BNL-224820-2023-TECH

EIC-ADD-TN-070

LASER-INDUCED POLARIZATION FOR THE ELECTRON-ION COLLIDER

K. D. Ranjbar, V. Ranjbar

September 2023

Electron-Ion Collider

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

DISCLAIMER

LASER-INDUCED POLARIZATION FOR THE ELECTRON-ION COLLIDER

K. D. Ranjbar*, E. Snyder, A. Snyder
Port Jefferson High School

Abstract

The use of an intense ultrashort laser pulse to induce electron polarization has been proposed in existing literature [6]. Utilizing the Python programming language, a code has been developed to recreate the local constant crossed-field approximation (LCFA) with the aim of determining values for transverse polarization given a nonzero initial polarization. It has been shown that over multiple laser shots, lower values of the quantum efficiency parameter are associated with higher transverse polarization output, yet require a greater number of shots to attain maximal polarization. Moreover, the quantum efficiency parameter has been redefined as a function of intensity for Ti:sapphire laser necessary to induce polarization in the Electron-Ion Collider.

INTRODUCTION

While electrons are fermions, lacking any known substructure, protons and neutrons derive their basic properties from constituent quarks and gluons, which are bound by the strong nuclear force. The Electron Ion Collider (EIC) has been designed to investigate the strong force by colliding intense beams of polarized electrons with protons and nuclei to reveal the arrangement of quarks and gluons within the atomic nucleus. Polarization of the electron beam is essential for effective collisions, (as most interactions are spin-dependent), and can be achieved by various means. It is known that electrons circulating in a storage ring particle accelerator will self-polarize due to the Sokolov-Ternov (ST) effect, a type of radiative spin-polarization whereby a particle's change in momentum caused by motion along a bent path results in the ejection of a photon (i.e., synchrotron radiation) and subsequent spin flip. Since transition to the spin-down state is more likely, up to 92.4% antiparallel transverse-plane polarization may be achieved over the course of minutes or hours– a relatively slow process [1]. Alternatively, it has been shown that an intense laser pulse can be used to polarize electrons in a matter of femtoseconds [3]. The interaction between an unpolarized beam and an intense laser field results in the transfer of energy to an outgoing gamma-ray photon through nonlinear Compton scattering. As in the ST effect, polarization is obtained through the loss of a photon and resultant spin flip. Experimental results as well as theoretical work have confirmed that the degree of polarization due to nonlinear Compton scattering varies with laser parameters as well as initial polarization [5]. Laser-induced polarization for the EIC is worth considering for several reasons: not only is polarization attained on a comparatively shorter time scale, but necessary parallel polarization, which would otherwise be countered by the ST effect, can also be achieved.

Two methods have been previously proposed for determining the degree of polarization in final state electrons. The first of which uses a density matrix to calculate the quantum state of the electrons (i.e., the course of how the electrons' properties change over time). The alternative method is known as the local constant crossed-field approximation (LCFA), used to estimate the results of the density matrix for a linearly polarized laser. The results of the LCFA have been shown to be consistent with those of the density matrix [6]. According to the LCFA approximation, the electron polarization vector– the vector that describes the degree of polarization within a system– across the transverse plane can be represented by the following equation:

$$\Xi_{\zeta'} = \frac{\alpha}{b\mathbb{P}} \int d\tau dt \left[\Xi_\zeta Ai_1 + \Xi_\zeta \frac{2Ai'}{z} + \frac{t}{1-t} \frac{Ai}{\sqrt{z}} sgn(\dot{h}) \right] \quad (1)$$

