Extreme Plasmonics for Laser-driven Sources

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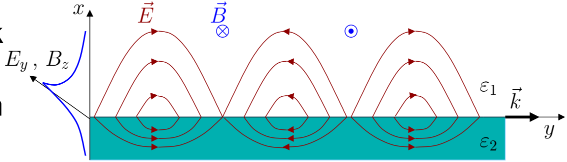
Surface plasmon (polariton)

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):

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

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

Three questions we started from

- Can we excite Surface Plasmon (polaritons) aka surface plasma waves using "extreme" laser pulses? (duration ~ 10 fs $= 10^{-14}$ fs, intensity $> 10^{18}$ W cm^{-2} at focus)
- How do SPs behave (if they exist at all) for strong fields with relativistic electron dynamics ($p_{\mathrm{osc}} \sim eE/\omega > m_e c$)?

  non-trivial theoretical issues: nonlinear response, boundary conditions, kinetic damping, wavebreaking . . .

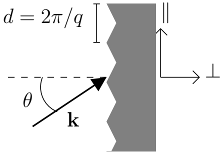
  A. Macchi, Phys. Plasmas **25** (2018) 031906
- Can we exploit coupling to SPs for enhancement of "secondary" sources of laser-driven radiation? (ions, electrons, XUV rays)

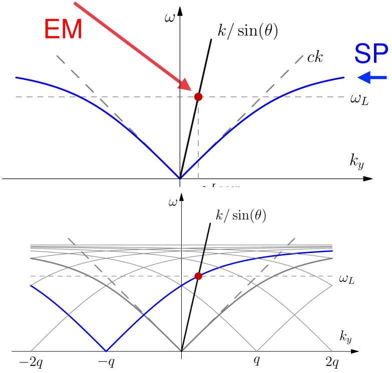
Coupling SPs to extreme laser pulses

SP coupling with EM wave ($\omega_L = ck$) requires phase matching:

$\varphi_{\text{EM}} = \varphi_{\text{SP}}$ where $\varphi = \mathbf{k}_{\|} \cdot \mathbf{r} - \omega t$

Grating structure required for matching at "resonant" angle(s)



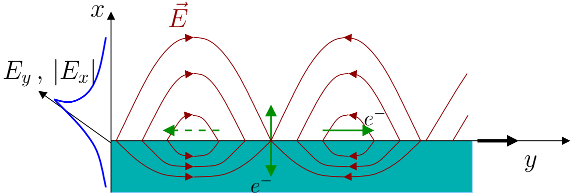


$$\sin\theta \simeq n\frac{\lambda}{d} - 1 \qquad (n \text{ integer})$$

Femtosecond pulses with ultrahigh contrast needed to preserve sharp interface and surface structuring against hydrodynamic expansion and prepulse effects

Electron heating and acceleration by SP fields

SPs enhance EM field near the surface $\longrightarrow$ generation of energetic electrons



Transverse electric field (E_x) enhances anomalous skin effect or "vacuum heating" (when electrons cross the target surface)
→ enhanced laser absorption, "hot" electrons into the target
→ energetic ions accelerated by sheath fields
First experimental evidence: Ceccotti et al, PRL **111** (2013) 185001

Longitudinal electric field (E_y) accelerates electrons along the surface by "surfing" the SP (phase velocity $v_p = \omega/k \lesssim c$)

Simple model of SP “surfing” acceleration

SP field on the vacuum side is electrostatic in the frame L' moving with phase velocity $\beta_{\rm p} = v_{\rm p}/c$ with respect to L (lab)

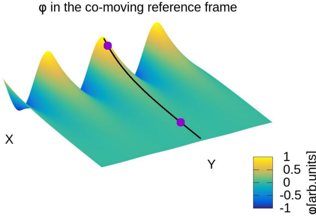
$\Phi' = -(\gamma_{\rm p} E_{\rm SP}/k) \mathrm{e}^{k'x} \sin k'y' \qquad k' = k/\gamma_{\rm p} \qquad \gamma_{\rm p} = (1-\beta_{\rm p}^2)^{-1/2}$

A “lucky” electron injected with velocity $v_{\rm p}$ goes downhill the potential $-e\Phi'$ acquiring an energy $W' = eE_{\rm SP}/k'$

