HEP-TEC 2025

Institute of Plasma Electronics
and New Methods of Acceleration
NSC “Kharkiv Institute of Physics and Technology”

DYNAMIC OF SELF-INJECTED BUNCHES AT LASER WAKEFIELD ACCELERATION IN AN INHOMOGENEOUS PLASMA

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ALIC

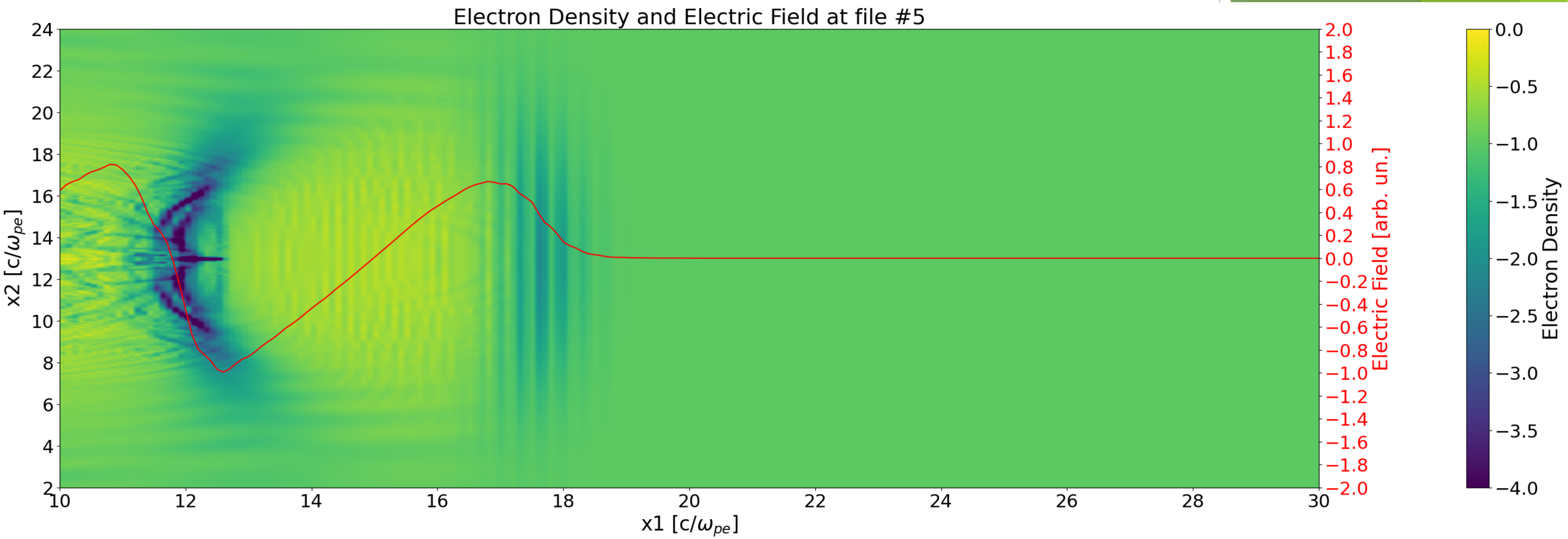
- Proposed concept of the Advanced Linear International Collider (ALIC) aims to revolutionize high-energy physics through Advanced and Novel Accelerators (ANA), in particular, Laser Wakefield Acceleration (LWFA), targeting unprecedented center-of-mass collision energies up to 30 TeV and a luminosity of 10^{36} $cm^{-2}s^{-1}$, thus enabling high-precision measurements of the Higgs boson's couplings to 1% precision and exploration of new particles with masses far beyond the reach of current colliders.

- Compared with current facilities, ALIC's compact design and high gradients would significantly lower costs and increase discovery potential. This innovation offers access to unexplored HEP phenomena and opening a new era for understanding the Standard Model.

Advantages of wakefield acceleration

- There is no limitation on accelerating gradient due to electric breakdown.
- High Acceleration Gradients: LWFA can sustain accelerating fields that are orders of magnitude larger than conventional radio-frequency accelerators, reaching gradients of hundreds of gigavolts per meter. This allows for the acceleration of particles to high energies over much shorter distances.
- Compactness: The high acceleration gradients enable the construction of more compact accelerators, which are beneficial for applications requiring reduced size and cost, such as compact free-electron lasers and particle colliders.

Wakefield acceleration



Plasma density distribution depending on longitudinal and transverse coordinates.

This figure illustrates the excitation of a wakefield in the plasma and the formation of a self-injected bunch.

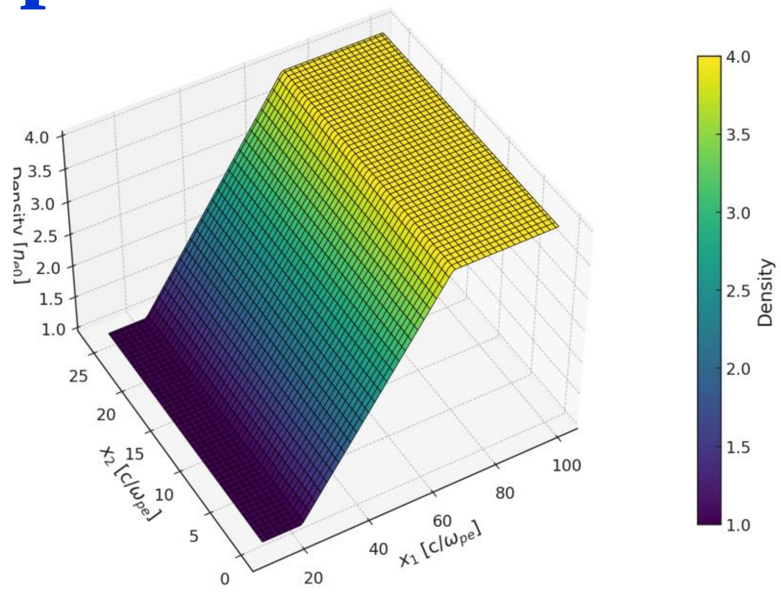
Purpose of research

In this paper by using 2.5D numerical simulation by the fully relativistic code OSIRIS.

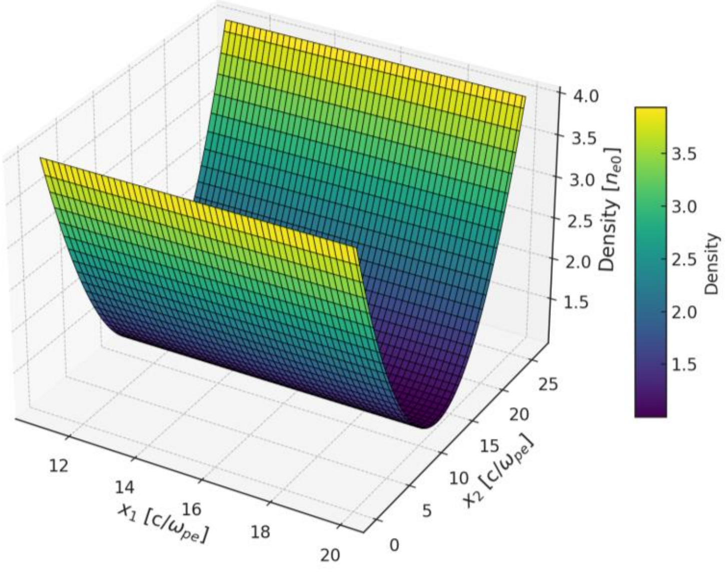
- The aim of this study was to investigate the dynamics and parameters of self-injected bunches depending on the plasma density, taking into account that the plasma is inhomogeneous. Clear advantages of using longitudinally and transversely inhomogeneous plasma were shown.
- Three cases were considered:
- 1) Homogeneous plasma in longitudinal and transverse directions;
- 2) inhomogeneous profile that linearly increasing along the axis;
- 3) radial profile parabolically increasing from the axis of the system with a homogeneous area along the axis.

