Generation of high-energy-density collimated electron-positron beam by a linear polarized laser-plasma interaction from a cone

Fei Shan1, Yanyun Ma1,2,3, Xiaohu Yang1, Guobo Zhang1, Lichao Tian1, Jing Jiang1, Xiaoxiao Li1, Long Ma1, Yun Yuan1, Peng Han1, Ye Cui1

1Department of Physics, National University of Defense Technology, Changsha 410073, China
2IFSA Collaborative Innovation Center, Shanghai Jiao Tong University, Shanghai 200240, China
3State Key Laboratory of NBC Protection for Civilian, Beijing 102205, China

Abstract. Electron-positron plasma has attracted much attention recently due to their unique properties. In this paper, we study the acceleration of electron-positron plasma in a cone by using PIC method. The electrons and positrons will be scattered by transverse ponderomotive force during the interaction between laser and electron-positron plasma. A new scheme is proposed to obtain high-energy dense collimated electron-positron plasma by a hollow gold cone. Transverse scattered electrons and positrons are pinched in the gold cone. Both electrons and positrons can be accelerated by ponderomotive force continuously and a dense collimated electron-positron plasma is produced. The energy of electrons and positrons obtained in the cone is much higher than the upper limit of electron energy obtained by ponderomotive force acceleration. The high quality electron and positron beam has great potential value in further research.

1. Introduction
Electron-positron plasma[1] exists widely in universe, and is a very closely associated with the physical phenomenon of astrophysics. Electron-positron plasma is quite different from traditional plasma which attract much attentions. With the development of chirped pulse amplification technology (CPA)[2], it is possible to produce electron-positron plasma in the laboratory, such as in the process of collisions between photons and ultra-intense laser[3], and so on. Up to now, a lot of works have been done on electron-positron plasma, and a lot of theoretical works have been done on the basic linear and nonlinear properties of electron-positron plasma with non-relativistic effects[4, 5]. Shen used circularly polarized laser to irradiate a thin Au target and obtained a high-density positrons[8]. In 2008, Liu used numerical simulation to study the electron-positron plasma waves under the relativistic effects, and many experimental studies are being explored[9].

The electrons and positrons are scattered by the transverse ponderomotive force of laser, and the transverse diffusion intensifies with the increase of the distance. Based on PIC simulation, we study the interactions between ultra-intense laser and electron-positron plasma and near neutral electron-positron beam is obtained. We explore new ways for the global acceleration of electron-positron plasma to break through the ponderomotive force acceleration energy limitation[11]. In this paper, we proposed a scheme to realize the global acceleration of electron-positron plasma by using a gold cone. Particle simulation
results show that a high speed dense collimated electron-positron plasma is produced. The detail acceleration process and acceleration mechanism are studied carefully.

2. Simulation model

In PIC simulation, a linear polarized laser with $\lambda_0 = 1\,\mu\text{m}$ is used. The simulation box is $40\lambda_0 \times 20\lambda_0 \times 1600 \times 800$ cells are used with 40 electrons macroparticles and 40 positrons macroparticles in each cell. The spatial-temporal profile of incident laser is $a = a_0 \exp(-t^2/\tau^2)\exp(-r^2/\sigma^2)$, where $a_0 = 12.4$. $\tau = 12T_0$, is the full width at half maximum (FWHM), where $T_0 = 3.36$ is the laser cycle and spot radius $\sigma = 4\lambda_0$. An opening gold cone is located between $5\lambda_0 \sim 60\lambda_0$, which is filled by a plasma layer of electron density of $100n_e$ and a thickness of $2\lambda_0$. The diameters of the left and right cone openings are $5\lambda_0$ and $1.5\lambda_0$. Respectively. Electron-positron plasma is located between $5\lambda_0 \sim 15\lambda_0$ with a density of $1n_e$, where $n_e = 1.1 \times 10^{27} / \text{m}^3$. The corresponding laser power is larger than 3 PW and the laser energy is about 269J.

![Au cone](image)

Figure 1. Schematic of the interaction between p-polarized laser and electron-positron plasma in a cone

3. Generation of electron-positron beam

Due to the effect of transversal ponderomotive force of laser field, electron-positron plasma accelerated by laser will occur transverse diffusion. Electron-positron beam cannot satisfy the requirement of high quality. It can suppress the space separation phenomenon by using tapered gold cone. Electron and positron reflux in the cone which make spontaneous magnetic field.

It can get electron-positron beam on the right side of cone at $73T_0$ as shown in figure 2. We plot electron density in the top part of the picture with positron density in the other part. In figure 2(a), it is obvious that electron and positron distribution is symmetrical inside the cone at $32T_0$. It is nearly neutral within a certain range of space. Also, the effect of $J \times B$ can be obviously observed, which is important for particles acceleration in initial phase. At $73T_0$, a collimating electron-positron beam is obtained. The radius of the beam is close to the right opening radius of cone as shown in figure 2(b).

