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Laser acceleration of monoenergetic protons by relativistic radiation pressure on an ultra-thin foil

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Laser acceleration of monoenergetic protons by relativistic pressure on an ultra-thin film

Minisymposium on New Aspects on Nonlinear Physics

Honoring Professor Lennart Stenflo on the occasion of his 70th birthday

Trieste, Italy, 23 August 2009

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Motivation and Outline

A. Lennart's early contributions to relativistic laser-plasma theory

B. Motivation: Monoenergetic protons have important applications in medical treatment and inertial confinement fusion

C. Laser acceleration is potentially an affordable alternative to traditional cyclotron acceleration

D. Comparison between theoretical and numerical results for thin target Radiation Pressure Acceleration (RPA)

E. 2D results — sheath stability.

F. Conclusions

Early contributions to relativistic laser-plasma interactions

Physica Scripta. Vol. 14, 320–323, 1976

Influence of a Circularly Polarized Electromagnetic Wave on a Magnetized Plasma

L. Stenflo

Physica Scripta. Vol. 21, 831–835, 1980.

On the Stability of a Magnetized Plasma in a Large Amplitude Circularly Polarized Wave

L. Stenflo

Department of Plasma Physics, Umeå University, Umeå, Sweden

PHYSICAL REVIEW A VOLUME 24, NUMBER 2 AUGUST 1981

Radiation from a relativistic electron beam in a molecular medium due to parametric pumping by a strong electromagnetic wave

L. Stenflo

Department of Plasma Physics, Umeå University, S-90187 Umeå, Sweden

H. Wilhelmsson

Institute for Electromagnetic Field Theory and Euratom-Fusion Research (EUR-NE), Chalmers University of Technology, S-41296 Göteborg, Sweden

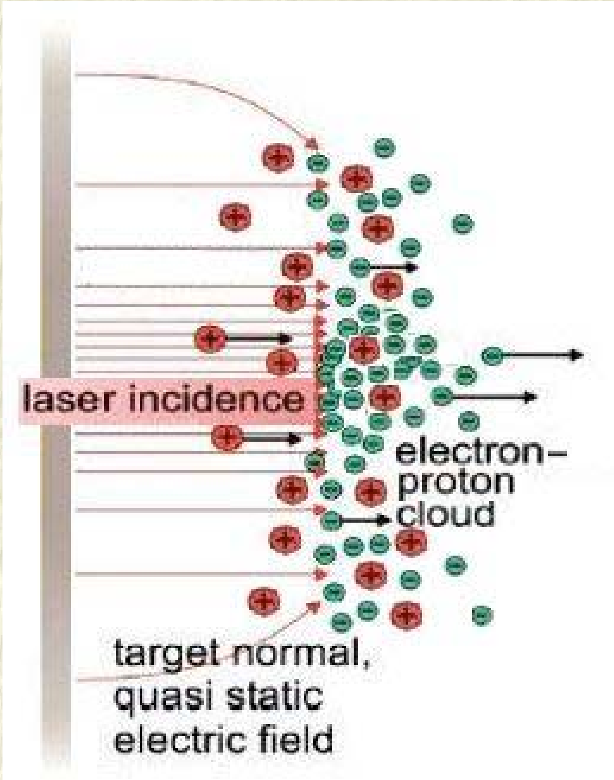
Physica Scripta. Vol. 23, 779–780, 1981

Self-Consistent Vlasov Description of a Magnetized Plasma in a Large Amplitude Circularly Polarized Wave

L. Stenflo

Department of Plasma Physics, Umeå University, Umeå, Sweden

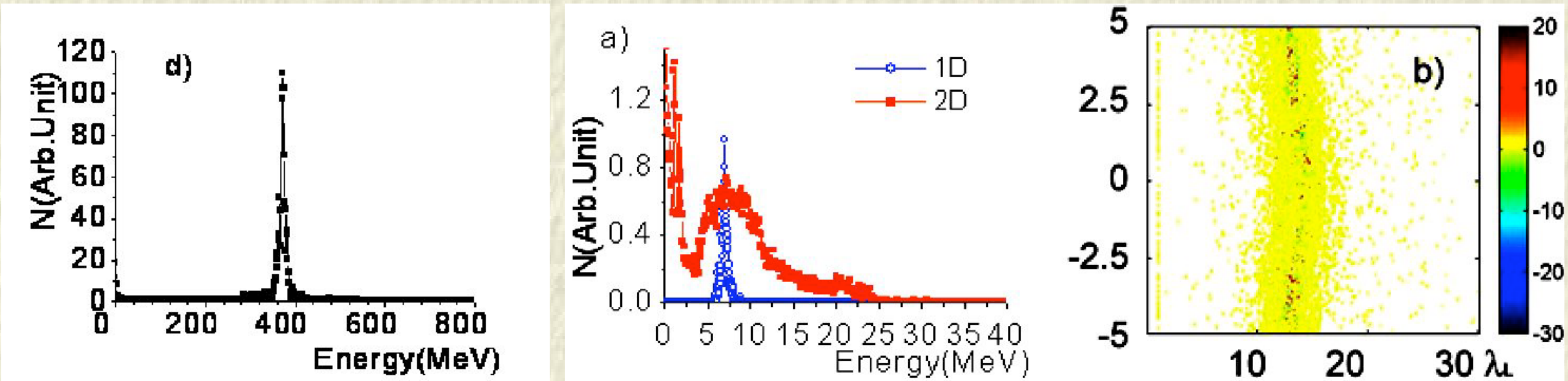
Radiation pressure acceleration (RPA) of thin foil



Protons accelerated together with electron cloud as a whole.
Could lead to mono-energetic ions in excess of $100\,\mathrm{MeV}$.

