Basics of Laser-Plasma Interaction (lecture 3/3)

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Advanced Summer School on
“Laser-Driven Sources of High Energy Particles and Radiation”
CNR Conference Centre, Anacapri, Italy, July 9-16 2017

Outline of Lecture 3

Light sail acceleration

- heating vs radiation pressure
- effects of laser polarization
- 3D effects

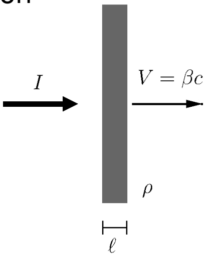
Radiation friction

- foundations of the problem
- classical Landau-Lifshitz theory
- macroscopic effects: magnetic field generation

Light Sail acceleration with lasers: a “dream bunch”?

Fast scaling and high efficiency of LS acceleration

$$\frac{\mathscr{E}_{\max}}{m_p c^2} = \frac{\mathscr{F}^2}{(2(\mathscr{F}+1))} \qquad \eta = \frac{2\beta}{1+\beta} = 1 - \frac{1}{1+\mathscr{F}^2}$$



$$\mathscr{F} = \frac{2I\tau_p}{\rho\ell} = \frac{Z}{A}\frac{m_e}{m_p}\frac{{a_0}^2}{\zeta}\omega\tau_p \qquad \left(\zeta = \pi\frac{n_e}{n_c}\frac{\ell}{\lambda}\right)$$

if $\beta \ll 1 \quad \rightarrow \quad \frac{\mathscr{E}_{\max}}{m_p c^2} \simeq \frac{\mathscr{F}^2}{2}, \quad \eta \simeq \mathscr{F}^2$

$\ell \simeq 10$ nm, $I \simeq 10^{21}$ W cm^{-2}, $\tau_p \gtrsim 10$ fs $\longrightarrow \mathscr{F} \sim 1$

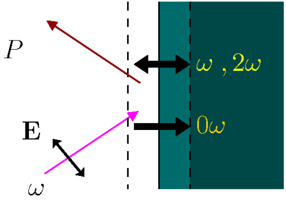
$\mathscr{F} = 1 \quad \longrightarrow \quad \mathscr{E}_{\max} = 235$ MeV, $\eta = 0.5$

coherent motion of the sail $\longrightarrow$ mononergetic ion spectrum

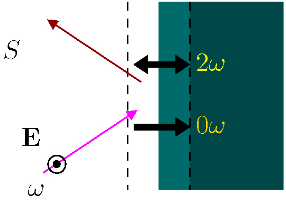
Optimal thickness $a_0 \simeq \zeta$ at the threshold of transparency

Forces on the sail

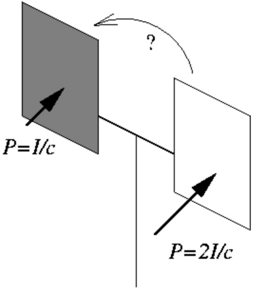
The radiation pressure on the sail arises from the *steady* ("0ω") ponderomotive force
The laser also exerts oscillating forces
P-polarization: $\mathbf{E}$-driven, $\Omega = \omega$
S-polarization: $\mathbf{v} \times \mathbf{B}$-driven, $\Omega = 2\omega$



Nonlinear oscillations across the surface cause electron heating
(the motion across a sharp gradient is non-adiabatic)
Heating is undesired (possibly detrimental) for radiation pressure acceleration



How to make radiation pressure dominant?

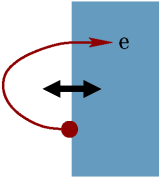


The "Optical Mill" rotates in the sense *opposite* to that suggested by the imbalance of radiation pressure: *thermal* pressure due to *heating* dominates

Enforcing radiation pressure dominance requires to suppress heating of the surface

For ultraintense lasers: radiation pressure push must overcome internal pressure due to the generation of "fast" electrons

“Vacuum heating” of electrons



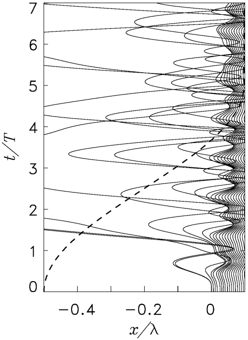
Single particle picture: oscillating forces drag electrons into the vacuum side and push them back in the plasma after an oscillation half-cycle

[Brunel, Phys. Rev. Lett. **59** (1987) 52;

Phys. Fluids **31** (1988) 2714]

