Mono-energetic ion acceleration from a foil by a circularly polarized laser pulses

M. Chen[1], A. Pukhov[1], X.Q. Yan[2], Z.M. Sheng[3]

[1]Institut fuer Theoretische Physik I, Heinrich-Heine-Universitaet, 40225 Duesseldorf, Germany

[2]Max-Planck-Institut fuer Quantenoptik,D-85748 Garching, Germany

[3]Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China

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Outline

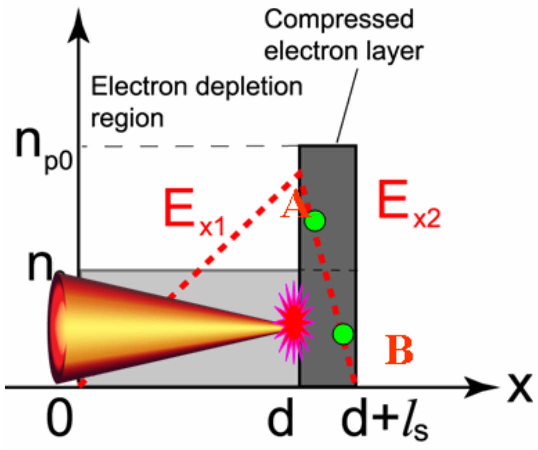
New recent theoretical progresses and their problems:

- Ion acceleration by use of circularly polarized laser pulse
- Multi-dimensional effects

Three possible solutions to the problems:

- Focusing by special laser modes
- Self-focusing of accelerated plasmas
- Shaped target

Ion acceleration by CP laser pulse interaction with foil

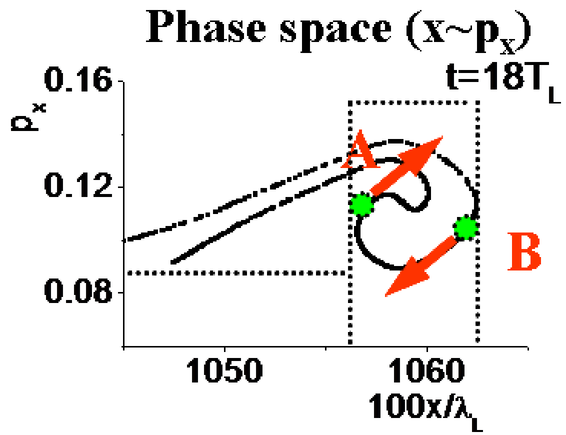


$$E_{x1} = E_0 x/d, (0 < x < d)$$

$$E_0 = 4\pi n_0 d$$

$$E_{x2} = E_0(1-(x-d))/l_s, (d < x < d + l_s)$$

$$\frac{dp}{dt} = \frac{E_L^2[t - x(t)/c]}{2\pi n_e l} |\rho(\omega')|^2 \frac{\sqrt{m_i^2c^2 + p^2} - p}{\sqrt{m_i^2c^2 + p^2} + p}$$



$$\ddot{\xi} = -\Omega^2 \xi, \qquad \Omega^2 = \frac{q_i E_0}{m_i l_s \gamma^3}$$

Rotating frequency in the phase space.

Rotation and condensation in phase space makes the mono-energetic character!!!

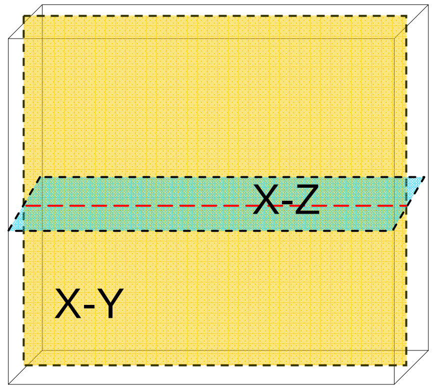
X.Q. Yan, *et al*., PRL 100, 135003 (2008);similar results can also be seen in: A.P.L. Robinson et al., New J. Phys. 10, 013021 (2008) and O. Klimo et al., PRSTAB 11, 031301 (2008)

