Enhanced laser-driven ion acceleration in a strong applied magnetic field

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・INTRODUCTION

Several tens of MeV protons are generated from a laser-produced compact plasma in the laser-driven proton acceleration scheme. Laser-driven protons can be used for various applications. These applications require high flux and energetic protons as well as a high conversion efficiency from laser to protons. Experiments were performed to improve these parameters by using various target structures and laser conditions, e.g. an ultra-thin foil, micro-structured foil, long-pulse laser.

In the target normal sheath acceleration (TNSA) mechanism, an intense laser pulse interacts with a foil surface and generates relativistic electrons.　A part of the electrons escapes from the foil to a vacuum and generate a strong sheath electric field at the rear surface of the foil. This sheath field accelerates protons from the rear surface of the foil to its normal direction. The relativistic electrons diverge generally in the lateral direction. This divergence weakens the strength of the sheath electric field.

Previous studies using two- and three-dimensional particle-in-cell simulations found that applying a strong axial magnetic field to the TNSA increases the maximum proton energy and coupling efficiency from the laser to protons [1, 2, 3]. The applied magnetic field provides two effects: (1) the magnetic field reduces the lateral divergence of the relativistic electrons and (2) the right-hand circular-polarized component of the incident laser continuously accelerates electrons gyrating in the magnetic field. Therefore, the applied magnetic field enhances the directionality and the strength of the sheath field, resulting in the generation of a high-flux and high-energy proton beams.

A strong magnetic field that can confine the relativistic electrons is required to realize this scheme experimentally. A laser-driven capacitor-coil can produce a 1-kT magnetic field [4, 5, 6]. The pulse duration of this magnetic field is about 1 ns, sufficiently long relative to the time scale of proton acceleration. It was confirmed in previous experiments that the magnetic field generated by a laser-driven magnetic field can confine relativistic electrons within a small spot.

We attempted to demonstrate enhancement of the TNSA performance using a laser-driven capacitor-coil. However, the experimental results clarified that the maximum energy and the number of protons decreased by using a laser-driven capacitor-coil. In this report, we identify the sources of the proton beam degradation which were not considered by the previous numerical predictions.

・EXPERIMENTAL SETUP

The experiment was conducted at the GEKKO-XII (GXII) and LFEX facilities. Three GXII beams were used to generate a strong magnetic field. Each GXII beam, which has 800 +/- 50 J of energy at 1054-nm wavelength, was focused to 50-μm diameter on one of the capacitor-plates of the target. When a single GXII beam was used, the laser-driven capacitor-coil generated 610 +/- 30 T of magnetic field at the coil center at 1.5 +/- 0.15 ns after the GXII peak. The coil has 500-μm diameter and 50-μm wire diameter.

The LFEX beam, which has 350 +/- 50 J of energy and 1054-nm wavelength, was irradiated on a plastic (CH) foil to accelerate a proton beam via the TNSA. The CH foil was placed on 50-μm-thick tantalum, which protected the CH foil from radiation and plasma generated at the capacitor-plate. The energy spectrum of the laser-accelerated protons was measured with the Thomson parabola energy spectrometer. The energy spectra of the accelerated electrons were also measured at 21 degrees from the normal axis of the rear surface of the CH foil.

The aluminum shield was placed 5 mm behind the foil to protect the rear surface of the CH foil from illumination by the uncompressed light of the LFEX reflected at the RCF stack surface. The LFEX system emits an uncompressed light pulse ahead of a compressed main pulse. This uncompressed light is specularly reflected on the grating surface. The direction of the uncompressed light is tilted a little from that of the compressed light. Thus, the uncompressed light does not hit the CH foil, but illuminates the RCF stack behind the CH foil 45 ns before the compressed pulse illumination. The reflected uncompressed light can heat the rear surface of the CH foil, reducing the TNSA performance.

・RESULTS

We measured the energy spectra of the proton beam, changing the delay between the magnetic field generation and proton acceleration. For the initial delay setting, the GXII and LFEX pulse peaks reached the targets simultaneously. A positive value for the delay means that the LFEX pulse peak arrives at the CH foil after the GXII pulse peak.