Monoenergetic acceleration of protons

1D and 2D PIC simulation results



Yan et al., PRL 100, 135003 (2008)

Theory of thin foil monoenergetic proton acceleration

Momentum equation of the foil

$$N_0 m_i \frac{d(\gamma v)}{dt} = F_{rad} = \frac{2I_0}{c}\left(\frac{1 - v/c}{1 + v/c}\right), \tag{1}$$

N_0 =surface number density of ions
$\gamma = (1 - v^2/c^2)^{-1/2}$ =relativistic gamma factor
I_0=radiation intensity (W/cm^2).

$$I_0 = \epsilon_0 \omega_0^2 A_0^2 c = \frac{\epsilon_0 \omega_0^2 m_e^2 c^3}{e^2} a_0^2,$$

where $a_0 = e|A_0|/m_e c$ and ω_0 =laser frequency.

Theory of thin foil monoenergetic proton acceleration

Equations (1) can be integrated to give

$$\frac{v(t)}{c} = \frac{g(t)^2 - 1}{g(t)^2 + 1}, \tag{2}$$

where
$g = \{2^{1/3}[h(t) + \sqrt{4 + h(t)^2}]^{2/3} - 2\}/\{2^{2/3}[h(t) + \sqrt{4 + h(t)^2}]^{1/3}\}$, $h(t) = (6P/T_L)t + 4$, and $P = 2T_L I_0/N_0 m_i c^2$. The position $z(t)$ of the foil is found from $dz/dt = v$, which can be integrated to give

$$\frac{z(t)}{\lambda_L} = \frac{1}{6P}\left[\left(\frac{1 + v/c}{1 - v/c}\right)^{3/2} - 3\left(\frac{1 + v/c}{1 - v/c}\right)^{1/2} + 2\right], \tag{3}$$

where v is given by (2).

Tripathi et al. Plasma Phys. Control. Fusion 51, 024014 (2009); Eliasson et al. New J. Phys. 11, 073006 (2009)

Optimal thickness

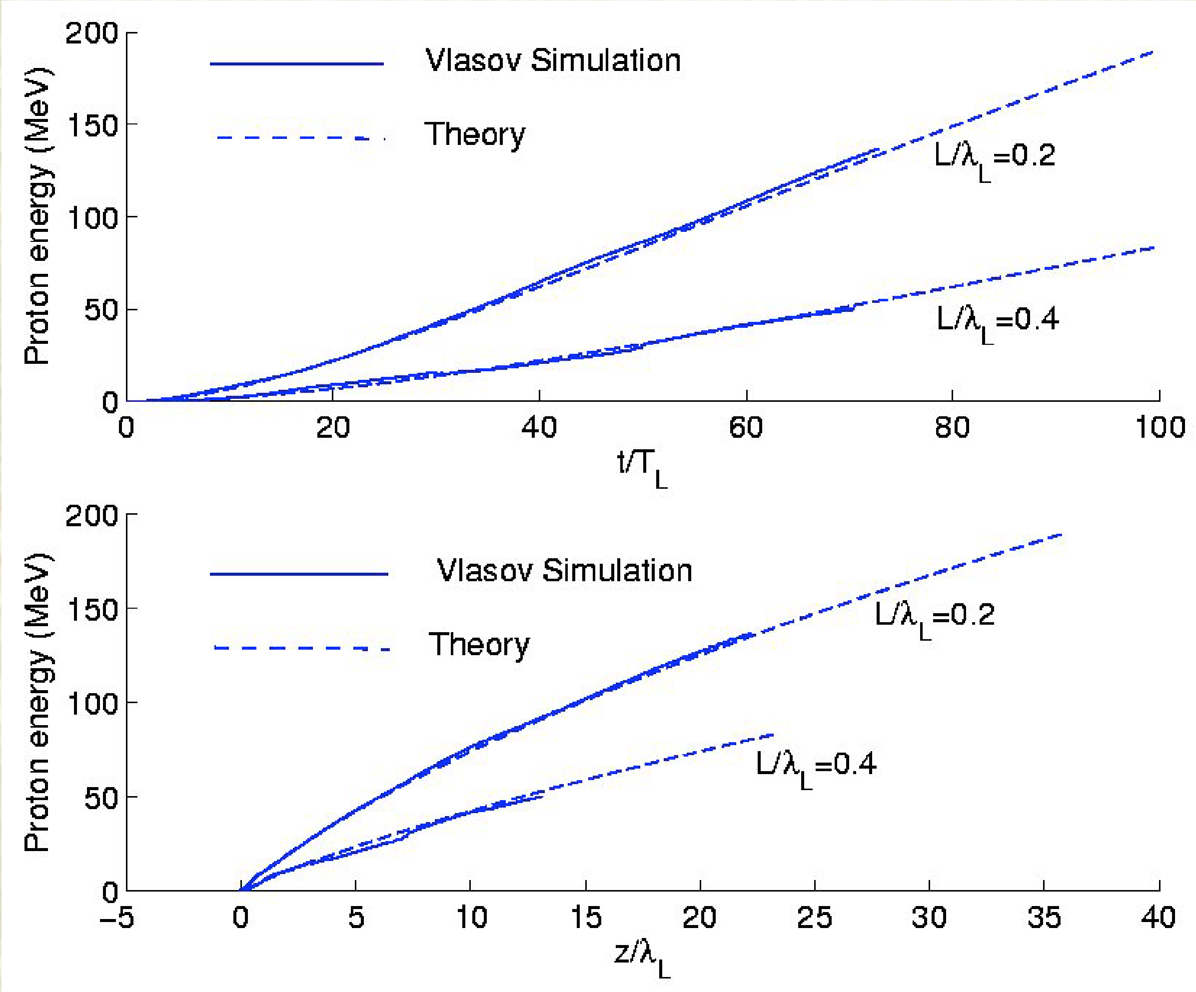
Optimal thickness when the radiation pressure is of the same size as the electrostatic force when all the electrons have been pushed to the rear end of the proton slab.

$$L_{opt} = \frac{\omega_0^2}{\omega_{pe}^2}\frac{\lambda_L}{\pi}a_0$$

$\omega_{pe}^2/\omega_0^2 = 10$ and $a_0 = 5$ gives $L_{opt} \approx 0.16\lambda_L$.

