Surface Plasmon-Driven Electron and Proton Acceleration

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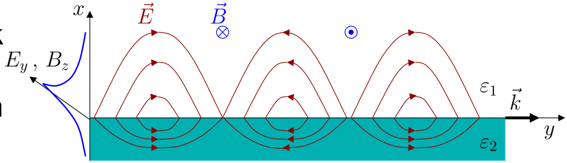
June 8, 2022

Example of Acceleration by a Strong Surface Wave

From: T. Katsouleas, “On the node of a wave”,
Nature **444** (2006) 688

Surface Plasmon (Polariton)[1]

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):

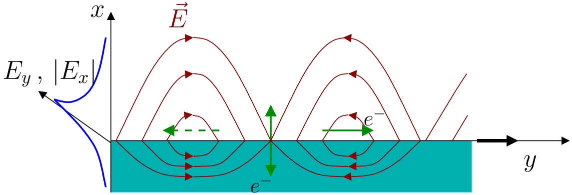
$$\varepsilon_1 = 1 \qquad \varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c(\omega)} < -1$$

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

[1] aka Surface Plasma Wave

Surfin' the Surface Wave

Can a SP accelerate electrons like a "bulk" plasma wave?



- longitudinal E-component (E_y)
- sub-luminal phase velocity $v_{\mathrm{p}} < c$

  (with $v_{\mathrm{p}} \to c$ when $\omega_p \gg \omega$)

$\rightarrow$ electrons may "surf" the SP

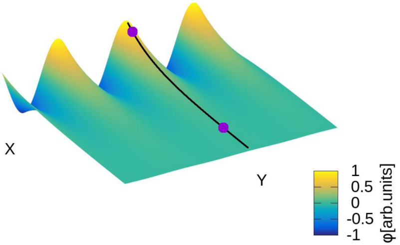
Simple Model of SP Acceleration - I

SP field on the vacuum side is electrostatic in the wave frame S' moving with phase velocity $\beta_\mathrm{p} = v_\mathrm{p}/c$ with respect to S (lab)
Electrostatic potential in S':

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

The motion is 2D: the energy gain depends on the “kick angle” from the top of the potential hill

φ in the co-moving reference frame



Simple Model of SP Acceleration - II

Assume as the most likely case an electron going downhill along the x-direction and acquiring an energy $W' = eE_{\text{SP}}/k'$

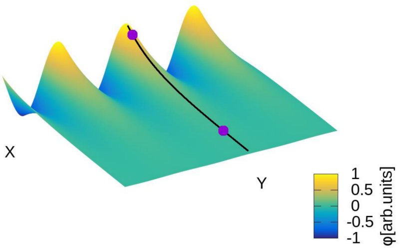
$$W \simeq \gamma_{\text{p}} W' \simeq m_e c^2 a_{\text{SP}} \frac{\omega_p^2}{\omega^2} \qquad (a_{\text{SP}} = eE_{\text{SP}}/m_e \omega c)$$

with ejection angle in L (for $W' \gg m_e c^2$)

$$\tan\phi_e = \frac{p_x}{p_y} \simeq \frac{1}{\gamma_{\text{p}}}$$

$\rightarrow$ high energy electrons are beamed near the surface ($\tan\phi_e \ll 1$)

φ in the co-moving reference frame



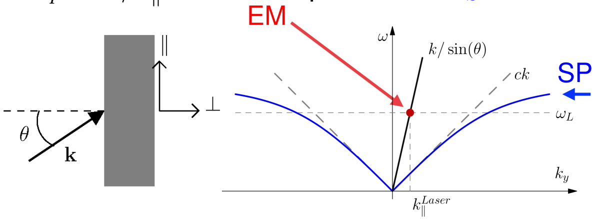
Exciting Surface Plasmons with Laser Light

Phase matching requirement between SP and plane EM wave ($\omega_{\rm EM} = |\mathbf{k}_{\rm EM}|c$):

$\varphi_{\rm EM} = \varphi_{\rm SP}$ where $\varphi = \mathbf{k}_{\parallel} \cdot \mathbf{r} - \omega t$

i.e. phase velocities $v_p = \omega / k_{\parallel}$ must be equal $v_{\rm EM} = v_{\rm SP}$

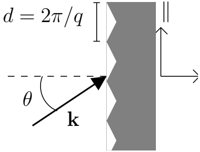
No matching with EM wave at a plane interface:

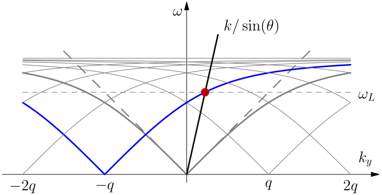


$$v_{\rm EM} = \frac{c}{\sin\theta} > c \qquad v_{\rm SP} = c\left(\frac{2 - \omega_p^2/\omega^2}{1 - \omega_p^2/\omega^2}\right)^{1/2} < c$$

Grating Coupling

Periodic grating:
"replica" (*)
of $\omega_{\mathrm{SP}}(k_{\|})$
enables matching





$k_{\mathrm{EM}\|} = k_{\mathrm{SP}} \pm nq \quad (n = 1, 2, \ldots)$

q: grating vector

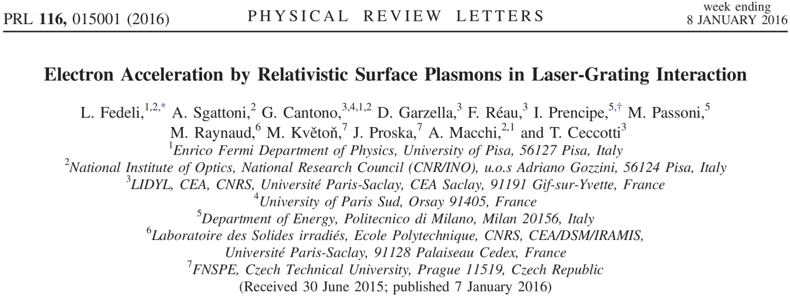
Matching occurs at "resonant" incidence angles (for $\omega_p/\omega \gg 1$)

$\sin\theta \simeq n\frac{\lambda}{d} - 1$ ($\equiv$ diffraction order along the surface)

- usually $n = 1$
- actually an infinite grating is not strictly required
(a local surface modulation may suffice)

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

Observation of “Surfing” Acceleration


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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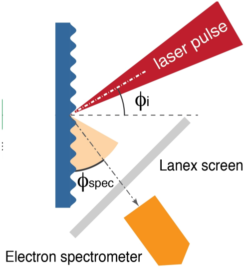
(Received 30 June 2015; published 7 January 2016)

LaserLAB experiment at SLIC, CEA Saclay

UHI laser: 25 fs pulse, $5 \times 10^{19}\ \mathrm{Wcm}^{-2}$, $a_0 = 4.8$

contrast $\gtrsim 10^{12}$ at 5 ps

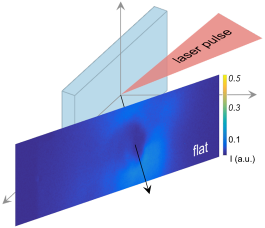
Observation of “Surfing” Acceleration

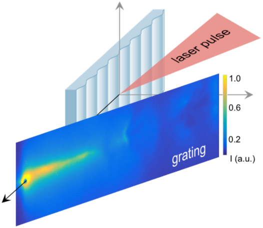


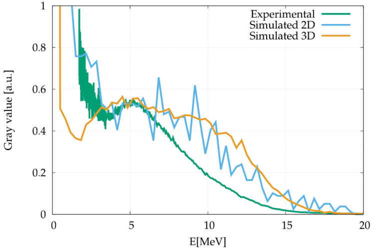
collimated ($\simeq 20°$ cone) electron emission near the surface tangent ($\phi \simeq 2°$)

multi-MeV energy, total charge $\simeq 100$ pC

Excellent agreement with 3D simulations

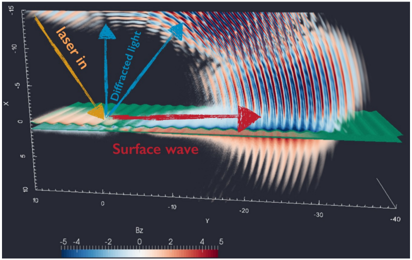


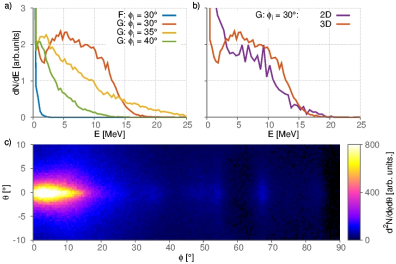




3D Simulations of the Experiment

Fully kinetic, EM Particle-In-Cell simulations with PICcante[2]





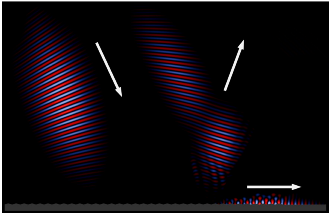
Simulations confirm excitation of relativistic SP and reproduce measurements quantitatively and in detail!

