A Relativistic Microscopic Laboratory: Superintense Laser-Plasma Interactions

Andrea Macchi

CNR/INO, Adriano Gozzini laboratory, Pisa, Italy

Enrico Fermi Department of Physics, University of Pisa, Italy

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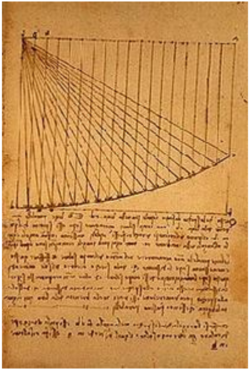
Focused Light-Matter Interaction: an Old Story . . .

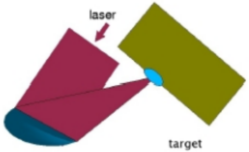
Archimedes' use of "Burning Mirrors" in the Siege of Syracuse; Giulio Parigi (~ 1600)
Uffizi Museum, Florence, Italy
Sunlight intensity: $I \simeq 10^{-1}\ \mathrm{Wcm}^{-2}$
tight focusing $\longrightarrow \simeq 10^{3}\ \mathrm{Wcm}^{-2}$



Leonardo da Vinci,
Codex Arundel (1480-1518),
British Library, London

The Dawn of Laser-Plasma Physics

"*The laser is a solution looking for a problem*"
(I. D'Haenens to T. Maiman, 1960)
Q-switched lasers (1962):
$I = 10^{13}\ \mathrm{Wcm}^{-2}$
$\longrightarrow$ matter is ionized and heated up to $\sim 10^9$ K: hot, dense plasma state
"*It should be possible to do many interesting experiments on such plasmas*"
J.Dawson, "On the Production of Plasma by Giant Pulse Lasers" *Phys. Fluids* **7** (1964) 981



Plasma generated by blasting droplets with a laser (ETH-Zurich/B.Newton)

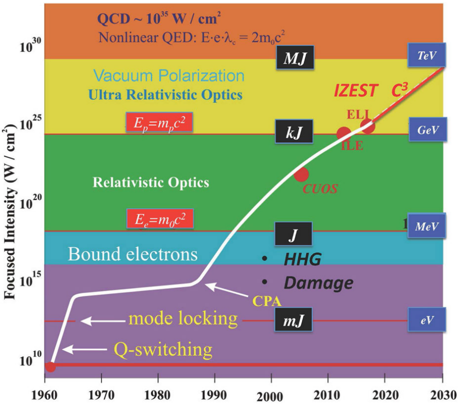
Present Day: Extreme Intensities

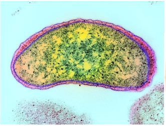
Chirped Pulse Amplification D.Strickland & G.Mourou (Nobel Prize 2018)

Focusing laser energy in space and time (few femtoseconds $= 10^{-15}$ s): "λ-cube" pulses

$I = 10^{22}$ W cm^{-2} ($\nearrow$)

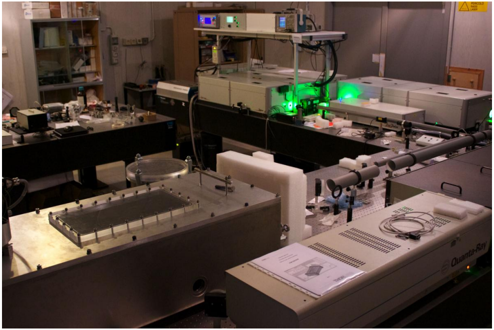
Note: every target is a plasma (instantaneous ionization)





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

Table-Top
A Relativistic ~~Microscopic~~ Laboratory:
Superintense Laser-Plasma Interactions



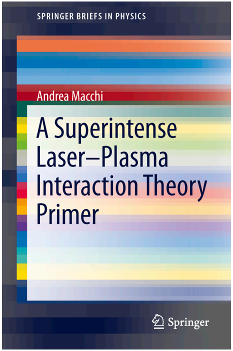
The 200 Terawatt laser system at Intense Laser Irradiation Laboratory, CNR/INO, Pisa

Some Compact References for Basics

(a selfish selection)

A. Macchi,
- *A Superintense Laser-Plasma Interaction Theory Primer* (Springer, 2013)

- *Basics of Laser-Plasma Interaction: a Selection of Topics*,
in: *Laser-Driven Sources of High Energy Particles and Radiation*,
Springer Proc. Physics **231** (2019) 25-49
arXiv:1806.06014



