High Energy Density Physics 4 (2008) 73–77

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

Evolution of photoionization two-stream instability in collisional plasma

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ARTICLE INFO

Article history:
Received 2 December 2007
Received in revised form 19 March 2008
Accepted 20 March 2008
Available online 28 March 2008

PACS:
52.35.Qz
42.55.Vc
52.38.−r

Keywords:
Plasma instability
Free electron laser
Photoionization
X-ray pulse
Gas jet plasma

ABSTRACT

A kinetic model which takes into account gas jet photoionization by an ultrashort linearly polarized EUV/X-ray free electron laser (FEL) pulse, a self-generated low frequency electric field, and elastic electron scattering on atoms is introduced to study the photoionization two-stream (PITS) instability. The evolution of PITS instability is described in terms of an integral equation for electron density perturbations. This paper presents a generalization of previous theories of the PITS instability in collisionless plasmas. The instability is produced by the anisotropy of photoionized electrons and is strongly affected by electron–atom collisions. Relaxation of the PITS instability is studied for different relations between the FEL pulse duration, the instability growth time, and the electron collision time.

1. Introduction

A new generation of free electron lasers (FEL) in laboratories such as DESY (Hamburg) [1] and LCLS (Stanford) [2] have made possible novel ways of producing photoionized plasmas during the interaction of ultrashort X-ray pulses with gas targets. Properties of such plasmas are defined by the electron distribution function which is anisotropic due to the classical nonrelativistic photoelectric effect [3]. Thus, FEL produced plasmas are quite different from plasmas created by conventional optical pulses. Instabilities due to the anisotropy of the electron velocity distribution function in FEL photoionized gases have recently been studied in Refs. [4,5]. It has been shown that for the current experimental parameters of FEL pulses the most important kind of plasma instability is a photoionization two-stream (PITS) instability with a typical growth rate on the order of an electron plasma frequency $\gamma_0 \sim \omega_{pe}$.

In recent studies [4,5], the PITS instability has been discussed in the collisionless limit. Given an anisotropic electron distribution function, the theory of the PITS instability [4,5] applies to weakly collisional plasmas where the electron collision time is much longer than the instability growth time, γ_0^{-1} and for FEL pulse durations that are much longer than γ_0^{-1}. However, these simplifying assumptions are often not easily satisfied. We will examine in this paper the evolution of the PITS instability for more realistic plasmas where these characteristic time scales are comparable and therefore the relaxation of an electron distribution to an isotropic state and the collisional dissipation of wave energy may be important. We will develop a kinetic model of the interaction of an ultrashort linearly polarized X-ray FEL pulse with a gas jet, which takes into account the creation of free electrons due to the photoeffect, the growth of an unstable quasistatic electric field, and electron collisions.

Unless the FEL reaches intensities and photon energies significantly higher than the current experimental values, the FEL produced plasma is weakly ionized and its evolution is dominated by electron–atom collisions with negligible contributions from Coulomb collisions. This particular case is a subject of our paper where both wave damping and the relaxation of the electron distribution function are governed by elastic electron scattering on atoms. The paper is organized as follows. In Section 2 we describe the electron distribution and relaxation of anisotropy in the photoionized plasma. The theoretical model of PITS instability in a collisional plasma is presented in Section 3. Section 4 is devoted to a description of relaxation of PITS instability. We conclude with a summary in Section 5.

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doi:10.1016/j.hedp.2008.03.001

2. Electron distribution function

An intense X-ray radiation source is able to ionize a gas by the classical nonrelativistic photoeffect [3]. Photoelectrons are ejected from atoms mostly in the direction of the X-ray polarization vector **e**. For a linearly polarized pulse, the electron velocity distribution is anisotropic and is similar to a distribution consisting of two contra-propagating electron streams of equal density. The evolution of the electron distribution function in such plasmas is determined by the photoionization cross-section $\sigma(\mathbf{v})$, the photon flux S_γ (in units of $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) of the ionized X-ray pulse and by the electron collisions which relax the anisotropy of the electron distribution function. In a plasma–FEL interaction region, where the plasma is nearly homogeneous, the distribution function of electrons, and f_e, satisfies the following kinetic equation:

$$\frac{\partial f_\mathrm{e}}{\partial t} = (n_\mathrm{a} - n_\mathrm{i})S_\gamma(t)\sigma(\mathbf{v}) + J_\mathrm{c}[f_\mathrm{e}], \tag{1}$$

