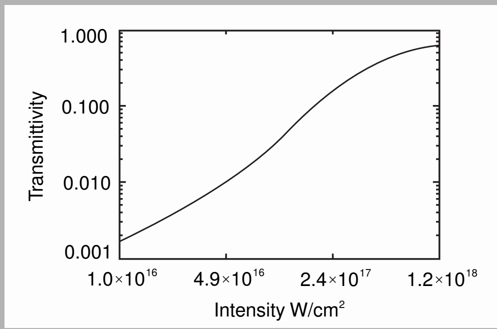
**Abstract:** For some time now anomalous transparency induced by high intensity laser light interacting with thin solid foils has been found experimentally [1] and several theoretical models have been suggested to explain this phenomena [2, 3]. In our present study based mostly on classical electrodynamics the increase of the transmittivity is the consequence of the more and more pronounced role of the frustrated total reflection in the plasma layer. We give a detailed analysis of the effect of the electron temperature of the plasma and of the angle of incidence of the laser light on the transmittivity.




The dependence of the transmittivity on the intensity of the incident laser light. The graphic has been made by the use of the following parameters: the wavelength of the incident laser light $\lambda = 785\,nm$, the angle of incidence $\theta_{in} = 20^\circ$ , the scale length of the plasma $l \sim 0.2\lambda$



# Intensity dependent anomalous transmittivity of thin plasma layers

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## 1. Introduction

The propagation of an intense laser pulse in a plasma layer is of interest for understanding laser plasma interactions and its most important application, the inertial confinement fusion. One of the most interesting phenomena is the transition from opacity to transparency of a plasma layer named anomalous transmission. When an intense laser light hits a thin solid foil high density plasma is formed. If the intensity of the laser light is high enough (near the relativistic threshold) and the duration of the pulse is short (shorter than 1 nanosecond) the transmittivity of the plasma can be approximately 1. Anomalous transmission of laser light through thin slabs of plasma has been observed in several experiments [1, 5]. The effect was observed in plasmas produced by relatively long (500 ps [5]) and short (30 fs [1]) laser pulses. Many authors attributed the optical transparency to the strong magnetic field induced by ionization or it has been supposed that this anomalous transparency is the result of mixing of two electromagnetic waves with appropriate frequencies.

In the present work we intend to present a detailed analytical solution which gives the transmission coefficient (the ratio between the amplitude of the transmitted and incident electric field ) and transmittivity (the ratio between the intensity of the transmitted and incident light ) of plasmas produced by laser pulses. Here we suppose, that the thickness of the thin foil is a few (10-20%) per cent of the wavelength of the incident laser pulse.

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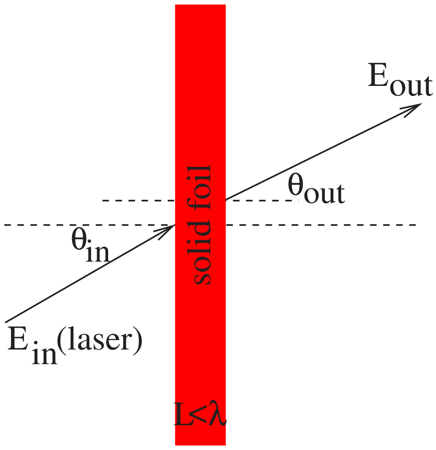


**Figure 1** The interaction of the laser light with the solid foil

## 2. The laser and foil interaction

In the present treatment we consider that a p-polarized monochromatic electromagnetic wave,
$\mathbf{E}_{in} = E_{in} \cdot exp[i(\omega t - \mathbf{kr})]$
impinges the solid thin foil. The angle of incidence is denoted by $\theta_{in}$. $\mathbf{k}$ represents the wave vector, $\omega$ the frequency of the laser light. The amplitude $E_{out}$ of the electric field and the direction of propagation ($\theta_{out}$) of the electromagnetic wave at the rear side of the foil is determined as a function of the parameters of the incident laser light. The sketch of the interaction can be seen in Fig. 1.

The laser light ionizes the thin solid foil and a plasma is created as a result of the ionization.

In our model we assumed that a parabolic electron density profile is formed, which is characterized by the $n(z) = const\_dens1 \cdot z^2 + const\_dens2$ as can be seen in Fig. 2. The z axis is perpendicular to the surface of the foil. $const\_dens2$ is equal with the maximal electron density and $const\_dens2$ is determined from the equation of charge conservation $\int_0^{L_{pl}} n(z)dz = L_{foil} * n_{foil}$, where $L_{foil}$ is the thickness of the foil and $n_{foil}$ is the electron density of the foil before the laser pulse arrives.

