I. Presentation of the radiative and QED physical processes relevant for the next generation of extreme intensity lasers

II. Regimes of interaction

III. Presentation of the radiative models

IV. Presentation of the multiphoton Breit-Wheeler pair creation model

V. Examples of simulations
Radiative and QED physical processes relevant for the next generation of extreme intensity lasers
Forthcoming short-pulse extreme intensity laser will soon reach the threshold of $10^{22}-10^{23} \text{ W/cm}^2$.

- **100 PW: ELI upgrade, XCELS**
  $(10^{23}-10^{24} \text{ W/cm}^2, 10\times10 \text{ PW beams})$

- **10 PW: Apollon, Vulcan, ELI**
  $(10^{22} - 10^{23} \text{ W/cm}^2, 150-300 \text{ J, 15-30 fs})$
Radiative and quantum electrodynamics effects will progressively come into play.

**Classical radiation cooling**

Continuous emission of relatively low-energy photons in comparison with the electron energy.

**Nonlinear inverse Compton scattering**

Stochastic emission of high-energy photon.
Radiative and quantum electrodynamics effects will progressively come into play.

**Multiphoton Breit-wheeler pair creation**

Creation a pair of electron-positron from the decay of a γ photon interacting with an electromagnetic field.
Radiative and QED effects will affect the particle dynamic and the overall energy balance of simulations

**Example of the laser thin-foil interaction**

- $10^{22}$ W/cm²: ~ 1 % absorption by radiation
- $10^{23}$ W/cm²: ~ 10 % absorption by radiation
- $10^{24}$ W/cm²: > 50 % absorption by radiation, significant production of pairs
Novel experimental configurations to study QED processes in laboratories will be soon accessible with extreme-intensity lasers.
Regimes of interaction
Radiative and QED effects depend on the electron/photon energy, the field strength and the interaction geometry

To determine the right regime of interaction, pay attention to these parameters

**Laser normalized intensity:**

\[ a_0 = \frac{A_0 e}{mc} \gg 1 \]

**Electron Lorentz factor:**

\[ \gamma_{\pm} = \sqrt{\frac{1}{1 - v_{\pm}^2/c^2}} \gg 1 \]

**Photon Lorentz factor:**

\[ \gamma_{\gamma} = \frac{\varepsilon_{\gamma}}{mc^2} \gg 1 \]

- \( \varepsilon_{\gamma} \): The photon energy
- \( m \): The electron mass
- \( c \): Speed of light in vacuum
- \( e \): Electron charge
- \( v_{\pm} \): Electron or positron velocity
Radiative and QED effects depend on the electron/photon energy, the field strength and the interaction geometry.

To determine the right regime of interaction, pay attention to these parameters.

The strength of the QED effects on an electron of Lorentz factor $\gamma$ and a photon of normalized energy $\gamma$ propagating in an electromagnetic field and depends on the following **Lorentz invariant quantum parameters**:

\[
\chi_\pm = \frac{\gamma_\pm}{E_s} \sqrt{\frac{E^2}{\gamma^2} + (E_\perp + v_\pm \times B)^2}
\]

\[
\chi_\gamma = \frac{\gamma_\gamma}{E_s} \sqrt{(E_\perp + c \times B)^2}
\]

- $E_\parallel$ Electric field parallel to the propagation direction
- $E_\perp$ Electric field orthogonal to the propagation direction
- $B$ Magnetic field
- $v_\pm$ Particle velocity
- $E_s$ Schwinger field
Local constant cross-field approximation

Electromagnetic fields are constant during the emission process

\[ \xi_1 = \frac{B^2 - E^2}{E_s^2} \ll 1 \]

\[ \xi_2 = \frac{B \cdot E}{E_s^2} \ll 1 \]

\[ \chi_\pm \gg \max (\xi_1, \xi_2) \]

\( E \)  Electric field

\( B \)  Magnetic field

\( E_s \)  Schwinger field
Quantum parameter minimum threshold

\[ \chi_{\pm} \leq 10^{-3} \]

