Advanced Concepts of Laser-Driven Ion Acceleration

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47th International Nathiagali Summer College
“High Power Laser Systems & Applications”
Islamabad, Pakistan, June 21, 2017

Reviews on ion acceleration (a selfish selection)

- A. Macchi, M. Borghesi, M. Passoni,
  Ion Acceleration by Superintense Laser-Plasma Interaction,
  Rev. Mod. Phys. **85** (2013) 571
- M. Borghesi, A. Macchi,
  Laser-Driven Ion Accelerators: State of the Art and Applications,
  in: *Laser-Driven Particle Acceleration Towards Radiobiology and Medicine* (Springer, 2016)
- A. Macchi,
  Laser-Driven Ion Acceleration,
  in: *Applications of Laser-Driven Particle Acceleration* (CRC press, 2018), arXiv:1711.06443

Outline

Short review of laser-driven ion acceleration

- Fast electron generation in solid targets
- Target Normal Sheath Acceleration
- Limits to TNSA: need for alternate schemes

Surface wave-driven acceleration

- "Peeler" geometry for proton acceleration
- Electron acceleration by surface plasmons

Light Sail acceleration

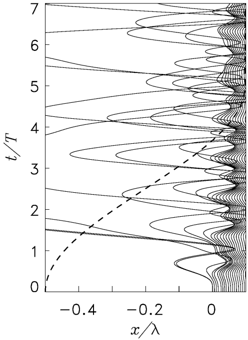
- Basic scalings
- Issues: transparency, instabilities, multispecies ...
- Experiments & state of the art
- Extreme intensity: unlimited acceleration?

Breaking of laser-driven surface oscillations

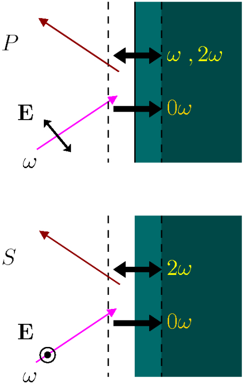
Interaction with solid targets:
laser-driven surface oscillations

P-polarization: $\mathbf{E}$-driven, $\Omega = \omega$

S-polarization: $\mathbf{v} \times \mathbf{B}$-driven, $\Omega = 2\omega$

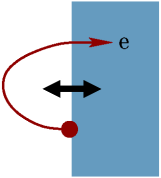


Because of the short gradient the oscillations tend to "break" and give energy to particles



Electrostatic simulation: self-intersection of trajectories, *wavebreaking* and generation of "fast" electron bunches

Generation of “fast” electrons



Single particle picture: oscillating forces drag electrons into the vacuum side and push them back in the plasma after an half-cycle
(strongly non-adiabatic motion)

Popular definitions:

“Vacuum heating” or “Brunel effect” if $\mathbf{E}$-driven at rate ω
[Brunel, Phys. Rev. Lett. **59** (1987) 52;
Phys. Fluids **31** (1988) 2714] “$\mathbf{J} \times \mathbf{B}$” heating if $\mathbf{v} \times \mathbf{B}$-driven at rate 2ω
[Kruer & Estabrook, Phys. Fluids **28** (1985) 430]

Empirical scaling for fast electron temperature

$$T_{\rm f} = m_e c^2 \left((1 + a_0^2/2)^{1/2} - 1 \right)$$

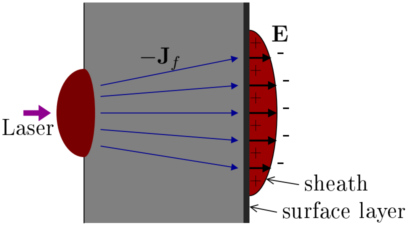
(so-called “ponderomotive” scaling) . . .

