ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPGW042

APPLICATIONS OF COMPACT LASER PLASMA ACCELERATOR (CLAPA) BEAMLINE IN PEKING UNIVERSITY*

D. Y. Li, J. G. Zhu, M. J. Wu, Q. Liao, X. H. Xu, Y. X. Geng, T. Yang, C. C. Li, X. Y. Hu, K. Zhu, J. E. Chen, Y. Y. Zhao, W. J. Ma, H. Y. Lu, C. Lin†, X. Q. Yan,
State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Abstract

Proton beam with energies less than 10 MeV, <1% energy spread, several to tens of pC charge can be stably produced and transported in Compact LAser Plasma Accelerator (CLAPA) at Peking University. The CLAPA beam line is an object–image point analysing system, which ensures the transmission efficiency and energy selection accuracy for proton beams with initial large divergence angle and energy spread. A spread-out Bragg peak (SOBP) is produced with high precision beam control, which is essential for cancer therapy. Other primary application experiments based on laser-accelerated proton beam have also been carried out, such as proton radiograph, stress testing for tungsten, irradiation of semiconductor sensor to simulate the space irradiation environment and so on.

INTRODUCTION

With the development of ultrahigh intensity laser technique, laser plasma accelerators have made great progresses since the concept was proposed by Tajima in 1979 [1]. Laser driven ion acceleration has become a widely studied research area due to its capability of accelerating ions over a distance of tens of μm by high gradient electrostatic sheath field (~TV/m) produced during the interaction of a high intensity laser with a solid target. During the past decades, several laser driven ion acceleration mechanisms such as target normal sheath acceleration (TNSA) [2-3], radiation pressure acceleration (RPA) [4-5] and breakout afterburner acceleration (BOA) [6] have been studied theoretically and experimentally.

A large number of protons per shot (up to ~ 10^{13}) [7], ultrashort duration (in the ps regime) [8] and low normalized RMS emittance (down to ~ 10^{-3} mm·mrad) [9] provide an innovative approach for its wide potential applications, such as proton radiography [10], generation of warm dense matter [11], material science [12] and cancer therapy [13]. However, a number of issues including the increase of proton energy and charge, reduced shot-to-shot fluctuations and improved proton beam spatial profile quality are still considered as main problems to be resolved. What's more, a beam line must be combined with laser driven ion acceleration to realize a monoenergetic proton beam from laser accelerated wide energy spread proton beam.

Recently, proton beam with different energies less than 10 MeV, <1% energy spread, several to tens of pC charge can be stably produced and transported in Compact LAser Plasma Accelerator (CLAPA) at Peking University. Combined with the CLAPA Beamline, several primary application experiments have been carried out, including generation of spread-out Bragg peak (SOBP) by accumulating mono-energetic proton beams with ±4% energy spread, stress testing for tungsten, irradiation of semiconductor sensor and so on.

CLAPA SYSTEM

Compact LAser Plasma Accelerator (CLAPA) laser system is a Ti: sapphire system based on double CPA technology with a central wavelength of 800 nm. Cross-polarized-wave (XPW) technique has been employed to enhance the laser temporal contrast. In laser driven proton acceleration experiments, the p-polarized laser pulse delivering 1.8 J with a duration of 30 fs was focused on solid targets by an f/3.5 off-axis parabolic (OAP) mirror at an incident angle of 30° with respect to the target normal direction. About 30% of the laser energy was contained in the 5 μm full width at half maximum diameter (FWHM) focal spot, corresponding to the laser intensity of 8×10^{19} W/cm^2. Under the condition of optimum parameters, stable proton acceleration to energies exceeding 10 MeV was achieved [14].

A beam line consisting of quadruple and bending electromagnets has been built as shown in Fig. 1. A quadrupole triplet lens is used to collect and focus wide energy spread proton beam from the laser acceleration section within a divergence angle of ±50 mrad. A 45° dipole magnet is used to select proton energy accurately following the quadrupole triplet lens. The image point of the quadrupole triplet lens is overlapped with the object point of the dipole magnet. At the image point of the diploe magnet, where an adjustable slit is installed to select a proton beam with a particular energy. After being analyzed, the mono-energetic proton beam will be refocused again by a quadrupole-doublet lens to the irradiation platform [15]. Proton beams with different MeV energies and <1% energy spread have been stably transported by CLAPA Beamline [16].