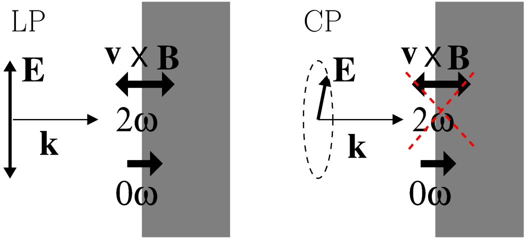
Collective picture: driven plasma oscillations across a sharp gradient “break” and give energy to particles

Electrostatic simulation with Dawson’s sheet model: self-intersection (*wavebreaking*) of fluid elements and generation of “fast” electron bunches



Circular polarization quenches heating

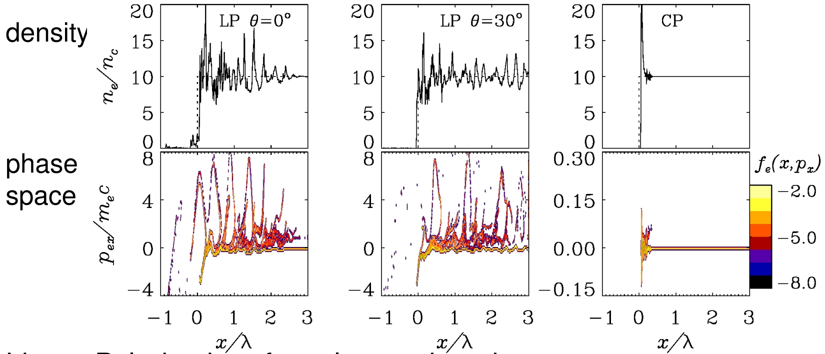
For Circular Polarization (CP) at normal incidence the 2ω component of the $\mathbf{v}\times\mathbf{B}$ force vanishes → longitudinal oscillations and heating of electrons are suppressed



Ions respond "smoothly" to steady component: radiation pressure dominates the interaction
[Macchi et al, Phys. Rev. Lett. **95** (2005) 185003]

Fast electron generation: effect of polarization

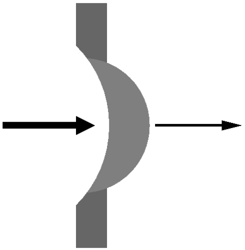
1D simulations of laser interaction with solid-density plasma



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

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

Fast gain Light Sail in 3D



Transverse expansion of the target reduces on-axis surface density $\rho\ell$

$\Rightarrow$ *light sail gets "lighter"*:

boost of energy gain

at the expense of the number of ions

[S.V.Bulanov et al, PRL **104** (2010) 135003]

LS equations accounting for self-similar transverse dilatation of target in D-dimensions ($D = 1, 2, 3$)

$$r_\perp(t) = \Lambda(t) r_\perp(0) \, , \qquad \sigma = \sigma(t) = \frac{\sigma(0)}{\Lambda^{D-1}(t)}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(\gamma\beta_\parallel) = \frac{2I}{\sigma(0)c^2}\Lambda^{D-1}(t)\frac{1-\beta_\parallel}{1+\beta_\parallel}$$

Model for target dilatation

Model: transverse kick due to ponderomotive force

$$\frac{\mathrm{d}p_\perp(t)}{\mathrm{d}t} \simeq -m_e c^2 \partial_r (1+a^2(r,t))^{1/2} \simeq 2 m_e c^2 a_0 r/w \qquad (a_0 \gg 1\,,\ r \ll w)$$

→ transverse momentum scales linearly with position

$$\frac{\mathrm{d}\Lambda}{\mathrm{d}t} = \frac{\dot{r}_\perp(t)}{\dot{r}_\perp(0)} = \frac{\alpha}{\gamma(t)}\,, \qquad \gamma(t) \simeq (p_\parallel^2 + m_i^2 c^2)^{1/2}\,, \qquad \alpha \simeq 2\frac{m_e a_0 c^2 \Delta t}{m_p w^2}$$

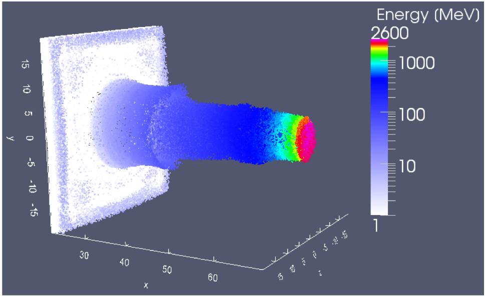
Solution in the $\gamma \gg 1$ limit $\gamma = \left(\frac{t}{\tau_k}\right)^k\,, \quad k = \frac{D}{D+2}$

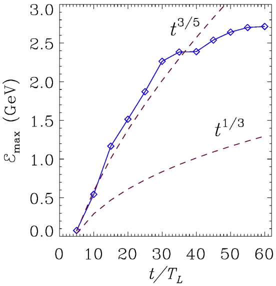
Fastest gain in 3D $\sim t^{3/5}$ with $\tau_{3/5} = (48/125\Omega\alpha)^{1/3}$

(note: mechanism is efficient in the relativistic regime).

