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Improved positron generation via laser plasma interaction utilising target front surface architecture: A review

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ABSTRACT

Positrons are electron antiparticles that are often produced in extreme astrophysical events, such as black holes and quasars. Positron production in the laboratory is typically done through plasma-laser interactions, utilizing the Bethe-Heitler process which involves the interaction of high-energy photons with the electromagnetic fields of atomic nuclei. One of the main challenges is to improve the efficiency of laser energy conversion into electron-positron pairs. This research utilizes a silicon microwire-based target surface structure to improve the positron production efficiency in laser plasma interactions. Particle-in-cell (PIC) simulations and experiments with the OMEGA EP laser system show that target structure 1 produces 50% more positrons than a flat surface target, with the conversion efficiency of laser energy to positrons increasing to 97%. This structure enables optimal laser energy focusing, resulting in efficient high-energy relativistic electrons to create electron-positron pairs. The results of this study show significant potential in the development of particle acceleration technology and applications in high-energy physics.

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1. INTRODUCTION

Astrophysical phenomena, including black holes, pulsars, and quasars, are extreme events that produce unusual, high-energy particles, such as positrons, which are the antiparticles of electrons, originating from perilous cosmic rays in space. Comprehending the physical features of positrons is essential for investigating these events. This research is challenging to execute in the laboratory because it requires modern equipment to replicate complicated phenomena in high-energy particle physics. Technologies like high-intensity lasers are required to accelerate electrons to generate gamma rays, which subsequently create electron-positron couples. The laser intensity employed to investigate extreme events in the laboratory can attain a maximum of 10^{20} W/cm², however the requisite greatest laser intensity must achieve a minimum of 10^{22} W/cm² [1].

A straightforward method for creating positrons is via the Bethe-Heitler process. Initially, relativistic electrons are produced for the Bremsstrahlung process. This procedure is conducted in laser plasma interaction (LPI). During the Bremsstrahlung process, electrons rapidly approach materials with a high atomic number (Z). It subsequently generates high-energy photons (gamma rays). Nonetheless, the generation of positrons necessitates a substantial quantity of relativistic electrons. This research paper employs a target structure to enhance the acceleration and amplification of electrons, hence improving the efficiency of electron-positron conversion. Utilising a target structure composed of silicon microwire will enhance the directionality of the laser energy towards the high Z material structure [1].

2. THEORITICAL REVIEW

2.1. Production of Electron-Positron Pairs

Pair production electron-positron pair production is the phenomena in which particle-antiparticle pairs of electrons and positrons are generated when high-energy photons, such as gamma rays, interact with an atomic nucleus of high atomic number.

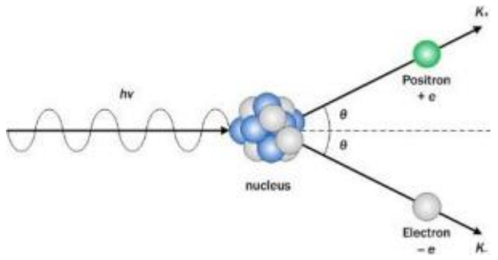


Figure 1. Generation of electron-positron couples.

2.2. Interaction of Laser Plasma with the Bethe-Heitler Process

The Bethe-Heitler process is a quantum phenomenon wherein high-energy photons, such as gamma-ray photons, interact with the electromagnetic field of atomic nuclei to produce electron-positron couples.

2.3. OMEGA EP Laser

The OMEGA EP (extended performance) laser is an enhancement of the OMEGA laser system at the University of Rochester's Laboratory of Laser Energetics (LLE). The initiative encompasses five primary objectives aimed at enhancing and broadening current research endeavours at LLE. These objectives include augmenting high energy density (HED) research capabilities, executing advanced heating experiments in conjunction with OMEGA, innovating new backlighter techniques for HED physics, bolstering the National Ignition Facility (NIF) to optimise its performance, and pursuing ultra-high intensity laser-matter interaction research.

