Beam collimation and transport of laser-accelerated protons by a solenoid field

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Abstract. A pulsed high field solenoid was used in a laser-proton acceleration experiment to collimate and transport the proton beam that was generated at the irradiation of a flat foil by a high intensity laser pulse. $10^{12}$ particles at an energy of 2.3 MeV could be caught and transported over a distance of more than 240 mm. Strong space charge effects occur, induced by the high field of the solenoid that forces all co-moving electrons down the the solenoid’s axis, building up a strong negative space charge that interacts with the proton beam. This leads to an aggregation of the proton beam around the solenoid’s axis and therefore to a stronger focusing effect. The collimation and transport of laser-accelerated protons is the first step to provide these unique beams for further applications like post-acceleration by conventional accelerator structures.

1. Introduction

Laser-accelerated ion beams have triggered an extensive discussion about their possible applications due to their unique beam parameters. Ultra-low emittances [1] and highest beam fluxes [2] were experimentally proven. The main problems that are still under strong investigations are the exponential energy spectrum and the high envelope divergence of the beams [3]. Many attempts were done to shape the energy distribution to a more mono-energetic one. Special targets with proton or carbon monolayers [4, 5] on the target surface were used as well as deuterated droplets [6]. Additionally, the beam divergence could be reduced by different techniques like the laser-triggered micro lens [7] or with hemi-spherical targets [8]. In another experiment a quadrupole doublet was used to guide the proton beam [9]. The drawbacks of these systems were either the complexity of the set-up or the high particle losses caused by the collimation device. To avoid this we have established an alternative to control the transport of laser-accelerated protons that uses a pulsed high field solenoid to collimate the beam directly behind the target foil. The coil of the solenoid consists of a brass helix with a length of 75 mm and its open aperture is 44 mm in diameter. This allows to catch nearly all protons at a particle
energy of 2.5 MeV. In the experiment the solenoid ran at 8.6 T. At these strong fields the magnetic pressure that causes high magnetic stress inside the coil is a main concern. The solenoid could successfully be tested up to 15 T which equals 90 MPa magnetic pressure.

2. Simulations

Several simulations were done to investigate the propagation of a proton beam through the solenoid. The simulation program was CST Particle Studio, which is based on the finite volume method used to solve the Maxwell equations. It includes a particle tracker as well as a PIC (particle-in-cell) solver. During the laser-plasma interaction not only protons but also electrons are accelerated in forward direction. Especially the co-moving electrons, i.e. electrons that travel at the same velocities as the proton beam, have to be considered in the simulations. Due to their much lower energies these electrons get forced down to the solenoid’s axis directly at the target position (the magnetic field strength at the target in a distance of 17 mm to the solenoid is around 0.95 T). This effect has strong influence on the proton propagation. The normally existing quasi neutrality of the beam is not preserved. Hence, the protons get attracted by the negative space charge of the electron beam, leading to a proton aggregation around the solenoid’s axis. Figure 1 shows the proton and electron beam inside the solenoid 2.75 ns after the laser has hit the target. Elec

![Figure 1. Electron (blue) and proton (cyan to red) flux through the solenoid. The beam has entered the solenoid from the left side of the picture. The electrons are circulating around the solenoid’s axis at their gyro radius, leading to a strong negative space charge that results in a proton beam aggregation around the axis.](image)

tron and electron beam inside the solenoid 2.75 ns after the laser has hit the target. Electrons can only be found in a very small radius around the solenoids axis (blue dots) and the strong proton aggregation can clearly be seen (green dots - lowest proton energy (1 MeV) - to red dots - highest proton energy (5 MeV)). This effect has strong influence on the proton beam transport and changes the beam profile. Three time steps of the propagation of the protons are shown in figure 2. No electrons are shown in this figure so that the proton aggregation around the axis gets much clearer. The energies of the particles are the same as in figure 1, (1 - 5) MeV. At the latest time step the aggregation starts to smear out. The electrons are not circulating around the axis anymore, because behind the solenoid the magnetic field lines diverge. This leads to a break up of the collimated electron beam and therefore to a broadening of the proton beam aggregation.

The total number of particles in the simulations were 49530. Each particle species was represented by a bunch with a Gaussian distribution with a total charge of $10^{-7}$ C which equals $6 \times 10^{11}$ electrons and protons, respectively. The mesh cells were 100 $\mu$m in all directions and the time step width was 407 fs.