Basics of Linear Plasma Optics

Wave equation for transverse waves ($\boldsymbol{\nabla} \cdot \mathbf{E} = 0$)

$$\left(\nabla^2 - \frac{1}{c^2}\partial_t^2\right)\mathbf{E} = \frac{4\pi}{c^2}\partial_t \mathbf{J}_\perp$$

Linearized non-relativistic equations ($|\mathbf{u}_e| \ll c$)

$$\partial_t \mathbf{u}_e = -\frac{e}{m_e}\mathbf{E} \qquad \mathbf{J} = -en_e\mathbf{u}_e \quad \text{(ions taken at rest)}$$

Plane monochromatic waves $\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0 \mathrm{e}^{i\mathbf{k}\cdot\mathbf{r}-i\omega t}$

$\longrightarrow$ linear refractive index $\quad \mathsf{n}(\omega) = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}$

$$k^2 = \mathsf{n}^2(\omega)\frac{\omega^2}{c^2} = \frac{\omega^2 - \omega_p^2}{c^2} \qquad \omega_p \equiv \left(\frac{4\pi e^2 n_e}{m_e}\right)^{1/2}$$

Basics of Nonlinear *Relativistic* Plasma Optics

Electron dynamics becomes relativistic when $\frac{|\mathbf{p}_e|}{m_e c} \sim \frac{e|\mathbf{E}_0|}{m_e \omega c} \equiv a_0 \gtrsim 1$

Nonlinear terms are important for $a_0 \gtrsim 1$:

$$\partial_t \mathbf{p}_e + \mathbf{u}_e \cdot \nabla \mathbf{p}_e = -e\mathbf{E} - \frac{e}{c}\mathbf{u}_e \times \mathbf{B}$$

$$\mathbf{J} = -en_e \mathbf{u}_e = -en_e \frac{\mathbf{p}_e/m_e c}{(1 + \mathbf{p}_e^2/m_e^2 c^2)^{1/2}}$$

$a_0 = 0.85(I\lambda^2/10^{18}\ \mathrm{Wcm^{-2}\mu m^2})^{1/2} \quad \rightarrow \quad \simeq 10^2$ present-day

Nonlinear refractive index[1] n_{NL} (as if $m_e \longrightarrow m_e\gamma \ldots$)

$$n_{NL} = \left(1 - \frac{\omega_p^2}{\gamma\omega^2}\right)^{1/2} \qquad \gamma = \left(1 + \left\langle \left(\frac{e\mathbf{E}}{m_e \omega c}\right)^2 \right\rangle\right)^{1/2} \equiv (1 + a^2/2)^{1/2}$$

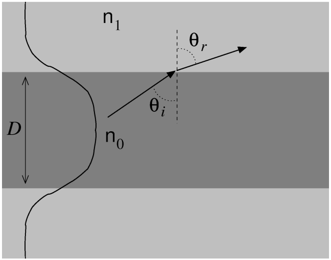
[1] to be used with caution ...

Relativistic Self-Focusing and Transparency

- For a laser beam n_{NL} is higher on the axis than at the edge:

$$n_0 = n_{NL}(a_0) > n_{NL}(0) = n_1$$

$\longrightarrow$ "optical fiber" guiding effect (Focusing overcomes diffraction for pulse power above a threshold value)



- Shift of the cut-off frequency for propagation:

$$k^2c^2 = \omega^2 - \frac{\omega_p^2}{\gamma} > 0 \quad \longleftrightarrow \quad \omega > \frac{\omega_p}{\gamma^{1/2}}$$

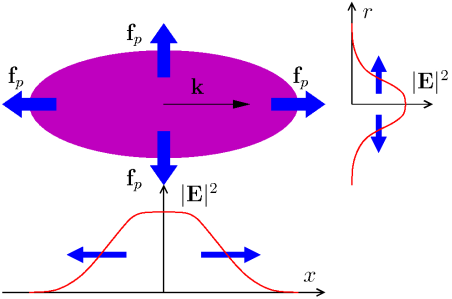
$\longrightarrow$ new "transparency" window $\omega_p > \omega > \omega_p/\gamma^{1/2}$

“Sweeping” the Plasma Density

The Lorentz force is intense enough to modify self-consistently the plasma density which cannot be assumed as uniform

On the average electrons are pushed out of higher field regions
(effects of EM pressure)

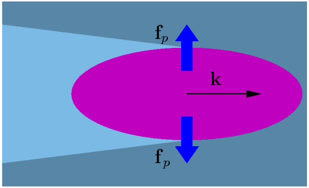
Example: a laser pulse of finite length and width pushes electrons in both longitudinal (x)
and radial (r) directions

