Radiation Pressure Acceleration: Perspectives and Limits

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Main coworkers

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Outline

- Theory of RPA “light sail” acceleration
- concept, some history, and mirror model
- expected scaling and features
- RPA dominance
- State of the art and experiments
- The future: “extreme light” regimes
- Conclusions

Recent ion acceleration reviews (parochial selection)

A. Macchi,
Ion Acceleration,
to appear in: *Applications of Laser-driven Particle Acceleration* (CRC press), in preparation

M. Borghesi, A. Macchi,
Laser-Driven Ion Accelerators: State of the Art and Applications,
in *Laser-Driven Particle Acceleration Towards Radiobiology and Medicine*, ed. by A. Giulietti (Springer, 2016)

A. Macchi, A. Sgattoni, S. Sinigardi, M. Borghesi, M. Passoni,
Advanced Strategies for Ion Acceleration using High Power Lasers,
Plasma Phys. Contr. Fus. **55** (2013) 124020

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

Other ion acceleration reviews

J. Schreiber, P. R. Bolton, K. Parodi,
“Hands-on” laser-driven ion acceleration: A primer for laser-driven source development and potential applications,
Rev. Sci. Instrum. **87**, 071101 (2016)

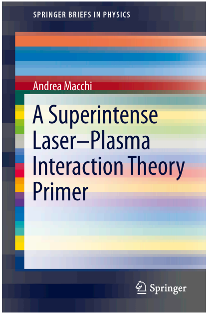
J. C. Fernández, et al,
Fast ignition with laser-driven proton and ion beams,
Nucl. Fusion **54** (2014) 054006

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

M. Borghesi et al,
Fast Ion Generation by High-Intensity Laser Irradiation of Solid Targets and Applications,
Fusion Science and Technology **49** (2006), 412

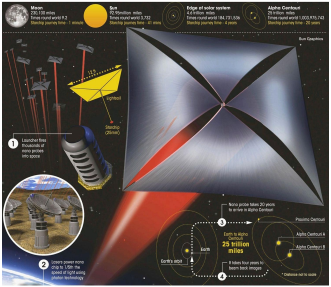
Tutorials for RPA (parochial, again)

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



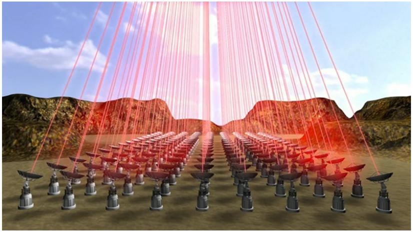
A. Macchi,
Theory of Light Sail Acceleration by Intense Lasers: an Overview,
High Power Laser Science and Engineering **2** (2014) e10

Starshot: laser-boosted light sails for space travel



(credit: Breakthrough Starshot, breakthroughinitiatives.org)

Critical analysis:
H. Milchberg, “Challenges abound for propelling interstellar probes”, Physics Today, 26 April 2016



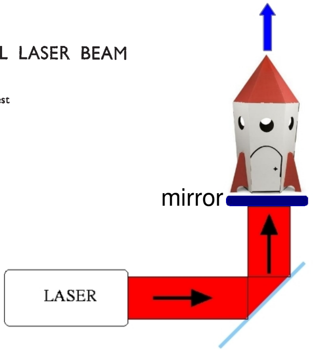
Early vision of laser-driven light sails (1966)

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

α-Centauri



Main problem foreseen at such time:
no deceleration possible → no stop, no return flight
(and no alien visitors!)

