Extreme strong field plasmonics: MeV electron and XUV harmonic pulses from grating targets

Andrea Macchi

CNR, Istituto Nazionale di Ottica, sez. Adriano Gozzini, Pisa, Italy

Dipartimento di Fisica Enrico Fermi, Università di Pisa, Italy

PLASMONICA 2018, Firenze, July 6, 2018

Outline

"*And Now for Something Completely (?) Different*"

- Surface Plasmon Polaritons driven by "extreme" pulses (high intensity, short duration)
- SPP-enhanced short-pulse radiation sources
  - protons
  - electrons (direct SPP "surfing" acceleration)
  - high (XUV) harmonics with angular selection
- A concept for single-cycle SPP generation (POSTER 39)
- EXTRA TOPIC (out of abstract): unipolar picosecond SPP (and THz generation?)

Plasmon coupling with "extreme" light?

- 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)
- Do such SPs exist at all in the regime of very strong fields,
  $\longrightarrow$ i.e. relativistic electron dynamics ($p_{\rm osc} \sim eE/\omega > m_e c$)?

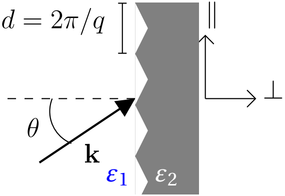
  not trivial issues: nonlinear response, kinetic damping, wavebreaking …

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

Laser and target requirements

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

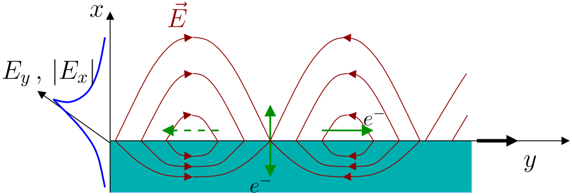


$$\varepsilon_1 = 1 \qquad \varepsilon_2 \simeq 1 - \frac{\omega_p^2}{\omega^2} \ll 1 \qquad \omega_p \gg \omega$$

- 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,†]

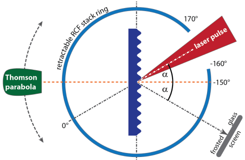
[1]*CEA/IRAMIS/SPAM, F-91191 Gif-sur-Yvette, France*
[2]*Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche, research unit "Adriano Gozzini," 56124 Pisa, Italy*
[3]*Dipartimento di Energia, Politecnico di Milano, 20133 Milano, Italy*
[4]*LULI, Université Pierre et Marie Curie, Ecole Polytechnique, CNRS, CEA, 75252 Paris, France*
[5]*FNSPE, Czech Technical University in Prague, CR-11519 Prague, Czech Republic*
[6]*Institute of Physics of the ASCR, ELI-Beamlines project, Na Slovance 2, 18221 Prague, Czech Republic*
[7]*CEA/DSM/LSI, CNRS, Ecole Polytechnique, 91128 Palaiseau Cedex, France*
[8]*CPHT, CNRS, Ecole Polytechnique, 91128 Palaiseau Cedex, France*
[9]*LULI, UMR7605, CNRS-CEA-Ecole Polytechnique-Paris 6, 91128 Palaiseau, France*
[10]*Dipartimento SBAI, Università di Roma "La Sapienza," Via A. Scarpa 14, 00161 Roma, Italy*
[11]*Dipartimento di Fisica "Enrico Fermi," Università di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy*

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

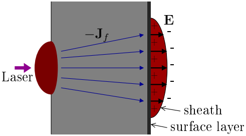
Grating-enhanced proton emission

LaserLAB experiment at SLIC, CEA Saclay

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

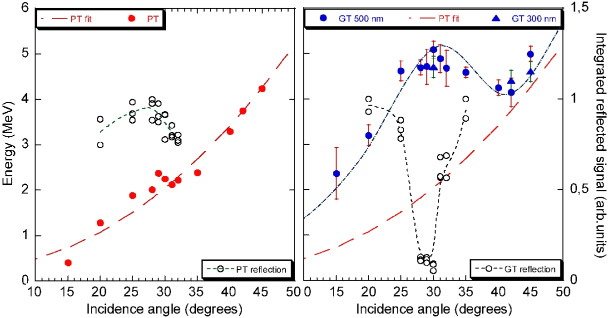


proton acceleration in the electron sheath at the target rear



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

$\phi_{\text{res}} = 30°$ $(d = 2\lambda)$



Observation of “surfing” acceleration on a SP

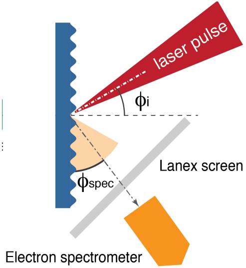
PRL **116,** 015001 (2016) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2016

