Surfin' Plasma Waves and Sailing with Light: the Sea of Laser-Plasma Accelerators

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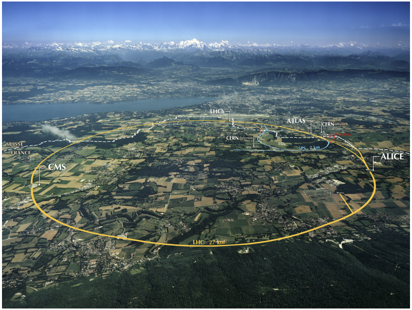
Enrico Fermi Department of Physics, University of Pisa, Italy

Lights of Tuscany, Pisa, May 16, 2025

“Standard” Particle Accelerators

SLAC (credit: Victor Blacus)



LHC (credit: Maximilien Brice, CERN)

from www.radiologyinfo.org

Why a Quest for New Accelerators?

- Go beyond current limitations
  - Energy
  - Pulse duration
  - Particle flux
  - Particle type (e.g. unstable particles)
- Adapt to applications
  - Particle radiotherapy (e.g. FLASH ⟶)
  - Diagnostics of matter
  - Driver for secondary sources (e.g. Free Electron Lasers)
  - Injectors for existing accelerators
- Reduce cost and size

Enhanced Radiotherapy at Ultra-High Dose

INTERNATIONAL JOURNAL OF RADIATION BIOLOGY
2022, VOL. 98, NO. 2, 127-135
https://doi.org/10.1080/09553002.2022.2009143

Taylor & Francis
Taylor & Francis Group

FLASH ultra-high dose rates in radiotherapy: preclinical and radiobiological evidence

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Pisa center for FLASH radiotherapy (CPFR) established in 2012 for interdisciplinary research

Need of compact sources at ultra-high flux and short duration

The Vision of “Collective” Acceleration

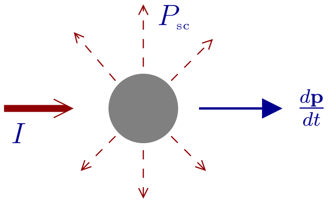
“The principles of coherent acceleration of charged particles”
V. I. Veksler, At. Energ. **2** (1957) 525

- accelerating field on each particle proportional to the number of accelerated particles
- automatic spatio-temporal synchronization between the particles and the accelerating field
- generation of quasi-neutral bunches with large numbers of particles

Example: Coherent “Radiation Drag” Acceleration

A small particle (radius $a \ll \lambda$, mass M) undergoing Thomson Scattering of an EM wave absorbs momentum

[Landau & Lifshitz, *The Classical Theory of Fields*, ch.78 p.250 (1962)]



$$\frac{\mathrm{d}p}{\mathrm{d}t} = \sigma_T I \propto P_{sc}$$

(absorbed momentum $\propto$ scattered power in rest frame of particle)

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

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

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

Extreme Laser Pulses

Chirped Pulse Amplification

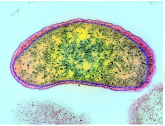
D.Strickland & G.Mourou

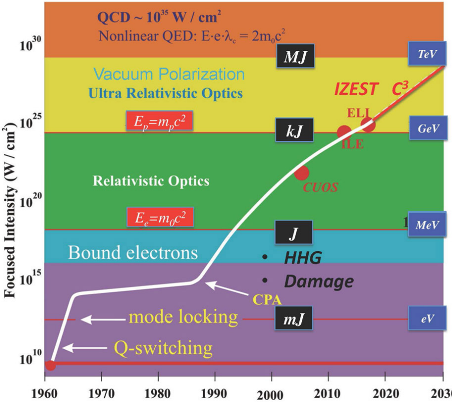
(Nobel Prize 2018)

"λ^3" pulses: extreme focusing of laser pulses in space and time (few femtoseconds $= 10^{-15}$ s):