3. RESEARCH METHODS

3.1. Production of Electron-Positron Pairs

Laboratory experiments have successfully produced e-e particle pairs using laser intensity of around 10^{20} W/cm². This method use a high-energy laser beam to accelerate electrons to MeV energy levels, which subsequently collide with a high-Z metal target, such as a metal foil layer. This collision initiates an electromagnetic cascade that generates positrons [2].

This arrangement employs two distinct approaches for positron generation. The initial phase is the trident process, wherein high-energy electrons directly interact with the electrostatic field of the target nucleus to generate electron-positron pairs. The second process is Bremsstrahlung and Bethe-Heitler, wherein accelerated electrons emit gamma rays through Bremsstrahlung, which subsequently interact with the nuclear field to generate electron-positron pairs. This approach facilitates positron production at moderate laser intensities; nevertheless, only a portion of the laser energy is transformed into particle pairs [2].

3.2. Interaction of Laser Plasma with the Bethe-Heitler Process

This process transpires solely if the photon possesses the energy to attain the rest mass energy of the electron, quantified as 2 mc², which is a minimum of 1.022 MeV, to generate the mass of the two particles. A robust nuclear field is crucial for preserving momentum and energy conservation, as the nucleus absorbs a portion of the photon’s momentum during the interaction [3]. Laser plasma interaction refers to the ionisation or generation of substantial positively charged ions and high-energy electrons resulting from the contact of a laser with plasma or gas, as depicted in Figure 2, which displays the simulation of this phenomenon.

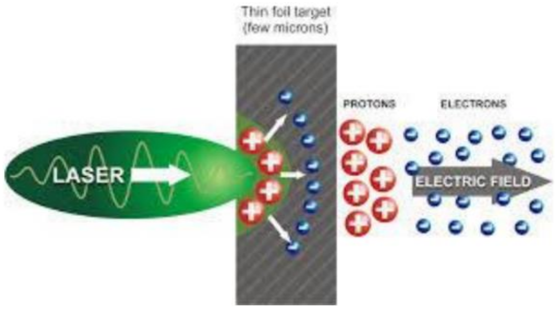


Figure 2. Diagram of laser-plasma interaction simulation.

The Bethe-Heitler process transpires when high-energy Bremsstrahlung photons, produced by the relativistic slowing of electrons in a nuclear field, decay into positron-electron pairs. Bremsstrahlung radiation imparts sufficient energy to photons to generate pairs inside the nuclear field, leading to the creation of positrons [3].

3.3. OMEGA EP Laser

The OMEGA EP laser system is situated in the newly constructed laser room adjacent to the OMEGA target room. The system comprises four beam pathways, two of which provide high-energy capabilities with short pulses. The system can provide up to 2.6 kJ of energy to the target for pulse widths ranging from 10 to 100 ps. At 1 picosecond, the system can produce 1 petawatt of optical power at the designated target. The focal spot size for the short pulse beam encompasses 80% of the energy within a 10 μm radius. The brief pulses can be aimed at the OMEGA target chamber or the new, specialised OMEGA EP target chamber [4].

3.4. Particle-in-Cell (PIC) Simulation

This method is frequently employed to investigate diverse physical phenomena, such as plasma instability, laser-matter interactions, and other applications in plasma physics. The used PIC code, Chicago, is a completely relativistic and electromagnetic PIC code, proficient in executing 1D, 2D, and 3D simulations. Chicago is capable of executing comprehensive kinetic computations when necessary, or fluid-particle simulations when suitable. Chicago's hybrid implicit Particle-in-Cell technique facilitates precise physical simulations of hohlraum blow-off plasmas utilising contemporary computational capabilities. This implicit algorithm facilitates plasma simulations on spatial sizes of several millimetres and temporal scales of tens of nanoseconds [5].

3.5. Experimental Design

Relativistic electron generation, Bremsstrahlung, and pair synthesis occur on the surface of the Au material, which possesses a high atomic number (Z = 79). This procedure is founded on the three-stage Bethe-Heitler principle. The target structure will be affixed directly to the Au surface [1].