Target Normal Sheath Acceleration (TNSA)

Physics: sheath formation by the fast electrons escaping the rear target surface

The $\mathbf{E}$-field in the sheath back-holds electrons and accelerates ions

Protons from surface impurity layer favored by initial position and highest Z/A ratio



$\mathbf{J}_f$: fast electron current

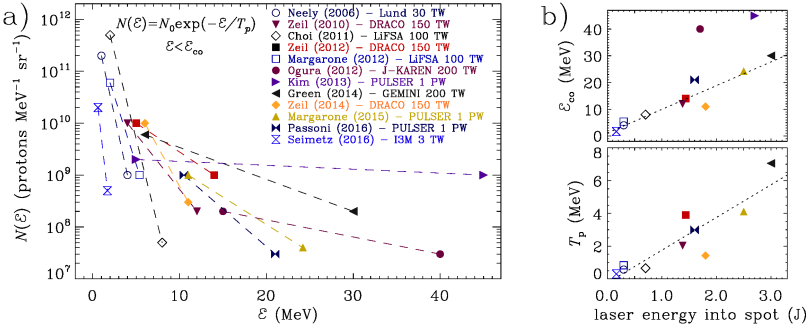
Naive model:

Sheath potential drop $\Delta\Phi \simeq T_\mathrm{f}$

Energy acquired by a "test" ion $\mathcal{E}_\mathrm{max} = Ze\Delta\Phi \simeq ZT_\mathrm{f}$

Expected scaling $\mathcal{E}_\mathrm{max} \propto (1 + a_0^2/2)^{1/2}$?

TNSA scaling needs full understanding . . .



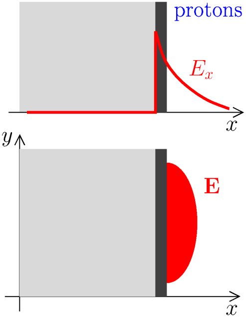
Data survey from experiments with high contrast, short pulse lasers and solid targets with full proton spectrum available [A. Macchi, arXiv:1212.06443 (2017)]

Proton energy scales almost linearly with pulse energy ($\propto a_0^2$)

Need to go beyond TNSA

- Scaling with pulse energy (even if linear) too low for applications with short pulse systems
- Proton spectra are typically exponential (thermal-like)

Why protons are not monoenergetic if they originate from the same position?

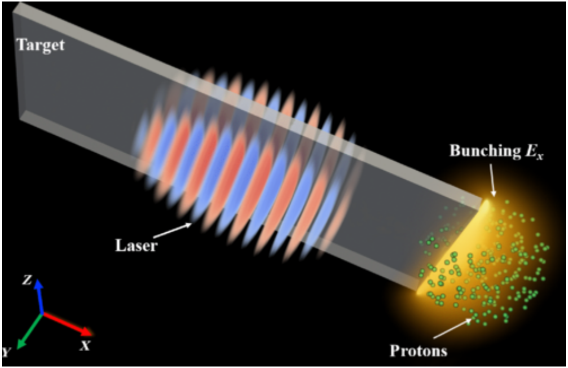


- sheath field is inhomogeneous in the transverse direction
- the proton number is high enough to screen the space-charge field of electrons

$\longrightarrow$ sharp $\mathbf{E}$-field gradient
$\longrightarrow$ broad spectrum even in planar 1D geometry

Proposed “Peeler” Proton Acceleration

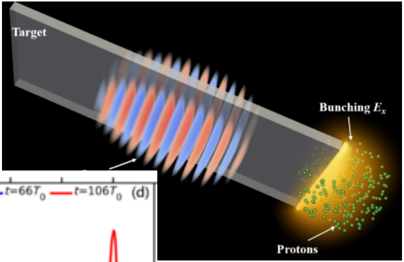
“A fs laser (red and blue) is incident on the edge of a micron-thick tape (grey) [. . .] Abundant electrons are accelerated forward by the intense laser.”

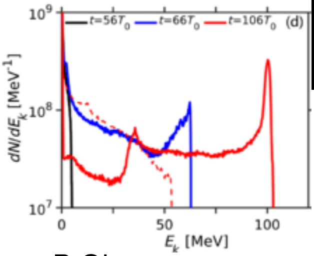


X.Shen, A.Pukhov, B.Qiao, Phys. Rev. X **11** (2021) 041002

Proposed "Peeler" Proton Acceleration

"[. . .] at the rear edge a longitudinal bunching field is established (yellow). Protons (green dots) are simultaneously accelerated and leading to a highly monoenergetic beam."





