Some Aspects of Laser Wakefield Acceleration of Self-injected Electron Bunch in a Metallic-Density Electron Plasma*

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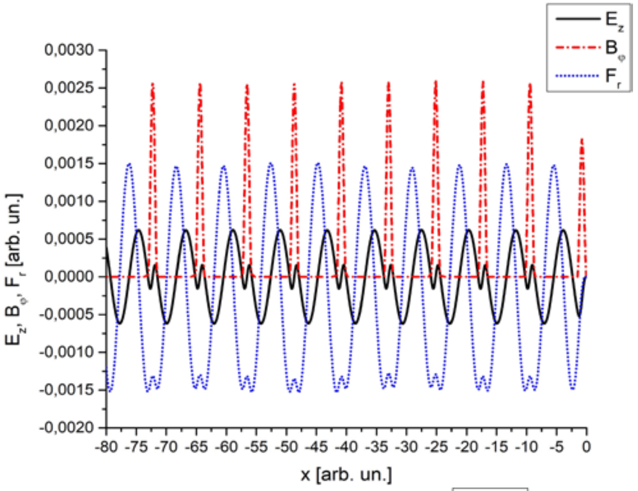
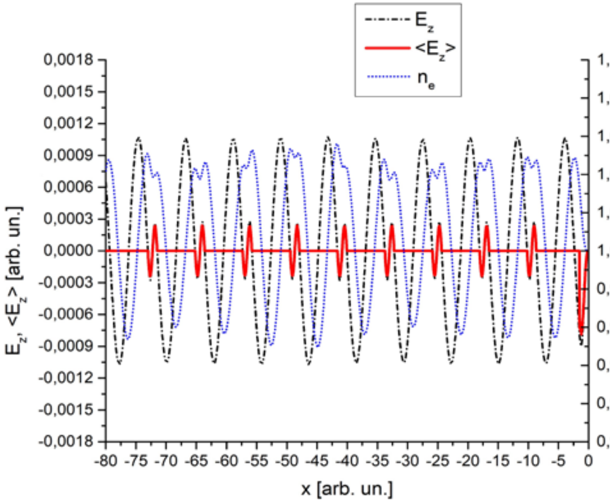
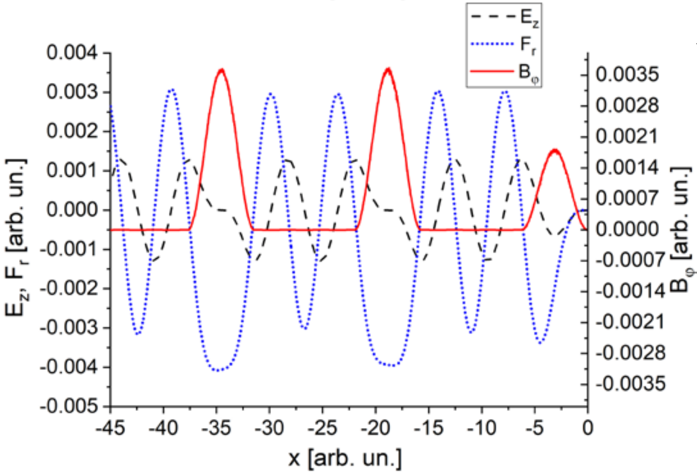




The off-axis radial focusing force F_r and off-axis magnetic field B_φ and also accelerating field E_z.
The on-axis plasma electron density n_e,
on-axis longitudinal wakefield E_z and $< E_z >$

- **Bunches length equals $^{\lambda}/_{2}$.**
- **the charge of all bunches is in √2 times larger than the charge of the 1st bunch.**
- **The interval between the 1st and 2nd bunches is (n+1/8)λ, n=1, 2, …**
- **The interval between other bunches is a multiple of λ.**

$$\gamma_b = 1000\ I_b = 0.3 \cdot 10^{-3} r_b = 0.1$$



- Bunches length equals $^{\lambda}/_{2}$.
- The charge of all bunches is in 2 times larger than the charge of the 1st bunch.
- The interval between bunches is 2.5λ.

- Plasma electron density is $n_e = 10^{11}\ cm^{-3}$
- Plasma wavelength is $\lambda = 10.6\ cm$
- Plasma frequency is $\omega_{pe} = 1.78 \cdot 10^{10} \frac{rad}{s}$
- $^{c}/_{\omega_{pe}} = 1.68\ cm$

The rest of the parameters can be found directly on the graphs and in the figure captions.

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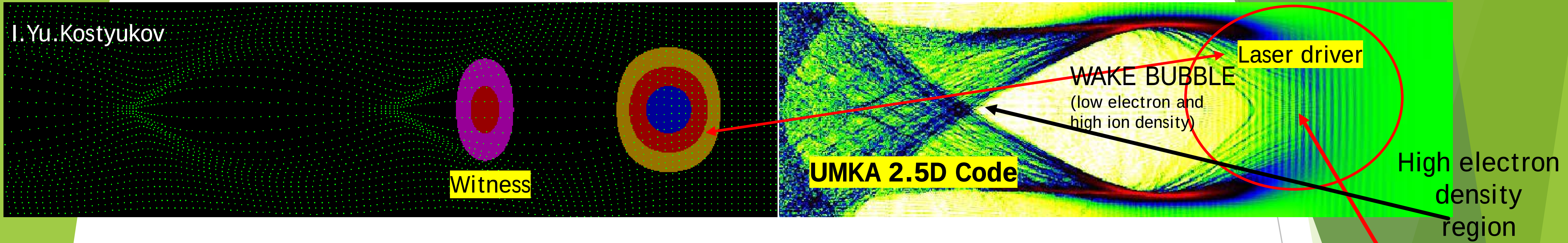
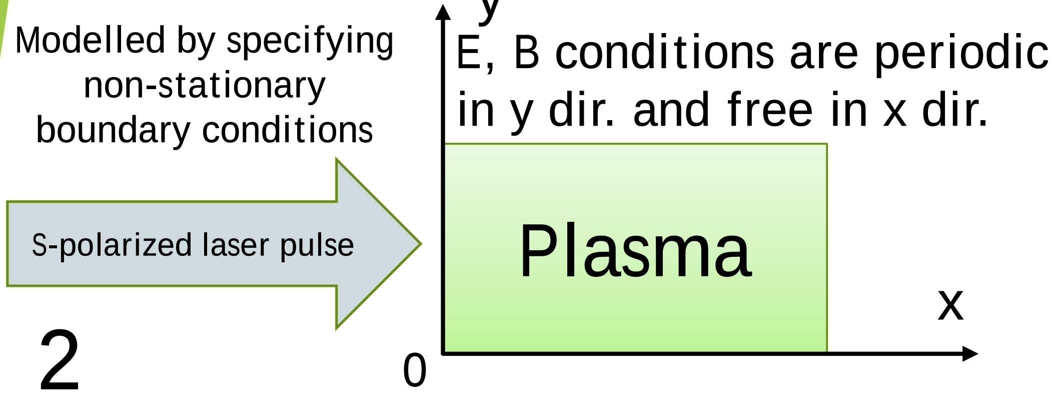