(BUT a scheme for deceleration and roundtrip travel was proposed:
R. L. Forward, *J. Spacecraft* **21** (1984) 187)

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

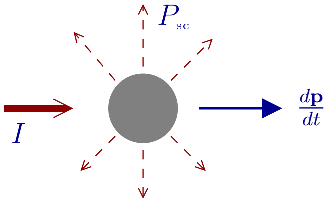
V. I. Veksler, At. Energ. **2** (1957) 525

- 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).



the absorbed momentum per unit time

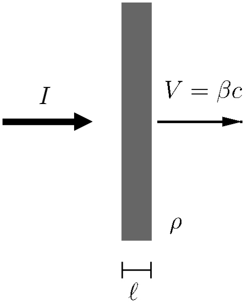
$\propto$ scattered power $P_{sc} = \sigma_T I$

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

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

Eq.(*) is the same as the light sail equation (mirror boosted by radiation pressure)

Light Sail 1D "mirror" model



Fast scaling of energy/nucleon

$$\mathcal{E}_{\text{max}} = m_p c^2 \frac{\mathcal{F}^2}{2(\mathcal{F}+1)}$$

$$\mathcal{F} \equiv \frac{2}{\rho \ell c^2} \int_0^\infty I(t')dt' \simeq \frac{2I\tau_p}{\rho \ell c^2}$$

$I = 10^{21}$ W cm^{-2}, $\tau_p = 30$ fs, $\ell = 10$ nm

$\longrightarrow \mathcal{F} \simeq 0.6$, $\mathcal{E}_{\text{max}} \simeq 105$ MeV

presently accessible with ultrathin foil targets and high-contrast pulses

High efficiency $\eta = \frac{2\beta}{1+\beta} \to 1 - \frac{1}{1+\mathcal{F}^2}$ (100% for $\beta \to 1$)

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

Transparency onset and "optimal" thickness

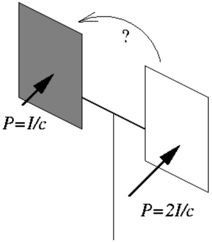
$$\mathscr{F} \simeq \frac{2I\tau_p}{\rho\ell} = 2\pi\frac{Zm_e}{Am_p}\frac{a_0{}^2}{\zeta}\frac{c\tau_p}{\lambda} \qquad a_0 = \left(\frac{I}{m_e n_c c^3}\right)^{1/2} \qquad \zeta = \pi\frac{n_e\ell}{n_c\lambda}$$

Onset of "relativistic" transparency and blowout of all electrons when $a_0 > \zeta \longrightarrow$ LS operation stops
Trade-off condition $a_0 \simeq \zeta \longrightarrow$ "optimized" scaling (for $\beta \ll 1$)

$$\mathscr{E}_{\mathrm{LS}}^{(\mathrm{opt})} = 2\pi^2 m_e c^2 \left(\frac{m_e}{m_p}\right)\left(\frac{Z}{A}\frac{c\tau_p}{\lambda}a_0\right)^2 \simeq 1.4\times 10^{-3}\ \mathrm{MeV}\left(a_0\frac{c\tau_p}{\lambda}\right)^2$$

$a_0 \sim 10$ with $\tau_p \sim (10-100)\lambda/c$ presently accessible

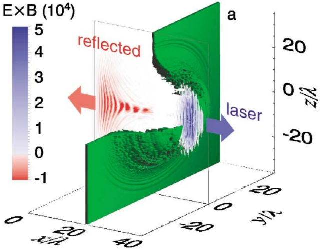
How to make radiation pressure dominant?



Target "heating" may counterbalance the RPA effect (as in the "optical mill" example)

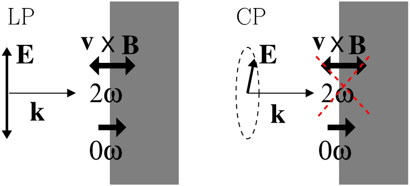
Esirkepov et al [PRL **92** (2004) 175003]: $I > 10^{23}$ W cm^{-2} is needed for RPA dominance (ion must become relativistic within one laser cycle)

Do we really need such laser?



RPA dominance at “feasible” intensities

Using circular polarization (CP) at normal incidence quenches “fast” electron production and makes RPA dominant at “any” intensity



[Macchi et al, PRL **95** (2005) 185003]

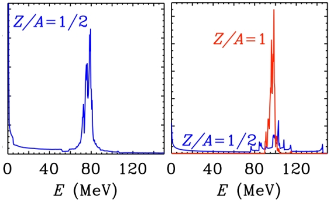
Further analysis suggest RPA dominance to begin also for linear polarization (LP) at $I \sim 10^{21}$ W cm^{-2}
[B. Qiao et al, PRL **108** (2012) 115002; Macchi, HPLSE 2 (2014) e10]

It makes sense to investigate RPA-LS with “today’s lasers”!

