Coherent Laser-Plasma Acceleration Examples and Recent Results

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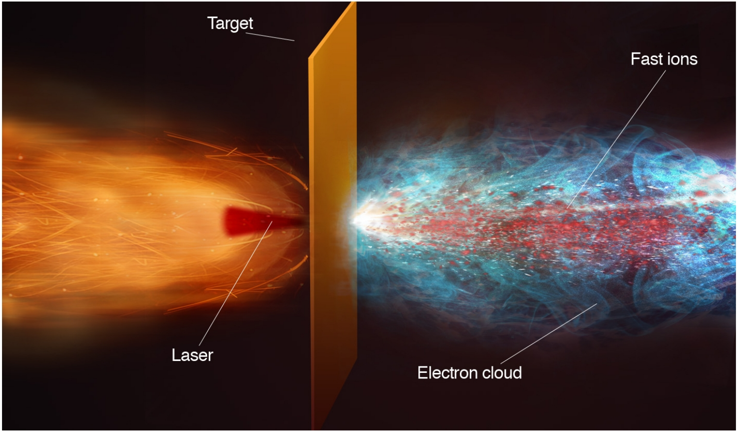
Summary of This Talk

A short review of self-organization examples in the context of laser-plasma acceleration of ions, electrons and photons:

- “Light Sail”acceleration dynamics
- Light-pressure driven Rayleigh-Taylor instability
- Electron acceleration and XUV harmonic generation by surface plasma waves

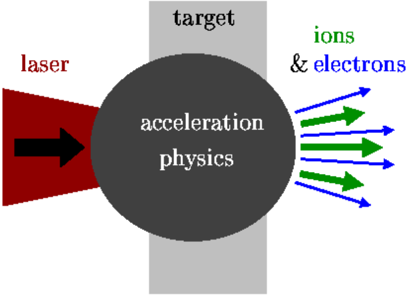
Laser-Plasma Ion Acceleration: Artist's View . . .

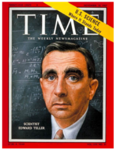


A. Macchi et al. Rev. Mod. Phys. **85** (2013) 571

Laser-Plasma Ion Acceleration: Physicist's View . . .

The "black box" hinders the acceleration mechanisms (not clear at time of discovery)
The acceleration physics is of collective (cooperative, coherent) nature, based on self-consistent, non-linear plasma dynamics (complex and difficult to control)





"*Is plasma involved? It can't work*"
(Edward Teller on an early proposal of controlled fusion)

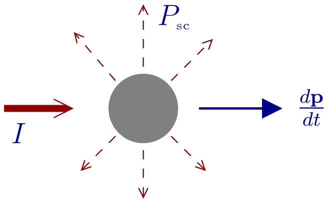
The Vision of “Coherent” Acceleration (1957)

“The principles of coherent acceleration of charged particles”
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
- principles realized in laser-plasma acceleration of ions!

Example: Coherent "Radiation Drag" Acceleration

Equations of motion for a particle (radius $a \ll \lambda$) undergoing Thomson Scattering of a plane EM wave ($P_{sc} = \sigma_T I$)



$$\frac{\mathrm{d}}{\mathrm{d}t'}(M\gamma' V') = \sigma_T \frac{I(t')}{c} \quad \text{(rest frame)}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(M\gamma V) = \sigma_T \frac{I(t_{rit})}{c} \frac{1 - V/c}{1 - V/c} \quad \text{(lab)}$$

For coherent scattering by a cluster with N $(\gg 1)$ particles

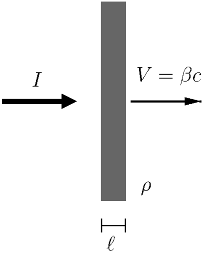
$$M \to NM$$
$$P_{sc} \to N^2 P_{sc}$$
$$\sigma_T \to N^2 \sigma_T$$

$\longrightarrow$ N-fold increase in acceleration (Veksler, 1957)

Light Sail Acceleration

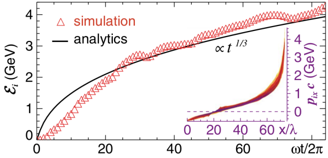
EoM for a plane perfect mirror boosted by radiation pressure ($2I/c$ in rest frame) is the same as for radiation drag of a particle

