SILMI Workshop on Frontiers in Intense Laser-Matter Interactions Theory
MPQ-Garching, March 1-3, 2010

Generation of tens of GeV quasi-monoenergetic proton bunches at intensity $10^{21} \sim 10^{23}$ W/cm^2

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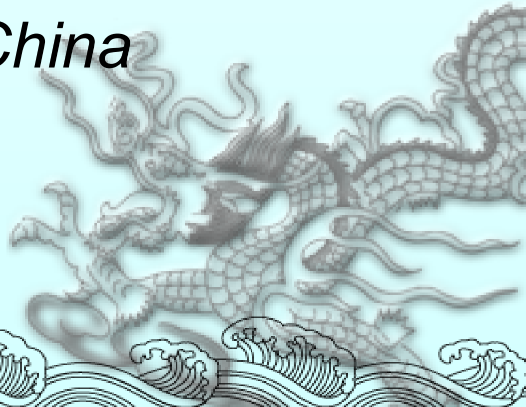

Collaborators

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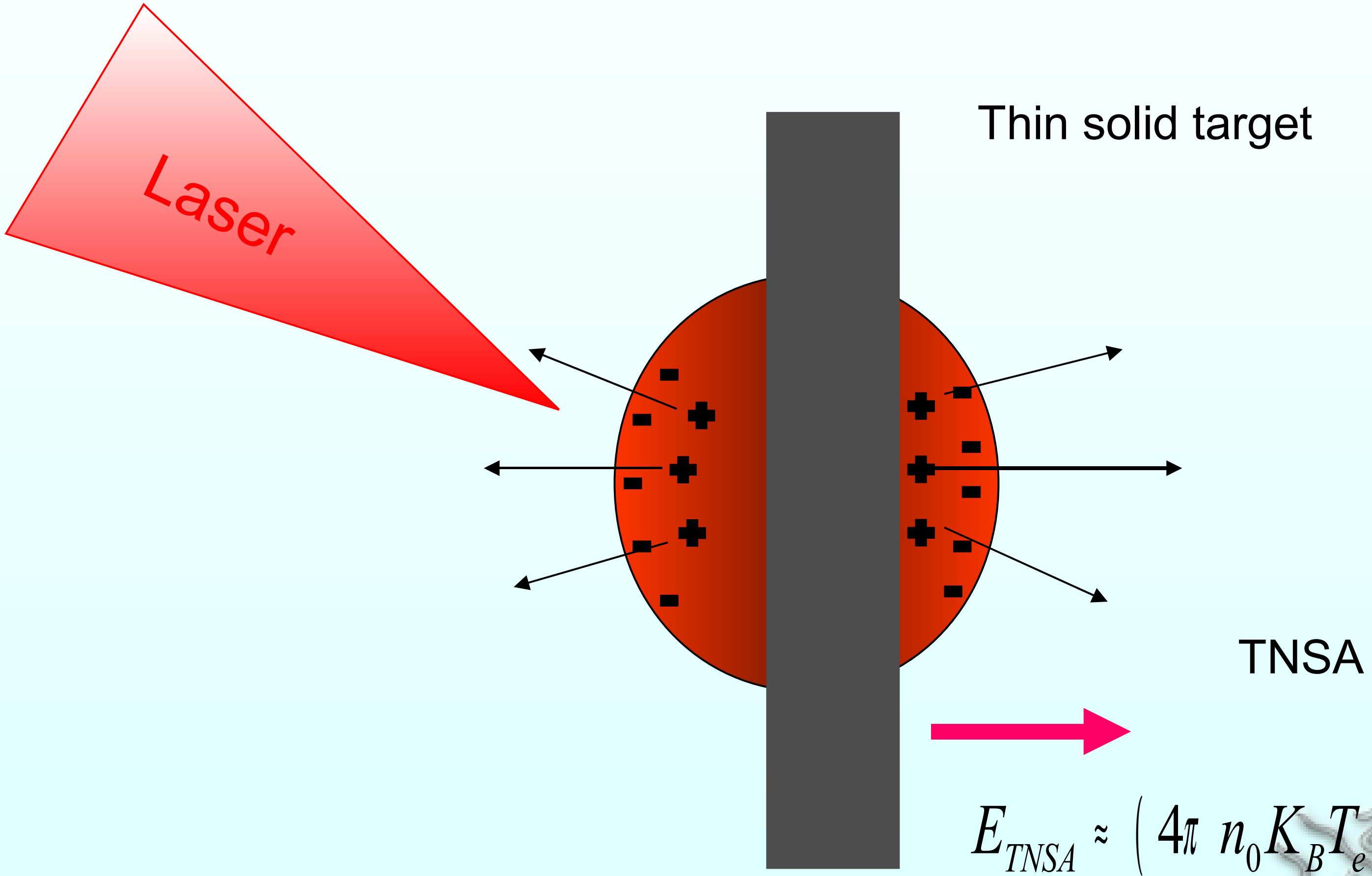
Laser-solid interaction for ion acceleration

