Transparency of near-critical density plasmas under extreme laser intensities

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Abstract
We investigated transparency of near-critical plasma targets for highly intense incident lasers and discovered that beyond relativistic transparency, there exists an anomalous opacity regime, where the plasma target tends to be opaque at extreme light intensities. The unexpected phenomenon is found to originate from the trapping of ions under exotic conditions. We found out the propagation velocity and the amplitude of the laser-driven charge separation field in a large parameter range and derived the trapping probability of ions. The model successfully interpolates the emergence of anomalous opacity in simulations. The trend is more significant when radiation reaction comes into effect, leaving a transparency window in the intensity domain. Transparency of a plasma target defines the electron dynamics and thereby the emission mechanisms of gamma-photons in the ultra-relativistic regime. Our findings are not only of fundamental interest but also imply the proper mechanisms for generating desired electron/gamma sources.

1. Introduction
One of the most important parameters in laser–plasma interactions (LPI), the critical density \( n_c \) defined by
\[
\omega_0 = \omega_p = \sqrt{4\pi n_c e^2/m_e} \quad \text{(laser frequency \( \omega_0 \) vs plasma frequency \( \omega_p \))}
\]
clarifies the underdense and overdense regimes. In the relativistic regime, relativity would impose an increase on the effective electron mass by its gamma-factor \( \gamma_e \). A rough estimation in most cases is \( \gamma_e \sim \sqrt{1 + a_s^2/2} \) [1], where \( a_s = c\omega_p/\omega_0 \). \( \omega_0 = \omega_p + \omega_\text{pe} \) is the dimensionless amplitude of the laser field \( E_0 \). Thus an initially overdense target \( (n_0 > n_c) \) can become transparent for sufficiently high laser intensities such that \( n_0/\gamma_e < n_c \), known as relativistic transparency (RT) [2–4]. More refining considerations should also account for the snow-plow effect. The strong laser ponderomotive force would push the electrons forward and pile them up in the interface to form an ultra-thin layer. The laser field then confronts plasma densities much higher than the initial ones. Hence the RT threshold for laser field is increased [5–9]. Other effects like electron temperature and pulse profile could also alter the threshold by some degree [10, 11]. These refinements offer better interpretations of the problem. The commonly accepted statement has remained in the sense that an overdense target would eventually become relativistically transparent as long as the laser is strong enough to fulfill \( n_0/\gamma_e < n_c \) and should remain so for the intensities beyond.

Nowadays, the quest for exploring new physics in the near–quantum electro-dynamics (QED) regime and for important applications as ion acceleration has led to the construction of next generation laser facilities like ELI, XCEL etc [12], aiming for intensities over 10^{23} \text{ W cm}^{-2}. Several aspects of LPI can be fundamentally changed in these extreme conditions, including MeV-gamma-photon emission [13–15], electron cooling [16–21] and even trapping [22–24] of electrons due to radiation reaction (RR). Under this context, we revisit plasma transparency in the near-QED regime, because it is not only of fundamental important but also...
distinguishes the electron dynamics and hence the photon emission process for potential applications. By one-dimensional (1D) analysis and particle-in-cell simulations, we predict that the relativistically transparent target can become opaque at extreme intensities. We found that the anomalous opacity results from more motive ions and RR effect in such an exotic parameter region.