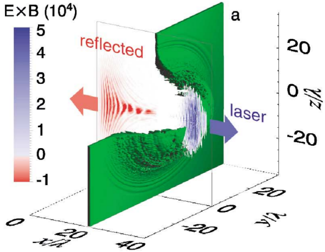
Landau & Lifshitz, *The Classical Theory of Fields* ch.78



$$\frac{\mathrm{d}(\gamma\beta)}{\mathrm{d}t} = \frac{2}{\rho\ell c^2} I\left(t - \frac{X}{c}\right)\frac{1-\beta}{1+\beta} \qquad \frac{\mathrm{d}X}{\mathrm{d}t} = \beta c$$

Analytical solution "observed" in simulations of thin foil acceleration at $\sim 10^{23}\ \mathrm{Wcm}^{-2}$

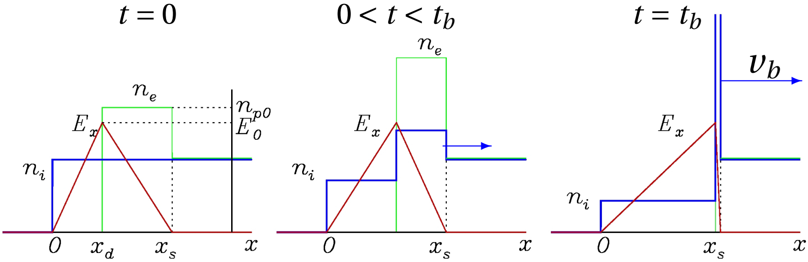




Esirkepov et al, PRL **92** (2004) 175003

Beyond the Mirror: Charge Separation Effects

Real targets are not perfect rigid mirrors: local light pressure separates charges until electrostatic tension balances $P_{\mathrm{L}} = 2I/c$
Space-charge field E_x accelerates and bunches ions in the skin layer $(x_d < 0 < x_s)$ until hydrodynamic "breaking" at $x = x_s$, $t = t_b$ produces a ion bunch with velocity v_b



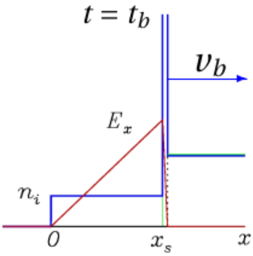
Macchi et al PRL **94** (2005) 165003

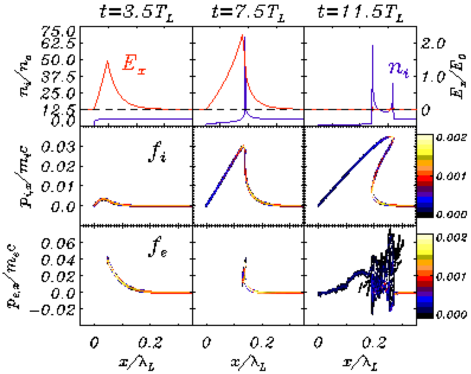
Ion Bunch Modeling and Dynamics

Simple model yields $\frac{v_b}{c} \simeq \left(\frac{Z m_e n_c}{A m_p n_e}\right)^{1/2}$ $\quad t_b \simeq \frac{c/\omega_p}{v_b}$

and velocity spectrum $0 < v_i < 2v_b$ $\quad$ (v_b: average front velocity)

PIC simulation: onset of electron heating at "breaking" ($t = t_b$)





From Ion Bunch to Light Sail

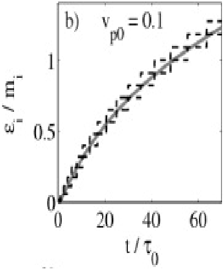
With proper choice of thickness a single ion bunch can be produced and re-accelerated as laser front advances

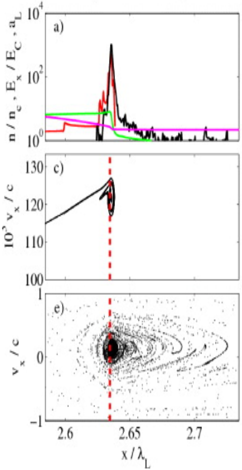
Macchi et al, PRL **103** (2009) 85003;

