Laser acceleration of particle in plasma

C. S. Liu

Electron can be accelerated by plasma wave: $v = \omega_p / k$

Acceleration gradient of plasma wave can be large

Maximum acceleration gradient limited by the wave breaking

$$v_{osc} \approx \frac{eE}{m\omega_p} \sim c \quad \text{or} \quad E_0[V/cm] = \frac{mc^2}{e}\left(\frac{\omega_p}{c}\right) = 0.96\sqrt{n_0[cm^{-3}]}$$

Non-relativistic wave-breaking amplitude

giving, $E_0 = 100\,\mathrm{GV/m}$, for $n_0 = 10^{18}[cm^{-3}], mc^2 \approx 0.5\,MeV, c/\omega_p \approx 1\mu m$

SLAC on a slab !!!

Relativistic wave-breaking amplitude

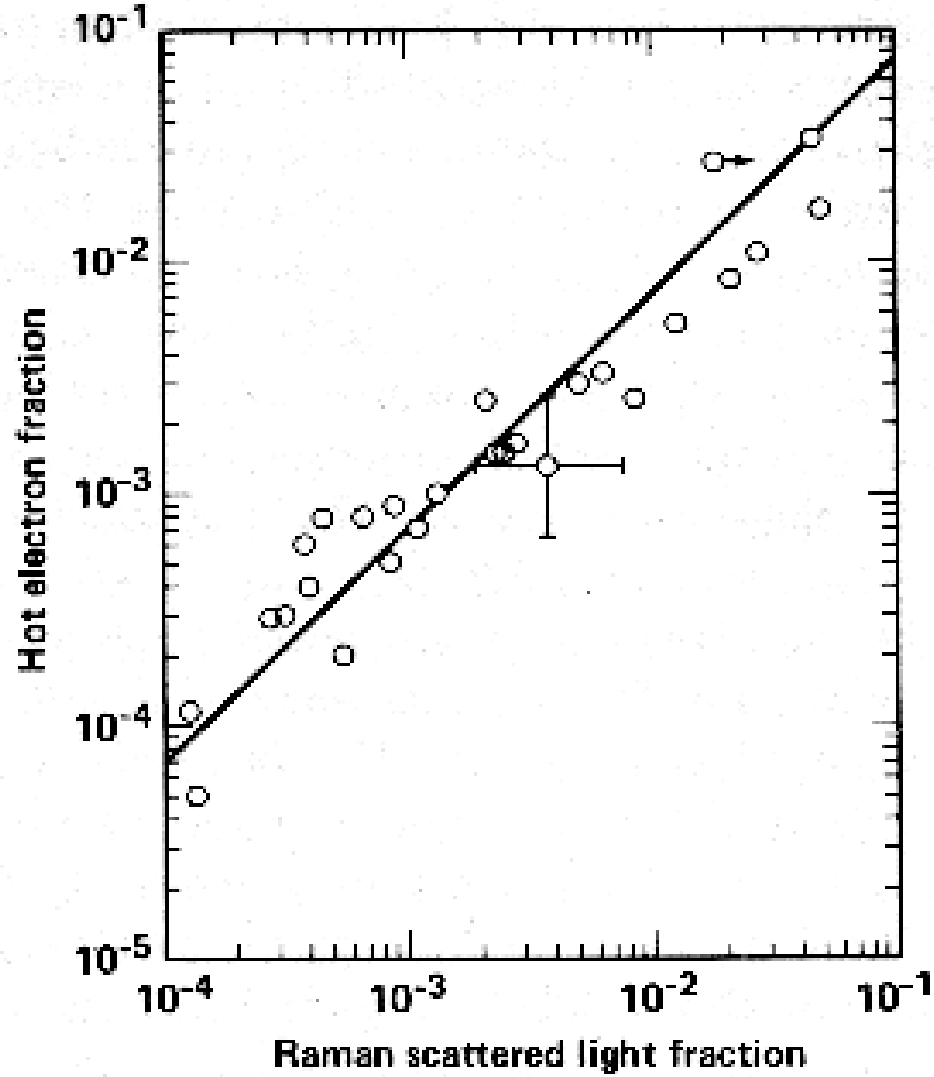
$$E_R[V/cm] = E_0\sqrt{\gamma_p - 1} \qquad E_R >> E_0$$

$\gamma_p = (1 - v_{ph}^2/c^2)^{-1/2}$ is the Lorentz factor for plasma wave

How to generate plasma wave ??

1. Mode conversion
2. Beat wave excitation with two laser pulses
3. Raman scattering
4. Relativistic wake plasma wave excitation by electron beam or short pulse laser

Raman scattering causes electron acceleration



Monoenergetic electron beam by short pulse laser

Observation of monoenergetic beam of electrons with energy 50-170 MeV by three groups.

