Plasma acceleration of polarized particle beams

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Abstract. Spin-polarized particle beams are of interest for applications like deepinelastic scattering, e.g. to gain further understanding of the proton's nuclear structure. With the advent of high-intensity laser facilities, laser-plasma-based accelerators offer a promising alternative to common radiofrequency-based accelerators, as they can shorten the required acceleration length significantly. However, in the scope of spinpolarized particles, they bring unique challenges.

This paper reviews the developments in the field of spin-polarized particles on the basis of the interaction of laser pulses and high-energy particle beams with plasma. The relevant scaling laws for spin-dependent effects in laser-plasma interaction, as well as acceleration schemes for polarized leptons, ions and gamma quanta are discussed.

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1. Introduction

The study of spin dynamics in plasma has gained significant interest in recent years, specifically in the scope of generating relativistic, spin-polarized particle beams. Earlier research with polarized particle beams has, e.g., utilized the polarization build-up over time due to the Sokolov-Ternov effect in storage rings or used pre-polarized electron or hadron sources in the case of linear accelerators. A review of spin dynamics in "conventional" accelerators was given by Mane in [1].

However, the developments in high-intensity lasers and the progress of plasma-based accelerators have brought the option of obtaining and accelerating polarized particle beams via laser-plasma interaction within reach. Extensive reviews on the progress in the laser-driven wakefield acceleration of electrons and the different acceleration schemes for ions have been given by Esarey and Macchi *et al.*, respectively [2, 3]. Reviews geared towards beam-driven wakefield accelerators were given by Hogan [4], and Adli and Muggli [5] in the specific case of a proton driver.

For applications where polarization persistence is a requirement, the dynamics of particle spin have to be thoroughly understood. These applications, e.g., include the areas of high-energy physics and nuclear fusion.

In the field of high-energy physics, polarized particle beams can be utilized for deep-inelastic scattering to improve the understanding of the proton nuclear structure [6] and are of general relevance to quantum chromodynamics [7]. For nuclear fusion, Goldhaber *et al.* proposed in [8] that the relevant cross-section depends on the relative spin orientation of the reactants. For the reaction $d + t \rightarrow \alpha + n$, the enhancement factor is approximately 50% [9]. For other reactions, like proton-Boron fusion, similar factors have been calculated [10]. Moreover, the understanding of spin effects in plasma has led to the idea of using polarization as a diagnostic tool for measuring the strength of electromagnetic fields in astrophysical plasma [11, 12].

This review provides an overview of the progress in the acceleration of spinpolarized particle beams via plasma-based acceleration schemes. The remainder of the introduction discusses the main spin-dependent effects that can become relevant during of high-intensity laser pulses or high-energy particle beams with plasma. Section 2 describes some of the experimental techniques involved with spin, ranging from the production of polarized particle beams to their detection. Results on polarized electrons and positrons are presented in section 3. Similarly, theoretical and experimental results on polarized ions are presented in 4. The production of polarized gamma quanta is described in 5. Lastly, a summary and a discussion of future prospects are found in section 6.

An extensive discussion of the effects relevant to laser-plasma based sources of polarized beams was given by Thomas *et al.* in [13], in which the main effects discussed are spin precession, spin-dependent trajectories and radiative polarization. A schematic overview of the various effects' connections is presented in Figure 1. In the following,



Figure 1. Schematic overview of the relevant effects affecting particle spin in laserplasma interaction. Reproduced under the terms of the CC-BY license from [13]. Copyright 2020, The Authors, published by American Physical Society.

we will detail the most relevant aspects of this discussion.

(i) Spin precession: The Thomas-Bargmann-Michel-Telegdi (T-BMT) equation [14, 15] describes spin precession according to the equation

$$\frac{\mathrm{d}\mathbf{s}}{\mathrm{d}t} = -\mathbf{\Omega} \times \mathbf{s} \;, \tag{1}$$

where

$$\mathbf{\Omega} = \frac{qe}{mc} \left[\Omega_B \mathbf{B} - \Omega_v \left(\frac{\mathbf{v}}{c} \cdot \mathbf{B} \right) \cdot \frac{\mathbf{v}}{c} - \Omega_E \frac{\mathbf{v}}{c} \times \mathbf{E} \right]$$
(2)

is the precession frequency. It depends on the prevalent electromagnetic fields \mathbf{E}, \mathbf{B} and the particle's velocity \mathbf{v} . Further, qe denotes the charge of the particle, m its mass and c is the vacuum speed of light. The prefactors

$$\Omega_B = a + \frac{1}{\gamma} , \qquad \Omega_v = \frac{a\gamma}{\gamma + 1} , \qquad \Omega_E = a + \frac{1}{\gamma + 1} , \qquad (3)$$

depend on the anomalous magnetic moment a and the Lorentz factor γ of the corresponding particle. The anomalous magnetic moment is defined as a = (g-2)/2 via the Landé g-factor. It can be calculated as higher-order loop corrections to the magnetic moment. For the electron it is $a_e \approx \alpha/(2\pi) \approx 10^{-3}$, for protons it is roughly m_p/m_e times larger.

Thomas *et al.* derived scaling laws for the precession frequency of electrons and protons in dependence of the dominant field strength $F = \max(|\mathbf{E}|, |\mathbf{B}|)$. In particular, they found the minimum depolarization time to be

$$T_{D,p} = \frac{\pi}{6.6a_e F} \,. \tag{4}$$

Within the scope of their paper, the minimum depolarization time is defined as the characteristic time at which the maximum angle between the original direction of the particle spin and the final state is on the order of $\pi/2$. As discussed later in more detail, particle beams preserve their polarization degree, as long as all particles are

subject to the same homogeneous field. If locally varying fields like oscillating laser fields are applied, the polarization is quickly lost due to the differences in precession frequency.

(ii) Spin-dependent trajectories: The most well-known example of spin-dependent trajectories is the Stern-Gerlach effect [16], in which particles carrying a magnetic moment μ are subject to a gradient magnetic field. The exerted force in that case is

$$\mathbf{F} = \nabla(\boldsymbol{\mu} \cdot \mathbf{B}) \ . \tag{5}$$

This description can be generalized to

$$\mathbf{F}_{\rm SG} = \left(\nabla - \frac{\mathrm{d}}{\mathrm{d}t} \nabla_{\mathbf{V}}\right) \left(\mathbf{\Omega} \cdot \mathbf{s}\right) \,. \tag{6}$$

For particles in the GeV-range, Thomas *et al.* find the following scaling laws for the maximum particle separation of electrons and protons in terms of the laser wavelength λ_L and the relativistic factor γ :

$$\Delta_e(\partial F = 0) \propto 0.3(2 + 3a\gamma)\lambda_L[\mu \mathrm{m}]^{-1}\gamma^{-1} , \qquad (7)$$

$$\Delta_p(\partial F = 0) \propto 0.3 \left(\frac{m_e}{m}\right)^2 \lambda_L[\mu \mathrm{m}]^{-1} \gamma^{-1} .$$
(8)

These scaling laws assume that the prevalent fields are somewhat homogeneous $(\partial F = 0)$ like it would be the case in plasma channels.

