International Conference on Ultrahigh Intensity Lasers

Efficient monoenergetic ion acceleration with electrostatic shock

Baifei Shen, Xiaomei Zhang and Liangliang Ji

Shanghai Institute of Optics and Fine Mechanics (SIOM),
CAS, China

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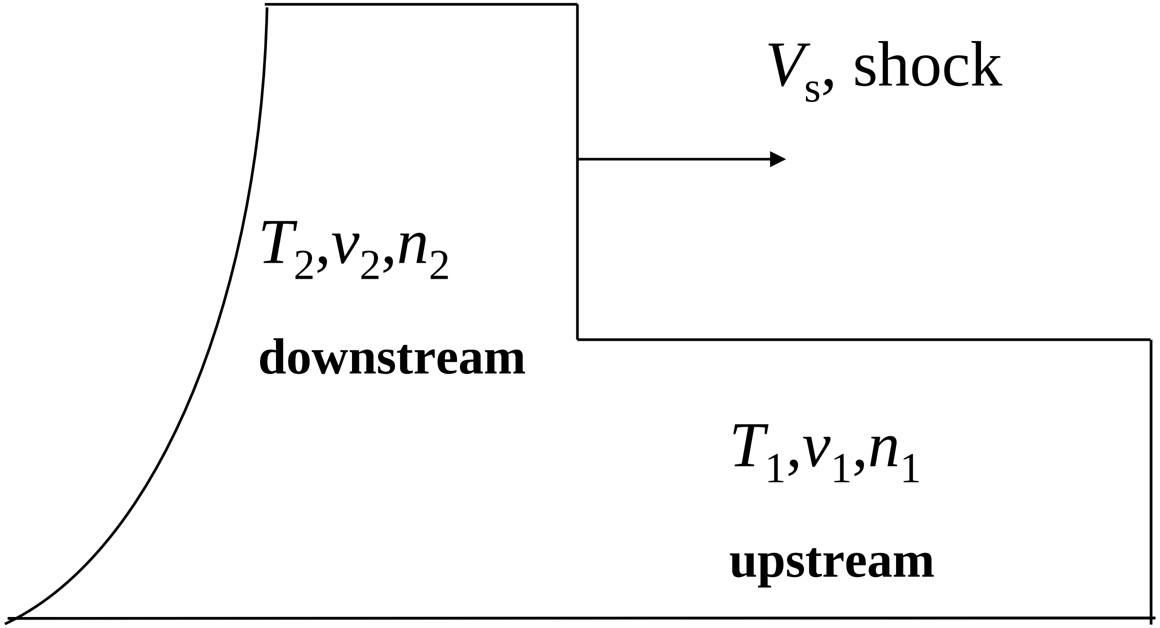
Outline

- When ions can be accelerated by an electrostatic shock?
- Shock acceleration by circularly polarized laser pulses
- Multi stage acceleration by shock and light pressure acceleration
- Quasi monoenergetic heavy ion beam accelerated by electrostatic shock

When ions can be accelerated by an electrostatic shock?

What is a shock?

A shock wave (or simply "shock") is a type of propagating disturbance. Shock waves are characterized by an abrupt, nearly discontinuous change in the characteristics of the medium. Across a shock there is always an extremely rapid rise in pressure, temperature and density of the flow.



We suppose $T_i=0<<T_e$ with T_e constant . If the quasi neutrality condition $N=N_i=N_e$ is satisfied, we have

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}(NV)=0$$

one-dimensional continuity equation

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}=-\frac{1}{NM}\frac{\partial}{\partial x}(NKT_e)$$

momentum equation

$$P=NKT_e$$

thermal pressure

If the charge neutrality condition breaks down,

Equations for electrons

$$\frac{d}{dt}(m\gamma\mathbf{v}) = -e[\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}] - \frac{1}{n_e}\nabla P$$

$$\mathbf{P}_c = m\gamma\mathbf{v} - (e/c)\mathbf{A}$$

$$= e[\frac{\partial\mathbf{A}}{\partial t} + \nabla\Phi - \mathbf{v}\times(\nabla\times\mathbf{A})] - T_e\nabla(\ln n_e)$$

$$\mathbf{P}_c = \nabla\Psi$$

$$\gamma\mathbf{v} = \mathbf{a} + \nabla\Psi$$

$$\frac{\partial\Psi}{\partial t} = \gamma - \phi - 1 + T_e\ln(n_e/n_0)$$

$$\gamma = \sqrt{1 + (\mathbf{a} + \nabla\Psi)^2}$$

If the forces on electrons are balanced,

$$\nabla\gamma = \nabla\phi - \frac{T_e}{n_e}\nabla n_e$$

If the charge neutrality condition breaks down,

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}(NV)=0$$

$$\frac{\partial E}{\partial x}\equiv-\frac{\partial^2\phi}{\partial x^2}=4\pi e(N-N_e)$$

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}=-\frac{e}{M}\frac{\partial\phi}{\partial x}$$

$$N_e=N_1e^{e\phi/KT_e}$$

Electrons react very quickly.

D. A. Tidman and N. A Krall, Shock waves in collisionless plasmas (Wiley-Interscience, New York, 1971).

Setting $\partial / \partial t = 0$,

$$NV = N_1 V_1 \qquad \frac{1}{2} M V_2{}^2 + e\phi = \frac{1}{2} M V_1{}^2$$

$$-\frac{\partial^2 \phi}{\partial x^2} = 4\pi e N_1 \left\{ \frac{V_1}{\left(V_1{}^2 - \frac{2e\phi}{M} \right)^{1/2}} - e^{e\phi / KT_e} \right\}$$

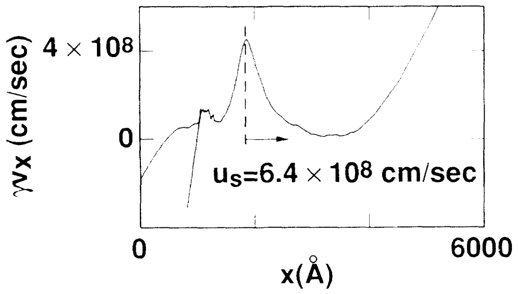
The physical solutions exist only when the Mach number

$$\mathrm{M} \equiv \frac{V_1}{(KT_e / M)^{1/2}} < 1.6$$

What happens if the Much number is larger than 1.6 ?

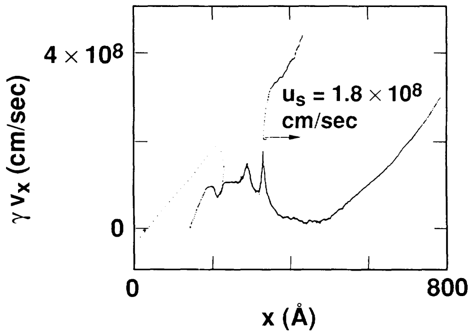
Some or all ions will reflect from the electrostatic filed. So ions may be accelerated this way.

Electrostatic shock driven by a linearly polarized laser pulse. When the Much number is larger than 1.6, ions are reflected.



