Pair production by high intensity picosecond laser interacting with thick solid target at
XingGuangIII

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An experiment for pair production by high intensity laser irradiating thick solid targets is present. The experiment used picosecond beam of the XingGuangIII laser facility, with intensities up to several $10^{19}\text{W}/\text{cm}^2$, pulse durations about 0.8ps and laser energies around 120J. Pairs were generated from 1-mm-thick tantalum disk targets with different diameters from 1mm to 10mm. Energy spectra of hot electron from target front surface represent a Maxwellian distribution and obey a scaling of $\sim(\lambda^2)^{0.5}$. Large quantity of positrons were observed at the target rear normal direction with a yield up to $2.8 \times 10^9 \text{ e}^+/\text{sr}$. Owing to the target rear surface sheath field, the positrons behave as a quasi-monoenergetic beam with peak energy of several MeV. Our experiment shows that the peak energy of positron beam is inversely proportional to the target diameter.

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1. Introduction

In recent years, positron generation by ultra-intense lasers interacting with high-Z solid targets has become a subject of interest to many research fields [1-10]. As a novel particle source, laser positron beams present some unique properties such as short pulse duration ($\sim\text{ps}$), high energy ($\sim\text{MeV}$), low emittance and high density ($\sim 10^{15} \text{ cm}^{-3}$), has the potential of injectors in electron-positron colliders [11]. Recent researches show that a relativistic pair-plasma can be also generated in the laboratory by this way [12,13]. High temperature pair plasma provides a new platform for the study of many astrophysical phenomena in laboratory [12-14].

When an ultra-intense laser pulse interacts with a solid foil target, there are many energy absorption processes that can generate hot electrons in different directions, such as vacuum heating, resonance absorption and ponderomotive heating. The relationship between the hot electron temperatures at different emission directions and laser intensity depends on the dominating absorption process in the interaction, which is mainly determined by pre-plasma scaling length, laser irradiation direction, laser intensity, laser polarization and also target thickness. Many experimental and theory works have been conducted to investigate these energy absorption processes with different laser and plasma conditions, and, consequently, different scaling laws were obtained, such as Wilks' ponderomotive scaling [16], Haines'

scaling[17], Beg's scaling[18], Tanimoto's scaling[19], Chen's scaling[20] and Pukhov's scaling[21].

Essentially, positrons were generated from relativistic hot electrons propagating in high Z target. There are two main processes to create positrons: the “Trident process” and the “Bethe–Heitler (BH) process.” The trident pair production is a direct interaction between an electron and a nucleus. The BH pairs are generated from the interaction between hot-electron-induced bremsstrahlung photons and nuclei, which are dominant for thick targets due to a much larger cross section [22].

At the end of the year 2013, XingGuang III (XGIII) laser facility at Research Center of Laser Fusion in China was put into operation. The XGIII is the unique facility in the world, which consists of one 1kJ nanosecond laser beam, one 0.7PW picosecond beam and one 0.6PW femtosecond beam [23]. Using the ps laser beam, we carried out two rounds of experiments to explore the positron generation in 2014 and 2015. In this paper, we report some new experiment results for pair production on the XGIII.

2. Experiments

2.1 Experimental Setup

The experiments were carried out on the XingGuangIII(XGIII) laser facility at the Science and Technology on Plasma Physics Laboratory in the Research Center of Laser Fusion. The XGIII was designed for high energy density and high field physics research, and consists of three laser beams. One ns beam was designed to provide maximum laser energy of 1000J in 1ω or 500J in 2ω with pulse duration of about 1-2ns. One ps beam with wavelength of 1053nm, duration from 0.5 to 10ps and peak energy of 370J has a peak power up to 0.7PW. By means of chirped pulse amplification technology, a less than 30fs ultra short beam is generated with peak energy up to 20J and peak power of 0.6PW. The synchronization time and the shot-to-shot timing jitter of the three laser beams are less than 1.32ps. The contrast ratio of ps and fs beams can reach to 10^8 .

The ps laser beam was used in the experiments to reach a high energy and high intensity laser condition. The ps laser was operated in duration of about 0.8ps with energy of 100-180 and beam size of 230mm×230mm. The laser was focused to a spot of 24 μ m (FWHM) containing 30% of the laser energy by an F/2.6 off-axis parabola mirror. The peak intensity was in the range of $1.5\sim 3\times 10^{19}$ W/cm².

Fig. 1 Sketch of pair generation experiment

A schematic of the experiment setup is shown in Fig. 1. The laser was s-polarized and incident on the solid targets with an angle of 15° . The targets were 1mm-thick tantalum cylinders with diameter between 1 and 10 mm. According to our previous theory and simulation research, 1mm-thick tantalum targets can sustain a total positron yield of up to $\sim 10^{10}$ with 100J and 10^{19} W/cm^2 high intensity laser. A electron magnetic spectrometer (EMS) was set in front of the target near the laser reflecting direction with a distance to target point of 690mm. Positrons were measured by a 0.6T electron-positron magnetic spectrometer (EPMS) which placed at the target back normal direction with a distance of 160mm from the entrance to the target point.