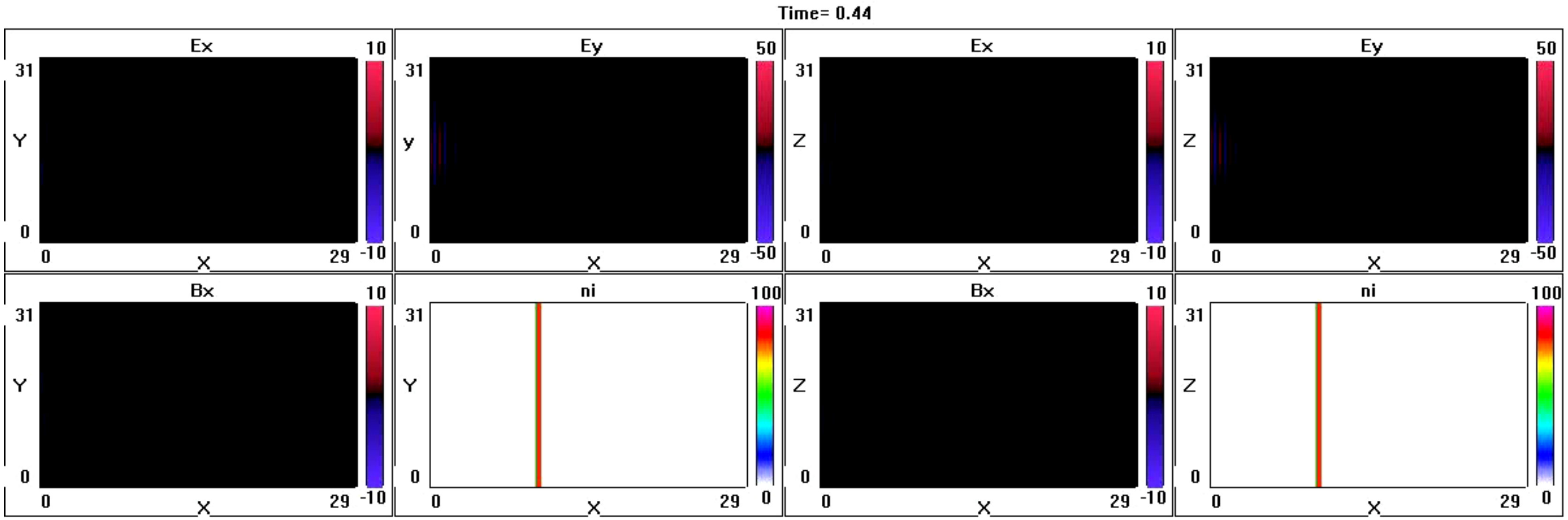
Multi Dimensional Effects

VLPL

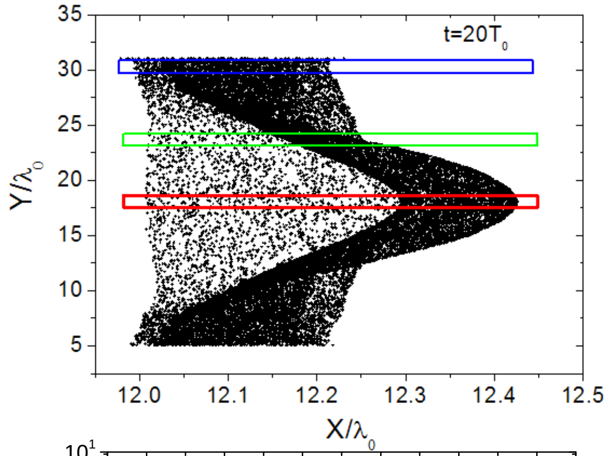
3D simulation :

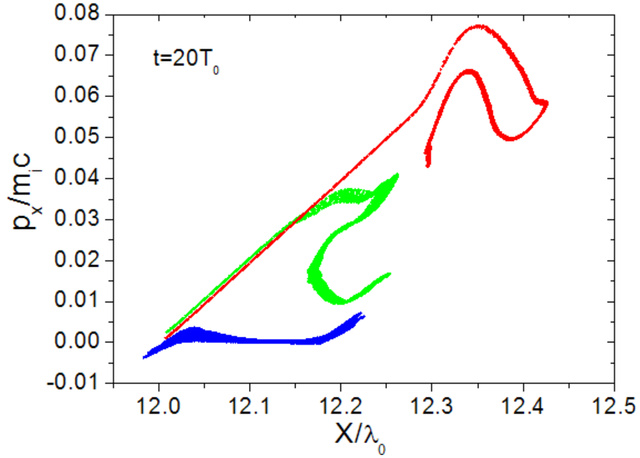
a=50, n/n_c=80, L=0.5λ, 26 T_L , w_r=5λ.

