Alexander Pukhov, Xiaofei Shen

Monoenergetic high-energy ion source: femtosecond Laser-Plasma Peeler

Межинститутский Семинар

11.09.2020

Overview

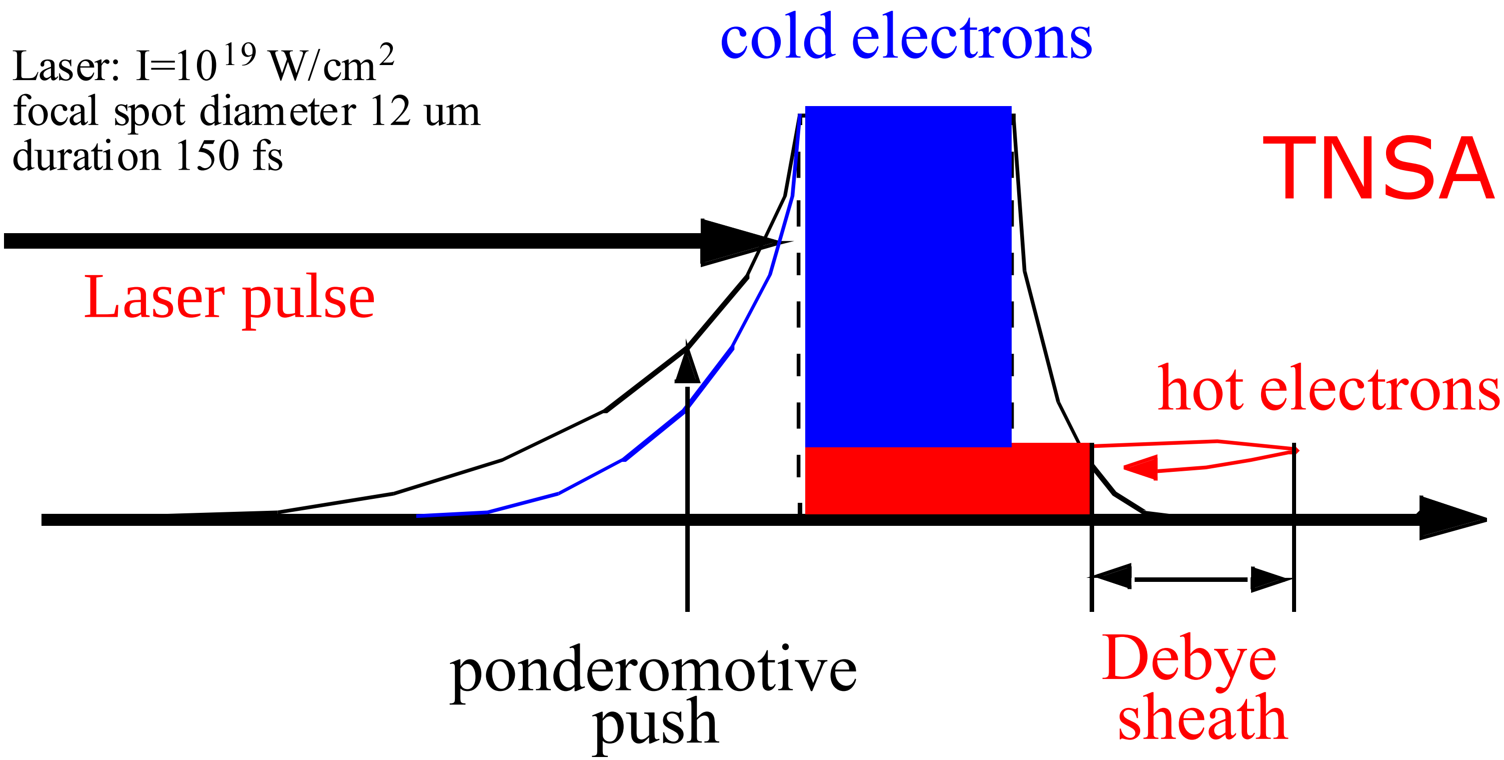
Shen, Pukhov, Qiao https://arxiv.org/abs/2009.04279

- Known regimes of ion acceleration
  TNSA, collisionless shock, RPA (and combinations)
- Importance of bunching accelerating field
- Novel ion acceleration regime **(*laser plasma peeler*)**
  Laser parallel to a microplate (tape)
- **Monoenergetic high energy proton acceleration**

Ion acceleration from solid targets

A.Pukhov, Phys. Rev. Lett. **86**, p.3562 (2001).

Laser: $I=10^{19}$ W/cm^2
focal spot diameter 12 um
duration 150 fs

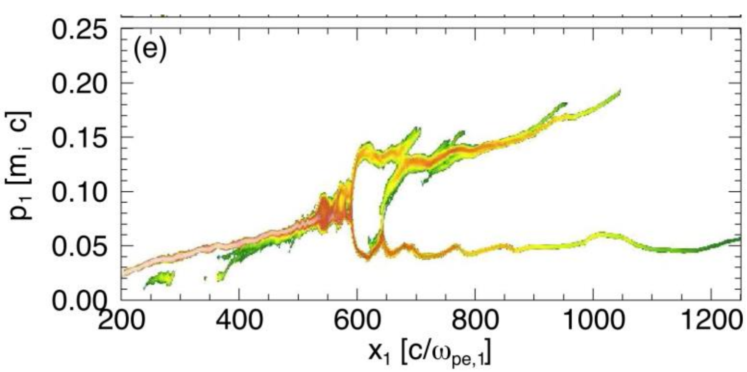


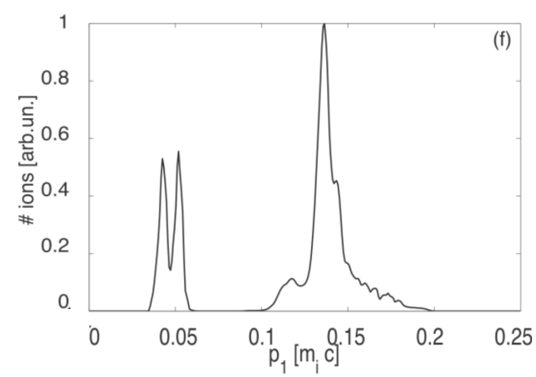
Ion acceleration from solid targets
Basic regimes

1. **TNSA** (P. Mora 2003): Exponential energy spectra

$$dN/d\mathcal{E} = (n_{i0}c_s t/\sqrt{2\mathcal{E}\mathcal{E}_0})\exp(-\sqrt{2\mathcal{E}/\mathcal{E}_0})$$

2. **Collisionless shock** (Denavit 1992, Silva 2004, Boella 2018)
Quasi-monoenergetic spectra possible for tailored plasma densities

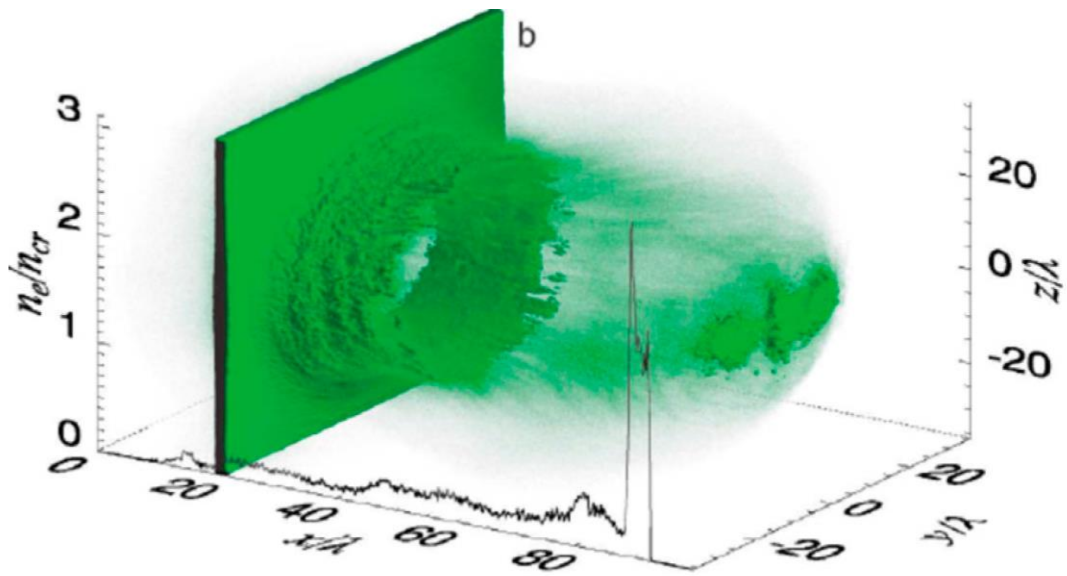




$\Delta E/E \sim 10\%$

Ion acceleration from thin foils

3. **RPA** *aka* **Light Sail** *aka* **Laser Piston**



Esirkepov 2004

Transverse instability of Light Sail (RPA, Laser Piston)

