Relativistic Plasmonics in Laser Ion Acceleration

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Complex Plasma Phenomena in the Laboratory and in the Universe
Accademia dei Lincei, Roma, January 19, 2015

Coworkers

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Outline

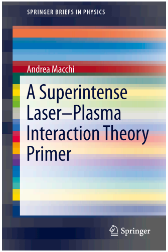
- Some history: from the coherent (collective) acceleration paradigm (1957) to the (re–)discovery of laser-driven proton beams (2000)
- High field plasmonics for enhanced acceleration: laser interaction with grating targets
  - Experimental results
  - Numerical simulations
- Light sail acceleration: Rayleigh-Taylor instability and plasmonics effects

Recent ion acceleration reviews (parochial selection)

A. Macchi, M. Borghesi, M. Passoni,
Ion Acceleration by Superintense Laser-Plasma Interaction,
Rev. Mod. Phys. **85** (2013) 571

A. Macchi, A. Sgattoni, S. Sinigardi, M. Borghesi, M. Passoni,
Advanced Strategies for Ion Acceleration using High Power Lasers,
Plasma Phys. Contr. Fus. **55** (2013) 124020

A. Macchi,
A Superintense Laser-Plasma Interaction Theory Primer (Springer, 2013)
Chap.5 "Ion Acceleration" (for absolute beginners)



Other ion acceleration reviews

H. Daido, M. Nishiuchi, A. S. Pirozhkov,
Review of Laser-Driven Ion Sources and Their applications,
Rep. Prog. Phys. **75** (2012) 056401

J.C. Fernández, B.J. Albright, F.N. Beg, M.E. Foord, B.M. Hegelich, J.J. Honrubia, M. Roth, R.B. Stephens, and L. Yin,
Fast ignition with laser-driven proton and ion beams,
Nucl. Fusion **54** (2014) 054006

The vision of “coherent” acceleration: Veksler (1957)

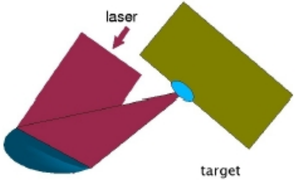
V. I. Veksler, At. Energ. **2** (1957) 525

- accelerating field on each particle proportional to the number of accelerated particles
- automatic synchrony between the particles and the accelerating field
- field localization in the region where the particles are
- acceleration of quasi-neutral bunches with large numbers of particles

The dawn of laser-plasma physics (1964)

"*The laser is a solution looking for a problem*" (D'Haenens to Maiman, 1960)
Q-switch (1962): $I \simeq 10^{13}$ W cm^{-2}

→ Production of keV ions via hot plasma expansion



THE PHYSICS OF FLUIDS VOLUME 7, NUMBER 7 JULY 1964

On the Production of Plasma by Giant Pulse Lasers

John M. Dawson
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey
(Received 10 October 1963; final manuscript received 10 March 1964)

Calculations are presented which show that a laser pulse delivering powers of the order of 10^{10} W to a liquid or solid particle with dimensions of the order of 10^{-2} cm will produce a hot plasma with temperatures in the range of several hundred eV. To a large extent the plasma temperature is held down by its rapid expansion and cooling. This converts much of the energy supplied into ordered energy of expansion. This ordered expansion energy can amount to several keV per ion. If the expanding plasma can be caught in a magnetic field and its ordered motion converted to random motion this might be utilized as a means for filling controlled thermonuclear fusion devices with hot plasma. Further, it should also be possible to do many interesting plasma experiments on such plasmas.

Modern ultraintense laser-matter interactions

Short (~ 10 fs $= 10^{-14}$ s) pulses of Petawatt (10^{15} W) power focused near diffraction limit ($w \sim 1\ \mu$m): $I \simeq 10^{22}$ W cm^{-2}
(Hercules Laser, CUOS, University of Michigan Ann Arbor, US)

Proposed ELI laser: 100 PW, 15 fs, $I > 10^{23}$ W cm^{-2}
A future vision: multi-fibre laser
[Mourou et al, Nature Photonics **7** (2013) 258]

