High Field Femtosecond Plasmonics for Laser-Driven Sources

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Outline

- Plasmon excitation by laser coupling with periodically modulated surfaces (gratings)
- Requirements for high field plasmonics
- Plasmon-enhanced secondary emissions
  - protons
  - electrons (direct surface plasmon acceleration)
  - high (XUV) harmonics with angular selection
- A concept for two-cycle plasmon generation

Main Contributing Authors

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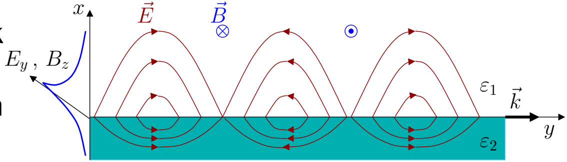
Other coworkers will be introduced later!

Surface plasmons

SP: building block of plasmonics (mostly studied in the *linear* regime)



SP excitation $\longrightarrow$ EM field confinement and enhancement

Interface between vacuum and simple metal or plasma:

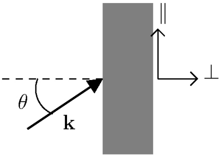
$$\varepsilon_1 = 1 \qquad \varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c(\omega)}$$

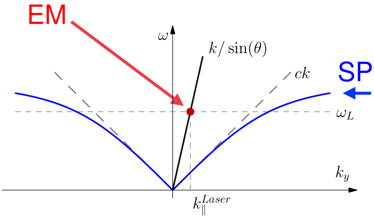
$$k = \frac{\omega}{c}\left(\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}\right)^{1/2} \qquad \omega < \frac{\omega_p}{\sqrt{2}} \qquad v_{\text{ph}} = \frac{\omega}{k} < c$$

Surface plasmon coupling with laser light

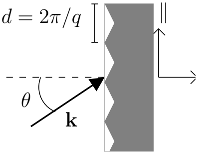
SP coupling with EM wave ($\omega_L = ck$) requires phase matching:
$\varphi_{\rm EM} = \varphi_{\rm SP}$ where $\varphi = \mathbf{k}_\parallel \cdot \mathbf{r} - \omega t$

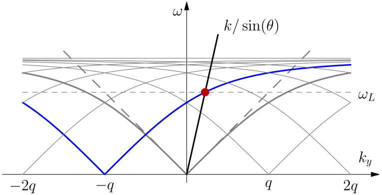
No matching with EM wave at a plane interface:
$\omega = ck = ck_\parallel / \sin\theta$





Periodic grating: "replica" (*) of $\omega_{\rm SP}(k_\parallel)$ enables matching





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

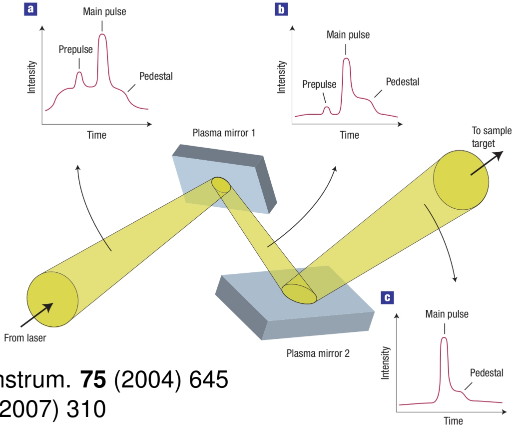
Exciting surface plasmons at high laser intensities?

- $I_L > 10^{16}$ W cm^{-2} $\longrightarrow$ instantaneous ionization
- free electrons available for plasmons (for any material)
- $I_L > 10^{18}$ W cm^{-2} $\longrightarrow$ relativistic electron dynamics
  ($a_L \equiv (eE_L/m_e\omega_L c) = 0.85(I_L\lambda_L^2/10^{18}\ \text{W cm}^{-2}\mu\text{m}^2)^{1/2} > 1$)
- no good relativistic theory for (nonlinear) SP available!
- some evidence from numerical simulations
  Macchi et al, Phys. Rev. Lett. **87** (2001) 205004
  Raynaud et al, Phys. Plasmas **14** (2007) 092702
- hydrodynamic expansion quickly washes the grating out
- prepulses cause early damage and expansion
- ultrashort (< 100 fs) high-contrast pulses available