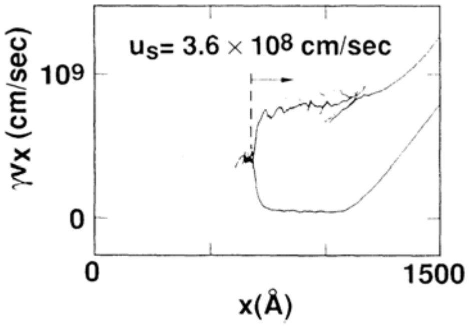
$I = 6.2\times10^{19}$ W/cm^2
$n_e/n_c = 24.$

M<1.6



$I = 10^{20}$ W/cm^2
$n_e/n_c = 390$

M=1.6



10^{21} W/cm^2
$n_e/n_c = 390$

M>1.6

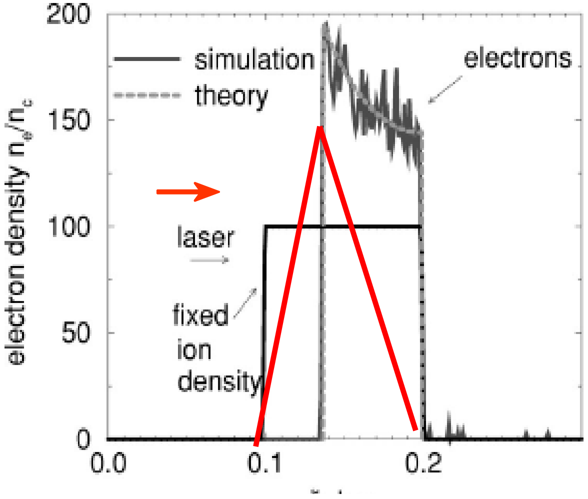
Ion phase plane for different simulation parameters.
Wavelength 0.8 μm, the thickness of the foil 60 nm.

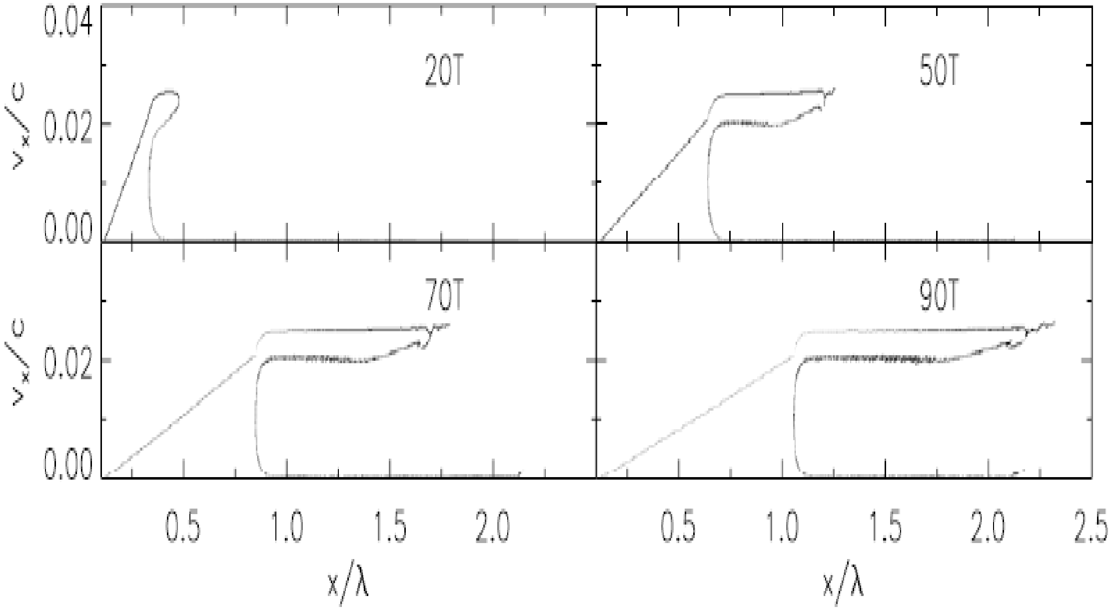
J. Denavit, Phys. Rev. Lett. 69, 3052 (1992)

Shock acceleration by circularly polarized laser pulses

Shock acceleration by a circularly polarized laser pulse

All ions are accelerated to the velocity of double shock velocity by the quasi stable electrostatic field.





Two flat-top structure in phase plane.
The ions on the higher flat are initially on the left of the electron layer.

$$E_z = -\partial\gamma/\partial\xi = [(2W + 2N_i\gamma - \gamma^2)(\gamma^2 - 1) - M^2]^{1/2}$$

$M=0$, $W=1/2-N_i$

Zhang et. al., Physics Letters A, 369,339（2007）.

The velocity of the electrostatic shock

$$\left.\begin{array}{l} 2a^2 dt = n_i m_i v_i dx \\ v_s = \dfrac{dx}{dt} \\ v_i = 2v_s \end{array}\right\} \quad v_s = \sqrt{\frac{1}{m_i}\frac{1}{n_i}}\,a.$$

For relativistic electrostatic shock,

$$I/c=-(1-\eta)I/c+n_i\gamma m_i v_s v_i,$$ **conservation of momentum**

$$I=(1-\eta)I+n_i(\gamma-1)m_i v_s c^2,$$ **conservation of energy**

$$\gamma=1/\sqrt{1-v_i^2} \qquad \eta=n_i v_s(\gamma-1)m_i/a^2$$

$N=n_\mathrm{i}v_\mathrm{s}$ **is the number of ions**

$$2a^2-n_i m_i v_s(\gamma-1)=n_i m_i v_s\gamma v_i,$$

The momentum and energy of electrons are neglected.

Because $$v_i = \frac{2v_s}{1+v_s^2},$$

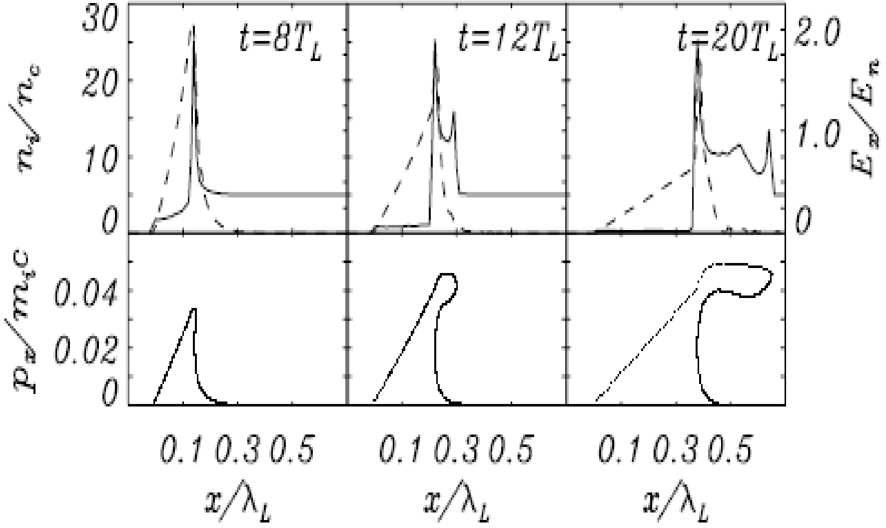
$$v_s = \frac{-\frac{a^2}{n_i m_i} + \sqrt{\left(\frac{a^2}{n_i m_i}\right)^2 + \frac{4a^2}{n_i m_i}}}{2}$$

