Surfin’ the Surface Wave: a New Approach to Plasma-based Acceleration

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Example of Acceleration by a Strong Surface Wave

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

Producing the Perfect Wave for Electrons

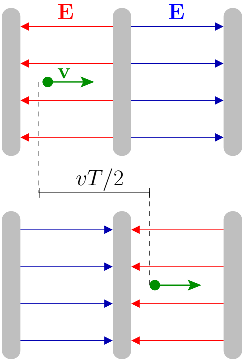
To accelerate either surfers or electrons a wave must have:

1. longitudinal force compoment
2. phase velocity $v_p \approx$ surfer velocity v

$\longrightarrow v_p \lesssim c$ for relativistic electrons

- LINAC principle: sequence of cavity with alternating fields

$$L \simeq vT/2 \simeq cT/2 = \pi c/\omega$$



A plasma wave in a cold plasma with phase velocity v_p can be seen as a sequence of "cavities" with $T = \pi/\omega_p$ and $L = v_p T_p$

$\omega_p = (4\pi e^2 n_e/m_e)^{1/2}$ plasma frequency

Tutorial: A. Macchi, Am. J. Phys. **88** (2020) 723

Wake Waves

An object (e.g. duck) moving at velocity V produces a wake of oscillations with $v_p = V$

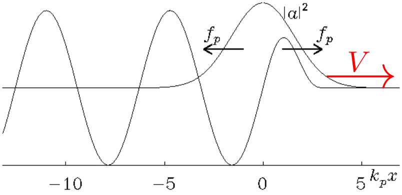
Bodensee at Bad Schachen, Lindau, Germany.

Photo by Daderot, Wikipedia, public domain.

Laser wakefield acceleration: a pulse of duration $\simeq \pi/\omega_p$ drives a plasma wake with $v_p = c(1-\omega_p^2/\omega^2)^{1/2} \lesssim c$

T.Tajima & J.Dawson,

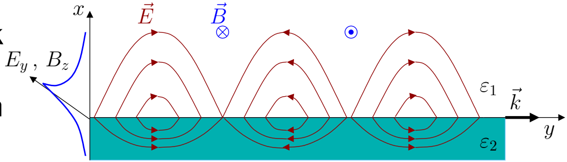
Phys. Rev. Lett. **43**(1979) 267



[Textbook: A. Macchi, *A Superintense Laser-Plasma Interaction Theory Primer* (Springer, 2013)]

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):

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

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

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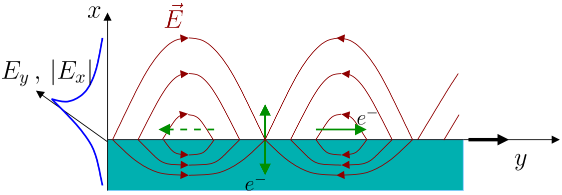
[1] aka Surface Plasma Wave

Surfin' the Surface Wave



SP can accelerate electrons much like "bulk" plasma waves:

- longitudinal E-component (E_y)
- phase velocity $v_\mathrm{p} \lesssim c$ (with $v_\mathrm{p} \to c$ when $\omega_p \gg \omega$)

Simple model predicts for maximum energy and emission angle (relative to surface):

$$\mathcal{E} \simeq m_e c^2 a_\mathrm{SP} \frac{\omega_p^2}{\omega^2} \qquad \tan\phi_e = \frac{p_x}{p_y} \simeq \frac{1}{\gamma_\mathrm{p}} \qquad \left(a_\mathrm{SP} \equiv \frac{eE_y}{m_e \omega c} \right)$$

Macchi et al, Phys. Plasmas **25** (2018) 031906; **26** (2019) 042114

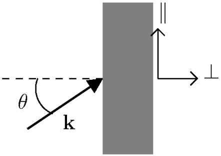
Exciting Surface Plasmons with Laser Light

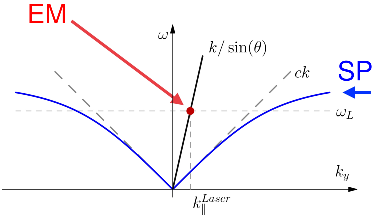
Phase matching requirement between SP and plane EM wave ($\omega_{\text{EM}} = |\mathbf{k}_{\text{EM}}|c$):

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

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

No matching with EM wave at a plane interface:

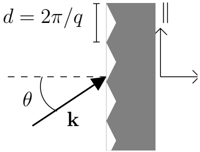


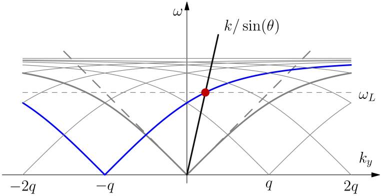


$$v_{\text{EM}} = \frac{c}{\sin\theta} > c \qquad v_{\text{SP}} = c\left(\frac{2 - \omega_p^2/\omega^2}{1 - \omega_p^2/\omega^2}\right)^{1/2} < c$$

Grating Coupling

Periodic grating:
“replica” (*)
of $\omega_{\text{SP}}(k_{\|})$
enables matching





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

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

The “Extreme” Interaction Regime

High laser irradiance: electron dynamics is relativistic and strongly nonlinear

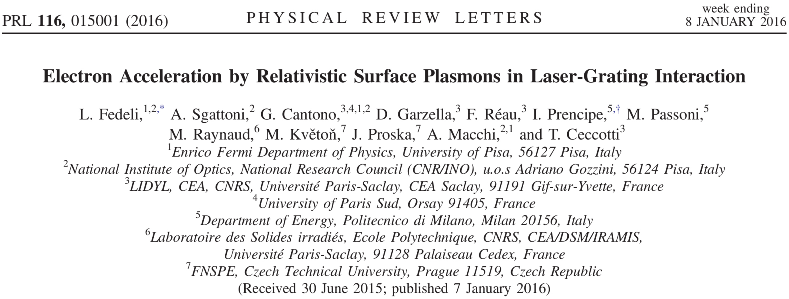
Relativistic parameter: $a_0 = \frac{eE}{m_e \omega c} = 0.85 \left(\frac{I\lambda^2}{10^{18}\ \mathrm{Wcm}^{-2}\mu\mathrm{m}^2} \right)^{1/2}$

