Light Sail Acceleration: Recent Results

Andrea Macchi

National Institute of Optics, National Research Council (CNR/INO), Pisa, Italy

Department of Physics “Enrico Fermi”, University of Pisa, Italy

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Main coworkers for this talk

A. Sgattoni[1,2], S. Sinigardi[3], M. Tamburini[1,4,*], F. Pegoraro[1,4], T. V. Liseykina[5], P. Londrillo[6], D. Doria[7], C. Scullion[7], S. Kar[7], L. Romagnani[8], M. Borghesi[7]

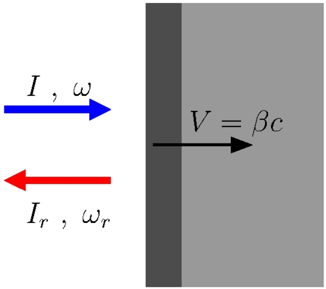
[1]CNR/INO, Pisa, Italy
[2]Dipartimento di Energia, Politecnico di Milano, Milan, Italy
[3]Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[4]Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Italy
[5]Institut für Physik, Universität Rostock, Germany
[6]INAF and INFN, Bologna, Italy
[7]Center for Plasma Physics, Queen's University of Belfast, UK
[8]LULI, École Polytechnique, Palaiseau Cedex, France
[*]presently at MPI-K, Heidelberg, Germany

Outline

- Quick review of the Radiation Pressure Acceleration concept
  - an argument for the onset of important RPA effects
- Quick review of the Light Sail concept
- Recent experimental results
  - VULCAN data: "fast" scaling
  - GEMINI data: polarization dependence
- Simulations for GEMINI experiments
- Simulations at ultra-high intensities (relativistic ions):
  - high gain regimes
  - instabilities and beam structuring

The “accelerating mirror” paradigm

Perfect mirror boosted by a plane wave: mechanical efficiency η and momentum transfer to mirror derived by Doppler shift and photon number conservation

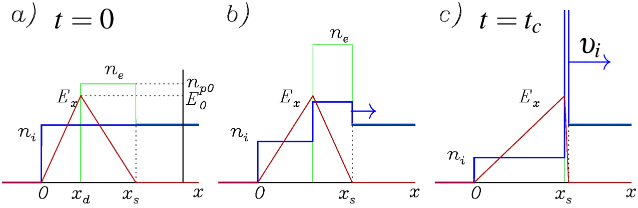


$$\frac{dP}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta} \qquad \eta = \frac{2\beta}{1+\beta}$$

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

Beyond the mirror: ion motion in the skin layer

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



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

$$n_c = \frac{m_e \omega^2}{4\pi e^2} \qquad \frac{\omega_p}{\omega} = \frac{n_e}{n_c} \qquad a_0 = \left(\frac{I}{m_e c^3 n_c}\right)^{1/2}$$

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:

$$v_i/c = 1/2 \quad \longrightarrow \quad a_0 \simeq 30 \left(\frac{n_e}{n_c}\right)^{1/2} > 300$$
$$\longrightarrow \quad I\lambda^2 > 10^{23}\ \text{W cm}^{-2}\mu\text{m}^2$$

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

Simple criteria for RPA "dominance" - II

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

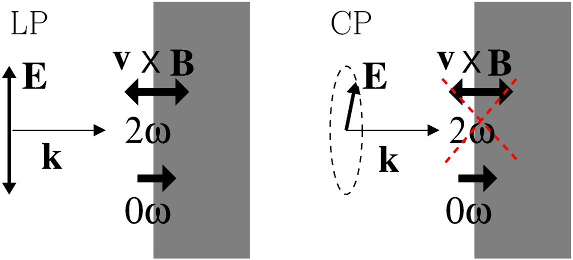
$$t_c < \pi/\omega \quad \longrightarrow \quad \frac{1}{2a_0}\left(\frac{Am_p}{Zm_e}\right)^{1/2} \simeq \frac{30}{a_0} < 1$$
$$\longrightarrow \quad I\lambda^2 > 1.2 \times 10^{21} \text{ W cm}^{-2}\mu\text{m}^2$$

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

See B.Qiao et al PRL **108** (2012) 115002, for a different argument leading to similar estimate

