Optimization of moderate-power laser pulse interaction with plasmas using quasistatic simulations

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Outline

How to modify quasistatic approximation (QSA) to simulate self-trapping process?

LWFA optimization by fast QSA simulations

Verification of optimal condition by general PIC simulation

Summary

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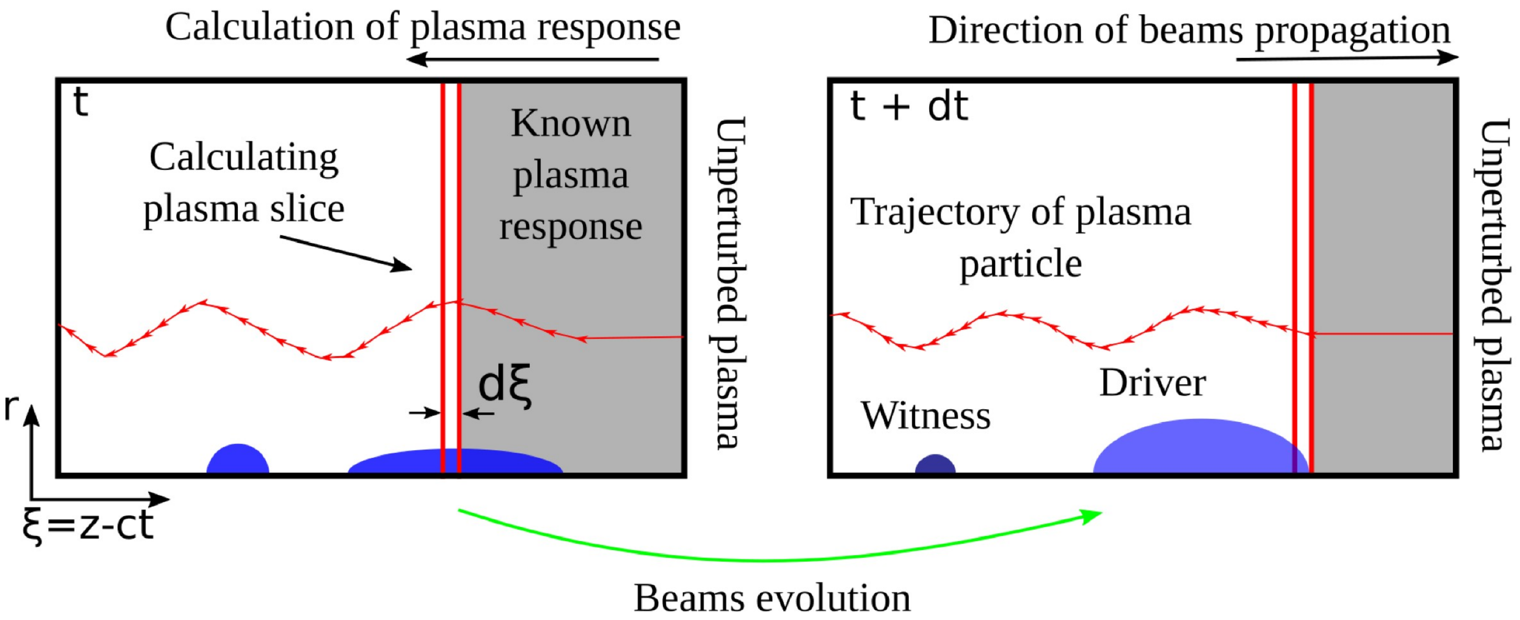
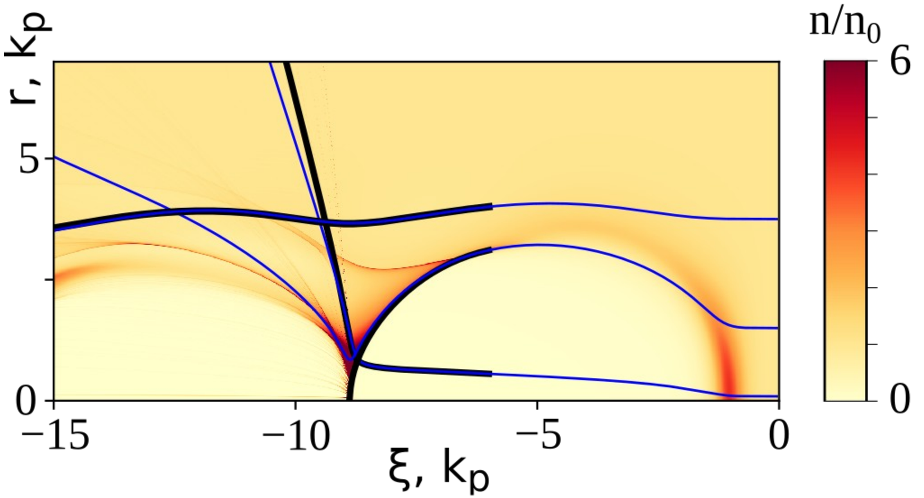
QSA and trapping



