Radiation Reaction and Nonlinear Compton Scattering in Intense Laser Interactions with Relativistic Electrons

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Outline

- How does RR that affect plasma dynamics at extreme light intensities?
- How can RR be measured: High-power laser experiments
- How to simulate RR effects in laser-plasma interactions?
- Narrowband Compton backscattering at high intensity
- What’s next: Radiative electron spin polarization with lasers
What is the correct equation of motion for a charged particle?

- Nonrelativistic force
  \[ m\ddot{x} = eE \]

- Larmor’s equation for radiated power
  \[ P = \frac{2}{3} \cdot \frac{d^2}{dt^2} = -\frac{2}{3} e^2 \dot{x} \cdot \ddot{x} = \dot{x} \cdot f_{RR} \]

- Lorentz-Abraham equation
  \[ m\ddot{x} = eE + f_{RR} = eE - \frac{2}{3} \alpha \dddot{x} \]


... has problems like runaway solutions ⇒ reduce order: Landau Lifshitz equation
Invariant Strong Field Parameters

1. Classical nonlinearity parameter

\[ a_0 = \frac{eA}{m} = \frac{eE}{m\omega} \approx 8.5\lambda_{\mu m} \sqrt{l_{20}} \sim 100 \]

- Energy density of the laser as seen in the electron rest frame
- Normalized average quiver momentum
- Relativistic optics, large amplitude plasma waves, ...
- Multi-photon effects

2. Quantum nonlinearity/efficiency parameter for a probe particle

\[ \chi = \frac{e}{m^3} \sqrt{|F_{\mu\nu}p^\nu|^2} = \frac{E_{\text{rf}}}{E_{\text{QED}}} \sim 2\gamma \frac{E}{E_{\text{QED}}} \sim \gamma \times 6 \times 10^{-4} \]

- QED experiments with present day lasers by colliding GeV electrons
- Self-accelerated regime \( \gamma \sim a_0 \)

- Longer wavelength: \( a_0 \uparrow \) and \( \chi \downarrow \);
- Shorter wavelength \( a_0 \downarrow \) and \( \chi \uparrow \)
Radiation Back-Reaction

- **Average radiation power:** Larmor formula
  \[
  \mathcal{I} = \frac{d\varepsilon}{dt} = -\frac{2\alpha}{3} \dot{u} \cdot \ddot{u} \sim \alpha m^2 \chi^2 \sim \alpha \omega^2 \gamma^2 a^2_0
  \]

- **Compare radiated energy** \( \Delta \varepsilon = \mathcal{I} T \)** to the particle energy** \( m\gamma \)
  \[
  \frac{\mathcal{I} T}{m\gamma} \sim \frac{\alpha \omega}{m} \gamma a^2_0 (\omega T) \sim \alpha \chi a_0 (\omega T)
  \]

- **Radiation dominated regime**
  \[
  R_C = \alpha \chi a_0 \sim 1
  \]
  e.g. \( a_0 \sim 100, \chi \sim 1 \): GeV electrons colliding with PW pulse

- **Classical vs. quantum** radiation reaction: Average energy of emitted photon
  \[
  \frac{\langle \omega \rangle}{m\gamma} \sim 0.46\chi
  \]
Semi-classical radiation reaction

\[
\frac{du^{\mu}}{d\tau} = f^{\mu\nu} u_{\nu} + \epsilon_{rad} g(\chi_e) [\eta^{\mu\nu} - u^\mu u^\nu] f_{\nu\kappa} f^{\kappa\lambda} u_{\lambda}
\]

Gaunt-factor models reduced radiated power

\[g(\chi_e) = \frac{\Pi(\chi_e)}{\Pi_{\text{class}}} \approx [1 + 4.8(1 + \chi_e) \ln(1 + 1.7\chi_e) + 2.44\chi_e^2]^{-2/3}\]

Quantum Regime: Emitted photons have quantum parameter

\[\chi_\gamma \lesssim \chi_e\]

Pair production effective for \(\chi_\gamma \gtrsim 0.1\)
Regimes of High-Intensity Plasma Interactions

High intensity particle physics

Radiation reaction = Lorentz force

Relativistic plasma physics

Laser wakefield accelerators

Deflected in a cycle

QED critical field

QED-plasma

$a = a_S$

Lorentz boost

Ion acceleration / laser-solid interactions

$E = E_F$

Degenerate plasma

$a = a_S / \alpha^{3/2}$

Electron number density [cm$^{-3}$]

$1 \times 10^{10}$

$1 \times 10^{15}$

$1 \times 10^{20}$

$1 \times 10^{25}$

$1 \times 10^{30}$

$0.1$

$1$

$10$

$100$

$1000$

$10000$

$100000$

$\lambda_D = 1 \text{ mm}$

$a^2 = a_S$

$a^2 = a_S / \alpha^{3/2}$

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Radiation Dominated High-Intensity Plasma Physics

Zhang NJP 2015, Del Sorbo NJP 2018

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Quantum Field Theory in Strong Fields

\[ L = \bar{\psi} \left( i \frac{\partial}{\partial t} - m - eA_{\mu} \bar{\psi} \gamma^\mu \psi \right) - \frac{1}{4} \mathrm{tr} F^2 - e A_{\mu} \bar{\psi} \gamma^{\mu} \psi \]

