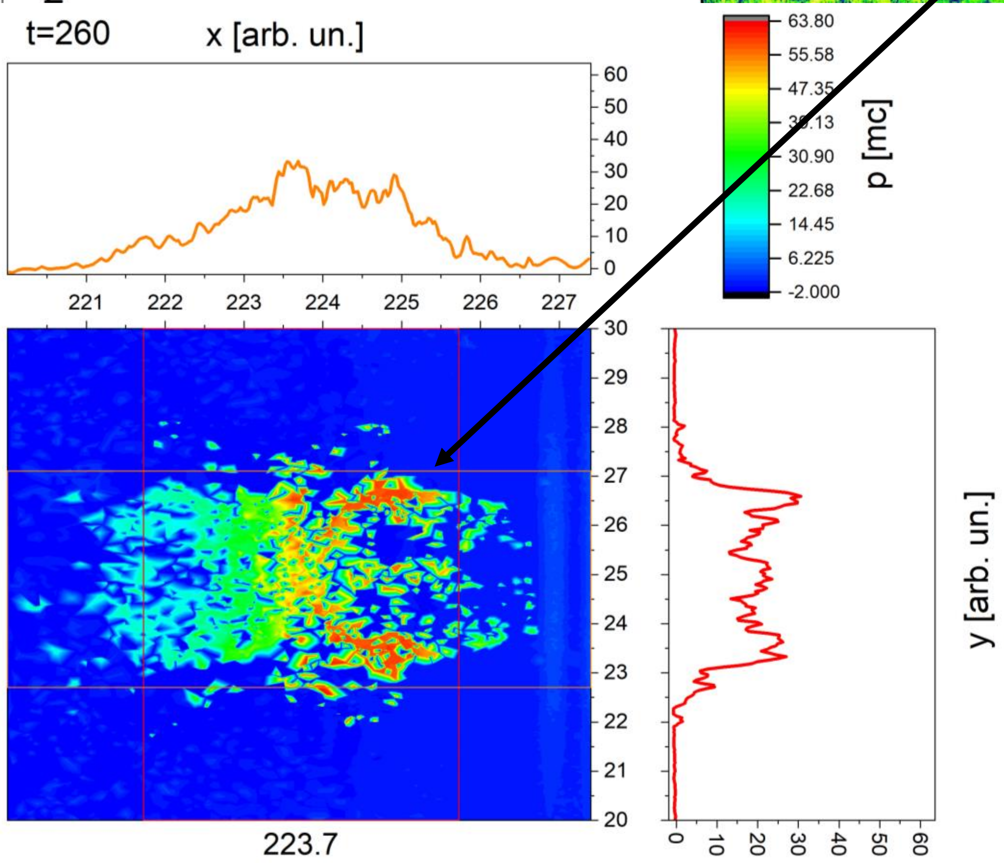
$$first\ laser\colon\ amplitude = 3$$

$$second\ laser\colon\ amplitude = 3$$



Q=0.54 pC





Q=1.96 pC

Wake perturbation of plasma electron density n_e and focusing force of the wakefield F_r (red line) excited by the laser pulse at the time $t = 160t_0$

Longitudinal (Px) pulse distribution (from x and y)

RESULTS OF SIMULATION

The energy is transferred to the wave. As a result, as we can see from the comparison of Slide 16 and Slide 11, in the case of self-injected bunches, both after the first and after the second laser pulses, the energy transfer from the bunches to the wave leads to an increase in the accelerating wakefield by about 28%. The accelerating gradient of the accelerating field at this moment reaches a value of 8 TV/m. Such rates of acceleration are possible due to the high density of the plasma. To implement such a regime, very powerful X-ray lasers are needed. A promising technology will make it possible to create compact and powerful charged particle accelerators. The mechanism of the formation of self-injected bunches makes it possible to obtain focused bunches of high energies (Slide 12), but it requires careful control of the parameters of the system and the moments in time when the wake process takes place.

RESULTS OF SIMULATION

When considering the second case with FLHM equals 4 for the first laser pulse and 6 for the second laser. FWHM equals 8 and 4, we can observe a similar picture: the effect of the combined laser-plasma acceleration leads to an increase of the accelerating wakefield amplitude. And thanks to the use of high dense plasma and an X-ray laser pulse, one can obtain accelerating gradients reaching several teravolts per meter. New self-injected bunches will be accelerated by the energy of the laser pulse and the previous self-injected bunches. We call this process the combined laser-plasma acceleration mode. Combined laser-plasma acceleration is considered as a process that will provide a significant acceleration rate of bunches of charged particles both during self-injection and for injection from outside.

Conclusions

- Numerical simulation demonstrates the transition from the laser-wakefield acceleration in metallic-density plasma to extra beam-driven wakefield acceleration that providing additional acceleration of self-injected electron bunch.

- At wakefield excitation by the laser pulse in metallic-density plasma electrons are accelerated in electric fields which approximately equal several teravolts per meter.

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Thanks you for your attention