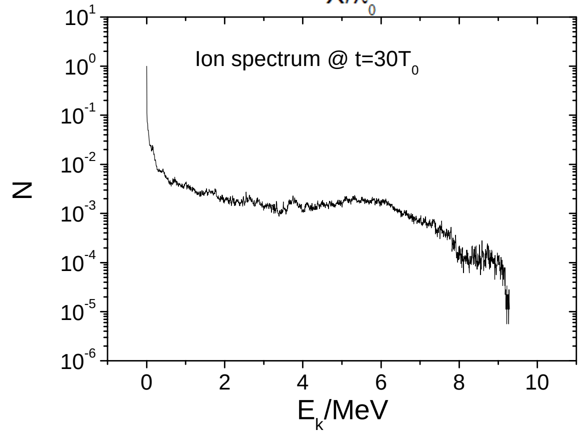




Multi Dimensional Effects







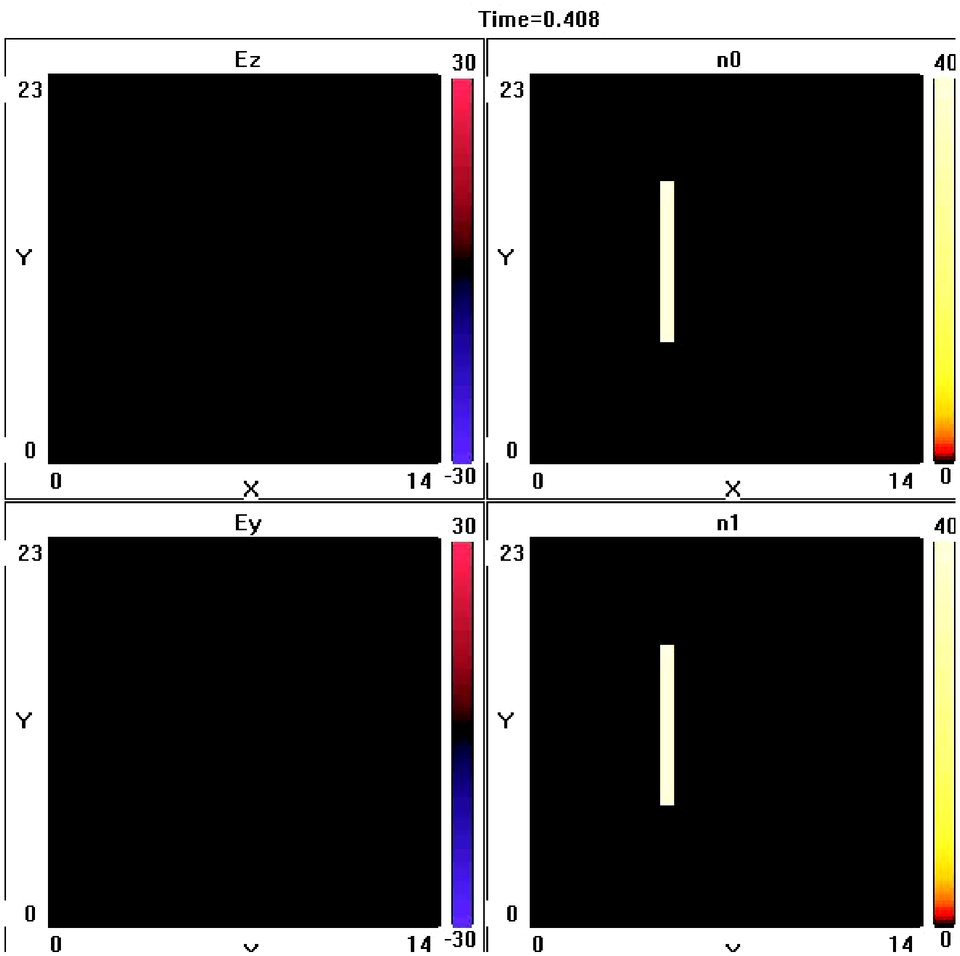
Potential problems:

- Target deformation and heating;
- Surface instability;
- Multi acceleration mechanism contribute!
- Mono-energetic character losing!

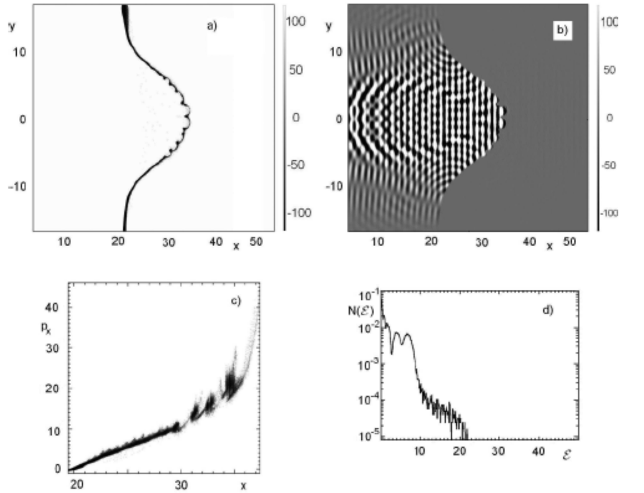
Since the target is not uniformly accelerated ($s(r) \propto I(r)t^2 \propto \exp(-r^2/r_0^2)t^2$), it is deformed and the laser pulse will laterally heat the electrons. The TNSA acceleration appears and later it broadens the final spectrum.

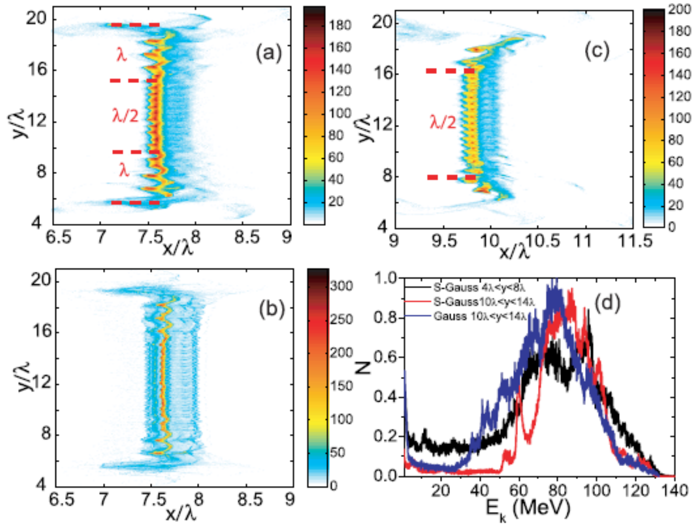
Super Gaussian pulse

VLPL



Instability break the acceleration structure



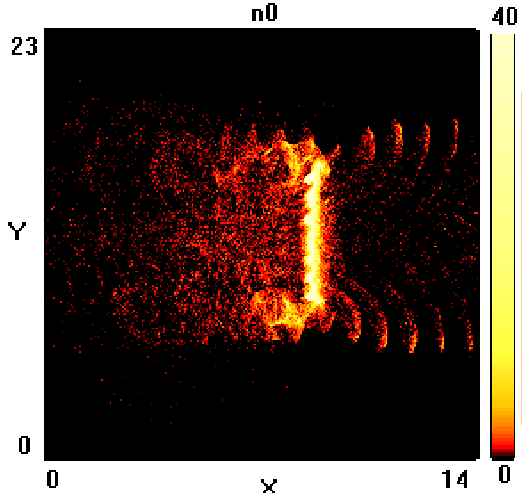


$$\frac{\partial p_x}{\partial t} = \frac{P}{n_0 l_0}\frac{\partial y}{\partial s}, \qquad \frac{\partial p_y}{\partial t} = -\frac{P}{n_0 l_0}\frac{\partial x}{\partial s},$$