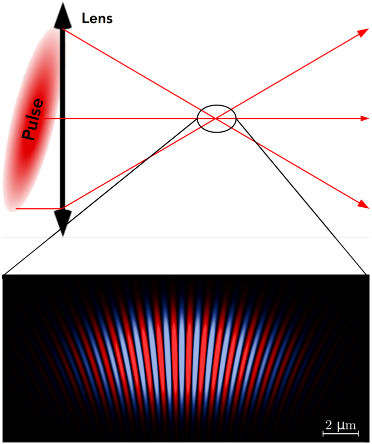
A.Sgattoni, L.Fedeli, S.Sinigardi et al, arXiv:1503.02464

[2] Particle-In-Cell Code for AdvaNced simulations on TiEr-0 systems

In-Pulse Rotation of Incidence Angle

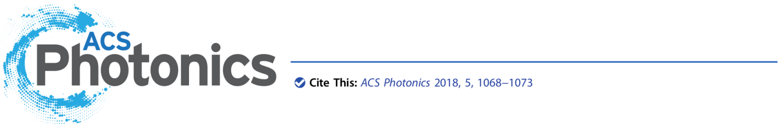
Inducing wavefront rotation (WFR) in the laser pulse the effective incidence angle rotates in time $\longrightarrow$ "resonant" condition holds only for an interval only shorter than the driving pulse





WFR obtained by focusing a tilted wavefront pulse

Near “Single-Cycle” Surface Plasmon Polariton



Cite This: *ACS Photonics* 2018, 5, 1068−1073

Few-Cycle Surface Plasmon Polariton Generation by Rotating Wavefront Pulses

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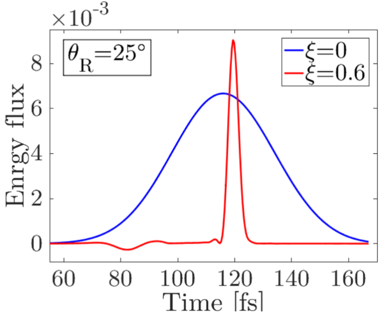
F. Pisani, L. Fedeli, A. Macchi, ACS Photonics **5** (2018) 1068

Near "Single-Cycle" Surface Plasmon Polariton

MEEP[3] simulations of
WFR pulse on Ag grating

SPP w/o and with WFR
duration: 3.8 fs (~ 1.4 cycles)

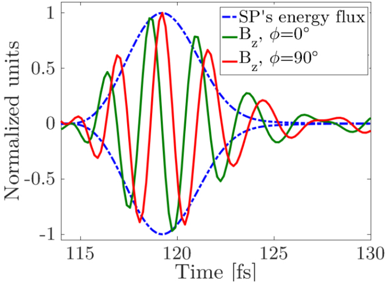


$E = E(r,z,t)\exp(-i\omega_L t + ir\xi t + \phi)$

ξ : WFR parameter

laser: 30 fs , $\lambda_L = 0.8\ \mu$m

dependence on
absolute phase ϕ



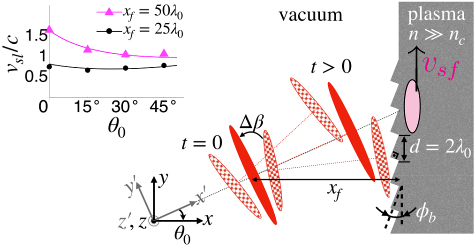
[3] http://ab-initio.mit.edu/wiki/index.php/Meep

WFR Enhancement of SPP Amplitude

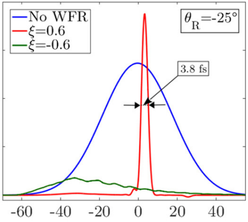
"Sliding focus" effect: WFR makes the laser spot move along the target with velocity

$$v_{sf} \simeq \frac{\Delta\beta\, x_f}{\lambda \cos^2\theta_0} \propto x_f \xi$$

(x_f: waist-to-target distance)



When $v_{sf} \simeq c$ the SPP is "sustained" along its propagation: increase of peak amplitude (Note the effect of the **sign** of ξ)



WFR Effect on Electron Acceleration

PHYSICAL REVIEW E **103**, L021201 (2021)

Letter

Ultrashort high energy electron bunches from tunable surface plasma waves driven with laser wavefront rotation

S. Marini,[1,2] P. S. Kleij,[1,2,3] F. Pisani,[3] F. Amiranoff,[2] M. Grech,[2] A. Macchi,[4,3] M. Raynaud,[1] and C. Riconda[2,*]
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S. Marini, P. Kleij, F. Pisani, F. Amiranoff, M. Grech, A. Macchi, M. Raynaud, C. Riconda
Phys. Rev. E **103** (2021) L021201