High energy gain in 3D LS simulations

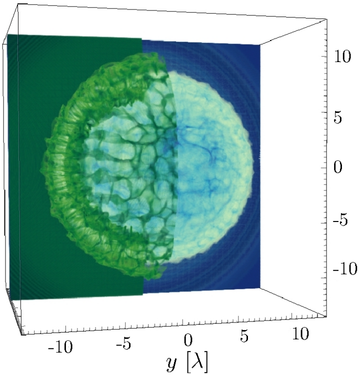
Laser: 24 fs, 4.8 μm spot, $I = 0.85 \times 10^{23}$ W cm^{-2} $\Longrightarrow$ 1.5 kJ
Target: $d = 1$ μm foil, $n_e = 10^{23}$ cm^{-3}



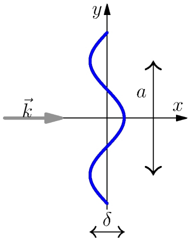


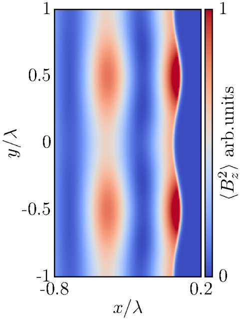
$\mathcal{E}_{\max} \simeq 2.6$ GeV $>$ 4X 1D model prediction
Macchi et al, Plasma Phys. Contr. Fus. **55** (2013) 124020;
Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

Rayleigh-Taylor instability in LS acceleration



target breakup into net-like structures with size $\sim \lambda$ (laser wavelength) and $\sim$ hexagonal shape





Explanation: Rayleigh-Taylor instability stimulated by radiation pressure modulation
Sgattoni et al, Phys. Rev. E **91** (2015) 013106

field enhancement in surface ripple valleys

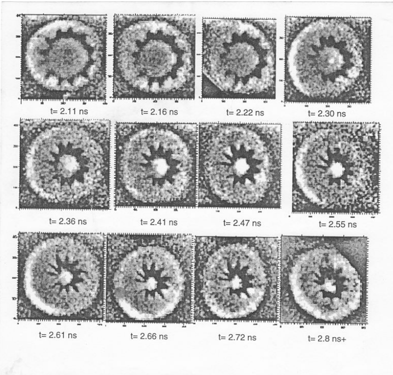
Rayleigh-Taylor Instability in space and lab

Crab Nebula, Hubble Space Telescope

Heavy fluid over a light fluid is unstable
(↑ gravity ↓ acceleration)

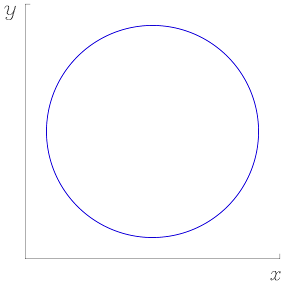
physicscentral.com

Laser-driven implosion for Inertial Confinement Fusion studies, 1995 (Wikipedia)



Introducing radiation friction - I

Example:
electron in a magnetic field $\mathbf{B}_0$



$\mathbf{f}_L = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}/c)$ Lorentz force

$$m_e \frac{d\mathbf{v}}{dt} = \mathbf{f}_L = -\frac{e}{c}\mathbf{v} \times \mathbf{B}_0$$

Solution: uniform circular motion

$|\mathbf{v}| = v =$ cost.

$K = \frac{1}{2} m_e v^2 =$ constant $\qquad \omega_c = \frac{eB_0}{m_e c} \qquad r = \frac{v}{\omega_c}$

Introducing radiation friction - II

But the electron radiates:

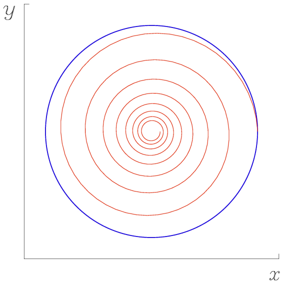
$$P_{\text{rad}} = \frac{2e^2}{3c^3}\left|\frac{d\mathbf{v}}{dt}\right|^2 = \frac{2e^2}{3c^3}\omega_c^2 v^2$$

(Larmor's formula for radiated power)

