Enhancing Positron Production Using Front-Surface Target Structures

S. Jiang,[1] A. Link,[1] D. Canning,[2] J. A. Fooks,[3] P. A. Kempler,[4] S. Kerr,[1] J. Kim,[5] M. Krieger,[2] N. S. Lewis,[4] R. Wallace,[1] G. J. Williams,[1] S. Yalamanchili,[4] and H. Chen[1]

[1]Lawrence Livermore National Laboratory
[2]Laboratory for Laser Energetics, University of Rochester
[3]General Atomics
[4]California Institute of Technology
[5]Center for Energy Research, University of California San Diego

Electron–positron pair plasmas generated by laser–solid interactions offer a wide range of potential applications in different fields, including astrophysics, material science, biology, etc. We report a target design that produced a substantial gain in relativistic electron–positron pair production using high-intensity lasers and targets with large-scale microstructures on their surface. Compared to an unstructured target, a selected Si microwire array target yielded a near-100% increase in the laser-to-positron conversion efficiency and produced a 10-MeV increase in the average emitted positron energy under nominally the same experimental conditions.

The experiment was performed on the OMEGA EP Laser System. A schematic diagram of the experimental setup is shown in Fig. 1(a). The target was irradiated using a short-pulse laser with a wavelength of 1.053 μm, an energy of 500 J, and a pulse length of approximately 700 fs. The peak intensity was estimated to be 4.5×10^{20} W/cm^2. Figures 1(b) and 1(c) show scanning electron microscope (SEM) images of two different target structures used in the experiment. Structure 1 was optimized through particle-in-cell (PIC) simulations of the hot-electron temperature prior to the experiment. For comparison, structure 2 showed detrimental effects on electron energies in simulations. The structures were made of Si microwires and were embedded in a thin plastic layer and then glued to a 1-mm-thick Au backing layer. The high-energy electrons generated and guided by the surface structures transport through the thick Au layer and induce pair production. The positron and electron spectra were measured by a spectrometer on the back side of the target along the laser direction (which was also the target normal direction).

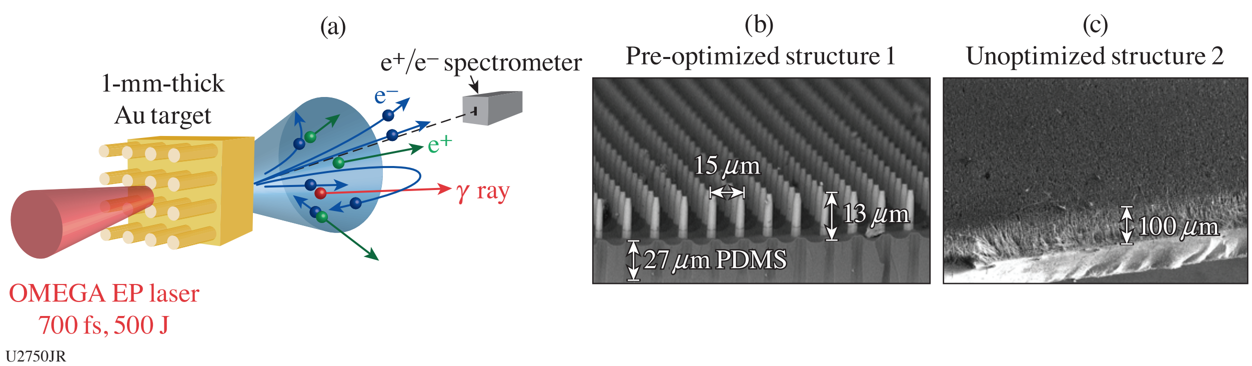

Figure 1
(a) Schematic diagram of the experimental setup; (b) SEM image of the pre-optimized target structure 1; (c) SEM image of the unoptimized structure 2. PDMS: polydimethylsiloxane.

The measured spectra for both types of structured targets as well as a flat unstructured target are shown in Fig. 2. Target structure 1 generated about 50% more positrons than the regular flat target, and its laser-to-positron conversion efficiency increased by ~97%. The spectrum peak also shifted from ~50 MeV for the flat target to ~60 MeV for structure 1. Structure 2 showed fewer as well as much lower energy positrons, in accordance with expectations since the length and spacing of the microwires encumber the laser focusing. The electron spectrum from structure 2 also showed the same trend, in agreement with the positron measurements. The electron spectra from the flat unstructured target and from structure 1 were mutually similar, however, with both having an electron temperature of about 21 MeV.