(iii) Radiative polarization: The Sokolov-Ternov effect describes the build-up of polarization due to spin flips during the emission of radiation [17]. As there is a slight difference in the probabilities for a flip from spin-up to spin-down compared to the opposite case, a particle beam can gain net polarization over time. This effect is commonly utilized in storage rings. The polarization of the beam builds up according to

$$P(t) = P_{\rm eq}[1 - \exp(-t/\tau_{\rm pol})], \quad P_{\rm eq} = \frac{P_{\uparrow} - P_{\downarrow}}{P_{\uparrow} + P_{\downarrow}}, \qquad (9)$$

where $P_{\uparrow}, P_{\downarrow}$ denote the different spin-flip probabilities.

The scaling laws for the characteristic polarization time in terms of beam energy and field strength found by Thomas et al. are

$$T_{\rm pol,electron} = \frac{10^{-7} \text{s}}{T_e [\text{GeV}]^2 F [\text{TV/m}]^3} , \qquad (10)$$

$$T_{\rm pol,proton} = \frac{10^{14} \text{s}}{T_p [\text{GeV}]^2 F [\text{TV/m}]^3} .$$

$$(11)$$

In their paper, Thomas *et al.* conclude that for most laser-plasma based accelerators (not including future high-intensity laser facilities), spin precession according to the T-BMT equation is the only effect of concern for polarization preservation, while the Stern-Gerlach force and the Sokolov-Ternov effect can mostly be neglected.

More extensive discussions on radiative spin dynamics have been given by several authors in the framework of QED, like studies on spin-dependent radiation reaction by

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Seipt *et al.* [18]. Geng *et al.* identified a spin-dependent deflection mechanism based on radiation reaction that occurs during laser-electron interaction [19]. The effect is shown to dominate the Stern-Gerlach force for electrons with 100s of MeV and 10 PW-class laser pulses. Over the years, various models describing radiative polarization have been proposed [20–24], which are discussed in more detail in the sections concerning polarized positrons and gamma quanta. A kinetic description for relativistic spin-polarized plasma was derived by Seipt and Thomas in [25]. Therein, QED effects are taken into account via Boltzmann-type collision operators and the approximation of locally constant fields.

The various effects discussed here, in particular the precession according to T-BMT and radiative polarization in the context of QED, have been incorporated into various particle-in-cell (PIC) codes [26, 27]. Moreover, nine-dimensional particle pushers for an accurate description for relativistic particles in strong fields have been proposed, e.g. by Li *et al.* [28].

2. Experimental techniques

In this section, we will cover aspects of targetry and polarimetry, in particular, how polarized targets for laser-plasma interaction may be produced and how the degree of polarization can be measured.

2.1. Targets

For the experimental realization of polarized beam generation from laser-induced plasmas, the choice of the target is the most crucial point. Several concepts can be found in literature, split into (i) pre-polarized targets, where the spins of the particles to be accelerated are already aligned before the acceleration process sets in, and (ii) unpolarized targets, which require a spin-selective ionization or injection during the acceleration process.

2.1.1. Pre-polarized targets The only polarized target that has been used so far for laser-plasma acceleration experimentally employs a jet containing nuclear polarized ³He gas [29]. This rare helium isotope has the advantage that it can be rather easily polarized at room temperature and be stored for many hours in a magnetic holding field (cf. Fig. 2). High degrees of nuclear polarization ($P \sim 40\%$) can be obtained in a gas jet at densities of a few times 10^{19} cm⁻³. The polarization for this and similar targets can be achieved via methods like metastability-exchange optical pumping [30] or spin-exchange optical pumping [31]. Data of an experiment at the PHELIX laser suggest persistence of this polarization after acceleration of the ³He ions to MeV energies [32]. A disadvantage of pre-polarized targets, such as ³He gas, is that a permanent magnetic holding field must be provided around the interaction zone in order to maintain the target polarization. In the case of ³He gas, the field strength requirement is rather low, on the order of a few mT, but great care has to be taken on the homogeneity of the holding field [29]. Such fields can either be provided by permanent-magnet assemblies or by a Helmholtztype coils. These have the disadvantage of requiring cooling (if mounted inside the laser-interaction chamber) but allow the initial ³He polarization to be rotated relative to the laser propagation axis, thus providing maximum flexibility in adjusting the beam polarization.

Gas targets containing high-density spin-polarized hydrogen (SPH) have been proposed for the acceleration of electrons (see Ref. [33, 34] and references therein) as well as proton or deuteron beams (see for example Ref. [35]). The SPH is produced through the photo-dissociation of unpolarized hydrogen halides and contains — dependent on the application — either electrons or protons/deuterons with high degrees of polarization. The principle behind these targets is to first align the molecular bond of diatomic gas molecules in the electric field of a linearly polarized laser pulse. This is followed by the photo-dissociation into molecular states with polarized valence electrons using a second, circularly polarized UV laser pulse. The hyperfine structure of hydrogen atoms then causes the polarization to oscillate from the electron to the proton (deuteron) and backwards, with a period of 0.7 ns. Finally, a third laser pulse drives the acceleration process. The advantage of these targets is that the polarized target material can be resupplied to the interaction zone at high rates, no magnetic holding fields are required and densities close to critical density can be achieved.

While the use of SPH targets seems rather straightforward for proton acceleration [35, 36], the acceleration of polarized electrons would first require the removal of unpolarized electrons from the accelerating plasma which are unavoidably present in the (otherwise unused) halide atoms. Two solutions have been put forward here, either removal via ionization [37] or spatial separation of the SPH from the unwanted photoproducts leaving behind only hydrogen atoms of high polarization (P = 90%) [34]. It remains to be seen which of these approaches will ultimately prove to be more practicable. A schematic detailing the production of polarized electrons from an HCl target is presented in Fig. 3.

According to Ref. [38], hyperpolarized cryogenic foils can be produced after the recombination of nuclear polarized hydrogen atoms from an atomic beam source to hydrogen-deuterium molecules. These could in principle be used as targets for plasma acceleration of polarized proton or deuterium beams. Due to their technically demanding realization [39], it has yet to be shown that this type of target is suitable for laser-plasma applications. A theoretical study of the polarization dynamics in the hydrogen isotope molecules, H_2 , D_2 , and HD can be found in Ref. [40]. It could be shown that in the presence of a static magnetic field the molecular rotation polarization can be transferred and maintained in the nuclear spin, providing highly nuclear-spin-polarized molecules (P > 90%).

Preliminary data from an experiment with metastable hydrogen atoms indicate that large nuclear polarizations can be produced in a so-called Sona transition unit [41]. It remains to be seen whether the technique can also be applied to ground-state atoms or molecules and thus be useful to produce polarized targets for laser-plasma acceleration.



Figure 2. Magnetic holding setup for the acceleration of polarized Helium-3. Reproduced under the terms of the CC-BY license from [29]. Copyright 2022, The Authors, published by MDPI AG.



Figure 3. (a) Potential experimental configuration for LWFA of spin-polarized electrons. (b) Schematic of polarized electron production from an HCl target using multiple lasers for alignment, photo dissociation and ionization. Reproduced under the terms of the CC-BY license from [37]. Copyright 2019, The Authors, published by IOP Publishing Ltd.

2.1.2. Unpolarized targets An unpolarized foil target was used for the first polarization measurement of laser-accelerated particles. The authors of Ref. [42] report on the TNSA acceleration of few-MeV protons from the rear surface of a gold foil. Since no polarization build-up of the protons during the acceleration was observed, it was concluded that prepolarized targets would be needed to produced polarized hadron beams.