A laser pulse driver moving through the plasma pushes electrons apart. This is due to the action on the electrons of the so-called pondermotor i.e. Millar force. As a result, it is possible to separate the charges, creating an excess of negative electrons in one region. Heavy ions remain inactive. One can avoid 100 MV/m limitation.

When a wakefield is excited, because of the nonlinear plasma processes laser pulse quickly expansion and destroying is observed. It can be solved by using of a capillary as a waveguide for laser pulse and by transferring of a laser energy to the self-injected electron bunches for further use them as drivers to accelerate witness. Second process was studied via numerical PIC simulation.

Pulse like $\cos^2$A in longitudinal direction and Gaussian in transverse direction



Parameters of numerical simulation

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

(homogeneous plasma)

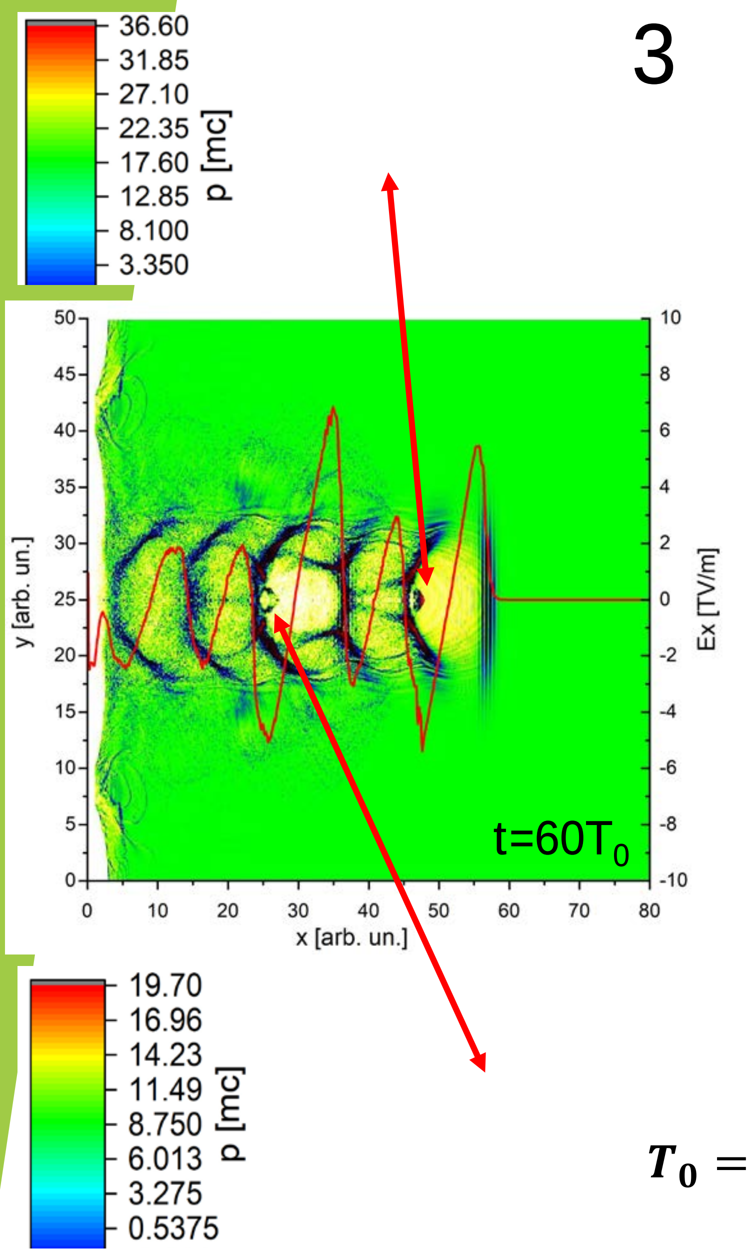
Laser frequency $\omega_0 = 7.51 \cdot 10^{17}\ {}^{rad}/_{s}$