Role of laser polarization

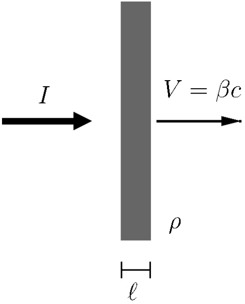
Suppress electron longitudinal oscillations and heating using Circular Polarization (CP) at normal incidence



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

Light Sail “accelerating mirror” model - I

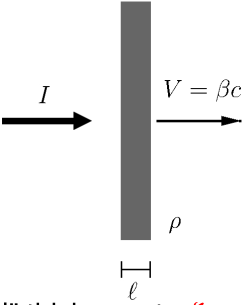
$$
\begin{aligned}
\mathscr{E}_{\text{max}} &\simeq m_p c^2 \mathscr{F}^2/(2(\mathscr{F}+1)) \\
&\simeq m_p c^2 \mathscr{F}^2/2 \qquad (\mathscr{F} \ll 1)
\end{aligned}
$$



$$
\begin{aligned}
\mathscr{F} &= \frac{2}{\rho\ell}\int_0^\infty I(t')dt' \simeq \frac{2I\tau_p}{\rho\ell} \\
&= 2\pi\frac{Zm_e}{Am_p}\frac{a_0^2}{\zeta}\omega\tau_p \qquad \zeta = \pi\frac{n_e\ell}{n_c\lambda}
\end{aligned}
$$

Favorable scaling with laser pulse fluence $\mathscr{F}$
100% efficiency in the relativistic limit
“Perfect” monoenergeticity for “rigid”, coherent sail motion

Light Sail "accelerating mirror" model - II



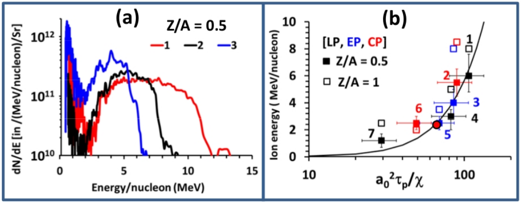
Issues with LS:

- need of ultrathin (nm) foils and ultrahigh contrast pulses
- heating and transverse deformation: expansion, loss of planarity

- relativistic transparency fixes "optimal" thickness to $\zeta \simeq a_0$
- "slow" gain with time in the relativistic limit
  $\mathscr{E}_{\text{ion}}(t) \propto \left(2It/\rho\ell c^2\right)^{1/3} \qquad (t \gg \rho\ell c^2/I\ ,\ \mathscr{E}_{\text{ion}} > m_p c^2)$;
  acceleration length limited by diffraction?

Evidence of $\mathscr{F}^2$ "fast" scaling on VULCAN

VULCAN laser, RAL/CLF:
Laser pulse: $t_p \simeq 800\ fs$
3×10^{20} W cm^{-2}
$\sim 10^9$ contrast
Target: $\sim 0.1\ \mu$m metal foil



- multispecies ($Z/A = 1, 1/2$) peaks observed ($\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$)
- peak energy scaling $\propto \left(a_0^2\tau_p/\zeta\right)^2$
- polarization dependence weak or absent
- spectral separation of different Z/A species

S.Kar, K.Kakolee, B.Qiao, A.Macchi et al, PRL **109** (2012) 185006

Open issues from LS-RPA experiments

Other LS investigations besides Kar et al.:
Henig et al, PRL **103** (2009) 245003
Steinke et al, PRST-AB **16** (2013) 11303
Aurand et al, NJP **15** (2013) 33031.

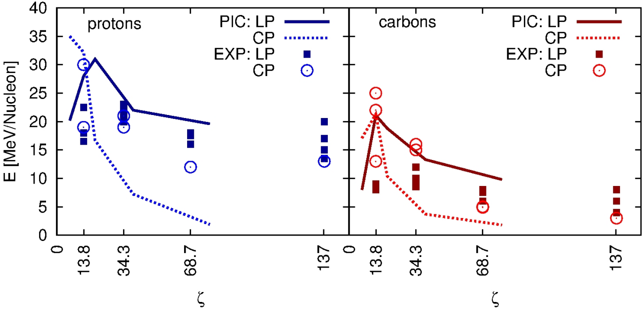
- limited effect of CP vs LP
- non-thermal but not monoenergetic energy spectrum
- species separation (as in multispecies expansion)

$\longrightarrow$ too much heating (e.g. due to target deformation) leading to post-RPA broadening?