No interaction between layers at different z –> no self-trapping

QSA and trapping



Blue lines — plasma electrons with QSA

$$\frac{d\vec{p}}{d\xi} = \frac{d\vec{p}}{dt}\frac{dt}{d\xi} = \frac{q}{v_z - 1}\left(\vec{E} + \left[\vec{v} \times \vec{B}\right]\right)$$

$$\frac{dr}{d\xi} = \frac{v_r}{v_z - 1}$$

Black lines — test electron tracking without QSA

$$\frac{d\vec{p}_b}{dt} = q_b\vec{E} + q_b\left[\vec{v}_b \times \vec{B}\right]$$

$$\vec{v}_b = \frac{\vec{p}_b}{\sqrt{m_b^2 + p_b^2}} \quad \frac{dr_b}{dt} = v_{br} \quad \frac{d\xi_b}{dt} = v_{bz} - 1$$

- Most of plasma electrons have the same trajectories in both cases.

- Wave structure can be calculated in QSA.

- Trajectories of fast electrons should be calculated in full model.

Thresholds for changing model*:
1. Energy (γ > 1.2)
2. Axis-crossing

*WAKE-code team:
PHYSICS OF PLASMAS 17, 063106 (2010)

LCODE simulation

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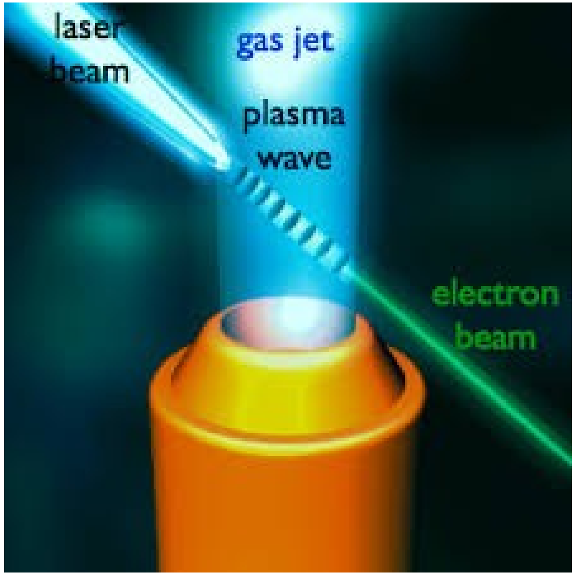
Parameter set

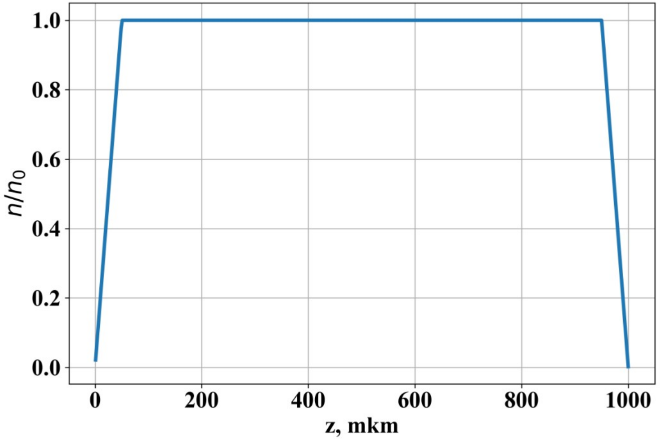
- Available system
- Self-trapping
- Short interaction distance

