Ion acceleration in the "extreme light" regime

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Main coworkers for this talk

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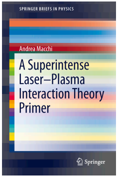
Recent reviews on ion acceleration

H. Daido, M. Nishiuchi, A. S. Pirozhkov,
Review of Laser-Driven Ion Sources and Their applications,
Rep. Prog. Phys. **75** (2012) 056401

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

A. Macchi, A. Sgattoni, S. Sinigardi, M. Borghesi, M. Passoni,
Advanced Strategies for Ion Acceleration using High Power Lasers,
EPS 2013 arXiv:1302.1775

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



SPRINGER BRIEFS IN PHYSICS
Andrea Macchi
A Superintense Laser–Plasma Interaction Theory Primer
Springer

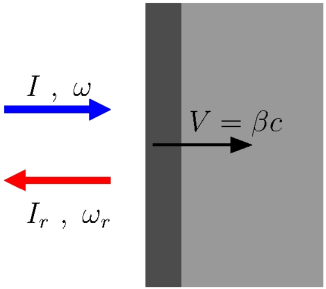
Outline

Focus: Radiation Pressure Acceleration at Ultrahigh Intensities

- RPA basics and dominance
- “Light Sail” acceleration
- ongoing experiments and present challenges
- perspectives for GeV acceleration
- “Hole Boring” acceleration

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

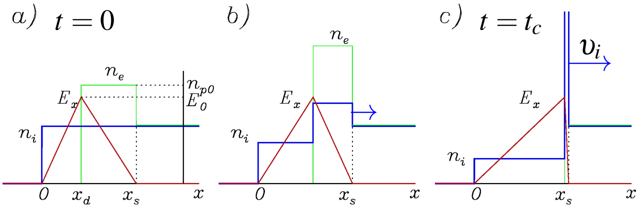


$$\frac{dP}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta} \qquad \eta = \frac{2\beta}{1+\beta}$$

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]



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

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

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:

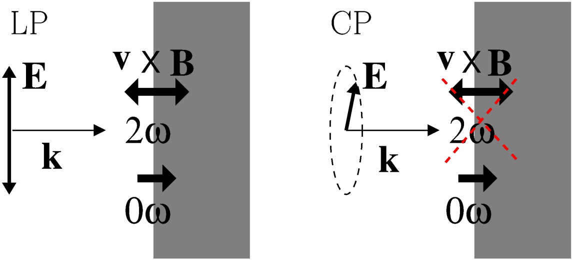
$$v_i/c = 1/2 \quad \longrightarrow \quad a_0 \simeq 30 \left(\frac{n_e}{n_c}\right)^{1/2} > 300$$

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

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

Simple criteria for RPA “dominance” - II

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

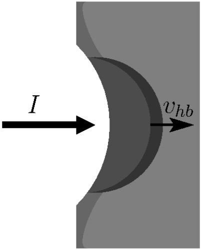
$$t_c < \pi/\omega \quad \longrightarrow \quad \frac{1}{2a_0}\left(\frac{Am_p}{Zm_e}\right)^{1/2} \simeq \frac{30}{a_0} < 1$$
$$\longrightarrow \quad I\lambda^2 > 1.2 \times 10^{21}\ \text{W cm}^{-2}\mu\text{m}^2$$

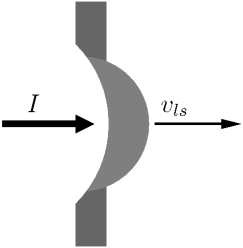
Consequence: important RPA effects in current experiments (also for Linear Polarization)

“Hole Boring” vs “Light Sail” RPA

Hole Boring (HB): thick target, “piston” push of the plasma surface

Light Sail (LS): push of whole thin foil target





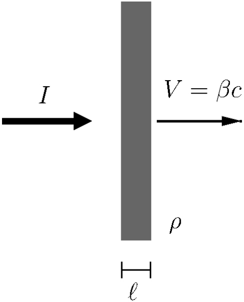
Energy scaling with intensity $v_{hb} \simeq (I/\rho c)^{1/2}$

Energy scaling with *fluence* (see next slide)

Light Sail formulas: thin, plane moving mirror model

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

$$\mathscr{F} = 2(\rho\ell)^{-1}\int_0^\infty I(t')dt' \simeq 2I\tau_p/\rho\ell$$



$$\mathscr{E}_{\text{ion}}(t) \propto \left(2It/\rho\ell c^2\right)^{1/3}$$

(for $t \gg \rho\ell c^2/I$, $\mathscr{E}_{\text{ion}} > m_p c^2$)

Favorable scaling with dimensionless laser pulse fluence $\mathscr{F}$

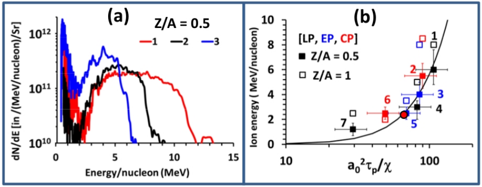
"Perfect" monoenergeticity for "rigid", coherent sail motion

