Radiation Pressure Acceleration

Andrea Macchi

National Institute of Optics, National Research Council (CNR/INO),
Adriano Gozzini research unit, Pisa, Italy

Enrico Fermi Department of Physics, University of Pisa, Italy

Chalmers University of Technology
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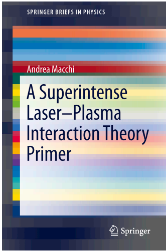
References for RPA basics (parochial selection)

A. Macchi, M. Borghesi, M. Passoni,
Ion Acceleration by Superintense Laser-Plasma Interaction,
Rev. Mod. Phys. **85** (2013) 571



A. Macchi,
A Superintense Laser-Plasma Interaction Theory Primer (Springer, 2013)
Chap.5 “Ion Acceleration” (for absolute beginners)

A. Macchi,
Theory of Light Sail Acceleration by Intense Lasers: an Overview,
High Power Laser Science and Engineering **2** (2014) e10

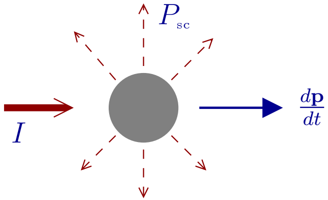
The vision of “coherent” acceleration: Veksler (1957)

V. I. Veksler, At. Energ. **2** (1957) 525

- accelerating field on each particle proportional to the number of accelerated particles
- automatic synchrony between the particles and the accelerating field
- field localization in the region where the particles are
- acceleration of quasi-neutral bunches with large numbers of particles

(Macro)-Particle Acceleration by Thomson Scattering

Acceleration of a particle undergoing Thomson Scattering
Landau & Lifshitz, *The Classical Theory of Fields*, ch.78 p.250 (1962).



$$\frac{dp}{dt} = \sigma_T \frac{I}{c} \frac{1-\beta}{1+\beta} \qquad (p = m\beta\gamma c)$$

$$\sigma_T I \propto P_{\mathrm{sc}}$$

absorbed momentum per unit time is proportional to scattered power

Veksler's idea: coherent scattering by a cluster of radius $a \ll \lambda$ with N $(\gg 1)$ particles, $P_{\mathrm{sc}} \to N^2 P_{\mathrm{sc}} \Rightarrow \sigma_T \to N^2 \sigma_T$

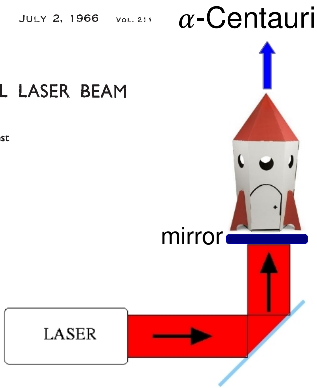
Early vision of radiation pressure acceleration (1966)

22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

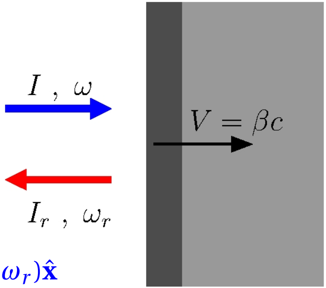
By PROF. G. MARX
Institute of Theoretical Physics, Roland Eötvös University, Budapest

A solution to “Fermi’s paradox”: “*Laser propulsion from Earth . . . would solve the problem of acceleration but not of deceleration at arrival . . . no planet could be invaded by unexpected visitors from outer space*”



Accelerating mirror model

Perfect mirror boosted by a plane wave: force on the mirror and mechanical efficiency η derived from Doppler shift and conservation of photon number N



$$I = \frac{N\hbar\omega}{\tau} \qquad \Delta\mathbf{p} = N\hbar(\mathbf{k}_i - \mathbf{k}_r) = N\frac{\hbar}{c}(\omega + \omega_r)\hat{\mathbf{x}}$$

$$\omega_r = \omega\frac{1-\beta}{1+\beta} \qquad \Delta t = \frac{\tau}{1-\beta} \qquad \frac{\Delta p}{\Delta t} = \frac{2I}{c}\frac{1-\beta}{1+\beta}$$

τ: pulse duration
Δt: reflection time

$$\eta \equiv \frac{\Delta\mathscr{E}}{I\tau} = \frac{N\hbar(\omega+\omega_r)}{N\hbar} = \frac{2\beta}{1+\beta}$$

