Monte-Carlo event generation for the interaction of x-ray laser fields and hot electrons
Polish-German WE-Heraeus Seminar & Max Born Symposium
December 6th, 2023 // Uwe Hernandez Acosta
Quantum Electrodynamics?

Neutron stars | Dirac-/Weyl materials | Particle colliders
Quantum Electrodynamics!

European XFEL
XFEL pulse as a driver

Monte-Carlo event generation for the interaction of x-ray laser fields and hot electrons
The parameter space: EuropeanXFEL

<table>
<thead>
<tr>
<th>$\omega_X$ [keV]</th>
<th>$\lambda_X$ [nm]</th>
<th>$I$ [W/cm$^2$]</th>
<th>$a_0$</th>
<th>$\tau$ [fs]</th>
<th>$N_{cycles}$</th>
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<tbody>
<tr>
<td>$\sim 10$</td>
<td>0.12</td>
<td>$10^{21}$</td>
<td>$\sim 10^{-3}$</td>
<td>20</td>
<td>$\sim 10^5$</td>
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</table>

Thomson scattering?  
locally-constant field approximation?

→ we need a more QED-like description & new tools!
Model: strong-field quantum electrodynamics

- Feynman-rule: vertex

\[ -ie\gamma^\mu (2\pi)^4 \delta^{(4)} (p-p'-k') \]

- vertex function

\[ \Gamma^\mu (l, p, p', k) = \Gamma^\mu_0 B_0 (l) + \Gamma^\mu_1 B_1 (l) + \Gamma^\mu_2 B_2 (l) \]

- Phase integrals

\[ B_0 (l) \bigg\{ \int_{-\infty}^{\infty} d\phi \exp (il\phi + iG(\phi)) \bigg\} = \frac{1}{A^\mu (\phi)} A^\mu (\phi) \]


First-order processes I
Compton scattering

\[ p p' \]
First-order processes II
Breit-Wheeler pair production

\[ k \gamma \rightarrow p p' \]

XFEL

- positron in the final state
  → "easy" to detect
- investigated in optical setups
  - seminal experiment: E-144@SLAC
  - upcoming: LUXE@Desy, E-320@FACET-II
→ no direct observation yet

threshold: \( \sqrt{s} = 2m_e \approx 1022 \text{ keV} \)
Second order process
Trident pair production

- positron in the final state
  → "easy" to detect
- threshold process
  • impact of spectral structure
- two vertex process
  • interesting physics
- no MeV partner photon needed
  • enabled by $e^-$ beam
Trident process
kinematically reachable

• $\sim 10 - 50$ MeV electron energy is sufficient
• conceivable electron sources
  • $e^-$ guns
  • stable kHz+mJ laser wake field accelerator

• laser-driven $e^-$ in thin targets
  @ HED/HIBEF
Trident process
previous insights are promising

- Subthreshold effects for $\sqrt{s} < 3m_e$!
- raw estimate:
  - $\sigma_{\text{trident}} \sim 10^{-5} \text{ mb}$
  - 1 nC electron beam
  - XFEL focused on 1 micron
  $\Rightarrow \sim 6000$ positrons

XFEL pulse as a driver

How many "ticks" will be in the pixel?
Particle-physics-like simulation workflow

- **Computational Model**
- **Differential cross sections**
- **Monte-Carlo event generation**
  - Showering and *clustering*
  - Transport
  - Detector simulation
- **Event reconstruction and Analysis**
  - *quick and dirty*

- **Machine**
  - (EuXFEL + e− beam)
- **Signal Transport/Amplification**
- **Detector**

[Stefan Gieseke - MCnet Vietnam summer school (2019)]
**Differential Cross Sections:** \( k_1, \ldots, k_M \rightarrow p_1, \ldots, p_N \)

- **Scattering Matrix Element**

\[
\begin{align*}
\text{Golden Rule} \\
d\sigma &= \frac{1}{4\mathcal{L}} \times \sum_{\sigma_1, \ldots, \lambda_1 \ldots} |\mathcal{M}|^2 \times \prod_{i=1}^{N} \frac{d^3p_i}{(2\pi)^3 2p_i^0} (2\pi)^4 H(k_1, \ldots, k_M, p_1, \ldots, p_N) \\
H_{\text{QED}}(k_1, \ldots, k_M, p_1, \ldots, p_N) &= \delta^4(k_1 + \cdots + k_M - (p_1 + \cdots + p_N)) \times \Theta(\text{cuts}) \\
H_{\text{sfQED}}(K, k_1, \ldots, p_1, \ldots; l, r, \ldots) &= \delta^4((l + r + \ldots)K + k_1 + \cdots - (p_1 + \ldots)) \times \Theta(\text{cuts})
\end{align*}
\]
Differential Cross-Section: get your hands dirty

