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

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INTRODUCTION

Laser-driven proton sources can deliver several tens of MeV particle energies from the compact, transient accelerating structure generated by laser-matter interactions at relativistic intensities. The future development of novel applications such as fast proton ignition requires improvements in the proton energy, beam divergence, and laser to proton energy conversion efficiency.

In target normal sheath acceleration (TNSA)[1], an intense laser pulse irradiating a flat solid-density target heats electrons and sets up a picosecond-duration and up to TV/m sheath field that gradually accelerates protons off the target surface. The proton beam quality is thus linked to the hot electron spectrum and the density distribution and lifetime of the sheath.

We have carried out two-dimensional and three-dimensional particle-in-cell simulations[2, 3] which indicate that nanosecond-duration sub-kT magnetic fields, accessible by capacitor-coil targets developed at ILE[4], suppress lateral sheath electron transport, increase electron heating and could deliver enhanced TNSA performance.

Experiments at the LFEX laser facility will be aimed at measuring for the first time the impact of an applied kT-level magnetic field on laser-driven proton acceleration in the TNSA regime. The LFEX laser facility is the only facility capable of generating a nanosecond-duration kT-level magnetic field, can simultaneously drive TNSA, and is also uniquely suited for investigating factors which affect the sheath dynamics such as electron heating and lateral transport. The capabilities of the LFEX laser facility will allow us to conduct a proof-of-principle experiment into the effects of strong magnetic fields in TNSA, including a magnetic field strength scan to observe the onset of magnetic field effects.

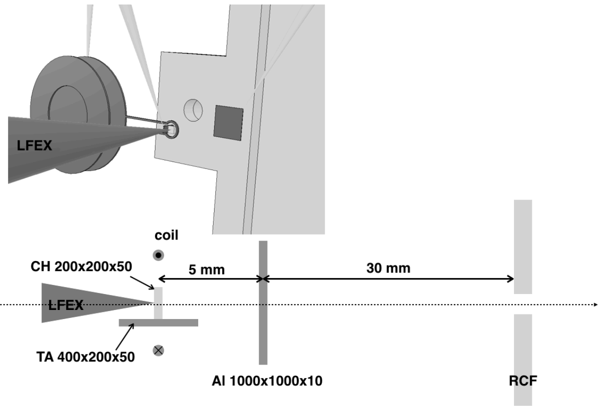

FIG. 1. Experimental setup for 3D design and 2D geometry. CH foil as a proton source was put on tantalum, which protect CH foil from some radiation. These targets are placed at the center of a coil. CH foil and tantalum's dimension are $200 \times 200 \times 50$ μm and $400 \times 200 \times 50$ μm. An aluminum foil was put 5 mm away from CH foil. It also protects CH foil from radiation. RCFs put 30 mm away from aluminum detect the proton beam. RCFs have a hole at center to pass the proton to Thomson parabola spectrometer.

EXPERIMENTAL SETUP

We used three GXII beams to generate a strong magnetic field and a single LFEX to accelerate proton beam via TNSA in this experiment. Experimental geometry is shown in Fig.1 Each GXII beam, which has 800 +/- 50 J of energy in 1054 nm of wavelength, is focused on capacitor-coil within xx of spot size. The capacitor-coil target might generate ~ 2 kT at coil center 1.2 ns after GXII peak with 500 um of coil diameter and 50 um of wire diameter[5]. LFEX, which has 350 +/- 50 J of energy in 1054 nm of wavelength, is irradiated to CH foil. CH foil was on a tantalum shield to be protected from radiation and a plasma generated on capacitor-coil. Accelerated proton beam was measure on a radiochromic film(RCFs) at 35 mm far from the foil. RCFs have a hole at its center, the spectra of a proton beam through the hole was measured by Thomson parabola ion spectrometer. The spectra of the accelerated electron were also measured. The aluminum shield put 5 mm away from the foil protects the rear surface of the foil from radiation.

RESULTS

Figure 2 shows the plots of maximum proton energy against the delay. 0 ps of a delay represents that GXII and LFEX reach the targets at the same time. A positive delay means that LFEX comes after the peak of GXII. An inset figure in Fig.2 shows the measured proton image without a capacitor-coil target. The maximum energy of this proton was 21.6 MeV. The lowest energy was 5.8 MeV with an application of B-field.