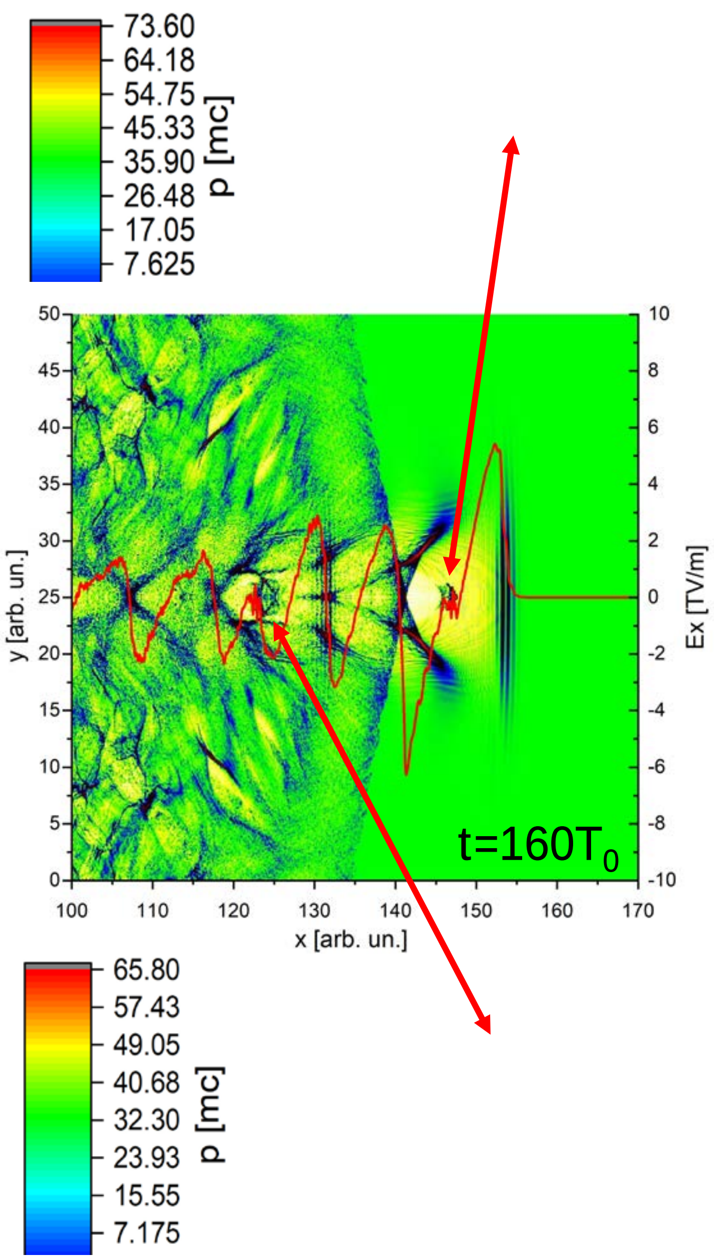
Laser wavelength λ= 25 nm

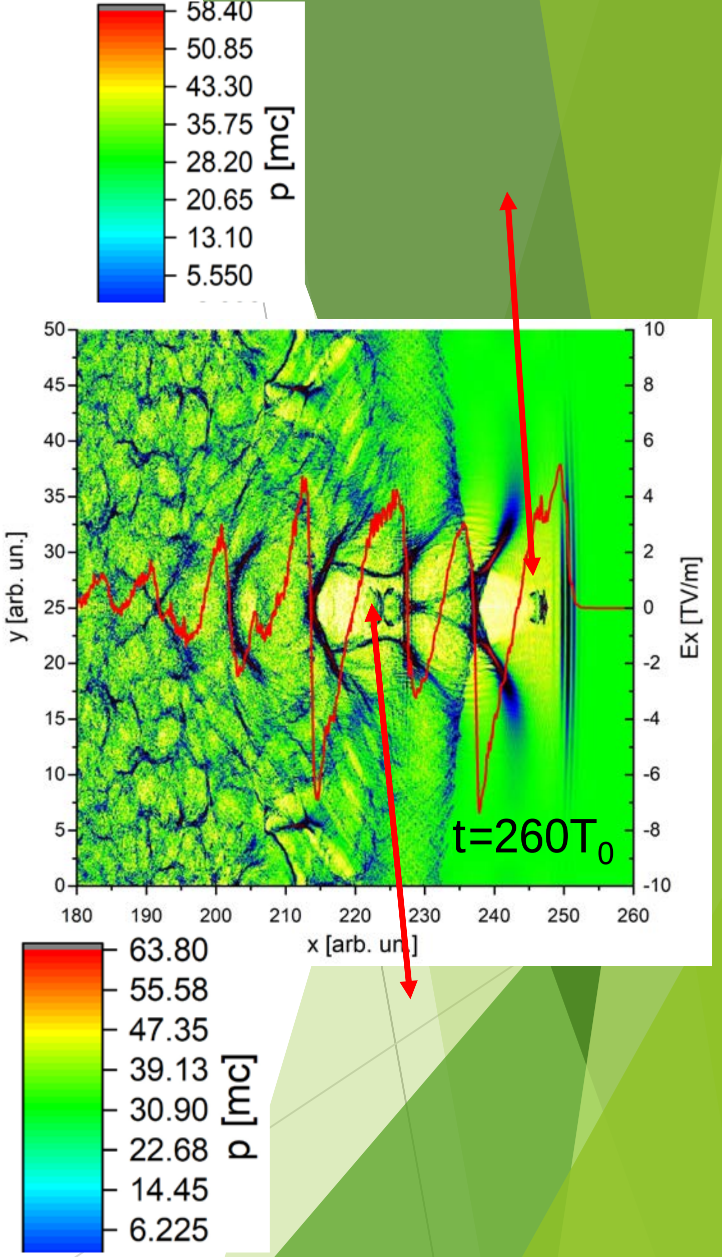
$$^{\omega_{pe}}/_{\omega_{laser}} = 0.1008$$

a = 1 => $E = 20.6\,\frac{TV}{m}$

Laser amplitudes a = 3
Simulation window:
800λ (length),
50λ (width)