Mangles et.al, Nature, 431, 535 (2004),

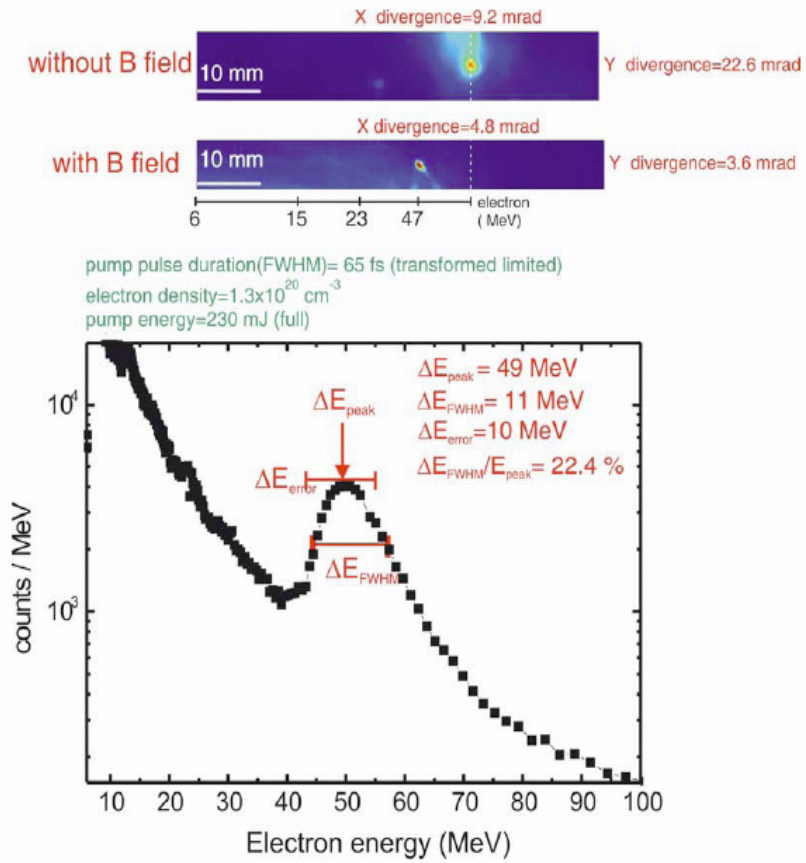
Faure et.al., Nature, 431, 541 (2004),

Geddes et.al., Nature, 431, 538 (2004)

First direct measurement of acceleration gradient;

eE=2.5 GeV/m ~ 10^3 of linac.

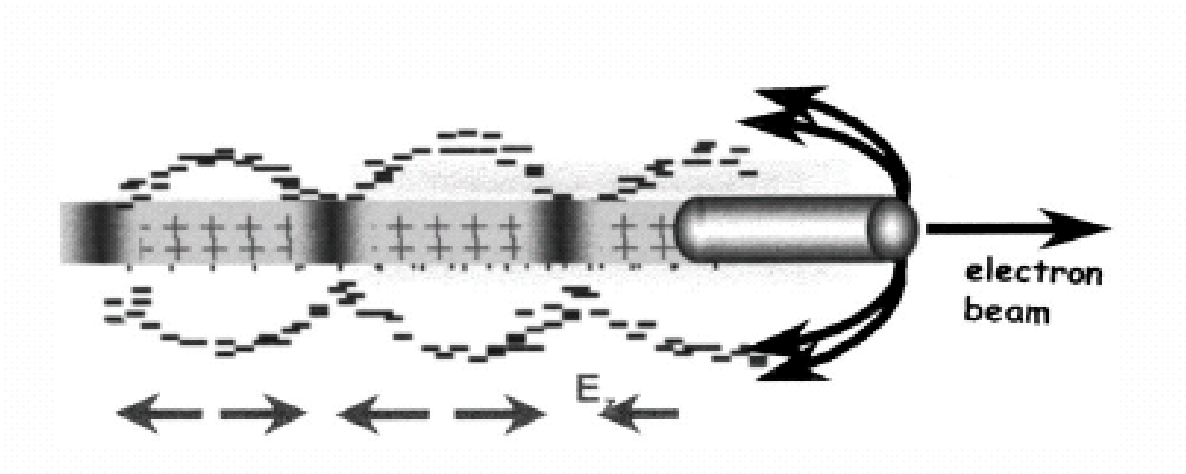
Electron energy spectrum for using 1-mm gas jet



✏ The beam divergence of the mono-energetic electron beam is only about 4 mrad. The energy spread is much less than 22%, with the measurement resolution limited by the electron beam size on the detector plane.

Chen, et.al.(Particle accelerator group, Academia Sinica, NCU)

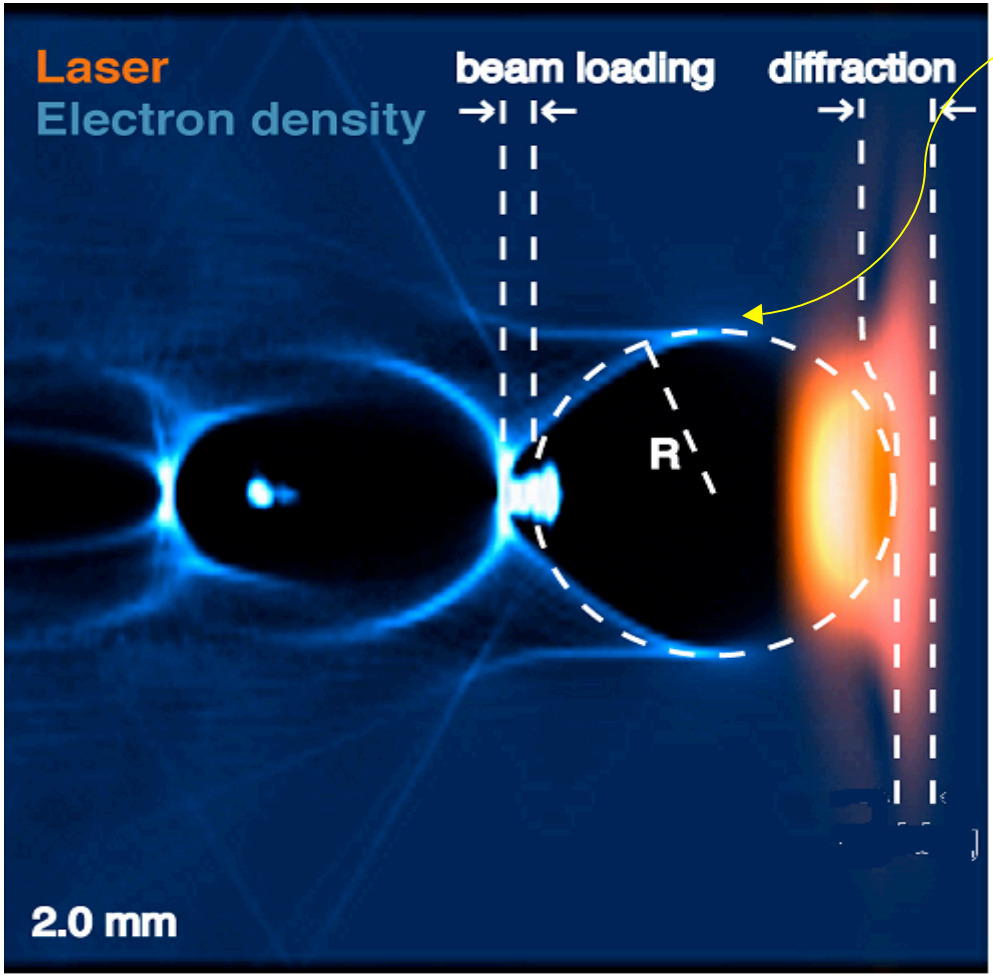
4) Relativistic wake plasma wave excitation by electron beam or short pulse laser