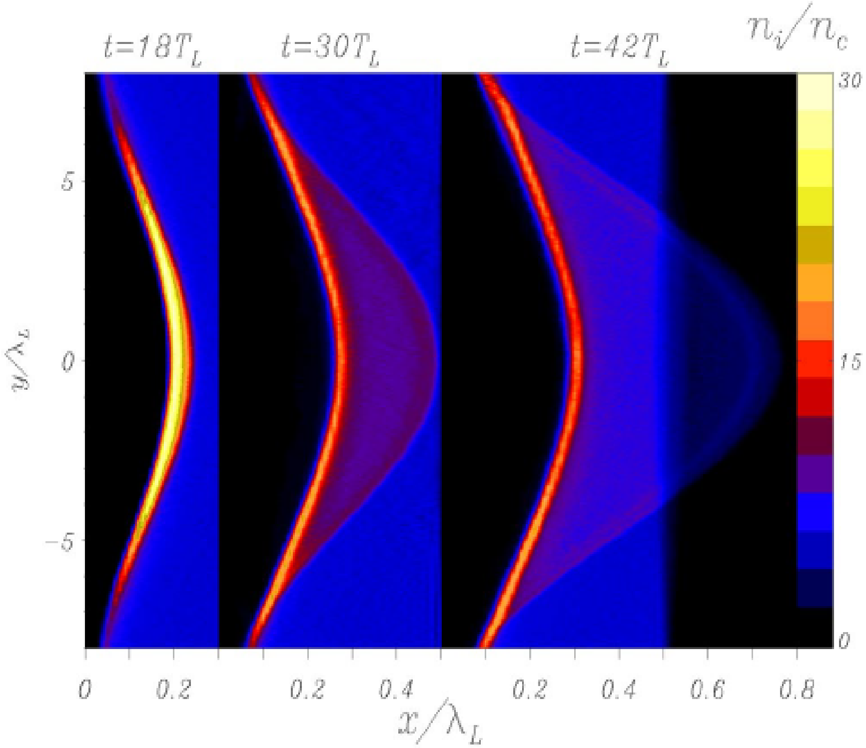
If $\gamma_s \ \square\ 1$ $$\gamma_s = a/\sqrt{2 n_i m_i}$$

$$v_s = \sqrt{\frac{1}{m_i}\frac{1}{n_i}}a.$$

Two dimensional simulation for ion acceleration by circularly polarized laser driven electrostatic shock

Simulation parameters： *the laser pulse rises from 0 to a*=2 in 5T, then keeps constant, $n_0 = 5n_c$, $T_i = T_e = 0$.

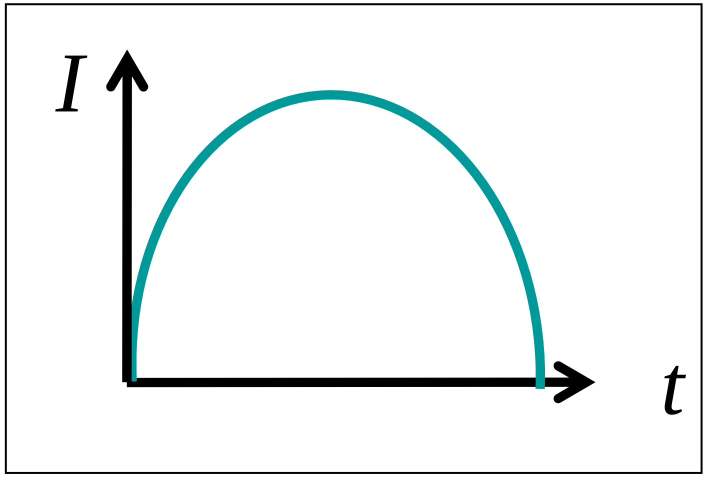


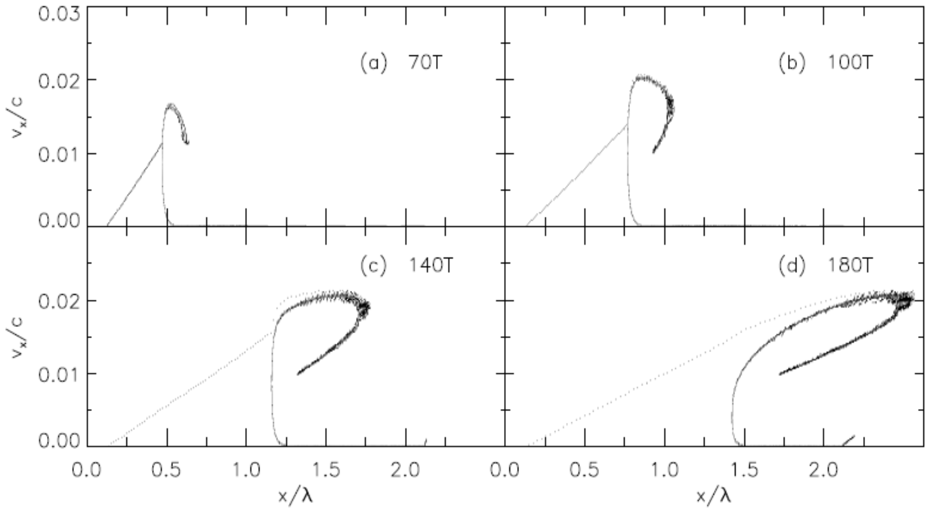


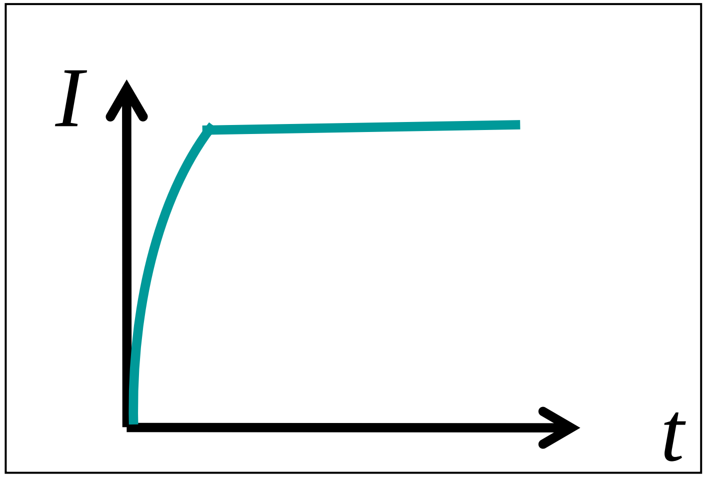
$$\frac{v_a}{c} = \sqrt{\frac{Z}{A}\frac{m_e}{m_p}\frac{n_c}{n_e}}a_L$$

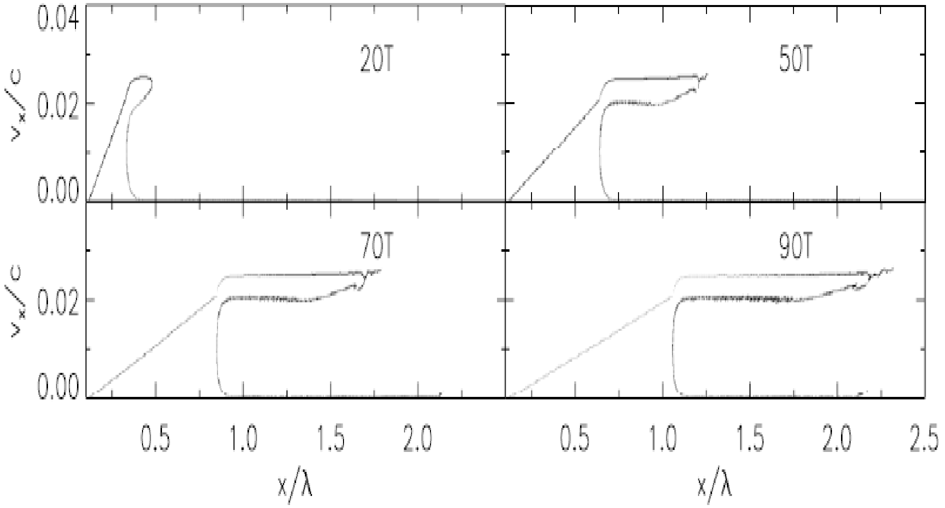
A. Macchi, PRL 94, 165003(2005)

