Superintense Light Interaction with Matter

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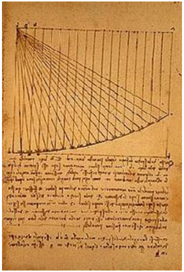
Lights of Tuscany, Pisa, December 17, 2015

Focused light interaction with matter: an old story

Archimedes' mirror burning Roman ships. Giulio Parigi, ab. 1600. Uffizi Gallery, *Stanzino delle Matematiche*, Florence, Italy

Leonardo da Vinci: Studies on reflection by burning mirrors. Codex Arundel (1480-1518), British Library, London.



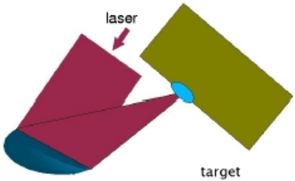
First attempts to "strongly" modify matter with intense light (heating, phase transition, ionization . . .)

Intensity of Sunlight: $I \simeq 1.4 \times 10^3$ W m^{-2}

with "ultimate" concentration $\sim 10^4 \rightarrow I \simeq 10^7$ W m^{-2} at focus

The dawn of laser-plasma physics (1964)

"*The laser is a solution looking for a problem*" (D'Haenens to Maiman, 1960)



Q-switched lasers (1962):
10 GW on $\sim 10^{-4}$ m spot
$\rightarrow I \simeq 10^{17}$ W m^{-2}
sufficient to ionize and heat matter up to billions degrees: hot, dense plasma state
J. Dawson, *Phys. Fluids* **7** (1964)

Plasma generated by blasting droplets with a laser 6000 times a second: an efficient UV source for lithography.
Credit: ETH-Zurich/B.Newton

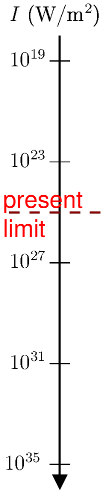
Modern Petawatt (10^{15} W) lasers

National Ignition Facility (US): $\sim$ 1 MJ/1 ns=1 PW
used to drive nuclear fusion by implosions (credit: LLNL, USA)

Extreme Light Infrastructure (ELI)
under construction: $\sim$ 150 J/15 fs=10 PW
"λ^3" pulse with intensities up to
$I > 10^{27}$ W m^{-2}
several other petawatt facilities
opening worldwide

extreme-light-infrastructure.eu

High field interaction regimes



- Instantaneous ionization:
laser field $E_L \gg e/r^2_{\text{Bohr}}$ atomic field

- "Relativistic" regime: electron oscillation momentum
$\mathbf{p}_{\text{osc}} = eE_L/\omega \gg m_e c$

- Dominance of radiation friction
(electron interaction with its own field)

- Collective QED effects, cascades, vacuum nonlinearity

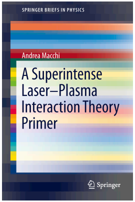
- Schwinger limit $E_L > m_e^2 c^3/e\hbar$ pair creation from vacuum

Relativistic nonlinear optics in plasmas

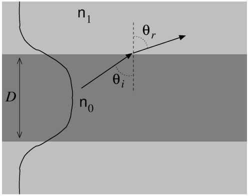
Relativistic dynamics makes electron response nonlinear:

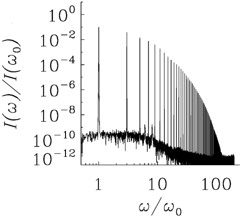
$$\mathbf{J}_\perp = -en_e\mathbf{v} = -en_e\frac{\mathbf{p}}{\gamma} = \frac{in_e e^2}{m_e\omega c}\frac{\mathbf{E}_L}{(1+(e|E_L|/\omega m_e c)^2))^{1/2}}$$

$\rightarrow$ “relativistic” self-focusing, high harmonic generation, self-induced transparency, electromagnetic solitons, . . .



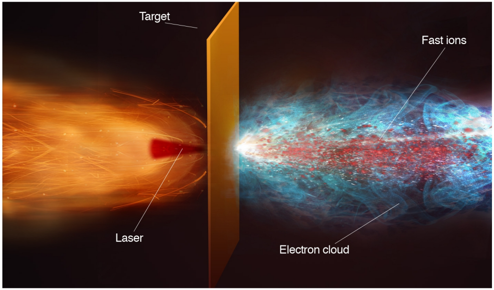
A. Macchi, “A Superintense Laser-Plasma Interaction Theory Primer” (Springer, 2013)





Development of laser-plasma ion accelerators

Artist's view of superintense laser pulse interaction with a thin solid target: a charge–neutralized, sub–picosecond multi–MeV, ion bunch is accelerated