Maximum electric field of the plasma wave

$$\frac{E_{max}}{E_0} = \frac{n_b}{n_0}$$

Laser wakefield acceleration and ion channel formation in laser



Micro magnetosphere

Relativistic self focusing

Laser power, $P \geq P_{cr}$ where

$$P_{cr} = 17\left(\frac{\omega^2}{\omega_p^2}\right) \text{GW}$$

Relativistic dielectric constant

$$\varepsilon = 1 - \frac{\omega_p^2}{\gamma\omega^2}$$

Relativistic effect $\rightarrow \gamma$ increases

Ponderomotive effect $\rightarrow \omega_p^2$ decreases

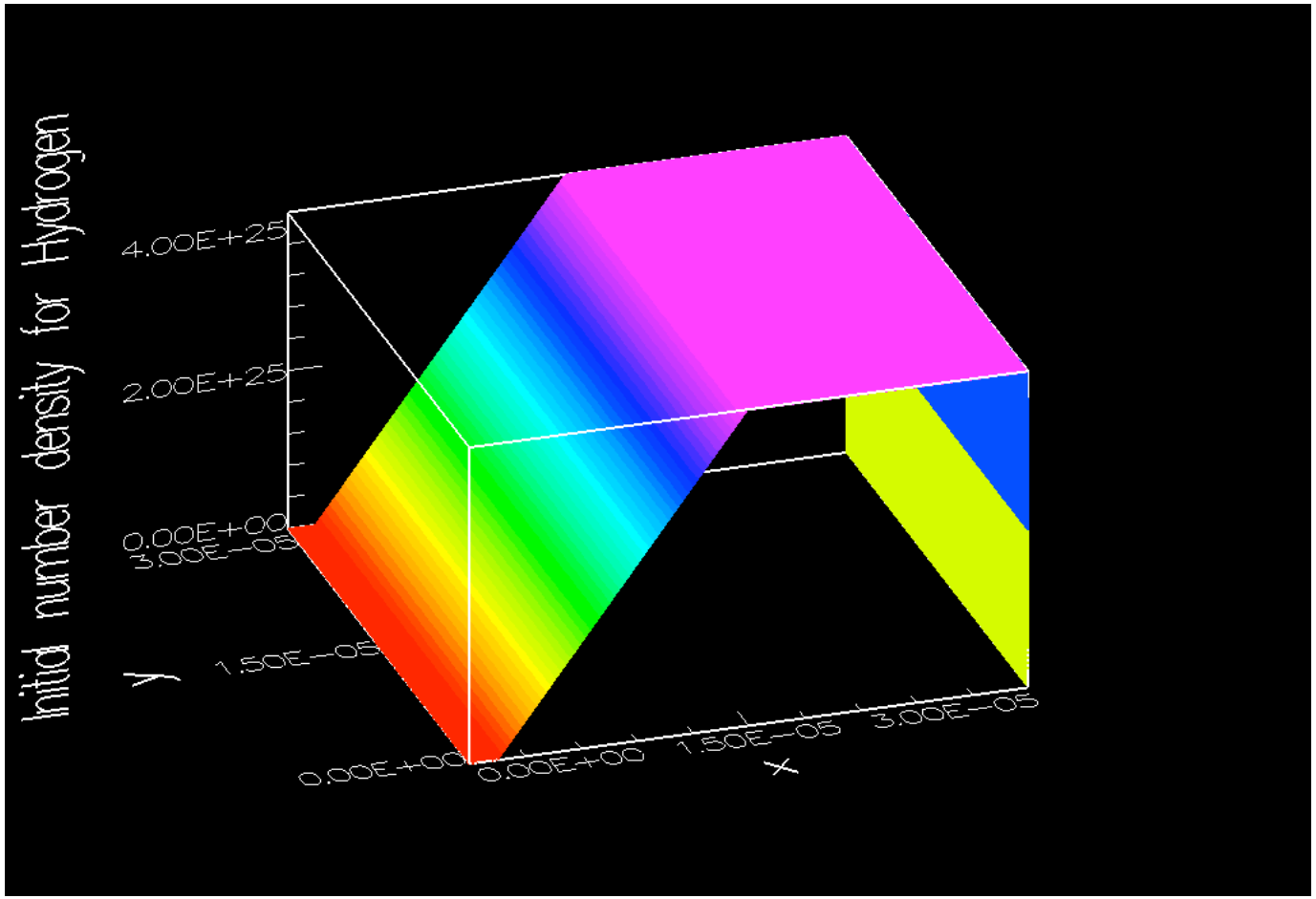
Resultant effect $\rightarrow$ ion channel formation