New J. Phys. **12** (2010) 045013

Light Sail motion emerges as the average over multiple re-acceleration stages

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





Multispecies Effects

- For coherent light sail motion all species move with same V

$\longrightarrow$ ideally same energy/nucleon for each Z/A

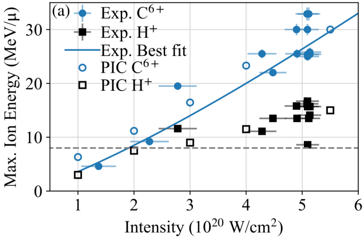
- self-organized acceleration is complicated by multiple ion species (e.g. no simple self-similar motion & bunching)
- LS proton acceleration requires tight control of target thickness and species spatial distribution (experimentally challenging)

  [see e.g. Macchi et al PRL **103** (2009) 85003;

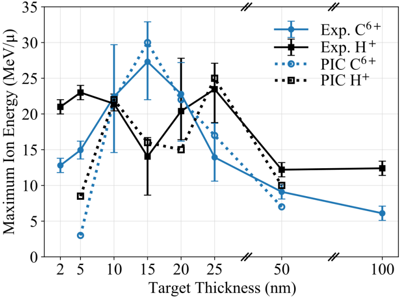
  Qiao et al PRL **105** (2010) 155002]
- Single species target contain hydrogen surface impurities: removal necessary (but not straightforward) to prevent multispecies dynamics

Impurity Removal for Carbon Ion Acceleration

Exploitation of picosecond prepulse for all-optical impurity removal
$\longrightarrow$ for 15 nm thickness the energy/nucleon is higher for C^{6+} than for protons (H^+)



McIlvenny et al PRL **127** (2021) 194801



Energy scaling $\propto I^{1.2}$ still limited by transparency onset

GEMINI laser, $I = 4.5\times10^{20}$ W cm^{-2}, $\tau_p = 45$ fs, $2-100$ nm thick C foils with H impurities

Possible Biomedical Application?

frontiers in Oncology

REVIEW
published: 17 January 2020
doi: 10.3389/fonc.2019.01563

Ultra-High Dose Rate (FLASH) Radiotherapy: Silver Bullet or Fool's Gold?

Joseph D. Wilson[1†], *Ester M. Hammond*[1†], *Geoff S. Higgins*[1†] *and Kristoffer Petersson*[1,2*†]

[1] *Department of Oncology, The Oxford Institute for Radiation Oncology, University of Oxford, Oxford, United Kingdom,*
[2] *Radiation Physics, Department of Haematology, Oncology and Radiation Physics, Skåne University Hospital, Lund, Sweden*

For Carbon ions only laser-driven accelerators may deliver the necessary flux in an ultrashort time

Public Coverage (FLASH-Stimulated?)

physicsworld

particle therapy

PARTICLE THERAPY | RESEARCH UPDATE

Intense radiation pressure enables selective acceleration of carbon ion beams

07 Dec 2021

Physics Today **75**, 1, 19 (2022); https://doi.org/10.1063/PT.3.4916

Mirror

Irish boffins' laser to help beat cancer

A laser selectively kicks carbon out of a foil

Experiments and simulations show how the shape of a laser's profile determines which target atoms make up the resulting ion beam.

Physics

A New Trick to Make Short-Pulse Ion Beams

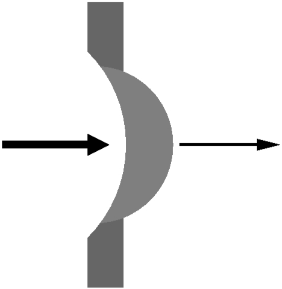
A new laser technique could lead to ultrashort-pulse, high-energy ion beams for medical use.