Tripathi et al. Plasma Phys. Control. Fusion 51, 024014 (2009)

Proton energy, theory vs. Vlasov simulation



$a_0 = 5$, $\omega_{pe}^2/\omega_0^2 = 10$.

Eliasson et al. New J. Phys. 11, 073006 (2009)

Vlasov-Maxwell simulation model

Proton and electron Vlasov equation

$$\frac{\partial f_i}{\partial t} + \frac{p_z}{m_i\gamma_i}\frac{\partial f_i}{\partial z} - e\frac{\partial \phi}{\partial z}\frac{\partial f_i}{\partial p_z} = 0,$$

$$\frac{\partial f_e}{\partial t} + \frac{p_z}{m_e\gamma_e}\frac{\partial f_e}{\partial z} + \frac{\partial (e\phi - m_e c^2\gamma_e)}{\partial z}\frac{\partial f_e}{\partial p_z} = 0,$$

where the ion and electron relativistic gamma factors are

$$\gamma_i = \sqrt{1 + \frac{p_z^2}{m_i^2 c^2}} \quad \text{and} \quad \gamma_e = \sqrt{1 + \frac{p_z^2}{m_e^2 c^2} + \frac{e^2|A|^2}{m_e^2 c^2}}.$$

Vlasov-Maxwell simulation model

Wave equation for the vector potential in Coulomb gauge
$\nabla \cdot \mathbf{A} = 0$

$$\frac{\partial^2 \mathbf{A}}{\partial t^2} - \frac{\partial^2 \mathbf{A}}{\partial z^2} + \Omega_{pe}^2 \mathbf{A} = 0,$$

Circularly polarized laser light
$\mathbf{A} = (1/2)A(z,t)(\widehat{\mathbf{x}} + i\widehat{\mathbf{y}})\exp(-i\omega_0 t)+$c.c. leads to

$$\left(\frac{\partial}{\partial t} - i\omega_0\right)^2 A - c^2 \frac{\partial^2 A}{\partial z^2} + \Omega_p^2 A = 0, \qquad \Omega_p^2 \simeq \frac{e^2}{\epsilon_0} \int \frac{f_e}{m_e \gamma_e} \, dp_z$$

Parallel electric field

$$\frac{\partial E_z}{\partial t} = \frac{e}{\epsilon_0} \int (v_{ez} f_e - v_{iz} f_i) \, dp_z, \qquad \frac{\partial E_z}{\partial z} = -\frac{\partial^2 \phi}{\partial z^2} = \frac{e}{\epsilon_0}(n_i - n_e),$$

Simulation methods and parameters

Eulerian code, using 4th-order difference schemes for z and p derivatives, and Runge-Kutta scheme for time-stepping.

One-dimensional box size: $32\lambda_L$, resolved with 2000 grid points.

Electron momentum space spanning $\pm 10\, m_e c$, resolved with 60 grid points.

Ion momentum space from $-30\, m_e c$ to $+1470\, m_e c$ resolved with 6000 grid points.

Physical parameters: amplitude $a = 5$, ion density $n/n_c = 10$, widths $L = 0.2\, \lambda_L$ (optimal), $L = 0.4\, \lambda_L$ and $L = 0.1\, \lambda_L$.

Plasma physics of proton acceleration

- Laser ponderomotive pressure acts on the electrons. Balance between electrostatic force and ponderomotive pressure leads to trapping of the electrons.

- Effective electric potential for electrons

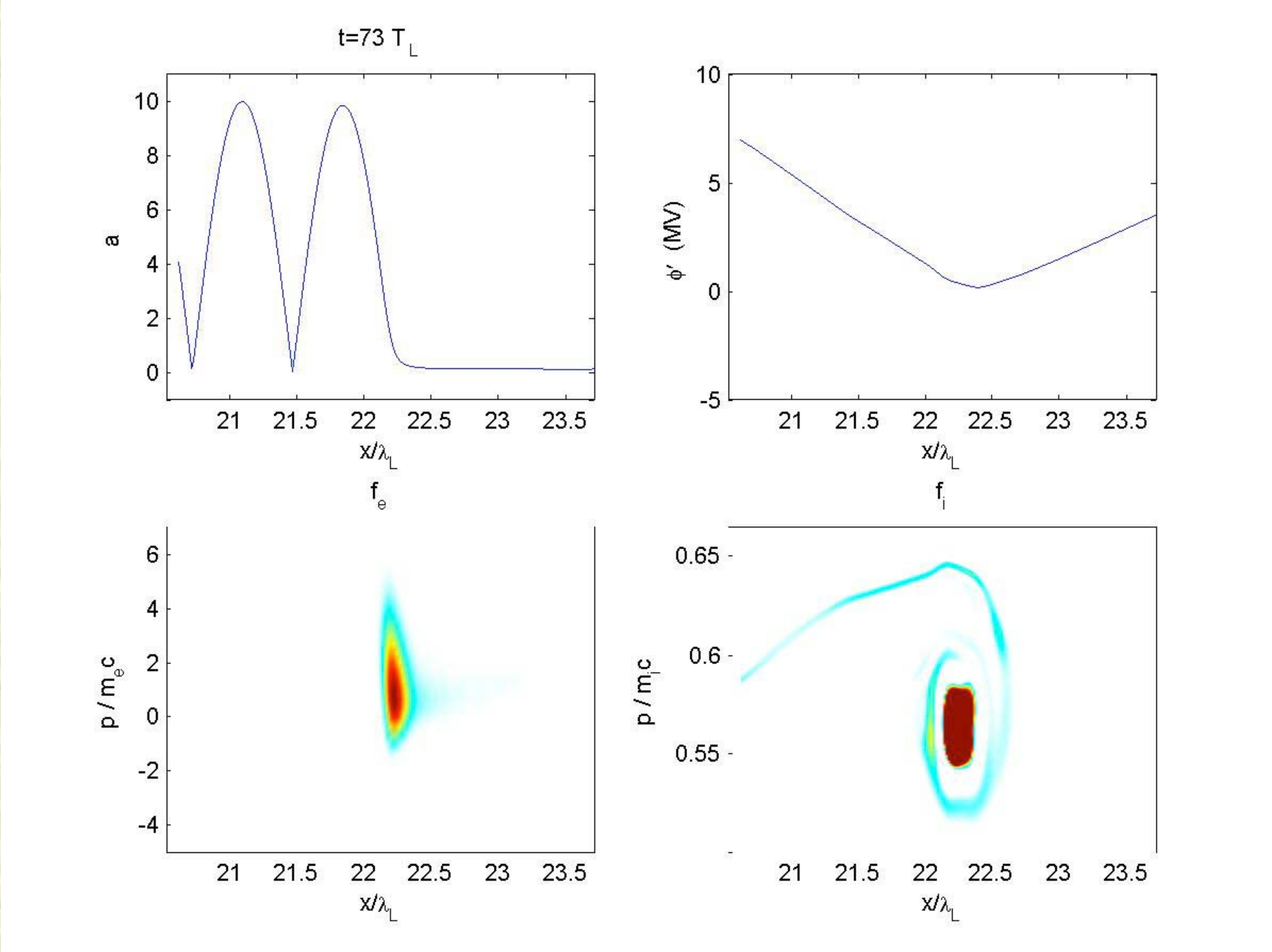
$$\phi'_e(z,t) = \phi - \frac{m_e c^2}{e}(\sqrt{1+a^2} - 1)$$