The effect of the shape of the laser pulse









The effect of the plasma temperature on shock acceleration

theory

- **Hamiltonian for ions with** $\xi = x - u_s t$

$$H_0 = \sqrt{m_i^2 c^4 + p_x^2 c^2} - u_s p_x + e\phi(\xi).$$

- **Ion momentum：**

$$p_x = \frac{u_s\left(h_0 - \beta\phi(\xi)\right) \pm \sqrt{\left(h_0 - \beta\phi(\xi)\right)^2 - \left(1 - u_s^2\right)}}{1 - u_s^2},$$

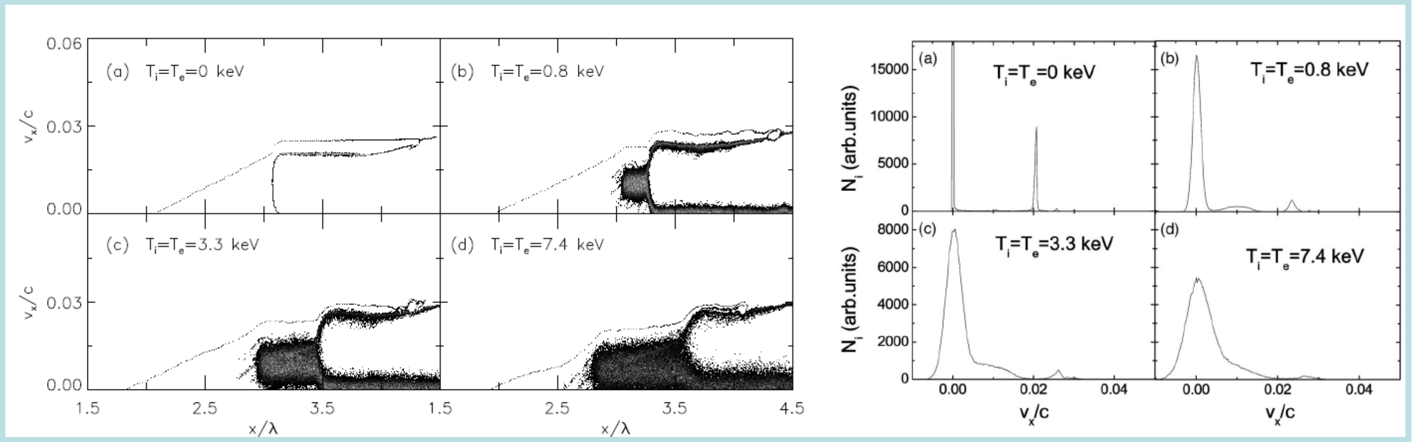
- **If ions are fixed， the balance of lighter pressure and electrostatic force gives**

$$E_x = -\frac{\partial\phi(\xi)}{\partial\xi} = (\gamma - 1)\left[(\gamma + 1)(2n_0 - \gamma - 1)\right]^{1/2},$$

- **Here**

$u_s \square \sqrt{a^2/(M_i N_i)}$ $p_x / m_i c \to p_x$ $\phi(\xi)/m_e c^2 \to \phi(\xi)$ $\beta = m_e / m_i$

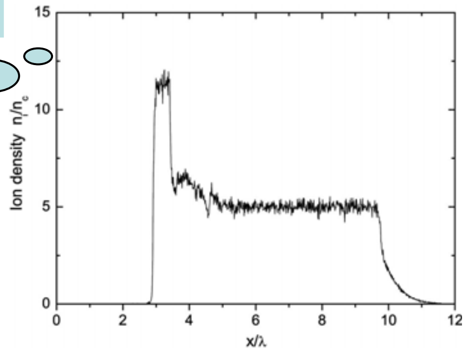
The effect of the plasma temperature on shock acceleration



the laser pulse rises from 0 to a=1 in 5T, then keeps constant, $n_0=5n_c$,

At time t=100T, ion distribution in phase plane and energy spectrum for different background ion temperature.

Density distribution of ion for $T_i=T_e=3.3$keV

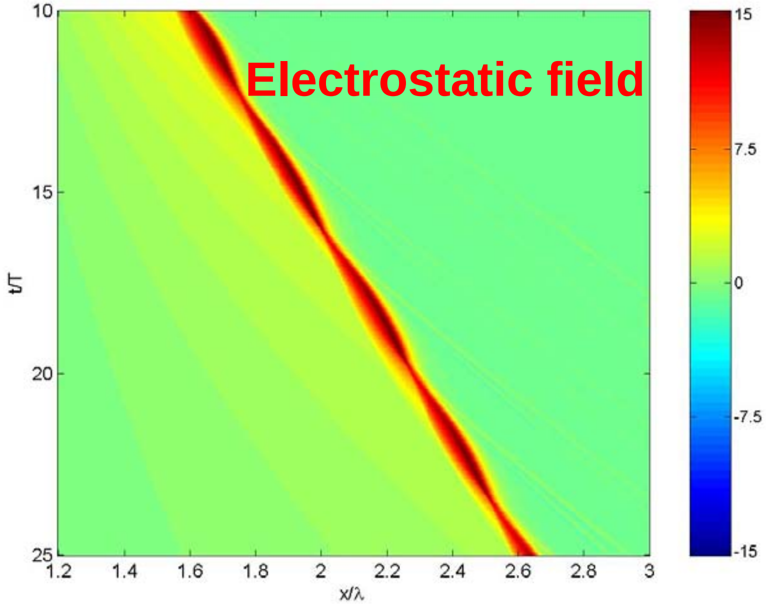


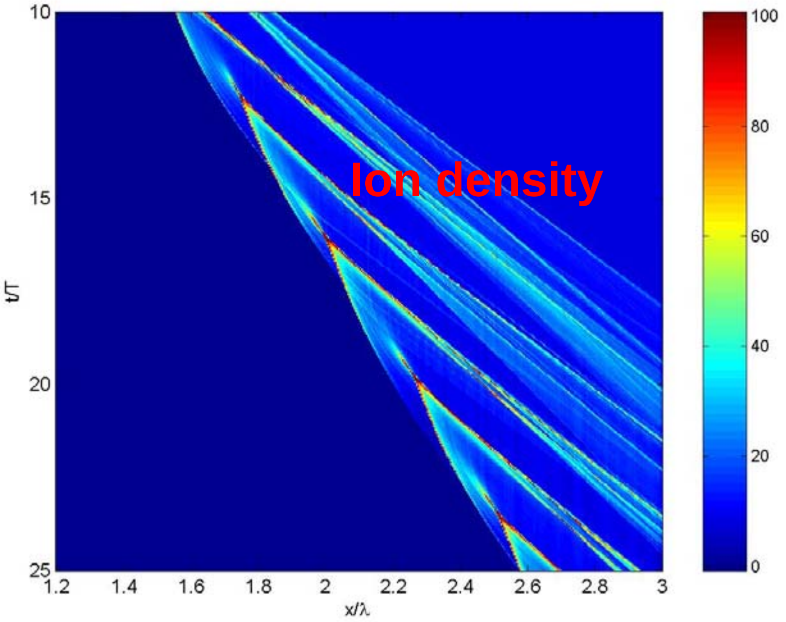
- **When background ion temperature is low, most ions are reflected from the shock. Only few ions go through the shock.**
- **When background ion temperature is high, many ions go through the shock.**
- **In order to obtain mono-energetic ion beam, the initial ion temperature should be low.**

