DE LA RECHERCHE À L'INDUSTRIE

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

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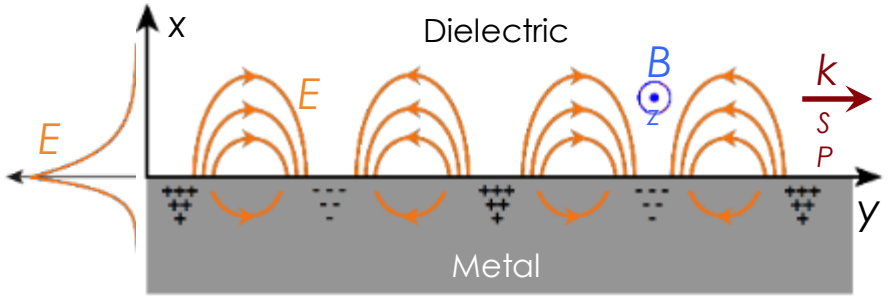
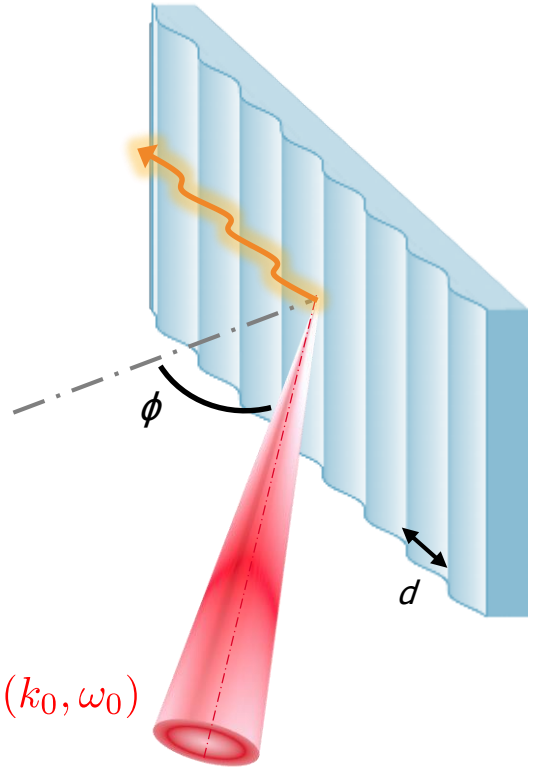
SPW matching conditions

Surface Plasmons (SPs): electron oscillation resonant modes at a steep metal-dielectric interface

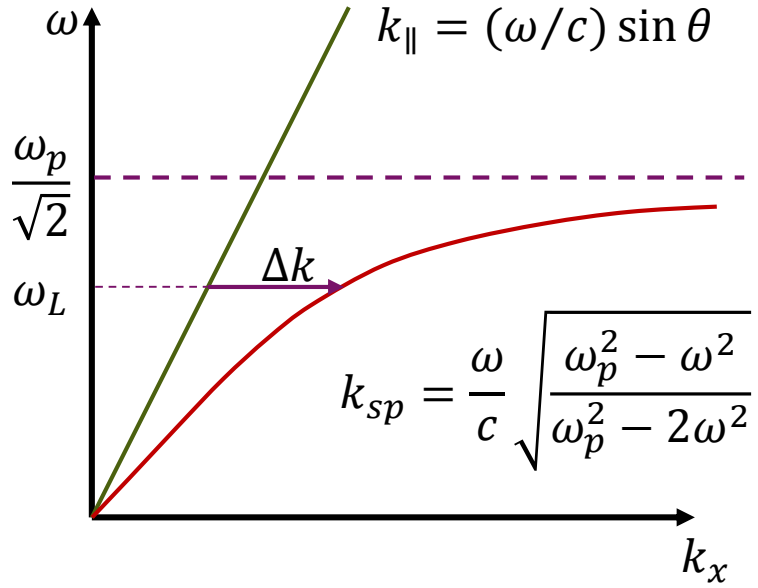


Dielectric = vacuum, $\varepsilon_M = 1$
Metal = laser-produced plasma, $\varepsilon_D = 1 - \frac{\omega_p^2}{\omega^2}$

$$\mathbf{k_{SP}}(\omega) = \frac{\omega}{\mathbf{c}}\sqrt{\frac{\varepsilon_\mathbf{M}\varepsilon_\mathbf{D}}{\varepsilon_\mathbf{M}+\varepsilon_\mathbf{D}}} \longrightarrow \mathbf{k_{SP}}(\omega) = \frac{\omega}{\mathbf{c}}\sqrt{\frac{\omega_\mathbf{p}^2-\omega^2}{\omega_\mathbf{p}^2-\mathbf{2}\omega^2}}$$



$$\begin{cases} k_\parallel = \dfrac{\omega}{c}\sin\phi + n\dfrac{2\pi}{d} \\ k_{sp} = \dfrac{\omega}{c}\sqrt{\dfrac{\omega_p^2-\omega^2}{\omega_p^2-2\omega^2}} \end{cases} \quad (\Delta k)$$



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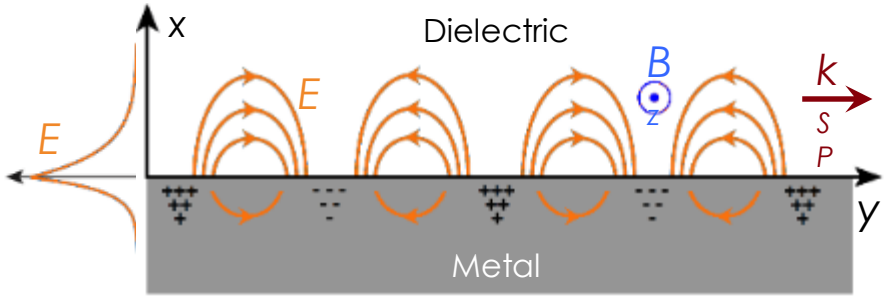

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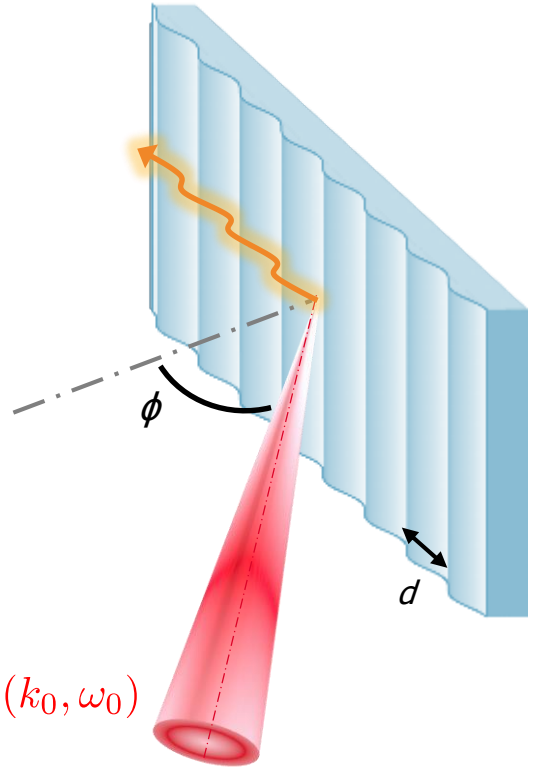
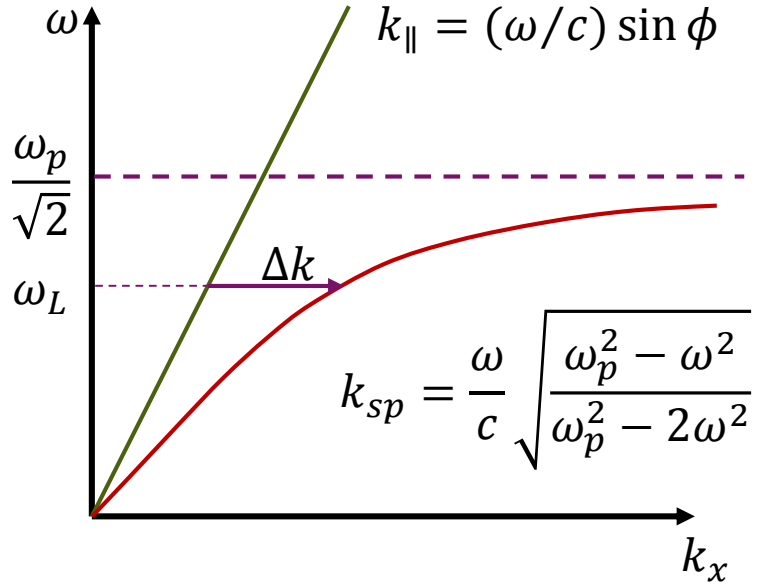
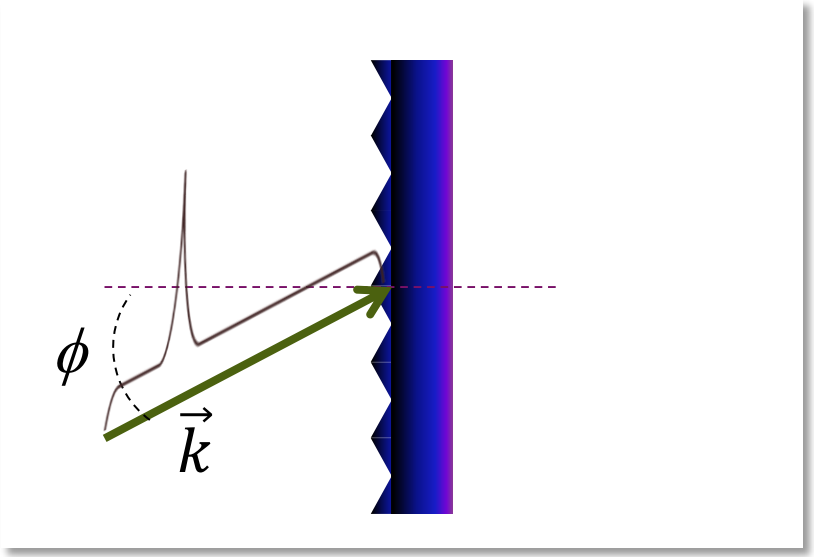


$$\frac{\omega}{c}\sin\phi + n\frac{2\pi}{d} = \frac{\omega}{c}\sqrt{\frac{\omega_p^2-\omega^2}{\omega_p^2-2\omega^2}}$$

$$\sin\phi_{res} + n\frac{\lambda}{d} \simeq 1 + \frac{1}{2}\frac{n_c}{n_e}$$

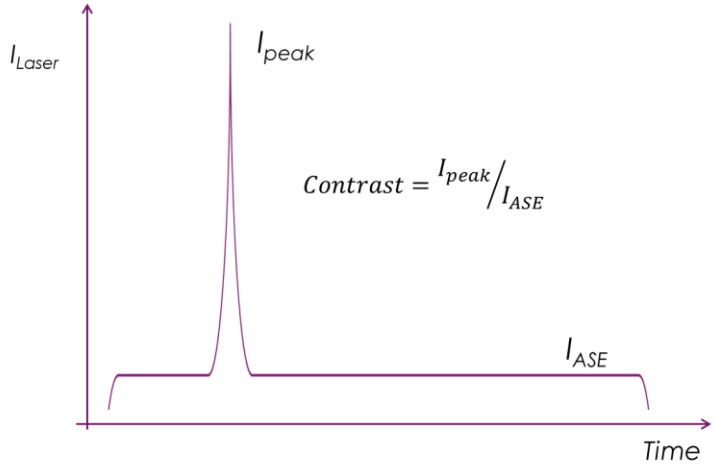


SPW matching conditions (experimental)



Too high ns ASE → Surface structure is washed out before the main peak fs peak arrival

