Final Report for DOE Grant# ER55150

Project Title: Physics and Novel Schemes of Laser Radiation Pressure Acceleration for Quasi-monoenergetic Proton Generation
PI: Chuan S. Liu
Co-PI: Xi Shao
Location: University of Maryland, College Park, MD 20742, USA
Performance Period: 2012-2016

1. Work Performed:

The main objective of our work is to provide theoretical basis and modeling support for the design and experimental setup of compact laser proton accelerator to produce high quality proton beams tunable with energy from 50 to 250 MeV using short pulse sub-petawatt laser. We performed theoretical and computational studies of energy scaling and Raleigh- Taylor instability development in laser radiation pressure acceleration (RPA) and developed novel RPA-based schemes to remedy/suppress instabilities for high quality quasimonoenergetic proton beam generation as we proposed. During the project period, we published nine peer-reviewed journal papers and made twenty conference presentations including six invited talks on our work. The project supported one graduate student who received his PhD degree in physics in 2013 and supported two post-doctoral associates. We also mentored three high school students and one undergraduate student of physics major by inspiring their interests and having them involved in the project.

The accomplishment of our work can be summarized as follows.

- We found from our work of 2D simulation of laser acceleration of single-ion foil that Rayleigh-Taylor instability significantly limits the acceleration time and consequently the proton energy. [Liu et al. 2012]
- We proposed a novel acceleration concept based on combined scheme of laser radiation pressure acceleration (RPA) and shielded Coulomb repulsion of multi-ion thin foil target [Liu *et al.*, 2013a]. Our theory and simulations not only show that this novel approach overcomes the energy and bandwidth limitations of target normal sheath acceleration (TNSA) and RPA alone by suppressing/delaying Rayleigh–Taylor instability, but also predicted that sub-petawatt lasers at existing facilities (e.g., LLNL) are suitable for performing the experiments.
- We also investigated laser thin gas target acceleration using CO_2 lasers and found that for sufficiently thin gas targets, the proton gas can be effectively accelerated by combining laser radiation pressure and shock acceleration. [He *et al.*,2012]
- To further verify our theoretical explanation and improve the acceleration efficiency, we also investigated a scheme of using polarization switch to increase electron temperature

and thus obtained a 33% boost in proton energy [*Liu et al.*, 2013b]. In addition, the theory of shielded Coulomb repulsion (SCR) model is generalized to 2D case which is validated through comparison with simulation for upto ~200 laser periods.

- We also investigated modifying the foil shape to suppress the expansion and instabilities and to improve the proton beam energy and quality [*Liu et al.*, 2013c]. Using a foil with dual-parabola shape, the ions in the center part of the foil will be separated out accelerated stably with quasi-monoenergetic property. This scheme could reduce the laser intensity by one order of magnitude in achieving the same proton energy.
- We also investigated the 3D effects on the laser proton acceleration with 3D PIC simulation [*Liu et al.*, 2013d]. This makes simulation closer to experimental setting and helps in estimating the proton energy outcome with realistic experimental parameters.
- Moreover, we investigated the dependence of the conversion efficiency from laser to proton energy on different laser spot sizes to support design and experimental setup [*Liu et al.*, 2013e]. It is found that the spot size plays a crucial role in determining the net charge of the electron-shielded carbon ion foil and consequently the efficiency of proton acceleration. We determined the scaling of the proton energy with respect to the laser spot size and obtained an optimal spot size for maximum proton energy flux. [Liu *et al.*, 2014]
- While experimentally applying the acceleration schemes mentioned above, one of the major limitations is that solid foil targets with ideal density and carbon-to-hydrogen ratio are difficult to produce. Therefore, we considered using long-wavelength CO_2 lasers to accelerate targets to reduce the critical density, which enables targets made of gases. In this case, both density (controlled by pressure) and composition (controlled by mixture ratio) could be arbitrarily assigned within a reasonable range. [Liu *et al.*, 2015]

