Radiation Damping Effects in High Intensity Laser Fields

QFEXT11, Benasque

Chris Harvey

Umeå University, Sweden

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Collaborators

- Anton Ilderton & Mattias Marklund (Umeå, Sweden)
- Tom Heinzl, Nicola Iji & Kurt Langfeld (Plymouth, UK)

Outline of Talk

Introduction

- Motivation for studying radiation damping,
- Governing equations.

Radiation damping

- Overview of radiation damping effects,
- Radiation damping induced electron capture,
- Mass shift,
- Plane wave limit.

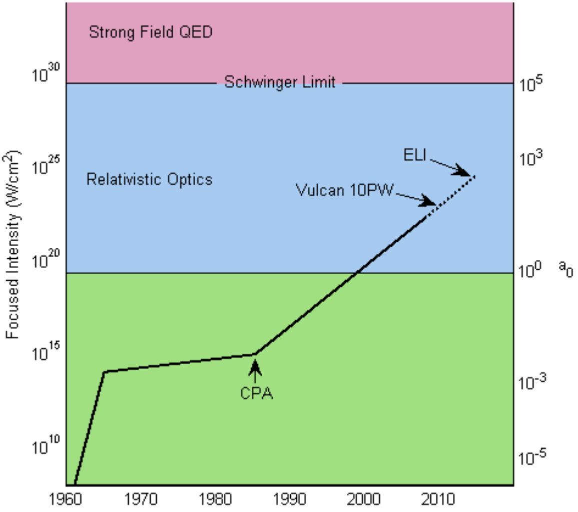
Nonlinear Compton Scattering

- Mass shift.

Conclusion

Introduction

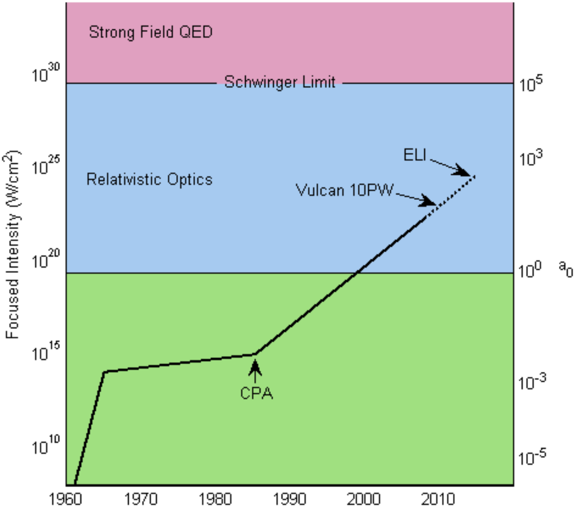
Laser intensities increasing ⟶ new physics.



[Adapted from Tajima and Mourou (2002)]

Introduction

Laser intensities increasing $\longrightarrow$ new physics.



[Adapted from Tajima and Mourou (2002)]

Schwinger Field

Vacuum pair prod

Quantum Effects

Vacuum birefringence....

Nonlinear Compton

Radiation Reaction

$F = F_{\text{Lorentz}} + F_{\text{Reaction}}$

Lorentz Force

$F_{\text{Lorentz}} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

Euler-Heisenberg Effective Action

$$\Gamma = -\int_0^\infty \frac{dT}{T} e^{-m^2 T} \int d^4x \int \mathcal{D}x \; e^{-S[x]}.$$

Worldline instanton – semiclassical – use classical paths.

Dunne and Schubert (2005)

Dunne, Wang, Gies, Schubert (2006)

$$S[x] = \int_0^T d\tau \left(\frac{1}{4}\dot{x}_\mu^2 + eA_\mu \dot{x}_\mu \right).$$

This Talk

Classical solutions with radiation reaction

Tom Heinzl, Anton Ilderton, Felix Karbstein

Tree level, Loops

Laser Intensity Parameter – a_0.

Laser beam characterised by the 'dimensionless laser amplitude'

$$a_0 = \frac{eE\lambda_L}{mc^2}.$$

- Ratio of the energy gain of the electron moving over a laser wavelength with the electron's rest mass.
- Classical quantity.