- Ions accelerated by the electrostatic force. Balance between the forward electrostatic force and backward inertial force in an accelerating frame leads to ion trapping in the potential well.

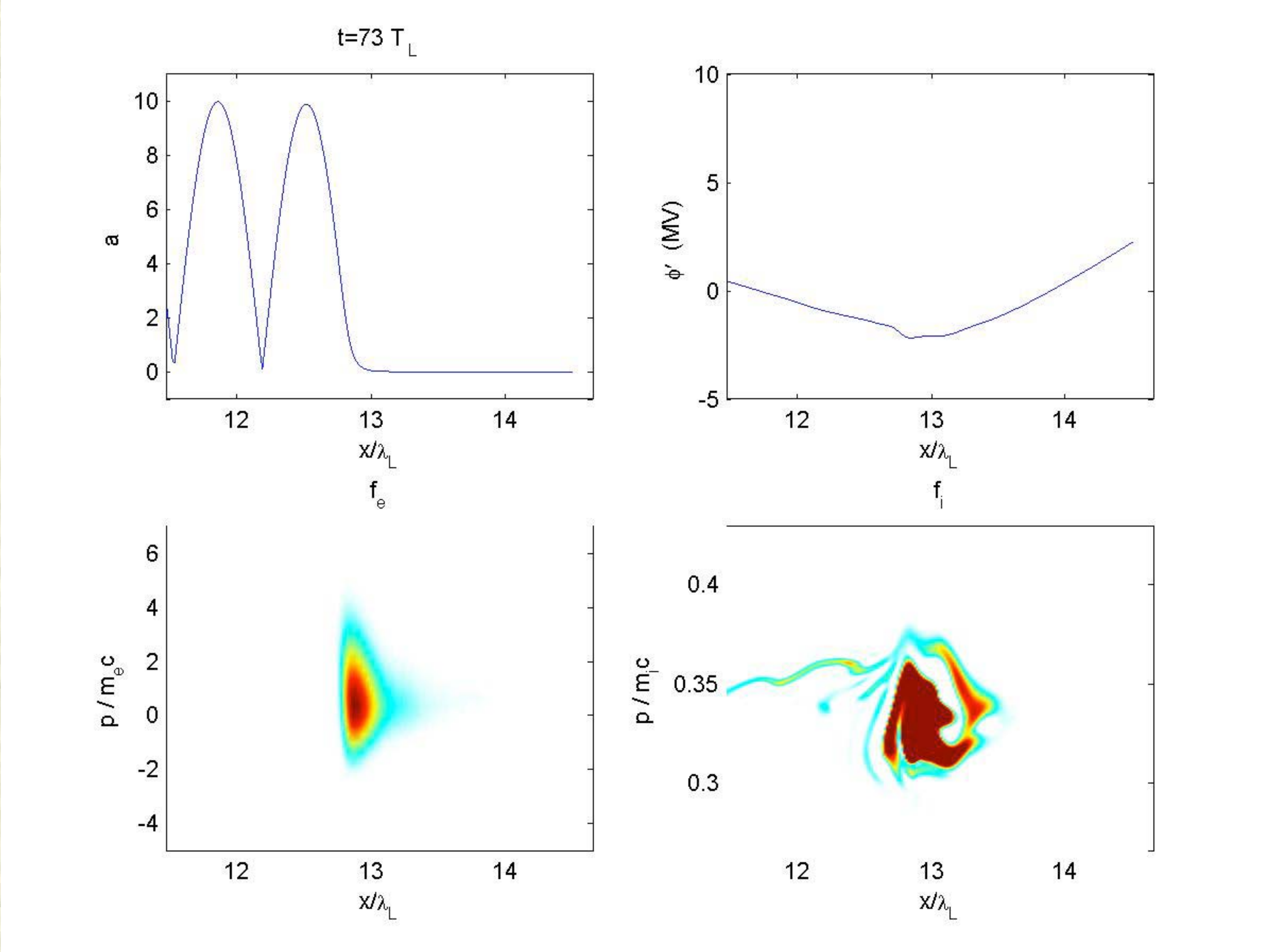
- Effective potential for ions in an accelerating frame

$$\phi'(z,t) = \phi(z,t) + \frac{F_{rad}}{eN_0} z,$$

Simulation optimal width $L = 0.2\lambda_L$.

