Supplementary information: Rotating attosecond electron sheets and ultra-brilliant multi-MeV γ-rays driven by intense laser pulses

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ABSTRACT

This document provides supplementary information to "Rotating attosecond electron sheets and ultra-brilliant multi-MeV γ-rays driven by intense laser pulses". It contains expanded simulation results and more discussions. The signatures of rotation of the relativistic electron sheet and the unique angular distribution for γ-photons are confirmed by the simulations. In the angular momentum transfer process, it is shown that the evolution of γ-photon energy and angular momentum is similar for linearly/circularly-polarized scattering pulses. The influence of the laser intensity a_0, the duration of the scattering laser pulse τ_1, the initial plasma density and the droplet radius are investigated. The robustness of the scheme has been also confirmed by the simulations with consideration of the pre-expansion of the micro-droplet target.

The density and angular distributions of γ-photons at $t = 45T_0$

Figure S1(a) shows the projection of 3D electron trajectories in the yoz plane between $t = 10T_0$ and $t = 60T_0$. Electrons are rotated around the optics axis in the fields of the vortex laser pulse. Figure S1(b) shows the density distribution of high-energy γ-photons with energy > 1 MeV situated at $x = 43.74\lambda_0$, $43.78\lambda_0$ and $43.88\lambda_0$ at $t = 45T_0$. The peak density of γ-photons decreases to $40n_c$ in comparison with that at $t = 35T_0$. Figure S1(c) shows the angular distribution of γ-photons ($E_p > 1$ MeV) at $t = 45T_0$. In the polarization plane xoy and the orthogonal plane xoz, the emission angles are consist with that at $t = 35T_0$. However, the distribution of γ-photon divergence is also split into two fragments at $\phi = 0^\circ$ or 180°. It is confirmed that the unique angular distribution of γ-ray photons may provide new signatures for Thomson backscattering experiments of the generation of γ-ray beams with BAM.

The simulation results in the case of circularly-polarized scattering pulses

Figure S2(a) shows the angular distribution of γ-photons ($E_\gamma > 1$ MeV) at $t = 35T_0$ in the case of circularly-polarized scattering pulses. The angular distribution is circularly-symmetric and the maximum emission angle is 4°, which is consist with the

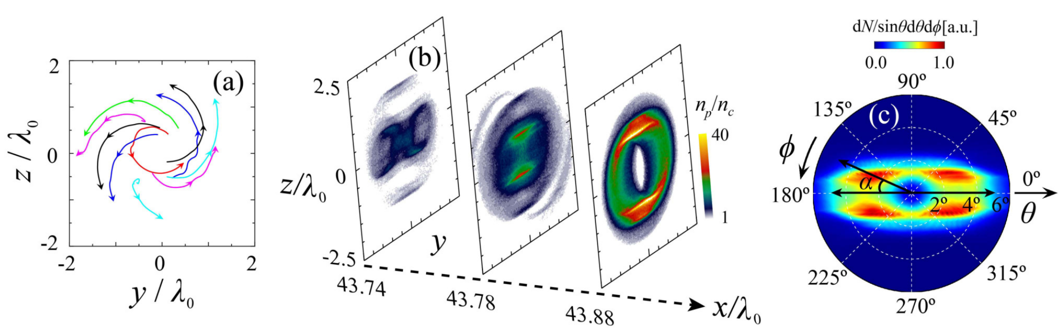

Figure S1. Projection of 3D electron trajectories in the yoz plane. (b) Density distribution and (c) angular distribution of high-energy γ-photons with energy > 1 MeV at $t = 45T_0$. The white and black arrows denote the polarization direction.

$\sqrt{\theta_e^2 + a_1^2/\gamma_e^2} \approx 4.2^\circ$. Therefore, the angular distribution of γ-photons is totally different from that in the case of linearly-polarized scattering pulses. Figure S2(b) shows that the γ-photon energy approaches eventually 100 MeV with an average energy of 16 MeV. However, the peak brilliance of the generated isolated attosecond γ-photons is 2.5×10^{24} photons s^{-1} mrad^{-2} mm^{-2} per 0.1% bandwidth at 4.6 MeV, which is lower than that of the linearly-polarized scattering pulse. We also investigate the evolution of the γ-photon energy and AM in the case of a circularly-polarized Gaussian scattering pulse with the same pulse energy. For a circularly-polarized Gaussian pulse, each photon carries $\hbar$ spin angular momentum (SAM). As shown in Fig. S2(c), the evolution of γ-photon energy and AM is similar in both cases, i.e., 0.037 J and 0.038 J, $2.8\times10^{16}\hbar$ and $3\times10^{16}\hbar$, respectively. This indicates that, the polarization of the scattering laser pulse does not influence the final photon energy and AM, since the energy and AM of the γ-photons originate mainly from the electron sheet.