1.1 Detailed Activities:

A. Laser thin multi-ion foil acceleration by a combination of laser radiation pressure acceleration (RPA) and shielded Coulomb repulsion (SCR)

We developed a novel scheme of laser acceleration of multi-ion foil such as foil composed of carbon and proton and demonstrated that carbon layer helps to slow down the development of Rayleigh-Taylor instability of the proton layer [*Liu et al.*, 2013a]. The two-step acceleration consists of an initial Radiation Pressure Acceleration (RPA) and the latter Shielded Coulomb Repulsion (SCR). During RPA, the laser ponderomotive force pushes the electrons forward, and the static electric field due to charge separation accelerates the ions. The protons are more accelerated than the carbon ions due to a larger charge-to-mass ratio. During later acceleration by SCR, the electron layer soon becomes underdense and transparent due to instabilities and the laser is not effective anymore. However, the protons continue to be accelerated by the Coulomb repulsion of the electron-shielded carbon ions. Particle-in-cell simulations with a normalized peak laser amplitude of a_0 = 5 [70 terra watt for 1 micron wavelength laser] show a resulting quasi-monoenergetic proton energy of about 70MeV with the foil made of 90% carbon and 10 hydrogen, in contrast to 10MeV using a single-ion hydrogen foil. Compared with pure hydrogen foil, in laser multi-ion acceleration, the acceleration time of is extended by ~ten times and the obtained proton energy is increased by ~6 times. We developed a theory interpreting the acceleration process and validated the theory with simulation.

This work suggests that employing the laser multi-ion foil acceleration scheme, the sub-petawatt lasers at existing facilities (e.g., Jupiter Laser Facility, Calisto Laser at LLNL) can potentially generate one hundred MeV protons.

B. Thin gas target acceleration by CO_2 laser

There are many experimental advantages for using gaseous proton targets for laser accelerations. We investigated the physics of quasi-monoenergetic protons accelerate ions by laser radiation pressure and shocks in thin gaseous targets. Previous experiments and simulations have demonstrated effective CO_2 laser acceleration of quasimonoenergetic protons from thick gaseous hydrogen target (of thickness tens of laser wavelengths) via hole boring and shock acceleration. We investigated an alternative novel acceleration scheme by combining laser radiation pressure acceleration with shock acceleration of protons in a thin gaseous target of thickness several laser wavelengths. The laser pushes the thin gaseous plasma forward while compressing it with protons trapped in it. We demonstrated the combined acceleration with two-dimensional particle-in-cell simulation and obtained quasi-monoenergetic protons ~44 MeV in a gas target of thickness twice of the laser wavelength irradiated by a circularly polarized CO_2 laser with normalized laser amplitude a_0=10.

C. Enhancement of proton energy by polarization switch in laser acceleration of multi-ion foils

We developed a scheme to significantly increase the energy of quasi-monoenergetic protons accelerated by a laser beam without increasing the input power [*Liu et al.*, 2013b]. This improvement is accomplished by first irradiating the foil several wave periods with circular polarization and then switching the laser to linear polarization. The polarization switch increases the electron temperature and thereby moves more electrons ahead of the proton layer, resulting in a space charge electric field pushing the protons forwards. The scaling of the proton energy evolution with respect to the switching time is studied, and an optimal switching time is obtained. The proton energy for the case with optimal switching time can reach about 80 MeV with an input laser power of 70 TW, an improvement of ~33% compared to the case without polarization switch.

D. Optimization of the energy conversion efficiency from laser to protons among different laser spot sizes

In previous studies of laser acceleration of a hydrogen foil by RPA, we used a Gaussian beam instead of a plain wave simply because it is more realistic. However, with multi-species foil, based on our derivation, one requirement for SCR to be effective is that the electrons should by partially evacuated from the vicinity of center axis, which implies a beam with finite spot size becomes a must, and the spot size plays a crucial role in determining the net charge of the electron-shielded carbon ion foil and consequently the efficiency of proton acceleration. Using a laser pulse with fixed input energy and pulse length impinging on a carbon-hydrogen foil, we found that a laser beam with smaller spot sizes can generate higher energy but fewer quasi-monoenergetic protons [*Liu et al.*, 2013e]. We studied the scaling of the proton energy with respect to the laser spot size and obtained an optimal spot size for maximum proton energy flux. Using the optimal spot size, we can generate an 80 MeV quasi-monoenergetic proton beam containing more than 10^8 protons using a laser beam with power 250 TW and energy 10 J, which are not difficult power and energy parameters to achieve in contemporary high-power laser facilities.

