FINAL REPORT FOR DOE GRANT DE-SC-000-1481

"Relativistic Plasma Physics Using Ultra-intense Lasers"

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Abstract

This report covers research activities, major results and publications supported by DE-SC-000-1481. This project was funded by the DOE OFES-NNSA HEDLP program. It was a joint research program between Rice University and the University of Texas at Austin. The physics of relativistic plasmas was investigated in the context of ultra-intense laser irradiation of high-Z solid targets. Laser experiments using the Texas Petawatt Laser were performed in the summers of 2011, 2012 and 2013. Numerical simulations of laser-plasma interactions were performed using Monte Carlo and Particle-in-Cell codes to design and support these experiments. Astrophysical applications of these results were also investigated.

1. Research Objective

The proposed research aims to study the interaction of ultra-intense laser interaction with high-Z solid thick targets. The scientific objectives include the physics of hot electron acceleration and transport, gamma-ray emission, the creation and transport of electron-positron pairs. To achieve these goals, experiments were conducted using the Texas Petawatt Laser in Austin, Texas, focused with the f/3 dielectric parabola in Target Chamber 1 (TC1) to irradiate thick high-Z solid targets. Numerical simulations were performed to help design the experiments and model the results. Astrophysical applications were also studied.

2. Methodology

A one-week trial run using the TPW was performed in summer 2011, followed by 3 weeks each in the summers of 2012 and 2013. The focusing optic of TPW was upgraded in 2012 with an f/3 dielectric parabola, capable of focusing a PW of laser power to $>10^{21}$W.cm^{-2}. To provide diagnostics for the hot electrons, positrons and gamma-rays, the Rice-UT teams developed several positron-electron-proton (e+e-p) magnetic spectrometers: covering low energy (0.1-0.2T, < 6 MeV), mid-energy (0.5T, 0.5-50 MeV) and high-energy (0.6T, 1-130MeV) using NdFeB magnets, two filter-stack-based gamma-ray spectrometers (FSS) with graded low-Z high-Z filters, a Forward Compton Electron gamma-ray spectrometer (FCES, see below), a scintillator-based gamma-ray spectrometer (SGS), plus a large number of gamma-ray dosimeters deployed on the outside wall of TC1 at various angles. All spectrometers use image plates (IP) to record the spectra, except the SGS which uses PMT and scope tracers. The detector response functions (DRF: energy vs. distance) of the magnetic spectrometers were generated by the (CERN) GEANT4 Monte Carlo code simulations, and subsequently calibrated using the LSU Mary Bird Perkins Cancer Center (MBPCC) clinical beam lines. The SGS module was provided by the PET group at MD Anderson Cancer Center in Houston as part of the Rice-MDA collaboration.

3. Major Results

The Rice-UT team completed 14 TPW shots in 2011, 67 shots in 2012 and 62 shots in 2013. Most of the 2011 and 2012 targets were made of gold, with a few copper and aluminum targets. 40% of the 2013 targets were made of platinum, with the rest gold. Even though the positron signal was marginal in 2011 due to low laser intensity, useful electron and gamma-ray data were obtained in 2011, which helped to improve the diagnostics used in 2012 and 2013. In 2012 and 2013, TPW performance was superior, with ~15% of shots reaching peak intensities ≥ 10^{21}W.cm^{-2}. As a result the electrons got extra hot with many detected above 100 MeV, creating copious amount of gamma-rays and pairs. The major results of the 2012 and 2013 experiments, based on subset of data analyzed so far, are summarized below.

(a) TPW e+/e- ratios agree well with Titan results for Au targets thinner than 3 mm, but rises sharply from 3 to 4 mm, clearly breaking away from the linear trend of thinner targets. This bodes well for even high e+/e- ratio for thicker targets. (b) The positron peak energy ranges from 6 to 23 MeV, while the electron peak energy stays constant at 12-15 MeV. For thin targets the positron energy correlates with proton energy, but is ~ 10 times higher. For all targets, laser forward direction (LF) gives higher e+ energy than target normal direction (TN). (c) As a group, long-narrow rod targets viewed off axis give higher e+/e- ratio than disk targets, rising nonlinearly with rod volume, and their positron spectra are also harder. (d) Absolute positron yield increases with thickness but plateaus after ~ 2 mm. (e) Up to ~10^{11}positrons/str were detected and the maximum e+ density outside the target is inferred to be ~ 10^{15}/cc. (f) The highest measured e+/e- ratios exceed 20% for both disk and rod targets. (g) Some electron spectra exhibit 2 distinct temperatures and kT is usually > ponderomotive temperature. (h) gamma-ray beam angle is measured to be ~ 15^{o} and maximum gamma yield reaches ~9% of laser energy. A Physical Review Letter on the pair results has been submitted (Liang et al 2013) and the gamma-ray results will be submitted to HEDP at year end 2013 (Henderson et al 2013). (i) For Pt targets, the positron peak energy is lower than for Au by ~ 3 MeV for a given thickness. (j) The Pt bremsstrahlung gamma yield is lower than the Au yield. Pt and Au are close in Z and density, but the electrical resistivity of Pt is ~ 5 times higher than Au. Thus the above differences could be related to the higher electrical resistivity, which inhibits the return current carried by conduction electrons. If these results are confirmed, this would be the first evidence that internal electromangetic fields generated by the short-pulse relativistic electrons play a critical role in gamma-ray production and positron acceleration, shedding important new light on the physics of hot electron transport in high-Z thick targets, with many potential applications.

