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POLARIZED PROTON BEAMS FROM LASER-INDUCED PLASMAS

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Abstract

We report on the concept of an innovative laser-driven plasma accelerator for polarized proton (or deuteron) beams with a kinetic energy up to several GeV. In order to modell the motion of the particle spins in the plasmas, these have been implemented as an additional degree of freedom into the Particle-in-Cell simulation code VLPL. Our first simulations for nuclear polarized Hydrogen targets show that, for typical cases, the spin directions remain invariant during the acceleration process. For the experimental realization, a polarized HCl gas-jet target is under construction where the degree of proton polarization is determined with a Lamb-shift polarimeter. The final experiments, aiming at the first observation of a polarized particle beam from laser-generated plasmas, will be carried out at the 10 PW laser system SULF at SIOM/Shanghai.

INTRODUCTION

The field of laser-induced relativistic plasmas and, in particular, of laser-driven particle acceleration, has undergone impressive progress in recent years. Despite many advances in the understanding of fundamental physical phenomena, one unexplored issue is how the particle (in particular hadron) spins are influenced by the huge magnetic fields inherently present in the plasmas [1–4].

Several mechanisms can potentially lead to a sizesable degree of polarization of laser-accelerated particle beams: first, a genuine polarization build-up from an unpolarized target by the laser-plasma fields themselves and, second, polarization preservation of pre-aligned spins during the acceleration despite of these fields. The work of our group aims at the first scenario using a novel dynamically polarized Hydrogen target.

Two effects are currently discussed to build up a nuclear polarization in the plasma: either the polarization is generated due to a spin-flip according to the Sokolov-Ternov effect, induced by the magnetic fields of the incoming laser pulse. Besides that, the spatial separation of spin states by the magnetic-field gradient, *i.e.* the Stern-Gerlach effect, may result in the generation of polarization for different beam trajectories [5].

In addition to these two mechanisms, all particle spins precess around the laser or plasma magnetic fields as characterized by the Thomas-Bargmann-Michel-Telegdi (T-BMT) equation describing the spin motion in arbitrary electric and magnetic fields in the relativistic regime.

The first and up to now only experiment measuring the polarization of laser-accelerated protons has been performed at the ARCturus laser facility at Heinrich-Heine University Düsseldorf [2]. Figure 1 schematically depicts the setup: for the measurements a 100-TW class Ti:Sa laser system with a typical pulse duration of 25 fs and a repetition rate of 10 Hz

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was used producing an intensity of several 10^{20} Wcm^{-2}. After impinging the laser pulse under a 45° angle on an (unpolarized) gold foil of 3 µm thickness, protons are accelerated according to the well-known Target Normal Sheath Acceleration (TNSA) mechanism [1] to an energy of typically a few MeV. They are heading towards a stack of Radio-Chromic-Film (RCF) detectors where the flux of protons is monitored. In order to measure the polarization of the proton bunches, the spin dependence of elastic proton scattering off nuclei is employed. At the particular proton energy Silicon is a suitable scattering material since it has a sizeable analyzing power and the scattering cross sections are known.

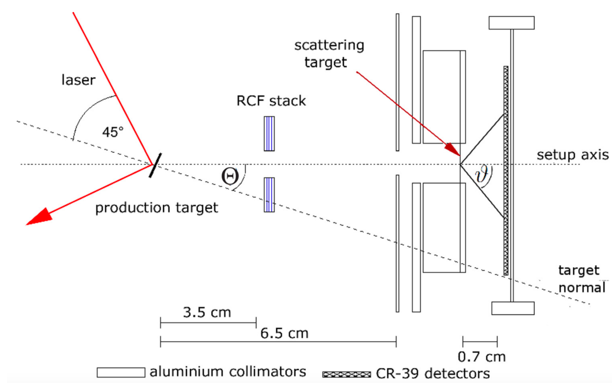

Figure 1: Schematic setup for the first proton polarization measurement [2].

