# Radiative and Quantum Electrodynamics processes in SMILEI

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

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III. Presentation of the radiative models

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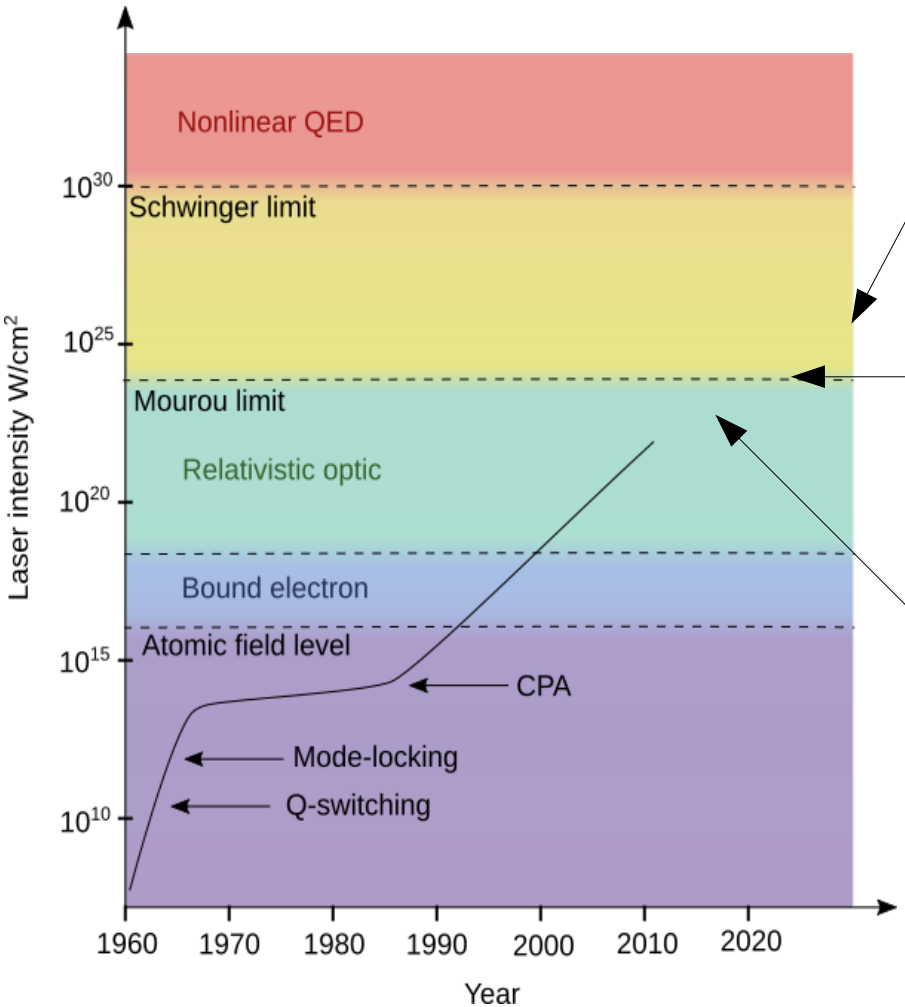
# Radiative and QED physical processes relevant for the next generation of extreme intensity lasers