“Ultraclean” high-contrast pulses

Ionization shutters (“plasma mirrors”) yield pulse-to-prepulse intensity contrast $> 10^{11}$

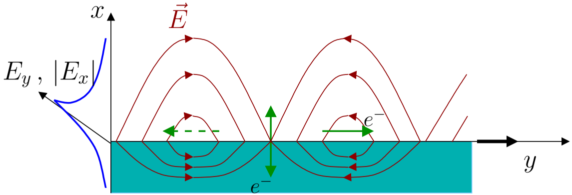
$\longrightarrow$ sub-wavelength structuring is preserved until the short pulse interaction



B. Dromey et al, Rev. Sci. Instrum. **75** (2004) 645
A. Levy et al, Opt. Lett. **32** (2007) 310
C. Thaury et al, Nature Physics **3** (2007) 424
figure from P. Gibbon, *ibid.* 369

Electron heating & acceleration by surface plasmons

SP enhances EM field near the surface → more energetic electrons



Transverse electric field (E_x) enhances anomalous skin effect or "vacuum heating" (when electrons cross the target surface)
→ high absorption of laser energy
→ "hot" electrons enter the target
→ energetic ions accelerated by sheath fields

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

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

T. Ceccotti,[1,*] V. Floquet,[1] A. Sgattoni,[2,3] A. Bigongiari,[4] O. Klimo,[5,6] M. Raynaud,[7] C. Riconda,[4] A. Heron,[8] F. Baffigi,[2] L. Labate,[2] L. A. Gizzi,[2] L. Vassura,[9,10] J. Fuchs,[9] M. Passoni,[3] M. Květon,[5] F. Novotny,[5] M. Possolt,[5] J. Prokůpek,[5,6] J. Proška,[5] J. Pšikal,[5,6] L. Štolcová,[5,6] A. Velyhan,[6] M. Bougeard,[1] P. D'Oliveira,[1] O. Tcherbakoff,[1] F. Réau,[1] P. Martin,[1] and A. Macchi[2,11,†]

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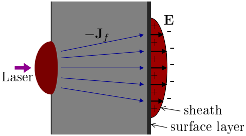
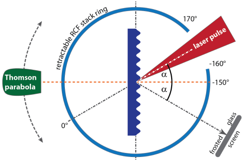
T. Ceccotti et al, Phys. Rev. Lett. **111** (2013) 185001

Grating-enhanced proton emission

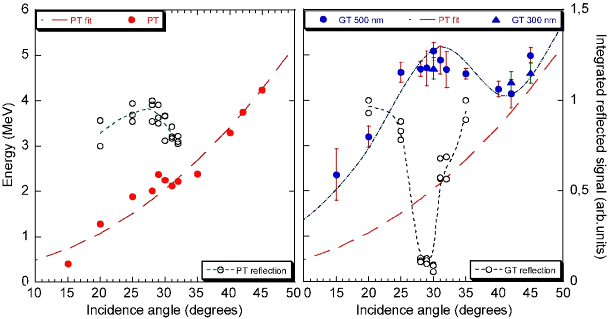
LaserLAB experiment at SLIC, CEA Saclay
laser UHI, 28 fs, 5×10^{19} Wcm^{-2}, $a_L = 4.8$
pulse contrast $\sim 10^{12}$

rear sheath acceleration →





$\sim$ 3X increase in proton energy with respect to “flat” targets near resonant angle
$\phi_{\text{res}} = 30°$ $(d = 2\lambda)$



Surface plasmon electron acceleration *in vacuum*

- Plasmon field on the vacuum side is purely electrostatic in frame L' moving with phase velocity $\beta_f = v_f/c$:

$$\Phi' = -\left(\frac{\gamma_f E_{\mathrm{SP}}}{k}\right) \mathrm{e}^{k'x} \sin k'y' \qquad k' = k/\gamma_f \qquad \gamma_f = (1-\beta_f^2)^{-1/2}$$

- "Lucky" electron injected with velocity v_f goes downhill the potential Φ' acquiring an energy $W' = eE_{\mathrm{SP}}\gamma_f/k$
- Energy gain and emission angle in the lab (L) frame in the strongy relativistic limit $W' \gg m_e c^2$

$$\mathcal{E}_f \simeq eE_{\mathrm{SP}}\gamma_f^2/k \simeq m_e c^2 a_{\mathrm{SP}}(n_e/n_c) \ , \quad \tan\phi_e = p_x/p_y \simeq 1/\gamma_f$$