Another major effort in 2013, which is a joint project between Rice and the PET group at MD Anderson Cancer Center in Houston, was to detect laser-created positron annihilation using a scintillator-based gamma-ray spectrometer (SGS). The MD Anderson group provided a highly sensitive PET camera built with mm-scale pixilated LYSO scintillators coupled to position-sensitive PMTs. Dr. Chaguine and Rice students designed a circuit with > ns time delay for PMT trigger to bypass the prompt gamma-rays, and tested the system during our 2013 run. Unfortunately, despite our best shielding efforts, the laser-driven EMP overwhelmed the electronics, and the true gamma signal was too difficult to extract from the recorded scope tracers. The lessons we learned in 2013 will guide our future efforts to pursue this technology. Completion of the analysis of our 2012-2013 data will occupy most of our effort in 2014 as TPW is scheduled to be shut down in 2014 for major upgrades. We hope to renew our experimental effort in 2015.

4. Personnel

The Rice PI is Prof. Edison Liang and the UT co-PI was Prof. Todd Ditmire. Other Rice co-Is include Profs. David Alexander and Matthew Baring. At Rice this grant partially supported 3 graduate students plus a large number of undergraduate students during the summers. At UT this grant partially supported 2 graduate students. Rice Research Scientist Dr. Petr Chaguine also received partial support from this grant. Two Rice postdoctoral fellows, Dr. Xin Wang and Dr. Wen Fu, were partially supported by this grant.

5. Publications

Below is a list of publications through December 2013 partially supported by DOE DE-SC-000-1481.

1. Edison Liang "Dissipation of Thin Current Sheets interacting with Nonlinear Alfven Waves in Relativistic Plasmas," submitted to *Astrophys. J.* ,arXiV 0902:4740 (under revision 2013).
2. Liu, W., Yin, L., Daughton, W., Albright, B., Li, H. and Liang, E. "Particle Energization in 3D Magnetic Reconnection of Relativistic Pair Plasmas", *Physics of Plasmas* 18, 052105 (2011).
3. Hastings, O. and Liang, E. "2.5D PIC Simulations of Relativistic Plasma Collisions", submitted to *Phys. Of Plasmas, arXiV 0803:1201* (under revision 2013).
4. Edison Liang "Intense Laser Pair Creation and Applications." *High Energy Density Physics* 6, 219 (2010).
5. Edison Liang "Applications of Laser-created Dense e+e- Plasmas." *Astrophysics and Space Science* 336, 279 (2011).
6. Alexander Henderson, Edison Liang, Pablo Yepes, Hui Chen, Scott Wilks "Monte Carlo Simulation of Pair Creation Using Petawatt Lasers." *Astrophysics and Space Science*, 336, 273 (2011).
7. Edison Liang "Relativistic, Pair-Dominated and Strongly Magnetized Plasmas." *Research Opportunities in Plasma Astrophysics* p.95, ed. P. Wieser (PPPL , 2010).
8. Edison Liang, Erin Dahlstrom and Kari van Grisven "Compton Cooling of Relativistic Electron-Positron Plasmas and Beams." *Physical Review Letters* to be submitted (2013).
9. Edison Liang, Bruce Remington and Dimitri Ryutov "High Energy Astrophysics Experiments using Ultra-intense Lasers." *Nature Physics* invited review 2011 (under revision 2013).
10. Matthew Levy, Andrea Kemp, Scott Wilks, L. Divol and Matthew Baring "Focusing of Intense Picosecond Laser Pulses in Cone Targets." *Physics of Plasmas*, 18, 103110 (2011).
11. Alexander Henderson, Edison Liang, Pablo Yepes, Hui Chen, Scott Wilks "Monte Carlo Simulation of Pair Creation Using Ultra-intense Lasers." *HEDP*, submitted 2012 (under revision 2013).
12. Edison Liang, Markus Boettcher, Ian Smith "Magnetic Field Generation and Particle Energization in Relativistic e+e- Shear Flows", *Astrophys. J. Lett.* 766. L19 (2013).

