Collimation of laser-produced proton beam

M. Takano\textsuperscript{1}, T. Nagashima\textsuperscript{1}, T. Izumiyama\textsuperscript{1}, Y. J. Gu\textsuperscript{1,2}, D. Barada\textsuperscript{1}, Q. Kong\textsuperscript{2}, P. X. Wang\textsuperscript{2}, Y. Y. Ma\textsuperscript{3}, W. M. Wang\textsuperscript{4}, and S. Kawata\textsuperscript{1}

\textsuperscript{1} Utsunomiya University, Utsunomiya 321-8585, Japan
\textsuperscript{2} Fudan University, Shanghai 200433, China
\textsuperscript{3} National University of Defense Technology, Changsha 410073, China
\textsuperscript{4} Inst. of Physics, CAS(Chinese Academy of Sciences), Beijing 100190, China

E-mail: mt136626@cc.utsunomiya-u.ac.jp, kwt@cc.utsunomiya-u.ac.jp

Abstract. In intense laser plasma interaction for particle acceleration several issues remain to be solved. In this paper we focus on a collimation of ion beam, which is produced by a laser plasma interaction. In this study, the ion beam is collimated by a thin film target. When an intense short pulse laser illuminates a target, target electrons are accelerated, and create an electron cloud that generates a sheath electric field at the target surface. Such the ion acceleration mechanism is called the target normal sheath acceleration (TNSA). The TNSA field would be used for the ion beam collimation by the electric field. We have successfully obtained a collimated beam in our particle-in-cell simulations.

1. Introduction
Accelerator is used in a various fields, such as industrial development, medical treatment, basic researches, etc: for example, a cancer treatment by an ion beam produced by the accelerator. The ion beam has the Bragg peak characteristic, and deposits the ion beam energy inside material. It would be possible to kill only the cancer cells without severe damages of normal cells [1, 2]. However, the conventional ion accelerator tends to be huge in its cost and its size. Therefore, laser accelerator has been proposed as an alternative one [3]. Laser driven particle accelerator is expected to contribute to the development of compact cost-effective accelerators. However, there are various issues in laser particle acceleration at present. The issues in the laser ion acceleration include the ion beam divergence, the energy spectrum control, the energy efficiencies from the laser to the ions [4], the ion beam collimation [2, 5-9] and the ion beam bunching [2]. The energy efficiency from the laser to ions was improved by a solid target with a fine sub-wavelength structure [8, 9] or by a near-critical density gas plasma [2].

In this paper, we study on an improvement of the quality of the ion beam in the laser-driven accelerator, and especially on the ion beam collimation. The ion beam collimation is realized by the holes behind the solid target in this paper [5-9].

Figure 1 presents the target model employed in this paper. A laser-produced proton beam is introduced to the solid structured aluminium target. At the target rear surface, larger holes are implemented to collimate the ion beam. The hole size is the order of the ion beam or larger than that for the effective collimation. At the laser side the target in Fig. 1 has many sub-wavelength holes, which contribute to the efficient laser energy absorption [2, 8, 9] and so to contribute to create the collimation.
field effectively. In this paper, we performed 2.5-dimensional particle-in-cell simulations [10] to study the ion beam collimation.

In addition to the collimation device in Fig. 1, S. Lund and his colleagues have proposed another collimation device using many thin foils [11]. The thin foils prevent the electron return current and also shields the ion beam self charge by the mirror charge so that the ion beam self magnetic field contributes to the ion beam collimation.

2. Simulation model for ion beam collimation

Figure 1 presents our particle simulation model for the ion beam collimation. The simulation box is 60 $\lambda$ in the longitudinal direction and 80 $\lambda$ in the transverse direction. The laser wave length $\lambda$ is 1.053 $\mu$m, the laser intensity is $1.0 \times 10^{19} \sim 1.0 \times 10^{20}$ W/cm$^2$, the laser pulse duration 100fs and the laser spot diameter 50.0 $\lambda$. The laser transverse and temporal profiles are in the Gaussian distribution.

The aluminium target density has a linear gradient scale from $0n_c$ to the maximum density of $462n_c$ with the linear density gradient over the target thickness in $x$. Here $n_c$ is the critical density. The laser illuminates the target from the left. The other parameter values are shown in Fig. 1. At the target rear the transverse TNSA (target normal sheath acceleration) electric field is generated as shown in Fig. 2 [5, 6].

The incoming proton beam is produced by a laser plasma interaction beforehand. This beam diameter is 10 $\lambda$. The hole diameter at the thin film target is larger than that of the ion beam. The distributions of the original proton beam divergence angle is about -10~10 degrees.