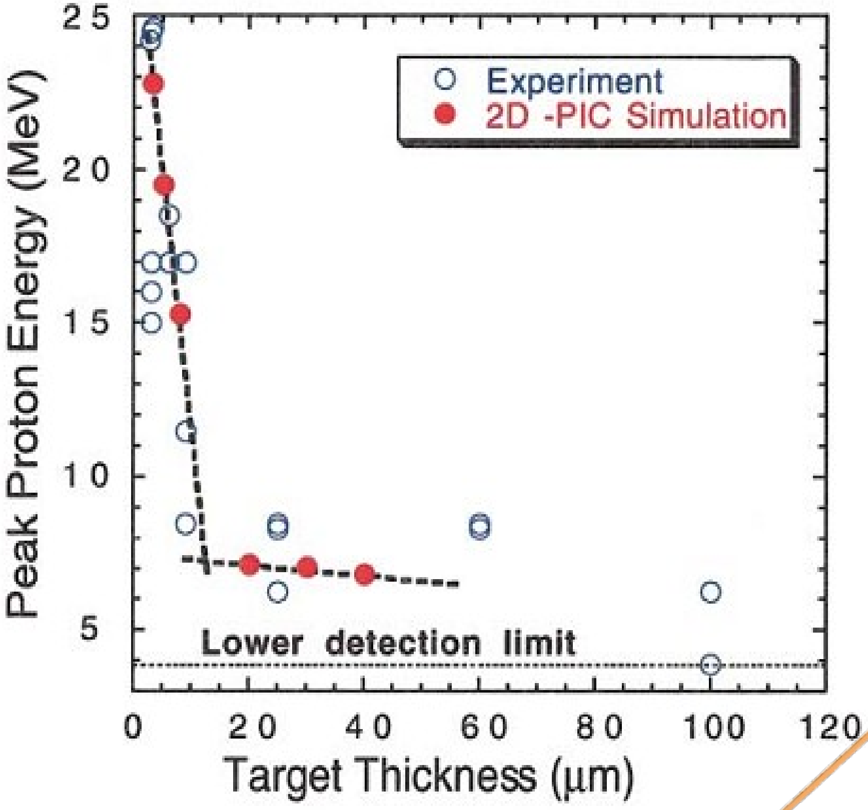


$$E_{TNSA} \approx \left(4\pi\, n_0 K_B T_e\right)^{1/2} \sim TeV/m$$

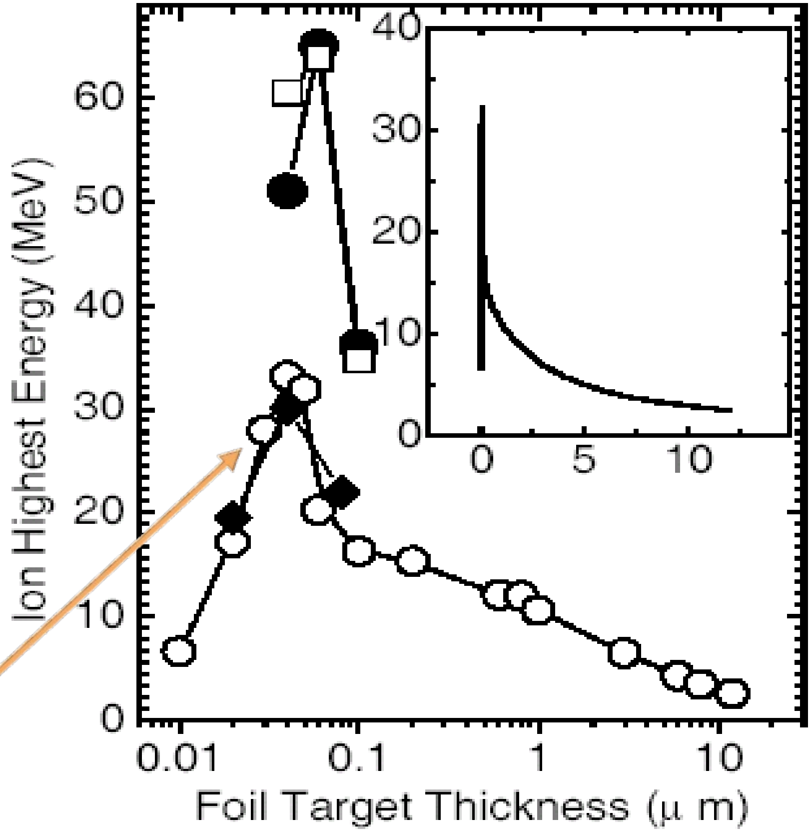
Because the acceleration distance is limited within the sheath, the ion energy cannot be very high!

Target thickness dependence on proton acceleration

A.J.Mackinnon et al., PRL 88, 215006 (2002)

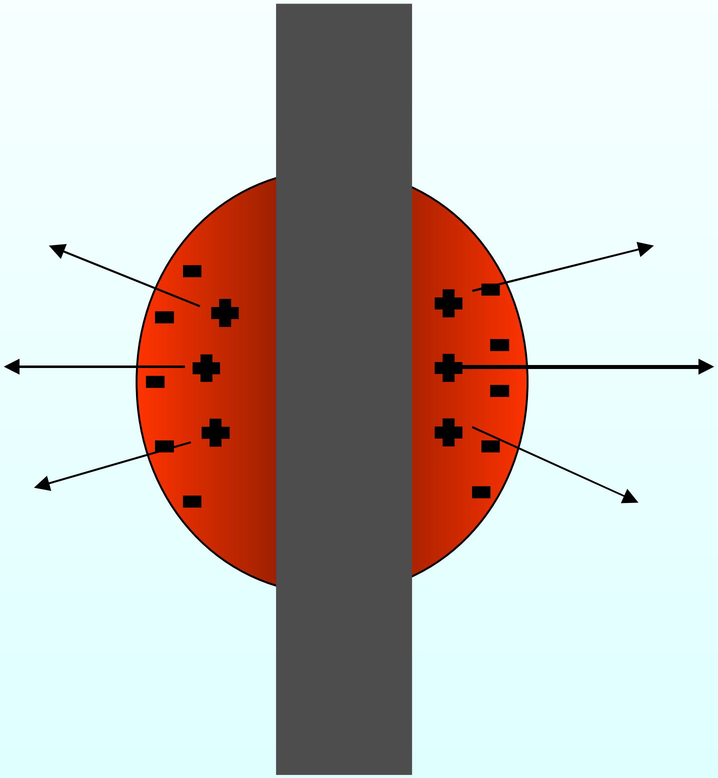


Q.L.Dong et al., *PRE 68, 026408 (2003)*

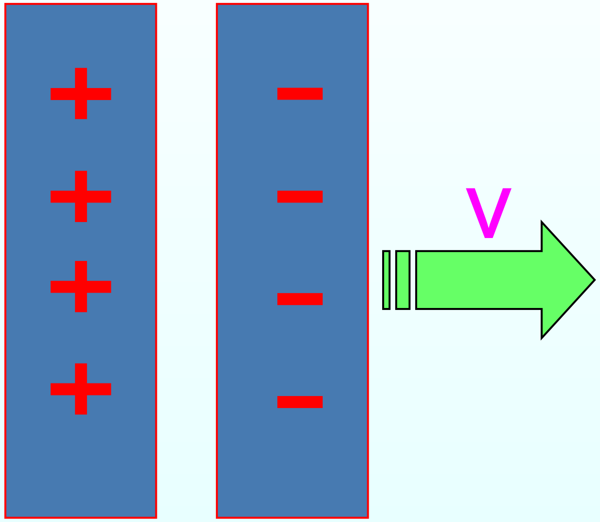


$$d_{optm} \approx (c/\omega_p)\sqrt{1+\mathbf{a}^2\tau/2}$$

From an immobile sheath/double layer to a moving sheath

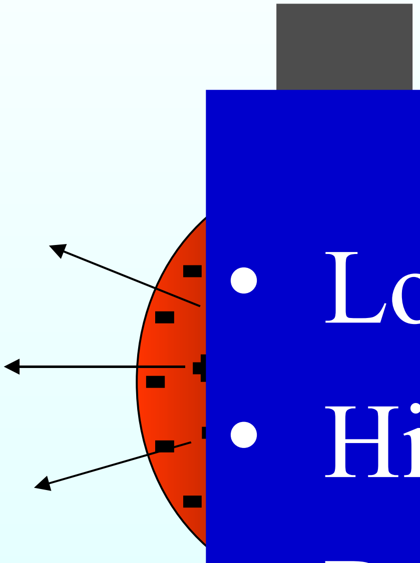


Thin solid target

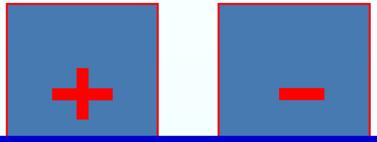


- Radiation Pressure Acceleration
- Break-out Afterburner
- Collisionless Electrostatic Shock
- Phase-Stable Acceleration