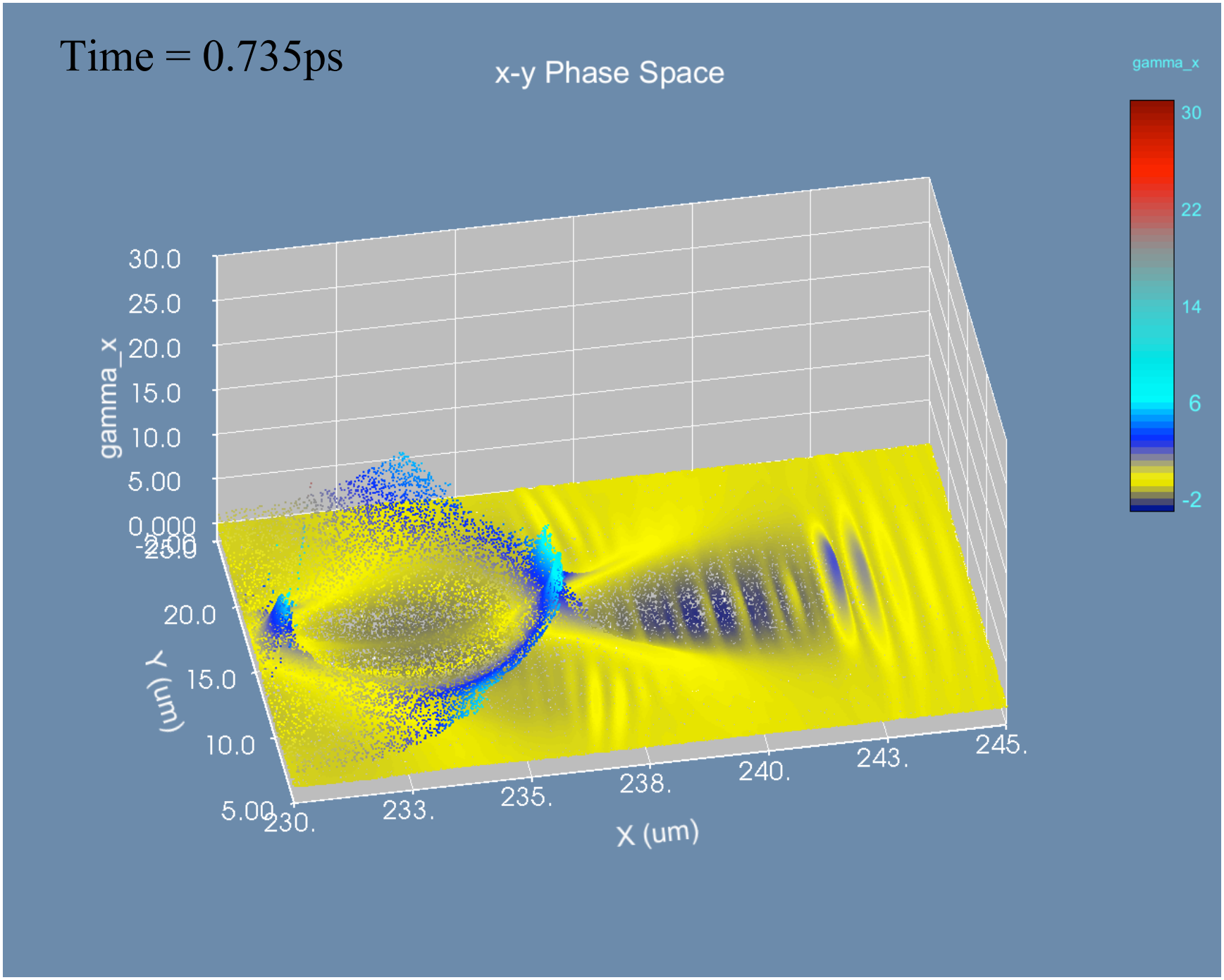
2D PIC Simulation of Injection and Acceleration of Mono-Energetic Electrons in a Laser Wake Field Accelerator by S. H. Chen and L. C. Tai