E. Analysis and Comparison of laser accelerated protons in 1D, 2D and 3D geometries

We compared the differences in the scheme of target normal sheath acceleration (TNSA) among different settings of dimensions. Multi-dimensional effects on ion acceleration by a normally incident linearly polarized intense laser pulse interacting with a thin solid target have been investigated numerically with laser parameters commercially available now. We have checked the effects of simulation geometries by running one, two, and three dimensional (1D, 2D, 3D) particle-in-cell simulations [*Liu et al.*, 2013d]. 3D simulation results show that, in the case of using a relatively thick target (in the opaque regime, i.e., 2 μm), electrons spread almost uniformly along two transverse directions. While in the case of using an ultra-thin target (in the relativistic-induced transparent regime, i.e., 100 nm), electrons spread more quickly along the direction orthogonal to the laser polarization direction especially at the early stage. Such an effect causes different estimation of electron temperatures in different simulation geometries. As a result, the maximum proton energy observed in 1D and 2D simulations is, respectively, about 3 and 2 times of that observed in 3D simulation.

F. Exploring the effect of target shaping in laser-produced quasi-monoenergetic proton beams

In radiation pressure dominated laser ion acceleration schemes, transverse target deformation and Rayleigh-Taylor instability develop quickly, break the acceleration structure, limit the final accelerated ion energy, and lower the beam quality. To overcome these issues, we propose a target design named dual parabola targets consisting of a lateral thick part and a middle thin part, each with a parabolic front surface of different focus positions [*Liu et al.*, 2013c]. By using such a target, through interactive laser and target shaping processes, the central part of the thin target will detach from the whole target and a micro-target is formed, resulting in stable acceleration of the central part of the target to high energy with high quality. Furthermore, this target design reduces the laser intensity required to optimize radiation pressure acceleration by more than 1 order of magnitude compared to normal flat targets with similar thickness and density. We demonstrated by two-dimensional particle-in-cell simulations that a quasi-monoenergetic proton beam with peak energy over 200 MeV and energy spread around 2% can be generated when such a solid target (with density $400n_c$ and target thickness $0.5\lambda_0$) is irradiated by a 100 fs long circularly polarized laser pulse at focused intensity 9.2×10^{21} W/cm^2.

G. Spot size dependence of laser accelerated protons in thin multi-ion foils

We present a numerical study of the effect of the laser spot size of a circularly polarized laser beam on the energy of quasi-monoenergetic protons in laser proton acceleration using a thin carbon-hydrogen foil. The used proton acceleration scheme is a combination of laser radiation pressure and shielded Coulomb repulsion due to the carbon ions. We observe that the spot size plays a crucial role in determining the net charge of the electron-shielded carbon ion foil and consequently the efficiency of proton acceleration. Using a laser pulse with fixed input energy and pulse length impinging on a carbon-hydrogen foil, a laser beam with smaller spot sizes can generate higher energy but fewer quasi-monoenergetic protons. We studied the scaling of the proton energy with respect to the laser spot size and obtained an optimal spot size for maximum proton energy flux. Using the optimal spot size, we can generate an 80 MeV quasi-monoenergetic proton beam containing more than 10^8 protons using a laser beam with power 250 TW and energy 10 J and a target of thickness 0.15 wavelength and 49 critical density made of 90% carbon and 10% hydrogen. The work was published in Physics of Plasmas. [Liu *et al.*, 2014]

