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Laser Acceleration of Monoenergetic Protons in Moving Double Layer from Thin Foil

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Introduction

- We present analytic theory of laser acceleration of monoenergetic protons by irradiation on a thin foil, reported by Yan et al., 2008 in simulations. The ponderomotive force pushes the electrons forward, leaving ions behind until the space charge field balances the ponderomotive force at distance Δ. For the target thickness $D=\Delta$, the electron sheath piled up at the rear surface is detached from the bulk ions and moves into vacuum, carrying with it the protons contained in the sheath width of the order of skin depth. These protons are trapped by the self field of the dense electron sheath and are collectively accelerated as a double layer by the laser ponderomotive force, giving proton energy ≈ 200 MeV at a=5, and pulse length 90 fs.

$$\vec{E}_i = i\vec{B}_i = (\hat{x} + i\hat{y})A_0 e^{-i(\omega t - \omega z/c)}$$

$$\vec{E}_R = -i\vec{B}_R = (\hat{x} + i\hat{y})RA_0 e^{-i(\omega t + \omega z/c)}$$

- $$\vec{E}_T = (\hat{x} + i\hat{y})A_T(z)e^{-i\omega t},$$

$$\vec{B}_T = -(\hat{x} + i\hat{y})\frac{c}{\omega}\frac{\partial A_T}{\partial z}(z)e^{-i\omega t}.$$

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}\frac{n_e}{n_0}\frac{1}{(1+a_T^2)^{1/2}} < 0$$