In Ref. [43], the use of a gas target containing a mixture of lithium and xenon atoms is proposed. It is predicted that polarized electron beams can be accelerated in a beam-driven plasma wakefield by in-situ injection of polarized electrons from the xenon atoms into the plasma wake generated from the lithium atoms. Similarly, a single-species target consisting of only ytterbium has been proposed [44]. This method requires the targeted ionization of specific orbitals with a circularly polarized laser pulse to achieve polarization.

2.2. Polarimetry

In order to be experimentally accessible, the information about beam polarization has to be converted into measurable quantities. This is generally achieved by sampling the spin projection of a large number of particles in a secondary scattering process that is sensitive to the spin direction. Both the scattering target and the particle detectors are typically combined in a single device, the so-called polarimeter. Such polarimeters are frequently used at conventional particle accelerators to measure beam polarizations or polarization-dependent scattering cross sections. However, at laser-plasma accelerators, particular challenges have to be overcome, such as the time structure of the beams and strong electromagnetic pulses induced by the accelerating laser. This often prohibits the use of sophisticated electronic detectors to resolve individual beam particles. Since the scattering processes in polarimeters crucially depend on the particle species and energy these must be carefully customized for the respective application.

The first polarimeter for laser-accelerated particles was used to measure the polarization of TNSA-accelerated, few-MeV protons at the 100 TW Arcturus laser facility, Düsseldorf [42]. The polarization measurement is based on the spin dependence of elastic proton scattering off nuclei in a silicon target. This scattering process has a non-vanishing analyzing power A_y which is a measure for the asymmetry of the scattered protons' angular distribution along the azimuthal angle for a given transversal beam polarization. Silicon is well suited as scattering target material at proton energies of a few MeV since high precision data for A_y are available from literature. The scattered protons were recorded behind the scattering target with CR-39 detectors for each individual laser shot. The authors of Ref. [42] conclude that polarizations down to $P \sim 20\%$ can be detected for particle bunches with a sufficiently high number of produced protons ($\sim 10^8$ with energies above 2.5 MeV).

A compact polarimeter for ³He ions with special emphasis on the analysis of shortpulsed beams accelerated during laser-plasma interactions is described in Ref. [45]. The polarimeter was tested at a tandem accelerator with unpolarized ³He beams and then used for the analysis of polarized laser-accelerated ions [32]. It is based on the detection of α particles in CR-39 stacks, emitted from the *d*-³He fusion reaction with non-vanishing A_y in a deuterated-polyethylene foil. The polarimeter is especially useful for the analysis of ³He ion beams in the few-MeV range, but also at lower energies down to 0.6 MeV. The accuracy of a beam polarization measurement, i.e., the minimal detectable ³He beam polarization, is estimated to be 21% for a typical laser-plasma experiment where roughly 10⁹ ³He ions enter the polarimeter.

An electron polarimeter for the LEAP project is being prepared at DESY, Hamburg [46]. For their expected electron beam energies of tens of MeV, Compton transmission polarimetry is the ideal method to measure the polarization. γ photons produced by bremsstrahlung are transmitted through an iron absorber magnetized by a surrounding solenoid, with rate and energy spectra depending on the relative orientation of the photon spin and the magnetization direction. The transmission asymmetry with

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respect to the magnetization direction is proportional to the initial electron polarization. Calibration measurements with unpolarized beams are in progress. At higher electron energies (100 MeV and above), the asymmetries for Compton transmission polarimetry decrease and this method becomes impractical. Mott-, Møller- or laser-Compton-polarimetry must be used instead, however, such polarimeters have not yet been developed for laser-plasma applications.

3. Polarized electrons and positrons

Within this section, we transition to the results obtained in – up to now – only theoretical studies of the acceleration of polarized lepton beams. Most of the results for electrons are concerned with wakefield acceleration. As mentioned in the previous section, most of the following setups are based on pre-polarized targets, and only a few make use of "single-step" schemes to polarize and directly accelerate the particles.

3.1. Electrons

A first investigation of polarized electron beams in wakefield acceleration was conducted by Vieira *et al.* in [47]. They showed that lower depolarization is observed for the highenergy stages of the accelerator. Analytical expressions for the depolarization of zeroemittance beams were derived. Further, it was shown that externally guided propagation is beneficial to polarization in comparison with self-guiding. The models are in good agreement with PIC simulations.

Further studies on spin precession in wakefields were performed by Pugacheva *et al.* in [48]. It was shown that the minimal depolarization occurs for electrons that are injected close to the maximum of the accelerating force with the wake's phase velocity. In a follow-up publication [49], the effects of synchrotron radiation on spin dynamics was discussed.

Wu *et al.* and Wen *et al.* extensively investigated the acceleration of polarized electrons in laser-driven wakefields (LWFA) by 3D-PIC simulations in [37, 50] for the first time. The simulations of Wu base their investigation on an HCl target in a density regime of 10^{18} cm⁻³. It was shown that for conventional Gaussian laser pulses, the strong azimuthal magnetic field in the induced wake structure is detrimental to the beam polarization. The results could be improved by utilizing Laguerre-Gaussian modes, which exhibit significantly weaker azimuthal fields during injection, leading to approx. 80% polarization. It was further concluded that the most significant changes in beam polarization occur during injection, while acceleration in regimes where $\gamma \gg 1$ only contributes marginally, since the spin precession according to the T-BMT equation is dependent on the Lorentz factor. In a separate publication, Wu *et al.* have investigated the azimuthal dependence of beam polarization in a wakefield and propose the use of an x-shaped slit as a means of improving the polarization degree [51]. The simulations indicate that beam polarization may be increased significantly (in their specific case

from 35% to approx. 80%) with this mechanism.

The influence of bubble geometry on spin dynamics was investigated by Fan *et al.* [52]. Spherical bubbles are shown to preserve polarization better than aspherical ones, where the net polarization direction can even reverse for oblate bubble shapes.

Yin *et al.* further investigated self-injection for LWFA in [53]. In particular, it is found that for longitudinal self-injection, that the electrons move around the laser axis and the net influence of the laser pulse as well as the contribution of the wakefield can be ignored. Accordingly, ultra-short electron beams with 99% polarization can be generated using longitudinal injection.

An alternative means of injection has been discussed in the form of colliding-pulse injection. Gong *et al.* proposed that the driving laser pulse collides with a weaker laser pulse, which leads to a heat-up of electrons in the region of their interaction [54]. Due to this heating, electrons can be injected into the wake. The mechanism is examined for the polarized HCl target at 10^{18} cm⁻³. In [55], the driving pulse is fixed at $a_0 = 2.5$ and $w_0 = 20 \ \mu$ m. The intensity and focal spot size of the laser pulse are varied, examining the influence on beam charge and polarization. It is found that similar spot size between driving and colliding pulse, as well as higher pulse intensity lead to an increase in charge, however at the cost of polarization (cmp. Fig. 4). Electron beams with 80% polarization with tens of pC can be generated using 10 TW-class laser systems; beams in excess of 90% polarization are achievable for lower charge.

Sun *et al.* proposed a dual-wake injection scheme [56], in which a tightly focused, radially polarized laser pulses propagates through a plasma with an abrupt density jump. This mechanism can be used to drive dual wakes in the quasi-blowout regime and produces electron beams as short as 500 attoseconds with a polarization exceeding 80%.