# Forthcoming short-pulse extreme intensity laser will soon reach the threshold of $10^{22}$-$10^{23}$ W/cm$^2$

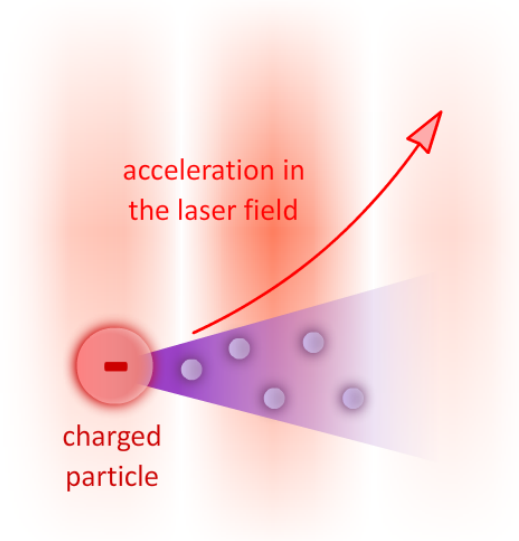



**EXASCALE: IZEST**
(compressed LMJ, NIF-class lasers?)

**100 PW: ELI upgrade, XCELS**
($10^{23}$-$10^{24}$ W/cm$^2$ , 10x10 PW beams)

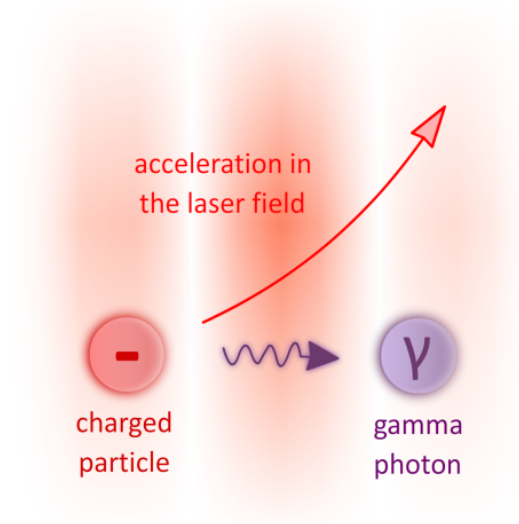
**10 PW: Apollon, Vulcan, ELI**
($10^{22}$ - $10^{23}$ W/cm$^2$ , 150-300 J, 15-30 fs)

# Radiative and quantum electrodynamics effects will progressively come into play




## Classical radiation cooling

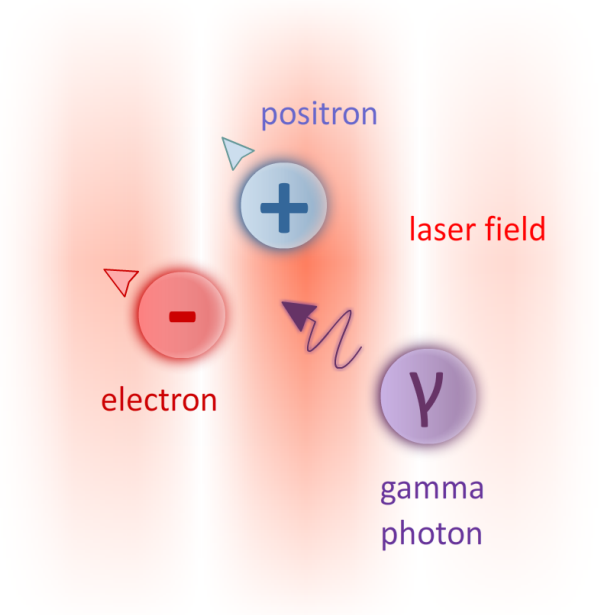
Continuous emission of relatively low-energy photons in comparison with the electron energy