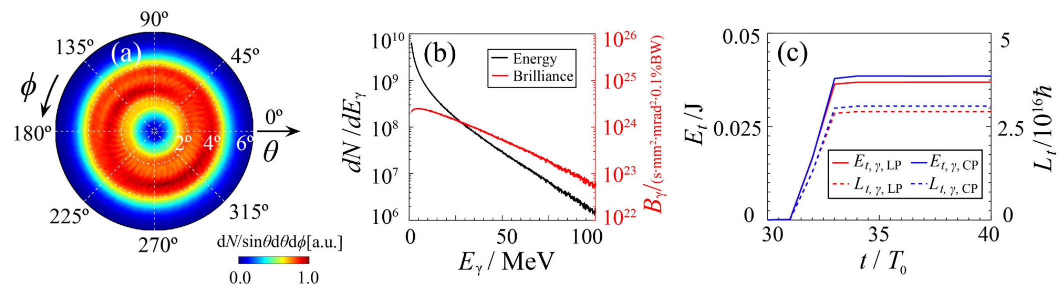

Figure S2. (a) Angular distribution, (b) energy spectrum and brilliance of high-energy γ-photons with energy > 1 MeV at $t = 35T_0$ in the case of circularly-polarized scattering pulses. (c) The evolution of the γ-photon energy and AM in linearly-polarized and circularly-polarized case.

The influence of the laser intensity

The laser longitudinal electric field dominates the electron acceleration in our scheme[1], and the average electron energy $\bar{E}_e \propto a_0$. Meanwhile, the total electron number $N_e \propto a_0$. Therefore, we can obtain the total electron energy $E_{t,e} \propto a_0^2$, which is consistent with the simulation results in Fig. S3(a). Since $E_\gamma = 4n\gamma_e^2/(1+a_1^2/2) \propto a_0^2$ and $N_e \propto a_0$, the total γ-photon energy $E_{t,\gamma} \propto a_0^3$. In the same way, we can also obtain the total AM of electrons or γ-photons, i.e. $L_{t,e} \propto a_0^2$ and $L_{t,\gamma} \propto a_0^3$, which is also consist with Fig. S3(b).

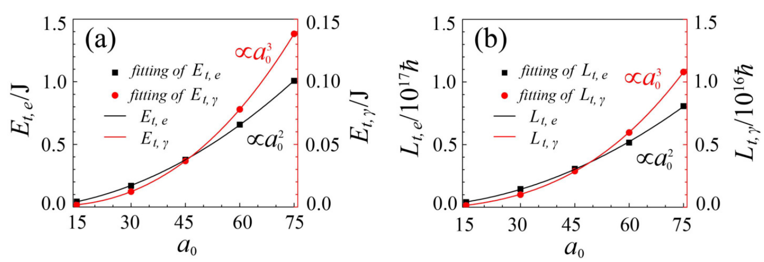

Figure S3. The influence of the laser intensity a_0 on the (a) total energy, and (b) total AM of γ-photons or electrons, respectively.

The influence of the plasma density

In order to investigate the influence of the plasma density, the initial electron density is set to $50n_c$ and other parameters keep unchanged. As shown in Fig. S4(a), an isolated attosecond electron sheet can also been generated when the plasma density increases. The density and energy distribution of electron bunch in the *xoy* plane is similar with that when the initial electron density is $10n_c$. The electron divergence angle is also $\sim 2^\circ$ at $t = 30T_0$, as seen in Fig. S4(c). The γ-photon energy approaches eventually 100 MeV with an average energy of 16.3 MeV, as shown in Fig. S4(d). The peak brilliance of the generated isolated attosecond γ-photons is up to 1.8×10^{25} photons s^{-1} mrad^{-2} mm^{-2} per 0.1% bandwidth at 4.3 MeV. Furthermore, the distribution of γ-photon divergence is also split into two fragments at $\phi = 0^\circ$ or 180°. In the polarization plane *xoy*, the maximum emission angle of γ-photons is 4.2°. In the orthogonal plane *xoz*, the emission angle approaches $\approx 2^\circ$. Therefore, the main simulation results keep unchanged when the initial electron density increases.