Energy gain W and emission angle ϕ_e in L for $W' \gg m_e c^2$

$W \simeq \gamma_{\rm p} W' \simeq m_e c^2 a_{\rm SP} \dfrac{n_e}{n_c} \qquad \tan\phi_e = \dfrac{p_x}{p_y} \simeq \dfrac{1}{\gamma_{\rm p}}$

$\rightarrow$ highly relativistic electrons are beamed near the target surface ($\tan\phi_e \ll 1$)



Numerical study of injection conditions and energy scaling:
Riconda et al, PoP **22** (2015) 073103

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

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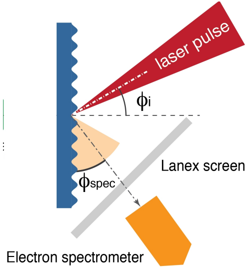
(Received 30 June 2015; published 7 January 2016)

LaserLAB experiment at SLIC, CEA Saclay

UHI laser: 25 fs pulse, 5×10^{19} Wcm^{-2}, $a_0 = 4.8$

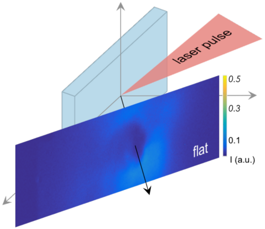
contrast $\gtrsim 10^{12}$ at 5 ps

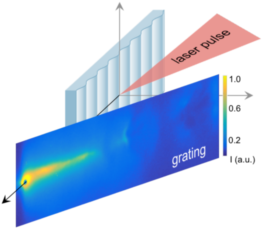
Features of SP electron acceleration

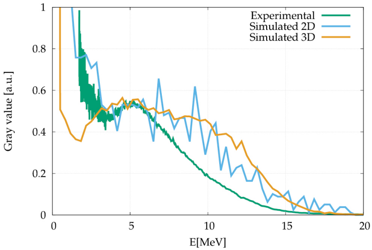


Sinusoidal gratings at SP resonance:
collimated ($\simeq 20^\circ$ cone) electron emission near the surface tangent ($\phi \simeq 2^\circ$)
multi-MeV energy, total charge $\simeq 100$ pC

- No such features for flat targets
- Excellent agreement with 3D simulations

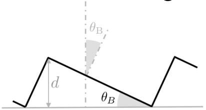




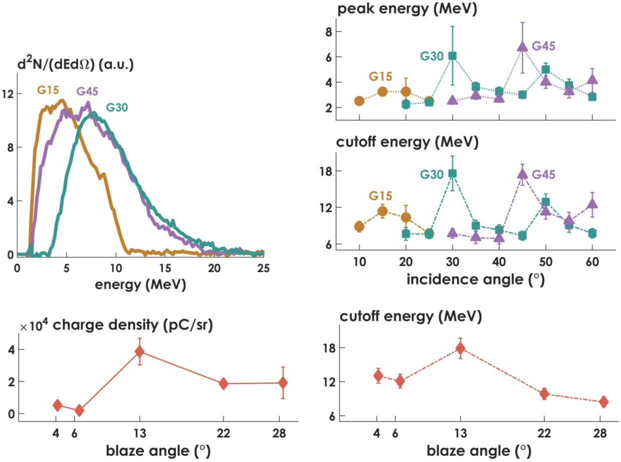


Optimizing SP electron acceleration

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



Use of available blazed gratings increase energy and charge up to 650 pC per bunch



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

High harmonic emission

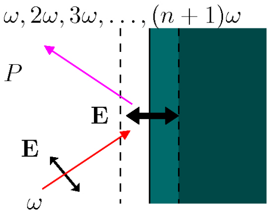
High laser harmonics (HH) up to the XUV range are emitted in specular reflection from flat targets

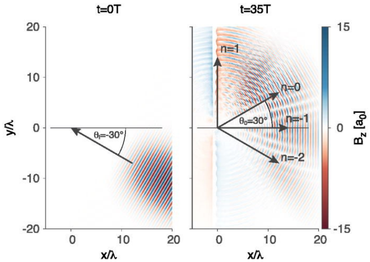
From gratings HH are separated at angles ϕ_{mn} according to:

$$\frac{n\lambda}{md} = \sin(\phi_i) + \sin(\phi_{mn})$$

(m: harmonic order, n: diffraction order, ϕ_i: incidence angle)

Expt: Cerchez et al, PRL **110** (2013) 065003





Idea: SP-enhanced HH with angular separation [Sim: Fedeli et al, APL **110** (2017) 051103]