Highest intensity so far $I = 10^{23}$ W cm^{-2}

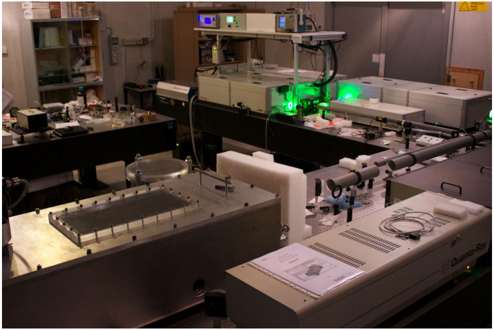
Yoon et al, Optica **8** (2021) 630





Mourou & Tajima, "Exploring fundamental physics at the highest-intensity-laser frontier", SPIE news, August 3, 2012

“Extreme” Physics on a Table Top



The 200 Terawatt laser system at Intense Laser Irradiation Laboratory, CNR/INO, Pisa

Nice Example of Acceleration by a Strong Wave

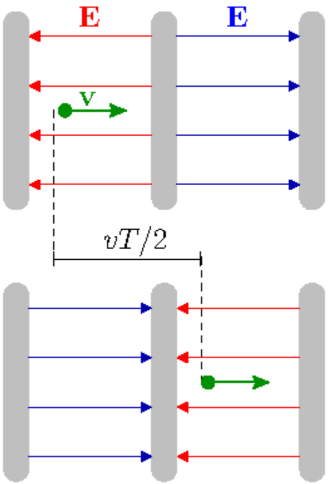
From: T.Katsouleas, *Nature* **444** (2006) 688

Looking for the Perfect Wave for Electrons

LINAC principle: a "fake" (non-propagating) wave created by localized oscillations in appropriate phase

An electron of velocity v crosses a cavity of length L within half the period T of $\mathbf{E}$-field so to "see" $\mathbf{E}$ as always accelerating

Idea: create a similar structure in a plasma where the maximum $\mathbf{E}$-field is not limited by electrical breakdown



Starting Point: Cold Plasma Oscillations

1D displacement of electrons $s(x,t)$

$v(x,t) = \partial_t s(x,t)$

Assumptions:

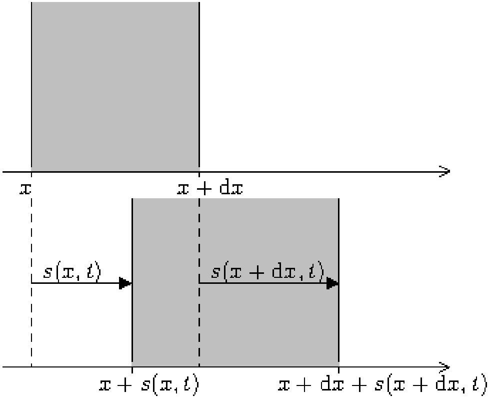
- $v(x,t) \gg$ thermal velocity
- immobile ions
- electrons do not overtake

General solution: localized oscillation at plasma frequency

$\omega_p = (4\pi n_e e^2/m_e)^{1/2}$

with arbitrary profile $\tilde{s}(x)$

$s(x,t) = \mathrm{Re}[\tilde{s}(x)\mathrm{e}^{-i\omega_p t}]$



(see e.g. *The Feynman Lectures on Physics*, vol.2, sec.7-3)

From Fake Wave to Wake Wave

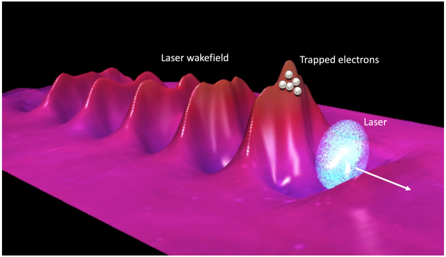
How to give a phase velocity to localized non-propagating oscillations?

