Ion Acceleration by Radiation Pressure in Thick and Thin Targets

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Outline

- Ion acceleration by Radiation Pressure Acceleration (using Circularly Polarized pulses):
  the thick ("Hole Boring") and thin target ("Light Sail") regimes
- thick targets: acceleration with few-cycle pulses and preplasma effects
- thin targets: the "Light Sail" (accelerating mirror) model revisited
Why Circular Polarization?

Using CP and normal incidence (an experimentalist's nightmare...) fast electron generation by the \( jX_\mathbf{B} \) force is strongly suppressed, maximizing radiation pressure and obtaining a “smooth” acceleration of the bulk target.


Studies of thick (semi-infinite) targets (“Hole Boring”):


Studies of ultrathin (sub-wavelength) targets (“Light sail”):

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Variations on the CP theme (side effects, structured targets, optimization studies ...)

X. Zhang et al, PRST-AB 12 (2009) 021301;
X.Q. Yan et al, arXiv: 0903.4584;

Experimental investigations are highly desired!!!
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X.Q.Yan et al, arXiv:0903.4584;

Experimental investigations now coming!!!
(LIBRA experiment at GEMINI, MBI experiment, ...)
Laser penetration discriminates thick vs. thin targets

In the early stage the laser pulse penetrates into the target creating an electron depletion \((0 < x < d)\) and an electron compression \((d < x < d + l_s)\) layer.

A balance between the electrostatic field \(E_x\) and the ponderomotive force (=local radiation pressure) is established.
In the early stage the laser pulse penetrates into the target creating an electron depletion \((0 < x < d)\) and an electron compression \((d < x < d + l)\) layer. A balance between the electrostatic field \(E_x\) and the ponderomotive force (local radiation pressure)

Laser penetration discriminates thick vs. thin targets. Ions in this layer \(d < x < d + l\) are accelerated "by RPA" (actually by the electric field balancing the radiation pressure on electrons).
In the early stage the laser pulse penetrates into the target creating an electron depletion \((0<x<d)\) and an electron compression \((d<x<d+l_s)\) layer.

Ions in the “front” layer of electron depletion \(0<x<d\) are accelerated by their own space-charge field (Coulomb explosion) and do not reach “RPA” ions.
“Hole boring” and thick vs. thin targets

A simple modeling for RPA of semi-infinite targets ("hole boring" regime) accounts for the dynamics observed in PIC data and gives scalings for ion energy and acceleration time

Macchi et al, PRL 94 (2005) 165003

The faster ions originate from the layer

\[ d < x < d + l_s \quad (l_s \approx c/2\omega_p) \]

The ions pile up at \( x \approx d + l_s \) and there "wavebreaking" and bunch formation occurs.
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A “thin” target should end here, i.e. have a thickness $\ell \approx d + l_s$ in order to allow “repeated” acceleration of the “fast” ion layer.
Thick Targets: “Hole Boring” Acceleration with Few-Cycle Pulses
Scaling laws in the hole boring regime

“Piston parameter”

$$\Pi \equiv \frac{I}{\rho c^3} = \frac{Z m_e n_c}{A m_p n_e} a_0^2$$

Cut-off velocity and energy for non-relativistic ions

[A.Macchi et al, PRL 94 (2005) 165003]

$$v_{i,m} = 2 \sqrt{\frac{Z m_e n_c}{A m_p n_e}} a_0 = 2 \sqrt{\Pi}$$

$$E_{i,m} = 4Z m_e c^2 \left(\frac{n_c}{n_e}\right) a_0^2 = 2m_i c^2 \Pi$$

Relativistic corrections accounting for laser energy depletion in the Lab frame


$$\frac{v_{i,m}}{c} = \frac{2 \sqrt{\Pi}}{1 + \sqrt{\Pi}}$$

$$E_{i,m} = 2m_i c^2 \frac{\Pi}{1 + 2\sqrt{\Pi}}$$
Hole Boring: Pro et Contra

- Ion energy scales with intensity, not with pulse energy

- For solid-densities only a few MeV energies may be obtained (maybe not sufficient even to cross the target!)

BUT

- with respect to “Light Sail” (requiring ultrathin targets) the scheme seems more robust and less prone to, e.g., prepulse effects

- HB works in “preplasma”: lower densities boost ion energy [Liseikina, Borghesi, Macchi, Tuveri, PPCF 50 (2008) 124033]

- if a moderately overdense gas or liquid jet can be used as a target, higher energies may be obtained in combination with high repetition rate
  - gas jet with CO2 laser? (collaboration with A.Sgattoni et al.)
  - liquid hydrogen jet with Ti:Sa laser?
Hole Boring Acceleration with Few-Cycle Pulses

Future laser systems may produce few-cycle pulses with intensities $>10^{22}$ W/cm$^2$ and high repetition rate.