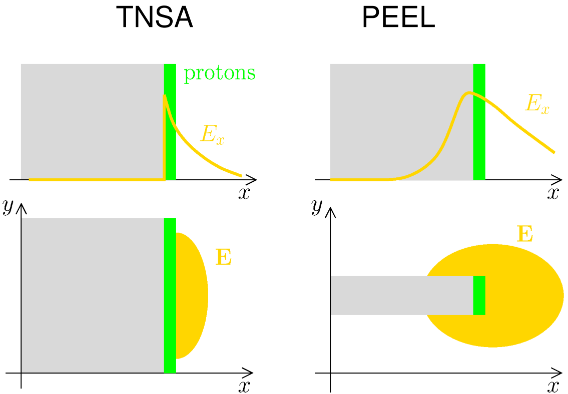
Pulse: 45 fs
7.8×10^{20} Wcm^{-2}
Target:
$n_e/n_c = 30$
$d = 50$ nm

X.Shen, A.Pukhov, B.Qiao,
Phys. Rev. X **11** (2021) 041002

Origin of Monoenergetic Proton Spectra

TNSA: fast electrons are less than protons in the layer which screen the $\mathbf{E}$-field producing a sharp gradient

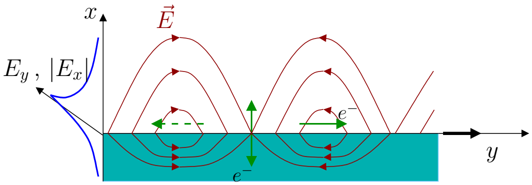
PEEL: protons are less than fast electrons and the space charge $\mathbf{E}$-field on the proton layer is spatially "smooth".



All protons experience almost the same field $\longrightarrow$ monoenergetic acceleration

New electron driver: Surface Plasma Wave

A SPW has the same properties eeded to accelerate electrons as a “bulk” plasma wakefield:



- longitudinal E-component (E_y)
- sub-luminal phase velocity $v_{\rm p} < c$ (with $v_{\rm p} \rightarrow c$ when $\omega_p \gg \omega$)

$\rightarrow$ electrons may “surf” the SPW

the SPW exists at the interface between vacuum and a solid-density plasma

$\rightarrow$ large number of accelerated electrons

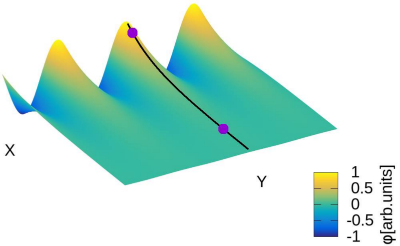
Simple Model of SPW Acceleration - I

SPW field electrostatic in the wave frame S'
moving with phase velocity $\beta_{\rm p} = v_{\rm p}/c$ with respect to S (lab)
Electrostatic potential in S':

$$\Phi' = -\left(\frac{\gamma_{\rm p} E_{\rm SPW}}{k}\right) e^{k'x} \sin k'y' \qquad k' = \frac{k}{\gamma_{\rm p}} \qquad \gamma_{\rm p} = (1-\beta_{\rm p}^2)^{-1/2}$$

The motion is 2D: the energy gain depends on the "kick angle" from the top of the potential hill

φ in the co-moving reference frame



Simple Model of SPW Acceleration - II

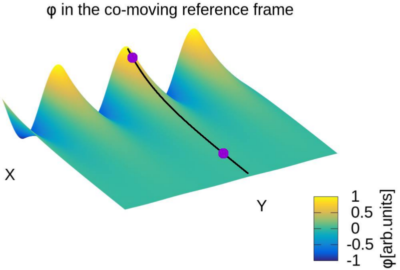
Assume as the most likely case an electron going downhill along the x-direction and acquiring an energy $W' = eE_{\text{SPW}}/k'$

$$W \simeq \gamma_{\text{p}} W' \simeq m_e c^2 a_{\text{SPW}} \frac{\omega_p^2}{\omega^2} \qquad \left(a_{\text{SPW}} = \frac{eE_{\text{SP}}}{m_e \omega c} \right)$$

with ejection angle in S
(for $W' \gg m_e c^2$)

$$\tan \phi_e = \frac{p_x}{p_y} \simeq \frac{1}{\gamma_{\text{p}}}$$

$\rightarrow$ high energy electrons are beamed near the surface ($\tan \phi_e \ll 1$)