Idea: let oscillations be excited by a moving perturbation (wake)

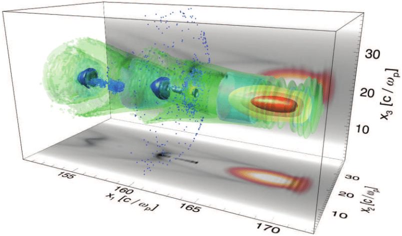
Bodensee at Bad Schachen, Lindau, Germany.
Photo by Daderot, Wikipedia, public domain.

Laser Wakefield

A short laser pulse
of duration $\simeq \pi/\omega_p$
excites a wake
with phase velocity
$v_p = v_{g\text{EM}} = c(1-\omega_p^2/\omega^2)^{1/2}$
T.Tajima & J.Dawson,
Phys. Rev. Lett. **43**, 267 (1979)



Source: *PRX* collection on
laser-plasma acceleration



EM pressure force pushes electrons at the front and back slopes of the laser pulse

3D simulation of a laser wakefield

Fonseca et al, *Plasma Phys. Control. Fusion* **50**, 124034 (2008)

Acceleration in a Plasma Wave – a Tutorial

Plasma waves in a different frame

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(Received 18 June 2019; accepted 15 May 2020)

A tutorial description of plasma waves in a cold plasma, with emphasis on their application in plasma-based electron accelerators, is presented. The basic physics of linear plasma oscillations and waves and the principle of electron acceleration in a plasma wave are discussed without assuming any previous knowledge of plasma physics. It is shown that estimating key parameters for plasma acceleration such as the maximum or "wave breaking" amplitude and the corresponding energy gained by electrons "surfing" the wave requires a relativistic and nonlinear analysis. This can be done with little mathematical complexity by using a Lorentz transformation to a frame co-moving at the phase velocity of the wave. The transformation reduces the problem to a second-order ordinary differential equation as originally found by Chian [Plasma Phys. **21**, 509 (1979)] so that the analysis can exploit the analogy with the mechanical motion of a particle in a potential well.

https://doi.org/10.1119/10.0001431

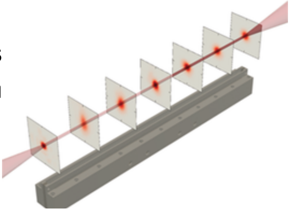
American Journal of Physics **88** (2020) 723

Recent Experimental Progress

10 GeV from a 30 cm-long plasma wake thanks to progress in laser guiding and electron injection (LBNL, US)

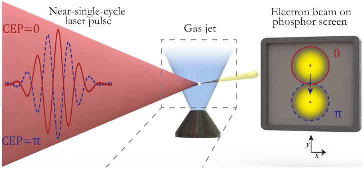
Picksley et al, *PRL* **133** (2024) 255001

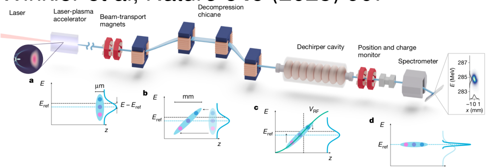
covered by Phys. Today and APS Physics



Manipulation of a laser-plasma generated bunch to match synchrotron beam quality (DESY, Germany)

Winkler et al, *Nature* **640** (2025) 907





Few-cycle laser driver at KHz rate (LOA, France)

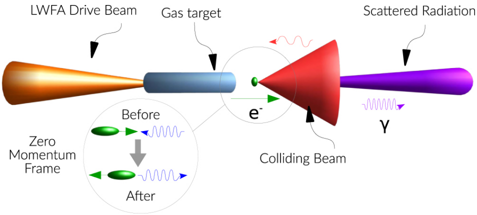
Huijts et al, *PRX* **12** (2022) 011036

See osiris.df.unipi.it/~macchi/TALKS for a short review on recent results

Strong Field Photon-Electron Collider

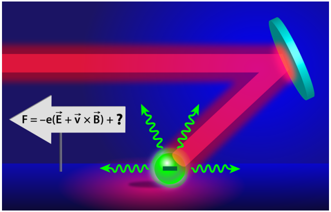
Laser field amplified by $(1+\beta_e)/(1-\beta_e) \simeq 2\gamma_e^2$ in electron rest frame