High efficiency but slow gain as $\beta \to 1$

Light Sail solutions in 1D - 1

$$\frac{d}{dt}(\gamma\beta) = \frac{2I(t-X/c)}{\sigma c^2}R(\omega')\frac{1-\beta}{1+\beta} \qquad \frac{dX}{dt} = \beta c \qquad (\sigma \equiv \rho\ell)$$

(notice the dependence of R on $\omega' = \gamma(1-\beta)\omega$ and of the pulse profile $I(t)$ on $w \equiv t - X/c$)

Assuming $R \simeq 1$

$$\frac{d}{dw}\left(\frac{1+\beta}{1-\beta}\right)^{1/2} = \frac{\gamma}{1-\beta}\frac{d\beta}{dw} = \frac{2I(w)}{\sigma c^2}$$

$$\left(\frac{1+\beta(w)}{1-\beta(w)}\right)^{1/2} - 1 = \frac{2}{\sigma c^2}\int_0^w I(w')dw' \equiv \frac{2F(w)}{\sigma c^2} \equiv \mathscr{F}(w)$$

$$\beta(w) = \frac{[1+\mathscr{F}(w)]^2 - 1}{[1+\mathscr{F}(w)]^2 + 1} \qquad \mathscr{E}_{\text{max}} = m_p c^2[\gamma(\infty) - 1] = m_p c^2 \frac{\mathscr{F}_\infty^2}{2[\mathscr{F}_\infty + 1]}$$

Fast scaling with pulse fluence (energy per unit surface)

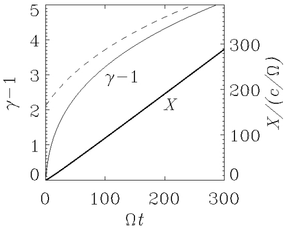
Light Sail solutions in 1D - 2

LS EoM can be integrated for constant intensity I (L&L - CTF)

$$\gamma(t) = \sinh(u) + \frac{1}{4\sinh(u)}\,, \qquad u \equiv \frac{1}{3}\text{asinh}(3\Omega t + 2)\,, \qquad \Omega \equiv \frac{2I}{\sigma c^2}$$

limiting cases ($\beta \ll 1$ and $\beta \simeq 1$, $(1+\beta)/(1-\beta) \simeq 4\gamma^2$)

$$\gamma(t) = \begin{cases} 1 + [1 - \exp(-2\Omega t)]^2/8 & (\Omega t \ll 1) \\ (3\Omega t/4)^{1/3} & (\Omega t \gg 1) \end{cases}$$



Relativistic transparency and optimal thickness

Thin plasma foil becomes transparent because of relativistic effects when

$$a_0 > \zeta \equiv \pi \frac{n_e}{n_c} \frac{\ell}{\lambda}$$

$a_0 = \left(\frac{I}{m_e n_c c^3} \right)^{1/2}$ (dimensionless amplitude)

$n_c = \frac{m_e \omega^2}{4\pi e^2}$ (cut-off density)

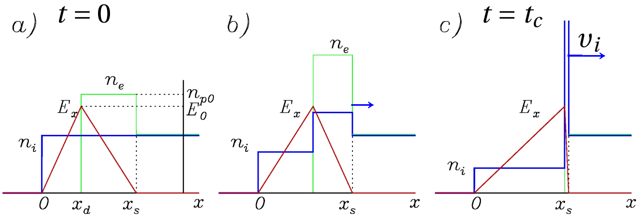
→ optimal thickness as trade-off between reduced mass and transparency: $a_0 = \zeta$

- Optimal condition appears accessible using ultrathin targets ($\ell \simeq 10^{-2}\lambda$, $\zeta \lesssim 10$)

Beyond the mirror: charge separation effects

Real targets are not perfect rigid mirrors: radiation pressure separates electrons from ions

Electrostatic tension balances $P_{\text{rad}} \simeq 2I/c$ and accelerates ions [Macchi et al PRL **94** (2005) 165003; **103** (2009) 85003]