GEMINI experiment

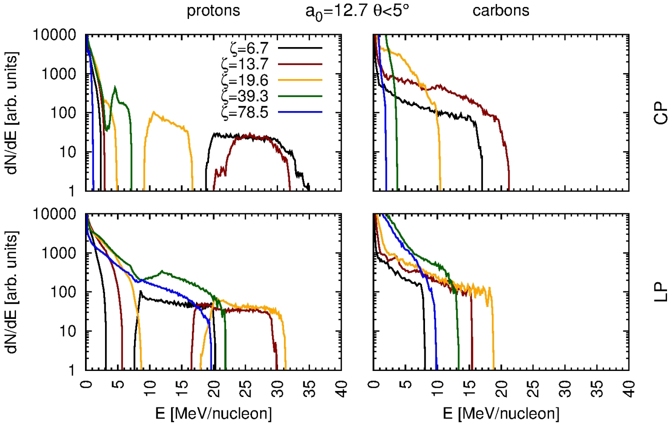
- Laser pulse:
  $t_p \simeq 40\ fs$, $w_0 \simeq 3\ \mu$m
  $I \simeq 3.5 \times 10^{20}$ W cm^{-2} $\quad (a_0 = 12.7)$
- Contrast: $> 10^9$
- Targets: $10 - 50$ nm C foils (with H impurities)

Ion energy vs thickness and polarization



- cut-off energy higher for CP vs LP for lowest thickness (both for protons and carbon ions)
- qualitative agreement with 2D PIC simulations (lines)

Ion spectra from 2D simulations

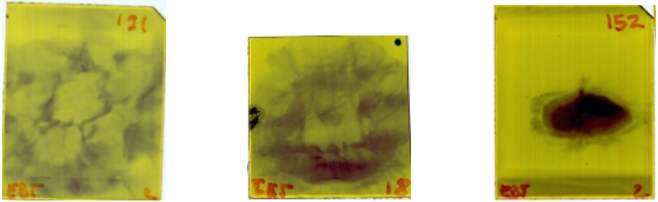


Peaked spectra observed for protons with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$

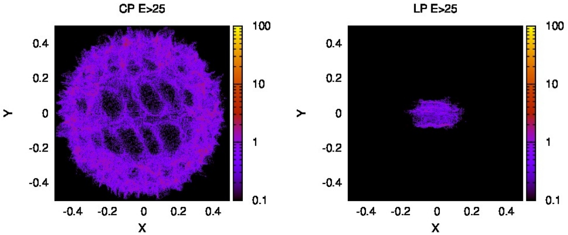
Structures in proton beam profiles

CP CP LP

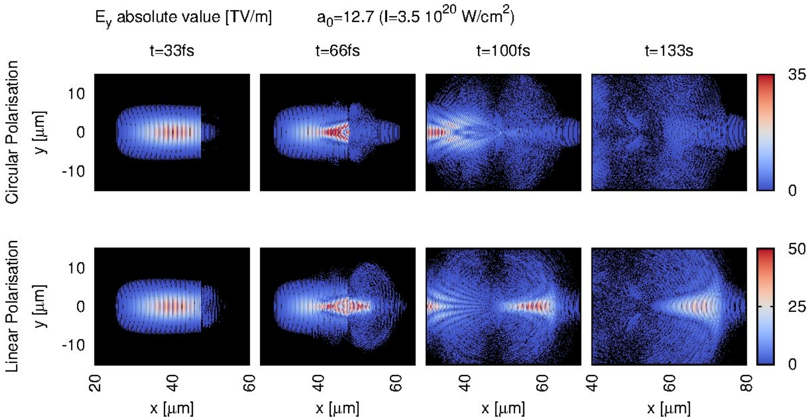
RCF images



Proton density integrated along propagation path from 3D simulations

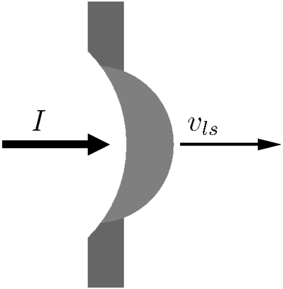


Pulse transmission vs polarization



Earlier breakthrough and stronger transmission for LP

Pushing LS forward: "unlimited" acceleration?



