Particle acceleration in laser-induced relativistic plasmas — a novel approach for polarized sources?

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Particle acceleration in laser-induced relativistic plasmas — a novel approach for polarized sources?

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Abstract. The physics of laser-plasma interactions has undergone dramatic improvements in recent years. By directing a multi-TW, ultrashort laser pulse onto a thin foil or a gas jet, it is nowadays possible to produce multi-MeV proton, ion and electron beams. Although much progress has been made in characterizing and improving the quality of such laser-generated beams, it is still an untouched issue whether the laser-generated beams are or can be spin-polarized and, thus, whether laser-based polarized sources are conceivable. To this end, one may either think of a selection of certain spin states through the huge magnetic field gradients that are inherently generated in the laser-generated plasmas, or of pre-polarized target particles which maintain their polarization during the rapid acceleration procedure. We have developed a method to measure the degree of polarization of protons that have been accelerated at the 200 TW laser facility ARCturus at Düsseldorf University. As a next step, measurements with unpolarized H_2 (for proton acceleration) and ^{3}He gas (for ^{3}He ions) are planned and, finally, pre-polarized ^{3}He will be used.

1. Introduction

In recent years, the physics of laser-induced particle acceleration has undergone extremely rapid development. Figure 1 depicts the Livingston plot for hadron and e^+e^- colliders, while Fig. 2 shows the analogous development of the achievable laser focus intensity over the last few decades and the corresponding characteristic energy of the plasma electrons. Conventional accelerator technology is about to reach fundamental and technological limits of the achievable particle energies. These limitations do not apply to laser-driven particle acceleration, where since the invention of chirped pulse amplification, the possible electron energies have increased rapidly into the GeV regime, with many-fold further improvements likely in the near future.

Ti:sapphire laser systems, like the ARCturus Laser at Heinrich Heine University Düsseldorf, operate at a pulse energy of a few J, compressed to a pulse length of values around 30 fs, reaching a pulse power of 100 TW and a focus intensity of approx. 10^{20} W/cm^2. To give a vivid impression of the light intensities present in the focus point one may imagine the average intensity of sunlight on the surface of the earth, given by the solar constant of 1367 W/cm^2,

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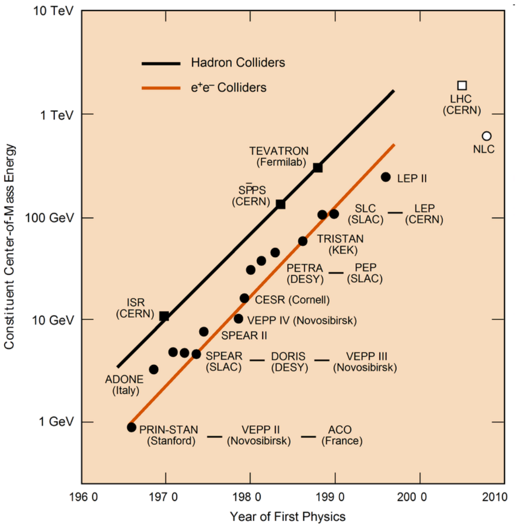

Figure 1. Livingstonplot for hadron and e^+e^- colliders.

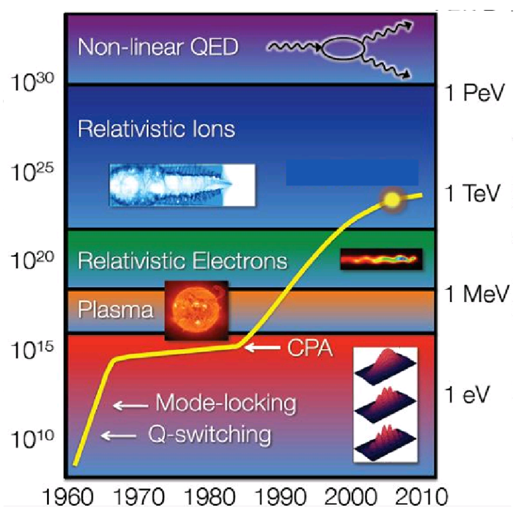

Figure 2. Development of laser intensities and characteristic electron energy during the last decades.

focused on the tip of a pencil (0.1 mm^2). By directing such a high-intense laser beam on a foil or a gas jet it is possible to generate a plasma in the focus point. Plasma electrons are driven from the target directly by the electromagnetic fields of the laser. The quasi-static electric field produced by this charge separation accelerates protons that are present in impurities of hydrocarbons on the foil target surface. For protons the maximum energy up-to-date is 67.5 MeV, produced at the Trident Laser Laboratory, Los Alamos [1]. Typical values of the maximum particle energies reached at the ARCturus facility are about 300 MeV for electrons and 10 MeV for protons.

However, fundamental and technological challenges still have to be mastered for the realization of reliable and continuously operating laser-plasma accelerators. The particle beams typically are poly-energetic with a broad angular distribution. The repetition rate of high intense lasers is limited to about 10 Hz which also sets limits to the luminosity of these accelerators.