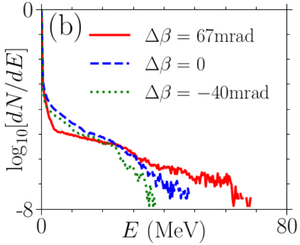
WFR Effect on Electron Acceleration

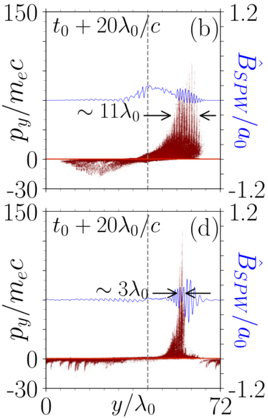
SMILEI open source PIC code

27 fs & 4×10^{19} W cm^{-2} laser pulse

WFR may double the cut-off energy of the electron bunch while shortening its duration down to 8 fs

(simulations by S. Marini and P. Kleij)





Grating Drawbacks

- grating targets are expensive
- need of ultrahigh contrast pulses to preserve the shallow modulation
- strong EM scattering losses of the SP propagating along the grating (inverse to the generation process)

  (might be reduced by having the grating only in the laser spot but would require perfect pointing stability)

$\longrightarrow$ Can we do surfing acceleration *without* a grating?

Dephasing vs Acceleration Length

Phase difference between SP and incident laser after propagating over a distance L:

$$\Delta\phi = (k_{\mathrm{EM}\|} - k_{\mathrm{SP}})L = \left(\frac{1}{v_{\mathrm{EM}}} - \frac{1}{v_{\mathrm{SP}}}\right)\omega L$$

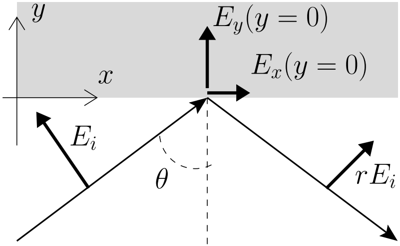
$$\Delta\phi \doteq \pi \quad \longrightarrow \quad L = \frac{\pi}{k_{\mathrm{SP}} - k_{\mathrm{EM}}} \equiv L_{\mathrm{dep}}$$

At grazing incidence $(\alpha = \pi/2 - \theta \ll 1)$ $\quad L_{\mathrm{dep}} \simeq \dfrac{\lambda}{\alpha^2 + n_c/n_e}$

If $L_{\mathrm{dep}} > L_{\mathrm{acc}}$ acceleration is not limited by dephasing

Coupling without Grating

To drive the SP efficiently
the incident EM field must have:
1) a non-vanishing component parallel to the surface (E_x)
$\longleftarrow$ reflectivity $R = |r|^2 < 1$



2) a E_x/E_y ratio close as possible to the value for the SP:

$$\left.\frac{E_{\mathrm{EM},x}}{E_{\mathrm{EM},y}}\right|_{y=0^+} = -\varepsilon\frac{1-r}{1+r}\frac{\cos\theta}{\sin\theta} \qquad \left.\frac{E_{\mathrm{SP},x}}{E_{\mathrm{SP},y}}\right|_{y=0^+} = -i|\varepsilon|^{1/2}$$

asymptotically equal for $\sin\theta \to 1$

Laser Spot Stretching Effects

At grazing incidence the laser spot is stretched along x
$\longrightarrow$ the intensity on target decreases

$$I(\theta) = I(0)\cos\theta = I(0)\sin\alpha$$

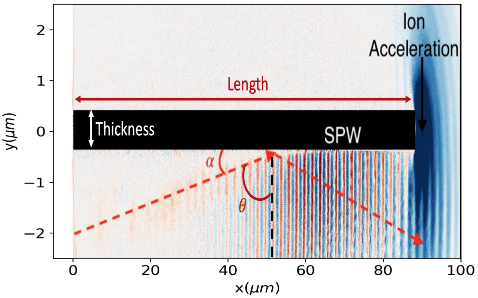
With respect to the case with grating (typical $\theta \lesssim 45°$) the effect on electron acceleration may be compensated by:

1. slow scaling of electron energy $\mathcal{E}_e \propto E_{\rm SP} \propto \sin^{1/2}\alpha$
2. no loss from radiative scattering
3. no saturation (observed in grating simulations at $a_0 \gtrsim 10$)

Strong (unknown) nonlinear effects on SP are prevented

Simulation Set-Up

PIC code EPOCH simulations by J. Sarma & A. McIlvenny



2D Cartesian geometry
Target: fully ionized Au with CH contaminant layer
electron density $n_e = 1.7 \times 10^{23}$ cm^{-3}
thickness $d = 0.8\ \mu$m
length $L_T = (90 - 200)\ \mu$m

