Short wavelength radiation in intense Laser-Plasma interactions

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Introduction
- Particle-in-Cell plasma simulation code
- Moving charged particles
- Laser-induced Coherent Synchrotron Emission
- Incoherent Synchrotron emission from nano-structure targets
- Self-injection into a plasma wakefield
- Betatron radiation
Laser-matter interaction

Target (solid density)

- Reflected + higher harmonics
- Laser Pulse
- Ponderomotive force: $F_p = e v \times B \sim -\nabla I$
  - Generalized, relativistic form: $F_p = -m_e c^2 \nabla \bar{y}$

- Hot electron cloud
- Transmitted X-ray
- Bremsstrahlung
- Accelerated ions

Short Pulse Laser interaction with Matter,
Paul Gibbon
Particles move on a grid (discretized space). They have charge and velocity to deposit *current density* on the *grid nodes*. This vector field is used to calculate the *electric field* according to Ampere's law:

\[
\frac{\partial E}{\partial t} = c^2 \nabla \times B - \frac{1}{\epsilon_0} j
\]

Then the *magnetic field* is calculated from Faraday's law:

\[
\frac{\partial B}{\partial t} = - \nabla \times E
\]

If the plasma is initially not neutral, then the electric field field has to be set (t=0):

\[
\nabla \cdot E_0 = \frac{\rho_0}{\epsilon_0} \quad \text{(Initial condition)}
\]

*E* and *B* can be external (*laser field*).
**PIC code**

**What is included?**

- Maxwell solver, self-consistent plasma dynamics
- Fully relativistic particle pusher
- Good diagnostics, spatial and temporal evolution of relevant quantities
- Statistical, numerical noise :(

**What is not (can be) included?**

- Field ionization and particle collisions
- Recombination, photon emission
- Plasma dynamics on ns time scale: fluid codes/models
- QED effects: gamma-rays, pair creation
- Cylindrical or spherical coordinate system
- etc...

Our tools:
- Vsim (Vorpal), EPOCH, Piccante, PIConGPU, LPIC, etc...

*Plasma Physics Via Computer Simulation, Birdsall & Langdon*
Radiating charges

According to Maxwell's equations moving charged particles emit EM waves!

Radiated Power:

\[ P = \frac{2}{3} \frac{q^2}{c^3} a^2 \]

In the relativistic case if \( \vec{v} \perp \vec{a} \)

\[ P = \frac{2}{3} \frac{q^2}{m^2 c^3} \gamma^2 \left( \frac{dp}{dt} \right)^2 \]

\( \gamma = (1 - \beta^2)^{-1/2} \)

\( \beta = \frac{v}{c} \)

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if \( \dot{v} = 0 \) ⇒ \( \omega_{osc}' = (1 + \beta) \gamma \omega_{osc} \)

Doppler shift

if \( \dot{v} \neq 0 \) ⇒ Broad spectrum is emitted- high harmonics
Coherent radiation: Atto-second pulses
In laser field

Laser electric field

Ponderomotive force

Nano-bunching!
Coherent radiation!

$F_p$

$F_L$

$\vec{V}_e$

Skin layer
Electron nano-bunching

P-polarization

$E_y < 0$

Electrons
Electron nano-bunching

\[ E_y < 0 \]

\[ E_y(x,t) = \frac{1}{2 \epsilon_0} \int_0^t j_y(x', t') \, dt' \]
Synchrotron spectrum

\[ I(\omega) \sim |\int dt \bar{\epsilon} \times [\bar{\epsilon} \times J(\vec{r},t)] \exp[i\omega(t - \bar{\epsilon} \cdot \vec{r}/c)]|^2 \]

\[ I(\omega) \sim |\int dt J_{\perp}(x,t) \exp[i\omega(t - x(t)/c)]|^2 \]

\[ x(t) = r(t) = \gamma \]

\[ \gamma = (1 - \dot{x}(t)^2/c^2)^{-1/2} \]

\[ \vec{V}_{\perp} \ll c \]

\[ \vec{V}_{\perp} \approx \vec{V}_{x} \approx c \]

Observer
\[ I(\omega) \sim \left| \int dt \vec{\varepsilon} \times [\vec{\varepsilon} \times J(\vec{r}, t)] \exp[i \omega(t - \vec{\varepsilon} \cdot \vec{r}/c)] \right|^2 \]

\[ I(\omega) \sim \left| \int dt J_\perp(x, t) \exp[i \omega(t - x(t)/c)] \right|^2 \]

\[ x(t) = r(t) = ? \]

\[ \gamma = (1 - \dot{x}(t)^2/c^2)^{-1/2} \]

\[ \dot{x}(t) \sim v(1 - t^{2n}) \Rightarrow \omega_{rs} \sim \gamma^{2n+1} \]

\[ I(\omega) \sim \omega^{2n+2} F(\omega) \]