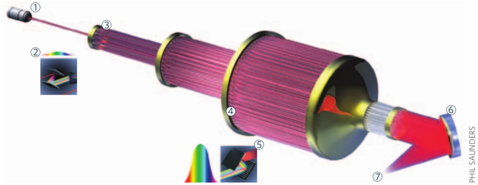
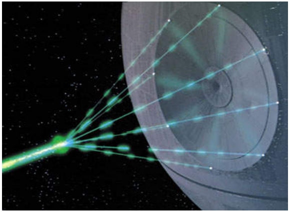
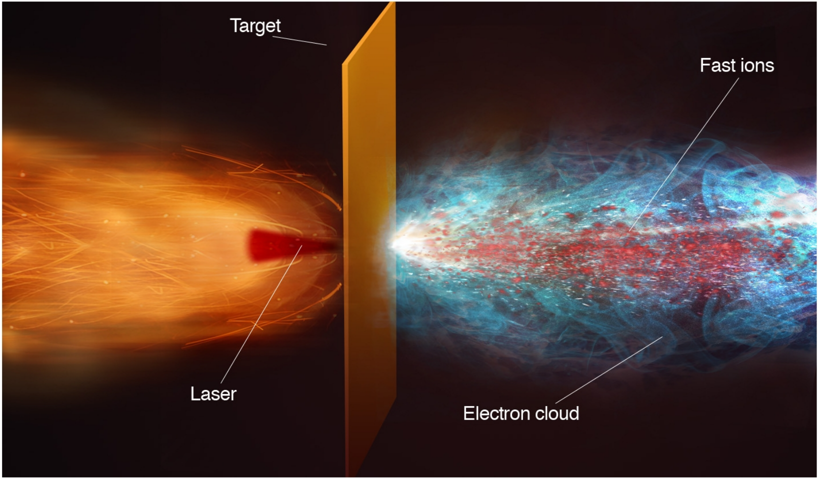


Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).



Multi-MeV protons from solid targets (2000)



Multi-MeV protons from solid targets (2000)

Up to 58 MeV protons observed at LLNL (Livermore) Petawatt

Snavely et al, PRL **85** (2000) 2945

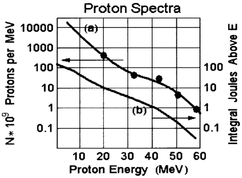
Other observations:

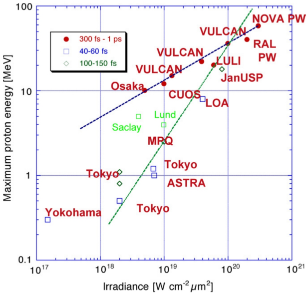
Clark et al, PRL **84** (2000) 670

Maksimchuk et al, PRL **84** (2000) 4108

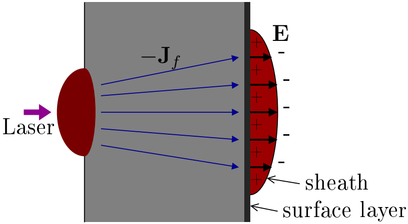
Protons have been observed and characterized in a large number of laboratories and for different laser pulse regimes

Figure from Borghesi et al, Plasma Phys. Contr. Fus. **50** (2008) 124040





Target Normal Sheath Acceleration (TNSA)



Physics: sheath field generation by "fast" relativistic electrons at the rear surface of a solid target

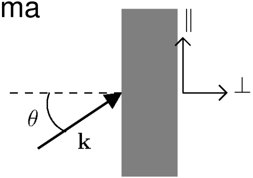
Need to increase ion energy and source efficiency especially for short-pulse (< 100 fs) lasers (compact size, high repetition rate)
→ enhance electron heating (higher T_e, higher absorption)

A strategy: achieving resonant coupling in solid targets

Looking for resonant coupling at the surface

Idea: enhancement of the surface field and of absorption by exciting a normal mode of the target plasma

Coupling requires matching of the phase $\varphi = \mathbf{k}_\parallel \cdot \mathbf{r} - \omega t$ between the laser $(\omega, k \sin\theta)$ and the resonant mode $(\omega_m, \mathbf{k}_m)$:



$$\omega \doteq \omega_m \qquad k_\parallel = k \sin\theta \doteq (k_m)_\parallel$$

Normal modes of step boundary metal/plasma: surface waves (SW)

SW are the building blocks of **plasmonics** (at low fields)

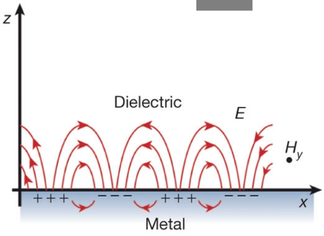
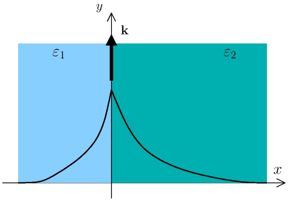


Fig.: Benson, Nature **480**, 193 (2011)

