Laser-Plasma Acceleration in a Skin Layer

Andrea Macchi

CNR, Istituto Nazionale di Ottica, Adriano Gozzini lab., Pisa, Italy

Dipartimento di Fisica Enrico Fermi, Università di Pisa, Italy

Indian Institute of Technology, Delhi, India
in the occasion of the P. K. Kaw legacy award 2020

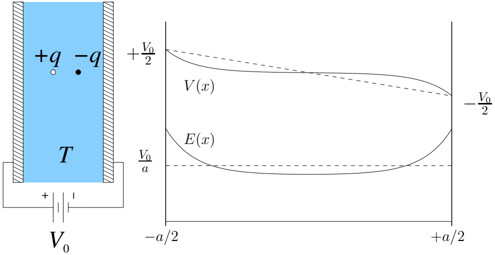
Outline

- How I got involved with plasmas
- Under the skin layer: solid density laser plasmas
- Faraday waves: laser plasmas vs alligators
- Back-rotating the optical mill with circular polarization
- Sailing before the light: interstellar travels, ion accelerators, Rayleigh-Taylor instabilities . . .
- High field relativistic plasmonics: surfin' surface waves, a plasmonic FEL, single cycle polaritons, . . .
- Acknowledgments

Very early inspiration sources . . .

As a 2nd year undergraduate, during the *Physics 2* (introductory electrodynamics) two particular examples attracted my curiosity:

- The concept of plasma and the Debye screening effect

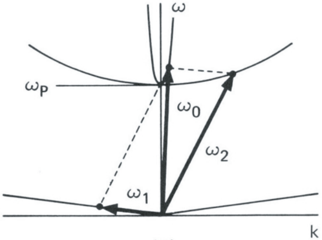


- The "skin effect" in a conductor at high frequency (mentioned in Pauli's *Electrodynamics*)

More early inspiration sources . . .

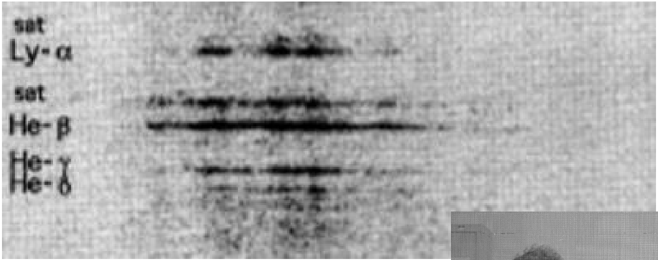
As a 4rd year undergraduate, in the (somewhat unconventional) plasma physics lectures given by Prof. F. Cornolti I was attracted by nonlinear laser-plasma physics, in particular by three-wave processes (*aka* parametric instabilities)

$$\omega_0 = \omega_1 + \omega_2 , \qquad \mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2 .$$



Prof. Kaw's works on the topic were a key reference (e.g. review papers in Advances in Plasma Physics **6** (1976))

. . . and thus it was laser-plasma physics

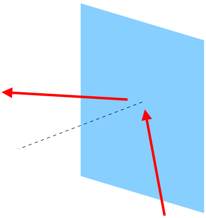


Time-resolved X-ray spectrum from Aluminum laser-produced plasma

Leo Gizzi, Tiberio Ceccotti, Serena Bastiani, AM at CNR/IFAM laboratory, 1994

The thin skin layer

Because of free electrons a metal is almost a perfectly reflecting mirror for light at visible (and lower) frequencies

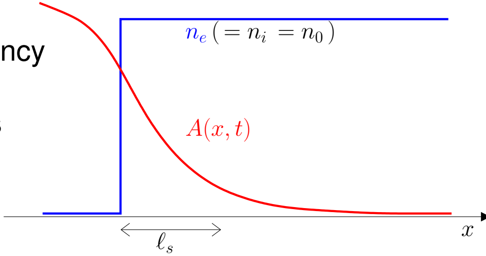


Refractive index $\mathrm{n}(\omega) = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}$

$$\omega_p = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$$ plasma frequency

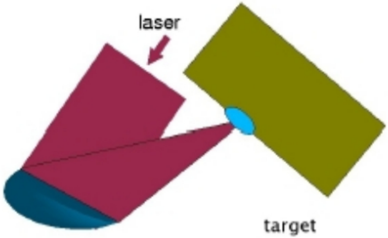
For $\omega < \omega_p$ the EM field is evanescent over the skin length

$$\ell_s = \frac{c}{(\omega_p^2 - \omega^2)^{1/2}} \ll \lambda = 2\pi\frac{c}{\omega}$$



Beyond the mirror . . .