Figure 1 shows the energy spectra of (a) laser-accelerated protons and (b) electrons measured at -260 ps and +180 ps delays, without the application of the laser-driven capacitor-coil. The proton spectra were measured at the normal direction of the CH foil rear surface. All of the proton spectra have a detection limit at 6 MeV because the Thomson parabola energy spectrometer cannot detect protons with energies less than 6 MeV. The energy spectra without the laser-driven magnetic field showed the highest maximum energy and the largest number of accelerated protons. On the other hand, when a magnetic field was applied to the CH foil, the maximum energy and the number of protons decreased as the delay increased, as shown by the red and blue lines in Fig.1. The degradation of the maximum energy and the number of protons indicate that the sheath electric field at the rear surface was weakened for unexpected reasons.

The energy spectra of the relativistic electrons were also observed at 21 degrees from the normal direction of the CH foil rear surface. In the low energy region below 1 MeV, the energy of the electron number peak shifted to higher energies compared to that without the magnetic field application as shown in Fig. 1 (b). This shift indicates the possibility of the existence of plasma around the CH foil. Plasma surrounding the CH foil can reduce the sheath electric field by Debye shielding, causing this shift.

When the laser-driven capacitor-coil was not irradiated by GXII beams, the LFEX laser interacts with a plasma at a sharp boundary between the CH foil surface and the vacuum because of a high laser pulse contrast of 10^{-11}. When GXII beams irradiate the capacitor-plate of the laser-driven capacitor-coil, a hot plasma stream is incident on the CH foil from the laser-plasma interaction region on the capacitor-plate. LFEX interacts with this plasma stream around the CH foil, causing an energy shift of the relativistic electrons. The long-scale plasma may also decrease the number of low-energy components of the relativistic electrons. The low-energy component of less than 1 MeV is also strongly affected by electric and magnetic fields. Therefore, the relativistic electrons are decelerated and scattered by electromagnetic fields in a hot-plasma cloud, which decreases the number of laser-produced electrons entering the detector.

In summary, we found that the proposed scheme to enhance the proton acceleration by using a laser-driven capacitor-coil is quite sensitive to the hot electrons and X-rays produced by the high-power laser. The number and

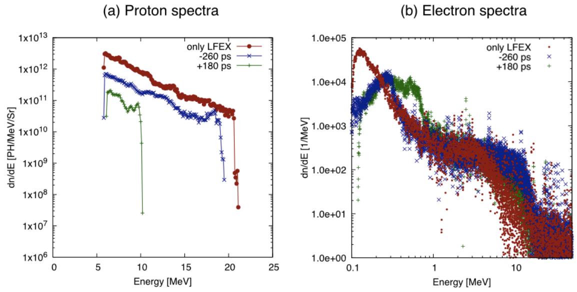

Fig.1. Energy spectra of laser-produced (a) protons and (b) electrons for no magnetic field (red・) and two delays: -260 ps (blue×), and +180 ps (green +), where a delay is a temporal separation between the application of a magnetic field and the proton acceleration.

maximum energy of protons decreased by increasing the delay between the magnetic-field-generation laser pulse and the proton-acceleration laser. An energy shift to high energies was observed in the electron energy spectra as the delay increased. This result indicates the possibility of hot electron irradiation and X-ray preheating. In the future experiment, some experimental design should be tested for a successful enhancement of TNSA.

・ACKNOWLEDGEMENT

The authors wish to thank the technical support staff of ILE at Osaka University for assistance with the laser operation, target fabrication, and plasma diagnostics. This work was supported through Collaboration Research Programs by the Institute of Laser Engineering at Osaka University (Grant Nos. 2018A1-Arefiev and 2019A1-Arefiev) and the Collaboration Research Program between the National Institute for Fusion Science and ILE (NIFS12KUGK057, NIFS15KUGK087, NIFS17KUGK 111, and NIFS18KUGK118), the Japanese Ministry of Education, Science, Sports and Culture through Grants-in-Aid, the Osaka University Scholarship for Overseas Research Activities 2018, the DOE Office of Science under Grant No. DE-SC0018312, KAKENHI (Grant Nos. 15KK0163, 16K13918, and 16H02245) and the Matsuo Research Foundation.

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