Need for a high contrast ratio

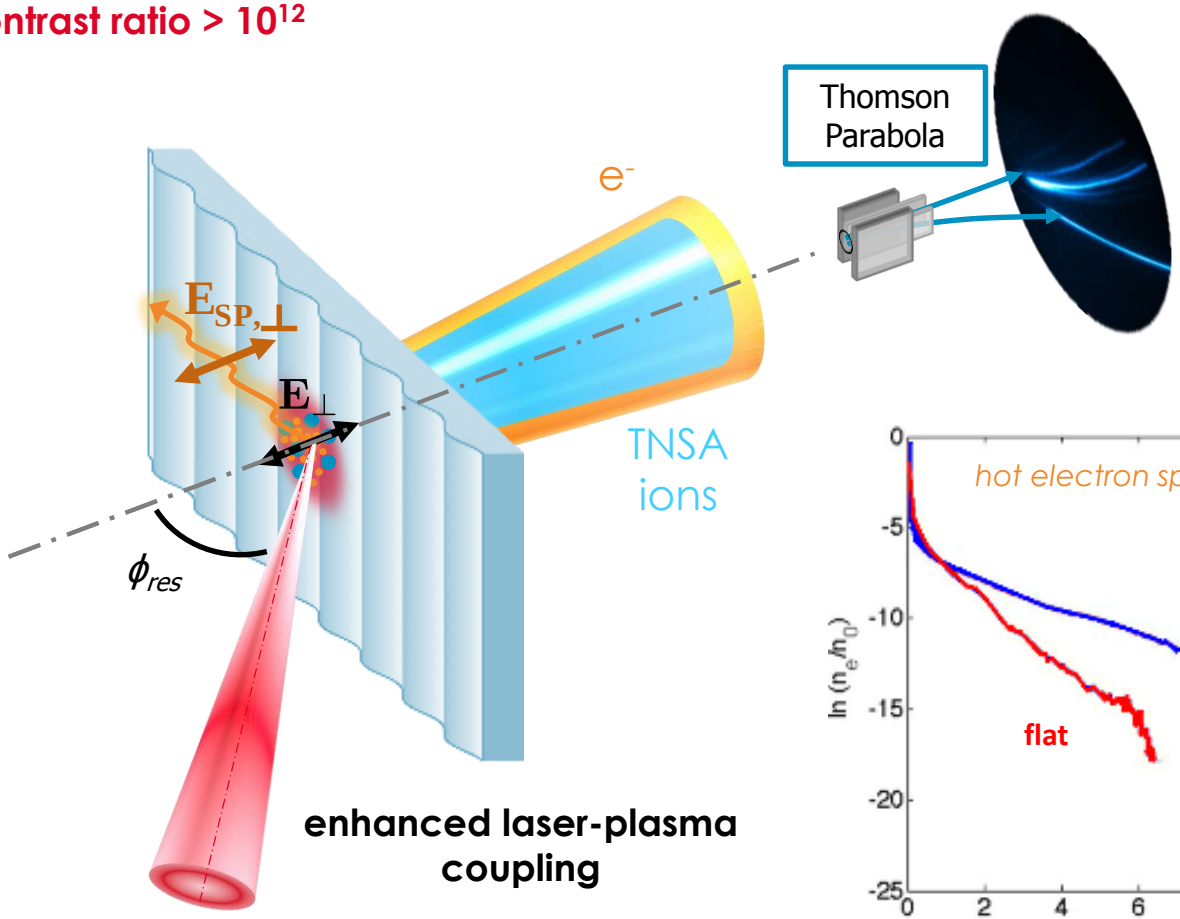


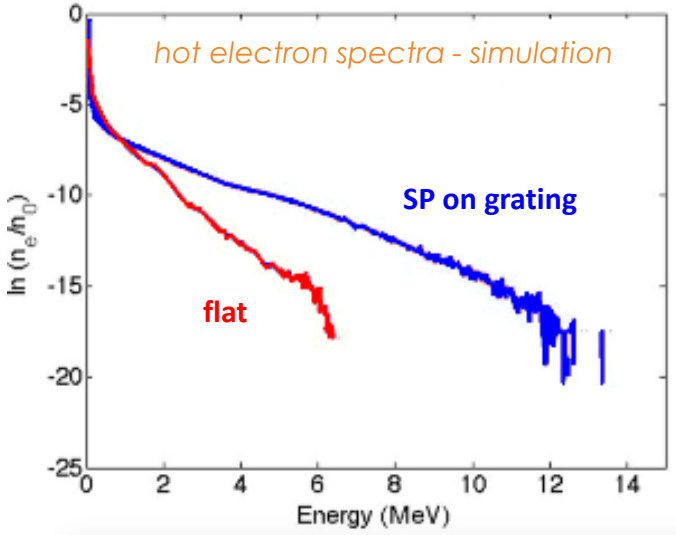
Relativistic regime (I_{laser} > 10^E18 W/cm²) → Contrast better than 10^E10

First experimental observation of relativistic SP resonant excitation

Laser UHI100 at CEA Saclay

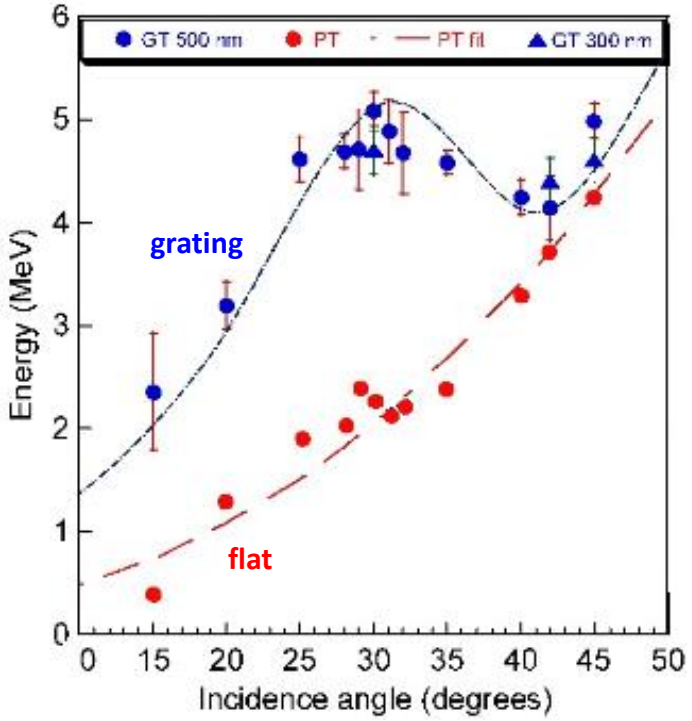
- ✓ High intensity I_L>5x10^{19} W/cm^2
- ✓ **Contrast ratio > 10^{12}**





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

2.5x increase of max E_p

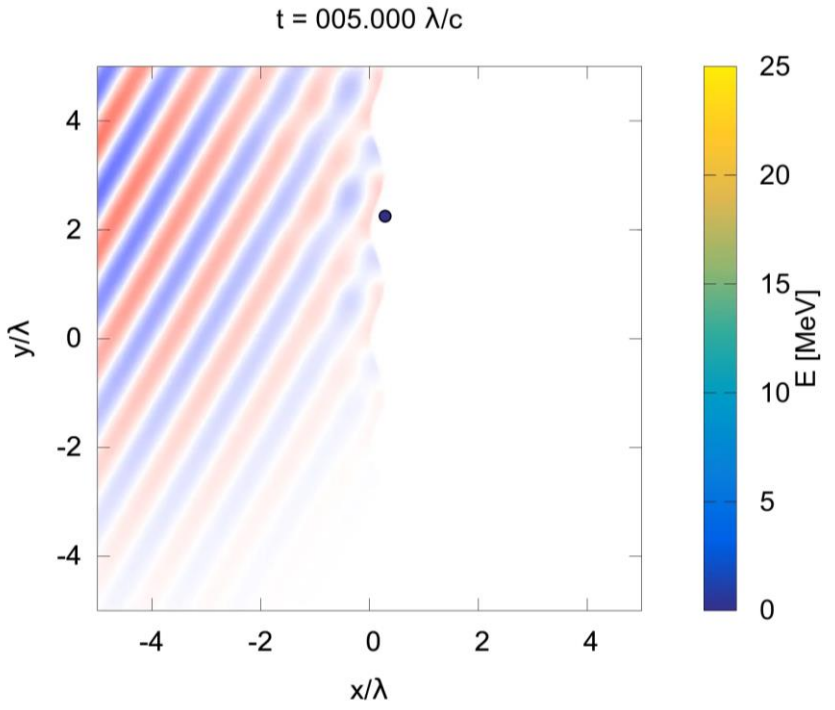


Ceccotti et al., Phys. Rev. Lett., **111**, 5001 (2013)

Surface plasmon acceleration in vacuum

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

$$k^2 = \frac{\omega^2}{c^2}\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2} = \frac{\omega^2}{c^2}\frac{\alpha - 1}{\alpha - 2} \qquad v_f = \frac{\omega}{k} = c\frac{(\alpha-2)^{1/2}}{(\alpha-1)^{1/2}} < c$$



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

$$\varepsilon_f \approx \frac{eE_{SP}\gamma_f^2}{k} \simeq m_e c^2 a_{SP}\left(\frac{n_e}{n_c}\right)$$

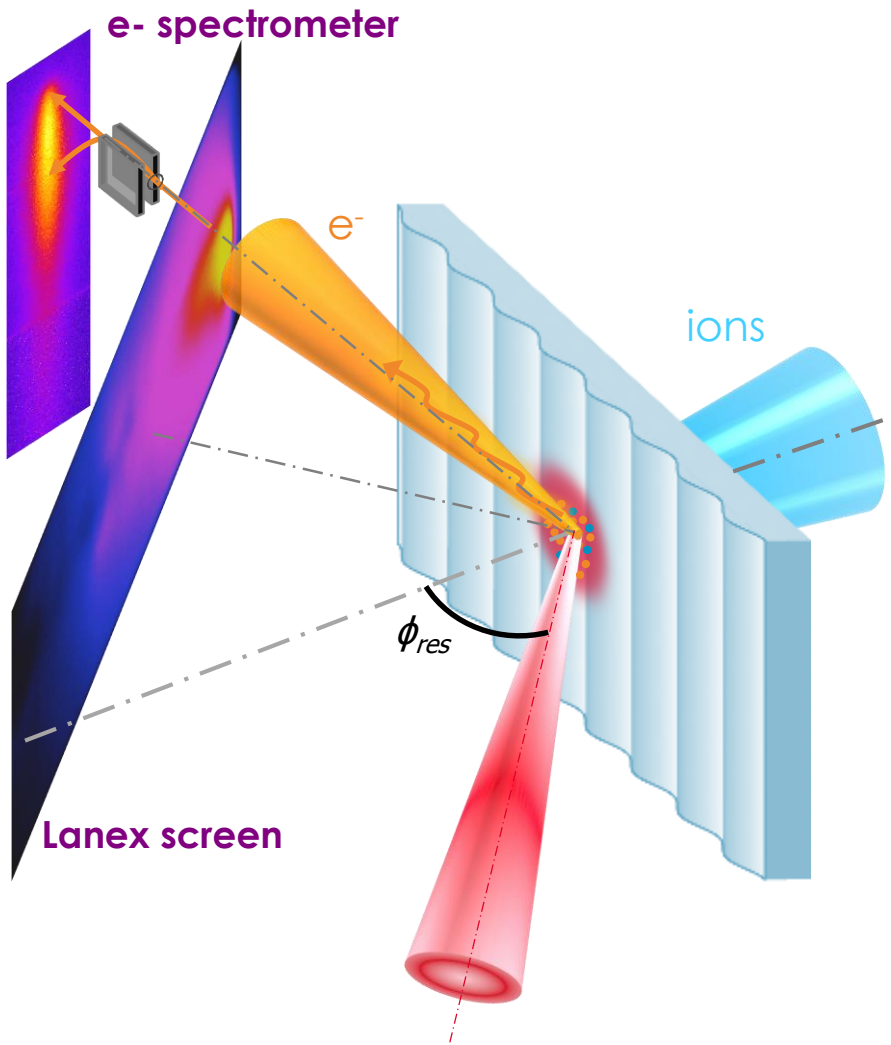
$$tan\phi_e = \frac{p_x}{p_y} \simeq \gamma_f^{-1}$$

