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Ultra-bright γ -ray emission by using PW laser irradiating solid target obliquely

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Abstract. By using intense laser irradiating a micro plane target obliquely, an enhanced γ -ray source is generated. Due to the superposition of the incident and the reflected laser pulses, electron bunches with density of $\sim 300n_c$ are extracted and accelerated. When these electron bunches separate from the edge of the target that the laser is leaving, they co-propagate with the laser field and emit dense γ -rays simultaneously. Simulation results show that the emitted γ photons are $253n_c$ dense with an averaged energy of ~ 12 MeV. The yield of γ photons is $\sim 7 \times 10^{12}$, achieving a high brightness of $\sim 4 \times 10^{23}$ photons/s/mm²/mrad²/0.1%BW. Influences of the laser intensity and the incident angle on the γ -rays emission are discussed. The γ -ray yield, the conversion efficiency from the laser to the γ -rays and the averaged γ -ray energy are increasing when irradiating a higher intensity laser. With the increasing of the incident angle, the peak photon density increases when the angle is smaller than 20° and then drops to a stable value, while the divergence decreases when the incident angle is smaller than $\sim 16^\circ$ and then increases.

Keywords: laser-plasma interaction, quantum electrodynamics, γ -ray emission

1. Introduction

γ -ray sources are widely used in various areas, including medical treatment[1], industrial measurement[2] and scientific research[3]. In laboratory, the main mechanism of γ -ray emission involves the bremsstrahlung emission, the synchrotron and the Compton scattering[4]. These regimes are all related to relativistic electrons. The laser-plasma interaction, as an efficient method of the electron acceleration, has been proposed and utilized to obtain γ -ray sources[5, 6, 7, 8, 9]. In recent years, the advent of PW laser facilities in the world opens a door for ultra-bright, high energy γ -ray sources.

Several different regimes related to electron acceleration mechanisms have been proposed, including Laser Wakefield Acceleration(LWFA) in laser-gas interaction[10], Ponderomotive Acceleration (PA) in laser-wire interaction[11, 12, 13] and Radiation Pressure Acceleration (RPA) in laser interacting with the solid target[14, 15]. However, the yield of γ photons is limited by the number of electrons accelerated, which causes that the brightness of γ -ray sources are lower than that provided by the conventional accelerators. Several configurations have been proposed to increase the number of trapping electrons, such as the cone[5], double cone[16] and channel[17]. These behave well in simulations while are difficult to fabricate in experiments. Besides, the properties of the radiation, such as the divergence and the size of the γ -ray source also need improving[3].

As an efficient acceleration regime, the obliquely irradiating method in laser-plasma interaction has attracted a lot of attention[18, 19, 20]. In oblique case, simulations show that electrons can be accelerated to GeVs with the laser intensity of 10^{21} - 10^{22} W/cm²[21]. High energy electron bunch with charge of 100 nC have also been obtained by a 200 TW laser obliquely irradiating in experiment[22]. Such a high charge electron bunch can emit dense photons efficiently when interacting with the intense laser field.

In this paper, we propose to use obliquely incident laser to irradiate a micro plane target to enhance the γ -ray emission. Due to the superposition of the incident and reflected laser pulse, electrons in the surface of the target can be extracted and form a series of electron bunches. These electron bunches are accelerated by the ponderomotive force in both parallel and perpendicular directions. After the laser passes through the edge of the surface that the laser is leaving, the electrons accelerated will separate from the surface and oscillate in the laser field to emit dense γ photons mainly by synchrotron radiation. We analyse the enhancement of the laser field and the motion of electrons in such a superposed field theoretically. And by using the QED theory, we demonstrate that dense γ -ray emissions are possible in this grazing incident scheme. We confirm these analyses by Particle-in-Cell (PIC) simulations, which indicate that the extracted electrons are as dense as $\sim 300n_c$ and can be accelerated to GeVs. Dense γ -ray emissions are observed in the simulations with an averaged energy of ~ 12 MeV and a brightness of $\sim 4 \times 10^{23}$ photons/s/mm²/mrad²/0.1%BW.