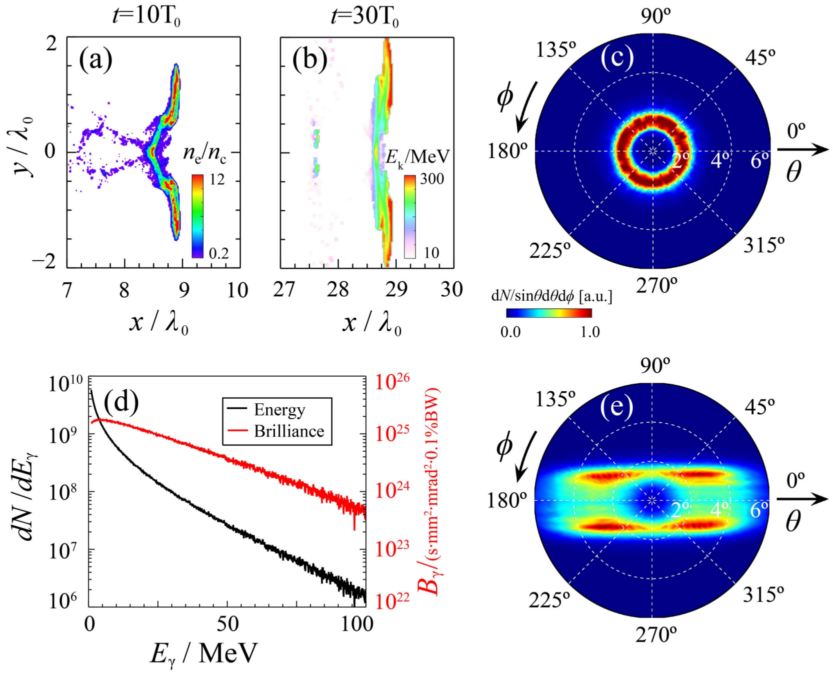

Figure S4. The simulation results for the case that the initial electron density is $50n_c$. (a) Electron density distribution at $t = 10T_0$ and (b) energy distribution at $t = 30T_0$ in the *xoy* plane. (c) The electron divergence angle at $t = 30T_0$. (d-e) The energy spectrum, brilliance, and angular distribution of high-energy γ-photons with energy > 1 MeV at $t = 35T_0$.

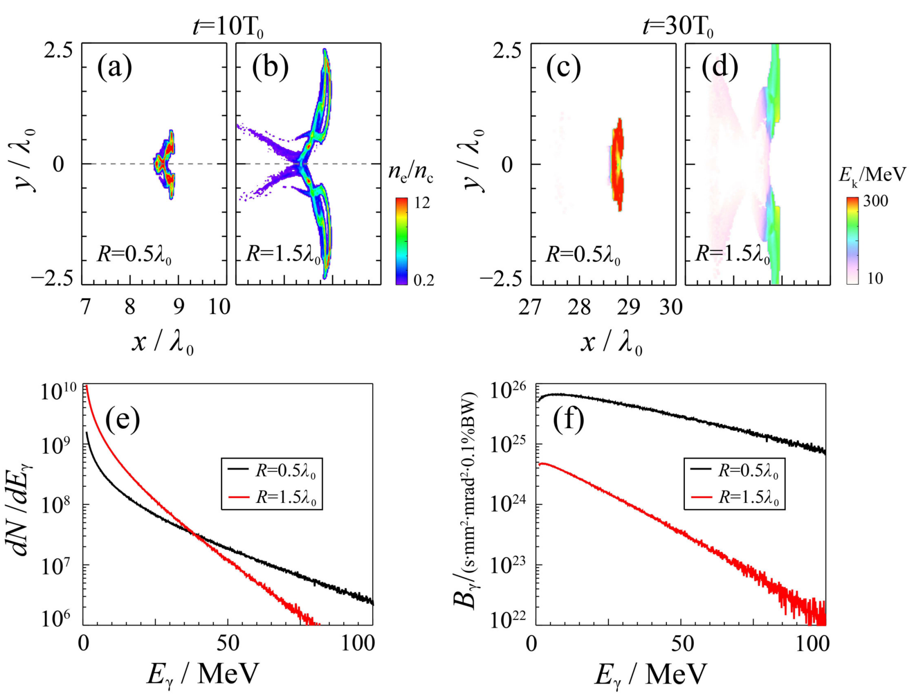

Figure S5. Electron density distribution at $t = 10T_0$ when the droplet radius (a) $R = 0.5\lambda_0$ and (b) $R = 1.5\lambda_0$. Electron energy distribution at $t = 30T_0$ when the droplet radius (c) $R = 0.5\lambda_0$ and (d) $R = 1.5\lambda_0$. The influence of the droplet radius on the (e) energy spectrum and (f) brilliance of γ-photons.