ILP SB Laser System

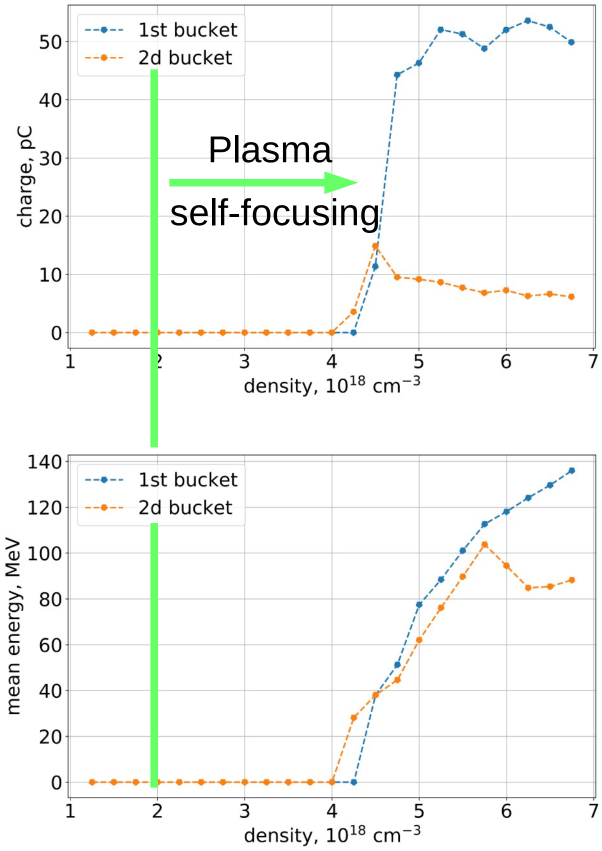
Energy (mJ)	300
Duration (fs)	20
Waist (mkm)	10
Power (TW)	14
Intensity (W/cm^2)	4.5 10^{18}
wavelength (nm)	810
a_0	1.45



Plasma density profile



Density scan

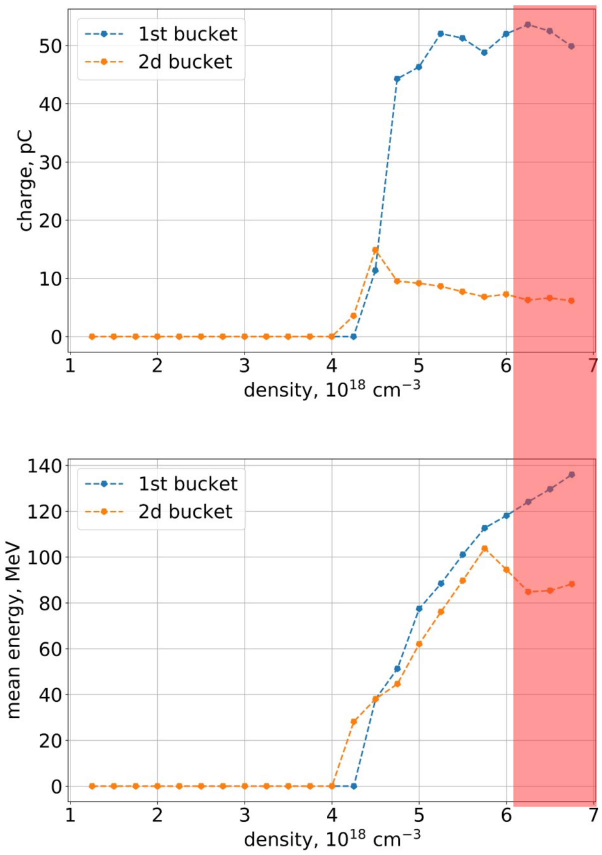


The self-trapping process begins in a plasma which is twice as dense as required for nonlinear self-focusing of the laser.

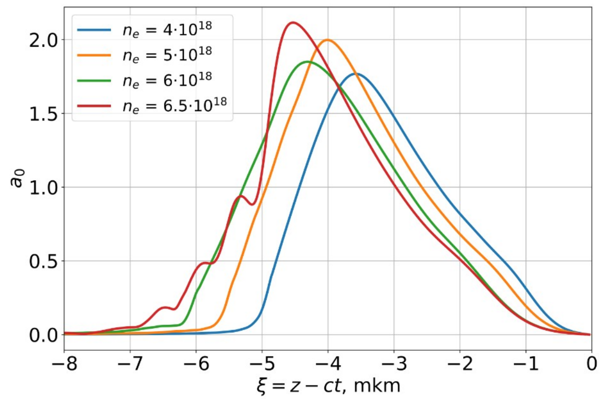
The beam charge and mean energy increase with increasing density.