Wan et al 2020

The target is fast heated
and destroyed
by transverse instabilities

$$\gamma_m \approx \sqrt{\gamma_{ei}^2 + \gamma_{\rm RT}^2},$$

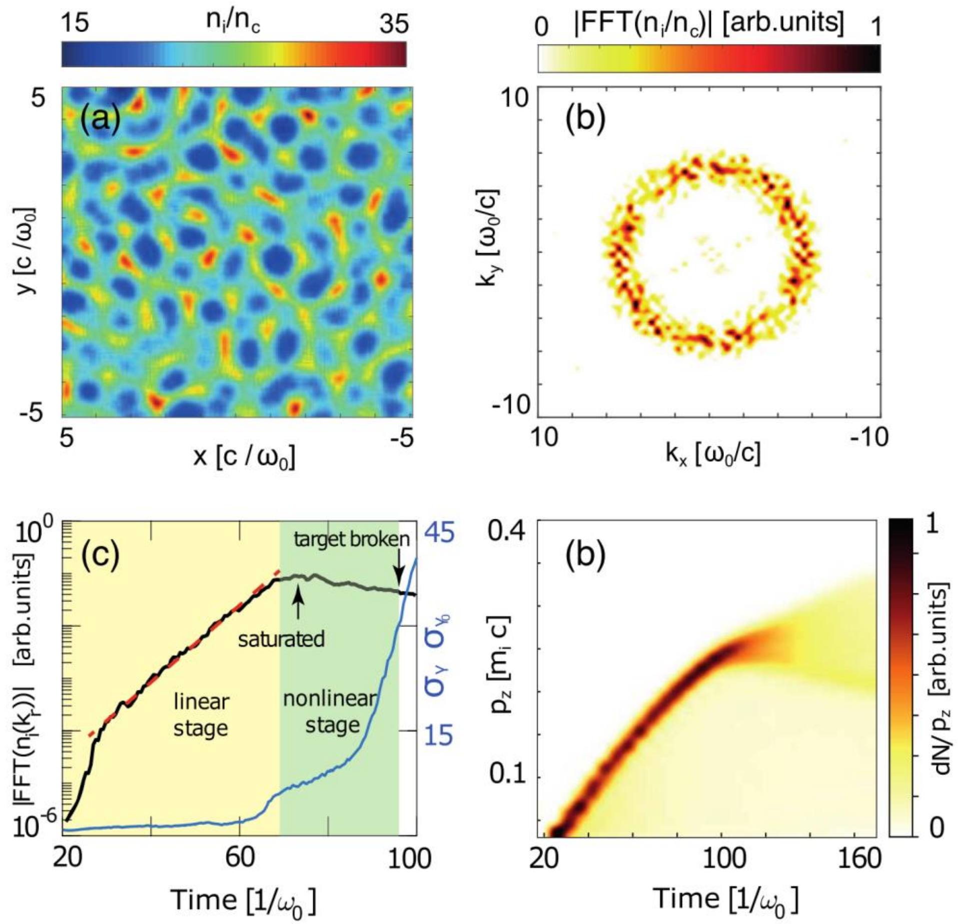
and the wave number of the fastest growing mode

$$k_{xm}^2 + k_{ym}^2 \simeq 2\kappa\omega_{pe}^2/v_{osc}^2,$$

where the terms

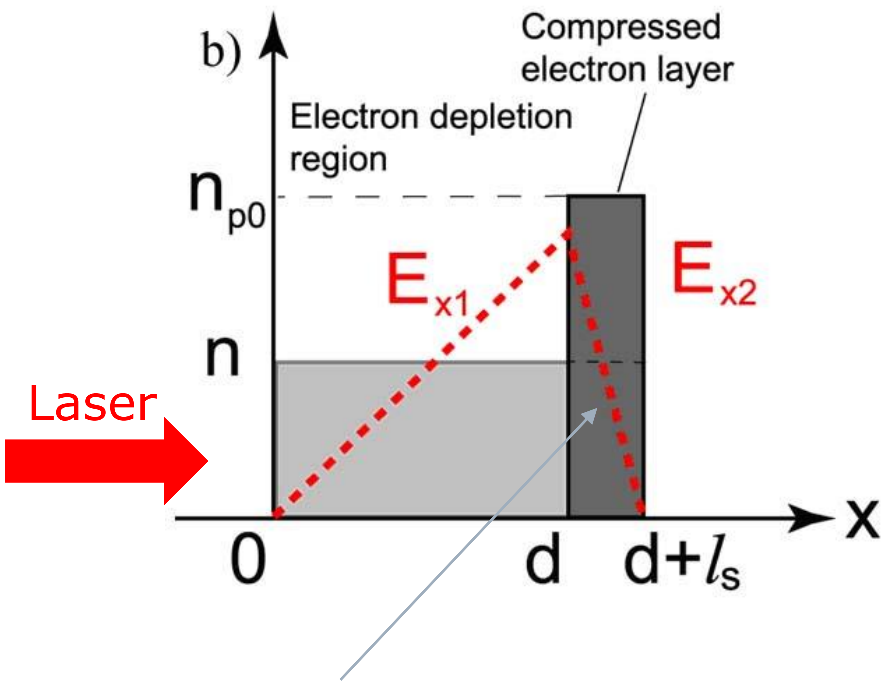
$$\gamma_{ei} \simeq 2(\omega_{pi}^2\omega_{pe})^{1/3}(\kappa m_e/m_i)^{1/6},$$

$$\gamma_{\rm RT} \simeq (\sqrt{\kappa/2}\alpha_{\rm in}\omega_{pe}/v_{osc})^{1/2},$$



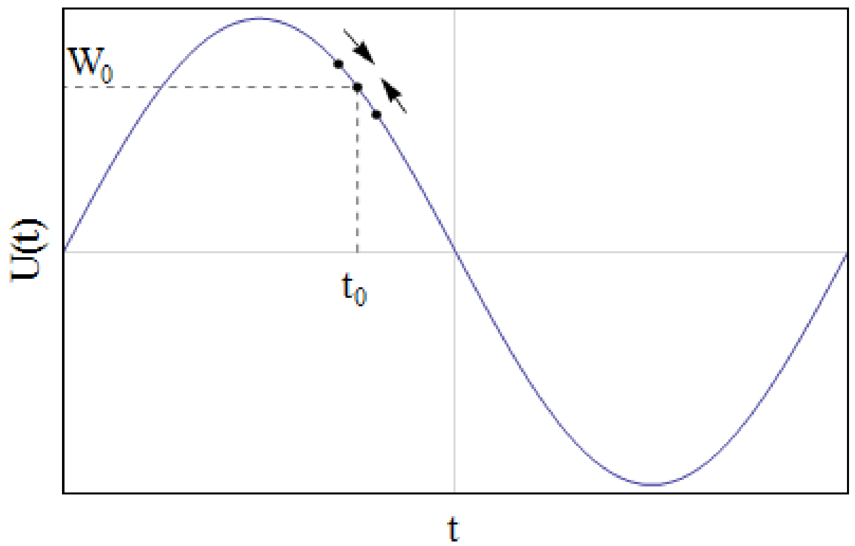
Bunching *E*-field in 1D Light Sail (Phase Stable Acceleration)