2. Anomalous opacity in 1D simulations

Prior to explaining the phenomenon, we first introduce a parameter that represents the degree of transparency. The normal approach usually measures reflectivity of the laser pulse $\eta$. This is improper at extreme intensities as the pulse moves at a velocity close to the light speed. The Doppler effect would greatly diminish the reflectivity regardless of transparency or opacity. From reflectivity alone it is unlikely to identify the two regimes. Instead, one can define transparency from the point view of the plasma. In underdense plasmas (in 1D situation), laser pulses propagate through and leave the electrons behind the interface. Hence electrons interact with the body of the pulse and deplete laser energy volumetrically. They gain very high momentum in both forward and backward directions. Contrarily, for completely opaque targets, the overdense electron layer formed at the interface would stop the laser field from further penetration. Laser energy is coupled to plasma through the spatially limited skin-layer, leading to forward moving electrons of relatively low momentum. The disparate dynamics indicate that the transition from opacity to transparency is correlated to whether electrons are left behind the interface or not. One then define a parameter $\eta$ by counting the number of electrons behind the interface $N_{\text{left}}$ and dividing it by the total number of electrons interacted (seen) by the laser $N_{\text{total}}$, i.e., $\eta = N_{\text{left}} / N_{\text{total}}$. We use the value of $\eta$ to measure the degree of transparency in the following. Apparently $\eta = 0$ represents opacity and 1 transparency. This definition will be validated throughout the analysis.

We restrict our analysis to 1D as RT is essentially a 1D problem. In all simulations using the code VLPL [25], trapezoidal pulse profiles and circular polarization are employed to exclude the effects of pulse profile and electron heating. The simulation box is $50\lambda_0$ long (laser wavelength $\lambda_0 = 0.8 \mu$m). The cell size is $\lambda_0/100$ and the time step is $0.008 T_0$ ($T_0$ is the laser period). Each cell is filled with 8 macro particles. The laser field rises in $2T_0$ and then stays constant. The target occupies an area from $x_0 = 30\lambda_0$ to $80\lambda_0$. The simulations involving RR and pair creation is done in a quasi-1D geometry using VLPL. That is the transverse dimensions $y$ and $z$ are set to be 1 laser wavelength and the laser spot-size is set to be infinity. Periodic conditions are employed for both particles and fields in these two directions. This produces the 1D geometry perfectly. We vary the laser amplitude $a_0$ and target density $n_0$. The interface location $x_I$ is taken at where the peak electrostatic charge separation field is halved. When the interaction is stabilized, we count the number of electrons left behind the interface $N_{\text{left}}$ and the total number of electrons interacted by the laser $N_{\text{total}} = (x_I - x_0)\eta_0$.

In figure 1, transparency (factor $\eta$) is shown as a function of the laser amplitude at three plasma densities $n_0 = 10n_c, 15n_c$ and $25n_c$. From figure 1(a), one sees that as the $a_0$ increases from 20 to 300, the amount of electrons left behind the interface increases dramatically, indicating a more transparent target due to relativity. This is consistent with the prediction of existed theories. However, the tendency turns away when it comes to the extreme intensity regime. For the amplitude beyond $a_0 \sim 300$, the factor $\eta$ does not go up, instead, it declines steadily through the high intensity region. This unusual phenomenon tells that at extreme intensities the target somehow becomes opaque rather than relativistically transparent. The anomalous opacity, as far as we know, has not been predicted in any previous studies. It is even more evident when RR is switched on, which is important for intensities $>10^{22}$ W cm$^{-2}$. At $a_0 \geq 750$ the target is absolutely opaque to the incident laser (see in figure 1(a) with RR). Similar behavior is seen for $n_0 = 15n_c$ in figure 1(b). In figure 1(c) at $n_0 = 25n_c$ anomalous opacity further dominates for all amplitudes.