## Nonlinear inverse Compton scattering

Stochastic emission of high-energy photon

# Radiative and quantum electrodynamics effects will progressively come into play



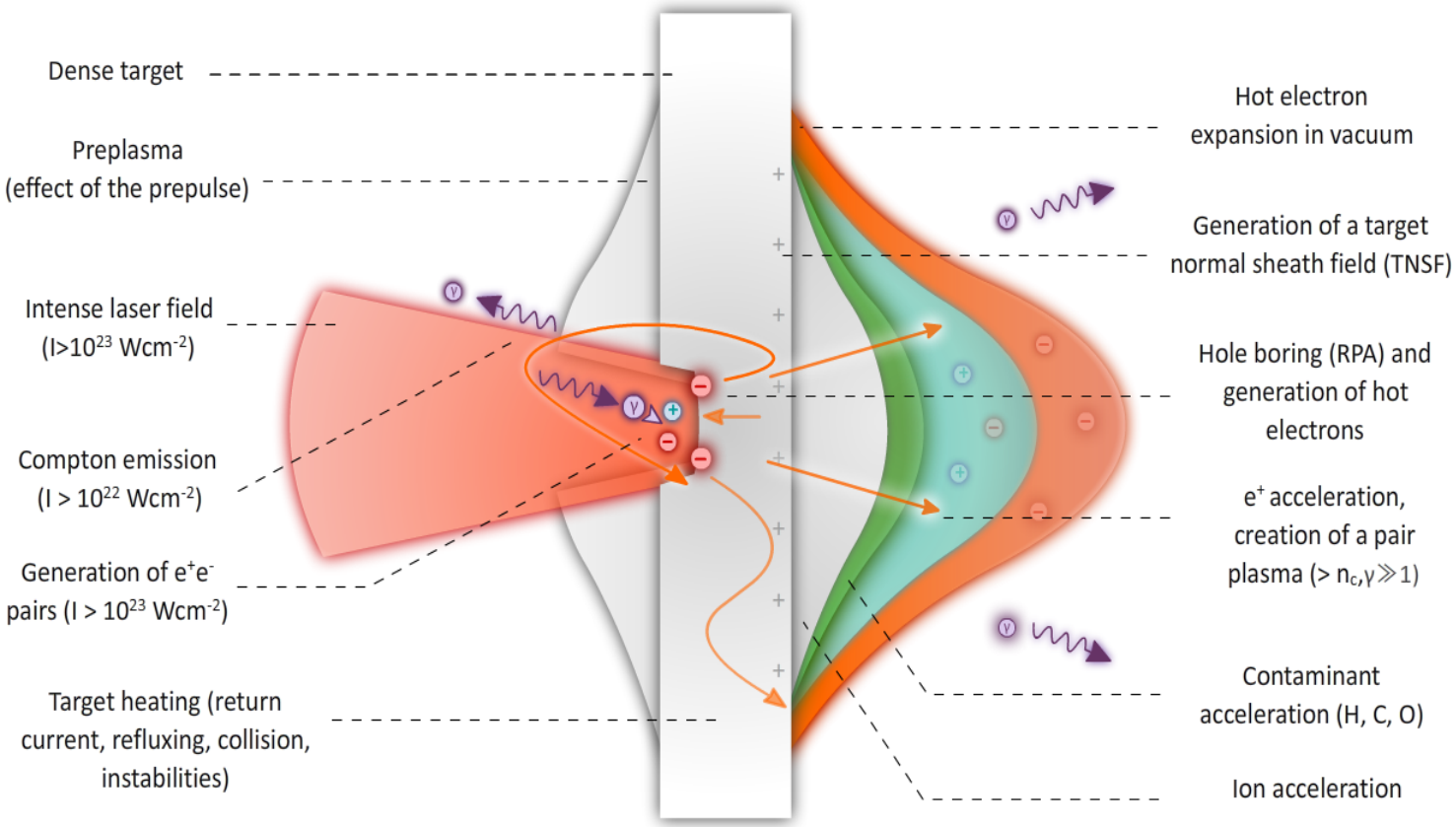

**Multiphoton Breit-wheeler pair creation**

Creation a pair of electron-positron from the decay of a γ photon interacting with an electromagnetic field

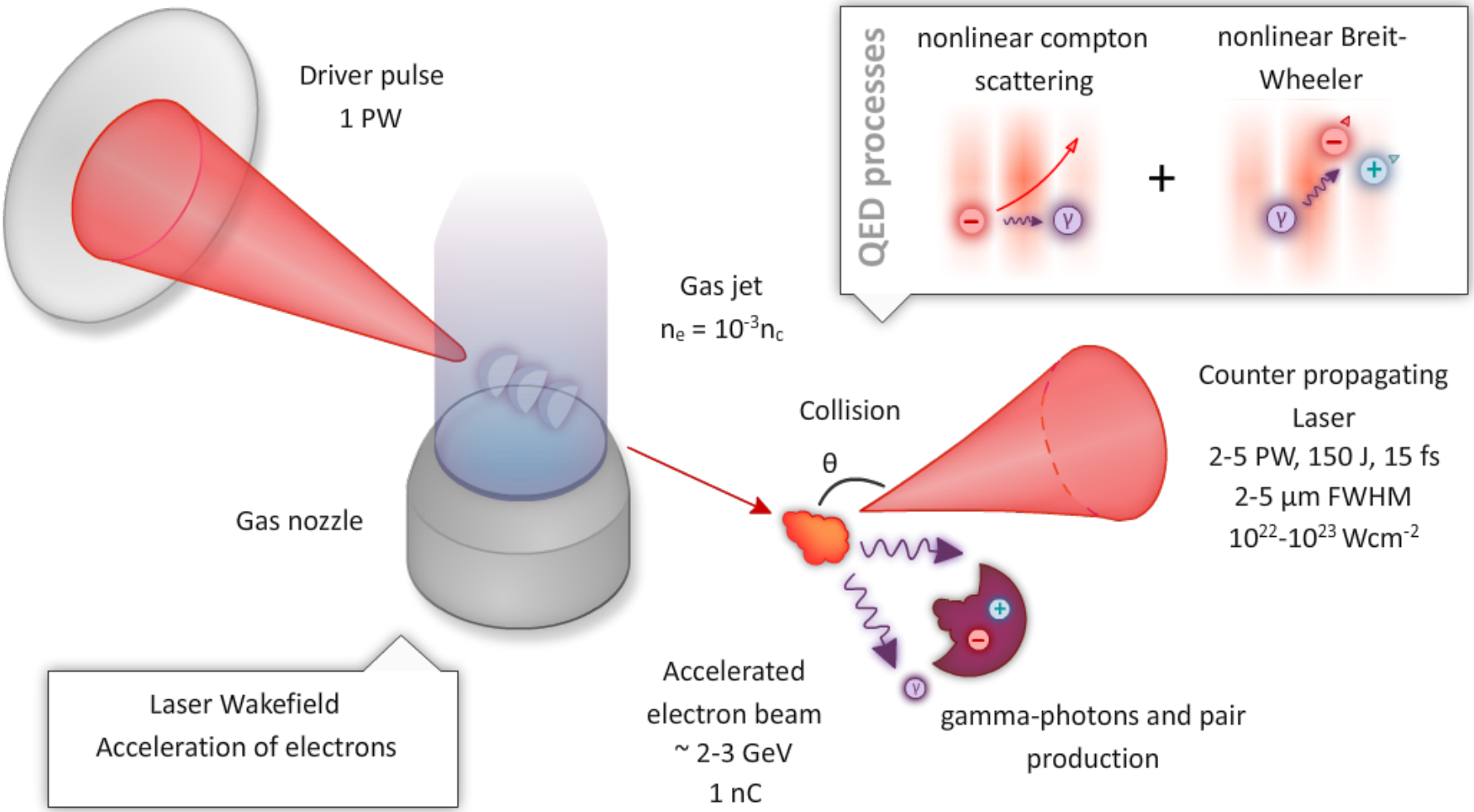
# Radiative and QED effects will affect the particle dynamic and the overall energy balance of simulations

