# Extreme high field plasmonics: electron acceleration and XUV harmonic generation from ultrashort surface plasmons

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Other contributors will be introduced in papers' headers!

# Plasmonics VS Plasmas

PHYSICS OF PLASMAS **25**, 031701 (2018)

## Preface to Special Topic: Plasmonics and solid state plasmas

Giovanni Manfredi[a)]
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Plasmonics, the study of the interaction of electromagnetic radiation with electrons in solids, is an exciting new field that has developed fast since the 1980s and is still growing steadily. Yet, plasma physicists have devoted little attention to it. This special collection would like to bridge the gap between plasmas and plasmonics and encourage plasma physicists to have their say in this burgeoning research field. *Published by AIP Publishing.* https://doi.org/10.1063/1.5026653

Our contribution: extending Plasmonics towards very high fields

# Three questions

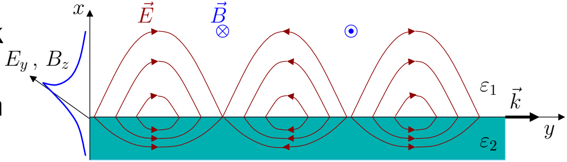
- Can we excite Surface Plasmon (polaritons) aka surface plasma waves using “extreme” laser pulses?
  (duration $\sim 10 \text{ fs} = 10^{-14} \text{ fs}$, intensity $> 10^{18} \text{ W cm}^{-2}$ at focus)
- How do SPs exist behave for very strong fields,
  i.e. with relativistic electron dynamics ($p_{\rm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

  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)

# 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):

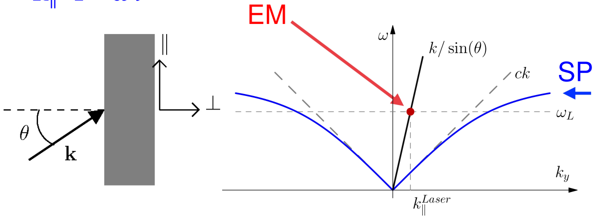
$$\varepsilon_1 = 1 \qquad \varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c(\omega)} < -1$$

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

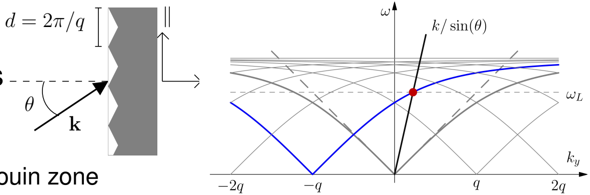
# Linear coupling of SP with laser light

SP coupling with EM wave ($\omega_L = ck$) requires phase matching:
$\varphi_{\text{EM}} = \varphi_{\text{SP}}$ 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 $\omega_{\text{SP}}(k_{\parallel})$ enables matching

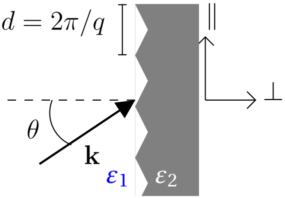



(*) folding in the Brillouin zone – Floquet-Bloch theorem

# Laser and target requirements for high fields

Assuming that SPs exist for very strong fields ...

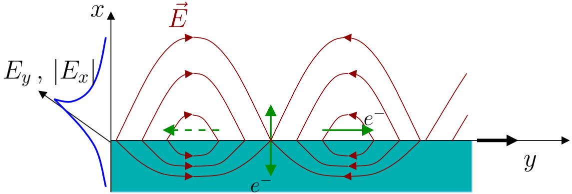
- Ultrafast field ionization provides free electrons instantaneously $\longrightarrow$ any target material (e.g. plastic) becomes a plasma
  Usually $\omega_p \gg \omega$




- Grating coupling with "resonant" angle
  $\sin\theta \simeq n\frac{\lambda}{d} - 1$ (usually $n = 1$)
  ("prism-based" configurations not suitable because of ionization)
- Femtosecond pulses with ultrahigh contrast preserve sharp interface and surface structuring against hydrodynamic expansion and early target damage and ionization by "prepulses"