Observation of SP-enhanced harmonics from gratings

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

Extreme Ultraviolet Beam Enhancement by Relativistic Surface Plasmons

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Experiment at SLIC, CEA Saclay

UHI laser: 25 fs pulse, 2×10^{19} Wcm^{-2}, $a_0 = 3$

contrast $\gtrsim 10^{12}$ at 5 ps

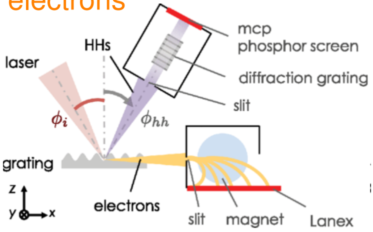
SP-enhancement and optimization of HH

Simultaneous measurements of HH & electrons

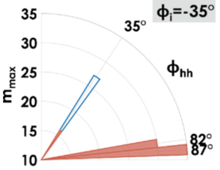
HH optimization via density profile tailoring (scalelength $L \simeq 0.1\lambda_L$) by a femtosecond prepulse

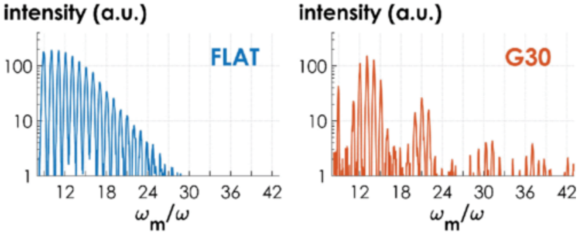
Kahaly et al, PRL **110** (2013) 175001

Notice: $L \sim$ grating depth!



Max HH order:
Flat: $m \simeq 25$ at $45°$
Grat: $m \simeq 37$ at $87°$





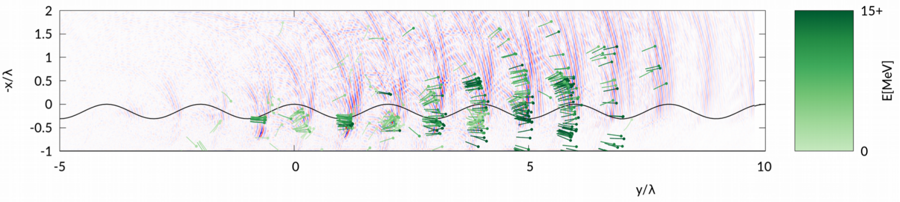
HH boosting by electron nanobunching

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

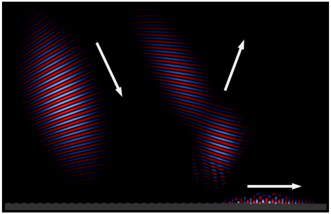
similar to collective instability operation in a Free Electron Laser

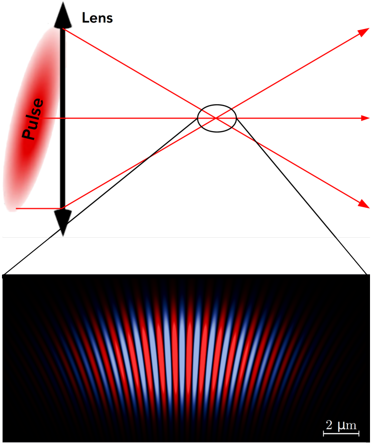
2D simulations by L. Fedeli



SP 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

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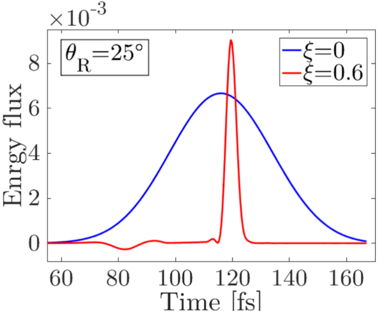
F. Pisani, L. Fedeli, A. Macchi, ACS Photonics **5** (2018) 1068

A near “single-cycle” SP

MEEP[1] simulations of WFR pulse on Ag grating (only linear response, no nonlinear dynamics)