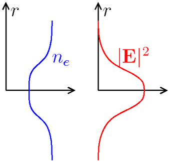


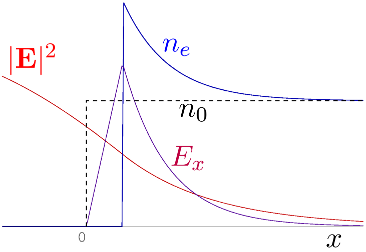
$$\mathbf{f}_p = \left\langle \rho \mathbf{E} + \frac{1}{c} \mathbf{J} \times \mathbf{B} \right\rangle$$

Self-focusing and Transparency Reexamined

SF: EM pressure in radial direction drills a low-density channel
$\rightarrow$ additional "optical fiber" effect
(*self-channeling*)







ST: EM pressure in longitudinal direction creates a pile-up of electrons
$\rightarrow$ increase of density and
local plasma frequency $\omega_p \propto n_e^{1/2}$, higher threshold for induced transparency

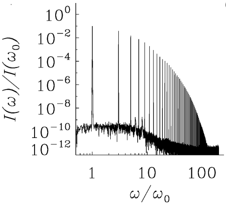
Dynamic Reflection: Oscillating Mirrors

In the interaction with a high-density plasma the Lorentz force drives surface oscillations at either ω (P-pol.) or 2ω (S-pol.)

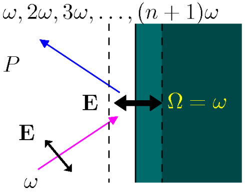
$\longrightarrow$ reflection from an oscillating mirror

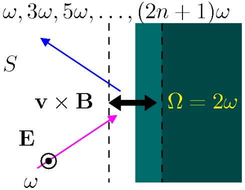
Mixing of incident frequency ω with multiples of mirror frequency Ω

$\longrightarrow$ high harmonic generation



$$\omega_n = \omega + n\Omega = \begin{cases} (n+1)\omega & (P) \\ (2n+1)\omega & (S) \end{cases}$$

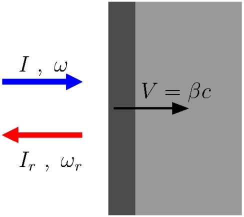




Harmonics are phase-locked $\longrightarrow$ can be used to "build" a shorter pulse

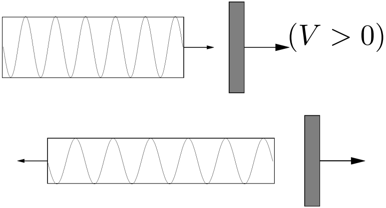
EM Pulse Modification by a Moving Mirror

Reflection can be studied
via Lorentz transformations
(constant V & normal incidence for simplicity)



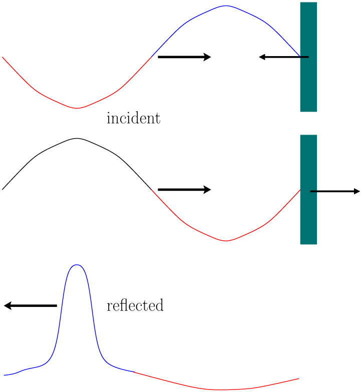
$$\omega_r = \frac{1-\beta}{1+\beta}\omega \qquad I_r = \frac{1-\beta}{1+\beta}I$$

Co-propagation ($V > 0$):
red-shift and temporal stretching of EM pulse, work done on the mirror (case shown)
Counter-propagation ($V < 0$):
blue-shift, temporal compression and amplification of EM pulse
(apply time reversal to case shown . . .)



Attosecond Pulse Train

High harmonic pulse is "spiky" in the time domain



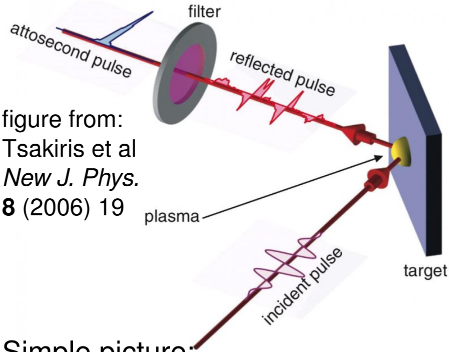


figure from:
Tsakiris et al
New J. Phys.
8 (2006) 19

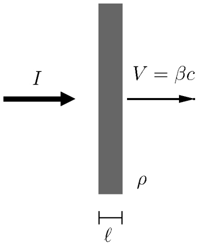
Simple picture:
successive half-cycles are alternately compressed-enhanced and stretched-quenched by the oscillating-in-phase mirror