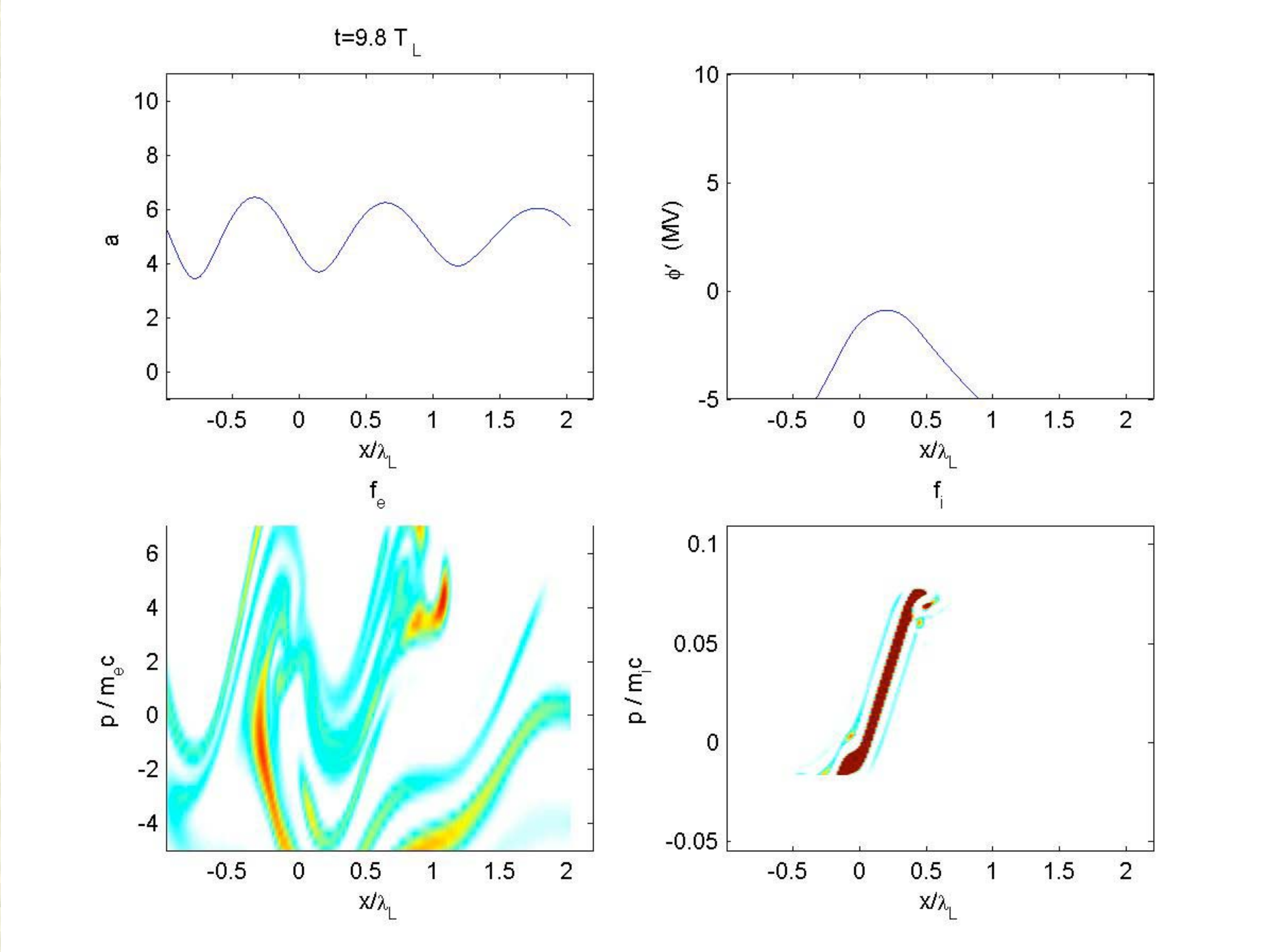


Simulation twice the optimal width $L = 0.4\lambda_L$.



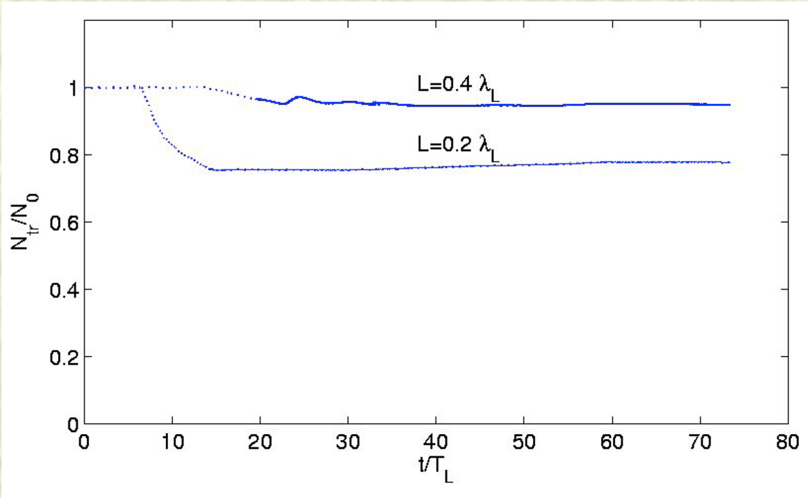
Wider energy spread, less acceleration.

Simulation half the optimal width $L = 0.1\lambda_L$.