The spectrometer will thereafter measure the quantity of electron-positron pairs in the last segment, as seen in Figure 3. The OMEGA EP laser operates at a wavelength of 1.053 μm, delivers an energy of 500 J, and has a pulse duration of approximately 700 fs. 80% of the laser pulse is directed at the 35 μm diameter focal area, with a peak intensity approximated at 4.5×10^{20} W/cm². These experimental results will be contrasted with the PIC simulation results [1].

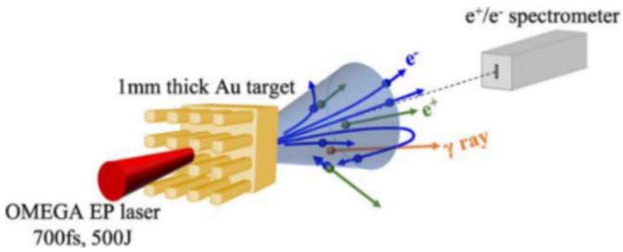


Figure 3. Schematic of experimental design.

The target structures for comparison in this experiment, with the laser intensity directed towards Au, consist of three types: structure 1, structure 2, and flat structure. Structure 1 is an array of silicon microwires (Si) with a diameter of 2 µm, a length of 13 µm, and a transverse center-to-center distance of 15 µm. Concurrently, the unoptimised structure 2 possesses a diameter of 3 µm, a length of 100 µm, and a transverse intercenter distance of 7 µm. Structure 2 exceeds the laser focal depth and possesses insufficient width to serve as the laser focal point, resulting in more frequent obstruction of the laser pulse and the generation of electrons with a diminished energy spectrum. Silicon microwire structure 2 was synthesised on silicon wafers using the vapor-liquid-solid technique, while structure 1 was fabricated by the deep reactive ion etching process. The microwires were subsequently affixed to a ~30 µm polydimethylsiloxane layer and bonded to a 1 mm thick Au layer [1].

3.6. Simulation Technique

The PIC simulation approach is executed in two phases: first, to delineate the LPI stage, and second, to analyse the electron transport process to Au utilising the Chicago code. This occurs due to the constraints of supercomputers in this form of simulation, rendering 3D simulation unfeasible. The LPI simulation process is delineated in two dimensions, specifically x and z, while velocity is quantified in three components: vx, vy, and vz, which are revised at each time step, with the observed region located 5 µm within the target. The electron transport simulation was conducted in a two-dimensional cylindrical shape [1]. The laser parameters employed are same for all three target surface specimens. The purpose of PIC simulation is to analyse an improved efficiency of laser to positron conversion in structure 1.

4. RESULTS AND DISCUSSIONS

4.1. Examination of LPI and Positron-Induced Electron Spectra on Target Structures

In Figure 4, target structure 1 generates 50% more positrons than the flat surface target and enhances the laser to positron conversion efficiency by approximately 97%. The peak quantity of positrons occurs at a photon energy level of around 60 MeV, whereas that of the flat surface is 50 MeV. The unoptimised structure 2 indicates that there is no enhancement in positrons due to the structure's obstruction of laser focussing. Nonetheless, the electron spectra for the flat target and structure 2 exhibit analogous graphs [1].

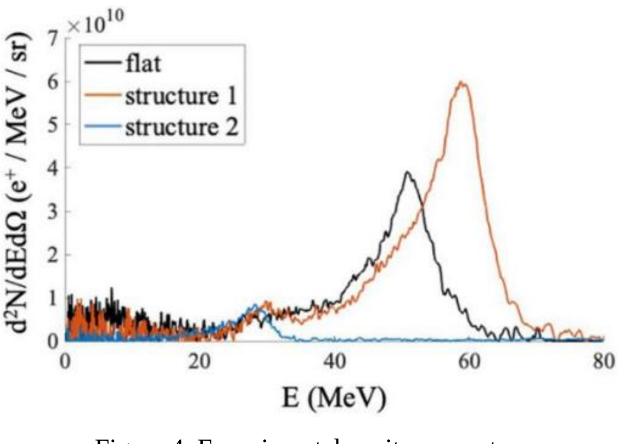
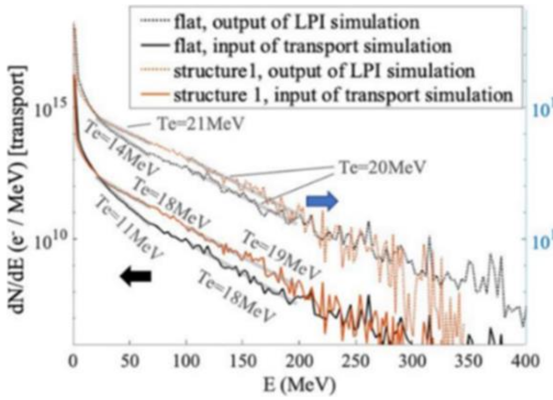


