Radiation Pressure Proton Accel. from Sub-critical Foils & Gaseous Targets

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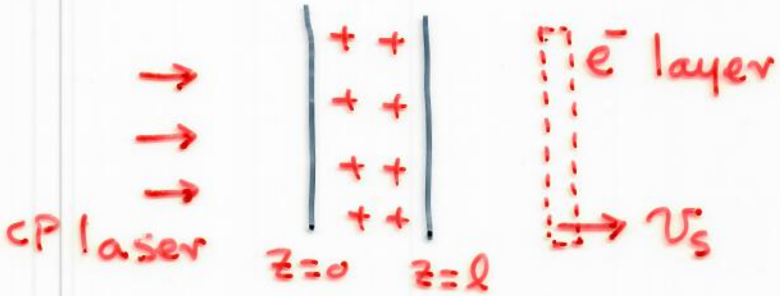
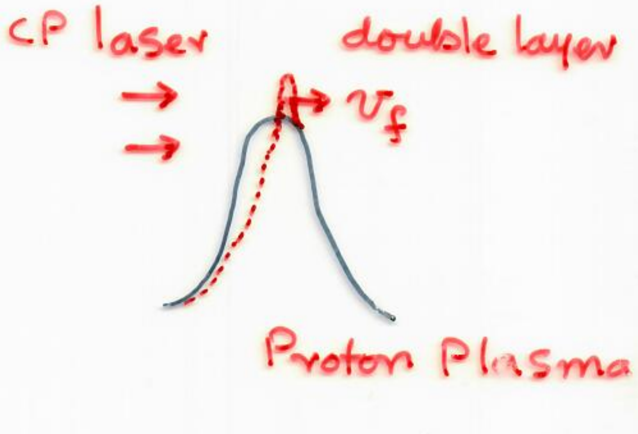
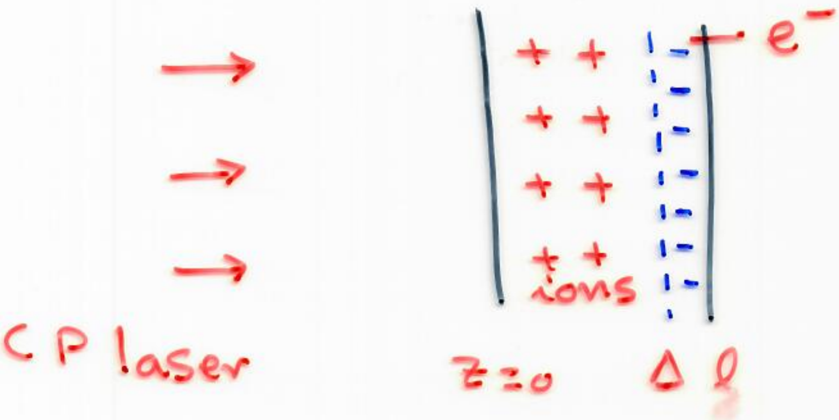
- Basic Physics of RPA
- Critical Foil Thickness
- Proton Accel: Subcritical Foils
- Double Layer Formation in Gas Targets
- Snow Plow Accel. of Upstream Protons
- Conclusions





2 RPA



Laser

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

$$I_0 = \frac{A_0^2}{\mu_0 c}$$

Ponderomotive Force on e^-

$$F_p = -mc^2 \frac{\partial}{\partial z}\gamma_e \quad , \quad \gamma_e = (1 + a_T^2)^{1/2}$$

$$a_T = \frac{e A_T}{m\omega c}$$

Radiation Pressure

$$\int F_p n_e \, dz = \frac{2 I_0}{c}$$

Pushes e^- to the rear $\Delta \sim l$

Space charge Field

$$E_s = \frac{n_0 e z}{\epsilon_0}$$

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Choose foil thickness l such that