# Electron heating and acceleration by SP fields

SPs enhance EM field near the surface ⟶ 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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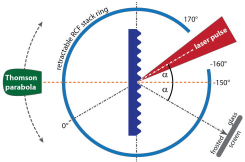
T. Ceccotti et al, Phys. Rev. Lett. **111** (2013) 185001

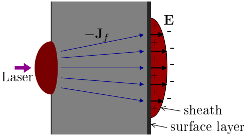
# Grating-enhanced proton emission

LaserLAB experiment at SLIC, CEA Saclay

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

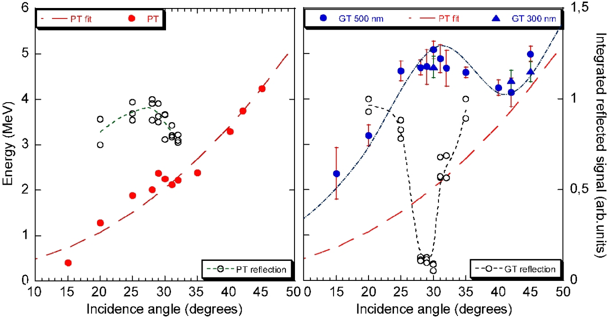



proton acceleration
in the electron sheath
at the target rear




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

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



# Simple model of SP "surfing" acceleration

- Plasmon field on the vacuum side is purely electrostatic in frame $L'$ moving with phase velocity $\beta_f = v_f/c$:
  $$\Phi' = -\left(\frac{\gamma_f E_{\text{SP}}}{k}\right) \mathrm{e}^{k'x} \sin k'y' \qquad k' = k/\gamma_f \qquad \gamma_f = (1-\beta_f^2)^{-1/2}$$
- A "lucky" electron injected with velocity $v_f$ goes downhill the potential $-e\Phi'$ acquiring an energy $W' = eE_{\text{SP}}\gamma_f/k$
- Energy gain and emission angle in the lab ($L$) frame in the strongy relativistic limit $W' \gg m_e c^2$
  $$\mathscr{E}_f \simeq eE_{\text{SP}}\gamma_f^2/k \simeq m_e c^2 a_{\text{SP}}(n_e/n_c)\,, \quad \tan\phi_e = p_x/p_y \simeq 1/\gamma_f$$

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

# 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]

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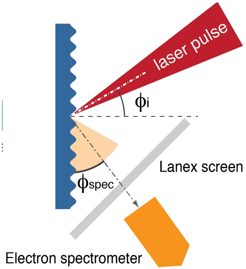
[7]*FNSPE, Czech Technical University, Prague 11519, Czech Republic*

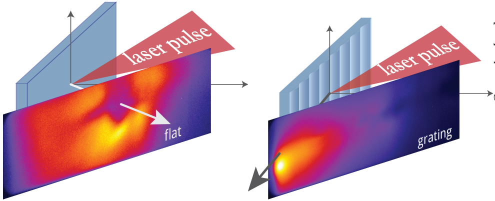
(Received 30 June 2015; published 7 January 2016)

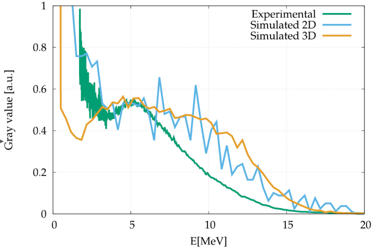
L. Fedeli et al, Phys. Rev. Lett. **116** (2016) 015001

# Features of SP electron acceleration



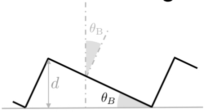

Sinusoidal gratings at SP resonance:
collimated ($\delta\phi \simeq 20°$) electron emission along the surface ($\phi \simeq 2°$)
multi-MeV energy, total charge $\simeq 100$ pC
- No such features for flat targets
- Excellent agreement with 3D simulations

