High Field Plasmonics and Laser-Plasma Acceleration (plus an extra topic)

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Outline

- Theory of plasmon excitation in targets with periodically modulated surfaces (gratings)
- Experimental results:
  - protons: enhanced Target Normal Sheath Acceleration (TNSA)
  - electrons: evidence for surface plasmon acceleration
- Simulations of light sail acceleration:
  plasmonic-enhanced Rayleigh-Taylor instability
- *Bonus topic:* Magnetic field generation by radiation friction

Coworkers

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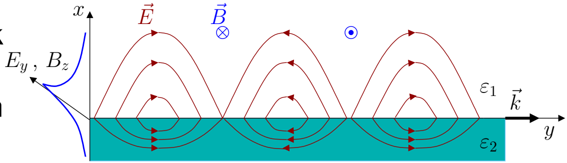
Surface plasmons

SP: building block of plasmonics (mostly studied in the *linear* regime)



SP excitation $\longrightarrow$ EM field confinement and enhancement

Interface between vacuum and simple metal or plasma:

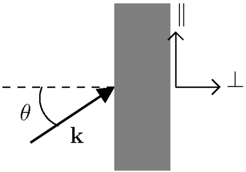
$$\varepsilon_1 = 1 \qquad \varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c(\omega)}$$

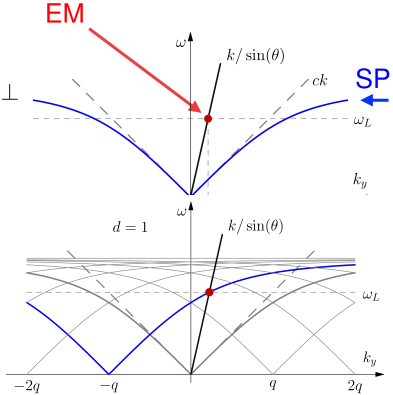
$$k = \frac{\omega}{c}\left(\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}\right)^{1/2} \qquad \omega < \frac{\omega_p}{\sqrt{2}} \qquad v_{\text{ph}} = \frac{\omega}{k} < c$$

Surface plasmon coupling in periodic media

Coupling with EM wave requires phase matching: $\varphi_{\mathrm{EM}} = \varphi_{\mathrm{SP}}$
where $\varphi = \mathbf{k}_{\parallel} \cdot \mathbf{r} - \omega t$

No matching with EM wave at a plane interface:
$$\omega = ck = \frac{ck_{\parallel}}{\sin\theta}$$

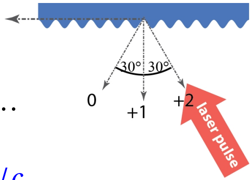




Matching possibile in a periodic medium (lattice vector q) thanks to the “replica” or folding in the Brillouin zone (Floquet-Bloch theorem) of $\omega_{\mathrm{SP}}(k_{\mathrm{SP}})$

Surface plasmon resonance in laser-grating interaction

Resonant matching with SP in a grating at an angle of incidence θ_{res}:



$$\frac{\omega}{c}\sin\theta_{\text{res}} \pm nq = k_{\text{SP}}(\omega) \qquad q = \frac{\pi}{d} \qquad n = 1, 2, \ldots$$

Solid targets $(\omega_p/\omega)^2 = n_e/n_c \gg 1 \longrightarrow k_{\text{SP}} \simeq \omega/c$
($\omega_{\text{SP}}(k_\parallel)$ weakly changes for shallow gratings)

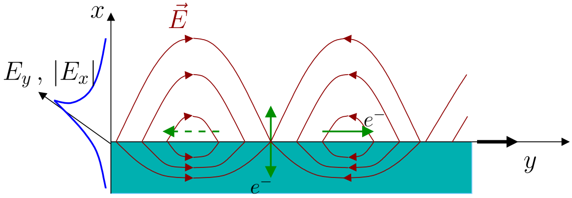
Coupling to superintense pulses requires high contrast, ultra-short ($\sim$ tens of fs) pulses to preserve the grating prior to, and during the interaction

Notice: SP theory not well developed in the relativistic, nonlinear regime

$$a_0 \equiv \frac{p_{\text{osc}}}{m_e c} = \frac{eE_L}{m_e \omega c} > 1 \qquad I\lambda^2 > 1.4 \times 10^{18} \text{ W cm}^{-2}\mu\text{m}^2$$