Yan et al 2008



Bunching field

Veksler 1944



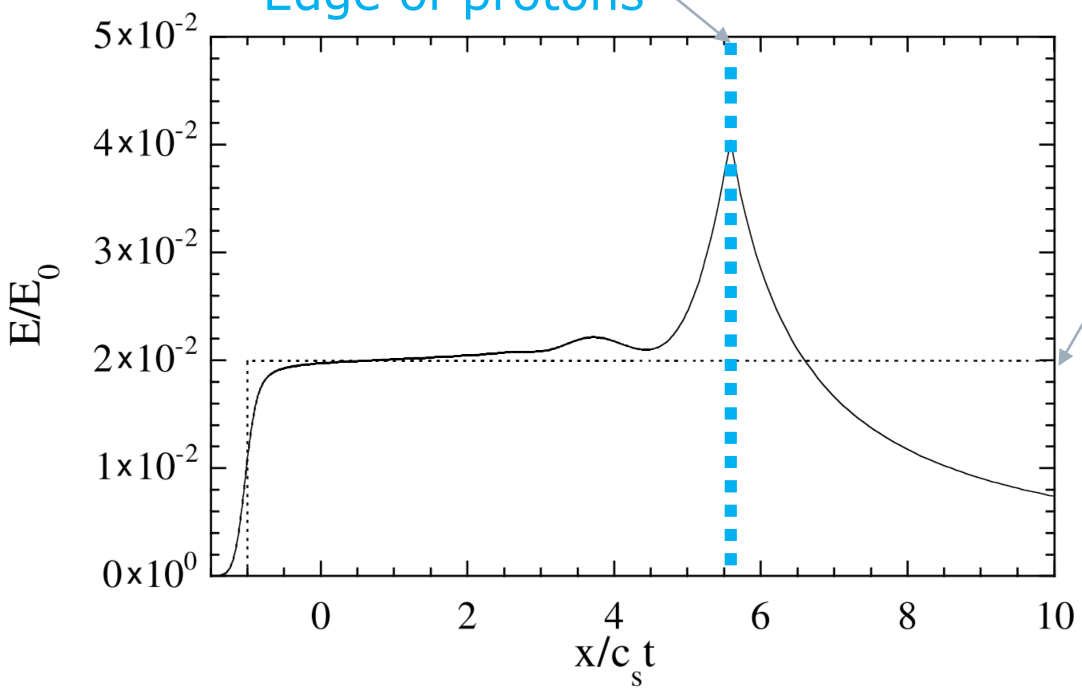
Synchrotron principle

TNSA: no bunching field

Mora 2003

Constant self-similar field: $E_{ss} = k_B T_e / e c_s t = E_0 / \omega_{pi} t,$

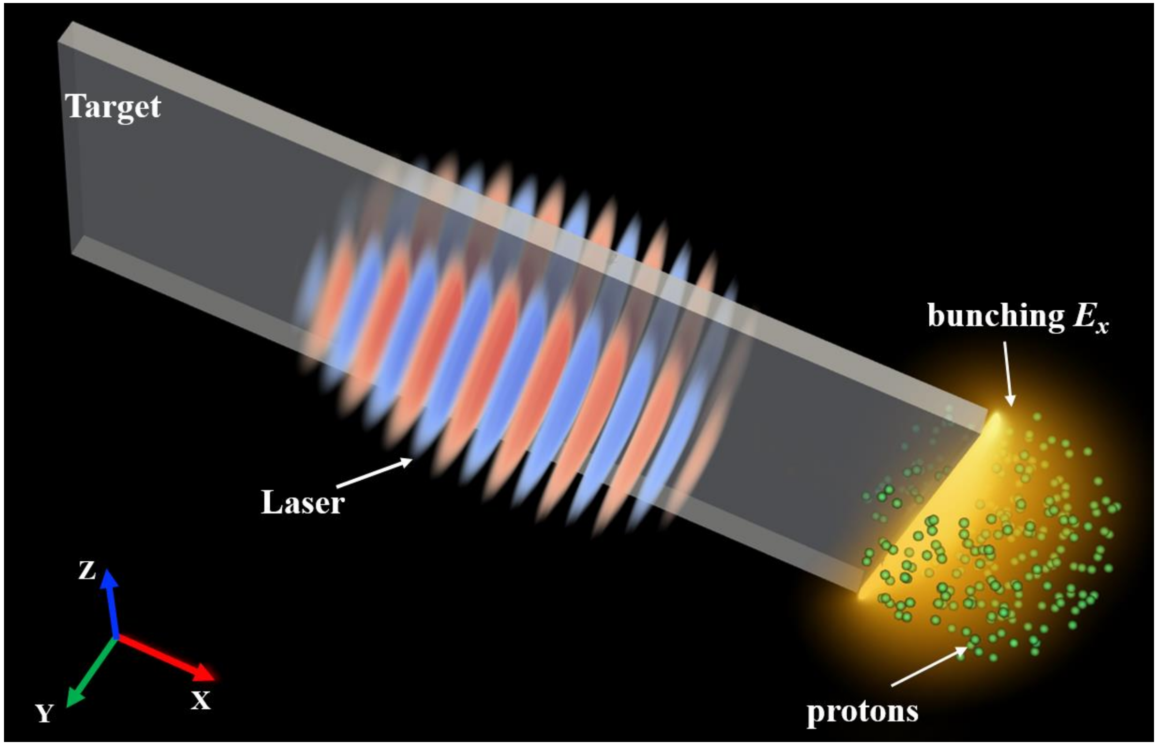
Edge of protons



The novel mechanism:
Monoenergetic Ion Acceleration by a Laser Parallel to a Microplate

Shen, Pukhov, Qiao https://arxiv.org/abs/2009.04279

Laser-Plasma Peeler

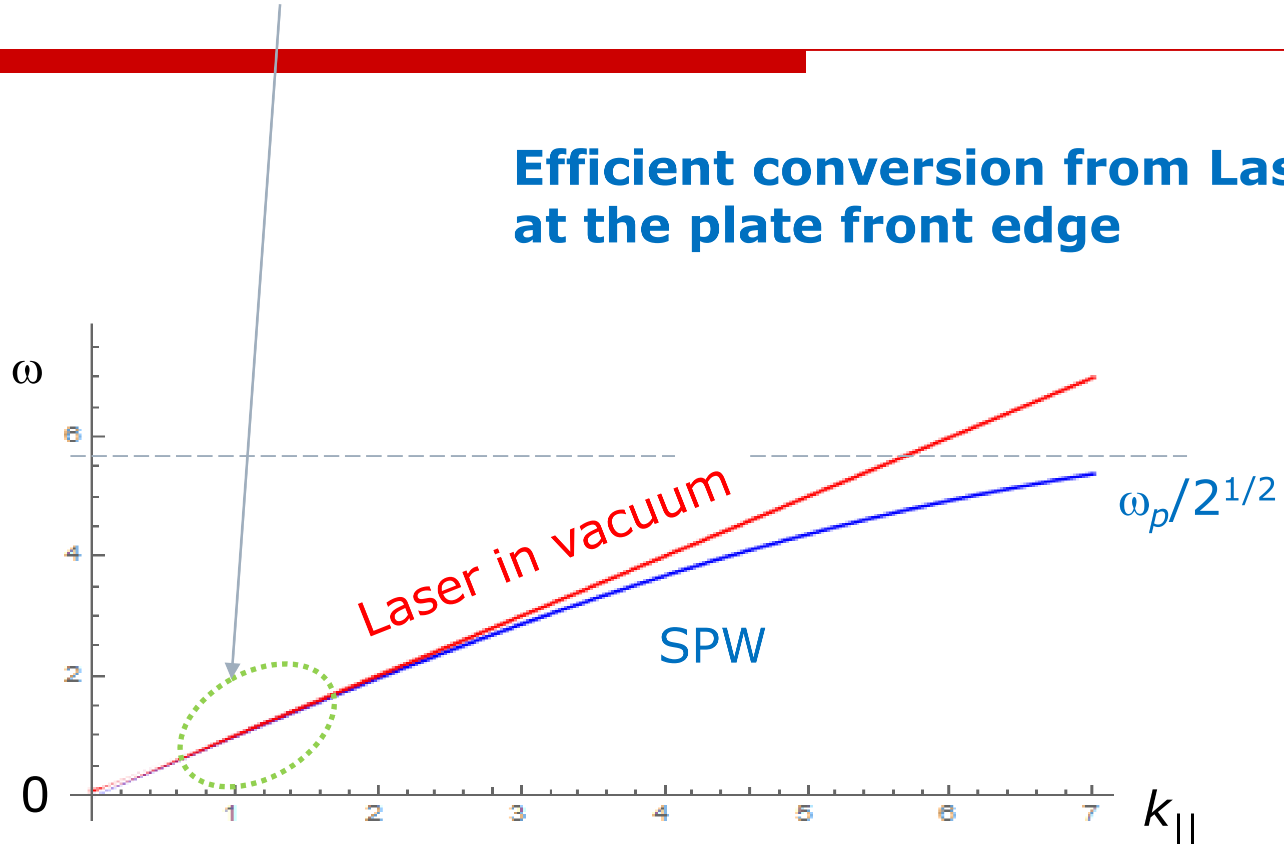


Laser:
a_0=19,
r=7.5λ, τ_L = 45fs
(50 J energy)

Plate (x,y,z):
43.75λ×0.75λ×45λ
n_e=30n_c
CH layer
thickness: 0.4λ,
C:H=1:1

Laser Quasi-Resonance with Surface Plasma Wave (SPW)

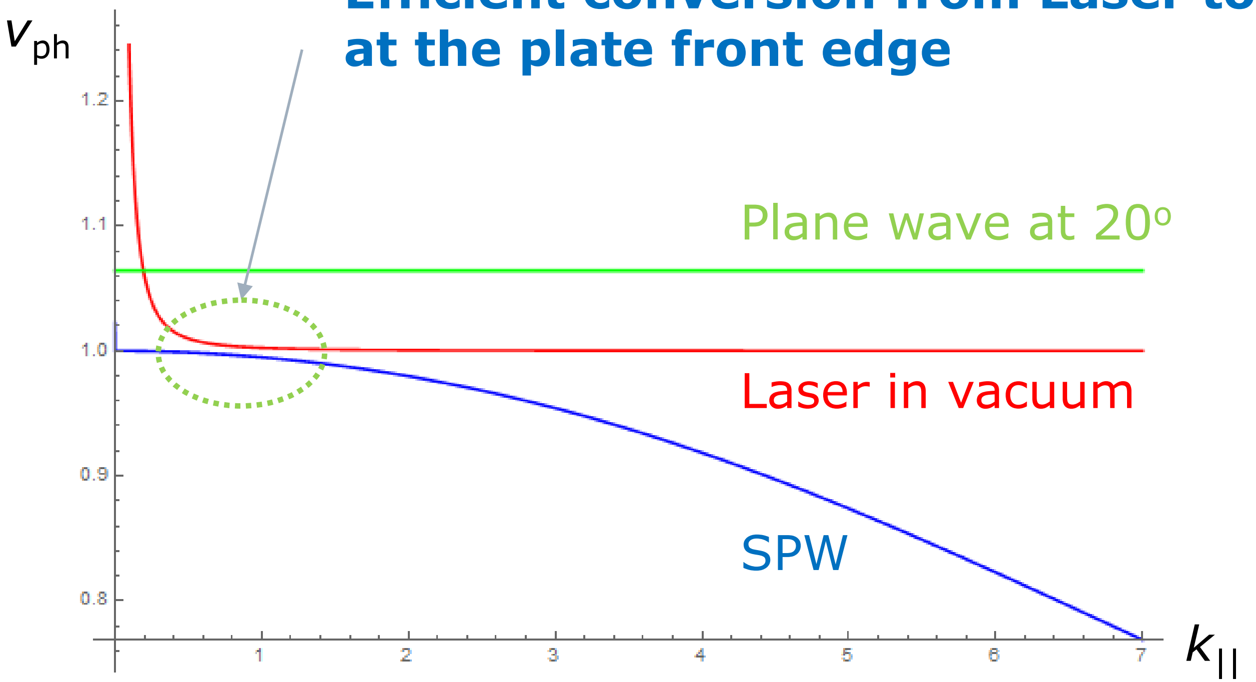
Efficient conversion from Laser to SPW at the plate front edge