LCODE simulation

Density scan



Laser pulse envelope after 1 mm interaction



Laser pulse envelope after 1 mm of plasma with a density of 6.5 10^{18} cm^{-3} has nonphysical oscillations at the tail.

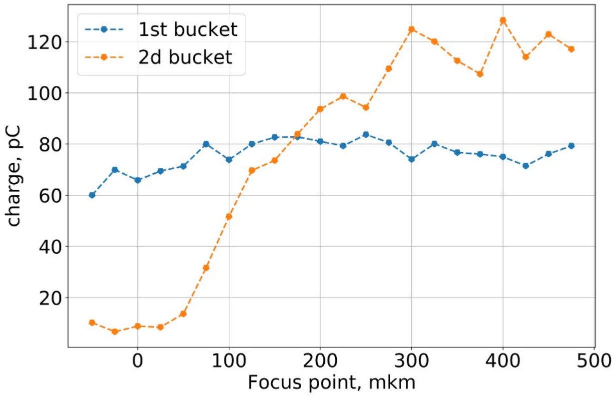
This indicates that envelope equation for describing laser pulse is no longer valid because the pulse has lost significant part of its energy.

Choosing a plasma with a higher density may lead to destruction of the trapped beam.

Plasma density above 6 10^{18} cm^{-3} is too dense for such laser pulse

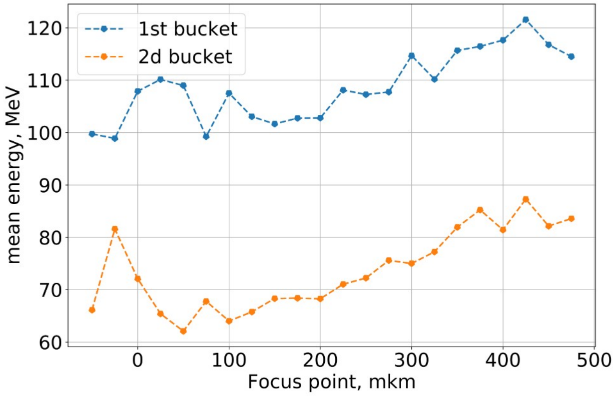
LCODE simulation

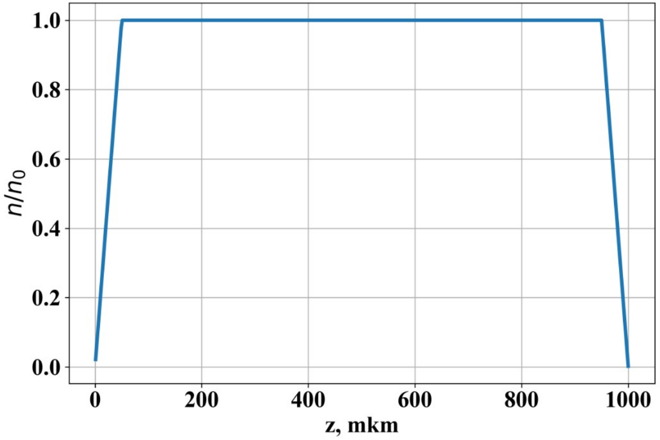
Focus point scan



Moving focus point to plasma leads to increase in trapped charge in second wave period but does not effect beam in the first wave period.

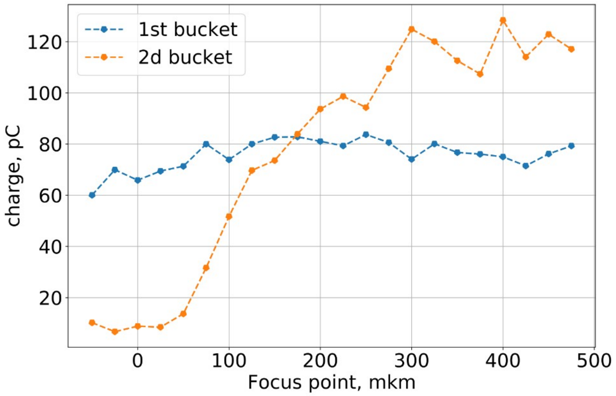
This parameter has little effect on the average energy of the captured particles.