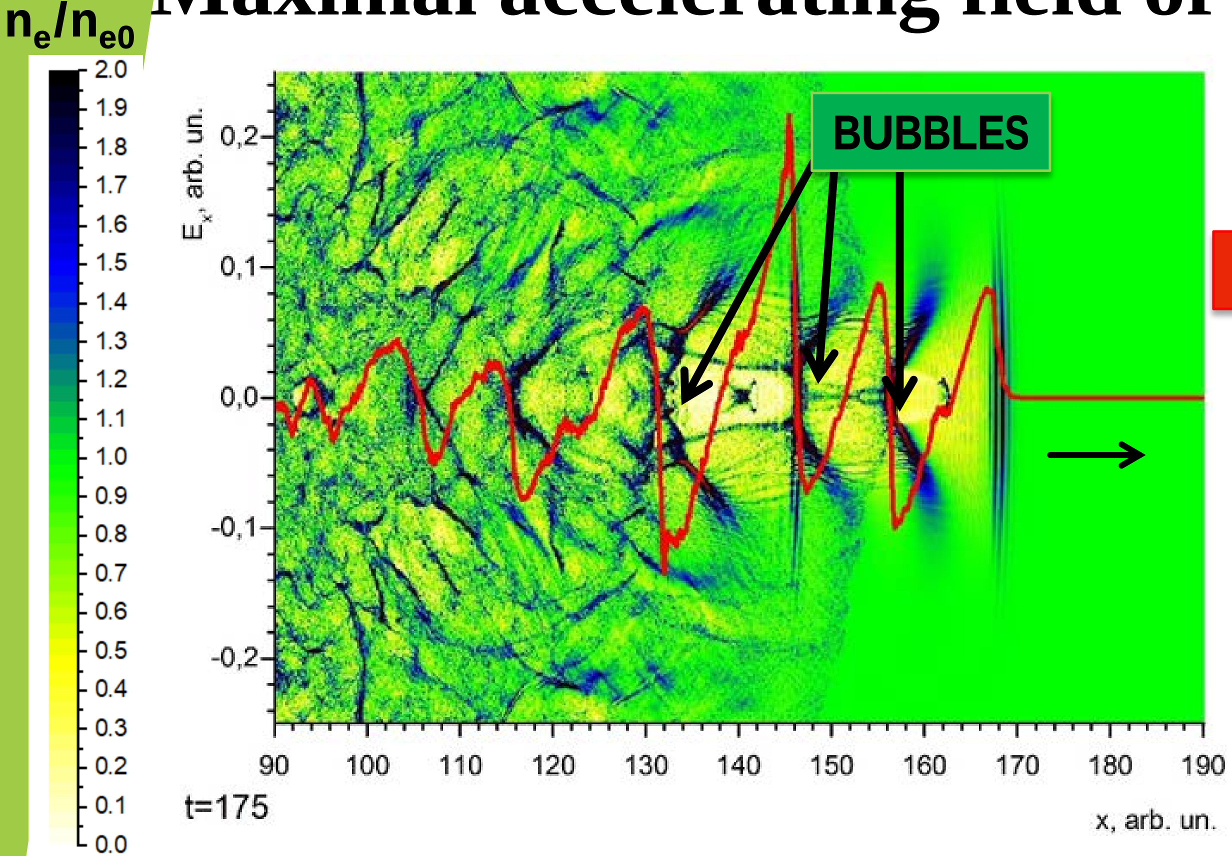
$$T_0 = 2\pi\omega_0^{-1}$$

Wake perturbation of plasma electron density n_e and longitudinal wakefield E_x (red line) excited by the laser pulse. Longitudinal (Px) pulse distribution

$first\ laser: half - length = 1,$
$half - width = 5$
$second\ laser: half - length = 2$

$half - width = 3$
$first\ laser: amplitude = 3$
$second\ laser: amplitude = 3$

Maximal accelerating field of about several teravolts per meter

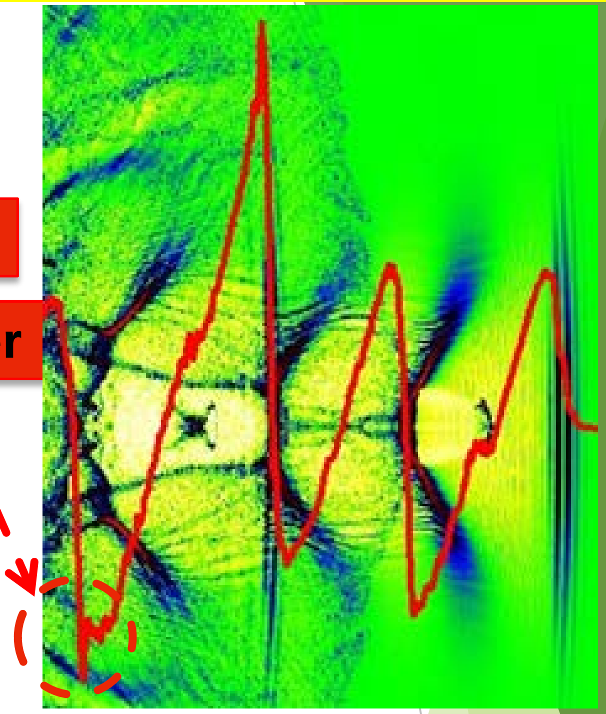


MAXIMUM

Accelerating field

Teravolts per meter

>>100 GV/m



UMKA 2.5D Code

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

$a = 1$ => E $= 20.6\,\frac{TV}{m}$

Laser pulses initial intensity $3 \cdot 10^{18}\,\frac{W}{cm^2}, \lambda = 25nm,$