$$y^1(y_0, \psi) \propto \exp[\Phi(\psi) - iky_0],$$

$$y^1 \propto \exp[(t/\tau_r)^{1/3} - iky_0]$$

$$\tau_r = \omega_0^{-1}(2\pi)^{3/2}R_0^{1/2}/(6k^{3/2}\lambda_0^2)$$



The modulation with period length of λ comes from the side boundary of the target. It transports to the center of the target and later will dominate. This makes target easily be heated.

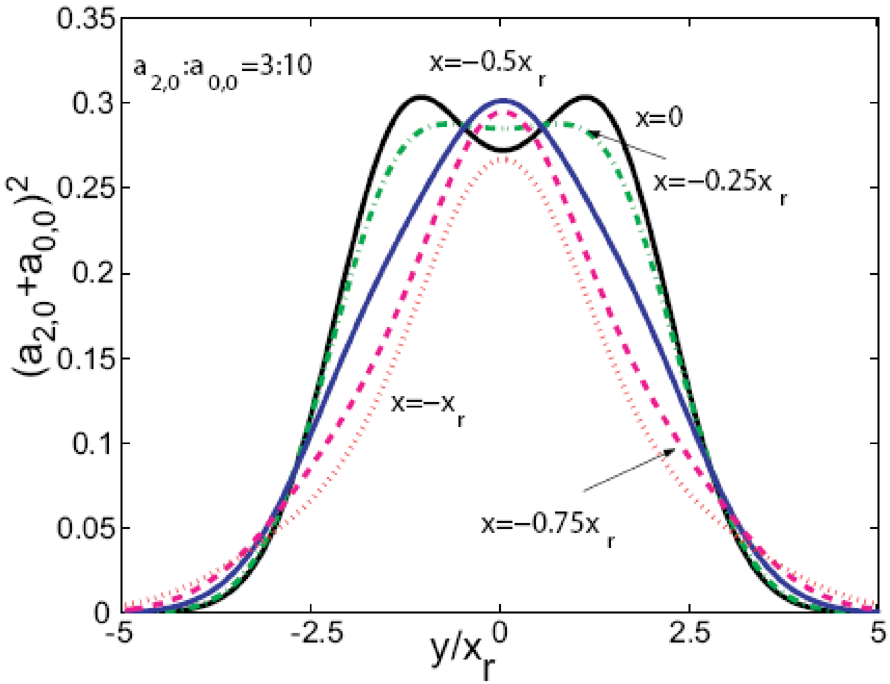
F. Pegoraro, S.V. Bulanov, PRL, 99, 065002

Possible resolutions 1

Using combined laser pulses whose centroid is moving

Tunable acceleration and focusing by special laser modes

Hermite laser pulse with mode (l,m)



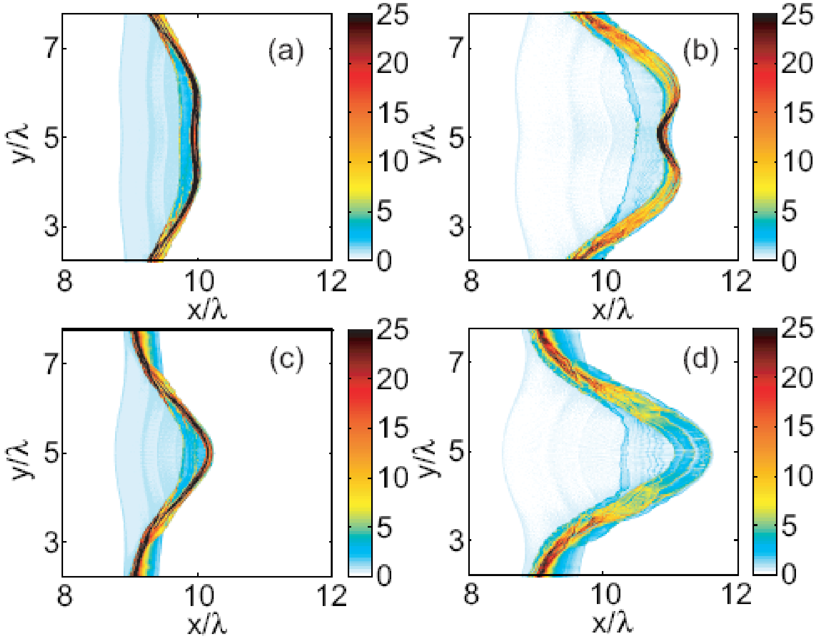
$$E^{l,m} = E_0^{l,m} H_l\left(\frac{y}{\sqrt{2}\sigma_\perp}\right) H_m\left(\frac{z}{\sqrt{2}\sigma_\perp}\right)\left(\frac{\sigma_{\perp 0}}{\sigma_\perp}\right)\exp\left[-\frac{r^2}{4\sigma_\perp^2} - \frac{(x-ct)^2}{4\sigma_z^2}\right]\sin\left[\omega t - kx + (m+n+1)\phi(x) + \phi_0 - \frac{kr^2}{2R(x)}\right]$$