Such short pulses could “concentrate” all their energy into the acceleration of a single ion bunch.

In combination with a liquid hydrogen jet they could provide an efficient, high repetition rate source of multi-MeV protons.

Case study:

Hydrogen slab with $n_e = 50 n_c = 8.6 \times 10^{22}$ cm$^{-3}$

CP laser pulse with $\lambda = 0.8 \mu$m and 2 cycles duration (FWHM).
Peak intensity $I = 4.9 \times 10^{22}$ W/cm$^2$ ($a_0 = 106$)

(suggestion by M.Borghesi & M.Zepf, QUB, Belfast)
The ion spectrum is improved by a density gradient

Step-like density profiles:
- multiple ion bunches
- multiple peaks in the ion spectrum, cut-off energy at \( \sim 140 \) MeV

(bunch production time is less than laser cycle)

Inhomogeneous density profile (3\( \mu \)m preplasma):
- single bunch produced
- spectrum dominated by single peak at \( \sim 180 \) MeV, <10% energy spread
Circular Polarization stabilizes CE phase effects

Laser-matter interaction with few-cycle pulses is sensitive to the Carrier-Envelope phase $\phi$:

$$E(t) = f(t) \sin(\omega t + \phi)$$

For linearly polarized pulses the ion spectrum is broad and strongly dependent on $\phi$:

For circular polarization, there is almost no dependence on $\phi$ because $|E(t)|^2$ is constant in this case.
2D simulations with the AlaDyn code

(C.Benedetti et al.)

\[ n_e = 50n_c \]

H slab
4\(\lambda\) preplasma

CP Gaussian pulse
2\(\lambda\)X2\(\lambda\)
\[ a_0 = 106 \]
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2\(\lambda\) \times 2\(\lambda\)

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2D simulations with the AlaDyn code

Bunch energy on the axis \( \sim 150 \text{ MeV} \)
in agreement with 1D results
2D simulations with the AlaDyn code

Bunch energy on the axis $\sim 150$ MeV in agreement with 1D results

Work in progress to:

- find optimal and “stable” conditions
- enhance/control energy spread
- check effects of pulse profile, focusing, etc.
Thin Foil Acceleration: the “Light Sail” Model Revisited
The “Light Sail” or (Accelerating Mirror) model

Model: a perfectly reflecting, rigid mirror of mass $M = \rho \ell S$ boosted by a plane light wave.

Mirror velocity as a function of the laser pulse intensity $I$ and duration $\tau$ and of the surface density $n_e \ell$ of the target:

\[
\beta(t) = \frac{(1 + \mathcal{E})^2 - 1}{(1 + \mathcal{E})^2 + 1}, \quad \mathcal{E} = \frac{2F(t)}{\rho \ell c^2} = 2\pi \frac{Z m_e a_o^2 \tau}{A m_p \zeta} \frac{Z m_e a_o^2 \tau}{A m_p}
\]

\[
F(t) = \int_0^t I(t')\,dt' \propto a_o^2 \tau, \quad \zeta = \pi \frac{n_e \ell}{n_c \lambda}
\]

G. Marx, Nature 211, 22 (1966)
The “Light Sail” or (Accelerating Mirror) model

The efficiency of the acceleration process can be obtained by a simple argument of conservation of “number of photons” plus the Doppler shift of the reflected light:

\[ N = \frac{IS\tau}{\hbar\omega}, \quad \omega_r = \omega \frac{1 - \beta}{1 + \beta} \]

\[ \eta = \frac{\mathcal{E}_{\text{abs}}}{\mathcal{E}_{\text{laser}}} = \frac{N\hbar(\omega - \omega_r)}{IS\tau} = \frac{2\beta}{1 + \beta} \]

\[ \beta \to 1 \Rightarrow \eta \to 1 \]

100% efficiency in the relativistic limit

G.Marx, Nature **211**, 22 (1966)  
Comparison of LS model with 1D PIC simulations

Laser pulse: $a_0 = 5-50$, $\tau = 8$ cycles (“flat-top” envelope)

Thin foil target: $n_e = 250n_c$, $\ell = 0.01-0.1\lambda$ ($\zeta = 7.8-78.5$)

A narrow spectral peak is observed for $a_0 < \zeta$.

The energy of the peak is in good agreement with the LS formula.

For $a_0 > \zeta$, the dynamics is dominated by a Coulomb explosion of the foil.