Need of ultrathin (nm) foils and ultrahigh contrast pulses

Limits: "slow" energy gain, foil transparency and deformation

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

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



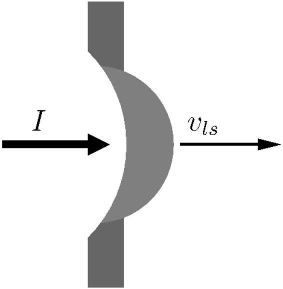
Multispecies ($Z/A = 1, 1/2$) peaks observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Up to $\simeq 10$ MeV/amu observed at high flux
Simulations suggest > 100 MeV/nucleon are within reach

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

see also: Steinke et al, PRST-AB **16**, 11303 (2013);
Aurand et al, NJP **15**, 33031 (2013)

Pushing LS forward: “unlimited” acceleration?

Transverse expansion of the target reduces surface density $\rho\ell$
$\Rightarrow$ “unlimited” acceleration possible
at the expense of the number of ions
[Bulanov et al, PRL **104** (2010) 135003]

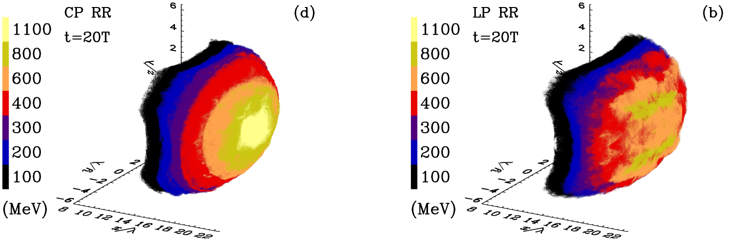


“Faster” gain $E_{\text{ion}}(t) \simeq \left(2It/\rho\ell c^2\right)^{3/5}$ predicted
Mechanism is effective for *relativistic* ions ($\mathscr{F} \gg 1$)

Limitation: relativistic transparency when $a_0 > \zeta \equiv \pi \dfrac{n_e}{n_c}\dfrac{\ell}{\lambda}$
Optimal trade-off when $a_0 \simeq \zeta$

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}, $Z/A = 1$, $\zeta \simeq a_0 \simeq 200$



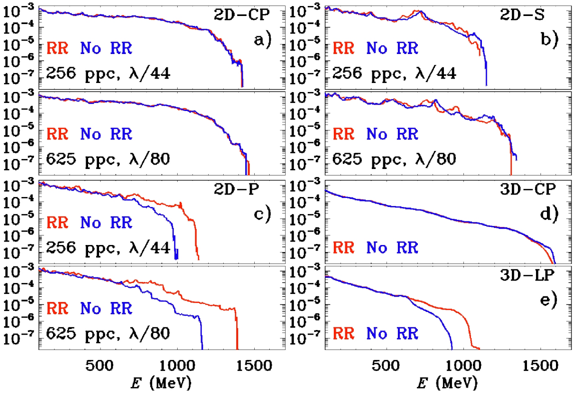
Circular Polarization (CP)
symmetric, collimated distribution
higher energy

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

[Tamburini, Liseykina, Pegoraro, 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)



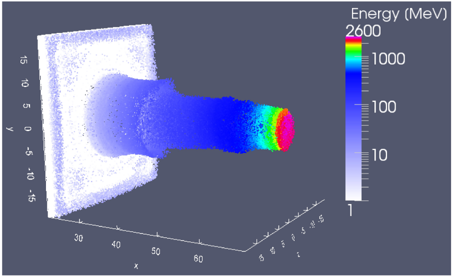
Effects of 2D vs 3D and of limited resolution are evident, but kept below physical effects

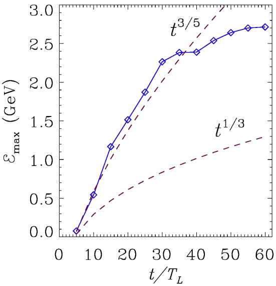
The “optimal” CP case is the most robust

(Ion energy is **higher** in 3D than in 2D **!**)

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

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



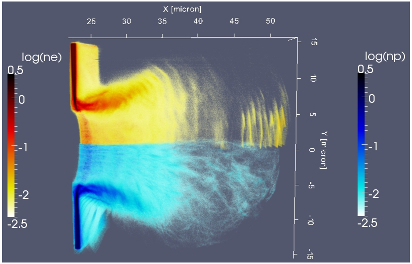


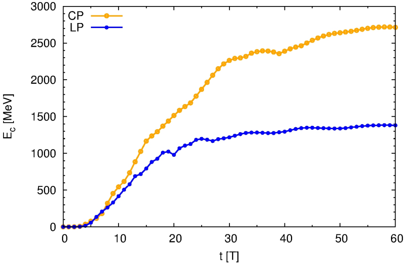
CP pulse: $\mathcal{E}_{\text{max}} \simeq 2.6$ GeV > 4 times 1D model prediction