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

Experimental observation of SP electron acceleration

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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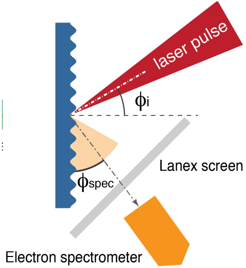
(Received 30 June 2015; published 7 January 2016)

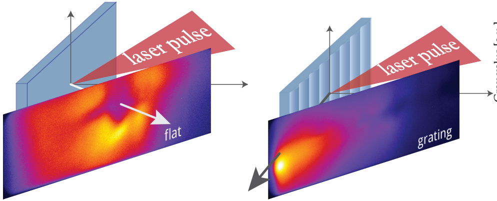
L. Fedeli et al, Phys. Rev. Lett. **116** (2016) 015001

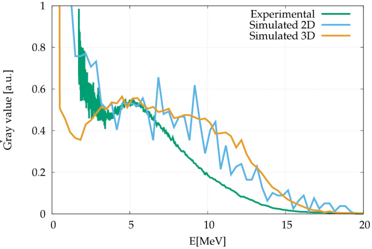
Features of SP electron acceleration



Sinusoidal gratings near resonant angle: collimated ($\delta\phi \simeq 20°$) electron emission along the surface ($\phi \simeq 2°$) with multi-MeV energy and total charge $\simeq 100$ pC

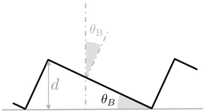
- No such features for flat targets
- Excellent agreement with 3D simulations

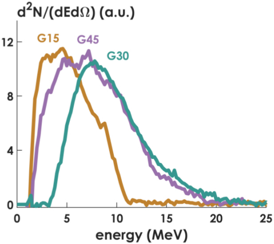


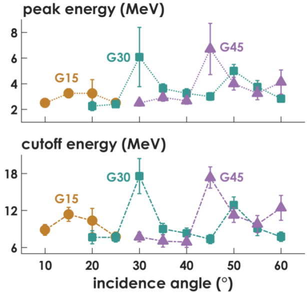


Optimizing SP electron acceleration

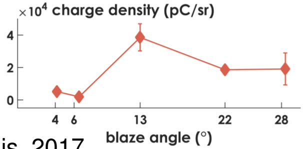
Dependence on grating period $\phi_{\rm res} = 15°, 30°, 45°$ and incidence angle

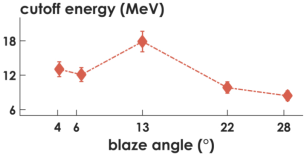






Blazed gratings increase energy and charge





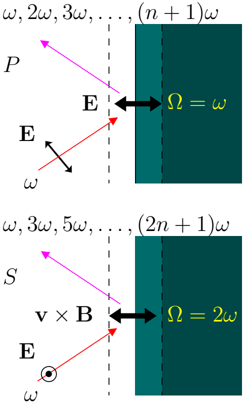
G. Cantono, PhD thesis, 2017

High harmonic emission

High harmonics (HH) of the laser frequency are observed in reflection from flat targets ("oscillating mirror" model accounts for selection rules)

From gratings HH are emitted at different angles ϕ_{mn} because of diffraction:
$n\lambda/md = \sin(\phi_i) + \sin(\phi_{mn})$
(m: harmonic order, n: diffraction order,
ϕ_i: incidence angle)
[Experiment: M.Cerchez et al,
Phys. Rev. Lett. **110** (2013) 065003]

Idea: have SP-enhanced HH with angular separation using "resonant" gratings



Numerical observation of SP-enhanced HH

APPLIED PHYSICS LETTERS **110**, 051103 (2017)

CrossMark

Relativistic surface plasmon enhanced harmonic generation from gratings

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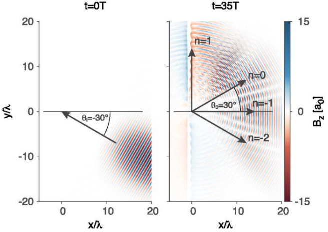
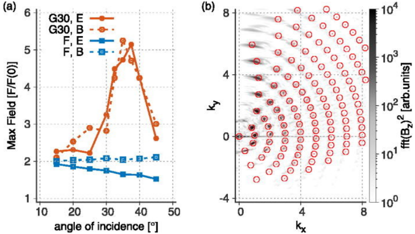
(Received 14 November 2016; accepted 20 January 2017; published online 1 February 2017)