Laser burns through. Poor acceleration.

Fraction of monoenergetic ions



Due to the acceleration, some ions are untrapped and spread out in energy. When the electric force of ion acceleration is less than the inertial force in an accelerating frame, then ions are untrapped. Approximate formula:

$$\frac{N_{tr}}{N_0} = 1 - \frac{2}{(2\pi)^2}\frac{\omega_0^4}{\omega_{pe}^4}\frac{\lambda_L^2}{L^2}a_0^2.$$

Gives $\sim 70\%$ for $L = 0.2$ and $\sim 95\%$ for $L = 0.4$.

Multiple dimensions ?

- Multiple dimensions: the Rayleigh-Taylor instability $\rightarrow$ fracturing of the foil and burn through of the laser light.

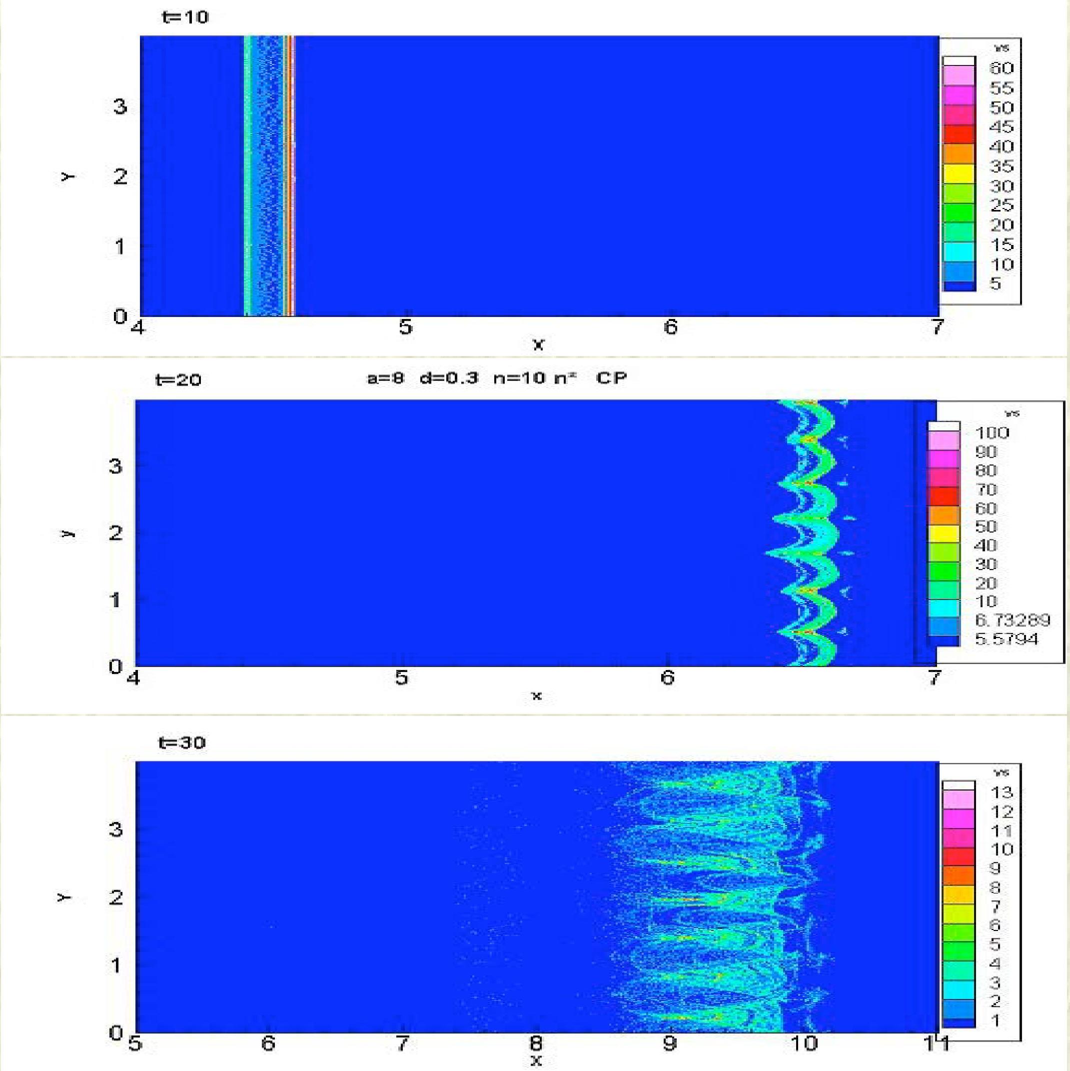
- Is it possible to find parameter regimes where the RT instability is stable enough?

- We have found regimes where protons are accelerated monoenergetically up to 200 MeV.

(2D PIC simulations: Thanks to Galina Dudnikova, U. Maryland.)