* Work supported by National Basic Research Program of China (Grant No. 2013CBA01502), National Natural Science Foundation of China (Grant Nos. 11025523, 10935002, 10835003 and J1103206) and National Grand Instrument Project (2012YQ030142).
† lc0812@pku.edu.cn

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPGW042

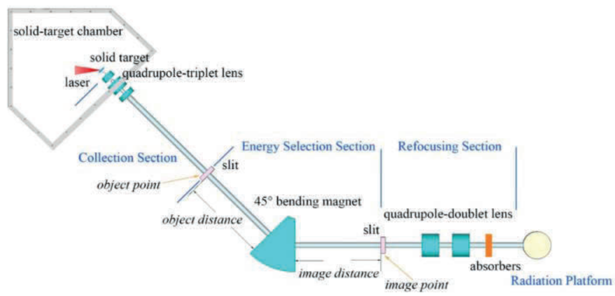

Figure 1: Layout of CLAPA Beamline.

PRIMARY APPLICATION EXPERIMENTS OF LASER PROTON ACCELERATION

Combined with the Beam line, some primary application experiments have been carried out with various proton parameters.

Spread-out Bragg Peak

For cancer therapy, the spread-out Bragg peak (SOBP) is necessary to make the proton beam cover the entire tumour region, enhancing treatment efficiency. Due to the exponential decay energy spectrum distribution of the laser accelerated protons, accumulate SOBP with mono-energetic protons requires higher control accuracy of the beam energy. In the irradiation experiment, a stack of three layers of calibrated HD-V2 radiochromic films (RCF) [17] on the irradiation platform was used to record the three-dimensional dose distributions, with a 30 μm aluminium foil in front of the half of the first RCF. The corresponding energies on each upper and lower half RCF in turn are 0.5 MeV, 1.8 MeV, 3.0 MeV, 3.6 MeV, 4.4 MeV and 4.9 MeV. 110 shots of protons with different energies and 4% energy spread were accumulated. The dose distributions of RCF at different depths are almost equal, which represents the possibility of achieve spread-out Bragg peak with laser accelerated protons beams as shown in Fig. 2.

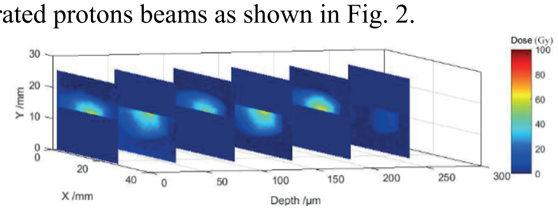

Figure 2: Dose distributions at different depths recorded on the RCF stacks.

Proton Radiography

The laser accelerated proton beam has micrometre scale source size, which is benefiting for the high quality proton image [18]. Space and time evolution of the transient electromagnetic fields has been obtained through proton radiograph by using the broad energy spectrum of the protons and radiochromic film (RCF) stack detectors. Meanwhile, for the static absorption imaging, the mono-energetic proton beam can eliminate the blurring effect caused by the superposition of protons with different energies on the RCF. High spatial resolution proton radiotherapy was achieved using a monoenergetic proton beam transported to the irradiation platform. An ant sample was imaged on the RCF by 10 shots of 5 MeV, 4% energy spread laser accelerated protons as shown in Fig. 3 with a spatial resolution of about 32 μm. The head, wing, and part of the internal tissue structures of the ant can be recognized in the proton images. Due to the high density sensitivity of the proton beams, it can be applied to detect the biological microstructures in medical science.