H. Laser acceleration of protons using multi-ion plasma gaseous targets

We present a theoretical and numerical study of the novel acceleration scheme by applying a combination of laser radiation pressure and shielded Coulomb repulsion in laser acceleration of protons in multi-species gaseous targets. By using a circularly polarized CO_2 laser pulse with a wavelength of 10 μm, much greater than that of a Ti:Sapphire laser, the critical density is significantly reduced, and a high-pressure gaseous target can be used to achieve an overdense plasma. This gives us a larger degree of freedom in selecting the target compounds or mixtures, as well as their density and thickness profiles. By impinging such a laser beam on a carbon-hydrogen target, the gaseous target is first compressed and accelerated by radiation pressure until the electron layer disrupts, after which the protons are further accelerated by the electron-shielded carbon ion layer. An 80 MeV quasi-monoenergetic proton beam can be generated using a half-sine shaped laser beam with peak power 70 TW and pulse duration of 150 wave periods. The work was published in New Journal of Physics. [Liu *et al.*, 2015b]

I. Nonlinear surface plasma wave induced target normal sheath acceleration of protons

The mode structure of a large amplitude surface plasma wave (SPW) over a vacuum–plasma interface, including relativistic and ponderomotive nonlinearities, is deduced. It is shown that the SPW excited by a p-polarized laser on a rippled thin foil target can have larger amplitude than the transmitted laser amplitude and cause stronger target normal sheath acceleration of protons as reported in a recent experiment. Substantial enhancement in proton number also occurs due to the larger surface area covered by the SPW. The work was published in Physics of Plasmas. [Liu *et al.*, 2015a]

J. Radiation Pressure Coupled Snow plow Acceleration of Protons

The radiation pressure acceleration of self-organized double layer in a hydrogen plasma environment and subsequent snow plow acceleration of upstream protons is investigated. The model has features of a circularly polarized CO_2 laser irradiated hydrogen gas jet, of peak density close to relativistic critical density that develops a steepened density peak of width less than a laser wavelength. The radiation pressure pushes electrons to the rear of the peak, forming a moving double layer. The latter reflects up-stream protons up till its velocity, where is the thickness of the foil of proton plasma frequency. The energy of the upstream protons is, where is the proton mass and. For Gaussian temporal profile of the laser and parabolic density profile of the upstream plasma, the proton energy distribution is sharply peaked, producing a mono-energetic beam.

K. Growth of Filament on Plane Uniform Laser in a Plasma in One and Two Dimensions

The growth of one and two dimensional filaments on a plane uniform laser in a plasma due to relativistic mass and ponderomotive nonlinearities with immobile ions is investigated. The intensity distribution of the filament is taken to be Gaussian in transverse coordinate or cylindrical coordinate. In the paraxial approximation we obtain the growth and saturation of the filament intensity. The saturation occurs when filament acquires relativistic intensity. Shorter spot size filaments grow more rapidly but attain lower saturation intensity.

