

Plasma currents and inverse bremsstrahlung absorption under strong dc/ac electric fields

Su-Ming Weng^{1,3}, Zheng-Ming Sheng^{2,1,‡}, and Jie Zhang^{2,1}

¹Beijing National Laboratory of Condensed Matter Physics, Institute of Physics, CAS, Beijing 100190, China

²Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China

³Theoretical Quantum Electronics (TQE), Technische Universität Darmstadt, D-64289 Darmstadt, Germany

E-mail: [‡]zmsheng@sjtu.edu.cn

Abstract. Plasma current induced by a strong dc electric field is studied by Fokker-Planck (FP) simulation. Based upon this, a hydrodynamic-like equation, similar to Spitzer's but without the weak-field limit, is given for calculating the current. This equation is suitable for application in hybrid-PIC simulations relevant to the fast ignition (FI) scheme. Furthermore inverse bremsstrahlung (IB) absorption is studied in a wide laser intensity range. In particular, we introduce an IB operator which is similar to Langdon's, but without the low laser intensity limit. This operator enables one to treat IB absorption properly in the inertial confinement fusion (ICF) schemes with the NIF/LMJ-scale laser intensity beyond 10^{15} W/cm².

1. Introduction

As is well known, a dc electric field will produce a current in plasma, while an ac electric field (usually laser field) induces IB absorption. Plasma current produced by a weak dc electric field can be well described by Spitzer's theory [1], and IB absorption in a low intensity laser can be treated consistently with the evolution of the electron distribution function (EDF) by Langdon's IB operator [2]. However, both Spitzer's theory and Langdon's operator are based on perturbation theory, assuming small anisotropy of EDF. Therefore, Spitzer's theory is valid only for $E_{dc} \ll E_c = m_e v_e \nu_{ei} / e$ and Langdon's operator for $E_{ac} \ll m_e v_e \omega / e$. Consequently, the observed electric conductivities are usually much lower than that predicted by Spitzer's theory in the non-weak dc electric fields [3], and Langdon's IB operator overestimates the absorption rates in an intense laser [4]. In the following sections, plasma dynamics in dc/ac electric fields are studied by a FP code [5], with a new equation introduced for calculating plasma currents and a modified IB operator for calculating absorption rate with high dc/ac electric field strength.

2. Plasma current in dc electric fields

Since the EDF is crucial to plasma properties, in Fig. 1 we draw the EDFs of plasma that obtained from FP code [5, 6] with ionic charge state $Z_i = 1$ under dc electric fields with different strengths. In the weak field, almost no shift of the EDF from $v = 0$ is seen. In the strong field, the EDF is almost collectively drifted away from $v = 0$. While the EDF in the moderate field is a hybrid of a stationary and drifting Maxwellian, as a bridge between the EDFs in weak and

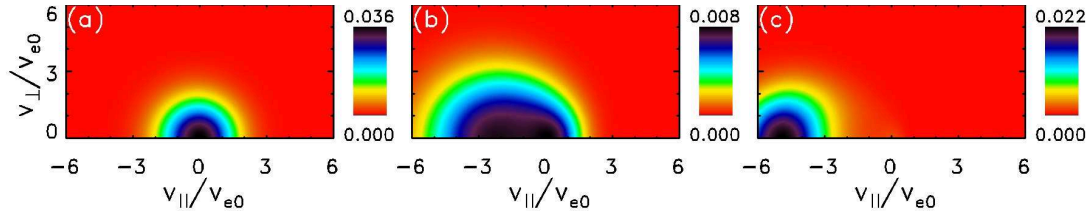


Figure 1. EDFs under different dc electric fields: (a) $0.01E_c$ after $500\tau_{ei}$, (b) $0.1E_c$ after $50\tau_{ei}$, and (c) $1.0E_c$ after $5\tau_{ei}$, where $\tau_{ei} = 1/\nu_{ei} = v_{e0}^3/(Z_i\Gamma^{e|e})$ and the EDF in unit of n_e/v_{e0}^3 .

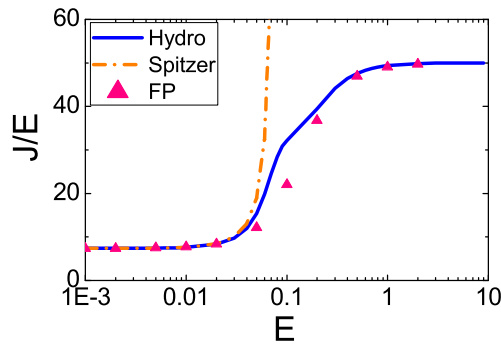


Figure 2. Plasma conductivities J/E as functions of dc electric field, obtained by Spitzer's model, by Eq. (2), and by FP code, at $t = 50\tau_{ei}$ after these electric fields are inducted into the plasmas with same initial parameters, where J/E in unit of $n_e e^2 \tau_{ei} / m_e$ and E in unit of E_c .