Plasma, laser and system parameters

Parameter	Value
Plasma density n_{e0}	$n_{e0} = 1{,}74 \cdot 10^{19}\ cm^{-3}$
Laser frequency	$2{,}35 \cdot 10^{14}\ rad/s$
Laser wavelength	$\lambda_l = 800\ nm$
$\omega_{laser}/\omega_{pe}$	10
Distance unit c/ω_{pe}	1.27 μm
Time unit $1/\omega_{pe}$	4.25 fs
The length of the simulation window	100
The width of the simulation window	26
Normalized vector potential a_0	2.3
Laser length	3.23
Laser radius r_l at focusing point	8.2



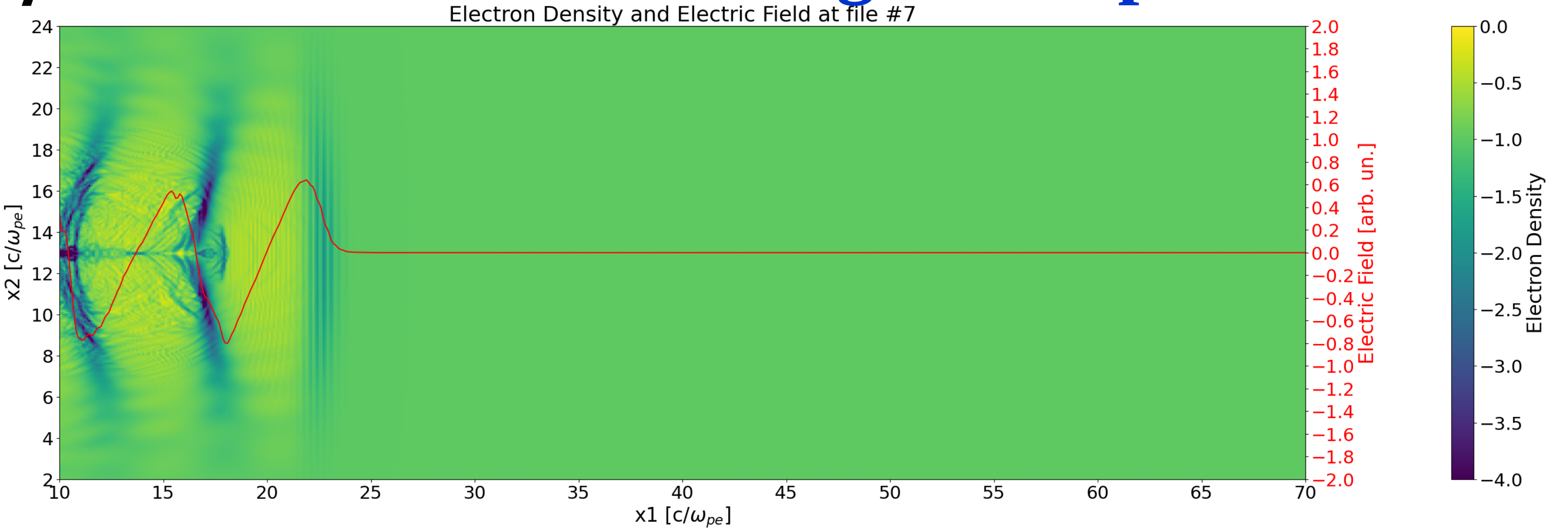
Inhomogeneous linearly increasing profile



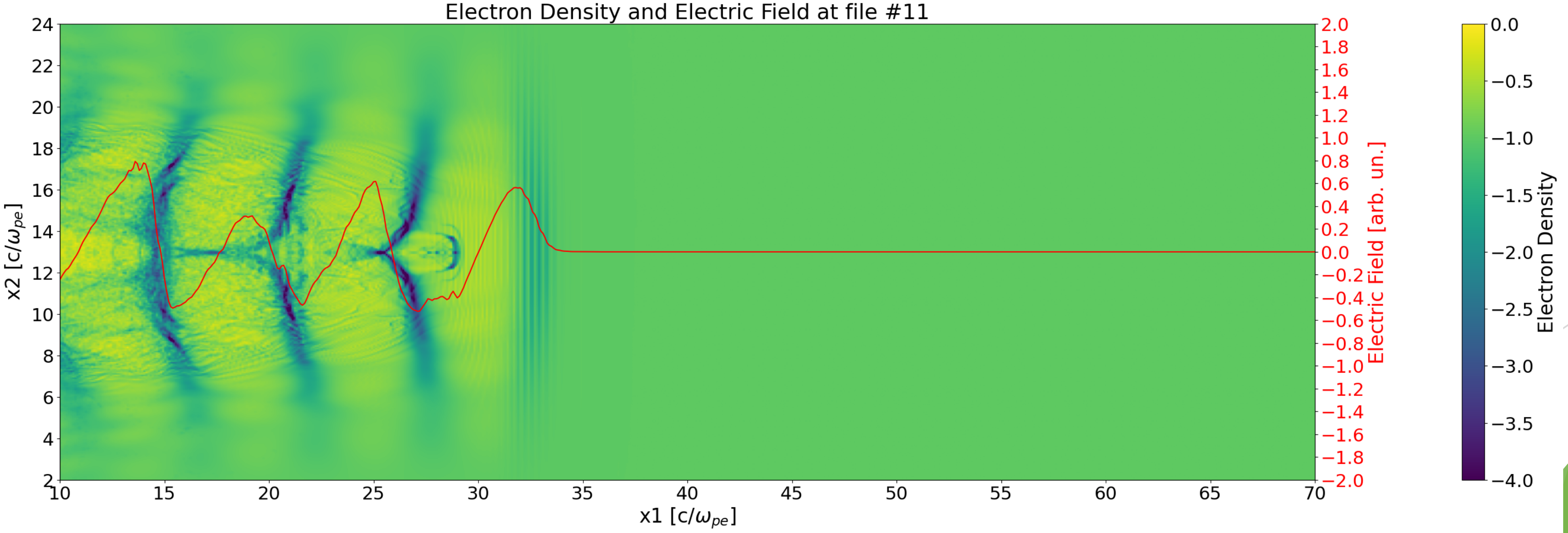
Parabolic radial profile
(along the x1 axis shorten for clarity)

Plasma electron density longitudinal profiles $n_e(x1)$, $n_e(x2)$.
The position of the laser pulse is shown.