Observation of “Surfing” Acceleration

PRL **116,** 015001 (2016) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2016

Electron Acceleration by Relativistic Surface Plasmons in Laser-Grating Interaction

L. Fedeli,[1,2,*] A. Sgattoni,[2] G. Cantono,[3,4,1,2] D. Garzella,[3] F. Réau,[3] I. Prencipe,[5,†] M. Passoni,[5] M. Raynaud,[6] M. Květoň,[7] J. Proska,[7] A. Macchi,[2,1] and T. Ceccotti[3]
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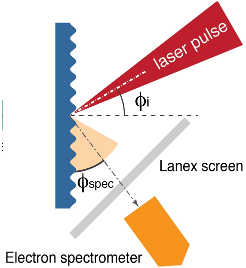
(Received 30 June 2015; published 7 January 2016)

LaserLAB experiment at SLIC, CEA Saclay

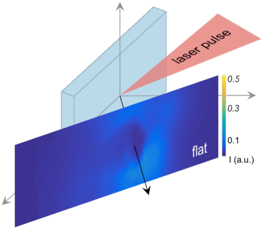
UHI laser: 25 fs pulse, $5 \times 10^{19}\ \mathrm{Wcm}^{-2}$, $a_0 = 4.8$

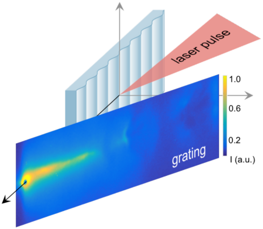
contrast $\gtrsim 10^{12}$ at 5 ps

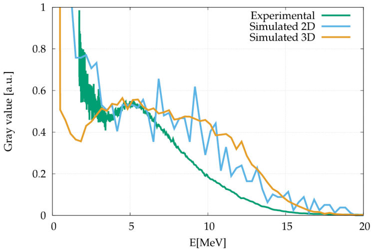
Observation of “Surfing” Acceleration



collimated ($\simeq$ $20°$ cone) electron emission near the surface tangent ($\phi \simeq 2°$)
multi-MeV energy, total charge $\simeq 100$ pC
Excellent agreement with 3D simulations

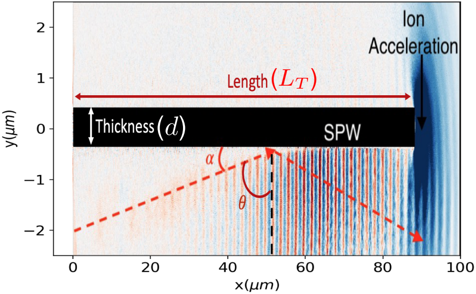






A simulation campaign

Aim: test tolerance of "peeler" acceleration with respect to grazing (non-parallel) & off-axis incidence (in view of scheduled experiments)

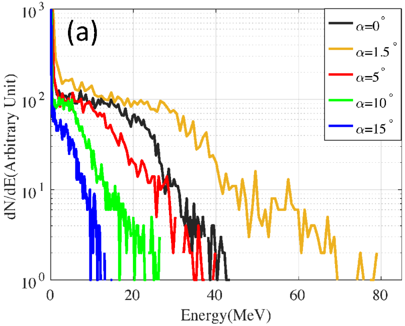


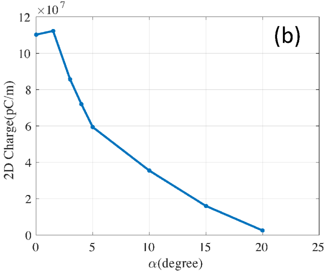
simulations by J. Sarma & A. McIlvenny (Queen's University Belfast)
PIC code EPOCH, 2D Cartesian geometry
$I = (0.34 - 7.8) \times 10^{20}\ \mathrm{Wcm}^{-2}$, 35 fs, $\lambda = 0.8\ \mu\mathrm{m}$, $a_0 = (5 - 19)$
$n_e = 1.7 \times 10^{23}\ \mathrm{cm}^{-3} = 100 n_c$, $d = 0.8\ \mu\mathrm{m}$, $L_T = (90 - 200)\ \mu\mathrm{m}$