Femtosecond pulse duration: target density profile preserved

- first investigation of SP in this regime (with unknown features: no relativistic SP theory available)
- SP may be driven to high amplitude close to “breaking” threshold with self-injection of electrons

Macchi et al, Phys. Plasmas **26** (2019) 042114

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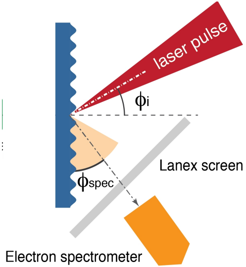
L. Fedeli et al, Phys. Rev. Lett. **116** (2016) 015001

Observation of “Surfing” Acceleration

Laserlab Europe



UHI laser: 25 fs pulse

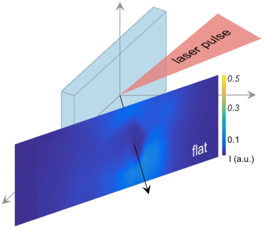
$5 \times 10^{19}\ \mathrm{Wcm}^{-2}$, contrast $\gtrsim 10^{12}$ at 5 ps

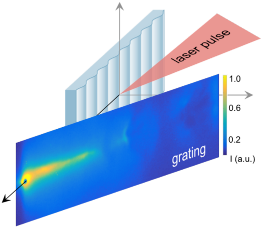
collimated ($\simeq 20^\circ$ cone) electron emission near the surface tangent ($\phi \simeq 2^\circ$)

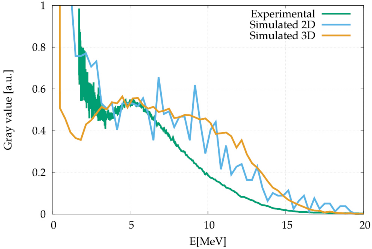
multi-MeV energy, Total charge $\simeq 100$ pC

(up to $\simeq 650$ pC with blazed gratings:

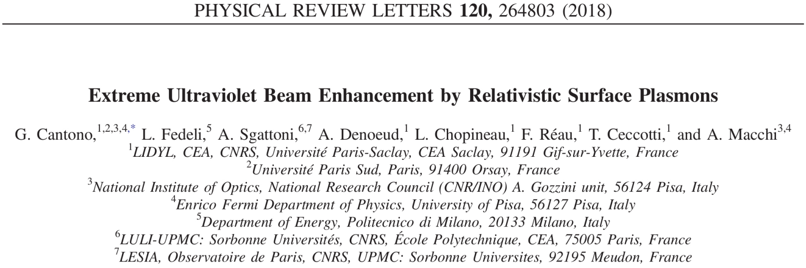
G. Cantono et al, Phys. Plasmas **25** (2018) 031907)







Observation of SP-enhanced XUV High Harmonics



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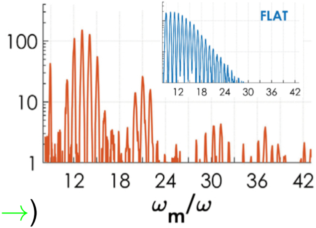
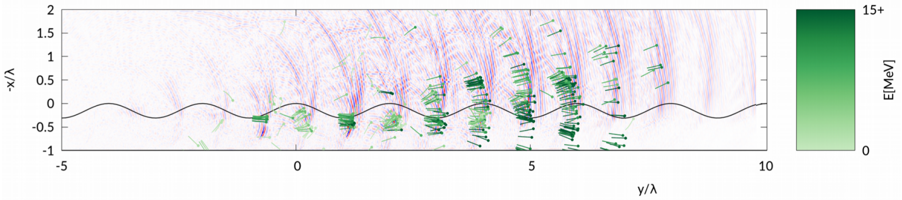
G. Cantono et al, *Phys. Rev. Lett.* **120** (2018) 264803

Observation of SP-enhanced XUV High Harmonics

Enhanced High Harmonic emission observed when Surface Plasmons are excited

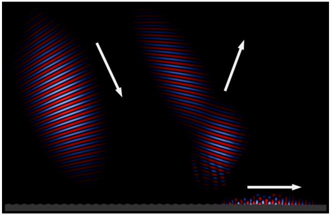


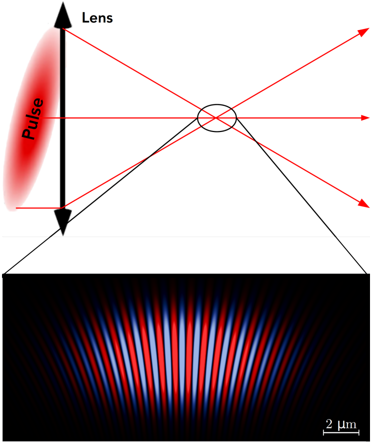
Simulations show coherent scattering from self-organized electron bunches (→) to produce quasi-collinear HH
(similar mechanism to collective instability in a FEL)



In-Pulse Rotation of Incidence Angle

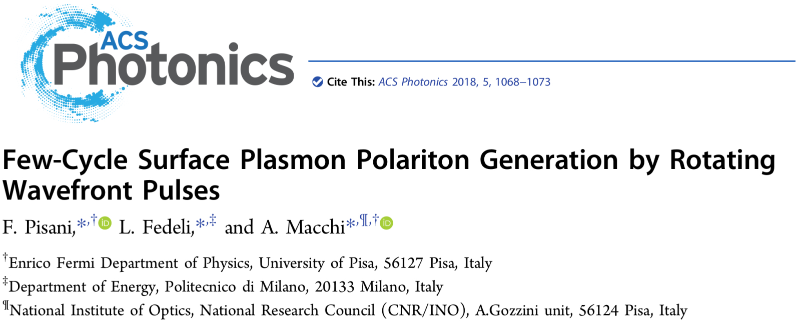
Inducing wavefront rotation (WFR) in the laser pulse the effective incidence angle rotates in time ⟶ "resonant" condition holds only for an interval shorter than the driving pulse