2. Publications and Presentations

2.1 Journal Publications:

1. Liu C S, Shao X, Liu T C, Su J J, He M Q, Eliasson B, Tripathi V K, Dudnikova G, Sagdeev R Z, Wilks S, Chen C D and Sheng Z M, *Laser Radiation Pressure Accelerator for Quasi-Monoenergetic Proton Generation and Its Medical Implications* Progress in Ultrafast Intense Laser Science VIII Springer Series in Chemical Physics vol 103, ed K Yamanouchi, M Nisoli, W T Hill, A W Castleman, J P Toennies, K Yamanouchi and W Zinth (Springer Berlin Heidelberg) pp 177–95 (2012).
2. He M-Q, Shao X, Liu C-S, Liu T-C, Su J-J, Dudnikova G, Sagdeev R Z and Sheng Z-M *Quasi-monoenergetic protons accelerated by laser radiation pressure and shocks in thin gaseous targets*, Phys. Plasmas, 19, 073116, doi:10.1063/1.4740053, (2012).
3. Liu T-C, Shao X, Liu C-S, He M, Eliasson B, Tripathi V, Su J-J, Wang J and Chen S-H, *Generation of quasi-monoenergetic protons from thin multi-ion foils by a combination of laser radiation pressure acceleration and shielded Coulomb repulsion*, New J. Phys. 15, 025026, doi: 10.1088/1367-2630/15/2/025026, (2013a).
4. Liu T-C, Shao X, Liu C-S, Eliasson B, Wang J and Chen S-H, *Enhancement of proton energy by polarization switch in laser acceleration of multi-ion foils*, Phys. Plasmas 20, 103112, doi: 10.1063/1.4826510, (2013b).
5. Liu J L, Chen M, Sheng Z M, Liu C S, Mori W B and Zhang J, *Stable laser-produced quasimonoenergetic proton beams from interactive laser and target shaping*, Phys. Rev. ST Accel. Beams **16**, 121301, doi: 10.1103/PhysRevSTAB.16.121301, (2013c).
6. Liu J-L, Chen M, Zheng J, Sheng Z-M and Liu C-S, *Three dimensional effects on proton acceleration by intense laser solid target interaction*, Physics of Plasmas 20, 063107, doi: 10.1063/1.4812458, (2013d).
7. Liu T-C, Shao X, Liu C-S, Eliasson B, Wang J and Chen S-H, *Spot Size Dependence of Laser Accelerated Protons in Thin Multi-Ion Foils*, Physics of Plasmas 21, 063102 (2014).
8. C. S. Liu, V. K. Tripathi, X. Shao, and T. C. Liu, *Nonlinear surface plasma wave induced target normal sheath acceleration of protons*, Physics of Plasmas 22, 023105 (2015a).
9. T.-C. Liu, X. Shao, C.-S. Liu, B. Eliasson, W. T. Hill III, J. Wang and S.-H. Chen, *Laser Acceleration of Protons Using Multi-Ion Plasma Gaseous Targets*, New Journal of Physics 17, 023018 (2015b).

2.2 Presentations:

1. He M-Q, Tripathi V, Liu C-S, Shao X, Liu T-C, Su J-J and Sheng Z-M, *Ion Acceleration in a Solitary Wave by Laser Pulse with Ramping-up Amplitude,* Annual Meeting of the APS Division of Plasma Physics, 57, 2012.
2. Liu C-S, Liu T-C, Shao X, He M, Eliasson B, Tripathi V, Su J-J, Wang J and Chen S-H, *Post-Laser Radiation Pressure Acceleration: Coulomb Acceleration of Mono-Energetic Protons*

by Electron-Screened Carbon Ions in Laser Irradiated Multi-Ion Targets, Annual Meeting of the APS Division of Plasma Physics, 57, 2012.