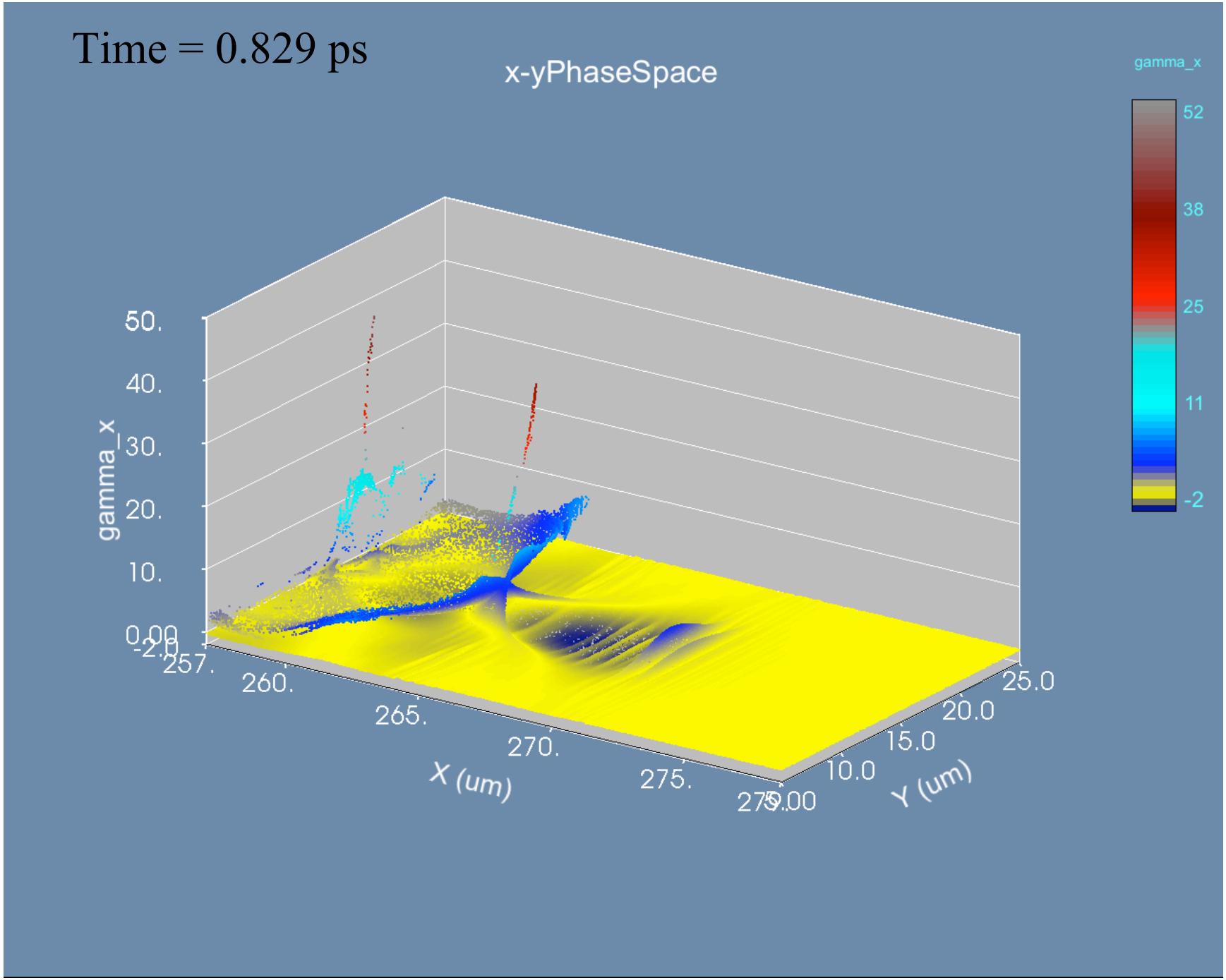
Academia Sinica

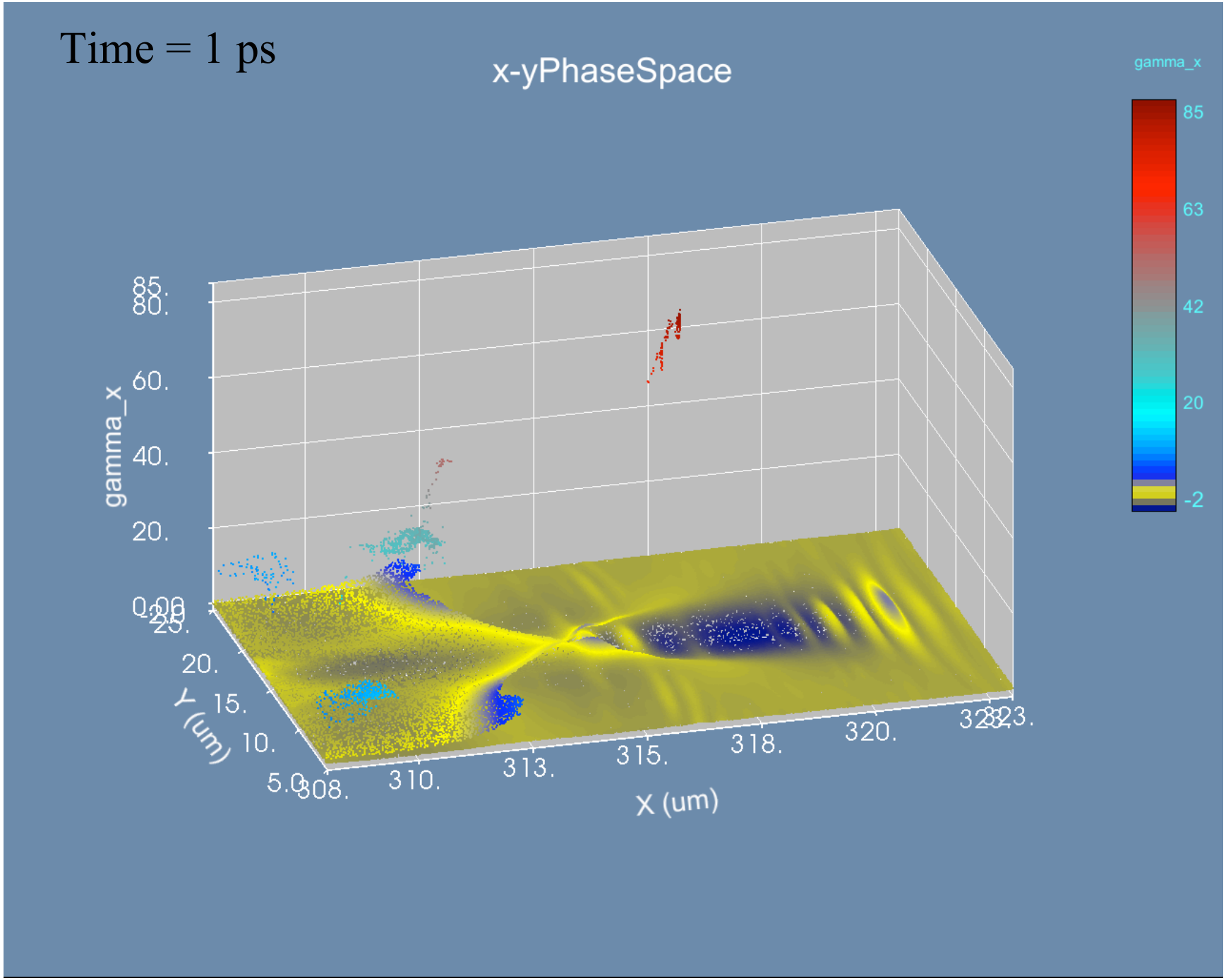
- Plasma Density = 4.0e25 m^-3
- Peak Laser Intensity = 8.0e+18 // W/cm
- Pulse Length (FWHM) = 45.0e-15 // s
- Laser Wavelength = 0.81e-06 // m
- Bandwidth = 0.027e-06 // m, for chirped pulse
- Waist Size = 4e-06 // m

