Dynamic focusing of laser driven positron jets by self-generated fields

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Abstract

Focusing effect of laser-driven positron jets by self-generated target sheath fields has been observed for the first time experimentally and the results are supported by the computational studies. In the experiment, OMEGA EP short-pulse (0.7 ps, 500 J) irradiates mm-size gold targets with a concave back surface and reference flat-surface targets. Both targets exhibited positrons with quasi-monoenergetic energy peaks while targets with concave curvature also showed increased number of positrons at the detector. The data is consistent with hybrid-PIC simulations confirming that the time-varying electric fields driven by electrons escaping from the target significantly change the trajectories of positrons. These simulations show a small radius of curvature on the rear side increases the relative focusing effect and the positrons to electrons ratio in the escaping plasma. For the smallest radius of curvature, positron jets that are up to 10 times denser can be achieved.

1. Introduction

Laser-driven pair (e⁻ e⁺) production has become of great interest as a fundamental physics topic, as it provides a unique capability to facilitate a relatively high yield of MeV-energy positrons. To date, experiments have generated positrons using high intensity lasers through a two-step process. First, a high intensity laser-plasma interaction accelerates a large number of MeV electrons which subsequently interact with a high atomic number (Z) target producing electron–positron pairs through either the trident or Bethe–Heitler mechanism with electron’s Bremsstrahlung radiation from traversing the target. This can be achieved with two separate targets where a laser pulse interacts with low-density plasma to drive a wakefield to accelerate electrons [1] or by directly irradiating the high Z target [2]. Direct positron generation holds a record for highest positron yield to date at \( N \approx 10^{12} \) and significant progress has been made for defining the experimental scaling parameters: positron yield for varying target geometries and laser parameters including intensity, pulse duration, and energy [3].

Astrophysically relevant collisionless shocks and gamma-ray burst related instabilities are potential applications for laser-driven positron beams. Currently, the overall number produced by current sources is inadequate to see shock-like plasma structure that requires a beam diameter of tens of skin depths. However, there have been considerable efforts to generate charge-neutral electron–positron pair beams in the laboratory for astrophysical instability study. Using quasineutral pair beams generated by laser-wakefield driven electron bunch [1], current-driven instability was measured [4] where the time scale (\( \sim 100 \) fs) of pair beam is limited by electron source. For positron generation with a direct laser interaction, one approach to increase the positron density is to focus the positrons to become a quasineutral beam. This has
been demonstrated previously [5] by applying an external magnetic fields using a Helmholtz coil to collimate expanding positron and electron population. In this experimental demonstration, a focused beam of both electrons and positrons, was observed as the two species have the identical Larmor radii. However, since a much larger number of electrons than positron escape the target, this approach will not lead to a quasi-neutral pair plasma and only a narrow band of energies of each population can be focus via this approach.

In this work, we employ an optimal target geometry to enable positron focusing while electrons independently expand into vacuum or are trapped in the target. This scheme utilizes target sheath fields that are driven as hot electrons simply escape from a target and therefore no external equipment is required to generate focusing fields. Beam focusing of protons with the target normal sheath acceleration (TNSA) mechanism has previously been demonstrated where focused intense protons allow effective isotropic heating of a secondary target up to 10s of eV [6, 7]. As a TNSA proton beam is a slow-moving, quasi-neutral plasma, its beam dynamic differs somewhat from the relativistic \( e^- e^+ \) pair beam case.

The positron beam focusing could also be advantageous to the positron accelerators. Positron wakefield acceleration is a research area that overlaps with high energy physics, as it can be an alternative to conventional radiofrequency acceleration, or used as injector stage for a linear accelerator (lepton collider).

A plasma wakefield can be excited by self-loaded positron bunches, laser driver or other particles including electrons and protons [8–11]. To enable stable wakefield acceleration, laser-driven positron bunches would need to be carefully controlled where the crucial properties of bunches include beam size, energy, density, and duration. As the size and radial momentum of positrons are controlled with focusing effect in this work, optimally focused positron bunch could be injected into plasmas.

This paper is organized as follows. In section 1, the experimental setup and results for the effect of the target’s rear side curvature as well as variations in the laser intensity. In section 2, simulation results for the flat target are presented. In section 3, these simulations results are contrasted with the results for curved target geometry used in the experiment. In section 4, simulation results for a variety of target shapes are shown and finally, in the last section, some concluding remarks.