Figure 4. Experimental positron spectra.

Figure 5 illustrates the electron spectra in the LPI simulation; the dashed line represents the original distribution in Cartesian coordinates, while the solid line denotes the distribution transformed into cylindrical coordinates. The right y-axis illustrates the electron distribution concerning energy via the LPI process, whereas the left y-axis represents the electron transport distribution. The units differ due to the plotted coordinates not reflecting the actual geometry. The electron temperature indicated in the spectra plot is labelled, with the simulation employing a temperature of 20 MeV, which closely approximates the experimental temperature of around 21 MeV [1].



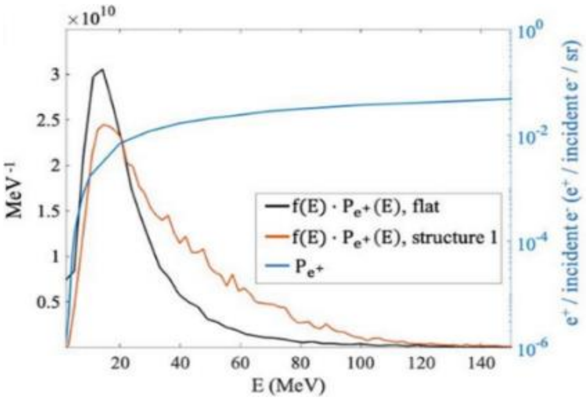
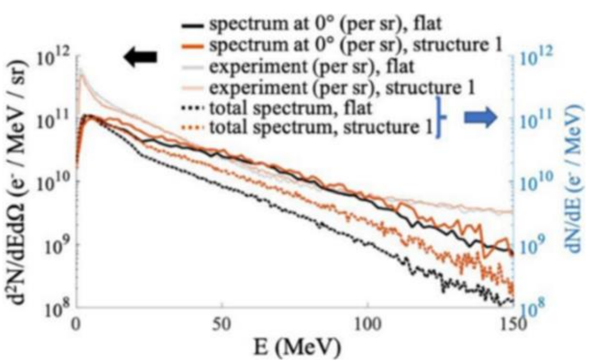


Figure 5. Electron spectra derived from LPI simulation. Figure 6. Electron spectra derived from LPI simulation.

The likelihood of positron creation escalates when the LPI-generated electrons possess energies of approximately 30 MeV and persists in increasing at elevated energies. In Figure 6, (E) ·pe+(E) for the black and red curves both reach a maximum at energies of 15 MeV. The peak likelihood of positron generation in structure 1 is observed within the energy range of 25 – 150 MeV. The flat surface target generates positrons at lower energies, resulting in a lesser positron distribution density compared to structure 1, which creates a greater quantity of positrons than the flat surface. The blue curve in this graph is generated without accounting for the field effect on positrons; it solely demonstrates the potential for pair creation resulting from LPI electrons. Nonetheless, the sheath field effect has minimal impact on high-energy LPI electrons due to the negligible total charge [1].



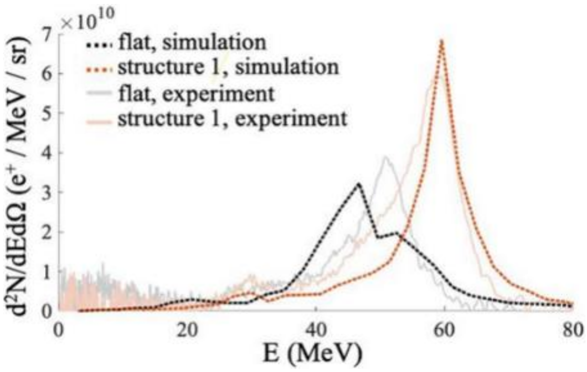


Figure 7. Total electron spectra and spectra at 0° angle. Figure 8. Simulated and empirical positron spectra.