To uncover the underlying mechanism, we take the case $n_0 = 10n_c$ for in-depth analysis. We record the electron and proton trails in three regimes: opacity ($a_0 = 20$), RT ($a_0 = 300$) and anomalous opacity ($a_0 = 1500$). The RR effect is switched off here and will be discussed later. In figure 1(d), electrons are snow-ploughed and moving ahead of the interface, creating a charge separation field that accelerates and reflects local protons during propagation. This is also referred to the hole-boring process for opaque targets [26, 27]. In the RT regime of figure 1(e), the interface moves so fast that a significant amount of protons are no longer trapped. The balance between the charge separation force and the Lorentz force exerted on the electrons is thus disrupted. Electrons by the interface are barely confined within the snow-ploughed layer. Instead, they move towards the incident pulse and spread along the whole pulse. As we discussed at the beginning, it means the target is getting transparent. Interesting enough, protons are accelerated forward again in the anomalous opacity regime, as illustrated in figure 1(f). Electrons move together with protons. In contrast to diverging in space as they do in figure 1(e), they are brought together to be more concentrated around the interface, where the laser field couples its energy to the electrons. The interaction process turns into more like the hole-boring one in figure 1(d), i.e., the target becomes opaque in this regime.
Since transparency/opacity is strongly associated with the proton/ion motion as we have seen, it will be insightful by considering the following two extreme cases: the protons are mobile in one case, and fixed in the other. We compare the two cases in figure 2, where the difference can be seen instantly from the electron trails and the charge separation field. In case one, protons are fully trapped and reflected. The electron and proton layers are so closely attached to each other that scale length of their charge separation field $E_x$ is limited to less than one laser wavelength, see in figure 2(a). Consequently, the electrostatic potential contained in the localized plasma field is much less than the laser ponderomotive potential. The electron motion is thus dominated by the ponderomotive force. Most electrons are restricted within the skin-layer and pushed forward by the laser field, corresponding to the opacity regime. One may confirm it from the phase space in figure 2(c). Conversely, for fixed protons, the charge separation field extends up to several laser wavelengths, as presented in figure 2(b). The contained electrostatic potential surpasses the laser ponderomotive potential. A large portion of electrons are distracted by the longitudinal field $E_x$. They escape the interface and gain energies in volume of the laser pulse (see also in figure 2(d)). We therefore work in the transparency regime.

The distinctive electron dynamics in each regime result in completely different radiation patterns. In the opacity regime for mobile protons (figure 2(a)), since electrons are primarily pushed forward, photons are mostly emitted in forward/transverse direction with divergence angle $\theta < 90^\circ$, as seen in figure 2(e). In the transparency regime (figure 2(b)), electrons are extracted from the interface and collide with the incident laser (see in figure 2(d)). The radiation is thus oriented backwards at $\theta \sim 180^\circ$ in figure 2(f). A remarkable consequence is induced on the electron energy and emitting efficiency. The peak momentum of electrons in the opacity regime is less than $p/m_e \sim 80$ whereas the one in the transparency regime is one magnitude higher $p/m_e \sim 800$. Enormous enhancement on photon emission is obtained in the latter. The peak and total energy is 4 MeV and 22.4 mJ, respectively, compared to 0.5 MeV and 0.06 mJ for the former.
3. Analytical model

The drastic difference induced by merely turning proton motions on and off leads to the conclusion that the charge separation field is strongly dependent on the trapping of protons. The latter is the origin of the electron dynamics and hence the transparency of the target. From the particle trails presented in figures 1(d)–(f), one infers that it is the trapping of protons corresponds to the opacity of the target. The problem is then directed to finding the trapping condition of ions in LPI. This usually depends on the propagation velocity, peak amplitude and the scale length of the plasma field. The propagation velocity of the wave front in an initially overdense plasma can be obtained by the conservation law of energy

\[ S \approx \frac{\epsilon_0 c}{4\pi} (\epsilon_i^{1/2} E_i^2 - \epsilon_r^{1/2} E_r^2) \]

and \( U \) the total energy in the system per unit length

\[ U = \frac{1}{8\pi} [(1 + \epsilon_i)E_i^2 + (1 + \epsilon_r)E_r^2 + \langle E_i^2 \rangle] + n_0 m_e c^2 (\gamma_n - 1). \]