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

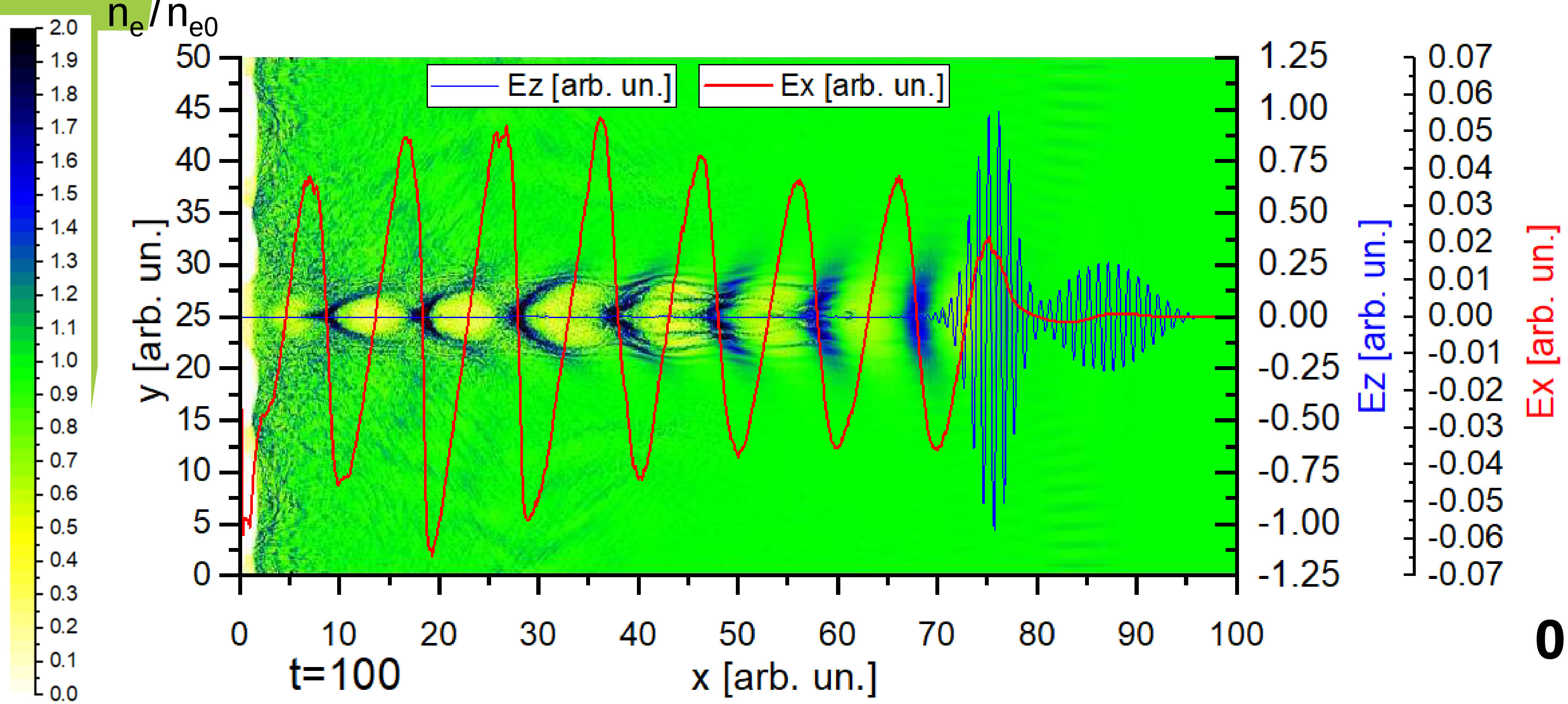
Second laser: length = 4λ, width = 4λ, amplitude a=3

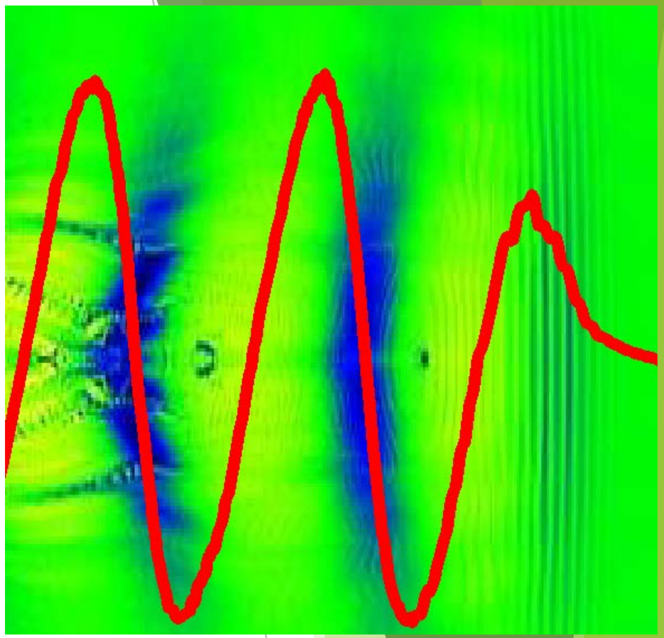
Simulation window: 800λ (length), 50λ (width)

TV/m accelerating gradient:

- **X-Ray lasers**
- **High-power pulses**
- **High-density plasma**

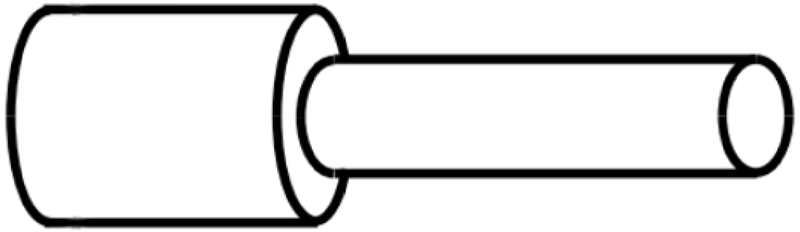
Wake perturbation of plasma electron density n_e and longitudinal component of the wakefield E_x (red line) excited by two identical laser pulses at the time $t = 175T_0$