Surface wave coupling: the matching problem

Plasma-vacuum interface

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



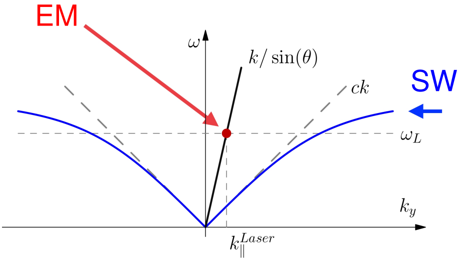
SW dispersion relation $\omega = \omega(k_\parallel)$

$$k_\parallel = \frac{\omega}{c}\left(\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}\right)^{1/2}$$

$$\omega < \omega_p/\sqrt{2} \qquad v_{\text{ph}} < c$$

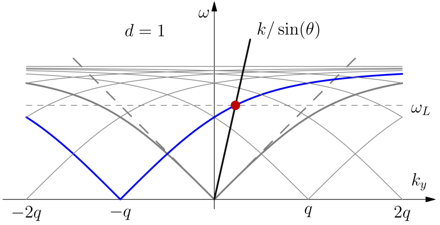
No matching with EM wave:

$$\omega = ck = \frac{ck_\parallel}{\sin\theta}$$



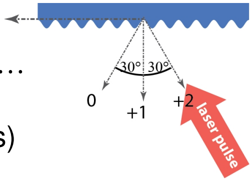
Surface wave matching in periodic structures

In a spatially periodic medium (period d) the "replica"[1] of $\omega_{SW}(k_\parallel)$ allows phase matching



Resonant coupling with EM wave is possible in a grating at an angle of incidence

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



($\omega_{SW}(k_\parallel)$ weakly changes for shallow gratings)

[1] equivalent to folding in the Brillouin zone (Floquet-Bloch theorem)

Plasmonics at high fields?

Aim: exploit plasmonic field enhancement and surface wave excitation in sub-wavelength (periodic) structures

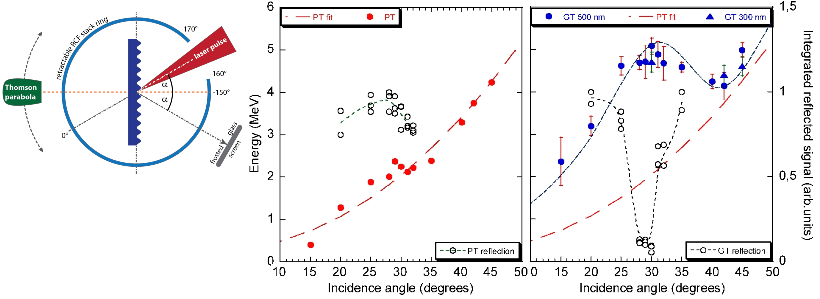
Issues for high intensity (and related approaches):

- hydrodynamics may wash target structuring out
  - use ultrashort pulses (10s of fs)
- prepulse effects may destroy structures at target surface
  - use high-contrast techniques (e.g. plasma mirrors)
- features of plasmonics and surface waves unknown in the high-field, nonlinear, relativistic regimes

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

Experimental evidence: grating-enhanced TNSA

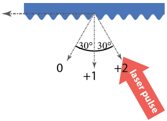
LaserLAB experiment at SLIC, CEA Saclay
laser UHI, 28 fs, 5×10^{19} W cm^{-2}, $a_0 = 4.8$
pulse contrast $\sim 10^{12}$

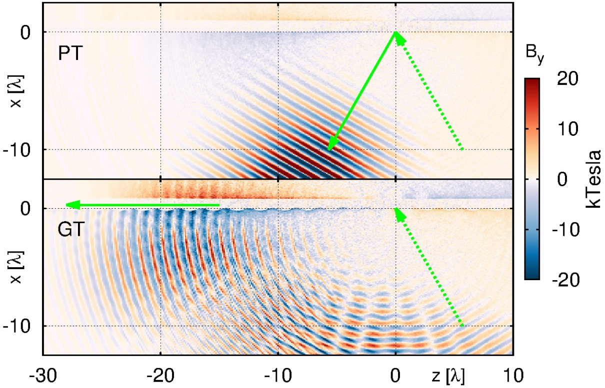


$\sim$ 3X increase observed in proton energy at resonant angle
T.Ceccotti et al, PRL **111** (2013) 185001

Surface wave in PIC simulations

Snapshots of EM fields show localized wave propagating along the surface at resonant angle of incidence (plus reflection at various diffraction orders)





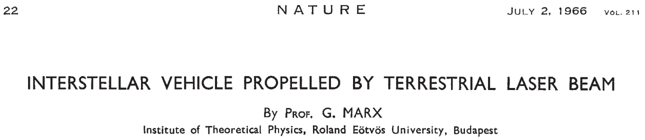
Beyond TNSA: searching for other mechanisms