Here \( E_i \) and \( E_r \) are the incident and reflected laser field, respectively; \( E_z \) is the longitudinal plasma field. The last term in equation (2) denotes the average electron kinetic energy per unit length (ions are fixed). For the incident and reflected lasers, \( \epsilon_i \) and \( \epsilon_r \) are the plasma dielectric constants. At very large intensities, one simply assumes \( E_i \sim 0 \) due to the strongly suppressed reflection and \( \epsilon_i = 1 - n_0 m_e \gamma_n \sim 1 \). Thereby the propagation velocity takes the form \( \beta_p = 1/(1 + \langle E_i^2 \rangle /2E_i^2 + 4\pi n_0 m_e c^2 (\gamma_n - 1) / E_i^2) \). The laser-driven charge separation field in plasma is presented in the form of wakefield. According the figure 2(d), the field strength is linearly distributed. By averaging its energy density over one plasma period, one has \( \langle E_i^2 \rangle = 2(4\pi n_0 d)^2/3 \), where...
The propagation velocity versus the self-similar parameter $S = a_0 n_0 / n_0$ (a) from simulations (dotted) and equation (3) (black solid); the peak amplitude of the plasma field as a function of the laser amplitude (b) for simulations (red square) and equation (4).

$d = \lambda_p e = \sqrt{\gamma_e n_e / n_0} \lambda_0$ is the plasma wavelength. Normalizing all the variables and taking $\gamma_e \approx \sqrt{1 + a_0^2} \approx a_0$ for circularly polarized lasers, the velocity becomes

$$\beta_e = \frac{1}{1 + \left(\frac{2\pi^2}{3} + 1\right)^{1/2}}.$$  \hspace{1cm} (3)

It follows from equation (3) that the interface propagation velocity in a near-critical plasma does not depend on the laser amplitude or plasma density separately, but rather on the similarity parameter $s = n_0 / a_0 n_e$ \[29\]. The factors in the denominator of equation (3) suggest that most of the laser energy is restored in the charge separation field rather than electrons. This description is confirmed by simulations in a broad parameter range. The simulations were run with $a_0 = 50, 300$ and $1000$ at various densities. As seen in figure 3(a), equation (3) describes the simulation results very well through the not-so-relativistic regime to ultra-relativistic one.

Trapping of the local ions is determined by the field at the laser–plasma interface is usually different from the one estimated from plasma wave. In the initially overdense regime, it can be derived by considering, in the rest frame of the moving interface, the balance of force exerted on electrons from the laser field and the longitudinal field (the factor 2 comes from the superposition of incident and reflected laser fields) \[30\]

$$E_{\text{ion}} = 2a_0 \frac{1 - \beta_e}{1 + \beta_e}.$$  \hspace{1cm} (4)

Together with equation (3) $E_{\text{ion}}$ is fully resolved for certain $a_0$ and $n_0$. The simulation results in figure 3(b) validates our analysis.

We consider the trapping condition for a rest ion in the moving field of amplitude $E_x$ and velocity $\beta_e$. The trapping probability is determined by the ratio between the electrostatic potential contained within the first half period of the longitudinal field and ion kinetic energy in the rest frame of the field, denoted by $\kappa = Z e \phi / E_{kx}$. The former is roughly estimated by $\phi' \approx E'_{\text{ion}} d' / 4 = E_{\text{ion}} \gamma_e d / 4$ while the latter is $E_{kx}' = (\gamma_e - 1) Am_e c^2$. The superscript denotes the quantities in rest frame of the propagating field. Substituting equation (4) yields the form

$$\kappa \approx Z \frac{\gamma_k}{A} \frac{1}{1836} \frac{\pi}{\gamma_e} \frac{a_0}{n_0} \frac{1 - \beta_e}{1 + \beta_e}.$$  \hspace{1cm} (5)

Here $Z$ and $A$ are the atomic number and mass number of the ion species. Combining equations (3) and (5), we calculated the $\kappa$ value as a function of the laser amplitude for different plasma densities. Apparently, the larger the $\kappa$ value is, the more likely the ions will be trapped and hence more opaque the plasma tends to be.