Energy loss due to radiation:

$$\frac{dK}{dt} = -P_{\text{rad}} \quad \longrightarrow \quad v(t) = v(0)e^{-t/\tau}$$

$$\tau = \frac{3m_e c^3}{2e^2\omega_c^2} = \frac{3c}{2r_c\omega_c^2} \qquad r_c = \frac{e^2}{m_e c^2}$$

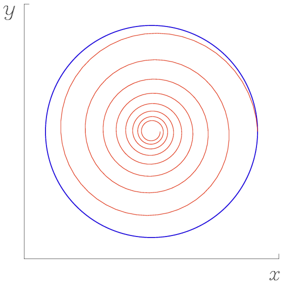


If $r(t) \simeq v(t)/\omega_c$, electron "falls" along a spiral

Introducing radiation friction - III

The Lorentz force does not describe the electron motion consistently: need to include an extra force

$$m_e \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \mathbf{f}_L + \mathbf{f}_{\text{rad}}$$



Work done by extra force = energy loss

$$\int_0^t \mathbf{f}_{\text{rad}} \cdot \mathbf{v} \mathrm{d}t = -\int_0^t P_{\text{rad}} \mathrm{d}t \longrightarrow \mathbf{f}_{\text{rad}} = -\frac{2e^2}{3c^3} \frac{\mathrm{d}^2\mathbf{v}}{\mathrm{d}t^2}$$

Physical interpretation: the electron is affected by the self-generated radiation field (radiation *reaction* or *self-force*)

Landau-Lifshitz classical approach

$\mathbf{f}_{\text{rad}} = -\frac{2e^2}{3c^3}\frac{\mathrm{d}^2\mathbf{v}}{\mathrm{d}t^2}$ is unsatisfying:

- unphysical "runaway" solutions $\mathbf{a}(t) = \mathbf{a}(0)\mathrm{e}^{t/\tau}$ $\left(\mathbf{a} = \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}\right)$
- need of "extra" initial condition $\mathbf{a}(0)$

LL iterative approach brings $\mathbf{f}_{\text{rad}} = \mathbf{f}_{\text{rad}}(\mathbf{E},\mathbf{B})$:

$$\mathbf{f}_{\text{rad}} = -\frac{2e^2}{3c^3}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}\right) \simeq -\frac{2e^2}{3c^3}\frac{\mathrm{d}}{\mathrm{d}t}\left(-\frac{e}{m_e}\mathbf{f}_L\right) = \frac{2e^3}{3m_ec^3}\left(\frac{\mathrm{d}\mathbf{E}}{\mathrm{d}t} - \frac{e}{m_ec}\mathbf{E}\times\mathbf{B}\right)$$

in the "instantaneous" frame where $\mathbf{v} = 0$ (note: $\frac{\mathrm{d}\mathbf{E}}{\mathrm{d}t} = (\partial_t + \mathbf{v}\cdot\nabla)\mathbf{E}$)

Note 2^{nd} term $\sim \frac{2}{3}\left(\frac{e^2}{m_ec^2}\right)\mathbf{E}\times\mathbf{B} = \frac{8\pi}{3}r_c^2\frac{\mathbf{S}}{c} \propto \sigma_T I$ "Thomson drag"

Landau & Lifshitz, *The Classical Theory of Fields*, 2nd Ed., par.76

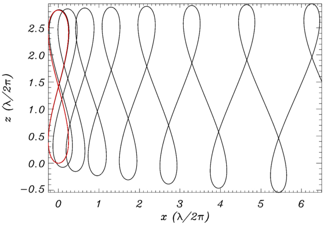
Relativistic Landau-Lifshitz RF force

Necessary generalization to relativistic regime yields

$$\mathbf{f}_{\text{rad}} = -\frac{2r_c^2}{3}\left\{\gamma^2\left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)^2-\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)^2\right]\frac{\mathbf{v}}{c} -\left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)\times\mathbf{B}+\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)\mathbf{E}\right]+\gamma\frac{m_e c}{e}\left(\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{E}+\frac{\mathbf{v}}{c}\times\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{B}\right)\right\}$$

Dominant term ($\sim -\gamma^2\mathbf{v}$) acts as a nonlinear friction force

Effect of including $\mathbf{f}_{\text{rad}}$ on the motion in a plane wave: accelerating drift of the figure-of-eight
(constraints of “no-acceleration” theorem are broken)



Including radiation friction in plasma modeling

- The electrodynamics of continous media (a mean field theory) considers only coherent emission ($\lambda \gg n_e^{-1/3}$) that governs the collective dynamics
- Electrons also emit incoherent radiation ($\lambda \ll n_e^{-1/3}$) which mostly escapes from the medium ($\omega \gg \omega_p$)
- The RF force accounts for the back-reaction of radiation emission at *all* ω's, but in practice only very high ω's are relevant (radiation power strongly scales with ω)
- Including RF in the modeling makes radiation losses consistent with plasma dynamics
- (All of this is only relevant for high fields and strongly relativistic electrons . . . which is where we are going!)