13. Devin Taylor, Edison Liang, T. Clarke, Gilliss Dyer, A. Henderson, X. Wang, P. Shagin, N. Riley, K. Serrato, M. Donovan, T. Ditmire "Hot Electron and Gamma Ray Production from Texas Petawatt Laser irradiating mm thick Gold Targets", *High Energy Density Phys.* 9, 363 (2013).
14. Edison Liang, "Gamma-ray and Pair Creation using Ultra-intense Lasers and Astrophysical Applications", *High Energy Density Physics* 8, 38 (2012).
15. Xin Wang, Wei Yu, and Edison Liang, "Electrostatic field acceleration of laser-driven ion bunch by using double layer thin foils" *Physics of Plasmas,* 19, 022101 (2012).
16. Wen Fu, Edison Liang et al, "Increase of the density, temperature and velocity of plasma jets driven by a ring of high energy laser beams", *HEDP* 9, 336 (2013).
17. H.S. Park et al., "Studying astrophysical Collisionless Shocks with counterstreaming plasmas from high power lasers", *HEDP* 8, 38 (2012).
18. J. Ross et al., "Characterizing counter-streaming interpenetrating plasmas relevant to astrophysical collisionless shocks", *Phys. Of Plasmas*, 19, 056501 (2012).
19. E. Liang, et al. "Relativistic e+e-ion Shear Flows and Applications to GRBs", *Astrophys. J. Lett.* in press (2013).
20. E. Liang et al. "Ultra-intense Short-Pulse Pair Creation using the Texas Petawatt Laser", *Phys. Rev. Lett.* submitted (2013).
21. A. Henderson et al. "Ultra-intense Gamma-ray emission by high-Z solid targets irradiated by the Texas Petawatt Laser", *HEDP*, to be submitted (2013).
22. M.J.Grosskopf et al. "Simulation of Laser-Driven, ablated plasma flows in collisonless shock experiments on Omega and the NIF", *HEDP,* 9, 192 (2013).
23. N.L. Kugland, et al. "Self-organized electromagnetic field structures in laser-produced counter-streaming plasmas", *Nature Phys*. 8, 809 (2012).
24. N.L. Kugland, et al. "Visualizing electromagnetic fields in laser-produced counter-streaming plasma experiments for collisionless shock laboratory astrophysics", *Phys. Of Plasmas*, 20, 056313 (2013).
25. M. G. Baring, M. Boettcher and E.J. Summerlin "Multiwavelength Probes of Relativistic Shocks in Blazar Jets" to appear in Proc. ``Fourth Meeting on High Energy Phenomena in Relativistic Outflows," eds. F. M. Rieger et al. *International Journal of Modern Physics*: Conference Series held in Heidelberg, Germany 23 -- 26 July, 2013 (2013).
26. M. C. Levy, S. C. Wilks, M. Tabak and M. G. Baring, "Conservation Laws and Conversion Efficiency in Ultraintense Laser-Overdense Plasma Interactions", *Physics of Plasmas*, 20, 103101, (2013).
27. M. C. Levy, S. C. Wilks and M. G. Baring, "Accelerating Piston Action and Plasma Heating in High-Energy Density Laser Plasma Interactions", *High Energy Density Physics*, 9, 198 (2013).
28. M. Boettcher, M. G. Baring and E.J. Summerlin, "Signatures of Relativistic Shock Acceleration in Blazar Emission", in *Proc. "Fifth International Meeting on High Energy Gamma-Ray Astronomy,"* eds. F. A. Aharonian, W. Hofmann and F. M. Rieger (AIP Conf. Proc. 1505) p. 622, held in Heidelberg, Germany 9 - 13 July, 2012 (2012).
29. E. J. Summerlin and M. G. Baring, "Diffusive Acceleration of Particles at Oblique, Relativistic, Magnetohydrodynamic Shocks", *Astrophys. J.,* 745, 63 (2012).
30. J. M. Burgess, R. D. Preece, M. G. Baring, et al., "Constraints on the Synchrotron Shock

Model for the Fermi GBM Gamma-Ray Burst 090820A", *Astrophys. J*. 741, 24 (2011).
31. M. C. Levy, A. J. Kemp, S. C. Wilks, L. Divol and M. G. Baring, "Focusing of Intense Subpicosecond Laser Pulses in Wedge Targets", *Phys. Of Plasmas*, 18, 103110 (2011).
32. A. B. Garson III, M. G. Baring and H. Krawczynski, "A Suzaku X-Ray Study of the Particle Acceleration Processes in the Relativistic Jet of Blazar Mrk 421", *Astrophys. J.*, 722, 358 (2010).