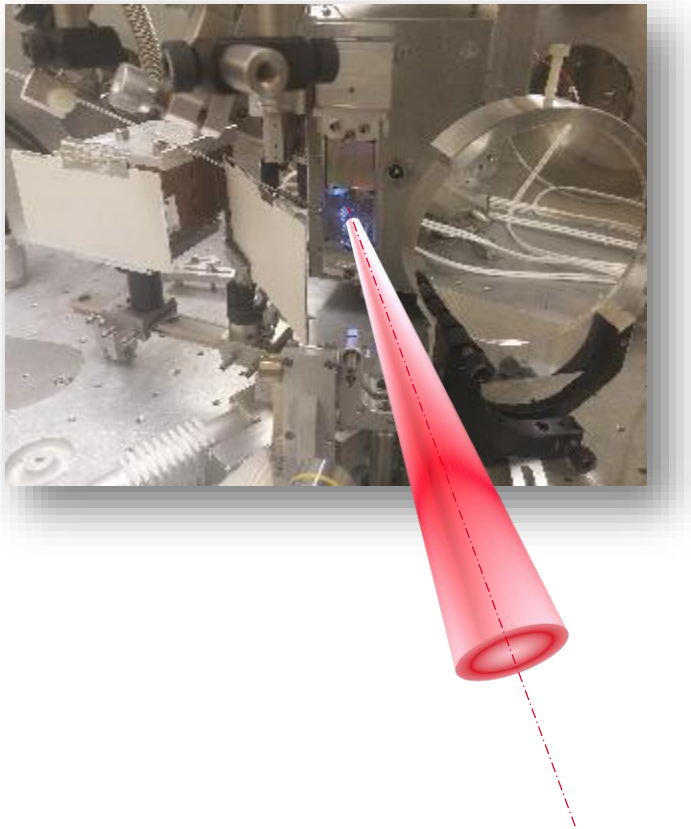
$$\ell_a = \varepsilon_f / eE_{SP} \simeq \lambda\alpha/2\pi$$

$(a_{SP} = eE_{SP}/m_e\omega c)$

First experimental observation of relativistic SP driven e⁻ acceleration

Laser UHI100 at CEA Saclay





L. Fedeli et al., Physical Review Letters **116**, 015001 (2016)

First experimental observation of relativistic SP driven e⁻ acceleration

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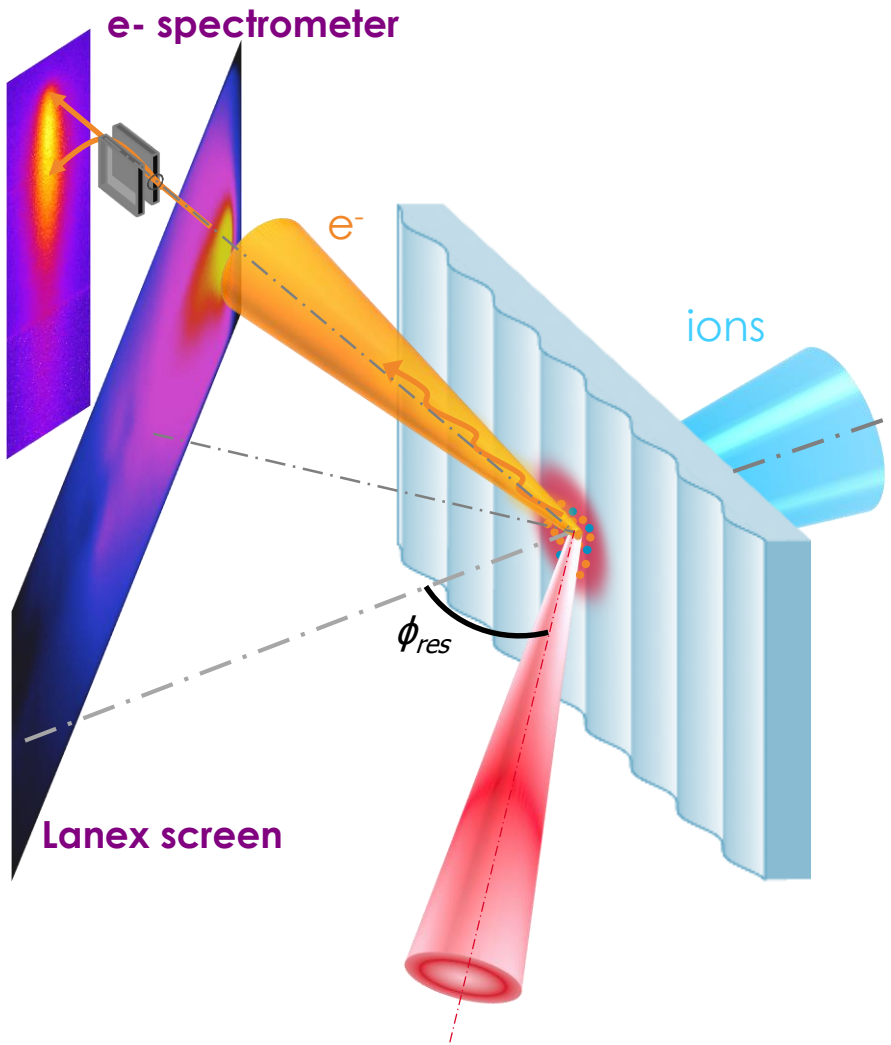

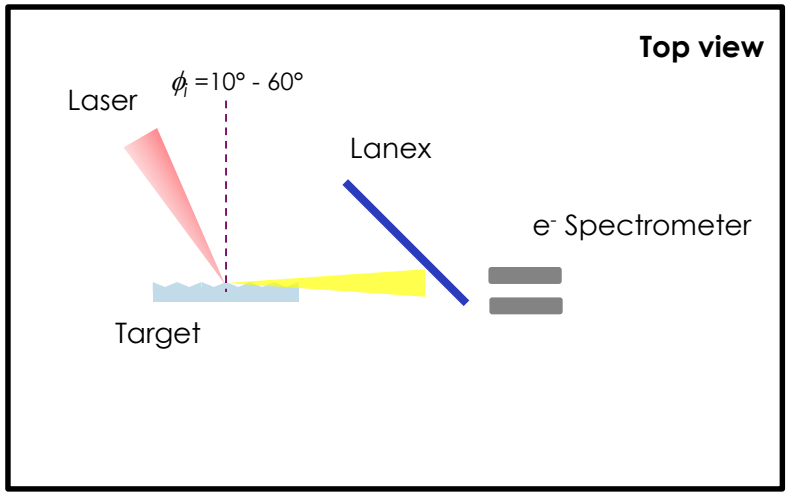

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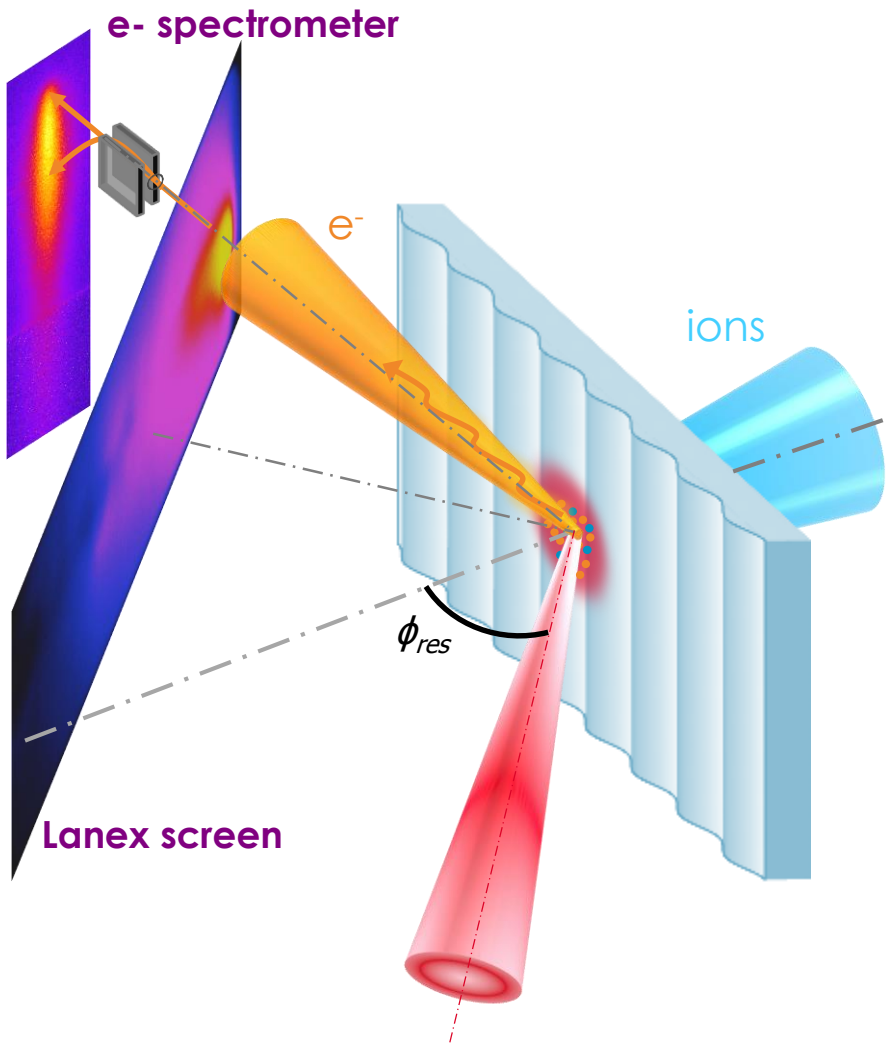
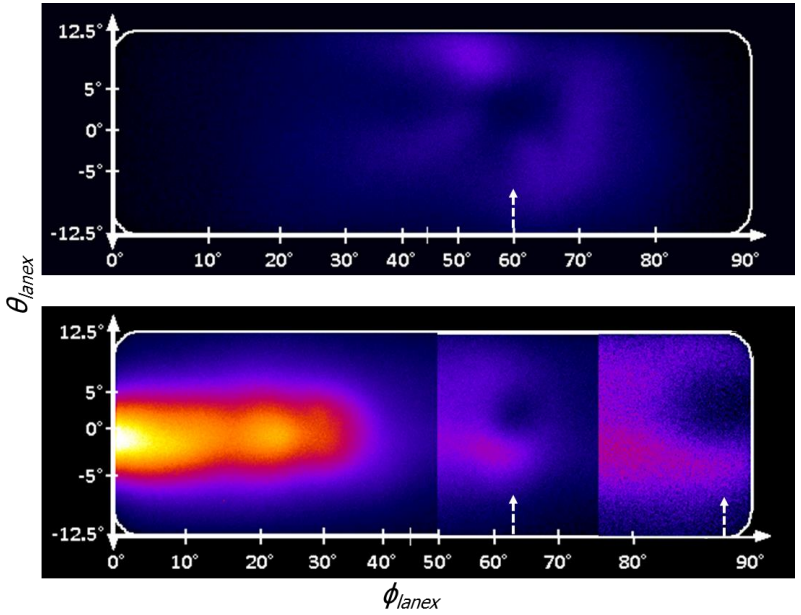
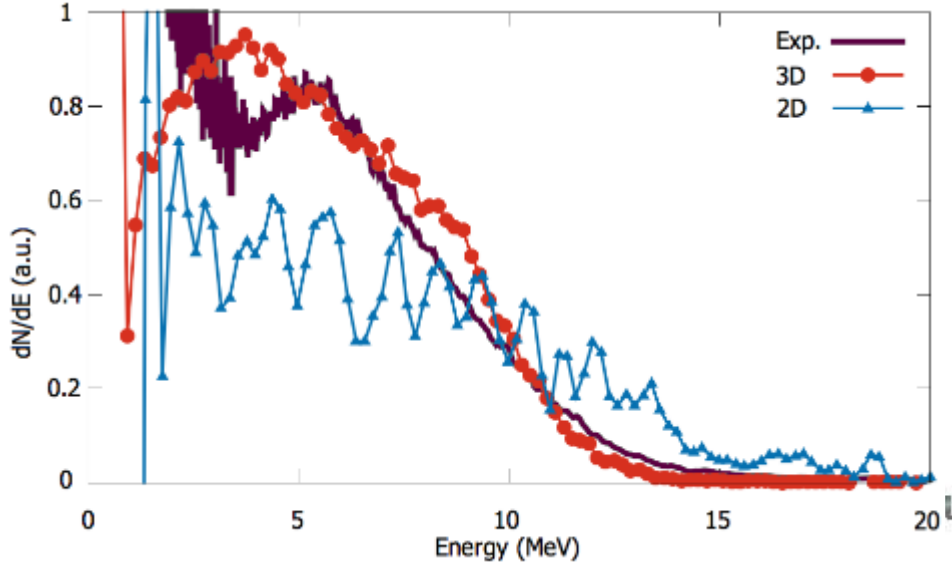




flat

grating



L. Fedeli et al., Physical Review Letters **116**, 015001 (2016)

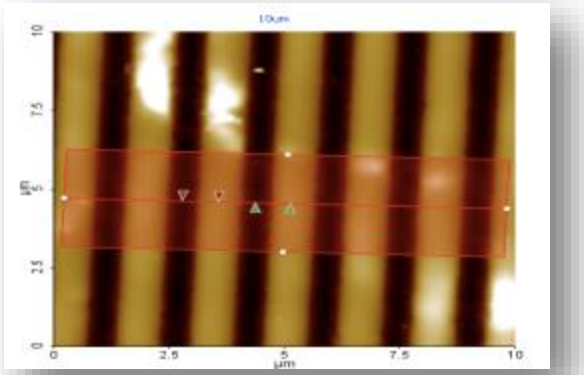
Systematic study of SP driven e⁻ acceleration