3. Experimental results

The experimental campaign was done at the PHELIX (Petawatt High Energy Laser for Ion eXperiments) facility at GSI - Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt, Germany. PHELIX delivers 700 fs short laser pulses with energies up to 150 J on target. This
Figure 2. Propagation of the proton beam through the solenoid (left side) to the RCF detector (right side) at different time steps. The strong aggregation of the proton beam due to the electron’s space charge is clearly visible. The color of the particles indicates their energy from the lowest value (blue) to the highest one (red).

The campaign was the first run of the laser system working at relativistic intensities and during the first shots laser-accelerated protons with energies exceeding 30 MeV could be observed. The main diagnostic used in the experiment were radiochromic films (RCF). These are dosimetry films sensitive to ionizing radiation. During irradiation the films turn from transparent to blue. The obtained optical density of the films gives information about the deposited dose or rather the proton numbers. An energy resolved measurement was done by using the film in a stack configuration [10].

The solenoid was placed 17 mm behind the target. As mentioned above the magnetic field strength was 8.6 T which let to a collimation of 2.5 MeV protons. Figure 3 shows the first six layers of three different RCF stacks, respectively. The energies (2.3 MeV - 7.6 MeV) belong to protons that are stopped in the specific RCF layer. The first six films on the left, figure 3 a), show the proton beam measured 40 mm behind the target without the solenoid in place. A well defined almost round beam could be observed. Figure 3 b) shows the reference shot at a distance of 130 mm behind the solenoid which equals 241 mm to the target. The solenoid was in place but turned off. Due to the strong divergence of the beam (25 degrees half opening angle) only a few particles are detected by the RCF. At energies higher than 6.0 MeV only a weak proton background is visible due to the fact that the number of protons for these energies is below the RCF detection threshold of $10^8$. In comparison figure 3 c) shows RCF films from a shot where the solenoid was in use. A strong signal could be measured for a proton energy of 2.3 MeV as expected from the simulations. The particle numbers exceed $10^{12}$ as well as for the first layer

Figure 3. The proton beam measured by RCF at a distance of 40 mm to the target a) and at a distance of 241 mm b). c) The proton beam measured behind the solenoid at the same position as b). Due to the collimation a strong proton signal was detected at 2.3 MeV particle energy. Even for higher energies a clear proton signal could be observed due to the additional focusing effect by the co-moving electrons.
of figure 3 a). The beam size is 39 mm in vertical and 42 mm in horizontal direction, marked by the red circle. A diameter of 40 mm was calculated by the simulations. Not only in the first layer but also in layer two to four a clear proton signal was detected. This happened due to the electron attraction on the proton beam. Normally, only a few particles are expected to be measured at energies higher than 2.5 MeV due to the strong divergence of the beam. Even particles up to 6 MeV are affected by the electron electric field leading to the strong signals in the RCF.

Additionally, strong beam modulations could be observed in the RCF layers when using the solenoid in comparison to a standard laser-proton acceleration without any collimation device. The reason is that eddy currents were induced in the target by the solenoid’s magnetic field (0.95 T at the target position) which let to a strong bending of the foil. Figure 3 shows a picture of the laser-plasma interaction zone. The front and rear plasma expansion can easily be identified. The induced eddy currents caused a bending of the target by 18 degrees. Simulations that were done with a 18 degrees bent target show that nearly 50 % of the protons get lost inside the solenoid and the the intensity maximum of the beam image at the RCF position is moved out of the center by 15 mm which can be seen as well in figure 3 c). For future experiments the bending will be suppressed by using non conductive targets.

![Figure 4](image_url) Image of the laser-plasma interaction. The picture shows a shot where the target got bent by the strong magnetic field of the solenoid inducing eddy currents in the target.

4. Conclusion
In this article we have shown that the collimation of a laser-accelerated proton beam by a pulsed high field solenoid is possible and leads to great results in terms of collimation efficiencies. $10^{12}$ protons could be transported over a distance of 241 mm. Inside the solenoid strong space charge effects occurred due to the co-moving electrons leading to a proton beam aggregation around the axis. This resulted in a stronger focusing of the beam so that even higher energies than the expected 2.3 MeV could be observed by the RCF.

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