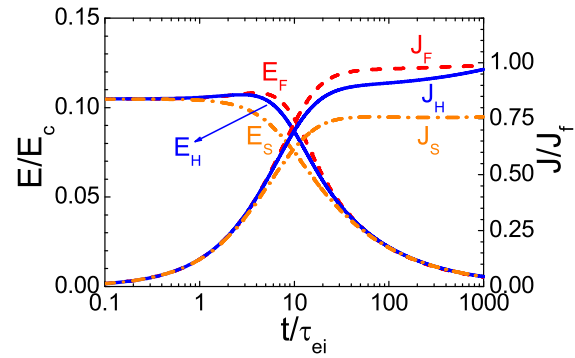


Figure 3. Electric field updated by Spitzer's (E_S), by hydrodynamic-like Eq. (2) (E_H), and by FP code (E_F), as well as the produced currents of these fields as a current of fast electrons $J_f = 3.5\text{GA}$ with a radius of $20\mu\text{m}$ transports into a uniform plasma with initial temperature of 500eV and density of 5gcm^{-3} .

strong field. Therefore, the EDFs in arbitrary dc electric fields can be expressed generally as

$$f(\mathbf{v}) = \delta \frac{n_e}{(2\pi v_{te1}^2)^{3/2}} \exp\left(-\frac{v^2}{2v_{te1}^2}\right) + (1 - \delta) \frac{n_e}{(2\pi v_{te2}^2)^{3/2}} \exp\left[-\frac{(\mathbf{v} - \mathbf{v}_d)^2}{2v_{te2}^2}\right], \quad (1)$$

where δ is the proportion of the stationary Maxwellian component, the first and second terms of RHS are the stationary and drifting Maxwellian components, respectively.

If we define parallel temperature $T_{\parallel} = m_e \int f(\mathbf{v}) v_{\parallel}^2 d\mathbf{v}$ and perpendicular temperature $T_{\perp} = m_e \int f(\mathbf{v}) v_{\perp}^2 d\mathbf{v} / 2$, it will be a good approximation to calculate plasma current as [6]

$$J = \sigma_0 E \left[1 - \exp\left(-\frac{t}{\tau_r}\right) \right] \exp\left(\frac{T_{\perp} - T_{\parallel}}{T_{\perp}}\right) \left(\frac{T_{\perp}}{T_0}\right)^{3/2} + n_e e \left[1 - \exp\left(\frac{T_{\perp} - T_{\parallel}}{T_{\perp}}\right) \right] \left(\frac{T_{\parallel} - T_{\perp}}{m_e}\right)^{1/2}, \quad (2)$$

where σ_0 is Spitzer's conductivity [1] for initial temperature T_0 , τ_r is the response time defined as the time when the current is $1 - 1/e$ (here e is Euler's number) of the final steady value, T_{\parallel} and T_{\perp} can be updated by $dT_{\parallel}/dt = 2JE - 2\nu_{ei}(v_{eff})(T_{\parallel} - T_{\perp})$ and $dT_{\perp}/dt = \nu_{ei}(v_{eff})(T_{\parallel} - T_{\perp})$, where $\nu_{ei}(v_{eff}) = Z_i \Gamma^{e|e} / v_{eff}^3$ is the effective e-i collision frequency with $v_{eff} = \sqrt{(T_{\parallel}^2 + 2T_{\perp}^2)/m_e}$. From Eq. (2) one can calculate plasma conductivity under a dc electric field of arbitrary strength. And it agrees well with FP code, while Spitzer's theory obviously overestimates the plasma conductivity in non-weak dc electric field as shown in Fig. 2.

As shown in Fig. 3, we simulate the generation of return current (RC) during the transport of a fast electron beam $J_f = 3.5\text{GA}$ in a plasma with $T_e = 500\text{eV}$ and density of 5gcm^{-3} . Since Spitzer model overestimates the conductivity, it underestimates the electric field and produces a RC only about $0.75J_f$. While our hydrodynamic-like equations give a good estimation of the electric field to produce the RC as large as J_f . Therefore, it is more suitable for treating the RC and the relevant joule heating during the fast electron transport in the FI targets [7].

