High intensity laser-grating interactions: a step towards relativistic plasmonics?

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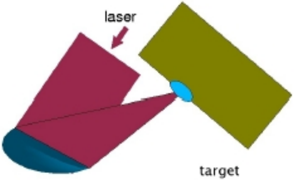
Ultrashort laser-solid interactions: what for?



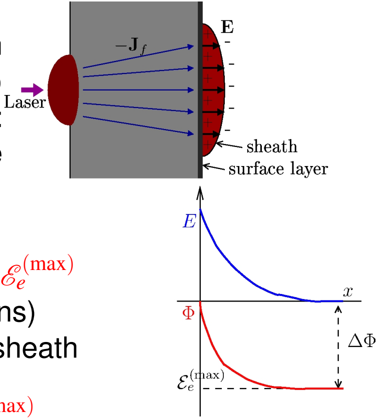
Ultrashort pulses: < 100 fs duration, up to $\sim 10^{20}$ W cm^{-2} intensity

Applications:

- laser-driven particle sources (electrons, ions)
- high harmonic generation for coherent ultrashort X-ray emission
- isochoric heating of matter

  efficient laser-target coupling is a key issue for these processes

Example: sheath acceleration of protons



Target Normal Sheath Acceleration (TNSA) is driven by "fast" ($\mathscr{E}_e \sim$ MeV) electrons generated in thin targets: protons from surface contaminants are accelerated in the rear sheath

TNSA picture "for dummies":

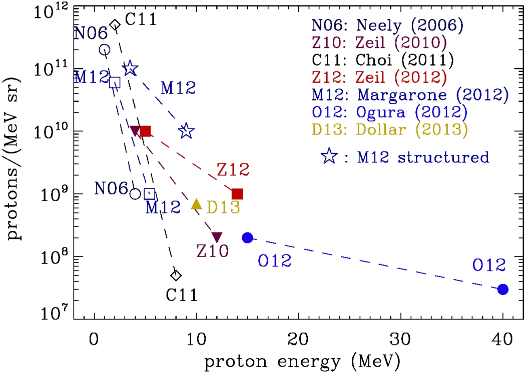
Potential drop for static sheath $e\Delta\Phi = \mathscr{E}_e^{(\max)}$ (sheath potential must confine electrons)

Energy gained by "test" proton in the sheath

$$\mathscr{E}_p = e\Delta\Phi = \mathscr{E}_e^{(\max)}$$

Efficient electron heating is key to TNSA

Recent TNSA data with “table-top” lasers



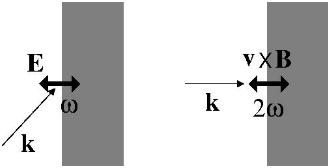
Intensity range:
$I = (1-5)\times 10^{19}$ W cm^{-2}
(empty symbols)
$I = (0.8-2)\times 10^{21}$ W cm^{-2}
(filled symbols)
Pulse duration range:
$\tau = 25-40$ fs
Target thickness range:
$\ell = 0.05-4.0\ \mu$m

Need to find strategies to increase absorption and fast electron energy to boost TNSA

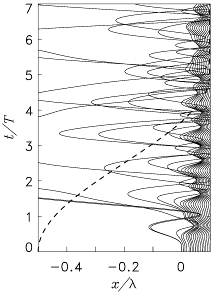
A. Macchi et al, Plasma Phys. Contr. Fus. **55**, 124020 (2013)

Fast electron generation: simple (rough) picture

The Lorentz force of the laser wave (amplitude E_L, frequency ω) drives periodic “push-pull” of electrons across the density gradient



Electrons perform “half-oscillations” on the vacuum side and re-enter in the plasma (where the EM field is screened) and are “absorbed” keeping a net momentum



$$p_e \sim p_{\rm osc} \sim eE_L/\omega \equiv m_e c a_0$$

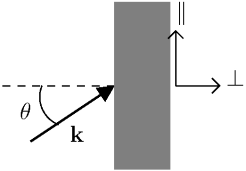
$a_0 = \left(\frac{eE_L}{m_e c\omega}\right) > 1 \longrightarrow$ relativistic electrons