$\longrightarrow$ Route to approach "strong field" QED regime



Arran et al, *Plasma Phys. Control. Fusion* **61** (2019) 074009

First results on testing radiation reaction models



Cole et al, *Phys. Rev. X* **8** (2018) 011020

Poder et al, ibid. 031004

Viewpoint: Macchi, *Physics* **11** (2018) 13

Ultimate goal: reach Schwinger field

$E_s = m_e c^3/e\hbar = 1.3 \times 10^{16}$ V/cm

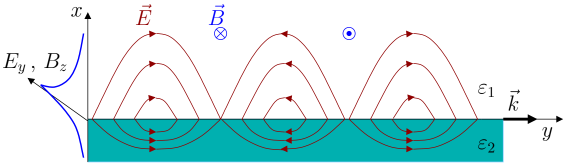
$\longrightarrow$ breakdown of "quantum vacuum"

Surfin' the Surface Plasma Wave

SPW are EM modes propagating along a sharp interface between vacuum and a dense plasma ($\omega_p > \sqrt{2}\omega$)

$\varepsilon_1 = 1$

$\varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} < -1$



Longitudinal **E**-field component (E_y) & phase velocity $v_p \lesssim c$

$\longrightarrow$ electrons can be accelerated along the surface

SPW can be excited by laser pulses on "grating" targets (for phase matching) or at grazing incidence

Review of SPW in intense laser-solid interactions:

Macchi et al, *Phys. Plasmas* **25** (2018) 031906; **26** (2019) 042114

Observation of Surface Acceleration of Electrons

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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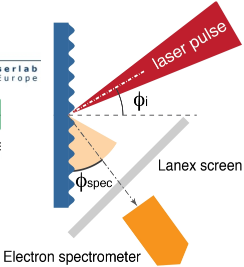
(Received 30 June 2015; published 7 January 2016)

LaserLAB experiment at SLIC facility, CEA Saclay, France

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

Observation of Surface Acceleration of Electrons

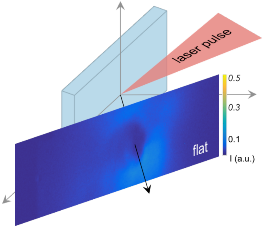


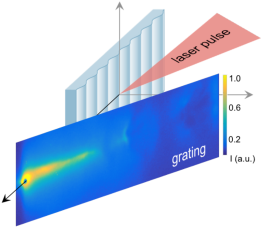
Collimated ($\simeq 20°$ cone) Multi-MeV electrons near the surface tangent ($\phi \simeq 2°$)

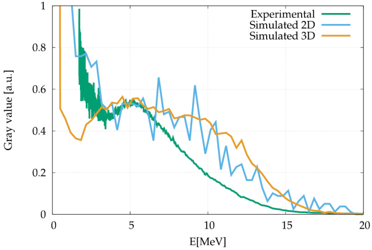
Large total charge up to $\simeq 650$ pC (value allowed by high plasma density)

Fedeli et al, *PRL* **116** (2016) 015001;

Cantono et al, *PoP* **25** (2018) 031906







Observation of SP-enhanced XUV High Harmonics

PHYSICAL REVIEW LETTERS **120,** 264803 (2018)

Extreme Ultraviolet Beam Enhancement by Relativistic Surface Plasmons

G. Cantono,[1,2,3,4,*] L. Fedeli,[5] A. Sgattoni,[6,7] A. Denoeud,[1] L. Chopineau,[1] F. Réau,[1] T. Ceccotti,[1] and A. Macchi[3,4]
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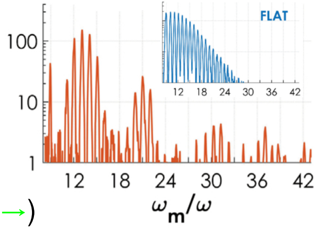
[7]*LESIA, Observatoire de Paris, CNRS, UPMC: Sorbonne Universites, 92195 Meudon, France*

