Angular momentum oscillation in spiral-shaped foil plasmas

Weifeng Gong \(^1\), Baifei Shen \(^1,3,4\), Lingang Zhang \(^1\) and Xiaomei Zhang \(^1,4\)

\(^1\) State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, People’s Republic of China
\(^2\) Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
\(^3\) Department of Physics, Shanghai Normal University, Shanghai, 200234, People’s Republic of China
\(^4\) Author to whom any correspondence should be addressed.

E-mail: bshen@mail.shcnc.ac.cn and zhxm@siom.ac.cn

Keywords: relativistic vortex beam, orbital angular momentum, oscillation

Abstract

Two types of spiral-shaped foils are investigated for generating significant angular momentum (AM) in plasmas by reflecting a relativistic Gaussian pulse into a vortex laser beam with the same topological charge. This is the first time to find that AM oscillation exists in specific spiral-shaped foils during laser-plasma interaction, while AM oscillation is not observed in other types of foils. Both three-dimensional particle-in-cell simulations and theoretical results have confirmed this finding. AM oscillation is demonstrated to be induced by the asymmetric field on the foil surface, and this asymmetric field can be modulated in order to strengthen or weaken the oscillation amplitude by redesigning the foil surface. AM oscillation is expected to bring insight into radiation, particle heating and other mechanisms with AM effects.

Introduction

Wave fronts can be twisted into vortices in many wave phenomena [1], such as in whirlpools and tornadoes. The phase of an optical vortex (OV) intertwines into multiple helices and remains a singularity at the spatial beam center. An example of this winding light is a Laguerre–Gaussian (LG) laser beam [2], which has a helical phase profile described by a modulation term \(\exp(\i \ell \phi)\), where \(\phi\) is the azimuthal coordinate and \(\ell\) is the integer topological charge, i.e. the LG mode order. In 1992, Allen et al [3] first demonstrated that an LG beam carries orbital angular momentum (OAM), which is proportional to the topological charge \(\ell\). Since that, LG beams have been widely investigated for its unique phase front and OAM, and new approaches to atomic or subatomic scale manipulation [4], ghost imaging [5], quantum entanglement [6] and terabit data transmission [7, 8] have been reported. Just as variation in linear momentum produces a force, the variation in angular momentum (AM) produces a torque. Previous researchers trapped absorbing dielectric particles in the dark center of a twisted light beam and set them into rotation. They attributed this to the torque produced by twisted light, thus allowing OAM to be transferred from light to particles [9–12].

The generation of light with OAM for relatively low intensity (generally below \(10^{16}\) W cm\(^{-2}\)) has been extensively discussed. Nowadays, relativistic laser pulses (above \(10^{19}\) W cm\(^{-2}\)) can be produced [13]. At such intensity, common materials will be destroyed instantly. However, a plasma has high damage threshold as an optical medium, which makes it possible to twist a relativistic Gaussian beam into an OV. Shi et al [14] proposed a ‘light fan’ scheme, i.e. a spiral-shaped foil plasma, that directly reshaped the phase front of a relativistic Gaussian beam to form an OV. Vieira et al [15] used a plasma as a nonlinear optical medium to amplify a seed laser with OAM via stimulated Raman scattering. Recently, Leblanc et al [16] put forward a kind of transient plasma hologram to experimentally generate vortex beams in diffracted order. One should note that the OAM density of the generated vortex beam can be as high as \(0.56\) kg m\(^{-1}\) s\(^{-1}\) [14]. With such high OAM density and doughnut intensity distribution, a relativistic laser vortex beam can be used for proton and positron acceleration.
generating an periodic phase changes from 0 to \( \ell \). Times, where each thickness period shows a descending trend \( \ell \) which we name as shown in the foil. These two approaches correspond to two types of spiral-shaped foils with two kinds of thickness design, The phase change can be correspondingly modulated based on the thickness of different transverse locations on the total phase of the re