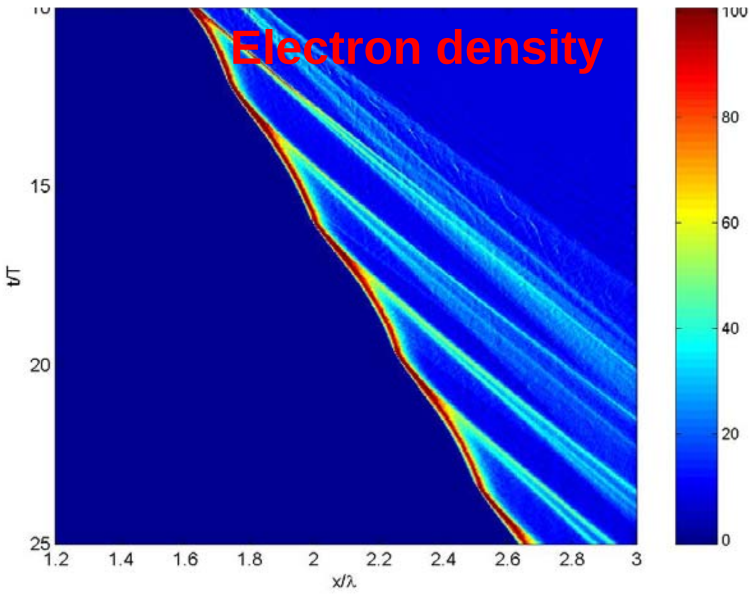
Zhang et. al., Physics of Plasmas, 14 113108（2007）

The oscillation structure when laser intensity is larger

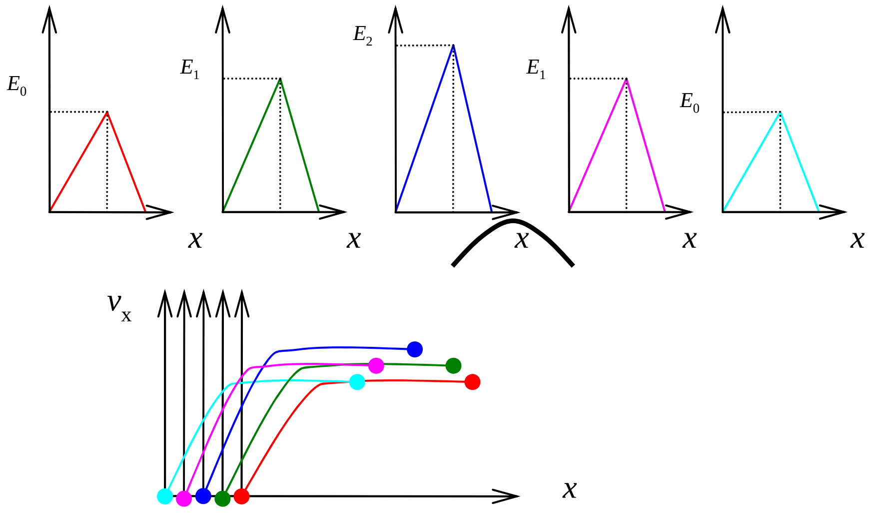
the laser pulse rises from 0 to *a*=10 in 5T, then keeps constant, $n_0 = 10n_c$, thickness 2 wavelengths,