Ξ_ζ describes the initial polarization of the beam in a range of [0,1], where 0 represents an absolute lack of polarization, and 1 represents absolute polarization. h describes the pulse shape function as $h = \cos(\phi + \phi_{CE}) \cos^2(\frac{\pi\phi}{2\Delta\phi})\Theta(\Delta\phi - |\phi|)$ for the vector potential, and $\dot{h}$ (derivative of h with respect to time) describes the shape of the electric field. The shape and asymmetry of a magnetic field produced by a laser are limited due to the inability to produce "unipolar" fields (where $h(-\infty) \neq h(\infty)$, and the potential for infrared divergences in scattering probabilities). The asymmetry of the magnetic field is maximal when the carrier envelope phase $\phi_{CE} = \frac{\pi}{2}$. The maximum of the asymmetry of $|A| \approx 0.17$ is achieved for a pulse duration of $\phi = 3.27$, and effectively becomes zero for $\phi > 8$ [6]. z is described as the the argument of the Airy functions: $Ai(z) = \frac{1}{2\pi} \int_{-\infty}^{\infty} ds e^{i\frac{s^3}{3} + izs}$ and their integrals $Ai_i(z) = \int_z^\infty dx Ai(x)$ with z being $z = z(t,\tau) = \left[\frac{t}{1-t} \frac{1}{|\dot{h}(\tau)|\chi_e} \right]^{\frac{2}{3}}$. This depends on the local value of the quantum efficiency parameter $\chi_e(\tau) \equiv \chi_e|\dot{h}(\tau)|$, which is calculated using the local value of the background field. τ denotes the proper time - a scalar quantity that is defined as the time interval between two events as measured by an observer who is located at the same position as the events. Mathematically, it is defined as the path-length of a timelike curve in space-time.

METHODOLOGY

Using python, it was possible to code a program to find final polarization amplitudes, given input values of ϕ, ϕ_{DE}, χ_e, and χ - although it is worth mentioning again that the

* ranjbark24@gmail.com

asymmetry of the magnetic field is maximal when the carrier envelope phase $\phi_{CE} = \pi/2$, and the maximum of the asymmetry of |A| ≈ 0.17 is achieved for a pulse duration of $\phi = 3.27$.

Github Link to the code can be accessed here: https://github.com/UnregiseredData/EIC-Laser. Looking back to Eq. 1, the LCFA approximation, it was possible to create a program function that took input values of the quantum efficiency parameter χ_e and returned values of transverse polarization Ξ_ζ. This was accomplished by splitting Eq. 1 into four different integrals, and then integrating them separately. Since the integral in question becomes increasingly divergent as χ_e approaches zero (due to the use of numerical methods for solving), it was necessary to perform a series of substitutions. Moreover, it is worth noting that the $-\frac{a}{b}$ found in the equation is canceled out with the $\frac{1}{\mathbb{P}}$, as the value of includes the term $-\frac{a}{b}$. In order to confirm the validity of the code, values for transverse polarization Ξ_ζ were plotted as a function of the quantum efficiency parameter χ_e for zero initial polarization. The results were consistent with those presented in existing literature [6], with a peak of .006 occurring at $\chi_e = 0.5$.

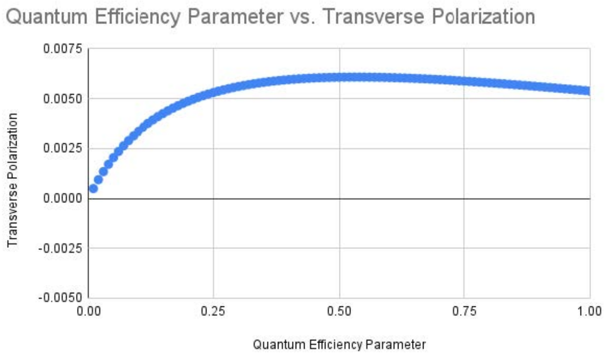

Figure 1: Quantum Efficiency Parameter χ_e vs. Transverse Polarization Ξ_ζ. the results are consistent with those presented in [6], with χ_e peaking at .5.