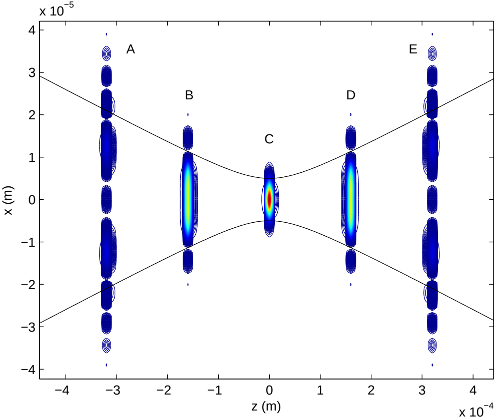
(Lorentz and gauge invariance [Heinzl and Ilderton,2009].)

With lasers can study phenomenology of high intensity $a_0 > 1$ and low energy $\omega \ll mc^2$ regime.

Classical Radiation Damping

Strong acceleration: electron's radiation will affect its motion.

- Simulate interaction of electron with realistic pulsed Gaussian beam.
- Assess the importance of radiation damping.
- Look for regimes where radiation damping prominent: test theory.



Governing Equations

Lorentz Abraham Dirac

$$m\dot{u}^{\mu} = eF^{\mu\nu}u_{\nu} - \frac{2}{3}\frac{e^2}{4\pi}(u^{\mu}\ddot{u}^{\nu} - u^{\nu}\ddot{u}^{\mu})$$

Problem

Runaway solutions: unphysical

Governing Equations

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Problem

Runaway solutions: unphysical

Well established solution: approximate $\ddot{u}$ terms using Lorentz force

Landau Lifshitz equation

$$\dot{u}^{\mu} = \frac{e}{m}F^{\mu\nu}u_{\nu} + \frac{2}{3}\frac{e^2}{4\pi}\left\{\frac{e}{m^2}\dot{F}^{\mu\nu}u_{\nu} + \frac{e^2}{m^3}F^{\mu\alpha}F_{\alpha}{}^{\nu}u_{\nu} - \frac{e^2}{m^3}u_{\alpha}F^{\alpha\nu}F_{\nu}{}^{\beta}u_{\beta}\,u^{\mu}\right\}$$

Perturbative expansion of LAD

- No runaway solutions.

Parameter Constraints

Two constraints on parameter values:

- Validity of Landau Lifshitz equation: radiation damping term smaller than Lorentz force term

$$\alpha\omega a_0\gamma^2 \ll mc^2.$$

- Classical regime: work done by laser field over a Compton wavelength

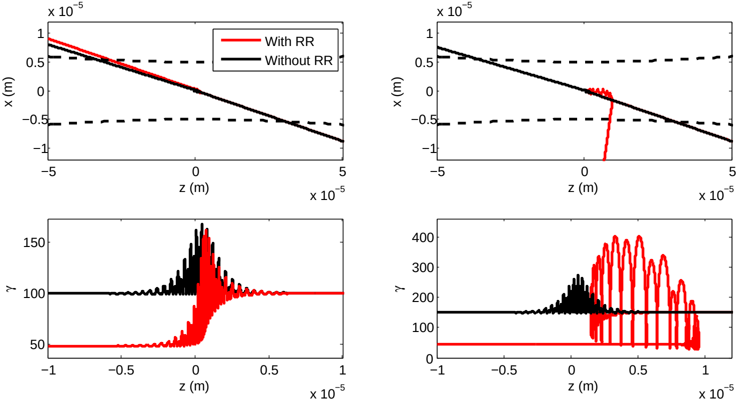
$$\chi \equiv \frac{e\hbar\sqrt{(F^{\mu\nu}u_\nu)^2}}{m^2c^4} \ll 1, \quad \Longrightarrow \quad \hbar a_0\gamma\omega \ll mc.$$

(Quantum effects dominate when $\chi \sim 1$.)

