Quantum radiation reaction

- Radiation reaction is the recoil force experienced by an accelerating charge when emitting electromagnetic radiation
- When the electric field in the particle's rest frame, $E_r = \gamma(E + u \times B)$, approaches the critical quantum field, $E_S$, the photon emission must be treated by quantum electrodynamics (QED), i.e. the quantum parameter $\eta = \frac{E_r}{E_S} = \frac{\gamma(E + u \times B)}{E_S} \rightarrow 1$
- Two quantum effects are studied
  - Radiation reaction energy loss is limited to $\hbar \omega \lesssim mc^2$
  - Stochastic nature of photon emission
- These effects will dominate the physics of next generation of laser-plasma interactions ($I \sim 10^{23} \text{ Wcm}^{-2}$), coupling QED and plasma physics

Experiment

- Wakefield accelerated electron beam ($\sim 1$ GeV) interacting with a counter propagating laser pulse ($I \sim 10^{21} \text{ Wcm}^{-2}$) $\rightarrow \eta \sim 0.3$
- During interaction, electrons lose energy due to radiation of high energetic photons
- Quantum radiation reaction effects are measured from the electron energy distribution
  - Electron mean energy loss is less than in classical theory by a factor $g$
  - Electron energy spectrum broadens due to stochastic emission, i.e. $\sigma^2/dt > 0$

Assumptions

- Laser pulse of $a = eE_t/mc_\alpha \gtrsim 10 \rightarrow$ photon emission is point-like, synchrotron-like spectrum
- Ultra-relativistic regime $(\gamma \gg 1) \rightarrow$ radiation reaction force is anti-parallel to direction of motion
- Quasi-classical kinetic equation: laser EM field is classical, but photon emission process is strong-field QED theory
- Emission probability only depends upon $\gamma$

Results

- A self-consistent system of equations solving the time evolution of the electron mean energy $\langle \gamma \rangle$ and variance $\sigma^2$
- Simple analytical expression for mean energy evolution
- Conditions for experimental observation of stochastic radiation are outlined
- Simplified expressions for Gaunt factor $g$ and $g_S$ are found in the range $0 \leq \eta \leq 10$

Conclusions

- Quantum effects can be studied independently
- Useful theory for the design of future experiments

Equations

- Time evolution of the electron mean energy
  $$\frac{d\langle \gamma \rangle}{dt} = -\frac{b^2}{\gamma C} (\gamma^2)$$

- Time evolution of the electron energy variance
  $$\frac{d\sigma^2}{dt} = -\frac{2b^2}{\gamma C} [\langle \gamma \rangle (\gamma^2) + \frac{b^2}{\gamma S} \langle \gamma \rangle^4]$$

Gaunt factor $g$ fit

The Gaunt factor is simplified to
$$g = \frac{3\sqrt{3}}{4\gamma} F(\eta, \chi) d\chi \rightarrow g \simeq (1 + 4.7\eta)^{-1}$$

Stochastic factor $g_S$ fit

The $g_S$ factor is simplified to
$$g_S = \frac{3\sqrt{3}}{4\gamma} \frac{\eta}{\sqrt{2}} F(\eta, \chi) d\chi \rightarrow g_S \simeq (1 + 13.5\eta + 17.8\eta^2)^{-1}$$

Mean and variance evolution

Analytical expression for the electron mean energy
$$\frac{1}{\langle \gamma \rangle} - \frac{1}{\langle \gamma \rangle} + 4.7 b \log(\langle \gamma \rangle) = -\frac{b^2}{\gamma C} t$$

Stochasticity threshold

- Initial $\langle \gamma \rangle$ and variance ratio $\sigma^2/\langle \gamma \rangle$ can ensure that $\sigma^2/\langle \gamma \rangle > 0$

References