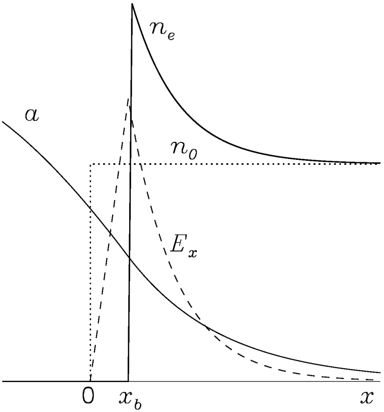
By tightly focusing an “extreme” laser pulse (several joules in a few femtoseconds) on a solid target of any material a plasma is created by instantaneous ionization



The intense laser-matter interaction in the skin layer involve light pressure effects, non-adiabatic electron motion, relativistic dynamics, harmonic generation, surface wave excitation, . . .
Much more than a simple mirror reflection!

Nonlinear forces in the skin layer

- The electron density profile is modified by the light pressure force and the induced charge separation field
- The EM wave equation is modified by density inhomogeneity and relativistic effects on electrons
- The resulting nonlinear problem may be solved analytically for a steady light pressure (and immobile ions)



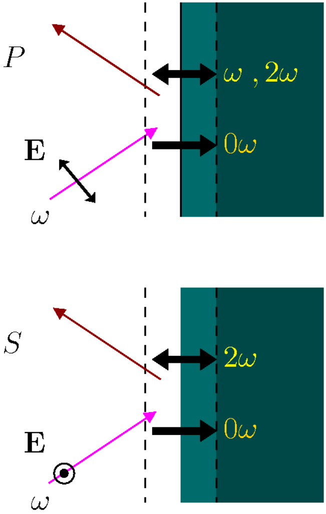
[see e.g. Cattani et al, Phys. Rev. E **62** (2000) 1234; Goloviznin & Schep, Phys. Plasmas **7** (2000) 1564]

Nonlinear oscillating forces

The oscillating components of the Lorentz force drive strong surface oscillations of the electron fluid

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

For linear polarization the 2ω force is stronger than the static (0ω) light pressure force: electrons are swept across the target-vacuum interface



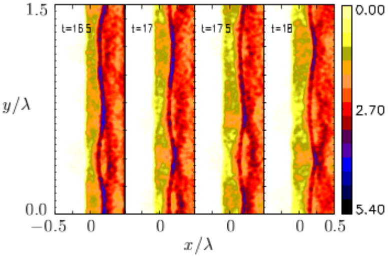
Parametric decay of 2ω oscillations

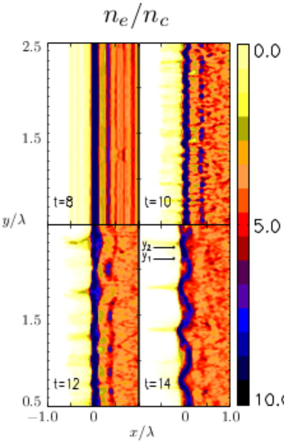
In simulations the planar 2ω oscillation is found to decay in two surface waves at ω ("period doubling")

A. Macchi, F. Cornolti, F. Pegoraro,

T. V. Liseikina, H. Ruhl, V. A. Vshivkov,

Phys. Rev. Lett. **87** (2001) 205004



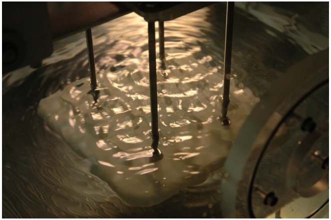


– *my own three-wave process!*

Analogy with Faraday waves

When the surface of a liquid is driven at a frequency Ω standing oscillating ripples of frequency $\Omega/2$ will appear

Two-surface wave decay driven by the $\mathbf{v} \times \mathbf{B}$ force is a laser-plasma version with $\Omega/2 = \omega_L$ (laser frequency)



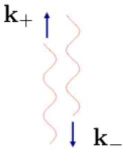
Alligators create Faraday waves during mating calls

Pictures courtesy of Moriarty Makes, www.moriartymakes.net

Theory of two-surface wave decay

A. Macchi, F. Cornolti, F. Pegoraro,
Phys. Plasmas **9** (2002) 1704

A key reference for SW in plasmas:
P. K. Kaw and J. B. McBride,
Phys. Fluids **13** (1970) 1784