2. Experimental setup and results

To demonstrate positron jet focusing, the experiment was conducted at Laboratory for Laser Energetics using OMEGA-EP laser with two different types of targets. As shown in the experimental setup, figure 1, one EP beam (500 J, 700 fs, 30 \( \mu \)m FWHM) irradiates the main gold target for pair jet production while the other beam (300 J, 700 fs) is sent to a secondary foil to generate probe protons for radiography. Probe protons deflected by field evolution around the main target are recorded on the radiochromic film stack.

Both lasers have a central wavelength of 1.054 \( \mu \)m. The electron–positron–proton-spectrometer (EPPS) was placed 540 mm behind the primary target to measure pair particle energy distribution with the solid angle of 3 \( \times \) 10\(^{-6} \) steradians. This spectrometer has been used for multiple previous experiments and has shown optimal signal ranges to distinguish positrons and protons [2, 3]. The reference target is a solid Au cylinder with 1 mm diameter and 1 mm length. The target design for beam focusing has a curved (concave) rear surface with 1 mm radius of curvature (shown on the right side of the figure 1).

Absolutely calibrated measurements of electron and positron spectra are shown in figure 2. For the same flat target, different laser energy cases are shown in (a) for 250 J and (b) for 500 J. In both cases, the electron energy distributions show two parts with different slope temperatures, \( T_{\text{hot}} \), fitted with Maxwellians. For the energy range up to \( \sim 7 \text{ MeV} \), \( T_{\text{hot}} \simeq 2.3 \text{ MeV} \) is analogous to what ponderomotive scaling [12], \( T_p = \frac{[1 + \alpha_0^2]^{1/2} - 1}{m_e c^2} \), predicts for the given laser intensity (7 \( \times \) 10\(^9 \) W cm\(^{-2} \)). Here, \( \alpha_0 = \frac{eE_0}{m_e \omega_l c} \) is the normalized laser field amplitude. For the higher energy part (\( E > 10 \text{ MeV} \)), \( T_c \simeq 18 \text{ MeV} \) far exceeds ponderomotive scaling. Maximum electron cut-off energy close to 100 MeV is also far above ponderomotive maximum energy limit, \( E_p = m_e c^2 \alpha_0^2 /2 = 13 \text{ MeV} \).

Similar to these results, higher temperature and cutoff energy than ponderomotive scaling have been measured previously for similar targets and laser parameters (> picosecond duration) [2, 3] where electron temperature marginally agrees with Pukhov scaling [13] and was inferred to arise from laser plasma interactions with an underdense plasma on the front side of the target from the intrinsic prepulse of the laser. Including both parts of the slope, total electron number increased by two as the laser energy doubled from 250 J to 500 J. Along with electrons, positron yield also increased by a factor of 2.5 with an increase in laser energy.

With the same laser energy of 500 J, the curved target case shown in figure 2(c) presents apparent quasi-monoenergetic character which peaks at about 55 MeV. In this narrow energy band, the number of positrons at the detector is significantly higher than the number of electrons in contrast to the flat target shots. This trend is consistently observed in additional shots with curved targets using 10 ps laser pulse.
where positron number at the energy peak increased by 2–4 compared to the reference shots, flat target case.