Energy and Charge at Grazing Incidence

Maximum energy and charge for $\alpha = 1.5°$

Cut–off energy doubles with respect to both $\alpha = 5°$ and $\alpha = 0°$ (parallel incidence)

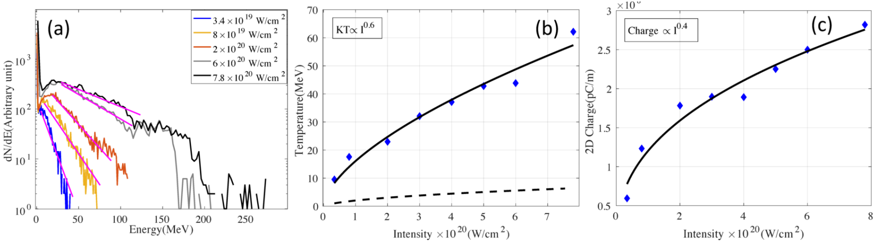




Peak charge density $\simeq 10^8$ pC m^{-1} in 2D corresponds to $\simeq 780$ pC in 3D

$I = 3.4 \times 10^{19}$ Wcm^{-2}

Scaling with Laser Intensity



a) electron spectra b) electron “Temperature” c) charge density

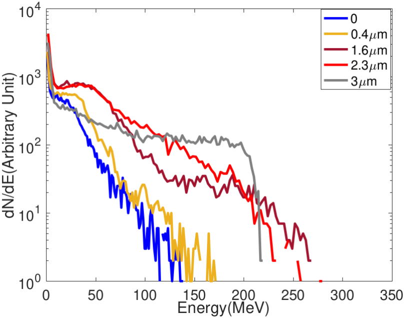
Grazing angle $\alpha = 5^\circ$

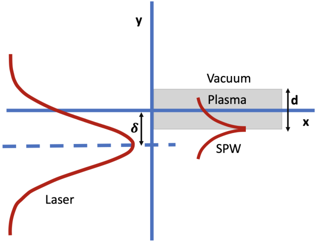
Temperature largely exceeds “ponderomotive” values (dashed line)

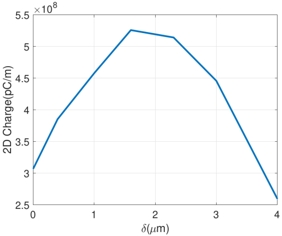
Peak charge density value $\simeq 3 \times 10^8$ pC m^{-1} in 2D corresponds to an estimate $\simeq 1.9$ nC in 3D

Parallel incidence

Energy and charge have maxima with the laser field *displaced* (by δ) from the target midplane







$I = 6 \times 10^{20}\ \mathrm{Wcm}^{-2}$

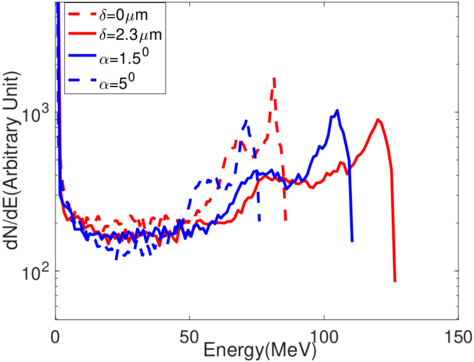
total 3D charge $\simeq 3.4\ \mathrm{nC}$ for $\delta = 1.6\ \mu m$

Proton Spectra from “peeler” acceleration

Highest cut-off energy is reached for parallel incidence with “shifted” pulse ($\delta = 2.3\ \mu\mathrm{m}$)

Slightly lower energy at grazing incidence ($\alpha = 1.5°$)

$I = 6 \times 10^{20}\ \mathrm{Wcm}^{-2}$



Non-perfect alignment yields better results!

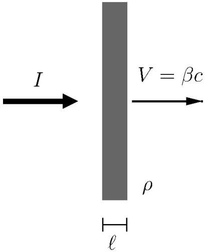
J. Sarma, A. McIlvenny, N. Das, M. Borghesi, A. Macchi, New. J. Phys. (2022) to be published

Light Sail acceleration: a “dream bunch” of ions?