LaserLAB experiment at SLIC facility, CEA Saclay, France

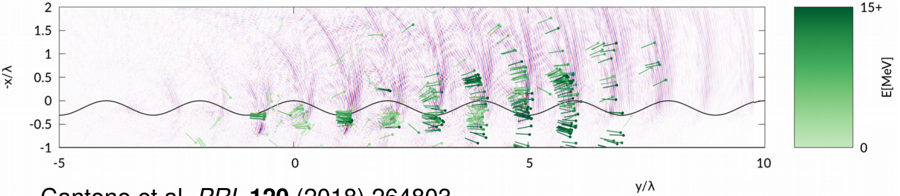
UHI laser: 25 fs pulse, 2×10^{19} Wcm^{-2}

Observation of SP-enhanced XUV High Harmonics

Enhanced High Harmonic emission observed when Surface Plasmons are excited



Simulations show coherent scattering from self-organized electron bunches (→) to produce quasi-collinear HH
(similar mechanism to collective instability in a FEL)



Cantono et al, *PRL* **120** (2018) 264803

The Quest for Ion Accelerators

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

$$\frac{d\mathcal{E}}{dx} \propto \frac{1}{\mathcal{E}^2}$$ (Coulomb scattering)

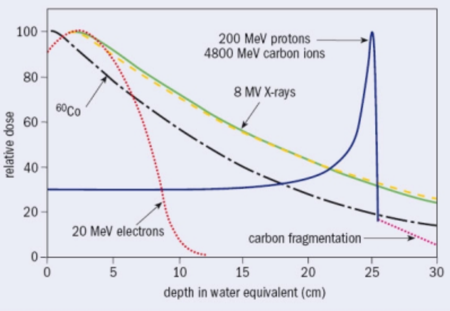


figure: Amaldi & Kraft, Rep. Prog. Phys. **68** (2005) 1861

(Foreseen) Applications:

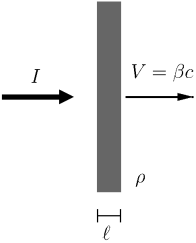
- oncology: ion beam therapy
- diagnostic of materials
- production of warm dense matter
- triggering of nuclear reactions, isotope production
- ultrafast probing of electromagnetic fields

Laser-boosted Light Sail

At normal incidence the cycle-averaged force per unit surface on a perfect mirror is $P = 2\frac{I}{c}$

("radiation pressure", Maxwell, 1874; Bartoli, 1876)

A thin mirror of finite mass is accelerated

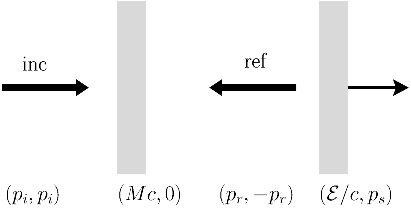


Originally proposed for interstellar travel (G. Marx, *Nature* **211** (1964) 22)

Re-discovered in 2016: Breakthrough Starshot project, endorsed by S. Hawking & F. Dyson

Light Sail as Ion Accelerator

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



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

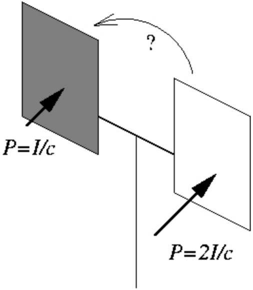
Using $\mathcal{E}^2 = M^2c^2 + p_s^2$ and $p_i c = \int_0^\infty I(t')\mathrm{d}t' \equiv Mc^2\mathcal{F}/2$

energy $\dfrac{\mathcal{E}}{Mc^2} = \dfrac{\mathcal{F}^2}{2(\mathcal{F}+1)}$ efficiency $\eta \equiv \dfrac{\mathcal{E}}{p_i c} = \dfrac{2\beta}{1+\beta}$

For $\ell \simeq 10$ nm and a 10 fs, $10^{21}\ \mathrm{W\,cm^{-2}}$ pulse

$\mathcal{E}_{\max} \simeq 200\ \mathrm{MeV/nucleon}\,,\ \eta \simeq 0.5$

Suppress Heating to Make Laser Pressure Dominant



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) faces

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

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

This is because the *thermal* pressure dominates due to stronger heating of the black face (in imperfect vacuum)
How to reduce heating in superintense laser interaction?