3. Simulations of a flat target

To validate experimental measurement and explain the dependency of positron beams on target-shape, a laser-driven pair jet was simulated using the implicit hybrid particle-in-cell (PIC) code LSP [14]. The simulation approach is shown in figure 3(a), where hot electrons are injected at the front of a target in 2D cylindrical (axisymmetric) geometry. Laser parameters (500 J, 1 ps, 30 \( \mu \)m, FWHM) and experimentally measured electron spectra characterize hot electron sources such as time-dependent electron density and forward drifting (energy) distribution. For these characterizations, the electron effective temperature, \( T_e \), increases in time and maintains 18 MeV temperature which is experimentally measured value. Energy coupling from laser to electron varies by changing the injected electron densities in repeated simulations until the escaped electron and positron spectra match experimental results where energy coupling of 25% matches best, showing positron peak at 60 MeV. The methodology of injecting an electron source in PIC simulations [7, 15] is well known and broadly used as it gives accurate results while avoiding computationally expensive simulations of laser-plasma interaction. Inside the Au target which is treated as a fluid background, electron transport and the creation of secondary particles are self-consistently described. LSP utilizes the Atzeni-Schavi-Davies formula [16] to calculate collisional stopping and scattering of energetic hot electrons and Lee–More–Desjarlais model [17] to describe conductivities of Au solid plasma. TIGER-series (ITS) code runs inline with the code at every time step, to compute Bremsstrahlung photon generation and secondary emission of positrons based on the Bethe–Heitler cross-section as PIC particles.
Figure 3. Simulation approach to understand positron generation and acceleration. (a) Simulations include the injection of hot electrons characterized from laser parameters, self-consistent electron transport with generation of gamma photons and positrons via Monte Carlo calculation, and particle acceleration by self-generated electromagnetic fields. (b) Snapshots of positron jet density at different times (7 ps, 11 ps, and 15 ps) from the two dimensional ($R-Z$ cylindrical coordinate) simulation. Energy distribution of both electrons and positrons measured in the target inside at 4 ps (c), out of target (flowing jets) at 7 ps (d), and 15 ps (e).

Traverse the target. Particle dynamics including their escape and acceleration are modeled by self-generated electromagnetic fields.

Snapshots of the positron jet generated from a reference flat target are shown in figure 3(b), where densities of different times (7 ps, 11 ps, and 15 ps) are plotted in one frame. In the simulation, the effect of the sheath fields on the escaping electron and positron populations becomes negligible at distance about 3 mm away from the target showing nearly ballistic motion afterwards. The simulation size, longitudinally 4.7 mm, and 3 mm in radius is sufficiently large to capture the dynamics. Energy distributions of both injected electrons and generated positrons are shown inside the target at 4 ps (c), and outside of the target (flowing jets) at both 7 ps (d), and 15 ps (e).

Inside the target, the number of $e^-$ and $e^+$ have about two orders of magnitude difference (shown in figure 3(c)). Most of the electrons are trapped in the target by electric potential built at the target-vacuum interface and less than 10% escape to the vacuum. In contrast, any positron which reaches the target-vacuum interface can escape but the positrons generated inside the target are less energetic than electron, the initial energy came from, and are therefore more collisional than the hot electrons. In vacuum, the number ratio between the two species becomes smaller and interestingly the peak of positrons, similar to a quasi monoenergetic profile, shifts toward high energy as shown in (d) $\sim$ 40 MeV and (e) $\sim$ 60 MeV. Evolving numbers and energies of both particles indicate that there is energy transfer from electron to positron.

The field evolution is presented in figure 4(a) where a strong field is built as many electrons start escaping after transporting through the 1 mm target at 5 ps. This field becomes weaker later as positrons are accelerated (neutralizing some of the charge imbalance) while additional surface conductivity of the target spreads the charge out more uniformly across the entire target surface, decreasing the maximum surface charge density. The remaining charge separation at near the beam front also contributes energy transfer between electrons and positrons as shown in a small peak of electric field at 9 ps. The electron number is much higher than generated positrons as shown in the snapshot of density-lineout (see figure 4(b)) both inside and outside of the target (rear side located at $z = 0$ um) and in a regime where the total number of generated positrons is insufficient to neutralize the target. Phase space ($P_z$ vs $Z$) of $e^-$ and $e^+$ are shown in (c) and (d) where electron velocity continuously decreases when transporting away from the target with some electrons turning around an returning to the target (negative velocity $P_z < 0$ electrons in the vacuum region). In contrast, positrons accelerate in time with the minimum energy that a positron has being upshifted by the electric potential. Since the variations in the electric field and the positrons both move roughly at the speed of light, the positrons which escape early in time (at larger distances in the phase space plot) are accelerated less eventually while those positrons which escape late and trail the escaping electron front show a near uniform increase in momentum.
4. Flat versus curved targets