Electron acceleration by surface plasmons

SP enhances EM field near the surface → more energetic electrons

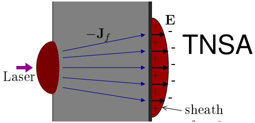


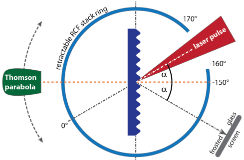
Transverse electric field (E_x) enhances anomalous skin effect or vacuum heating → "hotter" electrons enter the target → more energetic protons accelerated in the rear sheath

Longitudinal electric field (E_x) accelerates electrons along the surface by "surfing" the SP (phase velocity $v_f = \omega / k \lesssim c$)

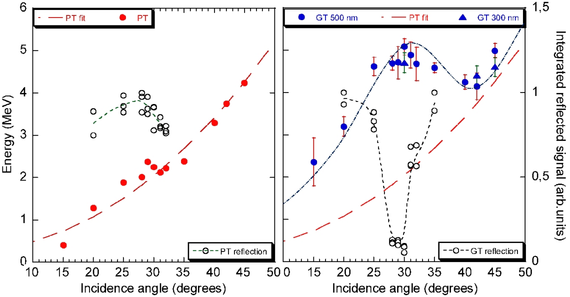
Grating-enhanced proton acceleration

LaserLAB experiment at SLIC, CEA Saclay
laser UHI, 28 fs, 5×10^{19} W cm^{-2}, $a_0 = 4.8$
pulse contrast $\sim 10^{12}$





$\sim$ 3X increase in proton energy at resonant angle $\theta_{\text{res}} = 30°$ $(d = 2\lambda)$



T.Ceccotti et al, PRL **111** (2013) 185001

Surface plasmon electron acceleration *in vacuum*

- Plasmon field on the vacuum side is purely electrostatic in frame L' moving with phase velocity $\beta_f = v_f/c$:

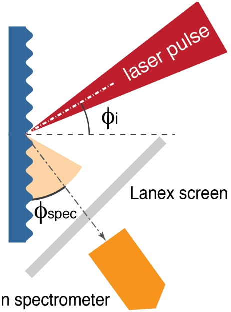
$$\Phi' = -\left(\frac{\gamma_f E_{\rm SP}}{k}\right) \mathrm{e}^{k'x} \sin k'y' \qquad k' = k/\gamma_f \qquad \gamma_f = (1-\beta_f^2)^{-1/2}$$

- "Lucky" electron injected with velocity v_f goes downhill the potential Φ' acquiring an energy $W' = eE_{\rm SP}\gamma_f/k$
- Energy gain and emission angle in the lab (L) frame in the strongy relativistic limit $W' \gg m_e c^2$

$$\mathcal{E}_f \simeq eE_{\rm SP}\gamma_f^2/k \simeq m_e c^2 a_{\rm SP}(n_e/n_c) \,, \qquad \tan\phi_e = p_x/p_y \simeq 1/\gamma_f$$

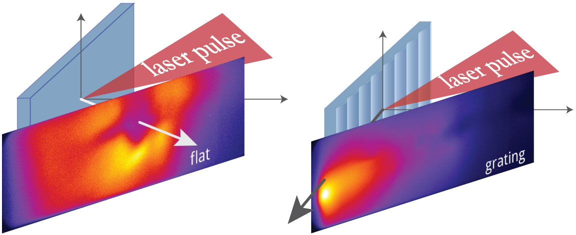
→ highly relativistic electrons are accelerated and beamed near the target surface ($\tan\phi_e \ll 1$)

Collimated near-tangent electron emission observed

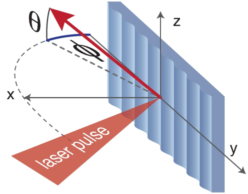


Imaging of electrons emitted from the front side of the target: evidence of narrow-angle, intense beam near the target surface for grating targets
No such beamed emission for flat targets!