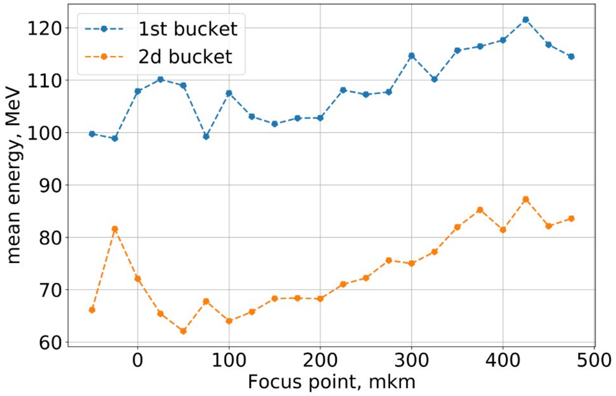


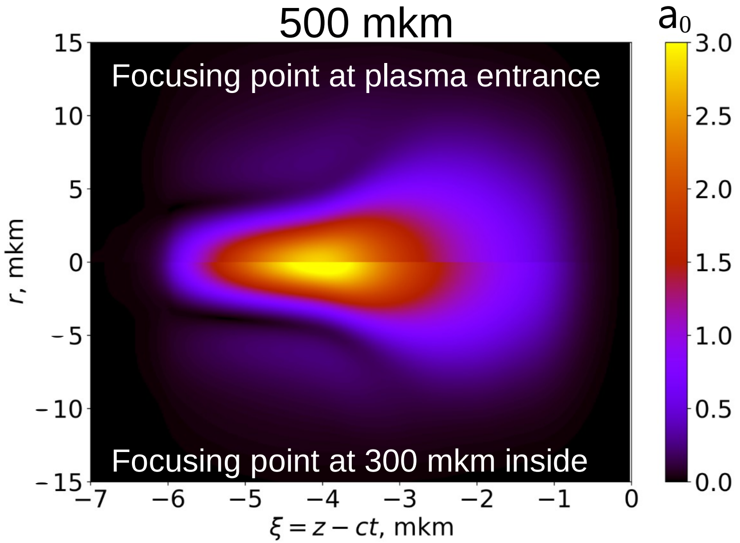


LCODE simulation

Focus point scan



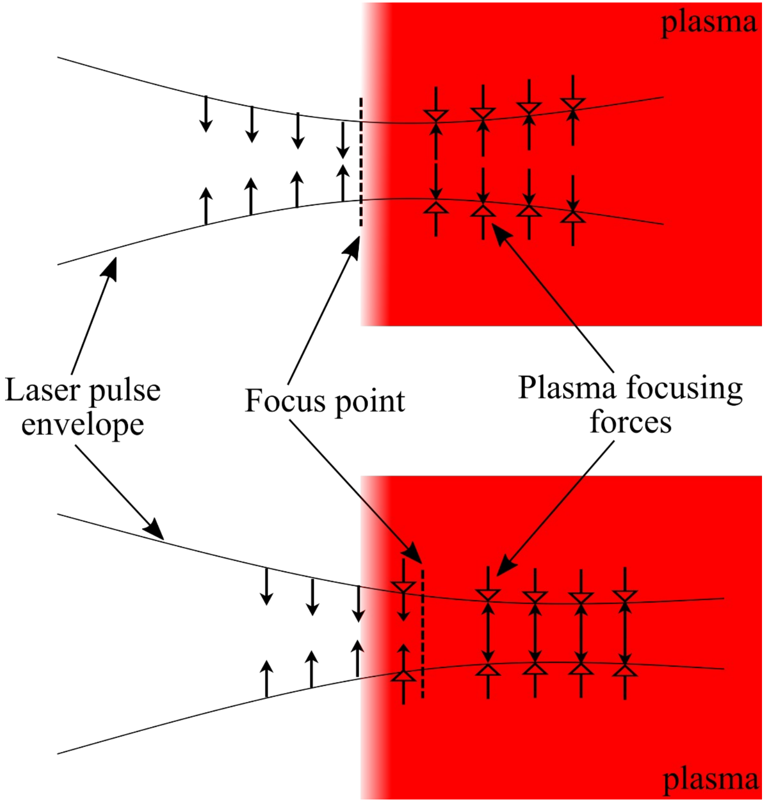


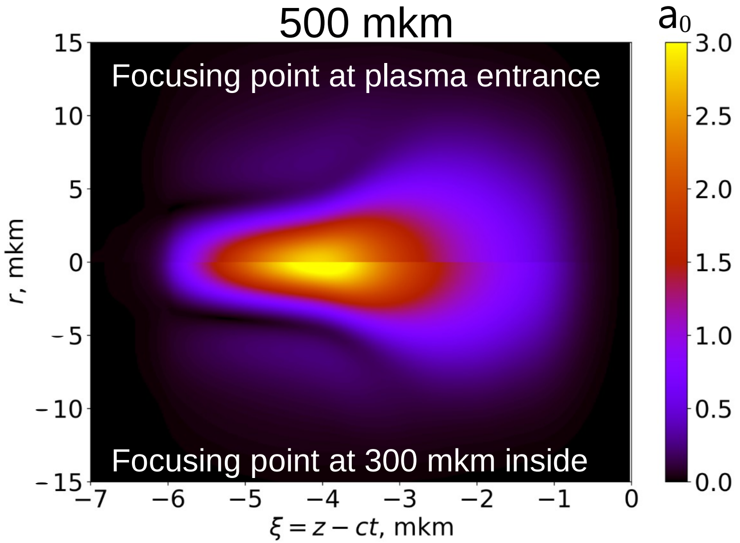


Laser pulse focused inside plasma retains small transverse size for a longer distance and reaches higher field intensity.

LCODE simulation

Gain of laser pulse focusing