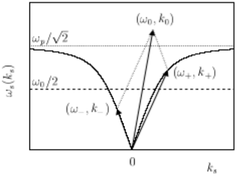


THE PHYSICS OF FLUIDS VOLUME 13, NUMBER 7 JULY 1970

Surface Waves on a Plasma Half-Space

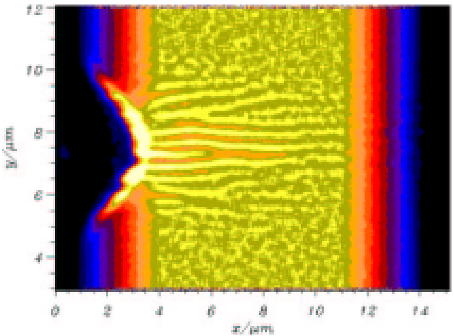
P. K. Kaw and J. B. McBride
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
(Received 28 November 1969)

The effect of density gradients and a finite temperature on the dispersion relation for surface waves on a plasma half-space has been investigated analytically. The full set of Maxwell's equations is used to obtain the dispersion of surface waves on a warm homogeneous plasma, thus complementing earlier work on the electrostatic mode. The *full* surface-wave dispersion relation is then derived for a cold plasma with arbitrary but weak density profile in the WKB limit. Finally, the dispersion of electrostatic surface modes on a cold plasma with a linear density profile of arbitrary strength is obtained. It is shown that when the density variation over a wavelength is very large, a new type of damped surface wave with a frequency higher than the surface plasma frequency is possible.



Surface rippling and fast electron generation

Our goal was to understand why the laser-plasma interface get rippled and the possible correlation with the current filamentation of high-energy ("fast") electrons generated at the surface



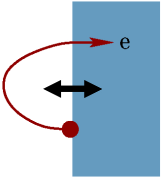
(of relevance to the Fast Ignition approach in Inertial Confinement Fusion)

collaboration with H. Ruhl & P. Mulser (TU Darmstadt) 1998–2000

Electron acceleration across the skin layer

Single particle picture: oscillating forces drag electrons into the vacuum side and push them back in the plasma after an oscillation half-cycle

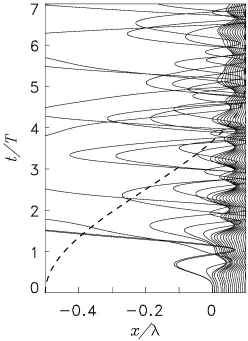
[Brunel, Phys. Rev. Lett. **59** (1987) 52]



Collective picture: driven plasma oscillations across a sharp gradient "break" and give energy to particles [see e.g.:

A. S. Sandhu, G. R. Kumar, S. Sengupta, A. Das, and P. K. Kaw, Phys. Rev. Lett. **95** (2005) 025005]

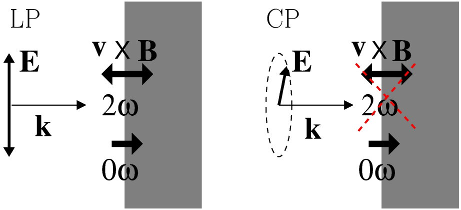
Electrostatic simulation (Dawson's sheet model): self-intersection (*wavebreaking*) of fluid elements and generation of "fast" electron bunches



Circular polarization quenches electron acceleration

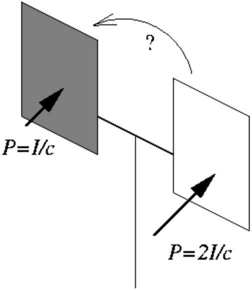
For Circular Polarization (CP) at normal incidence
the 2ω component of the $\mathbf{v} \times \mathbf{B}$ force vanishes
$\rightarrow$ longitudinal oscillations and electron acceleration are suppressed

[Macchi, Cattani, Liseykina, Cornolti, Phys. Rev. Lett. **95** (2005) 185003]



(In the beginning this was a test to show that TSWD is driven by the $\mathbf{v} \times \mathbf{B}$ force . . .)

Suppress heating to make light 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 which should be suppressed to maximize the light pressure push

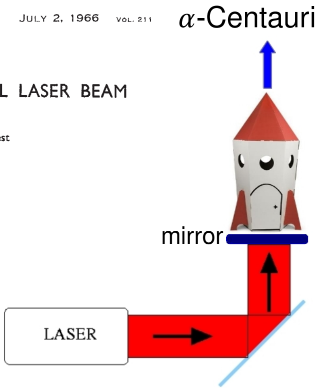
Sailing using laser light pressure (1966)