## 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:**

$$\gamma_\gamma = \varepsilon_\gamma / mc^2 \gg 1$$

| | |
|---|---|
| $\varepsilon_\gamma$ | 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 $\gamma_\pm$ and a photon of normalized energy $\gamma_\gamma$ propagating in an electromagnetic field and depends on the following **Lorentz invariant quantum parameters**:

**Particle quantum parameter:**

$$\chi_\pm = \frac{\gamma_\pm}{E_s}\sqrt{\mathbf{E}_\parallel^2/\gamma_\pm^2 + (\mathbf{E}_\perp + \mathbf{v}_\pm \times \mathbf{B})^2}$$

**Photon quantum parameter:**

$$\chi_\gamma = \frac{\gamma_\gamma}{E_s}\sqrt{(\mathbf{E}_\perp + \mathbf{c} \times \mathbf{B})^2}$$

$E_\parallel$ 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

$$\xi_1 = \frac{\mathbf{B}^2 - \mathbf{E}^2}{E_s^2} \ll 1$$

$$\xi_2 = \frac{\mathbf{B} \cdot \mathbf{E}}{E_s^2} \ll 1$$

$$\chi_\pm \gg \max\left(\xi_1, \xi_2\right)$$

$E$ 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

$I_0 \sim 10^{22}$ W/cm², $a_0 \sim 90$ at $\lambda = 1$ µm

- Weak impact on the target heating and ion acceleration

## Laser-electron beam collision

$I_0 \sim 10^{21}$ W/cm², $a_0 \sim 1$ at $\lambda = 1$ µm, electron beam energy ~ 100 MeV - 1 GeV

# Semi-quantum regime

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

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

## Laser-thin foil interaction

$I_0 \sim 10^{23}$ W/cm², $a_0 \sim 270$ at $\lambda = 1$ µm

- Stronger impact on the target heating and ion acceleration
- Energy loss in radiation can represent several percents

## Laser-electron beam collision

$I_0 \sim 10^{22}$ W/cm², $a_0 \sim 1$ at $\lambda = 1$ µm, electron beam energy ~ 100 MeV - 1 GeV

# Near-quantum regime

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

- Radiation reaction can not 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

$I_0 \sim 10^{24}$ W/cm², $a_0 \sim 850$ at $\lambda = 1$ µm

- Strong impact on the hole boring + TNSA, reduced ion energy

## Laser-electron beam collision

$I_0 \sim 10^{23}$ W/cm², $a_0 \sim 270$ at $\lambda = 1$ µm, electron beam energy ~ 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

$I_0 > 10^{24}$ W/cm², $a_0 > 850$ at $\lambda = 1$ µm

- Strong impact on the hole boring + TNSA, reduced ion energy

## Laser-electron beam collision

$I_0 \sim 10^{23}$ W/cm², $a_0 \sim 270$ at $\lambda = 1$ µm, electron beam energy ~ few GeV

# Pair creation regime

$\chi_\gamma \geq 0.1$

- Nonlinear Breit-Wheeler pair creation start to be important around $\chi_\gamma \sim 1$
- Maximum production rate around $\chi_\gamma \sim 10$