Dephasing length between laser and SPW L_{deph} ~ 30 μm

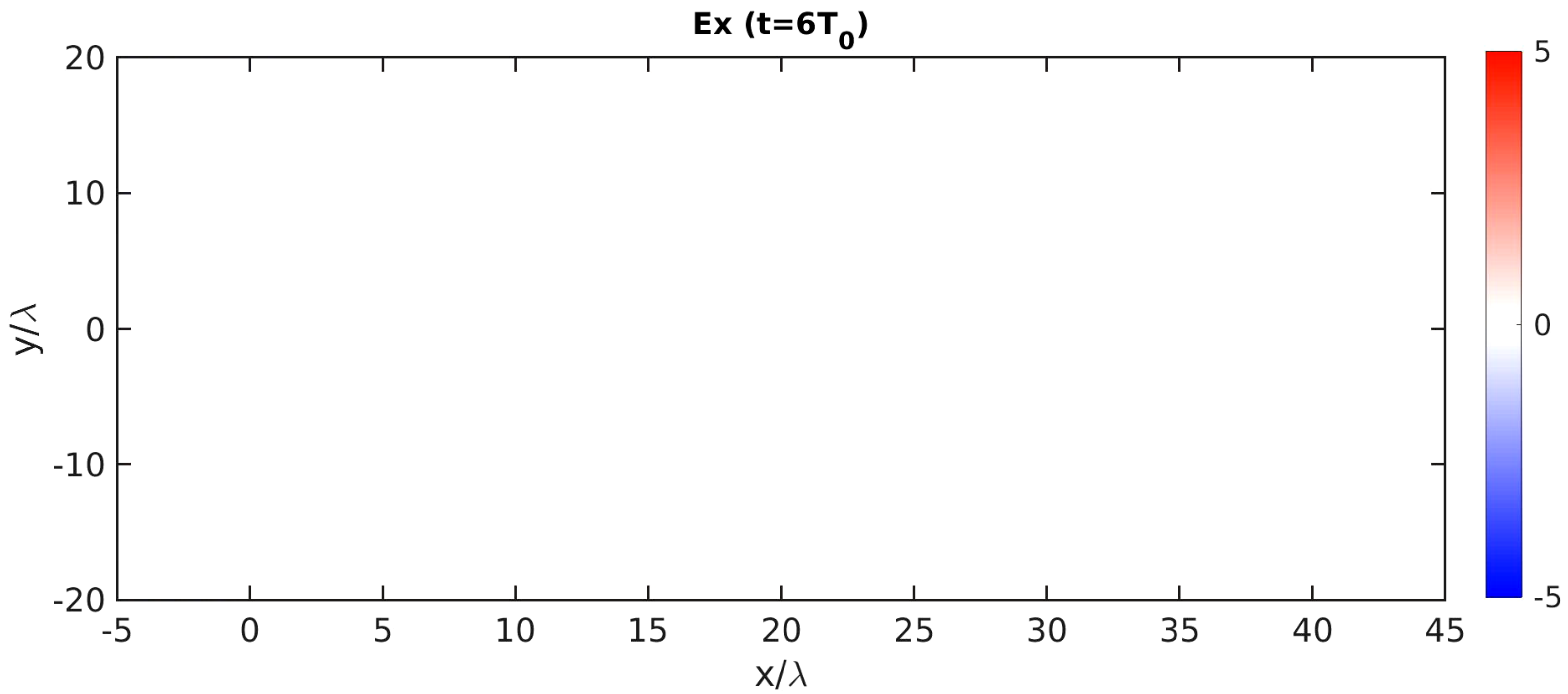
Comparison with grazing angle incidence

Efficient conversion from Laser to SPW at the plate front edge



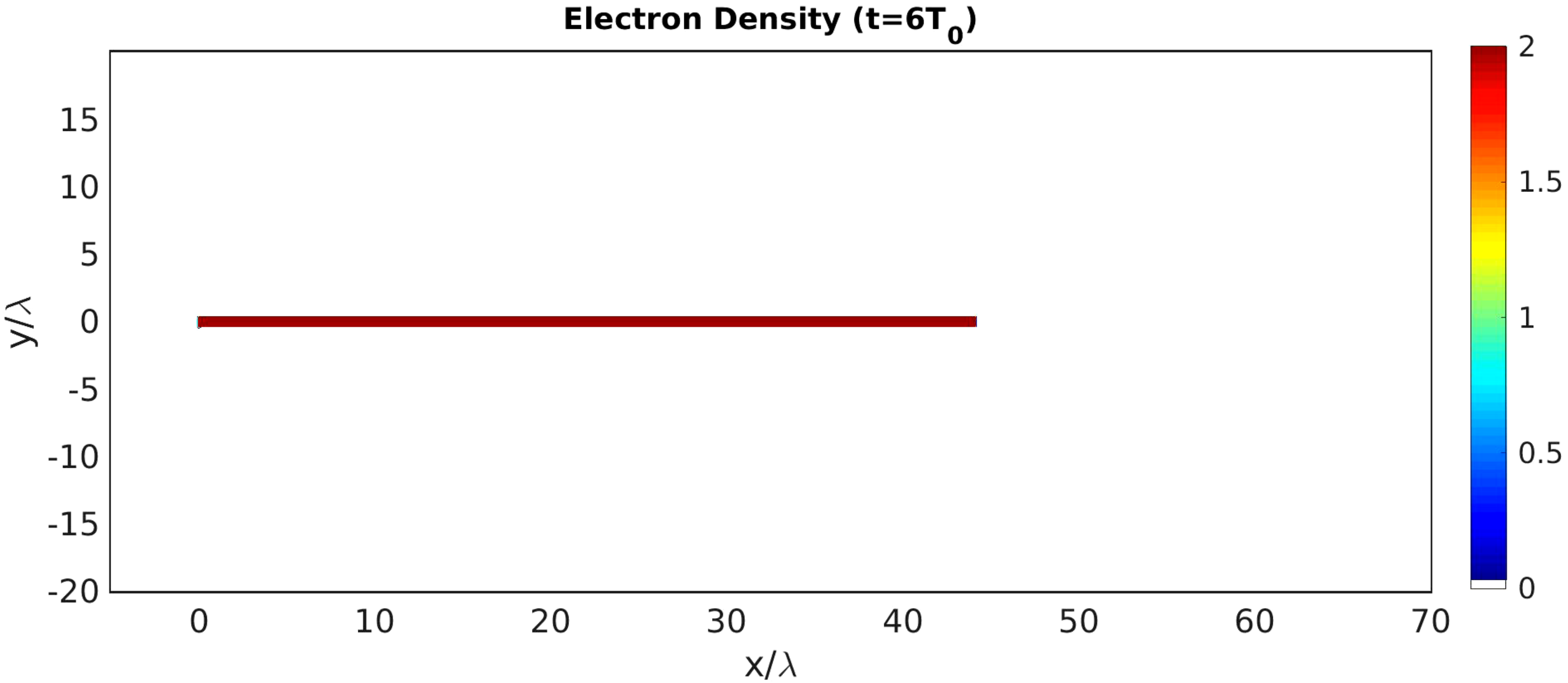
Dephasing length between laser and SPW L_{deph} ~ 30 μm

Strong Surface Plasma Wave excited

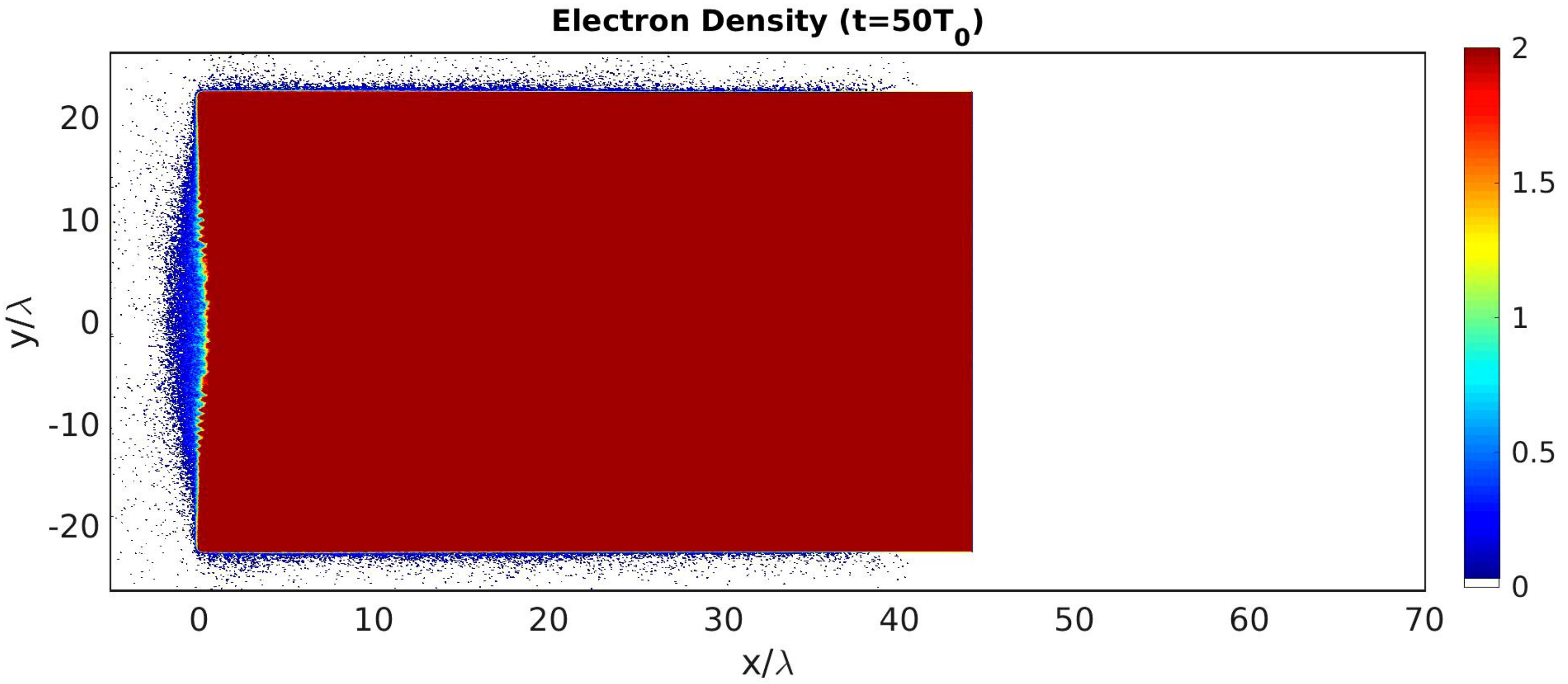


The field strength of SPW can reach 2×10^{13}V/m.