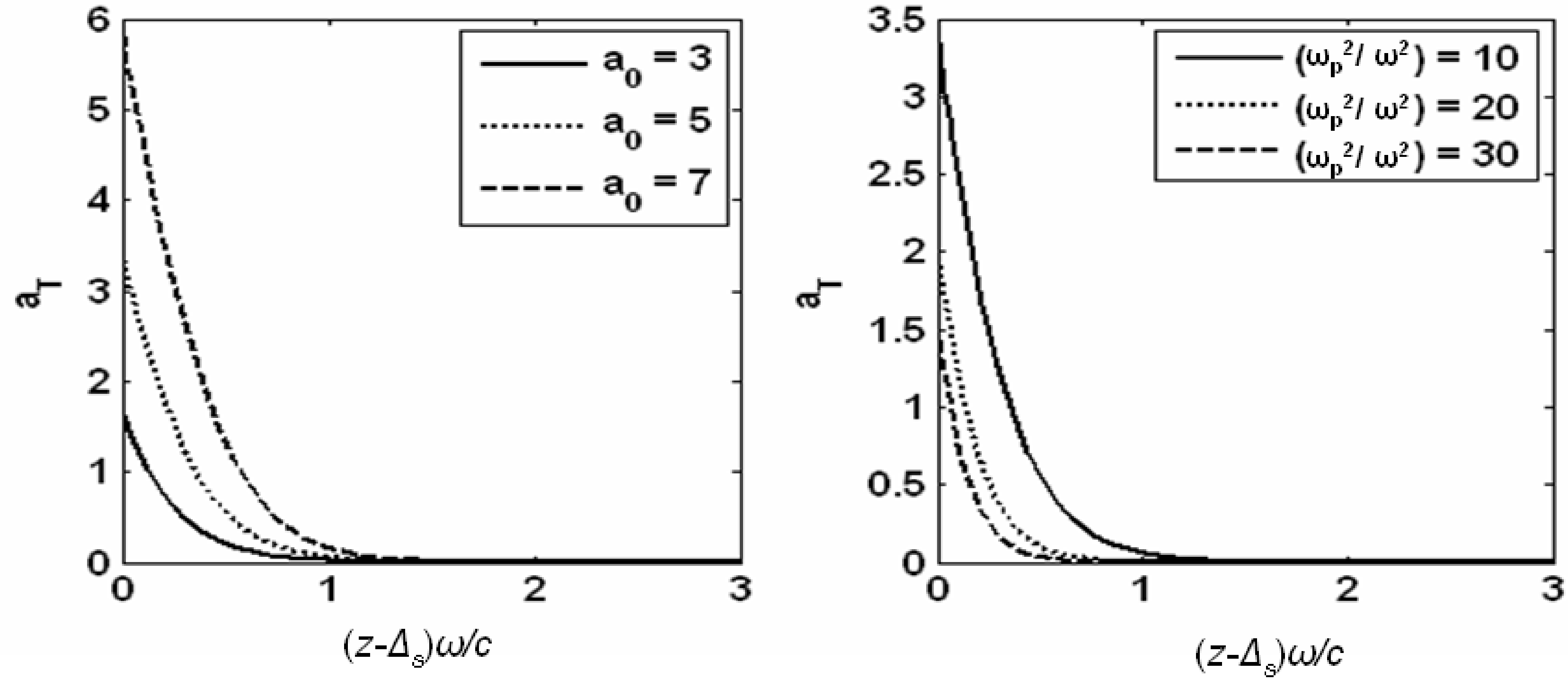
$$(1+R)a_0 = a_T(0)e^{i\phi_0},$$

$$(1-R)a_0 = \frac{c}{i\omega}\left.\frac{da_T}{dz}\right|_0 e^{i\phi_0},$$

$$\frac{d^2a_T}{dz^2} - \frac{\omega^2}{c^2}[\frac{\omega_p^2}{\omega^2}\frac{n_e}{n_0}\frac{1}{(1+a_T^2)^{1/2}} - 1]a_T = 0$$

$$\frac{da_T}{dz} = -[\frac{4\omega_p^2}{c^2}[(1+a_T^2)^{1/2} - 1] - \frac{\omega^2}{c^2}a_T^2]^{1/2}$$

$$a_T(0) = \frac{\omega}{\omega_p}a_0(2 + \frac{\omega^2}{\omega_p^2}a_0^2)^{1/2}$$



$$F_P = e\frac{\partial \phi_P}{\partial z} = -\frac{mc^2 a_T}{(1+a_T^2)^{1/2}}\frac{\partial a_T}{\partial z}$$

$$F = \int_0^\infty F_P n_0 dz = n_0 mc^2 a_0^2 \frac{\omega^2}{\omega_p^2} = 2I_0 / c$$

Electron density modification

$$eE_s = \partial / \partial z (e\phi_P)$$

$$\partial E_s / \partial z = 4\pi e (n_0 - n_e)$$

$$\frac{n_e}{n_0} = 1 + \frac{c^2}{\omega_p^2} \frac{\partial^2}{\partial z^2} (1 + a_T^2)^{1/2}$$

$$\frac{n_e}{n_0} = 1 + a_T^2 + \frac{c^2}{\omega_p^2} \frac{a_T^2}{1 + a_T^2} (\frac{\partial a_T}{\partial z})^2 - \frac{\omega^2}{\omega_p^2} a_T^2 (1 + a_T^2)^{1/2}$$