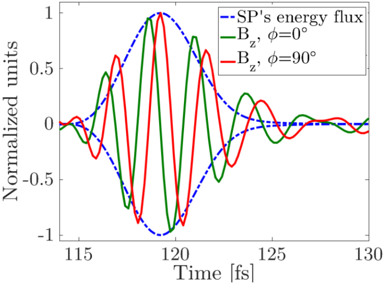


Dependence on absolute phase ϕ is apparent

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

ζ : WFR parameter

A 3.8 fs ($\sim$ 1.4 cycles) SP is generated from a 30 fs, $\lambda_L = 0.8\ \mu$m laser pulse



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

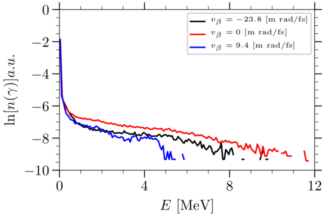
WFR at high fields: PIC simulations (in progress)

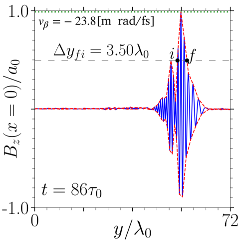
Smilei simulations

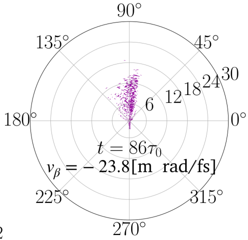
$a_0 = 1,\ c\tau_L = 10\lambda,\ w = 6\lambda,$
$\theta_{\rm res} = 30°,\ n_e = 20 n_c$

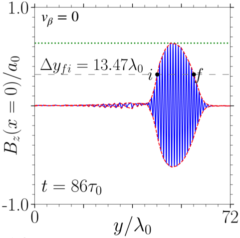
- SP shortening observed
- impact on electrons

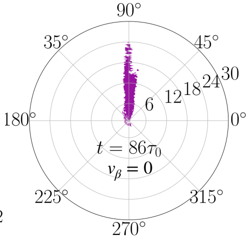
S. Marini, P. Kleji, M. Grech et al, Proc. EPS-DPP 2019











Summary

- Surface plasmon-enhanced emission has been demonstrated experimentally in the “relativistic” regime for MeV protons and electrons and for XUV photons
- Optimization of electrons via blazed gratings and of high harmonics via fs prepulse-produced sub-μm gradient

$\longrightarrow$ static and dynamic nanostructuring is effective!

- New generation mechanism for high harmonics correlated with electrons
- Particle-In-Cell simulations validated by comparison with experiments as a tool to explore new schemes
- Concept for generation of near single-cycle surface plasmons tested by simulations in the linear regime

Outlook - I

- Improve control in high field femtosecond plasmonics

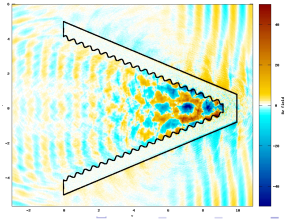
⟶ exploit wavefront rotation at high fields
[PIC simulation in progress]

⟶ optimized ad-hoc design of blazed gratings?
[MEEP simulation in progress]

⟶ use of transient laser-induced gratings?
S. Monchocé et al, Phys. Rev. Lett. **112** (2014) 145008

⟶ Test of plasmonic schemes in the high-field regime

Example: tapered waveguide for light nano-focusing and amplification
Original plasmonic concept:
M.Stockman, PRL **93** (2004) 137404
PIC simulation: L. Fedeli, PhD thesis
“High Field Plasmonics” (Springer, 2017)



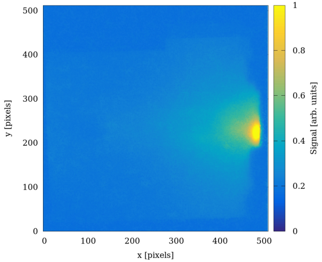
Outlook -II

- Higher electron energies? Simple model suggests that acceleration length is limited by the laser spot size

$\longrightarrow$ line focus possible?

- Feasibility and scaling at higher intensities?