Relativistic High Gain 3D Regime

For "extremely" tightly focused & intense pulses $\longrightarrow \gamma \gtrsim 1$ (GeV energies)

- Transverse expansion of the target reduces surface density $\rho\ell$
- Decrease of laser frequency in "sail" frame delays the transparency onset

$\longrightarrow$ enhanced self-regulated acceleration (at the expense of the number of ions)



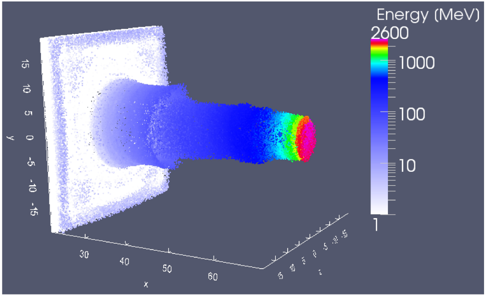
Analytical model shows faster & higher gain in 3D than in 1D:

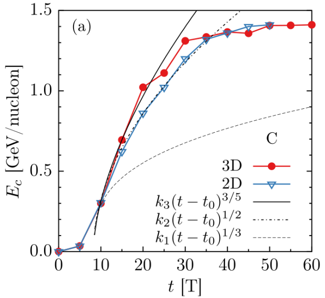
$$\gamma(t) = \left(\frac{t}{\tau_k}\right)^k \qquad k = \frac{D}{D+2} = \begin{cases} 1/3 & (1D) \\ 2/4 & (2D) \\ 3/5 & (3D) \end{cases}$$

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

Fast 3D Scaling in 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}

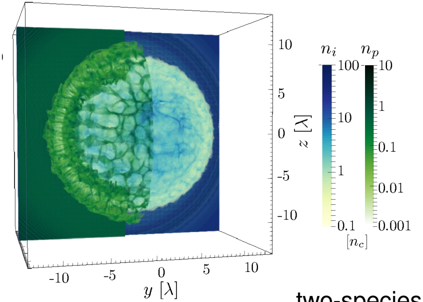




$\mathscr{E}_{\max} \simeq 2.6$ GeV > 4 X 1D prediction (still limited by transparency)

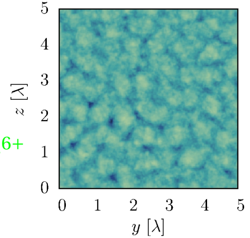
Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

Light Sail Rayleigh-Taylor Instability



3D light sail simulation: formation of net-like structures with size $\sim \lambda$ (laser wavelength) and ~ hexagonal shape

two-species target: H^+, C^{6+}

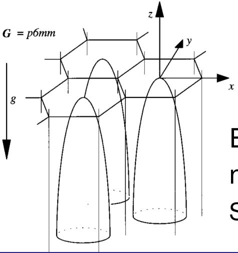


Interpretation: Rayleigh-Taylor instability driven by light pressure

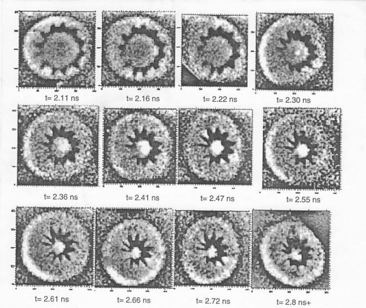
A. Sgattoni et al. Phys. Rev. E **91** (2015) 013106

see also: E. Ott, PRL **29** (1972) 1429; F. Pegoraro & S.V.Bulanov, PRL **99** (2007) 065002; B. Eliasson, New. J. Phys. **17** (2015) 033026

Rayleigh-Taylor Instability in Space and Lab



Heavy fluid
over a
light fluid
is unstable
(↑ gravity
↓ acceleration)

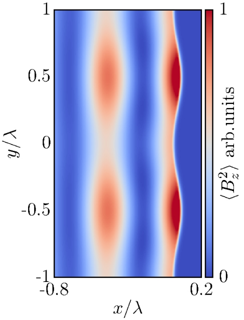


Inertial Confinement Fusion implosion, 1995

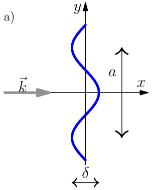
Exagon formation in RTI: an example of “spontaneous symmetry breaking”
S.I.Abarzhi, PRE **59** (1999) 1729