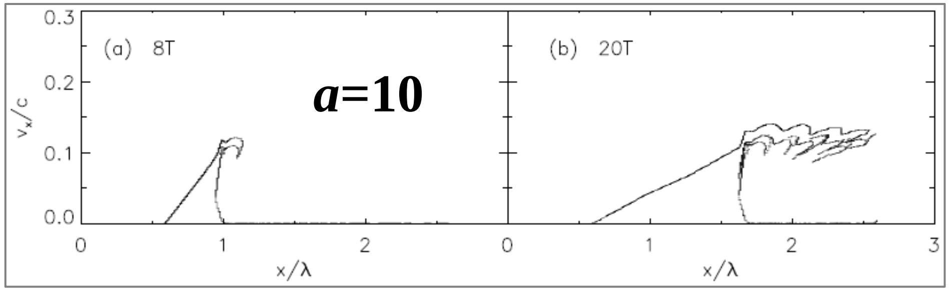


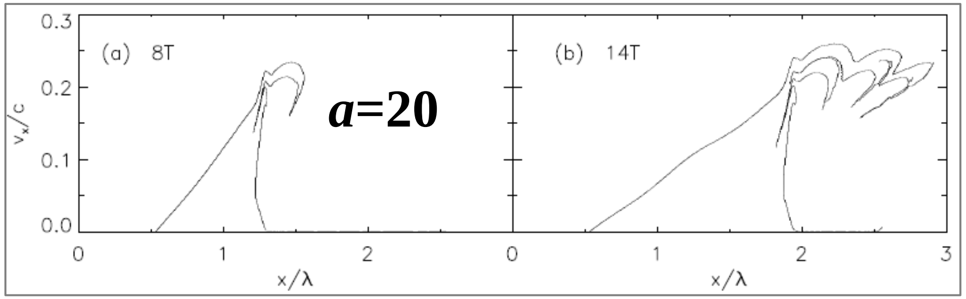


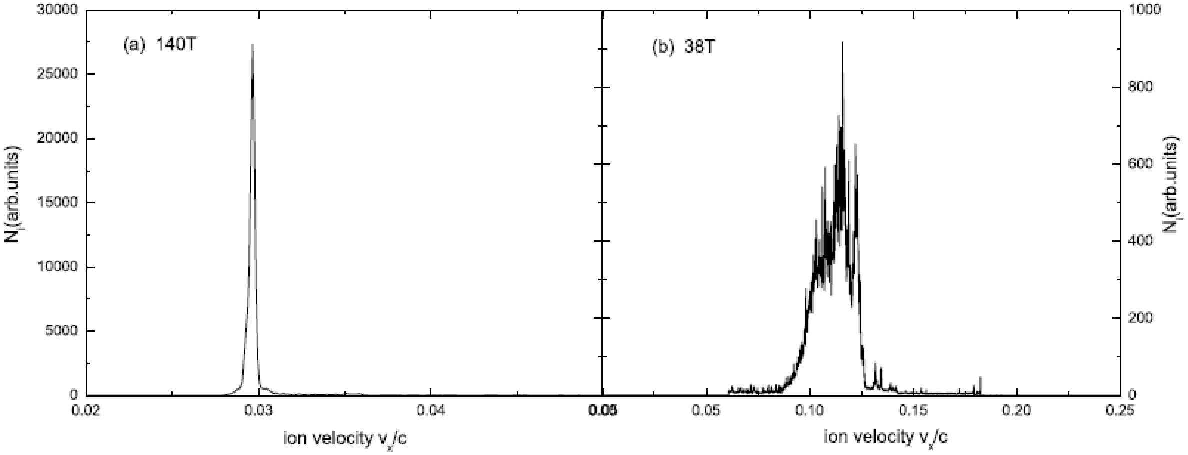
Modle



Velocity flat-tops





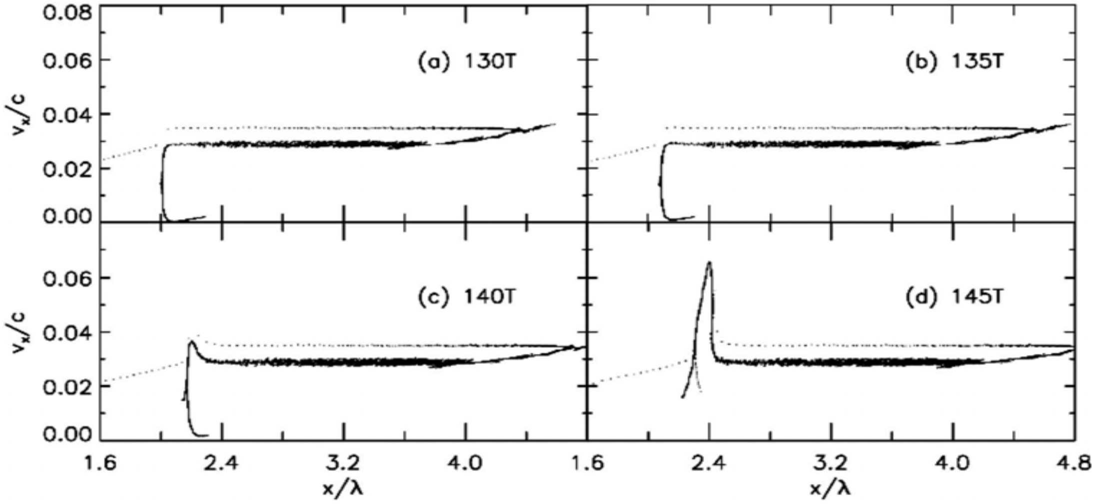


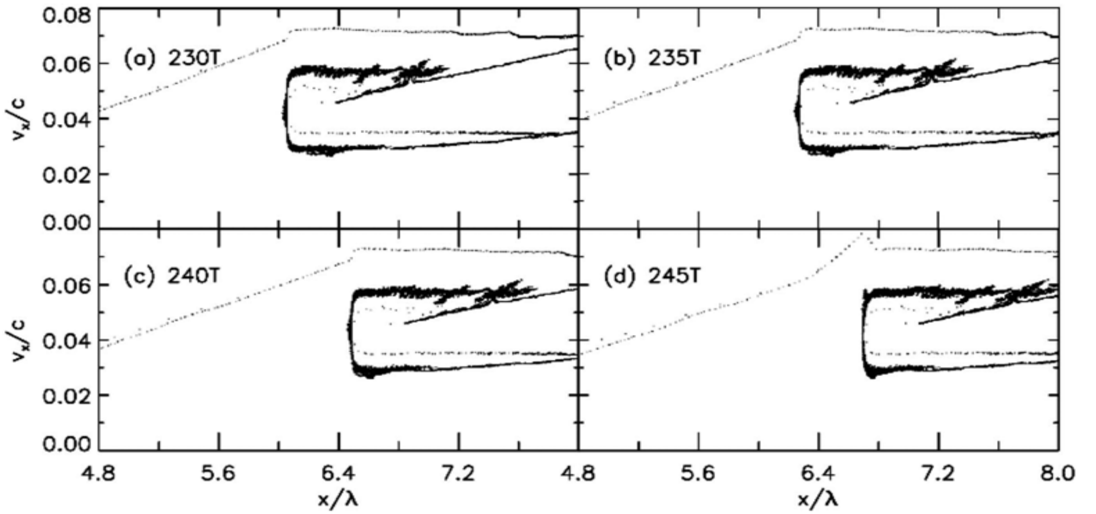
Multi stage acceleration by shock and light pressure acceleration

Two stage acceleration by circularly polarized laser pulse driven electrostatic shock

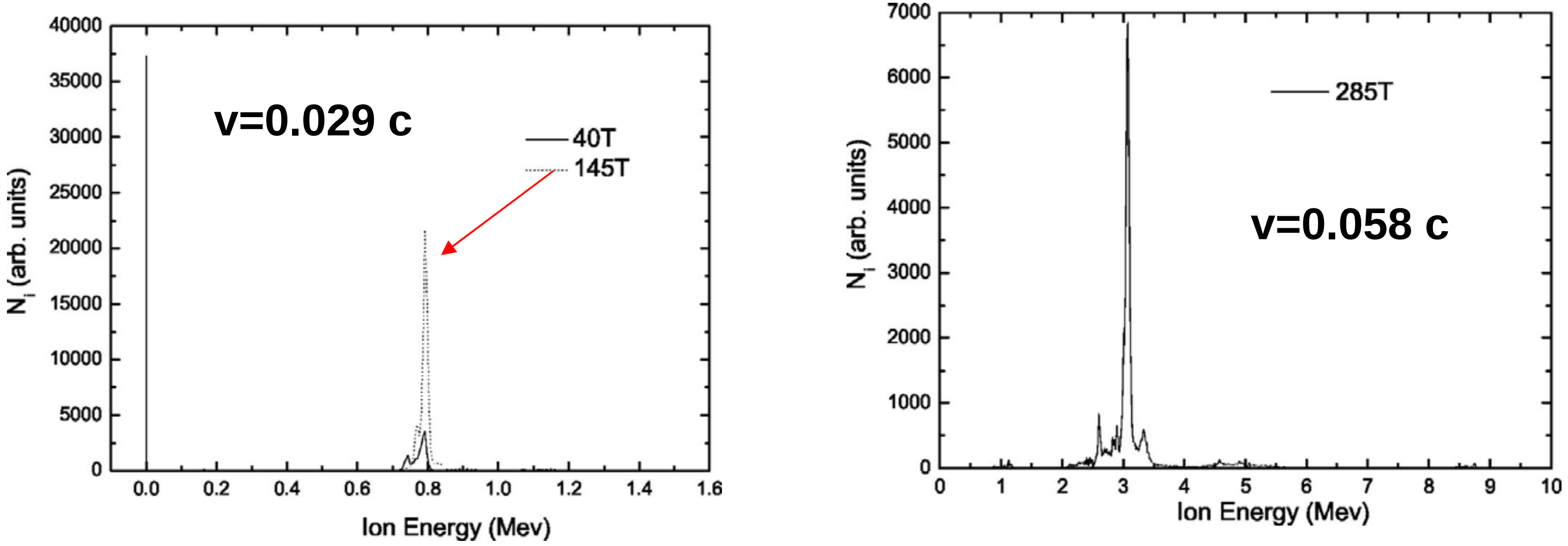
Simulation parameters： the laser pulse rises from 0 to a=2 in 5T, then keeps constant, $n_0 = 10n_c$, thickness 2 wavelengths, $T_i = T_e = 0$.

- **First stage acceleration**
- **Second stage acceleration**





Generation of quasi mono energetic ions: ion energy increases after the second stage acceleration



v=0.029 c

v=0.058 c

$t_1 = l_1 / v_{s1} = 2/0.0148\ T = 135\ T$

$t_2 = t_1 + l_2 / v_{s2} = t_1 + l_1 / v_{s1} = 2t_1 = 270T$

$$v = (v_1 + v_2)/(2v_1 v_2) \approx 2v$$

Zhang et. al., Physics of Plasmas, 14, 073101（2007).