Homogeneous plasma

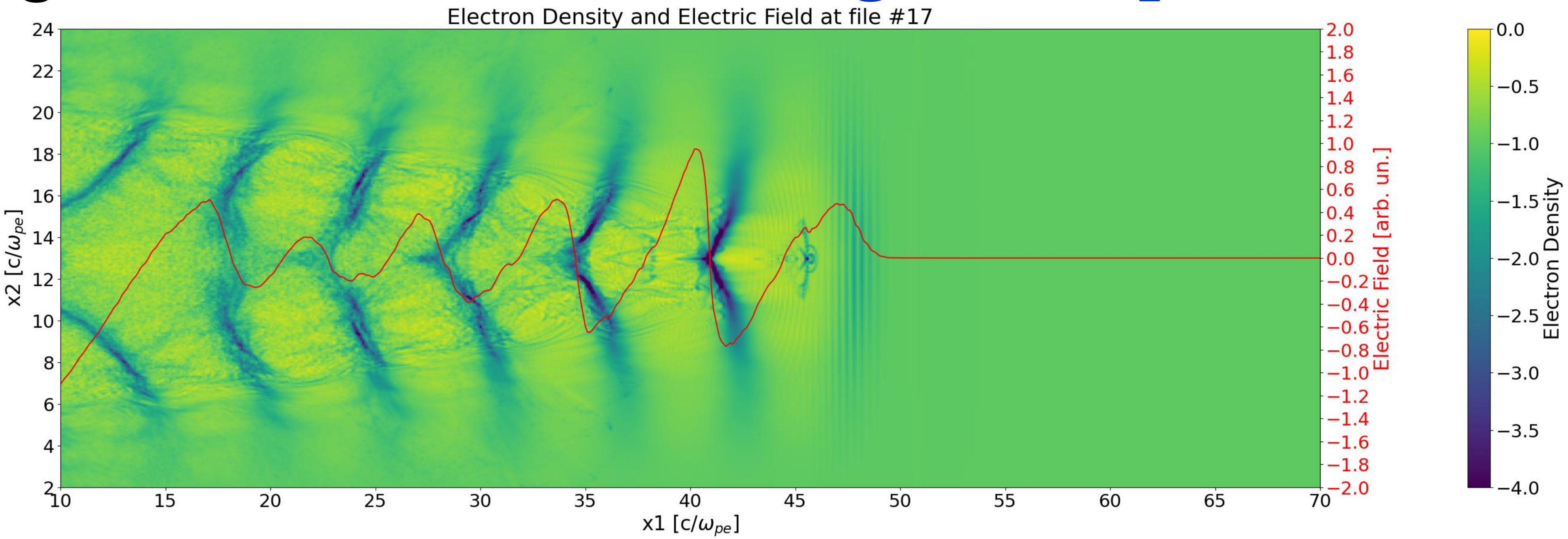


Density graph $n_e(x_1, x_2)$, longitudinal acceleration field $E_x(x_1)$. t=83,3 fs

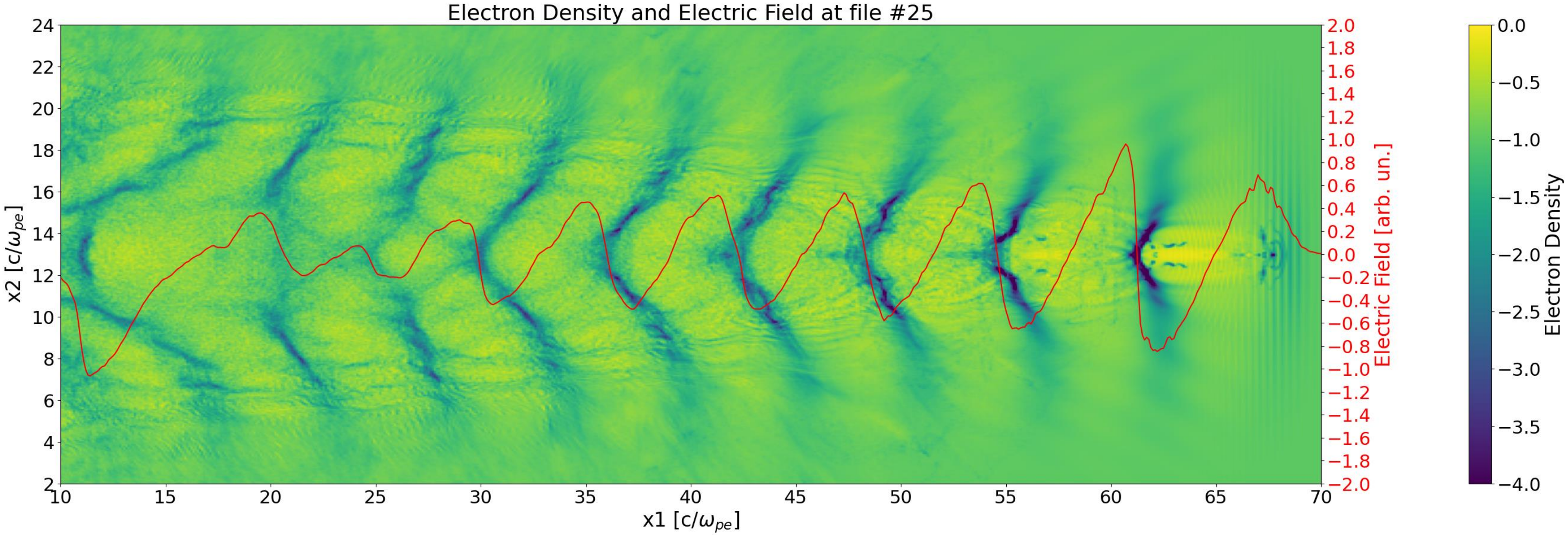


Density graph $n_e(x_1, x_2)$, longitudinal acceleration field $E_x(x_1)$. t=130,9 fs

Homogeneous plasma



Density graph $n_e(x_1, x_2)$, longitudinal acceleration field $E_x(x_1)$. t=202,3 fs