Energy & efficiency from the accelerated mirror model:

$$\frac{\mathcal{E}_{\max}}{m_p c^2} = \frac{\mathcal{F}^2}{(2(\mathcal{F}+1))} \qquad \eta = \frac{2\beta}{1+\beta} = 1 - \frac{1}{1+\mathcal{F}^2}$$

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



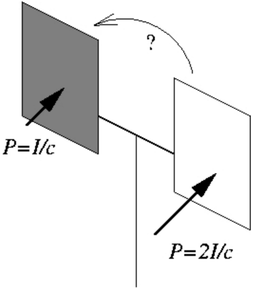
$$\left(\beta \ll 1 \quad \rightarrow \quad \mathcal{E}_{\max}/m_p c^2 \simeq \mathcal{F}^2/2\,, \quad \eta \simeq \mathcal{F}^2\right)$$
$$\ell \simeq 10 \text{ nm}\,,\ I \simeq 10^{21} \text{ W cm}^{-2}\,,\ \tau_p \gtrsim 10 \text{ fs}$$

$\longrightarrow \quad \mathcal{F} \simeq 1 \quad \mathcal{E}_{\max} \simeq 200$ MeV , $\eta \simeq 0.5$

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

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

Radiation pressure vs heating



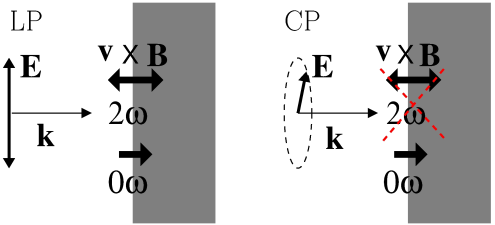
The “Optical Mill” (Crookes’ radiometer) rotates the *opposite* way to that suggested by the imbalance of radiation pressure: *thermal* pressure due to *heating* dominates

Enforcing radiation pressure dominance requires to suppress heating of the surface

Circular polarization quenches heating

Radiation pressure must overcome the fast electrons pressure
Circular Polarization (CP) & normal incidence:
the 2ω component of the $\mathbf{v} \times \mathbf{B}$ force vanishes
$\rightarrow$ longitudinal oscillations and electron heating are suppressed

Ions respond smoothly to steady force: radiation pressure dominates the interaction



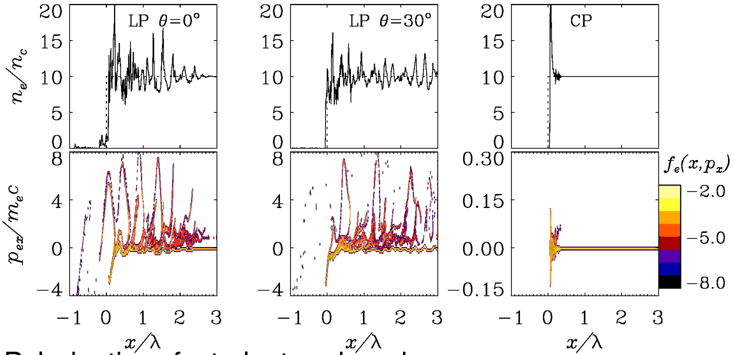
[Macchi et al, Phys. Rev. Lett. **95** (2005) 185003]

Fast electron generation: effect of polarization

1D simulations of laser interaction with solid-density plasma

density

phase space



Linear Polarization: fast electron bunches at rate ω (for $\theta = 30°$, P-pol.) or 2ω (for $\theta = 0°$)

Circular Polarization at $\theta = 0°$: no fast electrons ($(\mathbf{v} \times \mathbf{B})_{2\omega} = 0$)

Hurdles along the Light Sail route

- working with ultrathin targets requires extremely high contrast laser pulses to prevent distruction by prepulses
- transverse pulse profile and target bending bring longitudinal fields back and cause electron heating
- optimal working point ($a_0 = \zeta$) is at the self-induced transparency threshold: easy for laser pulse to break through the target (also favored by target expansion)
- solid target acceleration by laser light is prone to Rayleigh-Taylor instability
- in multispecies target, different ions tend to separate and a thin target is disassembled
- ...