Electron Acceleration by Relativistic Surface Plasmons in Laser-Grating Interaction

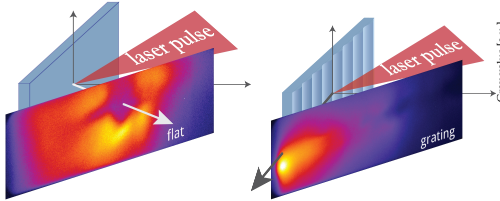
L. Fedeli,[1,2,*] A. Sgattoni,[2] G. Cantono,[3,4,1,2] D. Garzella,[3] F. Réau,[3] I. Prencipe,[5,†] M. Passoni,[5]
M. Raynaud,[6] M. Květoň,[7] J. Proska,[7] A. Macchi,[2,1] and T. Ceccotti[3]
[1]*Enrico Fermi Department of Physics, University of Pisa, 56127 Pisa, Italy*
[2]*National Institute of Optics, National Research Council (CNR/INO), u.o.s Adriano Gozzini, 56124 Pisa, Italy*
[3]*LIDYL, CEA, CNRS, Université Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette, France*
[4]*University of Paris Sud, Orsay 91405, France*
[5]*Department of Energy, Politecnico di Milano, Milan 20156, Italy*
[6]*Laboratoire des Solides irradiés, Ecole Polytechnique, CNRS, CEA/DSM/IRAMIS, Université Paris-Saclay, 91128 Palaiseau Cedex, France*
[7]*FNSPE, Czech Technical University, Prague 11519, Czech Republic*
(Received 30 June 2015; published 7 January 2016)

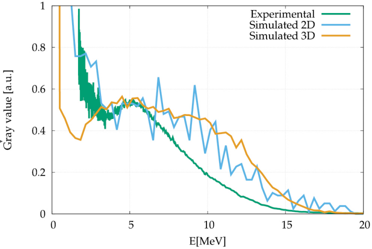
L. Fedeli et al, Phys. Rev. Lett. **116** (2016) 015001

Features of SP electron acceleration



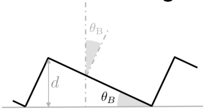
Sinusoidal gratings at SP resonance:
collimated ($\delta\phi \simeq 20°$) electron emission along the surface ($\phi \simeq 2°$)
multi-MeV energy, total charge $\simeq 100$ pC
- No such features for flat targets
- Excellent agreement with 3D simulations

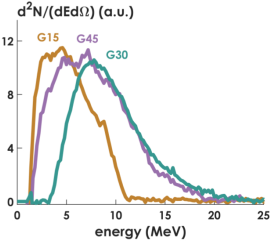


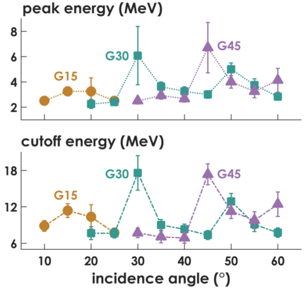


Optimizing SP electron acceleration

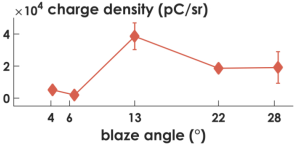
Dependence on
- grating period
($\phi_{\rm res} = 15°, 30°, 45°$)
- incidence angle

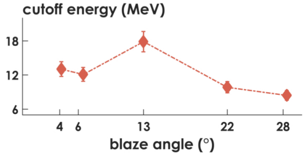






Blazed gratings increase energy and charge

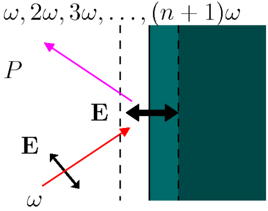




G. Cantono et al, Phys. Plasmas **25** (2018) 031907

High harmonic emission

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

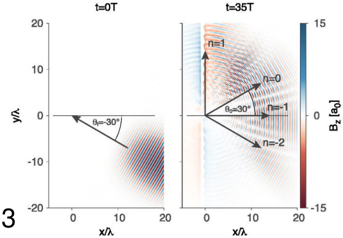


From gratings HH are separated at angles ϕ_{mn} according to:

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

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

Sim: Fedeli et al, APL **110** (2017) 051103



Idea: SP-enhanced HH with angular separation

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]
[1]*LIDYL, CEA, CNRS, Université Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette, France*
[2]*Université Paris Sud, Paris, 91400 Orsay, France*
[3]*National Institute of Optics, National Research Council (CNR/INO) A. Gozzini unit, 56124 Pisa, Italy*
[4]*Enrico Fermi Department of Physics, University of Pisa, 56127 Pisa, Italy*
[5]*Department of Energy, Politecnico di Milano, 20133 Milano, Italy*
[6]*LULI-UPMC: Sorbonne Universités, CNRS, École Polytechnique, CEA, 75005 Paris, France*
[7]*LESIA, Observatoire de Paris, CNRS, UPMC: Sorbonne Universites, 92195 Meudon, France*

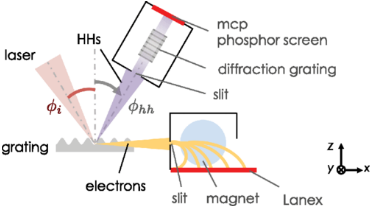
G. Cantono et al, Phys. Rev. Lett. **120** (2018) 264803

SP-enhancement and optimization of HH

Simultaneous measurements of HH and electrons

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

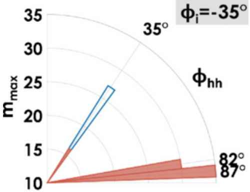
Notice: $L \sim$ grating depth!

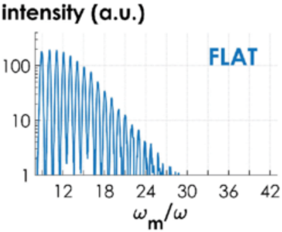


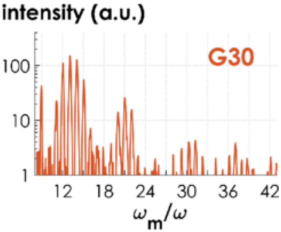
Max HH order:

Flat: $m \simeq 25$ at $45°$

Grat: $m \simeq 37$ at $87°$







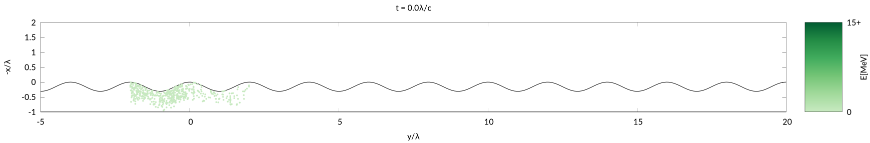
HH boosting by electron nanobunching

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

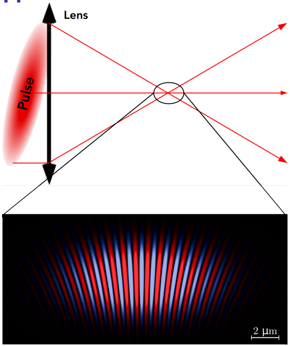
similar to collective instability operation in a Free Electron Laser

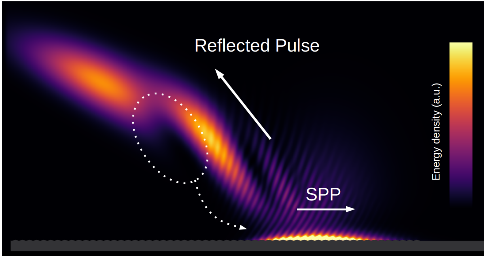
2D simulations by L. Fedeli



SP shortening by wavefront rotation

Pulse with Wavefront Rotation (WR):
incidence angle is "resonant" for a short time interval only
⟶ excitation of few-cycle SP



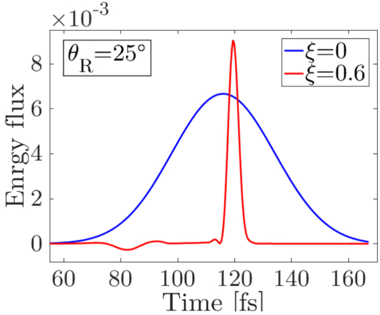


MEEP [1] simulations of WR pulse on Ag grating (only linear response, no nonlinear dynamics)

see Francesco Pisani's **POSTER 39**!