L. Fedeli et al, arXiv:1508.02328



Electron angular distribution and total charge

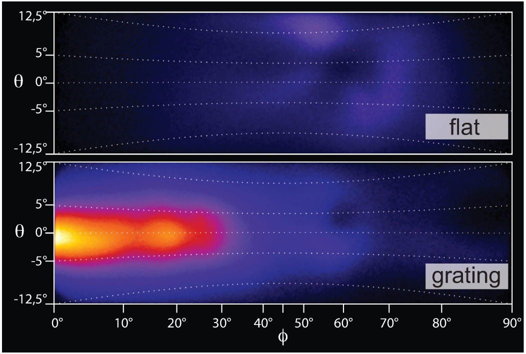


Target: 10 μm Mylar

$\phi_{\text{inc}} = \phi_{\text{res}} = 30°$

Angular spread

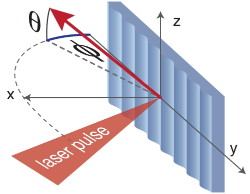
$\Delta\phi \simeq 20°$



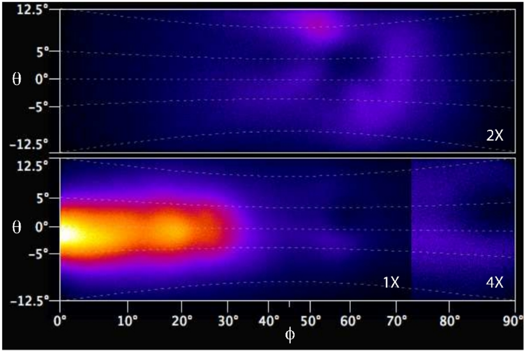
Shot-to-shot fluctuations $\delta\phi \sim \delta\theta \simeq 5°$ due to non-perfect planarity of foil target

Total charge in the electron bunch $Q = 100 \pm 15$ pc

“Holes” in angular distribution



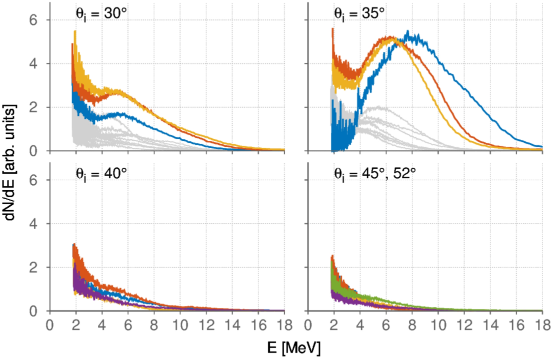
images with enhanced contrast



“Holes” in angular distribution observed in specular direction for both targets and for $m = 1$ diffraction order for gratings
Ponderomotive scattering by reflected & diffracted EM pulses?

Electron energy spectra from grating targets

Near resonance ($\phi_{inc} = 30° - 35°$) with spectrometer close to tangent $\phi_{spec} \simeq 2°$: strongly non-Maxwellian spectrum with peak at $6-8$ MeV, cut-off at $15-18$ MeV

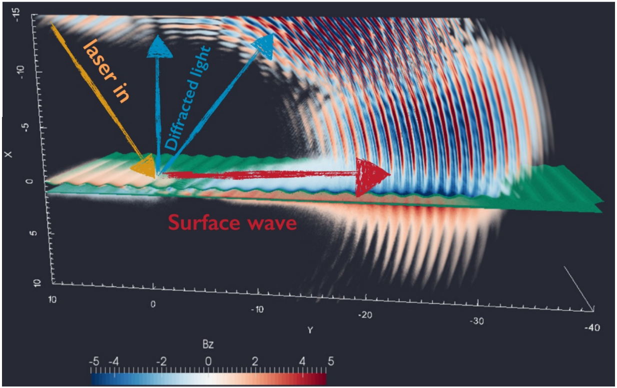


No spectra from flat targets over detection threshold!

