High Field, Short Pulse Plasmonics for Laser-Driven Sources

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PPLA 2019, Pisa, Ocotber 29, 2019

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Other coworkers will be introduced in papers' headers!

Two theses, three awards :-)

Giada Cantono
"*Relativistic plasmonics for ultra-short radiation sources*"
APS Outstanding Doctoral Thesis Research in Beam Physics Award 2019
& EPS-PPD PhD Research Award 2019

Luca Fedeli
"*High field plasmonics*"
EPS-PPD PhD Research Award 2017
& publication in Springer Theses collection

Outline

- Surface Plasmons driven by "extreme" pulses (high intensity, short duration)
- SP-enhanced short-pulse radiation sources
  - protons
  - electrons (direct SP "surfing" acceleration)
  - high (XUV) harmonics with angular selection
- A concept for single-cycle SP generation
- Unipolar picosecond hot electron-driven SP
  - beam steering of laser-accelerated protons

Surface Plasmons at very high fields?

Inspired by "ordinary" (linear) plasmonics ...

- Can we excite Surface Plasmon (polaritons) aka surface plasma waves using "extreme" laser pulses?
  (duration $\sim 10\ \mathrm{fs} - 1\ \mathrm{ps}$, intensity $> 10^{18}\ \mathrm{W\ cm^{-2}}$ at focus)
- Do such SPs exist at all in the regime of very strong fields,
  $\longrightarrow$ i.e. relativistic electron dynamics ($p_{\mathrm{osc}} \sim eE/\omega > m_e c$)?

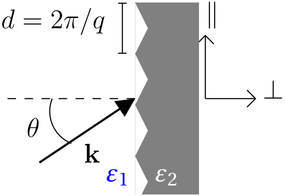
  not trivial issues: nonlinear response, kinetic damping, wavebreaking ...

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

Direct SP excitation by intense laser pulses

Assuming that SPs exist for very strong fields ...

- Ultrafast field ionization provides free electrons instantaneously $\longrightarrow$ any target material (e.g. plastic) becomes a simple metal

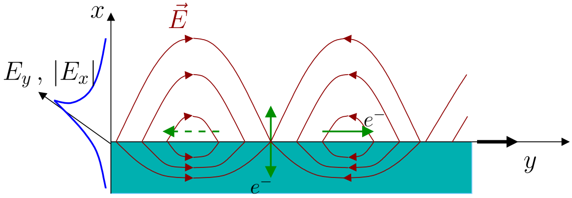


$$\varepsilon_1 = 1 \qquad \varepsilon_2 \simeq 1 - \frac{\omega_p^2}{\omega^2} \ll 1 \qquad \omega_p \gg \omega$$

- Grating coupling scheme ("prism-based" configurations not suitable)
- Femtosecond pulses with ultrahigh contrast to preserve sharp interface and surface structuring against early target damage and ionization by "prepulses"

Electron heating & acceleration by surface plasmons

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

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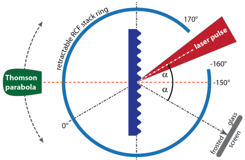
T. Ceccotti et al, Phys. Rev. Lett. **111** (2013) 185001