- **Strong field = many photons** \( N_\gamma \gg 1 \)
- **Bose enhancement factor** \( e \rightarrow e \sqrt{N_\gamma} \sim e \sqrt{\lambda \lambda_C n_\gamma} = a_0 \)
- **\( a_0 \) is effective interaction strength**
- **Transition to the Furry picture** \( A \rightarrow A + A_{\text{ext}} : \)

\[ L = \bar{\psi} \left( i \frac{\partial}{\partial t} - m - eA_{\text{ext}} \bar{\psi} \psi \right) - \frac{1}{4} \mathrm{tr} F^2 - e A_{\mu} \bar{\psi} \gamma^{\mu} \psi \]

- **Calculation of quantum processes using laser-dressed Volkov states**

\[ \text{D. M. Volkov, Z. Phys. 94, 250 (1935)} \]

A. Fedotov, arXiv:1612.02038

W. H. Furry, PR 81, 115 (1951)
Compton Backscattering at $a_0 \sim 1$

**Goal:** Narrowband, intense, short-pulse, collimated, bright $\gamma$-rays

**Problem:** $\gamma$ yield $\propto I_L$, ponderomotive broadening as $a_0 \sim 1$

**Solution:** Use optimized chirped pulses to compensate $a_0$-dep. red-shift

$$\omega(\varphi) \propto 1 + a^2(\varphi)$$

Radiation Reaction Experiment © RAL-Gemini

No monochromatic electron beams, but characteristic *edge feature*

\textcolor{red}{$\gamma$}-ray spectrum is synchrotron-like: Fit of critical energy

Correlation between electron and $\gamma$ signal

\textit{J. Cole et al, PRX 8, 011020 (2018).}
• Experimental results incompatible with "No RR"
• Cannot yet decide on classical/quantum emission regime
• UMich’s Hercules laser is getting upgrade to 500 TW
+ New 3PW Zeus laser @ Michigan will enable additional experiments

Theory and Simulation: Non-linear Compton

- Quantum electrodynamics in strong background fields

\[ L = \bar{\Psi} \left( i \partial - e \vec{A} - m \right) \Psi - \frac{1}{4} F^2 - e \bar{\Psi} \gamma_\mu \Psi A^\mu \]

- Each electron emits many photons

- Fully coherent quantum calculation impossible
- At high-intensity and for relativistic particle short formation length
  \( \Rightarrow \) Locally constant crossed field approximation (LCFA)
Quantum electrodynamics in strong background fields

$$L = \bar{\Psi} (i \dot{\Psi} - e A - m) \Psi - \frac{1}{4} F^2 - e \bar{\Psi} \gamma_\mu \Psi A^\mu$$

Each electron emits many photons

Fully coherent quantum calculation impossible

At high-intensity and for relativistic particle short formation length

$\Rightarrow$ Locally constant crossed field approximation (LCFA)
Quantum emission rates in locally constant crossed field $d\mathbf{R}/dk$, emission directed along the electron velocity

Classical propagation between emissions

Quantum corrected EOM

$$\frac{d\hat{\mathbf{p}}_{rad}}{dt} = -g(\chi)P_{class}\hat{\mathbf{p}},$$

Spreading of distribution

$$\frac{d\sigma^2}{dt} = \frac{\langle S \rangle}{m^2} - \frac{\Delta \gamma g(\chi)P_{class}}{m}$$

Ridders [...] AGR Thomas, JPP 2017, ...
Classical vs. Quantum RR

![Graph showing electron distribution and time evolution](image)

- **Initial**
- **Stochastic**
- **Modified classical**
- **Classical**

Ridders [...] AGR Thomas, JPP 2017
How good are the LCFA rates for finite $a_0 \sim 5...10$?

1. Strong-field QED calculation of the NLC spectra
2. Monte-Carlo simulation using LCFA rates with post-selection of single-emission orbits

Improved LCFA Rates

- LCFA is the leading asymptotic approximation for $a_0 \gg 1$, can we do better?
- Yes! Calculate next-to-leading term: Corrections $\propto 1/a_0^2$ due to field gradients.
- Problems at low energies and low intensities, which can been cured.
- Excellent agreement with QED even for $a_0 = 2$
Radiative spin-polarization because spin-flip rates $R_{↑↓} > R_{↓↑}$

- Sokolov-Ternov effect
- Well known from storage rings ($\chi \ll 1$) ...
- ... occurs on femtosecond time-scales with PW lasers ($\chi \sim 1$)

Sokolov & Ternov, "Synchrotron Radiation"
Spin-Polarization in PW–Laser Plasma Interactions

1. Laser wakefield accelerators for lepton–lepton colliders
   ⊗ HEP collider experiments need highly polarized beams
   Moortgat-Pick, Phys. Reports 2008

2. Studies of quantum radiation reaction
   ⊗ Radiation emission spin-polarizes electrons
   ⊗ Radiative losses are polarization-dependent
   Cole PRX 2018, Poder PRX 2018

3. Radiation and QED dominated collective plasma dynamics
   ⊗ Extreme intensities, absorption, cascades, rad. trapping, ...
   Bell & Kirk PRL 2008, Fedotov PRL 2010, Esirkepov PRA 2015, Magnusson 2018, Yakimenko PRL 2019, ..., ...
Oscillating field: Spin polarization averages to zero

$1\omega - 2\omega$ add constructively: larger $\chi \Rightarrow$ more spin flips when $\downarrow \equiv -e_y$

8 GeV electrons collide with 1 PW laser: $\sim 10\%$ polarization

Seipt et al arXiv:1904.12037, PRA accepted
Radiation dominated particle and plasma dynamics at high intensity
Experiments for distinguishing quantum and classical regimes of radiation reaction possible with present day high-power lasers
Narrowband Inverse Compton $\gamma$-ray sources by optimized chirped laser pulse to overcome ponderomotive broadening limit
Radiative polarization of electron beams

Thanks for Listening!