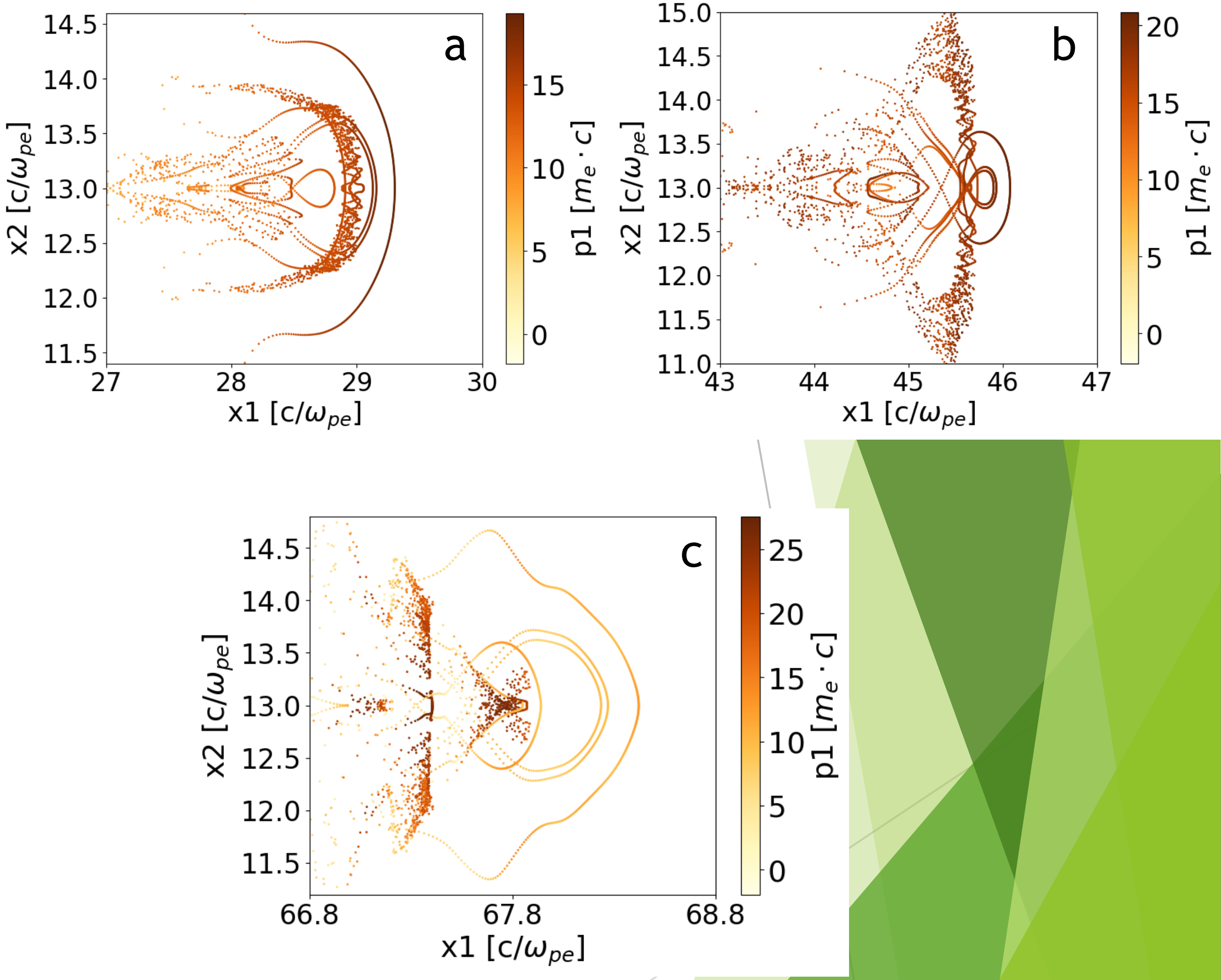


Density graph $n_e(x_1, x_2)$, longitudinal acceleration field $E_x(x_1)$. t=297,5 fs

Homogeneous plasma

Bunch parameter	Value		
	Time moment		
	11	17	25
	130.9 fs	202.3 fs	297.5 fs
Length	3.05 μm	4.06 μm	1.4 μm
Diameter	4.06 μm	5.08 μm	3.81 μm
Density (peak)	3.5 n_{e0}	4.1 n_{e0}	4.1 n_{e0}
Charge	290 pC	670 pC	140 pC
Average longit. momentum p_1	14.04 m_ec	17.23 m_ec	16.7 m_ec
Energy (peak)	18.3 m_ec^2 9.35 MeV	19.04 m_ec^2 9.73 MeV	26.6 m_ec^2 13.6 MeV

Parameters of self-injected bunches (homogeneous density distribution)



Longitudinal momentum of the bunch $p_1(x_1, x_2)$. (a) t=130.9 fs; (b) t=202.3 fs; (c) t=297.5 fs