2. Theoretical analysis

The schematic setup is shown in figure 1. When the ultra-intense laser pulse obliquely irradiates the solid target, the target can be ionized into plasmas. At the same time, electrons locating at the surface of the target are extracted due to the strong perpendicular components of the ponderomotive force. As the laser pulse propagates further, a series of electron bunches form along the surface. The electrons are accelerated in the x' direction due to the parallel ponderomotive force, as shown in the figure 1. At the right edge of the target, the accelerated electrons bunches will separate from the surface of the target and emit dense γ -rays in the extension direction of the surface. In this obliquely incident case, the transverse size of the target is comparable to the focal spot size of the laser. During the laser-target interaction process, the incident laser and the reflected laser keep superposing and enhance the electromagnetic field at the surface significantly. This superposition strengthens the extraction and acceleration of electrons obviously. As a result, the dense γ photons are generated due to the interaction of electrons and laser field.

Figure 1. Schematic setup for laser (red cone) obliquely incident onto the solid target (grey parallelogram). The Gaussian laser is incident from the left side of the simulation box and focused on the left edge of the target. The target is placed with an angle of $\theta = 20^\circ$. The target is made of aluminium with a thickness of $d = 1 \mu\text{m}$ and projected longitudinal length of L . The coordinate system (x', y') consists of two axes which are x' (along the surface of the target, named parallel direction) and y' (perpendicular to the surface plane, named perpendicular direction). The yellow solid lines are the incident laser rays, while the dashed orange lines are the reflected laser lights. The electric fields corresponding to the incident and the reflected laser are labelled as E^i and E^r respectively. The point (y_1, t_1) is set to be the position and time coordinates at which the reflected laser ray is reflected, the point (y_2, t_2) is used to mark the position and time coordinates of the incident ray that interfere with the reflected laser ray and (y, t) means the position y of the reflecting position at the time t of interference.

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Considering the p -polarized Gaussian laser pulse, the incident, the reflected electric fields and the phase difference between them are written as follows:

$$E^i = E_0 \exp(-y_2^2/\sigma_L^2) \exp(-\Delta t^2/\tau_L^2) \cos(kx_2 - \omega t), \quad (1)$$

$$E^r = E_0 \exp(-y_1^2/\sigma_L^2) \cos[k(x_1 + \frac{y_2 - y_1}{\sin 2\theta}) - \omega t], \quad (2)$$

$$\Delta\phi = 2\pi/\lambda_0[(y_2 - y_1)/\tan 2\theta + \lambda_0/2 - (y_2 - y_1)\sin 2\theta], \quad (3)$$

where E^i and E^r are the electric field of the incident and the reflected laser pulse respectively, E_0 is the amplitude of the electric field, σ_L is the size of the laser focal spot, τ_L is the duration of laser pulse, $\Delta t = t - t_2$ is the period between the time of interference and the time coordinate of the interference point, λ_0 is the wavelength of the laser, $\omega = 2\pi c/\lambda_0$ is the angular frequency of the laser, $k = 2\pi/\lambda_0$ is the wave number, $d_0 = y_2 - y_1$ is the difference of the off-axis distance between the reflected (the dashed orange lines in figure 1) and the incident laser rays (the yellow solid lines in figure 1), θ is the angle of the target with respect to the x axis, (y_1, t_1) and (y_2, t_2) are the y and time coordinates of the reflecting point and interference position, x_1 and x_2 are the corresponding x coordinates of the reflecting point and interference position, respectively.

According to the interference theory, the superposition of the incident and the reflected laser is given as follows:

$$E_t^2 = E_1^2 + E_2^2 + 2E_1E_2 \cos \Delta\phi \cos \theta, \quad (4)$$

Numerical calculation gives the maximum of the electric field are $E_{cal} \sim 1.74E_0$ at $y' \sim 0.7\lambda_0$.