The acceleration energy of proton decreased with the delay between GXII and LFEX. The delay corresponds to the strength of magnetic field so that magnetic field rises when

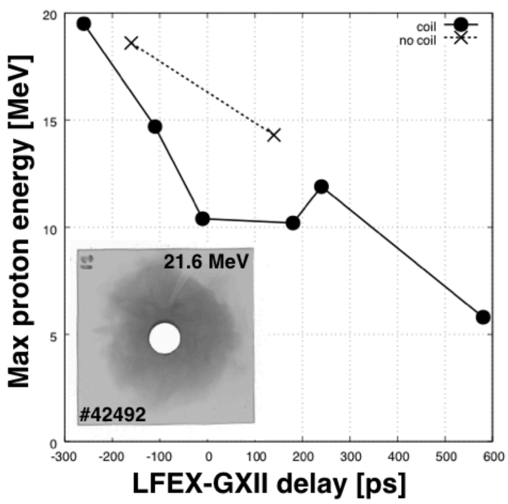

FIG. 2. Maximum proton energy against the delay between GXII and LFEX. Maximum proton energy decrease with the delay. Circles and solid line represent the proton energy using a coil. Crosses and dashed line represent the proton energy using only plates. Positive delay corresponds to that LFEX reaches the target after the peak of GXII beams. An inset figure shows the proton image obtained with only LFEX. The number in a figure shows the shot ID.

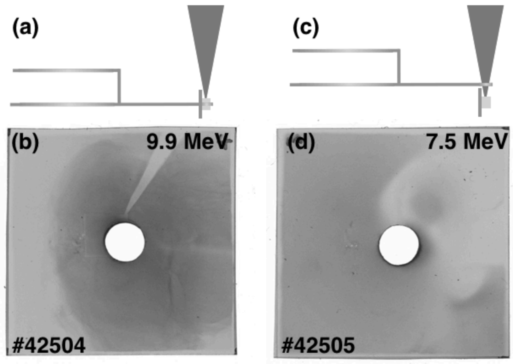

FIG. 3. Target arranges and obtained proton images. A proton source was put at a center of a coil in an original arrange(a). In this case, clear proton pattern having 9.9 MeV of maximum energy was observed at -10 ps(b). In the other arrange, a proton source was put 250 μm away from a center of a coil(c). The apparent difference in a proton image was observed at -30 ps. However, the maximum energy of proton (7.5 MeV) was lower than (c). Numbers shown in proton images represent a shot ID each other.

the delay increases. We expect that the maximum energy of the proton beam would increase with the delay in theory. However, the maximum energy of the proton beam decreased against our expectation. This decrease might be caused by the effect of radiation from a capacitor plate irradiated by GXII beams. The energy of three GXII beams is high enough to generate high energy x-ray. The high energy x-ray can heat a rear surface of the proton source, causing a deformation of the rear surface. A sheath electric field weakens due to the deformation of a rear surface generates and leads to lower acceleration.

The proton energy increased a bit at 230 ps. We hope this increase was the effect of the applied magnetic field.

We also carried out the experiments using the capacitor plates which do not have a coil to confirm the effect of radiation. In this case, the maximum proton energy was higher than proton energy in case of using a coil. These results indicate the radiation from the coil itself can heat the proton source apart from capacitor plates.

A large current flows in a coil after the laser irradiation. Ohmic heating due to the large current leads a coil expansion. The expanding coil may touch the tantalum shield and proton source. The experiment in other geometry was also performed to remove the possibility of a contact.

The clear change in proton images was observed changing the coil position. Figure 3 shows each target geometry and the obtained proton images. The proton source was put at the center of a coil in an original arrange as shown in Fig.3(a). The proton image measured having 9.9 MeV of maximum proton energy.at -10 ps was clear pattern (Fig.3(b)). In the other arrange, the proton source was put at 250 um away from the center of a coil as shown in Fig.3(c). The proton image measured at -30 ps on this arrange have a characteristic pattern shown in Fig. 3(d). It seems that the protons are collimated at the top right of a hole. However, the maximum energy of proton in this geometry was 7.5 MeV, lower than the energy in the original arrange. The radiation from a coil itself may still have caused this decrease.

SUMMARY

In summary, the proton acceleration using a capacitor-coil in this experiment is pretty sensitive to the influence of radiation which is generated when GXII laser irradiates a capacitor-coil target. The acceleration energy of proton decreased with the delay between GXII and LFEX. This was caused by the radiation from a capacitor plate. And a decrease of proton energy was suppressed using only the capacitor plates. Results indicate the radiation from the coil itself can heat the proton source.

The evident change in proton images was observed changing the coil position. However, the maximum energy of proton was still small due to radiation.

We used the shield for generated radiation, but it did not work in this experiment. For the future experiment, we need to improve the counterplan of the generated radiation.

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