Homogeneous plasma

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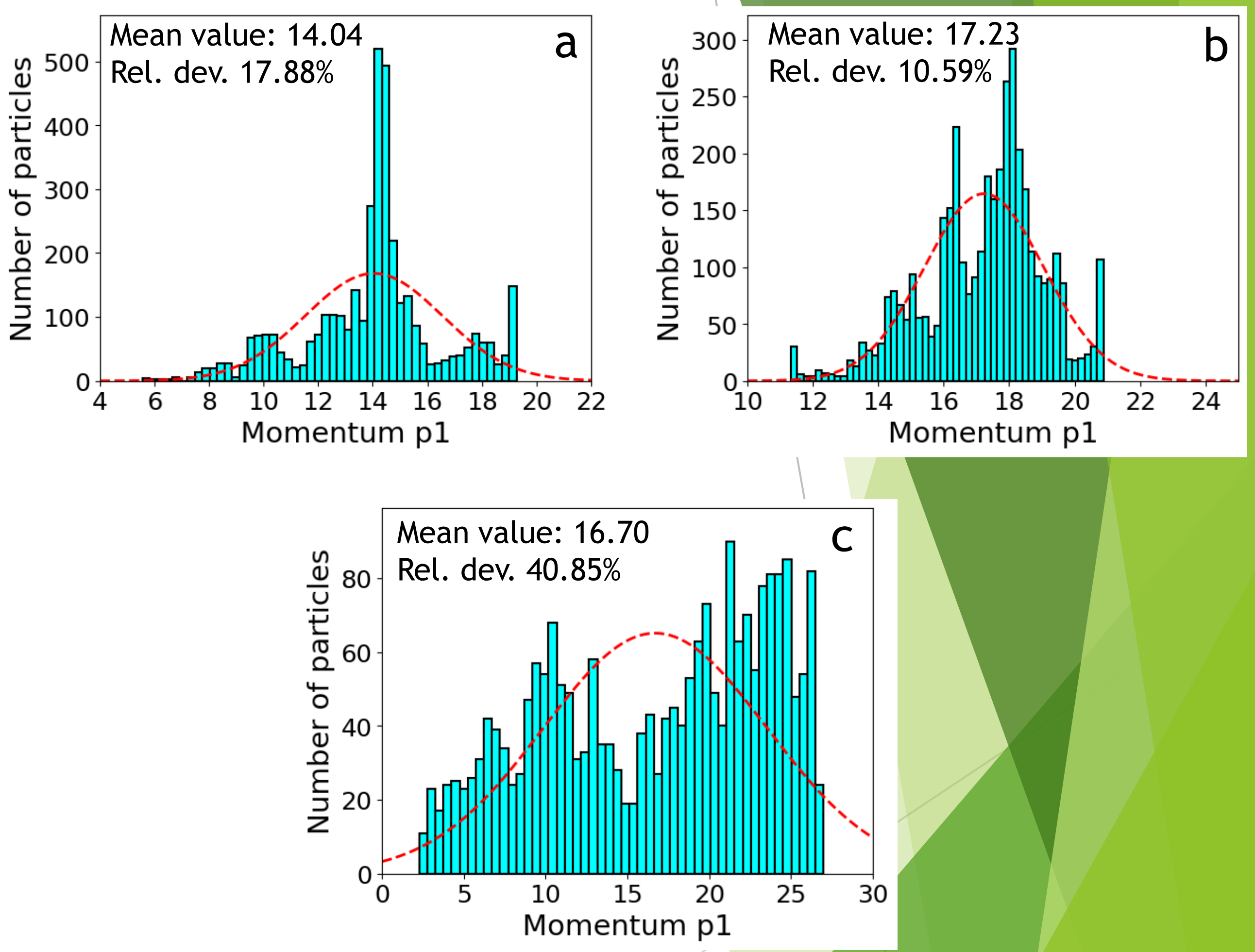
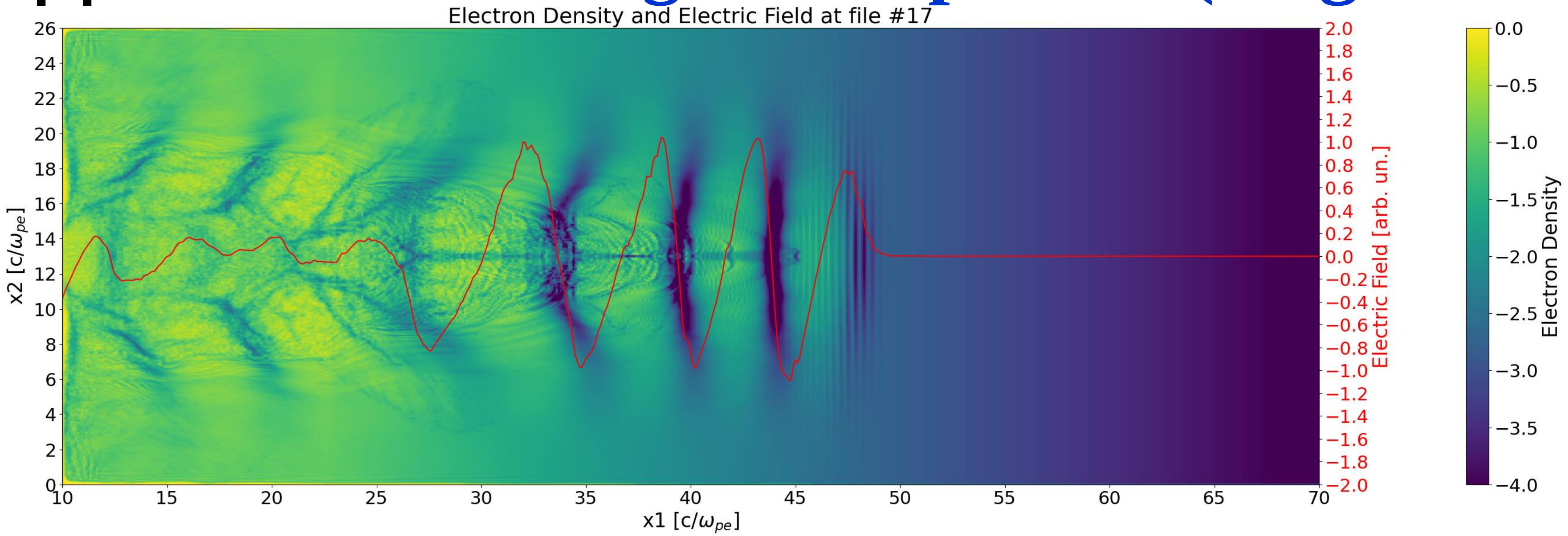
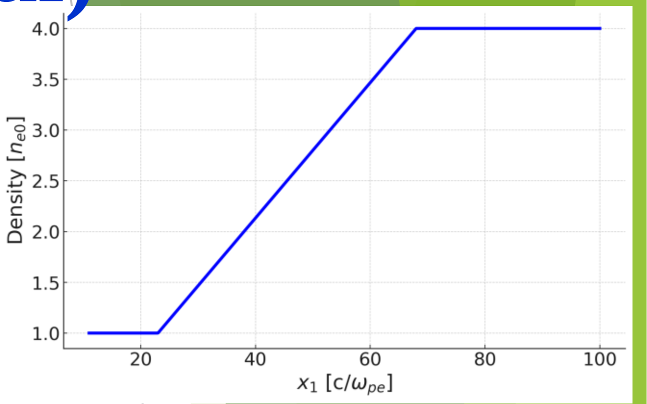


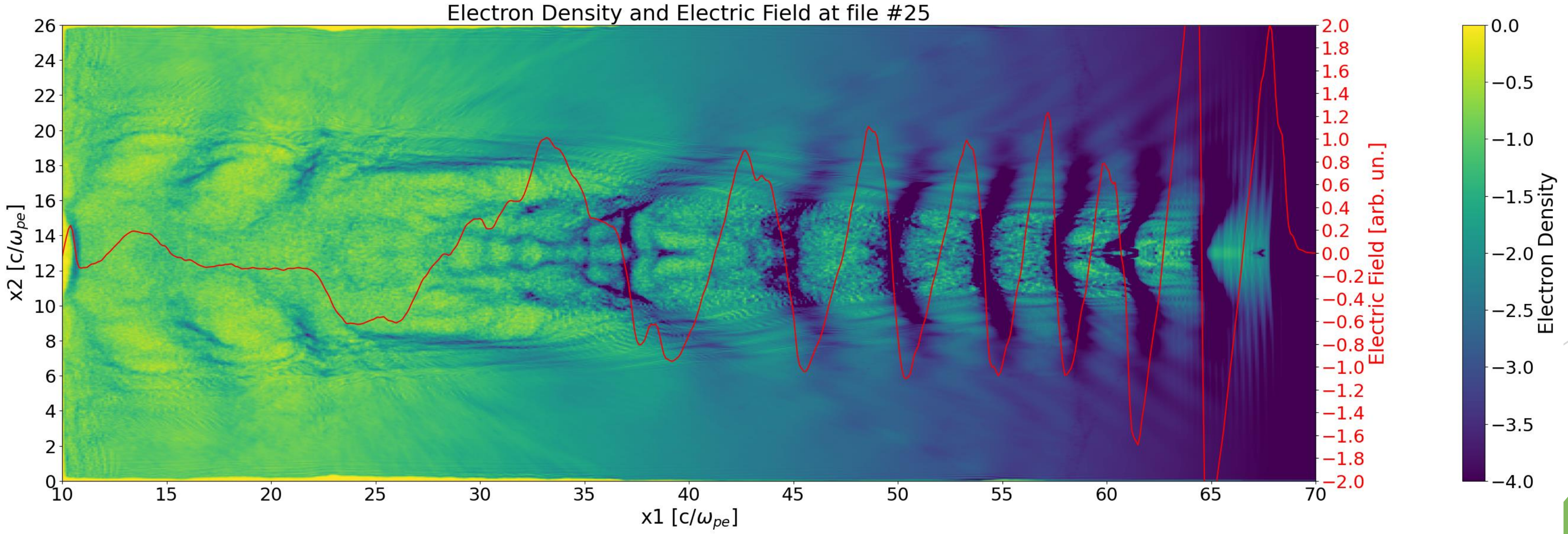
Longitudinal momentum distribution p_1.
(a) t=130.9 fs; (b) t=202.3 fs; (c) t=297.5 fs