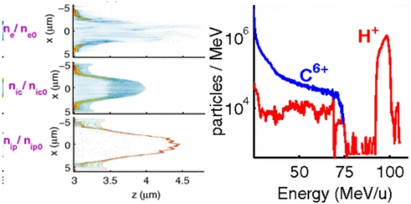
Multispecies effects

In the "rigid" LS model all species move with same V
$\rightarrow$ same energy/nucleon for each Z/A value

Actually only a rear layer is boosted in LS mode $\rightarrow$ proton acceleration favored (may be tailored by target engineering)
[Macchi et al, PRL **103** (2009) 085003]



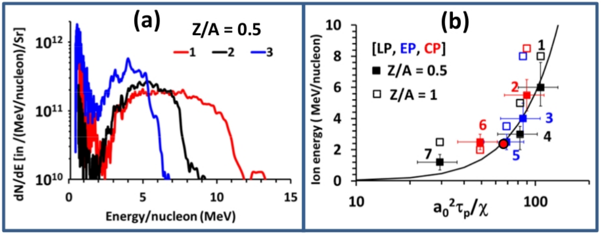
Partial laser transmission pushes some electrons away ("leaky LS") stabilizing proton acceleration
[Qiao et al, PRL **105** (2010) 155002]



Evidence for $\mathscr{F}^2$ scaling (VULCAN)

Laser pulse: $t_p \simeq 800$ fs , $I = (0.5 - 3) \times 10^{20}$ W cm^{-2}
Target: $\sim (0.05 - 0.8)$ μm metal foils

$a_0 \simeq (6.9 - 15.5)$
$\zeta \simeq (60 - 1200)$
$\mathscr{F}_{\text{max}} \simeq 2 \times (Z/A)$



Multispecies ($Z/A = 1, 1/2$) spectral peaks with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Up to $\simeq 10$ MeV/nucleon with $\mathscr{F}^2$-scaling on average

S. Kar, K. F. Kakolee, B. Qiao, A. Macchi, M. Cerchez, D. Doria, M. Geissler, P. McKenna, D. Neely, J. Osterholz, R. Prasad, K. Quinn, B. Ramakrisna, G. Sarri, O. Willi, X. Y. Yuan, M. Zepf, M. Borghesi, PRL **109** (2012) 185006

Higher ion energy for circular polarization (GEMINI)

Laser pulse: $t_p \simeq 45$ fs

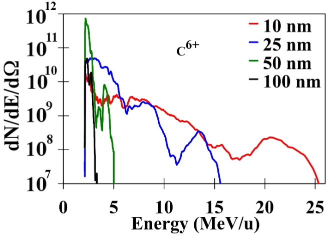
$I = 6 \times 10^{20}$ W cm^{-2}

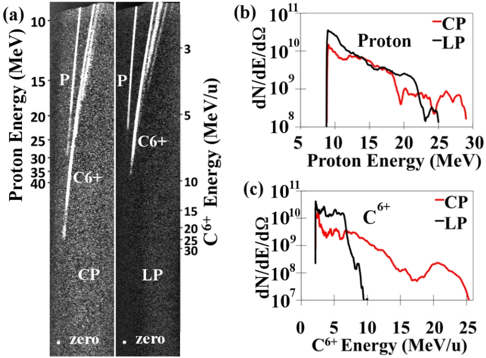
Target: $10 - 100$ nm

amorphous Carbon foils

$a_0 \simeq 16$, $\zeta \simeq (14 - 140)$

$\mathscr{F}_{\text{max}} \simeq 1 \times (Z/A)$





Energy increases with decreasing thickness

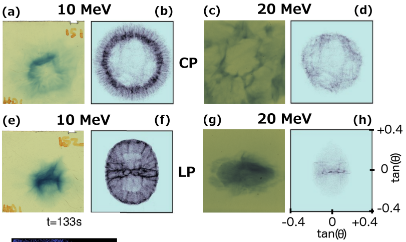
[C.Scullion, D.Doria, L-Romagnani, A.Sgattoni, K.Naughton, D.R.Symes, P.McKenna, A.Macchi, M.Zepf, S.Kar, and M.Borghesi, submitted]