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



Breakthrough Starshot proposal (2016): laser propulsion of sail probes to reach Alpha Centauri in 20 years

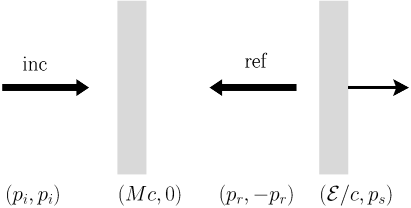
breakthroughinitiatives.org

A critical analysis:

H. Milchberg, *Physics Today*, 26 April 2016

Light Sail as Ion Accelerator

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



$$p_i + Mc = p_r + \mathcal{E}/c$$
$$p_i = -p_r + p_s$$

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

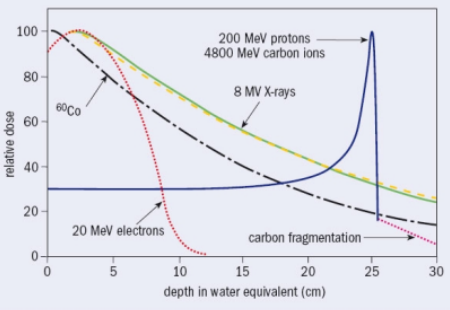
energy $\frac{\mathcal{E}}{Mc^2} = \frac{\mathcal{F}^2}{2(\mathcal{F}+1)}$ efficiency $\eta \equiv \frac{\mathcal{E}}{p_i c} = \frac{2\beta}{1+\beta}$

For $\ell \simeq 10$ nm and a 10 fs, 10^{21} W cm^{-2} pulse
$\mathcal{E}_{\max} \simeq 200$ MeV/nucleon , $\eta \simeq 0.5$

What Is a Laser Ion Accelerator Good For?

Ion energy deposition in matter is localized at the stopping point (Bragg peak) because of Coulomb scattering $\mathrm{d}\mathcal{E}/\mathrm{d}x \propto \mathcal{E}^{-2}$

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



Application in oncology (ion beam therapy):
deeply seated tumor can be destroyed while reducing damage in surrounding tissue)
energy window: 65–250 MeV/nucleon
Suitable alternative to conventional ion accelerators?

Is Ultra-High and -Fast Dose Delivery Beneficial?

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 light ions only laser-plasma accelerators may deliver the necessary flux

Recent Results: Carbon Ion Acceleration

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

Featured in Physics

Selective Ion Acceleration by Intense Radiation Pressure

A. McIlvenny,[1,†] D. Doria,[1,2] L. Romagnani,[1,3] H. Ahmed,[1,4] N. Booth,[4] E. J. Ditter,[5] O. C. Ettlinger,[5] G. S. Hicks,[5] P. Martin,[1] G. G. Scott,[4] S. D. R. Williamson,[6] A. Macchi,[7,8] P. McKenna,[6] Z. Najmudin,[5] D. Neely,[4,*] S. Kar,[1] and M. Borghesi[1,‡]

[1]*Centre for Plasma Physics, Queens University Belfast, Belfast BT7 1NN, United Kingdom*
[2]*Extreme Light Infrastructure (ELI-NP) and Horia Hulubei National Institute for R & D in Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului Street, 077125 Magurele, Romania*
[3]*LULI–CNRS, Ecole Polytechnique, CEA, Universit Paris-Saclay, F-91128 Palaiseau cedex, France*
[4]*Central Laser Facility, Rutherford Appleton Laboratory, Oxfordshire OX11 0QX, United Kingdom*
[5]*The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, London SW7 2BZ, United Kingdom*
[6]*SUPA, Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom*
[7]*Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche (CNR/INO), research unit Adriano Gozzini, Pisa 56124, Italy*
[8]*Dipartimento di Fisica Enrico Fermi, Università di Pisa, Pisa 56127, Italy*

A. McIlvenny et al, *Phys. Rev. Lett.* **127** (2021) 194801

Experiment with GEMINI laser (RAL/CLF, UK)

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

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

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.