Plasmonic Imprint on Light-Driven RTI

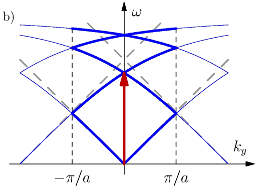
The EM field at a rippled surface of spatial period d is modulated
The P-component is resonantly enhanced when $d \sim \lambda$ due to the excitation of surface plasmons



Sgattoni et al,
PRE **91** (2015) 013106



geometry



matching conditions

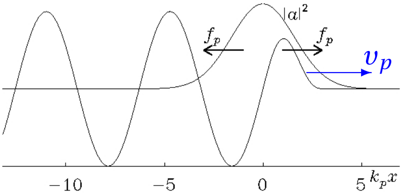
The resulting modulation of laser light pressure provides a spatial seed for RTI

Electron Acceleration in Plasma Waves

Much like surfers electrons can gain energy by longitudinal plasma waves when "injected" close to the phase velocity $v_p = \omega/k$ (provided $v_p < c$)

Plasma-based acceleration of electrons exploits wake waves at $v_p \lesssim c$ driven either by short laser pulses or charged particle bunches [see e.g. A.Macchi, "*A Superintense Laser-Plasma Interaction Theory Primer*" (Springer, 2018), chap.4; Am. J. Phys. **88** (2020) 723]

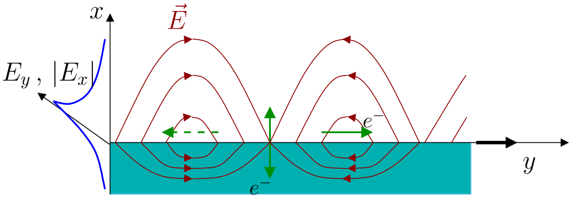
T. Katsouleas, Nature **444** (2006) 688



Electron Acceleration in Surface Plasma Waves

SPW can be excited at a sharp laser-plasma interface
(by using "grating" targets, shooting on edge or at grazing incidence:
see e.g. J. Sarma et al. New J. Phys. **24** (2022) 073023)

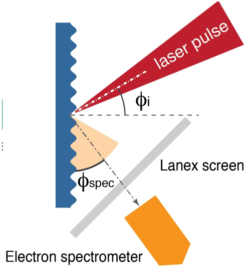
SPW have:
- longitudinal electric field component (E_y)
- phase velocity $v_p \lesssim c$



↓

electrons are accelerated along the surface by "surfing" the SPW

Observation of “Surfing” Electrons



Experiment at SLIC, CEA Saclay (France)

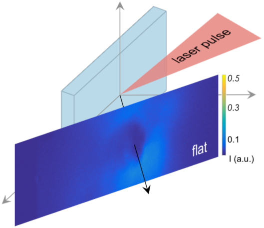
Collimated ($\simeq 20°$ cone) multi-MeV electrons near the surface tangent ($\phi \simeq 2°$)

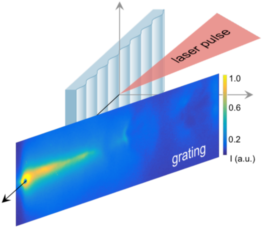
Large total charge up to $\simeq 650$ pC

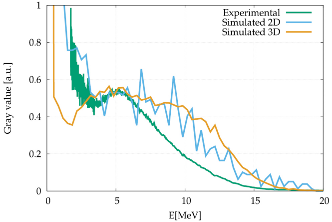
Efficient self-injection in the SPW!

L.Fedeli et al. PRL **116** (2016) 015001

G.Cantono et al. PoP **25** (2018) 031906



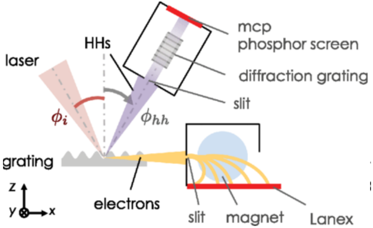




Observation of XUV High Harmonics

Spectrally enhanced HH nearly collinear with electrons are observed when SPW are excited

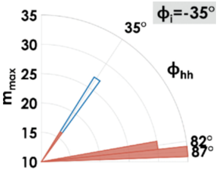
G.Cantono et al. PRL **120** (2018) 264803