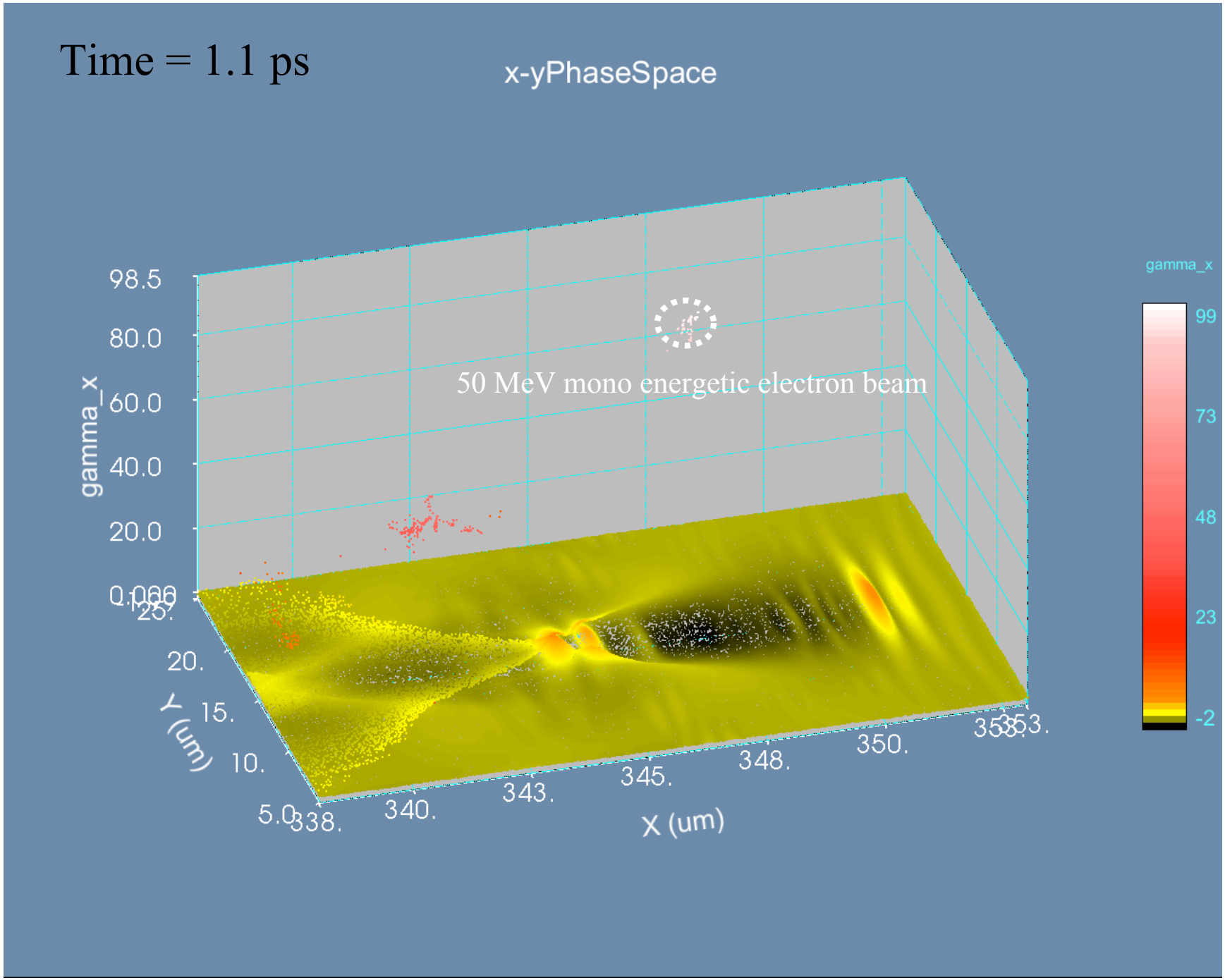
Initial Plasma Density




Time = 0.735ps
x-y Phase Space
gamma_x
30
22
14
6
-2
gamma_x
30.0
25.0
20.0
15.0
10.0
5.00
0.000
-25.0
Y (um)
20.0
15.0
10.0
5.00
230.
233.
235.
238.
240.
243.
245.
X (um)