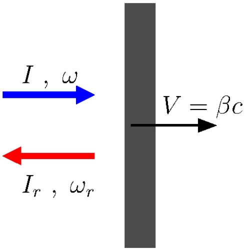


Principle of coherent (or collective) acceleration [Veksler (1957)]: accelerating field and particle energy are proportional to the number of particles accelerated

Macchi, Borghesi, Passoni, "Ion acceleration by superintense laser-plasma interaction", *Rev. Mod. Phys.* **85** (2013) 751

Light Pressure Acceleration

Basic model of mirror boosted by light: force and mechanical efficiency η easily derived by Doppler shift and photon number conservation



$$\frac{dP}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta} \qquad \eta = \frac{2\beta}{1+\beta} \qquad I = N\frac{\hbar\omega}{c}$$

[see also: Simmons & McInnes, *Am. J. Phys.* **61** (1992) 205]

Light pressure was introduced by Maxwell (1874) but also independently (1876) by Adolfo Bartoli (born in Florence, student of Physics in Pisa) on the basis of thermodynamics arguments [Bartoli, *Nuovo Cimento* **15** (1884) 193]

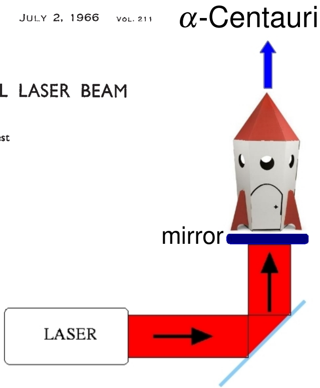
Early vision of laser-driven acceleration (1966)

22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

By PROF. G. MARX
Institute of Theoretical Physics, Roland Eötvös University, Budapest

A solution to “Fermi’s paradox”: “*Laser propulsion from Earth . . . would solve the problem of acceleration but not of deceleration at arrival . . . no planet could be invaded by unexpected visitors from outer space*”

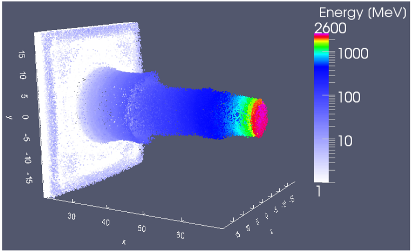


(BUT a scheme for deceleration was proposed: R. L. Forward, *J. Spacecraft* **21** (1984) 187)

Our research on light pressure acceleration

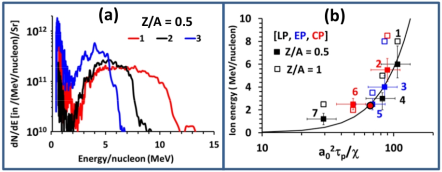
Theory and simulation:

A. Macchi et al, *Phys. Rev. Lett.* **94** (2005) 165003; **103** (2009) 085003. M. Tamburini et al, *New J. Phys.* **12** (2010) 123005; *Phys. Rev. E* **85** (2012) 016407; A. Sgattoni et al, *Appl. Phys. Lett.* **105** (2014) 084105; *Phys. Rev. E* **91** (2015) 013106.



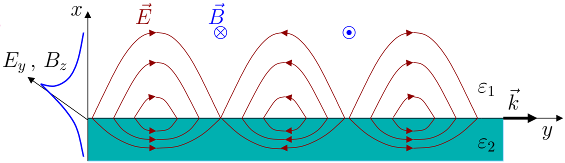
Experiment (collaboration with Queen's University of Belfast and many others):

S. Kar et al, *Phys. Rev. Lett.* **100** (2008) 225004; **109** (2012) 185006

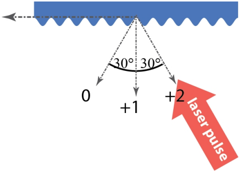


Plasmonics: catching light with a grating

Surface Plasmons are collective electron modes propagating at a metal-vacuum interface



SP allow light confinement and field enhancement and can be excited by EM waves incident on a grating or other microstructures

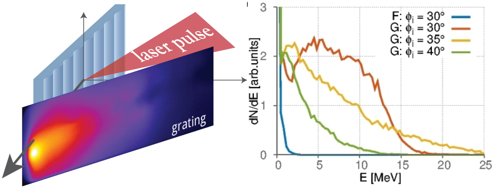


Plasmonics has several applications (biosensors, nanoelectronics, photovoltaics . . .)
Our challenge: extend plasmonics into the high field regime (nonlinear, relativistic, . . .)