To estimate the magnitude of possible polarizing magnetic fields in case of the Düsseldorf experiment, Particle-In-Cell (PIC) simulations were carried out with the fully relativistic 2D code EPOCH [6]. A B-field strength of $\sim 10^4$ T and gradients of around 10^{10} Tm^{-1} are to be expected. Although these values are much higher compared to those at conventional accelerators, they are yet too small to align the proton spins and, thus, should not lead to a measurable proton polarization [2]. This prediction matches the experimental finding of zero proton polarization.

An important conclusion from this experiment thus is that for measuring a sizesable proton polarization both, a stronger laser pulse with an intensity of about 10^{23} Wcm^{-2} and an extended gas instead of a thin foil target would be required. Such a scenario has been theoretically considered (without taking into account spin effects) in a paper by Shen *et al.* [7]. Due to the larger target size, the interaction time between the laser accelerated protons and the B-field is increased. It amounts to approximately 3.3 ps and is much larger than the typical time scale (about 0.1 ps) for spin motion given by the Larmor frequency and, thus, a spin manipulation seems possible.

PARTICLE SPIN DYNAMICS

We have implemented particle-spin effects into the 3D PIC simulation code VLPL (Virtual Laser Plasma Lab) in order to make theoretical predictions about the degree of proton-spin polarization from a laser-driven plasma accelerator [8, 9]. These calculations consider all relevant effects that may lead to the polarization of proton beams [10].

The Sokolov-Ternov effect is, for example, employed in classical accelerators to polarize the stored electron beams where the typical polarization build-up times are minutes or longer. This effect can, therefore, be neglected in the case of laser-induced acceleration. We refer to our forthcoming publication Ref. [10] for a more quantitative derivation.

Our assessment for the Stern-Gerlach force [10] shows that non-relativistic proton beams with opposite spins are separated by not more than $\Delta_p \approx 9.3{\cdot}10^{-7}\,\lambda_\mathrm{L}$ with the laser wavelength λ_L. Moreover, the field strengths is of the order of $E \approx B \approx 10^5$ T and the field gradients $\nabla|\mathbf{B}| \approx 10^5$ T/R with the laser radius R, typically $\lambda_\mathrm{L}/R = 1/10$ and a characteristic separation time would be $t = 100\,\omega_\mathrm{L}^{-1}$, where ω_L is the laser frequency. Thus, the force on the given length scale is too weak and the Stern-Gerlach effect does not have to be taken into account for further simulation work on proton-spin tracking.

For charged particles the spin precession in arbitrary electric and magnetic fields is given by the T-BMT equation in CGS units:

$$\begin{aligned}\frac{d\mathbf{s}}{dt} = -\frac{e}{m_\mathrm{p}c}\Bigg[\left(a_\mathrm{p} + \frac{1}{\gamma}\right)\mathbf{B} - \frac{a_\mathrm{p}\gamma}{\gamma+1}\left(\frac{\mathbf{v}}{c}\cdot\mathbf{B}\right)\frac{\mathbf{v}}{c} \\ -\left(a_\mathrm{p} + \frac{1}{1+\gamma}\right)\frac{\mathbf{v}}{c}\times\mathbf{E}\Bigg]\times\mathbf{s} = -\vec{\Omega}\times\mathbf{s}\,.\end{aligned} \quad (1)$$

Here $\mathbf{s}$ is the proton spin in the rest frame of the proton, e is the elementary charge, m_p the proton mass, c the speed of light, the dimensionless anomalous magnetic moment of the proton $a_\mathrm{p} = \frac{g_\mathrm{p}-2}{2} = 1.8$ with the g-factor of the free proton g_p, γ the Lorentz factor, $\mathbf{v}$ the particle velocity, $\mathbf{B}$ the magnetic field, and $\mathbf{E}$ the electric field, both in the laboratory frame. Since $\vec{\Omega}$ always has a component perpendicular to $\mathbf{s}$, the single spins in a polarized particle ensemble precess with the frequency $\omega_\mathrm{s} = |\vec{\Omega}|$. For protons with an energy in the range of a few GeV, $\gamma \approx 1$ and $1 \gtrsim \mathbf{v}/c$, so that:

$$\omega_\mathrm{s} < \frac{e}{m_\mathrm{p}c}\sqrt{(a_\mathrm{p}+1)^2\,\mathbf{B}^2 + \left(\frac{a_\mathrm{p}}{2}\right)^2\mathbf{B}^2 + \left(a_\mathrm{p} + \frac{1}{2}\right)^2\mathbf{E}^2}\,. \quad (2)$$