Electron Dynamics in Optical Fields

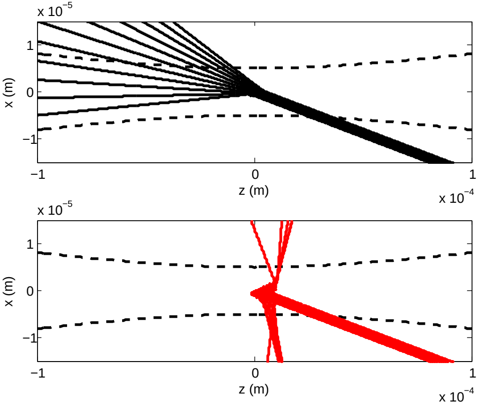
C. Harvey and M. Marklund (*to appear*)

$a_0 = 150,\ \gamma_0 = 100.$ $a_0 = 250,\ \gamma_0 = 150.$



Electron Beam Size Effects

Radiation damping induced capture stable with respect to size of electron beam. $a_0 = 250$, $\gamma_0 = 100$.



Radiation Damping Effects

C. Harvey and M. Marklund (*to appear*)

Find that radiation damping causes:

- net energy loss.
- deflection/reflection of the electron.

(Significant change to trajectory and therefore to emission spectra.)

Introduce displacement measure D:

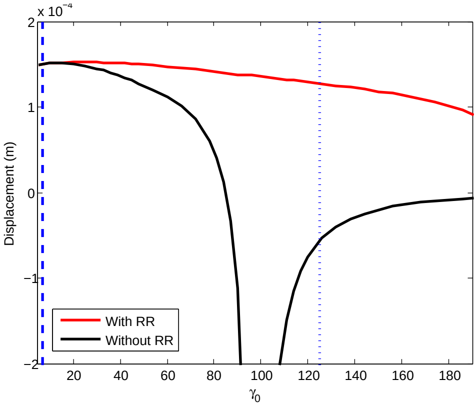
- longitudinal displacement of electron (compared to where it would be if no field present).

Fix a_0 and consider displacement as a function of γ_0.

Radiation Damping Induced Electron Capture

C. Harvey and M. Marklund (*to appear*)

$a_0 = 250$



Regime $2\gamma_0 > a_0$, $a_0 \gg 1$: damped electron displaced, undamped electron not displaced

- radiation damping induced electron capture.

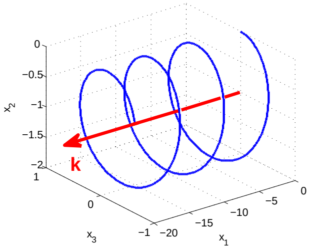
Condition $2\gamma_0 > a_0$: onset of reflection for head on collisions with plane waves.

Di Piazza, Hatsagortsyan, Keital (2009).

Intensity Dependent Mass Shift

Electron in a plane wave exhibits a 'quiver' motion.

- Typically too small to be resolved by laser field.
- Proper time average: quasi momentum q.
- Square q to obtain mass shift



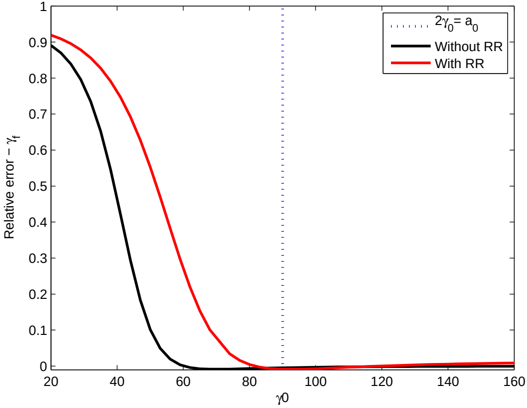
$$m^2 \longrightarrow m_*^2 \equiv q^2 = m^2(1 + a_0^2).$$

Condition $2\gamma_0 = a_0$ defines centre-of-mass frame.

Harvey, Heinzl, Ilderton (2009).

Plane Wave Approximation

- Compare Gaussian beam results with plane wave approximation.
- When $2\gamma_0 > a_0$ plane wave gives accurate estimation of net energy change.



In the plane wave approximation strong field QED calculations possible.

- Solution to Dirac equation Volkov (1935)

Intensity Dependent Mass Shift (Again!)

The mass shift also occurs in the QED calculation:

- Apply kinetic momentum operator $\hat{p} - eA = i\partial - eA$ to Volkov solution,
- Take time average: quasi momentum q,
- Effective electron mass: $m^2 \longrightarrow m_*^2 \equiv q^2 = m^2(1 + a_0^2)$,

  Sengupta (1952), Brown and Kibble (1964)

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  Sengupta (1952), Brown and Kibble (1964)

This is exactly the same mass shift as we had in the classical theory!