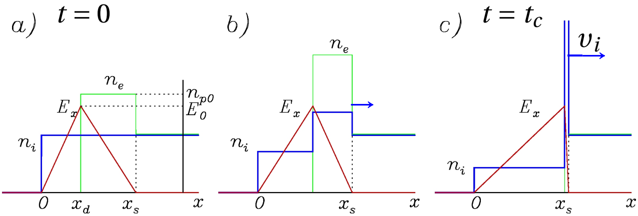


An ion bunch is formed as ions exit the skin layer

Ion motion in the skin layer

Simple model gives ion bunch velocity v_i at “overtake” time t_c

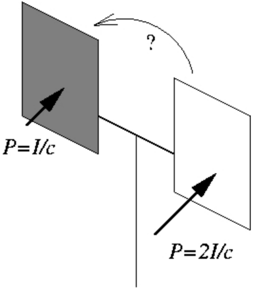
$$\frac{v_i}{c} \simeq \left(\frac{Zm_e n_c}{Am_p n_e}\right)^{1/2} a_0 \quad \text{at} \quad t = t_c \simeq \frac{c/\omega_p}{v_i} = \frac{1}{\omega_p a_0}\left(\frac{Am_p n_e}{Zm_e n_c}\right)^{1/2}$$



LS motion is the “average” of repeated ion bunch acceleration

[M.Grech et al, New J. Phys. **13** (2011) 123003]

How to make radiation pressure dominant?



The "Optical Mill" rotates in the sense *opposite* to that suggested by the imbalance of radiation pressure: *thermal* pressure due to *heating* dominates

Enforcing radiation pressure dominance requires to suppress heating of the surface

For ultraintense lasers: radiation pressure push must overcome internal pressure due to the generation of "fast" electrons

Simple criteria for RPA "dominance" - I

Heuristic criterion:
ions must respond promptly to charge separation
(before electrons heat up too much → expansion dominates)

Ions become promptly (nearly) relativistic sticking to electrons when:

$$v_i/c = 1/2 \quad \longrightarrow \quad a_0 \simeq 30 \left(\frac{n_e}{n_c}\right)^{1/2} > 300$$

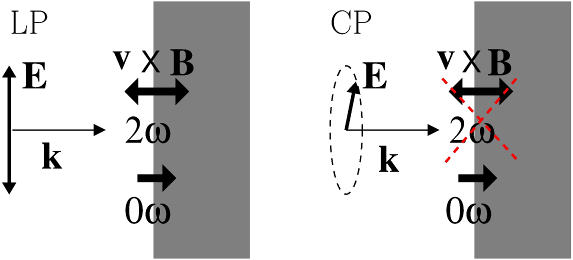
$$\longrightarrow \quad I\lambda^2 > 10^{23}\ \text{W cm}^{-2}\mu\text{m}^2$$

→ RPA dominance expected at ultra-high intensities (yet to be reached!)

[see also: Esirkepov et al, PRL **92** (2004) 175003]

Simple criteria for RPA “dominance” - II

Suppress electron longitudinal oscillations and heating using Circular Polarization at normal incidence



Ions respond “smoothly” to steady component:
RPA dominance at “any” intensity
[Macchi et al, PRL **95** (2005) 185003]

Simple criteria for RPA “dominance” - III

Ions move across the skin layer within a laser halfcycle: prompt “cancellation” of charge separation

$$t_c < \pi/\omega \quad \longrightarrow \quad \frac{1}{\pi a_0}\left(\frac{Am_p}{Zm_e}\right)^{1/2} \simeq \frac{19}{a_0} < 1$$

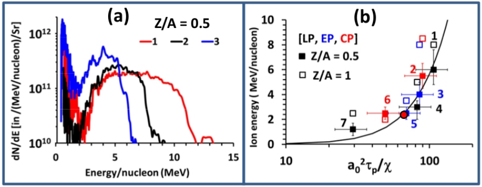
$$\longrightarrow \quad I\lambda^2 > 5 \times 10^{20} \text{ W cm}^{-2}\mu\text{m}^2$$

Consequence: important RPA effects in current experiments (also for Linear Polarization)

[A. Macchi, High Power Laser Science and Engineering **2** (2014) e10]

$\mathscr{F}^2$ scaling experimentally observed

VULCAN laser, RAL/CLF:
Laser pulse: $t_p \simeq 800$ fs
3×10^{20} W cm^{-2}
Target: ~ 0.1 μm metal foil

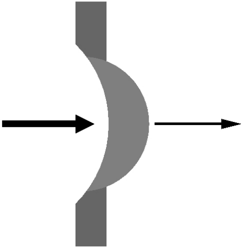


Multispecies ($Z/A = 1 \div 1/2$) peaks observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Up to $\simeq 10$ MeV/nucleon observed with $\mathscr{F}^2$-scaling on average
Simulations suggest > 100 MeV/nucleon are within reach

Kar, Kakolee, Qiao, Macchi et al, PRL **109** (2012) 185006

Significant non-RPA effects observed: broad spectra, species separation, weak dependence on polarization . . .