Unresolved issues and limitations of TNSA:

- broad (~ exponential) energy spectrum
  (slow progress from engineered targets)
- slow scaling with laser intensity ($\mathscr{E}_{\text{max}} \sim I^{1/2}$)
- high repetition rate not easy with thin solid targets
- structured targets may be complex and/or expensive

→ need to explore alternative mechanisms

Early vision of radiation pressure acceleration (1966)

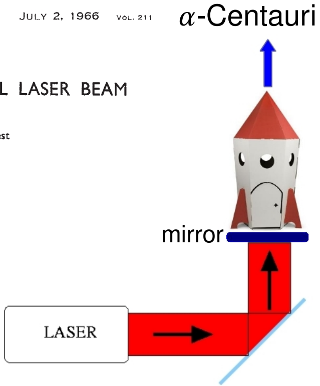


22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

By PROF. G. MARX

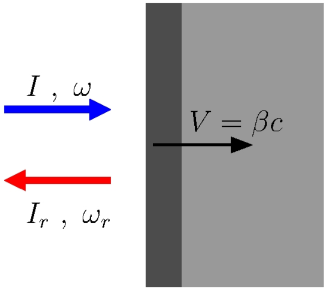
Institute of Theoretical Physics, Roland Eötvös University, Budapest



A solution to "Fermi's paradox": "*Laser propulsion from Earth . . . would solve the problem of acceleration but not of deceleration at arrival . . . no planet could be invaded by unexpected visitors from outer space*"

The accelerating mirror model of RPA

Perfect mirror boosted by a plane wave: mechanical efficiency η and momentum transfer to mirror derived by Doppler shift and photon number conservation

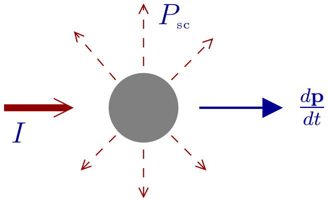


$$\frac{dp}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta} \qquad \eta = \frac{2\beta}{1+\beta}$$

High efficiency ($\eta \to 1$) but slow gain ($dp/dt \to 0$) as $\beta \longrightarrow 1$

Analogy with Acceleration by Thomson Scattering

Light Sail equations of motion have the same form as those of a particle undergoing Thomson Scattering
Landau & Lifshitz, *The Classical Theory of Fields*, ch.78 p.250 (1962).



$$\frac{dp}{dt} = \sigma_T I \propto P_{sc}$$

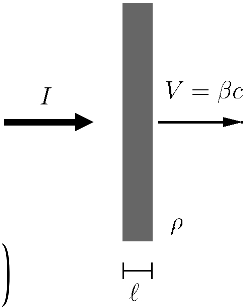
Veksler's idea: coherent scattering by a cluster of radius $a \ll \lambda$ with N $(\gg 1)$ particles, $P_{sc} \to N^2 P_{sc} \Rightarrow \sigma_T \to N^2 \sigma_T$

Light Sail formulas, scaling, and needs

$$\begin{aligned}\mathcal{E}_{\text{max}} &= m_p c^2 \mathcal{F}^2/(2(\mathcal{F}+1)) \\ &\simeq m_p c^2 \mathcal{F}^2/2 \qquad (\mathcal{F} \ll 1)\end{aligned}$$

$$\mathcal{F} = 2(\rho\ell)^{-1}\int_0^\infty I(t')dt' \simeq 2I\tau_p/\rho\ell$$

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



Favorable scaling with normalized fluence $\mathcal{F}$

"Perfect" monoenergeticity for "rigid", coherent sail motion

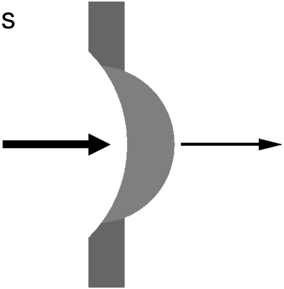
Need of ultrathin (nm) foils and ultrahigh contrast pulses

Circular polarization to reduce undesired heating

Issues: slow energy gain, heating, transparency, deformation . . .