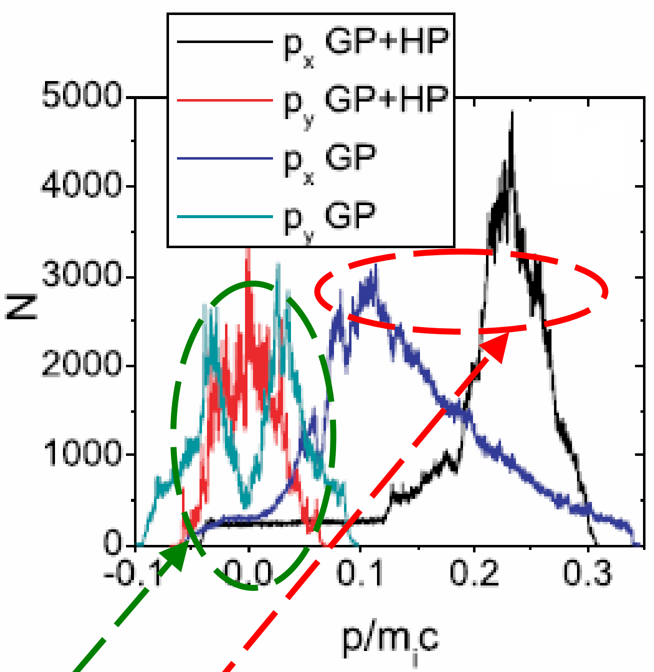
We take (2,0) and (0,0) modes and set $a_{(2,0)}:a_{(0,0)}$=3:10. The figure shows the transversal intensity profile of the combined laser pulses at different distance from the focus plane. Pulse centroid moves in the transverse plane.

Following we show some of our preliminary results.

Ion collimation and energy increase

2D simulation: $a=9$, $n/n_c=25$, $L=0.2\lambda$, $w_r=2\lambda$.



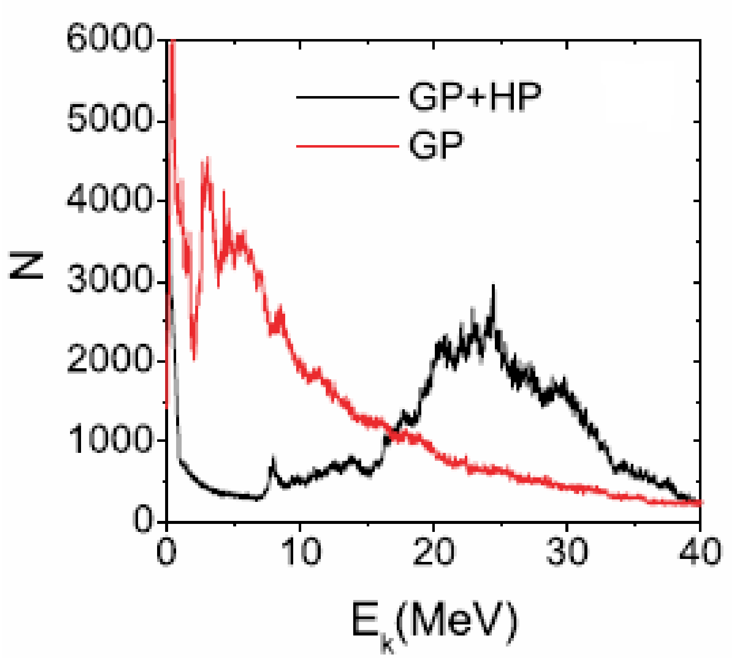


Ion density distribution at $t=20T_0$ and $t=25T_0$. (a,b) combined laser modes are used; (c,d) only Gaussian pulse is used.

Longitudinal and transversal momenta distribution for the two conditions at $t=25T_0$.

1. Transversal momenta are reduced in the combined laser modes case, which makes the ion beam to be collimated.
2. Peak value of longitudinal momenta has been increased.

Energy Spectrum



Energy Spectrum of the accelerated ions at t=25T_0.

Tunable parameters:

1. a(0,0):a(2,0), decides the intensity concave depth;
2. wr(0,0):wr(2,0), decides the intensity concave width;
3. Target position, decides the acceleration and focusing distance.
4. By optimization, the results should be much better.