From an immobile sheath/double layer to a moving sheath



Thin solid target



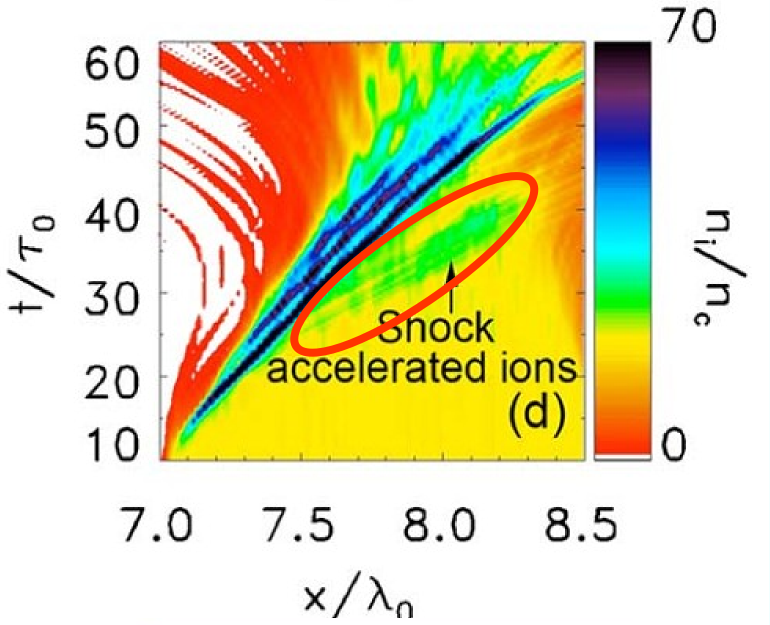
ion

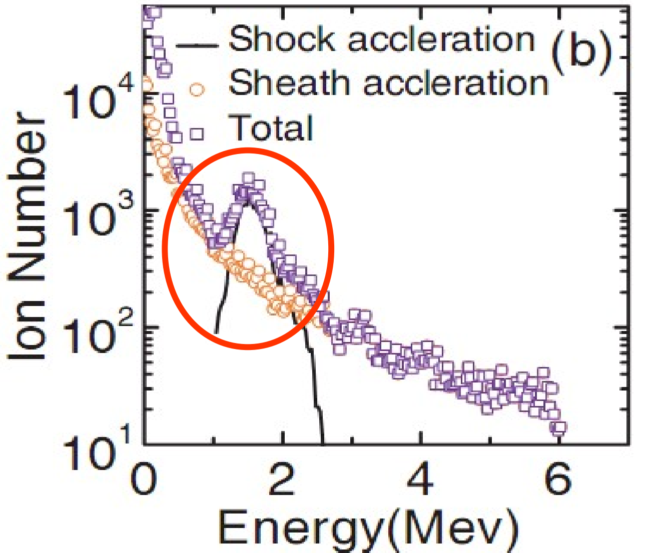
ock

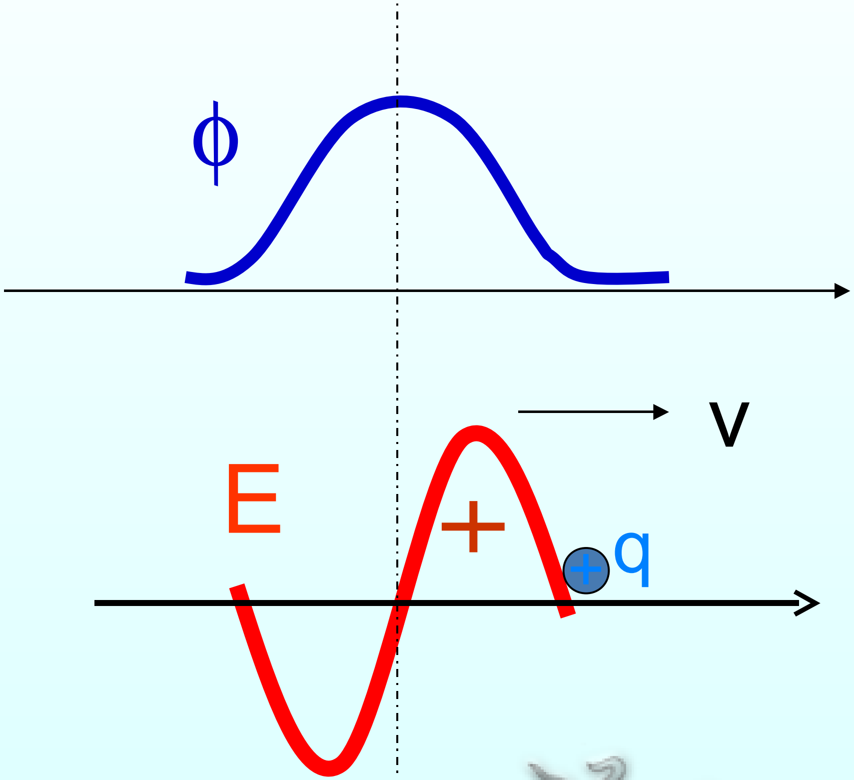
•Phase-Stable Acceleration

- Long acceleration distance
- High peak energy
- Reduced energy spread

Acceleration by a Collisionless Electrostatic Shock Wave

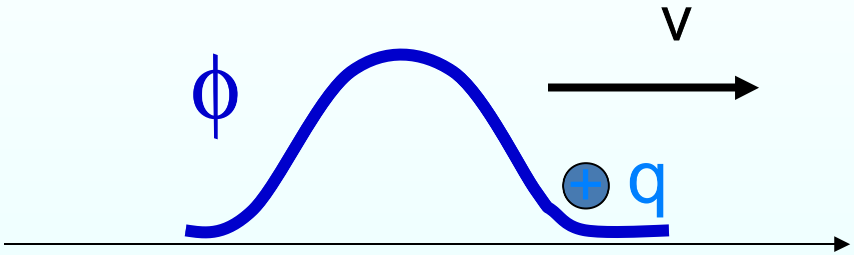






M.-Q. He et al., PRE 76,035402 (R) (2007).
Min Chen et al., PoP 14, 053102 (2007).

Energy gain in moving double layers



How to make the double layer moving faster?

$$\gamma_{\max} = \gamma_{\beta}^{2}\left(\Delta\phi_{\max} + \gamma_{\beta}^{-1} + \beta\sqrt{\Delta\phi_{\max}^{2} + 2\gamma_{\beta}^{-1}\Delta\phi_{\max}}\right)$$

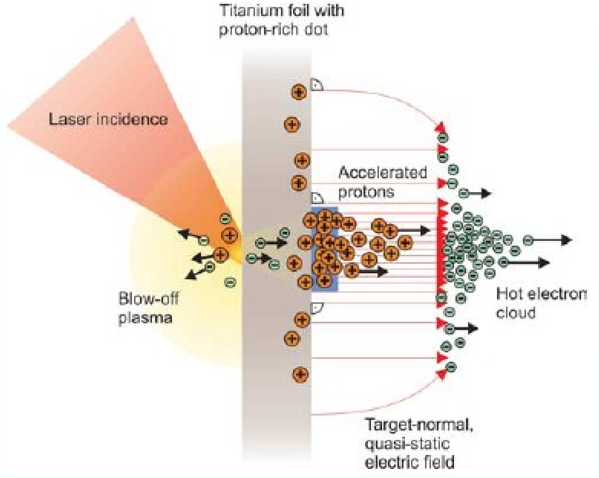
$$If \quad \beta \to 0, \qquad \gamma_{\max} = \Delta\phi_{\max}$$

$$If \quad \beta \to 1, \qquad assume \quad \Delta\phi_{\max} >> \gamma_{\beta}^{-1}$$

$$\boxed{\gamma_{\max} \approx 2\gamma_{\beta}^{2}\Delta\phi_{\max}}$$

If $\Delta\phi_{\max}$=5MeV, γ_{β}=10,
$\gamma_{\max}$ → 1GeV

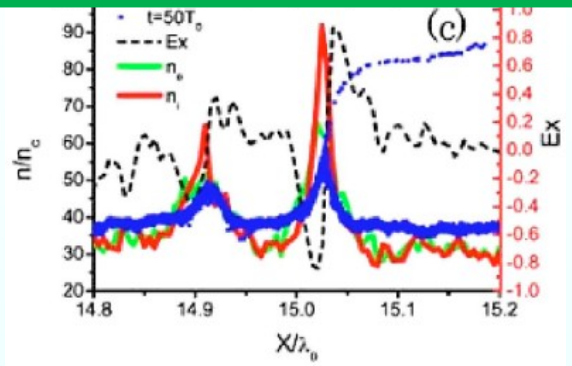
TNSA → RPA (CESA, BOA, RPA/PSA)



Target Normal Sheath Acceleration (TNSA)

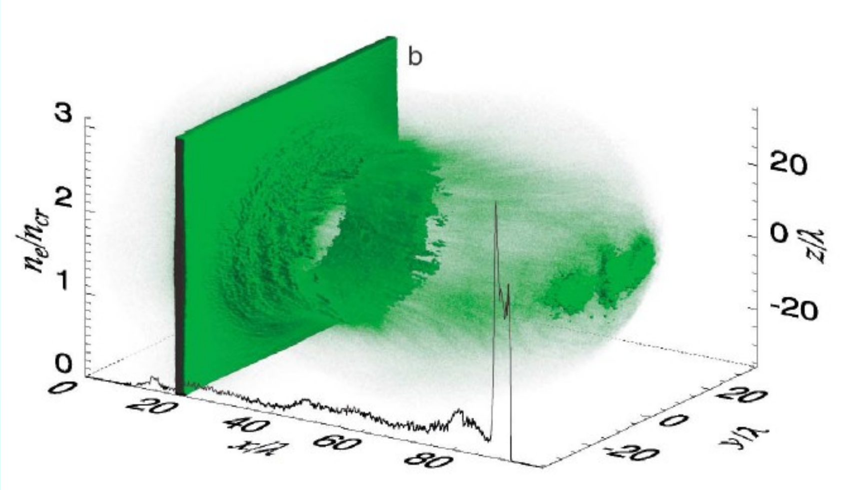
H. Schwoerer *et al*., Nature **439**, 2006(445)