We can estimate the factor $\kappa$ in the two regions. When the field propagates at very low velocity, i.e., $\beta_e \ll 1$, we have $\gamma_k - 1 \approx \beta_e^2 / 2$ and $\sqrt{(1 - \beta_e)/(1 + \beta_e)} \approx 1$. Equation (5) is approximated to $\kappa \sim a_0^{-1/2}$, suggesting that at certain plasma density, the target becomes more transparent as laser amplitude increases. This trend is consistent with RT predicted by existing theories. On the other hand, in the ultra-relativistic regime where $\beta_e \sim 1$, one has $\sqrt{(1 - \beta_e)/(1 + \beta_e)} \approx 1/2\gamma_e$ and the factor scales as $\kappa \sim a_0$. It is such a scaling that indicates the anomalous opacity at extreme intensities since the factor rises as the laser field gets stronger. The scalings are summarized in equation (6).
in the small velocity region and the trapping condition affected by the RR, using the code VLPL. It employs a QED model to calculate RR and that the RR can modify the dispersion relation of EM wave propagation in the RT regime.

4. Effect of RR

Anomalous opacity comes from the fact that the propagation velocity is limited to the speed of light, while the charge separation field keeps increasing due to the higher laser amplitude. These trends are clearly demonstrated in figure 3. Consequently, compared to the RT regime, it is easier for protons to catch up the propagation piston and get trapped in the near-QED regime. According to equation (5), plasmas made of higher charge-to-mass species tend to more transparent than lower ones, provided the plasma electron density is the same. This also explains the results in [5]. The charge-to-mass ratio also implies considerable difference in terms of absorption and radiation [31]. Transition from transparency to opacity also happens by slightly increasing the plasma density [8], still within the expectation of existed theories though.

4. Effect of RR

At these extreme light intensities, RR effect must be taken into account. It has been shown in previous studies that the RR can modify the dispersion relation of EM wave propagation in the RT regime [32]. Here we focus on the trapping condition affected by the RR, using the code VLPL. It employs a QED model to calculate RR and \( e^-/e^+ \) pair creation [33, 34]. When it becomes important, we found that it further strengthens the unique phenomenon, as introduced in figures 1(a)–(c). The tending-to-be opaque plasma becomes completely opaque, forming a clear transparency window as one can tell. We therefore compare the results of \( a_0 = 800 \) and \( n_0 = 10n_e \) by switching RR on and off.

In figure 5 we display the longitudinal field and the electron phase space distribution. One sees the distinctive patterns between the two. When RR is off, both the bipolar field and the phase space show a standard plasma oscillation (see in figure 4(a)). On the contrary, once RR is switched on, there is no sign of plasma oscillation. Electrons undergo sub-oscillations in the combining laser and plasma fields. Their backward motion is strongly suppressed by RR so that most of them would stay in the \( p_e \geq 0 \) region, as illustrated in figure 4(b). In other words, RR is so strong that the electrons colliding with the laser pulse are slowed down and even reflected by the laser field. Similar phenomenon has also been observed in previous studies [20]. It results in a positive plasma field in the whole interaction region. Both the amplitude and the scale length are much larger than the former. Under the same laser–plasma condition, the latter is obviously much more favorable for ion trapping. Consequently, anomalous opacity is greatly enhanced due to the RR effect at extreme light intensities.

Another important QED effect in the exotic regime is the electron–positron pair creation. This process is automatically triggered in the VLPL code using a QED-based Monte-Carlo algorithm. As seen in our previous studies, pair creation becomes considerable for laser intensities approaching \( 10^{25} \text{ W cm}^{-2} \) [35], corresponding a
laser field of over \( a_0 \sim 2000 \), while the proton trapping and hence the anomalous opacity is already obvious at \( a_0 \sim 1000 \). As such pair creation rarely modifies the physical picture of transparency here. We expect its effect on opacity to be more notable when considering heavier ions, for the latter require stronger laser fields to get trapped. That may encounter pair creation issue.

5. Conclusions

In conclusion, we have discovered an anomalous opacity regime at extreme laser intensities and revealed that this is due to the ion dynamics. It is further enhanced by RR. Our finding predicts distinctive particle dynamics and radiation patterns in different regimes. This does not only provide insights to the fundamental physics in the exotic near-QED regime, but also imply possible applications in high-energy high-efficiency gamma-ray radiation sources.

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