The quantum efficiency parameter, χ_e, is roughly defined as a measure of field strength. In traditional radiative polarization, where the electromagnetic field is weak, $\chi_e = e\sqrt{|(F^{\mu\nu}p_\nu)^2|}/m^3 << 1$ [4] in which e is the fundamental electric charge, F is the electromagnetic tensor, p is momentum, and m is the electron mass. χ_e can also be defined as the product of the nonlinearity parameter $\xi = 8.55\sqrt{\lambda^2[\mu m]I[10^{20}W/cm^2]}$, with wavelength λ and intensity I , and the laser frequency in the electron rest frame $b = k \cdot p/m^2$, with $k \cdot p$ being the dot product of the photon k momentum vector and the electron p momentum vector. In a strong field where rapid polarization occurs due to frequent spin flips, $\chi_e = \xi b$ is approximately 1, and $\xi >> 1$ [6]. Since the electron momentum vector that constitutes b is defined as $p = m\gamma v$, where v represents the electron velocity and γ is the Lorentz factor, it stands that $b = k \cdot (m\gamma v)/m^2 = k \cdot (\gamma v)/m$ (note that Planck's constant and the speed of light are not shown, as they are held equal to 1 in order to produce a measurement in terms of energy). The frequency in the electron rest frame without respect to mass, $k \cdot (\gamma v) = \omega_L$, is equal to $2\gamma\omega_0$, where ω_0 is the frequency in the lab rest frame [2]. This is because $\omega_0 = 2\pi f_0$, in which f_0 , the linear frequency, can be rewritten as c/λ_0 to yield $\omega_0 = 2\pi c/\lambda_0$. In the case of the electron rest frame, $\omega_L = 2\pi c/\lambda_L = 2\pi c(2\gamma)/\lambda_0$, as $\lambda_L = \lambda_0/\gamma(1 - \cos(\phi))$ due to the doppler effect, and it is assumed that the laser hits the beam head-on from an angle of π. ω_0 can then be substituted into the equation, giving $\omega_L = \omega_0 2\gamma$. Therefore,

$$\chi_e = 8.55\sqrt{\lambda^2[\mu m]I[10^{20}W/cm^2]}(2\gamma\omega_0/m) \qquad (2)$$

RESULTS

To observe the effect of multiple laser shots, the code was modified to run a for loop that re-inputted the calculated transverse polarization 1000 times given an initial polarization of 0 and χ_e values of .5 [Fig. 2 (a)], .7 [Fig. 2 (b)], .1 [Fig. 2 (c)], and .01 [Fig. 2 (d)]. It has been shown that for χ_e = .5, polarization plateaus at about 40% after 350 shots. Assuming a laser repetition rate of 10 Hz (standard for Ti:Sapphire), maximal polarization can be achieved in about 35 seconds. Moreover, for χ_e = .7, polarization levels at 29.7% after 250 shots , and for χ_e = .1, polarization levels at 83.3% after 800 shots, with one laser shot per every 7800 orbits. By contrast, when χ_e = .01, polarization increases linearly at approximately .045% per shot (within the domain of 0 to 1000 shots). As shown in Fig.2., lower quantum efficiency values correspond to greater maximal polarization. However, the number of shots necessary to reach the plateau threshold– and to an extent time taken– similarly increases. In the case of the EIC, rapid polarization is preferable, particularly for parallel-polarized bunches that, if exposed to the electromagnetic field for a prolonged period of time, will experience depolarization due to the ST effect. In order to optimize duration and final state polarization, a χ_e value in the range of .1 is ideal.

Using Eq. 2, it was possible to represent the quantum efficiency parameter χ_e as a function of wattage. For a typical Ti:sapphire laser, the value of ω_0 is approximately 1.55 eV. When imputed into $b = 2\gamma\omega_0/m$, along with a γ value of 35255.1 for the EIC and electron mass of .5109989(10^6)eV, the frequency in the electron rest frame was calculated to be approximately .21388. Thus, when b was substituted into Eq. 2, along with a value of λ = 800 nm for a standard Ti:Sa laser, the equation could be rewritten as: $\chi_e = 1.4629\sqrt{I[10^{20}W/cm^2]}$, or $\chi_e = 1.4629\sqrt{W/(\pi r^2 \times 10^{20})}$ when intensity was normalized with respect to spot size (i.e., the laser beam's minimum diameter after passing through a focusing lens, given by the formula $S = \frac{4M^2\lambda f}{\pi d}$ with beam quality parameter M^2 ,wavelength λ, lens focal length f, and diameter at the lens surface d). Subsequently, wattages in gigawatts for hypothetical fixed spot sizes of diameters 25×10^{-5} cm, 6×10^{-5} cm, and 4×10^{-5} cm were plotted against χ_e, as depicted in the following diagram:

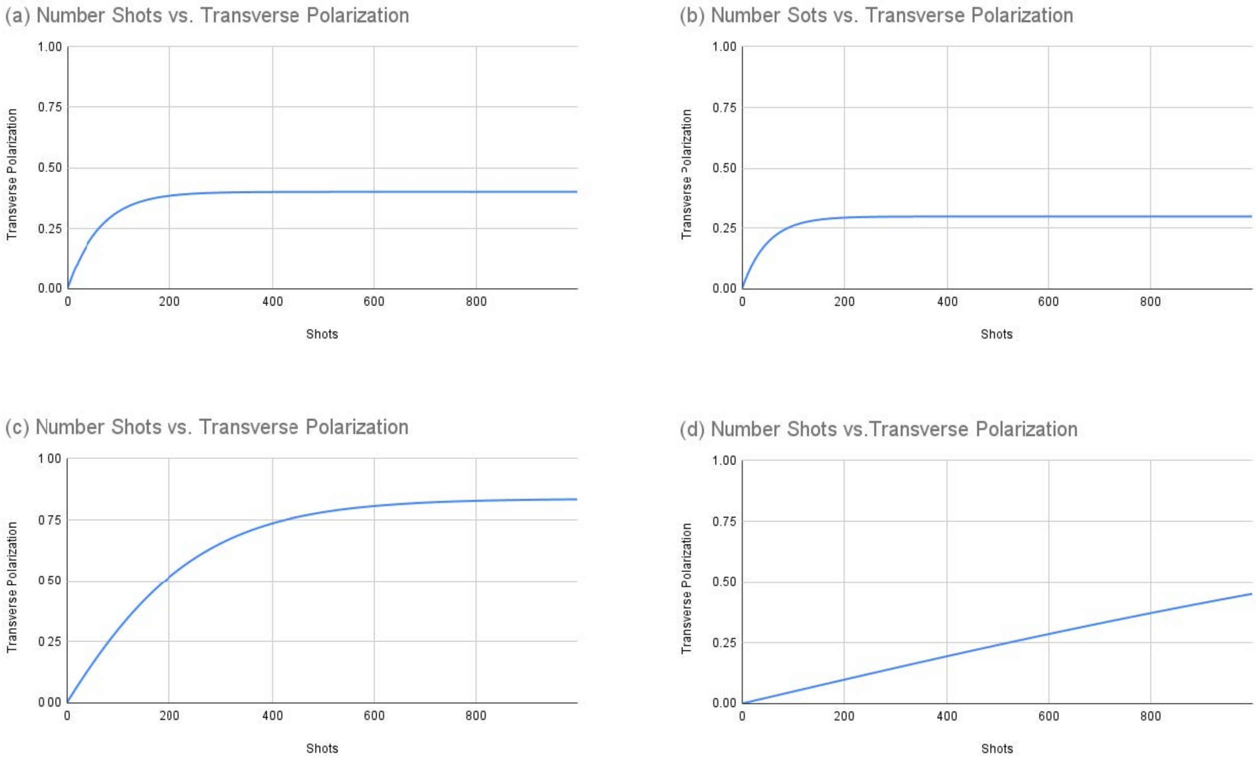

Figure 2: Number of shots vs. transverse polarization for χ_e = .5 (a), .7 (b), .1 (c), and .01(d). Although polarization plateaus at greater values when χ_e is low, the number of shots (and by extension time) necessary to achieve maximal polarization is longer. Note that the effects of resonances and the electromagnetic field are not accounted for.

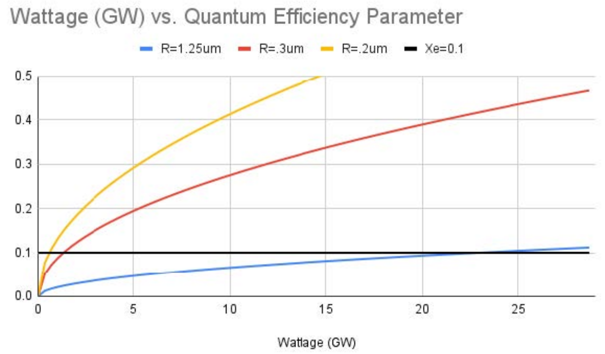

Figure 3: Plot of wattage in GW versus the quantum efficiency parameter χ_e , in which Blue = 25×10^{-5} cm, Red = 6×10^{-5} cm, Yellow = 4×10^{-5} cm.

It can be seen that Eq. 2, with χ_e set equal .1, is satisfied by a wattage of roughly 23 GW for a spot size of 25×10^{-5} cm, 1.3 GW for spot size 6×10^{-5} cm, and .59 GW for spot size 4×10^{-5} cm.