Whole foil accelerated by light pressure

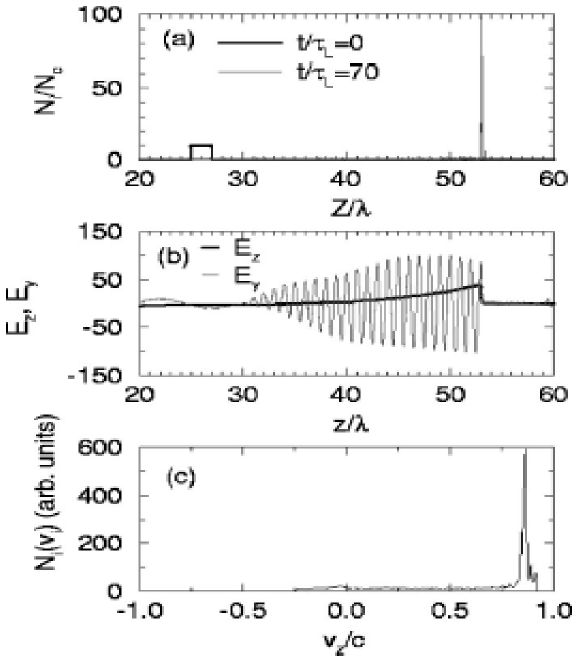


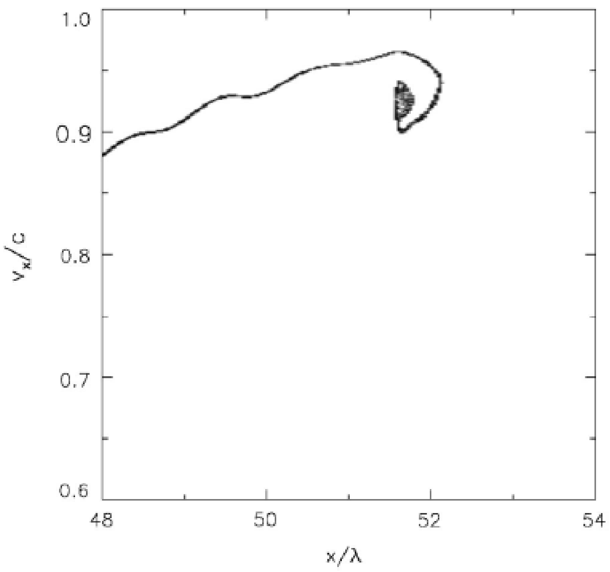
FIG. 6. The ion density distribution (a), normalized laser and static electric field (b), and ion velocity distribution (c) after 70 laser cycles. The plasma layer of density $N_i=10$ and thickness $2\lambda_L$ is initially at $\xi/2\pi=25$. The laser pulse is $a_1=100[\sin(\phi_1)\hat{x}+\cos(\phi_1)\hat{y}]\sin(\phi_1/80)$, $0<\phi_1=\omega_L t-k_L z\leqslant 80\pi$.

Foil: density $n=10n_c$

thickness=$2\lambda_L$

Laser: a=100

20 laser cycles



Baifei shen et. al., Phys. Rev. E, 64, 056406(2001)

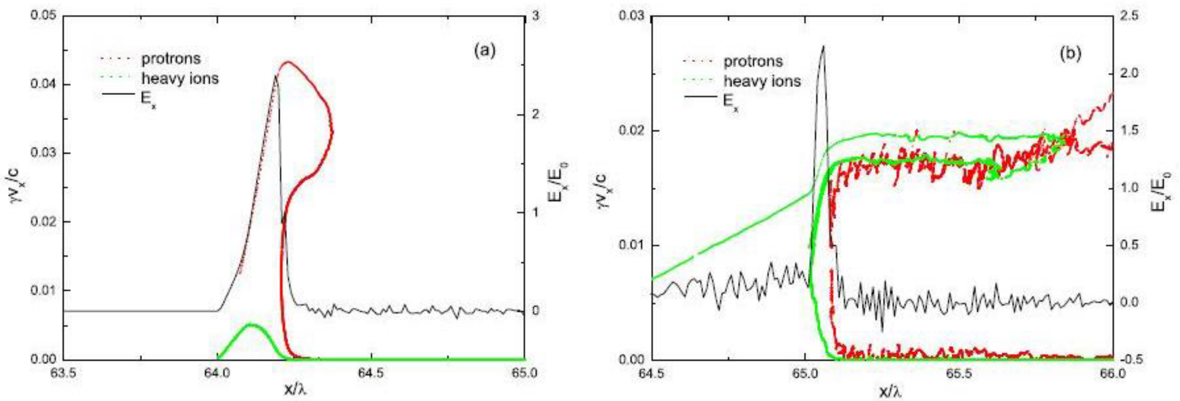
X. Zhang, Baifei Shen et al., Phys. Plasmas 14, 123108(2007)

Quasi monoenergetic heavy ion beam accelerated by electrostatic shock

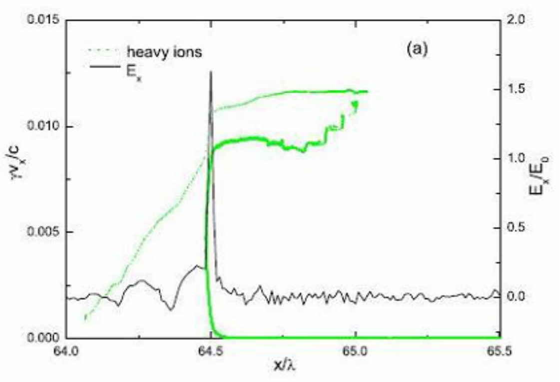
Shock acceleration for mixed plasmas

$$a = 2, n_{e0} = 10, m_{i1} = 1836, m_{i2} = 18360, n_{i1} = 8, n_{i2} = 2, T_e = T_i = 0$$

The target is between *x*=64μm and *x*=72μm



The ratio of number density of proton and heavy ion is $n_{i1}:n_{i2}$=8:2. (a) *t*=80T (b)160T.



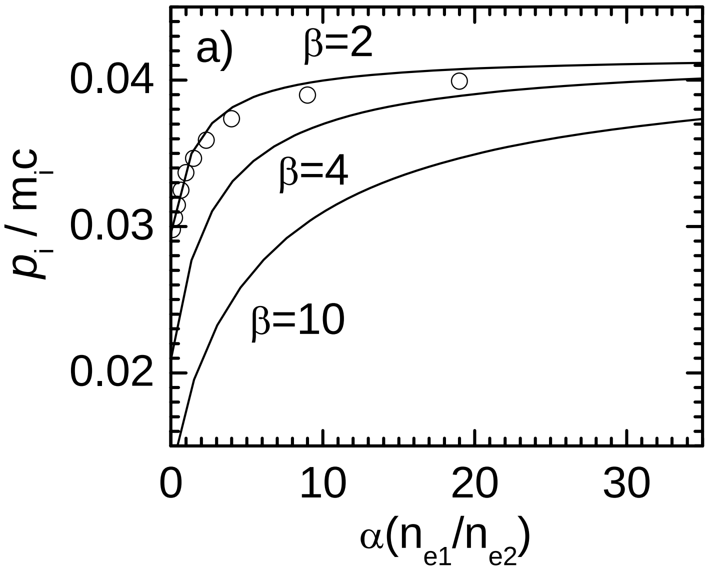
Pure heavy ions

◆ **Initially protons are accelerated to 0.0295 c, then protons and heavy ions reach a same velocity 0.018 c.**

$u_s \approx \sqrt{a^2/(m_i n_i)}$ **For pure protons，0.0295c；For pure heavy ions，0.0094c**