Pulse: $\lambda = 0.8\ \mu$m ($n_e = 100 n_c$)
Gaussian profiles, width $6.5\ \mu$m, duration 35 fs (FWHM)
intensity $I = (0.34 - 7.8) \times 10^{20}$ Wcm^{-2}
"relativistic" parameter $a_0 = (5 - 19)$

Electron Spectrum for Different Angles

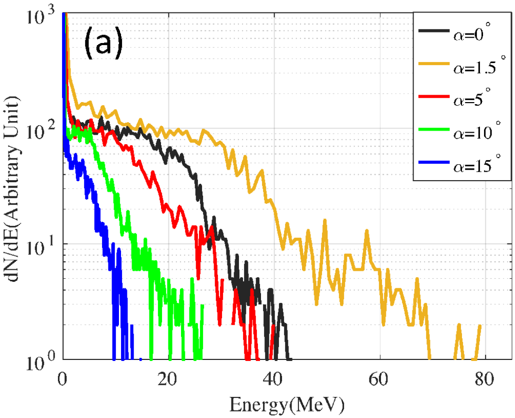
Maximum energy for $\alpha = 1.5°$

Cut–off value doubles with respect to both $\alpha = 5°$ and $\underline{\alpha = 0°}$ (**parallel** incidence, to be discussed later)

($\simeq$ 20 MeV obtained with gratings for similar parameters[4])

$I = 3.4 \times 10^{19}\ \mathrm{Wcm}^{-2}$

$L_T = 90\ \mu\mathrm{m}$



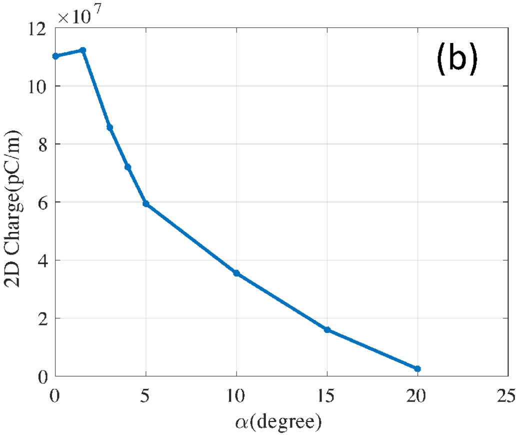
[4]Cantono et al, PoP **25** (2018) 031907

Accelerated Charge for Different Angles

Peak value $\simeq 10^8\ \mathrm{pCm}^{-1}$ in 2D corresponds to $\simeq 780\ \mathrm{pC}$ in 3D ($\simeq 660\ \mathrm{pC}$ obtained with blazed gratings for similar parameters[5])

$I = 3.4 \times 10^{19}\ \mathrm{Wcm}^{-2}$

$L_T = 90\ \mu\mathrm{m}$



[5] Cantono et al, PoP **25** (2018) 031907

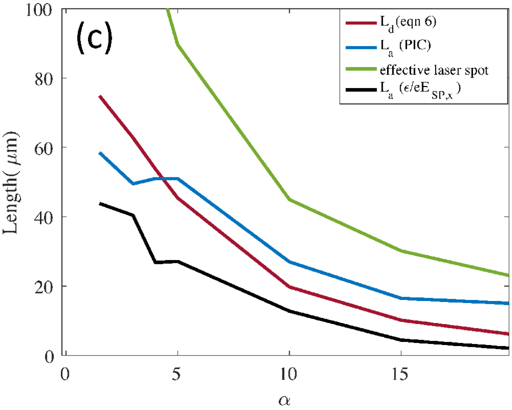
Acceleration Length for Different Angles

Two different estimates of the acceleration length ($L_{\rm acc}$) are fairly close to the dephasing length $L_{\rm dep}$ as a function of α

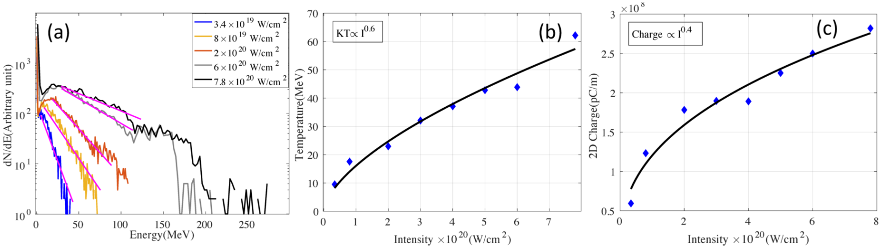
Spot width on target $L_S > L_{\rm dep}$ (could be further optimized)