While the development of laser-induced particle accelerators is rigorously driven forward, one completely unexplored issue is, whether the laser-generated beams are or can be spin-polarized. Since many high-energy and nuclear-physics experiments require polarized beams it is vital to investigate this possibility.

2. Search for polarization effects

In our experiments high magnetic fields are formed in the laser-generated plasmas mainly by the current of escaping hot electrons and the return currents in the target. These fields usually have values in the order of 10^4 T in the center of the focus and decrease over 10 or 20 μm radially away from the beam axis of the laser pulse, producing very high field gradients of the order of 10^{10} T/m. This is illustrated in Figs. 3 and 4, which show the quasi-static magnetic field distributions simulated with a Particle-in-Cell code.

Similar to the effect in a Stern-Gerlach apparatus one might expect the particles to encounter forces, that are quantized according to their spin orientation. There are several concerns however about the quantitative effect on the proton trajectories.

A fundamental concern is the "Bohr's hypothesis" (described by Pauli [2]), who stated that according to the uncertainty principle, spin states of electrons, or any other charged particle, cannot be separated by a magnetic force on the electron dipole moment. Bohrs argument holds

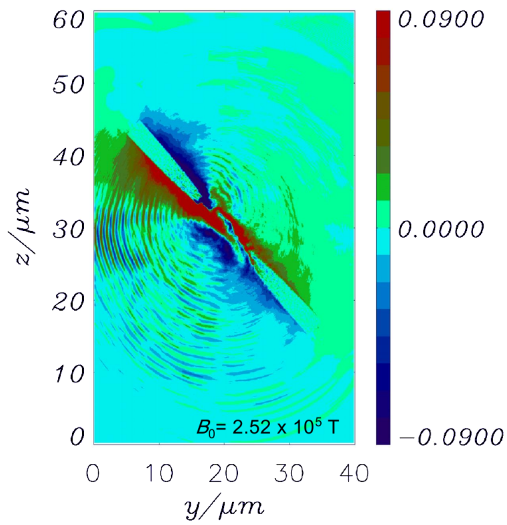

Figure 3. Magnetic fields in and around a foil target of 3 μm thickness. The incident angle of the laser pulse is is 45° to the target normal.

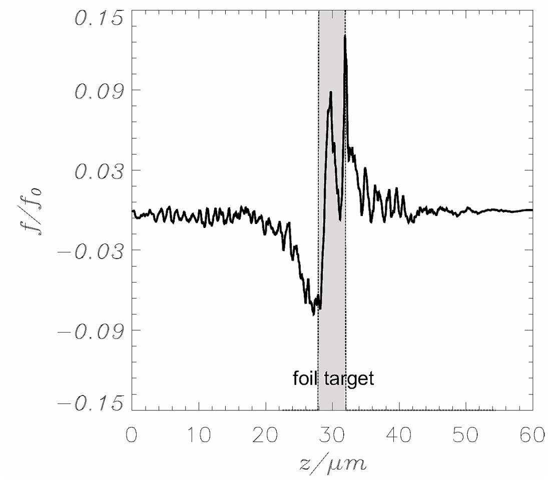

Figure 4. Cut through the two-dimensional field distribution of Fig. 3 along $z = y + 10$ μm.

for protons as well, since it is based on the uncertainty in the Lorentz force, that acts on the particle. However, in 2002 Garraway and Stenholm showed, that it is in principle possible to achieve spin-separation for charged particles under certain conditions, such that a particle beam of small diameter passes through the field region and remains a sufficiently long time in an interaction free region afterwards [3] — conditions that may be fulfilled in laser-plasma experiments. On the other hand, if there exists no separation of the particle spins by self-generated magnetic fields of the plasma, this clears the way for a second scenario, which is to use polarized targets, like frozen spin targets for protons. If the polarization of the particles is preserved during the laser-induced acceleration the produced beams would carry a polarization in the order of magnitude of the initial target polarization. To date there has been no investigation — neither theoretical nor experimental — it has been investigated, whether the conditions during laser-induced acceleration meet the requirements leading to an observable spin-separation. Conversely, an observation of polarized beams from laser-induced plasmas could settle the long-standing discussion whether the Stern-Gerlach effect is also detectable for charged particles.

3. Setup for the measurement of the polarization of laser-accelerated protons

For the measurement of the degree of polarization of the laser-accelerated protons, the spin dependence of the elastic scattering of protons off silicon nuclei was used. A setup was developed and optimized for a proton energy range around 3 MeV, consisting of a beam monitor, a set of aluminium and lead collimators, the secondary scattering target and CR-39 detectors. The complete setup is depicted in Fig. 5. As rate monitor a stack of RadioChromic Films (RCF) was used, that is located 2.5 cm away from the production target. These are self-developing films that change colour and optical density when irradiated by ionizing radiation. The RCF detectors were calibrated, so that a calculation of the deposited energy from the colour depth is possible. Through a hole with 0.5 cm diameter a part of the beam passes the RCF detectors and arrives at a first set of collimators. An aluminium collimator with an aperture of 1 mm a part of the beam is selected, thus defining the emission angle of the protons that are used for