where n_a is the initial density of a gas of neutral atoms, $n_\mathrm{i} = n_\mathrm{e}$ are the ion and electron densities which are increasing in time, $J_\mathrm{c}[f_\mathrm{e}]$ is the electron–neutral collision term. The differential photoeffect cross-section can be written in a simple form $\sigma(\mathbf{v}) = (3/4\pi v^2)\sigma_\mathrm{abs}\delta(v - v_0)\cos^2\Theta$, here σ_abs is the total cross-section of photoionization which defines X-ray absorption, Θ is the angle between direction of electron emission and the vector **e**, $v_0 = \sqrt{(2/m_\mathrm{e})(\hbar\omega_\gamma - I)} \ll c$ is the absolute value of photoelectron velocity, m_e is the electron mass, c is the speed of light, $\hbar\omega$ is the X-ray photon energy, and I is the ionization energy of an atom. The collisional term $J_\mathrm{c}[f_\mathrm{e}]$ in Eq. (1) for the case of weakly ionized plasmas, $n_\mathrm{i} = n_\mathrm{e} \ll n_\mathrm{a}$, can be written in following simplified form:

$$J_\mathrm{c}^\mathrm{en}[f_\mathrm{e}] = \nu_\mathrm{en}(\bar{f}_\mathrm{e} - f_\mathrm{e}), \tag{2}$$

where $\nu_\mathrm{en}(v)$ is the electron–neutral collision frequency and the bar above electron distribution function denotes averaging over all directions of the velocity vector, $\bar{f}_\mathrm{e}(v,t) = \int f_\mathrm{e}(\mathbf{v},t)\mathrm{d}\Omega_\mathbf{v}/4\pi$.

Eq. (2) describes temporal evolution of the electron distribution function. It accounts for two processes: photoionization which increases the electron density and leads to an anisotropy in the electron velocity distribution and electron–atom collisions which relax plasma to an isotropic state. Assuming, that the photoionization process starts at $t = 0$ when $n_\mathrm{e} = 0$ we find the solution to Eq. (2) in the following form:

$$f_\mathrm{e}(\mathbf{v},t) = \psi(v)\left[A(t) + B(t)\cos^2\Theta\right], \quad \psi = \frac{\delta(v - v_0)}{4\pi v^2},$$

$$A(t) = \nu_\mathrm{en}\int_0^t \mathrm{d}t' n_\mathrm{e}(t')\mathrm{e}^{-\nu_\mathrm{en}(t-t')}, \quad B(t) = 3\int_0^t \mathrm{d}t'\frac{\partial n_\mathrm{e}(t')}{\partial t'}\mathrm{e}^{-\nu_\mathrm{en}(t-t')},$$

$$n_\mathrm{e}(t) = n_\mathrm{a}\left[1 - \exp\left(-\int_0^t \mathrm{d}t' S_\gamma(t')\sigma_\mathrm{abs}\right)\right] \simeq n_\mathrm{a}\int_0^t \mathrm{d}t' S_\gamma(t')\sigma_\mathrm{abs}. \tag{3}$$

Assuming that the photon flux density S_γ has a finite duration in time, τ, the electron density $n_\mathrm{e}(t)$ grows in time from $t = 0$ until it reaches maximum value n_0 at $t > \tau$. Two functions $A(t)$ and $B(t)$ characterize the number of isotropic and anisotropic electrons, respectively. The electron distribution function (3) can be used to calculate two effective electron temperatures: a longitudinal temperature (along the polarization vector **e**) $T_\parallel$, and a transverse temperature (across the polarization vector **e**) $T_\perp$. We find from Eq. (3) in the limit of $\nu_\mathrm{en}t \ll 1$, $T_\parallel = (9/5)T$, $T_\perp = (3/5)T$, and $T = m_\mathrm{e}v_0^2/3$, where $(T_\parallel + 2T_\perp)/3$ is the averaged temperature. The degree of the anisotropy of the plasma temperature that is created by a polarized X-ray pulse is $T_\parallel/T_\perp = 3$ [4].