Comparison of LS model with 1D PIC simulations

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Thin foil target: $n_e=250n_c$, $\ell=0.01-0.1\lambda$ ($\zeta=7.8-78.5$)

Energy spectra vs. $a_0$ and $\ell$:

Laser pulse: \( a_0 = 5-50 \), \( \tau = 8 \) cycles ("flat-top" envelope)

Thin foil target: \( n_e = 250n_c \), \( \ell = 0.01-0.1\lambda \) (\( \zeta = 7.8-78.5 \))

Energy spectra vs. \( a_0 \) and \( \ell \):

- A narrow spectral peak is observed for \( a_0 < \zeta \). The max energy is at \( a_0 = \zeta \) (dotted line)
- The energy of the peak is in good agreement with the LS formula (dashed black line)

3D simulations “support” 1D modeling

Gaussian intensity profiles lead to early “burnthrough” due to lateral expansion of the target. Supergaussian “flat-top” profiles, keeping a “quasi-1D geometry” are needed for efficient acceleration and to ensure high collimation and monoenergeticity.

However, some questions remain...

- What determines the “optimal thickness” condition $a_0 < \zeta$?

- Does the foil remain neutral after the acceleration?

- A “puzzle”: the CPA peak contains only $\sim 30\%$ of all the ions (and $\sim 64\%$ of their energy)

  → Only part of the foil is accelerated?

  → Why there is very good agreement of the energy with the LS formula when using the whole mass of the target (and not $\sim 30\%$ of it)?
Nonlinear reflectivity accounts for optimal thickness

Ultrathin slab model: \( n_e(x) = n_0 \ell \delta(x) \), foil thickness \( \ell \ll \lambda \)

Total radiation pressure in rest frame \( P_{\text{rad}} = (2I/c)R \)

Nonlinear reflectivity \( R = R(\zeta, a_0) \) can be computed analytically approximated (but rather precise) formula:

\[
R \approx \frac{\zeta^2}{\zeta^2 + 1} \quad \text{for} \quad a_0 < \zeta
\]

\[
R \approx \frac{\zeta^2}{a_0^2} \quad \text{for} \quad a_0 > \zeta
\]

\( P_{\text{rad}} \) does not depend on \( a_0 \) for \( a_0 > \zeta \) ! (since \( I \sim a_0^2 \))

The maximum boost of the foil is at \( a_0 \approx \zeta \)
Modified energy formula for $R<1, a_0<\zeta$


$$\beta(t) = \frac{(1 + \mathcal{E} - \zeta^{-2})^2 + (1 + \mathcal{E} - \zeta^{-2})\sqrt{(1 + \mathcal{E} - \zeta^{-2})^2 + 4\zeta^{-2} + 2\zeta^{-2} - 2}}{(1 + \mathcal{E} - \zeta^{-2})^2 + (1 + \mathcal{E} - \zeta^{-2})\sqrt{(1 + \mathcal{E} - \zeta^{-2})^2 + 4\zeta^{-2} + 2\zeta^{-2} + 2}}$$

$$\mathcal{E} = \frac{2F(t)}{\rho \ell c^2} = 2\pi \frac{Z m_e a_0^2 \tau}{A m_p \zeta}$$

$$F(t) = \int_0^t I(t') dt' \propto a_0^2 \tau, \quad \zeta = \pi \frac{n_e \ell}{n_c \lambda}$$

Useful for “extremely ultrathin” foils $\zeta \approx 1-10$. 
Balance of radiation and electrostatic pressures

For $a_0 < \zeta$ the maximum electrostatic pressure $P_{es}$ (corresponding to complete electron depletion) exceeds the radiation pressure; electrons are held back (for circular polarization and quasi-equilibrium conditions!)

$$P_{rad} = (2I/c)R < P_{es} = 2\pi(e n_0 \ell^2)$$ for $a_0 < \zeta$

$$P_{rad} = P_{es}$$ for $a_0 = \zeta$

If $a_0 < \zeta$ and $\zeta > 1$, $R \approx 1$ and no electrons are pushed away (the ponderomotive force at the rear surface is zero)

For $a_0 \to \zeta$ all the electrons must pile up near the rear surface in order to establish the equilibrium between $P_{rad}$ and $P_{es}$.