Spectrum variability (**gray** lines) related to beam direction fluctuations due to the small acceptance angle of the spectrometer

Three-dimensional simulations

PICcante open source code on 16384 cores of BlueGene/Q FERMI at CINECA, Italy

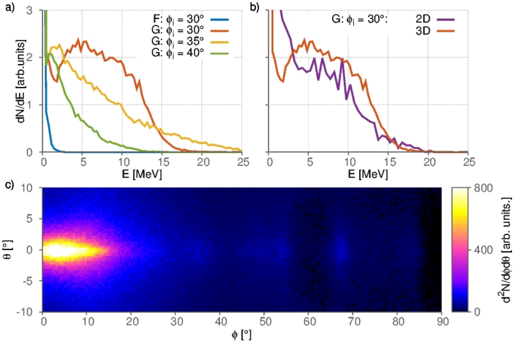


Target: 1 μm foil, $n_e/n_c = 50$ Box: $(80 \times 60 \times 60)\lambda^3$
Resolution: $\Delta\mathbf{r}/\lambda = (70, 51, 34)$, 196 particles/cell

Simulations vs experiment

3D simulations confirm SP-enhancement of electron flux and energy and reproduce accurately and quantitatively:

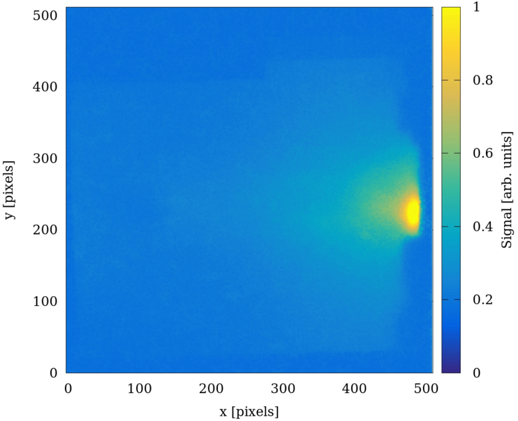
- energy spectrum
- angular distribution including "ponderomotive holes"



In 3D sim $a_{\text{SP}} \simeq 1$, $n_e/n_c = 50 \longrightarrow$ theory: $\mathscr{E}_f \simeq 25$ MeV, $\phi_e \simeq 8°$

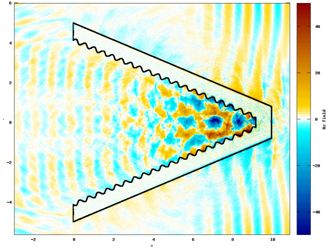
Preliminary results at higher intensity

Raw lanex image from PULSER laser at GIST, Korea
$I = 5 \times 10^{20}$ W/cm^2
pulse contrast $\sim 10^{10}$ at 50 ps
Beamed emission from grating targets still observed
→ future exploration of ultra-relativistic regime
(also with ELI?)



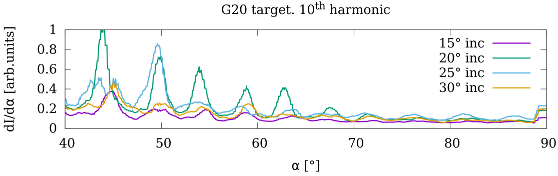
High field plasmonics with gratings: what next?

Some ideas under testing with PIC simulations:



tapered waveguide for light nano-focusing and amplification
(Original plasmonic concept: M.Stockman, PRL **93** (2004) 137404)

Plasmonic enhancement and angular selection of high harmonics from gratings



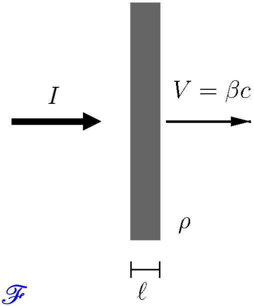
Work in progress . . .

Light Sail acceleration

"Accelerated mirror" 1D model:

$$\mathscr{E}_{\text{max}} = m_p c^2 \frac{\mathscr{F}^2}{(2(\mathscr{F}+1))}$$

$$\mathscr{F} = \frac{2}{(\rho\ell)} \int_0^{\infty} I(t')dt' \simeq \frac{2I\tau_p}{\rho\ell}$$

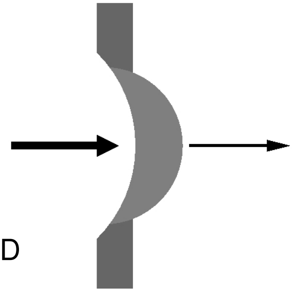


Favorable scaling with normalized fluence $\mathscr{F}$
100% efficiency in the relativistic limit (accessible with ELI)
"Perfect" monoenergeticity for "rigid", coherent sail motion

Issue: slow energy gain → stability, laser diffraction, ...