Thin Gratings

Heat embossed Mylar
thickness: 10 um
peak to valley depth: 250 nm
sinusoidal profile

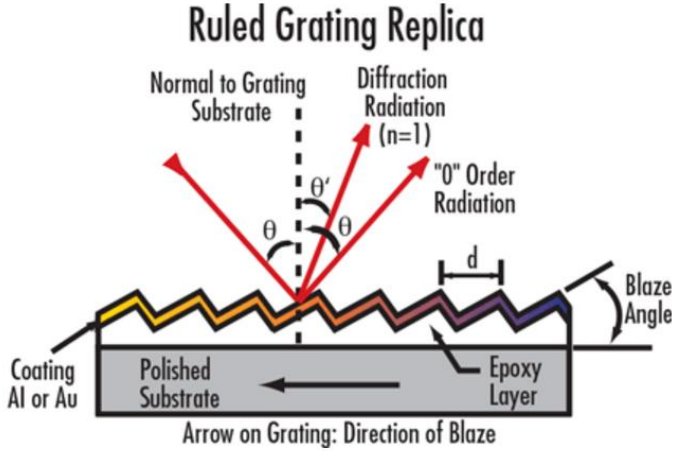
for n=1:	d	Φ_{res}
G15	1.4	15°
G30	2	30°
G45	3.4	45°

SEM picture of engraved Mylar foils

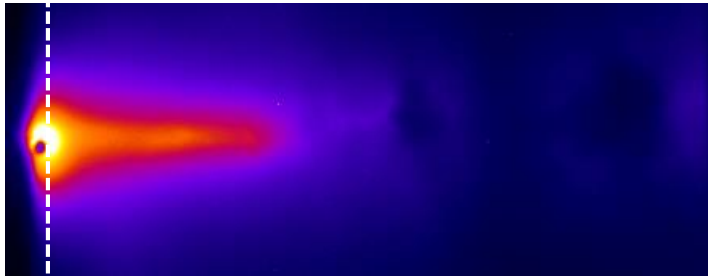


Solid gratings (9.5 mm thick):

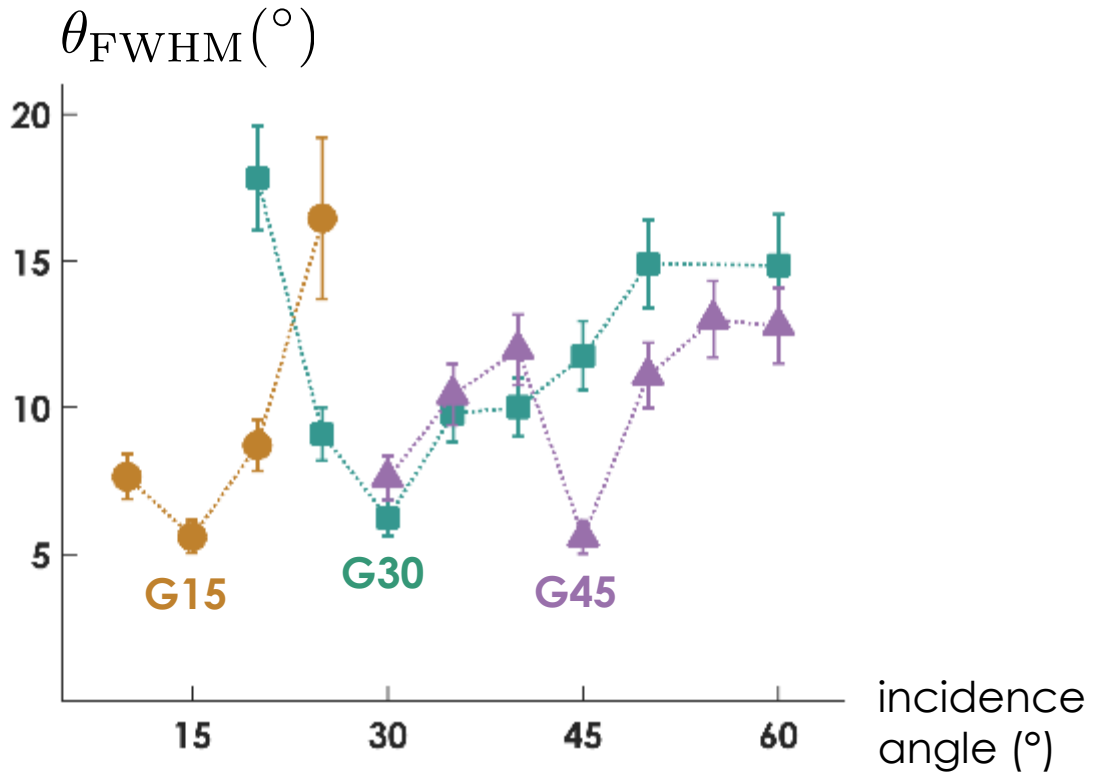
Glass substrate + Al coating
ϕ_{res} =30°
blaze angles: 4°, 6°, 13°, 22° and 28°



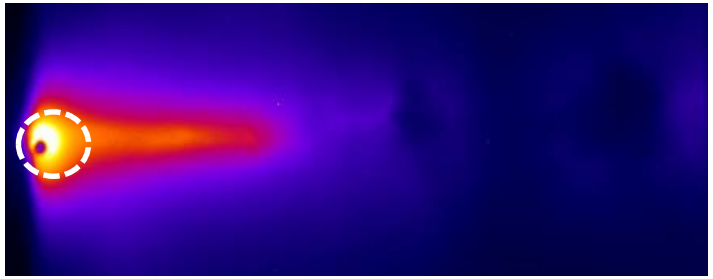
Different gratings at resonance produce collimated, intense, energetic electron bunches.



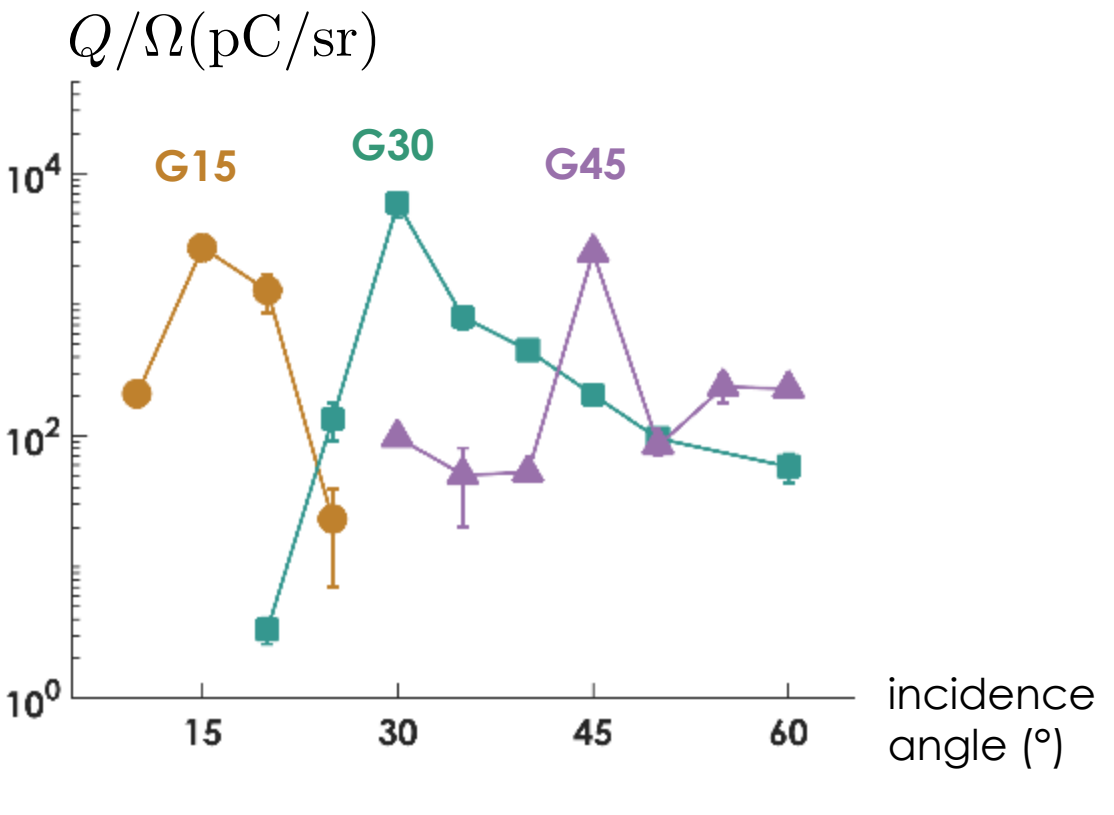
at resonance:	G15	G30	G45
angular divergence FWHM (deg)	5.5	6.1	5.6



Different gratings at resonance always produce collimated, intense, energetic electron bunches.



at resonance:	G15	G30	G45
angular divergence FWHM (deg)	5.5	6.1	5.6
charge in the bunch (pC)	120	280	110



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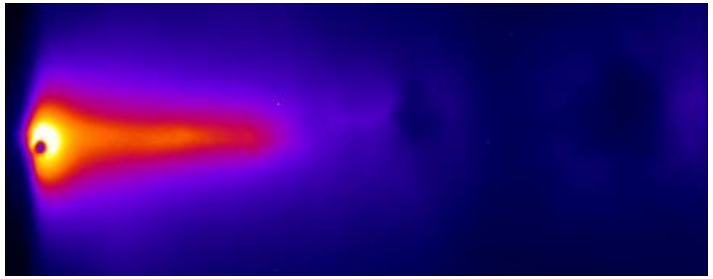

at resonance:	G15	G30	G45
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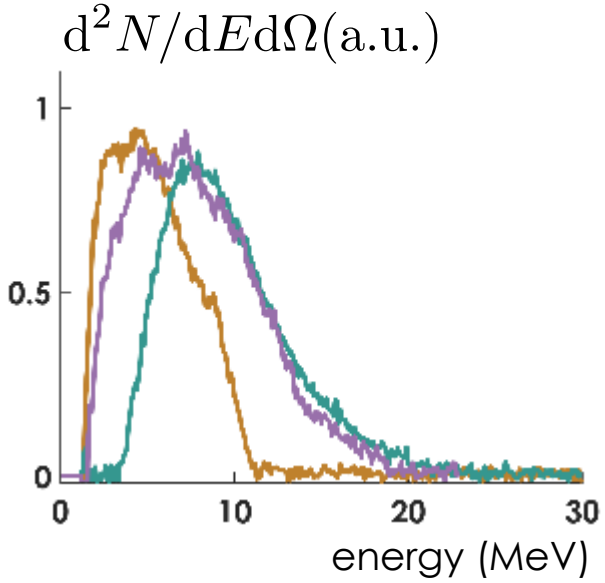

