Spin polarization of electrons interacting with ultra-intense laser pulses

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1 Introduction

At laser intensities $I > 10^{21}$ W/cm^2, which can already be reached by present day ultra-intense lasers such as Gemini, light-matter interactions start to be influenced by quantum electrodynamic (QED) effects. With next-generation ultra-intense lasers (expected to reach intensities of $I \gtrsim 5 \times 10^{22}$ W/cm^2, e.g. the proposed Vulcan 10 PW upgrade), one will be able to fully reach the new 'QED-plasma' regime, where the dynamics of matter at the focus is characterized by the interplay of relativistic plasma and 'strong-field' QED processes. Understanding how QED processes can modify the plasma's behaviour is of fundamental interest not only for laboratory investigations of extreme astrophysical environments, but will have consequences for potential applications of these lasers, ranging from compact particle accelerators to x/gamma-ray sources.

Recent experiments performed at Gemini showed evidence for quantum effects in radiation reaction [1, 2], i.e. in the energy loss of laser accelerated electrons as they interact with another laser pulse and emit gamma radiation. Another—less investigated yet no less interesting—aspect of quantum radiation reaction is that it affects the dynamics of the electron spin. It is long known that electrons in a storage ring slowly self-polarize via the Sokolov-Ternov effect [3] due to an asymmetry in the rate of spin flip transitions. Here, we report on our recent investigations of ultra-fast spin polarization of electrons interacting with ultra-intense laser pulses [4, 5].

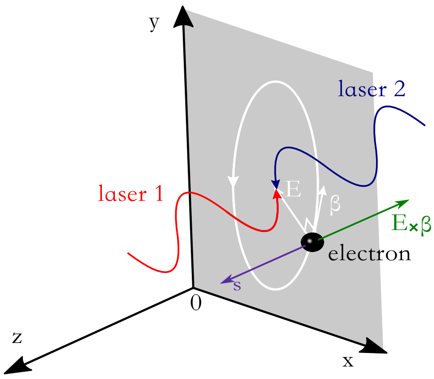

Figure 1: A standing wave may be produced by two counter-propagating circularly polarized lasers. At the magnetic node ($z = 0$) the electric field $\boldsymbol{E}$ rotates with a constant amplitude, causing electrons in this plane to perform rotational motion. The electrons tend to align their spin antiparallel to the vector $\boldsymbol{E} \times \boldsymbol{\beta}$.

2 Rotating Electric Field

We first focus on the case of a rotating electric field, $\boldsymbol{E}(t)$ and $\boldsymbol{B} = 0$, which is the field configuration at the magnetic nodes of two counter-propagating circularly polarized laser pulses. For ultra-relativistic electrons, the orbital dynamics in a strong laser field can be described by the quantum corrected and approximated Landau-Lifshitz radiation reaction force equation [5],

$$\frac{d\boldsymbol{p}}{dt} = -e(\boldsymbol{E} + \boldsymbol{\beta} \times \boldsymbol{B}) - \frac{2}{3}\alpha m^2 g(\eta)\eta^2 \frac{\boldsymbol{p}}{\|\boldsymbol{p}\|}\,, \tag{1}$$

with $\boldsymbol{p} = \gamma m \boldsymbol{\beta}$ as the relativistic momentum, $\gamma = 1/\sqrt{1-\boldsymbol{\beta}^2}$ and $\boldsymbol{\beta}$ as the Lorentz factor and the normalized velocity, respectively. The constants m and e are the electron mass and the elementary charge, and we use units with $\hbar = c = 1$.

The quantum efficiency parameter of the electron η equals the electric field in the electron's instantaneous rest frame $E_{\rm RF}$ in units of the Sauter-Schwinger field $E_S = m^2/e$ and determines the importance of quantum effects. The Gaunt factor $g(\eta)$ takes into account the reduced radiated power in the quantum regime. In principle $g(\eta)$ itself is spin-dependent, but the effect of this is small and so not considered here, see [5]. Note that in this approach the stochasticity of photon emission is not taken into account.

The electrons motion in the electric field rapidly reaches a steady state rotation with constant γ when the radiative losses balance the acceleration due to the electric field. In this case the electron's Lorentz factor is given by $\left[\frac{2\omega}{3m}\, g(\eta)\, \gamma^4\right]^2 + \gamma^2 = a_0^2$, with $\omega = 2\pi/\lambda$ being the laser frequency and $a_0 = 855\sqrt{I\lambda^2/(10\mathrm{PW})} \gg 1$ the dimensionless laser amplitude [4, 5].