$$\mathscr{E}_{\text{ion}}(t) \propto \left(\frac{It}{\rho\ell c^2}\right)^{1/3} \qquad \left(t \gg \frac{\rho\ell c^2}{I}, \mathscr{E}_{\text{ion}} > m_p c^2\right)$$

Fast gain Light Sail in 3D



Transverse expansion of the target reduces on-axis surface density $\rho\ell$
$\Rightarrow$ sail gets "lighter": **boost of energy gain** at the expense of the number of ions

Faster gain $\mathscr{E}_{\text{ion}}(t) \propto \left(\frac{It}{\rho\ell c^2}\right)^{3/5}$ predicted in 3D

[S.V.Bulanov et al, "Unlimited ion acceleration by radiation pressure", PRL **104** (2010) 135003]

Mechanism is effective for *relativistic* ions ($\mathscr{F} \gg 1$)

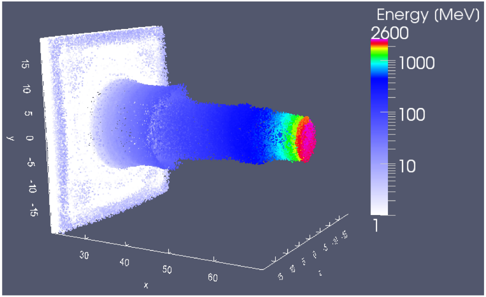
Need to explore this regime with fully 3D simulations over long time scales

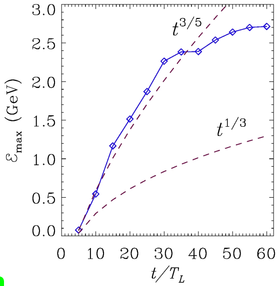
ALADYN code [C. Benedetti, A. Sgattoni, G. Turchetti, P. Londrillo, IEEE Trans. Plasma Science **36** (2008) 1790]

High energy gain in 3D LS simulations (H foil)

Laser: 24 fs, 4.8 μm spot, $I = 0.85 \times 10^{23}$ W cm^{-2} $\Longrightarrow$ **1.5 kJ**

Target: $d = 1$ μm foil, $n_e = 10^{23}$ cm^{-3}, $\pi \left(\frac{n_e}{n_c}\right)\left(\frac{d}{\lambda}\right) \simeq a_0 \simeq 200$





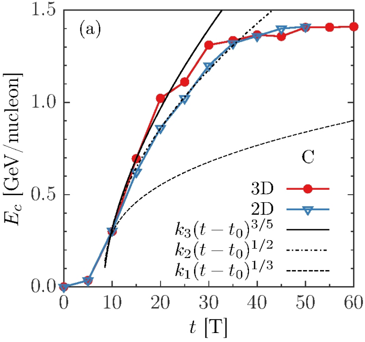
$\mathcal{E}_{\text{max}} \simeq 2.6$ GeV $>$ **4X 1D model prediction**

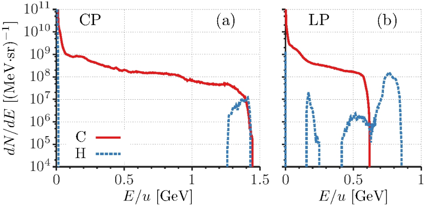
Macchi et al, PPCF **55** (2013) 124020;

Sgattoni et al, APL **105** (2014) 084105

High energy gain in 3D LS simulations (CH foil)

C+H double layer foil , $n_C = (64/6)n_c$, $n_H = 8n_c$

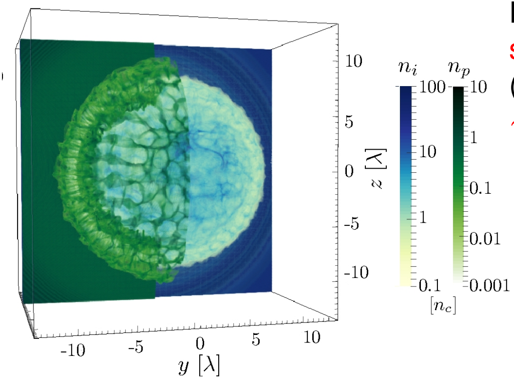




Circular vs Linear Polarization: Higher energy and narrower H spectrum for CP

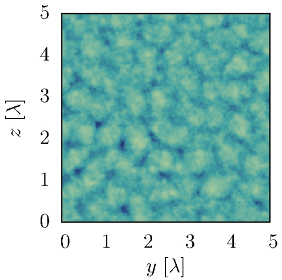
Onset of transparency stops acceleration and is faster in 3D than in 2D → similar final energy in 2D and 3D (~1.4 GeV for CP)