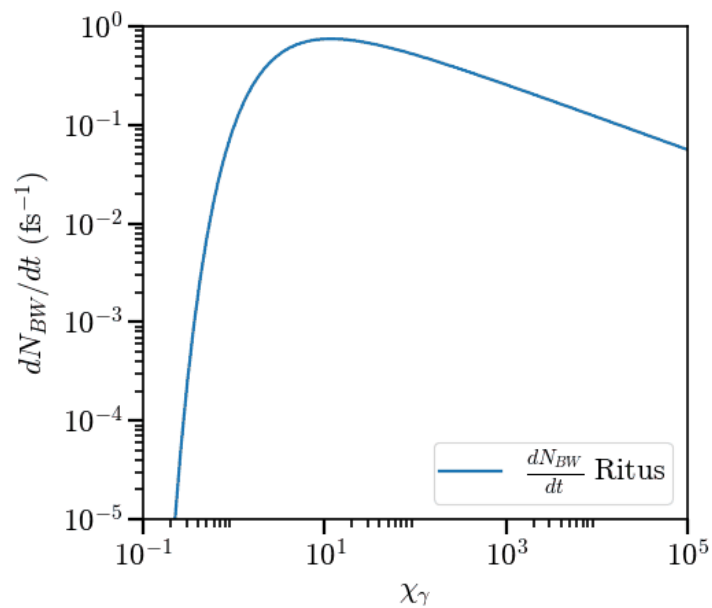
Laser-thin foil interaction

$I_0 \sim 10^{24}$ W/cm², $a_0 \sim 850$ at $\lambda = 1$ µm

- Strong impact on the hole boring + TNSA, reduced ion energy

Laser-electron beam collision

$I_0 \sim 10^{23}$ W/cm², $a_0 \sim 270$ at $\lambda = 1$ µm, electron beam energy ~ few GeV



# Radiative and QED effects depend on the electron/photon energy, the field strength and the interaction geometry

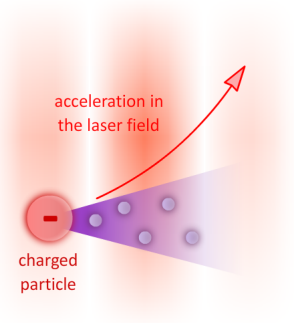
| Regime / Quantum parameter | Impacts | Thin foil – laser interaction | Electron beam – laser collision |
|---|---|---|---|
| **Quantum regime/pair creation** $\chi_\gamma \geq 0.1$ | Important creation of pairs | $I_0 \sim 10^{24}$ W/cm², $a_0 \sim 850$ at $\lambda = 1$ µm<br>Creation of a pair plasma on the rear target | $I_0 \sim 10^{23}$ W/cm², $a_0 \sim 270$ at $\lambda = 1$ µm, electron beam energy ~ few GeV |
| **Quantum regime** $\chi_\pm \geq 1$ | Strong recoil<br>Emission of high-energy gamma photons | $I_0 \sim 10^{24}$ W/cm², $a_0 \sim 850$ at $\lambda = 1$ µm<br>Strong impact on the hole boring + TNSA, reduced ion energy | |
| **Semi-quantum regime** $\chi_\pm \sim 10^{-2} - 10^{-1}$ | Strong continuous damping | $I_0 \sim 10^{23}$ W/cm², $a_0 \sim 270$ at $\lambda = 1$ µm | $I_0 \sim 10^{22}$ W/cm², $a_0 \sim 1$ at $\lambda = 1$ µm, electron beam energy ~ 100 MeV - 1 GeV |
| **Classical regime** $\chi_\pm \sim 10^{-3} - 10^{-2}$ | Continuous damping<br>Emission of many neglegible-energy photon | $I_0 \sim 10^{22}$ W/cm², $a_0 \sim 90$ at $\lambda = 1$ µm<br>Weak impact on the target heating and ion acceleration | $I_0 \sim 10^{21}$ W/cm², $a_0 \sim 1$ at $\lambda = 1$ µm, electron beam energy ~ 100 MeV - 1 GeV |

# Presentation of the radiative models

# The Landau-Lifshitz classical radiation model

**Validity :** $\chi_\pm \leq 10^{-2} \quad \gamma_\pm \gg 1$

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




$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_{Lorentz} + \boxed{\mathbf{F}_{rad}} \qquad \mathbf{F}_{rad} = -P_{rad}\frac{\mathbf{u}}{u^2 c}$$

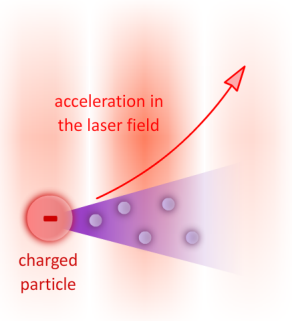
Derived from the Landau-Liftshitz model approximated at high gamma factors