Eventually circular polarization does it better

PRL **119,** 054801 (2017) PHYSICAL REVIEW LETTERS week ending 4 AUGUST 2017

Polarization Dependence of Bulk Ion Acceleration from Ultrathin Foils Irradiated by High-Intensity Ultrashort Laser Pulses

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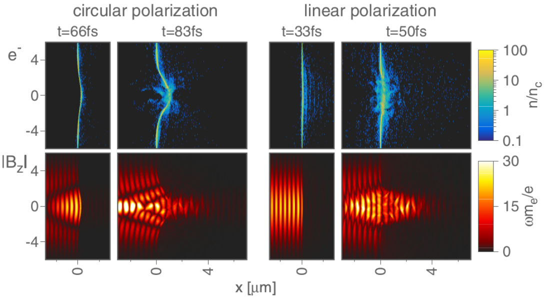
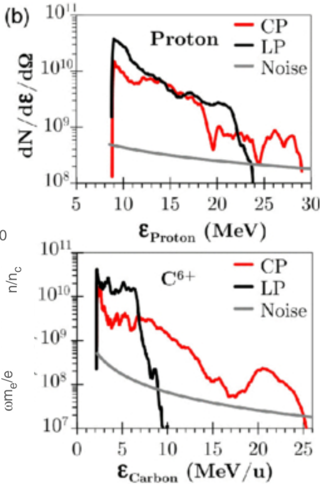
(Received 23 May 2016; published 2 August 2017)

GEMINI laser (CLF, UK)
$\tau_p = 45$ fs, $I = 6 \times 10^{20}$ W cm^{-2},
$10 - 100$ nm thick CH foils

Eventually circular polarization does it better

- CP yields larger cut-off energies and spectral peaks for both species
- simulations show transparency-limited acceleration and do not reproduce proton spectrum well





Exploiting the prepulse: acceleration of Carbon ions

PHYSICAL REVIEW LETTERS **127,** 194801 (2021)

Featured in Physics

Selective Ion Acceleration by Intense Radiation Pressure

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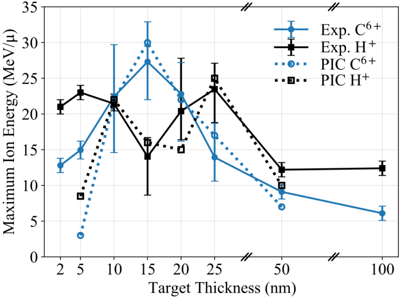
GEMINI laser (CLF, UK)

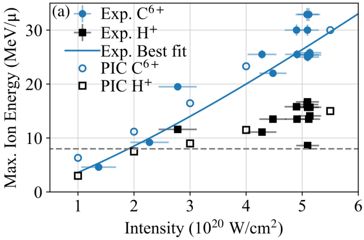
$\tau_p = 45$ fs, $I = 4.5 \times 10^{20}$ W cm^{-2},

$2 - 100$ nm thick C foils with H impurities

Exploiting the prepulse: acceleration of Carbon ions

For 15 nm thickness
the energy/nucleon
is higher for Carbon ions
Simulating the ps prepulse
interaction shows removal of
impurity protons (H^+)





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

Public coverage

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

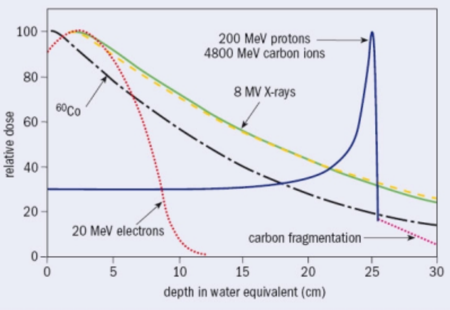
Experiments and simulations show how the shape of a laser's profile determines which target atoms make up the resulting ion beam.

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.

What is a dream ion bunch good for?



Energy deposition by ions in matter is strongly localized at the stopping point (Bragg peak)

figure: U. Amaldi & G. Kraft, Rep. Prog. Phys. **68** (2005) 1861

(Foreseen) Applications:

- oncology: ion beam therapy
- triggering of nuclear reactions, isotope production
- production of warm dense matter
- diagnostic of materials
- ultrafast probing of electromagnetic fields

A Carbon ion driver for the FLASH effect?