22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

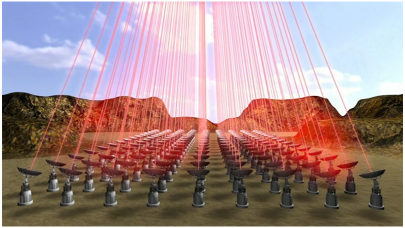
By PROF. G. MARX
Institute of Theoretical Physics, Roland Eötvös University, Budapest

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*”



Rediscovering laser sailing (2016)

Breakthrough Starshot project
breakthroughinitiatives.org

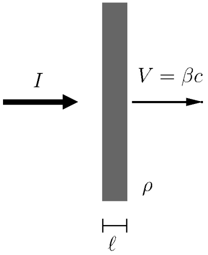


Critical analysis of (un)feasibility:
H. Milchberg, “Challenges abound for propelling interstellar probes”, Physics Today, 26 April 2016

Light Sail acceleration: a “dream ion bunch”?

Energy per nucleon and efficiency for a plane mirror accelerated by light pressure:

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



where $\mathscr{F} = \dfrac{2I\tau_p}{\rho\ell}$ (τ_p: pulse duration)

if $\ell \simeq 10$ nm , $I \simeq 10^{21}$ W cm^{-2} , $\tau_p \gtrsim 10$ fs

$\longrightarrow \mathscr{F} \sim 1 \longrightarrow \quad \mathscr{E}_{\max} = 235$ MeV , $\eta = 0.5$

coherent mirror motion $\longrightarrow$ mononergetic ion spectrum

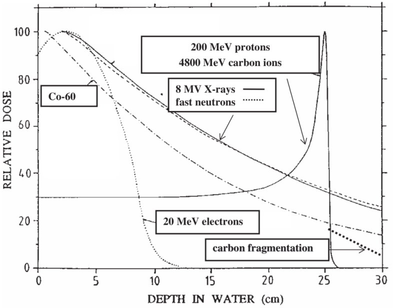
Proposal of superintense laser-driven LS:

T. Zh. Esirkepov et al, Phys. Rev. Lett. **92** (2004) 175003

What is a dream ion bunch good for?

Energy deposition in matter strongly localized at the Bragg peak

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



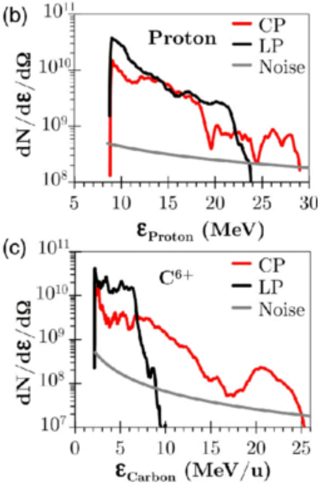
Foreseen applications:

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

Circular polarization does it better . . .

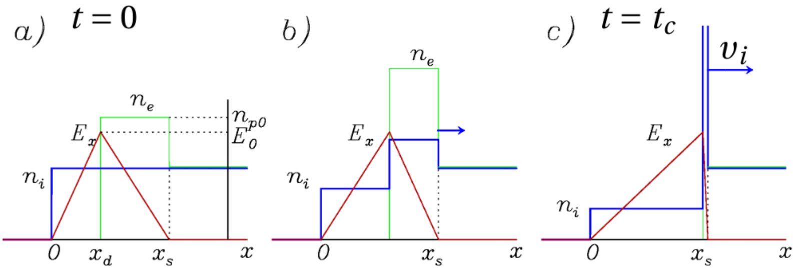
GEMINI laser (CLF, UK)
$\tau_p = 45$ fs, $I = 6 \times 10^{20}$ W cm^{-2},
$10-100$ nm thick CH foils
CP yields larger cut-off energies and spectral peaks for both H^+ and C^{6+}

C.Scullion, D.Doria, L.Romagnani, A.Sgattoni, K.Naughton, D.R.Symes, P.McKenna, A.Macchi, M.Zepf, S.Kar, M.Borghesi,
Phys. Rev. Lett. **119** (2017) 054801
(longstanding collaboration with M.Borghesi, S.Kar and others in Belfast since 2005)



. . . but there is more physics behind the mirror . . .

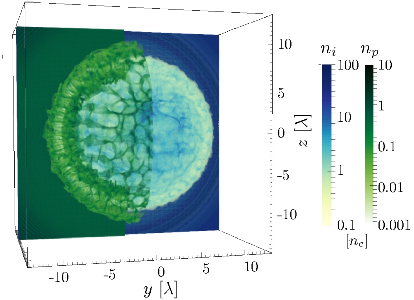
EM momentum is transfered to ions in the skin layer by the charge-separation field. The process is highly dynamical, non-steady, and involves wavebreaking effects



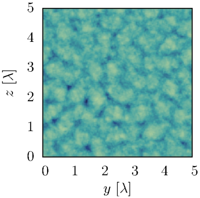
A. Macchi, F. Cattani, T. V. Liseykina, F. Cornolti, PRL **94** (2005) 0165003

A. Macchi, S. Veghini, F. Pegoraro, PRL **103** (2009) 085003

. . . and (of course) instabilities!