Under the assumption $|\mathbf{B}| \approx |\mathbf{E}| \approx F$ this simplifies to:

$$\omega_\mathrm{s} < \frac{e}{m_\mathrm{p}c}F\sqrt{\frac{9}{4}\,a_\mathrm{p}^2 + 3\,a_\mathrm{p} + \frac{5}{4}}\,. \quad (3)$$

As a consequence, a conservation of the polarization of the system is expected for times

$$t \ll \frac{2\pi}{\omega_\mathrm{s}} \approx \frac{2\pi}{3.7\frac{e}{m_\mathrm{p}c}F} \quad (4)$$

for $a_\mathrm{p} = 1.8$. For the typical field strengths in our first simulations (*cf.* Fig. 2) of $F = 5.11\cdot10^{12}$ V/m $= 17.0\cdot10^3$ T, the preservation of the spin directions is estimated for times $t < 1$ ps. This time is sufficiently long taking into account

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that the simulation time is $t_{\mathrm{sim}} = 0.13\,\mathrm{ps} \ll 1\,\mathrm{ps}$, so the polarization is maintained during the entire simulation according to the T-BMT equation.

PARTICLE-IN-CELL SIMULATIONS

In order to reproduce the results of our experiment presented above and to verify the quantitative estimates of Ref. [2], 3D simulations with the VLPL code including spin tracking have been carried out on the supercomputer JURECA [11].

It is important to note that to simulate the plasma behavior, a PIC code first defines a three-dimensional Cartesian grid which fills the simulated volume where the plasma evolves over the simulated time. Not each physical particle is treated individually but they are substituted by so-called PIC particles. This is why the continuous spin vector of a PIC particle represents the mean spin of all substituted particles. Thus, not the spin of each single particle is simulated but the polarization P of every PIC particle. The sum of spin vectors of different PIC particles within a specific volume (polarization cell) corresponds to the local polarization of the ensemble [10, 12].

Figure 2 shows preliminary simulation results for proton-spin tracking with VLPL. An acceleration of the proton sheath due to the TNSA mechanism is evident. From the simulated strength of the magnetic field behind the target (acting on the accelerated protons) we estimate a proton polarization preservation for at least 0.18 ps. This is much longer than the time needed to accelerate the protons.

Thus, the VLPL simulations demonstrate polarization conservation according to the T-BMT equation when acceleration by the TNSA mechanism takes place [12]. In other words, a compact target would be needed in which the nuclear spins are already aligned at the time of irradiation with the accelerating laser. Unfortunately, solid foil targets suitable for laser acceleration with the TNSA mechanism are not available so far and their experimental realization would be extremely challenging. In solid targets used for classical accelerator experiments Hydrogen nuclear polarization mostly results from a static polarization, *e.g.*, in frozen spin targets [13].

The only gaseous target material with a density sufficient for laser acceleration are hyper-polarized ^{3}He [14, 15] or Xe which are, of course, not suitable for proton acceleration. For Hydrogen until now only polarized atomic beam sources based on the Stern-Gerlach principle [16] are available, which have the disadvantage of a much too low particle density. In order to provide a (dynamically) polarized Hydrogen gas target for laser-plasma applications, a new approach is needed.