WFR obtained by focusing a tilted wavefront pulse

Near “Single-Cycle” Surface Plasmon Polariton



ACS Photonics

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

Few-Cycle Surface Plasmon Polariton Generation by Rotating Wavefront Pulses

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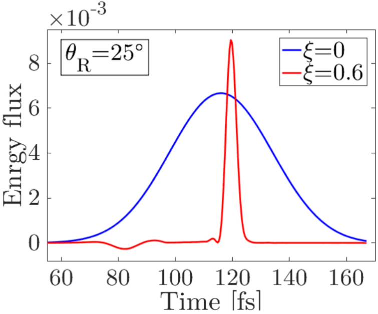
F. Pisani, L. Fedeli, A. Macchi, ACS Photonics **5** (2018) 1068

Near “Single-Cycle” Surface Plasmon Polariton

MEEP[2] simulations of
WFR pulse on Ag grating

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

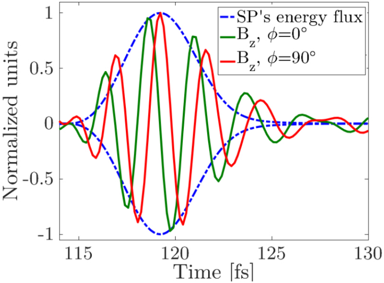


$E = E(r, z, t) \exp(-i\omega_L t + ir\xi t + \phi)$

ξ : WFR parameter

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

dependence on
absolute phase ϕ



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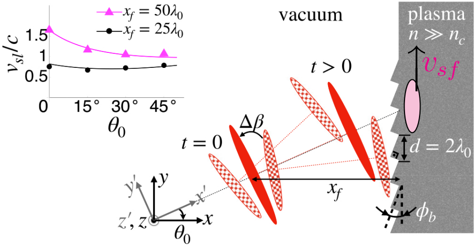
[2] http://ab-initio.mit.edu/wiki/index.php/Meep

WFR Enhancement of SPP Amplitude

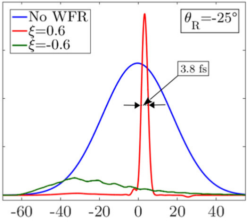


"Sliding focus" effect: WFR makes the laser spot move along the target with velocity

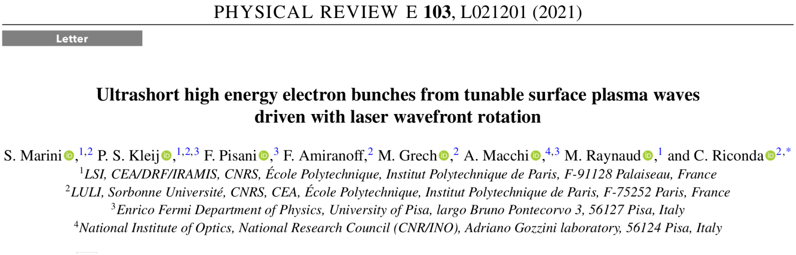
$$v_{sf} \simeq \frac{\Delta\beta\, x_f}{\lambda \cos^2\theta_0} \propto x_f \xi$$

(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

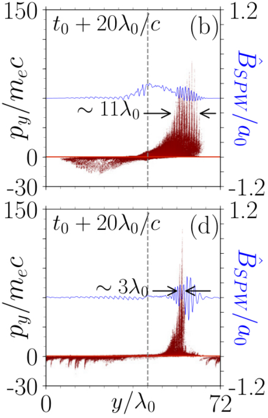
WFR Effect on Electron Acceleration

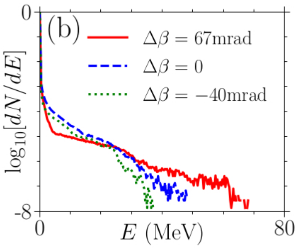
SMILEI open source PIC code

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)





waiting for experiments . . .

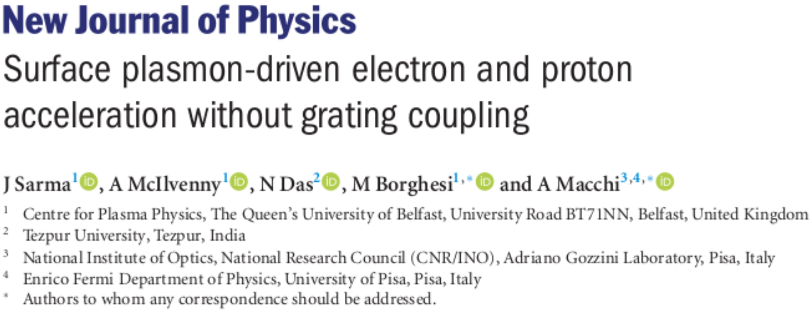
Grating Drawbacks

- grating targets are expensive
- need of ultrahigh contrast pulses free from spurious "prepulses" to preserve the shallow modulation from early damage
- 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)

⟶ Can we do surfing acceleration *without* a grating?