Possible resolutions 2

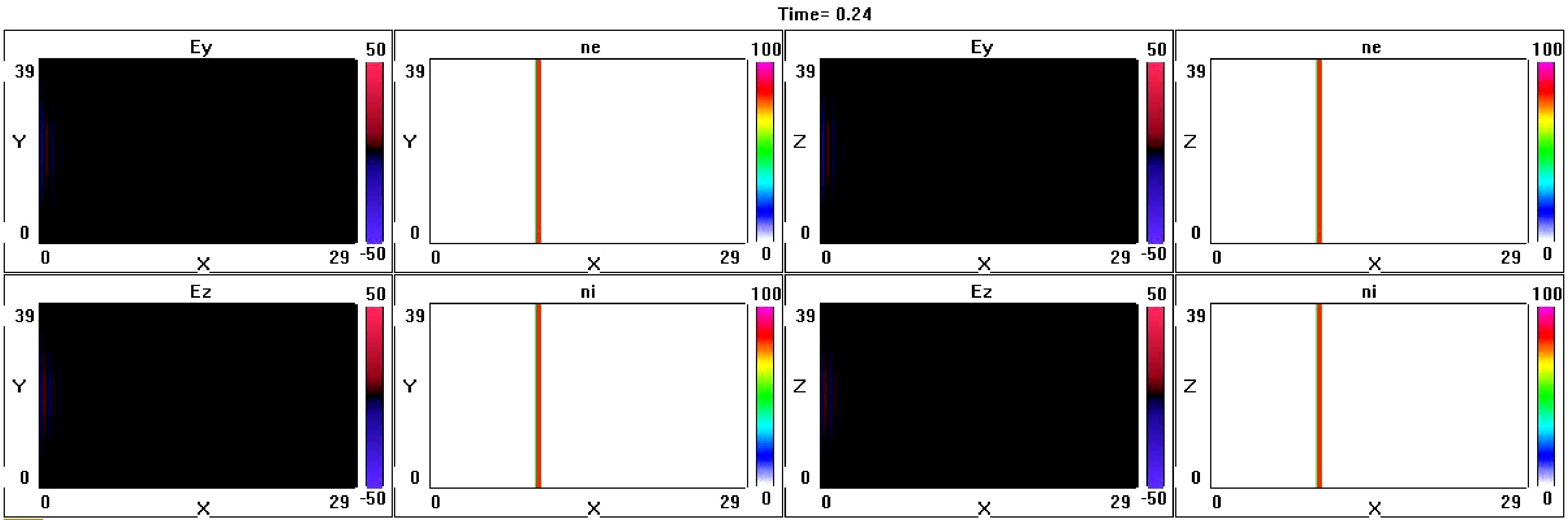
Optimize laser width

Self focusing of accelerated plasmas

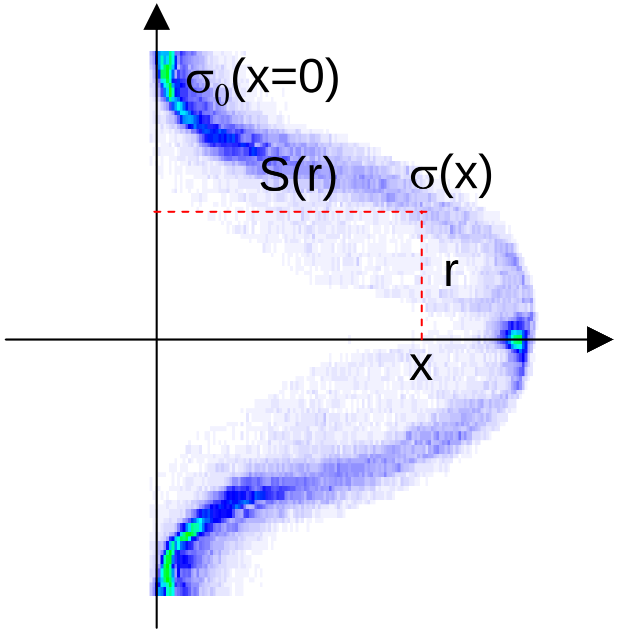
Self focusing of accelerated plasmas

3D simulation:

a=50, n/n_c=80, L=0.5λ, 26 T_L , w_r=10λ.



Possible mechanisms



$$x(r) \propto \frac{I}{n_0 m_i d c} t^2 \propto \alpha t^2 e^{-r^2/r_0^2}$$

$$\sigma(x,r) = \sigma_0(r) / \sqrt{1 + 4r^2 x^2(r) / r_0^4}$$
$$= \sigma_0(r) / \sqrt{1 + 4r^2 \alpha^2 t^4 e^{-2r^2/r_0^2} / r_0^4}$$

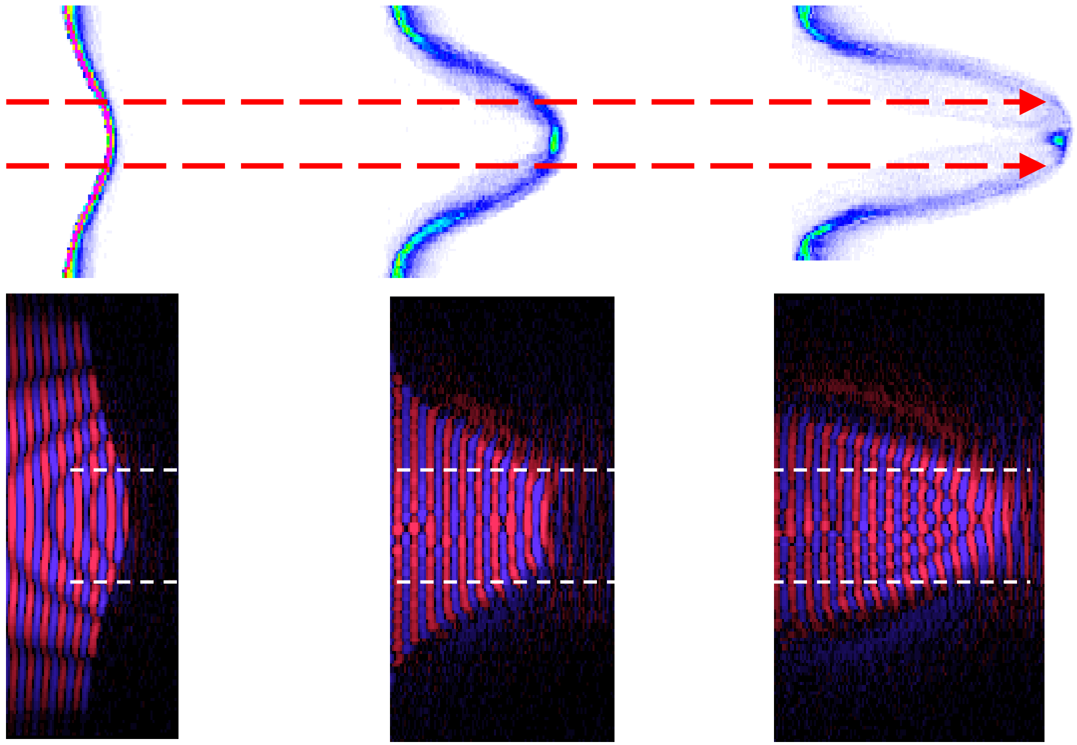
$$r = r_0 / \sqrt{2}, \sigma = \sigma_{\min}$$