This type of profile is more realistic that the exponentially decaying intensity profile which has been supposed in our previous model [4].

Supposing that the ions form a static background, the dielectric function and the index of refraction of the plasma is defined as a function of the electron density and the electron temperature. The dielectric function is:

$$\epsilon(z) = 1 - \frac{n(z)}{n_{cr}} + i\frac{\nu(\mu, z)}{\omega}\frac{n(z)}{n_{cr}}, \qquad (1)$$

where $\omega_p^2(z) = 4\pi n(z)e^2/m$ denotes the local plasma frequency and $\nu(\mu, z) = 2.91 \cdot 10^{-5} \cdot n(z) \cdot T_e^{-1.5}(\mu) \cdot Z[1/s]$ denotes the electron-ion collision frequency. $n_{cr}$ represents the critical density and is defined as the density where the local plasma frequency equals the laser frequency. $Z$ is the atomic number of the target material and $T_e(\mu)$ is the electron temperature. According to our assumption the temperature depends on the intensity parameter $\mu$ as $T_e(\mu) = T_e(max) \cdot \mu^2$. We consider the maximal electron temperature being 1keV. Let us use the following notations:
$c(z) = 1 - \frac{n(z)}{n_{cr}}$ and $d(z) = \frac{\nu}{\omega}\frac{n(z)}{n_{cr}}$.
The index of refraction can be given as a function of $c(z)$ and $d(z)$ (see [6]):

$$\eta(z) = \{\sin^2\theta_{in} + \left[(c(z) - \sin^2\theta_{in})^2 + d(z)^2\right]^{\frac{1}{2}} \times \qquad (2)$$

$$\times \cos^2\left(0.5 \cdot \mathrm{arctg}\frac{d(z)}{c(z) - \sin\theta_{in}}\right)\}^{\frac{1}{2}}.$$

The ionization degree, $w$ is related to the intensity parameter $\mu = \frac{eE}{mc\omega} = 10^{-9}\sqrt{I}[W/cm^2]\lambda[\mu m]$ ($I$ denotes the intensity of the incident laser light and $\lambda$ is the wavelength of the laser light) by the use of the Keldish formulae $w = const1 \cdot \exp\left(-\frac{const2}{\mu}\right)$. In the determination of the constants of the density profile ($const\_dens1, const\_dens2$) the value of the ionization degree is also taken into account.

In the above mentioned equation $const2 = -\frac{4}{3}\frac{\mu}{\hbar\omega} \cdot \sqrt{\frac{2*A^3}{mc^2}}$, where $A$ is the ionization energy and $\hbar$ is the Planck constant and c the light velocity. To determine $const1$ we supposed that the whole foil is photoinized when the intensity parameter reaches unity.

## 3. The structure of the plasma

In the case of plasmas with parabolic density profile it is worth to distinguish three separate regions from the point of view of the optical density. There are two optically thin, i.e. underdense regions (where the electron density is smaller than the critical density) and an optically dense, i.e. overdense region (where the electron density is higher than the critical density). The electromagnetic field penetrates into the underdense plasma to the surface determined by the classical reflection point, which is still in the underdense plasma and is defined as the surface where total reflection takes place. This way the underdense region can also be divided into two regions: one region is situated between the vacuum and the classical turning point (denoted by ud1) and the second region is situated between the classical turning point and the critical surface (denoted by ud2). In Fig. 3 are shown the consecutive layers having different optical densities. The optical properties are characterized by the index of refraction $\eta_{ud1}$, $\eta_{ud2}$, $\eta_{ud}$ and $\eta_{od}$, where the index denotes the layer. $\eta_0 = 1$ is the index of refraction of the vacuum.