$$\frac{2 I_0}{c} = n_0 e l E_s \,, \quad E_s = \frac{n_0 e l}{\epsilon_0}$$

↑ space charge force on e^- layer per unit area

Critical Foil Thickness

$$l_{cr} = \sqrt{2}\, a_0 \frac{n_{cr}}{n_0} \frac{\lambda_L}{2\pi}$$

$$a_0 = \frac{e A_0}{m \omega c} \,, \quad \lambda_L : \text{laser wavelength}$$

Double Layer Acceleration

$$g = \frac{2 I_0 / c}{m_p n_0 l_{cr}}$$

$$g' = g \frac{1 - v_f / c}{1 + v_f / c}$$

v_f : foil velocity

Proton energy $\mathcal{E}_p \sim t^{1/3}$

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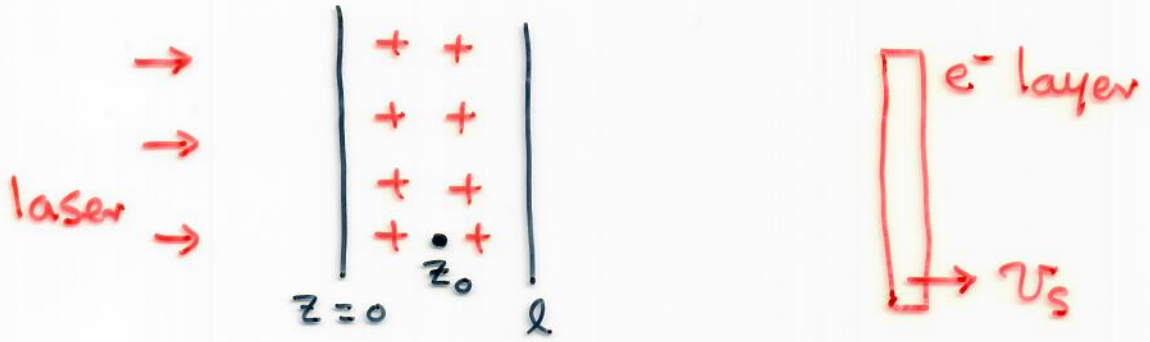
RPA of Subcritical Foil, $l < l_{cr}$



- Electron layer is detached from the foil when

$$\frac{2I_0}{c} > n_0 e l E_s$$

- As e⁻ layer moves radiation pressure on it decreases. It acquire steady state velocity v_s,

$$\frac{2I_0}{c}\,\frac{1 - v_s/c}{1 + v_s/c} = n_0 e l E_s \;, \quad E_s = \frac{n_0 e l}{\epsilon_0}$$

$$\frac{v_s}{c} = \frac{1 - l^2/l_{cr}^2}{1 + l^2/l_{cr}^2}$$

- Ion located at z_0 experiences a constant force $= -\frac{n_0 e^2}{\epsilon_0} z_0$

No sheet crossing

- Proton Energy at $z = z_p$

$$m_p c^2 (\gamma_p - 1) = \frac{n_0 e^2}{\epsilon_0} z_0 z_p$$

- Proton catches up with e^- layer at

$$z_p = \frac{2 v_s / c}{\alpha_p (1 - v_s^2/c^2)}$$

$$\alpha_p = 2\sqrt{2}\,\pi\, a_0 \frac{m}{m_p} \frac{z_0}{l_{cr}}$$

$$\mathcal{E}_p = \frac{1}{2} m_p c^2 \left(\frac{l_{cr}^2}{l^2} - \frac{l^2}{l_{cr}^2} \right)$$

$$\sim 1.2 \text{ GeV} \quad \text{for} \quad l / l_{cr} \simeq 0.6$$

- $\mathcal{E}_p$ is independent of z_0. All protons acquire same energy if v_s is maintained constant.