1. Ion acceleration, target deformation
2. Instability makes the density clumps
3. Density reduces, target becomes transparency, laser front evolves
4. Ion focusing

Possible mechanisms

1. One possible reason is due to self-generated magnetic fields because of Weibel instabilities.
2. The other possible reason is due to **pulse front self-evolution**.

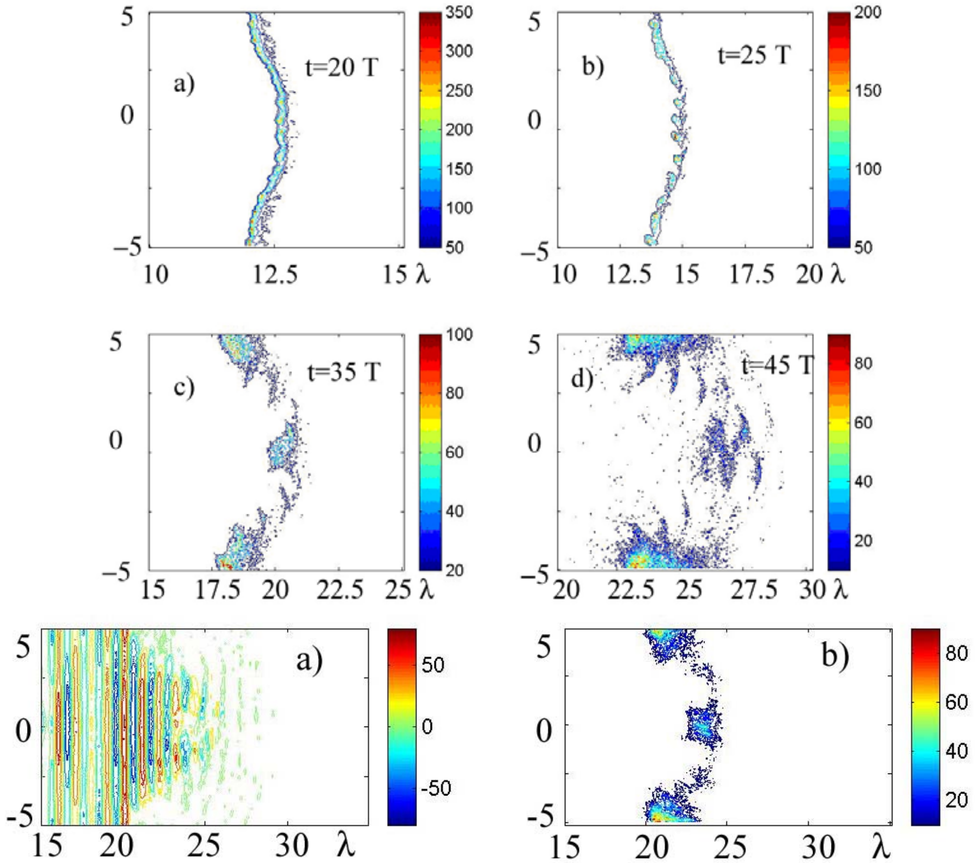
Target acceleration, broken and density decreasing!

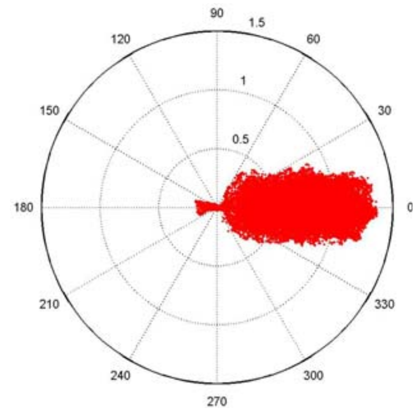


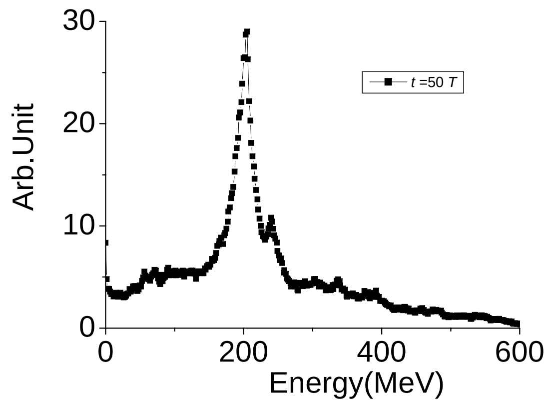
Pulse front evolution: Broaden and curvature changes!