Inhomogeneous plasma (longitudinal)





Density graph $n_e(x_1, x_2)$, longitudinal acceleration field $E_x(x_1)$. t=202,3 fs

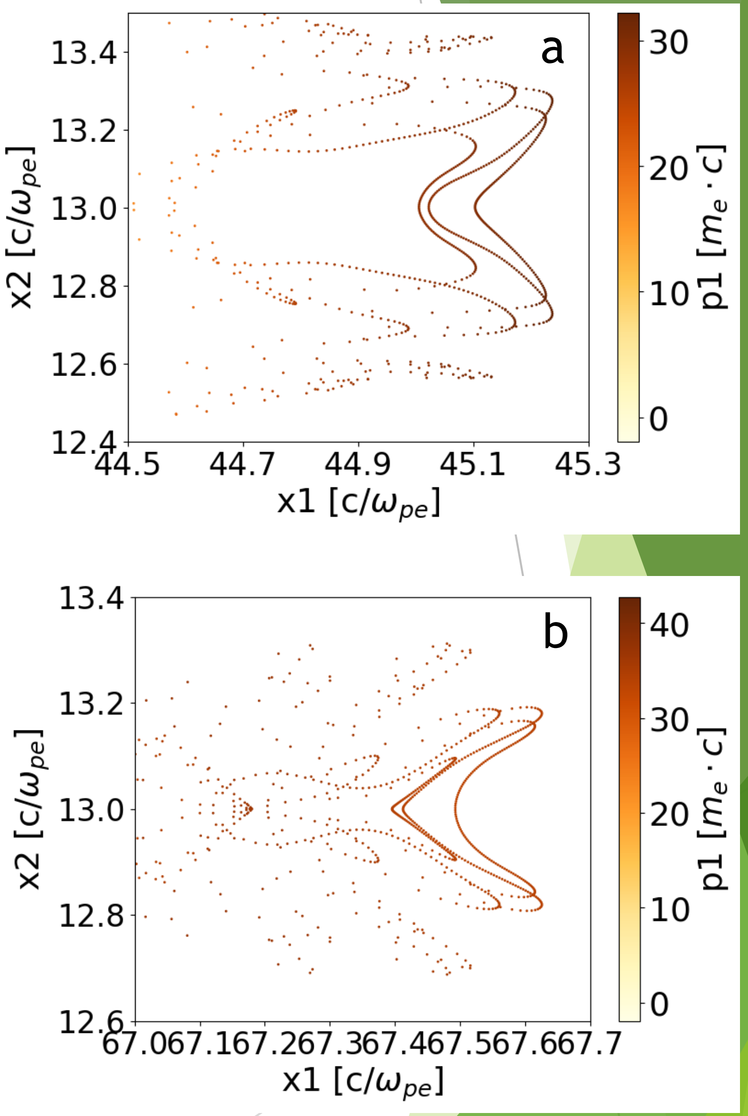


Density graph $n_e(x_1, x_2)$, longitudinal acceleration field $E_x(x_1)$. t=297,5 fs

Inhomogeneous plasma (longitudinal)

Bunch parameter	Value	
	Time moment	
	17	25
	202.3 fs	297.5 fs
Length	1.02 µm	0.89 µm
Diameter	1.4 µm	1.02 µm
Density (peak)	3.8 n_{e0}	7.5 n_{e0}
Charge	16 pC	140 pC
Average longit. momentum p_1	28.63 $m_e c$	34.13 $m_e c$
Energy (peak)	31.25 $m_e c^2$ 15.97 MeV	36.19 $m_e c^2$ 18.5 MeV

Parameters of self-injected bunches (inhomogeneous density distribution)



Longitudinal momentum of the bunch $p_1(x_1, x_2)$. (a) t=202.3 fs; (b) t=297.5 fs

Inhomogeneous plasma (longitudinal)