Abundant electrons are peeled off and accelerated by DLA and SPW

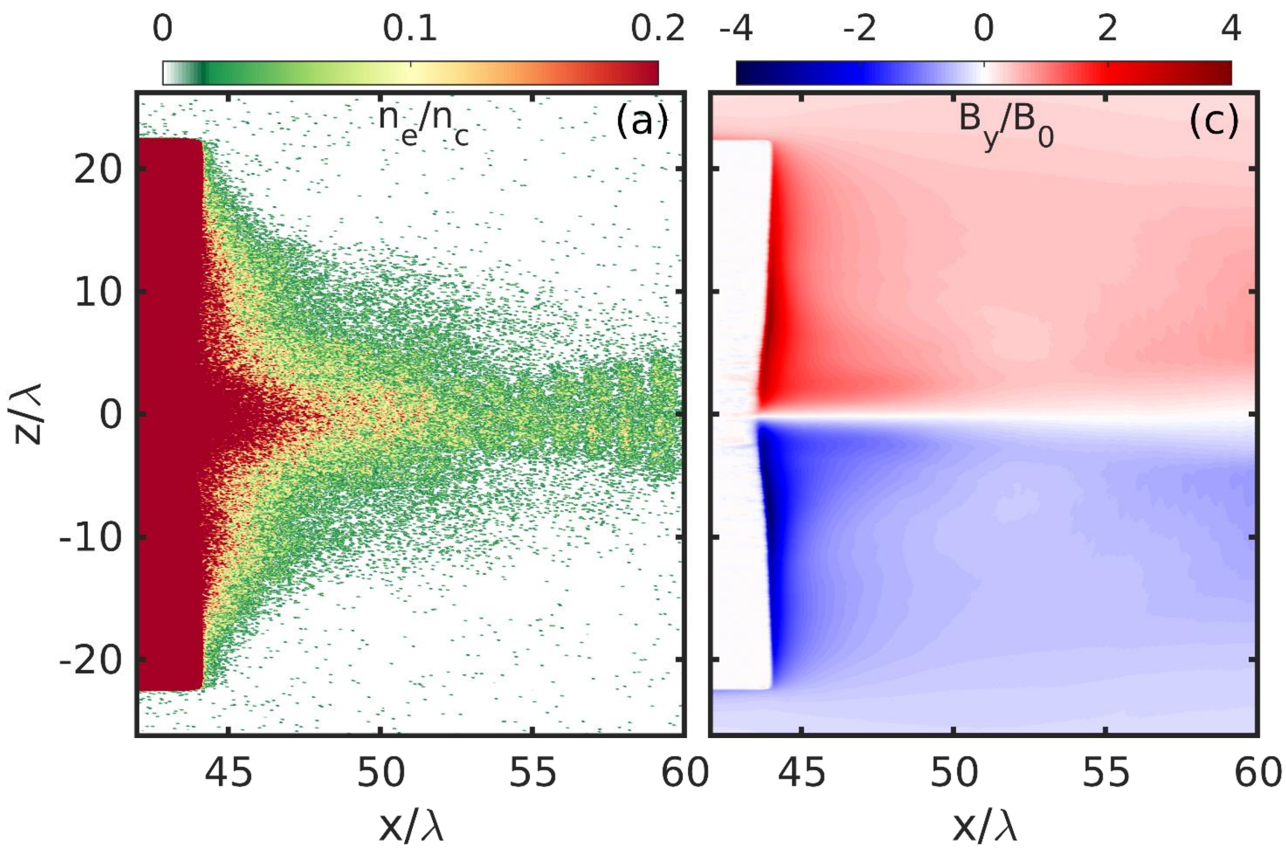


Peeled away electrons are focused behind the plate by B_y

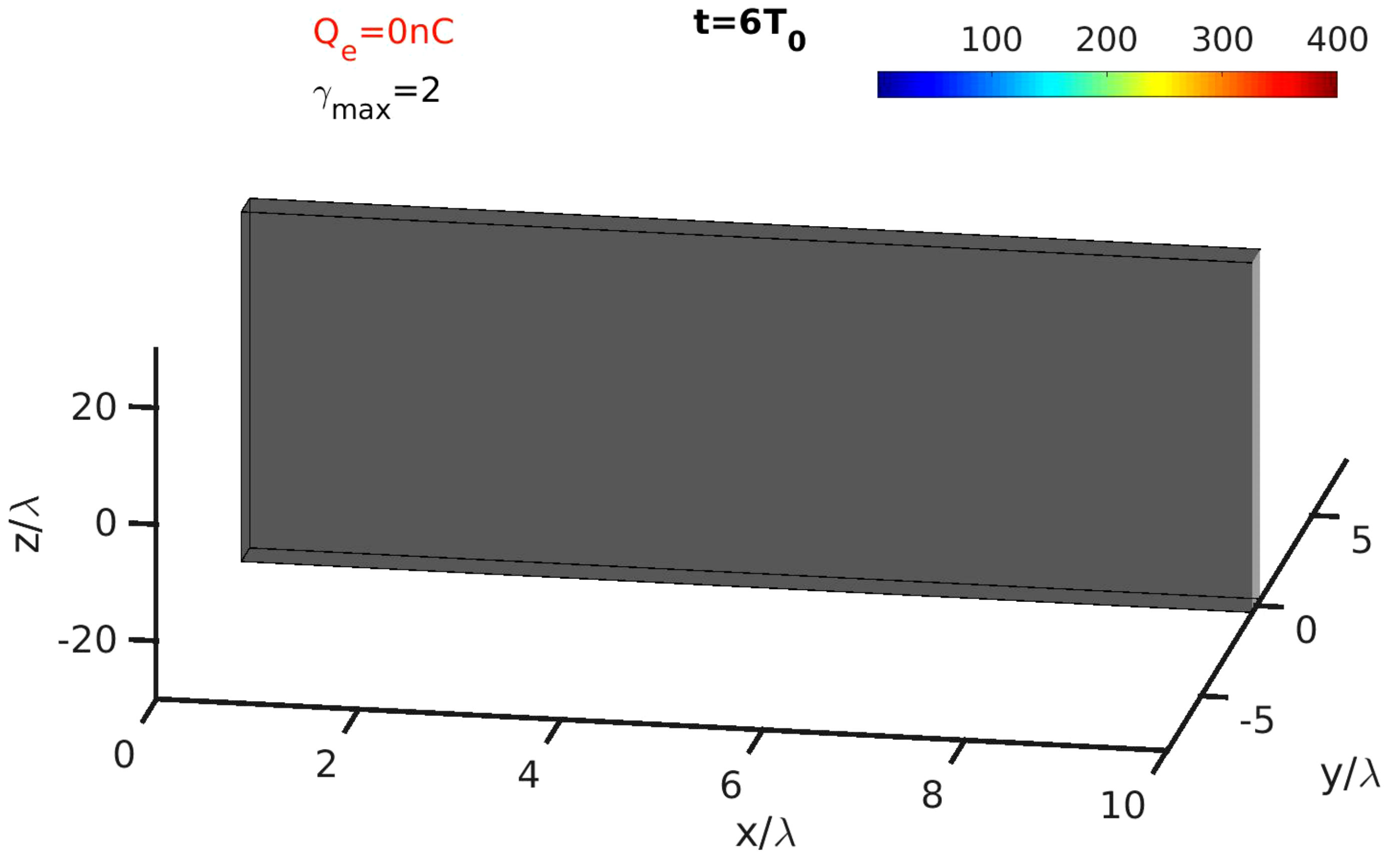


The space charge of electrons behind the plate can reach 50nC, far larger than that of protons (2.7nC).

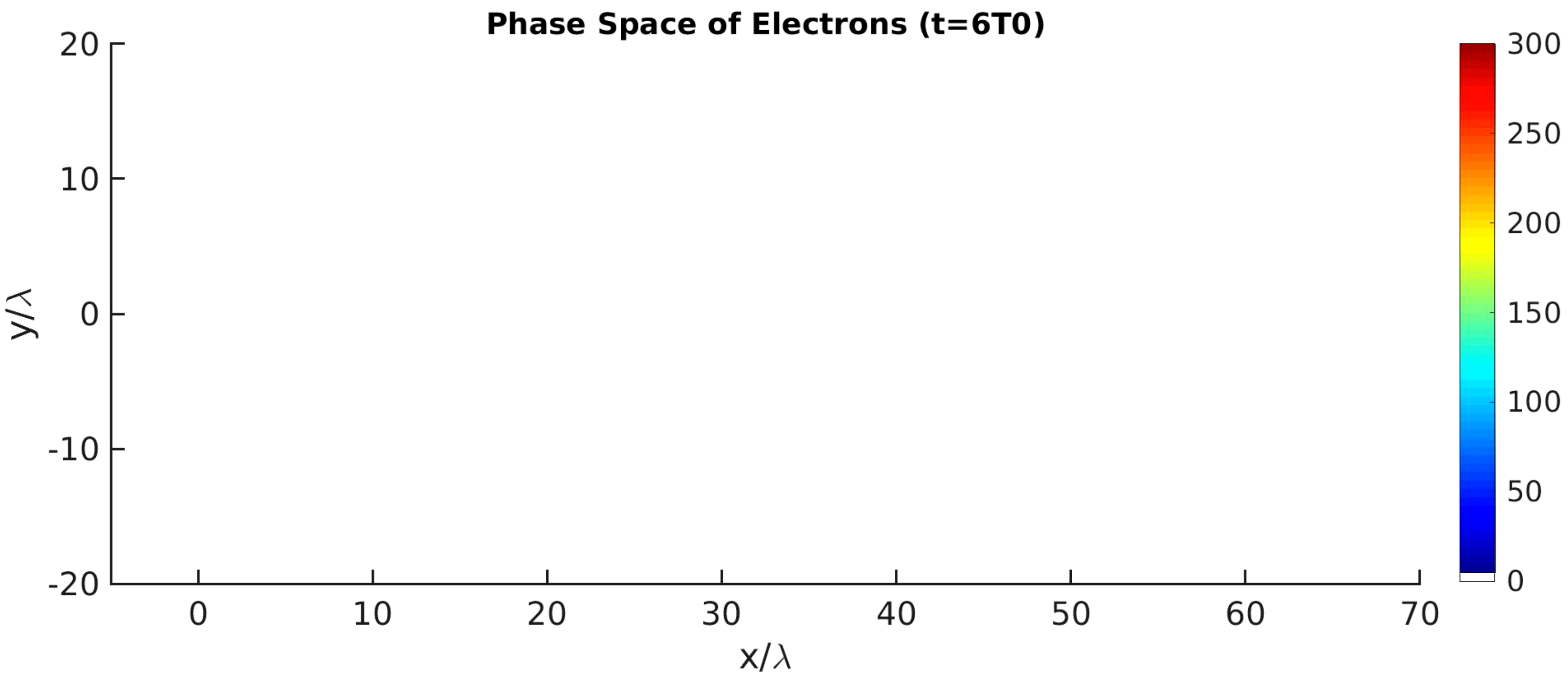
Peeled away electrons are focused behind the plate by B_y