RF-induced angular momentum absorption

- A CP laser pulse carries “spin” angular momentum (AM) classical expression:

$$L_z = \int_0^\infty \ell_z(r) 2\pi r \mathrm{d}r = -\int_0^\infty \frac{r}{2c\omega} \partial_r I(r) 2\pi r \mathrm{d}r$$

- in QM, each photon has spin $\hbar$ independently of ω

→ absorption of photons leads to AM absorption (AMA)

- Strong radiation emission from a laser plasma

→ (many) low-frequency (laser) photons are converted into (few) high-frequency (γ-ray) photons

→ RF inclusion should induce strong AMA in the plasma

→ mechanical torque on electrons

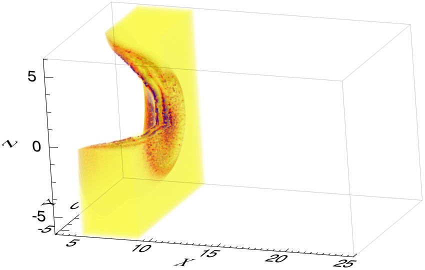
RF-induced "inverse Faraday" effect

- The AMA-induced torque on electrons drive a solenoidal current

$\rightarrow$ generation of an axial magnetic field

- note 1: inverse Faraday effect (IFE) is somewhat a misnomer, but used since its discovery
- note 2: circular electron orbits in a CP pulse do *not* generate a steady axial field! Note also that the physics is at the edge of the beam ($\ell_z \propto \partial_r I(r)$)
- model for IFE in a plasma, with criticism of earlier theories: M. Haines, PRL **87** (2001) 135005
- Idea: use IFE-generated magnetic field as a RF signature in (extremely intense) laser-plasma interactions

Searching for IFE in 3D thick target simulations



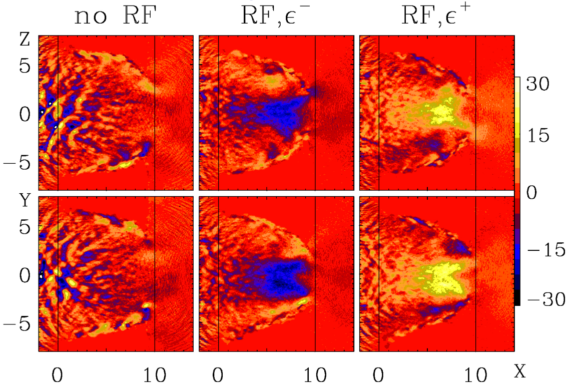
$\lambda = 0.8\ \mu$m
$n_e = 90 n_c = 1.6 \times 10^{23}$ cm^{-3}
$a_0 = (200 - 600)$
$I = (0.9 - 7.8) \times 10^{23}$ W cm^{-2}
$U = (0.4 - 4) \times 10^3$ J

Laser pulse at waist (target boundary)

$$\mathbf{a}(x=0,r,t) = a_0 \left(\hat{\mathbf{y}}\cos(\omega t) \pm \hat{\mathbf{z}}\sin(\omega t)\right) \mathrm{e}^{-(r/r_0)^n - (ct/r_l)^4}$$

$n = 2$ (Gaussian profile) or $n = 4$ (super-Gaussian)
$r_l = 3\lambda$, $r_0 = 3.8\lambda$

Gigagauss axial magnetic fields induced by RF



B_x

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

No axial field without RF
Sign of B_x changes with laser pulse helicity

T. V. Liseykina, S. V. Propruzhenko, A. Macchi, New J. Phys. **18** (2016) 072001

Unexpected (and embarassing) hype . . .

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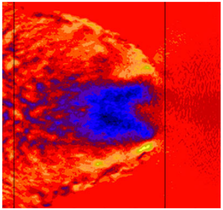
'Radiation friction' could make huge magnetic fields with lasers

Jul 19, 2016 2 comments



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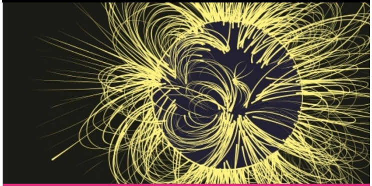
New method for generating superstrong magnetic fields

August 10, 2016

Science alert



Physicists have calculated a whole new way to generate super-strong magnetic fields

Stronger than any magnetic field on Earth.