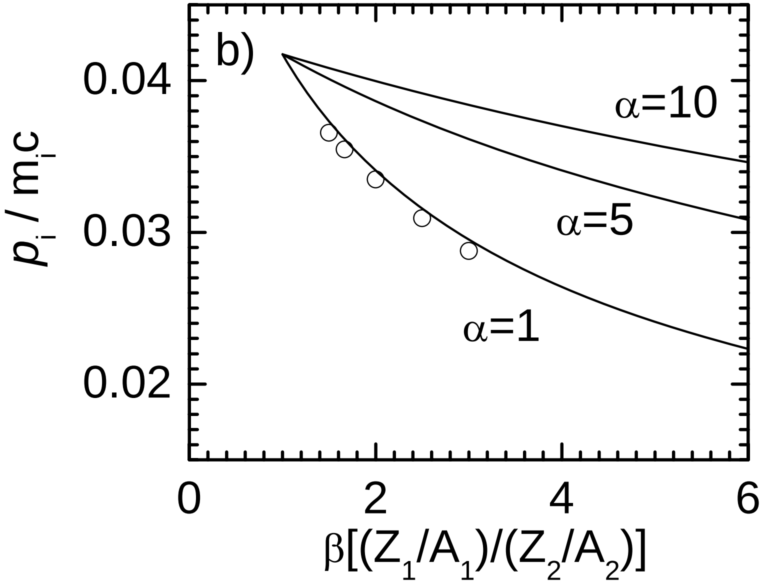
$$\frac{I}{c} = -\eta \frac{I}{c} + \left(n_{e1}\frac{\mathrm{A}_1}{\mathrm{Z}_1} + n_{e2}\frac{\mathrm{A}_2}{\mathrm{Z}_2}\right) m_p v_i v_a \qquad I = \eta I + \left(n_{e1}\frac{\mathrm{A}_1}{\mathrm{Z}_1} + n_{e2}\frac{\mathrm{A}_2}{\mathrm{Z}_2}\right)\frac{m_p v_i^2}{2} v_a$$

$$v_i / c = 2v_a / c \approx 2\sqrt{\frac{n_c}{n_{e1}\mathrm{A}_1/\mathrm{Z}_1 + n_{e2}\mathrm{A}_2/\mathrm{Z}_2}}\sqrt{\frac{m_e}{m_p}}a_L$$



$$a_L = 2$$

$$n_e = 5n_c$$



Quasi monoenergetic heavy ion beam accelerated by electrostatic shock

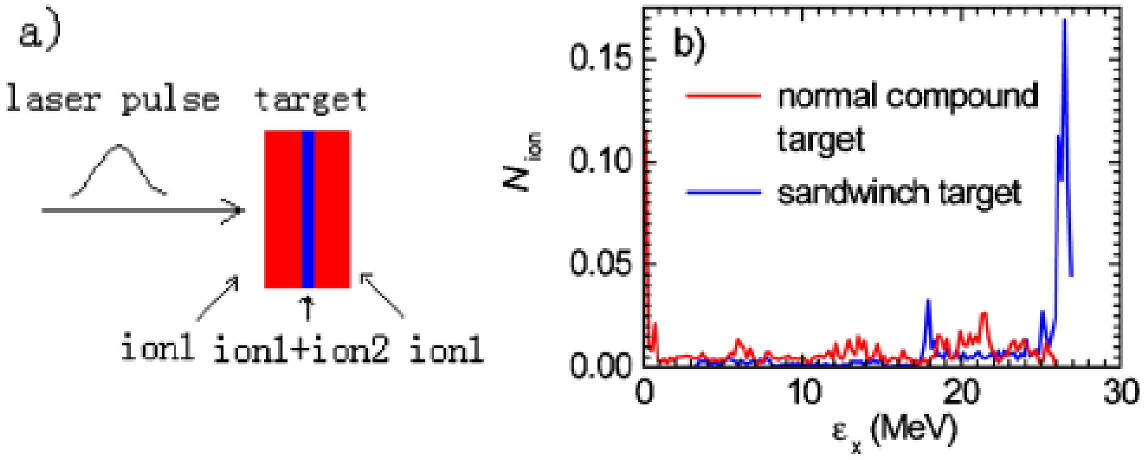
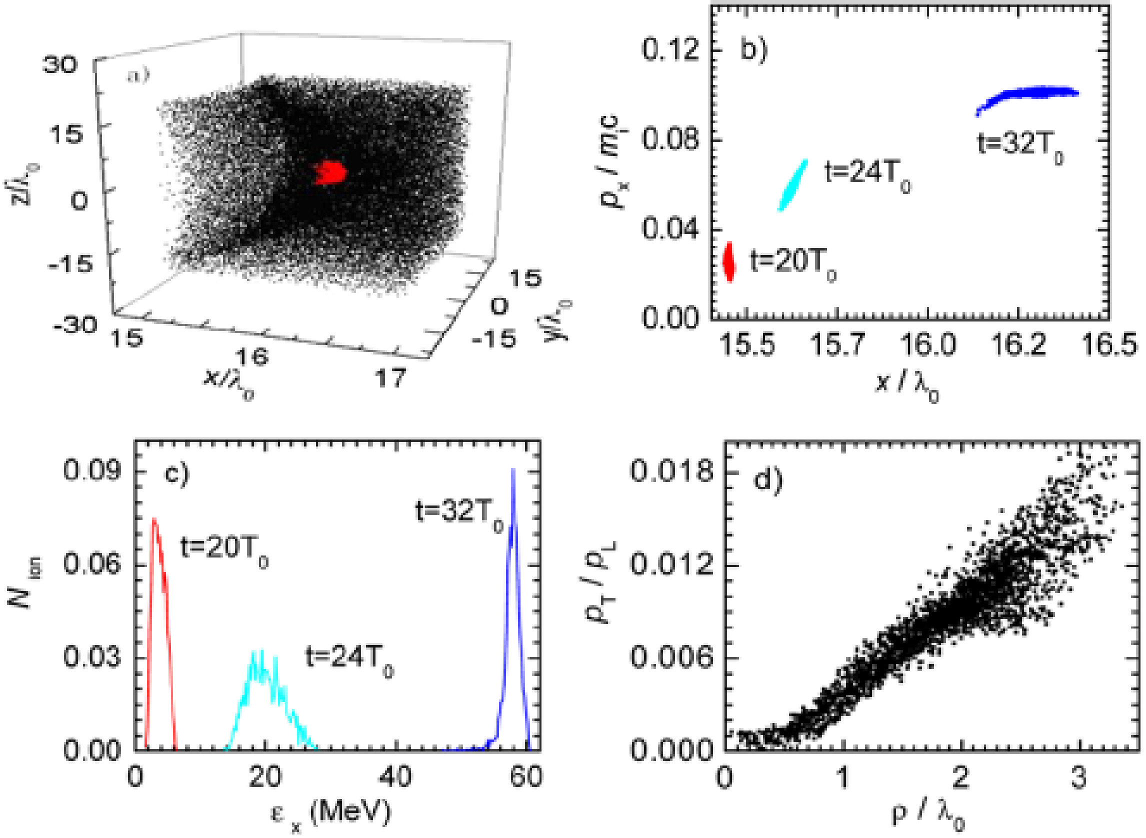


FIG. 3 (color online). Sandwich target scheme (a) and energy spectrum of normal compound target (red solid) and sandwich target (blue solid) (b) at $t = 240T_0$ for a Gaussian laser pulse with peak amplitude $a_L = 4$ and FWHM of $22T_0$. The inside central compound layer (hydrogen and carbon) is $0.2\lambda_0$ thick with $\alpha = 1$, and the outer two light-ion layers (hydrogen) are both $0.9\lambda_0$ thick.

Quasi monoenergetic heavy ion beam accelerated by electrostatic shock



a=6

N=5n$_c$

Liangliang Ji，Baifei Shen et al., Phys. Rev. Lett. 101, 164802, 17 Oct. 2008

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