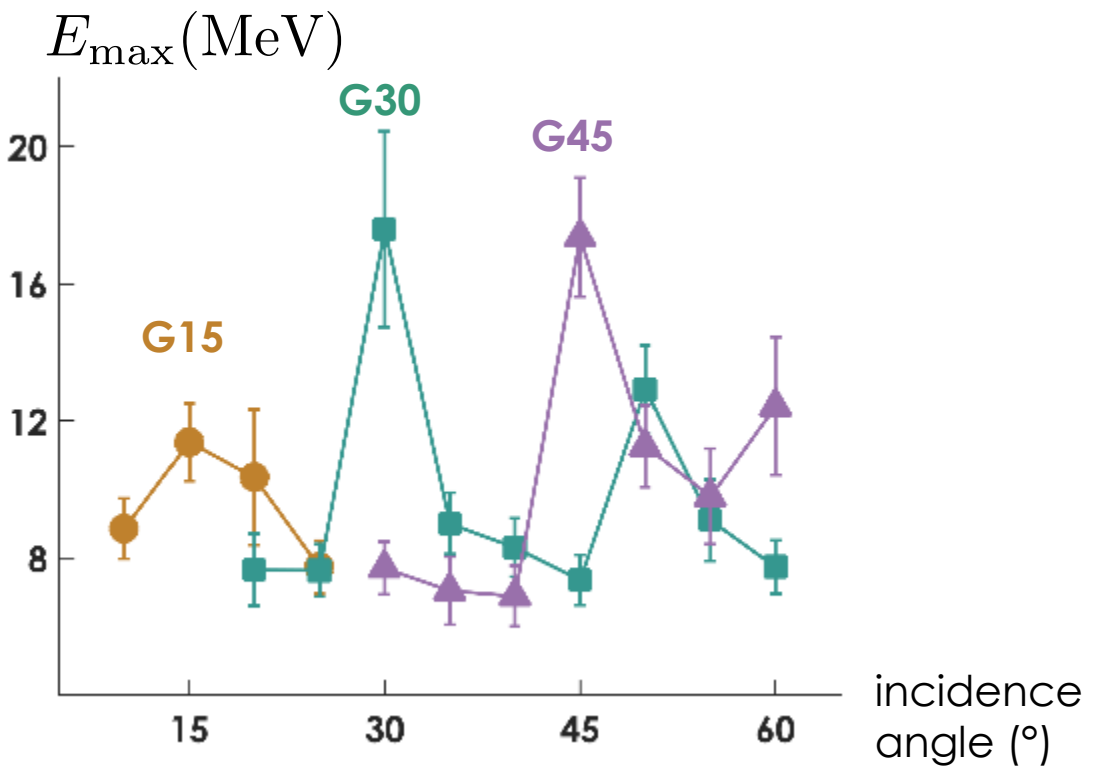

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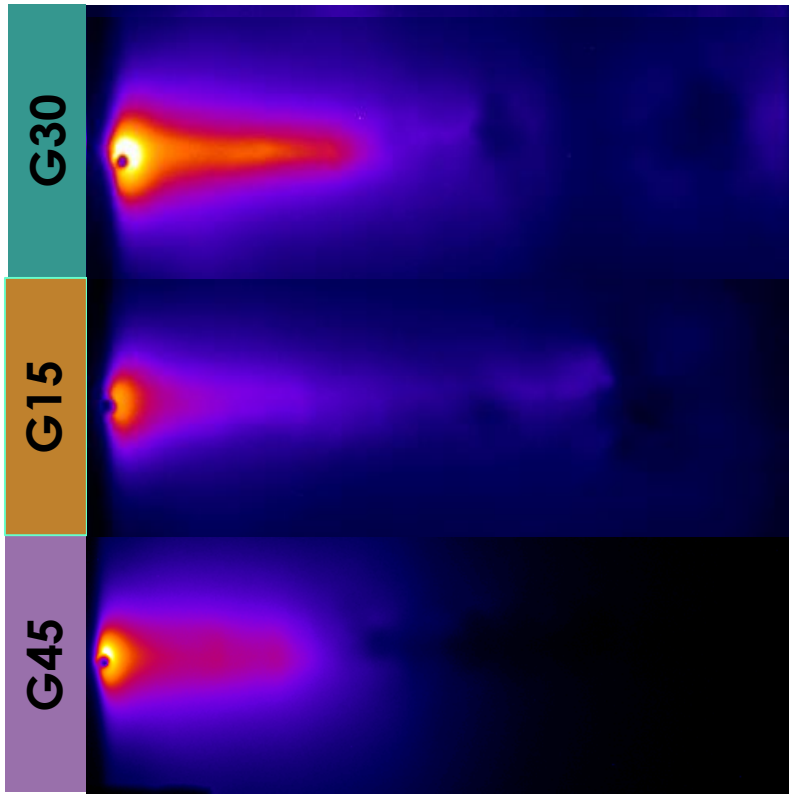

at resonance:	G15	G30	G45
angular divergence FWHM (deg)	5.5	6.1	5.6
charge in the bunch (pC)	120	280	110
maximum energy (MeV)	11	18	17
$\Delta\theta$ (deg)	0.7	0.2	0.3
$\Delta\phi$ (deg)	0.2	0.05	0.1

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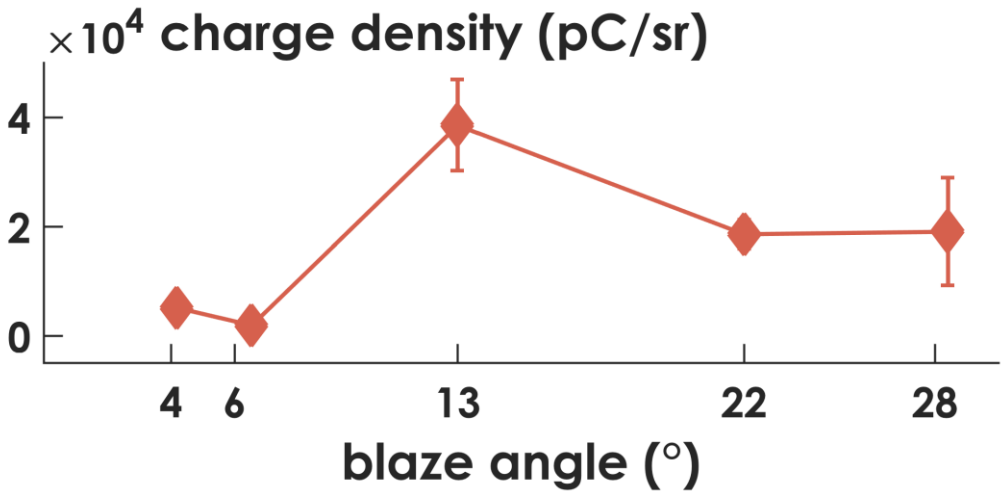

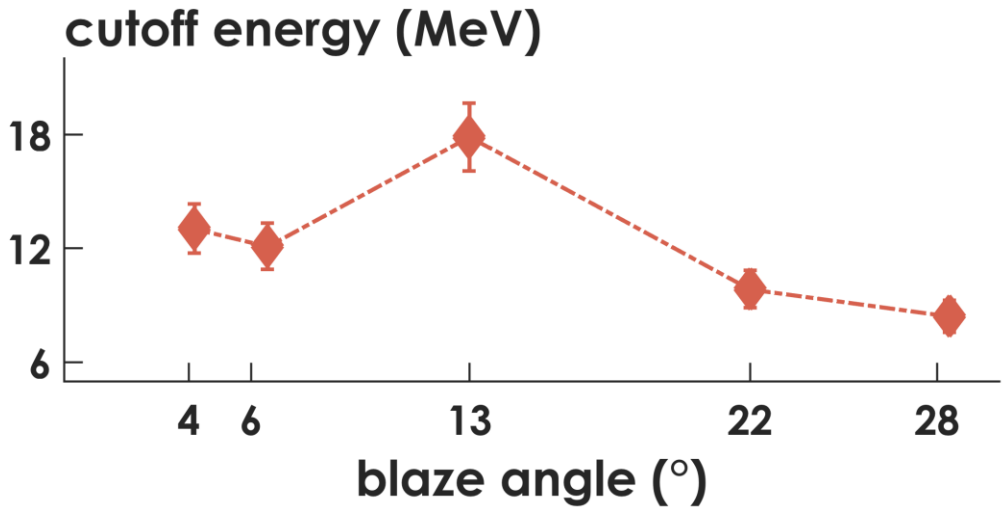

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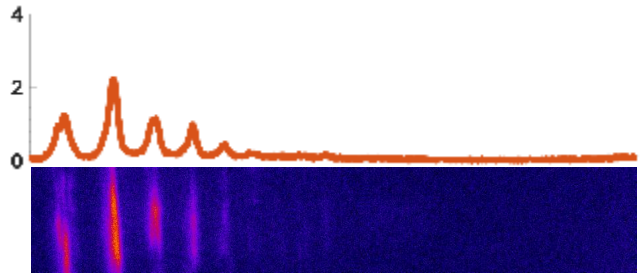
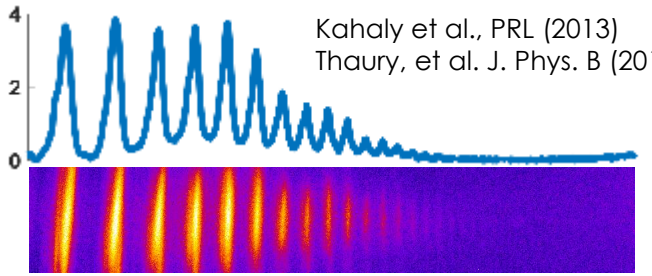
at resonance:	SG4	SG6	SG13	SG22	SG28
angular divergence FWHM (deg)	7	5.8	5.4	4.7	13
charge in the bunch (pC)	310	120	2300	1100	1700
maximum energy (MeV)	13	12	18	10	8.5
$\Delta\theta$ (deg)	0.8	0.5	0.2	0.2	0.6
$\Delta\phi$ (deg)	0.05	0.05	0.05	0.05	0.2

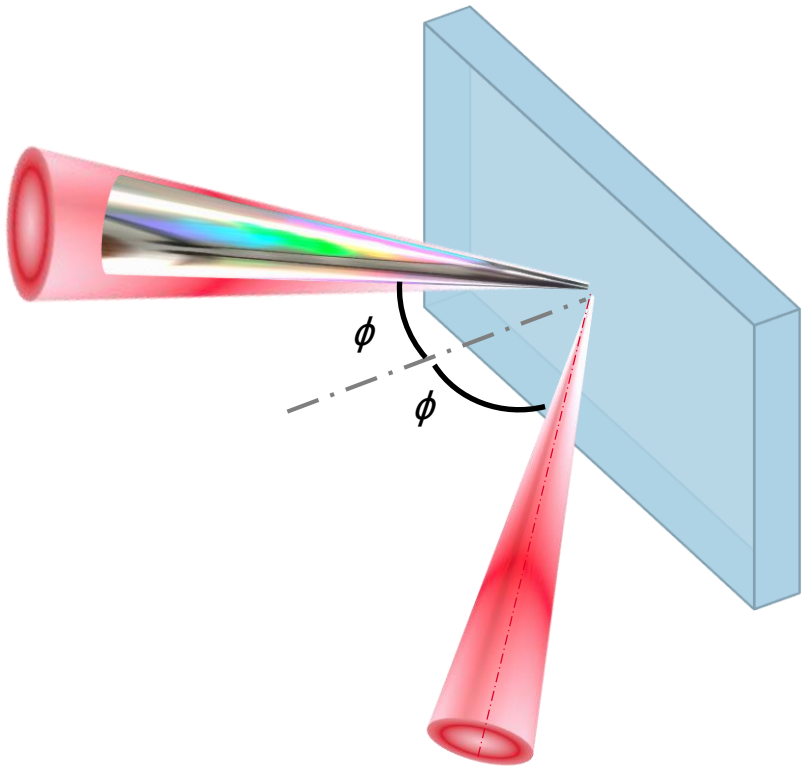
High order harmonic generation and SP resonant excitation