Peeling away of large-charge, high-energy electron bunches



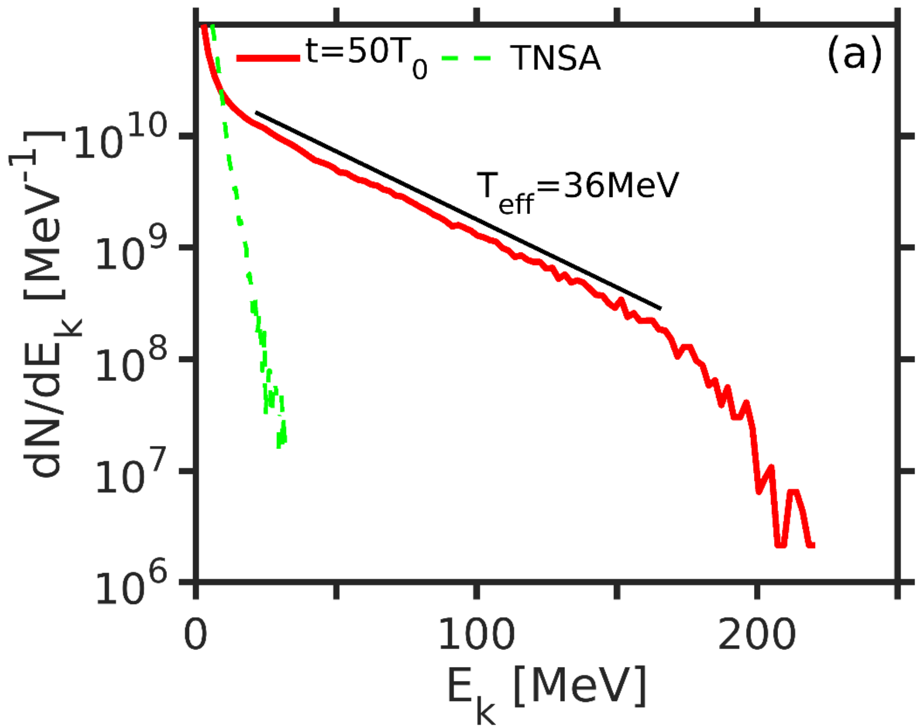
Peeling away of large-charge, high-energy electron bunches



Energy spectrum of electrons

Shen, Pukhov, Qiao https://arxiv.org/abs/2009.04279

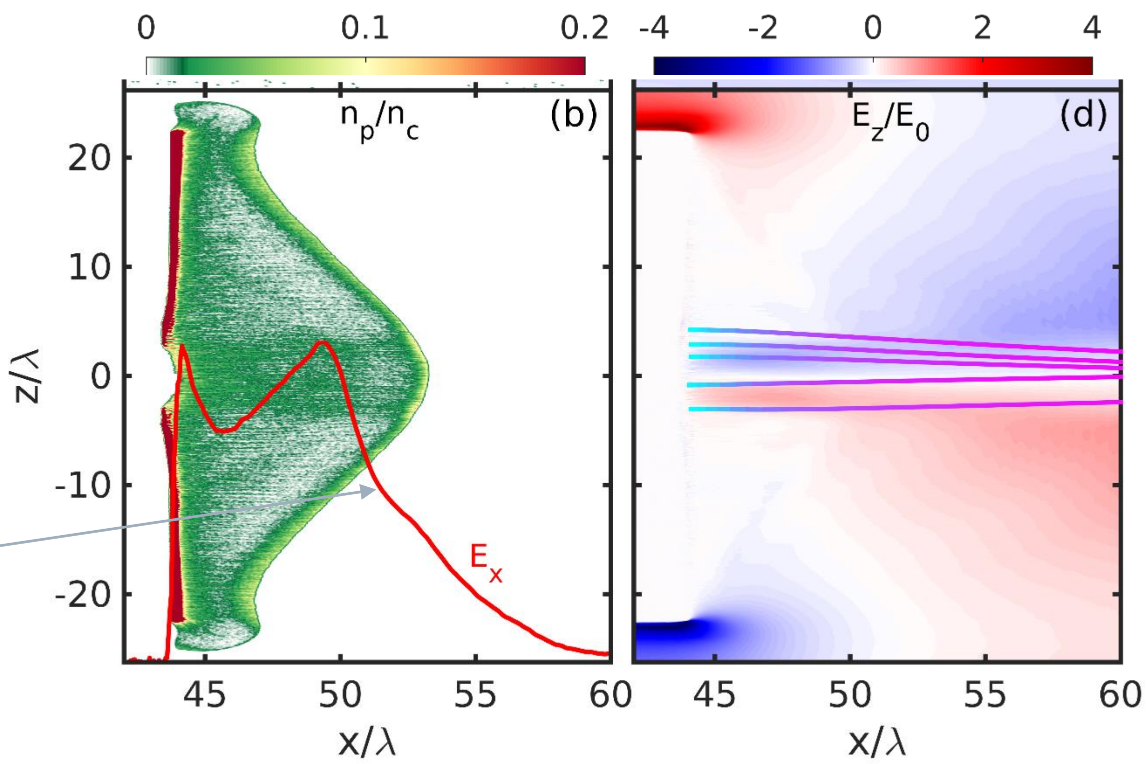
The effective temperature ***T_{eff}*****=36 MeV** is far larger than the ponderomotive scaling (6.4 MeV)



Protons longitudinal bunching and transverse collimation

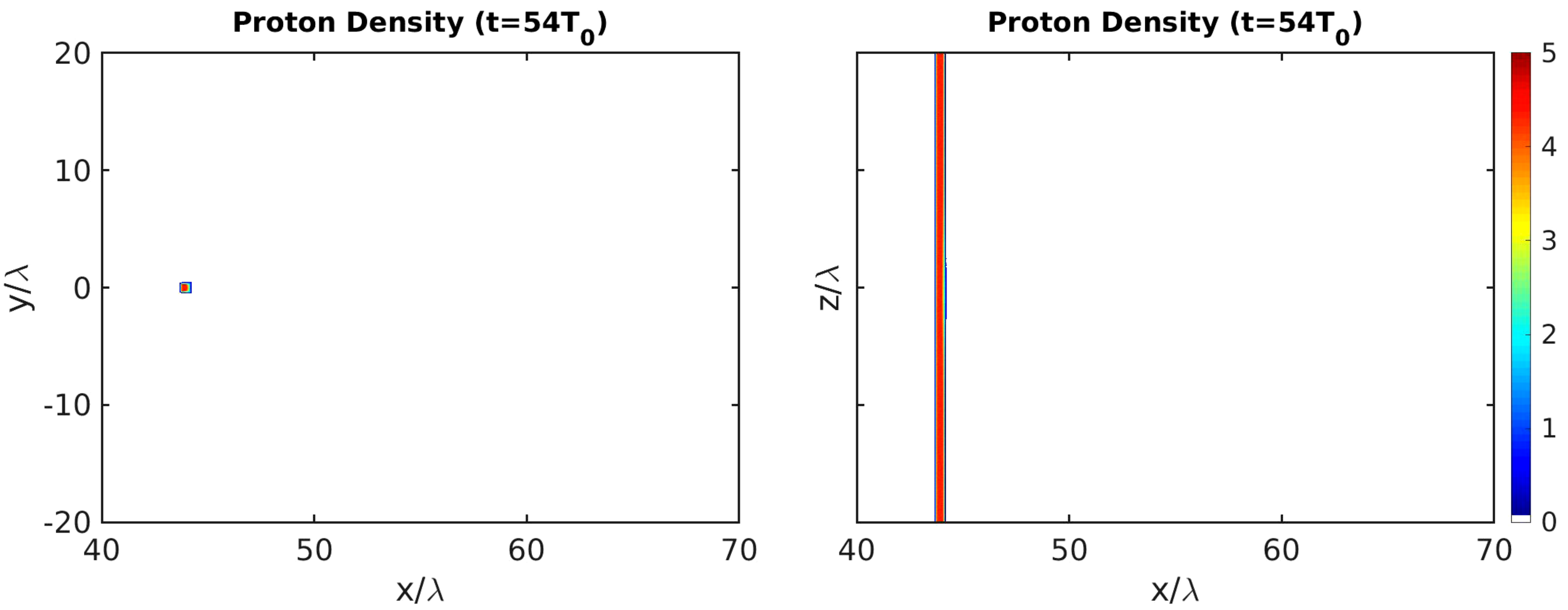
Shen, Pukhov, Qiao https://arxiv.org/abs/2009.04279