The case of beam-driven wakefields was first discussed by Wu *et al.* in [57]. Therein, the influence of driving beam parameters on the witness are studied. Analytical scaling laws for beam polarization in dependence of the peak current are derived, which show that polarization decreases for increases flux. Up to 7.5 kA of electrons with 80% polarization are obtained from simulations, which is comparable to their LWFA results with respect to the polarization degree.

The aforementioned studies for laser- and beam-driven wakefields generally assume a pre-polarized target, meaning that target preparation and acceleration is a two-step process. Nie *et al.*, however, proposed methods to achieve polarized electron beams *insitu* [43]. The electrons are injected into the wakefield and simultaneously polarized via the ionization of the outermost p orbital of the utilized noble gas. In the publication, a target consisting of lithium and xenon is used. An electron drive beam ionizes only the lithium and generates the wakefield. A circularly polarized laser pulse is then used to strong-field ionize the $5p^6$ electron of the xenon atoms. These electrons are spinpolarized and can be accelerated to approx. 2.7 GeV in 11 cm. A net polarization of about 31% is achieved with this setup. In a subsequent publication, Nie *et al.* investigate the potential of single-species (ytterbium) plasma photocathodes for polarized beams



Figure 4. Dependence of beam charge and polarization degree, as well as emittance and peak current, on parameters of the colliding laser pulse. The driving laser pulse is fixed to $a_0 = 2.5$ and $w_0 = 20 \ \mu\text{m}$. Reproduced under the terms of the CC-BY license from [55]. Copyright 2023, The Authors, published by American Physical Society.

[44]. Here, the electron beam predominantly ionizes the outer 6s electrons and drives the wakefield. A CP laser pulse is then used to inject the $4f^{14}$ electrons which is shown to deliver 56% net polarization with 15 GeV in 41 cm. The setup is shown in Figure 5.

Beyond the concept of wakefield acceleration from pre- or unpolarized targets in the setting of classical physics, other studies have focused on the radiative polarization dynamics of electrons in intense electromagnetic fields, like Tang *et al.* [23]. Seipt *et al.* proposed the polarization of high-energy electron beams using pulsed bi-chromatic laser fields [18]. As a potential application, Gong *et al.* showed that initially unpolarized targets of near-critical density can be used as a diagnostic tool for transient magnetic fields [11]. Similarly, the radiative polarization of electrons during current filamentation instability offers a novel pathway to study astrophysical plasma [12]. Further references on radiative polarization can be found in the introductory part of this review as well as the section concerning polarized gamma quanta.

3.2. Positrons

The work on polarized positron beams is currently divided between the production and the acceleration of these beams. In contrast to electrons, no pre-polarized targets of positrons can be produced, therefore production via processes like Breit-Wheeler pair



Figure 5. The single-species photocathode scheme for polarized electrons. (a), (b) show the plasma and beam density around the laser focus and after driver pinching, respectively. (c), (d) show the Yb ion density at the corresponding time steps. Reproduced under the terms of the CC-BY license from [44]. Copyright 2022, The Authors, published by American Physical Society.

creation is necessary.

Chen *et al.* proposed the use of two-color laser pulses for the generation of polarized positron beams [58]. It is shown that the spin asymmetry in strong external fields together with the asymmetric two-color laser field leads to the creation of beams with up to 60% polarization.

An alternative method is described by Li *et al.*: when a high-intensity CP laser pulses interacts with a longitudinally polarized, relativistic electron beam, a highly polarized positron beam can be created via the non-linear Breit-Wheeler process [59]. The polarization is transferred from the electrons to the positrons by high-energy photons. The method is shown to produce positron beams with 40%-60% polarization and low angular divergence on a femtosecond time scale.

Liu *et al.* found the polarization of intermediate gamma quanta to be of significance for the polarization of electron-positron pairs produced in the non-linear Breit-Wheeler process [60]. The setup is shown in Fig. 6. They find that an average polarization of 30% can be obtained, which is then accelerated in a wakefield driven by a hollow electron beam without significant depolarization.

A method utilizing laser-solid interaction has been proposed by Xue *et al.* [61]. A high-intensity laser pulse is used to ionize a solid foil. The accelerated electrons are accelerated and generate gamma quanta via non-linear Compton scattering which decay into polarized positrons in a quasi-static magnetic field. The angle of irradiation is found



Figure 6. (a) The hollow driver and an electron seed beam propagate in z-direction. (b) The driver beam generates the wakefield structure, and the seed is irradiated by a two-color laser pulse in order to produce positrons. (c) The polarized positrons are then trapped and accelerated in the wakefield. Reproduced under the terms of the CC-BY license from [60]. Copyright 2022, The Authors, published by American Physical Society.

to determine the configuration of the quasi-static field, which in turn, allows tuning of the polarization degree. The scheme delivers polarization on a 70%-level with 0.1 nC per shot. Zhao *et al.* investigated cascaded Compton scattering and Breit-Wheeler pair production on a more general level with respect to polarization transfer in [62].

4. Polarized ions

While single-step methods of polarization and acceleration have been proposed for polarized electron beams, no such options are currently known for ion beams. This means in particular that any theoretical research on ions has considered maintaining a high degree of spin polarization from initially polarized targets. In this section, we describe the progress on polarized ion beams from laser-plasma interaction.

A first experimental study by Raab *et al.* showed that no net polarization is obtained during laser-solid interaction [42]. The first proof-of-principle experiment on laser-based acceleration of polarized ³He was realized by Zheng *et al.* at the PHELIX facility in GSI Darmstadt [32]. The experiment was conducted with a 50 J laser pulse and a duration of 2.2 ps. The laser parameters were found to be optimal in a preceding simulation study by Engin *et al.* for the helium target [63]. The ³He target has a density of 10^{19} cm⁻³ and is extensively described in [29]. Due to the density and length of the target, the ions were mostly expelled in the direction transverse to laser propagation and reached energies of several MeV. Further simulations by Gibbon *et al.* indicated that shortening the interaction length could increase the amount of ions being accelerated in forward direction [64].

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In the following, several theoretical results on ion acceleration for both current and near-future laser parameters are discussed. As the preparation of solid-state based, pre-polarized targets is difficult, the theoretical results mostly consider targets with near-critical density.

4.1. Magnetic Vortex Acceleration

Due to the restrictive target parameters currently available for polarized ion sources, Magnetic Vortex Acceleration (MVA) is one of the few feasible acceleration mechanisms. The process was first described by Bulanov *et al.* in [65] without considering spin polarization. A more detailed analysis of the MVA process can be found in the work by Park *et al.* [66].

In the context of polarized protons, MVA was first investigated by Jin *et al.* in [35] by means of particle-in-cell simulations. They investigated the interaction of a multi-PW laser pulse in the range $a_0 = 25 - 100$ with a pre-polarized HCl target. The target has an electron density of $0.36n_{\rm crit}$ and is has a flat-top profile with steep edges. In the case of $a_0 = 25$, 0.26 nC of protons with up to 53 MeV and a polarization of 82% were observed. An increase in laser energy was shown to reduce the polarization: for a laser pulse with $a_0 = 100$, 3.1 nC were accelerated to 152 MeV, however with a lower polarization of only 56%.