As it was shown [6] in the case of steep density profiles the distance between the classical turning point and the critical surface can only be a few per cent of the wavelength of the laser light and the index of refraction of the

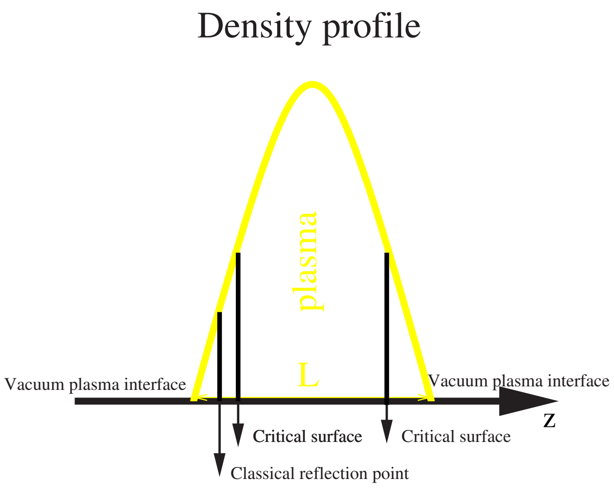


**Figure 2** The dependence of electron density profile normalized to the critical density on the normalized coordinate $z/\lambda$

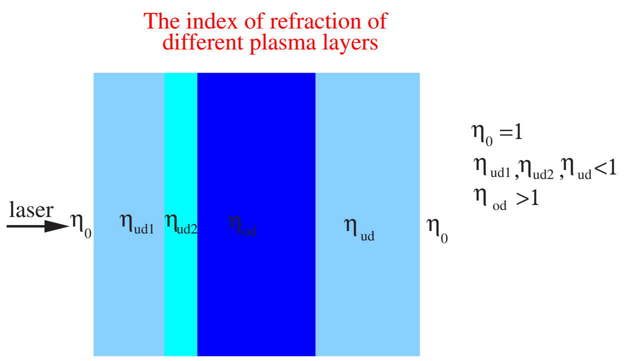


**Figure 3** The index of refraction corresponding to the electron density profile sketched on the right side

layers bounding the layer denoted ud2 is higher than the index of refraction of this layer. This way the electromagnetic wave does not totally reflect and frustrated internal total reflection takes place. The phenomenon, that the light could penetrate into an optically rare medium from an optically dense medium even if the angle of incidence is larger than the angle of total reflection is called frustrated total internal reflection. The effect is more interesting if behind the optically rare media is situated an optically dense medium, as it is in our case. As a consequence of frustrated internal total reflection the wave can penetrate in the overdense region as an inhomogeneous electromagnetic wave. It is known that the amplitude of the electric field is enhanced near the surface determined by the classical reflection point. The thickness of the layer ud2 is very small the amplitude of the electromagnetic field penetrates in the overdense region without decay.

The direction of propagation of the laser light at the rear of the foil can be given directly by the Snell-Descartes formulae because $\eta_0 \sin\theta_{in} = \eta_0 \sin\theta_{out}$, where $\eta_0 = 1$ is the index of refraction of the vacuum. This way $\theta_{out} = \theta_{in}$, so the direction of propagation at the backside of the foil will be the same as the direction of propagation of the incident laser light.

## 4. The transmission of the laser light

The thickness of each plasma layer is just a few nanometers. We suppose that the direction of propagation of the laser light cannot follow the rapid change of the electron density. This way we considered the plasma being formed by four consecutive layers having constant dielectric function. The dielectric function is determined by calculating its average value for each layer.

The transmission of the laser light through the plasma was calculated summing up the changes of the amplitude of the electric field at the interface of the different plasma layers. The amplitude of the electric field changes when the light penetrates from the vacuum in the layer ud1. The transmission coefficient can be given by the Fresnel formulae:

$$t_{0,ud1} = \frac{2}{\frac{\epsilon_{ud1}}{\epsilon_0} + \sqrt{\frac{\epsilon_{ud1}-\epsilon_0 \sin^2\theta_{in}}{\epsilon_{ud1}(1-\sin^2\theta_{in})}}}. \tag{3}$$

The thickness of this layer is very small, so we will neglect the decay of the wave during its propagation in this media.

Because of frustrated total internal reflection in the layer ud2 we don't know exactly how the laser propagates in this media. We calculated the transmission of the wave through this layer as an infinitesimal layer. The transmission coefficient of this thin layer is given by:

$$t_{FTR} = \frac{1 + t_{ud1,ud2} t_{ud2,od} exp(i\delta)}{1 - r_{ud1,ud2} r_{ud2,od} exp(2i\delta)}, \tag{4}$$

where $\delta = \frac{2\pi}{\lambda} dz \sqrt{\eta_{ud2}^2 - \eta_{ud1}^2}$ .