- Limit on Foil Thickness

$$l > l_{skin} = a_0^{1/2} c / \omega_p$$

$$a_0 \geq \frac{n_0}{2 n_{cr}} \frac{l_{cr}^2}{l^2}$$

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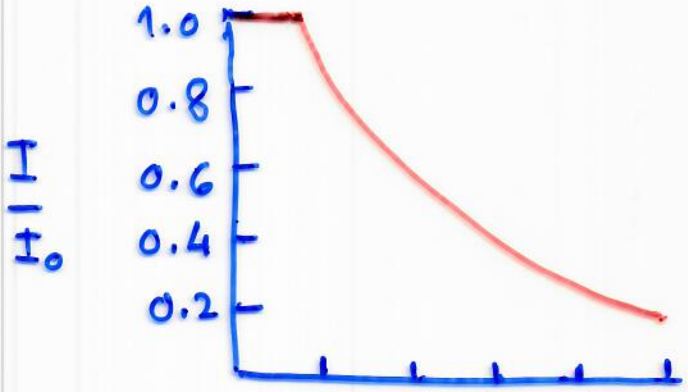
- **Pulse Shape for Minimum Proton Energy Spread**

As the ions cross the e^- layer the ion space charge pull on e^- layer decreases, so must the laser intensity to keep v_s constant

$$I = I_0 \frac{t_s}{t}\left(1 - \frac{v_s}{c}\right) \qquad \text{for } t > t_s\left(1 - \frac{v_s}{c}\right)$$

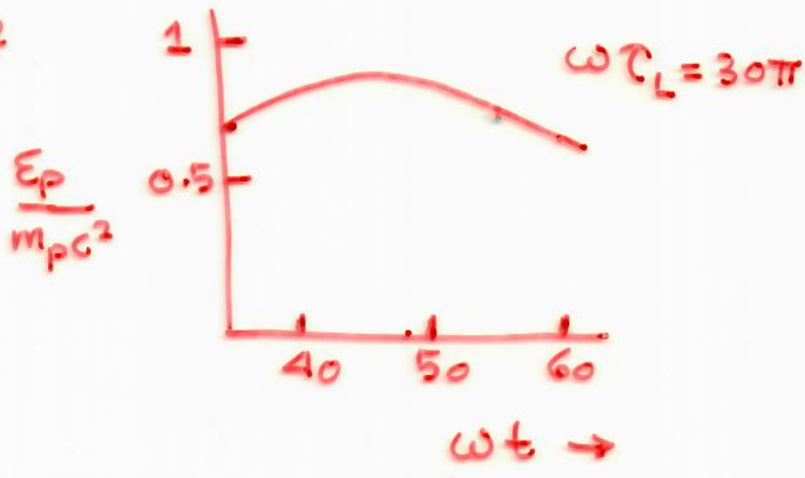
$$= 1 \qquad \text{for } t < t_s\left(1 - \frac{v_s}{c}\right)$$

$$t_s = \frac{1}{8\sqrt{2}\,\pi a_0} \frac{m_p}{m} \frac{l_{cr}}{l} \left(\frac{l^2}{l_{cr}^2} + \frac{l_{cr}^2}{l^2}\right)^2 \frac{2\pi}{\omega}$$

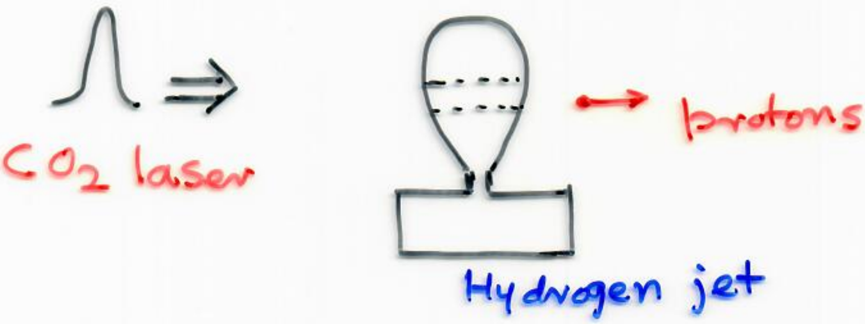


- Gaussian Pulse

$$I = I_0 e^{-(t - z/c)^2/\tau_L^2}$$



RPA of Gaseous Target : CO_2 laser



- Palmer et al. PRL <u>106</u>, 14801 (2011)

CP laser : $I \leq 10^{16}$ W/cm² $(a_0 \lesssim 0.5)$

$L_n \sim 825\,\mu m$, $n_{0max} = 10\, n_{cr}$

$\varepsilon_p \sim 1$ MeV   hole boring accel.