Transverse expansion of the target reduces surface density $\rho\ell$

$\longrightarrow$ "unlimited" acceleration possible at the expense of the number of ions

$\longrightarrow$ "faster" gain $E_{\text{ion}}(t) \simeq \left(2It/\rho\ell c^2\right)^{3/5}$ predicted

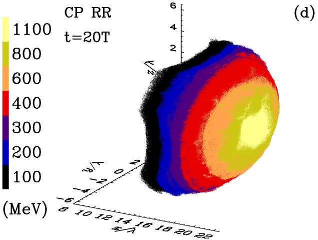
[S.V.Bulanov et al, PRL **104** (2010) 135003]

Mechanism is effective for *relativistic* ions ($\mathscr{F} \gg 1$)

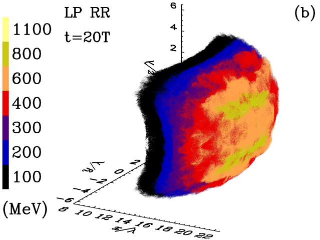
Relativistic motion may also relax the relativistic transparency thanks to laser frequency downshift in the "sail" frame $\longrightarrow a_0 \gtrsim \zeta$

3D simulations of RPA-LS with “extreme” pulses

Laser: 24 fs, 8 μm spot, $I = 1.7 \times 10^{23}$ W cm^{-2}, $U = 1.5$ kJ
Target: 1 μm foil, $n_e = 1.1 \times 10^{23}$ cm^{-3}, $Z/A = 1$, $\zeta \simeq a_0 \simeq 200$



Circular Polarization (CP)
symmetric, collimated distribution
higher energy

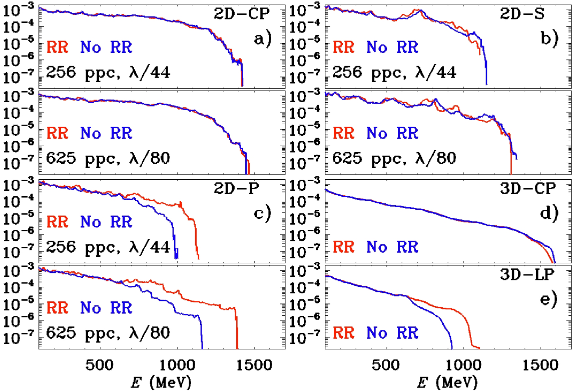


Linear Polarization (LP)
asymmetric two-lobe distribution
lower energy

[M.Tamburini, T.Liseykina, F.Pegoraro, A.Macchi, PRE **85** (2012) 016407]

3D, radiation friction, and numerical resolution effects

Comparison of spectra for 3D vs. 2D for S/P polarization (LP), same/higher resolution, with/without radiation friction (RR)



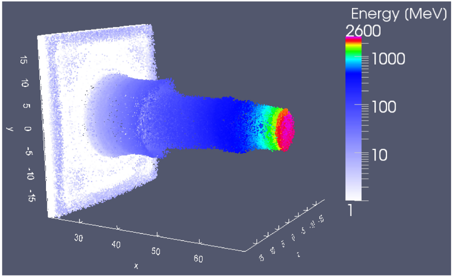
For CP:

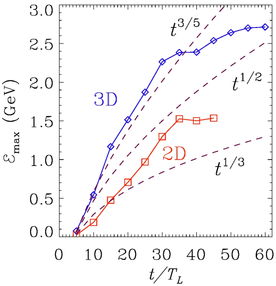
- simulation results are affected very weakly by limited resolution and RR effects
- ion energy is higher in 3D than in 2D

[M.Tamburini, T.Liseykina, F.Pegoraro, A.Macchi, PRE **85** (2012) 016407]

High energy gain in 3D RPA-LS simulations - I

Simulation with ALaDyn PIC code on CINECA/FERMI super-computer up to longer times: $60\ T$ vs $20\ T$