0.73 TV/m **0.74 TV/m**

Wake perturbation of plasma electron density n_e , longitudinal wakefield amplitude E_x (red line), laser field amplitude E_z (blue line)



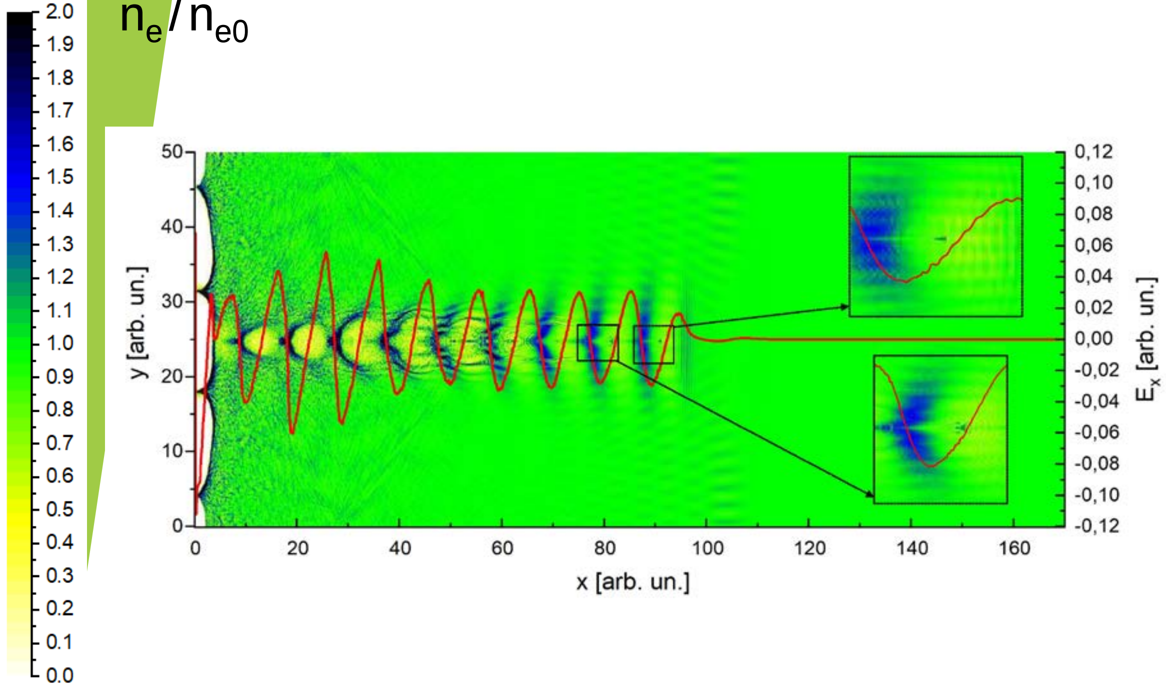
Laser pulse shaped on radius, length and amplitude

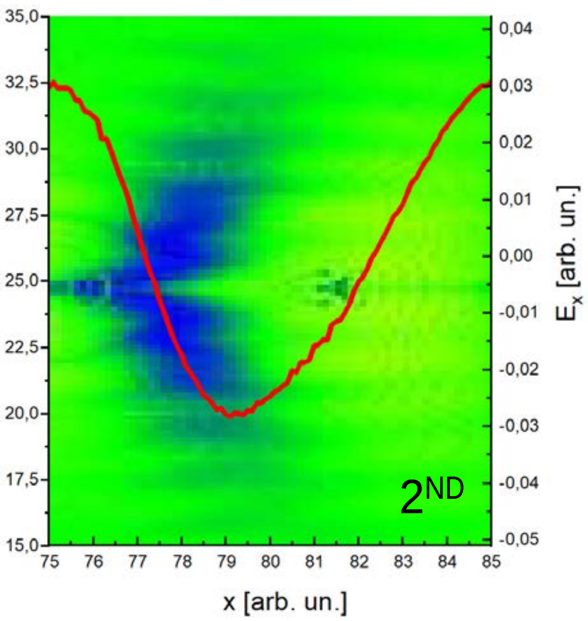
Laser number	**a**	**Radius**	**Length**
1	1	1	8
2	1.732	2	4

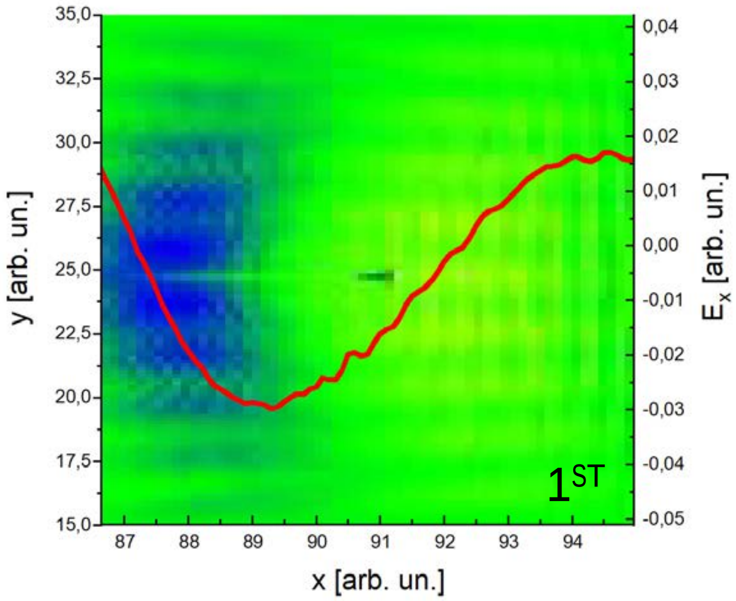
Plasma density $n_e = 1.8 \cdot 10^{22}\ cm^{-3}$

