Understanding the Dynamics of Particles in Intense Laser Fields

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Introduction

Laser intensities increasing

- Increasing the range of accessible physics

Signatures of QED in upcoming facilities

- Numerical code to model Compton scattering
- Particle trajectories altered by discrete emissions

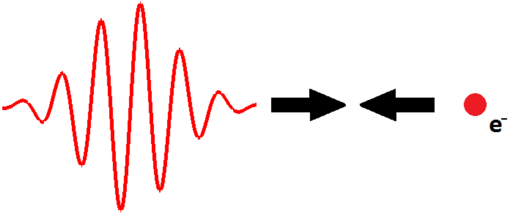
Optimising focussing efficiency

- Pair production in e-dipole fields

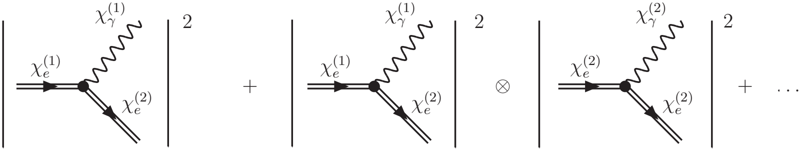
Compton Scattering

Laser field $F^{\mu\nu}(\phi)$, $\phi = k \cdot x$
Intensity $a_0 = eE/\omega mc$

Electron momentum
$p^\mu(\phi) = m\gamma(c, \mathbf{v})$



Main contributions to Compton scattering [Di Piazza *et al*, PRL 2010]



More on RR and QED: Talk by Anton [Ilderton & Torgrimsson, 2013]

Quantum Effects

As intensity increases quantum effects become important

$$\chi_e \equiv \frac{e\hbar}{m^3c^4}\sqrt{(F_{\mu\nu}p^\nu)^2} \sim \gamma\frac{E}{E_{\mathrm{cr}}}$$

Quantum effects dominate when $\chi_e \sim 1$

Consider the regime

- $a_0, \gamma \gg 1$: quantum effects important
- $\chi_e \lesssim 1$: neglect pair production

Compton scattering

Compton Scattering

High intensity limit $a_0 \gg 1$

- Radiation formation length $\sim \lambda/a_0 < \lambda$
- Laser can be considered constant w. r. t. photon emission

Under the condition $a_0,\ \gamma \gg 1$

- any field appears locally constant and crossed

Photon emission probability [Narozhnyi, Nikishov & Ritus, 1963]

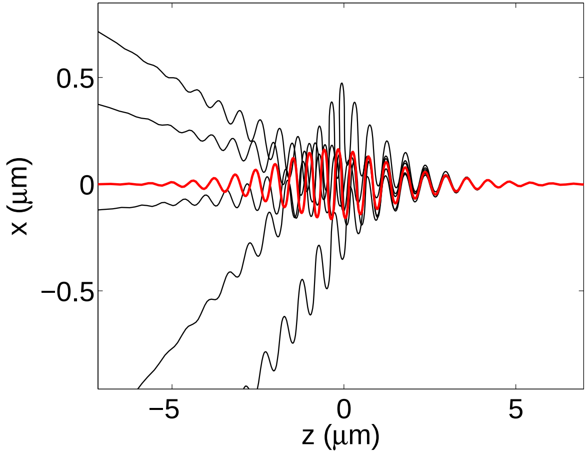
$$d\Gamma(\chi_\gamma) = \frac{\alpha m c^2}{\sqrt{3}\pi\hbar\gamma\chi_e}\mathcal{K}_{\chi_e}(\chi_\gamma)d\chi_\gamma, \quad \chi_\gamma = \frac{e\hbar}{m^3c^4}\sqrt{-(F_{\mu\nu}\kappa^\nu)^2}$$

'SIMLA' code: determines via a statistical event generator

Compton Scattering

Green & Harvey, *to appear*

$a_0 = 150,\ \gamma = 200$



Moving to Higher Intensities...