$I = 3.4 \times 10^{19}\ {\rm Wcm}^{-2}$

$L_T = 200\ \mu{\rm m}$



Scaling with Laser Intensity



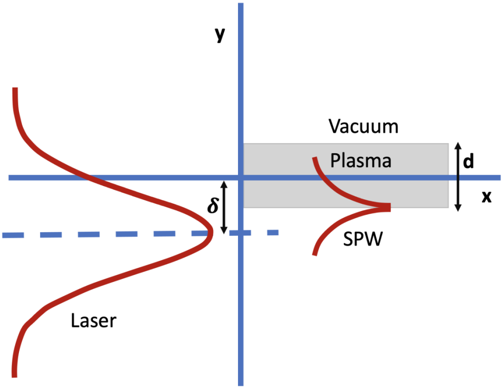
a) electron spectra b) electron “Temperature” c) charge density

Temperature exceeds “ponderomotive” values
$(T_{\rm p} = m_e c^2(\sqrt{(1+a_0^2/2)}-1))$ by one order of magnitude
Peak charge density value $\simeq 3\times10^8$ pCm^{-1} in 2D corresponds to an estimate $\simeq 1.9$ nC in 3D

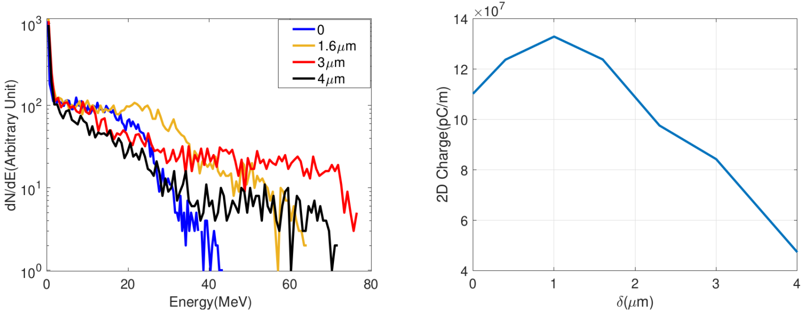
Parallel Incidence

For **parallel** incidence ($\alpha = 0°$) the laser pulse will interact with the (left) short edge of the target

Additional parametric dependence on the "focal spot shift" δ $\equiv$ distance between the laser propagation axis and the target midplane (surface at $y = -\delta/2$)



Effect of δ on Spectra and Charge (Low I)



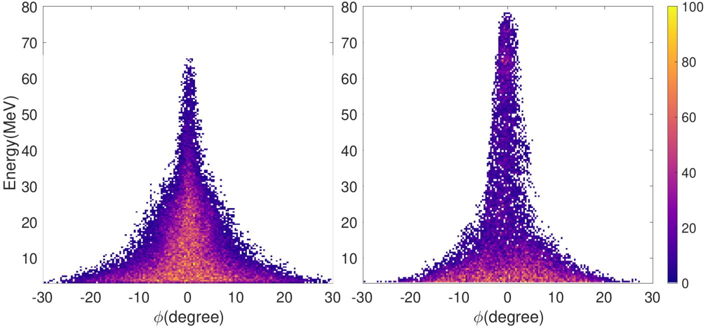
a) electron spectra

b) charge density

$I = 3.4 \times 10^{19}\ \mathrm{Wcm}^{-2}$

Maximum values are *not* for $|\delta| \leq d/2$

Electron Collimation

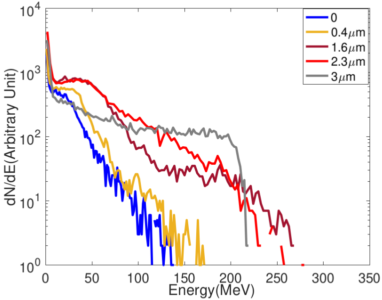


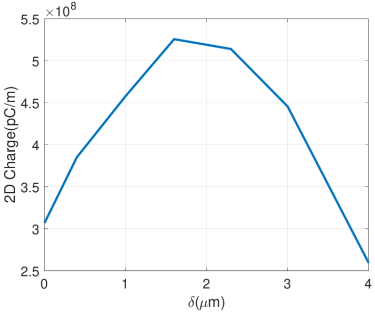
a) $\delta = 0$ b) $\delta = 3\ \mu\mathrm{m}$

$I = 3.4 \times 10^{19}\ \mathrm{Wcm}^{-2}$

Electrons are strongly collimated with almost symmetrical distribution even for "asymmetrical" interaction with $\delta \neq 0$