EXPERIMENTAL REALIZATION

For the experimental realization of our new concept for a dynamically polarized ion source, three major components are required: a suitable laser system to provide the target polarization, a vacuum interaction chamber including a gas

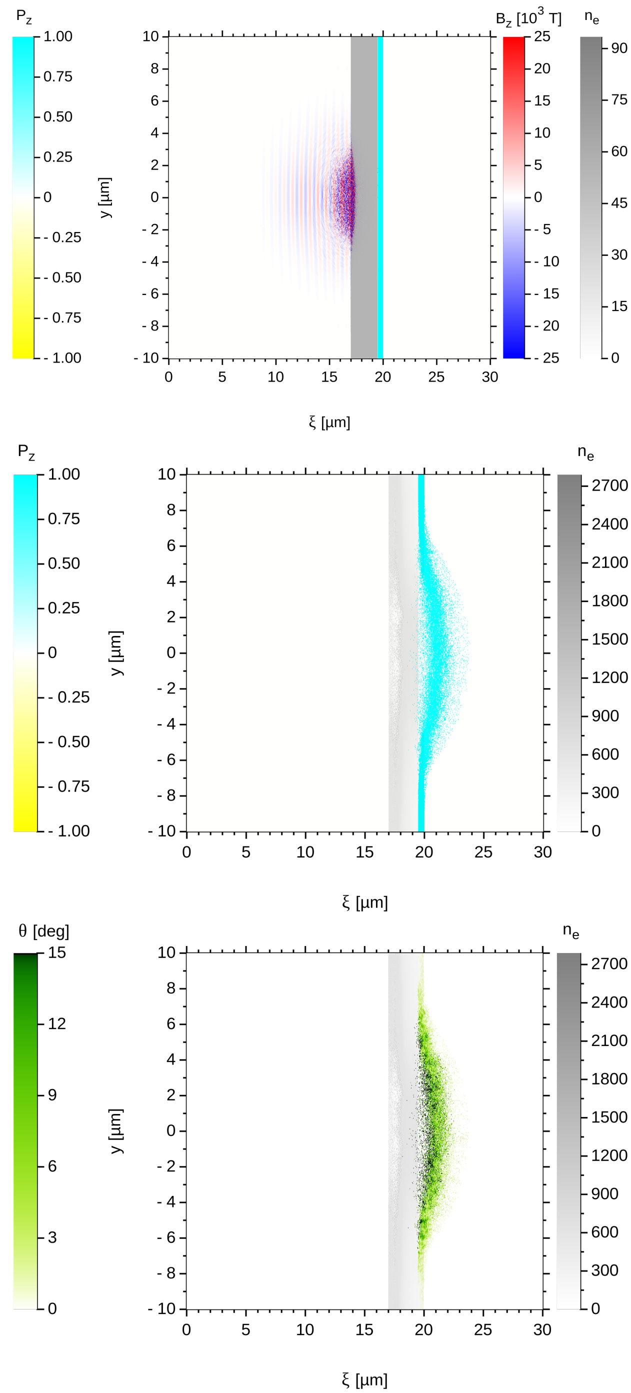

Figure 2: 3D VLPL simulation showing the conservation of proton polarization from an Aluminum foil target (2.5 µm, 35 n_{cr}) covered with a fully polarized proton layer (0.5 µm, 117 n_{cr}) at simulation times 32.5 fs (top) and 130 fs (center, bottom). The upper two figures show the degree of proton polarization, while in the lower their spin-rotation angle (relative to the initial value $\sigma = (0, 0, 1)$) is depicted. The of Gaussian-shape laser pulse ($\lambda_{\mathrm{L}} = 800$ nm, normalized laser amplitude $a_0 = 12$, 25 fs duration, 5 µm focal spot size) enters the simulation box from the left. The grid cell size is $h_x = 0.025$ µm and $h_y = h_z = 0.05$ µm, n_e represents the electron density.

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jet at the interaction point with the accelerating laser, and a polarimeter. The schematic view of this setup is depicted in Fig. 3.

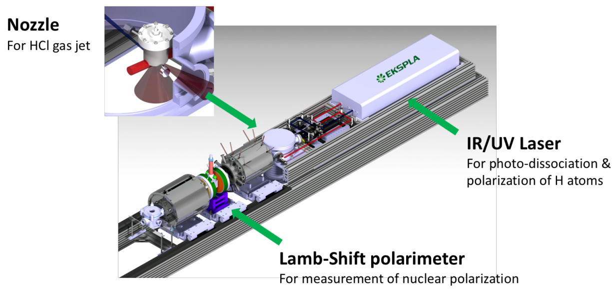

Figure 3: Schematic view of the setup for the proton polarization measurement using a polarized Hydrogen gas target.