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*

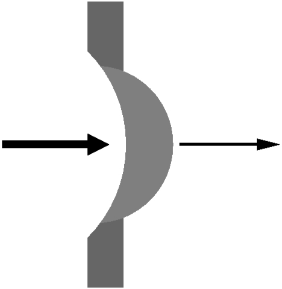
For Carbon ions only laser-driven accelerators may deliver the necessary flux

Extreme intensity: Light Sail "unlimited"?

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

$\longrightarrow$ enhanced acceleration at the expense of the number of ions

[S.V.Bulanov et al. "Unlimited ion acceleration by radiation pressure" PRL **104** (2010) 135003]



Energy gain in the relativistic regime is faster in 3D than in 1D:

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

Analytical model for multi-D Light Sail

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

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

Impulsive transverse kick by ponderomotive force

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

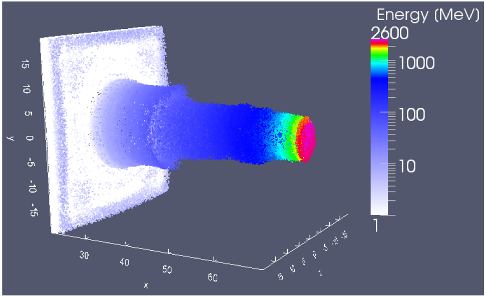
$\rightarrow$ transverse momentum scales linearly with position

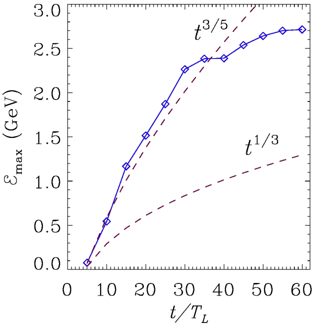
$$\frac{\mathrm{d}\Lambda}{\mathrm{d}t} = \frac{\dot{r}_\perp(t)}{\dot{r}_\perp(0)} = \frac{\alpha}{\gamma(t)} , \qquad \gamma(t) \simeq (p_\parallel^2 + m_i^2 c^2)^{1/2} , \qquad \alpha \simeq 2\frac{m_e a_0 c^2 \Delta t}{m_p w^2}$$

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

Fast scaling in 3D confirmed by simulations

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

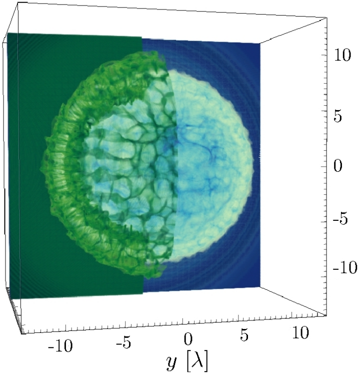




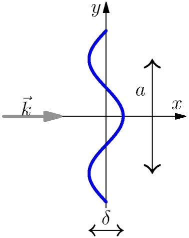
$\mathcal{E}_{\rm max} \simeq 2.6$ GeV $>$ 4 X 1D prediction (still limited by transparency)

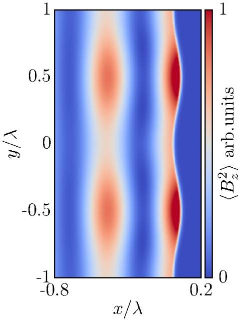
Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

Light Sail Rayleigh-Taylor instability



target breakup into a net of structures with size $\sim \lambda$ (laser wavelength)





Explanation: Rayleigh-Taylor instability stimulated by radiation pressure modulation
Sgattoni et al, Phys. Rev. E **91** (2015) 013106

field enhancement in surface ripple valleys

Conclusions & Perspectives

Need to go beyond TNSA and "re-boost" the field

Surface wave-driven "peeler" acceleration:

- very promising simulation results (> 100 MeV monoenergetic protons with present-day-lasers)
- experimental investigation urgently needed

Light Sail acceleration:

- "all-optical" Carbon ion acceleration demonstrated
- interest as a test source for "Flash" therapy
- source optimization and tigther control needed
- promising scaling at "extreme" intensities (instabilities may be an issue)