2.2 The electron-positron magnet spectrometer

Magnetic spectrometer was widely used in laser plasma interaction experiment for charged particle detection [14,15]. Actually, the EPMS was a dipole magnet, consisting of two neodymium-iron-boride (NdFeB) magnets with a gap of 20mm. In our design, the magnetic field strength was 0.6T, and desired measurement energy range was 1MeV to 60MeV. In the magnetic field of EPMS, electrons and positrons were deflected to different directions, and deflection distance was determined by their kinetic energy. The dispersion curve can be calculated by particle tracing program, shown in Fig.2. The magnetic spectrometer can be calibrated adopting radioactive source and electron accelerator, detail can be found in Ref.[14]. The energy resolution of the spectrometer is determined mainly by dispersion ability at detector plane and input aperture structure. With a 4mm collimating aperture, and the energy resolution of our EPMS was almost round 10% in full detection energy range. The EMS at the target front has the similar structure but 0.2T magnetic field strength, and designed to detect electrons only.

Fig.2 Deflection distance and energy resolution of EPMS at detector planes.

Image plates were used as recorder and placed on both sides of the EPMS. The image plate was sensitive to X-ray, electron and ions, and widely used in laser plasma interaction experiments. There are many researches on responding and attenuation characteristics of image plates, such as Ref.24-27. With these previously works, absolute number of electrons or positrons can be obtained from recorded signal intensity. The uncertainty of electron and positron yield from image plates is mainly comes from calibration error, signal attenuation error and image plate read-out error, bringing the total fractional uncertainty u_{n_e}/n_e to about 20% for each data point.

Due to the high sensitivity of image plates, shielding is very important for positron measurements, which can largely decrease the background radiation from the PW laser interactions. In our experiments, the EPMS was covered by lead with 10cm thickness for the front side and 2cm thickness for the other sides. The image plates were also wrapped in 20 μ m aluminum foil to prevent heavy ions entering the EPMS from the collimator. Typical result of EPMS is shown in Fig. 3.

Fig. 3 Typical result of EPMS. The background noise has been removed in spectra as in Ref.3.

2.3 Hot electron temperature and uncertainty

The spectra of hot electron usually subject to a Maxwellian distribution $N_e = A \exp(-E/kT)$.

The hot electron temperature kT can be determined by fitting the experimental electron spectrum using the distribution function. In our data analysis, a linear regression was used by transform the exponential distribution function to a linear function $\ln(n_e) = -\frac{1}{kT}E + \ln A$.

For one-variable linear regression problem, $y = f(x) = kx + b$ (the data points (x, y) come from measurement, $f(x)$ is desired regression function), a least-squares fitting can be used to calculate the constants k and b of the fitting line function[28].

The slope $k = \frac{N \sum xy - \sum x \sum y}{\Delta}$, and the intercept $b = \frac{\sum x^2 \sum y - \sum x \sum xy}{\Delta}$.

Here, $\Delta = N \sum x^2 - (\sum x)^2$, N is the number of experimental data points (x, y) . Uncertainty

of k can be assessed by $u_k = u_y \sqrt{N/\Delta}$. In the experiment, uncertainty u_y contains three parts,

measurement random uncertainty u_{ym} , system uncertainty u_{ys} and uncertainty u_{yx} from measured value of x . Usually, the three parts are independent, the uncertainty

$$u_y = \sqrt{u_{ym}^2 + u_{ys}^2 + u_{yx}^2}.$$

The uncertainty u_{ym} means the deviation of the measurement value, $u_{ym}^2 = \frac{1}{N-2} \sum_{i=1}^N (y_i - f(x_i))^2$.

Measurement system uncertainty u_{ys} mainly comes from the error of electron yield measured by

image plate. According to the error propagation theory, $u_{ys} = \left| \frac{\partial y}{\partial n_e} \right| u_{n_e} = \frac{u_{n_e}}{n_e}$. The uncertainty u_{yx}

can be concerned by linear fitting function, $u_{yx}^2 = \frac{1}{N-2} \sum_{i=1}^N (k u_x)^2$. The uncertainty in energy

measurement mainly determined by the energy resolution of EPMS, and give $u_x/x \sim 20\%$. Finally,

uncertainty of temperature can be obtained, $kT = -1/k$, and uncertainty $u_{kT} = \left| \frac{\partial kT}{\partial k} \right| u_k = \frac{u_k}{k^2}$.

In our experiments, even the uncertainty of each parts were higher than 15%, but the data shows good coincidence with the exponential distribution, and the uncertainty of temperature is about 10%-15%. The detailed discussion of uncertainty in measurements can be found in Ref.28.