A publication by Reichwein *et al.* studied the effect of density-down ramps at the end of the target on the final beam quality [67]. The same HCl target was used, however with different lengths of down-ramps in the range of 0-80 μ m. The polarization of the final proton beam was shown to remain largely robust against changes of the ramp length. Longer ramps mostly affected the spatial focusing of the beam as the transverse extent of the plasma channel and, in turn, the induced fields are changed. Ramps of significant length can, however, lead to reduced beam polarization, since a longer ramp changes the focusing of protons into the beam, introducing also particles of different spin orientation.

Since the ions in MVA interact with the strong laser and plasma channel fields directly, the degree of beam polarization is strongly limited by the intensity of the laser pulse. In agreement with the theoretical scaling laws of Thomas *et al.* [13], higher intensities lead to higher beam energy but at the cost of reduced polarization. Thus, in [68] a dual-pulse MVA setup was introduced to mitigate these effects. Two laser pulses with a carrier envelope phase difference of π propagate through the target side-by-side with some transverse displacement. Both of the pulses induce their own MVA process, i.e. two plasma channels will be formed.

In the space between the two plasma channels, an accelerating region with weaker depolarizing fields is formed (cmp. current density in Fig. 7). This leads to the formation of a central filament which obtains energies similar to the comparable singlepulse MVA setup, but with higher polarization. In [68], polarization of 77% was obtained for two pulses with $a_0 = 100$, while a single-pulse setup of the same total laser energy



Figure 7. Transverse cut of the current density profile of the dual-pulse MVA scheme. Note the two distinct plasma channels with an accelerating region in their middle. Reproduced under the terms of the CC-BY license from [68]. Copyright 2022, The Authors, published by American Physical Society.

only led to 64%. The dual-pulse scheme was also shown to improve on the angular spectrum of the accelerated beam, as instabilities were mitigated by the presence of the second laser pulse.

4.2. Collisionless Shock Acceleration

In MVA, the polarization of the ion beam decreases since the oscillating laser fields directly interacting with the ions. This is different in Collisionless Shock Acceleration (CSA), where a more homogeneous field is used to accelerate the ions. In the context of polarized ion beams, multiple setups utilizing a solid foil in front of the near-critical density polarized target were proposed. When the laser pulse irradiates the solid foil, it heats up the electrons and induces a shock wave with rather homogeneous electric field. The gaseous component can then be reflected by the shock wave and accelerated to high energies. The general mechanism of CSA is detailed, e.g., in [69].

In [70], Yan and Ji first suggested the use of CSA for polarized proton beams. Their setup consisted of a laser pulse of $a_0 = 20 - 80$ irradiating a 2 μ m Carbon foil which is placed in front of a near-critical, polarized HCl target. Proton beams with tens of MeV and a polarization on a 90%-level were obtained. A subsequent study by Yan *et al.* investigated the use of a microstructured foil [71], where the structures were utilized to increase the temperature and the number of hot electrons. Accordingly, the energy of the reflected protons was increased.

The aforementioned studies have been extended by Reichwein *et al.* to the case of polarized ³He and to higher laser intensities [72]. A schematic of the setup is shown in Fig. 8. Similarly to the results with protons, high polarization is achieved with CSA. In



Figure 8. Schematic of the setup for Collisionless Shock Acceleration. A solid Carbon foil is placed in front of the near-critical density, polarized Helium-3 target. Reproduced under the terms of the CC-BY license from [72]. Copyright 2024, The Authors, published by IOP Publishing Ltd.

particular, the degree polarization remains in the range of 90% for intensities of $a_0 = 100-200$. Moreover, the publication investigated the influence of radiation reaction on the acceleration process. As the electrons radiate part of their energy, the electromagnetic field structure of the system and, subsequently, the ion motion is changed. This leads to a reduction in energy, but an increase in beam charge, since more Helium ions can be trapped inside the accelerating field. The polarization remains largely unaffected by radiation reaction.

An alternative pathway to CSA was suggested by Yan *et al.* in [73], where no additional foil is necessary to drive CSA. A CO₂ laser with a wavelength of 10 μ m was used, which gives a critical plasma density comparable to the density achieved in prepolarized targets created by photo-dissociation. This allows a laser pulse in the intensity range of $10^{17} - 10^{18}$ W/cm² to be used. The shock front is created by the long laser pulse (3 ps) that piles up protons. A spectral peak energy of approximately 2 MeV was found, with a cut-off energy of about 7 MeV. The polarization remained > 80% in a large parameter range.

4.3. Other mechanisms

Hützen *et al.* also considered the acceleration of ions using a bubble-channel structure for multi-PW laser systems [74]. The acceleration scheme is based on work by Shen *et al.* [75]. Both HCl and HT plasma with a densities in the range of 10^{19} - 10^{21} cm⁻³ and a length of 600 μ m are considered. The plasma is irradiated by a high-intensity laser pulse of up to $a_0 = 223$, leading to the formation of a wide plasma channel. At the leading edge of this channel structure, polarized particles are piled up and accelerated to energies in the multi-GeV range. The investigation of this mechanism was extended by Li *et al.* in [76]. Here the protons are pre-accelerated by a CP laser pulse, and subsequently trapped and further accelerated in the front region of a wakefield bubble. The ratio of hydrogen and tritium is found to be crucial for the efficiency of the acceleration. If chosen correctly, a polarized proton beam can be accelerated up to GeV-level in the



Figure 9. Proton spin polarization for the pure Hydrogen foil (a)-(b), as well as the Aluminium-Hydrogen composite target (c)-(d). Reproduced under the terms of the CC-BY license from [36]. Copyright 2019, The Authors, published by Cambridge University Press.

wakefield structure.

The acceleration of polarized ions from hypothetical, overdense targets was considered by Hützen *et al.* in [36]. Two sets of PIC simulations were carried out: at first a fully polarized Hydrogen layer of 1 μ m thickness and $128n_{\rm crit}$ density was considered (see Fig. 9). The second set of simulations considered a 2.5 μ m aluminium layer at $35n_{\rm crit}$ with a shorter polarized proton layer with 0.5 μ m thickness. The dominant acceleration mechanism in both setups was found to be Target Normal Sheath Acceleration (TNSA). In the former case, preservation of proton polarization for up to 0.24 ps was observed, while for the latter case it was found to be preserved for 0.18 ps seconds.

5. Polarized gamma quanta

In this section, we discuss the generation of polarized gamma-ray photons in the interaction between a high-intensity laser pulse and plasmas (or charged particle beams). The interest in studying polarized gamma-ray photons driven by high-intensity lasers is motivated by the fact that both the practical application of the polarized gamma-ray photons have practical applications including nuclear physics [77], high-energy physics [78, 79],

and astrophysics [80, 81]. Moreover, the photon polarization can carry the additional degree of freedom of information to help retrieve the in-situ electron dynamics in the ultrarelativistic laser or beam driven plasmas [82].

