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

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

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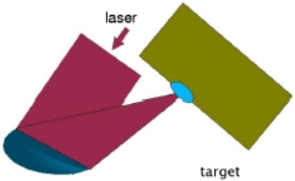
Ultrashort laser-solid interactions: what for?



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

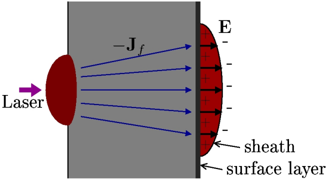
Applications:

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

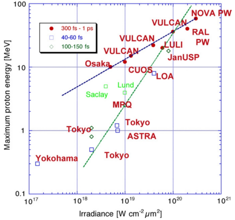
  efficient laser-target coupling is a key issue for these processes

Example: sheath acceleration of protons

Target Normal Sheath Acceleration (TNSA) is driven by “fast” (multi-MeV) electrons generated in thin targets: protons from surface contaminants are accelerated in the rear sheath



Connection with some classic problems:
- stochastic acceleration of electrons
- sheath formation and ion acceleration
- plasma expansion into vacuum



Many experiments in various laser regimes:
the key is higher laser absorption into electrons

Surface waves

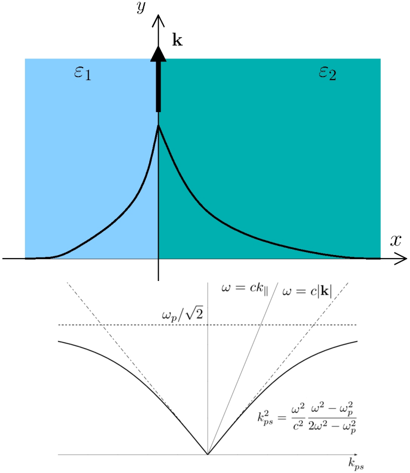
A steep plasma-vacuum interface supports surface waves

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

Dispersion relation $\omega = \omega(k)$ for flat interface

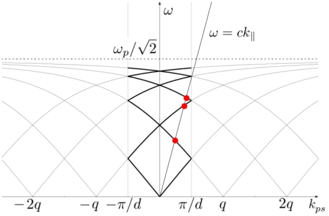
$$k = \frac{\omega}{c}\left(\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}\right)^{1/2}$$

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



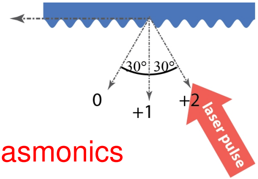
Surface wave dispersion in periodic structures

Folding of $\omega_{SW}(k)$ in Brillouin zone (Floquet-Bloch theorem) allows phase matching with EM wave
$\omega = k_{\|}c/\sin\theta \quad v_{\text{ph}} = c/\sin\theta > 1$
Figure: M.Lupetti, M.Sc. Thesis, 2011



Coupling with EM wave possible in a grating having spatial period d for resonant angle of incidence

$$\sin\theta_{\text{res}} + \lambda/d = \left(\frac{1-n_e/n_c}{2-n_e/n_c}\right)^{1/2} \quad (\lesssim 1)$$



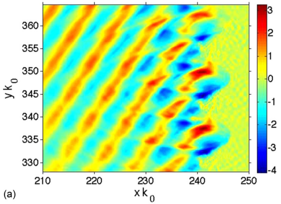
Laser-grating coupling: "building block" of plasmonics

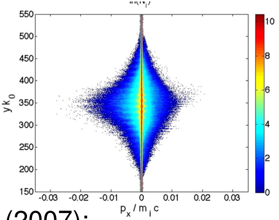
Surface wave coupling in the “relativistic” regime

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

$$a_0 \equiv \frac{p_{\text{osc}}}{m_e c} > 1 \longrightarrow I\lambda^2 > 1.4 \times 10^{18} \text{ W cm}^{-2}$$