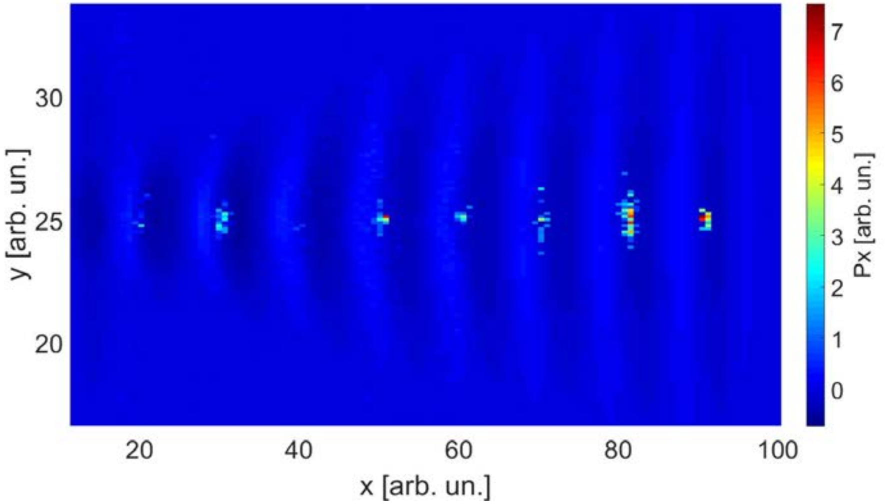
$a = 1$ **=>** **E** $= 20.6\frac{TV}{m}$**. Intensity** $10^{18}\ W/cm^2$

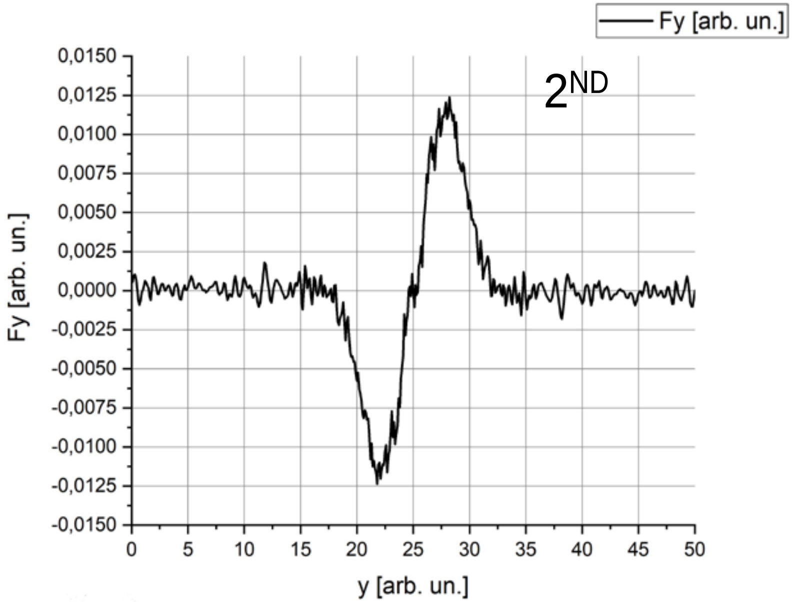
Laser wavelength $\lambda = 25\ nm$

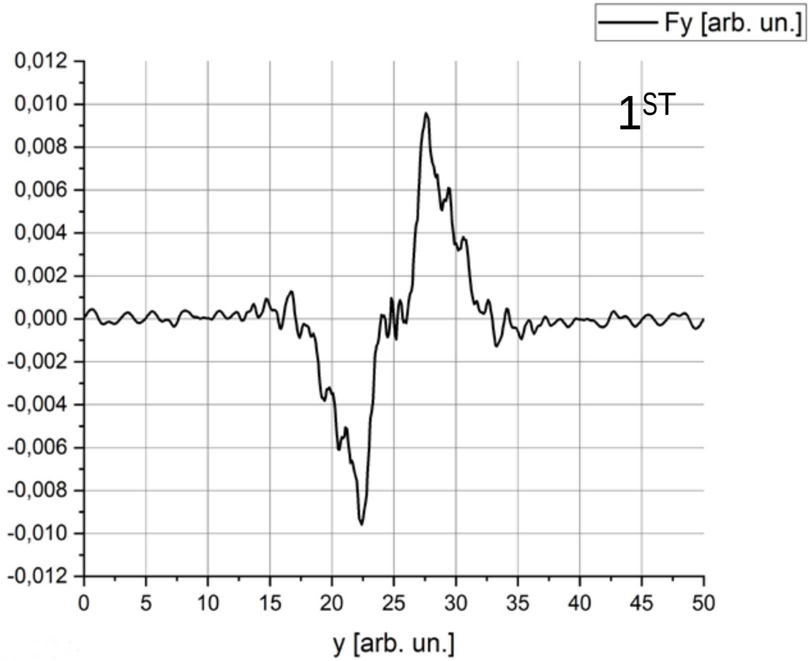












Longitudinal momentum

Focusing force

Conclusion

- The focusing of a sequence of relativistic positron bunches is investigated.
- The excitation of a wakefield in a plasma of metal density by an X-ray laser pulse is investigated.
- The regime of combined laser-plasma acceleration was considered.
- It was shown that self-injected bunches, which are formed as a result of the wakefield excitation, moving along the wake bubble, fall into the decelerating phases of the wakefield. They transfer energy to the wake wave, which results in an increase in the amplitude of the accelerating field.
- An accelerating field was obtained, the amplitude of which reaches several teravolts per meter.
- The excitation of the wakefield by a sequence of shaped lasers is investigated.
- The formation of self-injected bunches with a small spatial size, which are located in the regions of the uniform longitudinal wakefield and zero radial focusing wake force is considered.