Introduction to Electron Acceleration by Plasma Waves

Plasma waves in a different frame

A. Macchi[a)]
National Institute of Optics, National Research Council (CNR/INO), Adriano Gozzini laboratory, 56124 Pisa, Italy and Enrico Fermi Department of Physics, University of Pisa, 56127 Pisa, Italy

(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**, 723 (2020)

Nice Example of Acceleration by a Strong Wave

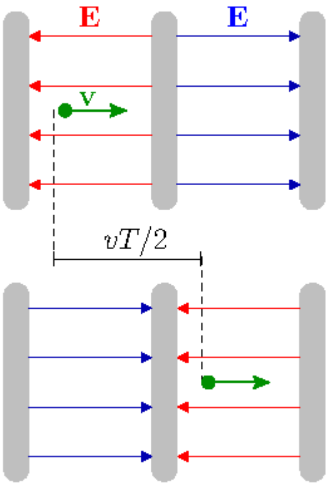
From: T.Katsouleas, *Nature* **444** (2006) 688

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



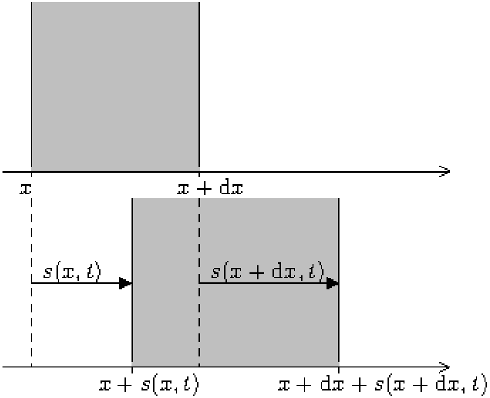
Starting Point: Cold Plasma Oscillations

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 ω_p witi arbitrary profile $\tilde{s}(x)$



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

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.

Plasma Wake Waves

A traveling delta-kick force $f(x,t) = m_e u_0 \delta(t - x/V)$ displaces electrons by $s_0 = u_0/\omega_p$ at the overtaking time $t = x/V$
$\longrightarrow$ wake of plasma oscillations with phase velocity $v_p = V$

$$s(x,t) = \begin{cases} 0 & (t < x/V)\ , \\ s_0 \cos\left(\omega_p(t - x/V)\right) & (t > x/V)\ . \end{cases}$$

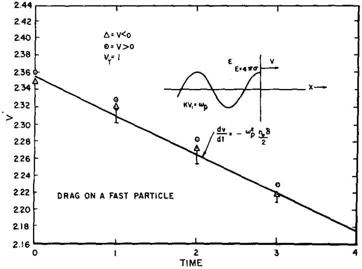


FIG. 6. The drag on a fast sheet.

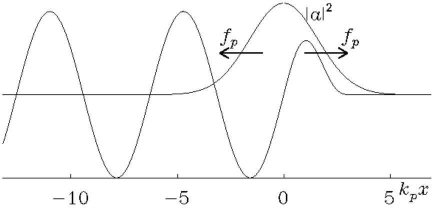
Example: a charge bunch penetrating a plasma loses its energy to the wake (collective stopping)

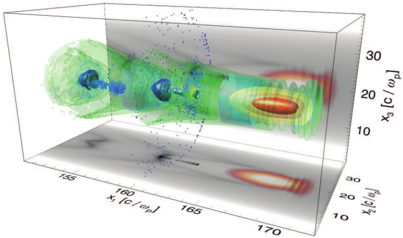
J. Dawson, *Phys. Fluids* **5** (1962) 445

Laser Wakefield

A short laser pulse
of duration $\simeq \pi/\omega_p$
excites a wake
with phase velocity
$v_p = v_{g\mathrm{EM}} = c(1-\omega_p^2/\omega^2)^{1/2}$

T.Tajima & J.Dawson,
Phys. Rev. Lett. **43**, 267 (1979)





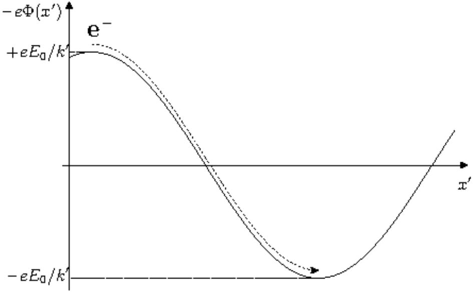
EM pressure force pushes electrons at the front and back slopes of the laser pulse

3D simulation of a laser wakefield

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

Energy Gain Estimate in the Wave Frame

In a reference frame S' moving with the phase velocity v_p with respect to the laboratory S the wave field is time-independent and can be derived by an electrostatic potential $\Phi(x')$