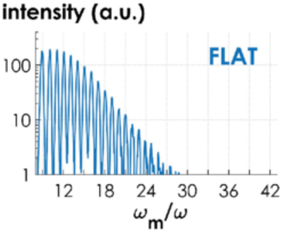


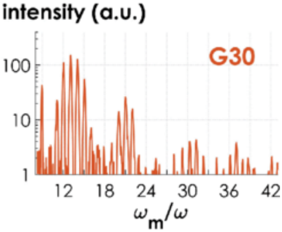
Max HH order:

w/o SPW: $m \simeq 25$ at $45°$

with SPW: $m \simeq 37$ at $87°$







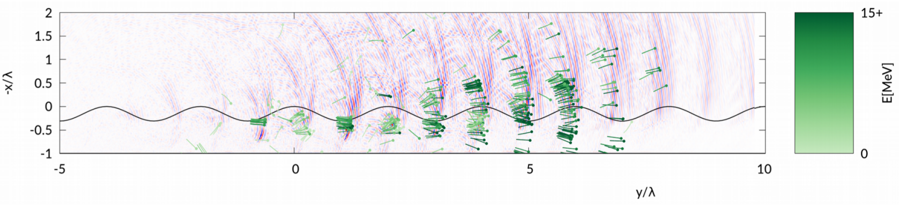
Boosting of HH by Electron Nanobunching

Electrons (→) trapped and accelerated by the SP self-organize into short bunches

Coherent scattering of the laser field by the electron bunches produce bright quasi-collinear HH

(similar to collective instability operation in a Free Electron Laser)

2D simulations by L. Fedeli



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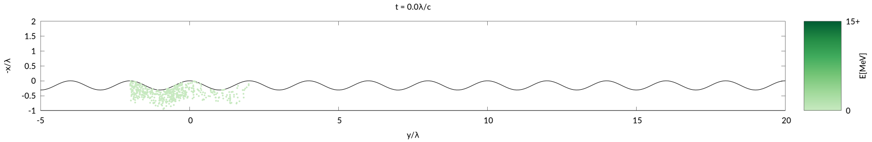

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  Phys. Rev. E **91** (2015) 013106
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- G. Cantono, L. Fedeli, A. Sgattoni, A. Denoeud, L. Chopineau, F. Reau, T. Ceccotti, A. Macchi, *Extreme ultraviolet beam enhancement by relativistic surface plasmons*, Phys. Rev. Lett. **120** (2018) 264803
- J. Sarma, A. McIlvenny, N. Das, M. Borghesi, A. Macchi, *Surface Plasmon-Driven Electron and Proton Acceleration without Grating Coupling*, New J. Phys. **24** (2022) 073023

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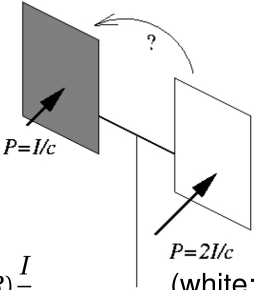
osiris.df.unipi.it/~macchi/TALKS/

EXTRA SLIDES

Heating Suppression for Light Pressure Dominance



The "Optical Mill" (Crookes radiometer) rotates in the *opposite* way to that suggested by the imbalance of light pressure between white (reflecting) and black (absorbing) plates

$$P = (1+R)\frac{I}{c}$$

(white: $R \simeq 1$, black: $R \simeq 0$)

Thermal pressure dominates due to stronger heating of the black plate in the imperfect vacuum of bulb

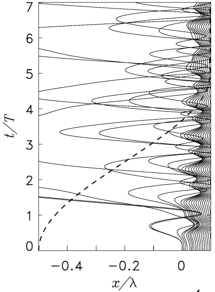
In laser-driven light sail acceleration heating must be suppressed for efficiency at not-so-extreme intensities ($I = 10^{18} - 10^{21}$ Wcm^{-2})

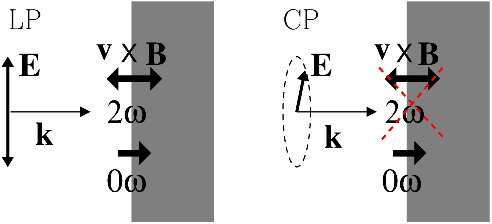
Circular Polarization Quenches Heating

Normal incidence & linear polarization (LP): electrons perform non-adiabatic oscillations driven by the $\mathbf{v} \times \mathbf{B}$ force across the sharp density gradient