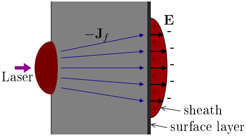
Grating-enhanced proton emission

LaserLAB experiment at SLIC, CEA Saclay

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

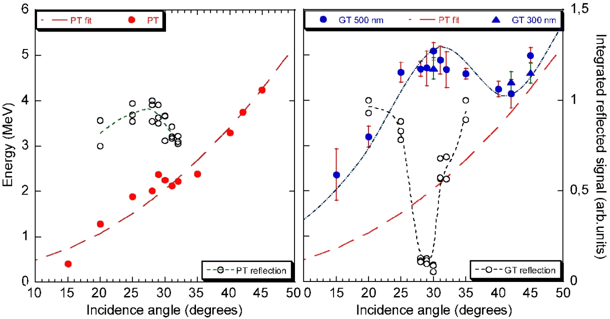


proton acceleration in the electron sheath at the target rear



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

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



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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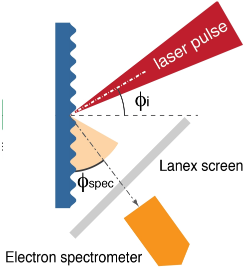
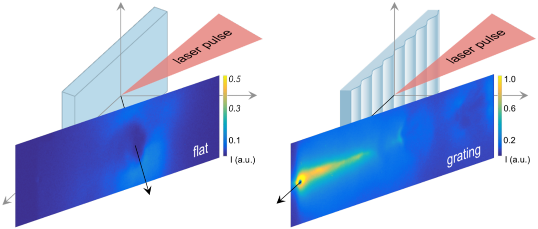
(Received 30 June 2015; published 7 January 2016)

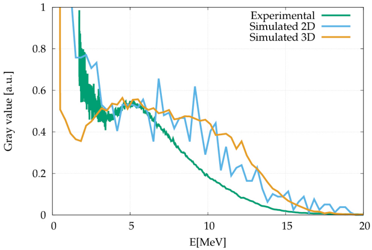
L. Fedeli et al, Phys. Rev. Lett. **116** (2016) 015001

Features of SP electron acceleration



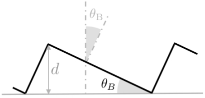
Sinusoidal gratings at SP resonance:
collimated ($\simeq 20°$ cone) electron emission near the surface tangent ($\phi \simeq 2°$)
multi-MeV energy, total charge $\simeq 100$ pC
- No such features for flat targets
- Excellent agreement with 3D simulations

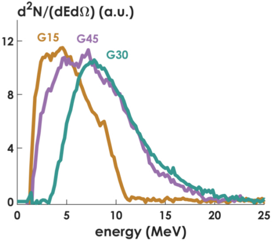


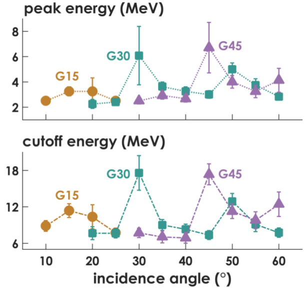


Optimizing SP-enhanced electron emission

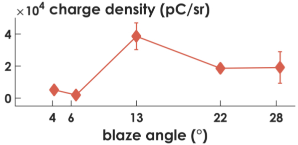
Dependence on
- grating period
$(\phi_{\text{res}} = 15°, 30°, 45°)$
- incidence angle

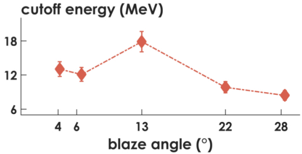






Use of available blazed gratings increase energy and charge up to 650 pC per bunch





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

High harmonic emission

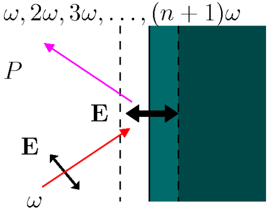
High laser harmonics (HH)
up to the XUV range are emitted
in specular reflection from flat targets

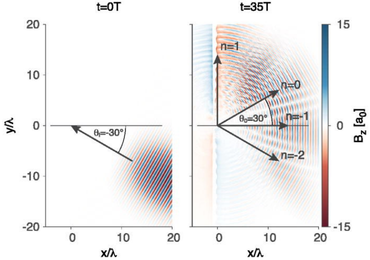
From gratings HH are separated at angles ϕ_{mn} according to:

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

(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

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]
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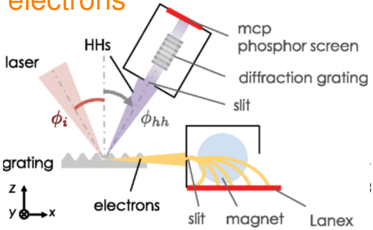
G. Cantono et al, Phys. Rev. Lett. **120** (2018) 264803

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

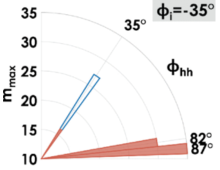
Kahaly et al, PRL **110** (2013) 175001

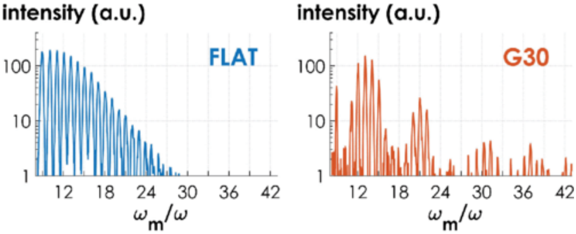
Notice: $L \sim$ grating depth!