Figure 1. Two types of spiral-shaped foils (SPFs and MPFs) used in simulations irradiated by a relativistic Gaussian beam. Each foil has 8\( \ell \) parts arranged as steps in a spiral staircase, where the step interval is \( \lambda/16 \). The color bars in the upper right represent the phase difference of the reflected beam on different transverse locations. The color bars also mark the thickness of each step indirectly, which implies that the thickness of SPF is proportional to \( \ell \), while the thickness of MPF is fixed. Each foil has a substrate of 0.5\( \lambda \) thickness to ensure the laser pulse is totally reflected.

with donut wakefields [17–19], high-order vortex harmonics generation [20–23], vortex gamma-ray and attosecond twisted beam generation [24–26], ultrashort twisted particle beam generation [27–30], and other novel phenomena [31, 32]. Recently, when researchers studied the generation of relativistic vortex beams, they found that the plasma carries an equivalent amount of inverse AM after interaction with the laser according to the AM conservation [14]. This balance can be seen as a special OAM transfer mechanism as well. Although the generation of plasma AM is claimed to originate from the torque of the generated vortex beam [18], the exact dynamics that cause the plasma AM are still unclear. However, a plasma with huge AM has great potential in generating very strong longitudinal magnetic fields [33–36], and may bring insight into laboratory astrophysics [37]. Therefore, an investigation into the evolution of plasma AM during vortex pulse generation is necessary.

In this paper, we investigate the inverse AM obtained by the particles, when two types of structured foils are used to generate a relativistic vortex pulse with specific topological charge by reflecting a relativistic linearly polarized Gaussian pulse. We observe the oscillation of AM for both electrons and protons in simulations for the first time, and not all structured foils experience the AM oscillation process. This unique feature implies that the existence of AM oscillation is directly influenced by the foil structure. Moreover, the net AM of particle is also ascribed to the foil structure, because the incident linearly polarized Gaussian pulse does not possess any AM, neither spin nor orbital. Unlike particles, the laser gradually gains OAM without oscillation during the interaction with both types of structured foils. Both the laser and particle AM have been checked, and the AM conservation basically holds in our simulations. We provide a theoretical explanation of this dynamic process.

Theoretical model

Since our structured foils are designed to generate relativistic vortex beams with specific topological charge \( \ell \), the total phase of the reflected beam requires a change of \( \ell \times 2\pi \) within one full annular loop, where the center is a singularity. Generally, two approaches can be put forward. One requires that the phase changes gradually from 0 to \( \ell \times 2\pi \) over the full loop, while the other includes \( \ell \) periodic phase changes from 0 to \( 2\pi \). The phase change can be correspondingly modulated based on the thickness of different transverse locations on the foil. These two approaches correspond to two types of spiral-shaped foils with two kinds of thickness design, as shown in figure 1. One type has descending thickness over a clockwise loop (see the bottom row in figure 1), which we name ‘Single period spiral-shaped foil (SPF)’ in this paper. The thickness of the other type is periodically repeated \( \ell \) times, where each thickness period shows a descending trend (see the left column in figure 1); this type is named ‘Multiple period spiral-shaped foil (MPF)’. To ensure the reflected laser pulse has a vortex structure, the foil surface is stepped into 8\( \ell \) parts, where the thickness interval is \( \lambda/16 \). Thus, all these steps combine into an equivalent reflective SPP with total thickness difference of \( \ell \times \lambda/2 \), generating an \( \ell \)-order laser vortex. As shown in figure 1, the color of each step reveals phase changes of the reflected light in a far-field plane, which also indicates the thickness of each step. Each foil has an additional substrate with
thickness of 0.5λ to ensure complete reflection. Figure 1 shows examples of SPF and MPF, and the thickness variation with azimuth φ for different spiral-shaped foils are shown in figure 2.