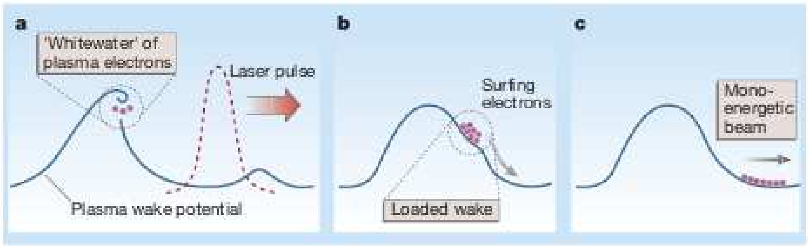
A "lucky" test electron moving from the top to the bottom of the potential hill with initial velocity $v'_{x0} = 0$ (hence $v_{x0} = v_p$ in the lab frame) will get the maximum energy gain possible $\mathcal{E}_{\max}$

Wave Amplitude Limit: Wavebreaking

The electron density must remain positive:

$$n_e = n_0 + \delta n_e > 0 \quad \Leftrightarrow \quad |\delta n_e| < n_0$$

$\delta n_e \longrightarrow n_0$ as $u_0 \longrightarrow v_p$: "self-acceleration" of wave electrons
$\longrightarrow$ singularity in density profile, "breaking" of the wave
Onset of wavebreaking leads to self-injection of electrons



[T. Katsouleas, *Nature* **431** (2004) 515]

Maximum Energy Estimate

- Assuming $v \simeq c$ and combining optimal injection ($v_{x0} = v_p$) with wavebreaking amplitude, Tajima & Dawson obtained

$$\mathcal{E}_{\max} = 4m_e c^2 \gamma_p^2$$

$\gamma_p = (1 - v_p^2/c^2)^{-1/2} \gg 1$

- Objection! An incorrect wavebreaking threshold was used
- Using improved estimate from a fully nonlinear (but anlytically accessible . . .) model:

$$\mathcal{E}_{\max} = 4m_e c^2 \gamma_p^3$$

[Esarey & Pilloff, *Phys. Plasmas* **2**, 1432 (1995); Macchi *AJP* (2020)]

- Note the substantial increase by a factor γ_p

Issues: Acceleration Length, Injection, . . .

$L_{\rm acc}$ = how long must my plasma wave be to allow the maximum energy gain = (max energy)/(max force)

$$L_{\rm acc} = \frac{W_{\rm max}}{eE_{\rm WB}} \simeq 2\sqrt{2}\frac{c}{\omega_p}\gamma_p^{5/2} \quad \left(= \gamma_p L'_{\rm acc} = \frac{1}{2}\lambda'_p\right) .$$

- Plasma wave length $\simeq L_{\rm acc} \gg$ laser diffraction length: optical guiding needed (preformed channel, capillary tube, relativistic effect . . .)
- Self-injection and nonlinear regime not optimal for beam quality and mono-energetic spectrum: "external" injection needed
- . . .

The Dream Goes On . . .

Nature **431**, issue 7008, 30 September 2004

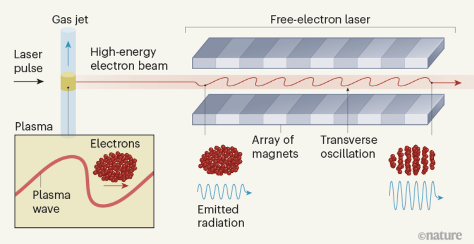
Current energy record: 8 GeV [BELLA group at Berkeley: Gonsalves et al, *Phys. Rev. Lett.* **122**, 084801 (2019)]

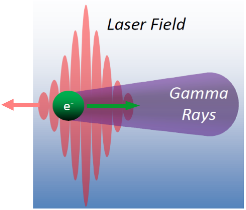
Progress achieved by several groups in beam quality, stability and reproducibility, . . .

Application: Generation of Secondary Radiation

LWFA electrons used as a compact driver in a
Free Electron Laser

Wang et al, *Nature* **595** (2021) 516





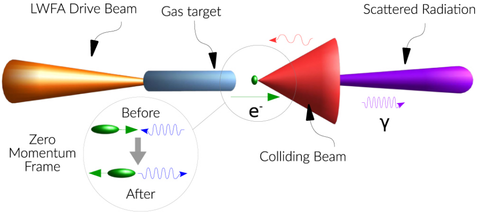
Replacing the undulator with a a counter-propagating laser pulse: "all-optical" FEL by Thomson Scattering

Nonlinear TS with high intensity laser and strongly relativistic electrons generate Gamma-rays with $\omega_\gamma \simeq a_0^3\omega$