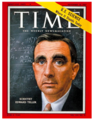


3D light sail simulation: formation of net-like structures with size $\sim \lambda$ (laser wavelength) and $\sim$ hexagonal shape



Interpretation: Rayleigh-Taylor instability driven by light pressure

A.Sgattoni, S.Sinigardi, L.Fedeli, F.Pegoraro, A.Macchi, Phys. Rev. E **91** (2015) 013106



"Is plasma involved? It won't work" (E. Teller)

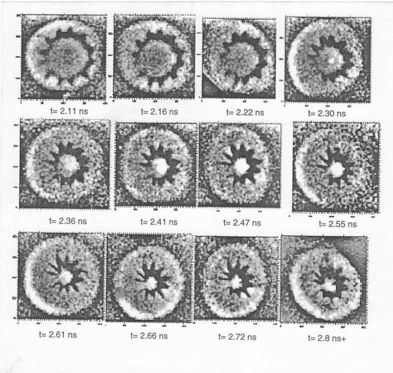
Rayleigh-Taylor Instability in space and lab

Crab Nebula (Hubble)

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

physicscentral.com

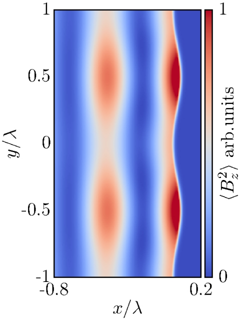
Laser-driven implosion forICF, 1995 (Wikipedia)

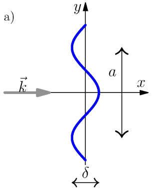


Symmetry analysis of nonlinear RTI:
S.I.Abarzhi, PRE **59** (1999) 1729

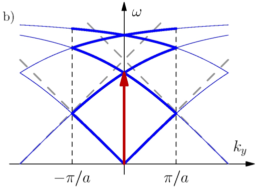
Plasmonic effects on RTI

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





geometry



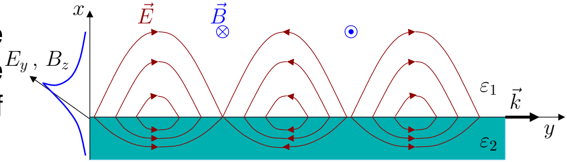
matching conditions

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

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

Surface plasmon polaritons

SPP (aka Surface Plasma Waves) are a building block of plasmonics



The SPP field is confined near the surface with strong localization and enhancement

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

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

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

Bridging the gap

PHYSICS OF PLASMAS **25**, 031701 (2018)

Preface to Special Topic: Plasmonics and solid state plasmas

Giovanni Manfredi[a)]
Université de Strasbourg, CNRS, Institut de Physique et Chimie des Matériaux, UMR 7504, F-67000 Strasbourg, France

(Received 22 February 2018; accepted 26 February 2018; published online 19 March 2018)

Plasmonics, the study of the interaction of electromagnetic radiation with electrons in solids, is an exciting new field that has developed fast since the 1980s and is still growing steadily. Yet, plasma physicists have devoted little attention to it. This special collection would like to bridge the gap between plasmas and plasmonics and encourage plasma physicists to have their say in this burgeoning research field. *Published by AIP Publishing.* https://doi.org/10.1063/1.5026653

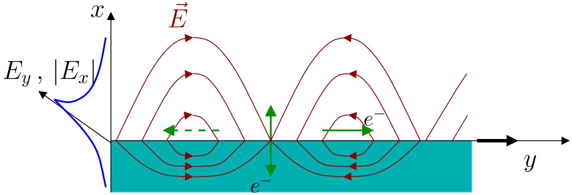
two papers from our group in this PoP collection

Our goal: extending blueplasmonics towards very high fields and deep into the relativistic dynamics regime

Strong collaboration with C. Riconda (LULI) and T. Ceccotti (CEA)

Surfin' the Surface Wave

Can a SP accelerate electrons like a "bulk" plasma wave? (e.g. laser-plasma wakefield acceleration)



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

→ electrons may "surf" the SP and gain high energy

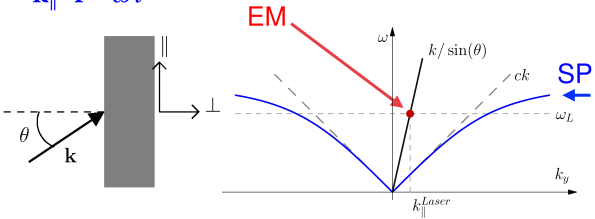
we attempted the experiment . . .