**Overhead :** low (vectorized)

# The corrected Landau-Lifshitz radiation model

**Validity :** $\chi_\pm \leq 10^{-1} \quad \gamma_\pm \gg 1$

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

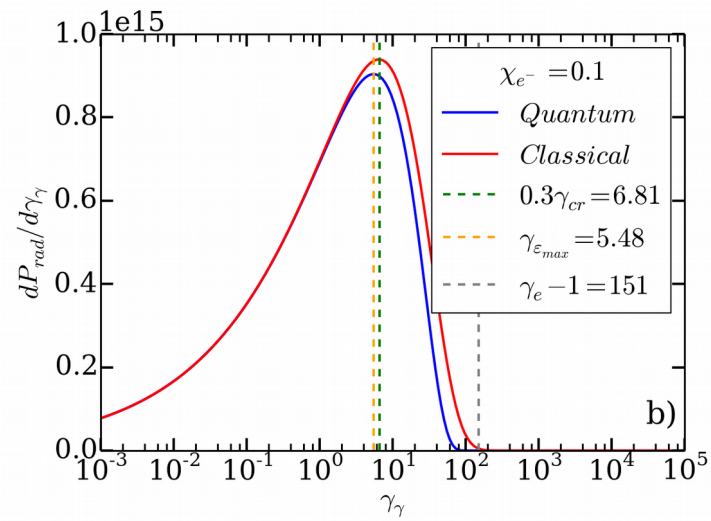



$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_{Lorentz} + \mathbf{F}_{rad} \qquad \mathbf{F}_{rad} = -P_{rad}\, g\left(\chi_\pm\right) \frac{\mathbf{u}}{u^2 c}$$

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

**Overhead :** low (vectorized)

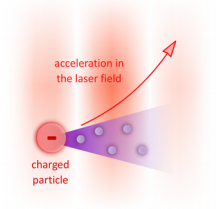
Fig. : Importance of the quantum correction when the quantum parameter reaches 0.1.



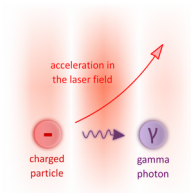
# The Fokker-Planck radiation of Niel *et al.*

**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**




$$\mathbf{F}_{rad}dt = \left(\boxed{-P_{rad}\ g\left(\chi_\pm\right)} + \boxed{mc^2\sqrt{R\left(\chi_\pm,\gamma_\pm\right)}dW}\right)\frac{\mathbf{u}}{u^2c}$$




$$R(\chi,\gamma) = \frac{2}{3}\frac{\alpha^2}{\tau_e}h(\chi)$$

$h(\chi)$ computed from the Compton cross-section

dW is a Wiener process of variance dt

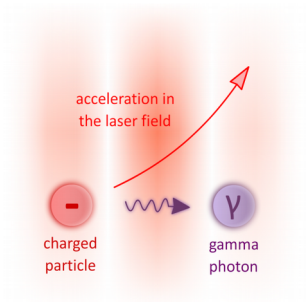
**Overhead :** high (partly vectorized) / under improvement

F. Niel et al., ArXiv:1707.02618 (2017)

# The Monte-Carlo (MC) photon emission process

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

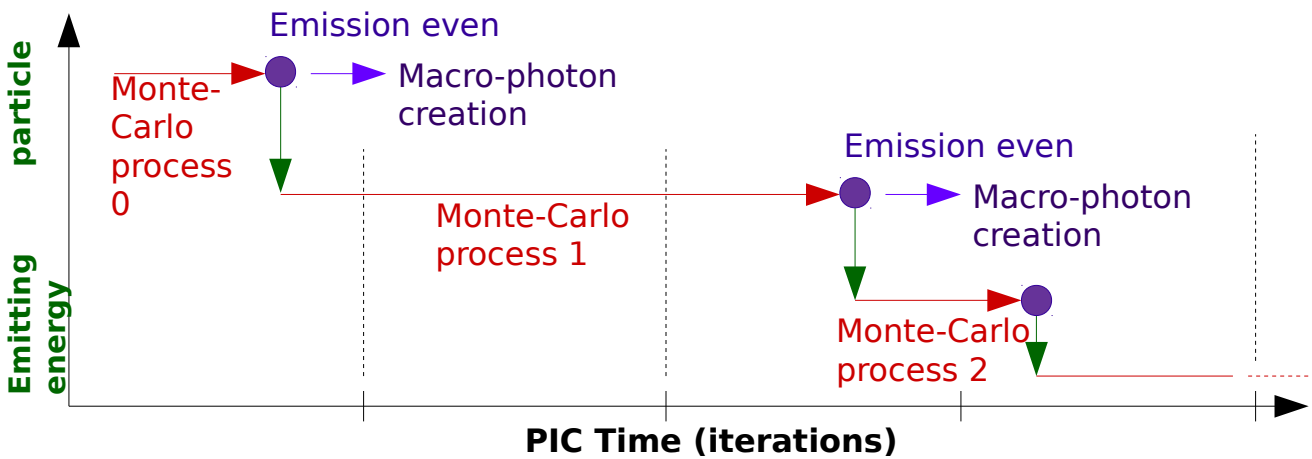
**Principles :** Monte-Carlo process




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

Cumulative1 distribution function computed from the Compton photon energy function for the random drawing of the emitted photon energy1