PART 1

1. Where do you see HEP applications of advanced accelerators in 30 years? There are a lot of HEP applications of advanced accelerators for today. I think that they will be developed widely in the future. For example, phase-contrast technique which allows to see the smallest details can help to solve a lot of medical and technical problems and to provide biological researches. X-rays, which can be generated by the betatron oscillations of high-energy particles, can be used to study high-density plasma, which is observed in inertial fusion. High energy particles are widely used in microelectronics. In particular, for surface modification, particle implantation, etching. Considering that in the coming decades, Moore's law may well lead to a crisis when it will be impossible to achieve the required nanoscale in electronics, the use of higher energies can increase the efficiency of manufacturing. Accelerators can be used for physical research, in particular, for example, for heating plasma confined by a magnetic field.

2. What intermediate physics applications/steps do you see until a HEP linear collider? I see the intermediate steps before reaching the final concept of the accelerator in the search for new acceleration methods. An essential problem in modern accelerators is the phenomenon of electrical breakdown, which occurs at acceleration gradients exceeding 100MV/m in conventional linear accelerators and several GV/m in dielectric accelerating structures. The wakefield acceleration method can help to avoid this limitation and provide acceleration gradients of several teravolts per meter. The development of this method can become an important step towards a modern high-energy accelerator.

3. What is the synergy with related fields? The creation of high-energy linear accelerators, especially with the use of the wakefield, requires close cooperation of a large number of related fields. The wake acceleration method can help to avoid this limitation and provide acceleration gradients of several teravolts per meter. The development of this method can become an important step towards a modern high-energy accelerator. For implementation, it is required to create a short high-power x-ray laser pulse, to develop technology of shaped laser pulse formation, to develop high-speed photo and video, create a plasma, confine a plasma, focus, and directly accelerate charged particles. These are separate areas from which knowledge must be applied.

4. What is the role of your work here? The role of my research is in the numerical simulation of processes that allow obtaining significant values of the accelerating wakefield and looking for optimal values, geometry and accelerating medium. I think that this research will significantly reduce resources when conducting experiments on wake acceleration. In some accelerators, it is even possible to do without external injection. The studies presented earlier allow the use of self-injected bunches with the required parameters for subsequent acceleration. Additional studies on coherent addition and suppression of instabilities upon excitation of a wakefield in an inhomogeneous plasma only expand the possibilities for creating wakefield accelerators.

PART 2

1. What are the important milestones for the next 10 years to get there from today?

2021-2022	**2023-2024**	**2025-2026**	**2027-2028**	**2029-2030**
Numerical simulation of main principles and finding for optimal parameters for wakefield excitation in high (metal) density plasma, plateau formation on accelerating wakefield for electron-witness-bunch and on decelerating wakefield for driver-bunches in dielectric accelerator.	Systematization of principles, search for new opportunities for modeling and attempts to create approximate theories of wakefield expiation, simulation of point electron bunch self-injection by shaped laser pulse, of homogeneous and identical focusing of train of positron bunches in plasma.	Preparing for laboratory testing. Calculation and approval of the future laboratory facility. Prototyping. Beginning the creation of a laboratory installation, simulation of plateau formation on the accelerating wakefield and zero radial wake force.	Completion of the laboratory setup, testing and confirmation of the simulation results. completion of laboratory research and preparation for expanding the facility to a full-fledged high-energy accelerator, simulation of homogeneous and identical focusing of short train of laser pulses.	Completion of the accelerator modification. Preparation and start of physical researches. Preparing for the second accelerator to wind on the model of the first, simulation of real solid state as accelerating medium.

PART 2

2. What additional support is needed to achieve these? Additional computing power and funding are required to build laboratory facilities. Also collaboration with another laboratories is required.

3. What should be proposed as deliverables until 2026? Please list in order of priority. In the near future, it is proposed to simulate the excitation of a wakefield in a plasma and to obtain large accelerating fields, combined laser-plasma acceleration and a plateau formation on accelerating wakefield for electron-witness-bunch and on decelerating wakefield for driver-bunches in dielectric accelerator, simulation of point electron bunch self-injection by shaped laser pulse, simulation of homogeneous and identical focusing of train of positron bunches in plasma, simulation of plateau formation on the accelerating wakefield and zero radial wake force, simulation of homogeneous and identical focusing of short train of laser pulses, simulation of real solid state as accelerating medium.

4. Is the R&D work for each of those deliverables already funded and, if not, what additional resources / support would be needed? There are certain projects that need additional funding.

PART 3

1. What key R&D needs can be achieved in existing R&D facilities? There are many high-power lasers and devices for creating high-density plasma. However, for full implementation, it needed new separate equipment. To begin with, it needed access (remote) to the computing power. It is required to create a short high-power x-ray laser pulse, to develop technology of shaped laser pulse formation, to develop high-speed photo and video.

2. What is the role of the already planned future facilities in Europe and world-wide?

Planned future properties such as Eupraxia are essential. They implement the wake acceleration scheme, develop and draw attention to this area.

3. What can be done with the existing and planned funding base?

We think that the existing and planned funding base will allow us to do a lot. In particular, it is possible to complete studies on numerical modeling and begin to create an accelerator that uses the wake principle for high-density plasma and X-ray laser pulses.

4. Is a completely new facility needed?

A complete answer to this question is possible after a detailed analysis. It is likely that the existing capacity is sufficient. Existing equipment can be upgraded. A short high-power x-ray laser pulses can be created using developed technology; technology of shaped laser pulse formation can be developed.

5. Are additional structures needed beyond existing networks and projects, e.g. a design study for a collider or an advanced accelerator stage?

The question requires additional researches. The creation and maintenance of high-density plasma are required, as well as using X-ray lasers with intensities reaching the value $10^{23} - 10^{24}\, {}^{W}/_{cm^2}$ and with photon energy $\sim 10\ \mathrm{keV}$.