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

Looking for resonant coupling

Idea: enhancement of the surface field and of absorption by exciting a normal mode of the target plasma

Resonant coupling requires matching of the phase $\varphi = \mathbf{k}_\parallel \cdot \mathbf{r} - \omega t$ between the laser and the resonant mode characterized by $(\omega_m, \mathbf{k}_m)$:

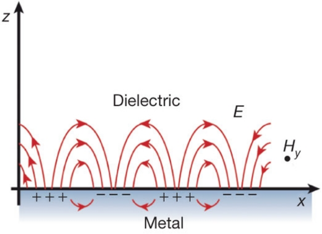


$$\omega \doteq \omega_m \qquad k_\parallel = k\cos\theta \doteq (k_m)_\parallel$$

Normal modes of step boundary metal/plasma: surface waves

figure from:

O.Benson, Nature **480**, 193 (2011)



Surface wave coupling: the matching problem

Plasma-vacuum interface

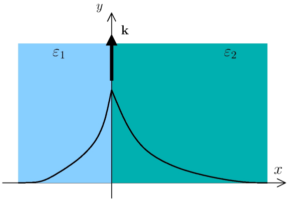
$$\varepsilon_1 = 1 \quad \varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c}$$

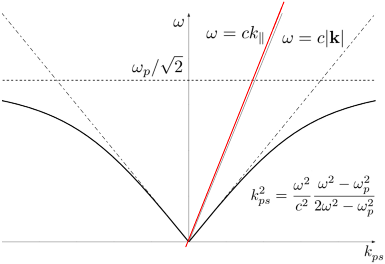
Dispersion relation $\omega = \omega(k)$

$$k = \frac{\omega}{c}\left(\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}\right)^{1/2}$$

$$\omega < \omega_p/\sqrt{2} \qquad v_{\text{ph}} < c$$

No matching with $\omega = ck_\parallel$

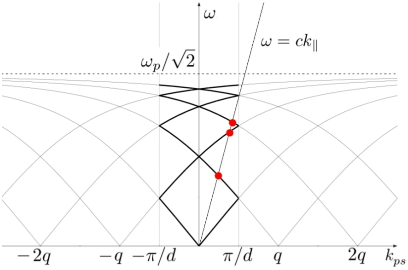




Surface wave matching in periodic structures

In a spatially periodic medium with period d, folding of $\omega_{SW}(k)$ in the Brillouin zone $|k| < \pi/d$ (Floquet-Bloch theorem) allows phase matching

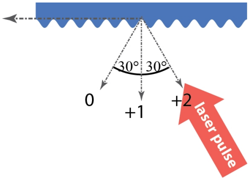
Figure: M.Lupetti, M.Sc. Thesis, 2011



Resonant coupling with EM wave is possible in a grating at an angle of incidence

$$\sin\theta_{\text{res}} + \lambda/d = \left(\frac{1-\omega_p^2/\omega^2}{2-\omega_p^2/\omega^2}\right)^{1/2}$$

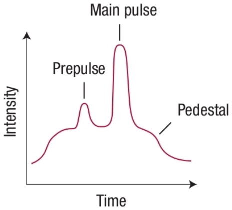
(provided $\omega_{SW}(k)$ does not change much)



Earlier work on laser-grating interaction

Coupling of laser field with surface waves is a “building block” of plasmonics: the art of light concentration and manipulation on the sub-wavelength scale

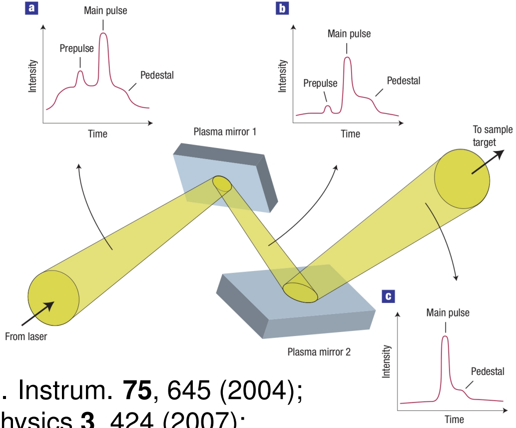
Experiments performed since 1990’s at high intensity have been limited by prepulse effects causing distruption of shallow grating structure before short pulse interaction



A general issue: do surface waves exist in a high-field, nonlinear and relativistic regime?