The incident relativistic Gaussian beam we use here can be written as

$$a(\text{Gauss}) = a_0 \exp\left(-\frac{r^2}{w^2}\right) \exp\left[-\frac{(t - x/c)^2}{\Delta t^2}\right] \exp\left[-i\frac{k r^2}{2 R}\right] \exp[i\psi] \exp[i\omega t - ikx],$$

where $a_0 = eE/cm_0\omega$ is the normalized dimensionless laser amplitude, $w = w_0\sqrt{1 + x^2/x_0^2}$ is the spot size, $k = 2\pi/\lambda$ is the wave number, $R = (x_0^2 + x^2)/x$ is the radius of phase front, $\psi = \arctan(x/x_0)$ is the Gouy phase, and $x_0$ is the Rayleigh range. For ease of calculation, one thickness period of the foil is simply regarded as a perfectly smooth spiral mirror whose surface inclines with azimuthal position, i.e. the position of the spiral surface along the x axis is $x = \ell \lambda \phi/4\pi$. When the incident Gaussian pulse arrives at this surface, the laser field is rearranged by asynchronous reflection. According to the Fresnel equations, we replace each section by different SPFs and MPFs, as depicted in figure 1. The pulse is ultrashort, with duration of $\Delta t = 13.3$ fs.

Three-dimensional (3D) particle-in-cell (PIC) simulations

We implement our scheme in a 3D PIC simulation based on EPOCH code [39]. The linearly y polarized driving Gaussian pulse with $\lambda = 0.8$ μm wavelength propagates along the x axis and impinges on the spiral-shaped foil in figure 1. The pulse is ultrashort, with duration of $\Delta t = 13.3$ fs. The radius of waist of the pulse is $w_0 = 3$ μm, and the peak amplitude is $a_0 = 3.4$. The foil, with its front spiral surface located at $x = 13.0$ μm and a radius of $r_0 = 6$ μm, has a density of 100n$_e$, where $n_e = n_0 m_e c^2/e^2$ is the critical density. The simulation box is 18 μm (x) × 20 μm (y) × 20 μm (z) with 720 × 800 × 800 cells and PFC = 8 for both protons and electrons. At $t = 40$ fs, the entire laser pulse has entered the simulation box from the left boundary, and interacts with the foil, as shown in figure 3(a).

At $t = 90$ fs when the relativistic laser beam is totally reflected by different SPFs and MPFs (see figure 3(b)), its electric field $E_\ell$ has been twisted into a vortex beam, where the $\ell = 1, 2, 3, 4$ cases are selected as examples. We select a transverse section of $E_\ell$, as depicted in figures 3(c), (e), (g), (i), (k), (m), (o). As predicted, vortex laser pulses with the same topological charge $-\ell$ can be generated from SPF and MPF. As a result, the incident laser pulse obtains huge longitudinal OAM. The laser OAM within the simulation box is of $10^{-17}$ kg m$^2$ s$^{-1}$ order from the formula $\tilde{L} = n_c \int\int P \times (\vec{E} \times \vec{B}) \, d\tau$, which is close to the value reported in [14].

Figure 2. The thickness variation with the azimuth φ of different spiral-shaped foils, divided into SPF and MPF separately.
According to the AM conservation, the foil should gain equivalent AM with opposite sign. Thus, a higher topological charge of the laser vortex induces higher net AM for the foil, and the processes of obtaining net AM for both protons and electrons in the corresponding foil are recorded in figures 3(d), 3(f), 3(h), 3(j), 3(l), 3(n), 3(p). Inside the foil, protons finally obtain a net AM of $-1.0 \times 10^{17} \text{ kg m s}^{-2}$ from the formula $\vec{L} = \sum \vec{g} \times m \vec{u}$, about one order of magnitude higher than that for electrons. During the interaction process, electrons are easily moved by the laser electromagnetic field, and then drag protons along with them through a charge separation field. This process is similar to the radiation process acceleration, but in the azimuthal direction. Thus, the angular velocity of protons is expected to be lower than that of electrons. Both the proton’s huge mass (3 orders higher) and the lower angular velocity (two orders lower) contribute to the final net AM of protons. For example, in the MPF of $\ell = 2$ case at $t = 90$ fs, the net AMs are $-2.3 \times 10^{17} \text{ kg m}^2 \text{s}^{-1}$ for protons and $-1.3 \times 10^{16} \text{ kg m}^2 \text{s}^{-1}$ for electrons, their average angular velocities are $-5.7 \times 10^5 \text{ m s}^{-1}$ and $-3.3 \times 10^4 \text{ m s}^{-1}$, respectively. One should note that the net AM for protons in an SPF is obviously larger than that in an MPF for the same $\ell$, as shown in figures 3(f) and 3(h) for the $\ell = 2$ cases, and similar comparisons for the $\ell = 3$ and $\ell = 4$ cases. This is because each discontinuity on a structured foil contributes a negative part to total AM. Figure 1 shows that there are more discontinuities in an MPF than those in an SPF for the same $\ell$, so the net AM of an MPF is lowered more seriously. Thus, the net AM difference between MPF and SPF is attributed to the discontinuity. Moreover, when the misalignments exist between the incident laser and the foil, the OAM of reflected laser will decrease to some extent. Because the laser spot does not focus on the foil center, the reflected OV becomes unperfect, and finally causes the decrease of the OAM.