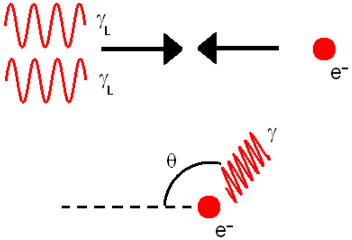
The condition $2\gamma_0 = a_0$ defines the centre-of-mass frame.

Example: Nonlinear Compton Scattering

C. Harvey, T. Heinzl and A. Ilderton PRA **79** 063407 (2009)

Most important process that can be observed with current intensities.

- Electrons in collision with high intensity laser,
- Electron absorbs n laser photons γ_L of momentum k,
- Emits one photon γ of momentum k',

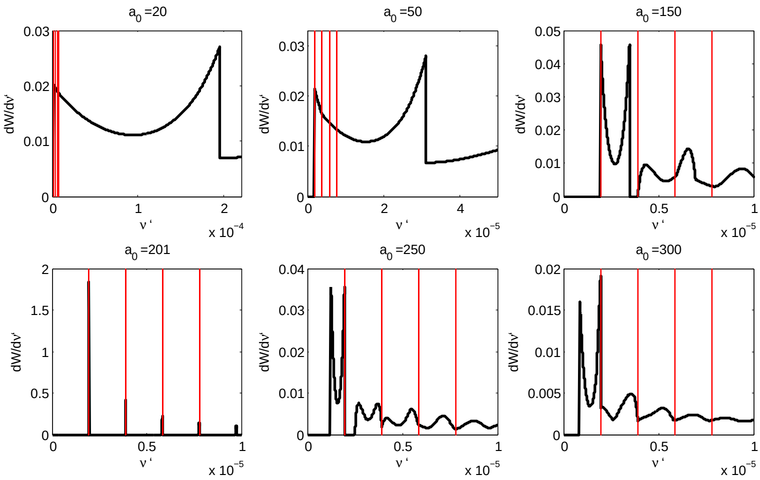


$$q_\mu + nk_\mu \longrightarrow q'_\mu + k'_\mu,$$

centre-of-mass

$$\mathbf{q} + n\mathbf{k} = \mathbf{0} \quad \Longrightarrow \quad a_0 = 2\gamma_0.$$

Spectral Flow ($\gamma_0 = 100 \implies a_{0,\mathrm{CoM}} = 200$)



Emission harmonics collapse to line spectra in the centre-of-mass frame.

Summary

New generation of high intensity lasers: new physics.

Classical domain: RR effects will become important:

- Radiation reaction induced electron capture,
- Stable with respect to electron beam width,
- Occurs when $2\gamma_0 > a_0$,
- Plane wave approximation good,
- $\Longrightarrow$ mass shift important.

Beyond classical: nonlinear Compton scattering

- Mass shift important.

Summary/Outlook

Current facilities

Classical (LF) approximation good

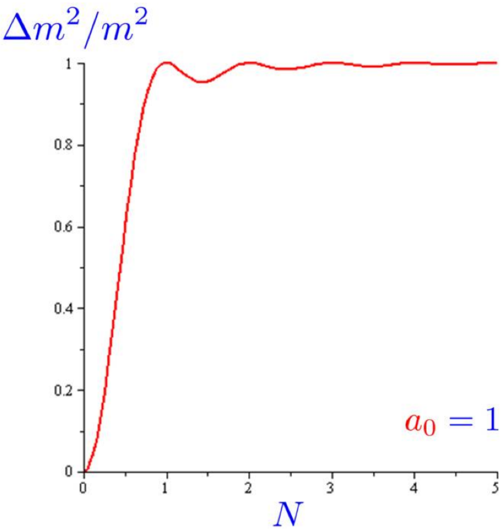
New facilities

Classical radiation reaction and QED effects

Questions to address:

- When does the classical theory break down?
- When do quantum effects become important?
- Better understanding of the mass shift.

Appendix: The Mass Shift



T. Heinzl

Finite pulse duration effects.

Mass shift $\Delta m = m_*^2 - m^2$.

Number of cycles N.