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

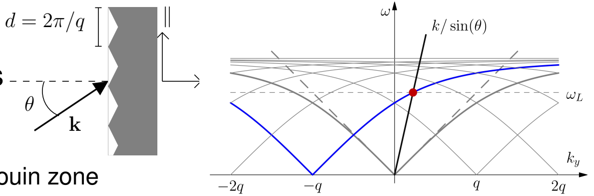
Surface plasmon coupling with laser light

SP coupling with EM wave ($\omega_L = ck$) requires phase matching:
$\varphi_{\text{EM}} = \varphi_{\text{SP}}$ where $\varphi = \mathbf{k}_\parallel \cdot \mathbf{r} - \omega t$

No matching with EM wave at a plane interface:
$\omega = ck = ck_\parallel / \sin\theta$



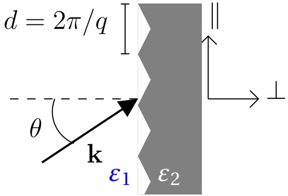
Periodic grating: “replica” (*) of $\omega_{\text{SP}}(k_\parallel)$ enables matching



(*) folding in the Brillouin zone – Floquet-Bloch theorem

Laser and target requirements for high fields

- Ultrafast field ionization provides free electrons instantaneously $\longrightarrow$ any target material (e.g. plastic) becomes a plasma (usually $\omega_p \gg \omega$)



- Grating coupling at "resonant" angle
  $\sin\theta \simeq n\frac{\lambda}{d} - 1$ (usually $n = 1$)
  ("prism-based" configurations not suitable because of ionization)
- Femtosecond pulses with ultrahigh contrast preserve sharp interface and surface structuring against hydrodynamic expansion and early target damage and ionization by "prepulses"

Observation of “surfing” acceleration on a SP

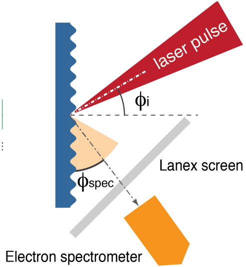
PRL **116,** 015001 (2016) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2016

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)

LaserLAB experiment at SLIC, CEA Saclay
UHI laser: 25 fs pulse, 5×10^{19} Wcm^{-2}, $a_0 = 4.8$
contrast $\gtrsim 10^{12}$ at 5 ps

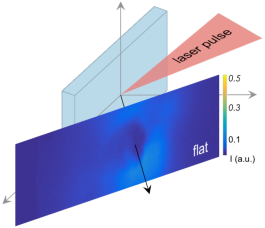
Experimental results

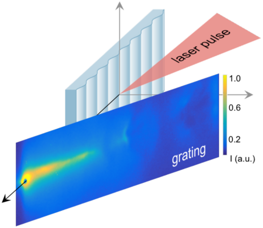


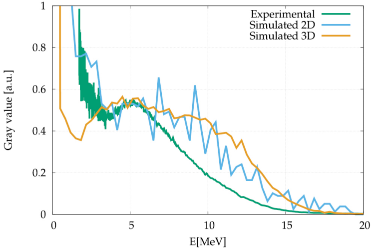
collimated ($\simeq 20°$ cone) electron emission near the surface tangent ($\phi \simeq 2°$)

multi-MeV energy, total charge $\simeq 100$ pC

Excellent agreement with 3D simulations

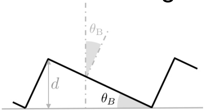


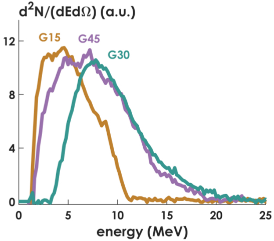


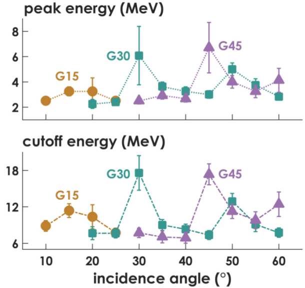


Optimizing surface plasmon electron acceleration

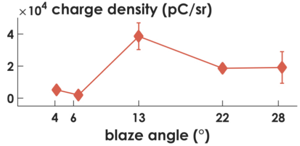
Dependence on
- grating period
($\phi_{\rm res} = 15°, 30°, 45°$)
- incidence angle