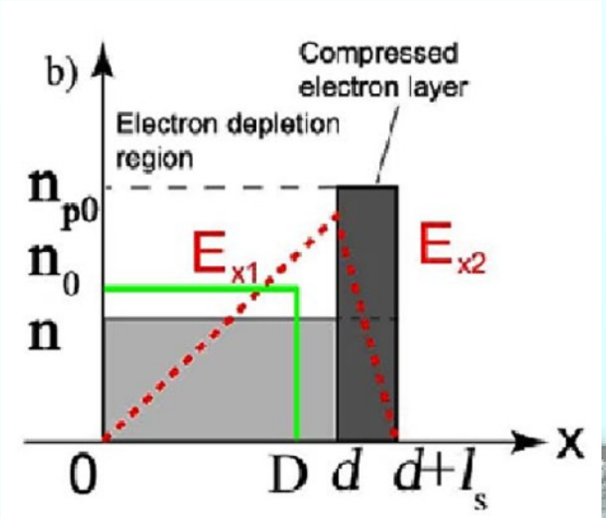
B. M. Hegelich *et al*., Nature **439**, 2006(441)



Collisionless Electrostatic Shock Acceleration (CESA)

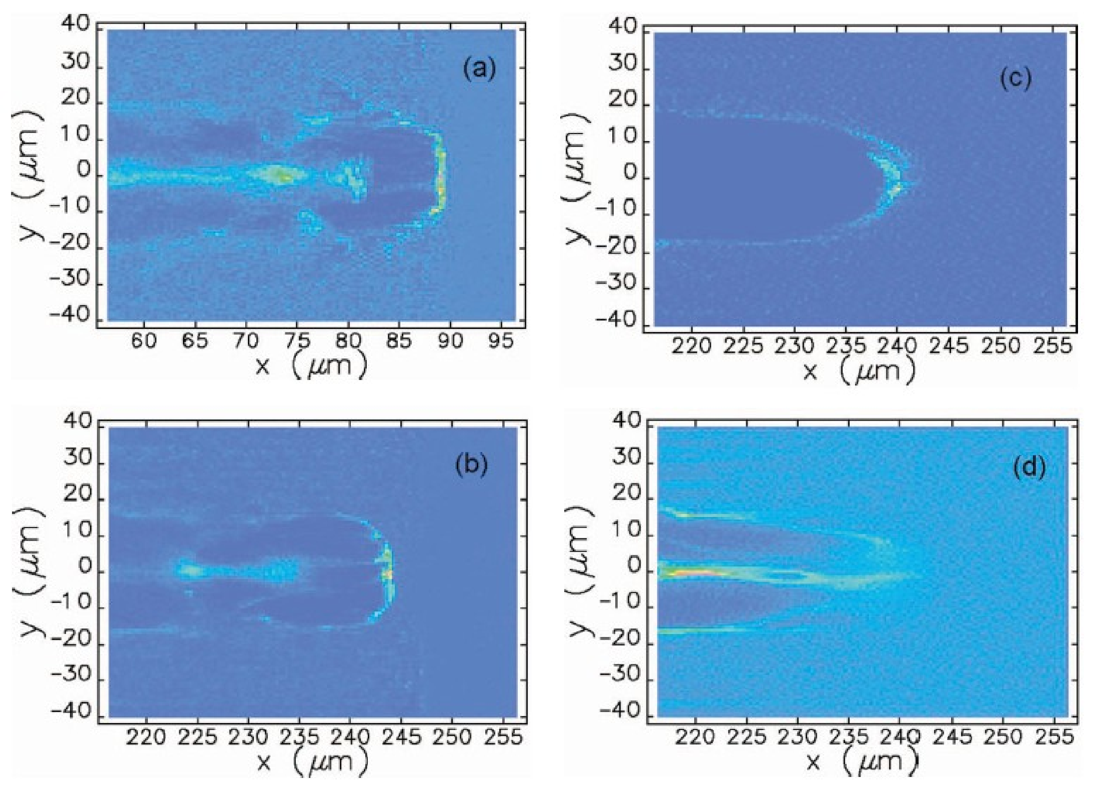
M. Chen *et al*., Phys. Plasmas **14**, 2007(053102)
L.O.Silva et al., Phys.Rev.Lett. 92,015002 (2004)

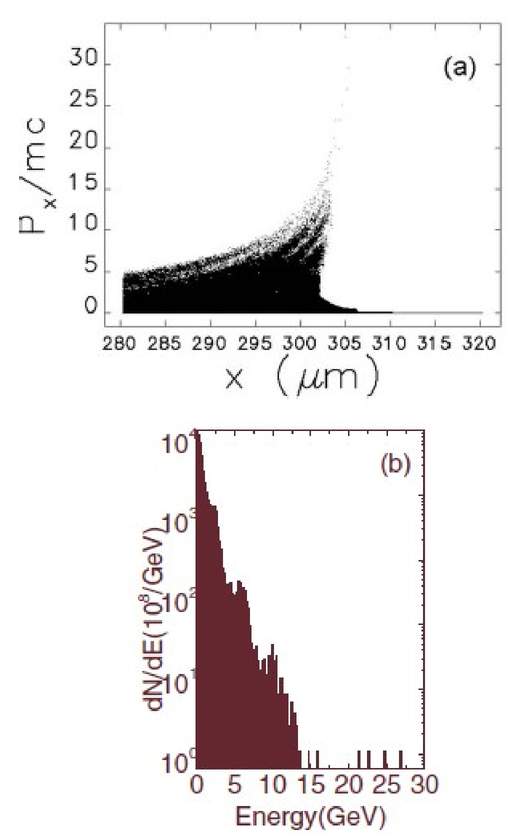




Radiation Pressure Acceleration (RPA) /Phase Stable Acceleration (PSA)

T. Esirkepov *et al*., Phys. Rev. Lett. 92, 2004(175003)
X.-Q. Yan *et al*., Phys. Rev. Lett. 100, 2008(135003)
………





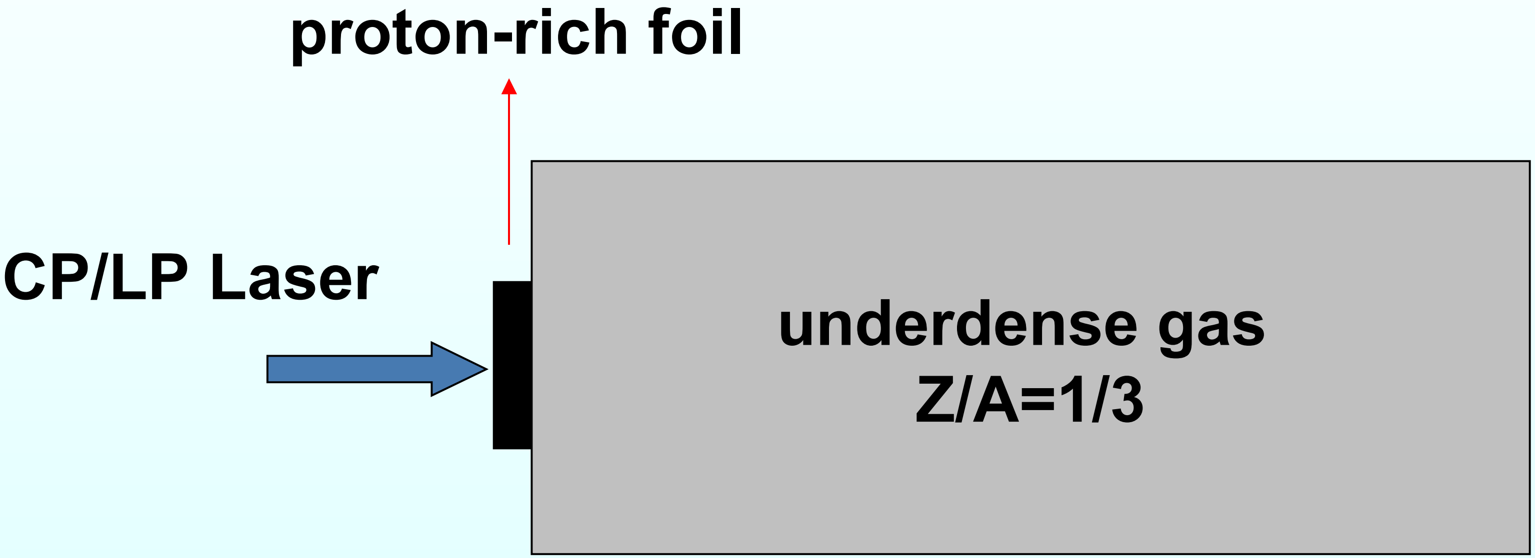
Wakefield Acceleration of protons

Target with mixed ions, low trapping protons, 100% energy spread.