When the pulse focus point is in the plasma, the plasma forces amplify optical focusing of radiation.

This results in higher laser intensity and a larger plasma wave amplitude.

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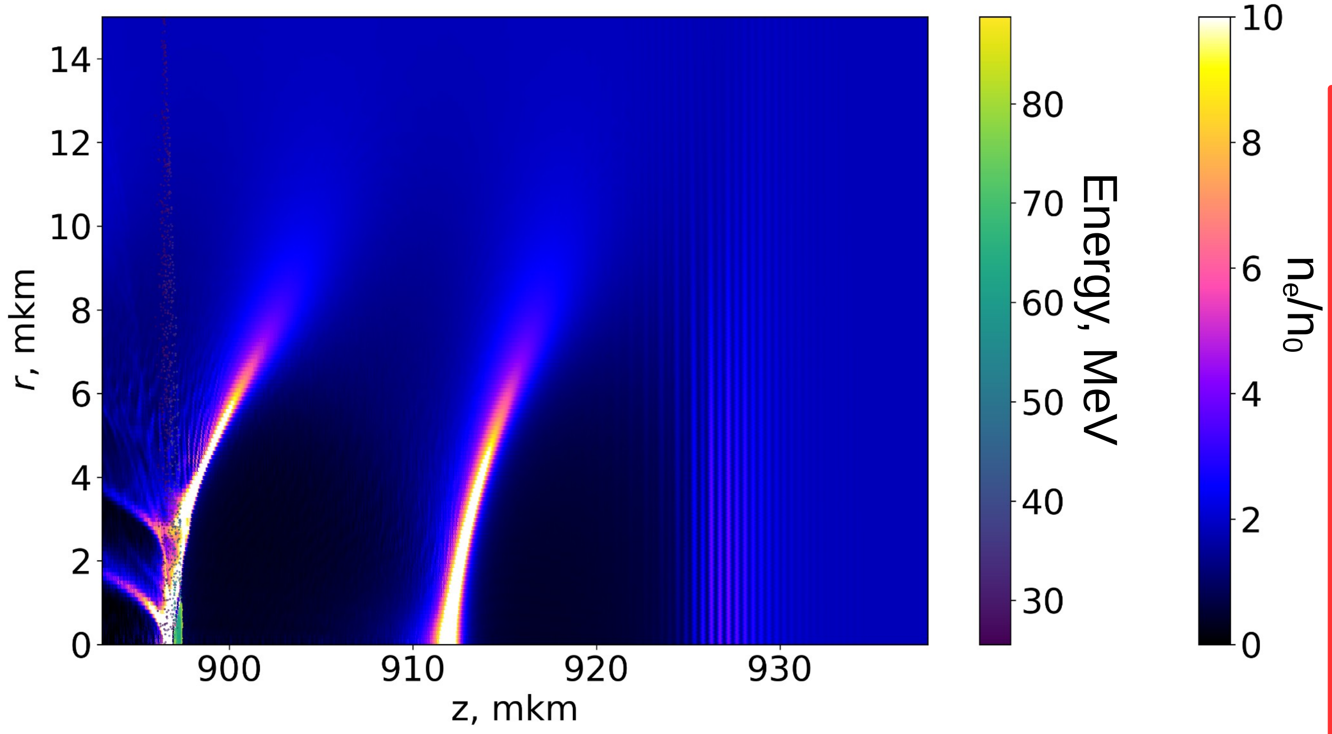
Full simulation with usual PIC code



In the general PIC simulation, the electron beam is generated only in the second bucket, which is different from the previous simulation.