5.1. Polarized Multi-GeV gamma-photon beams via Single-Shot Laser-Electron Interaction

Recently, by considering the photon polarization effect, Li et al. [83] investigated the generation of circularly polarized (CP) and linearly polarized (LP) γ -rays via the interaction of an ultraintense laser pulse with a spin-polarized counter-propagating ultrarelativistic electron beam. Pre-polarized energetic electrons collide with the laser pulse to experience nonlinear Compton scattering in the quantum radiation-dominated regime as shown in Fig. 10, where a GeV pre-polarized electron beam is set to collide with a counter-propagating laser pulse with a relativistic intensity. The study develops a Monte Carlo method based on the locally constant field approximation (LCFA) that employs electron-spin-resolved probabilities for polarized photon emissions. Li et al. [83] show efficient ways for the transfer of electron polarization to high-energy photon polarization. The results demonstrate that multi-GeV CP (LP) γ -rays with polarization of up to about 95% can be generated by a longitudinally (transversely) spin-polarized electron beam, with a photon flux meeting the requirements of recent proposals for the vacuum birefringence measurement in ultra-strong laser fields. The high-energy, high-brilliance, and high-polarization γ -rays generated in this process are also beneficial for other applications in high-energy particle physics, light sources, and laboratory astrophysics. Recently, using the quantum operator method by Baier and Katkov to calculate the polarization-resolved probabilities within the quasi-classical approach and LCFA, Chen *et al.* [84] presented a detailed derivation of fully polarizationresolved probabilities for high-energy photon emission and e^-e^+ pair production in ultra-strong laser fields. These probabilities, accounting for both electron spin and photon polarization of incoming and outgoing particles, are crucial for the development of QED Monte Carlo simulations and QED-particle-in-cell codes.

In subsequent studies, Wan *et al.* [85] investigated the interaction between an unpolarized 10 GeV electron beam and a counter-propagating linearly polarized laser pulse (with a peak intensity $a_0 \approx 50$ and pulse duration $\tau \approx 50$ fs) using the same semiclassical Monte Carlo approach. They found that high-energy, linearly polarized γ ray photons are generated during the interaction through nonlinear Compton scattering, with an average polarization degree exceeding 50%. These photons further interact with the laser fields, leading to electron-positron pair production via the nonlinear Breit-Wheeler process. Photon polarization is found to enhance the pair production yield by over 10%. To understand the influence of photon polarization on pair production, Dai *et al.* [86] using fully polarization-resolved Monte Carlo simulations to examined the correlation between photon and electron (positron) polarization in the multiphoton Breit-Wheeler process, where a 10 GeV electron beam is set to collide with a counter-



Figure 10. Scenarios of generating CP and LP γ -rays via nonlinear Compton scattering. (a) An arbitrarily polarized (AP) laser pulse propagating along +z direction and head-on colliding with a longitudinally spin-polarized electron bunch produces CP γ -rays rays. (b) An elliptically polarized laser pulse propagating along +z direction and colliding with a transversely spin-polarized (TSP) electron bunch produces LP γ -rays. The major axis of the polarization ellipse is along the x axis. Reproduced with permission from [83]. Copyright 2020, American Physical Society.



Figure 11. Scenario for the generation of LP γ -ray photons via nonlinear Compton scattering. An ultra-strong LP laser pulse, polarized along the *y*-axis and propagating along the *x*-direction, irradiates a near-critical density hydrogen plasma followed by an ultra-thin Al foil. Reproduced under the terms of the CC-BY license from [87]. Copyright 2020, The Authors, published by AIP Publishing.

propagating elliptically polarized laser pulse with a peak intensity $a_0 = 100$, pulse duration $\tau \approx 27$ fs, and the ellipticity $\epsilon = 0.03$. They found that the polarization of produced e^-e^+ is reduced by 35% and the pair yield is decreased by 13% if the intermediate photon polarization is taken into account.

5.2. Polarized high-energy brilliant gamma-ray sources via laser-plasma interaction

It is worth emphasizing that the numerical study of polarized γ -ray photons via singleshot laser-electron interaction is based on a test particle simulation [83–86]. This means that collective effects of charged particles, such as self-generated electric and magnetic fields, are not taken into account. Recently, Xue et al. [87] studied about the generation of highly-polarized high-energy brilliant γ -rays via laser-plasma interaction, where plasma collective effects are self-consistently considered by implementing the electron-spin-resolved probabilities for polarized photon emission in PIC simulations. By utilizing PIC simulations, Xue et al. [87] show that when an ultraintense LP laser pulse irradiates a near-critical-density (NCD) plasma target followed by an ultra-thin aluminum (Al) foil, the electrons in the NCD plasma are first accelerated by the driving laser via direct laser acceleration to ultrarelativistic energies and then collide with the light pulse reflected by the Al foil. The PIC simulations of this all-optical scheme show that brilliant LP γ -ray photons are produced via nonlinear Compton backscattering with photon energy up to hundreds of MeV and an average LP polarization degree of $\sim 70\%$. This high LP polarization degree is reasonable since the driving laser pulse is a fully polarized light with a LP degree of 100%. Alternatively, instead of using the double layer target in Fig. 11 to generate γ -ray photons via nonlinear Compton backscattering, Xue et al. [87] also calculate photon emission by considering a conical gold target filled with an NCD hydrogen plasma. When the ultraintense LP light impinges the NCD target inside the Au cone, the bulk plasma electrons are pushed forward and the consequent current density sustains a strong quasi-static self-generated magnetic field. For the forward moving electrons, the self-generated magnetic field provides a restoring force to enable electrons' betatron oscillation inside guided plasma channel in the conical Au target, in which emitted γ -ray photons concentrate in the angular region $\theta < 20^{\circ}$, and the cutoff energy exceeds 450 MeV. In this scheme, the LP degree can reach $\sim 50\%$ for the energetic part of emitted photons.

By employing the similar scheme of the combination of laser wakefield acceleration and plasma mirror as shown in Fig. 12, Wang *et al.* [88] found that a brilliant CP γ -ray beam could be generated in a weakly nonlinear Compton scattering regime with moderate laser intensities of $a_0 \approx 3$, where the helicity of the driving laser pulse is transferred to the emitted γ -photons. The authors claimed that the calculated average polarization degree of γ -photons reaches $\sim 61\%(20\%)$ with a peak brilliance of $\gtrsim 10^{21}$ photons/(s· mm²· mrad²· 0.1% BW) around 1 MeV (100 MeV) [88]. Besides, Wang *et al.* also investigated the transfer mechanism of spin angular momentum during the transition from linear to nonlinear processes [89]. Their findings suggest that to achieve high-energy, high-brilliance, and high-polarization gamma rays, increasing the laser intensity is crucial for an initially spin-polarized electron beam. However, for an initially unpolarized electron beam, it is also necessary to increase the electron beam's energy, in addition to boosting laser intensity.



Figure 12. Schematic for all-optical generation of brilliant CP γ -ray beam via singleshot laser plasma interaction by combining a plasma mirror and an electron beam produced from wakefield acceleration. Reprinted with permission from [88]. Copyright 2022, Optica Publishing Group.

5.3. Application: deciphering in situ electron dynamics of ultrarelativistic plasma

From Li *et al.* [83] and Xue *et al.* [87], one can find that γ -ray photons with high LP degree of $P_{\rm LP} > 70\%$ can be produced via nonlinear Compton backscattering. These highly polarized γ -ray photons have various applications in laboratory astrophysics and high-energy physics. On the other side, the new degree of freedom of information provided by photon polarization indicates that the γ -photon polarization could be a useful tool to retrieve the in-situ transient dynamics of plasma electrons. The successful decoding of field properties nearby the event horizon of black holes [90] has re-stimulated the interest in measurements based on photon polarization [91]. While polarized light is vulnerable to magneto-optic disturbance [92], the high-frequency γ -photon is robust during penetration of the plasma depth [93]. Previously, the celestial γ -ray emission was observed to understand the star-forming galaxies [94], accretion flows around black holes [95], and active galactic nuclei [96]. In contrast to the routinely detected quantities of arrival time, direction, and energy, the γ -photon polarization (GPP), provides new insights on the relativistic jet geometry [97] and magnetic field configuration [98], which allows to identify the cosmic neutrino scattering [99], dark matter annihilation [81], and acceleration mechanisms surrounding crab pulsars [100]. All these progresses appeal to a laboratory platform to simulate and examine the GPP associated with the plasma phenomena.