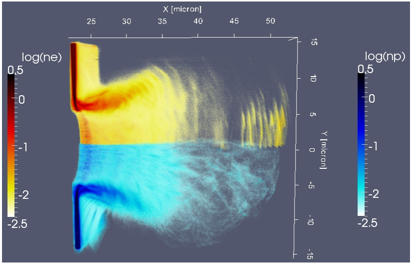


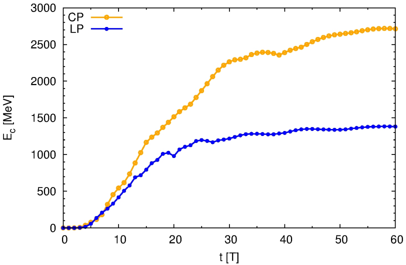


CP pulse: $\mathscr{E}_{\text{max}} \simeq 2.6$ GeV > 4 times 1D model prediction
Good agreement with Bulanov's $\sim t^{3/5}$ scaling in 3D

High energy gain in 3D RPA-LS simulations -II

Simulation with ALaDyn PIC code on CINECA/FERMI supercomputer up to longer times: $60\ T$ vs $20\ T$





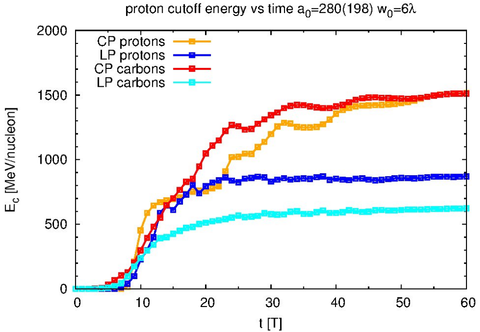
Energy increase stopped by the onset of transparency
Higher gain (2X) with CP with respect to LP

High energy gain in 3D RPA-LS simulations -III

Simulation with ALaDyn PIC code on CINECA/FERMI super-computer up to longer times: $60\ T$ vs $20\ T$

More “realistic” target:
C ($Z/A = 1/2$) foil
with H ($Z/A = 1$) layer

$\mathscr{E}_{\text{max}} \simeq 1.5$ GeV
~ 2.5 times 1D model prediction



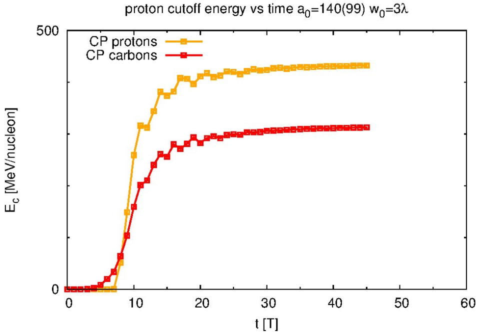
C and H reach same energy/nucleon asymptotically for CP case

High energy gain in 3D RPA-LS simulations -IV

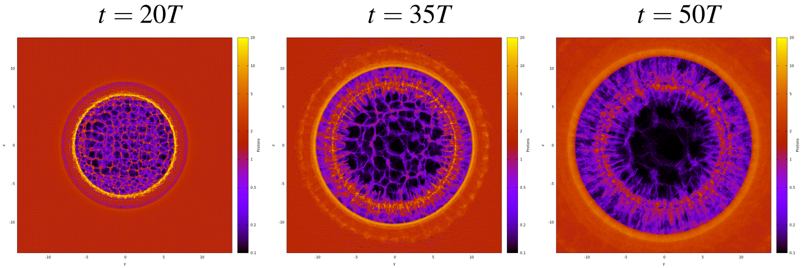
(Preliminary) Simulation with reduced energy:
4 μm spot, $I = 4 \times 10^{22}$ W cm^{-2}, $\zeta \simeq a_0 \simeq 100$, $U = 100$ J

- Energy still higher than in 1D case, but lower gain with respect to fully relativistic regime

- Separation of species in energy spectrum



Growth of transverse structures



Seed of transverse perturbation already appears during acceleration stage (well before transparency onset)

Conclusions

- VULCAN and GEMINI data support typical features of "Light Sail" acceleration:
  - "fast" energy scaling
  - role of polarization
- several issues need to be addressed:
  - heating and post-acceleration effects
  - ion beam modulation (transverse instability?)
- 3D simulations for ELI-class lasers reveal high-gain regimes of relativistic ion acceleration for circular polarization
  - instabilities possibly also present

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