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



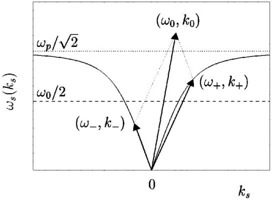


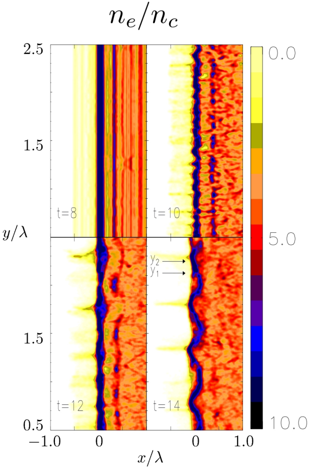
M. Raynaud et al, Phys. Plasmas **14**, 092702 (2007);
A. Bigongiari et al, *ibid.* **18**, 102701 (2011); **20**, 052701 (2013)

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



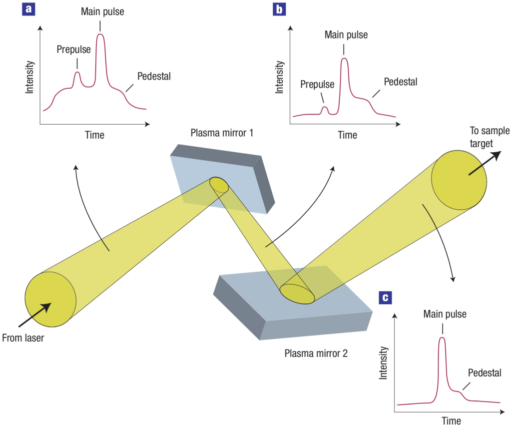


A. Macchi et al, Phys. Rev. Lett. **87**, 205004 (2001); Phys. Plasmas **9**, 1704 (2002)

Need for ultrahigh contrast: plasma mirrors

Pedestal and pre-pulses might destroy the surface structure before short pulse arrival

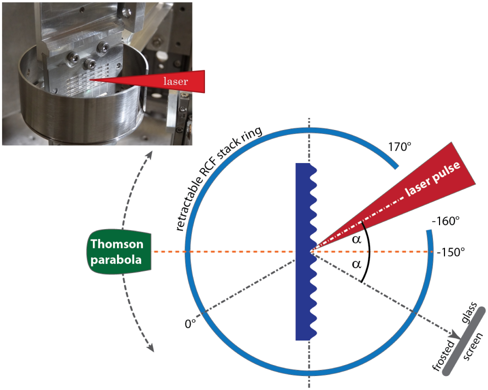
Use of double plasma mirror yielding $\sim 10^{12}$ contrast at SLIC facility (CEA Saclay) allows high-intensity interaction



C. Thaury et al, Nature Physics **3**, 424 (2007); figure from P. Gibbon, *ibid.*, 369.

Experimental set-up

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

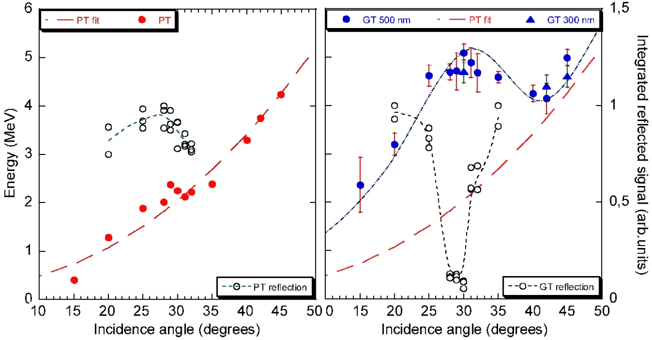


Grating:
- $d = 2\lambda \rightarrow \theta_{\text{res}} = 30°$
- depth $\delta = 0.3 - 0.5\mu$m

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

Plane target vs grating

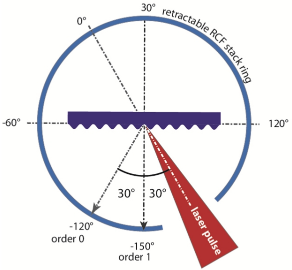
Proton energy cut-off $\mathscr{E}_{\text{max}}$ and reflected light vs incidence angle:
- broad maximum (minimum) around $\theta_{\text{res}} = 30^\circ$
- $\sim$2.5X enhancement in $\mathscr{E}_{\text{max}}$ at θ_{res}, $\sim$2 at small angles