→ the compression layer is much thinner than the foil
→ only a fraction of the foil is accelerated
1D PIC simulations confirm model suggestions

Laser pulse: $a_0 = 30$, $\tau = 8$ cycles ("flat-top" envelope)
Thin foil target: $n_e = 250n_c$, $\ell = 0.04\lambda$, $\zeta = 31.4$, 
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![Graph showing $n_i$, $n_e$, $E_x$, $E_L$ over $x/\lambda$ at $t=0.2$.](image)
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Electrons pile up in a very thin layer at the rear surface as expected; almost no electrons leave the foil.
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Only the ions in the thin compression layer are pushed by RPA; the effectively accelerated "foil" is thinner and is negatively charged (excess of electrons)
“Excess” electrons leave the foil after the pulse

Laser pulse: \( a_0 = 30 \), \( \tau = 8 \) cycles (“flat-top” envelope)
Thin foil target: \( n_e = 250 n_c \), \( \ell = 0.04 \lambda \), \( \zeta = 31.4 \),
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\[ t = 11.5 \]
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Thin foil target: $n_e = 250n_c$, $\ell = 0.04\lambda$, $\zeta = 31.4$,
“Light Sail” RPA is not “front side” acceleration

The effective acceleration of only a thin rear layer implies that the scheme may work in double-layer targets (either manufactured or “natural”- hydrogen impurities on the surface) and might be used for the acceleration of protons.

Note: This may explain why the “transition to RPA dominance” was observed in numerical experiments for double layer targets.

[T.Esirkepov et al., PRL 96, 105001 (2006)]

Such simulations were performed for linear polarization, showing a “transition to RPA dominance” at $I>10^{23}$ W/cm$^2$ (“Laser-Piston”) which has not a simple explanation (strongly relativistic effects probably need to be considered).

[T.Esirkepov et al., PRL 92, 175003 (2004)]
Simulation of double layer target

Laser pulse: $a_0 = 30$, $\tau = 8$ cycles ("flat-top" envelope)

Thin foil target: $n_e = 250n_c$, $\ell = 0.04\lambda$, $\zeta = 31.4$, C and H layers
Simulation of double layer target

Laser pulse: $a_0 = 30$, $\tau = 8$ cycles ("flat-top" envelope)
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![Graph showing simulation results](image-url)
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Thin foil target: $n_e = 250n_c$, $\ell=0.04\lambda$, $\zeta=31.4$, C and H layers
Simulation of double layer target

Laser pulse: $a_0 = 30$, $\tau = 8$ cycles ("flat-top" envelope)
Thin foil target: $n_e = 250 n_c$, $\mathcal{L} = 0.04 \lambda$, $\zeta = 31.4$, C and H layers
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ion spectrum, $t = 16.0000$
The effective mass of the foil

We are left with one question:

*Why the foil velocity is given by the LS formula where the whole mass (=thickness) of the foil must be used BUT only a thinner, lower mass “foil” is accelerated?*

Energy stored in the electrostatic field $E_x$:

$$U_{es} = U_{es}(t) = \int_0^{X(t)} \frac{E_x^2(x, t)}{8\pi} dx$$

“Conversion efficiency” into electrostatic energy $\eta_{es}$:

$$\frac{dU_{es}}{dt} = \frac{1}{8\pi} E_x^2[X(t), t] \frac{dX}{dt} = \frac{1}{8\pi} E_0^2 \beta c$$

$$\eta_{es} = \frac{1}{I} \frac{dU_{es}}{dt} = 2\beta \left(\frac{d}{\ell}\right)^2 \left(\frac{\zeta}{a_0}\right)^2$$

For $a_0 = \zeta$, the depletion width $d \approx \ell$ thus $\eta_{es} \approx 2\beta$:

most of the stored energy is converted into electrostatic energy
The effective mass of the foil

We are left with one question:

**Why the foil velocity is given by the LS formula where the whole mass (≡thickness) of the foil must be used BUT only a thinner, lower mass “foil” is accelerated?**

Stored electrostatic energy ≡ inertial mass

\[
\text{total mass=}
\]
\[
\text{accelerated ions mass + “electrostatic mass” = initial mass of the foil}
\]

the effective conversion into ion energy < \(\frac{2\beta}{1+\beta}\)


For \(a_0=\zeta\), the depletion width \(d\approx\ell\) thus \(\eta_{es}\approx2\beta\):

most of the stored energy is converted into electrostatic energy
Conclusions

- Hole boring RPA:
  - more “robust”
  - less favorable scaling
  - preplasma control may improve the energy spectrum
  - interesting for next-future few-cycle interactions
    and if suitable “flowing”, moderate-density targets
    can be used

- Light Sail RPA:
  - (much) more challenging
    (ultra-high contrast pulse needed, flat-top profiles important...)
  - very attractive for energy and efficiency
  - revisited LS model accounts for most of the numerical
    observations
  - in principle suitable for double-layer targets
    and proton acceleration

This talk may be downloaded from
www.df.unipi.it/~macchi/talks.html