Max HH order:

Flat: $m \simeq 25$ at $45°$

Grat: $m \simeq 37$ at $87°$





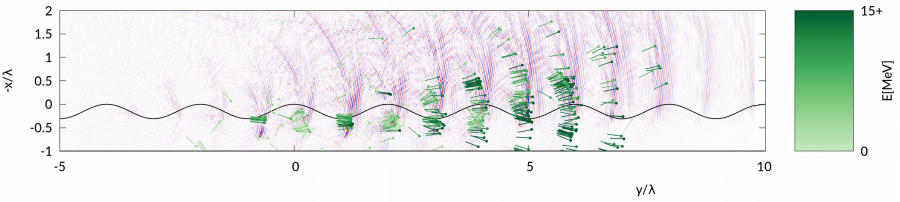
HH boosting by electron nanobunching

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

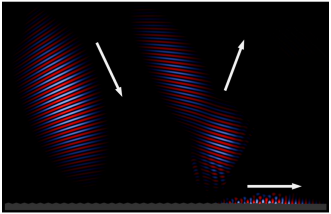
similar to collective instability operation in a Free Electron Laser

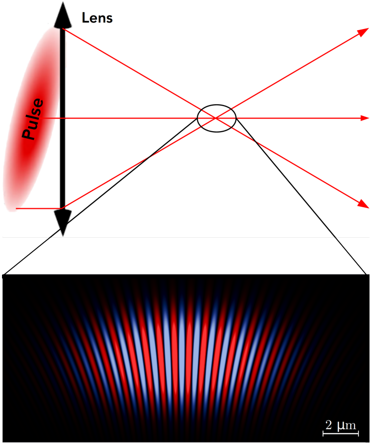
2D simulations by L. Fedeli



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

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

[†]Enrico Fermi Department of Physics, University of Pisa, 56127 Pisa, Italy
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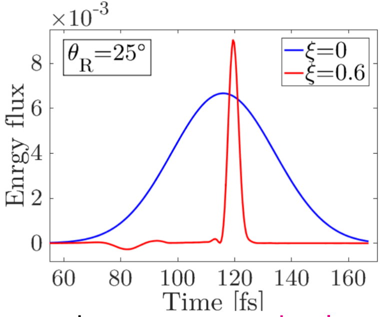
F. Pisani, L. Fedeli, A. Macchi, ACS Photonics **5** (2018) 1068

A near "single-cycle" SP

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

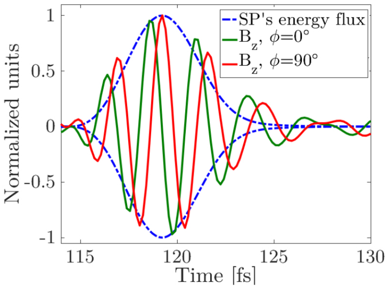


Dependence on absolute phase ϕ is apparent

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

ζ : WFR parameter

A 3.8 fs (~ 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

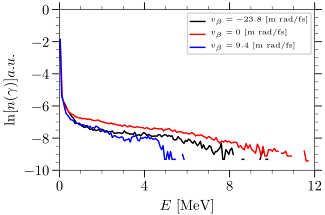
WFR at high fields: PIC simulations (work in progress)

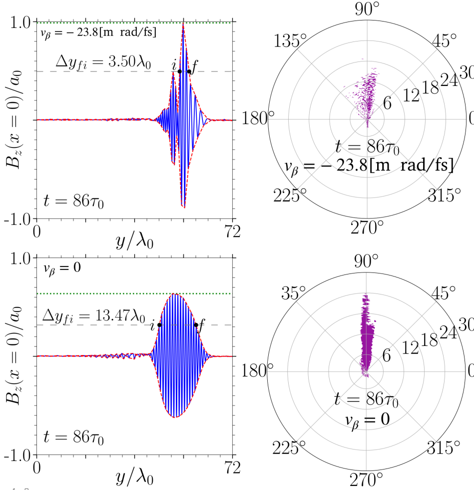
Smilei) Particle-In-Cell code

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

- SP shortening observed
- impact on electrons

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





First observation of unipolar picosecond SP

PRL **102,** 194801 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Laser-Driven Ultrafast Field Propagation on Solid Surfaces