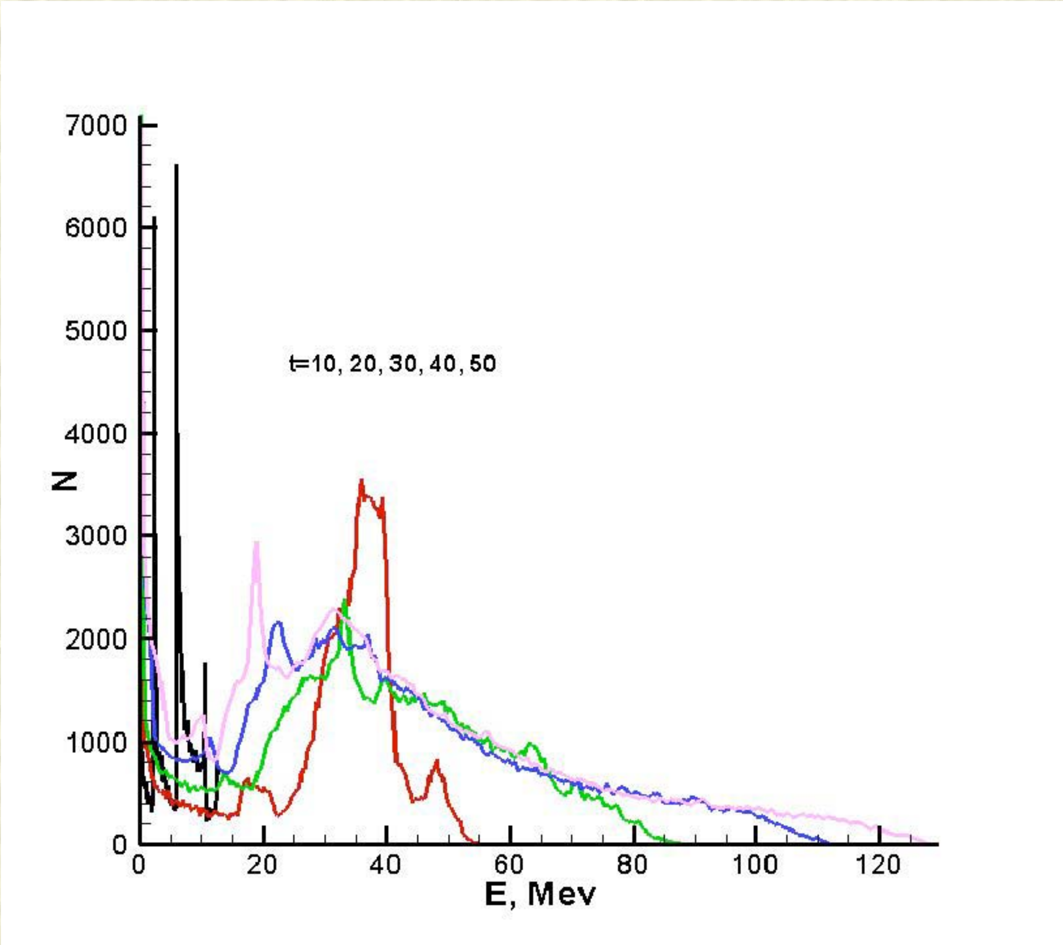
Rayleigh-Taylor instability destroys the foil

$a = 8$, $n/n_c = 10$.



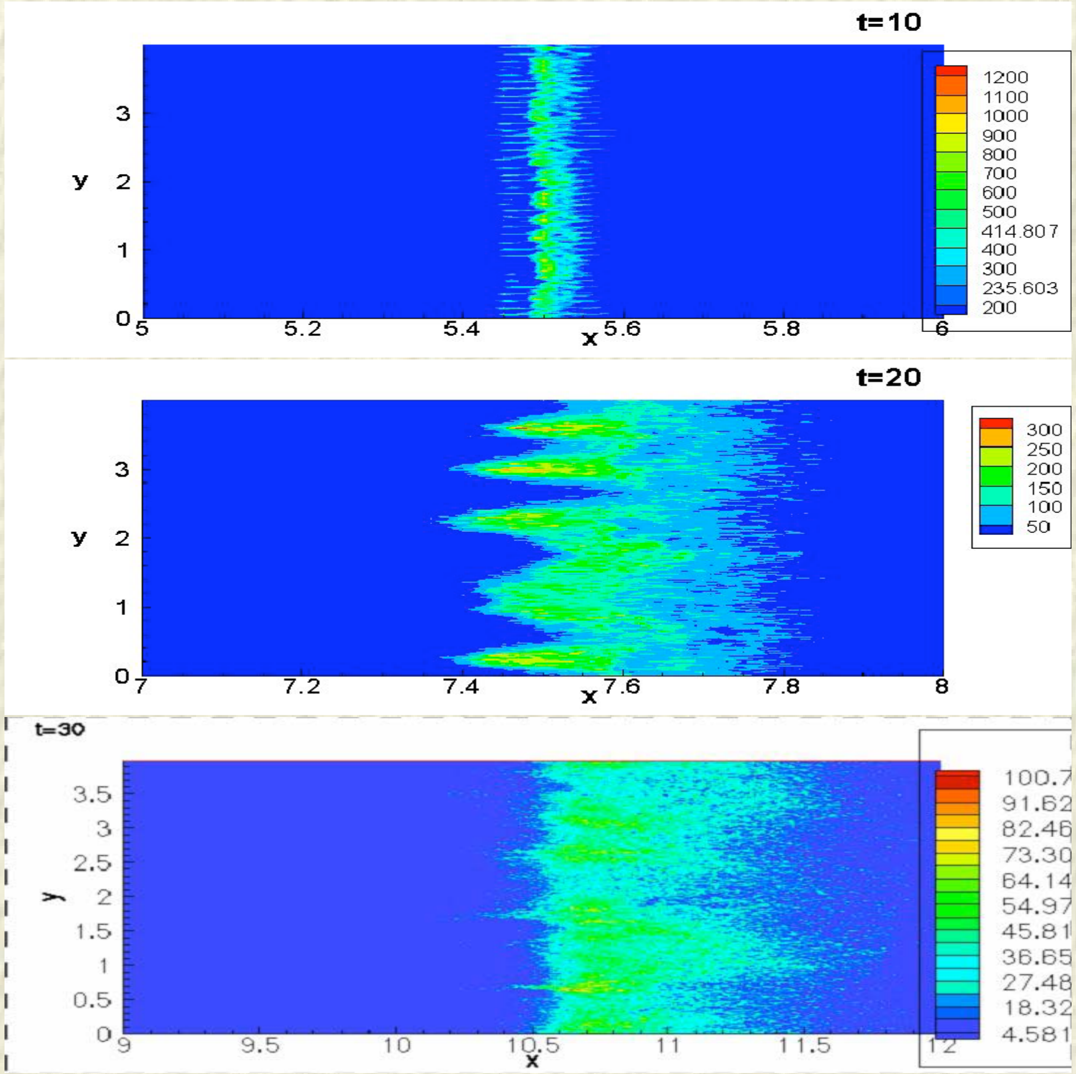
Wide energy spectrum

$a = 8$, $n/n_c = 10$.