Circular Polarization Quenches Heating

PRL **94,** 165003 (2005) PHYSICAL REVIEW LETTERS week ending 29 APRIL 2005

Laser Acceleration of Ion Bunches at the Front Surface of Overdense Plasmas

Andrea Macchi,[1,*] Federica Cattani,[2] Tatiana V. Liseykina,[2,†] and Fulvio Cornolti[2]
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(Received 2 November 2004; revised manuscript received 31 January 2005; published 29 April 2005)

PRL **103,** 085003 (2009) PHYSICAL REVIEW LETTERS week ending 21 AUGUST 2009

"Light Sail" Acceleration Reexamined

Andrea Macchi,[1,2,*] Silvia Veghini,[2] and Francesco Pegoraro[2]
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(Received 13 May 2009; published 18 August 2009)

(PRL Editors did not like the original Dylan-like title "LSA *revisited*" . . .)

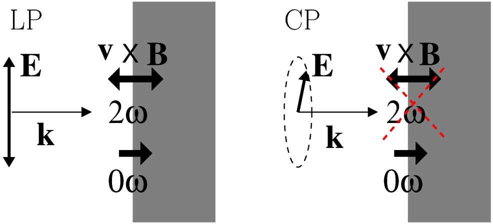
Circular Polarization Quenches Heating

Electrons are heated due to laser-driven non-adiabatic oscillations across the laser-vacuum interface

For circular polarization (CP) & normal incidence the 2ω component of the $\mathbf{v} \times \mathbf{B}$ force vanishes

→ longitudinal oscillations and electron heating are suppressed

Ions respond smoothly to the electrostatic field which balances the steady laser pressure



Macchi et al, *PRL* **95** (2005) 185003; **103** (2009) 085003

Enhanced Light Sail with Circular Polarization

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

C. Scullion,[1] D. Doria,[1,*] L. Romagnani,[2] A. Sgattoni,[3,†] K. Naughton,[1] D. R. Symes,[4] P. McKenna,[5] A. Macchi,[3,6] M. Zepf,[1,7] S. Kar,[1] and M. Borghesi[1,‡]
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(Received 23 May 2016; published 2 August 2017)

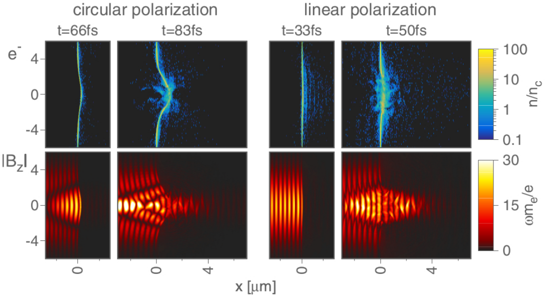
$\tau_p = 45$ fs, $I = 6 \times 10^{20}$ W cm^{-2}

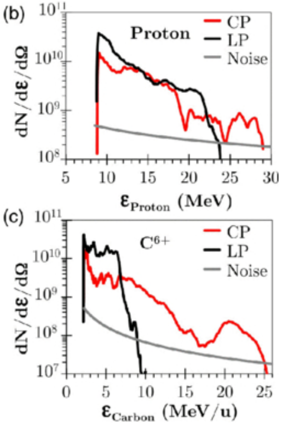
$10 - 100$ nm thick CH foils

Enhanced Light Sail with Circular Polarization

- CP brings larger cut-off energies & spectral peaks for both species
- simulations show that acceleration is limited by the onset of transparency