K. Quinn,[1,*] P. A. Wilson,[1] C. A. Cecchetti,[1,†] B. Ramakrishna,[1] L. Romagnani,[1] G. Sarri,[1] L. Lancia,[2] J. Fuchs,[2] A. Pipahl,[3] T. Toncian,[3] O. Willi,[3] R. J. Clarke,[4] D. Neely,[4] M. Notley,[4] P. Gallegos,[4,5] D. C. Carroll,[5] M. N. Quinn,[5] X. H. Yuan,[5] P. McKenna,[5] T. V. Liseykina,[6,‡] A. Macchi,[7] and M. Borghesi[1]

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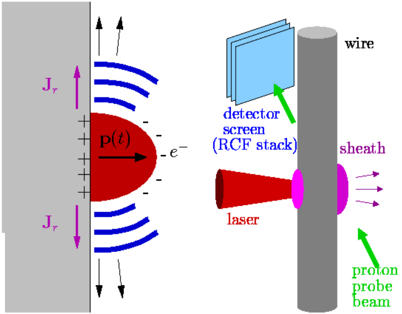
(Received 28 January 2009; published 14 May 2009)

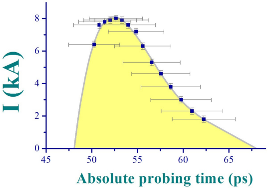
K. Quinn et al, Phys. Rev. Lett. **103** (2009) 194801

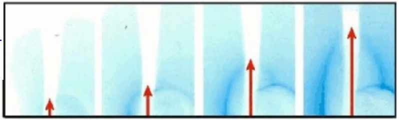
Unipolar SP driven by hot electron sheath

Escaping “hot” electrons in laser-solid interaction act as a pulsed giant dipole antenna for unipolar SPs which drive the charge neutralization of the target



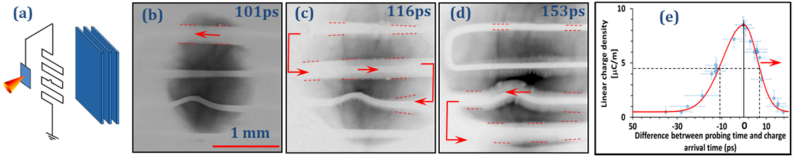
SP probed by a picosecond proton pulse





K. Quinn et al PRL **103** (2009) 194801

Efficient propagation along a folded wire



The unipolar pulse propagates as a Sommerfeld-Zenneck wave with low losses and dispersion along ~cm distances carrying ~kA current and $\sim 10^8$ V m^{-1} electric field

Experiment on ARCTURUS laser (30 fs, $\gtrsim 10^{20}$ W cm^{-2}), Düsseldorf

S. Kar et al, Nature Comm. **7** (2016) 10792

Demonstrated also on TARANIS (600 fs, $\gtrsim 10^{19}$ W cm^{-2}), Belfast

H. Ahmed et al, Scient. Rep. **7** (2017) 10891

and recently on VULCAN (H. Ahmed et al, in preparation)

Application: steering of laser-accelerated protons

nature COMMUNICATIONS

ARTICLE

Received 22 Jun 2015 | Accepted 20 Jan 2016 | Published 18 Apr 2016

DOI: 10.1038/ncomms10792 OPEN

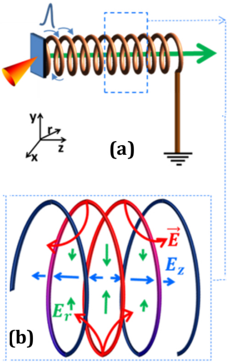
Guided post-acceleration of laser-driven ions by a miniature modular structure