Fast gain RPA due to transverse expansion

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



Fast gain $E_{\text{ion}}(t) \simeq \left(\frac{2It}{\rho\ell c^2}\right)^{3/5}$
predicted in 3D
[Bulanov et al, 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
Foreseen ELI laser parameters - `www.eli-beams.eu/`

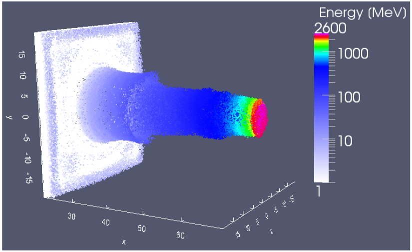
3D simulation campaign: LSAIL project

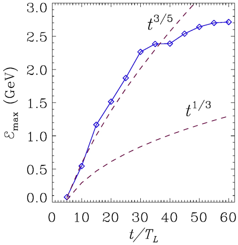
(Large Simulations of ion Acceleration by Intense Lasers)

- PRACE award for access to FERMI BlueGene/Q at CINECA, Italy
- Typical set-up: 4096×1792^2 grid points, 2×10^{10} particles, 16384 cores used
- Particle-In-Cell (PIC) codes:
  - ALADYN: C. Benedetti, A. Sgattoni, G. Turchetti, P. Londrillo, IEEE Trans. Plasma Science **36** (2008) 1790
  - PICCANTE: Open Source code
    (L.Fedeli, A.Sgattoni, S.Sinigardi, et al)
    `github.com/ALaDyn/piccante`

High energy gain in 3D RPA-LS simulations

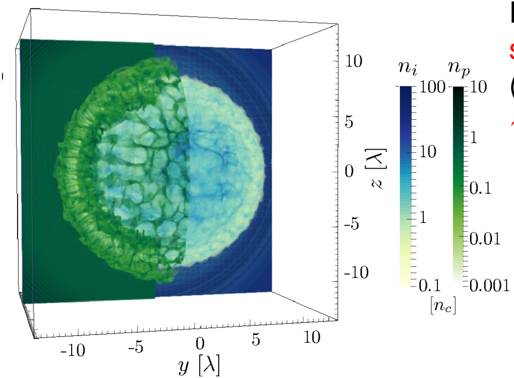
Laser: 24 fs, 4.8 μm spot, $I = 0.85 \times 10^{23}$ W cm^{-2} $\Longrightarrow$ **1.5 kJ**
Target: 1 μm foil, $n_e = 1.1 \times 10^{23}$ cm^{-3}, $a_0 \simeq 200$





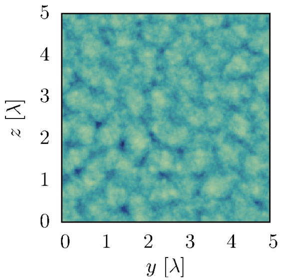
$\mathcal{E}_{\text{max}} \simeq 2.6$ GeV > 4 times 1D model prediction
Macchi et al, Plasma Phys. Contr. Fus. **55** (2013) 124020
Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

Transverse structures in ion density



Two species target - protons and carbon ions

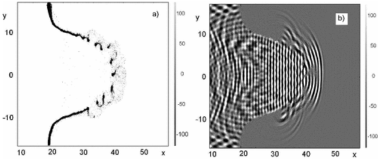
Formation of net-like structures with size $\sim \lambda$ (laser wavelength) and $\sim$ hexagonal shape

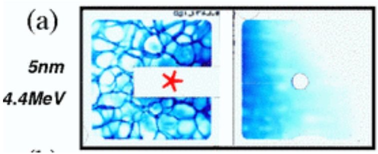


What is the origin of structures and of the dominant scale?

Rayleigh-Taylor Instability in RPA?

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]





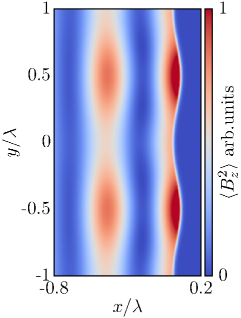
2D simulation
[F.Pegoraro & S.V.Bulanov, PRL **99** (2007) 065002]

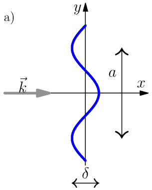
Experimental indication from accelerated ion beam profile structures [C.Palmer et al, PRL **108** (2012) 225002]

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

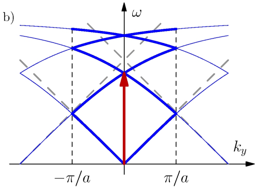
Plasmonic modulation of radiation pressure

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

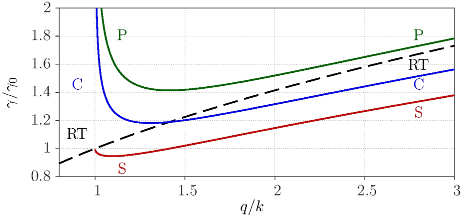
The resulting modulation of laser light pressure provides a spatial seed for RTI

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 with modulated pressure:

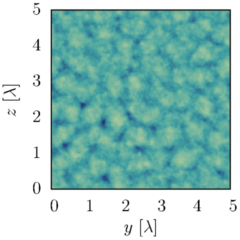
$$P \simeq P_0(1+K(q)\delta\cos qy)\,, \qquad K(q) = \begin{cases} -(q^2-k^2)^{1/2} & (S) \\ k^2(q^2-k^2)^{-1/2} & (P) \\ (k^2-q^2/2)(q^2-k^2)^{-1/2} & (C) \end{cases}$$

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



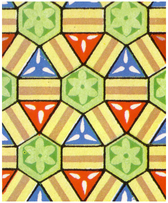
S-polarization
P-polarization
C-ircular polarization
RT: no modulation ($\delta = 0$)

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



Persian glazed tile

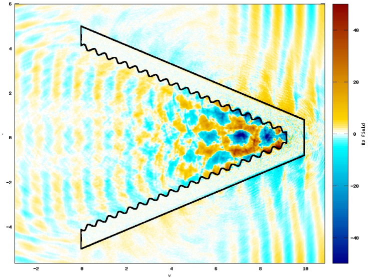
A. Sgattoni, S. Sinigardi, L. Fedeli, F. Pegoraro, A. Macchi, PRE (2015), arXiv:1404.1260

Relativistic high field plasmonics: what next?

Idea: exploit ideas from plasmonics into high field regime
Example: plasmonic amplification

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

If 100X field amplification confirmed for ultraintense lasers, 10^{25} W cm^{-2} intensity is reached!


PIC simulation by L. Fedeli

Conclusions and perspectives

- Evidence of surface wave excitation in laser-grating interaction at relativistic intensity throgh proton acceleration measurements

! short-pulse, high contrast interaction sensitive to sub-wavelength structuring

→ possible to develop plasmonic structures for field manipulation and enhancement in the high field regime

- Role of plasmonic effects in the Rayleigh-Taylor instability during radiation pressure acceleration

→ issue for RPA of ions with ELI-class laser?

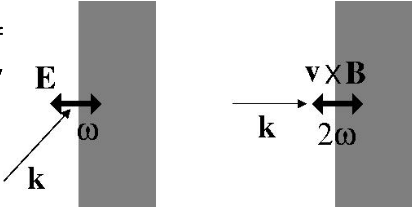
Funding acknowledgments

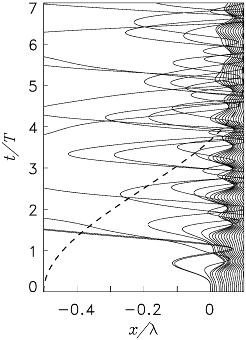
- LASERLAB-EUROPE, grant No. 284464, EU's 7th Framework Programme, proposal n.SLIC001693.
- PRACE supercomputing award, project LSAIL, for access to resource FERMI BlueGene/Q™ at CINECA (Italy)
- MIUR (Italy):
- FIR project "Superintense Ultrashort Laser-Driven Ion Sources"
- PRIN project "Laser-Driven Shock Waves"

EXTRA SLIDES

Fast electron generation: a simplified picture

Needs laser-driven push-pull of electrons across the density gradient



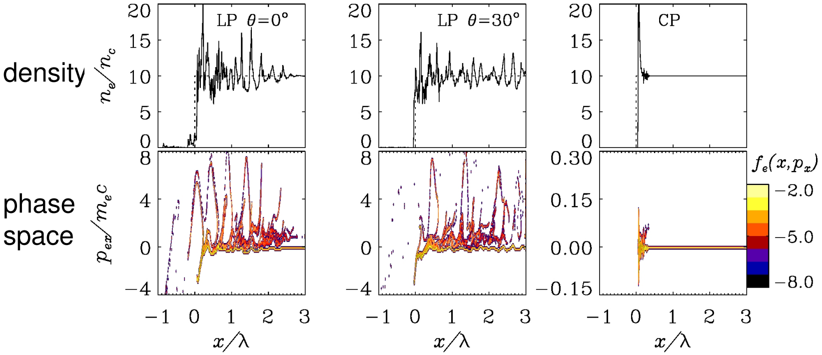


Electrons perform “half-oscillations” in vacuum and re-enter in the plasma with approximately the “quiver” energy

Oscillations driven by:

- $\mathbf{E}$ for P–polarization
- $\mathbf{v}\times\mathbf{B}$ for S–polarization or normal incidence

Fast electron generation: 1D simulations



Linear Polarization: fast electron bunches at rate ω (for $\theta = 30^\circ$, P-pol.) or 2ω (for $\theta = 0^\circ$)