Surprisingly, we find that the time evolution of plasma AM is totally different between SPF and MPF cases. For an SPF with $\ell = 1, 2, 3$, the longitudinal AMs for both protons and electrons oscillate with time, and the amplitudes of AM oscillation in SPF cases reduce with an increasing $\ell$, as shown in figures 3(d), 3(h) and 3(l).
However, the AMs for both protons and electrons do not oscillate in MPF cases for \( \ell' = 2, 3, 4 \), as shown in figures 3(i), (j) and (n). This phenomenon implies that the structure of MPF eliminates the AM oscillation effect. We see that both cases for \( \ell' = 4 \) do not have AM oscillation, which is worth raising. One should also note that the AM oscillation frequency is the same as the laser field frequency, and thus the AM oscillation may be aroused by the first harmonic of the laser field directly. Unlike the general particle oscillation, the particle AM oscillation acts in a new azimuthal direction. Thus, this effect may have an impact in some physical process aroused by the particle oscillation, such as ultraviolet radiation [41], high harmonic generation [20], particle heating [42, 43], and so on, and then transfer AM to the electromagnetic field.

### Analysis and discussion

As mentioned above, the AM oscillation is strongly related to the transient laser field which also induces quiver motion for particles in the transverse direction. Thus, it can be expected that the AM oscillation originates from such quiver motion [44], which is confirmed by the following analytical results. However, the charge separation field and the subsequently net AM is not included in our theoretical model, because it is very complicated to describe such field on the step-like foil surface. As an example, we consider electron motion under the interaction of the incident Gaussian pulse and reflected vortex pulse with singularity, as described by equations (1) and (2) respectively. These two pulses simultaneously interact with the periodic helical surface of the foil. On the surface, both pulses are assumed to have the same transverse electric field distribution due to the continuous boundary condition between the foil and vacuum. The motion of an electron can be described by

$$ n_e \frac{\partial \vec{p}_e}{\partial t} + (\vec{u}_e \cdot \nabla) \vec{p}_e = -en_e \vec{E} - en_e \vec{u}_e \times \vec{B}, $$

where \( \vec{E} \) and \( \vec{B} \) are the superposition of the incident and reflective laser fields (electric and magnetic); \( n_e, \vec{u}_e, \) and \( \vec{p}_e \) are the number density, velocity, and linear momentum of an electron. Here, \( n_e (\vec{u}_e \cdot \nabla) \vec{p}_e \) and \( -en_e \vec{u}_e \times \vec{B} \) are nonlinear terms and complicated to do the calculation. However, the residue linear terms are enough to illustrate AM oscillation problem. Thus, we neglect the nonlinear terms, and assume that the electrons in the foil oscillate along the polarization direction, affected by the mere linear terms. Therefore, equation (3) can be simplified as

$$ n_e \frac{\partial \vec{p}_e}{\partial t} = -en_e \vec{E}, $$

in which only the quiver motion is included. In the interior of the foil, we assume the laser field decays exponentially with a skin depth \( l_x = c/\omega_{pe} = 0.012 \mu m \). We integrate the longitudinal AM of all electrons throughout the foil:

$$ \vec{L} = \sum (\vec{r} \times \vec{p}_e) = \int_V n_e (\vec{r} \times \vec{p}_e) d\vec{r}, $$

where \( V \) represents the spatial domain of the foils for integration, which is quite different between SPF and MPF. As a result, we obtain different situations for the SPF and MPF cases, as shown in equation (6). More details can be found in supplementary material, which is available online at stacks.iop.org/NEWJPHYS/21/043022/mmedia.