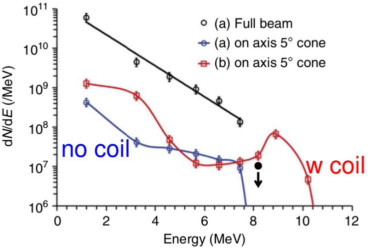
Satyabrata Kar[1], Hamad Ahmed[1], Rajendra Prasad[2], Mirela Cerchez[2], Stephanie Brauckmann[2], Bastian Aurand[2], Giada Cantono[3], Prokopis Hadjisolomou[1], Ciaran L.S. Lewis[1], Andrea Macchi[3,4], Gagik Nersisyan[1], Alexander P.L. Robinson[5], Anna M. Schroer[2], Marco Swantusch[2], Matt Zepf[1,6,7], Oswald Willi[2] & Marco Borghesi[1]

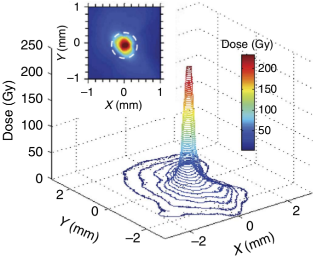
S. Kar et al, Nature Comm. **7** (2016) 10792

Collimation and post-acceleration of protons

SP traveling along coil structure:
synchronization with protons
longitudinal **E**-field for energy enhancement
radial **E**-field for collimation







Satyabrata Kar,
“Beam focusing and accelerating system”,
patent 20160379793 (2016)

Summary

- Successful exploitation of “relativistic” propagating surface plasmons for improvements of short pulse sources (protons, electrons, XUV harmonics)
- Spatio-temporal optimization at sub-micrometer and femtosecond scales demonstrated
- New concept for SPP shortening at the sub-cycle limit
- Laser-driven transient charge separation as antenna for unipolar SP exploited for steering of laser-accelerated protons

Outlook - I

- Improve control in high field femtosecond plasmonics

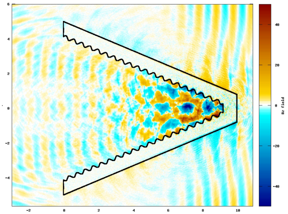
⟶ exploit wavefront rotation at high fields
[PIC simulation in progress]

⟶ 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)



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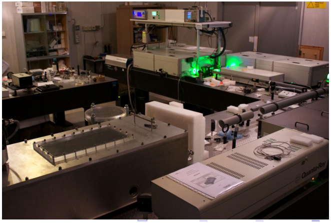
⟶ Test of plasmonic schemes in the high-field regime

Experimental activity at CNR/INO/ILIL in Pisa with 100 TW laser? (pulse contrast enhancement under development)



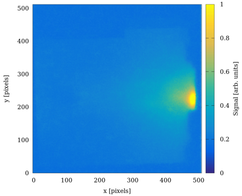
Outlook -II

- 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



- Exploit picosecond SP for THz pulse generation? (near single-cycle, high fields)

Two review papers

- A. Macchi, G. Cantono, L. Fedeli, F. Pisani, T. Ceccotti, *Extreme high field plasmonics: electron acceleration and XUV harmonic generation from ultrashort surface plasmons*, Phys. Plasmas **26** (2019) 042114 [Special issue with invited talks from APS/DPP meeting 2018]
- A. Macchi, *Surface plasmons in superintense laser-solid interactions*, Phys. Plasmas **25** (2018) 031906 [Invited paper for Special Topic collection "Plasmonics and solid state physics"]

Funding acknowledgments

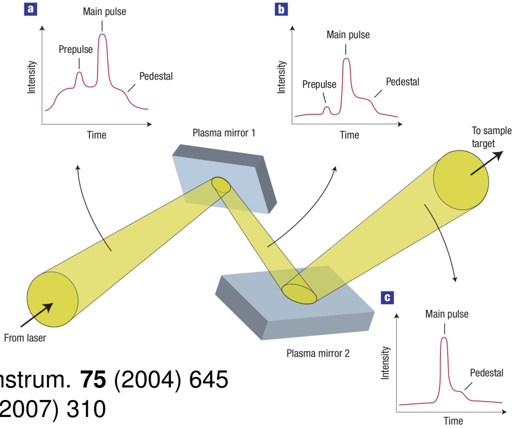
- LASERLAB-EUROPE, grant No. 284464, EU's 7th Framework Programme, proposals SLIC001693-SLIC002004.
- "Investissement d'Avenir" LabEx PALM (Grant ANR-10-LABX-0039)
- Triangle de la physique (contract nbr. 2014-0601T ENTIER)
- Czech Science Foundation project No. 15-02964S
- PRACE & ISCRA & LISA awards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