B.-F. Shen *et al*., Phys. Rev. E **76**, 2007 (055402)

RPA+Laser wakefield acceleration

L.L. Yu et al., submitted to NJP



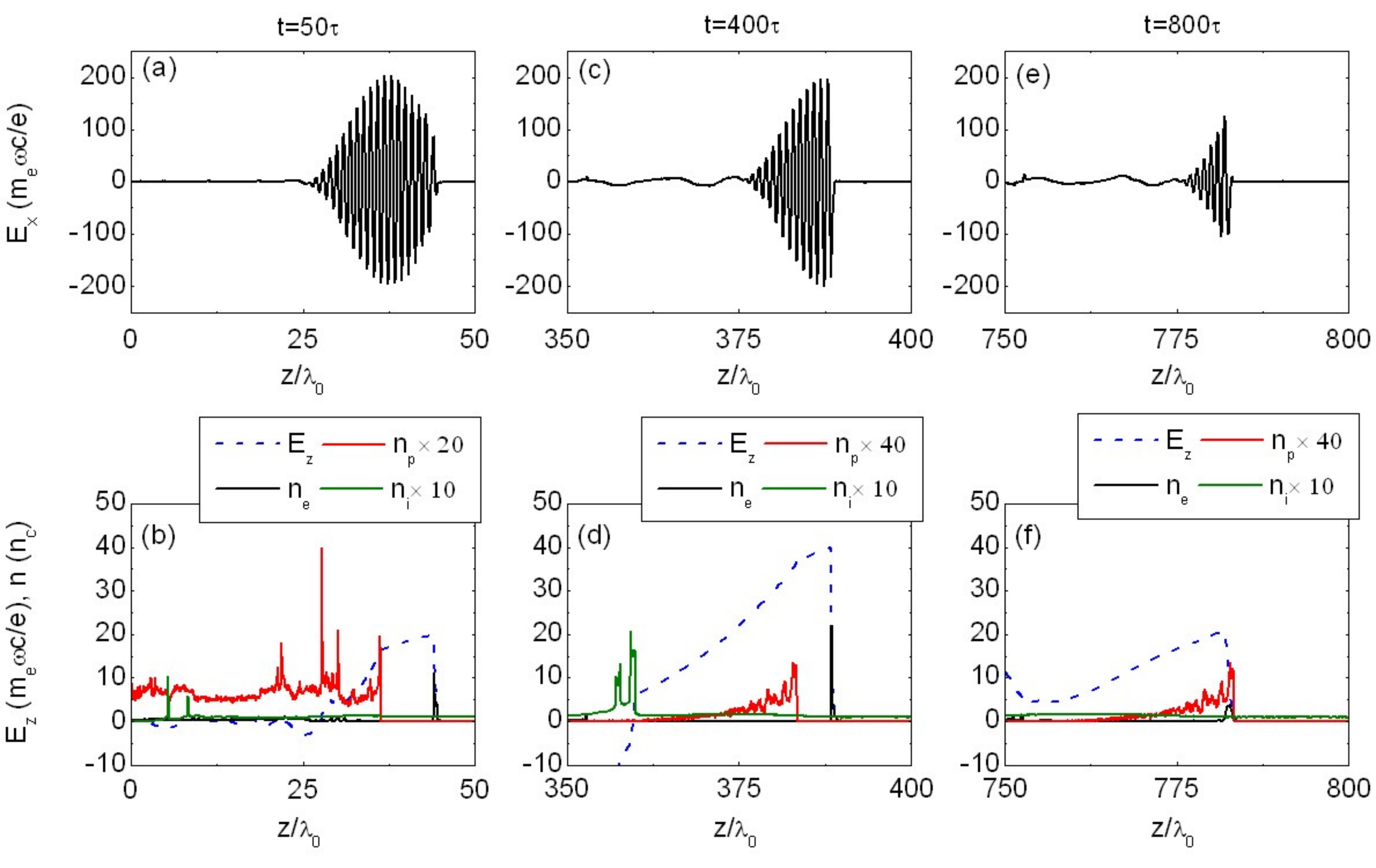
Two conditions:

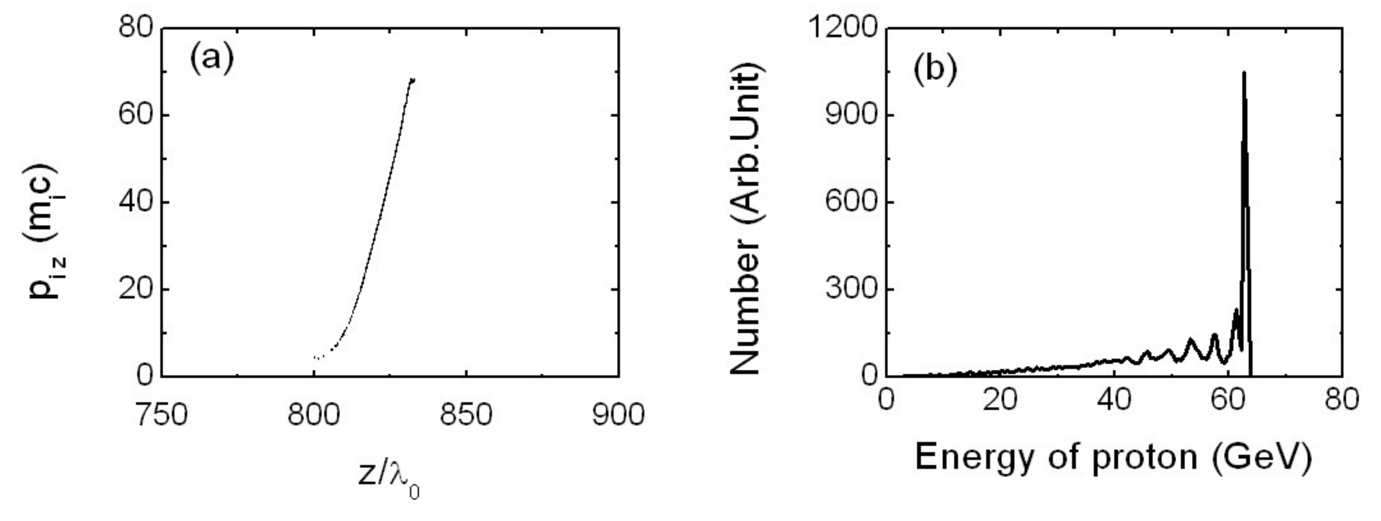
- ◆ Protons in the high-density foil can be pre-accelerated to the GeV level in the RPA regime.
- ◆ The laser pulse can obviously transmit the overdense foil to generate wakefields in the underdense plasma.