3. Inverse bremsstrahlung absorption in ac electric fields

Since the EDF oscillates with $\mathbf{u} = -u_0 \sin(\omega t)\mathbf{e}_z$ ($u_0 = eE/m_e\omega$ is the peak electron oscillating velocity) in an intense laser, it is more convenient to rewrite FP equation in the oscillating system (v', θ') with transformation $\mathbf{v}' = \mathbf{v} - \mathbf{u}$ as $\partial f'/\partial t = C'_{ei}(f') + C'_{ee}(f')$, where $C'_{ee}(f')$ is identical to $C_{ee}(f)$, and $C'_{ei}(f')$ is given by

$$C'_{ei}(f') = \frac{\nu_{ei}^*}{2} \left[\frac{u^2 + 2uv' \cos \theta' + u^2 \cos^2 \theta'}{v'} \frac{\partial f'}{\partial v'} + \frac{2u \sin \theta' (v' + u \cos \theta')}{v'} \frac{\partial^2 f'}{\partial v' \partial \theta'} \right. \\ \left. + \frac{v'^2 + 2uv' \cos \theta' + u^2 \cos 2\theta'}{v'^2 \tan \theta'} \frac{\partial f'}{\partial \theta'} + (u \sin \theta')^2 \frac{\partial^2 f'}{\partial v'^2} + \left(\frac{v' + u \cos \theta'}{v'} \right)^2 \frac{\partial^2 f'}{\partial \theta'^2} \right], \quad (3)$$

with $\nu_{ei}^* = Z_i \Gamma^{e|e} / (u^2 + 2uv' \cos \theta' + v'^2)^{3/2}$. Using Legendre expansion $f' \simeq f'_0(v') + f'_1(v') \cos \theta'$ and assuming $\partial f'_1/\partial t \simeq -i\omega f'_1$ for $\omega \gg \nu_{ei} \equiv Z_i \Gamma^{e|e} / v_e^3$ (which is usually fulfilled), we get

$$\frac{\partial f'_0}{\partial t} \simeq \frac{u^2}{3v'^2} \frac{\partial}{\partial v'} \left[v'^2 \nu'_{ei} g(v'_{ei}) \frac{\partial f_0}{\partial v'} \right] + C'_0, \quad (4)$$

where C'_0 is the e - e collision term only relevant to f'_0 and $g(v'_{ei}) = 1 - b(v'_{ei}/\omega)^2 / [1 + b^2(v'_{ei}/\omega)^2]$ with $\nu'_{ei} = Z_i \Gamma^{e|e} / (u^2 + v'^2)^{3/2}$ and $b = (2u^2 + 5v'^2) / 5v'^2$. However, it is still difficult to integrate Eq. (4) over time for arbitrary ratios u_0/v_e . By numerical simulation, we find that [8]

$$\frac{\partial f'_0}{\partial t} \simeq \frac{u_0^2}{6v'^2} \frac{\partial}{\partial v'} \left[v'^2 \nu'_{eff} g(v'_{eff}) \frac{\partial f_0}{\partial v'} \right] + C'_0, \quad (5)$$

which can generate the absorption rate in good quantitative agreement with that obtained from our FP code for $0.2 \leq u_0/v_e \leq 65$ as shown in Fig. 4, where $\nu'_{eff} = Z_i \Gamma^{e|e} / (v'^2 + u_0^2/\zeta)^{3/2}$ with $\zeta = 3.84 + (142.59 - 65.48u_0/v_e) / [27.3u_0/v_e + (u_0/v_e)^2]$.

In Fig. 4, we compare the absorption rates R calculated from different models. At low intensity R obtained from all methods agrees well with each other and increase linearly with the intensity as predicted [4]. However, Langdon's IB operator has already overestimated R when $I = 10^{14} \text{W/cm}^2$ with $u_0 \simeq 2v_e$, and this deviation grows dramatically to several orders of magnitude with increasing intensity, while R calculated from our IB operator decreases slowly with the intensity and still shows a very good quantitative agreement with FP simulation and molecular dynamic simulation [9] at $I > 10^{14} \text{W/cm}^2$. This illustrates that our IB operator can produce the proper absorption rate at high laser intensity and can be used as the generalized version of Langdon's IB operator for a variety of practical applications [10].

As an example, we simulate the IB heating of Ref. [11], which is relevant to indirect drive ICF scheme. For $T_e = 284 \text{eV}$, which is the peak temperature in the non-magnetic case at 440 ps in Ref. [11], u_0/v_e is about 0.96, and it will be larger for other lower temperatures. Therefore, Langdon's IB operator, which is valid for $u_0/v_e \ll 1$, is no longer suitable for treating IB absorption in this case. In Fig. 5, we compare the absorption rates and temperatures obtained from different models. It is found that our IB operator accurately estimates the absorption rate. However, Langdon's operator results in an overestimated absorption rate and an overheated plasma, which may affect the heat transport and subsequent processes in the ICF scheme [11].