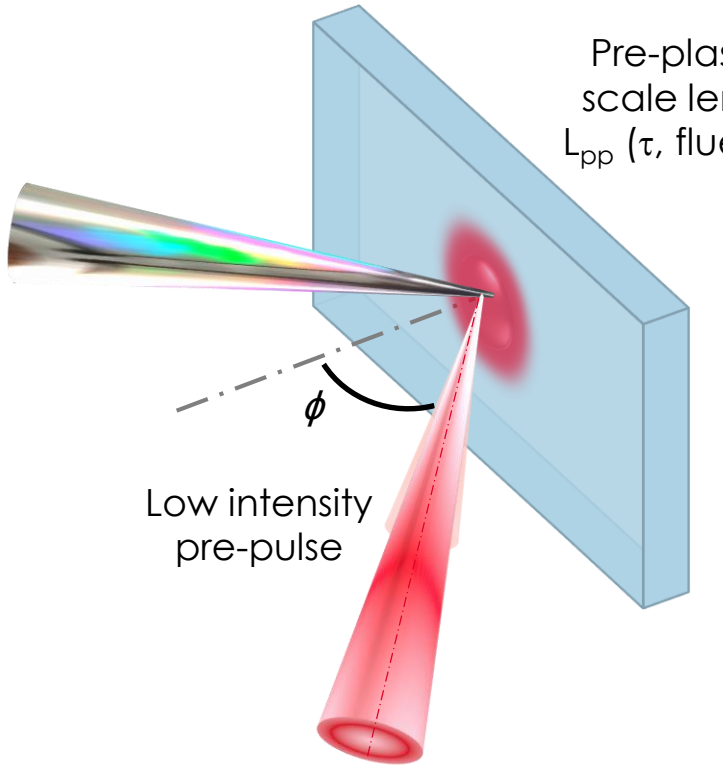




Kahaly et al., PRL (2013)
Thaury, et al. J. Phys. B (2010)

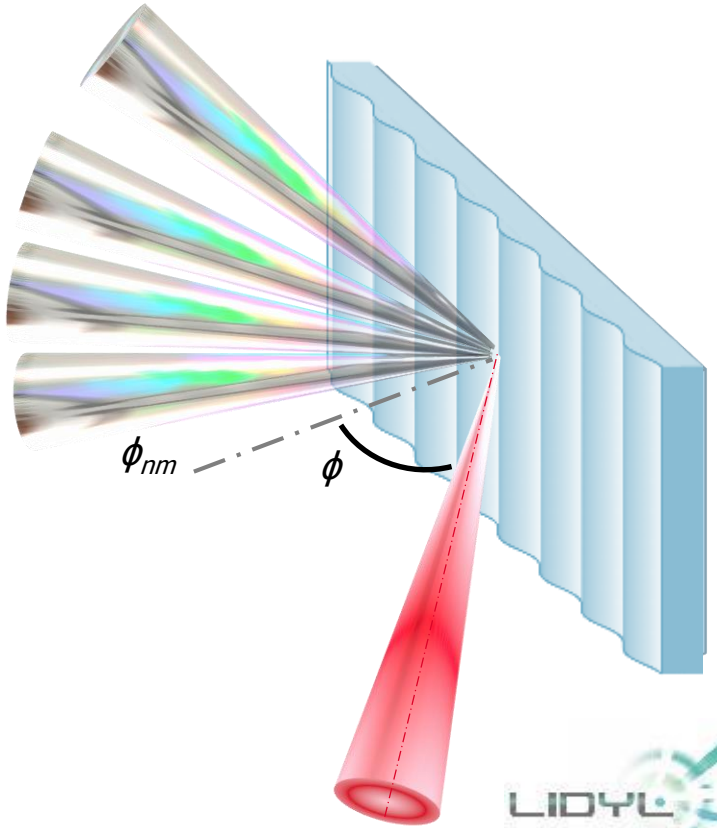
$$n\lambda/md = \sin\phi_i + \sin\phi_{mn}$$



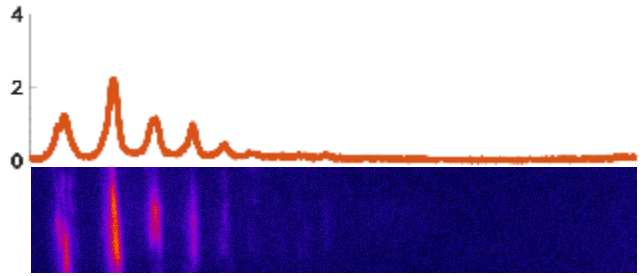


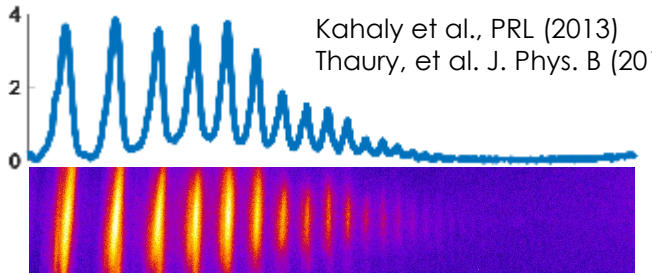
Pre-plasma
scale length
L_{pp} (τ, fluency)

Low intensity
pre-pulse



High order harmonic generation and SP resonant excitation





Kahaly et al., PRL (2013)
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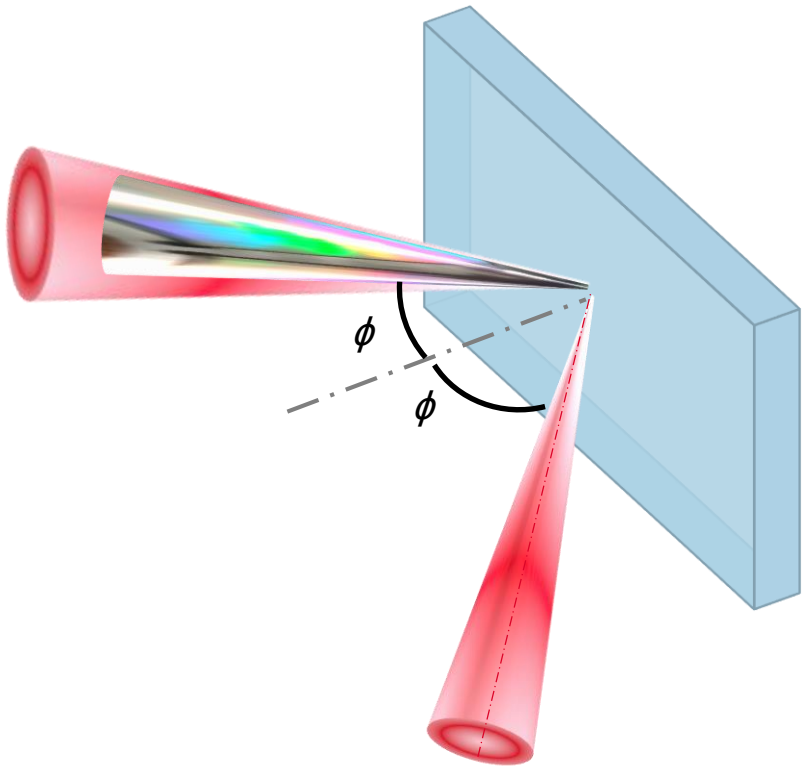
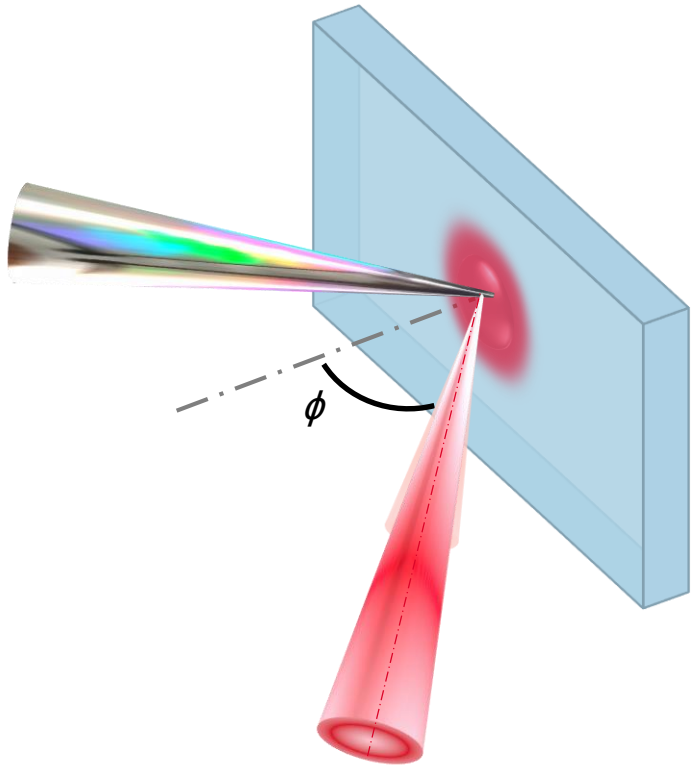
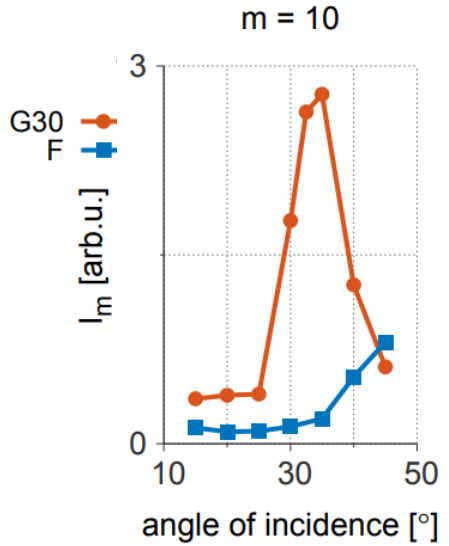