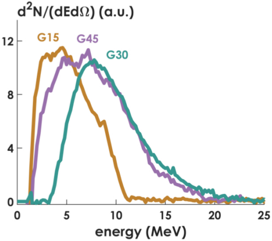


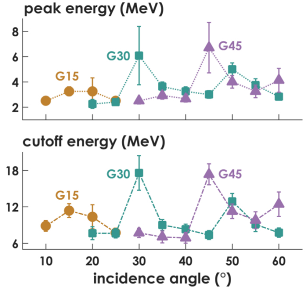



# Optimizing SP electron acceleration

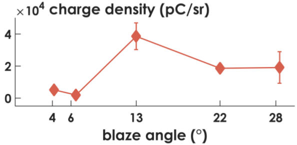
Dependence on
- grating period
($\phi_{\text{res}} = 15°, 30°, 45°$)
- incidence angle

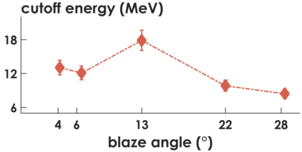



Blazed gratings increase energy and charge up to 650 pC per bunch

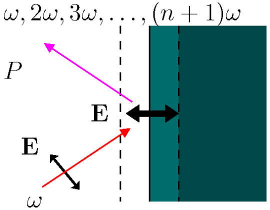



G. Cantono et al, Phys. Plasmas **25** (2018) 031907

# High harmonic emission

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

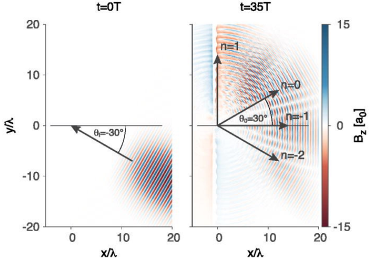



From gratings HH are separated at angles $\phi_{mn}$ according to:

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

($m$: harmonic order, $n$: diffraction order, $\phi_i$: 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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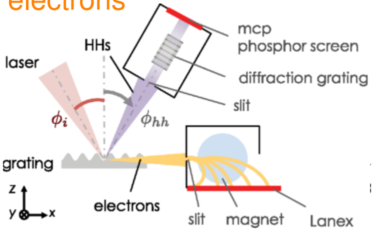
G. Cantono et al, Phys. Rev. Lett. **120** (2018) 264803

# 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

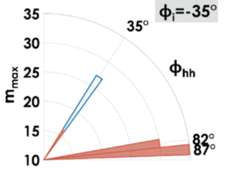
Kahaly et al, PRL **110** (2013) 175001

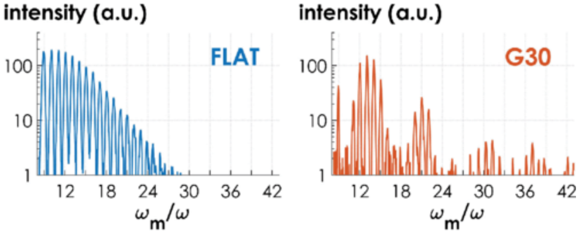
**Notice**: $L \sim$ grating depth!

Max HH order:

Flat: $m \simeq 25$ at $45°$

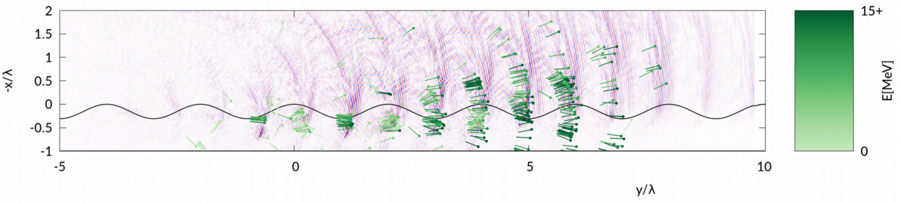
Grat: $m \simeq 37$ at $87°$



# 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



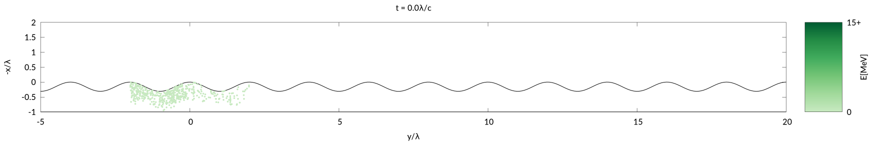
# HH boosting by electron nanobunching (the movie)

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

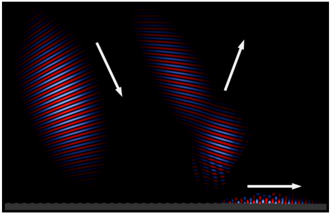
similar to collective instability operation in a Free Electron Laser

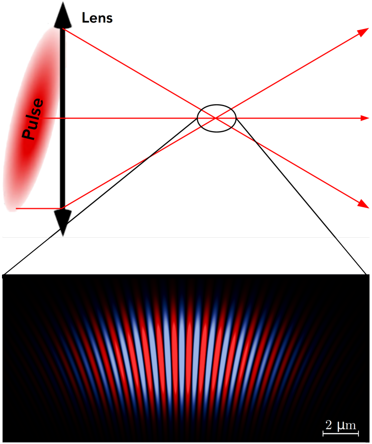
2D simulations by L. Fedeli



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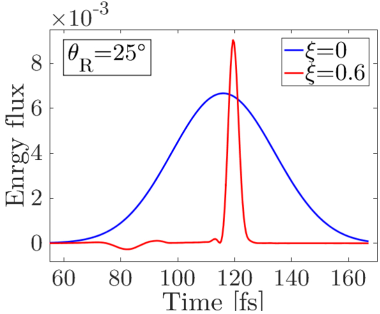
F. Pisani, L. Fedeli, A. Macchi, ACS Photonics **5** (2018) 1068

# A near "single-cycle" SP

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

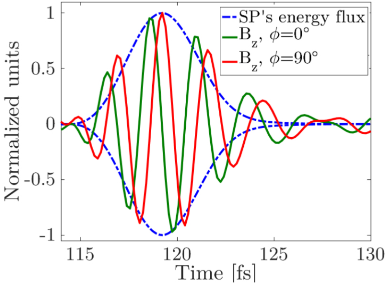



Dependence on absolute phase $\phi$ is apparent

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

$\zeta$ : 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

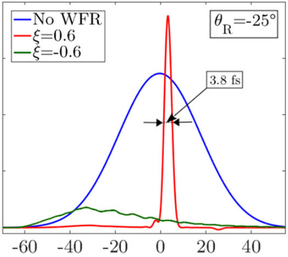


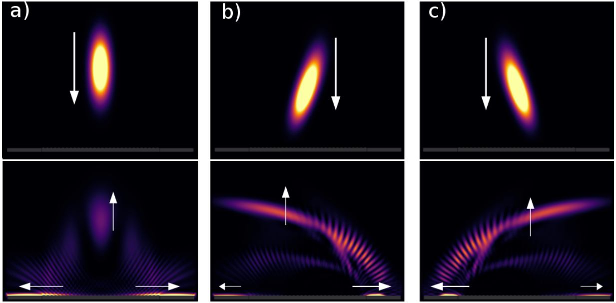

[1] http://ab-initio.mit.edu/wiki/index.php/Meep

# 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

# 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-$\mu$m 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

- Improve control in high field femtosecond plasmonics

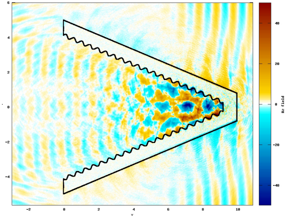
⟶ use of transient laser-induced gratings?