Because of the electron extraction and the return current formation, quasi-static electric and magnetic fields are generated. These quasi-static fields, together with the laser field, act on the electrons close to the surface. Assuming the static electric field is $E_{y'}^s = k_E y' m_e \omega c / \lambda_0 e$ and the static magnetic field is $B_z^s = k_B y' m_e \omega c / \lambda_0 e$, where $k_E > 0$ and $k_B > 0$ are constants for electric and magnetic fields, respectively[19]. The parallel and perpendicular laser electric fields are $E_{||} = E_l \sin \theta$ and $E_{\perp} = E_l \cos \theta$, respectively. The magnetic field still follows the z axis with the value of $B_z = E_l / v_{ph}$, where $v_{ph} = c / \cos \theta$ is the phase velocity of the laser field. Then the equations of electrons motion are:

$$dp_{||}/dt = -e[E_{||} + v_{\perp}(B_z + B_z^s)] + F_{d||}, \quad (5)$$

$$dp_{\perp}/dt = -e[E_{\perp} + E_{y'}^s - v_{||}(B_z + B_z^s)] + F_{d\perp}, \quad (6)$$

$$d\gamma/dt = -e/(m_e c^2)[E_{||}v_{||} + v_{\perp}(E_{\perp} + E_{y'}^s)] + F_{d||}v_{||} + F_{d\perp}v_{\perp}, \quad (7)$$

where $p_{||}$, $p_{\perp}$, $v_{||} = dx'/dt$ and $v_{\perp} = dy'/dt$ are the parallel and perpendicular momenta and velocity components of electrons, $F_{d||} = -\frac{e^4}{6m_e^2 c^4 \pi \epsilon_0} \gamma^2 \beta_{||} [(\vec{E} + \vec{v} \times \vec{B})^2 - (\vec{v} \cdot \vec{E})^2]$ and $F_{d\perp} = -\frac{e^4}{6m_e^2 c^4 \pi \epsilon_0} \gamma^2 \beta_{\perp} [(\vec{E} + \vec{v} \times \vec{B})^2 - (\vec{v} \cdot \vec{E})^2]$ are the parallel and perpendicular components of radiation reaction force[23], where ϵ_0 is the permittivity of free

space. Considering the ponderomotive force, which is mainly from the oscillation of electromagnetic field and has been involved implicitly in both of equation (5) (6), can be written as $F_p = -\frac{e^2}{4m_e\omega^2}\nabla E^2$ [24]. Because of the superposition of the electromagnetic field, the ponderomotive force behaves in a complicated pattern. It can be about $10^{-3}N$, which is much higher than the electric field force. Therefore, electrons from the surface of the target can be expelled due to the perpendicular ponderomotive force. In the direction parallel to the surface of the target, the parallel component of ponderomotive force can accelerate electrons to high energy.

In Quantum Electrodynamics (QED) range, the probability of the photon emission is related to the parameter $\eta = e\hbar|F_{\mu\nu}p^\nu|/m_e^3c^4 \approx \gamma|E_\perp + \vec{v} \times \vec{B}|/E_s$ (where $F_{\mu\nu}$ is the field tensor, $E_s = m_e^2c^3/e\hbar = 1.3 \times 10^{18} \text{ V/m}$ is the Schwinger field, i.e., the critical field of QED)[25]. For the motion of electrons in the x' direction, the parallel component is $\eta_{\parallel} = \gamma|E_{\parallel} + v_\perp \times B|/E_s = \gamma|E_{\parallel} + \beta_\perp cB_z|/E_s$, while the perpendicular component is $\eta_\perp = \gamma|E_\perp - v_{\parallel} \times B|/E_s = \gamma|E_\perp - \beta_{\parallel} \times cB_z|/E_s$. Normally, the $\eta_\perp \ll \eta_{\parallel}$, thus the γ -rays emission are mainly due to the perpendicular oscillation of electrons. The probability rate of a photon emitting from an electron with γ and η is described as: $dN_\gamma/dt = \sqrt{3}\alpha\eta h(\eta, \chi)/2\pi\tau_e\gamma$ [26], where α is the fine structure constant, $\tau_e = \hbar/m_e c^2 = 1.288 \times 10^{-6} \text{ fs}$, $\chi = \hbar|F_{\mu\nu}k^\nu|/(2m_e cE_s)$ is the QED parameter which is important for the electron-positron pair production and $h(\eta, \chi)$ is only the function of η here. The Lorentz factor γ of the electron oscillating in the intense electromagnetic field is approximately $\gamma \sim a = eE\lambda_0/2\pi m_e c^2 = 8.4 \times 10^2 (I_{24}\lambda_{\mu\text{m}}^2)^{1/2}$ (where I_{24} is the intensity of laser in the unit of 10^{24} W/cm^2 and $\lambda_{\mu\text{m}}$ is the wavelength of the laser in the unit of μm)[27]. The γ in our scheme is $\gamma \sim a_0 = 270$. Using the relations: $E_{\parallel} = E_{cal} \sin \theta$, $B_z = E_{cal}/v_{ph}$ and $v_\perp \sim c$, then $\eta_{\parallel} \sim 0.3$. Analysis shows that the electrons can be accelerated to GeVs, i.e. $\gamma_{max} > 10^3$. That leads to $\eta_{\parallel} > 1$, which means the dense photons emission is possible.