Oscillating (2ω) term vanishes for circular polarization (CP)

→ suppression of electron heating





Light pressure $(0\omega$ term) dominates & ions respond smoothly to steady force

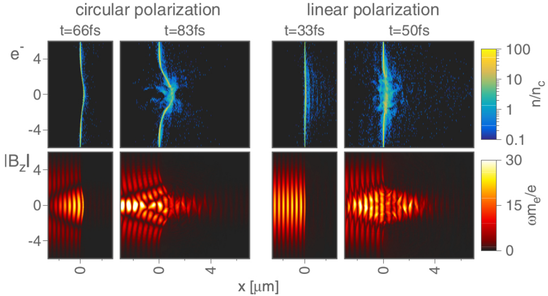
Macchi et al.

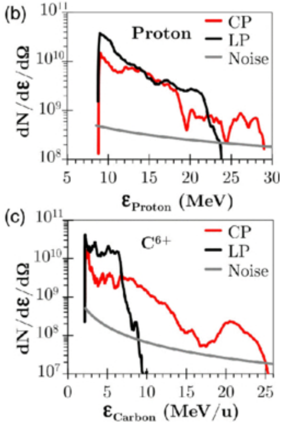
PRL **95** (2005) 185003

Energy spectrum improvement for circular polarization

GEMINI laser, $\tau_p = 45$ fs, $I = 6 \times 10^{20}$ W cm^{-2}, 15 nm thick CH foils, CP vs LP

- experiment: CP brings higher energies & spectral peaks for both species
- simulations: transparency-limited acceleration, proton spectrum not well reproduced

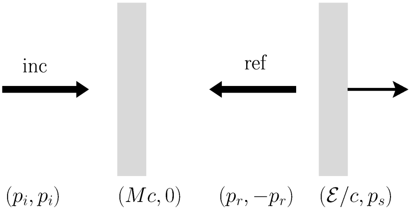




C.Scullion et al, PRL **119** (2017) 054801

Light Sail energy from conservation laws

Conservation of 4-momenta in "collision" between laser pulse and moving mirror (mass $M = \rho\ell$)



$$
\begin{aligned}
p_i + mc &= p_r + \mathscr{E}/c \\
p_i &= -p_r + p_s
\end{aligned}
$$

Using $\mathscr{E}^2 = M^2c^2 + p_s^2$ and $p_i = \int_0^\infty \frac{I(t')}{c}\mathrm{d}t' \equiv \frac{Mc}{2}\mathscr{F}$

energy $\quad \frac{\mathscr{E}}{Mc^2} = \frac{\mathscr{F}^2}{2(\mathscr{F}+1)} \quad \left(\simeq \frac{\mathscr{F}^2}{2} \text{ for } \beta = \frac{p_s c}{\mathscr{E}} \ll 1\right)$

efficiency $\quad \eta = \frac{\mathscr{E}}{p_i c} = \frac{2\beta}{1+\beta}$ $\longrightarrow$ 100% in the $\beta \to 1$ limit

Foreseen laser sailing . . .

R.Forward (1964)
G.Marx (1966)


TESTING NEWBORNS FOR GENETIC RISKS · TRUE COLORS OF DINOSAURS

SCIENTIFIC AMERICAN

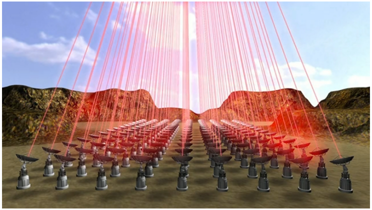
MISSION TO ALPHA CENTAURI

Tiny laser-powered probes traveling at near light speed take aim at a star

BUG BATTLE
Gene switches fight a corn pest

NEW TURING TESTS

HOW POVERTY HURTS KIDS' BRAINS
Could a simple remedy help?