**MPF:**

\[
L = \begin{cases} 
\frac{4 \sqrt{\pi} en_e E_y w_0^3 x}{3 \omega} \frac{kl_i^2}{1 + k_i^2l_i^2} \cos \omega t, & \ell' = 1, \\
0, \quad \ell' = 2, 3, 4, \ldots 
\end{cases}
\]

**SPF:**

\[
L = \begin{cases} 
\frac{4 \sqrt{\pi} en_e E_y w_0^3 x}{3 \omega} \frac{kl_i^2}{1 + k_i^2l_i^2} \cos \omega t, & \ell' = 1, 3, 5 \ldots \text{(odd)}, \\
\frac{4 - \ell'^2}{\pi \sqrt{\pi} en_e E_y w_0^3 x} \frac{kl_i^2}{1 + k_i^2l_i^2} \sin \omega t, & \ell' = 2, \\
\frac{2\omega}{1 + k_i^2l_i^2} \frac{kl_i^2}{1 + k_i^2l_i^2} \sin \omega t, & \ell' = 4, 6, \ldots \text{(even)}.
\end{cases}
\]

From this result, we find that the AM of electrons does not oscillate during the interaction in all MPF cases with \( \ell' > 1 \), but non-oscillating AM only occurs in some SPF cases with even \( \ell' > 2 \). In addition, in the other SPF cases with AM oscillation, the oscillation frequency is equal to the laser frequency \( \omega \), which implies the oscillating electric field induces AM oscillation during the interaction. In order to confirm the accuracy of calculation of equation (6), we plot the AM curves for electrons in figure 4 with pink lines in the SPF cases for \( \ell' = 1, 2, 3, 5 \), where oscillations are predicted to happen. Meanwhile, the PIC simulation results are shown in figure 4 with red stars for the same \( \ell' \), which shows that the theoretical lines from equation (6) and simulation
points are in good agreement. However, the PIC results after 80 fs deviate below the theoretical lines, implying the net AM amounts first increase and then saturate. Here we should note our theoretical calculations do not include the nonlinear effects (for instance, the pondermotive force), which are probably the source of the net AM.

As for protons, the Lorentz force in the laser electromagnetic field is just opposite to that of electrons. Thus, we can describe the motion of a proton as

$$\mathbf{n}_i \left( \frac{\partial \mathbf{p}_i}{\partial t} + (\mathbf{u}_i \cdot \nabla) \mathbf{p}_i \right) = e n_i \mathbf{E} + e n_i \mathbf{u}_i \times \mathbf{B},$$

where $n_i$, $\mathbf{u}_i$, and $\mathbf{p}_i$ are the number density, velocity, and linear momentum of a proton. Based on this, the calculated AM of protons is the same as electrons except an opposite sign.

We can explain the different oscillation situations for SPF and MPF cases in an intuitive way, and we take the cases of $\ell^2 = 2$ as examples in the following. Firstly, as shown in figures 5(a) and (d), an MPF and an SPF have different foil structures, so they cause different distributions of electric field on the foil surface $\mathbf{E}_{surf}$ when a Gaussian pulse impinges on either one, as shown in figures 5(b) and (e). Here, the electric field distribution on each step of the foil is cut out as a fan-shaped view, and then all the views are spliced together to obtain $\mathbf{E}_{surf}$ in figures 5(b) and (e). It can be seen that the electric filed on the MPF surface is always symmetric about the foil center, but such symmetry seldom exists in the SPF case. Secondly, one should note that only the electrons within the skin depth are influenced by the electromagnetic field, so the spatial distribution of electron momentum $\mathbf{p}_e$ is directly linked with $\mathbf{E}_{surf}$. Therefore, we see different spatial distributions of current density $\mathbf{j}$ between the MPF and SPF cases, and their traits of symmetry are consistent with $\mathbf{E}_{surf}$, as shown in figures 5(c) and (f). Here we use the current density $\mathbf{j}$ to represent the electron momentum $\mathbf{p}_e$ for convenience, since $\mathbf{j}$ can be determined by $\mathbf{p}_e$ through $\mathbf{j} = n_e q_e \mathbf{u}_e = n_e q_e \gamma \mathbf{p}_e / m_e$. Thirdly, the electron AM is calculated in the following formula,