DISCUSSION

The exact explanation as to why lower values of the quantum efficiency parameter χ_e correlate with greater final state polarization remains somewhat ambiguous. Evidently, repeated interaction with the laser pulse results in non-trivial effects that contradict expectations based on the behavior of χ_e when initial polarization equals zero. Perhaps the same mechanism responsible for polarization decline as illustrated in Fig. 1 when quantum efficiency values exceed .5 is at work. Likely, this mechanism relates to the envelope asymmetry of the ultrashort laser pulse, whereby polarization builds up in the first half cycle of the monochromatic wave before being partially negated, resulting in an incomplete cancellation. When initial polarization equals zero, Eq. 1 is performed without respect to its first two terms (zero is inputted for Ξ_ζ); once incorporated for a nonzero initial polarization, the proportional relationship between the Airy functions and Ξ_ζ that constitutes these terms alters the behavior of the function in response to various χ_e values.

It should additionally be noted that the aforementioned trend may be attributed to the code's use of numerical methods to solve integrals; as the value of the quantum efficiency parameter χ_e approaches zero, the integral in question becomes increasingly divergent. Although the issue was addressed by performing a substitution, it is still important to exercise a degree of caution when examining the results. Assuming the validity of the correlation observed in Fig. 2., lower quantum efficiency values are preferable, as they are associated with weaker field strengths. The weaker a laser's field strength, the higher its repetition rate. Thus, a greater number of shots can be fired per second, increasing the frequency of interaction with the beam. Simply put, although more shots may be required to attain maximal polarization, the process does not *necessarily* take longer, and depolarization due the ST effect for a parallel-polarized beam can be minimized. Albeit, for χ_e values below .01, the durational drawbacks of an excessive shot number despite a higher repetition rate outweigh the benefits of improved polarization output.

CONCLUSIONS

The use of an intense ultrashort laser pulse to induce electron polarization has been previously proposed in existing literature [6] , [5]. Utilizing the Python programming language, a code has been developed to replicate the local constant crossed-field approximation with the aim of determining values for transverse polarization given a nonzero initial polarization. It has been shown that polarization for lower values of the quantum efficiency parameter,

χ_e (i.e., weaker field strengths) yield higher final transverse polarization output, yet require a larger number of shots to achieve maximal polarization. The mechanisms responsible for this phenomenon are worth further investigation– particularly those relating to envelope asymmetry and the associated cancellations. While a greater number of shots is necessary to maximize polarization when χ_e is small, the repetition rate for weaker field strengths is significantly greater, hastening polarization buildup. Thus, assuming typical Ti:sapphire spot size, a laser wattage that corresponds to χ_e values falling between .01 and .1 is optimal. Laser-induced polarization is especially relevant for the Electron-Ion Collider, as it provides a means of countering polarization loss due the ST effect for parallel-polarized bunches. Moreover, depolarization brought on by resonances and lattice imperfections in the machine can be avoided by polarizing the beam just prior to collision, lessening reliance on the magnetic manipulation of bunch spins. Beyond the EIC, laser-induced polarization also has potential applications in CERN's Future Circular Collider.

REFERENCES

[1] A. A. Sokolov and I. M. Ternov, Dokl. Akad. Nauk SSSR **153** (1963) no.5, 1052-1054

[2] T. Heinzl, [arXiv:2203.01245 [hep-ph]].

[3] D. Del Sorbo, D. Seipt, T. G. Blackburn, A. G. R. Thomas, C. D. Murphy, J. G. Kirk and C. P. Ridgers, Phys. Rev. A **96** (2017) no.4, 043407 doi:10.1103/PhysRevA.96.043407 [arXiv:1702.03203 [physics.plasm-ph]].

[4] V. Baier and V. Katkov, "Radiative Polarization of Electrons in a Magnetic Field". Soviet Physics JETP, 25(5), 1422-1426. (1967) `http://www.jetp.ras.ru/cgi-bin/dn/e_025_05_0944.pdf`

[5] D. Seipt, doi:10.3204/DESY-PROC-2016-04/Seipt [arXiv:1701.03692 [physics.plasm-ph]].

[6] D. Seipt, D. Del Sorbo, C. P. Ridgers and A. G. R. Thomas, Phys. Rev. A **98** (2018) no.2, 023417 doi:10.1103/PhysRevA.98.023417 [arXiv:1805.02027 [hep-ph]].