- Radiation reaction negligible
- No impact on particle energy
Classical regime

\[ \chi_{\pm} \in \left[10^{-3}, 10^{-2}\right] \]

- Radiation reaction can be seen as a slow continuous energy damping
- Emission of many photons of negligible energy in comparison with the emitting particle energy

Laser-thin foil interaction

\[ I_0 \sim 10^{22} \text{ W/cm}^2, \ a_0 \sim 90 \text{ at } \lambda = 1 \mu\text{m} \]
- Weak impact on the target heating and ion acceleration

Laser-electron beam collision

\[ I_0 \sim 10^{21} \text{ W/cm}^2, \ a_0 \sim 1 \text{ at } \lambda = 1 \mu\text{m}, \]
- Electron beam energy \( \sim 100 \text{ MeV} - 1 \text{ GeV} \)
Semi-quantum regime

\[ \chi_{\pm} \in [10^{-2}, 10^{-1}] \]

- Radiation reaction can still be seen as a continuous energy damping
- Stronger slow down

Laser-thin foil interaction

\[ I_0 \approx 10^{23} \text{ W/cm}^2, \ a_0 \approx 270 \text{ at } \lambda = 1 \mu\text{m} \]
- Stronger impact on the target heating and ion acceleration
- Energy loss in radiation can represent several percents

Laser-electron beam collision

\[ I_0 \approx 10^{22} \text{ W/cm}^2, \ a_0 \approx 1 \text{ at } \lambda = 1 \mu\text{m}, \]
electron beam energy ~ 100 MeV - 1 GeV
Near-quantum regime

\[ \chi_{\pm} \in [10^{-1}, 1] \]

- Radiation reaction can no longer be seen as a continuous energy damping
- Emission of photons with individual energies no longer negligible
- Stochastic effects come into play (recoil effect)

Laser-thin foil interaction

\[ I_0 \sim 10^{24} \text{ W/cm}^2, \ a_0 \sim 850 \text{ at } \lambda = 1 \mu\text{m} \]
- Strong impact on the hole boring + TNSA, reduced ion energy

Laser-electron beam collision

\[ I_0 \sim 10^{23} \text{ W/cm}^2, \ a_0 \sim 270 \text{ at } \lambda = 1 \mu\text{m}, \text{ electron beam energy } \sim \text{ few GeV} \]
Near-quantum regime

\[ \chi_{\pm} \geq 1 \]

- Emission of photons with high individual energies, potentially of the order of the emitting particle energy
- Important Stochastic effects (strong recoil)

Laser-thin foil interaction

\[ I_0 > 10^{24} \text{ W/cm}^2, \quad a_0 > 850 \text{ at } \lambda = 1 \mu\text{m} \]
- Strong impact on the hole boring + TNSA, reduced ion energy

Laser-electron beam collision

\[ I_0 \sim 10^{23} \text{ W/cm}^2, \quad a_0 \sim 270 \text{ at } \lambda = 1 \mu\text{m}, \text{ electron beam energy } \sim \text{ few GeV} \]
Pair creation regime

\[ \chi \sim 0.1 \]

- Nonlinear Breit-Wheeler pair creation start to be important around \( \chi \sim 1 \)
- Maximum production rate around \( \chi \sim 10 \)

Laser-thin foil interaction

\[ I_0 \sim 10^{24} \text{ W/cm}^2, \quad a_0 \sim 850 \text{ at } \lambda = 1 \text{ \mu m} \]
- Strong impact on the hole boring + TNSA, reduced ion energy

Laser-electron beam collision

\[ I_0 \sim 10^{23} \text{ W/cm}^2, \quad a_0 \sim 270 \text{ at } \lambda = 1 \text{ \mu m}, \text{ electron beam energy } \sim \text{ few GeV} \]
Radiative and QED effects depend on the electron/photon energy, the field strength and the interaction geometry