Acceleration with No Grating Attached



New Journal of Physics

Surface plasmon-driven electron and proton acceleration without grating coupling

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J. Sarma et al, New J. Phys. **24** (2022) 073023

Dephasing vs Acceleration Lengths

Revisiting (un-)matching between SP and incident laser pulse: phase difference after propagating over a distance L

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

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

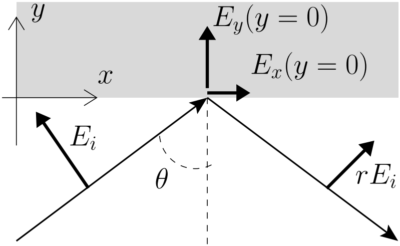
At grazing incidence $(\alpha = \pi/2 - \theta \ll 1)$ $\qquad L_{\mathrm{dep}} \simeq \frac{\lambda}{\alpha^2 + \omega^2/\omega_p^2}$

Acceleration is not limited by dephasing when

$$L_{\mathrm{dep}} > L_{\mathrm{acc}} = \frac{\mathcal{E}_{\mathrm{max}}}{eE_{\mathrm{SP}}} \simeq \frac{\lambda}{\pi}\frac{\omega_p^2}{\omega^2}$$

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:

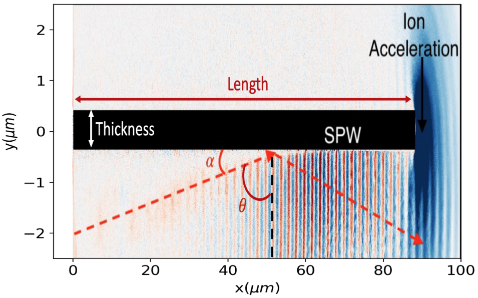
$$\left.\frac{E_{\mathrm{EM},x}}{E_{\mathrm{EM},y}}\right|_{y=0^+} = -\varepsilon\frac{1-r}{1+r}\frac{\cos\theta}{\sin\theta} \qquad \left.\frac{E_{\mathrm{SP},x}}{E_{\mathrm{SP},y}}\right|_{y=0^+} = -i|\varepsilon|^{1/2}$$

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

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
$n_e = 1.7 \times 10^{23}\ \mathrm{cm}^{-3}$
thickness $d = 0.8\ \mu\mathrm{m}$
length $L_T = (90 - 200)\ \mu\mathrm{m}$



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

Electron Energy Increase at Grazing Incidence

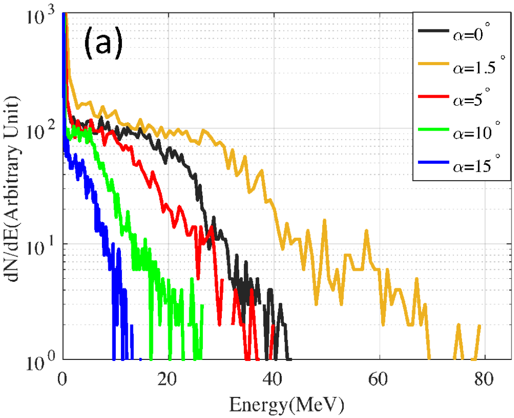
Maximum energy for $\alpha = 1.5°$

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

($\simeq$ $20\ \mathrm{MeV}$ obtained with gratings for similar parameters[3])

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

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



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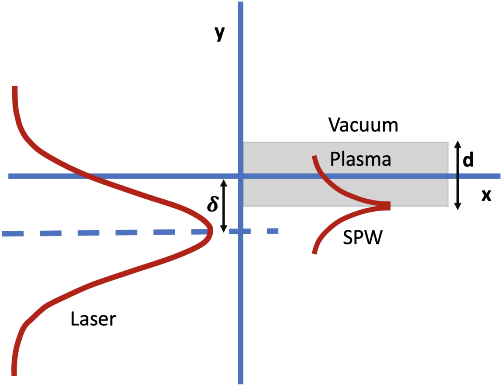
[3] Cantono et al, PoP **25** (2018) 031907

Parallel Incidence

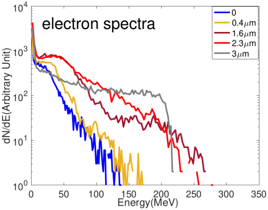
For **parallel** incidence ($\alpha = 0^\circ$) the laser pulse will interact with the (left) short edge of the target

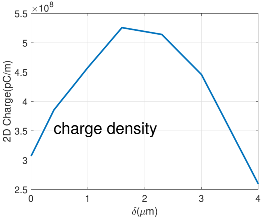
Additional parametric dependence on the "focal spot shift" δ $\equiv$ distance between the laser propagation axis and the target midplane (surface at $y = -\delta/2$)

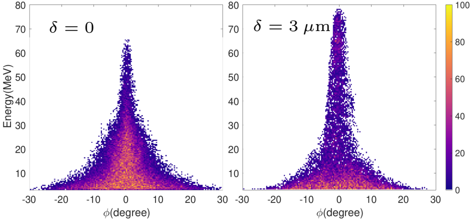


Enhancement by “Spot Shift” at Parallel Incidence

$I = 6 \times 10^{20}\ \mathrm{Wcm}^{-2}$
$\mathcal{E}_{\max} \simeq 250\ \mathrm{MeV}$
for $\delta \simeq 2\ \mu\mathrm{m}$
Total charge $\simeq 3.4\ \mathrm{nC}$
(3D estimate)
for $\delta = 1.6\ \mu\mathrm{m}$

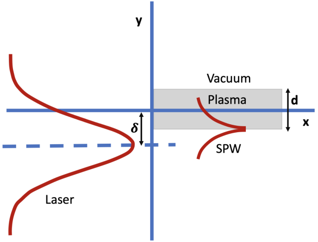






Energy-angle distributions ($I = 3.4 \times 10^{19}\ \mathrm{Wcm}^{-2}$)
Electrons are strongly collimated with almost symmetrical distribution even for “asymmetrical” interaction with $\delta \neq 0$

On the Effect of “Spot Shift”



Similar coupling conditions
as for grazing incidence:

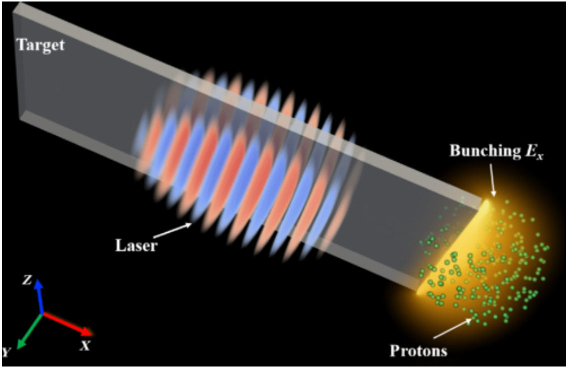
Laser field components (in vacuum)

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

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

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.”