Fast gain Light Sail in 3D



Transverse expansion of the target reduces on-axis surface density $\rho\ell$
⇒ *light sail gets "lighter"*:
boost of energy gain
at the expense of the number of ions
[S.V.Bulanov et al, PRL **104** (2010) 135003]

LS equations accounting for self-similar transverse dilatation of target in D-dimensions ($D = 1, 2, 3$)

$$r_\perp(t) = \Lambda(t) r_\perp(0) \,, \qquad \sigma = \sigma(t) = \frac{\sigma(0)}{\Lambda^{D-1}(t)}$$

$$\frac{d}{dt}(\gamma\beta_\parallel) = \frac{2I}{\sigma(0)c^2}\Lambda^{D-1}(t)\frac{1-\beta_\parallel}{1+\beta_\parallel}$$

Model for target dilatation

Model: transverse kick due to ponderomotive force

$$\frac{dp_\perp(t)}{dt} \simeq -m_e c^2 \partial_r (1+a^2(r,t))^{1/2} \simeq 2 m_e c^2 a_0 r / w \qquad (a_0 \gg 1, r \ll w)$$

→ transverse momentum scales linearly with position

$$\frac{d\Lambda}{dt} = \frac{\dot{r}_\perp(t)}{\dot{r}_\perp(0)} = \frac{\alpha}{\gamma(t)}\,, \qquad \gamma(t) \simeq (p_\parallel^2 + m_i^2 c^2)^{1/2}\,, \qquad \alpha \simeq 2\frac{m_e a_0 c^2 \Delta t}{m_p w^2}$$

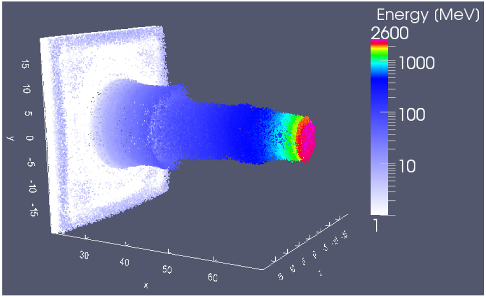
Solution in the $\gamma \gg 1$ limit

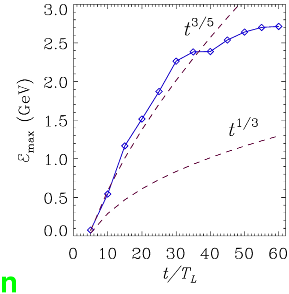
$$\gamma = \left(\frac{t}{\tau_k}\right)^k\,, \qquad k = \frac{D}{D+2}$$

Fast gain in 3D $\sim t^{3/5}$ with $\tau_{3/5} = (48/125\Omega\alpha)^{1/3}$.

High energy gain in 3D LS simulations

Laser: 24 fs, 4.8 μm spot, $I = 0.85 \times 10^{23}$ W cm^{-2} $\Longrightarrow$ **1.5 kJ**
Target: $d = 1$ μm foil, $n_e = 10^{23}$ cm^{-3}

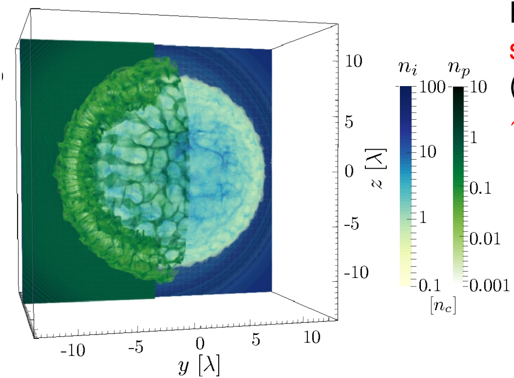




$\mathcal{E}_{\max} \simeq 2.6$ GeV $>$ **4X 1D model prediction**

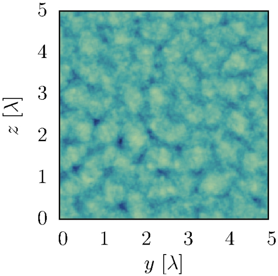
Macchi et al, Plasma Phys. Contr. Fus. **55** (2013) 124020;
Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

