Resonant excitation of surface plasma waves in the relativistic regime: electron bunches and high order harmonic generation

G. Cantono$^{1,2,3}$, T. Ceccotti$^1$, L. Fedeli$^{2,3}$, A. Sgattoni$^2$ and A. Macchi$^{2,3}$

$^1$PHI/LIDYL, CEA, CNRS, Université Paris-Saclay, France
$^2$CNR/INO, Laboratorio Adriano Gozzini, Pisa, Italy
$^3$Dipartimento di Fisica Enrico Fermi, Università di Pisa, Pisa, Italy
Surface Plasmons (SPs): electron oscillation resonant modes at a steep metal-dielectric interface

Dielectric = vacuum, $\varepsilon_M = 1$
Metal = laser-produced plasma, $\varepsilon_D = 1 - \frac{\omega_p^2}{\omega^2}$

$$k_{SP}(\omega) = \frac{\omega}{c} \sqrt{\frac{\varepsilon_M \varepsilon_D}{\varepsilon_M + \varepsilon_D}}$$

$$k_{SP}(\omega) = \frac{\omega}{c} \sqrt{\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}}$$

$$k_\parallel = \frac{\omega}{c} \sin \phi + \frac{2\pi}{d}$$
$$k_{SP} = \frac{\omega}{c} \sqrt{\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}}$$

$$k_\parallel = (\omega/c) \sin \theta$$

$$\Delta k = \omega_L / \sqrt{2}$$
**SPW matching conditions**

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k_{SP}(\omega) = \frac{\omega}{c} \sqrt{\frac{\varepsilon_M \varepsilon_D}{\varepsilon_M + \varepsilon_D}} \quad \rightarrow \quad k_{SP}(\omega) = \frac{\omega}{c} \sqrt{\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}}
\]

\[
\frac{\omega}{c} \sin \phi + n \frac{2\pi}{d} = \frac{\omega}{c} \sqrt{\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}}
\]

\[
\sin \phi_{res} + n \frac{\lambda}{d} \approx 1 + \frac{1}{2} n_e
\]
SPW matching conditions (experimental)

Too high ns ASE $\Rightarrow$ Surface structure is washed out before the main peak fs peak arrival

Need for a high contrast ratio

Relativistic regime ($I_{\text{laser}} > 10^{18} \text{ W/cm}^2$) $\Rightarrow$ Contrast better than $10^{10}$
First experimental observation of relativistic SP resonant excitation

Laser UHI100 at CEA Saclay
✓ High intensity $I > 5 \times 10^{19} \text{ W/cm}^2$
✓ Contrast ratio $> 10^{12}$

Bigongiari et al., Phys. Plasmas 18, 102701 (2011)

2.5x increase of max $E_p$

Electrons can be directly accelerated **along the target surface** by the SP intense fields.

\[
k^2 = \frac{\omega^2}{c^2} \frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2} = \frac{\omega^2}{c^2} \frac{\alpha - 1}{\alpha - 2} \quad v_f = \frac{\omega}{k} = c \frac{(\alpha - 2)^{1/2}}{(\alpha - 1)^{1/2}} < c
\]

Energy gain, emission angle and acceleration length in the laboratory frame in the strongly relativistic limit \( W' \gg m_e c^2 \)

\[
\varepsilon_f \approx \frac{eE_{SP} \gamma_f^2}{k} \approx m_e c^2 a_{SP} \left( \frac{n_e}{n_c} \right) \quad \tan \phi_e = \frac{p_x}{p_y} \approx \gamma_f^{-1} \quad \ell_a = \varepsilon_f/eE_{SP} \approx \lambda \alpha/2\pi
\]

\( a_{SP} = eE_{SP}/m_e \omega c \)
First experimental observation of relativistic SP driven e⁻ acceleration

Laser UHI100 at CEA Saclay

First experimental observation of relativistic SP driven e⁻ acceleration

Laser UHI100 at CEA Saclay

First experimental observation of relativistic SP driven $e^-$ acceleration

Laser UHI100 at CEA Saclay

Systematic study of SP driven $e^-$ acceleration

**Thin Gratings**
Heat embossed Mylar
thickerness: 10 µm
peak to valley depth: 250 nm
sinusoidal profile

<table>
<thead>
<tr>
<th>Model</th>
<th>$d$ (µm)</th>
<th>$\phi_{res}$ (°)</th>
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<tbody>
<tr>
<td>G15</td>
<td>1.4</td>
<td>15°</td>
</tr>
<tr>
<td>G30</td>
<td>2</td>
<td>30°</td>
</tr>
<tr>
<td>G45</td>
<td>3.4</td>
<td>45°</td>
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**Solid gratings** (9.5 mm thick):
Glass substrate + Al coating
$\phi_{res} = 30°$
blaze angles: 4°, 6°, 13°, 22° and 28°
Different gratings at resonance produce collimated, intense, energetic electron bunches.

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<td>7</td>
<td>5.8</td>
<td>5.4</td>
<td>4.7</td>
<td>13</td>
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<tr>
<td>charge in the bunch (pC)</td>
<td>310</td>
<td>120</td>
<td>2300</td>
<td>1100</td>
<td>1700</td>
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High order harmonic generation and SP resonant excitation

\[ \frac{n \lambda}{md} = \sin \phi_i + \sin \phi_{mn} \]
High order harmonic generation and SP resonant excitation

\[ \sin \phi_i = \sin \phi_{res} \]
High order harmonic generation and SP resonant excitation

Electron spectrometer (2-30 MeV)

XUV spectrometer: spectral range $\omega_H/\omega_L = [9,45]$

$35^\circ$ incidence, NO preplasma

Flat

0-150 bit range

0-40 bit range

G30

specular

twd tangent

$33^\circ$  $34^\circ$  $36^\circ$  $82^\circ$  $83^\circ$  $84^\circ$  $85^\circ$

$N^{th}$

12  10  8  6  4  2
High order harmonic generation and SP resonant excitation

XUV spectrometer: spectral range $\omega_H/\omega_L=[9,45]$

Electron spectrometer (2-30 MeV)

35° incidence, NO preplasma

10th harmonic from 2D PIC simulation

Flat @45° inc
G30 @35° inc

specular
twd tangent
High order harmonic generation and SP resonant excitation

Electron spectrometer (2-30 MeV)

XUV spectrometer: spectral range $\omega_H/\omega_L = [9, 45]$

Best HH efficiency for:
- High order harmonic generation
- SP resonant excitation

$\phi_{res}$

$0-255$ bit range
$0-150$ bit range

$35^\circ$ incidence, WITH optimized preplasma

Flat

$N^h$

specular

$33^\circ$ $34^\circ$ $36^\circ$ $82^\circ$ $83^\circ$ $84^\circ$ $85^\circ$

$G30$

$L_{pp} \sim 0.13\lambda \simeq 100$ nm
(smaller than the grating depth)
The **maximum harmonic order** is higher with gratings at resonance. Electrons at tangent are still detected despite the pre-plasma.
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Summing up

- Ultra-high contrast laser systems allow to access high field plasmonic
- SPW do improve laser-target coupling and result in enhanced proton and electron acceleration
- High energy and charge (> 2nC), low divergence electron beams driven by SPW have been observed and characterized for different kinds of grating
- Increase of high order harmonic production far from specular reflected laser beam
- Open issues: no theory for plasmonic at relativistic intensities
  
electron beam properties: emittance, duration
Thank you for your attention

giada.cantono@cea.fr     tiberio.ceccotti@cea.fr