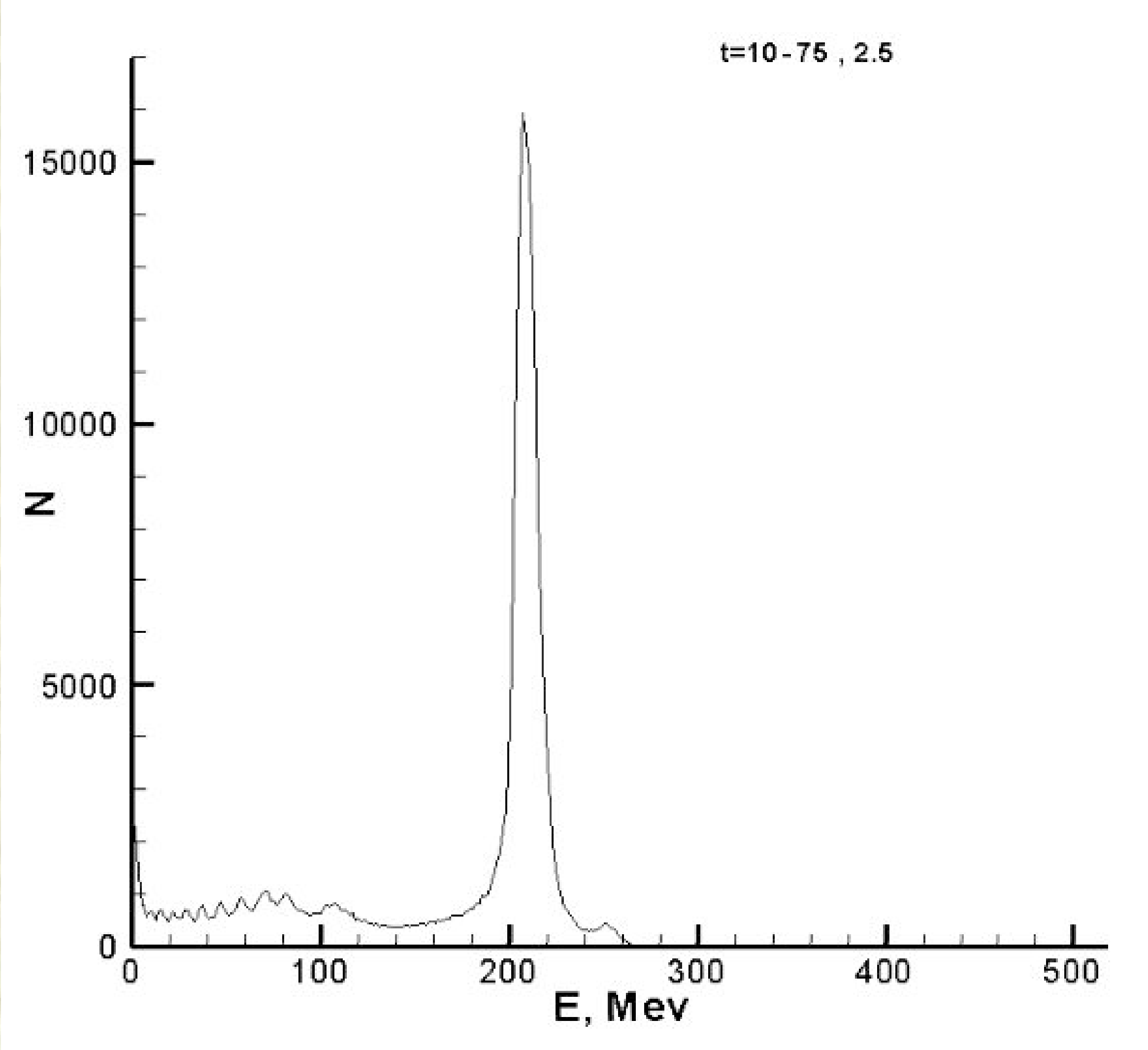


Rayleigh-Taylor instability stabilized ?

Higher intensity and larger density.



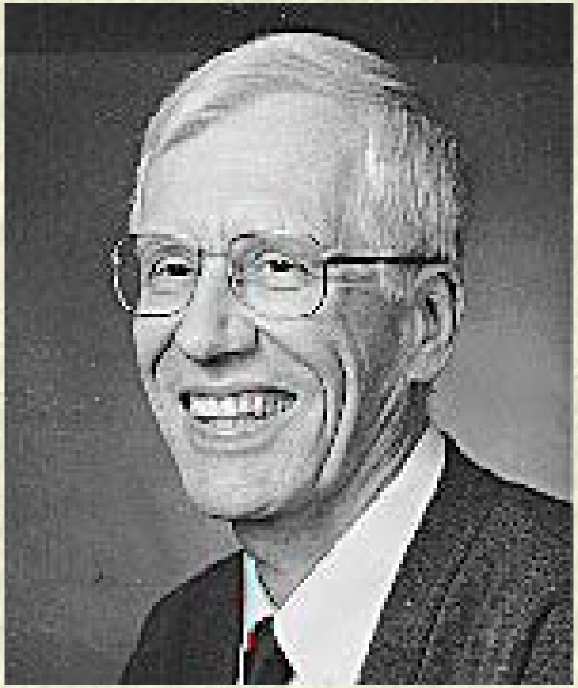
2D PIC simulation: Acceleration to 200 MeV.



Summary

More theory, simulation and experiment needed!

... and last but not least ...



Happy Birthday!