- Haberberger et al., Nat. Phys. <u>8</u>, 95 (2012)

LP laser , $I \lesssim 6.6 \times 10^{16}$ W/cm² $(a_0 = 1.5 - 2.5)$

$n \sim 3-5\, n_{cr}$

steepened density profile

$\varepsilon_p \simeq 22$ MeV , 1% energy spread

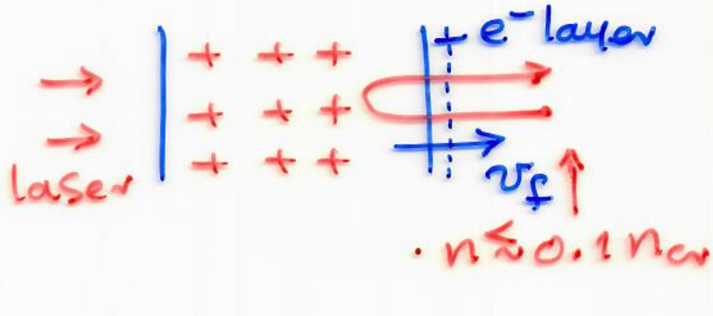
shock reflected upstream protons

- Liangliang Ji, A. Pukhov, B. Shen, New J. Phys <u>16</u>, 063047 (2014).

Dragging Field Proton Accel.

$a_0 \sim 200$, $n_0 \gg n_{cr}$

$\varepsilon_p \gtrsim 100$ GeV



Model Problem : Reflection from Density Hill

$$\omega_p^2 = \omega_{p2}^2 \ , |z| < \ell$$
$$= \omega_{p1}^2 \ , |z| > \ell$$

$$\frac{\omega_{p2}^2}{\omega^2} - 1 = 1 - \frac{\omega_{p1}^2}{\omega^2}$$

Intensity Transmission Coeff.

$$T = \frac{1}{\cosh^2(\omega \alpha \ell / c)} \ , \quad \alpha = \left(\frac{\omega_{p2}^2}{\omega^2} - 1 \right)^{1/2}$$

$$\simeq 0.06 \qquad \text{for } \omega_{p2}^2/\omega^2 = 1.1 \ ,$$
$$\ell = \lambda_L = 2\pi c/\omega$$

Radiation Pressure

$$F = \frac{2I}{c}(1 - T) \simeq \frac{2I}{c}$$

pushes the e^-, creating a double layer

Hill Creation from Parabolic Profile

$$\omega_p^2 = \omega_{p0}^2 \left(1 - \frac{z^2}{L_n^2}\right) \ , \quad |z| < L_n$$
$$= 0 \qquad \text{otherwise}$$

- Gaussian Pulse (CP)

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

$$A^2 = A_0^2\, e^{-(t - z/c)^2/\tau_L^2}$$

- Low amp. portion reflects from

$$z = -z_0 = -L_n\sqrt{1 - \omega^2/\omega_{p0}^2}$$

- High amp. portion (peak) reflects from

$$z = -z_m = -L_n\sqrt{1 - \omega^2\gamma_0/\omega_{p0}^2}$$

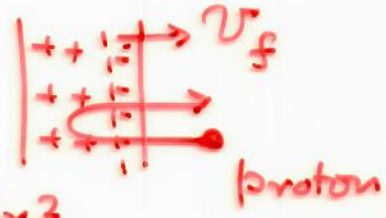
- Critical layer propagates with velocity

$$v_c \sim L_n/\tau_L$$

- For $a_0 > 2.5$, this is close to the speed of ions accel. by radiation pressure. Profile is steepened by a succession of pulses.