To increase field amplitude

- Increase laser power
- More efficient focussing

Theoretical maximum focussing efficiency: *e*-dipole pulse [Gonoskov *el al* PRA 2012]

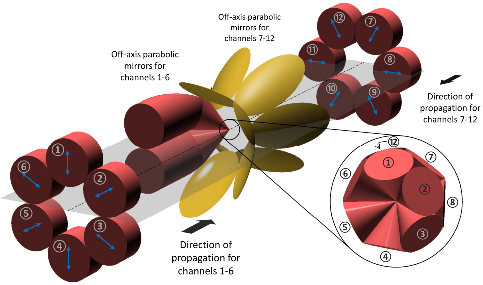
- Structural similarities with dipole fields
- Satisfies Maxwell's equations

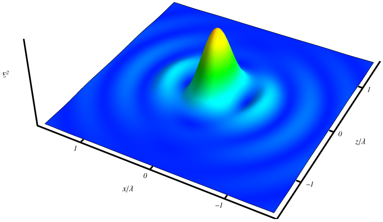
Requires 4π focussing

- Can mimic pulse using double belt geometry
- Reach 90% of theoretical maximum

Generating a Dipole Pulse

Bashinov, Gonoskov, Gonoskov, Harvey, Ilderton, Kim, Marklund, Mourou, Sergeev 2013





Pair Production Theory

The quantities relevant to pair production are the local Lorentz invariants [Schwinger, 1951]

$$\mathcal{S} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \quad \text{and} \quad \mathcal{P} = -\frac{1}{4} \tilde{F}_{\mu\nu} F^{\mu\nu} \; .$$

In an dipole pulse we have $\mathcal{P} = \mathbf{E} \cdot \mathbf{B} = 0$.

Calculate number of pairs using locally-constant-field estimate [Bulanov *et al*, 2004]

$$N = \frac{1}{4\pi^3 \lambda\!\!\!^{-}_c{}^4} \int \mathrm{d}^4x \; \epsilon^2(x) \exp\left[-\frac{\pi}{\epsilon(x)} \right] ,$$

where $\epsilon = \sqrt{\mathcal{S} + |\mathcal{S}|}/E_S$, E_S the critical (Schwinger) field and $\lambda\!\!\!^{-}_c = \hbar/mc$ is the (reduced) Compton wavelength.

Calculating the Number of Pairs

Gonoskov, Gonoskov, Harvey, Ilderton, Kim, Marklund, Mourou, Sergeev, 2013

Integral can be evaluated using Monte Carlo methods.

	$\lambda = 1\,\mu$m	$\lambda = 0.8\,\mu$m	$\lambda = 0.4\,\mu$m
1660 PW	1 (5.5 kJ)	10^3 (4.4 kJ)	10^{10} (2 kJ)
1120 PW	10^{-4} (3.7 kJ)	1 (3 kJ)	10^8 (1.5 kJ)
320 PW	10^{-23} (1.1 kJ)	10^{-14}(0.85 kJ)	1 (0.43 kJ)

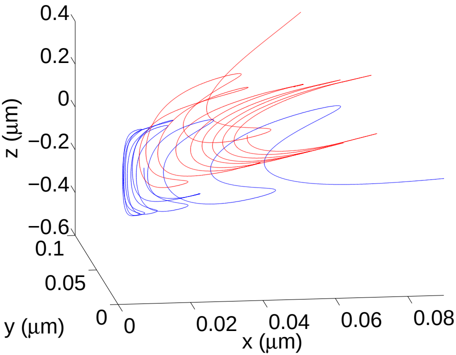
Pair production threshold for $\lambda = 0.8\mu$m is 1120PW.

Behaviour of the Pairs After Creation

Field is focussed to a very small region of space

- Model trajectories classically
- Include radiation damping

Find that the particles recirculate



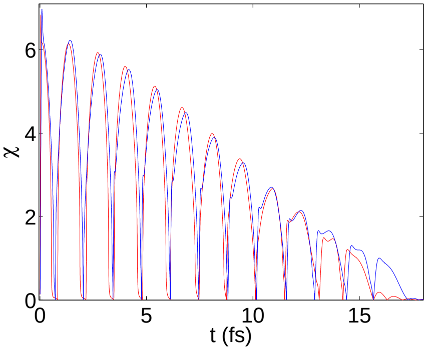
Behaviour of the Pairs After Creation

Need to consider if additional QED processes will occur

Track the quantum efficiency parameter

$$\chi_e = \frac{e\hbar}{m^3 c^4}\sqrt{p_\mu T^{\mu\nu} p_\nu}$$

When χ_e approaches unity quantum effects will start to become important



Summary

SIMLA: Numerical code to model Compton scattering

- Particle trajectories altered by discrete emissions
- Signatures of QED in upcoming facilities

Moving to higher intensities

- Laser generated dipole pulses: maximum possible focussing efficiency
- Pair generation threshold for optical laser: 1120PW
- Once created, pairs recirculate: additional physics