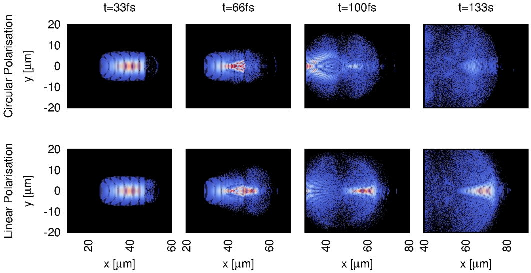
Proton beam structures and transparency (GEMINI)

Different proton beam structures for LP and CP

- RCF images
- 3D PIC simulations

(A. Sgattoni, ALADYN code)





Structures are related to the onset of transparency (stronger for LP)

[comparison: Gonzalez-Izquierdo et al, Nature Phys. **12** (2016) 505]

Some comments on VULCAN and GEMINI experiment

- Evidence for fast LS caling (VULCAN) and higher energy for CP (GEMINI) has been obtained
- Experiments report record energies (25 MeV cut-off on GEMINI) and fluxes ($> 10^{11}$ MeV^{-1}sr^{-1} on VULCAN) for C^{6+} ions, with narrow band spectra
- On VULCAN, broad spectra and weak dependence on polarization suggest important effect of target deformation for “long” pulse duration
- On GEMINI, the onset of transparency appears to limit the energy gain (~70 MeV foreseen from “optimal” 1D scaling)
- Transparency onset probably faster in 3D
- “RPA features” less apparent on protons

RPA-LS with pulse shaping

[H. Bin et al, PRL **115** (2015) 064801; also on GEMINI]

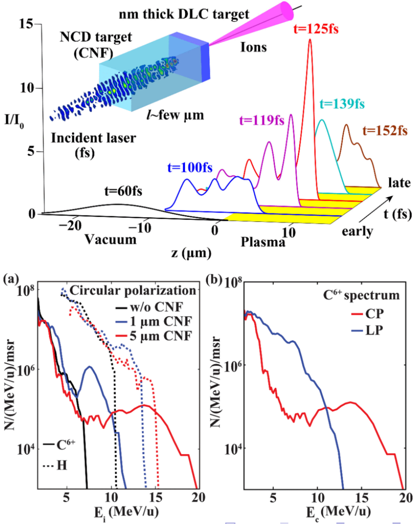
Laser pulse: $t_p \simeq 45$ fs

$I = 2 \times 10^{20}$ W cm^{-2}

Target: ~ 10 nm

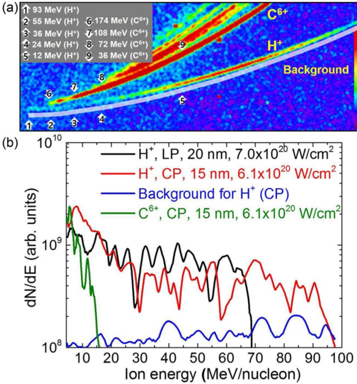
Diamond-Like Carbon foils covered with $\sim \mu$m low density Carbon Nanotube Foams for spatio-temporal pulse steepening

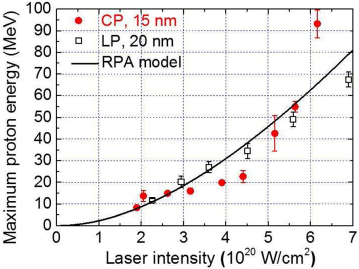
Higher energies and prominent RPA features observed with CNF



93 MeV protons from LS at GIST?

I.J.Kim, K.H.Pae, I.W.Choi, C.-H.Lee, H.T.Kim, H.Singhal, J.H.Sung, S.K.Lee, H.W.Lee, P.V.Nickles, T.M.Jeong, C.M.Kim, and C.H.Nam, Phys. Plasmas **23** (2016) 070701