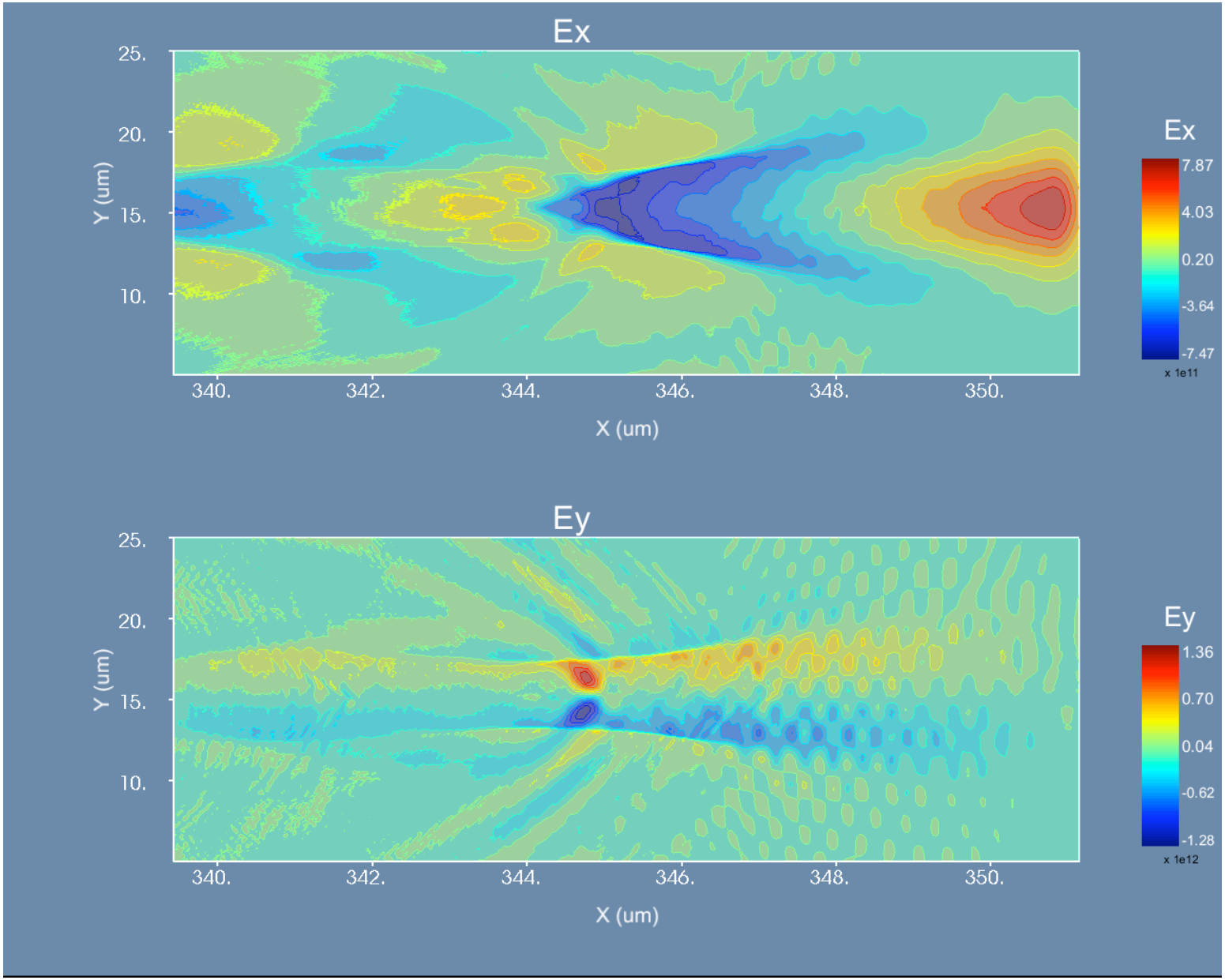

Time = 0.829 ps
x-yPhaseSpace
gamma_x
52
38
25
11
-2
50.
40.
30.
20.
10.
0.00
-2.0
gamma_x
257.
260.
265.
270.
275.
X (um)
0.00
10.0
15.0
20.0
25.0
Y (um)


Time = 1 ps
x-yPhaseSpace
gamma_x
85
63
42
20
-2
gamma_x
85.
80.
60.
40.
20.
0.00
25.
20.
15.
10.
5.0
Y (um)
308.
310.
313.
315.
318.
320.
323.
X (um)


Time = 1.1 ps
x-yPhaseSpace
50 MeV mono energetic electron beam
gamma_x
98.5
80.0
60.0
40.0
20.0
0.000
25.
20.
15.
10.
5.0
Y (um)
338.
340.
343.
345.
348.
350.
353.
X (um)
gamma_x
99
73
48
23
-2

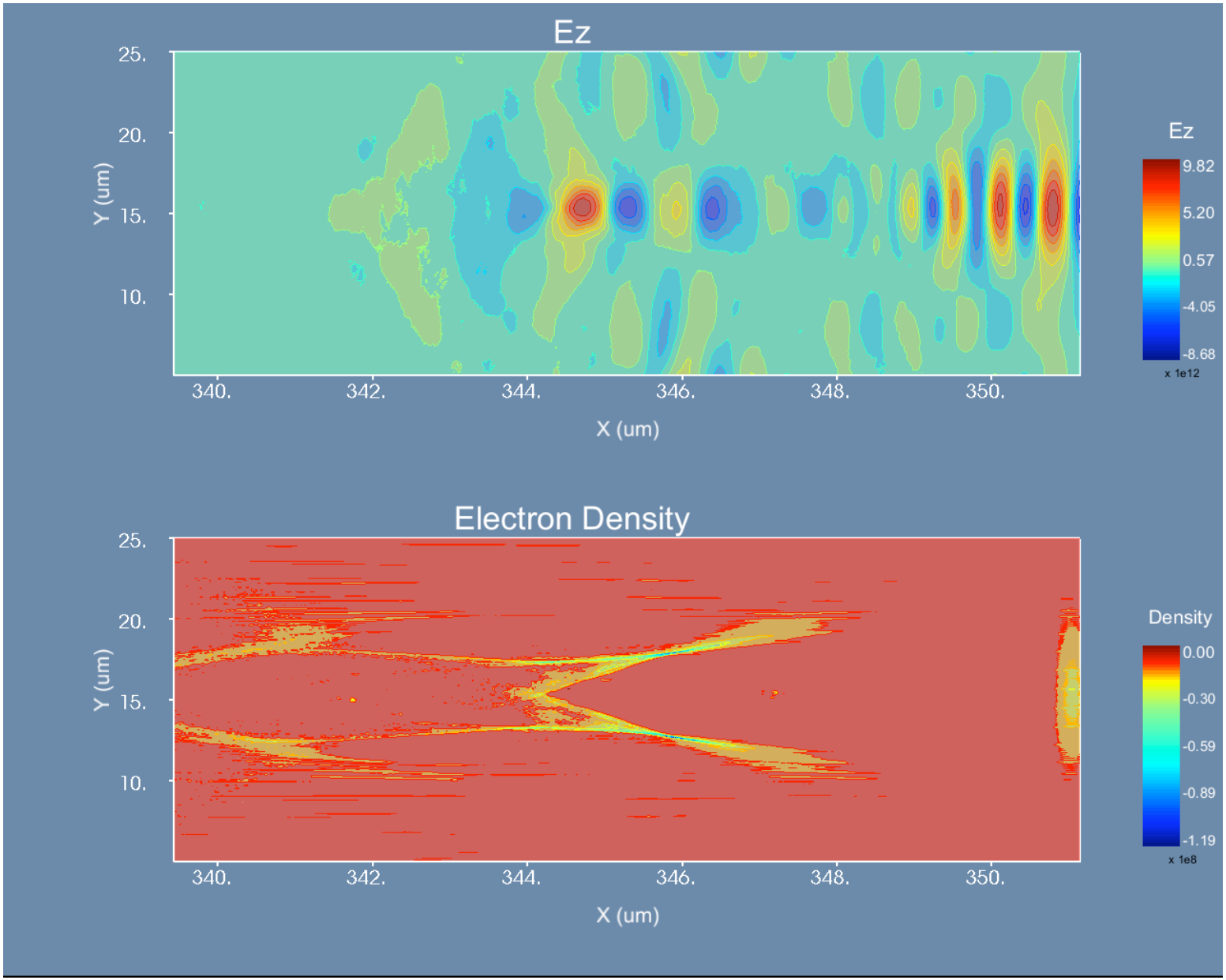
The wake field bunches the electrons in real space.