Independent of the PIC iteration / particle pusher




**Overhead :** high (not vectorized)

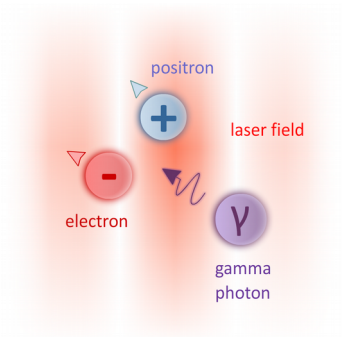
R. Duclous *et al.*,Plasma Physics and Controlled Fusion, 53 (1), 015009 (2011) ; M. Lobet et al., J. Phys.: Conf. Ser. 688, 012058 (2016)

# Presentation of the Multiphoton Breit-Wheeler pair creation model

# The Monte-Carlo pair creation emission process

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

**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

Monte-Carlo time independant of the PIC iteration / particle pusher

**Overhead :** high (not vectorized)

# Examples of simulations

# Radiative model comparison using particle tests

Laser pulse

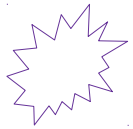
I = $10^{23}$ W/cm² ($a_0$=270)

λ= 1 µm

FWHM of 33 fs (10 laser periods)

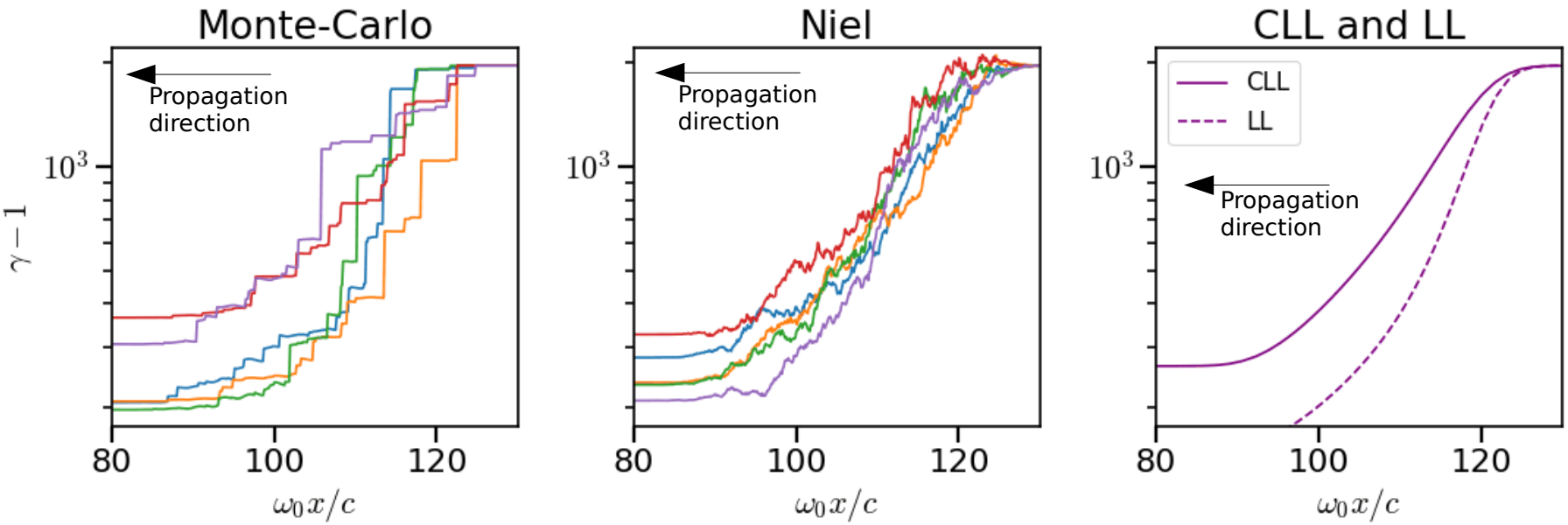
Gaussian order 4

Head-on interaction



1 GeV electron beam

$$\max \chi \sim 2\gamma_- \frac{E_0}{E_s} \sim 1$$



# Generation of pairs

Laser pulse

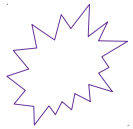
I = $10^{23}$ W/cm² ($a_0$=270)