<table>
<thead>
<tr>
<th>Regime / Quantum parameter</th>
<th>Impacts</th>
<th>Thin foil - laser interaction</th>
<th>Electron beam - laser collision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantum regime/pair creation</strong></td>
<td>Important creation of pairs</td>
<td>( I_0 \sim 10^{24} \text{ W/cm}^2, a_0 \sim 850 ) at ( \lambda = 1 \mu\text{m} )</td>
<td>( I_0 \sim 10^{23} \text{ W/cm}^2, a_0 \sim 270 ) at ( \lambda = 1 \mu\text{m} ), electron beam energy ( \sim ) few GeV</td>
</tr>
<tr>
<td>( \chi_\gamma &gt; 0.1 )</td>
<td></td>
<td>Creation of a pair plasma on the rear target</td>
<td></td>
</tr>
<tr>
<td><strong>Quantum regime</strong></td>
<td>Strong recoil</td>
<td>( I_0 \sim 10^{24} \text{ W/cm}^2, a_0 \sim 850 ) at ( \lambda = 1 \mu\text{m} )</td>
<td></td>
</tr>
<tr>
<td>( \chi_\pm \geq 1 )</td>
<td>Emission of high-energy gamma photons</td>
<td>Strong impact on the hole boring + TNSA, reduced ion energy</td>
<td></td>
</tr>
<tr>
<td><strong>Semi-quantum regime</strong></td>
<td>Strong continuous damping</td>
<td>( I_0 \sim 10^{23} \text{ W/cm}^2, a_0 \sim 270 ) at ( \lambda = 1 \mu\text{m} )</td>
<td>( I_0 \sim 10^{22} \text{ W/cm}^2, a_0 \sim 1 ) at ( \lambda = 1 \mu\text{m} ), electron beam energy ( \sim ) 100 MeV - 1 GeV</td>
</tr>
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<td>( \chi_\pm \sim 10^{-2} - 10^{-1} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Classical regime</strong></td>
<td>Continuous damping</td>
<td>( I_0 \sim 10^{22} \text{ W/cm}^2, a_0 \sim 90 ) at ( \lambda = 1 \mu\text{m} )</td>
<td>( I_0 \sim 10^{21} \text{ W/cm}^2, a_0 \sim 1 ) at ( \lambda = 1 \mu\text{m} ), electron beam energy ( \sim ) 100 MeV - 1 GeV</td>
</tr>
<tr>
<td>( \chi_\pm \sim 10^{-3} - 10^{-2} )</td>
<td>Emission of many negligible-energy photon</td>
<td>Weak impact on the target heating and ion acceleration</td>
<td></td>
</tr>
</tbody>
</table>
Presentation of the radiative models
The Landau-Lifshitz classical radiation model

**Validity:** \( \chi \leq 10^{-2} \quad \gamma \gg 1 \)

**Principles:** Modification of the momentum equation by the addition of a friction term to model the radiation damping

\[
\frac{dp}{dt} = F_{Lorentz} + F_{rad}
\]

\[ F_{rad} = -P_{rad} \frac{u}{u^2 c} \]

Derived from the Landau-Lifshitz model approximated at high gamma factors

**Overhead:** low (vectorized)
The corrected Landau-Lifshitz radiation model

Validity: \( \chi \leq 10^{-1} \quad \gamma \gg 1 \)

Principles: Modification of the momentum equation by the addition of a friction term to model the radiation damping

\[
\frac{dp}{dt} = F_{\text{Lorentz}} + F_{\text{rad}} \quad F_{\text{rad}} = -P_{\text{rad}} g(\chi) \frac{u}{u^2 c}
\]

Derived from the Landau-Lifshitz model at high gamma factors. Include a quantum correction derived from the QED cross-section.

Overhead: low (vectorized)

Fig.: Importance of the quantum correction when the quantum parameter reaches 0.1.
The Fokker-Planck radiation of Niel et al.