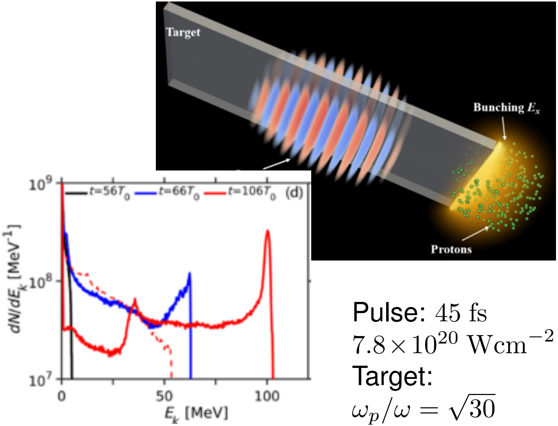


3D simulations with VLPL and EPOCH codes

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.”

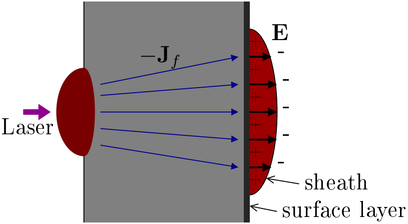


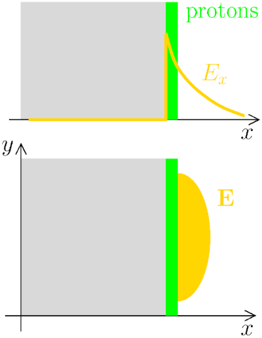
Pulse: 45 fs
7.8×10^{20} Wcm^{-2}
Target:
$\omega_p/\omega = \sqrt{30}$
$d = 50$ nm

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

Origin of Monoenergetic Proton Spectra

Protons from surface impurity layer are accelerated in a sheath generated by “hot” electrons (Target Normal Sheath Acceleration)





For a standard “wide” target the $\mathbf{E}$-field is inhomogeneous both tranversally and longitudinally (due to self-screening by protons) $\longrightarrow$ broad proton spectra

Review on ion acceleration:

A. Macchi, M. Borghesi, M. Passoni,

Rev. Mod. Phys. **85** (2013) 751

Origin of Monoenergetic Proton Spectra

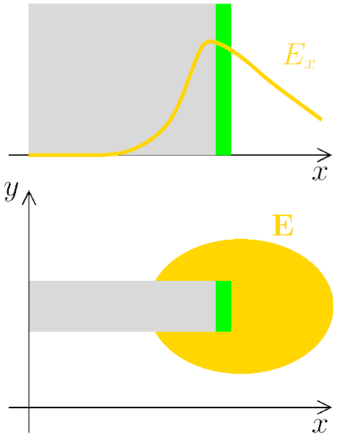
"Peeler" scheme reduces proton number with transverse localization and exploits high electron charge produced by SP-driven acceleration

Protons are now less than hot electrons: no $\mathbf{E}$-field screening

$\mathbf{E}$-field is spatially "smooth" in both directions

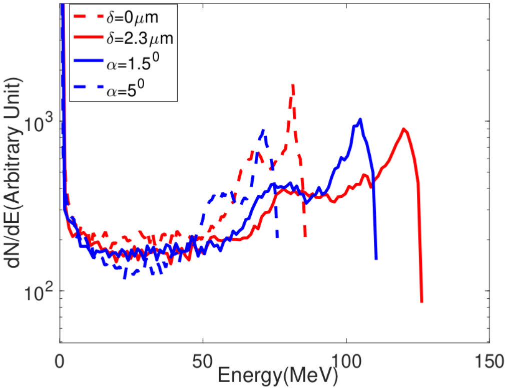
$\longrightarrow$ all protons see the same field

$\longrightarrow$ monoenergetic acceleration



Proton Spectra: 2D Simulation

Highest cut-off energy is reached for parallel incidence with "shifted" pulse ($\delta = 2.3\ \mu\mathrm{m}$) ($\sim$X 2 increase with respect to $\delta = 0$) Slightly lower energy at grazing incidence ($\alpha = 1.5^\circ$) $I = 6 \times 10^{20}\ \mathrm{Wcm}^{-2}$



Conclusions

- Superintense laser-driven Surface Plasmons drive
  - “surfing” acceleration of high charge electron bunches
  - XUV high harmonics by coherent scattering
- Perspectives for:
  - near single-cycle SP generation
  - SP-driven acceleration without grating coupling
  - “peeler” monoenergetic proton acceleration

Download this talk:

https://osiris.df.unipi.it/ macchi/talks.html

EXTRA SLIDES

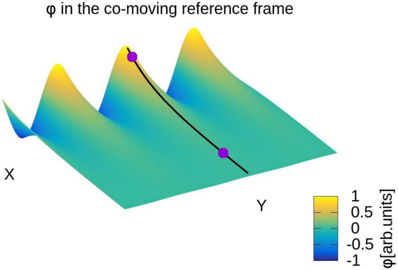
Simple Model of SP Acceleration - I

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



Simple Model of SP Acceleration - II

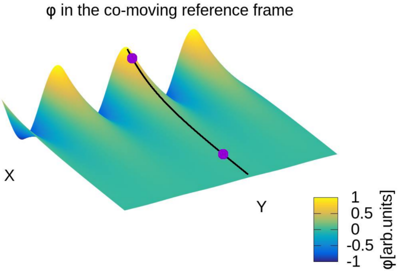
Assume as the most likely case an electron going downhill along the x-direction and acquiring an energy $W' = eE_{\mathrm{SP}}/k'$