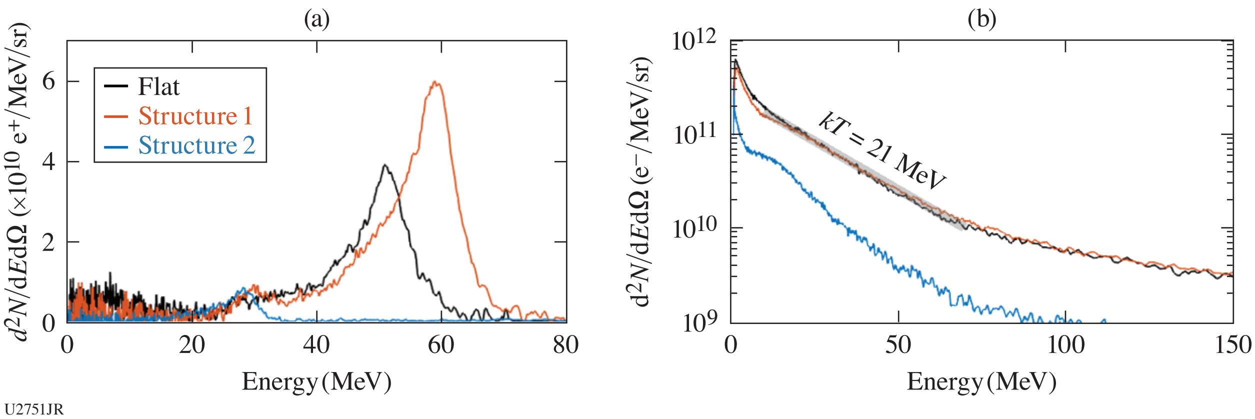

Figure 2
Experimentally measured spectra for (a) positrons and (b) electrons. Different colors indicate the results from different targets under the same laser conditions.

We have performed multiple simulations to model the entire process and explain the observed phenomena. We adopted a two-stage approach since the laser–plasma interaction was modeled with a 2-D Cartesian PIC simulation and the electron transport and pair production process was modeled with a 2-D cylindrical simulation. The simulations successfully reproduced the experimental results. Compared to a flat target, structure 1 generated more high-energy (tens to hundreds of eV) electrons. Two acceleration mechanisms are responsible for these electrons, including the loop-injected direct acceleration,[1] which is associated with any targets having moderate scale-length pre-plasma, and the structure-guided direct laser acceleration, which occurs only with the structured target.[2] We have also found strong Weibel instabilities near the critical-density surface for both target types, which largely widens the electron divergence, explaining why the electron spectra measured at 0° look similar for both the flat and the structure 1 target. The energy of positrons is largely determined by the sheath field on the back side of the target. The simulations suggested that the integrated sheath voltage for structure 1 is about 10 MV higher than for the flat target, which is consistent with the measured energy difference between their positron peaks.

In summary, front-surface target structures have been shown experimentally to substantially enhance the positron yield and energy. The follow-up simulations explain the entire process of how the laser–plasma interaction that is manipulated by the target structure affects the yield and energy of positrons. The agreement between the simulated and experimental spectra indicates the possibility of further target optimization using two-stage PIC simulations.

We thank the OMEGA EP team for laser operation and technical support. This work was performed under the auspices of the U.S. DOE by LLNL under Contract DEAC5207NA27344, and funded by LDRD (#17ERD010). The fabrication of Si microwire arrays was supported through the Office of Science of the U.S. Department of Energy under Award No. DE- SC0004993. Additional support for this work was provided by the Lockheed Martin Corporation (Award 4103810021). We thank the staff at the Kavli Nanoscience Institute at Caltech for their technical assistance with fabrication.

1. A. G. Krygier, D. W. Schumacher, and R. R. Freeman, Phys. Plasmas **21**, 023112 (2014).
2. S. Jiang *et al.*, Phys. Rev. Lett. **116**, 085002 (2016).