High intensity laser-grating interactions

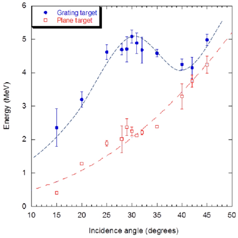
Electron acceleration by “surfing” the Surface Plasmons in the relativistic regime

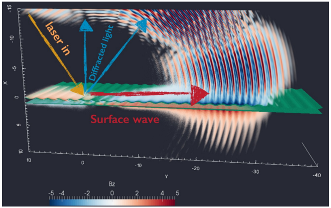
L. Fedeli et al, *Phys. Rev. Lett.* (2016) in press



Proton acceleration boosted by SP-enhanced absorption

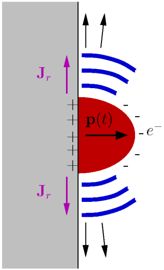
T. Ceccotti et al, *Phys. Rev. Lett.* **111** (2013) 185001





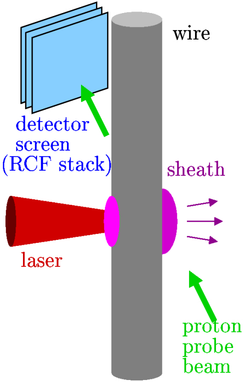
Collaboration with CEA and CNRS Paris-Saclay, France, and others

Excitation of picosecond, unipolar high field SP

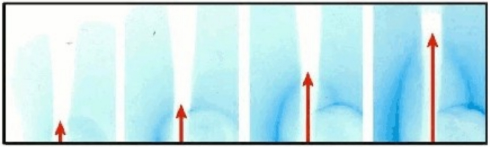


A transient laser-driven charge separation acts as a giant "antenna" for unipolar SPs of picosecond duration

K. Quinn et al, *Phys. Rev. Lett.* **102** (2009) 194801



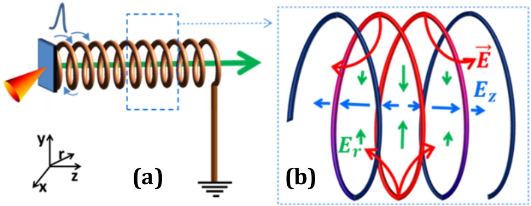
Experimental proton images

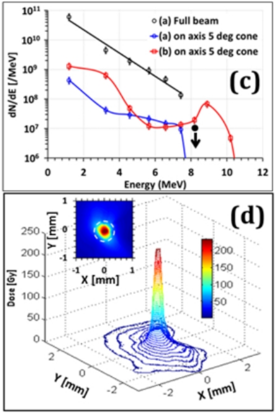


Applications: THz pulse generation, bioelectrics, ultrafast control of particle beams

Application to advanced laser-plasma ion acceleration

The SP current pulse is sent along a coil to be used as a synchronized wave for proton focusing and post-acceleration





S. Kar (QUB Belfast), UK patent;
S.Kar, H.Ahmed, R.Prasad, M.Cerchez, S.Brauckmann, B.Aurand, G.Cantono, P.Hadjisolomou, C.L.S.Lewis, A.Macchi, G.Nersisyan, A.P.L.Robinson, A.M.Schroer, M.Swantusch, M.Zepf, O.Willi, M.Borghesi, “A laser-driven travelling-wave ion accelerator”, Nature Communications (2016), in press

The race to extreme light continues . . .

The several applications foreseen and the possibility to investigate “exotic” regimes (e.g. collective QED) drive the development of more high power facilities

Some 10 PW lasers in construction across Europe:

ELI (1.5 kJ/150 fs), APOLLON (150 J/15 fs), VULCAN (300 J/30 fs) . . .

A future vision: multi-fibre laser for Exawatt (10^{18}) power

[Mourou et al, *Nature Photonics* **7** (2013) 258]

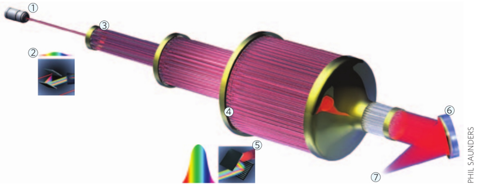
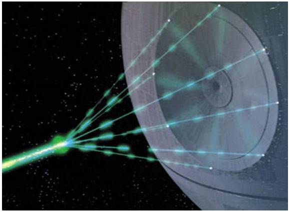


Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).



. . . as well as applications involving plasmas

A lightsaber based only on laser technology looks unfeasible, BUT a plasma-based one might work (at least, partially!)

G. Sarri
(QUB Belfast)
"How to build a real lightsaber",
The Guardian,
December 11, 2015