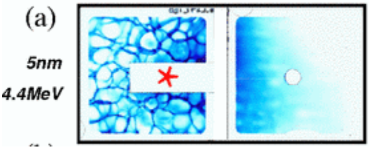


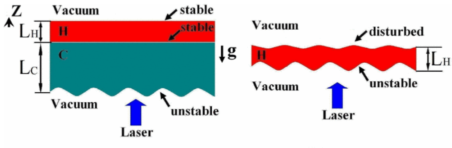
- broad, modulated spectrum
- large gap between C^{6+} and H^{+} energies
- difference between CP and LP only for the highest intensity point

Rayleigh-Taylor Instability in RPA-LS

Accelerated thin foil of areal density σ is unstable with growth rate $\gamma = (2Iq/\sigma c)^{1/2}$ (q: wavevector) [Ott, PRL **29** (1972) 1429]

RTI signature in ion beam profile structures?
(VULCAN data, $\sim 5 \times 10^{20}$ W cm^{-2})
[Palmer et al, PRL **108** (2012) 225002]





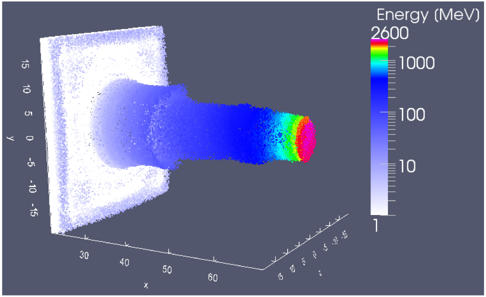
(a) C-H case (b) H case

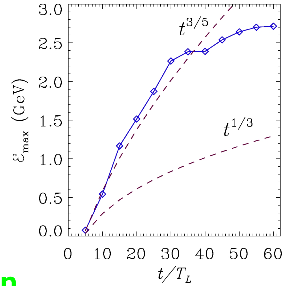
In a multispecies target RTI may be buffered in the heavy ion layer preserving stable LS acceleration of protons

[T.-P. Yu et al, PRL **105** (2010) 065002;
S. Steinke et al, PRSTAB **16** (2013) 011303]

RPA-LS at extreme intensity: 3D simulation

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}



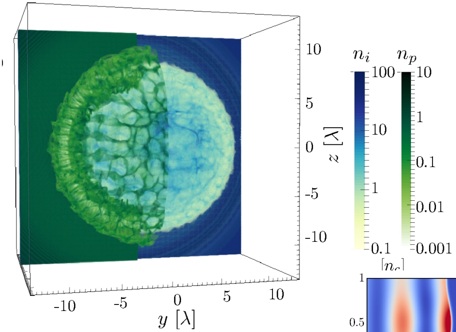


$\mathcal{E}_{\text{max}} \simeq 2.6$ GeV $>$ **4X 1D model prediction**

Theory: S.V.Bulanov et al, PRL **104** (2010) 135003

3D sim: A.Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

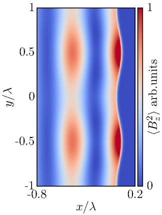
RTI at extreme intensity: 3D simulation

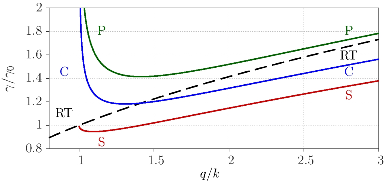


Formation of net-like structures with size $\sim \lambda$ and ~hexagonal shape for both C^{6+} and H^+

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

RTI seed from the polarization-dependent transverse modulation of radiation pressure





Conclusions and outlook

- There has been progress in “Light Sail” radiation pressure acceleration with present-day lasers (fast scaling, polarization dependence, no evident instability . . .)
- There are open issues and contradictory indications from theory and/or experiments (broad spectra, proton vs heavier ion acceleration, role of transparency . . .)
- Tighter experimental control (e.g. laser polarization, target composition, pulse shaping . . .) and further understanding of physics (e.g. multispecies dynamics, . . .) are important
- Foreseen “extreme” regimes looks promising (GeV ions) but with additional issues (e.g. instabilities)