λ= 1 µm

FWHM of 33 fs (10 laser periods)

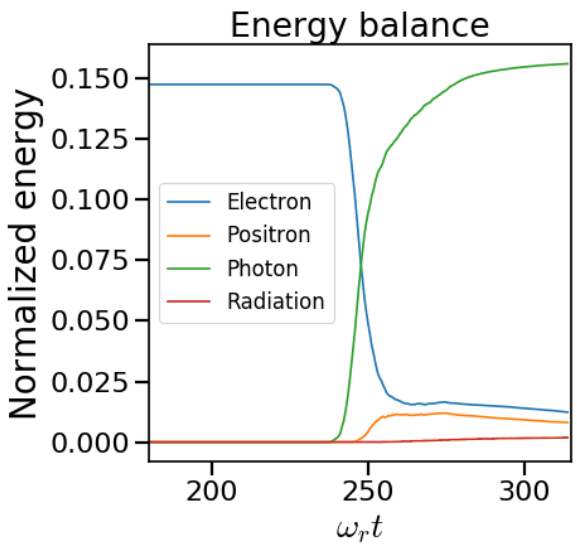
Gaussian order 4

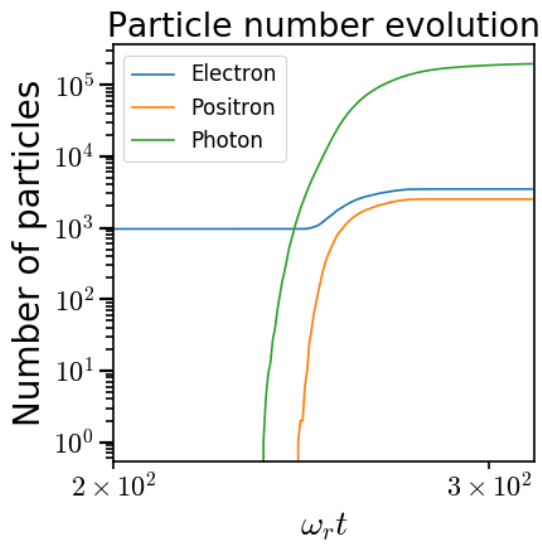
Head-on interaction

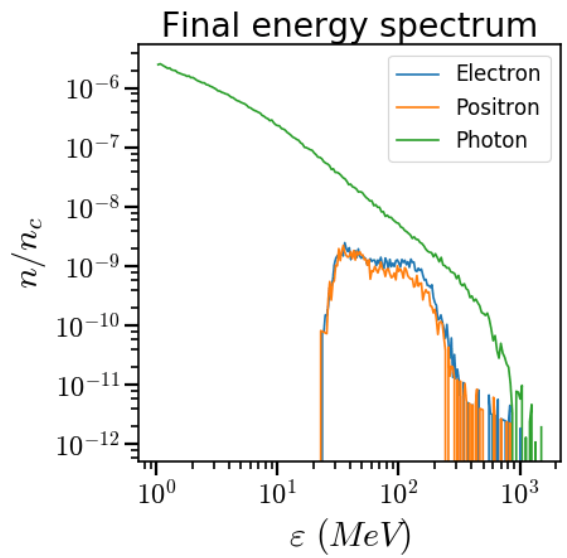


4 GeV electron beam

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



# Conclusion

# Different models implemented for different regimes of interaction

| **Quantum parameters** | **Interaction regime** | **Models** |
|---|---|---|
| $\chi_\gamma \geq 0.1$ | **Pair creation regime** | Emission/propagation of macro-photon as for macro-particles<br>Monte-Carlo pair creation process on the photon species |
| $\chi_\pm \geq 1$ | **Quantum radiation emission regime** | Monte-Carlo emission process |
| $\chi_\pm \sim 10^{-2} - 10^{-1}$ | **Near quantum regime** | Monte-Carlo emission process<br>Fokker-Planck radiation model of Niel *et al.* |
| $\chi_\pm \sim 10^{-2} - 10^{-1}$ | **Semi-quantum regime** | Fokker-Planck radiation model of Niel *et al.*<br>Corrected Landau-Lifshitz model |
| $\chi_\pm \sim 10^{-3} - 10^{-2}$ | **Classical regime** | Corrected Landau-Lifshitz model<br>Classical Landau-Lifshitz model |

# Implementation availability

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

**SMILEI version 3.3**

Future related features :
- Particle and photon merging process

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