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

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

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

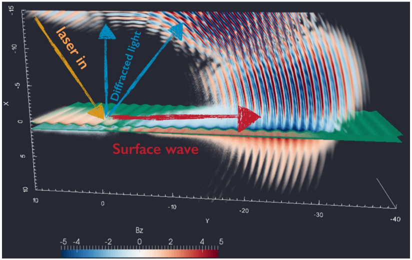
→ high energy electrons are beamed near the surface ($\tan\phi_e \ll 1$)

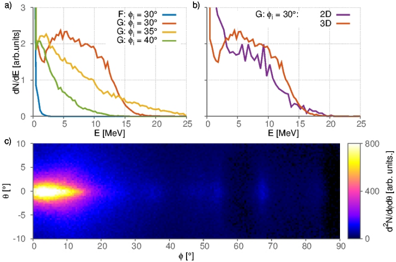


3D Simulations

PICcante code[4]

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





Simulations match experimental observations quantitatively and in detail

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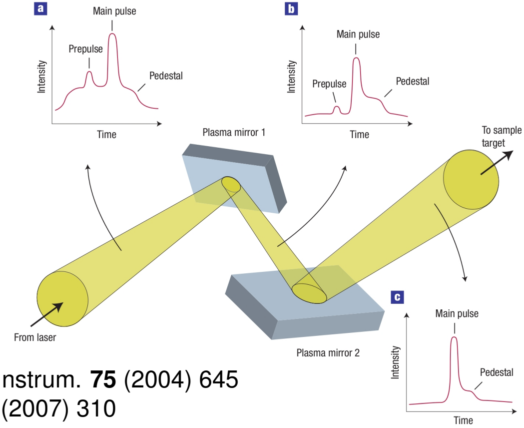
[4] Particle-In-Cell Code for AdvaNced simulations on TiEr-0 systems

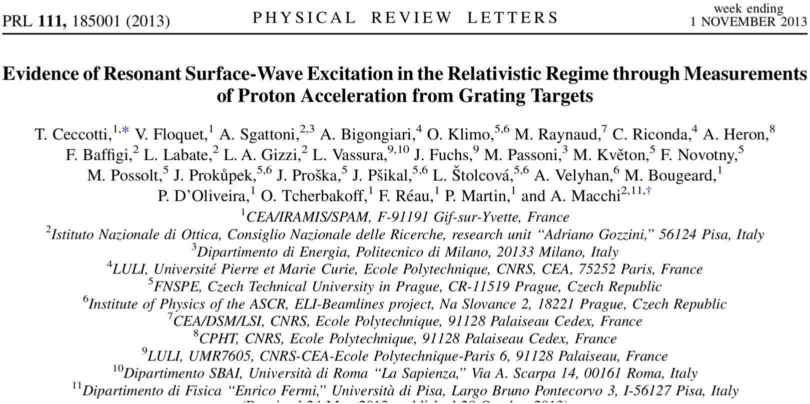
“Ultraclean” high-contrast pulses

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

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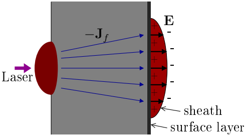
T. Ceccotti et al, Phys. Rev. Lett. **111** (2013) 185001

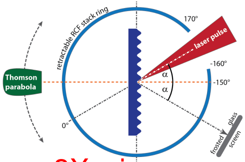
Grating-enhanced proton emission

LaserLAB experiment at SLIC, CEA Saclay

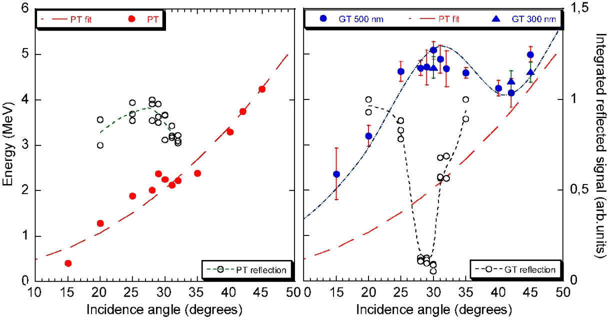
28 fs pulse, $5 \times 10^{19}\ \mathrm{Wcm}^{-2}$, contrast $\sim 10^{12}$



proton acceleration in the electron sheath at the target rear

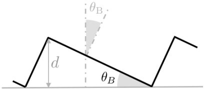


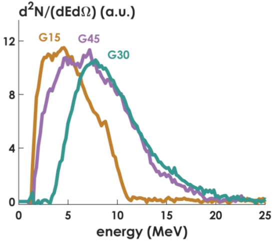
$\sim$ 3X increase in proton energy with respect to "flat" targets near resonant angle $\phi_{\text{res}} = 30°$ $(d = 2\lambda)$

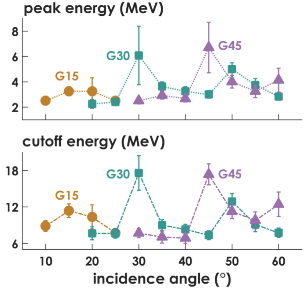


Optimizing SP-enhanced electron emission

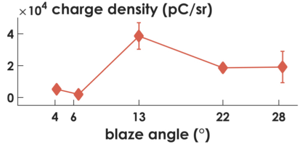
Dependence on
- grating period ($\phi_{\mathrm{res}} = 15°, 30°, 45°$)
- incidence angle

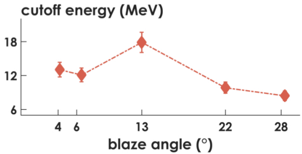






Use of available blazed gratings increase energy and charge up to 650 pC per bunch

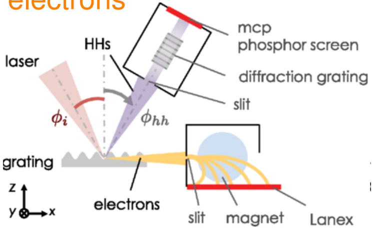




G. Cantono et al, Phys. Plasmas **25** (2018) 031907

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

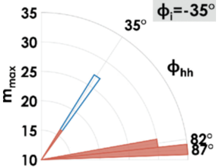
Kahaly et al, PRL **110** (2013) 175001

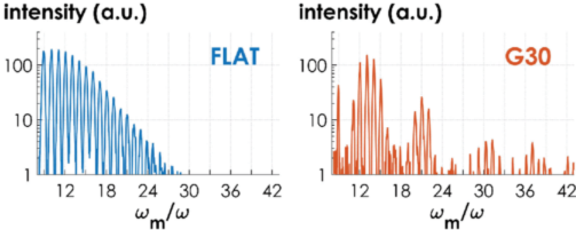
Notice: $L \sim$ grating depth!