Time = 1.1 ps

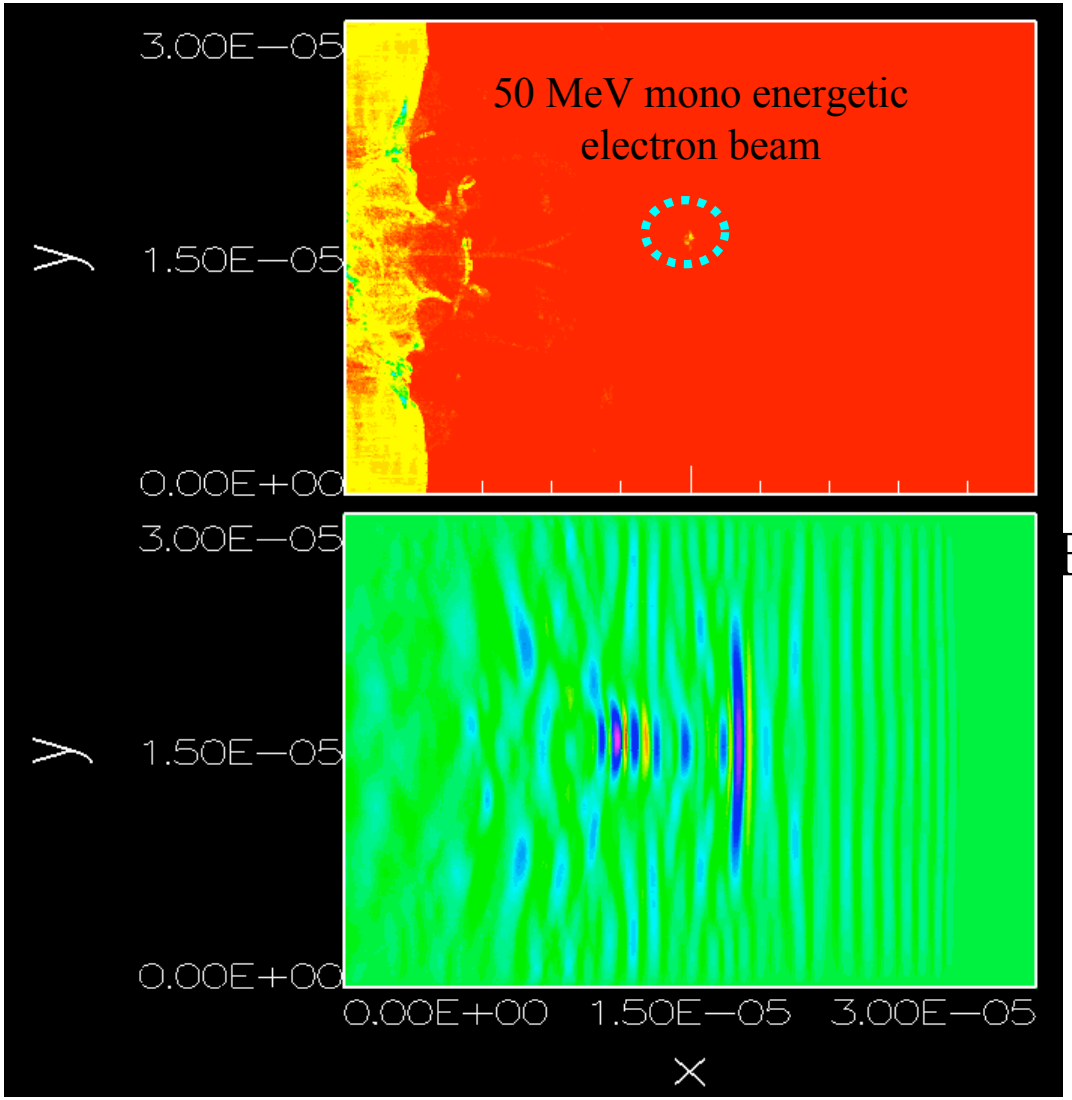


The modulated laser field traps electrons and push electrons moving with the laser pulse.

Time = 1.1 ps



The modulated laser field traps electrons and push electrons moving with the laser pulse.
(The plasma is turned off at time = 1.33 ps)



Time = 1.43 ps

E_z of laser pulse