The simulated electron spectra findings closely resemble the experimental electron spectra, with the curves of both spectra overlapping in the energy range of 40 – 110 MeV (Figure 7). Meanwhile, the electron spectra at low energy levels differ between models and experiments due to the slower distribution of electrons observed in experimental measurements. The total electron spectra of structure 1 exhibit a greater quantity of high-energy electrons compared to the spectra at 0º degrees. It is important to note that the positrons generated originate from all the electrons that are displaced in various directions following the bombardment of the gold nucleus.

The comparison of positron distribution at a 0° angle in both simulation and experiment is illustrated in Figure 8. This demonstrates that the quantity of positrons produced by structural target 1 exceeds that of the flat surface target [1].

5. CONCLUSION

The augmentation of positron production via the target surface of the silicon microwire structure in the LPI process has been demonstrated to yield 50% more particles than the flat structure, as evidenced by a comparison of PIC simulation and experimental results. When the silicon microwire structure 1, possessing the ideal focussing spot size, is affixed to the Au target layer, the laser will be concentrated to generate high-energy relativistic electrons, therefore maximising their intensity and facilitating positron creation. In contrast, the unoptimised structure 2 fails to effectively concentrate the laser onto the gold. Consequently, the laser energy is not concentrated to generate intense gamma rays during the pair creation process.

REFERENCES

[1] Jiang, S., Link, A., Canning, D., Fooks, J. A., Kempler, P. A., Kerr, S., Kim, J., Krieger, M., Lewis, N. S., Wallace, R., Williams, G. J., Yalamanchili, S., & Chen, H. (2021). Enhancing positron production using front surface target structures. *Applied Physics Letters*, **118**(9).

[2] Chen, H., Wilks, S. C., Meyerhofer, D. D., Bonlie, J., Chen, C. D., Chen, S. N., Courtois, C., Elberson, L., Gregori, G., Kruer, W., Landoas, O., Mithen, J., Myatt, J., Murphy, C. D., Nilson, P., Price, D., Schneider, M., Shepherd, R., Stoeckl, C., Tabak, M., Tommasini, R., & Beiersdorfer, P. (2010). Relativistic quasimonoenergetic positron jets from intense laser-solid interactions. *Physical review letters*, **105**(1), 015003.

[3] Williams, G. J., Barnak, D., Fiksel, G., Hazi, A., Kerr, S., Krauland, C., Manuel, M.E., Nagel, S. R., Park, J., Peebles, J., Pollock, B. B., Beg, F. N., Betti, R., & Chen, H. (2016). Target material dependence of positron generation from high intensity laser-matter interactions. *Physics of Plasmas*, **23**(12).

[4] Maywar, D. N., Kelly, J. H., Waxer, L. J., Morse, S. F. B., Begishev, I. A., Bromage, J., Dorrer, C., Edwards, J. L., Folnsbee, L., Guardalben, M. J., Jacobs, S. D., Jungquist, R., Kessler, T. J., Kidder, R. W., Kruschwitz, B. E., Loucks, S. J., Marciante, J. R., McCrory, R. L., Meyerhofer, D. D., Okishev, A. V., Oliver, J. B., Pien, G., Qiao, J., Puth, J., Rigatti, A. L., Schmid, A. W., Shoup III, M. J., Stoeckl, C., Thorp, K. A., & Zuegel, J. D. (2008). OMEGA EP high-energy petawatt laser: progress and prospects. *Journal of Physics: Conference Series*, **112**(3), 032007.

[5] Thoma, C., Welch, D. R., Clark, R. E., Rose, D. V., & Golovkin, I. E. (2017). Hybrid-PIC modeling of laser-plasma interactions and hot electron generation in gold hohlraum walls. *Physics of Plasmas*, **24**(6).