Max HH order:

Flat: $m \simeq 25$ at $45°$

Grat: $m \simeq 37$ at $87°$



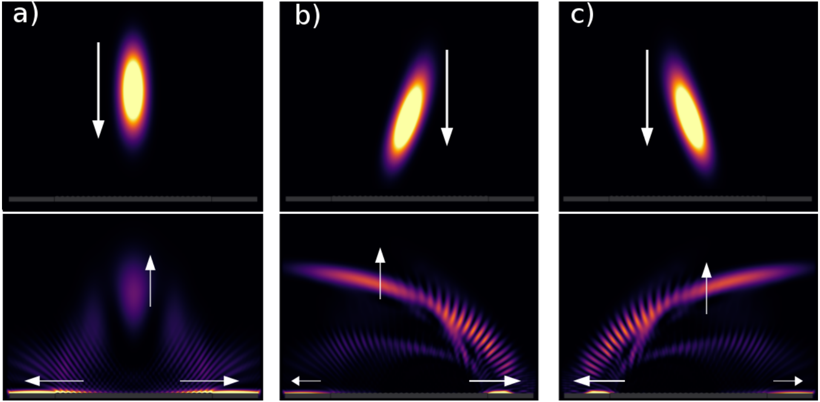


Effect of WFR Direction

Normal incidence: excitation of two symmetric SPs)

a): no rotation b): counterclockwise rotation c): clockwise rotation

Note the scattering from the grating ⟶ radiative loss of energy



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 $\theta \lesssim 45^\circ$) the effect on electron acceleration may be compensated by:

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

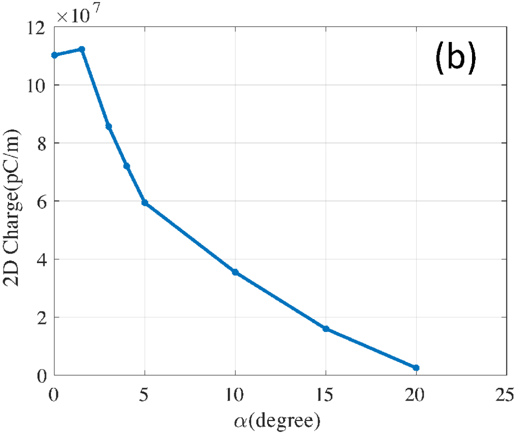
Strong (unknown) nonlinear effects on SP are prevented

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])

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

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



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

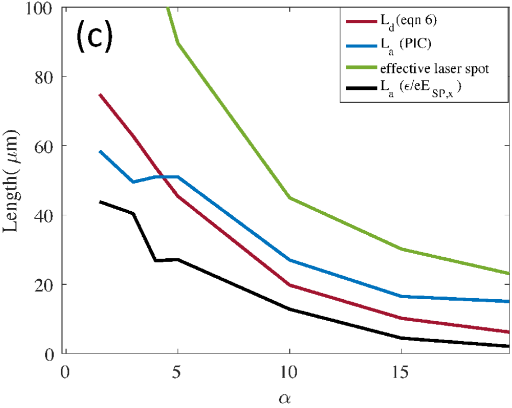
Acceleration Length for Different Angles

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

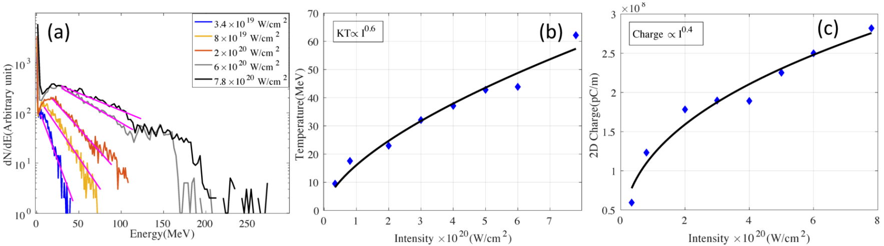
Spot width on target $L_S > L_{\rm dep}$ (could be further optimized)

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

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



Scaling with Laser Intensity



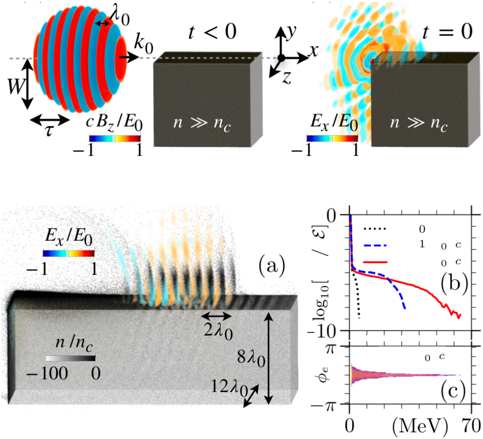
a) electron spectra b) electron “Temperature” c) charge density

Temperature exceeds “ponderomotive” values $(T_\mathrm{p} = m_e c^2(\sqrt{(1 + a_0^2/2)} - 1))$ by one order of magnitude
Peak charge density value $\simeq 3 \times 10^8 \ \mathrm{pCm}^{-1}$ in 2D corresponds to an estimate $\simeq 1.9 \ \mathrm{nC}$ in 3D

A Possibly Similar Observation?