3. Simulations

We perform 2D PIC simulations with the open source code EPOCH-QED[28]. The target is fully ionized aluminium with an electron density of $600 n_c$, where $n_c = 1.1 \times 10^{21} \text{ cm}^{-3}$ means the critical density of plasma for the laser wavelength $\lambda_0 = 1 \mu\text{m}$. The initial temperature of electrons is set to be 1 keV. As shown in figure 1, the thickness of the target is $d = 1 \mu\text{m}$, which ensures that the target cannot be bored and the thickness has almost no influence on the physics process. The laser is p -polarized Gaussian laser pulse with the dimensionless amplitude profile of $a = a_0 \exp(-y^2/\sigma_L^2) \exp(-t^2/\tau_L^2)$, where $a_0 = 270$ (corresponding to the laser intensity of $I_L = 1 \times 10^{23} \text{ W/cm}^2$), $\sigma_L = 5\lambda_0$ is the radius of focal spot and $\tau_L = 4T_0$ is the laser duration (where $T_0 = \lambda_0/c$ is the laser period). We set the laser to propagate along the x -axis and focus on the left edge of the target. The size of the simulation box is $x \times y = 20\lambda_0 \times 20\lambda_0$. We use 1000×1000 cells with 42 pseudoparticles per cell to sample this simulation box. To guarantee the accuracy of the simulation, the length of the grid needs to be smaller than

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both the skin length of the plasma $\delta = c/\omega_p$ and Debye length $\lambda_D = \sqrt{\varepsilon_0 k_B T_e / n_e e^2}$, where $\omega_p = \sqrt{n_e e^2 / \varepsilon_0 m_e}$ is the electron plasma frequency, n_e is the electron density, k_B is the Boltzmann constant, T_e is the temperature of the electron. The grid size in our simulation meets the demand of the skin length. Since the Debye length for plasma increases with the temperature, when the intense laser irradiating the surface, the plasma temperature can increase to MeV scale. That leads to the very large Debye length. Therefore, the size of the simulation box can confirm the accuracy of the results. For photons emission, we only count the photons with energy higher than 1 MeV.

The maximum electric field for the laser used in our simulations is $E_0 = \sqrt{8\pi c I_L / 10^7} \text{ V/m} = 8.68 \times 10^{14} \text{ V/m}$. The maximum given by the simulations is $E_{sim} \sim 1.56 E_0$ at $y' \sim 0.7 \lambda_0$, which agrees well with the theoretical results as shown before. To analyse the motion of electrons, it is essential to resolve the electric field into two components which are parallel and perpendicular to the surface respectively, i.e., $E_{\parallel}$ and $E_{\perp}$. Figure 2 shows the distribution of parallel and perpendicular electric fields in the converted coordinate system (x', y') at $8 T_0$ (the time when the maximum of the electric field occurs) and $14 T_0$ (when the laser passes through the right edge of the target). In figure 2(a) and figure 2(b), it is obviously that the incident and the reflected laser interfere and the laser fields are enhanced significantly. This also causes a higher phase velocity of the laser propagation $v_{ph} = c / \cos \theta$. In figure 2(b), at the place with negative electric field, both the parallel and perpendicular ponderomotive forces are positive because of the decrease of the field strength. These cause the accelerations of electrons in both directions, i.e., the electrons are expelled from the surface and accelerated simultaneously. Due to the transverse motion, the accelerated electrons will drop in the phase with deceleration force and dephase with the laser pulse. These extraction and acceleration processes occur when the laser pulse travels along the target surface until it leaves the right edge. Figure 2(c) and figure 2(d) display the patterns of both the $E_{\parallel}$ and $E_{\perp}$ after the accelerated electrons pass through the right edge of the target. Since the incident and the reflected laser have different propagation directions, which can cause the separation of these two laser pulses, as shown in figure 2(d). After that, the accelerated electrons only feel the effect from the incident laser pulse and interact with it with generation of high energy γ -ray emission.