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

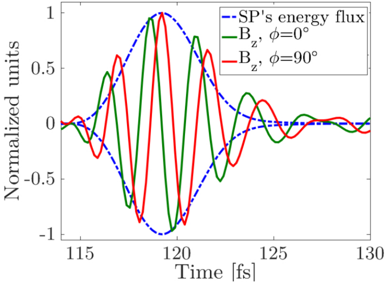
A near “single-cycle” SP



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

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

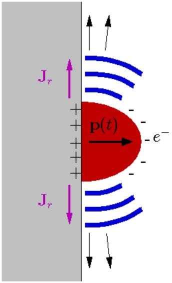


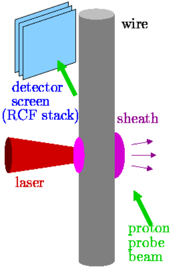
Dependence on absolute phase ϕ is apparent

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

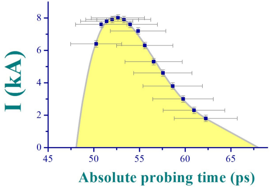
EXTRA TOPIC: unipolar laser-driven SPP

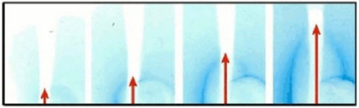
The escape in vacuum of “hot” electrons acts as a pulsed giant dipole antenna for unipolar Sommerfeld-Zenneck Surface Plasmon Polaritons which drive the charge neutralization of the target





SPP observed via probing by a picosecond proton pulse





A. Macchi, Phys. Plasmas **25** (2018) 031906
review paper for special issue “Plasmonics & Solid State Physics”

First observation of unipolar pulse

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]

[1]*Department of Physics and Astronomy, Queen's University Belfast, Belfast BT7 1NN, United Kingdom*
[2]*Laboratoire pour l'Utilisation des Lasers Intenses, École Polytechnique, 91128 Palaiseau, France*
[3]*Institut für Laser–und Plasmaphysik, Heinrich-Heine-Universität, D-40225 Düsseldorf, Germany*
[4]*Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Oxfordshire OX11 0QX, United Kingdom*
[5]*SUPA, Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom*
[6]*Max Planck Institute for Nuclear Physics, Heidelberg, Germany*
[7]*CNR/INFM/polyLAB, Dipartimento di Fisica "E. Fermi," Pisa, Italy*

(Received 28 January 2009; published 14 May 2009)

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

Application: steering of laser-accelerated protons . . .

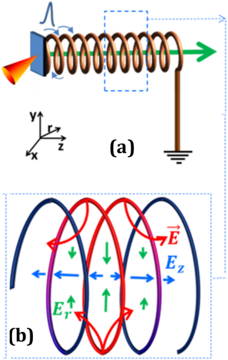
nature COMMUNICATIONS

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]



SPP along a coil structure as a wave electric field collimator for protons

S. Kar et al, Nature Comm. **7** (2016) 10792
S. Kar, “Beam focusing and accelerating system”, patent 20160379793 (2016)

. . . and possible applications in THz Physics

- Picosecond duration of transient antenna fields
  → intense THz pulse generation
  (near single-cycle, high intensity)

  A. Gopal et al, Phys. Rev. Lett. **111** (2013) 074802
  S. Tokita et al, Sci. Reports **5** (2015) 8268
  A. Poye et al, Phys. Rev. E **91** (2015) 043106
  S. Mondal et al, Opt. Express **25** (2017) 17511

Conclusion and outlook

- Existence of Surface Plasmon Polaritons in the “extreme” strong field regime (relativistic electrons) confirmed
- SPP exploited successfully for improvements of short pulse sources (protons, electrons, XUV harmonics)
- Spatio-temporal optimization at sub-micrometer and femtosecond scales demonstrated

$\longrightarrow$ “all-optical” laser-produced gratings?

- New concept for SPP shortening at the sub-cycle limit

$\longrightarrow$ even shorter radiation pulses? Other plasmonics applications?

- Laser-driven transient charge separation as antenna for unipolar SPP and intense THz pulses

Main Contributing Authors

Giada Cantono[3,4,2,1,⋆], Andrea Sgattoni[1,5], Luca Fedeli[6,2,1], Francesco Pisani[2], Tiberio Ceccotti[4], Caterina Riconda[5]

[1] *CNR/INO, Pisa, Italy*
[2] *Dipartimento di Fisica Enrico Fermi, Università di Pisa, Italy*
[3] *CNRS-CEA/LIDYL, Universitè Paris-Saclay, Gif-sur-Yvette, France, and Universitè Paris Sud, Orsay, France*
[4] *CNRS-CEA/LIDYL, centre du Saclay, Gif-sur-Yvette, France*
[5] *Universitè P. et M. Curie, Sorbonne Universities, CNRS, École Polytechnique/LULI, CEA, Paris, France*
[6] *Dipartimento di Energia, Politecnico di Milano, Italy*

[⋆] *Now at Department of Physics, University of Lund, Sweden*

Other coworkers introduced in papers' headers!