Simulations comparing the beam dynamics of the flat targets to the curved targets with a curvature radius of 1 mm are shown in figure 5. The primary difference between the two cases (figure 5(a)) is the development of a radial (transverse) electric field from the curvature of the target surface. In both cases, there is a positive radial electric field along the outer radius of the target from the electrons which escape through the target’s sides rather than through the back surface. However, in the curved target case, a radial inward field develops due to the shape which is a focusing field for escaping positrons. Focusing fields start forming when electrons escape the target, roughly 4 ps after the injection due to their transport through the 1 mm target. The fields are maximized at 6 ps then quickly diminish as shown in (b) due to the finite duration of the electron beam. Figure 5(c) shows a radial phasespace distribution at the $z = 0$ plane which due to the influence of the focusing field, positrons for the curved target have negative $v_r$ indicated there is a focusing of the positrons while all of the positrons in the flat case have positive $v_r$ (inherited from the natural divergence of the electron beam in the target) and are always expanding away from the target.

Final positron spectra from two target cases are shown in figure 5(d) where positrons are measured at the end of simulation box using the same solid angle of the experiment. In the curved case, mono-energetic positron peak shifts from approximately 60 MeV to 50 MeV but the number of positrons which reach the detector surrogate more than double. This decrease in mean positron energy is a consequence of the target curvature which exhibits overall somewhat weaker electric fields in longitudinal direction, $E_z$, due to transverse spreading of the space charge along the surface since electrons reach this surface earlier in time. This trend is comparable to experimental measurement (see figures 2(b) and (c)) validating the positron beam focusing due to naturally occurring fields from curved target geometry.
5. Simulations for advanced focusing effects

Beyond experimental modeling, further simulations have been carried out to understand field dynamics with target design and maximize beam focusing effects. First of all, the focusing for targets with different radii of concave curvature are compared. In figures 6(a) and (b), the overall trend of positron density depending on the radius of curvature is shown where the radii are 1 mm and 0.5 mm for (a) and (b) respectively. With the smaller radius of curvature, lower beam divergence and higher density in the focused region, near $Z \sim 0.2$ cm, are seen (b). In addition, positrons escaping from two different surfaces of the target (rear surface and cylindrical wall) are apparently distinguished due to strong field at the target corner: positron bunch below $R = 0.1$ cm in figure 6(b) stems from the target rear side and the part of the bunch expand up to $R = 0.1$ cm at 12 ps. This trend is not clear from the flat target (shown in figure 3) or larger radius case (figure 6(a)). This separation is caused by strong fields (both $E_z$ and $E_r$) arising from the edge of the target. A quantitative comparison is made in the plot (d) where positrons as a function of energy are measured in the range of $0 < R < 400 \mu$m. The total positron number, integration of each plot, shows that the curvature with $R = 0.5$ mm has more than twice of positrons than the flat target case and as was the case from section 2, the overall energy upshift of the positrons is decreased with the improved focusing. The cylindrical shell attached to the curved target (figure 6(c)) also shows interesting results as the positron energy spectrum shifts toward lower energy. This shift is due to hot electrons migrating through shell structure resulting in reduced longitudinal acceleration fields and more focusing effect for lower energy positrons. Positrons from this type of structure that works as a moderator are potentially beneficial for applications such as defect detection and imaging [18].

Figure 7 shows the evolution of the escaped positrons in time as they transport away from the target’s rear surface for the curved target with $R = 0.5$ mm radius of curvature case. In phase space (comparison of $p_r$ and $p_z$) plots, main beam (dense part shown with bright green to yellow) moves toward higher $p_r$ in time as positrons are accelerated by the electric field while positron’s radial momentum ($p_r$) shows varying features as it evolves in time. First at all times, the highest energy positrons, in this example those with much energies greater than 50 MeV, are always diverging from the axis while the lower energy positrons are focused. At 8 ps, the positrons have escaped the target and transport roughly 1.5 mm from the target. Focusing effects maximize as indicated by large negative momentum, $p_r$ which is the focusing direction. Here, the radial electric field developed in pair beam (mostly electrons) can be described with electron momentum equation, $E_z \approx -\nabla P_e/(en_e)$, where $P_e$ and $n_e$ are electron pressure and electron density respectively. Initially when electrons start leaving the curved rear surface, there are more electrons near the target than escaped ones in vacuum, generating a radially positive pressure gradient resulting in focusing electric field $E_z < 0$. However, as positrons move away from the target, the field that positrons experience is
dominantly generated by electron beam which expands radially leading $E_r > 0$. Thus positrons diverge later time as shown in (a) 12 ps. Those positrons have Positron focusing depending on their energy lead to a broad focal length, from the target rear surface to the focused region, spanning from 500 $\mu$m to 1000 $\mu$m, which corresponds to $R$ and 2$R$. Here $R$ is the geometric focal length of target curvature. Thus, for the case of curved target with $R = 750 \mu$m, positrons show strong focusibility in the range of $Z = 750 \sim 1500 \mu$m.