Most energetic ions collimated in 10° cone

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

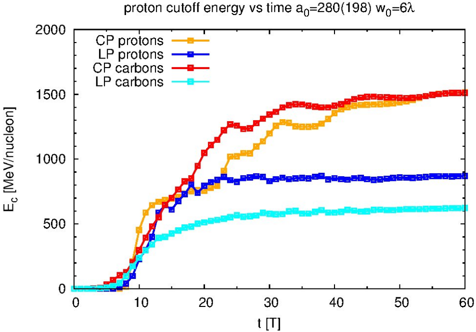
Higher gain (2X) with CP with respect to LP

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

Simulation with ALaDyn PIC code on CINECA/FERMI supercomputer 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



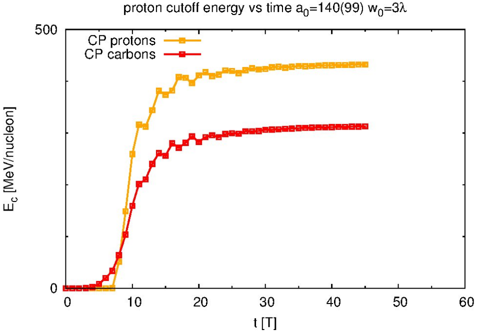
C and H reach same energy/nucleon asymptotically for CP case

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



Hole Boring RPA: theoretical results

Energy/nucleon accounting for relativistic effects:

$$\mathscr{E}_{\mathrm{HB}} = 2m_p c^2 \frac{\Pi}{1+2\Pi^{1/2}} , \qquad \Pi = \frac{I}{\rho c^3} = \frac{Z}{A}\frac{m_e}{m_p}\frac{n_c}{n_e} a_0^2 .$$

- Scaling with intensity I: interesting for very short pulses
- Ion dynamics in the skin layer leads to peaked spectra
- Good tolerance to preplasma effects
- Unfavorable scaling with density

→ use low-density target $n_e \gtrsim n_c$ if available

Hole Boring RPA with gas H target and CO_2 laser

Narrow proton spectra at $\mathscr{E}_{\text{peak}} = 0.8 - 1.2$ MeV ($\Delta\mathscr{E}/\mathscr{E}_{\text{peak}} \simeq 20\%$ spread) observed from H gas jet at $n_e = 4 - 8n_c$ using CP, $I = 6.5 \times 10^{15}$ W cm^{-2} CO_2 ($\lambda = 10\ \mu$m) pulses

Scaling with I/n_e and number of protons consistent with HB acceleration

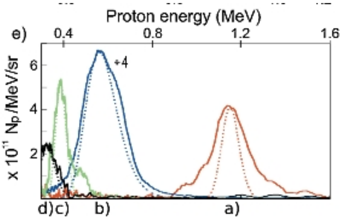


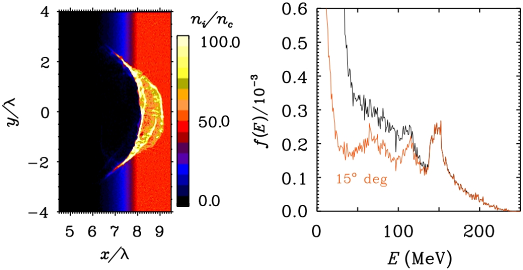
FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{\text{max}} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{\text{cr}}$, (b) $I = 5.5$, $n = 6.1n_{\text{cr}}$, (c) $I = 5.9$, $n = 7.6n_{\text{cr}}$, (d) $I = 5.7$, $n = 8.0n_{\text{cr}}$ (I in units of 10^{15} W cm^{-2}). (e) Background subtracted (solid lines) and also corrected (dashed lines) spectra. Heights of corrected spectra adjusted to match those of raw lineouts. Lineout corresponding to (b) reduced 4× to fit on the same scale.

Palmer et al, PRL **106** (2011) 14801

Hole Boring RPA with liquid H target and 0.8μm laser?

Proton spectra with peak at $\mathscr{E}_{\text{peak}} = 150$ MeV in 2D simulations for H liquid jet at $n_e = 50n_c$ using CP, $I = 5 \times 10^{22}$ W cm^{-2} two-cycle pulse

A.Macchi, C.Benedetti, NIMA **620**, 41 (2010)



Promising scheme for next-generation “extremely” short lasers?

[see also: A.P.L.Robinson et al, PoP **18**, 056701 (2011); PPCF **54**, 115001 (2012)]

Conclusions and perspectives for RPA

Light Sail RPA:

- evidence for fast scaling and peaked proton/C spectra
- predicted high gain in relativistic ion (GeV) regime: promising for next-generation ELI class lasers
- “delicate” ultrathin targets required, may need wide spot (and large energy), spectrum not monoenergetic as hoped

Hole Boring RPA:

- evidence in CO_2 laser-gas jet interactions
- possible option for “extreme” pulses, not-so-prone to ultrahigh contrast
- requires development in low-density target preparation

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  - FERMI BlueGene/Q$^{\text{TM}}$, PRACE award (project LSAIL – “Large Scale Acceleration of Ions by Lasers”)