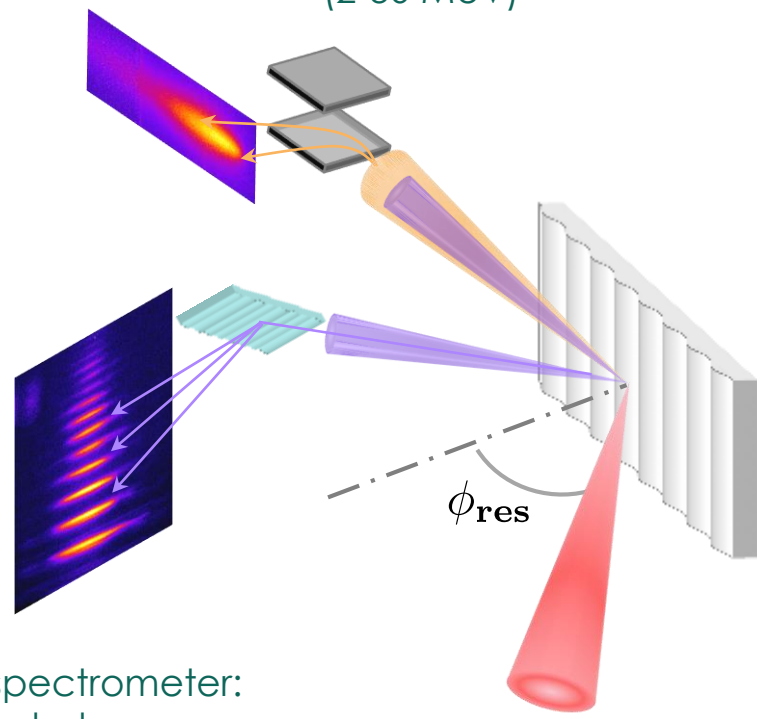
$$\sin\phi_i = \sin\phi_{res}$$



Fedeli et al., APL, ***110*** *(5), 051103 (2017)*

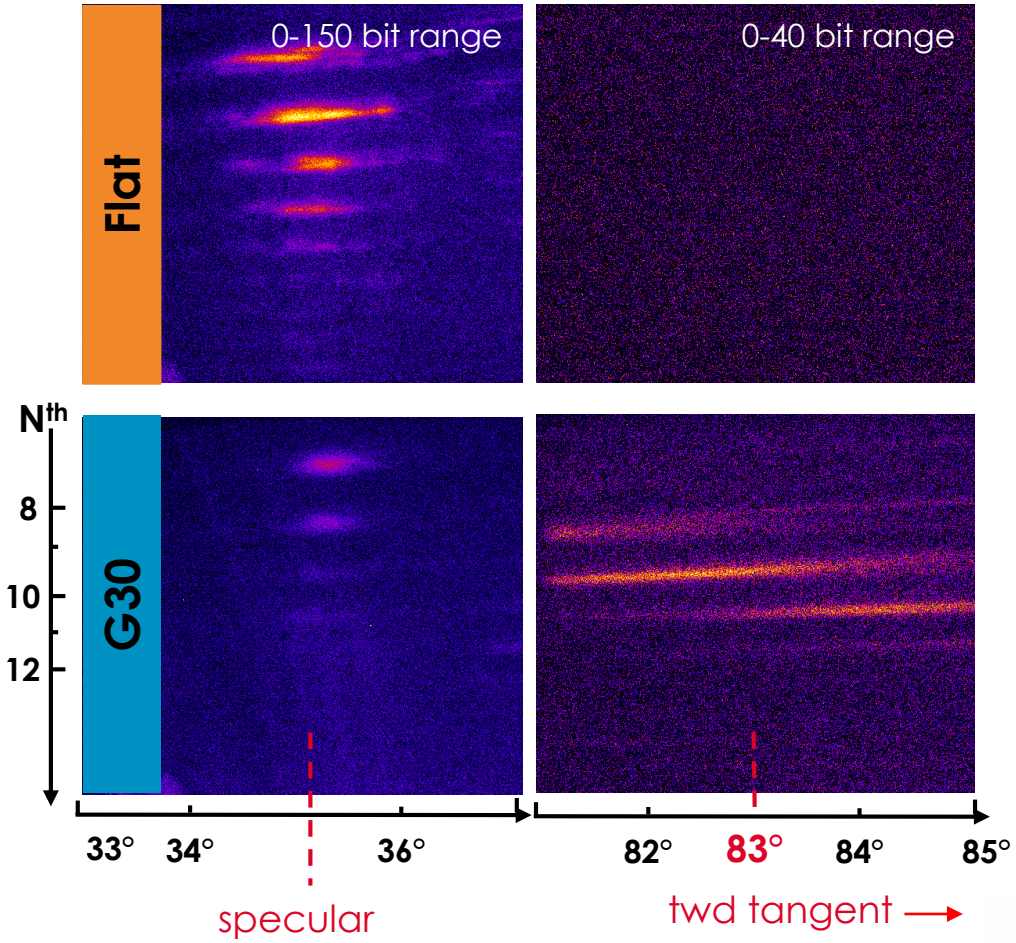
High order harmonic generation and SP resonant excitation

Electron spectrometer
(2-30 MeV)



XUV spectrometer:
spectral range
ω_H/ω_L=[9,45]

35° incidence, NO preplasma



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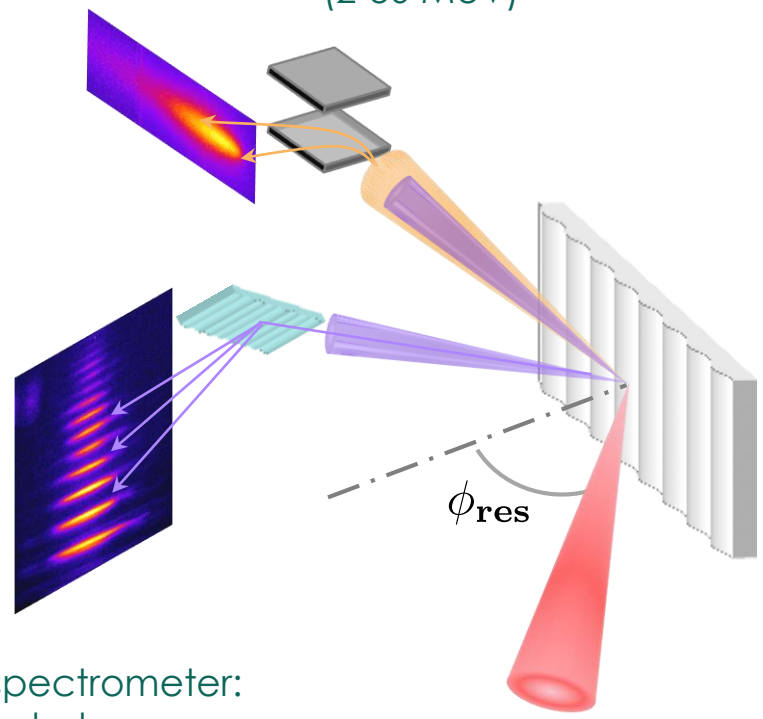

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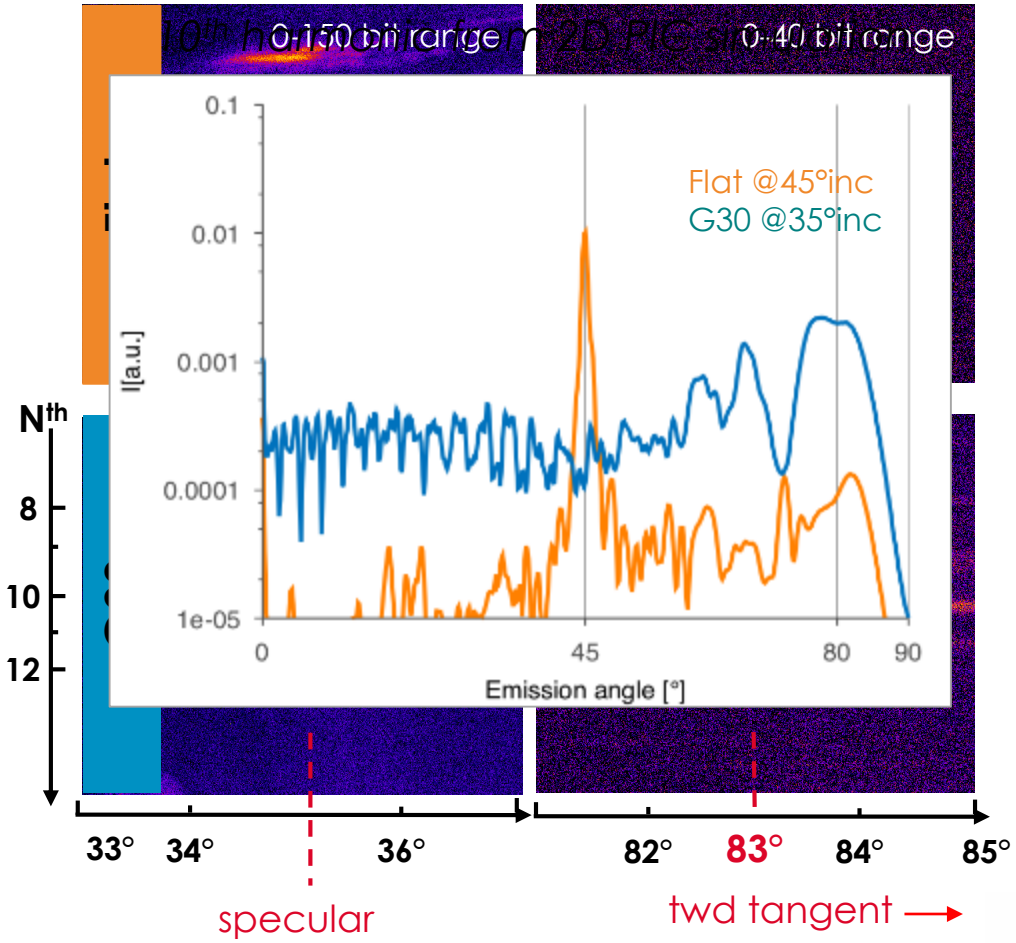
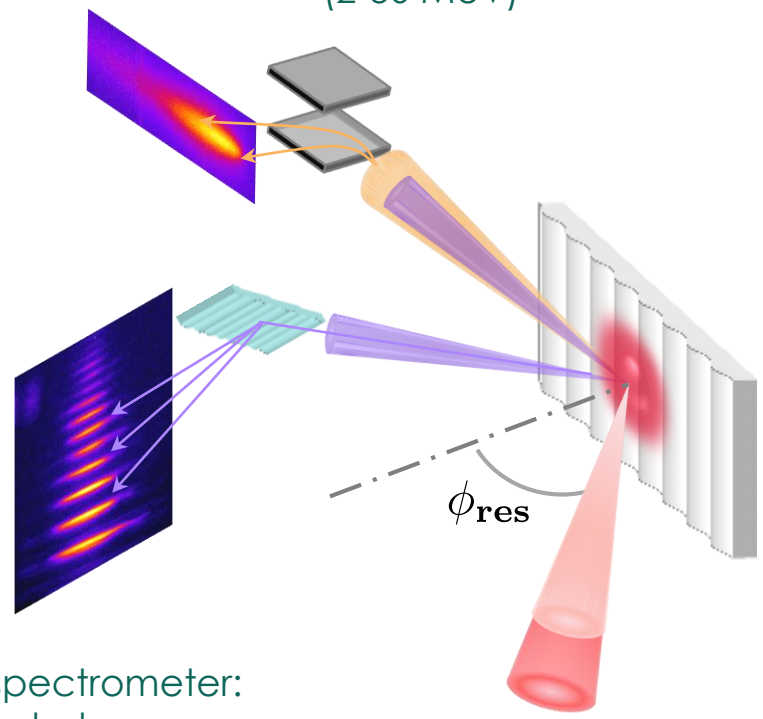
ω_H/ω_L=[9,45]

35° incidence, NO preplasma



High order harmonic generation and SP resonant excitation

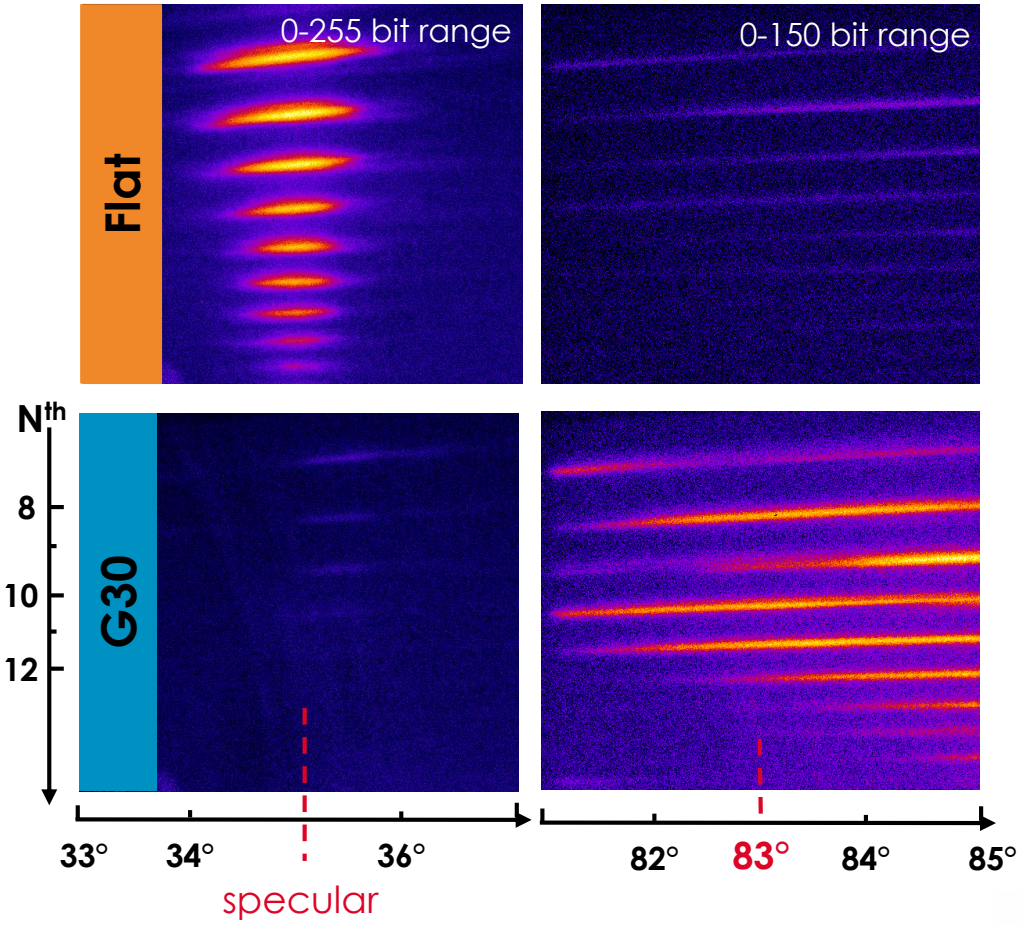
Electron spectrometer
(2-30 MeV)