We will discuss stability of the collisional photoionized plasma that is described by the electron distribution function (3). In the case of a short FEL pulse, $\tau \ll \gamma_0^{-1}$, and in the absence of collisions, $\nu_\mathrm{en} \ll \gamma_0$, the typical growth rate of PITS instability is $\gamma_0 \approx 0.3\omega_\mathrm{pe}$ [4]. In the following study, the PITS instability is described for the conditions where all three time scales: τ, γ_0^{-1}, and ν_en^{-1} could have comparable magnitudes, $\tau \sim \gamma_0^{-1} \sim \nu_\mathrm{en}^{-1}$.

3. PITS instability in the collisional plasma

The electron distribution function satisfies the following kinetic equation:

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} - \frac{e}{m_\mathrm{e}}\mathbf{E}\frac{\partial f}{\partial \mathbf{v}} = (n_\mathrm{a} - n_\mathrm{i})S_\gamma(t)\sigma(\mathbf{v}) + J_\mathrm{c}[f], \tag{4}$$

where the electric field, **E**, is determined by the Poisson equation and e is the electron charge. The linearized form of Eq. (4) for the deviation of the electron distribution function, $\delta f = f - f_\mathrm{e}$, from the background state, f_e (3), and the Poisson equation for the perturbation of an electric field **E** read

$$\frac{\partial \delta f}{\partial t} + \mathbf{v}\frac{\partial \delta f}{\partial \mathbf{r}} - \frac{e}{m_\mathrm{e}}\mathbf{E}\frac{\partial f_\mathrm{e}}{\partial \mathbf{v}} = J_\mathrm{c}[\delta f], \quad \mathrm{div}\,\mathbf{E} = -4\pi e\delta n, \quad \delta n = \int \delta f d^3 v. \tag{5}$$

The fastest growth of the PITS instability takes place in the direction along the polarization vector ($\mathbf{k}\|\mathbf{e}$, where $\mathbf{k}$ is the wave vector of the perturbation) [4,5]. For this reason, we will study perturbations along this direction. Also, we will assume that the perturbations are characterized by short scale spatial variations corresponding to $R \gg 1/k$, where R is a focal spot size of the FEL pulse. This allows the spatial inhomogeneity in the background state of the plasma to be neglected.

After performing a Fourier transform we find an equation for the spatial Fourier component of the perturbation of the electron distribution function, which is denoted by the subscript $\mathbf{k}$,

$$\delta f_\mathbf{k}(t) = \int_0^t \mathrm{d}t'\,\mathrm{e}^{-\nu_\mathrm{en}(v)(t-t')}\,\mathrm{e}^{-i\beta\cos\theta}\left\{\nu_\mathrm{en}(v)\langle\delta f_\mathbf{k}(t')\rangle + 4\pi i\frac{e^2\delta n_\mathbf{k}(t')}{m_\mathrm{e}kv}\right.$$
$$\left.\times\left[\left(A(t')v\psi' + 2B(t')\psi\right)\cos\theta + B(t')\left(v\psi' - 2\psi\right)\cos^3\theta\right]\right\}, \tag{6}$$

where θ is the angle between velocity of an electron and the wave vector $\mathbf{k}$, $\beta = kv(t - t')$, and ψ' is the derivative of the function ψ with respect to v. For definiteness, in what follows we assume collision frequency to be proportional to the absolute value of electron velocity, $\nu_\mathrm{en}(v) = v\nu_\mathrm{en}/v_0$. After averaging over the angles in Eq. (6) one can derive

$$\delta\bar{f}_\mathbf{k}(v,t) = \frac{4\pi e^2}{m_\mathrm{e}kv}\int_0^t \mathrm{d}t'\delta n_\mathbf{k}(t')\left[2\psi\Pi(\beta,t') + v\psi'\Phi(\beta,t')\right], \tag{7}$$

where we have introduced the following functions:

$$\Phi(\beta,t) = \mathrm{e}^{-s\beta}[A(t)G_1(\beta) + B(t)G_2(\beta)]$$
$$+ s\int_0^\beta \mathrm{d}\xi\,\mathrm{e}^{-s\xi}Q(\beta - \xi)[(A(t)G_1(\xi) + B(t)G_2(\xi))],$$

$$\Pi(\beta,t) = \mathrm{e}^{-s\beta}B(t)[G_1(\beta) - G_2(\beta)]$$
$$+ s\int_0^\beta \mathrm{d}\xi\,\mathrm{e}^{-s\xi}B(t)Q(\beta - \xi)(G_1(\xi) - G_2(\xi)),$$