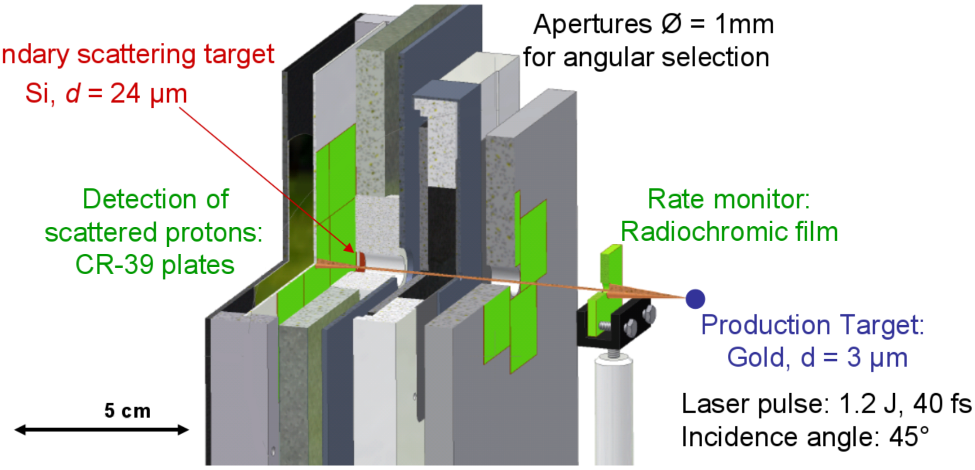

Figure 5. Technical drawing of the setup for proton-polarization measurements.

the polarization measurement. One centimeter behind this, the next collimator of aluminium with a thickness of 0.5 cm and an aperture of about 2 mm blocks secondary particles that are produced at the edges of the first collimator. For the scattering of the protons a silicon target of 24 μm thickness was used. Cross sections and analyzing power of the Si(p, p')Si reaction was provided by measurements at the Tandem accelerator at the University of Cologne [4]. The data are shown in Fig. 6. The beam to be analyzed has an angular divergence of approx. 1° and hits

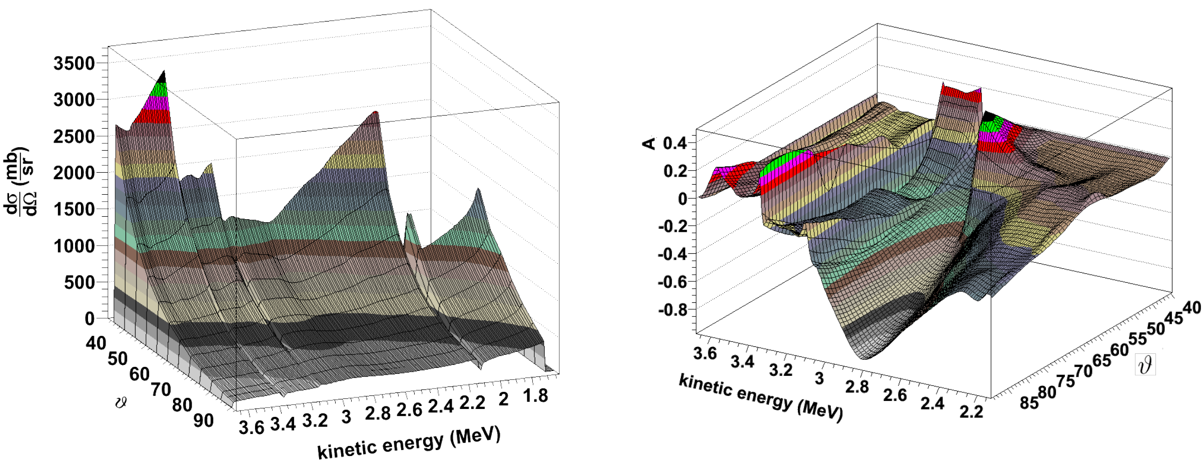

Figure 6. Cross section and analyzing power

the target in an area of 2 mm diameter. Behind the scattering target solid state nuclear track detectors of CR-39 are placed, which cover a scattering angle ϑ of up to 68° and the complete azimuthal range ϕ from 0° to 360°. These detectors have been chosen due to their insensitivity to the γ and X-ray background radiation from the plasma target.
The setup was optimized during a first measurement in Spring 2010. An experiment with higher statistics, that should allow us to draw unambiguous conclusions about the degree of polarization of protons accelerated in foil targets was carried out in Nov. 2010. These data are currently being analysed.

4. Outlook

In the long term, the study of ions accelerated in gas jet targets is planned, since there is the possibility to use pre-polarized ^{3}He as target material. Acceleration of α particles from ^{4}He gas jet targets have already been observed [5], which is expected to work just as well for ^{3}He. During a usual ionization process the electrons are removed consecutively from the atom. The single ionized ^{3}He has a very short relaxation time of the spin-polarization, which is the reason why currently, no polarized sources for ^{3}He ions are available. The strong electric fields of a high intense laser, however, might be able to remove the two electrons within a ps or less, sustaining the nuclear spin during the acceleration process.

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