However, electron trapping does not occur when moving the focus point at the entrance to the plasma or when using a plasma with a lower density, as predicted by QSA simulations.

	E, MeV	RMS, MeV	ε_n, mm mrad	Q, pC
FBPIC	77	16	8	20
LCODE	75	30	4	120

FBPIC simulation

Summary

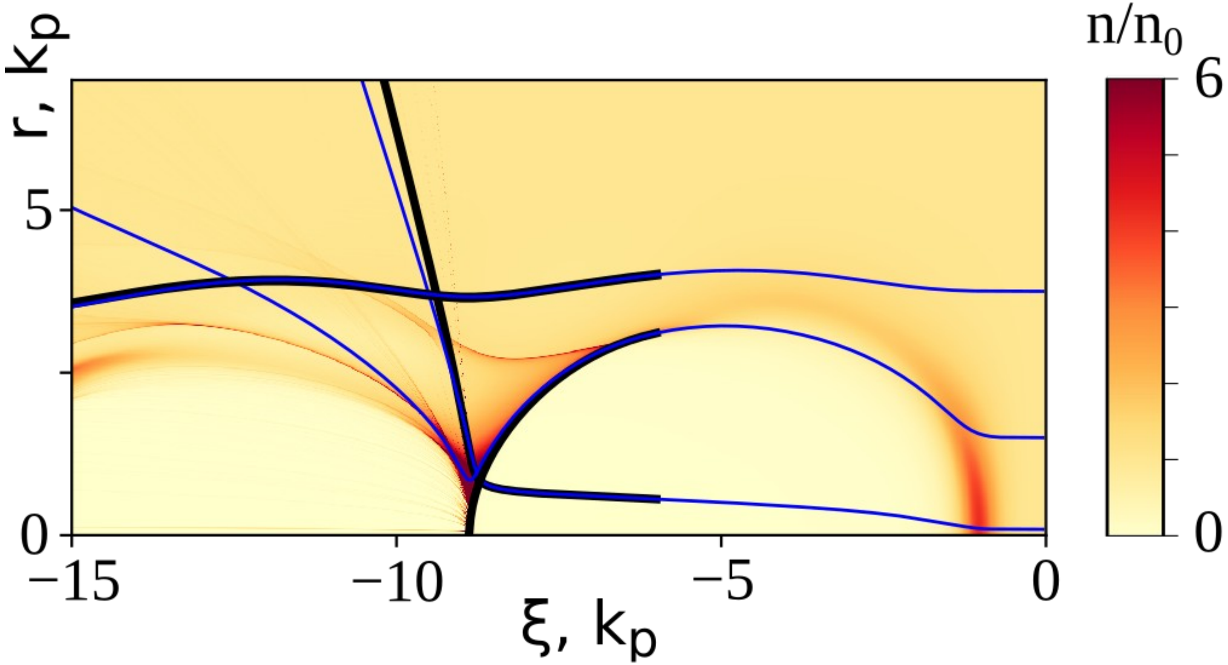
Focusing laser pulse inside the plasma allows to initiate self-trapping process for laser systems of a moderate power.

The code with QSA approximation speeds up parameter scans but the results have to be checked by conventional PIC simulations.

Further developments of QSA extension will allow one to carry out a global study and optimization of parameters for different experimental conditions without using computationally demanding simulations in the future.

Thank you!