Energy spectrum and dispersion angle

2D simulation: a=50, n/n_c=80, L=0.5λ, 26 T_L , w_r=10λ.







X.Q. Yan, M. Chen, Z.M. Sheng *et al*., submitted

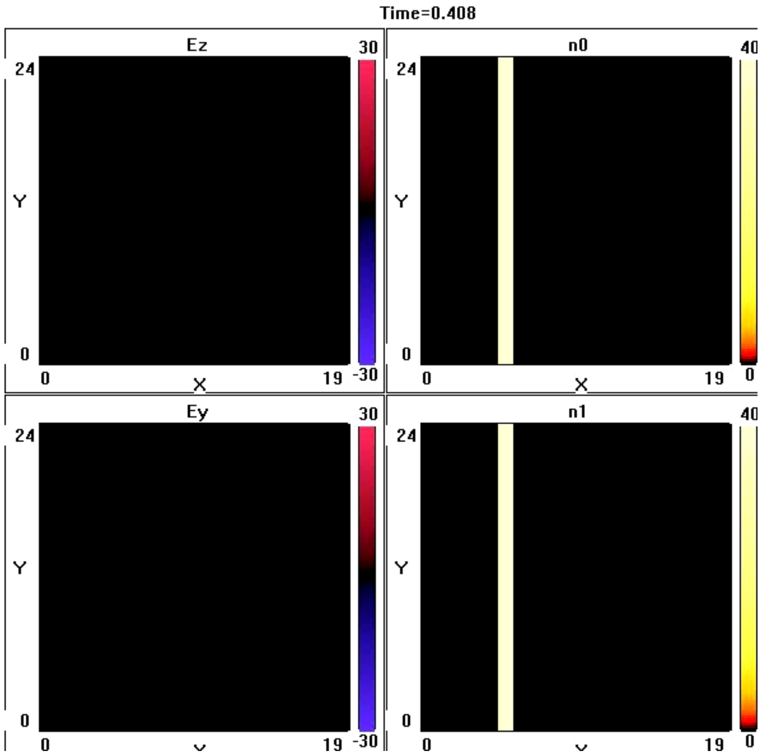
Shaped Target

VLPL

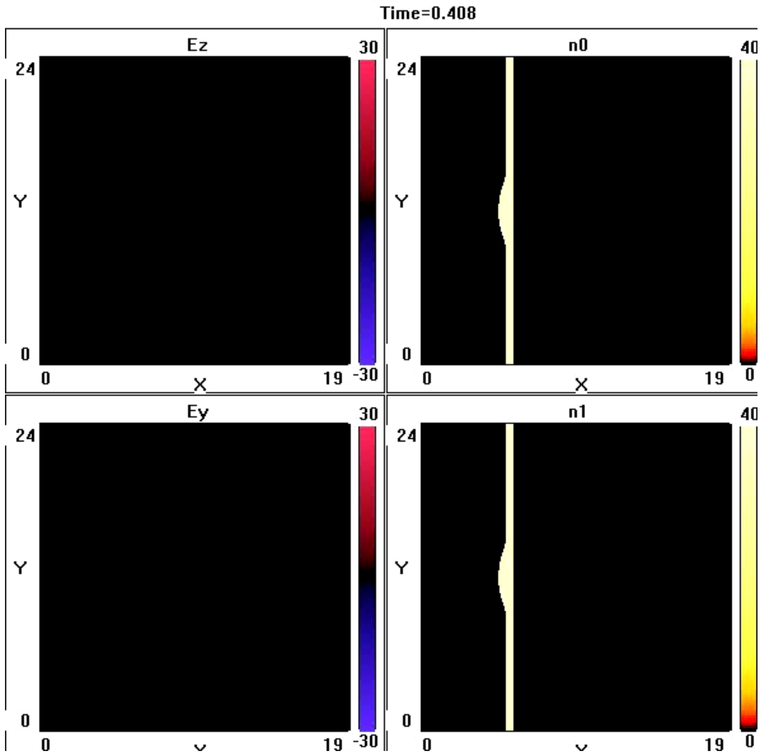
According to the transverse intensity profile of the incident laser pulse, we modify the target shape to be sure the acceleration in the different target region the same.

Gaussian pulse → Thickness distribution with Gaussian profile;

Super Gaussian pulse → Flat target.



Flat target



Shaped target

Summary:

- Multi dimensional effects during the CP laser interaction with foil targets have been checked.
- Super Gaussian pulse can partly solve the above problems.
- By use of combined laser modes, pulse centroid moves in the transverse plane which makes the ion acceleration and focusing tunable.
- In some conditions, self-focusing of accelerated plasmas happens due to the self evolution of the pulse front and self-generated magnetic fields.
- Shaped target can make uniform acceleration of the target, suppress the target deformation and heating, keep the acceleration structure for a long time.


Thanks for your attention!