"Parasitic" lanex image from PULSER laser (GIST, Korea)
$I = 5 \times 10^{20}$ W/cm^2
Beamed near-tangent emission from grating still observed



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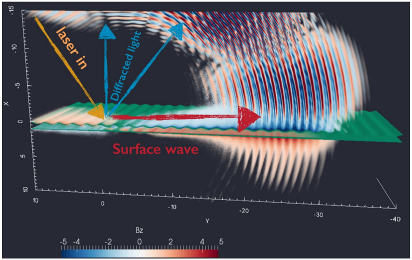
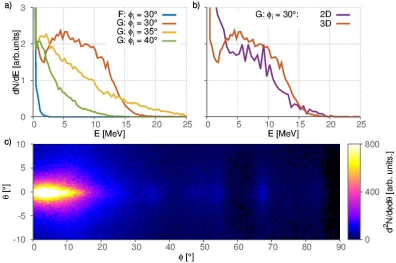
- LASERLAB-EUROPE, grant No. 284464, EU's 7th Framework Programme, proposals SLIC001693-SLIC002004.
- "Investissement d'Avenir" LabEx PALM (Grant ANR-10-LABX-0039)
- Triangle de la physique (contract nbr. 2014-0601T ENTIER)
- Czech Science Foundation project No. 15-02964S
- PRACE & ISCRA & LISA awards for access to FERMI BlueGene/Q™ and MARCONI at CINECA (Italy)

EXTRA SLIDES

3D simulations of the experiment

Fully kinetic, EM Particle-In-Cell simulations with PICcante open source code[2] on 16384 cores of BlueGene/Q FERMI at CINECA, Italy





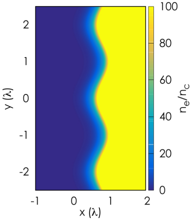
Simulations confirm excitation of relativistic SP and reproduce measurements quantitatively and in detail!

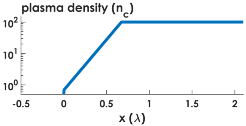
[2] available at http://aladyn.github.io/piccante

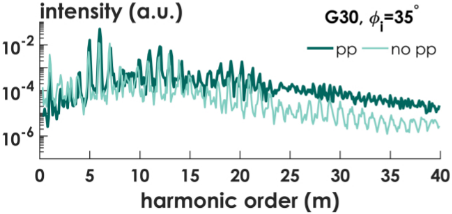
Preplasma optimization of HH

A further ~x 10 enhancement of HH is obtained by adding a preplasma (pp) of scalelength $L \sim 0.1\lambda_L$ in front of the target
(effect known in flat targets with preplasma produced by controlled fs prepulse)

Issue: $L \sim \delta$ (grating depth) can coexist with modulation in real experimental conditions?



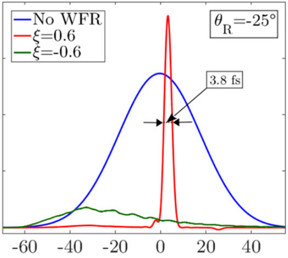


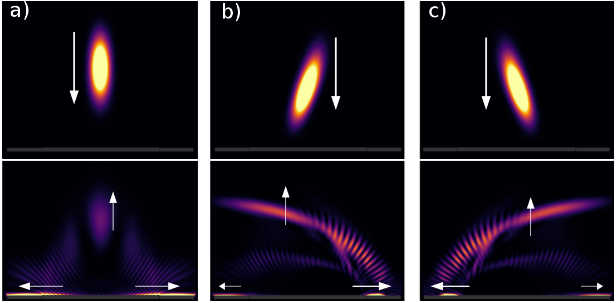


2D simulations
Giada Cantono, PhD thesis, 2017

Effect of WFR sign

With WFR the "incidence point" ((centroid of laser field at the target plane) slides along the target surface
Sliding must be parallel to SP velocity ($\xi > 0$) for shortening effect (spoiled for $\xi < 0$)





Normal incidence: excitation of two symmetric SPs)
a): no rotation
b): counterclockwise rotation
c): clockwise rotation

First evidence from proton emission

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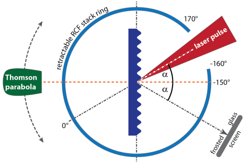
T. Ceccotti et al, Phys. Rev. Lett. **111** (2013) 185001

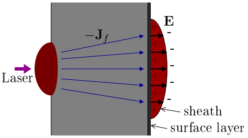
Grating-enhanced proton emission

LaserLAB experiment at SLIC, CEA Saclay

28 fs pulse, 5×10^{19} Wcm^{-2}, contrast $\sim 10^{12}$



proton acceleration in the electron sheath at the target rear



~ 3X increase in proton energy with respect to "flat" targets near resonant angle

$\phi_{\text{res}} = 30^\circ \quad (d = 2\lambda)$