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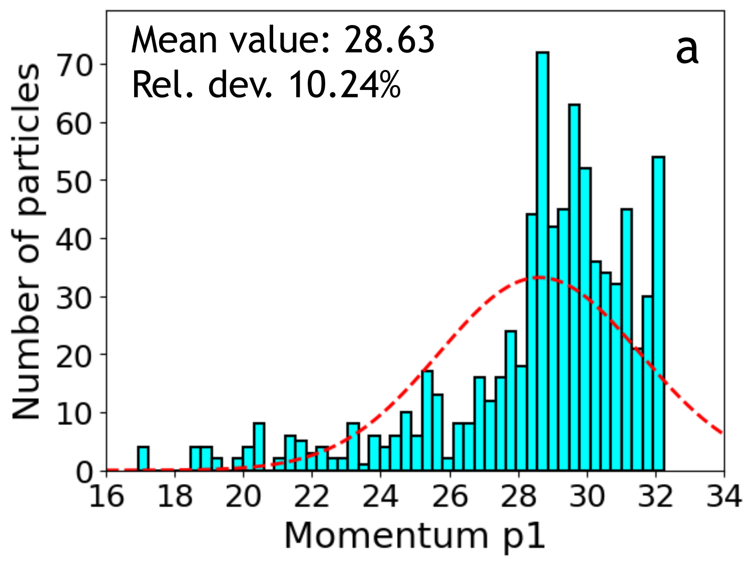
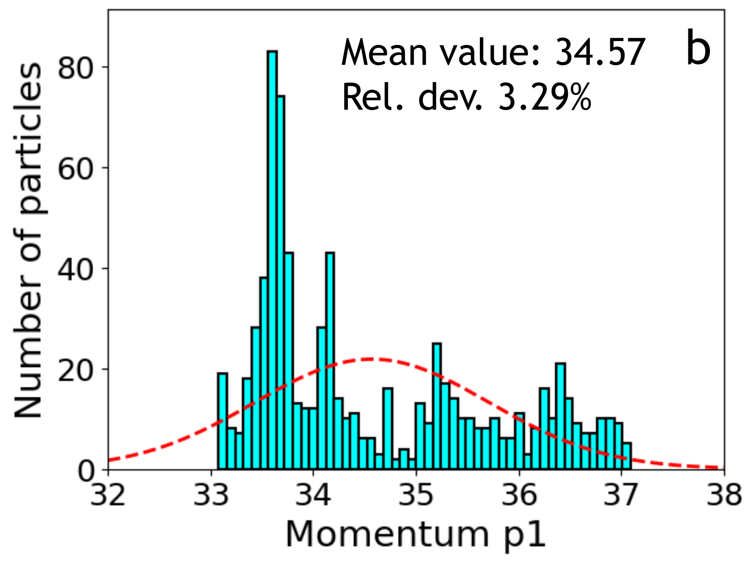
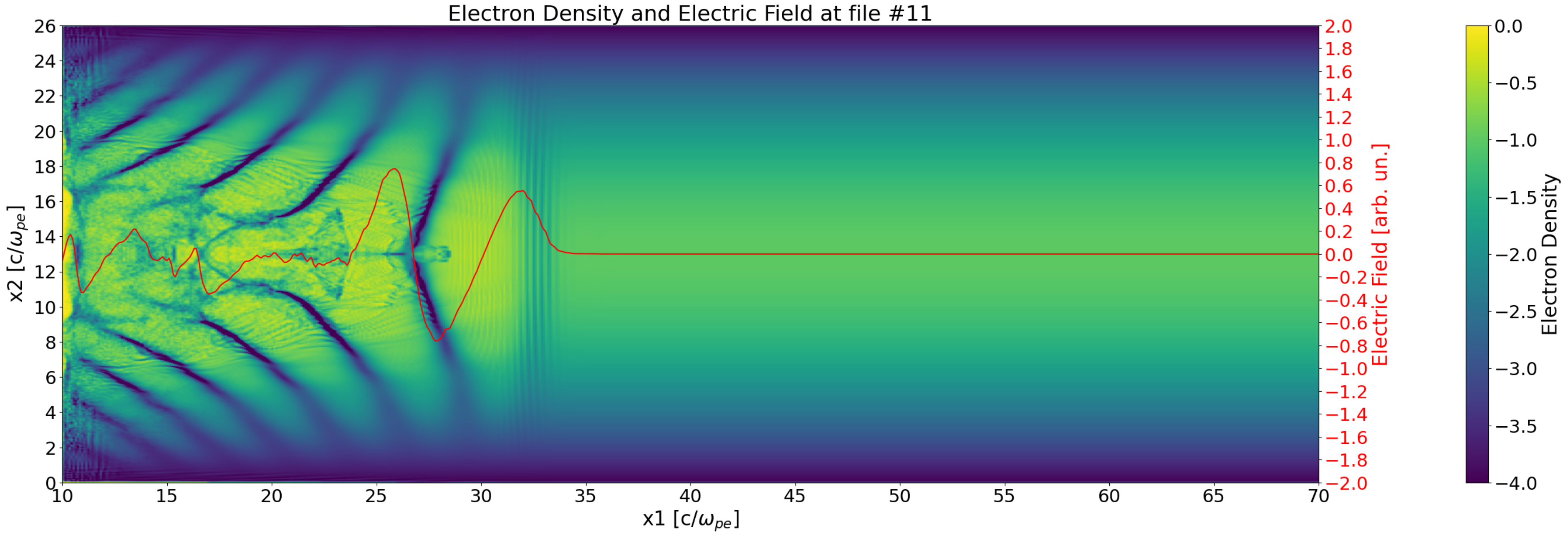
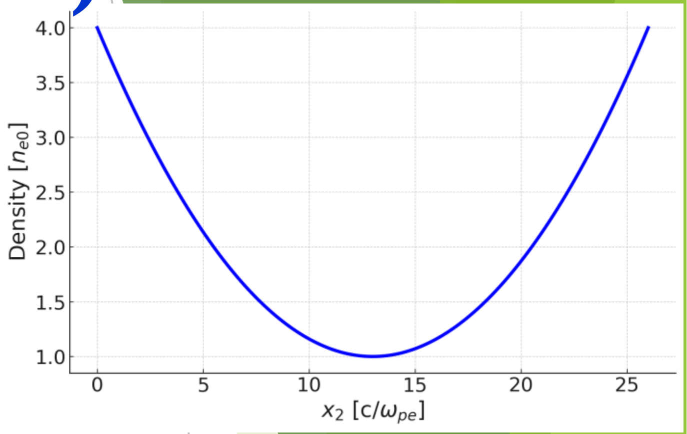




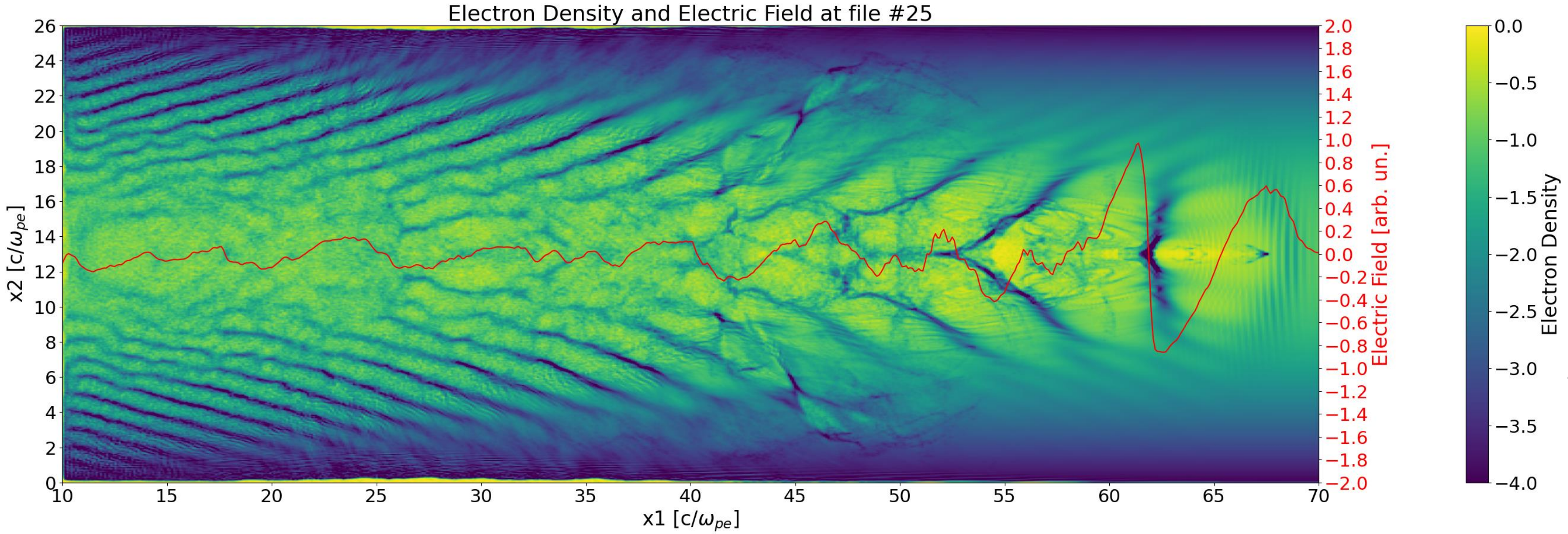
Longitudinal momentum distribution p_1. (a) t=202.3 fs; (b) t=297.5 fs

Inhomogeneous plasma (transverse)





Density graph $n_e(x_1, x_2)$, longitudinal acceleration field $E_x(x_1)$. t=130,9 fs