As material of the gas target, Hydrogen halides are a viable option [17, 18]. A Hydrogen chloride (HCl) target is preferred in this case due to the rather high polarizability and the easy availability. The HCl gas is injected into the interaction chamber through a standard gas nozzle with a high-speed short-pulse piezo valve that can be operated at 5 bar inlet-gas pressure to produce a gas density in the range of $\sim 10^{19}$ cm^{-3}. Few millimeters below the nozzle, the interaction between gas and laser beams takes place.

The polarizing laser system is a pulsed Ni:YAG laser from EKSPLA [19]. Its peculiarity is the quasi-simultaneous output of the fundamental wavelength at 1064 nm and the fifth harmonic (213 nm). The repetition rate of the laser system is 5 Hz and the pulses are of 170 ps duration which is sufficiently short with regard to the transfer time of the electron spin polarization to the nucleus due to hyperfine interaction ($\sim$ 1 ns) [17]. The linearly polarized 1064 nm beam with a pulse energy of 100 mJ is focused with an intensity of $\sim 10^{11}$ Wcm^{-2} into the interaction chamber to align the HCl bonds (*cf.* Fig. 4). By this, the signal intensity is increased by an enhancement factor $x \approx 2$ assuming an interaction parameter of $\Delta\omega = 49$ and, thus, $\ll\cos^2\theta\gg = 6/7$ since the polarizability interaction is governed by a $\cos^2\theta$ potential with the angle θ between the molecular axis and the electric field distribution [20].

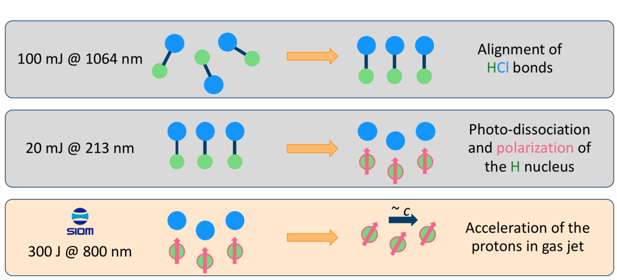

Figure 4: Schematic overview of the production of polarized proton beams.

At the same time, but under a 90° angle, the circularly polarized fifth harmonic with an energy of 20 mJ is focused into the vacuum chamber to an intensity of $\sim 10^{12}$ Wcm^{-2} to interact with the aligned HCl molecules. These are subsequently photo-dissociated by UV excitation via the $A^1\Pi_1$ state, which has a total electronic angular-momentum projection of $\Omega = +1$ along the bond axis. Hence, the resulting H and Cl(^{2}P$_{3/2}$) photofragments conserve this +1 projection of the laser photons, producing H and Cl(^{2}P$_{3/2}$) atoms each with the projections of approximately $m_s = +1/2$ (so that they sum up to +1), and thus the H-atom electron spin is approximately $m_s = +1/2$ [21]. In a weak magnetic field (Zeeman region), all H atoms are in a coherent superposition of the total angular momentum states $|F, m_F\rangle$ with the coupling $\mathbf{F} = \mathbf{S} + \mathbf{I}$ of the electron spin $\mathbf{S}$ and the nuclear spin $\mathbf{I}$. When the electron spin is fixed due to the polarization of the incident laser beam, *e.g.*, $m_s = +1/2$, then only the spin combinations $|m_s = +1/2, m_I = +1/2>$ and $|+1/2, -1/2>$ can be found in the free Hydrogen atoms. The hyperfine state $|+1/2, +1/2> = |F = 1, m_F = +1>$ is an eigenstate and will stay unchanged in time. Since the states $|-1/2, +1/2>$ and $|+1/2, -1/2>$ are not eigenstates, they are linear combinations of the $|F = 1, m_F = 0>$ and $|F = 0, m_F = 0>$ eigenstates, which have different energies. Therefore, atoms produced in the $|+1/2, -1/2>$ state will oscillate to $|-1/2, +1/2>$ and back. If now the electron-polarized Hydrogen atoms are produced during a very short time $t < 1$ ns, they will oscillate in phase. Therefore, after 0.35 ns only the spin combinations $|+1/2, +1/2>$ and $|-1/2, +1/2>$ can be found. As a consequence the electron polarization of the Hydrogen atoms, produced by the laser beam, is transferred into a nuclear polarization. If now the Hydrogen atoms are quickly ionized and accelerated, the out-coming protons will remain polarized, even if they undergo spin precessing according to the T-BMT equation [17].