Bunching field

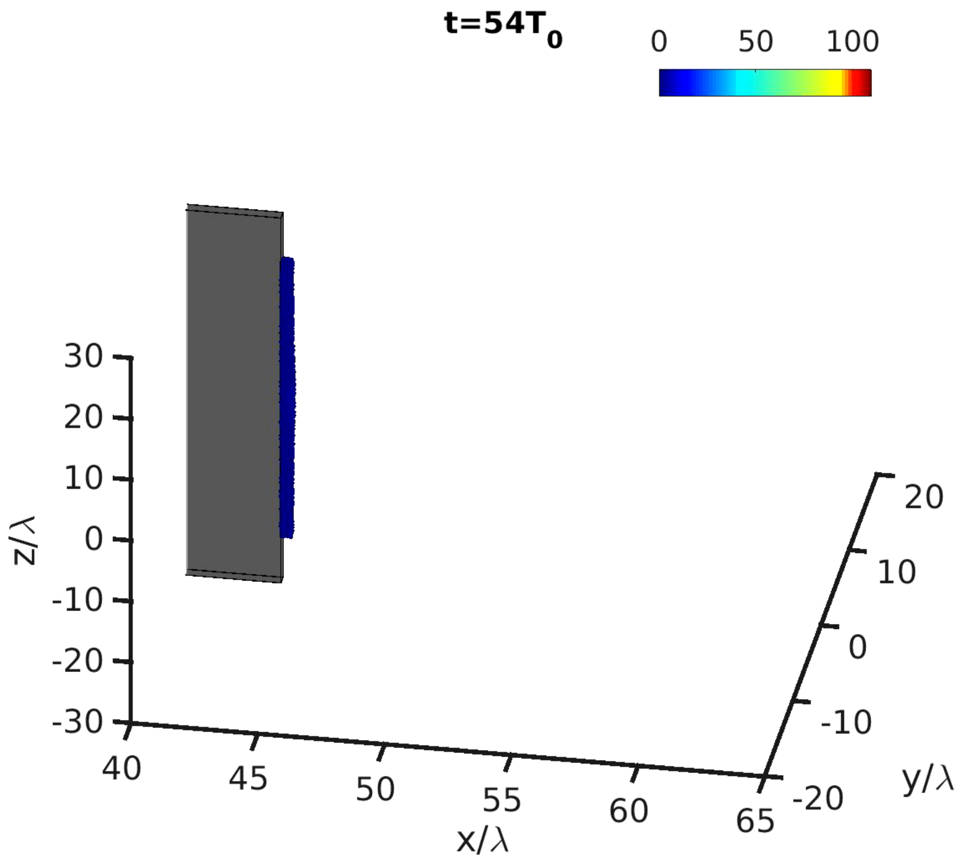


Lines in (d) represent the trajectories of protons.

High energy protons form density peak

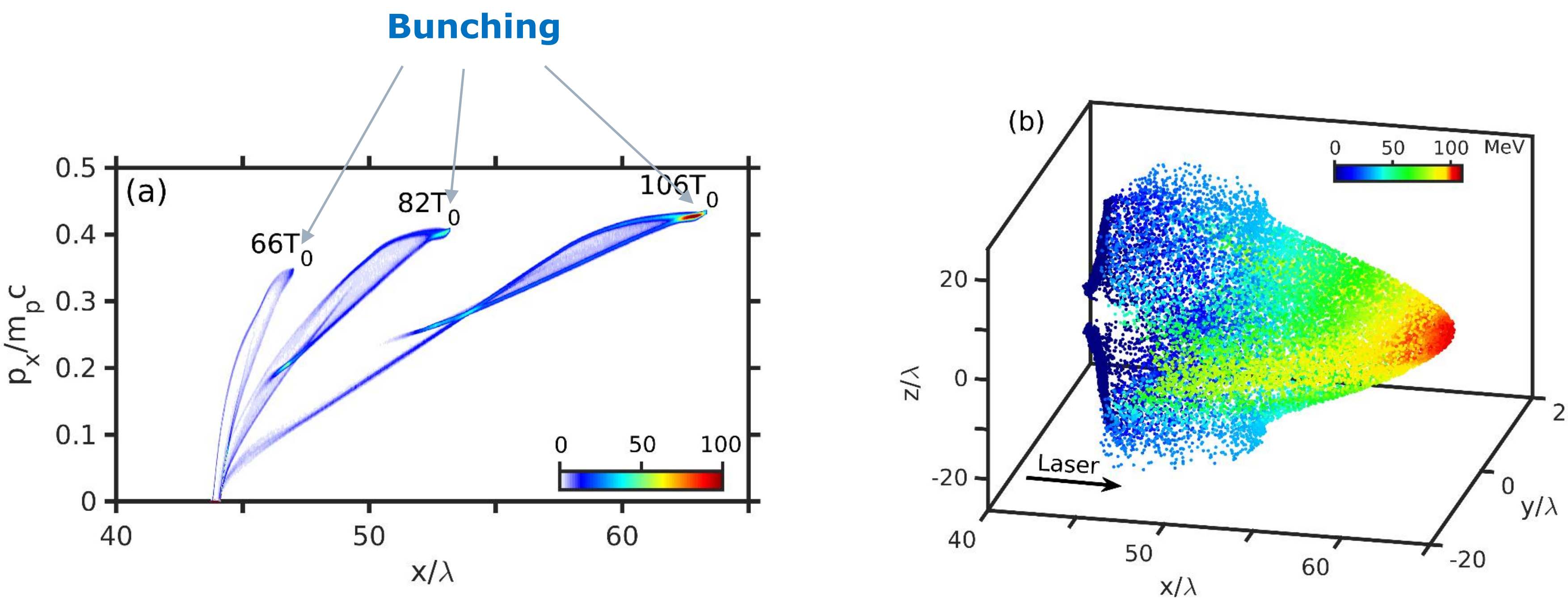


Distribution of protons in 3D space



Bunching in proton phase space

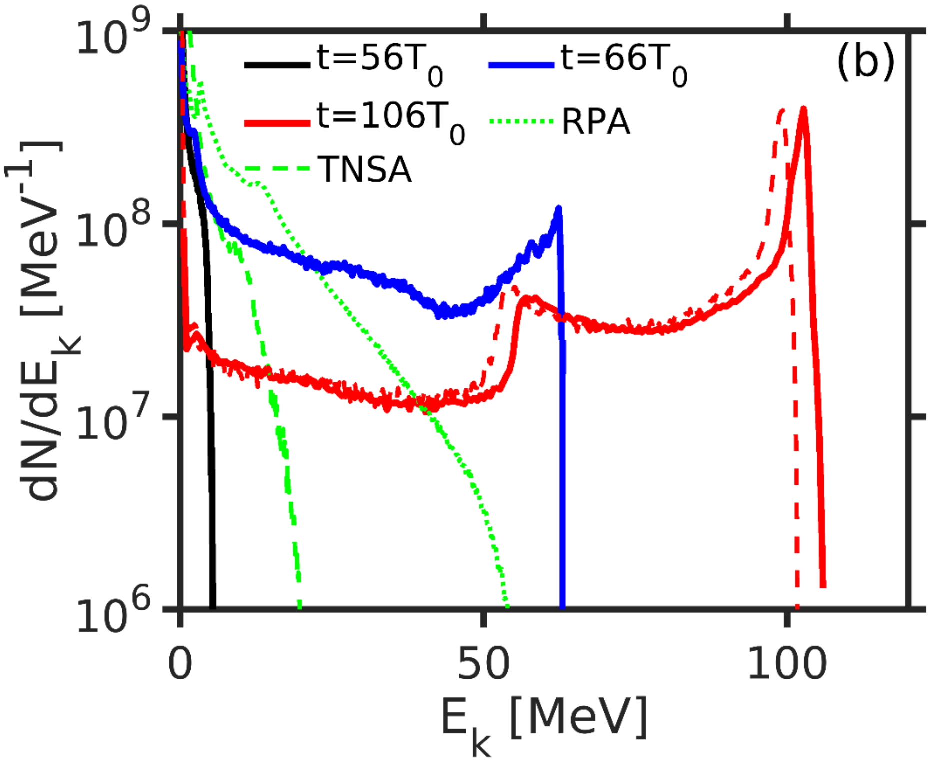
Shen, Pukhov, Qiao https://arxiv.org/abs/2009.04279



Proton phase space is compressed continuously by the longitudinal electric field.

pukhov@tp1.hhu.de

Monoenergetic proton beams with 1% level energy spread

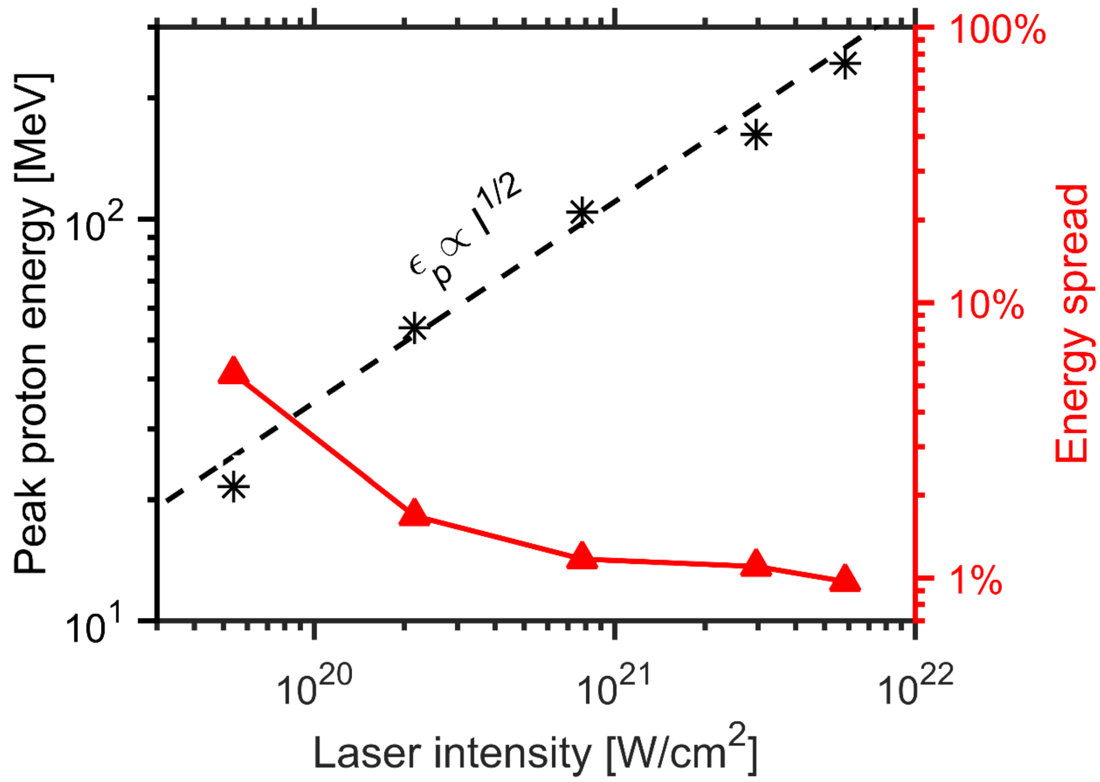


A high-energy quasi-monoenergetic proton beam, with peak energy >100MeV, energy spread about 1.17% and particle number 8×10^8 (0.13nC) is obtained.