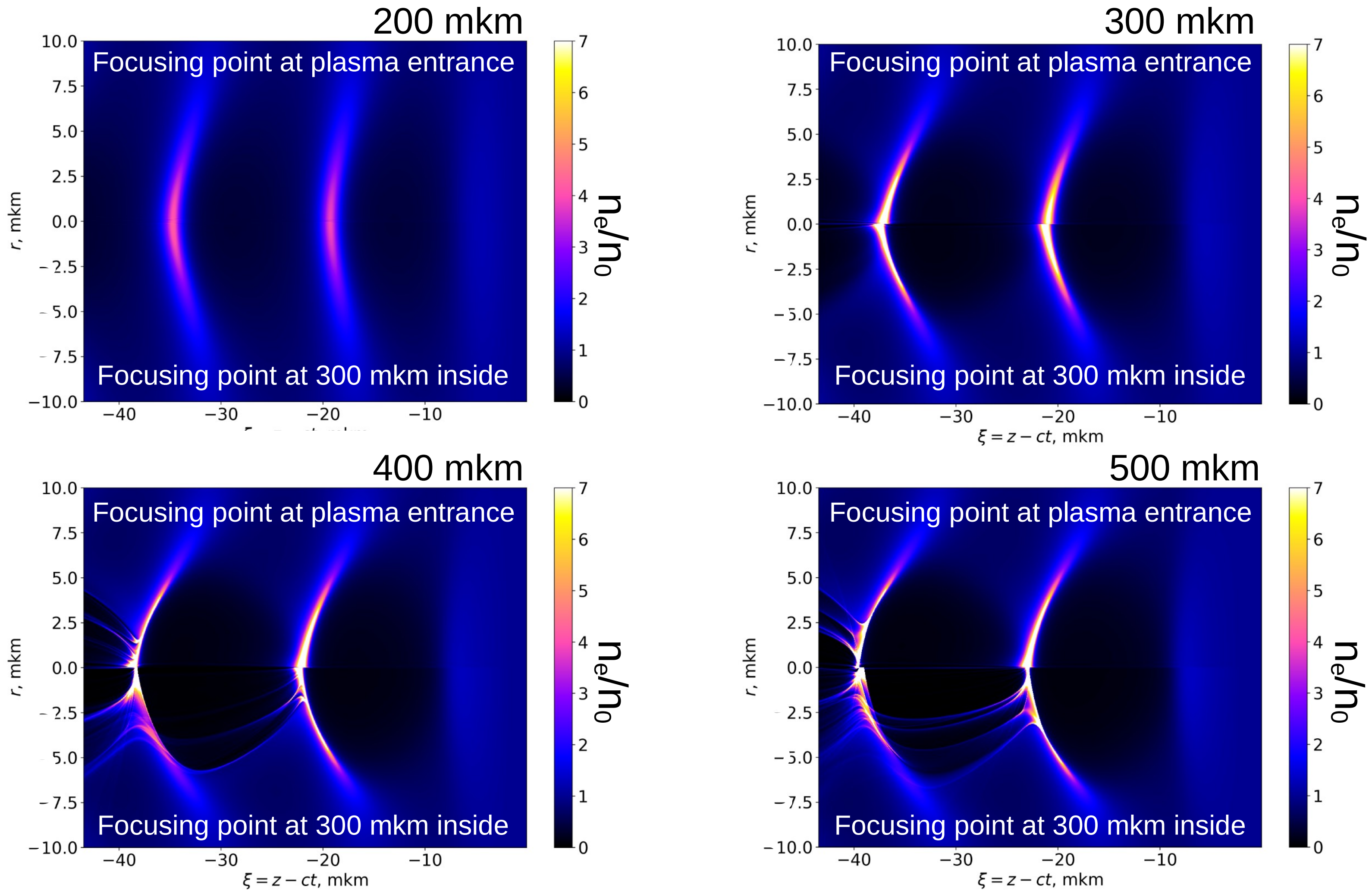
QSA and trapping



Driver parameters:

$a_0 = 3.5$
$\tau_0 = 1/\omega_p$
$r_0 = 2.6/k_p$
$k_0 = 30k_p$

Blue lines — plasma electrons with QSA
Black lines — test electron tracking without QSA


200 mkm
Focusing point at plasma entrance
Focusing point at 300 mkm inside
r, mkm
n_e/n_0
300 mkm
Focusing point at plasma entrance
Focusing point at 300 mkm inside
$\xi = z - ct$, mkm
400 mkm
Focusing point at plasma entrance
Focusing point at 300 mkm inside
$\xi = z - ct$, mkm
500 mkm
Focusing point at plasma entrance
Focusing point at 300 mkm inside
$\xi = z - ct$, mkm

Wakefield comparison