Validity $\chi_\pm \leq 1 \quad \gamma_\pm \gg 1$

Principles: Extension of the corrected Landau-Lifshitz model with an operator that takes into account **diffusive stochastic effects**

\[
F_{rad} dt = \left( -P_{rad} \, g \left( \chi_\pm \right) + mc^2 \sqrt{R \left( \chi_\pm, \gamma_\pm \right)} dW \right) \frac{u}{u^2 c}
\]

\[
R(\chi, \gamma) = \frac{2}{3} \frac{\alpha^2}{\tau_e} h(\chi) \quad h(\chi) \text{ computed from the Compton cross-section}
\]

$dW$ is a Wiener process of variance $dt$

Overhead: high (partly vectorized) / under improvement

The Monte-Carlo (MC) photon emission process

Validity: \[ \chi_\pm \geq 10^{-2} \quad \gamma_\pm \gg 1 \quad a_0 \gg 1 \quad \chi_\pm \gg \max(\xi_1, \xi_2) \]

Principles: Monte-Carlo process

Random drawing of an optical depth computed from the Compton photon emission rate

Cumulative distribution function computed from the Compton photon energy function for the random drawing of the emitted photon energy

Independent of the PIC iteration / particle pusher

Overhead: high (not vectorized)

Presentation of the Multiphoton Breit-Wheeler pair creation model
The Monte-Carlo pair creation emission process

Validity: \( \chi_\gamma \geq 10^{-2} \quad \gamma_\gamma \geq 2 \quad a_0 \gg 1 \quad \chi_\pm \gg \max(\xi_1, \xi_2) \)

Principles: Applied on macro-photon species (from the Compton or initialized)

Monte-Carlo process

Optical depth computed from the multiphoton Breit-Wheeler annihilation rate

Cumulative distribution function for the random drawing of the created electron and positron energy from the multiphoton Breit-Wheeler energy distribution

Overhead: high (not vectorized)
Examples of simulations
Radiative model comparison using particle tests

Laser pulse
I = 10^{23} \text{ W/cm}^2 (a_0=270)
\lambda= 1 \mu\text{m}
FWHM of 33 fs (10 laser periods)
Gaussian order 4

Head-on interaction

1 \text{ GeV electron beam}

\text{max } \chi \sim 2\gamma \frac{E_0}{E_s} \sim 1
Generation of pairs

Laser pulse
I = $10^{23}$ W/cm² ($a_0=270$)
λ = 1 µm
FWHM of 33 fs (10 laser periods)
Gaussian order 4

Head-on interaction

4 GeV electron beam

max $\chi \sim 2\gamma \frac{E_0}{E_s} \sim 10$

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Energy balance

Particle number evolution

Final energy spectrum
Conclusion
Different models implemented for different regimes of interaction

<table>
<thead>
<tr>
<th>Quantum parameters</th>
<th>Interaction regime</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_\gamma \geq 0.1$</td>
<td><strong>Pair creation regime</strong></td>
<td>Emission/propagation of macro-photon as for macro-particles Monte-Carlo pair creation process on the photon species</td>
</tr>
<tr>
<td>$\chi_\pm \geq 1$</td>
<td><strong>Quantum radiation emission regime</strong></td>
<td>Monte-Carlo emission process</td>
</tr>
<tr>
<td>$\chi_\pm \sim 10^{-2} - 10^{-1}$</td>
<td><strong>Near quantum regime</strong></td>
<td>Monte-Carlo emission process Fokker-Planck radiation model of Niel et al.</td>
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<td>$\chi_\pm \sim 10^{-2} - 10^{-1}$</td>
<td><strong>Semi-quantum regime</strong></td>
<td>Fokker-Planck radiation model of Niel et al. Corrected Landau-Lifshitz model</td>
</tr>
<tr>
<td>$\chi_\pm \sim 10^{-3} - 10^{-2}$</td>
<td><strong>Classical regime</strong></td>
<td>Corrected Landau-Lifshitz model Classical Landau-Lifshitz model</td>
</tr>
</tbody>
</table>
Radiation reaction processes:
- Classical and corrected Landau-Lifshitz
- Niel et al.
- Monte-Carlo with or without macro-photon creation

Multi-photon Breit-Wheeler:
- Monte-Carlo pair creation process

Future related features:
- Particle and photon merging process

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