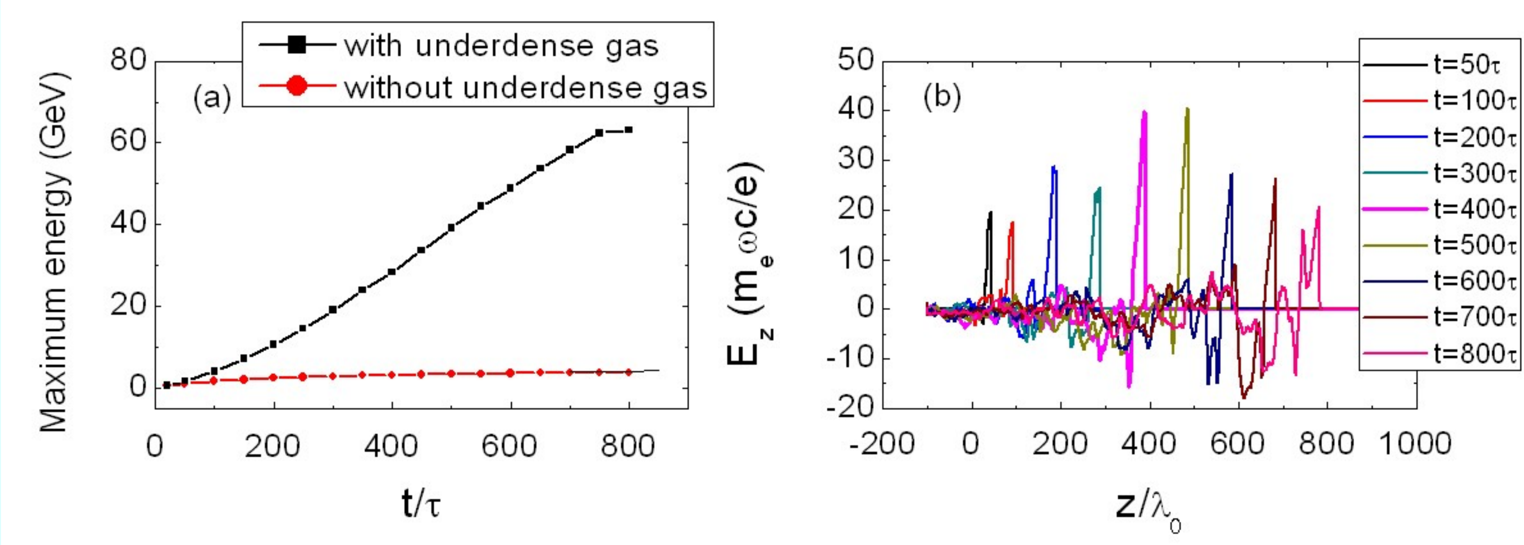
One-dimensional PIC simulations

$$n_p = 15n_c, D_p = 1\lambda_0, n_i = 0.1n_c, L = 800\lambda_0$$

$$a = a_0 \sin^2(\pi t / T), a_0 = 200, t_L = 25\tau$$





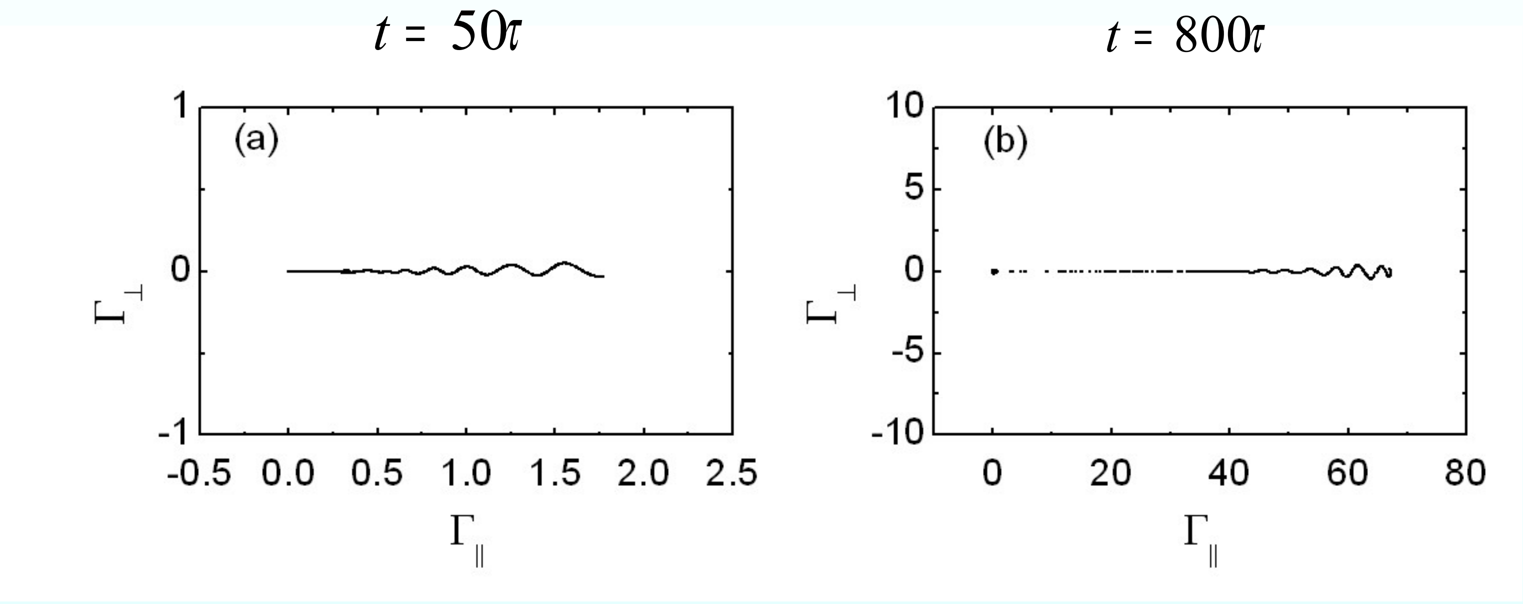


About 10% of protons are trapped and accelerated to over 60GeV

$$\bar{E}_{z,\max} \sim \text{٢٨.٩٢} m_e \omega c / e$$

$$W_{\max} = e\bar{E}_{z,\max} L_{acc} \sim \text{٦٩.٦}\,\mathrm{GeV}$$

Contributions from longitudinal and transverse fields

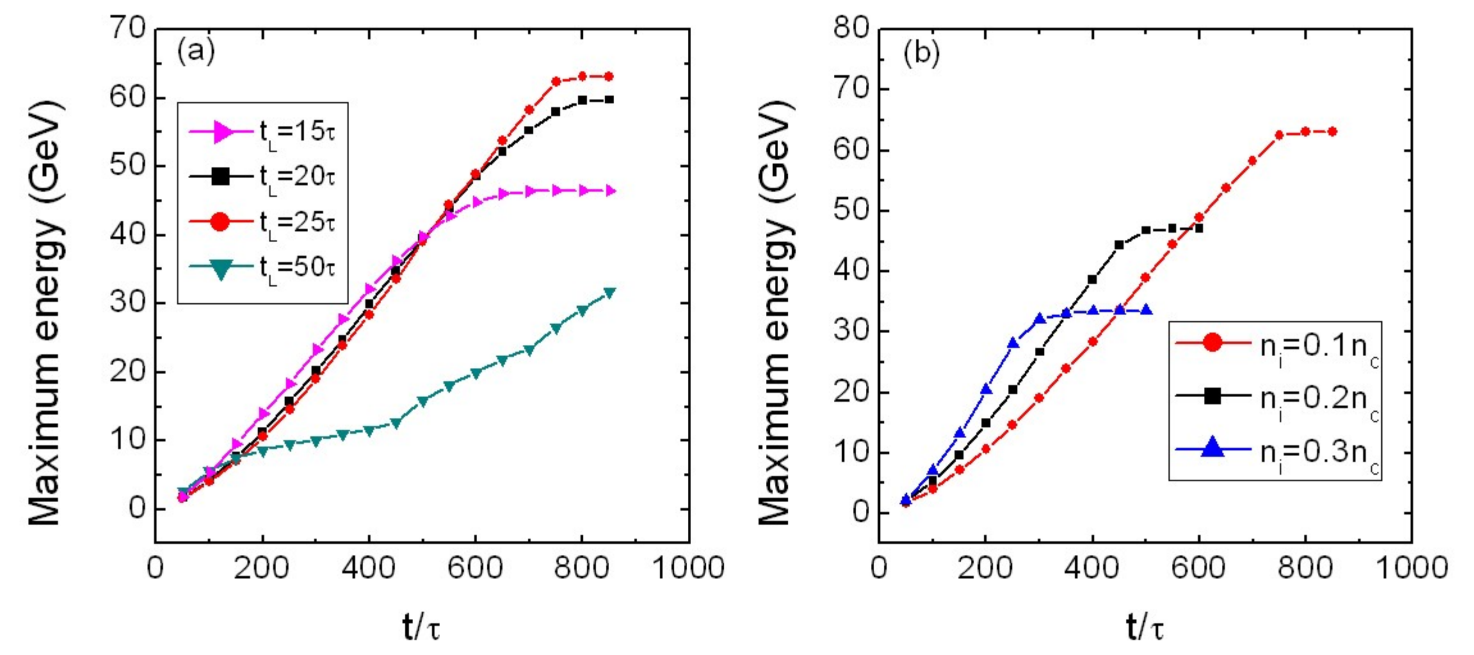


$$\Gamma_z = \int_0^t dt' E_z v_z, \qquad \Gamma_\perp = \int_0^t dt' E_\perp v_\perp$$

◆ Protons gain energy mainly from the wakefield acceleration rather than from the direct laser acceleration in underdense plasma region.