$$L_x = \sum (y_p e_z - z_p e_y) = \int_{\mathbb{R}^2} [y P_{e_z}(y, z) - z P_{e_y}(y, z)] \, dy \, dz,$$
Figure 5. (a), (d) The sketch showing an MPF and an SPF of $\ell = 2$. (b), (e) Electric field distribution on the foil surface $E_{\text{surf}}$ in the $y-z$ plane at $t = 64.5$ fs when the peak of the laser pulse interacts with an MPF and an SPF of $\ell = 2$. (c), (f) The current density distribution $J_y$ in the $y-z$ plane at the corresponding time, obtained by summing the spatial density value along the $x$ direction.

Figure 6. (a) A redesigned spiral-shaped foil (thick solid line) with modified surface used to generate a vortex beam with a topological charge of $-1$. The AM oscillation of particles is weakened in this figure compared with the corresponding SPF case (thin dashed–dotted line) with $\ell = 1$. (d) A redesigned spiral-shaped foil (thick solid line) with modified surface used to generate a vortex beam with a topological charge of $-3$. The AM oscillation of particles is strengthened in this figure compared with the corresponding SPF case (thin dashed–dotted line) with $\ell = 3$. (b), (e) Electric field distribution $E_y$ in the $y-z$ plane at $x = 6.8 \mu m$ and $t = 90$ fs for the corresponding foils. (c), (f) Corresponding time-dependent longitudinal AM (in the $x$ direction) of protons and electrons (represented by blue and red solid lines).
where $\vec{E}$ is the electron momentum density integrated along the $x$ direction. Here, the first term can be neglected because the electron momentum is mostly occupied with the $y$ component due to the incident $y$-polarized laser pulse. In the MPF case, we find the central symmetry in $J_y$ or $P_y$ at the $S_{yz}$ plane, that is, $P_y(y, z) = P_y(-y, -z)$. This condition leads to a zero for the integration, so we obtain $AM_x = 0$. During the interaction, the central symmetry always exists in both $\vec{E}_{surf}$ and $\vec{J}$, so the electron AM is slow varying without any oscillation. In the SPF case, such symmetry in $J_y$ or $P_y$ is broken, so the integrated electron AM has a surplus and oscillates with the laser field. As stated above, we find that the broken central symmetry in the electric field on the foil surface results in the AM oscillation for electrons. The analysis for protons is similar as electrons, so we can draw the same result.

Since AM oscillation for both proton and electron depend on the structure of the foil surface, we can redesign the foil surface to strengthen or weaken AM oscillation, and meanwhile properly generate an OV with specific topological charge. Figures 6(b) and (e) show that vortex pulses with topological charges of $-1$ and $-3$ are also generated using the redesigned spiral-shaped foils shown in figures 6(a) and (d), and the foil thicknesses along the azimuthal direction are different from SPF. In the $\ell' = 1$ case, part of the surface is lowered by $0.5\lambda$ compared with the corresponding SPF case to ensure the vortex structure of the reflected pulse. Based on this, which part of the surface is lowered determines the electric field distribution on the foil surface and its central symmetry. As a result, the oscillation strength of the particle AM is much smaller than that in the SPF case (see figures 3(d) and 6(c)) because the central symmetry is increased. In the $\ell' = 3$ case, one part of the surface is lowered while the other part is lifted by $0.5\lambda$ compared with the corresponding SPF case, and the oscillation becomes stronger than that in the SPF case (see figures 3(l) and 6(f)) due to the reduced central symmetry. These results further convince us that heavier asymmetry induces stronger oscillation, thus providing an effective method to modulate the AM oscillation strength for potential applications and gaining a deeper physical understanding regarding the origin of AM. In addition, more discontinuities added onto the foil surface decreases the net AM of protons (see figures 3(l) and 6(f)), which coincides with our aforementioned comparison between the net AM in SPF and MPF.