Transverse structures in ion density



Two species target - protons and carbon ions

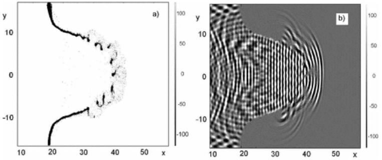
Formation of net-like structures with size $\sim \lambda$ (laser wavelength) and $\sim$ hexagonal shape



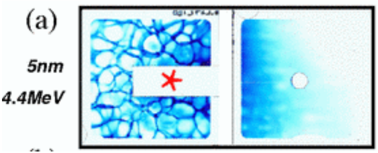
What is the origin of structures and of the dominant scale?

Rayleigh-Taylor Instability in LS?

Thin foil target of areal density σ accelerated by a laser of intensity I is unstable with growth rate $\gamma = (P_0 q/\sigma)^{1/2}$ with $P_0 = 2I/c$ and q the wavevector [Ott, PRL **29** (1972) 1429]



2D simulation
[F.Pegoraro & S.V.Bulanov, PRL **99** (2007) 065002]

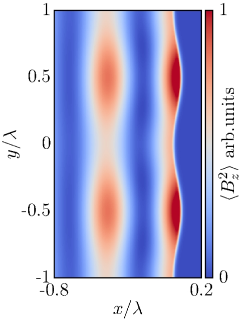


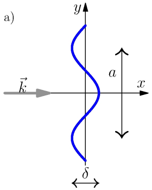
Experimental indication from accelerated ion beam profile structures [C.Palmer et al, PRL **108** (2012) 225002]

What sets the dominant wavevector $q \sim (2\pi/\lambda)$?

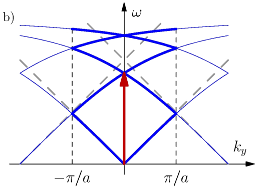
Plasmonic modulation of radiation pressure

The EM field at a rippled surface (e.g. 2D reflecting, sinusoidal grating of period d) is modulated with plasmonic enhancement of the P-component when $d \sim \lambda$





Geometry



Matching with surface plasmons

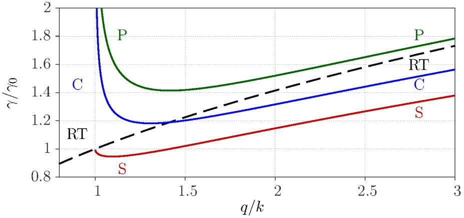
The resulting modulation of laser light pressure provides a spatial seed for RTI

Thin foil RTI with self-consistent pressure modulation

Model: reflection from shallow 2D grating of depth δ (first order in δ/λ) + modified Ott's theory[1] with modulated pressure:

$$P \simeq P_0\left(1 + K(q)\delta\cos qy\right), \qquad K(q) = \begin{cases} -(q^2-k^2)^{1/2} & (S) \\ k^2(q^2-k^2)^{-1/2} & (P) \\ (k^2-q^2/2)(q^2-k^2)^{-1/2} & (C) \end{cases}$$

$$\gamma = (P_0/\sigma)^{1/2}\left[\left(q^2 + K^2(q)/4\right)^{1/2} + K(q)/2\right]^{1/2}$$

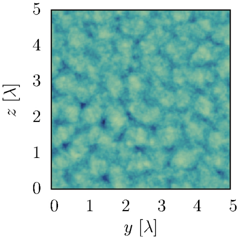


S-polarization
P-polarization
C-ircular polarization
RT: no modulation ($\delta = 0$)

[1] E. Ott, PRL **29** (1972) 1429

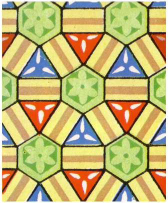
Symmetry of RTI structures

Hexagonal-like structures generated by nonlinear evolution of RTI: an example of spontaneous symmetry breaking in a classical system with "wallpaper" p6m symmetry