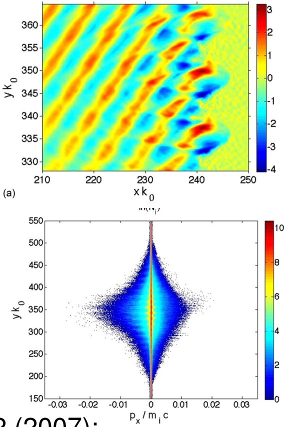
Need for ultraclean pulses: plasma mirrors

Plasma mirrors yielding $\sim 10^{12}$ pulse-to-prepulse contrast allow to preserve target structuring until the short pulse interaction



B. Dromey et al, Rev. Sci. Instrum. **75**, 645 (2004);
C. Thaury et al, Nature Physics **3**, 424 (2007);
figure from P. Gibbon, *ibid.*, 369.

Surface wave coupling in the “relativistic” regime



No theory for SW in the nonlinear, high field, relativistic electrons regime

$$a_0 > 1 \longrightarrow I\lambda^2 > 1.4 \times 10^{18}\ \mathrm{Wcm}^{-2}\mu\mathrm{m}^2$$

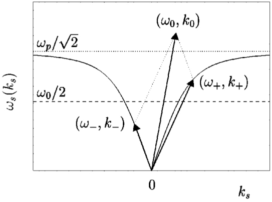
However, particle-in-cell simulations show enhancement of absorption, electron heating and ion acceleration for laser-grating interactions up to $I\lambda^2 \sim 10^{20}\ \mathrm{Wcm}^{-2}\mu\mathrm{m}^2$

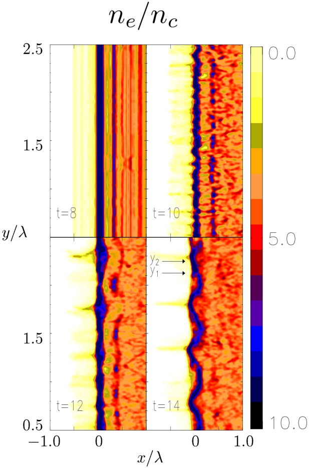
M. Raynaud et al, Phys. Plasmas **14**, 092702 (2007);
A. Bigongiari et al, *ibid.* **18**, 102701 (2011); **20**, 052701 (2013)

Another early evidence for relativistic SW

Laser-driven periodic surface oscillations decay in two surface waves via a period-doubling process; similarity to Faraday Waves (Ripples) in a liquid

No grating necessary for nonlinear phase matching

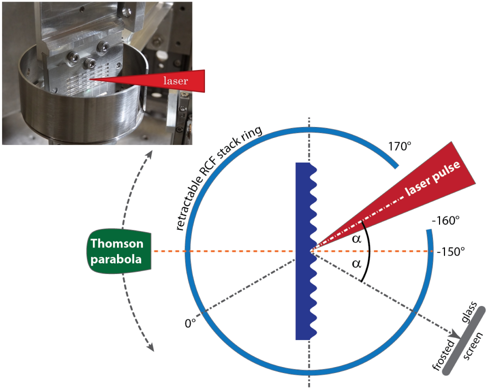




A. Macchi et al, Phys. Rev. Lett. **87**, 205004 (2001); Phys. Plasmas **9**, 1704 (2002)

Experimental set-up

LaserLAB experiment at SLIC, CEA Saclay
laser UHI, 28 fs, 5×10^{19} W cm^{-2}, contrast $\sim 10^{12}$

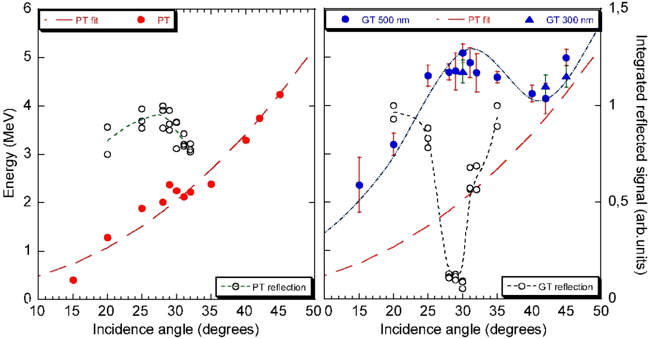


Grating:
- $d = 2\lambda \rightarrow \theta_{\text{res}} = 30^\circ$
- depth $\delta = 0.3 - 0.5\mu$m