Using a Lamb-Shift polarimeter the polarization of an atomic Hydrogen ensemble can be measured in a multi-step process [22, 23]. One important condition is that the atomic beam can be efficiently converted into metastable atoms in the 2S$_{1/2}$ state by ionization with an electron-impact ionizer and a charge reversal in cesium vapor. With a spin filter, individual hyperfine sub-states are selected by applying a static magnetic field, an electric quench field and a high-frequency transition. By varying the resonance condition when changing the magnetic field, single hyperfine components can be detected. Finally, the transition into the ground state within the quenching process is verified by Lyman-α radiation emitted at 121.5 nm. The intensity of the individual hyperfine components allows to measure their occupation number and, therefore, calculate the polarization of incoming protons and, in combination with an ionizer, even for Hydrogen atoms. The entire setup, including laser system, interaction chamber and Lamb-Shift polarimeter, is realized over a length of less than 5 m as a table-top experiment.

As indicated in Fig. 4, the final experiments with the polarized gas target, aiming at the first observation of a polarized proton beam from laser-induced plasmas, will be performed

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at the 10 PW laser system SULF (Shanghai Superintense-Ultrafast Lasers Facility) at SIOM (Shanghai Institute of Optics and Fine Mechanics). Theoretical calculations indicate the acceleration of protons out of a gas jet to the GeV energy range for this laser system operated at 300 J energy, 30 fs pulse energy and a focused intensity of $> 10^{22}$ Wcm^{-2} at 1 shot/min. It is predicted that the protons are accelerated in a so-called electron bubble-channel structure [24]. Compared to a traditional electron bubble the plasma density is much higher than the critical density of a relativistic laser pulse for a plasma containing mainly heavy ions such as chlorine. This results from reflections of the laser light from the highly compressed electron layers and self-focusing. As a consequence, only the acceleration of protons but not of heavy ions is expected. Moreover, it has been shown theoretically that in this acceleration scheme protons, which are trapped in the bubble region of the wake field, can be efficiently accelerated in the front of the bubble, while electrons are mostly accelerated at its rear [24]. After the acceleration process the proton polarization will be determined by a detector similar to that one used for our Düsseldorf experiment, but with different scattering foil material to account for the higher proton energies.

Regarding a source for laser-accelerated polarized $^3He^{2+}$ ions from a pre-polarized ^3He gas target an experiment is planned to be conducted at PHELİX, GSİ Darmstadt [14, 15, 25, 26].

DISCUSSION AND CONCLUSION

To summarize, the T-BMT equation, describing the spin precession in electromagnetic fields, has been implemented into the VLPL PIC code to simulate the semi-classical spin motion during laser-plasma interactions. One crucial result of our simulations is that a target containing polarized Hydrogen nuclei is needed for producing polarized relativistic proton beams. A corresponding gas-jet target, based on dynamic polarization of HCl molecules, is now being built at Forschungszentrum Jülich. From a simultaneous interaction of the fundamental wavelength of a Nd:YAG laser and its fifth harmonic with HCl gas, nuclear polarized H atoms are created. Their nuclear polarization will be measured and tuned with a Lamb-shift polarimeter. First measurements, aiming at the demonstration of the feasibility of the target concept, are scheduled for fall 2018. The ultimate experiment will take place in 2019 at the 10 PW SULF facility to observe a up to GeV polarized proton beam from laser-generated plasma for the first time.

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