◆ The direct coupling of the laser energy to the protons cannot happen below the proton relativistic threshold intensity ~10^{24} W/cm^2.

Effects of laser duration and underdense plasma density

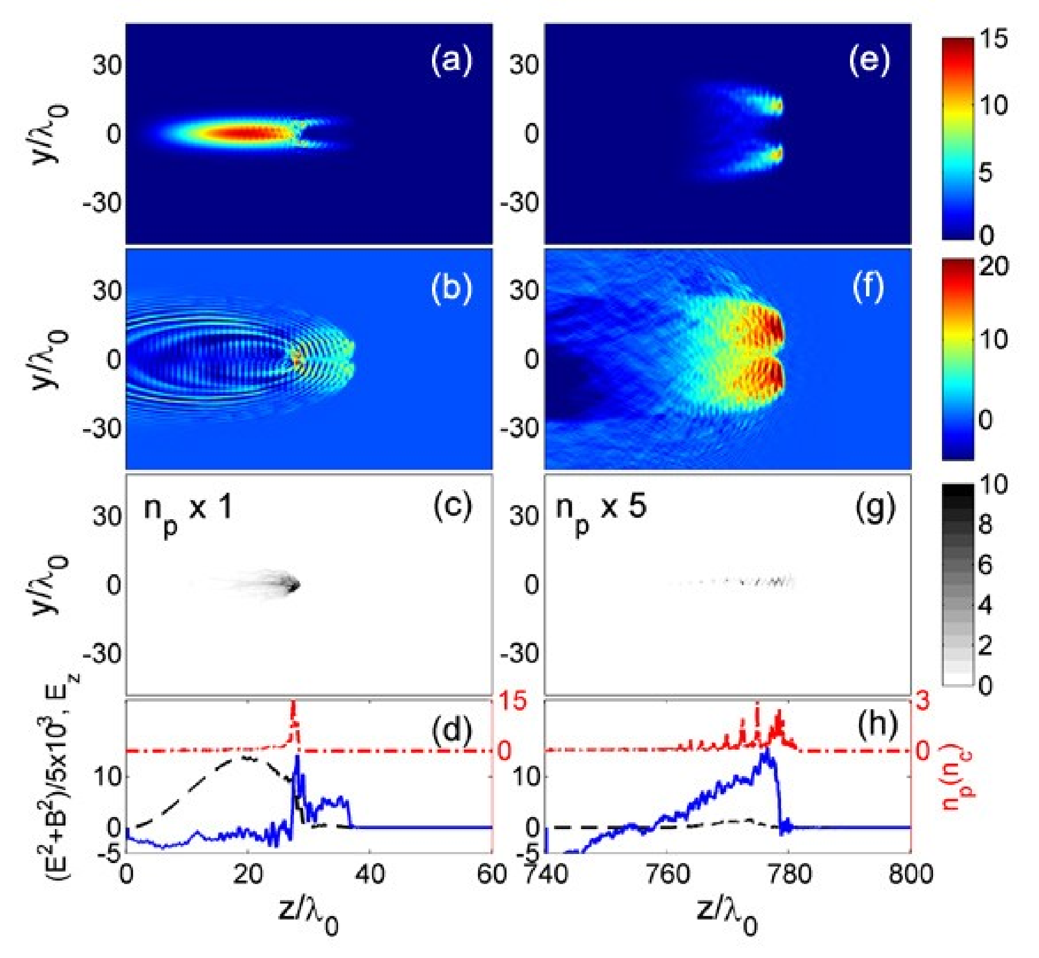


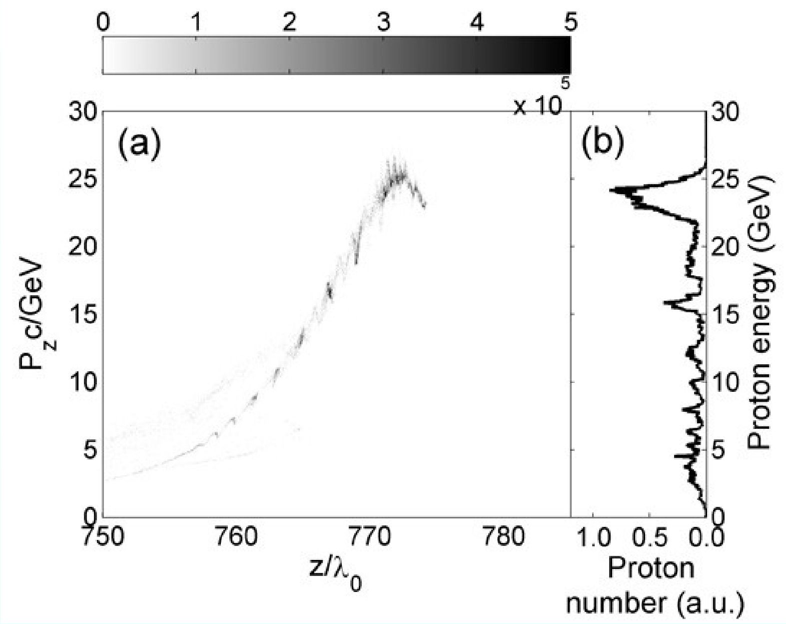
the etching velocity of the laser pulse front increases with density