It is worth noting that the role of hot electron parameters is slightly different for the focusing field and the accelerating field. Since the focusing field is strongly affected by an electron pressure near the target surface, both electron density, $n_e$, and electron temperature $T_e$ are important, whereas for acceleration, higher $T_e$ helps electrons overcome self-generated potential and keeps electric fields at positron beam front showing similarity with acceleration field $E \sim T_e/(eL_n)$ at near ion beam front in TNSA beam [19]. This feature is confirmed with test simulations where electron sources with the fixed total energy but different $T_e$, $n_e$ are injected. For example, the source with 4 times higher $T_e$ has 4 times less $n_e$ compared to the other source. The results show a comparable focusing field from both electron sources while the source with a higher $T_e$ keeps stronger acceleration field resulting in higher peak energy of the positron spectrum. Recall that a source with a higher $T_e$ produces more positrons due to BH cross-section [20] dependence on energy. The electron source with $4 \times T_e$ and $\frac{1}{4} \times n_e$ results in 25% increase in positrons inside the target and 70% increase in escaped positrons. Thus, higher $T_e$ arising from the intense laser is overall beneficial. Given laser intensity, additional structure or shaped target can boost electron energy, higher $T_e$, [21, 22] which will be applicable for future work with a similar concept of this work.

Time-dependent focusing of positrons as discussed in figure 7(a) results in time-varying positron to electron ratio in a pair beam. In figure 7(b), positron’s relative numbers to electron are presented where particles measured within the radius of 300 $\mu$m and 600 $\mu$m are shown with black squares and red circles, respectively. In the overall energy range, electrons are dominant, an order higher than positrons, but the number of electrons those energies are near the positron’s monoenergetic peak can be similar to the number of positrons. In this comparison, particles within 20 MeV energy bandwidth centered by positron peak are taken into account. As positrons are focused in time, $e^+ / e^−$ ratio increases where the value of 1 indicates charge neutralization in pair beam. A higher ratio is shown in the range, $R < 300 \mu$m, beam central part, reflecting that positron focusing and neutralization have spatial and temporal variation.

6. Conclusion

We report the first experimental demonstration of focusing of a laser-driven positron beam with self-generated fields and a computational study that explains the controlled beam dynamics. From the experiment carried out using the OMEGA EP short-pulse (1 ps, 500 J), positrons were generated and accelerated with high-temperature electrons, $T_e \sim 18$ MeV. In the measured spectra, the positron number at near the quasi-monoenergetic energy peak increased when using a curved target compared to the flat target case. This result indicates that positrons escaping from the curved target are focused toward the laser axis, on the line of the target center, for a certain distance before they eventually expand. The measurement of proton-radiography indirectly presents that the evolution of fields arising from the pair-jet is highly
dependent on the shape of the target rear side. Experimental results were modeled with hybrid-PIC simulations where the time-varying fields driven by escaping hot electrons significantly change the trajectories of the positrons showing a good agreement with experimentally measured positron spectra.

Further simulations describe a dependency of beam focusability and the charge neutrality of pair beam on the radius of target curvature. With a severe curvature, denser positron beam, overall $\times 2$ and $\times 10$ for specific energy range, are observed compared with the flat target case. Focusing of relativistic positrons appear to be different from heavy particles such as protons in that they show relatively broad focal length spanning from the target geometric focal length, $R$, to $2R$. While positrons escaping the target early time maintain their diverging motion, ones generated relatively later experience focusing fields built at the target rear resulting in separated two positron groups. Beyond the curved shape, the positron beam is effectively manipulated by the additional structures so that the beam density varies and the monoenergetic peak shifts. This self-control of positrons without an extra device can be beneficial for applications that require a narrow range of energy peak, localized positrons, and specific charge neutrality.

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