EXTRA SLIDES

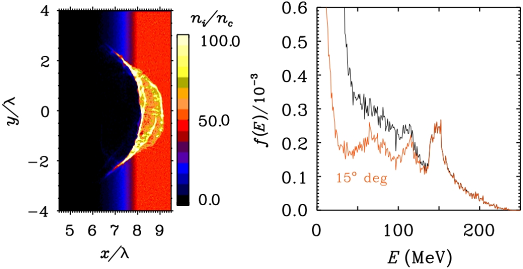
Perspectives for Hole Boring RPA?

Interesting as “bulk” acceleration mechanism: large number of ions (albeit at low energy)

Due to $\mathscr{E}_{\mathrm{HB}} \sim (I/\rho)$ scaling high energy may be obtained for extreme intensity pulses and reduced density targets

Proton spectra with peak at ~150 MeV in 2D simulations for H liquid jet at $n_e = 50 n_c$ using CP, $I = 5 \times 10^{22}$ W cm^{-2} two-cycle (~5 fs) pulses

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

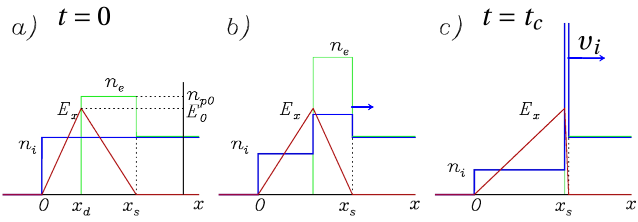


[see also Robinson et al, PoP **18**, 056701 (2011); PPCF **54**, 115001 (2012)]

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]

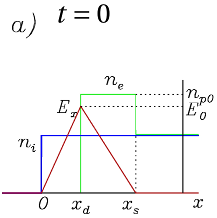


An ion bunch is formed as ions exit the skin layer

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]

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:

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

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

→ 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” - III

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

$$t_c < \pi/\omega \quad \longrightarrow \quad \frac{1}{\pi a_0}\left(\frac{Am_p}{Zm_e}\right)^{1/2} \simeq \frac{19}{a_0} < 1$$
$$\longrightarrow \quad I\lambda^2 > 5 \times 10^{20}\ \mathrm{W\ cm^{-2}\mu m^2}$$

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

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

Fast gain Light Sail in 3D

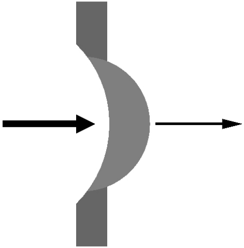
Transverse expansion of the target reduces on-axis surface density $\rho\ell$

$\Rightarrow$ *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

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

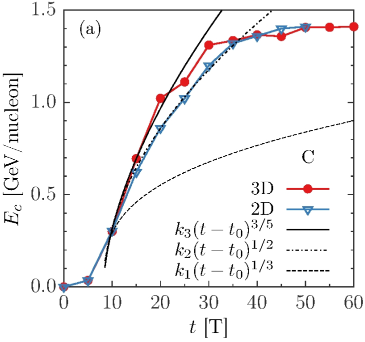
Solution in the $\gamma \gg 1$ limit

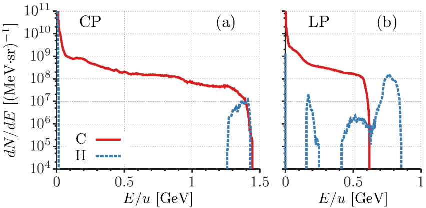
$$\gamma = \left(\frac{t}{\tau_k}\right)^k, \qquad k = \frac{D}{D+2}$$

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 (CH foil)

C+H double layer foil , $n_C = (64/6)n_c$, $n_H = 8n_c$





Circular vs Linear Polarization: Higher energy and narrower H spectrum for CP

Onset of transparency stops acceleration and is faster in 3D than in 2D → similar final energy in 2D and 3D (~1.4 GeV for CP)