EXTRA SLIDES

“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

Simple model of SP "surfing" acceleration

SP field on the vacuum side is electrostatic in the frame L' moving with phase velocity $\beta_p = v_p/c$ with respect to L (lab)

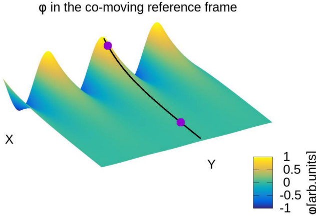
$\Phi' = -(\gamma_p E_{SP}/k)\mathrm{e}^{k'x}\sin k'y' \qquad k' = k/\gamma_p \qquad \gamma_p = (1-\beta_p^2)^{-1/2}$

A "lucky" electron injected with velocity v_p goes downhill the potential $-e\Phi'$ acquiring an energy $W' = eE_{SP}/k'$

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

$$W \simeq \gamma_p W' \simeq m_e c^2 a_{SP} \frac{n_e}{n_c} \qquad \tan\phi_e = \frac{p_x}{p_y} \simeq \frac{1}{\gamma_p}$$

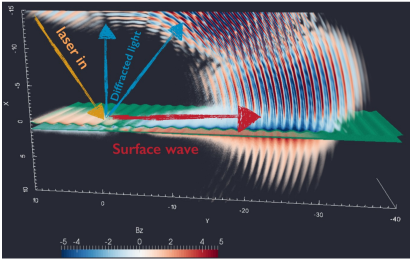
→ highly relativistic electrons are beamed near the target surface ($\tan\phi_e \ll 1$)

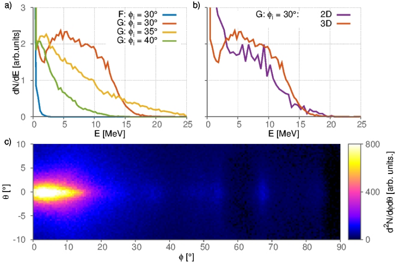


Numerical study of injection conditions and energy scaling: Riconda et al, PoP **22** (2015) 073103

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





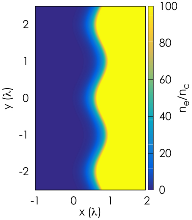
Simulations confirm excitation of relativistic SP and reproduce measurements quantitatively and in detail!

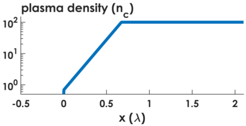
[2] available at http://aladyn.github.io/piccante

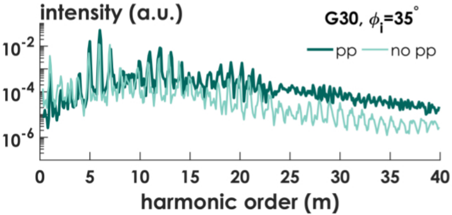
Preplasma optimization of HH

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?



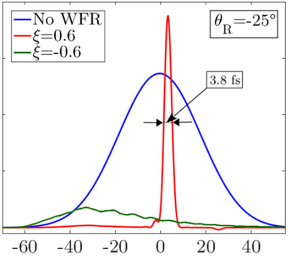


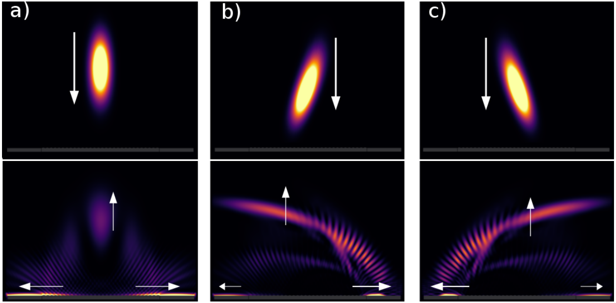


2D simulations
Giada Cantono, PhD thesis, 2017

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