$\longrightarrow$ compromise between target lightness and reflectivity





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

Light Sail Acceleration of Carbon Ions

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

Featured in Physics

Selective Ion Acceleration by Intense Radiation Pressure

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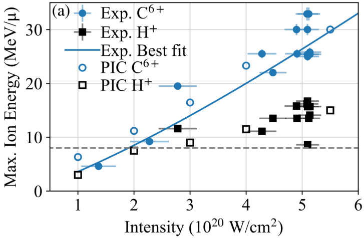
GEMINI laser (RAL/CLF, UK) $\tau_p = 45$ fs, $I = 4.5 \times 10^{20}$ W cm^{-2}

$2 - 100$ nm thick C foils (H impurities removed)

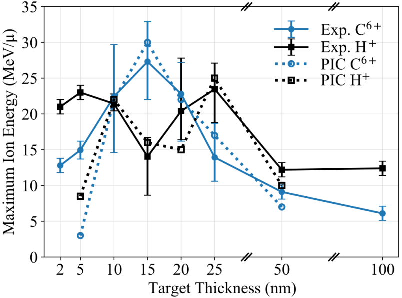
33 MeV/nucleon C^{6+} energy ions observed

Light Sail Acceleration of Carbon Ions

For 15 nm thickness
the energy/nucleon
is higher for C^{6+} ions
A picosecond prepulse
removes impurity protons (H^+)



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



Energy scaling $\propto I^{1.2}$ still
limited by transparency onset
Suitable driver for FLASH
studies using C ions?

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

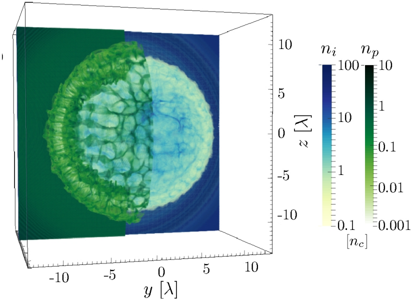
Experiments and simulations show how the shape of a laser's profile determines which target atoms make up the resulting ion beam.

Physics

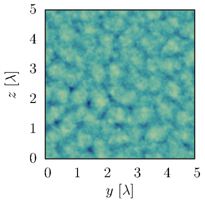
A New Trick to Make Short-Pulse Ion Beams

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

Light Sail Instability



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



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

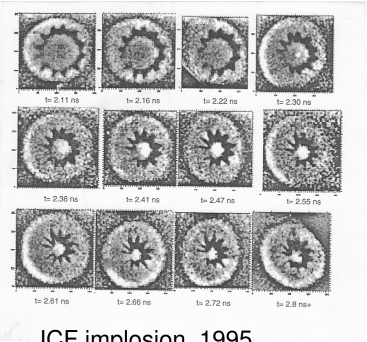
Interpretation: Rayleigh-Taylor instability driven by light pressure & seeded by surface plasmon excitation with $k_\perp \simeq 2\pi/\lambda$

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

Rayleigh-Taylor Instability in Space and Lab

Crab Nebula (Hubble)

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

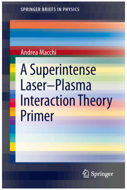


ICF implosion, 1995

Exagon formation in RTI is an example of “spontaneous symmetry breaking” in a classical system

S.I.Abarzhi, *PRE* **59** (1999) 1729

Suggestions for Summer Reading (a Selfish Selection)



Laser-Plasma theory: A. Macchi,
- *A Superintense Laser-Plasma Interaction Theory Primer* (Springer, 2013)
(2nd deeply revised edition in press!)

Surface plasma wave reviews:
AM et al, *Phys. Plasmas* **25** (2018) 031906; **26** (2019) 042114

Ion acceleration reviews:
- AM, M. Borghesi, M. Passoni, *Rev. Mod. Phys* **85** (2013) 751
- AM, arXiv:1711.06443

Tutorial on plasma waves: AM, *Am. J. Phys.* **88** (2020) 723

Find everything at https://osiris.df.unipi.it/~macchi/