Diagnostics:
- Thomson Parabola for proton detection
- Radio-Chromic Film (RCF) "ring" for radiation emission at any angle
- Reflected light

Plane target vs grating

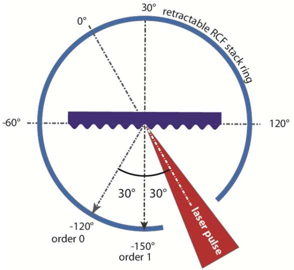
Proton energy cut-off $\mathscr{E}_{\text{max}}$ and reflected light vs incidence angle:
- broad maximum (minimum) around $\theta_{\text{res}} = 30^\circ$
- $\sim$2.5X enhancement in $\mathscr{E}_{\text{max}}$ at θ_{res}, $\sim$2 at small angles

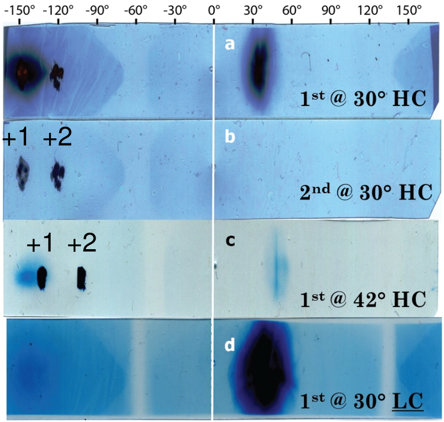


PT: plane target
GT: grating target
● $\mathscr{E}_{\text{max}}$, GT, $\delta = 0.5\ \mu$m
▲ $\mathscr{E}_{\text{max}}$, GT, $\delta = 0.3\ \mu$m
● $\mathscr{E}_{\text{max}}$, PT
○ reflected light

Grating signatures on RCF

Diffraction orders produce angle-dependent “burn spots” for High Contrast (HC), not observed with Low Contrast (LC)

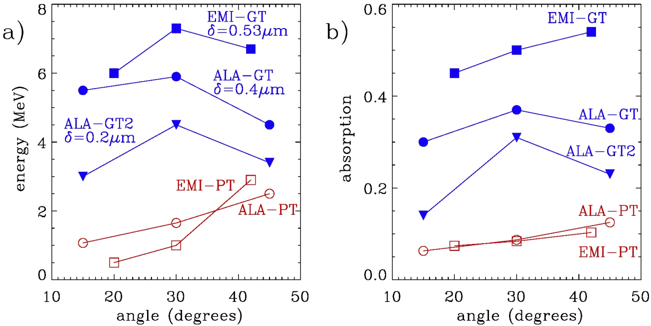




Comparison with PIC simulations

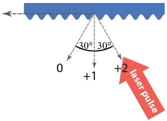
Two simulations campaigns with Particle-In-Cell codes **EMI2D** (CPhT, École Polytechnique) and **ALADYN** (Italy) fairly reproduce experimental trend

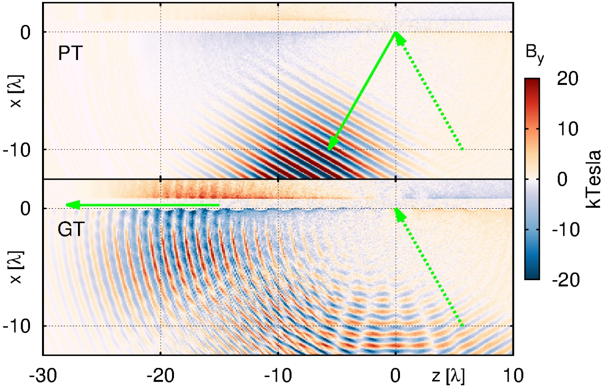
(2D simulations, different set-up for the two codes)