The influence of the droplet radius

Here we keep other parameters unchanged, but increase the droplet radius from $0.5\lambda_0$ to $1.5\lambda_0$. Figure S5(a)-(d) show the influence of droplet radius on the density and energy distribution of electrons. By increasing the droplet radius, it is interesting to see that the transverse size of the isolated electron sheet rises while the electron energy decreases. Figure S5(e)-(f) show the influence of droplet radius on the energy spectrum and brilliance of γ-photons. The γ-photon energy approaches eventually 100 MeV with an average energy of 23.6 MeV when $R = 0.5\lambda_0$, while the maximal γ-photon energy is 80 MeV with an average energy of 11.8 MeV when $R = 1.5\lambda_0$. The peak brilliance of the generated isolated attosecond γ-photons is 4.9×10^{24} photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% bandwidth at 2.4 MeV when $R = 1.5\lambda_0$. The peak brilliance rises to 6.9×10^{25} photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% bandwidth at 8.8 MeV when $R = 0.5\lambda_0$.

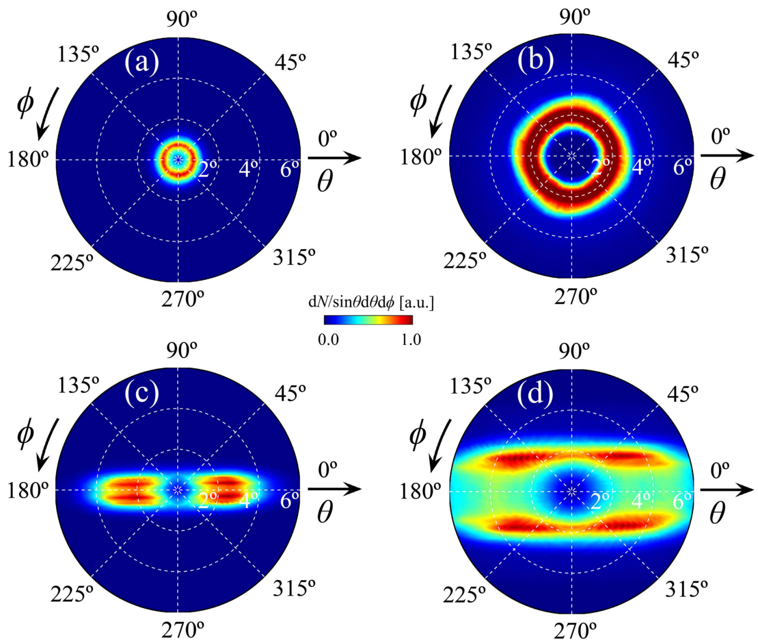

Figure S6. The influence of the droplet radius on the divergence angle distribution of (a-b) electrons and (c-d) γ-photons. The panel (a) and (c) are corresponding to $R = 0.5\lambda_0$. The panel (b) and (d) are corresponding to $R = 1.5\lambda_0$.

Figure S5(a)-(d) show the influence of the droplet radius on the divergence angle distribution of electrons and γ-photons. The inner transverse ponderomotive force F_{tr} increases when the radial coordinate r decreases in the Laguerre-Gaussian laser field. Therefore the electrons are subjected to larger F_{tr} when the droplet radius is smaller. The electron divergence angle is $\sim 1^\circ$ when $R = 0.5\lambda_0$, which is much smaller than that when $R = 1.5\lambda_0$. Furthermore, the distribution of γ-photon divergence is also split into two fragments at $\phi = 0^\circ$ or 180° in both cases. In the polarization plane xoy, the maximum emission angle of γ-photons is 3.5° and 5.5° when $R = 0.5\lambda_0$ and $1.5\lambda_0$. In the orthogonal plane xoz, the emission angle approaches $\approx 1^\circ$ and 2.5° when $R = 0.5\lambda_0$ and $1.5\lambda_0$.

The influence of the preplasmas

Figure S7 presents the simulation results with consideration of the pre-expansion of droplet target. In this simulation, we assume a annular pre-expansion of droplet with the density linearly increasing from 0 to $10n_c$ over a distance of $0.5\lambda_0$. As shown in the figure, the isolated electron sheet is dense, with maximal density up to $12n_c$ at $t = 10T_0$. The maximal electron energy is up to 300 MeV at $t = 30T_0$. As compared to the simulation results without consideration of pre-expansion in the primary manuscript, the electron density and energy are at the same level.

Table 1. The influence of the duration of the scattering laser pulse τ_1 on the total number, total energy, beam angular momentum (BAM), and peak brilliance of γ-photons with $E_\gamma > 1$ MeV.