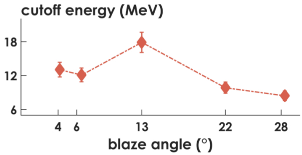






Blazed gratings increase energy and charge up to 650 pC per bunch





G. Cantono et al, Phys. Plasmas **25** (2018) 031907

Observation of SP-enhanced harmonics from gratings

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

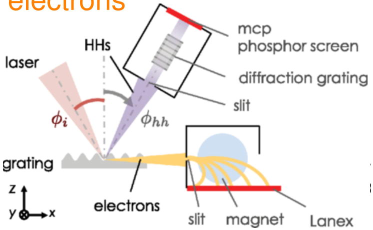
Extreme Ultraviolet Beam Enhancement by Relativistic Surface Plasmons

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

Experimental results

Simultaneous measurements of HH & electrons



HH optimization via density profile tailoring (scalelength $L \simeq 0.1\lambda_L$) by a femtosecond prepulse

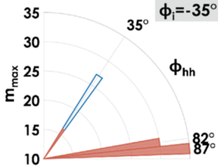
Kahaly et al, PRL **110** (2013) 175001

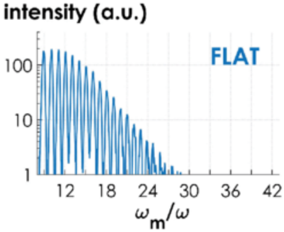
Note: $L \sim$ grating depth!

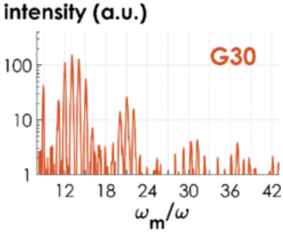
Max HH order:

Flat: $m \simeq 25$ at $45°$

Grat: $m \simeq 37$ at $87°$







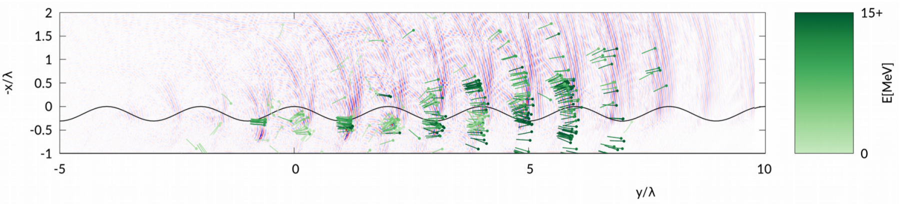
Boosting harmonics by electron nanobunching

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

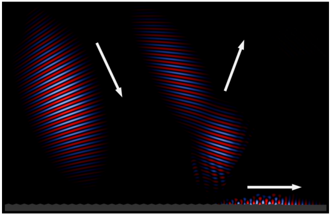
similar to collective instability operation in a Free Electron Laser

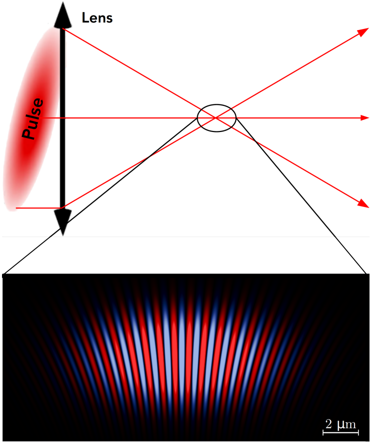
2D simulations by L. Fedeli



Surface plasmon shortening by wavefront rotation

Wavefront Rotation (WFR):
the effective incidence angle rotates during the laser pulse
⟶ "resonant" condition for a short temporal interval only
⟶ excitation of a SP (much) shorter than the laser pulse?





WFR obtained by focusing a tilted wavefront pulse

Proposed scheme for few-cycle SP generation

ACS Photonics

Cite This: *ACS Photonics* 2018, 5, 1068–1073

Few-Cycle Surface Plasmon Polariton Generation by Rotating Wavefront Pulses

F. Pisani,[*,†] L. Fedeli,[*,‡] and A. Macchi[*,¶,†]

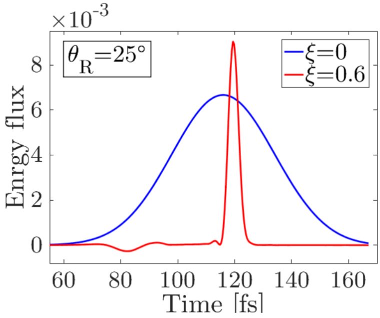
[†]Enrico Fermi Department of Physics, University of Pisa, 56127 Pisa, Italy
[‡]Department of Energy, Politecnico di Milano, 20133 Milano, Italy
[¶]National Institute of Optics, National Research Council (CNR/INO), A.Gozzini unit, 56124 Pisa, Italy