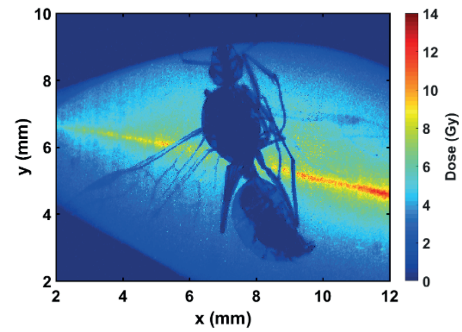

Figure 3: Image of the ant sample on the RCF.

Stress Testing for Materials

Due to the features of ultrashort duration and large proton charge, laser accelerated proton beam can provide a high proton flux irradiation environment to analyze stress testing for materials in the harsh conditions [19], for example tungsten, as the first wall material in a Tokamak device for nuclear fusion. In the experiment, in order to obtain higher charge density, the 1×1 cm tungsten sample was placed 4 cm behind the 5 μm plastic targets. 66 shots of laser accelerated proton beam, with a total of about 10^{10} protons per shot, were deposited on the tungsten sample with 1Hz repetition rate. Scanning electron microscope (SEM) image reveals that after the proton irradiation, the initially smooth surface shows cracks, fractures and holes, which is similar to the stress testing results using conventional irradiation methods as shown in Fig. 4.

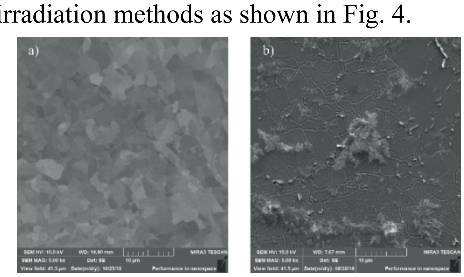

Figure 4: SEM images of the tungsten sample before (a) and after (b) laser accelerated proton irradiation.

Irradiating Semiconductor Sensors for Simulation of Space Irradiation Environment

Laser accelerated protons can be used to simulate the space environment effect. Irradiation test has been done on the AICHI magnetic field sensor of FY3 Satellite for total dose effect. The sensor was fixed at the focal spot of the first quadrupole triplet lens. 25 shots of protons with 5.6 MeV central energy were accumulated on the sensor. A

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPGW042

RCF covered 90 μm thickness aluminium foil was put next to the sensor for dose detection. The frequency response test before and after irradiated with 10 Krad (100 Gray) is shown in Fig. 5. The response decreases significant at frequencies less than 1 Hz.

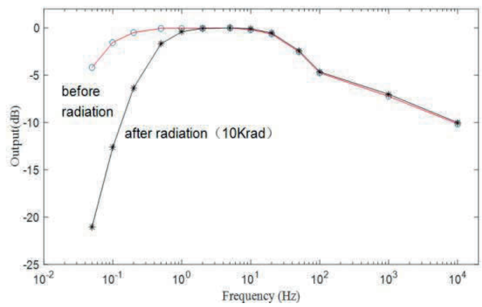

Figure 5: The response of semiconductor sensors corresponding to different frequencies.

CONCLUSION

With CLAPA Beamline, several primary irradiation experiments with laser accelerated proton beams have been carried out. The feasibility of laser protons application in different filed has been verified. In particular, a spread-out Bragg peak (SOBP) is produced, which also revealed the high precision beam control of CLAPA platform.

REFERENCES

[1] T. Tajima and J. M. Dawson, "Laser electron accelerator", *Phy. Rev. Lett.*, vol. 43, no. 4, p. 267, Jul. 1979, doi:10.1103/PhysRevLett.43.267

[2] S. C. Wilks *et al.*, "Energetic proton generation in ultra-intense laser–solid interactions", *Physics of Plasmas*, vol. 8, no. 2, pp. 542-549, 2001, doi:10.1063/1.1333697

[3] P. Mora, "Plasma expansion into a vacuum", *Phy. Rev. Lett.*, vol. 90, no. 18, p. 185002, May. 2003, doi:10.1103/PhysRevLett.90.185002