Surface wave in simulations

Snapshots of EM fields show localized wave propagating along the surface at resonant angle of incidence (plus reflection at various diffraction orders)



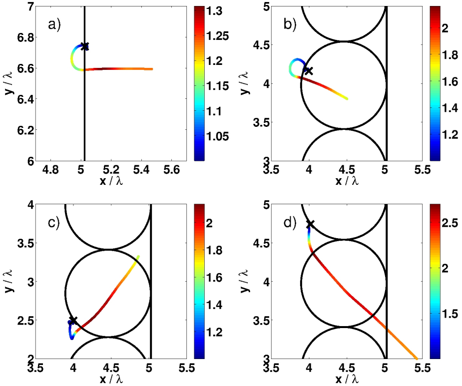


Enhanced electron heating out of resonance

Stochastic heating at a modulated interface is more efficient than in plane targets: electrons have more “re-entering trajectories” available

Effect observed in microsphere-covered targets

(PIC sim. by O. Klimo et al)



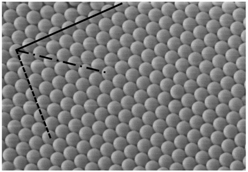
V. Floquet et al, J. Appl. Phys. **114**, 083305 (2013)

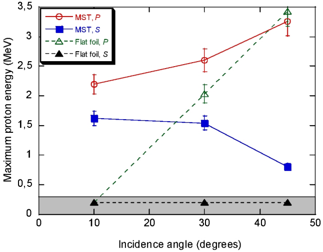
Experiment on microsphere-covered targets

Measurements taken in same campaign at SLIC

Some enhancement of proton energy observed only at small angles of incidence

(compare with Margarone et al, Phys. Rev. Lett. **109**, 234801 (2012))





V. Floquet et al, J. Appl. Phys. **114**, 083305 (2013)

Conclusions: open issues and future work - I

From the point of view of using grating targets for "enhanced" proton acceleration:

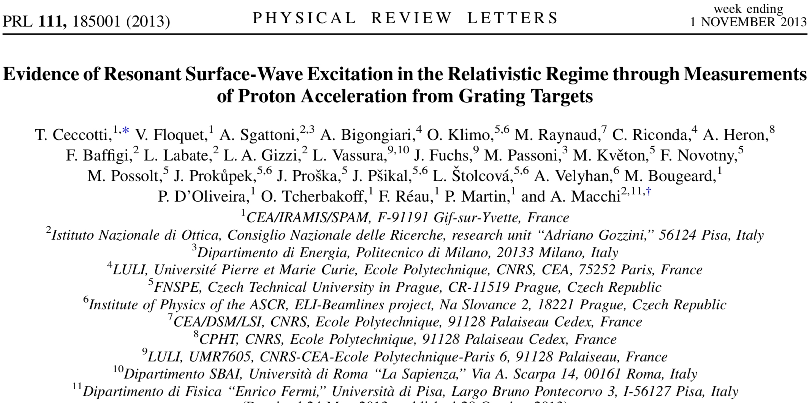
- energy increase at resonant angle does not exceed maximum energy in plane targets at grazing incidence: need to test different (larger) angles
- grating structure (and also microsphere covering . . .) did not work with very thin foils: need to use smarter materials to guarantee target integrity
- efficiency of grating effect for longer pulses (delivering more energy) uncertain because of hydrodynamics on ~ 100 fs temporal scale
- is it feasible to embed gratings in a complex target design (e.g. microcones, . . .)?

Conclusions: open issues and future work - II

- From a point of view of “general interest”:
- First experimental indication of surface waves in the regime of relativistic electrons

  possible next steps:
- work out theory of nonlinear, relativistic SW
- investigate detailed mechanism of energy absorption and electron acceleration by SW
- design plasmonics applications in the high fields regime, exploiting the SW resonance

Main reference



PRL **111,** 185001 (2013) PHYSICAL REVIEW LETTERS week ending 1 NOVEMBER 2013

Evidence of Resonant Surface-Wave Excitation in the Relativistic Regime through Measurements of Proton Acceleration from Grating Targets

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

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- FIRB-MIUR (Italy) project SULDIS – ("Superintense Ultrashort Laser-Driven Ion Sources")
- . . .

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