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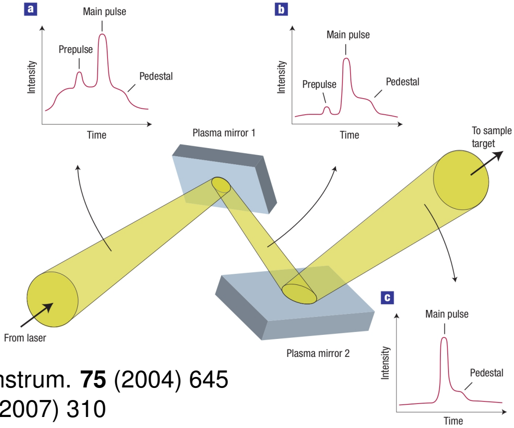
- LASERLAB-EUROPE, grant No. 284464, EU's 7th Framework Programme, proposals SLIC001693-SLIC002004.
- "Investissement d'Avenir" LabEx PALM (Grant ANR-10-LABX-0039)
- Triangle de la physique (contract nbr. 2014-0601T ENTIER)
- Czech Science Foundation project No. 15-02964S
- PRACE & ISCRA & LISA awards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

EXTRA SLIDES

"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

Surface plasmon electron acceleration *in vacuum*

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

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

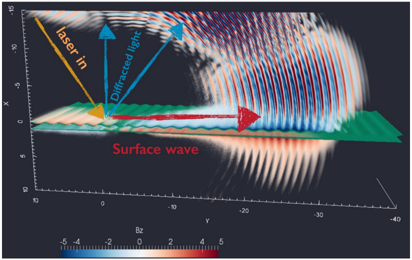
- "Lucky" electron injected with velocity v_f goes downhill the potential Φ' acquiring an energy $W' = eE_{\mathrm{SP}}\gamma_f/k$
- Energy gain and emission angle in the lab (L) frame in the strongy relativistic limit $W' \gg m_e c^2$

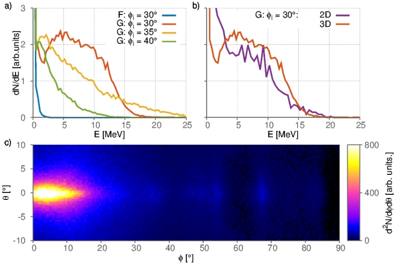
$$\mathscr{E}_f \simeq eE_{\mathrm{SP}}\gamma_f^2/k \simeq m_e c^2 a_{\mathrm{SP}}(n_e/n_c) \,, \quad \tan\phi_e = p_x/p_y \simeq 1/\gamma_f$$

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

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





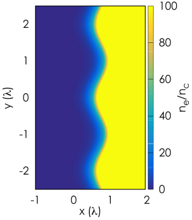
Simulations confirm excitation of relativistic SP and reproduce measurements quantitatively and in detail!

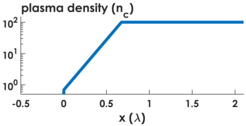
[2] available at http://aladyn.github.io/piccante

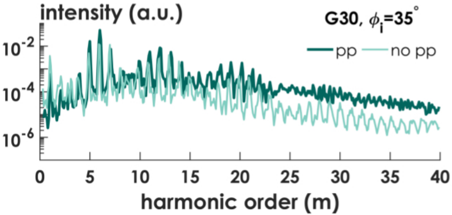
Preplasma optimization of HH

A further $\sim$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?







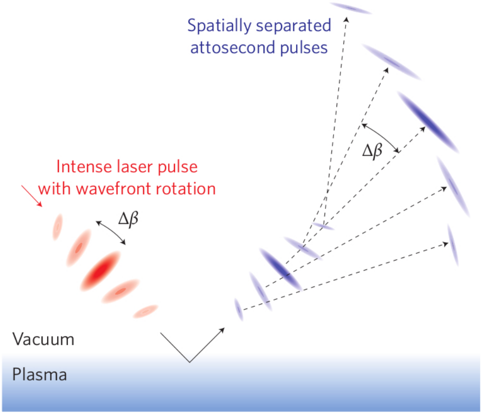
2D simulations
Giada Cantono, PhD thesis, 2017

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