L. Fedeli et al, Appl. Phys. Lett. **110** (2017) 051103

2D simulation results on SP-enhanced HH

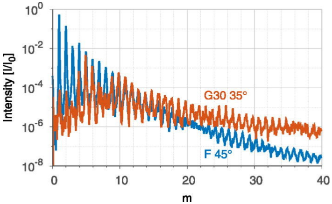




HH emitted at angles predicted by diffraction formula (circles O in **k**-space) with strongest emission in near-tangent direction

~x 2.5 field enhancement near ϕ_{res}

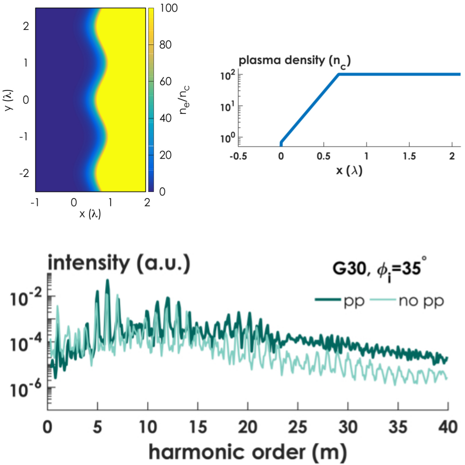
⟶ ~x 10^2 HH intensity with respect to flat target for high orders ($m > 20$)



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)

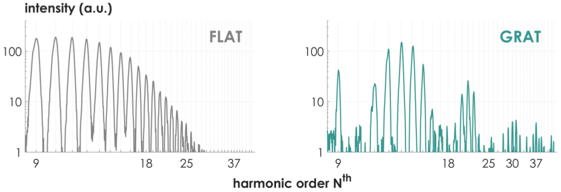
Issue: $L \sim \delta$ (grating depth) can coexist with modulation in real experimental conditions?

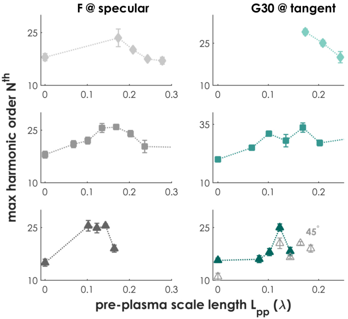


2D simulations
Giada Cantono, PhD thesis, 2017

Experimental results on SP-enhanced HH

HH spectra show up to $m \simeq 37$ at $87°$ for gratings vs $m \simeq 25$ at $45°$ (specular) for flat targets





Maximum HH yield for preplasma scalelength $L \simeq 0.1\lambda_L$

HH intensity is comparable for flat targets and gratings but with different angular distribution

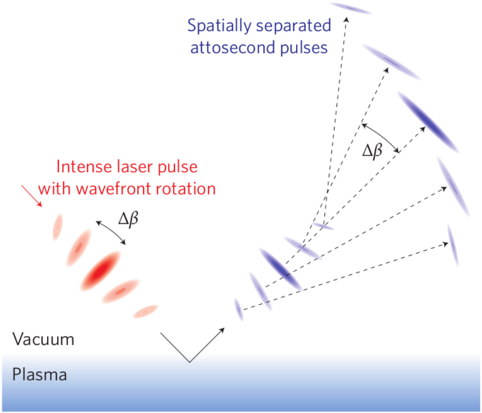
Giada Cantono, PhD thesis, 2017

Interaction with rotating wavefront pulses

Wavefront Rotation (WR) of the driving pulse is used to spatially separate intense HH pulses generated near different maxima of the field ("attosecond lighthouse")

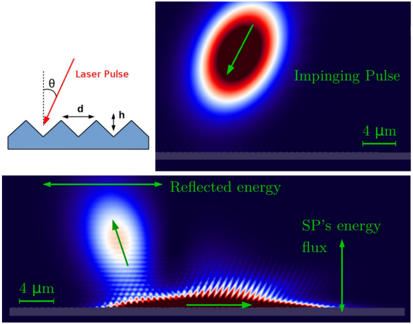
WR can be seen as a continuous temporal variation of the incidence angle

Inspiration: what happens with gratings?