Conclusion

In summary, two types of structured spiral-shaped foils (SPF and MPF) are investigated for generating relativistic vortex pulses with specific topological charge $\ell'$ using an ultra-intense femtosecond Gaussian pulse. The vortex pulse carries massive OAM. According to AM conservation, an equivalent amount of AM is transferred to the foil and results in rotation. However, the AM of the foil is not always smoothly increasing. Under specific conditions, this process is accompanied by oscillation. The AM oscillation pattern is analyzed for SPF and MPF, and the consistency of PIC simulations and theoretical calculation shows that the oscillation originates from particle quiver motion and central symmetry of the laser field on the foil surface.

As stated above, AM oscillation is a dynamic process originating from the collective quiver motion of all electrons or protons in the foil, and such oscillation is found to depend on the foil structure, or precisely, the central asymmetry of the electric field on the foil surface. This finding convinces us that the nature of AM oscillation is a mere asymmetry problem, and it is unrelated to net AM of particle. Whether the particle AM of a specific foil oscillates or not can be known by making asymmetry analysis. Due to the oscillatory characteristic of this phenomenon, we can expect that new AM effects may happen in radiation emitted by electrons, particle heating, and other mechanisms with potential applications. In addition, AM primarily carried by protons implies a similar process as ion radiation pressure acceleration mechanism. For radiation pressure acceleration, both the laser electric field and ponderomotive force initially combine to affect electrons, and then accelerate protons through a charge separation field between the electrons and protons. Similar to this longitudinal acceleration, the net AM of the protons predicts an angular acceleration and subsequently rotation of the protons. For instance, when the net AM of proton does not oscillate in the MPF case, the foil may be continuously and steadily driven to rotate with extremely large torque. As the net AM in the foil grows with topological charge $\ell'$ nearly linearly to the current extent, we expect realization of an ultrafast microscopic motor driven with an ultra-intense laser. Moreover, it is also predictable that the interaction between a relativistic laser pulse and a spiral-shaped foil will result in twisted high harmonics, as we use a vortex oscillation mirror model on the foil surface [20].

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant Nos. 11674339, 11335013), the Ministry of Science and Technology of the People’s Republic of China (Grant Nos. 11335013).
2016YFA0401102, 2018YFA0404803), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB16) and Innovation Program of Shanghai Municipal Education Commission.

**ORCID iDs**

Baifei Shen [https://orcid.org/0000-0003-1021-6991](https://orcid.org/0000-0003-1021-6991)