F. Pisani, L. Fedeli, A. Macchi, ACS Photonics **5** (2018) 1068

A near "single-cycle" SP

MEEP[1] simulations of
WFR pulse on Ag grating

SP w/o and with WFR
duration: 3.8 fs (~ 1.4 cycles)

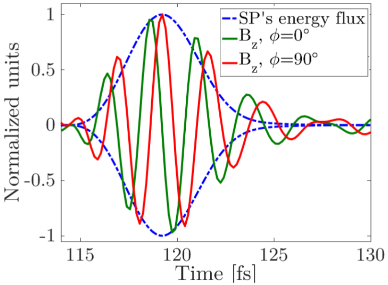


$E = E(r,z,t)\exp(-i\omega_L t + ir\zeta t + \phi)$

ζ : WFR parameter

laser: 30 fs , $\lambda_L = 0.8\ \mu$m

dependence on
absolute phase ϕ



[1] http://ab-initio.mit.edu/wiki/index.php/Meep

WFR effect on electron acceleration by a SP

PHYSICAL REVIEW E **103**, L021201 (2021)

Letter

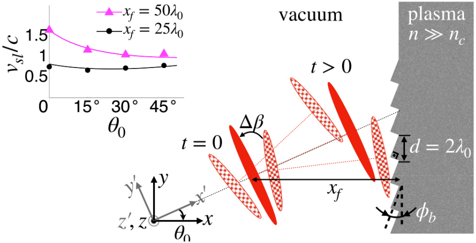
Ultrashort high energy electron bunches from tunable surface plasma waves driven with laser wavefront rotation

S. Marini,[1,2] P. S. Kleij,[1,2,3] F. Pisani,[3] F. Amiranoff,[2] M. Grech,[2] A. Macchi,[4,3] M. Raynaud,[1] and C. Riconda[2,*]
[1]*LSI, CEA/DRF/IRAMIS, CNRS, École Polytechnique, Institut Polytechnique de Paris, F-91128 Palaiseau, France*
[2]*LULI, Sorbonne Université, CNRS, CEA, École Polytechnique, Institut Polytechnique de Paris, F-75252 Paris, France*
[3]*Enrico Fermi Department of Physics, University of Pisa, largo Bruno Pontecorvo 3, 56127 Pisa, Italy*
[4]*National Institute of Optics, National Research Council (CNR/INO), Adriano Gozzini laboratory, 56124 Pisa, Italy*

S. Marini, P. Kleij, F. Pisani, F. Amiranoff, M. Grech, A. Macchi, M. Raynaud, C. Riconda
Phys. Rev. E **103** (2021) L021201

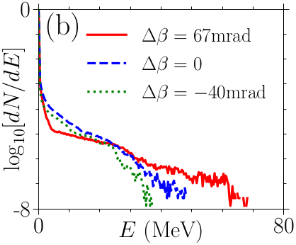
WFR enhancement of SP and electron acceleration

The WFR induces a "sliding focus" effect which sustains a higher peak amplitude of the few-cycle SP



Simulations show that shorter and more energetic electron bunches are generated by tuning the WFR velocity and the distance between laser waist and target

waiting for the experiment . . .



Thanks to mentors and collaborators . . .

Thanks to Francesco Ceccherini, Dieter Bauer, Caterina Riconda, Fulvio Cornolti, Francesco Pegoraro, Vitali Vshivkov, Tanja V. Liseykina, Marco Borghesi and Peter Mulser, Hartmut Ruhl, Sergey V. Bulanov, Sergey Propruzhenko, Antonino Di Piazza, Enrique Conejero Jarque, Satyabrata Kar, Tiberio Ceccotti, . . .

. . . and to people from whom I learned a lot

Giannandrea Inchingolo, Luca Fedeli, Anna Grassi, Giada Cantono, Andrea Sgattoni, Amritpal Singh Nindrayog, Marta d'Angelo, Paula Kleij, . . .
and Matteo Tamburini, Stefano Sinigardi, Francesco Pisani, Silvia Veghini, Sara Tuveri, Alessandra Bigongiari, Cosimo Livi, Anna Giacobbe, Mattia Lupetti, Marco Battaglini, . . .