Circular Polarization at $\theta = 0^\circ$: *no fast electrons* ($(\mathbf{v} \times \mathbf{B})_{2\omega} = 0$)

Fast electron generation: typical parameters

- Typical energy (“ponderomotive scaling”)

$$\mathscr{E}_f = m_e c^2(\gamma - 1) \sim m_e c^2 \left(\sqrt{1 + a_0^2/2} - 1 \right)$$

a_0: “relativistic” amplitude parameter

$$a_0 = \left(\frac{I\lambda^2}{10^{18}\ \text{W/cm}^2} \right)^{1/2} = \frac{eE_L}{m_e \omega c} = \frac{p_{\text{osc}}}{m_e c}$$

- conversion efficiency $\eta_f \simeq 10^{-2} - 10^{-1}$
- density $n_f \simeq 10^{20} - 10^{21}\ \text{cm}^{-3}$
- current density $\sim 10^{12}\ \text{A/cm}^2 \rightarrow 10\ \text{MA}$ over the laser spot

Static modeling of TNSA

Assume fast electrons in Boltzmann equilibrium with density n_e and temperature T_e as the only parameters to evaluate sheath extension L_s and potential drop $\Delta\Phi$

$$L_s \simeq \lambda_D = (T_e/4\pi e^2 n_e)^{1/2}\,, \qquad \Delta\Phi \simeq T_e/e$$

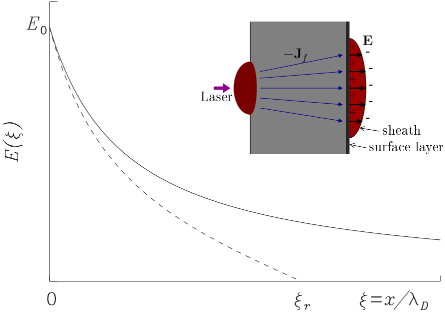
Energy gain by a "test" ion in the static sheath:

$$\mathscr{E}_{\text{max}} = Ze\Delta\Phi \simeq ZT_e$$

⚠ : exact treatment yields

$$L_s \to \infty \qquad \Delta\Phi \to \infty$$

if Boltzmann's distribution is not "truncated" at high energy



Charging and "truncation" by electron escape

- An isolated, warm plasma in "real" 3D space gets charged due to the escape of $N_{\rm esc}$ electrons with energy $> U_{\rm esc}$ (since the binding potential is limited)
- For a simple spherical emitter of radius R having N_0 electrons at T_e:

$$N_{\rm esc} = N_0 \exp(-U_{\rm esc}/T_e) \qquad U_{esc} = e^2 N_{\rm esc}/R$$

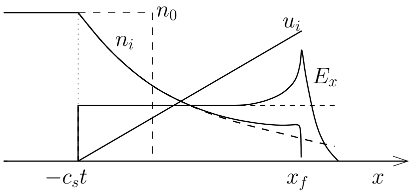
- Message: cut-off energy $U_{\rm esc}$ (hence $\mathscr{E}_{\rm max}$) depends on target density, size, ...
- ⚠: the system is neither steady nor in Boltzmann equilibrium, the target is neither isolated nor grounded, ...

Dynamic modeling of TNSA

Plasma expansion model: isothermal rarefaction wave solution "patched" at the ion front where quasi-neutrality breaks down

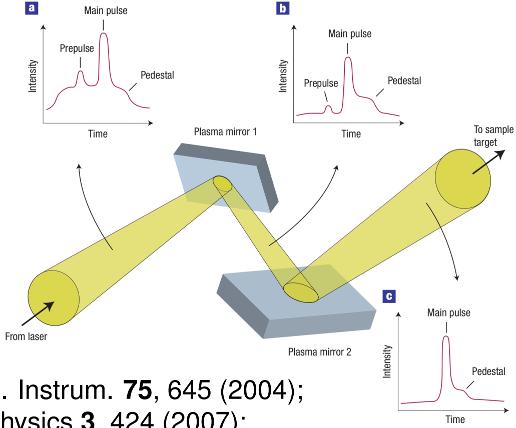
$$c_s = \left(\frac{ZT_e}{m_i}\right)^{1/2}, \quad u_f \equiv u_i(x_f) = c_s[2\ln(\omega_{pi}t)+1], \quad \mathscr{E}_{\max} = \frac{m_i}{2}u_f^2 \propto ZT_e$$

⚠: ion energy diverges due to infinite energy reservoir!
assume finite model (e.g thin foil expansion) with $T_e(t)$
assume finite acceleration time (extra patch)