**References**

[1] Nye J F and Berry M V 1974 Proc. R. Soc. A 336 165–90
[2] Yao A M and Padgett M J 2011 Adv. Opt. Photonics 3 161–204
[3] Allen L, Beiersbergen M W, Speerew J R C and Woerdman J P 1992 Phys. Rev. A 45 8185–9
[4] Padgett M J and Bowman R 2011 Nat. Photon. 5 343–8
[5] Jack B, Leach I, Romero J, Franke-Arnold S, Ritsch-Marte M, Barnett SM and Padgett MJ 2009 Phys. Rev. Lett. 103 083602
[6] Fickler R, Lapkiewicz R, Plick WN, Krenn M, Schaeff C, Ramelow Sand Zeilinger A 2012 Science 338 640–3
[7] Bozovicin N, Yue Y, Ren Y, Tur M, Kristensen P, Huang H, Willner AE and Ramachandran S 2013 Science 340 1545–8
[8] Wang J 2017 Chin. Opt. Lett. 15 030005–9
[9] He H, Friese ME, Heckenberg NR and Rubinsztein-Dunlop H 1995 Phys. Rev. Lett. 75 826–9
[10] Simpson NB, Dholakia K, Allen L and Padgett MJ 1997 Opt. Lett. 22 52–4
[11] Garces-Chavez V, McClion D, Padgett MJ, Dultz W, Schmitzer H and Dholakia K 2003 Phys. Rev. Lett. 91 093602
[12] O’Neil AT, MacVicar I, Allen L and Padgett MJ 2002 Phys. Rev. Lett. 88 035601
[13] Mourou GA, Tajima T and Bulanov SV 2006 Rev. Mod. Phys. 78 309–71
[14] Shi Y, Shen BF, Zhang LG, Zhang XM, Wang WP and Xu ZZ 2014 Phys. Rev. Lett. 112 235001
[15] Vieira J, Trines R M, Alves E P, Fonseca R A, Mendonça J T, Bingham R, Norreys P and Silva L O 2016 Nat. Commun. 7 10371
[16] Leblanc A, Denœud A, Chopineau L, Mennerat G, Martin P and Quéré F 2017 Nat. Phys. 13 640–3
[17] Zhang X M, Shen B F, Zhang L G, Xu J C, Wang X F, Wang W P, Yi L Q and Shi Y 2014 New J. Phys. 16 123051
[18] Vieira J and Mendonça J T 2014 Phys. Rev. Lett. 112 215001
[19] Mendonça J T and Vieira J 2014 Phys. Plasmas 21 033107
[20] Zhang X M, Shen B F, Shi Y, Wang X F, Zhang L G, Wang W P, Xu J C, Yi L Q and Xu Z Z 2015 Phys. Rev. Lett. 114 173901
[21] Vieira J, Trines R M, Alves E P, Fonseca R A, Mendonça J T, Bingham R, Norreys P and Silva L O 2016 Phys. Rev. Lett. 117 265001
[22] Zhang X M, Shen B F, Shi Y, Zhang L G, Ji L L, Wang W F, Xu Z Z and Tajima T 2016 New J. Phys. 18 083046
[23] Denœud A, Chopineau L, Leblanc A and Quéré F 2017 Phys. Rev. Lett. 118 035302
[24] Liu C et al 2016 Phys. Plasmas 23 093120
[25] Hernández-García C, Rego L, San Román J, Picón A and Plaja L 2017 High Power Laser Sci. Eng. 5 e3
[26] Turpin A, Rego L, Picón A, San Román J and Hernández-García C 2017 Sci. Rep. 7 43888
[27] Baumann C and Pukhov A 2018 Phys. Plasmas 25 083114
[28] Fu J B, Zhou C T, Jiang K, Huang T W, Zhang H, Cai T X, Cao J M, Qiao B and Ruan S C 2018 New J. Phys. 20 063004
[29] Vieira J, Mendonça J T and Quere F 2018 Phys. Rev. Lett. 121 054801
[30] Hu L X, Yu T P, Lu Y, Zhang G B, Zou D B, Zhang H, Ge Z Y, Yin Y and Shao F Q 2019 Plasma Phys. Control. Fusion 61 025009
[31] Zhang L G, Shen B F, Zhang X M, Huang S, Shi Y, Liu C, Wang W P, Xu J C, Pei Z K and Xu Z Z 2016 Phys. Rev. Lett. 117 113904
[32] Wang W P, Shen B F, Zhang X M, Zhang L G, Shi Y and Xu Z Z 2015 Sci. Rep. 5 8274
[33] Naseri N, Bychenkov V Y and Romizs W 2010 Phys. Plasmas 17 083010
[34] Wu D and Wang J W 2017 Plasma Phys. Control. Fusion 59 094010
[35] Nuter R, Korneev P, Thiele I and Tikhonchuk V 2018 Phys. Rev. E 98 033211
[36] Shi Y, Vieira J, Trines R, Bingham R, Shen B F and Kingham R J 2018 Phys. Rev. Lett. 121 145002
[37] Bulanov SV, Esirkepov T Z, Habs D, Pegoraro F and Tajima T 2009 Eur. Phys. J. D 55 483–507
[38] Berry M V 2004 J. Opt. A: Pure Appl. Opt. 6 259–68
[39] Arber T D et al 2015 Plasma Phys. Control. Fusion 57 113001
[40] Esirkepov T, Borghesi M, Bulanov SV, Mourou G and Tajima T 2004 Phys. Rev. Lett. 92 175003
[41] Corde S, Ta Phuoc K, Lambert G, Fitour R, Malka V, Rousse A, Beck A and Lefebvre E 2013 Rev. Mod. Phys. 85 1–48
[42] Denavit J 1992 Phys. Rev. Lett. 69 3052–5
[43] Wilks S C, Kruer W L, Tabak M and Langdon A B 1992 Phys. Rev. Lett. 69 1383–6
[44] Umstadter D 2003 J. Phys. D: Appl. Phys. 36 161–5