- Moving Double Layer in Upstream Plasma

$$n_0 m_p l \frac{dv_f}{dt} = \frac{2I}{c}\,\frac{1 - v_f/c}{1 + v_f/c} - 2 n_u m_p v_f^2 \gamma_f^2$$



Moving Double layer

10 • At time t moving ion layer extends upto

$$z_f = \frac{n_0 e^2 l t^2}{2 \epsilon_0 m_p}$$ (non-relativistic limit)

• Potential Diff. across the layer

$$\phi_s = \frac{n_0 e z_f^2}{2 \epsilon_0 (1 + z_f / l)}$$

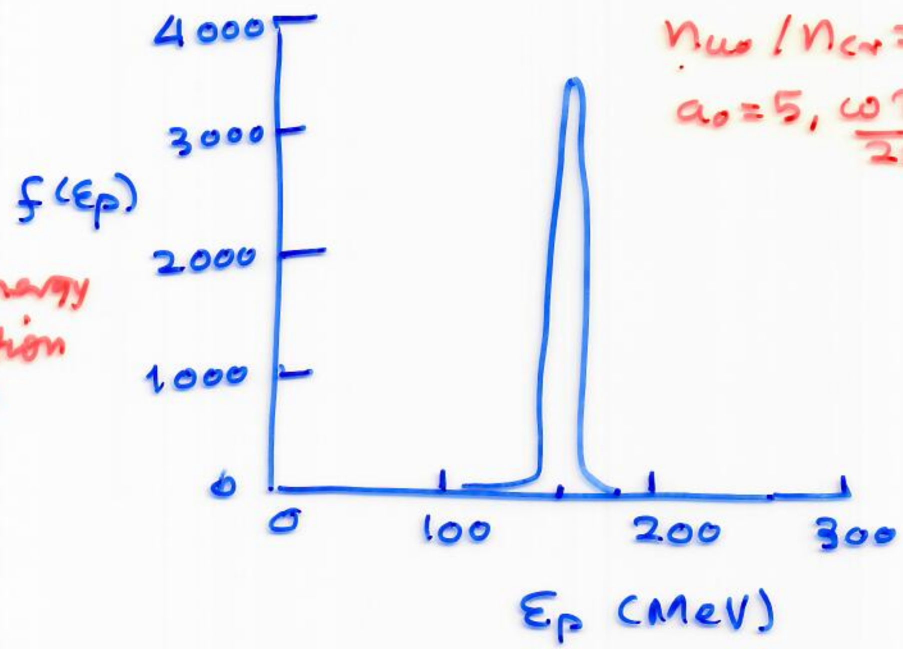
Max. Proton Energy (for which reflection is possible)

$$\mathcal{E}_p \simeq 2 m_p v_f^2 = 2 m \omega_p^2 \sqrt{z_f l}$$

Relativistic Case: Gaussian Beam / Parabolic n_u

$$\frac{dv_f}{dt} = \frac{2 a_0^2 c^2}{\gamma_f^3 l} \frac{n_{cr}}{n_0} \frac{m}{m_p} \frac{1 - v_f/c}{1 + v_f/c} - \frac{n_{u0} v_f^2}{n_0 l \gamma_f}\left(1 - \frac{z^2}{L_n^2}\right)$$

$$a_0^2 = a_{00}^2 \, e^{-(t - z/c)^2 / \tau_L^2}$$



$n_{u0} / n_{cr} = 0.4$

$a_0 = 5$, $\frac{\omega \tau_L}{2\pi} = 30$

Proton energy distribution function

Conclusions

- Subcritical thickness foils provide higher acceleration due to extended time for proton accel.
- Suitable tailoring of pulse is needed
- Gaussian pulse gives finite energy spread.
- R-T instability may be a major concern.
- CP CO_2 laser - gas jet interaction with density peak close to relativistic n_{cr} appears a promising scheme for upstream proton accel. (via reflection).
- 2 D effects need to be investigated.