Transverse structures in ion density



Two species target -
protons and carbon ions

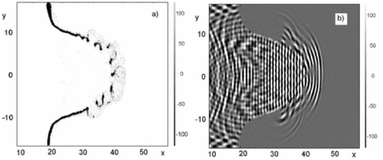
Formation of net-like structures with size $\sim \lambda$ (laser wavelength) and $\sim$ hexagonal shape



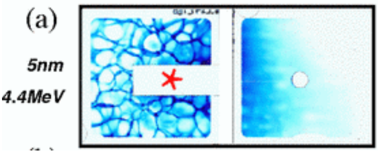
What is the origin of structures and of the dominant scale?

Rayleigh-Taylor Instability in LS?

Thin foil target of areal density σ accelerated by a laser of intensity I is unstable with growth rate $\gamma = (P_0 q/\sigma)^{1/2}$ with $P_0 = 2I/c$ and q the wavevector [Ott, PRL **29** (1972) 1429]



2D simulation
[F.Pegoraro & S.V.Bulanov, PRL **99** (2007) 065002]

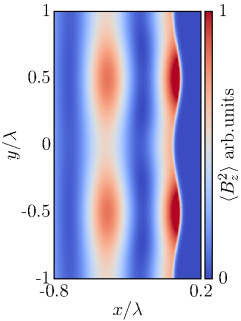


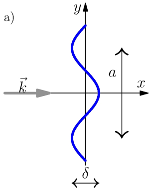
Experimental indication from accelerated ion beam profile structures [C.Palmer et al, PRL **108** (2012) 225002]

What sets the dominant wavevector $q \sim (2\pi/\lambda)$?

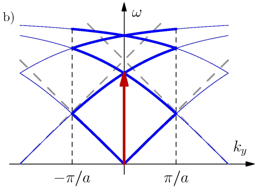
Plasmonic modulation of radiation pressure

The EM field at a rippled surface (e.g. 2D reflecting, sinusoidal grating of period d) is modulated with plasmonic enhancement of the P-component when $d \sim \lambda$





Geometry



Matching with surface plasmons

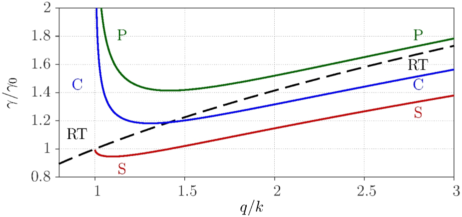
The resulting modulation of laser light pressure provides a spatial seed for RTI

Thin foil RTI with self-consistent pressure modulation

Model: reflection from shallow 2D grating of depth δ (first order in δ/λ) + modified Ott's theory[1] with modulated pressure:

$$P \simeq P_0\left(1 + K(q)\delta\cos qy\right), \qquad K(q) = \begin{cases} -(q^2-k^2)^{1/2} & (S) \\ k^2(q^2-k^2)^{-1/2} & (P) \\ (k^2-q^2/2)(q^2-k^2)^{-1/2} & (C) \end{cases}$$

$$\gamma = (P_0/\sigma)^{1/2}\left[\left(q^2+K^2(q)/4\right)^{1/2} + K(q)/2\right]^{1/2}$$



S-polarization

P-polarization

C-ircular polarization

RT: no modulation ($\delta = 0$)

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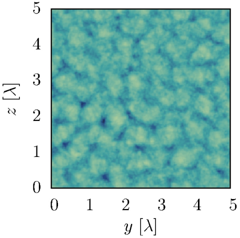
[1] E. Ott, PRL **29** (1972) 1429

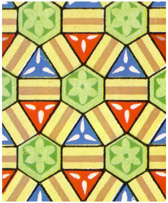
Symmetry of RTI structures

Hexagonal-like structures generated by nonlinear evolution of RTI: an example of spontaneous symmetry breaking in a classical system with “wallpaper” p6m symmetry



S.I.Abarzhi, PRE **59** (1999) 1729
D.Schattschneider, Amer. Math. Monthly **85** (1978) 439

A. Sgattoni, S. Sinigardi, L. Fedeli, F. Pegoraro, A. Macchi, PRE **91** (2015) 013106



Persian glazed tile