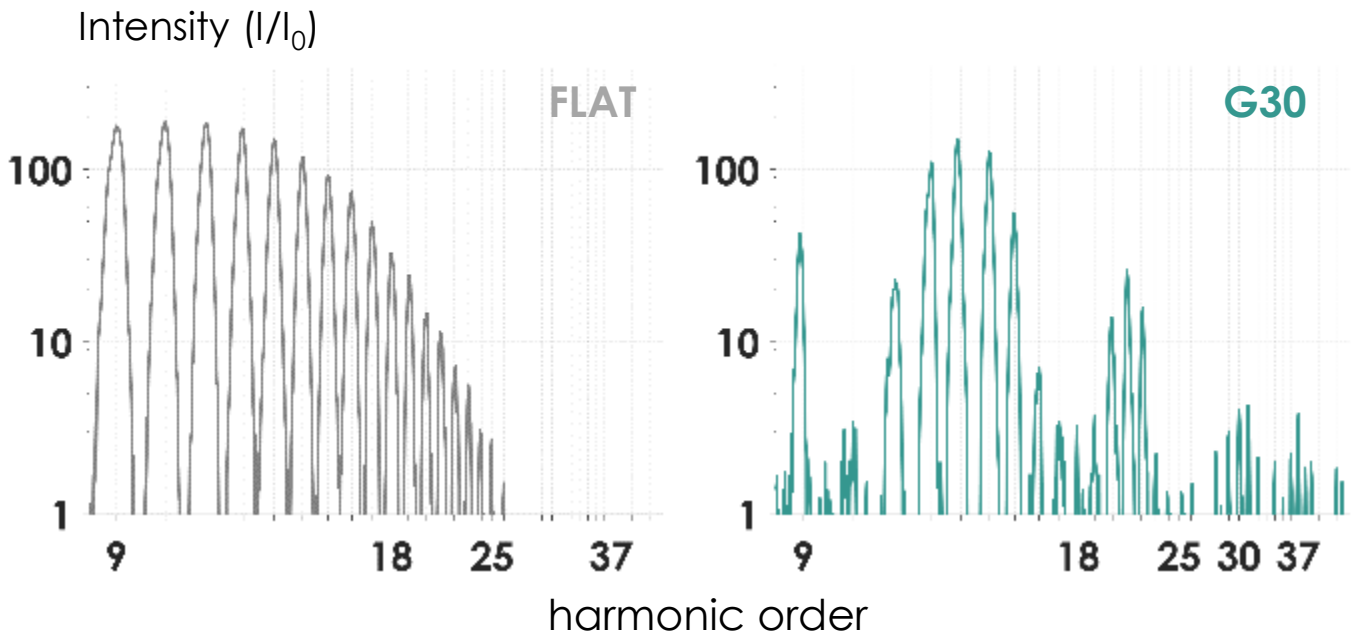
XUV spectrometer:
spectral range
ω_H/ω_L=[9,45]

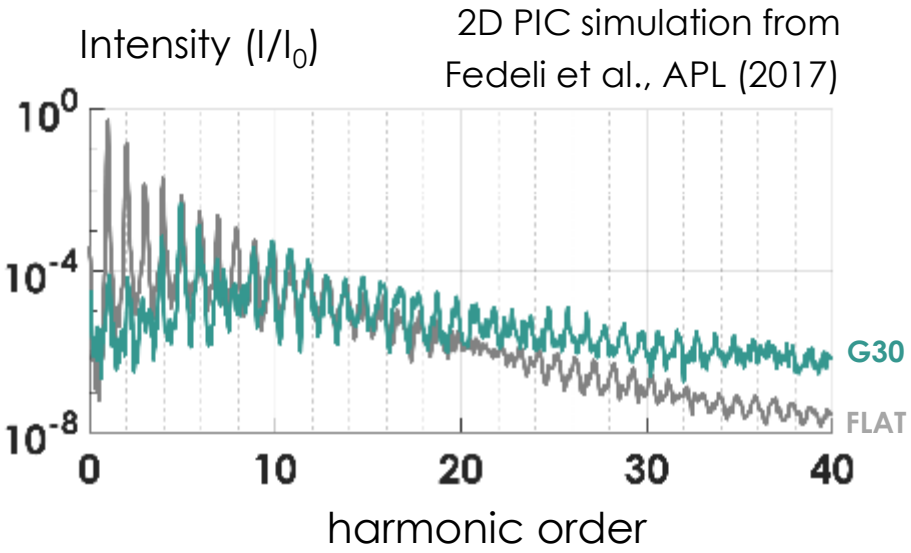
Best HH efficiency for:
$L_{pp} \sim 0.13\lambda \simeq 100$ nm
(smaller than the grating depth)

35° incidence, WITH optimized preplasma



The **maximum harmonic order** is higher with gratings at resonance.
Electrons at tangent are still detected despite the pre-plasma.





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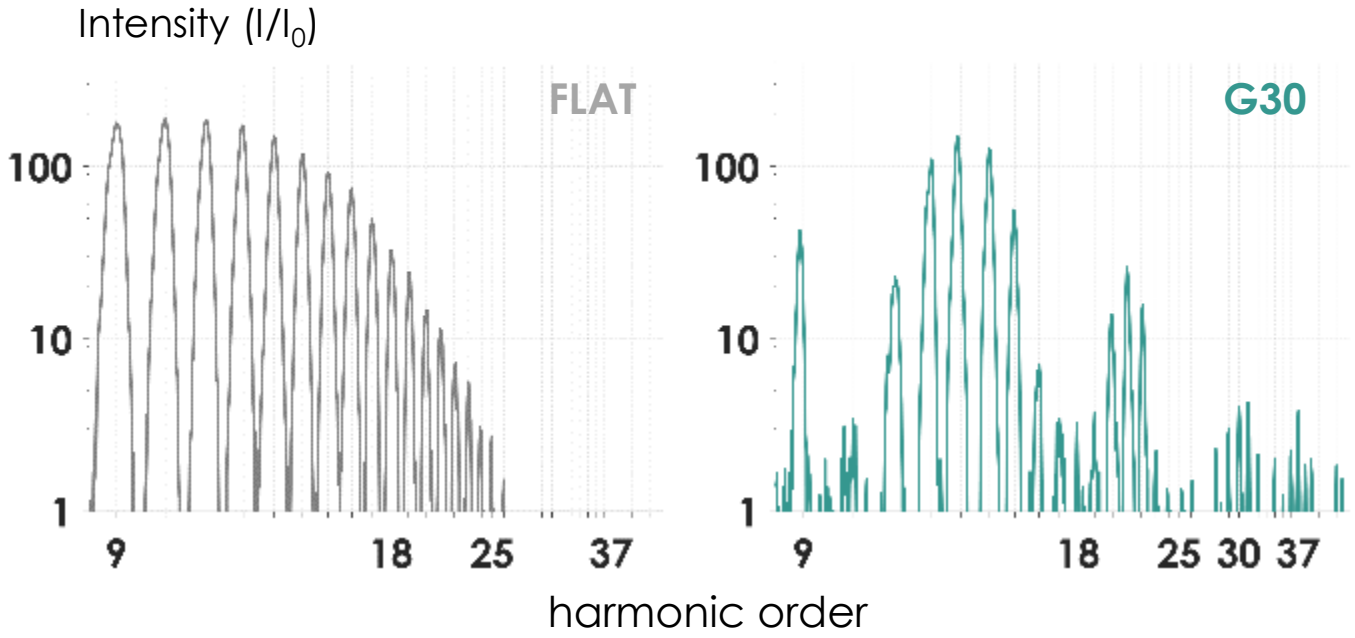
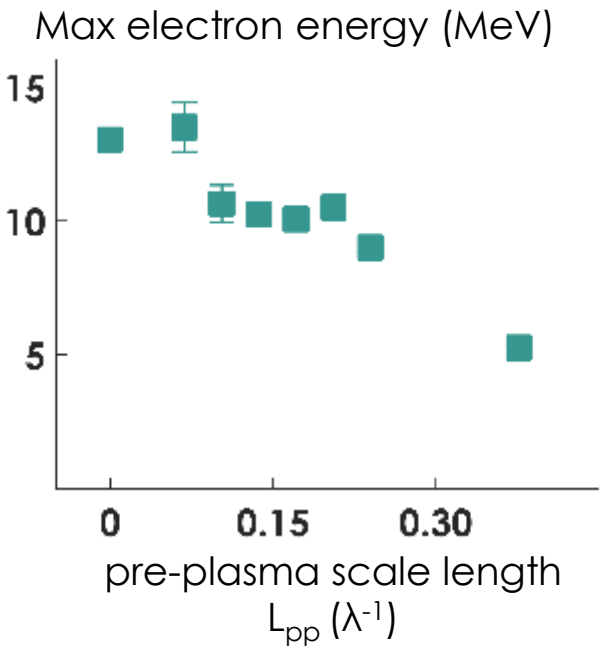
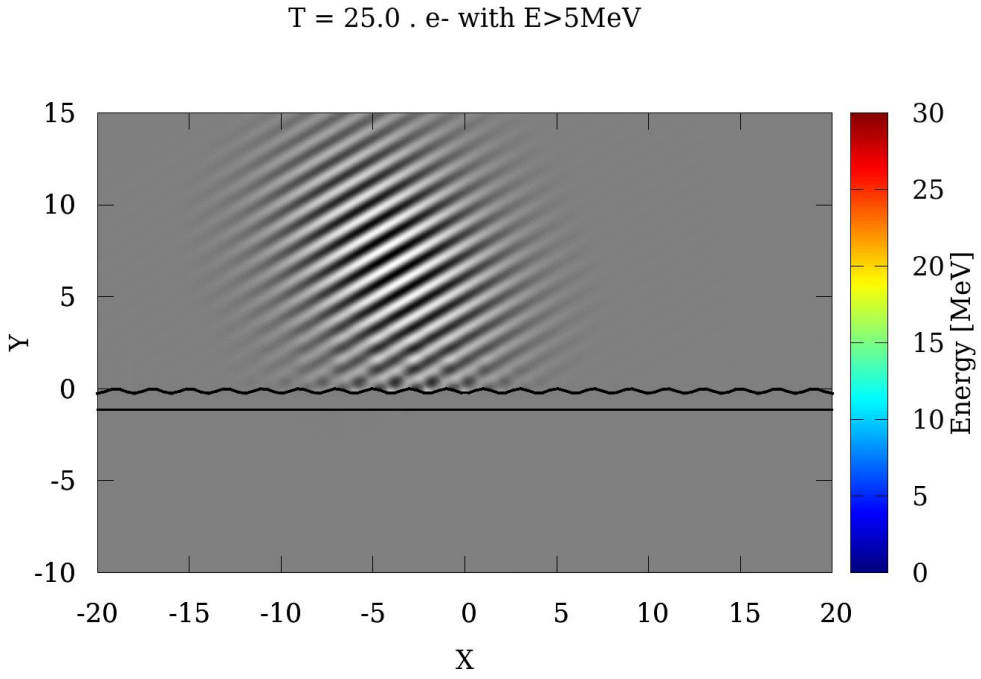




Summing up

- 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

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