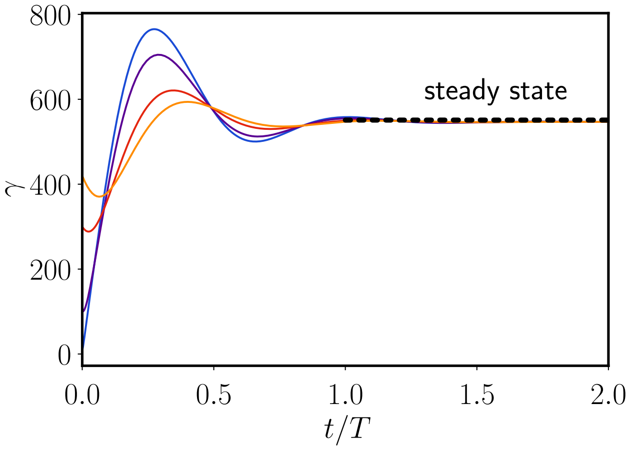

Figure 2: Electrons that start orbiting in the rotating electric field with $a_0 = 600$ and with different initial energies reach the steady state very fast.

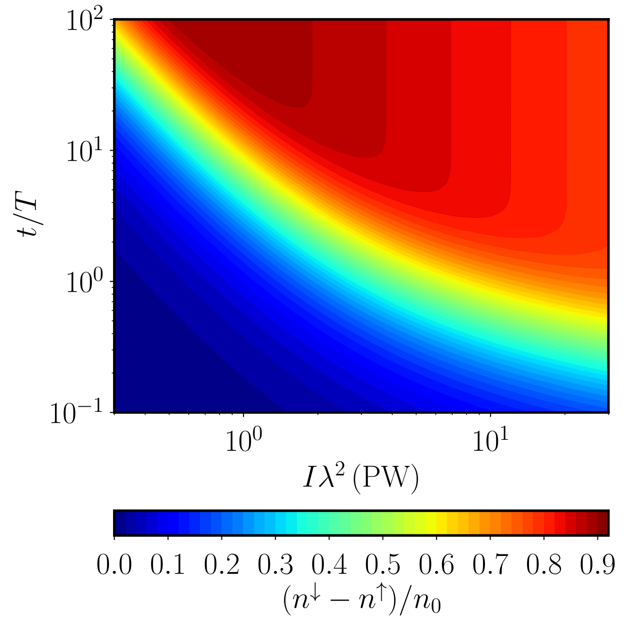

Figure 3: Degree of electron spin polarization, as a function of laser intensity and time normalized to the laser period.

In order to describe the spin dynamics of the rotating electrons we split the population of plasma electrons into two fractions with their spins aligned or anti-aligned to a direction $\boldsymbol{\zeta}$. In a rotating electric field we find a global non-precessing spin polarization basis $\boldsymbol{\zeta} \parallel \boldsymbol{E} \times \boldsymbol{\beta}$ which ensures that the spin-up and spin-down electrons do not mix (by means the classical dynamics, i.e. spin precession).

The number density of those fractions evolve according to the master equations

$$\begin{aligned} \frac{d}{d\tau} n^{\uparrow} &= \frac{d\mathbb{P}^{\downarrow\uparrow}}{d\tau} n^{\downarrow} - \frac{d\mathbb{P}^{\uparrow\downarrow}}{d\tau} n^{\uparrow} \\ \frac{d}{d\tau} n^{\downarrow} &= \frac{d\mathbb{P}^{\uparrow\downarrow}}{d\tau} n^{\uparrow} - \frac{d\mathbb{P}^{\downarrow\uparrow}}{d\tau} n^{\downarrow} \end{aligned} \tag{2}$$

where $\tau = t/\gamma$ is the electron's proper time and the gamma-ray photon emission rates $d\mathbb{P}^{ss'}/d\tau$ describe the transitions from one spin state to the other [3].