- Decide Model: QED/sfQED
- Choose Scattering Process: $e^- + \gamma \rightarrow e^- + \gamma$
- Generate Feynman Diagrams
- DAG
- Optimize DAG
- Schedule
- Execute and calculate result
Directed acyclic graphs - simplified
Optimization for target architecture

Monte-Carlo event generation for the interaction of x-ray laser fields and hot electrons

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How to generate events

total cross section

\[ \sigma \approx \frac{1}{N} \sum_{u \in R[g]} \frac{d\sigma}{d \cos \theta(u)} g(u) \sim w_u \]

sample drawing (unweighting)

\[ (u, w_u) \rightarrow (\tilde{u}, 1) \]
NN-Enhanced sampling [WIP: Tom Jungnickel]


- **Neural importance-sampling** [Bothmann et al. SciPost Physics, 8(4):069, 2020]

borrowed from [Müller, et al. ACM Transactions on Graphics (ToG) 38.5 (2019)]
Neural importance-sampling: Pulsed-perturbative Compton

\[ \bar{\omega}' := \frac{\omega'}{\omega'_{\text{max}}(\cos \theta)} \]

\[ \Delta \phi = 20 \]

preliminary results!
Pulsed-perturbative Compton events - preliminary results

- LO pulsed-perturbative QED
- $\omega_X = 40$ keV on electron at rest
- pulse profile: $\cos^2\left(\frac{\pi \phi}{2\Delta \phi}\right) \prod_{2\Delta \phi} (\phi)$

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<th>photons_p3</th>
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</table>

Monte-Carlo event generation for the interaction of x-ray laser fields and hot electrons

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Pulsed-perturbative Compton events - preliminary results

$\Delta \phi = 50$

$\Delta \phi = 500$
Trident + Compton (perturbative): preliminary results
inclusive electron distribution

Monte-Carlo event generation for the interaction of x-ray laser fields and hot electrons

Uwe Hernandez Acosta
Trident process: preliminary results
exclusive electron distribution
# QED.jl - Strong-field particle physics code

[https://github.com/QEDjl-project](https://github.com/QEDjl-project)

## Requirements

- open source
- written in Julia
- user-friendly
- modularised
- extensible
- performant
- CPU + GPU

## Base Packages

- QEDmc.jl
  - (D)RNG, Vegas, MCMC,...
- QEDbase.jl
  - Lorentz vectors, spinors,...
- QEDio.jl
  - hepMC3, openPMD, LHA,...

## Physics Packages

- QEDmodels.jl
  - pQED, sfQED,...
- QEDphasespaces.jl
  - RAMBO/MAMBO, SARGE,...
- QEDfields.jl
  - em. fields, spectra, ...

## Event Generation

- QEDprocesses.jl
  - concrete processes,
  - *generic* Feynman diagram generation
- QEDevents.jl

## Applications

- QEDinCell.jl
- QEDcascades.jl
- ?

---

### Monte-Carlo event generation for the interaction of x-ray laser fields and hot electrons

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Proof-of-concept release: soon!
QED.jl - Strong-field particle physics code

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Proof-of-concept release: soon!
• Collaborators

Michael Bussmann
Simeon Ehrig
Klaus Steiniger
Tom Jungnickel
Anton Reinhard

Prof. Burkhard Kämpfer

Prof. Thomas Cowan
PD Toma Toncian

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Parameter space
Where are we?

\[ \omega \sim 10^{-3}, \lambda \sim 10^{21}, a_0 \sim 10^{-3}, \tau \sim 10^5 \]

- decoherence assumption breaks
  → interactions accumulate over several XFEL wave-cycles
  → modeled with higher order processes and spectral extensions

- almost monochromatic
  • \( K \sim 1.5 - 9 \) ⇒ higher harmonics?

- high-precision description available
  → pulsed-perturbative QED
EuXFEL pulse as a driver
Trident for dark matter exclusion

[Gakh et al. PRD 101 (2020) 7]

![Diagram of XFEL pulse interaction](image)

- Dark photon
  - hypothetical dark matter candidate
  - massive photon-like particle
    - kinematically mixing with photons

[Holdom. PLB 166 (1986)]

- sensitive for lower pair energy
- full control over the pure-QED background