D. an der Brügge and A. Pukhov, arxiv:1111.4133 (2011)
Transversal motion

\[ I(\omega) \sim \left| \int dt J_\perp(x,t) \exp\left[i\omega(t-x(t)/c)\right] \right|^2 \]

\[ \nu_\perp \sim J_\perp \approx \alpha_0 t^n \]

PHYSICS OF PLASMAS 17, 033110 (2010)

Transversal motion

\[ I(\omega) \sim | \int dt J_\perp(x,t) \exp[i \omega (t - x(t)/c)]^2 \]

\[ \nu_\perp \sim J_\perp \approx \alpha_0 t^n \]

\[ E_\perp \sim a_\perp(t') \frac{4 \gamma^2}{(1 + \gamma^2 t'^2)^2} \]

\[ a_\perp = \exp(-t^2) \quad \text{or?} \quad a_\perp = \exp(-t^n) \]

What is the correct approximation?
Are higher values of “n” also possible?

\[ n=5, \gamma = 4 \quad \text{(Super-Gauss)} \]
\[ n=5, \gamma = 4 \quad \text{(Gauss)} \]
\[ n=5, \omega_{rs} = 20 \omega_0 \]

Physics of Plasmas 17, 033110 (2010)

Harmonic spectrum

The electric field emitted in the coherent cone:

\[ 0.1 < \theta < 0.3 \]

Fourier transform of the attopulse (compared to model spectrum)

Such spectrum will never be measured in the far-field.
Next steps...
Incoherent radiation: Femto-second X-ray flashes
Nano-forest target

The laser pulse can accelerate electrons between the nanorod, thus the energy conversion efficiency is much higher.

3D Simulation:
- nanorod radius: 50 nm
- Distance: 600 nm

http://arxiv.org/abs/1509.04951
Particle trajectories

2D Simulation

Is the betatron resonance possible?

Radiation is incoherent!
In 3D

The electrons do not cross the nanowires, they always go around them. In this case the electrons gain energy continuously from the laser field and in the case of resonance only the wire length limits the maximum energy.

Zs. Lecz, A. Andreev, Physics of Plasmas, 24, 033113, (2017)
Emission radiation

\[ I_L = 4 \cdot 10^{20} \, \text{W/cm}^2 \]

\[ d_w \approx 90 \, \text{nm} \]

\[ L_w \approx 30 \, \mu\text{m} \]

\[ D_{sp} \approx 1.0 \, \mu\text{m} \]
Underdense plasma
Linear and non-linear regimes

At low intensity the ponderomotive force repels weakly the plasma electrons and linear wave is generated behind the driver with a sinusoidal density modulation.

At higher intensity more electrons are repelled and the restoring ion space charge accelerates them to relativistic velocity. Thus the plasma wavelength becomes longer and the charge distribution gets distorted.

E. Esarey et al., REVIEWS OF MODERN PHYSICS, VOLUME 81, 1229 (2009)
Bubble formation

In the frame moving with the driving beam!

Condition for injection: \( v_e > v_b \approx c \)
Non-uniform plasma: density down-ramp

Plasma wavelength: \( \lambda_p = \frac{c}{\omega_p} = c \sqrt{\frac{\epsilon_0 \gamma m_e}{(e^2 n_e)}} \)

The velocity of the back of the bubble decreases.
The electron entering the crossing region needs to have a longitudinal velocity larger than the velocity of the crossing region.
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If the density profile is steep enough electrons are continuously injected!
Density ramps on the mm level result in continuous injection of plasma electrons.

PHYS. REV. ACCEL. BEAMS 20, 091301 (2017)
Three types of electrons

Only a small amount of electrons enters the crossing region. They can spend a long time there and contribute to the space charge field. When the current density reaches a critical value electrons get ejected transversally and the injection stops temporarily.
Ejected electrons

Condition for transversal ejection:

\[ r_g = \gamma m_e v_x / eB_\theta \]

\[ r_g = R_c \approx \lambda_p \]
Ejected electrons

Ejected electrons

Condition for transversal ejection:

\[ r_g = \gamma m_e v_x / eB_\theta \]

Radial force:

\[ \frac{dp_r}{dt} = -eE_r + v_x B_\theta \]
This type of injection requires:
- Long density ramps for charge accumulation in the CR
- High energy beams for long depletion length
- High charge (intensity) beams to drive a non-linear wakefield or bubble
The electrons injected later are accelerated to higher energy, because of the non-uniform electric field of the bubble. The field is stronger in the back of the bubble. The bunched structure is preserved!

Possible application: Multi-color Thomson scattering.
THANK YOU FOR YOUR ATTENTION!