3. Liu T-C, Shao X, Liu C-S, He M, Eliasson B, Tripathi V, Su J-J, Wang J and Chen S-H *Design of Laser Profile in Boosting the Energy of Monoenergetic Protons Accelerated by Radiation Pressure and Shielded Coulomb Repulsion,* Annual Meeting of the APS Division of Plasma Physics, 57, 2012.
4. Batpurev T, Cao J, Xie W, Liu T-C, Shao X and Liu C-S, *Comparative Study of Radiation Dosage Distribution and Medical Implication of Quasi-monoenergetic Proton Generated from Laser Acceleration of Ultra-thin Foil,* Annual Meeting of the APS Division of Plasma Physics, 57, 2012.
5. Liu T-C, *The generation of quasi-monoenergetic protons by combination of laser radiation pressure acceleration and shielded Coulomb repulsion*, National Central University, Chungli, Taiwan, Jan., 2013. (**Invited**)
6. C. S. Liu, *Laser Acceleration of Charged Particles in Plasmas,* National Taiwan University, Taipei, Taiwan, Sept., 2013. (**Invited**)
7. C. S. Liu, *Laser Acceleration of Charged Particles in Plasmas,* Indian Institute of Technology, India, Apr., 2013. (**Invited**)
8. Liu C-S, Liu T-C and Shao X, *Laser Acceleration of Proton with Multi-Ion Plasma Gaseous Targets*, Annual Meeting of the APS Division of Plasma Physics **58**, (2013).
9. Liu T-C, Shao X and Liu C-S, *Scaling on Spot Size in Laser Acceleration of Protons Using Multi-Ion Foils*, Annual Meeting of the APS Division of Plasma Physics **58**, (2013).
10. Shao X, Liu T-C, Liu C-S, Eliasson B, Wang J and Chen S-H, *Generation of Monoenergetic Protons by Laser Acceleration of Multi-Ion Foils with Polarization Switch*, Annual Meeting of the APS Division of Plasma Physics **58**, (2013).
11. Liu T-C, Shao X, Liu C-S, Eliasson B, Wang J and Chen S-H, *Generation of Monoenergetic Protons by Laser Acceleration of Multi-Ion Foils with Polarization Switch*, 25th North American Particle Accelerator Conference, (2013).
12. Shao X, Hill W, Liu C-S, Liu T-C, Su J-J, Eliasson B, Chen S-H and Wang J, *Laser Acceleration of Multi-ion Thin Foil Target*, 25th North American Particle Accelerator Conference, (2013).
13. Liu C-S, Liu T-C, He M-Q and Shao X, *Laser Acceleration of Protons in Gaseous Plasma*, Workshop on "Intense Laser and Beam Plasma Interactions" in Honor of Professor Chan Joshi's 60th Birthday, (2013). (**Invited**)
14. Shao X, Liu C-S, Liu T-C, He M-Q and Su J-J, *Generation of Quasi-Monoenergetic Protons by Laser Acceleration*, Seminar, Laboratory for Laser Plasmas in Shanghai Jiao Tong University, (2013). (**Invited**)
15. Liu C-S, *Laser Acceleration of Charged Particles in Plasmas*, Indian Institute of Technology Delhi, (2013). (**Invited**)
16. X. Shao, T.-C. Liu, C.-S. Liu, B. Eliasson, W. Hill, J. Wang and S.-H. Chen, *Laser Acceleration of Protons Using Multi-Ion Plasma Gaseous Targets and Its Medical Implications, 56th Annual Meeting of the APS Division of Plasma Physics*, New Orleans, Louisiana, October, 2014.

17. T.-C. Liu, X. Shao, C.-S. Liu, B. Eliasson, W. Hill, J. Wang and S.-H. Chen, *Spot size dependence of laser accelerated protons in thin multi-ion foils,* 56th Annual Meeting of the APS Division of Plasma Physics, New Orleans, Louisiana, October, 2014.
18. J. Murray, G. Dudnikova, T.-C. Liu, D. Papadopoulos, R. Sagdeev and J.J. Su, *Comparison of short-lived medical isotopes activation by laser thin target induced protons and conventional cyclotron proton beams,* 56th Annual Meeting of the APS Division of Plasma Physics, New Orleans, Louisiana, October, 2014.
19. T.-C. Liu, X. Shao, C.-S. Liu, W. T. Hill, III, B. Eliasson, J. Wang and S.-H. Chen, *Laser Acceleration of Protons Using Neon-Proton Gaseous Targets,* ISUILS13 International Symposium on Ultrafast Intense Laser Science, Jodhpur, India, October, 2014.
20. T.-C. Liu, X. Shao, C.-S. Liu, C. Zhuang, B. Eliasson, J. Wang and S.-H. Chen, *Effects of Laser Spot Sizes in Laser Driven Proton Therapy*, Biophysical Society 59th Annual Meeting, Baltimore, Maryland, February, 2015.

3. Students and researchers supported by the project:

Dr. Chuan Liu and Xi Shao were partially supported by the project. One graduate student of physics major and two post-docs have worked on the project. One undergraduate (Reid Poluhovich) and three high school students (Archis Sathe, Zhu Zhuang and Wang Xie) worked on the project. The works by these high school students were presented as a student poster in the APS Plasma Division conference held in Rhode Island in October, 2012 and in 59th Biophysical Society Annual Meeting.