Effect of δ on Spectra and Charge (High I)



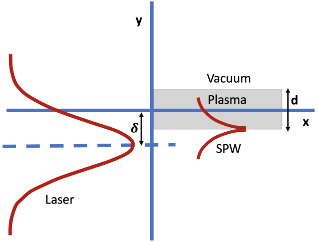


a) electron spectra

b) charge density

$I = 6 \times 10^{20}$ Wcm^{-2}
Total 3D charge would be $\simeq 3.4$ nC for $\delta = 1.6\ \mu$m

On the effect of “shift” δ



Similar coupling conditions
as for grazing incidence:

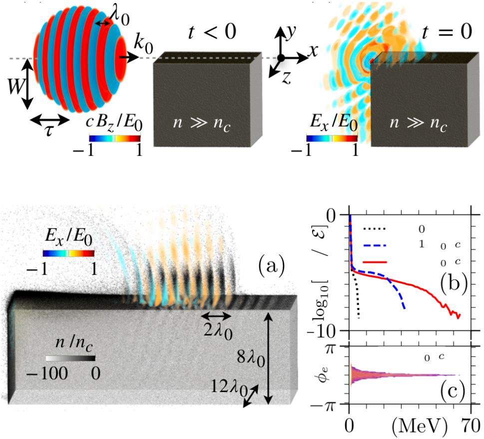
Laser field components (in vacuum)

$$E_{\mathrm{EM},y} \simeq E_0 \exp\left(-(y+\delta)^2/w^2\right) \exp\left(ik_{\mathrm{EM},x}\right)$$
$$E_{\mathrm{EM},x} \simeq 2y/(ik_{\mathrm{EM},x}w^2) \exp\left(-(y+\delta)^2/w^2\right) \exp\left(ik_{\mathrm{EM},x}\right)$$
$$\left|\frac{E_{\mathrm{EM},x}}{E_{\mathrm{EM},y}}\right|_{y=-d/2} \simeq \frac{(\delta-d/2)\lambda}{\pi w^2}$$

For $w = 3.9\mu\mathrm{m}$, the $|E_x|/|E_y|$ ratio at the surface ($y = -d/2$) for $\delta = 2.3$ μm is the same as for $\alpha = 1.7°$.

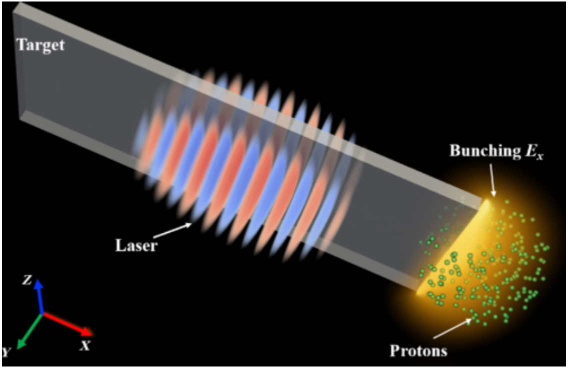
A Possibly Similar Work?

S.Marini, P.Kleij, M.Grech, M.Raynaud, C.Riconda,
"Electron acceleration by laser plasma wedge interaction"
arXiv:2202.08226



Proposed "Peeler" Proton Acceleration

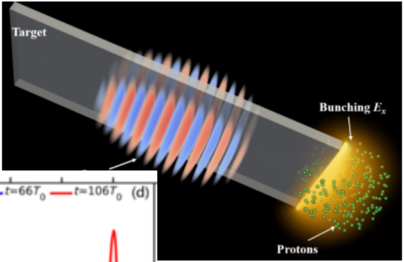
"A fs laser (red and blue) is incident on the edge of a micron-thick tape (grey) [. . .] Abundant electrons are accelerated forward by the intense laser."

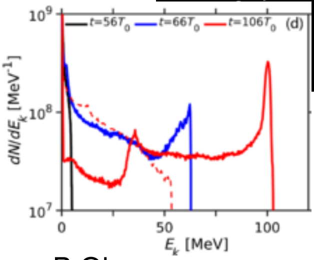


X.Shen, A.Pukhov, B.Qiao, Phys. Rev. X **11** (2021) 041002

Proposed "Peeler" Proton Acceleration

"[. . .] at the rear edge a longitudinal bunching field is established (yellow). Protons (green dots) are simultaneously accelerated and leading to a highly monoenergetic beam."