3D SMILEI simulations

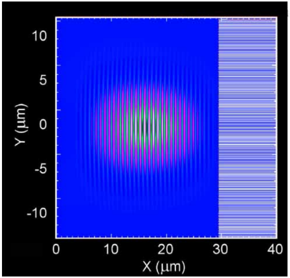
S.Marini, P.Kleij, M.Grech, M.Raynaud, C.Riconda, “Electron acceleration by laser plasma wedge interaction” arXiv:2202.08226

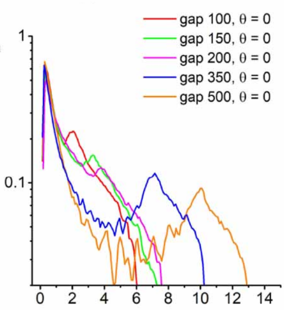


Earlier Numerical Observation?

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

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

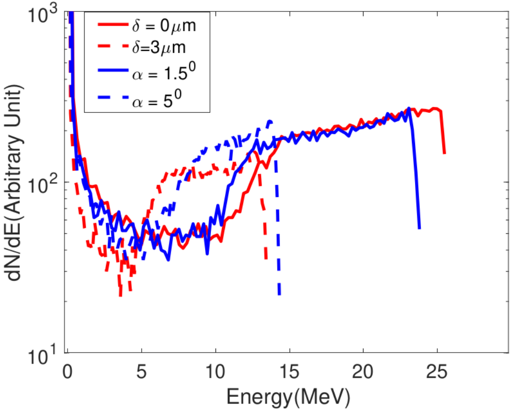




G. Cristoforetti et al, Plasma Phys. Control. Fusion **62** (2020) 114001

Proton Spectra: 2D simulation (Low I)

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



Proton Spectra: 3D simulation (preliminary)

- electron spectra similar to 2D
- Shen et al.'s proton spectra reproduced

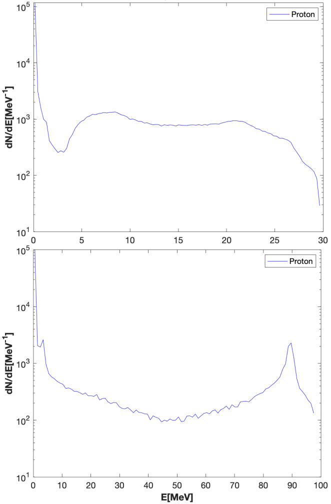
For a lower energy pulse (GEMINI class) the proton spectrum is deeply affected

- Geometrical effect on proton acceleration?
- Insufficient electron production?

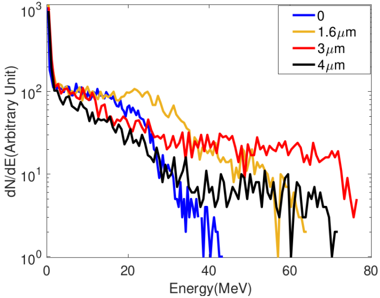
$I = 6 \times 10^{20}\ \mathrm{Wcm}^{-2}$

pulse width $3\ \mu$m

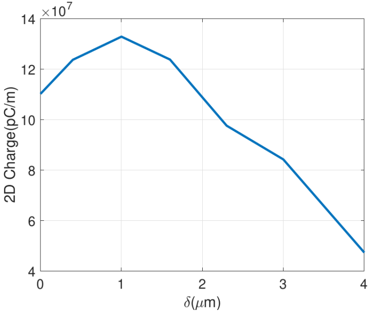
(4 times narrower than Shen's)



Effect of δ on Spectra and Charge (Low I)



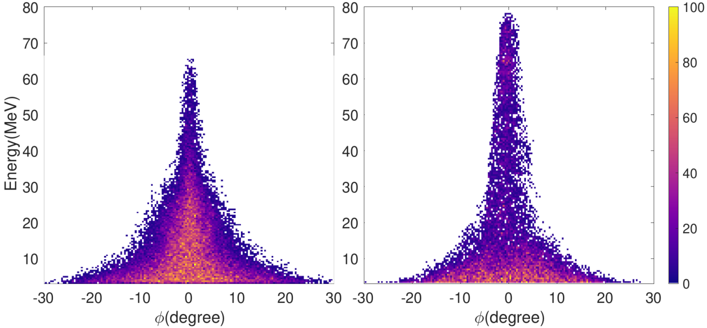
a) electron spectra



b) charge density

$I = 3.4 \times 10^{19}\ \mathrm{Wcm}^{-2}$
Maximum values are *not* for $|\delta| \leq d/2$

Electron Collimation

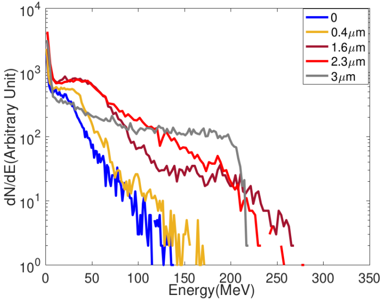


a) $\delta = 0$ b) $\delta = 3\ \mu\text{m}$

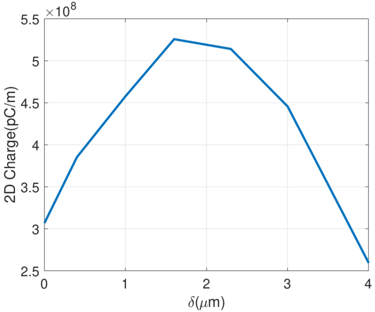
$I = 3.4 \times 10^{19}\ \text{Wcm}^{-2}$

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

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

Total 3D charge would be $\simeq 3.4\ \mathrm{nC}$ for $\delta = 1.6\ \mu\mathrm{m}$