Figure 3(a) shows the photon density in the normal coordinate system after the accelerated electrons pass through the right edge of the target at $14 T_0$. The density of γ -ray emitted is $253 n_c$, which is mainly contributed by the dense electron bunches extracted. Besides, the emitted γ -rays propagate along the extension line of the surface of the target with a small divergence. Figure 3(b) displays the distributions of $\eta_{\parallel}$ (only considering $\eta_{\parallel} > 0.1$ which means the QED effects are non-negligible) and $\beta_{\perp}$ of the electrons in the converted coordinate system (x', y') together with both the electric and magnetic fields on the surface of the target. Because of the synthetic action of the $E_{\parallel}$, $\beta_{\perp}$ and B_z , there are several peaks of $\eta_{\parallel}$, which corresponds to the peaks of $E_{\parallel}$, $\beta_{\perp}$ and B_z . Besides, the density of γ -ray emitted also relates to the density of the high energy

Figure 2. The distribution of electric fields parallel (a,c) and perpendicular (b, d) to the surface of the target in the coordinate system (x', y') (where x' is axis along the surface of the target and y' is perpendicular to the surface) at $8T_0$ and $14T_0$ respectively.

electrons. Therefore, the positions of dense γ -ray emissions correspond to the positions of the high energy electron bunches (the position where dense blue points appear in figure 3(b)). When the electron bunches travel into the vacuum, they still emit high energy γ -rays along the x' axis direction until they dephase from the laser field.

To analyse the energy of the γ -rays, the acceleration processes of the electrons are important. Figure 4(a) gives the electrons density along the surface of the target. It is shown that electron bunches with density of $\sim 300n_c$ are extracted. When the laser passes through the right edge of the target at $14T_0$, the electrons separate from the surface and propagate together with the incident laser pulse in the x' axis. The figure 4(b) shows the spectra of three specific times, which indicates that electrons can be accelerated to ~ 5 GeV. Theoretically, the ponderomotive force can be written as $F_p = -\frac{e^2}{4m_e\omega^2}\nabla E^2$, which is $\sim 5 \times 10^{-3}$ N at $14T_0$. The acceleration length is about $\lambda_0/4$. Then the electron can reach the maximum energy of $E_{eP} = 7.8$ GeV. In addition, the high energy electrons lose energy by radiation simultaneously. The radiated power is $P_\gamma = \frac{2\alpha}{3} \frac{m_e c^2}{\tau_c} \eta^2 g(\eta)$ [25]. The radiation time is estimated as $T_0/4$, then the energy loss

Figure 3. (a) The distribution of photon density in the (x, y) coordinate system at $14 T_0$. The white dashed box displays the position of the target. (b) The distribution of $\eta_{||}$ (red points), $2\beta_{\perp}$ of electrons (blue points), $E_{||}$ (black solid line), and cB_z (green solid line) in the (x', y') coordinate system at $14 T_0$.

Figure 4. (a) The distribution of electron density in the normal (x, y) coordinate system at $14 T_0$. (b) The electron spectra at $8 T_0$, $12 T_0$ and $14 T_0$, respectively.

by radiation is $E_{eR} = 0.65 \text{ GeV}$. Therefore, the maximum of electron energy can be estimated as $E_{eP} - E_{eR} = 7.2 \text{ GeV}$, which is higher than the simulation results. This reduction is mainly because that the electrons have been decelerated to lower energy at $14 T_0$. These high energy electrons interact with the laser fields can emit high energy photons.