S.I.Abarzhi, PRE **59** (1999) 1729
D.Schattschneider, Amer. Math. Monthly **85** (1978) 439

A. Sgattoni, S. Sinigardi, L. Fedeli, F. Pegoraro, A. Macchi, PRE **91** (2015) 013106



Persian glazed tile

Summary and perspectives for high field plasmonics

- Experimental evidence of surface plasmon excitation in laser-grating interaction at relativistic intensity
  - enhanced TNSA of protons
  - direct acceleration of electrons by surface plasmons

→ interest as an electron source?

→ development of plasmonic approaches to EM field manipulation and enhancement in the relativistic regime?

- Plasmonic enhancement in the Rayleigh-Taylor instability during Light Sail acceleration

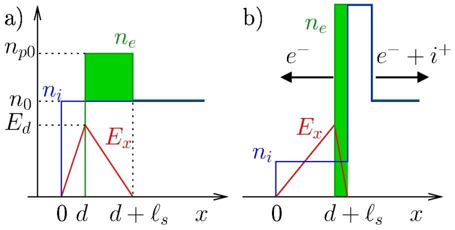
→ issue for high-gain regime of radiation pressure acceleration with ELI-class laser?

Radiation Friction effects in thick targets

Simulations show major RF losses for thick $d \gg \lambda$ targets driven by CP pulses (losses are negligible for thin targets)
Naumova et al, PRL **102** (2009) 25002; Schlegel et al, PoP **16** (2009) 83103; Nerush & Kostyukov, PPCF **57** (2015) 35007

We developed a model based on radiation from "returning" electrons in pulsed "piston" RPA

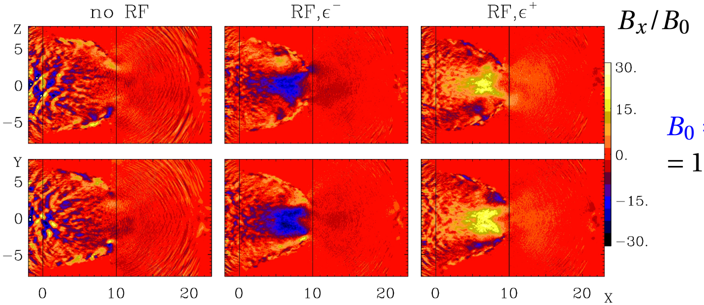
$$\eta_{\rm rad} \simeq \frac{4\pi}{3}\frac{r_c}{\lambda}a_0\gamma^2 \sim a_0^3$$



$\eta_{\rm rad} \to$ 100% for $a_0 \simeq 400 \to I_L \simeq 7\times10^{23}$ W cm^{-2}

Inverse Faraday Effect due to Radiation Friction

Dissipation due to RF leads to absorption of photon “spin”
→ transfer of EM angular momentum to electrons
→ generation of solenoidal current and axial magnetic field B_x



$B_0 = m_e\omega c/e$
$= 1.34 \times 10^8$ G

3D PIC simulation find $B_x \simeq 20$ GG only with RF included and polarization-dependent sign

Theory and scaling laws for RF-IFE

IFE saturation mechanism: electric field generated by $c\nabla\times\mathbf{E} = -\partial_t \mathbf{B}$ slows electrons down and transfers angular momentum to ions

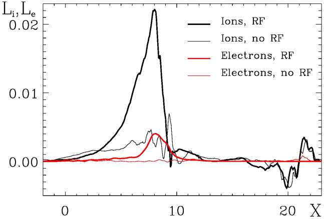
M. Haines, PRL **87** (2001) 135005

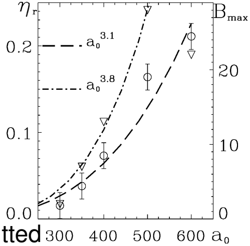
Theoretical estimate of maximum B_x:

$$\frac{B_{\max}}{B_0} \simeq \eta_{\text{rad}} \frac{r_l \lambda}{r_0^2} a_0 \sim a_0^4$$

(r_0, r_l: laser pulse radius and length)

Scaling of both η_{rad} and $B_{\max}$ with a_0 fairly agree with 3D simulation





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