[4] T. Esirkepov *et al.*, "Highly Efficient Relativistic-Ion Generation in the Laser-Piston Regime", *Phy. Rev. Lett.*, vol. 92, no. 17, p. 175003, Apr. 2004, doi:10.1103/PhysRevLett.92.175003

[5] X. Q. Yan *et al.*, "Generating High-Current Monoenergetic Proton Beams by a Circularly Polarized Laser Pulse in the Phase-Stable Acceleration Regime", *Phy. Rev. Lett.*, vol. 100, no. 13, p. 135003, Apr. 2008, doi:10.1103/PhysRevLett.100.135003

[6] L. Yin *et al.*, "Three-dimensional dynamics of breakout after-burner ion acceleration using high-contrast short-pulse laser and nanoscale targets", *Phy. Rev. Lett.*, vol. 107, no. 4, p. 045003, Jul. 2011, doi:10.1103/PhysRevLett.107.045003

[7] E. L. Clark *et al.*, "Measurements of Energetic Proton Transport through Magnetized Plasma from Intense Laser Interactions with Solids", *Phy. Rev. Lett.*, vol. 84, no. 4, p. 670, Jan. 2000, doi:10.1103/PhysRevLett.84.670

[8] B. Dromey *et al.*, "Picosecond metrology of laser-driven proton bursts", *Nature Communications*, vol. 7, p. 10642, 2016, doi:10.1038/ncomms10642

[9] T. E. Cowan *et al.*, "Ultralow emittance, multi-MeV proton beams from a laser virtual-cathode plasma accelerator", *Phy. Rev. Lett.*, vol. 92, no. 20, p. 204801, May. 2004, doi:10.1103/PhysRevLett.92.204801

[10] M. Borghesi *et al.*, "Laser-produced protons and their application as a particle probe", *Laser and Particle Beams*, vol. 20, no. 2, pp. 269-275, Apr. 2002, doi:10.1017/S0263034602202177

[11] P. K. Patel *et al.*, "Isochoric Heating of Solid-Density Matter with an Ultrafast Proton Beam", *Phy. Rev. Lett.*, vol. 91, no. 12, p. 125004, Sep. 2003, doi:10.1103/PhysRevLett.91.125004

[12] M. Barberio *et al.*, "Laser-accelerated proton beams as diagnostics for cultural heritage", *Scientific Reports*, vol. 7, p. 40415, 2017, doi:10.1038/srep40415

[13] S. D. Kraft *et al.*, "Dose-dependent biological damage of tumour cells by laser-accelerated proton beams", *New Journal of Physics*, vol. 12, p. 085003, 2010, doi:10.1088/1367-2630/12/8/085003

[14] Y. X. Geng *et al.*, "Generating Proton Beams Exceeding 10 MeV Using High Contrast 60TW Laser", *Chinese Physics Letters*, vol. 35, no. 9, p. 092901, 2018, doi:10.1088/0256-307X/35/9/092901

[15] J. G. Zhu *et al.*, "Beam Line Design of Compact Laser Plasma Accelerator", *Chinese Physics Letters*, vol. 34, no. 5, p. 054101, 2017, doi:10.1088/0256-307X/34/5/054101

[16] J. G. Zhu *et al.*, "Experimental demonstration of a laser proton accelerator with accurate beam control through image-relaying transport", submitted to *Phys. Rev. ST Accel. Beams.*

[17] X. H. Xu *et al.*, "Detection and analysis of laser driven proton beams by calibrated Gafchromic HD-V2 and MD-V3 radiochromic films", *Review of Scientific Instruments*, vol. 90, p. 033306, 2019, doi:10.1063/1.5049499

[18] F Nürnberg *et al.*, "Radiochromic film imaging spectroscopy of laser-accelerated proton beams", *Review of Scientific Instruments*, vol. 80, p. 033301, 2009, doi:10.1063/1.3086424

[19] M. Borghesi *et al.*, "Laser-accelerated particle beams for stress testing of materials", *Nature Communications*, vol. 9, no. 1, p. 372, 2018, doi:10.1038/s41467-017-02675-x