For ultra-relativistic electrons interacting with ultra-intense laser pulses with $a_0 \gg 1$, the formation length of the photons becomes very short, and the field can be considered constant over the formation region. Thus, rates $dN^{ss'}/d\tau$ are well described by the photon emission rates in constant crossed or constant magnetic field [3].

Solving the master equations for an ensemble of initially unpolarized electrons, i.e. with $n^{\uparrow} = n^{\downarrow} = n_0/2$, we find the time-evolution of the degree of polarization $(n^{\downarrow} - n^{\uparrow})/n_0$. This is plotted in Fig. 3, as a function of laser intensity $I\lambda^2$. For instance for $I\lambda^2 = 10$ PW the time-scale to reach significant polarization of the electron plasma is on the order of the laser oscillation time. Here we assumed that the electrons orbit with steady state energy from the beginning. Taking into account the time-evolution of the energy, as they reach the steady state, gives small corrections [5] to the degree of polarization and so can be safely neglected.

3 Spin Precession Away From the Magnetic Node

It had been shown that electron orbits are unstable at the magnetic node and electrons migrate away from there. Once that happens $\boldsymbol{B} \neq 0$ and the electron spin starts precessing classically due to the action of the Bargmann-Michel-Telegdi (BMT) equation [6]. In Fig. 4, we plot the time for the spin expectation value to undergo significant precesssion. The spin-precession time is defined as the time the expectation value of the spin takes to differ by 50% from its initial value.

If the spin precession time is very short the electrons will only remain spin polarised very close to the magnetic node. This gives an upper limit on the spin polarization for electrons off the magnetic node, which is shown by the color map in Fig. 4, showing that we can expect a degree of spin polarization higher than 30%, for $a_0 = 600$, and for electrons initially less than 1% of a laser wavelength from the magnetic node. Analogously, for $a_0 = 2000$, we expect a 70% degree of spin polarization for electrons initially less than 1% of a laser wavelength off the magnetic node.

4 Discussion and Outlook

In more general field configurations we cannot find a global non-precessing basis. Then, the classical spin-precession needs to be tracked by means of the BMT

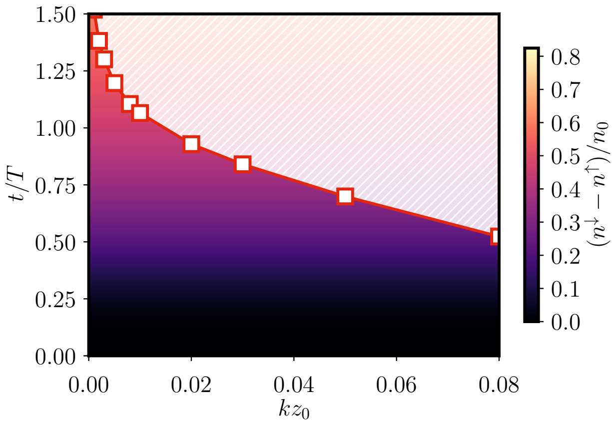

Figure 4: Spin precession time (red symbols and curve) as a function of the electron initial position off the magnetic node. The degree of spin polarization as a function of time is shown as contour-plot.

equation. In addition, generalized spin-flip rates are necessary because, as a result of the classical spin-precession, the electrons polarization will not be parallel to the local non-precessing direction at the moment of emission.

We have calculated these generalized photon emission rates using the density matrix formalism and will implement them into single-particle tracking and particle-in-cell laser-matter simulation codes. This will allow us to investigate electron spin-polarization in more realistic field configurations in order to find prospective scenarios for an experimental verification of those effects at high-power laser facilities.

Spin polarisation of plasmas may have consequences for their dynamics. For example an excess of σ-polarized gamma-ray photons may modify the rate of pair production in pair cascades induced when the laser intensity exceeds 10^{24} W/cm^2. Spin polarization could also enhance the radiation reaction force on electrons and positrons in the plasma by up to 15%, enhancing the power radiated by the plasma by the same percentage. This spin polarization effect should therefore be included in the modelling of next-generation laser-matter interactions. The possibility of producing spin-polarized electrons and positrons with ultra-intense lasers also opens up new application for example polarised electrons are used in the spin-polarized electron spectroscopy. Finally, the study of the behaviour of electron spin in high-intensity laser-matter interactions will allow us to test our models of quantum radiation reaction with more finesses than has been done before, which is interesting in its own right.

5 Acknowledgements

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