![Electron and positron density distributions](image)

Figure 2. Electron and positron density distributions at $32T_0$ (a) and $73T_0$ (b)
After being ejected from the cone, the radius of electron-positron beam becomes larger with time revolution and density becomes lower for absence of pinch effect. The focusing effect of laser disappears after the beam leaving the cone and the energy of electron-positron beam does not have obviously increase. It can keep basic shape unchanged in space with time.

The electron and positron energy spectrum of the beam and momentum phase space at 73T<sub>e</sub> in the whole simulation area are shown in figure 3. According to the statistic of electron and positron energy spectrum, the maximum energy is far beyond the limitation of ponderomotive acceleration (10<sup>20</sup> W/cm<sup>2</sup> ~ 24 MeV), reaching 130 MeV. The energy of the particles in electron-positron beams was calculated respectively in figure 3(a). The electron and positron energy spectrum lines coincide approximately, indicating the consistency of being accelerated by ponderomotive force in space. Figure 3(b) is the momentum phase space diagram of electron and positron. The distance between the peak transverse momentums is 0.5λ<sub>e</sub>. Particles at the front of the laser pulse will get a greater ponderomotive force. Thus, particles with high energy in the front will push other particles to gain energy. So that the whole electron-positron beam is kept in the front of laser. Electron-positron beam moves along the direction of laser because of the pinch effect of cone. When the opening of cone is lager, it is easier for laser to squeeze the particle forward and accelerate them.

![Figure 3. (a) Energy spectra of electron and positron; (b) Momentum P<sub>x</sub> of electron and positron](image)

The left opening radius of cone is similar to the size of the laser focal spot, so that the laser pulse can fully interact with the cone. The oscillation action of the laser electric field makes the effect of J×B obviously, which can greatly improve the particle energy gain. Energy increases linearly due to the ponderomotive force in the cone. It no longer increases significantly after beam leaves the cone from the right opening.

**4. Discussions**

It will further pinch the electron-positron beam to inhibit divergence. Interaction between laser and cone can continue to compress electron-positron plasma. Particle beam density increases under the condition of gold cone. The laser continuously promote the cone to guarantee the sustainable effect of the ponderomotive force on the particle beam. Laser tight focusing effect makes the laser intensity increase, which continues to accelerate the particles to gain more energy.

Electron and positron are bound in cone and move along the direction of laser. Trajectories are concentrated in space. Due to the pinch of Au cone, electron-positron beam transverse size consistent with the Au cone opening radius. The distribution of particles is relatively concentrated. In figure 4(a) shows that divergence angle is about 10<sup>°</sup>. In figure 4(b) shows the energy density of electron. Due to the effect of ponderomotive force, energy density of particles beam can be increased greatly. The maximum energy density reaches 1.06×10<sup>16</sup> J/m<sup>3</sup>.
The laser pulse interacts with the electron-positron plasma, producing current which cause electron and positron to be subjected $J \times B$ force. They deflect in the same direction according to Lorentz’s Law. We plot electric field $E_y (m_\gamma c / e)$ and magnetic field $B_z (m_\gamma / e)$ in figures 5(a) and 5(b). Electron and positron are bound in the cone because of magnetic field. It meets the proportion relationship in the corresponding position when $E_y \equiv c \times B_z$. Multiple factors ensure the quality of beams of stability. When the particles are completely ejected from the cone, the pinch effect of cone will disappear. Energy will be no significantly changed because of transverse diffusion.

Different radius of cone will also affect the electron-positron beam quality. Through the influence of laser focusing effect, maximum energy of electron will be changed as the laser intensity increases. The cone is located in 5μm ~ 60μm with electron-positron plasma in 5μm ~ 15μm. Parameters of laser is not changed. Radius was taken 0.9μm, 1.5μm, 2μm, 2.5μm, 3μm. We get the particles energy with different radius as shown in figure 6. The influence of cone radius is mainly in the effect of laser tight focusing. There is no obvious linear relationship between the radius of cone and energy at the same time. Laser intensity is changed nonlinearly in the process of laser tight focusing.
5. Conclusions
The opening radius of cone affects the focusing effect of laser in cone. The smaller the radius is, the bigger the effect is. Electron-positron beam will gain more energy. After the beam is ejected from the cone, its energy will not change significantly up to 160 MeV. It is far beyond the energy limit of ponderomotive force acceleration in the single-electron theory. The relationship between energy and laser is obtained $E \propto a_0^2$. The pinch effect of cone makes the laser intensity further enhanced so that the particles continue to be accelerated and break through the limitation of ponderomotive force acceleration. There is no clear linear relationship between the radius of cone and energy at the same time. Laser intensity is changed nonlinearly in the process of laser tight focusing.

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