Strong Field Photon-Electron Collider

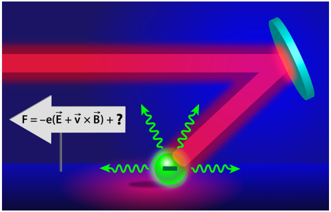
Laser field amplified by $(1+\beta_e)/(1-\beta_e) \simeq 2\gamma_e^2$ in electron rest frame

$\longrightarrow$ 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

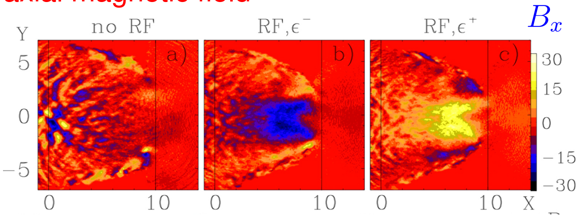
Ultimate goal: reach Schwinger field

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

$\longrightarrow$ breakdown of "quantum vacuum"

Radiative Generation of Gigagauss Magnetic Fields

Many optical photons destroyed to generate a Gamma-photon
$\longrightarrow$ for circular polarization many angular momentum quanta $\hbar$ "disappear" into the plasma
$\longrightarrow$ induced rotation of electron population with generation of axial magnetic field



3D simulation units:
$B_0 = m_e c\omega/e$
$= 1.34 \times 10^8$ G

No axial field without radiative losses included
Sign of B_x changes with laser pulse helicity

T. V. Liseykina, S. V. Propruzhenko, A. Macchi, *New J. Phys.* **18** (2016) 072001

Unexpected Hype . . .

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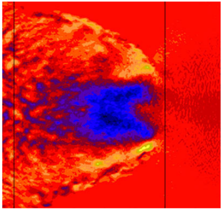
'Radiation friction' could make huge magnetic fields with lasers

Jul 19, 2016 2 comments



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New method for generating superstrong magnetic fields

August 10, 2016

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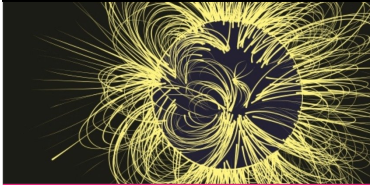
How to Create the World's Strongest Magnet

Science alert

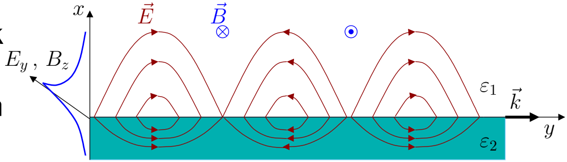


Physicists have calculated a whole new way to generate super-strong magnetic fields

Stronger than any magnetic field on Earth.

Surface Plasmon (aka Surface Plasma Wave)

SP: a building block of plasmonics (mostly studied in the *linear* regime)



SP excitation $\longrightarrow$ EM field confinement and enhancement

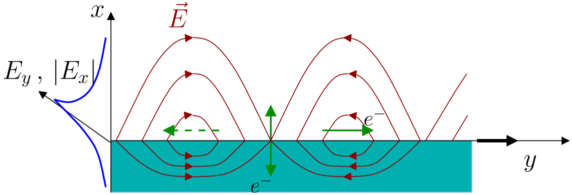
Interface between vacuum and "simple metal" (cold plasma):

$$\varepsilon_1 = 1 \qquad \varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c(\omega)} < -1$$

$$k = \frac{\omega}{c}\left(\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}\right)^{1/2} \qquad \omega < \frac{\omega_p}{\sqrt{2}} \qquad v_{\mathrm{p}} = \frac{\omega}{k} < c$$

Surfin' the Surface Wave?

Can a SP accelerate electrons like a "bulk" plasma wave?

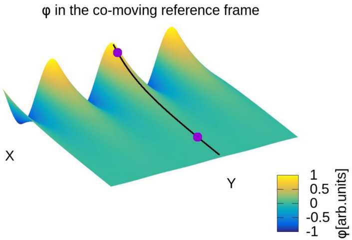


- longitudinal E-component (E_y)
- sub-luminal phase velocity $v_\mathrm{p} < c$

  (with $v_\mathrm{p} \to c$ when $\omega_p \gg \omega$)

$\rightarrow$ electrons may "surf" the SP

The energy can be estimated in the wave frame as for a "bulk" plasma wave but accounting for 2D motion



Observation of Surface Plasmon Acceleration

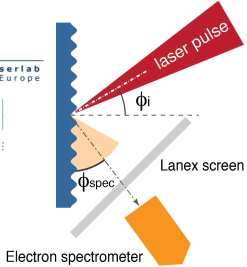
PRL **116,** 015001 (2016) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2016