Duration	$\tau_1 = 3T_0$	$\tau_1 = 6T_0$	$\tau_1 = 10T_0$
Total Number	1.1×10^{10}	2.1×10^{10}	3.5×10^{10}
Total Energy /J	0.019	0.037	0.057
BAM / $\hbar$	1.5×10^{16}	2.8×10^{16}	4.5×10^{16}
Peak Brilliance /photons s^{-1} mrad^{-2} mm^{-2} per 0.1%BW	10^{25} at 4.1 MeV	9.3×10^{24} at 4.3 MeV	3.3×10^{25} at 3.8 MeV

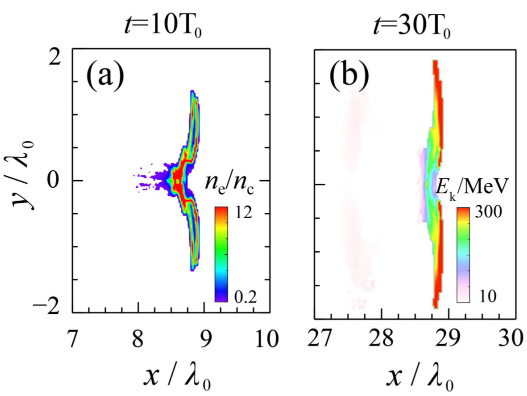

Figure S7. Testing the effect of the pre-pulse. (a) Electron density distribution at $t = 10T_0$ and (b) energy distribution at $t = 30T_0$ in the *xoy* plane when taking into account the target expansion due to prepulse.

The influence of the duration of the scattering laser pulse

In order to investigate the influence of the duration of the scattering laser pulse, τ_1 is set to $3T_0$, $6T_0$ and $10T_0$, and other parameters keep unchanged. The duration of the counter-colliding laser pulse τ_1 determine the photon number when other laser parameters keep fixed. Therefore, τ_1 significantly affects the total number, total photon energy, beam angular momentum (BAM), and thus the energy spectrum and brilliance of attosecond γ-rays via nonlinear Thomson scattering.

Table 1 shows the influence of the duration of the scattering laser pulse τ_1 on the total number, total energy, beam angular momentum (BAM), and peak brilliance of γ-photons with $E_\gamma > 1$ MeV. Figure S8 shows the energy spectrum and brilliance of γ-photons when τ_1 is set to $3T_0$, $6T_0$ and $10T_0$. It is shown that the total number, total photon energy and BAM are proportional to the duration τ_1. As the duration τ_1 increases, the number, energy and BAM of γ-photons also rise. When the duration $\tau_1 = 10T_0$, the peak brilliance of the generated isolated attosecond γ-rays exceed 10^{25} photons s^{-1} mrad^{-2} mm^{-2} per 0.1%bandwidth. For example, the duration of γ-rays in the nonlinear Thomson scattering can be approximately formulated as $\tau_\gamma = \tau_e + \tau_1/(4\gamma_e^2)$. Here, the duration of the γ-ray pulse τ_γ is mainly determined by the electron bunch duration τ_e, since $\gamma_e \gg 1$ for relativistic rotating electron sheets. Furthermore, the maximum emission angle, and the average energy of γ-photons is the same, since these parameters are mainly decided by the rotating attosecond electron sheets. The electron energy and BAM are also transferred to the γ-photons for the same proportion when τ_1 is set to $3T_0$ or $10T_0$.

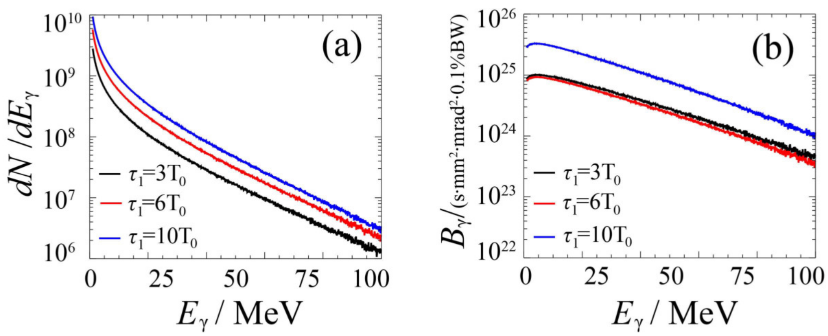

Figure S8. The influence of the duration of the scattering laser pulse τ_1 on the (a) energy spectrum and (b) brilliance of γ-photons with $E_\gamma > 1$ MeV.

References

1. L. X. Hu, T. P. Yu, Z. M. Sheng, J. Vieira, D. B. Zou, Y. Yin, P. McKenna, and F. Q. Shao, Sci. Rep. **8**, 7282 (2018).