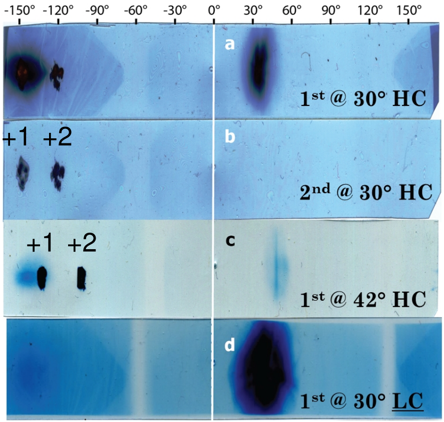


PT: plane target
GT: grating target
● $\mathscr{E}_{\text{max}}$, GT, $\delta = 0.5\ \mu$m
▲ $\mathscr{E}_{\text{max}}$, GT, $\delta = 0.3\ \mu$m
● $\mathscr{E}_{\text{max}}$, PT
○ reflected light

Grating signatures on RCF

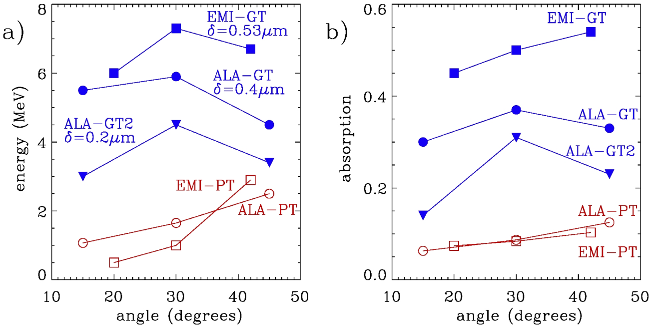
Diffraction orders produce angle-dependent "burn spots" for High Contrast (HC), not observed with Low Contrast (LC)





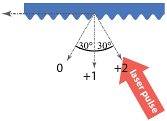
Comparison with PIC simulations

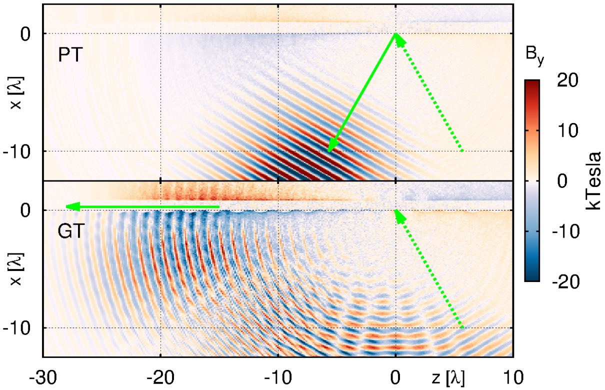
Two simulations campaigns with Particle-In-Cell codes EMI2D (CPhT, École Polytechnique) and ALADYN (Italy) fairly reproduce experimental trend
(2D simulations, different set-up for the two codes)



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)



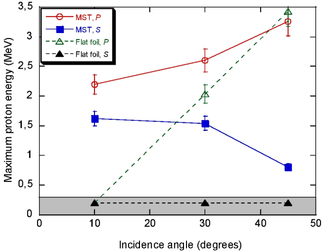


Enhanced heating out of resonance

Stochastic electron heating at a modulated interface is more efficient than in plane targets for small angles of incidence

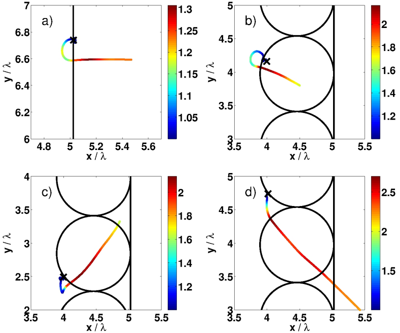
Similar effect in microsphere-covered targets (same campaign)

experiment



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

simulation (O. Klimo et al)



Conclusions and future work - I

- First experimental indication of surface waves in the regime of relativistic electrons

  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

Conclusions and future work - II

Planned further experiments:

- maximize proton energy via advanced grating targets:
  - find best choice for d and δ
  - use of new materials for very thin targets
- impact of SW excitation on other types of emission
  - electrons
  - high harmonics (XUV coherent emission)

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