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]
[1]*Enrico Fermi Department of Physics, University of Pisa, 56127 Pisa, Italy*
[2]*National Institute of Optics, National Research Council (CNR/INO), u.o.s Adriano Gozzini, 56124 Pisa, Italy*
[3]*LIDYL, CEA, CNRS, Université Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette, France*
[4]*University of Paris Sud, Orsay 91405, France*
[5]*Department of Energy, Politecnico di Milano, Milan 20156, Italy*
[6]*Laboratoire des Solides irradiés, Ecole Polytechnique, CNRS, CEA/DSM/IRAMIS, Université Paris-Saclay, 91128 Palaiseau Cedex, France*
[7]*FNSPE, Czech Technical University, Prague 11519, Czech Republic*
(Received 30 June 2015; published 7 January 2016)

L. Fedeli et al, *Phys. Rev. Lett.* **116** (2016) 015001
LaserLAB experiment at SLIC facility, CEA Saclay, France
UHI laser: 25 fs pulse, $5 \times 10^{19}\ \mathrm{Wcm}^{-2}$, $a_0 = 4.8$

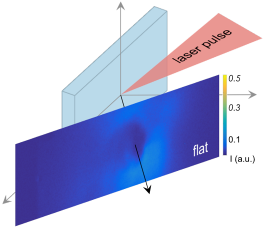
Observation of Surface Plasmon Acceleration

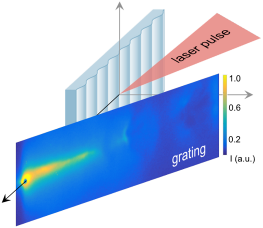


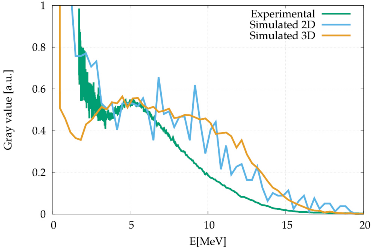
collimated ($\simeq$ $20°$ cone) electron emission near the surface tangent ($\phi \simeq 2°$)

multi-MeV energy, total charge $\simeq 100$ pC (value allowed by high plasma density)

exploitation & developments in progress . . .







Observation of SP-enhanced High Harmonics

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

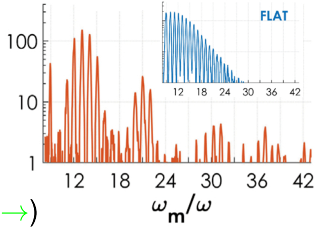
Extreme Ultraviolet Beam Enhancement by Relativistic Surface Plasmons

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]
[1]*LIDYL, CEA, CNRS, Université Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette, France*
[2]*Université Paris Sud, Paris, 91400 Orsay, France*
[3]*National Institute of Optics, National Research Council (CNR/INO) A. Gozzini unit, 56124 Pisa, Italy*
[4]*Enrico Fermi Department of Physics, University of Pisa, 56127 Pisa, Italy*
[5]*Department of Energy, Politecnico di Milano, 20133 Milano, Italy*
[6]*LULI-UPMC: Sorbonne Universités, CNRS, École Polytechnique, CEA, 75005 Paris, France*
[7]*LESIA, Observatoire de Paris, CNRS, UPMC: Sorbonne Universites, 92195 Meudon, France*

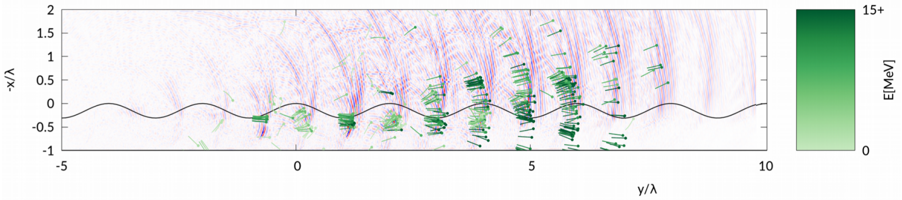
G. Cantono et al, *Phys. Rev. Lett.* **120** (2018) 264803

Observation of SP-enhanced 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)



Conclusions: Laser-Plasma Interactions Offer New . . .

- framework of nonlinear "relativistic" optics
- ion and electron accelerators with unique qualities (high flux, short duration, optical control, . . .) for specific applications
- class of experiments in unexplored QED regime
- concepts inspired by other areas of photonics (e.g. surface plasmons)

Laser wakefield acceleration is more technologically "mature" with respect to applications than other concepts but further developments are in progress