The divergences of the photons at $8 T_0$, $12 T_0$ and $14 T_0$ are shown in the figure 5(a). It shows that most of the photons emitted are from the x' axis direction with a small divergence angle of 31° , which is due to the guiding of the target surface. The spectra of γ -rays at $8 T_0$, $12 T_0$ and $14 T_0$ are shown in figure 5(b). It shows that the cut-off energy of γ -rays are $\sim 2 \text{ GeV}$. Theoretically, the energy of the emitted γ -rays is $h\nu_S = 0.44\eta E_e \approx 2.42 \text{ GeV}$ (setting the $\eta = 1$ and $E_e = 5.5 \text{ GeV}$)[27]. This confirms that the simulation results are reasonable. The yield of γ photons at $14 T_0$ is $\sim 7 \times 10^{12}$

Figure 5. (a) Divergences of photons emitted at $8T_0$ (black solid line), $12T_0$ (red dashed line) and $14T_0$ (blue dash-dot line). (b) The photon spectra at $8T_0$ (black line), $12T_0$ (yellow line) and $14T_0$ (red line), respectively.

with averaged energy of 12.9 MeV. The size of the γ -ray source can be estimated as $2\ \mu\text{m} \times 2\ \mu\text{m}$ with a $0.54 \times 0.54\ \text{rad}^2$ divergence, the brightness of the γ -ray source in this scheme is $\sim 4 \times 10^{23}$ photons/s/mm²/mrad²/0.1% BW. Such a ultra-bright γ -ray source is useful to create to dense electron-positron pairs when colliding with an intense laser.

4. Discussion

In order to show the robustness of the model. We discuss the dependence of three key parameters of γ -ray emission, i.e., the number of γ -rays emitted N_γ , the averaged γ -ray energy E_γ and the conversion efficiency (CE) of the laser to γ -rays in different laser intensity conditions. As shown in figure 6, all these three parameters increase as the laser intensity grows. However, the number of γ photons increases with laser intensity more drastically. That is because that both the number of electrons extracted and the probability of the photon emission increase with the laser intensity. The conversion efficiency of the laser to γ -rays increases to over 10% when the laser intensity is higher than 3×10^{23} W/cm². Therefore, the obliquely incident laser scheme is robust in a range of laser intensity.

In addition, the angle of the target also has important impact on γ -ray emissions since it plays a key role in the superposition effect and the confinement of electrons at the surface. As shown in figure 7(a), the peak density of emitted photons increases when the incident angle is smaller than 20° . The main reason is that, at the beginning of the laser-target interaction, the superposition effect for the larger incident angle is more intense than that for the smaller angle (as shown in figure 7(b)). However, the maximum of the electric field for the larger incident angle is lower when incident angle is greater than 15° , which causes the decrease of the peak density of photons when the incident angle is greater than 20° . When the incident angle is larger than 25° , as displayed in

Figure 6. The parameters N_γ , E_γ and CE changes with the laser intensity increases. The symbols shown in the figures are the simulations points.

figure 7(a), the peak photon density tends to be stable. This is due to the change of the matching condition between the focal spot size of the laser and the transverse dimension of the target. The divergence shows a different pattern. It decreases before the incident angle is $\sim 16^\circ$ and then increases. This is mainly caused by the lower electric field when the incident angle is smaller than 15° and the higher electric field when the incident angle is larger than 15° . The changes of divergence for different incident angles are so small that they have little impact on the brightness of the γ -ray sources in this regime. Therefore, the obliquely incident regime can work for small incident angle, while the best results can be achieved at incident angle $\theta = 20^\circ$.

5. Conclusion

The obliquely incident laser is utilized to irradiate a solid target to generate ultra-bright collimated γ -ray source. The laser spot size is comparable to the transverse dimension of the target, which allows the laser field to interact with the surface during its propagation. The fields around the surface are enhanced to 1.5 times due to the superposition of the incident and reflected laser pulses. Such an intense field can drag out dense electron bunches and accelerate them to GeVs in the direction parallel to the target surface. When these high energy electrons leave the target and propagate into the vacuum, they interact with the incident laser continuously and create dense and high energy γ -rays. The results indicate that $\sim 7 \times 10^{12}$ γ photons with averaged energy of 12.9 MeV are emitted along the direction parallel to the surface with a small divergence of 31° , which achieve a brightness of $\sim 4 \times 10^{23}$ photons/s/mm²/mrad²/0.1%BW.

Figure 7. (a) The influence of the laser incident angle on the peak density (the black solid line with square symbols) and the FWHM divergence (the red dashed line with inverted triangle symbol) of the emitted photons. (b) The evolution of the electric field of the laser for different incident angles. The black, dark cyan, red and magenta lines represent the incident angle 10°, 15°, 20° and 25° respectively.

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