J. A. Wheeler et al, Nature Phot. **6** (2012) 829

Ultrashort plasmon generation using WR



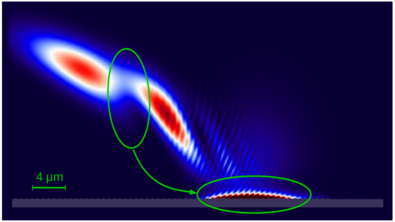
MEEP[1] simulations of short pulse incidence on Ag grating (only linear response, no nonlinear dynamics)

Francesco Pisani,

M.Sc. (*Laurea*) thesis, 2017

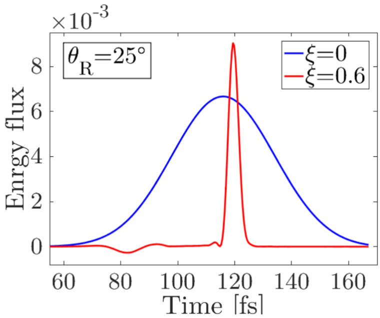
With WR the pulse is incident at θ_{res} for a short time only

$\longrightarrow$ excitation of few-cycle SP!



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

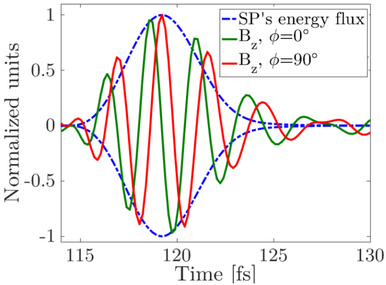
A “two-cycle” surface plasmon



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

ζ: WR parameter

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



Dependence on absolute phase ϕ is apparent

Francesco Pisani,

M.Sc. (*Laurea*) thesis, 2017

Summary and Outlook - 1

- Surface plasmon-enhanced emission has been demonstrated experimentally in the nonlinear "relativistic" regime for high-energy protons, electrons and photons (as XUV coherent high harmonics)
- Optimization of electron acceleration via blazed gratings and of high harmonics via prepulse-produced gradient

$\longrightarrow$ static and dynamic nanostructuring possible!

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

$\longrightarrow$ route to control in high field femtosecond plasmonics

Summary and Outlook - 2

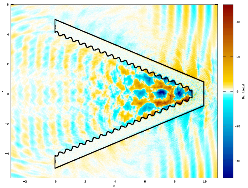
- Particle-in-cell simulations validated by comparison with experiments (with excellent agreement in 3D)

$\longrightarrow$ test of plasmonic schemes in the high-field regime

- Concept for generation of few-cycle surface plasmons tested by simulations in the linear regime

$\longrightarrow$ next steps: design experiments, investigate nonlinear regime (enhanced “attosecond lighthouse”?)

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)



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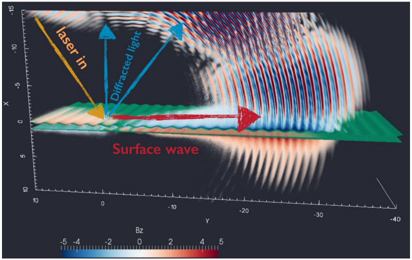
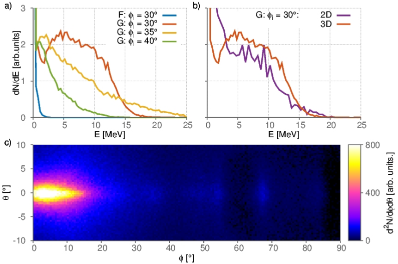
- Triangle de la physique (contract nbr. 2014-0601T ENTIER)
- Czech Science Foundation project No. 15-02964S
- PRACE & ISCRA & LISA awards for access to FERMI BlueGene/Q™ and MARCONI at CINECA (Italy)

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!

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

Preliminary results at higher intensity

Raw lanex image from PULSER laser at GIST, Korea

$I = 5 \times 10^{20}$ W/cm^2

pulse contrast $\sim 10^{10}$ at 50 ps

Beamed emission from grating targets still observed

$\rightarrow$ future exploration of ultra-relativistic regime (also with ELI?)