3. Ion beam collimation

Figure 2 shows the simulation results of the transverse direction electric field generated by the laser irradiation. The electric field required for the collimation of the ion beam is generated between the walls very clearly.

Figure 3 shows the results for the proton beam collimation. Initially the proton beam had the wide angle divergence (solid line). If the collimation device was not used, the angle divergence was increased as shown in Fig. 3(b) (short-dotted line). However, when the collimation device was employed, the angle divergence was reduced successfully as shown in Fig.3(c) (long-dotted line) and the proton beam width was kept short as shown in Fig. 4. Full width at half maximum is 1.01 degree as shown in Fig.3(c) (long-dotted line).

Figure 4 shows the results for the spatial distribution of the protons. If the collimation device was not used, the proton beam width was increased as shown in Fig. 4(b). However, when the collimation device was employed, the proton beam width was kept thin as shown in Fig.4(c).
We also examine the effect of laser intensity on the collimation. Figure 5 shows the results for the divergence angle distributions for the proton beam at 400fs at the laser intensity of (a) $1.0 \times 10^{19}$ W/cm$^2$, (b) $5.0 \times 10^{19}$ W/cm$^2$ and (c) $1.0 \times 10^{20}$ W/cm$^2$. At the laser intensity of $1.0 \times 10^{19}$ W/cm$^2$, the electric field required for the collimation of the ion beam is not enough to generated between the wall. The collimation device does not reduces well the proton transverse divergence as shown in Fig. 5(a). At the laser intensity of $1.0 \times 10^{20}$ W/cm$^2$, the excessive electric field is created between the walls; the ion beam is over focused, and the focused beam protons diverge again after the focusing as shown in Fig. 5(c). At the laser intensity of $5.0 \times 10^{19}$ W/cm$^2$, the collimation device reduces the proton transverse divergence successfully as shown in Fig. 5(b) (solid line).

Figure 6 shows the results for the spatial distributions of the protons at 400fs at the laser intensities of (a) $1.0 \times 10^{19}$ W/cm$^2$, (b) $5.0 \times 10^{19}$ W/cm$^2$ and (c) $1.0 \times 10^{20}$ W/cm$^2$. The arrows in Fig. 6 indicate the velocity direction of typical protons.
4. Conclusions
We proposed the collimation device in intense laser plasma interaction. The simulation results demonstrated that the collimation device reduced the proton divergence successfully. We found that there is an optimum value for the laser intensity in the thin film target collimation device.

Acknowledgements
This study is partly supported by MEXT, JSPS, CORE (Center for Optical Research and Education, Utsunomiya Univ.), ASHULA project (JSPS Asia Core to Core Program: Asian Core Program for High Energy Density Science Using Intense Laser Photons), and ILE / Osaka University.

References
[1] Bulanov S V and Khoroshkov V S 2002 Plasma Phys. Rep. 28 453
[2] Kawata S, Izumiyama T, Nagashima T, Takanao M, Barada D, Kong Q, Gu Y J, Wang P X, Ma Y Y and Wang W M 2013 Laser Therapy 22 103
[3] Tajima T and Dawson J M 1979 Phys. Rev. Lett. 43 267
[4] Robinson A P, Bell A R and Kingham R J 2006 Phys. Rev. Lett. 96 035005
[5] Sonobe R, Kawata S, Miyazaki S, Nakamura N and Kikuchi T 2005 Phys. Plasmas 12 073104
[6] Miyazaki S, Kawata S, Sonobe R and Kikuchi T 2005 Phys. Rev. E 71 056403
[7] Nakamura M, Kawata S, Sonobe R, Kong Q, Miyazaki S, Onuma N and Kikuchi T 2007 J. Appl Phys 101 113305
[8] Nodera Y, Kawata S, Onuma N, Limpouchm J, Klimo O and Kikuchi T 2008 Phys. Rev. E 78 046401
[9] Takahashi K, Kawata K, Satoh D, Ma Y Y, Barada D, Kong Q and Wang P X 2010 Phys. Plasmas 17 093102
[10] Lasinski B F, Langdon A B, Hatchael S P, Key M H and Tabak M 1999 Phys. Plasmas 6 2041
[11] Lund S M, Cohen R H and Ni P A 2013 Phys. Rev. ST Accel. Beams 16 044202

Figure 6. Spatial distributions of protons at (a) the laser intensity $1.0 \times 10^{19}$ W/cm$^2$, at (b) the laser intensity $5.0 \times 10^{19}$ W/cm$^2$ and for (c) the laser intensity $1.0 \times 10^{20}$ W/cm$^2$. The laser intensity $5.0 \times 10^{19}$ W/cm$^2$ reduces the proton transverse divergence successfully. The arrows indicate the velocity direction of typical protons.