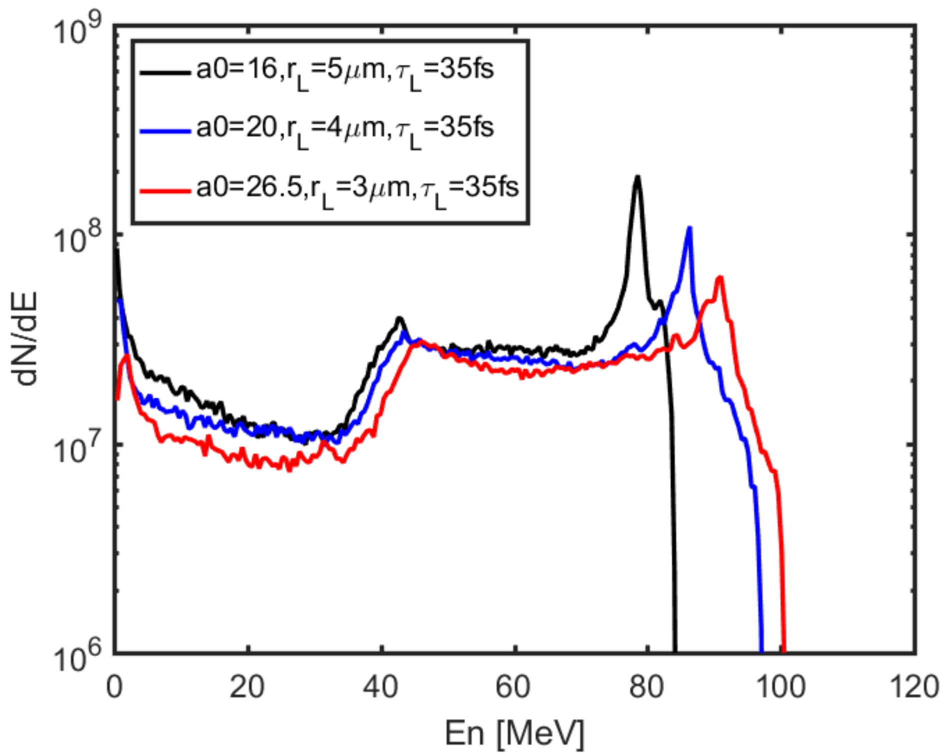
Scaling law

Shen, Pukhov, Qiao https://arxiv.org/abs/2009.04279

$\epsilon_p \sim 3.5\ (I_0/I_{18})^{1/2}$ MeV

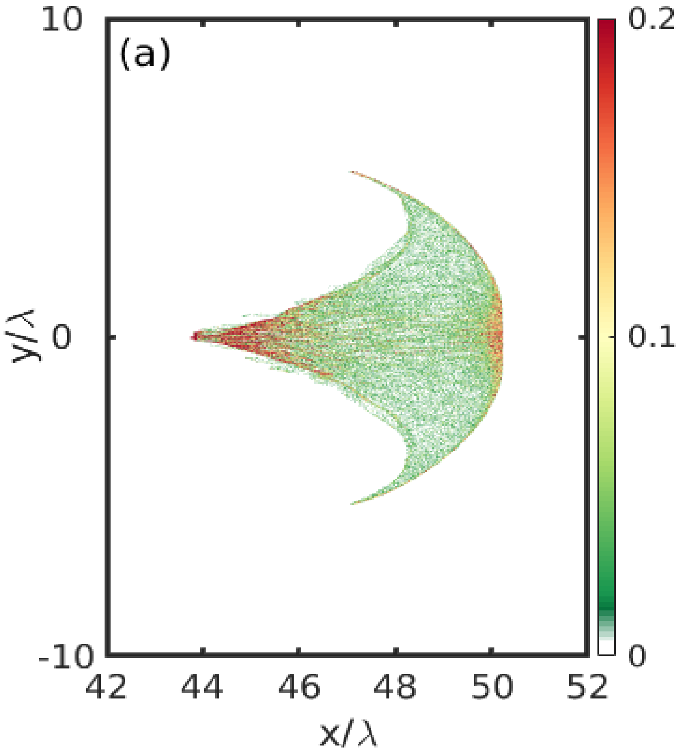


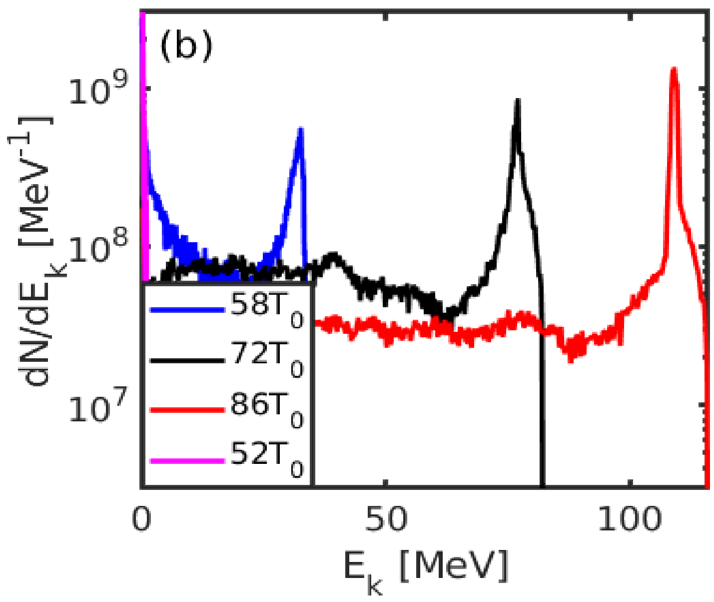
Proton energy spectra with laser pulse energy 23J



Quasi-monoenergetic proton beams with peak energy ~80MeV, energy spread about 2~4% and particle number 2×10^8 (0.033nC) can be obtained.

2D simulations with realistic plasma density

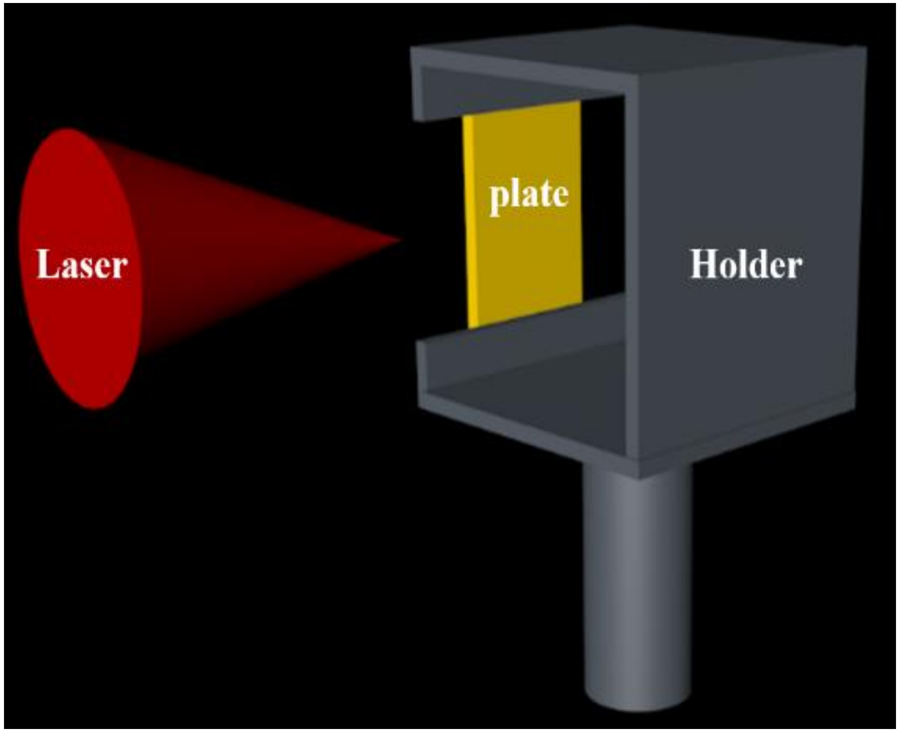




Plasma density is 2000 n_c.

Theoretician’s suggestion for an experimental configuration

Laser-Plasma Peeler



Summary

Shen, Pukhov, Qiao https://arxiv.org/abs/2009.04279

- **Laser is in quasi-resonance with SPW when incident parallel to a microplate**
- **Efficient electron peeling and acceleration along the plasma surface**
- **Huge space charge of peeled away electrons forms bunching electron field at the rear edge**
- **Monoenergetic high energy proton acceleration**