Breakthrough Starshot (2016)

breakthroughinitiatives.org

Critical analysis of (un)feasibility:

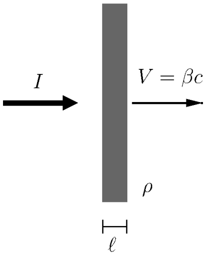
H.Milchberg, Phys. Today, 26 April 2016

Light Sail with extreme light on nanofoils

Energy/nucleon & efficiency from the 1D mirror model

(τ_p: laser pulse duration)

$$\mathscr{F} = \frac{2I\tau_p}{\rho\ell} = \frac{Z}{A}\frac{m_e}{m_p}\frac{{a_0}^2}{\zeta}\omega\tau_p \qquad \left(\zeta = \pi\frac{n_e}{n_c}\frac{\ell}{\lambda}\right)$$



Optimal thickness $a_0 \simeq \zeta$ at threshold of relativistic transparency

$$\mathscr{E}_{\max} \simeq 2\pi^2\frac{(m_e c)^2}{m_p}\left(\frac{Z}{A}\frac{c\tau_p}{\lambda}a_0\right)^2$$

$\ell \simeq 10$ nm , $I \simeq 1.6 \times 10^{21}$ W cm^{-2} ($a_0 = 22$) , $\tau_p = 40$ fs

$\longrightarrow \quad \mathscr{E}_{\max} \simeq 150$ MeV , $\eta \simeq 50\%$

Coherent motion of the sail $\longrightarrow$ mononergetic ion spectrum

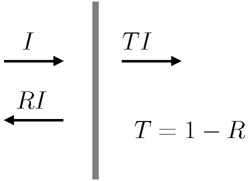
A dream ion beam? ...

Transparency of ultrathin plasma foil

1D model with relativistic nonlinearity

$n_e(x) \simeq n_0 \ell \delta(x)$ (ℓ: foil thickness)

[V.A.Vshivkov et al, Phys. Plasmas **5** (1996) 2727]

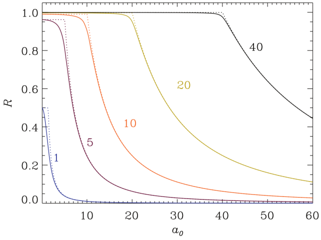


Nonlinear reflectivity:

$$R \simeq \begin{cases} 1 & (a_0 < \zeta) \\ \dfrac{\zeta^2}{{a_0}^2} & (a_0 > \zeta) \end{cases} \qquad \zeta \equiv \pi \frac{n_0 \ell}{n_c \lambda}$$

The transparency threshold $a_0 \simeq \zeta$ depends on areal density $n_0 \ell$

(note: it is *not* $n_e < n_c \gamma$ with $\gamma = (1 + a_0^2)^{1/2}$)



Analytical model for multi-D Light Sail

Self-similar transverse dilatation $r_\perp(t) = \Lambda(t) r_\perp(0)$

$$\sigma = \sigma(t) = \frac{\sigma(0)}{\Lambda^{D-1}(t)}\,, \qquad \frac{\mathrm{d}}{\mathrm{d}t}(\gamma\beta_\parallel) = \frac{2I}{\sigma(0)c^2}\Lambda^{D-1}(t)\frac{1-\beta_\parallel}{1+\beta_\parallel} \qquad (D = 1,2,3)$$

Impulsive transverse kick by ponderomotive force

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

→ transverse momentum scales linearly with position

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

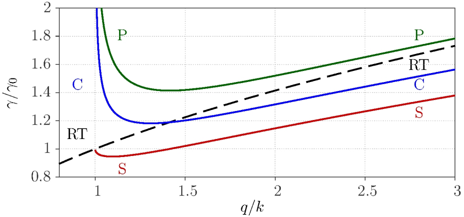
Solution in the $\gamma \gg 1$ limit $\quad \gamma = \left(\frac{t}{\tau_k}\right)^k, \quad k = \frac{D}{D+2}$

Thin foil RTI with self-consistent pressure modulation

Model: reflection from shallow 2D grating of depth δ
+ modified Ott's theory [PRL **29** (1972) 1429]
with modulated pressure:

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

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



S-polarization
P-polarization
C-ircular polarization
RT: no modulation ($\delta = 0$)