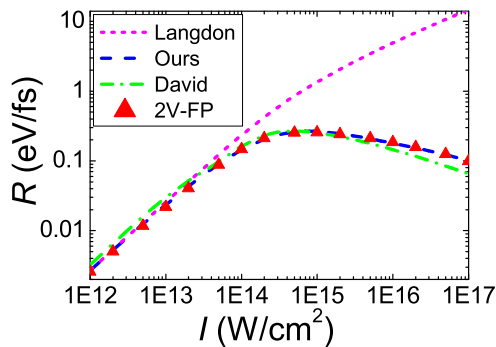


Figure 4. The absorption rates R VS laser intensity obtained from FP code, Langdon's IB operator, our IB operator, and David's fitted formula (6) in Ref. [9] from molecular dynamic method. The parameters are: $n_e = 10^{20} \text{ cm}^{-3}$, $T_{e0} = 10 \text{ eV}$, $Z_i = 1$, and laser wavelength $\lambda = 1.06\mu\text{m}$.

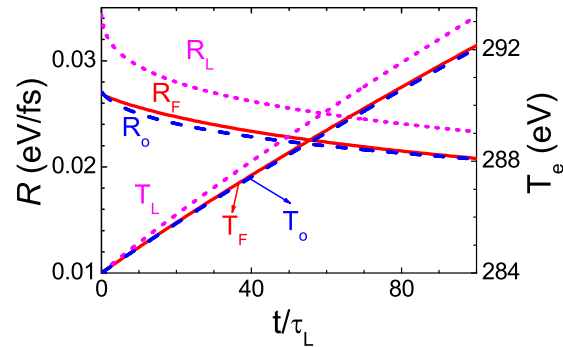


Figure 5. The absorption rates R and plasma temperatures T_e updated by FP code (R_F and T_F), Langdon's IB operator (R_L and T_L), and our IB operator (R_o and T_o). The parameters are: electron density of $1.5 \times 10^{19} \text{ cm}^{-3}$, initial temperature of 284 eV , ionization state of $Z_i = 7$, laser wavelength of $1.054\mu\text{m}$, and intensity of $6.3 \times 10^{14} \text{ W/cm}^2$.

4. Summary

We have found that the EDF in a dc electric field can be presented as a hybrid of a stationary and drifting Maxwellian. According to the form of EDF, we derive the hydrodynamic-like Eq. (2), which can be used as Spitzer's model but without the weak-field limit. For fast electron transport in the FI targets, it is found that the RC obtained with Eq. (2) can compensate the beam current almost completely, whereas the one obtained with Spitzer's model cannot. Furthermore we have studied the IB absorption in a wide range of laser intensity. It is found that if $u_0 > v_e$ the absorption will be inhibited with the increasing intensity. Based upon the simulation, we have introduced an IB operator without the low laser intensity limit. A simulation example relevant to the indirect drive ICF scheme shows that our IB operator provides a better evaluation of the absorption rate than Langdon's at high intensity over a few times of 10^{14} W/cm^2 .

Acknowledgments

This work was supported by the NSFC (grants No. 10674175, 60621063), National High-Tech ICF Committee of China, and National Basic Research Program of China (grants No. 2007CB815101, 2007CB815105). One of the authors (S.M.W.) wants to thank Professor P. Mulser of the Technische Universität Darmstadt for fruitful discussions and suggestions and acknowledges support from the Alexander von Humboldt Foundation.

References

- [1] Cohen *et al.* 1950 *Phys. Rev.* **80** 230; Spitzer L *et al.* 1953 *Phys. Rev.* **89** 977.
- [2] Langdon A B 1980 *Phys. Rev. Lett.* **44** 575.
- [3] Benage J F *et al.* 1999 *Phys. Rev. Lett.* **83** 2953; Lencioni D E, *Phys. Fluids* **14** 566.
- [4] Pert G J 1995 *Phys. Rev. E* **51** 4778.
- [5] Weng S M, Sheng Z M, and He M Q *et al.* 2006 *Phys. Plasmas* **13** 113302.
- [6] Weng S M, Sheng Z M, and He M Q *et al.* 2008 *Phys. Rev. Lett.* **100** 185001.
- [7] Mason R J, 2006 *Phys. Rev. Lett.* **96** 035001; Hauer A, and Mason R J, 1983 *Phys. Rev. Lett.* **51** 459.
- [8] Weng S M, Sheng Z M, and Zhang J, 2009 *Phys. Rev. E* **80** 056406.
- [9] David N, Spence D J, and Hooker S M 2004 *Phys. Rev. E* **70** 056411.
- [10] Bell A R, and Kingham R J 2003 *Phys. Rev. Lett.* **91** 035003 and reference therein.
- [11] Ridgers C P, Kingham R J, and Thomas A G R 2008 *Phys. Rev. Lett.* **100** 075003