III. Experiment results and discussion

Fig. 4 Plot of the measured temperature of hot electron from target front (red dots) and rear (red squares) surface as functions of laser intensity. Least square fits to the data as red line and red dash line show the scaling of electron temperature on XGIII. Also plotted are the ponderomotive scaling (blue line) in Ref. [16], Haines's scaling (black line) in Refs. [17], and Beg's experimental scaling (green line) in Ref. [18], and Pukhov's scaling (purple line) in Ref. [21].

The measured slope temperature of hot electrons from the target front surface versus the incident laser intensity is shown in Fig.4. The uncertainty of laser intensity is about 25%, which mainly comes from the uncertainties from the measurements of laser energy ($\sim 10\%$), laser pulse length ($\sim 15\%$), and focal spot size ($\sim 20\%$). A least square fit to the experimental points shows that the fast electron temperature scales as $T_{hot}[\text{MeV}] \approx 0.18(I_{18}\lambda_{\mu m}^2)^{1/2}$,

where T_{hot} , I_{18} , and $\lambda_{\mu m}$ are the electron temperature, the laser intensity in units of 10^{18}W/cm^2 , and the wavelength in microns, respectively. The Haines' scaling[17] was deduced from a fully relativistic analytic model which based on energy and momentum conservation. As shown in Fig.4, Comparing with Beg's scaling, our results from the front target are much closer to Haines' scaling and lower than ponderomotive scaling. This may be attributing to the different direction of our measurement with that of the ponderomotive scaling.

Temperature of hot electron from the target rear surface is much higher than that from target front. The heating mechanism of the forward propagation electrons is quite different from the reflection. In our opinion, the electrons is mainly direct accelerated by a channeling laser pulse in near-critical plasma, which proposed by Pukhov[21]. According to Pukhov's scaling, the hot electron temperature grows like the square root of the laser intensity,

$T_{hot}[\text{MeV}] \approx \alpha(I_{18}\lambda_{\mu m}^2)^{1/2}$, where the coefficient α is determined by preformed plasma

scale length L , and $\alpha \approx 1.5$ when $L=30\mu m$. In this scaling, as the decreasing of the scale length, the coefficient α is also decreased. In Chen's experiments [12], the laser contrast

ratios of different facilities are about 10^6 - 10^7 , and the hot electron temperature appears to fit the Pukhov's scaling. Due to the higher contrast ratio of XGIII laser facility ($\sim 10^8$), a shorter scale length was expectant. In our estimation, the scale length of plasma is about $15\mu\text{m}$, which is much shorter than the scale length of the Pukhov's scaling. Considering this difference of the scale length, a corrected coefficient $\alpha \approx 1$ is appropriate for our experiment, according to the simulations of Ref. 21, as shown in Fig.4.

For a high Z thick target with several millimeters, measured electron temperature from rear target will be further increased due to the energy spectrum hardening when hot electron passing through the target. Our Monte Carlo simulation (Fig.5) shows that, after passing through 1mm-thick tantalum, the low energy electrons will largely absorbed, especially energy less than 5MeV, and make the electron temperature raise slightly.

Fig.5 Monte Carlo simulation of energy spectrum handing. Incident electrons obey Maxwellian distribution with temperature of 10MeV, blue line. The green curve shows the electron spectrum after transmitting 1mm-thick tantalum. The linear fitting (red line) shows the temperature of high energy part of transmitted electrons is about 10.9MeV.

Fig. 6 Positron energy spectra for different target diameter of 1mm(a), 2mm(b) and 10mm(c). The dependence of positron peak energy on target diameter is also shown in (d).

Figure 6 shows positron energy spectra for different targets with diameter from 1mm to 10mm. In all shots, the positrons represent a quasi-monoenergetic structure with peak energy of several MeV and energy spread of near 50%. Highest peak energy near 10MeV was obtained with the 1mm diameter target. In our opinion, even for a thick target, the positrons were still accelerated by target rear sheath field, which has been approved by Chen's previous experiments [5]. Different from Chen's result, our experiment shows that the peak energy of positron beam is inversely proportional to the target diameter. Due to the sheath field, positrons also tend to anisotropic distribution in space. In our experiment, at target normal direction, a maximum positron yield up to $2.8 \times 10^9 \text{ e}^+/\text{sr}$ emerges from a 2mm diameter target. We develop a sheath field model to explain the dependence of peak energy of positron on target

diameter and analyze the positron yield, which will be discussed in a separate paper.

IV. Conclusion

A new experiment for laser positron generation on the XGIII laser facility was reported. In the experiment, the hot electron temperature has been found in agreement with an experimental scaling as $\sim(I\lambda^2)^{0.5}$. Positrons accelerated by target rear sheath field represent a quasi-mono-energetic distribution. The peak energy of the positron spectrum has been found to scale linearly with the reciprocal of the target diameter. Maximum positron yield up to 2.8×10^9 e⁺/sr was observed for a 2-mm-diameter target.

These new results show that sheath field acceleration is an efficiency way to get high energy, high density and low emittance positron beams. With this novel laser-based positron source, some potential applications can be put forward, e.g., injector of traditional accelerators, laboratory astrophysics and fundamental positronium studies.

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