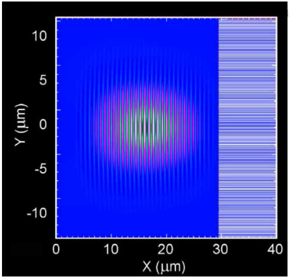
Pulse: $45\ \mathrm{fs}$
$7.8 \times 10^{20}\ \mathrm{Wcm}^{-2}$
Target:
$n_e/n_c = 30$
$d = 50\ \mathrm{nm}$

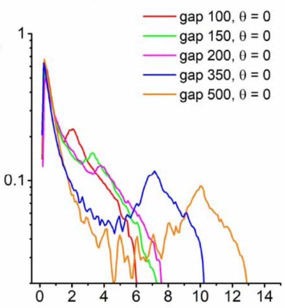
X.Shen, A.Pukhov, B.Qiao, Phys. Rev. X **11** (2021) 041002

Earlier Numerical Observation?

2D simulations of an array of parallel foils:
electron acceleration attributed to SP
peaked proton spectra appear for large gaps

Pulse: 30 fs
$2.8 \times 10^{20} \text{ Wcm}^{-2}$
Target: $n_e/n_c = 60$
$d = 0.6 \ \mu\text{m}$





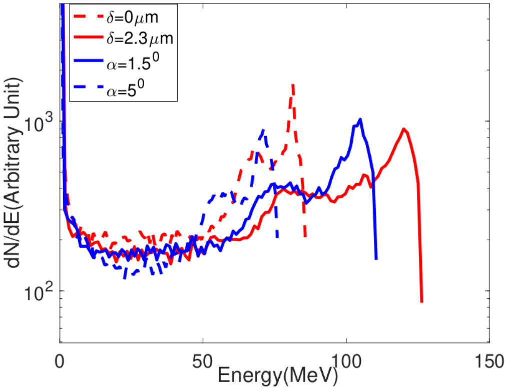
Cristoforetti et al, Plasma Phys. Control. Fusion **62** 114001

Proton Spectra (High I)

Highest cut-off energy is reached for parallel incidence with "shifted" pulse ($\delta = 2.3\ \mu\text{m}$)

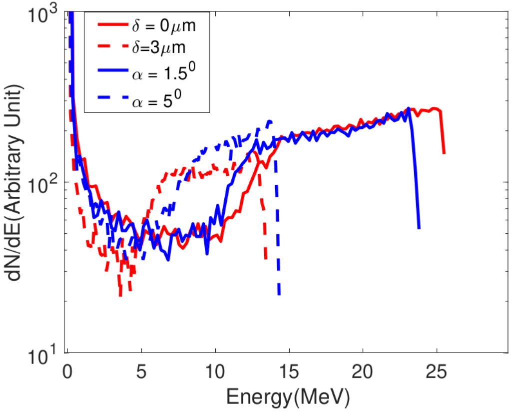
Slightly lower energy at grazing incidence ($\alpha = 1.5°$)

$I = 6 \times 10^{20}\ \text{Wcm}^{-2}$



Proton Spectra (Low I)

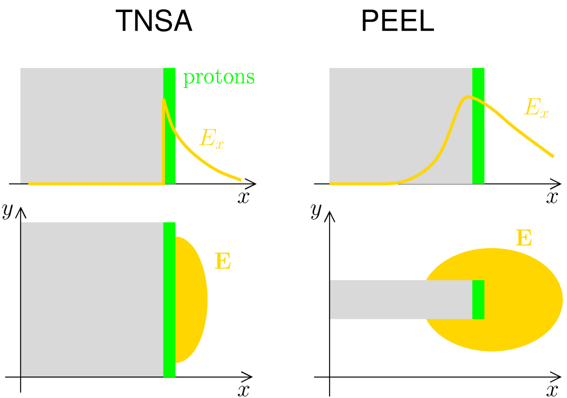
Sharply peaked spectra are not apparent for lower intensity
$I = 3.4 \times 10^{19}$ Wcm^{-2}



Origin of Monoenergetic Proton Spectra

TNSA: fast electrons are less than protons in the layer which screen the $\mathbf{E}$-field producing a sharp gradient

PEEL: protons are less than fast electrons and the space charge $\mathbf{E}$-field on the proton layer is spatially "smooth".



All protons experience almost the same field $\longrightarrow$ monoenergetic acceleration

Conclusions

- Surface Plasmons may be efficiently excited at grazing incidence
- The SP wave is sustained along a distance sufficient to accelerate electrons to high energies
- The “peeler” geometry exploits the high charge SP-driven electrons for efficient mono-energetic acceleration of protons

Coming soon:
J. Sarma, A. McIlvenny, N. Das, M. Borghesi, A. Macchi, “Surface Plasmon-Driven Electron and Proton Acceleration without Grating Coupling” (under review)