Recently, Gong *et al.* [82] found that the angular pattern of γ -photon linear polarization is explicitly correlated with the dynamics of the radiating electrons, which provides information on the laser-plasma interaction regime. Using 3D-PIC simulations, Gong *et al.* [82] studied the polarization-resolved γ -photon emission in plasma driven by a circularly polarized laser pulse [see Fig. 13]. The simulation results showed that the collective orientation of the γ -photons' LP resembles a spiral shape with the rotation tendency determined by the acceleration status of the radiating electrons. To characterize the degree of rotation tendency, Gong *et al.* introduced the spiral tendency $\delta\phi$, as the deviation of the orientation of γ -photon LP with respect to the azimuthal direction.



Figure 13. The schematic for γ -ray photon emissions from a plasma interacting with a laser pulse. (b) The LP orientation is along the local azimuthal direction. The analytically predicted LP orientation for the electron undergoing acceleration (c) and deceleration (d). The simulated γ -photon LP for the time at (e) t = 10 and (f) 40 fs, with the LP degree $P_{\rm LP}$ and the normalized number distribution $d^2N_{ph}/\sin\theta d\theta d\phi$. (g) The time evolution of the electron energy spectrum $dN_e/d\varepsilon_e$, the polarization orientation $\delta\phi$, and the kinetic energy ε_e . Reproduced under the terms of the CC-BY license from [82]. Copyright 2022, The Authors, published by American Physical Society.

In the moderate QED regime $\chi_e < 1$, the direction of the emitted γ -photon LP is primarily parallel to the acceleration direction perpendicular to the electron momentum, $\mathbf{a}_{\perp} \equiv \mathbf{a} - (\mathbf{a} \cdot \hat{\mathbf{v}})\hat{\mathbf{v}}$, where the hat symbol denotes the unit vector. Thus, the polarization orientation is derived as $\hat{a}_{\perp,y} \approx -\sin\phi \left(\frac{\Gamma}{\epsilon\gamma_e} + \frac{\kappa_b\cos\theta}{\epsilon\Gamma}\right) - \frac{(-\beta \cdot \mathbf{E})\cos\phi}{\gamma_e}$ and $\hat{a}_{\perp,z} \approx \cos\phi \left(\frac{\epsilon\Gamma}{\gamma_e} + \frac{\epsilon\kappa_b\cos\theta}{\Gamma}\right) - \frac{(-\beta \cdot \mathbf{E})\sin\phi}{\gamma_e}$, where $\beta = \mathbf{v}/c$, $\theta = \arctan[(p_y^2 + p_z^2)^{1/2}/p_x]$ and $\phi = \arctan(p_z, p_y)$. When the electron energy gain is negligible, i.e. $-\beta \cdot \mathbf{E} = 0$, the orientation of the γ -photon LP is along the azimuthal direction $\hat{\mathbf{a}}_a = (-\sin\phi, \cos\phi)^{\intercal}$, which collectively resembles multiple concentric rings with each polarization segment along the azimuthal direction [see Fig. 13(b)]. The deviation of the γ -photon LP orientation from the azimuthal direction is quantified by $\delta\phi \in [-90^\circ, 90^\circ]$, which is the relative angle between $\hat{\mathbf{a}}_{\perp}$ and $\hat{\mathbf{a}}_a$ and is calculated as

$$\delta\phi \approx \arcsin\left\{\frac{-\boldsymbol{\beta}\cdot\mathbf{E}}{\sqrt{\left[\Gamma + \left(\gamma_e\kappa_b\cos\theta/\Gamma\right)\right]^2 + (\boldsymbol{\beta}\cdot\mathbf{E})^2}}\right\}.$$
(12)

If the radiating electron is undergoing acceleration with $-\boldsymbol{\beta} \cdot \mathbf{E} > 0$ $(-\boldsymbol{\beta} \cdot \mathbf{E} < 0)$, the GPP orientation $\delta \phi > 0$ $(\delta \phi < 0)$ corresponds to the counter-clockwise (clockwise) spiral tendency in the angular distribution of γ -photon LP as shown in Fig. 13(c) [Fig. 13(d)]. The 3D-PIC simulation results of the orientation of the emitted γ -photon LP exhibit a counter-clockwise spiral tendency at t = 10 fs [Fig. 13(e)] reproducing well the analytical prediction for the accelerating electron. Here, the averaged polarization angle is $\delta \phi \approx 30.6^{\circ}$ and the LP degree $P_{\text{LP}} \approx 15.3\%$. The clockwise spiral tendency

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in Fig. 13(f) implies the deceleration of plasma electrons occurring later at t = 40 fs. The time-resolved $\delta \phi$ explicitly reflects the electrons being predominantly accelerated (decelerated) at $t \leq t_s^{\varepsilon_e}$ ($t \geq t_s^{\varepsilon_e}$) [see Fig. 13(g)], where $t_s^{\varepsilon_e} \sim 35$ fs is the electron energy saturation time. The correlation between the spiral tendency of photon LP $\delta \phi$ and electron in-situ dynamics demonstrates that the retrieving method of utilizing the information of photon polarization might be beneficial for better understanding of phenomena in broad high-intensity interaction scenarios including ion acceleration, direct laser acceleration, high-harmonic generation, brilliant photon emission, ultradense nanopinches, and e^-e^+ pair plasma cascades.

5.4. Application: exploring electron slingshot acceleration in relativistic preturbulent shocks

As a versatile information carrier of multi-messenger astrophysics [101–103], photon polarization is critical for measuring the magnetic configuration nearby black holes [104] and crab nebulae [105], and for analyzing the particle acceleration in the blazar's jet [106]. Recent studies about relativistic collisionless shocks (RCSs) have attracted great attention since RCSs could instigate electron stochastic acceleration, akin to the Fermi process [107, 108], which has been well recognized as sources of energetic electrons in the universe. Therefore, the question arises whether the polarization feature of spontaneously emitted photons can be employed to reveal some new acceleration mechanisms in a RCS.

In a latest study, Gong *et al.* [109] found that photon polarization information can be utilized to explore the new mechanism of electron slingshot acceleration in counterstreaming plasma. They focused on the transient electron dynamics in the transition to turbulence nearby the counter-streaming interface of an unmagnetized pair-loaded relativistic collisionless shock precursor, which is potentially associated with the outflow of GRBs.