$$v_{\text{etch}} = \omega_{p,i}^2 / \omega^2$$

C. D. Decker *et al.*, Phys. Plasmas **3**, 1996(2047)

Two-dimensional PIC simulations



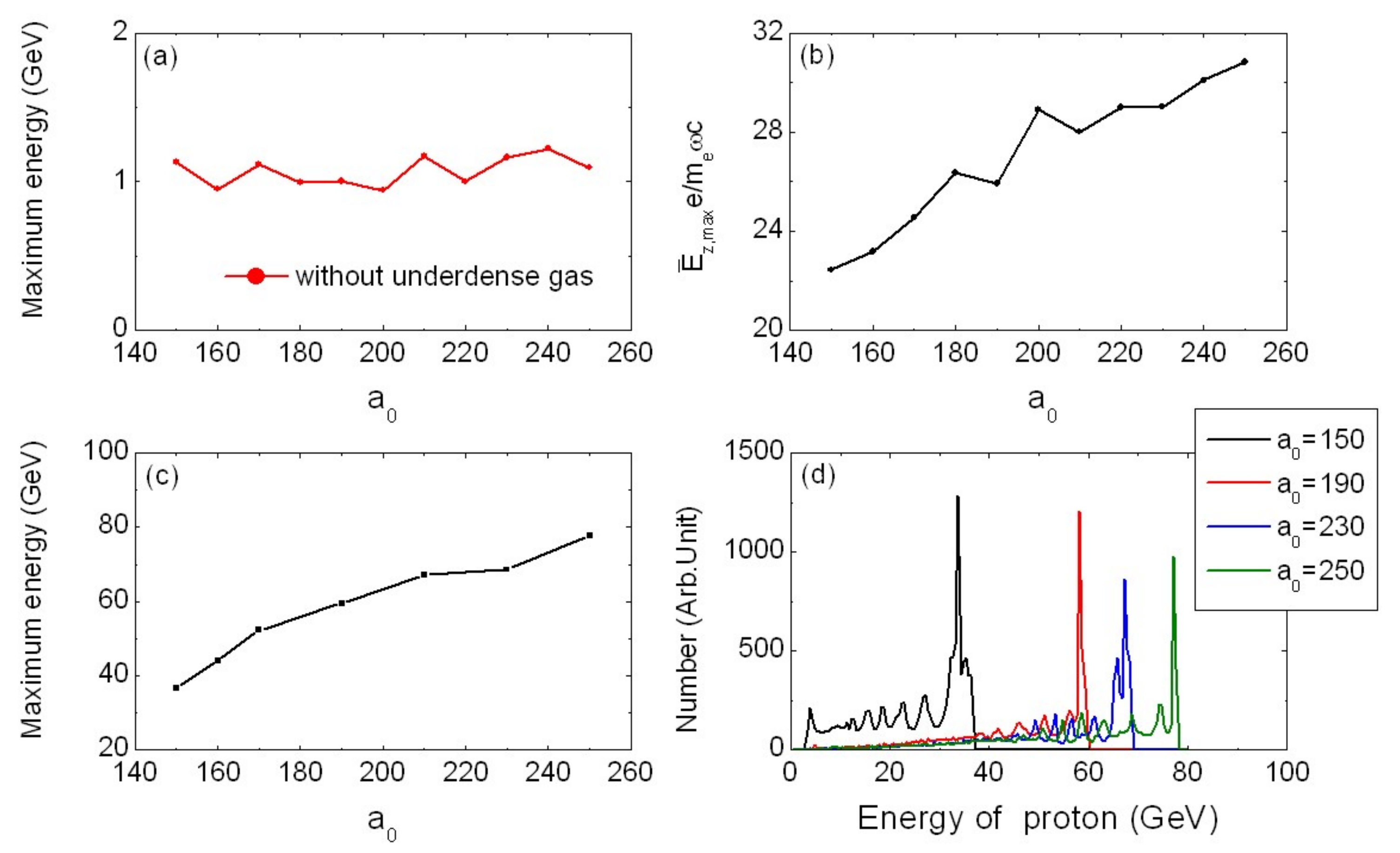


$$n_p = 50n_c, 1\lambda_0 \times 4\lambda_0$$

$$n_i = 0.2n_c, L = 800\lambda_0$$

$$a_0 = 200, t_L = 20\tau, r_0 = 8\lambda_0$$

In the laser intensity range of 10^{21}~10^{23} W/cm^2 (1D PIC)



A laser pulse with the duration of $t_L = 25\tau$ and a proton foil with the thickness of $D_p = \lambda_0$ is used when $150 \le a_0 \le 250$.

Energy Scaling

$$\gamma_{\max} = \gamma_\beta^2 (\Delta\phi_{\max} + \gamma_\beta^{-1} + \beta\sqrt{\Delta\phi_{\max}^2 + 2\gamma_\beta^{-1}\Delta\phi_{\max}})$$

$$\gamma_{\max} \approx 2\gamma_\beta^2 \Delta\phi_{\max} \quad for \quad \beta \to 1$$

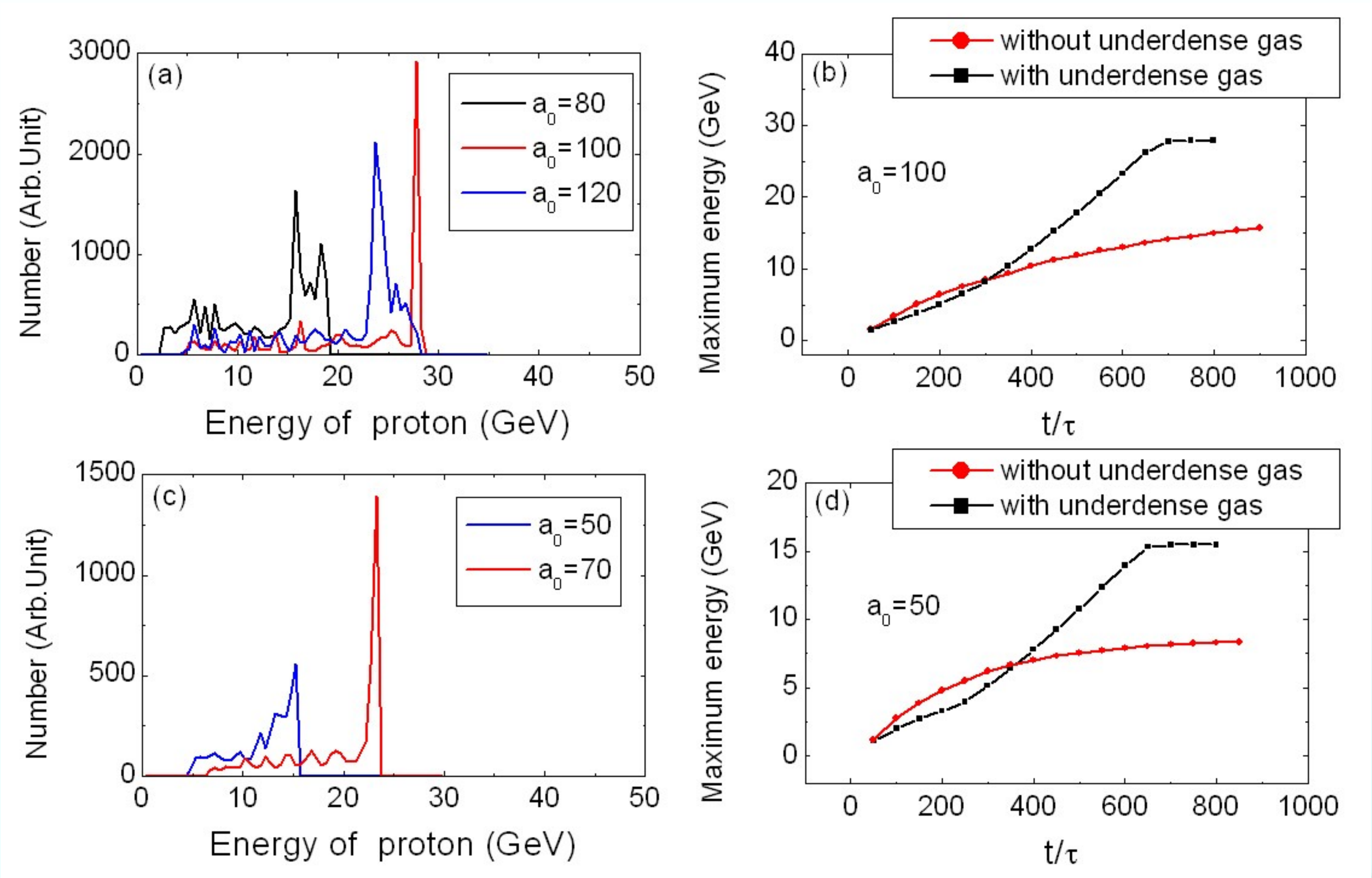
$$\gamma_\beta = (1-\beta^2)^{-1/2} \approx \omega\gamma_0^{1/2}/\omega_p \sim \omega a_0^{1/2}/\omega_p$$

$$\Delta\phi_{max} \sim a_0^{1/4\sim 1/2}$$

$$\gamma_{max} \propto a_0^{5/4\sim 3/2}$$

Simulation shows that $\gamma_{\max} \propto a_0$

In the laser intensity range of 10^{21}~10^{23} W/cm^2 (continued)



A longer laser pulse: $t_L = 50\tau$

A thinner proton foil: $D_p = \lambda_0 / 2$ when 80 <a_0 <150

$D_p = \lambda_0 / 3$ when 50 <a_0 <80

Conclusion

- We proposed a new scheme of proton acceleration with the combination of RPA and laser wakefield acceleration using an ultraintense CP laser pulse. This scheme is realized with a target consisting of a thin overdense proton-rich foil followed by a low-density gas region behind.
- By controlling the areal density of the thin protonfoil and the intensity and duration of the incident laser pulse, as well as the underdense plasma density, the pre-accelerated protons can be trapped in the positive field region and accelerated over along distance to very high energies.
- Simulations demonstrate that this mechanism can work in wide laser intensity range such as 10^{21} ～ 10^{23} W/cm^{2}, and the proton energy scales with the square root of the laser intensity.