The transmission coefficients has analogous form with $t_{0,ud1}$. The reflection coefficient $r_{ud1,ud2}$ is:

$$r_{ud1,ud2} = \left(1 - \varphi\sqrt{\frac{\phi}{\epsilon_{2ud}}}\right) \Big/ \left(1 + \varphi\sqrt{\frac{\phi}{\epsilon_{ud2}}}\right) \tag{5}$$

$$\varphi = \frac{\epsilon_{ud1}}{\epsilon_{ud2}}, \phi = \frac{\epsilon_{ud2} - \epsilon_{ud1}\sin^2\theta_{in}}{(1-\sin^2\theta_{in})}.$$

and $r_{ud2,od}$'s form is analogous with $r_{ud1,ud2}$'s form.

After the wave passes the overdense region it passes the underdense region (characterized by $\eta_{ud}$) and enters the vacuum. The transmission coefficients are analogous with $t_{0,ud1}$.

Collecting the changes of the amplitude of the electric field: $t_{0,ud1} * t_{FTR} * t_{od,ud} * t_{ud,0}$ at any interface we obtained the transmission coefficient of the plasma as a function of the parameters of the electron density profile and the intensity parameter. Squaring the transmission coefficient the transmittivity can be obtained.

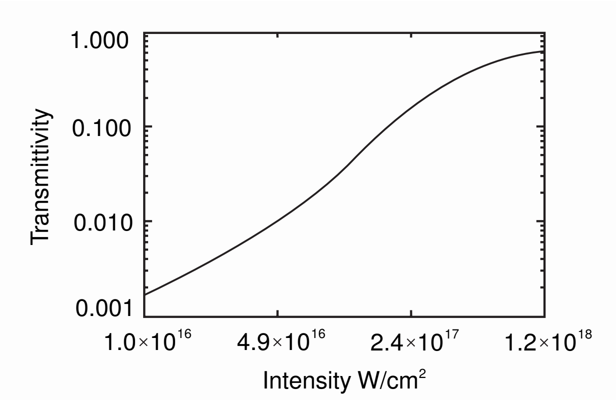


**Figure 4** The dependence of the transmittivity on the intensity of the incident laser light. The graphic has been made by the use of the following parameters: the wavelength of the incident laser light $\lambda = 785\ nm$, the angle of incidence $\theta_{in} = 20°$ , the scale length of the plasma $l \sim 0.2\lambda$

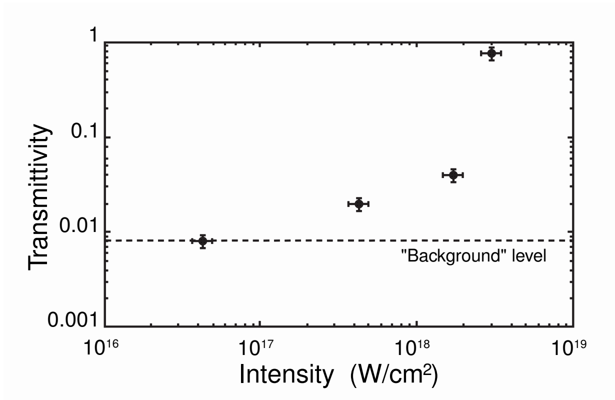


**Figure 5** The experimental dependence of the transmittivity on the intensity of the incident laser light. [1] (the wavelength of the incident laser light $\lambda = 785nm$, the angle of incidence $\theta_{in} = 20°$ , the scale length of the plasma $l \sim 0.2\lambda$)

## 5. Results and conclusions

We obtained the transmission coefficient and transmittivity of the plasma as a function of different parameters. The transmittivity mainly depends on the intensity of the incident laser light.

The dependence of the transmittivity on the intensity can be seen on Fig. 4. The transmittivity increases as the intensity parameter increases. To have an easier base for comparing the experimental and theoretical data we plotted the transmittivity as a function of the intensity. It can be seen, that the transmittivity is approximately 1, if the intensity is approximately $10^{18} W/cm^2$ which means that the intensity parameter is unity. The calculations has been made for the same parameters which has been used in the experimental work presented by Giuletti et al. in [1]. The results obtained by Giulietti & all can be seen in Fig. 5. The parameters are the wavelength of the incident laser light $\lambda = 785nm$, angle of incidence $\theta_{in} = 20°$, the scale length of the plasma $l \sim 0.2\lambda$. A good correspondence has been found between the experimental data and the theoretical results.

According to our assumption the role of the frustrated total internal reflection cannot be neglected, because just in this way can the wave penetrate into the overdense region without pronounced decay. In this case the losses in the plasma are compensated by resonance absorption. Using this really simplified model and taking into account the role of the frustrated total internal reflection one should obtain good correspondence between the theoretical and experimental results in spite of the simplicity of the model.

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