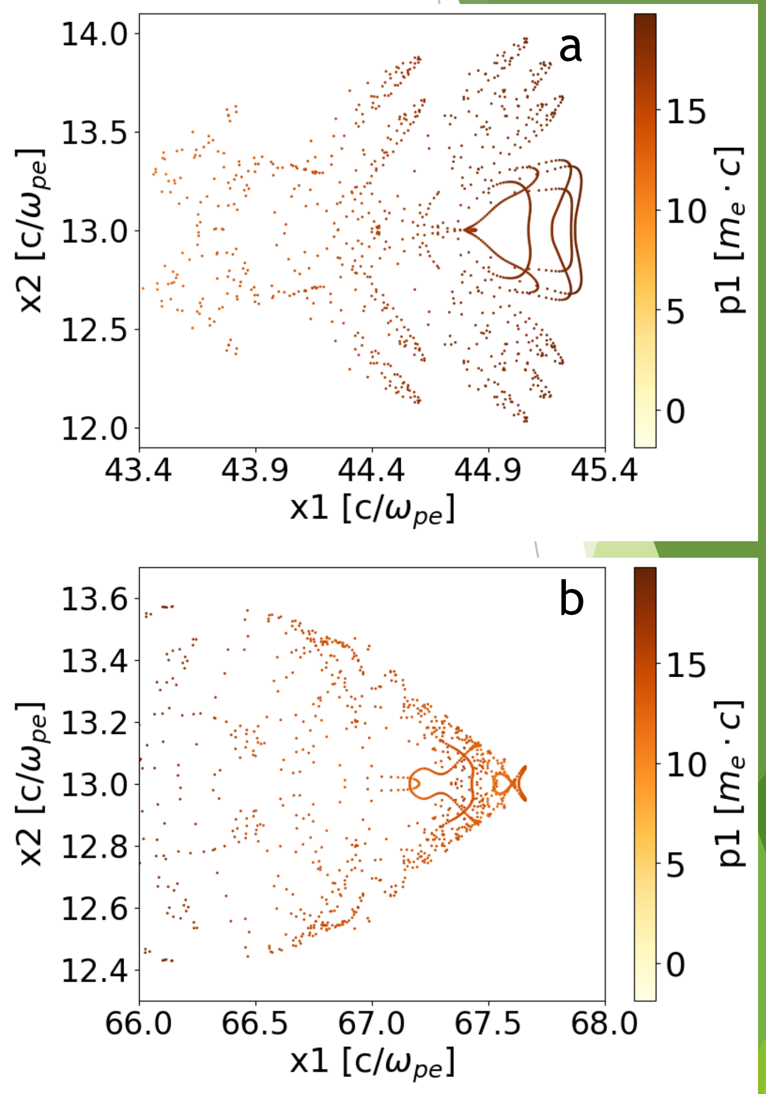


Density graph $n_e(x_1, x_2)$, longitudinal acceleration field $E_x(x_1)$. t=297,5 fs

Inhomogeneous plasma (transverse)

Bunch parameter	Value	
	Time moment	
	17	25
	202.3 fs	297.5 fs
Length	2.54 μm	0.89 μm
Diameter	2.79 μm	1.02 μm
Density (peak)	1.5 n_{e0}	4.8 n_{e0}
Charge	49 pC	51 pC
Average longit. momentum p_1	17.41 m_ec	14.04 m_ec
Energy (peak)	18.84 m_ec^2 9.63 MeV	17.26 m_ec^2 8.82 MeV

Parameters of self-injected bunches (inhomogeneous density distribution)



Longitudinal momentum of the bunch $p_1(x_1, x_2)$. (a) t=202.3 fs; (b) t=297.5 fs

Inhomogeneous plasma (transverse)

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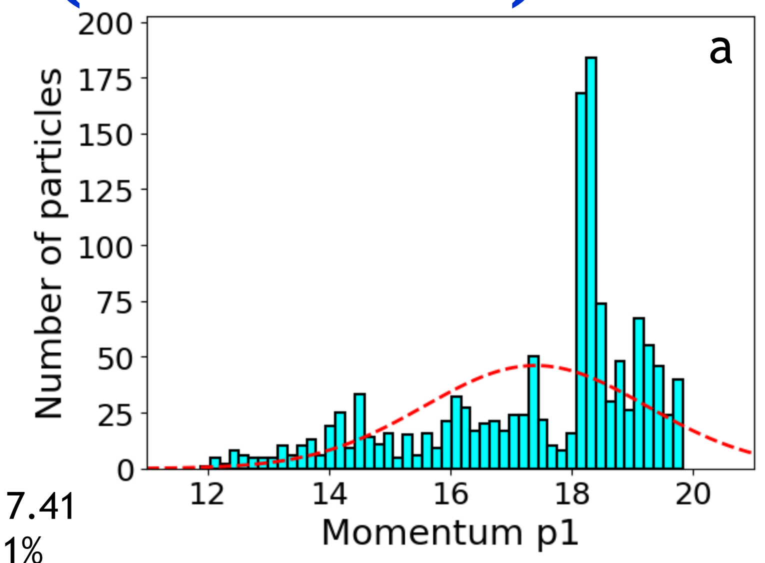
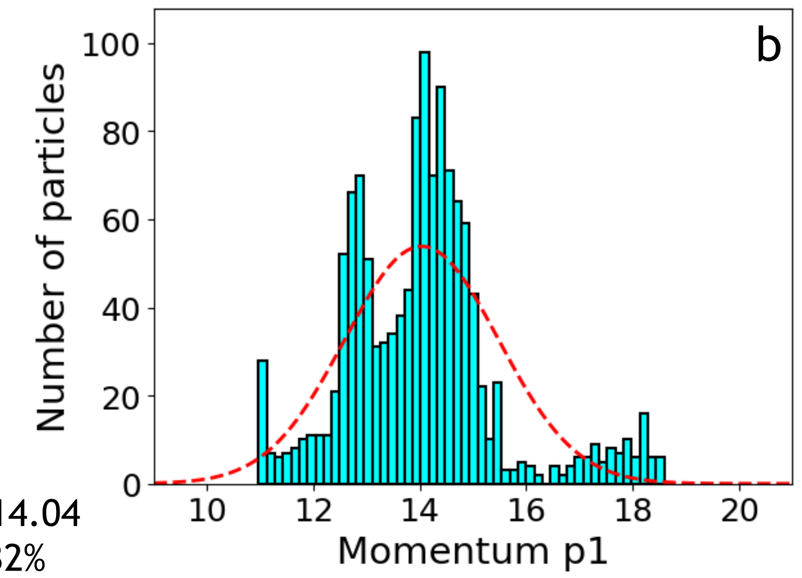


Mean value: 17.41
Rel. dev. 10.51%



Mean value: 14.04
Rel. dev. 10.32%

Longitudinal momentum distribution p_1.
(a) t=202.3 fs; (b) t=297.5 fs

Conclusions

- The results of the studies demonstrated that the use of longitudinally inhomogeneous plasma leads to an increase of the stay time of the bunch in the acceleration phase (250.8 fs in comparison of 159.4 fs in the homogeneous case). In the homogeneous case, the maximum field observed at the end of the acceleration phase is 0.156 TV/m, in the inhomogeneous case the maximum field increases by 2.38 times. In addition, 2 times increase in the longitudinal momentum value is observed.
- In the case of transverse inhomogeneity, a waveguide effect is observed relative to the laser pulse. In addition, the parabolic inhomogeneous transverse distribution leads to transverse stabilization of the bunch at more duration - 297.5 fs.

Thank you for your attention