S. Monchocé et al, Phys. Rev. Lett. **112** (2014) 145008

- Numerical and experimental investigation of single-cycle surface plasmons at high fields

⟶ 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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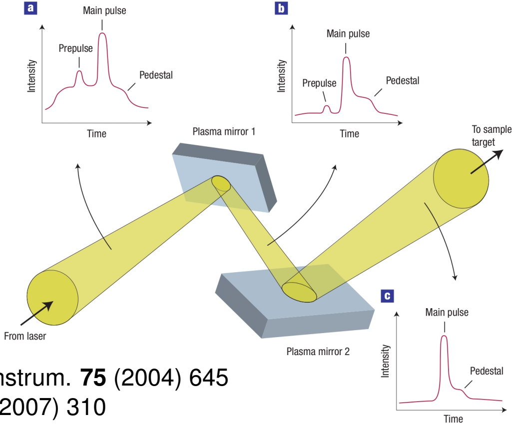
- PRACE & ISCRA & LISA awards for access to FERMI BlueGene/Q™ and MARCONI at CINECA (Italy)

# EXTRA SLIDES

# “Ultraclean” high-contrast pulses

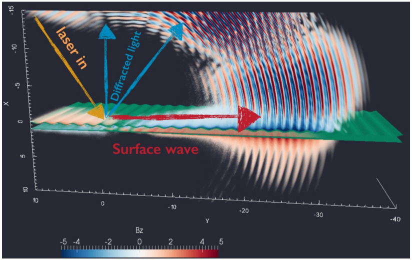
Ionization shutters (“plasma mirrors”) yield pulse-to-prepulse intensity contrast $> 10^{11}$ $\longrightarrow$ sub-wavelength structuring is preserved until the short pulse interaction

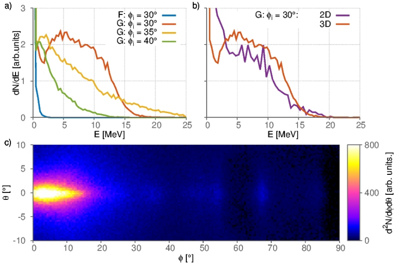



B. Dromey et al, Rev. Sci. Instrum. **75** (2004) 645
A. Levy et al, Opt. Lett. **32** (2007) 310
C. Thaury et al, Nature Physics **3** (2007) 424
figure from P. Gibbon, *ibid.* 369

# 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



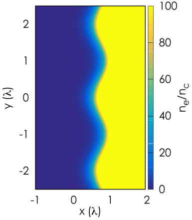



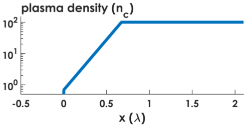

Simulations confirm excitation of relativistic SP and reproduce measurements quantitatively and in detail!

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

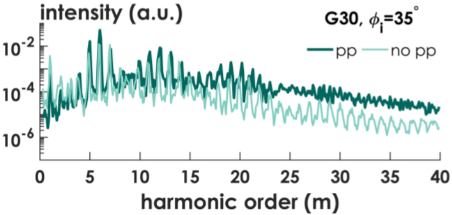
# Preplasma optimization of HH

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?



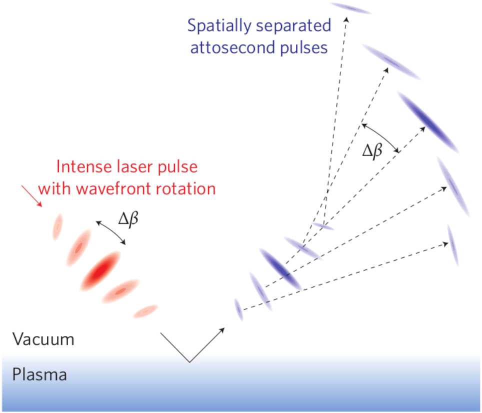

2D simulations
Giada Cantono, PhD thesis, 2017

# 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