Ponderomotive force with reflectivity R^2

$$F = (I_0 / c)(1 + |R|^2)$$

$$I_0 |R|^2 = I_0 - FV_f$$

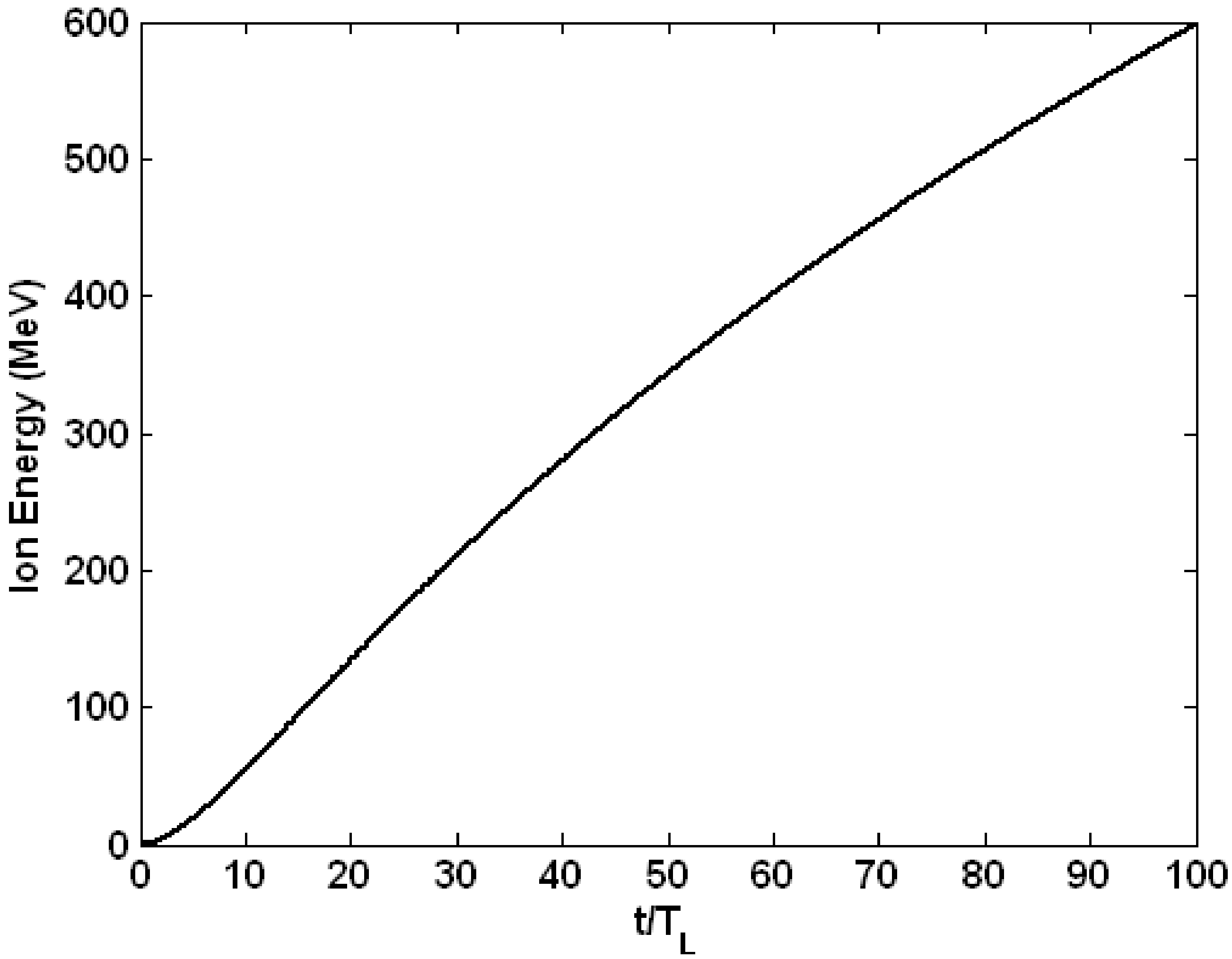
$$|R|^2 = \frac{1 - V_f / c}{1 + V_f / c}, F = \frac{2I_0 / c}{1 + V_f / c}$$

Ponderomotive acceleration of the moving layer

$$\frac{d(\gamma_f V_f)}{dt} = \frac{2I_0}{m_i n_0 l_s c} \frac{1 - V_f / c}{1 + V_f / c}$$

$$\gamma_f = (1 - V_f^2 / c^2)^{-1/2}$$

$$\left(\frac{1 + V_f / c}{1 - V_f / c}\right)^{3/2} + 3\left(\frac{1 + V_f / c}{1 - V_f / c}\right)^{1/2} = 6R\frac{t}{T_L} + 4$$



Ion Energy (MeV)
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
t/T_L