Gong *et al.* [109] carried out 2D simulations of counter-streaming RCSs, see Fig. 14. The snapshot of the electron density n_e in Fig. 14(a) exhibits that the filamentation exclusively exists at the front of the RCS interface. Between two adjacent filaments, an electron focusing point emerges, and following that, two oblique density strips stretch out [see Fig. 14(b)]. Behind the strips, the coherent filaments and focusing points disappear while the turbulence shows up. It has to be highlighted that the photons with energy $\varepsilon_{ph} \equiv \hbar \omega_{ph} > 10^{-2} \hbar \omega_{ph}^m$ are primarily emitted by electrons nearby the interface, where $\omega_{ph}^m \sim 10^8 \omega_{pe}$ is the photon cut-off frequency and \hbar Planck's constant. The degree of photon's linear polarization along the direction of the electron's transverse acceleration is characterized by the Stokes parameter Q [110], formulated as

$$Q = \frac{\varepsilon_e(\varepsilon_e - \varepsilon_{ph})K_{\frac{2}{3}}(\zeta)}{[\varepsilon_e^2 + (\varepsilon_e - \varepsilon_{ph})^2]K_{\frac{2}{3}}(\zeta) - \varepsilon_e(\varepsilon_e - \varepsilon_{ph})\tilde{K}_{\frac{1}{3}}(\zeta)},\tag{13}$$

where $K_n(\zeta)$ is the modified secondary Bessel function, $\widetilde{K}_{1/3}(\zeta) = \int_{\zeta}^{\infty} K_{1/3}(z) dz$, $\zeta = 2\varepsilon_{ph}/[3\chi_e(\varepsilon_e - \varepsilon_{ph})]$, and $\varepsilon_e = \gamma_e m_e c^2$ the electron energy; $\chi_e \equiv (e\hbar/m_e^3 c^4)|F_{\mu\nu}p^{\nu}|$ is



Figure 14. The dynamics of a counter-streaming plasma interface: The electron density n_e at $t = 80\pi/\omega_{pe}$ for the case with ion fraction of (a) $\eta = 0.4$ and (b) $\eta = 0.01$, where lines present the typical electron moving tendency with stars marking the photon emission and the histograms display the spatial distribution of emitted photons with $\omega_{ph} > 10^{-2}\omega_{ph}^{m}$. (c) Photon LP degree $\langle Q \rangle$ and energy spectra $\omega_{ph}dN_{ph}/d\omega_{ph}$ vs ω_{ph} . (d) $\langle Q \rangle$ and $dN_{ph}/d\theta_{ph}$ vs θ_{ph} . Reproduced under the terms of the CC-BY license from [109]. Copyright 2023, The Authors, published by American Physical Society.

the electron quantum strong-field parameter with the field tensor $F_{\mu\nu}$, and the electron four-momentum p^{ν} . At $\chi_e \ll 0.1$, $\partial \mathcal{Q}/\partial \varepsilon_{ph} > 0$ predicted by Eq. (13) manifests a monotonic dependence of \mathcal{Q} on ω_{ph} , because for the higher-frequency radiation the formation length is shorter and the preservation of the local polarization degree is improved. This monotonic dependence is confirmed by the results of $\eta = 0.01$ [see Fig. 14(c)(d)], where electrons experience stochastic acceleration and the photon emission is isotropic in the angular space. However, for $\eta = 0.4$ [see Fig. 14(c)(d)], the averaged polarization degree $\langle \mathcal{Q} \rangle$ versus ω_{ph} exhibits non-monotonic dependence, with a polarization dip $\Delta \mathcal{Q}_{\omega} \approx 4.5\%$ and a bandwidth ratio $\mathcal{B}_{\omega} \equiv \omega_{ph}^m / \omega_{ph}^* \sim 10^3$, contradictory to the aforementioned monotonic dependence. Here, ω_{ph}^* is the local maximum point of the function $\langle \mathcal{Q} \rangle$ vs ω_{ph} [see Fig. 14(c)]. Utilizing the correlation between the work contribution and the non-monotonic dependence of photon polarization, *Gong et al.* [109] identified the mechanism of electron slingshot acceleration.

5.5. Vortex gamma-ray photons

Vortex gamma-ray photons are high-energy photons that carry intrinsic orbital angular momentum (OAM) in addition to their intrinsic spin angular momentum [111–115]. Characterized by a helical wavefront structure, these photons exhibit a quantized twist, allowing them to have unique properties that differ from ordinary gamma rays. Vortex photons have been successfully generated across the visible to X-ray range using techniques such as optical mode conversion, high harmonic generation, and coherent radiation from helical undulators or laser facilities [116–119]. As the new degree of freedom of information is carried by the vortex state, vortex gamma-ray photons have broad applications in various fields, including astrophysics, strong-laser physics, particle physics, and nuclear physics [120–124]. However, the generation of vortex gamma photons remains a big challenge.

With the rapid progress of ultraintense laser techniques, the theoretical schemes of generating vortex gamma-ray photons have been extensively proposed, where most of the studies utilize Compton backscattering to obtain high energy and OAM gamma-ray photons [111, 125–135]. Nevertheless, most of these studies have only considered vortex beams with collective OAM in laser-plasma interactions, the intrinsic OAM carried by gamma-ray photons is still unclear.

Recently, a quantum electrodynamical scattering theory has been considered to characterize the multiphoton absorption and the process of angular momentum transfer in the generation of vortex gamma-ray photons. For instance, Ababekri et al. [136] explored the generation of vortex gamma photons through nonlinear Compton scattering of ultrarelativistic electrons in a circularly polarized laser pulse. They discuss the vortex phase structure of the scattering matrix element, the transformation of the vortex phase to the emitted photon, and the radiation rate for vortex gamma photons. Guo et al. [137] investigated the production of gamma-ray photons with large intrinsic OAM via nonlinear Compton scattering. Gamma-ray photons carrying controllable OAM quantum numbers from tens to thousands of units are generated when employing vortex electrons at moderate laser intensities. Jiang et al. [138] studied the generation of vortex gamma photons with controllable spin and orbital angular momenta via nonlinear Compton scattering of two-color counter-rotating CP laser fields. They find that the polarization and vortex charge of the emitted gamma photons can be controlled by tuning the relative intensity ratio of the two-color CP laser fields. Utilizing the quantum radiation theory could lead to a better understanding of the properties of the emitted vortex gamma-ray photons, which potentially opens new opportunities in hadron, atomic, nuclear, particle, and high-energy physics.

6. Summary and future prospects

Over the last few years, the area of laser-plasma based acceleration methods for spinpolarized particle beams has significantly evolved. This is in parts due to the advances in general plasma-based accelerator research as well as the recent studies on the generation of polarized particle sources.

Up to now, most of the proposed mechanisms rely on pre-polarized targets, which come with certain restrictions on the maximum attainable density and size. Only a few results suggest the utilization of *in-situ* setups as in the case of polarized electron beams [43, 44]. In the regime of QED physics, the methods rely on radiative polarization [20, 23]. For pre-polarized targets, it has become obvious in most of the theoretical studies that the injection phase of the particles into the accelerating structure is the most crucial for the preservation of polarization. The subsequent acceleration phase, where $\gamma \gg 1$ was shown to only marginally contribute to depolarization. The recent proof-of-principle results with ³He give hope that laser-plasma based polarized targets are a feasible approach [32].

The next logical step in this field will be experimental verification of the proposed setups for electron and ion acceleration, since the amount of theoretical studies currently outweighs experimental results. The generation of polarized positrons and gamma quanta will further rely on any advances in general accelerator research, as high-intensity laser pulses and/or high-energy electron beams are necessary for many of these schemes.

These might become feasible with near-future laser facilities like ELI [139], XCELS [140] or SULF/SEL at SIOM [141].

If upcoming experiments further confirm the feasibility of laser-plasma based sources of polarized particles, they will be of significant interest to the community of high-energy physics for deep-inelastic scattering experiments or the fusion community in the scope of polarized fusion for improved cross sections.

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