Need for ultraclean pulses: plasma mirrors

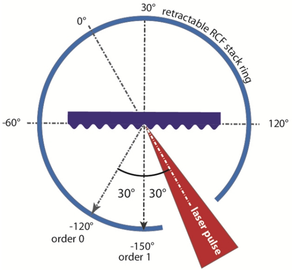
Plasma mirrors yielding $\sim 10^{12}$ pulse-to-prepulse contrast allow to preserve target structuring until the short pulse interaction

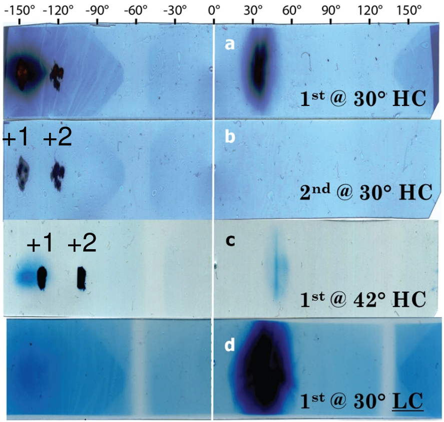


B. Dromey et al, Rev. Sci. Instrum. **75**, 645 (2004);
C. Thaury et al, Nature Physics **3**, 424 (2007);
figure from P. Gibbon, *ibid.*, 369.

Grating signatures on RCF

Diffraction orders produce angle-dependent "burn spots" for High Contrast (HC), not observed with Low Contrast (LC)

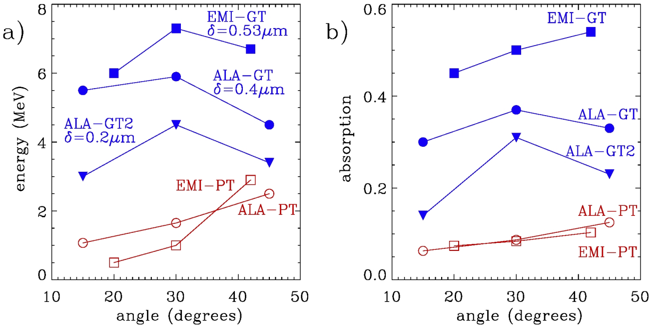




Comparison with PIC simulations

Two simulations campaigns with Particle-In-Cell codes EMI2D (CPhT, École Polytechnique) and ALADYN (Italy) fairly reproduce experimental trend

(2D simulations, different set-up for the two codes)

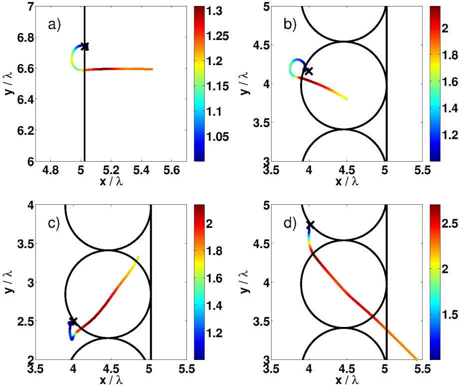


Enhanced electron heating out of resonance

Stochastic heating at a modulated interface is more efficient than in plane targets: electrons have more “re-entering trajectories” available

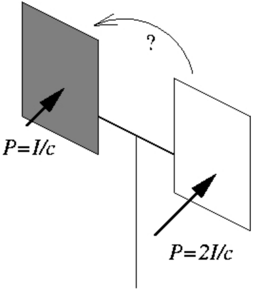
Effect observed in microsphere-covered targets

(PIC sim. by O. Klimo et al)



V. Floquet et al, J. Appl. Phys. **114**, 083305 (2013)

How to make radiation pressure dominant?



The “Optical Mill” rotates in the sense *opposite* to that suggested by the imbalance of radiation pressure: *thermal* pressure due to *heating* dominates

Enforcing radiation pressure dominance requires to suppress heating of the surface
Possible solution for ultraintense lasers: circular polarization

Relativistic transparency and optimal thickness

Thin plasma foil becomes transparent because of relativistic effects when

$$a_0 > \zeta \equiv \pi \frac{n_e}{n_c} \frac{\ell}{\lambda} \qquad n_c = \frac{m_e \omega^2}{4\pi e^2} \text{ (cut-off density)}$$

→ optimal thickness as trade-off between reduced mass and transparency: $a_0 = \zeta$

- Diamond-Like Carbon ultrathin (nm) targets

→ avoid "prepulses" to cause early target disruption

- ultrahigh-contrast systems
- wide spots (and large energy), supergaussian intensity profiles to avoid strong deformation ?