Electron-ion equilibration time and threshold for parametric decay instability in laser-produced plasmas

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The thresholds for parametrically excited second-harmonic emissions from laser-produced plasmas from planar, slab targets of carbon, aluminum, and copper have been experimentally measured using a 20-J–5-nsec, Nd:glass laser system at a pump wavelength of 1.0641 μm. Theoretical estimates of these thresholds are obtained, taking into account the homogeneous as well as inhomogeneous and isothermal state of the plasma governed by the electron-ion equilibration time. A critical analysis of the agreement as well as disagreement of the experimental measurements with the existing theories is presented in detail.

I. INTRODUCTION

The study of parametrically excited second-harmonic emissions is a useful tool for understanding the physics of parameter decay instability (PDI) in laser-produced plasma experiments. The first evidence of parametric decay instability in laser-plasma experiments was reported by Tanaka *et al.*[1] and was later confirmed by Sinha and Kumbhare.[2] Tanaka *et al.*[1] used the 24-beam, 1.054-μm Omega laser which had a pulse width of 1 nsec. They experimentally measured the threshold for PDI for a 15-μm scale length plasma produced from CH, Cu, and Ta-coated spherical and glass microballoons and reported it to be 5×10^{13} W/cm^2. From the theory given by Perkins and Flick[3] they approximately estimated a threshold of 2×10^{13} W/cm^2 and attributed the difference between experimentally observed and theoretically estimated values as that due to the inverse bremsstrahlung absorption which reduces the effective pump intensity available for the PDI. The limitation of their approximate formula is that they ignored the homogeneous term as given by Perkins and Flick[3] and did not give the details of the ratio of electron and ion temperatures, which also controls the theoretical estimate of the threshold value.

There are three existing theoretical expressions for the threshold of PDI. The first one is the homogeneous theory given by Liu and Kaw,[4] which is valid for nonisothermal plasma, that is, $T_e > T_i$, where T_e and T_i are electron and ion temperatures. The second theory is that of Perkins and Flick[3] for inhomogeneous plasma, which is valid for weakly damped ion-acoustic modes and is applicable for $T_e > T_i$. The third theory is that of Liu[5] for an inhomogeneous plasma, which is valid for heavily damped ion-acoustic modes and is applicable in the case when $Z_a T_e \approx T_i$, where Z_a is the average ionization state. The condition for the applicability of these theories is determined by the electron-ion equilibration time which decides whether the plasma is isothermal or nonisothermal, and further leads us to conclude whether the ion-acoustic modes are heavily or weakly damped. Therefore one has to be careful in choosing a particular theoretical deduction for the estimate of the PDI threshold.

II. EXPERIMENTAL RESULTS

The experiments were conducted, using a 20-J–5-nsec, Nd:glass laser amplifier system with Nd:YAG (YAG denotes yttrium aluminum garnet) oscillator, on vertically positioned planar slab targets of carbon, aluminum, and copper. The incident beam which was p polarized had a wavelength of 1.0641 μ and had an average angle of incidence of nearly $\pi/20$, and $2\omega_0$ emissions were observed at an angle $3\pi/4$ from the forward direction of the incident beam. The detector system consisted of a Pacific Instrument Incorporated (U.S.A.) MP 1018B grating monochromator, coupled with an RCA-7265 photomultiplier tube with an S-20 response and a Tektronix 7834 storage oscilloscope. An aspheric $f/1.33$ lens was used to focus the beam onto the target. Intensity measurements in the focal plane, using a focal spot camera, gave a focal spot of diameter R equal to 40 ± 5 μm, which was free of hot spots. The scattered light was inferred to be collected approximately from the $0.8n_c$ layer, where n_c represents the critical electron density. This inference of the emission region was obtained from the calculation based on the peak shift as explained in the discussion section. The detailed experimental setup and measurement techniques are given in our earlier papers[2,6] and the details of temperature diagnostics are also given in our paper on temperature and turbulence diagnostics.[7] Density scale length L in the underdense region was estimated to be 45 ± 5 μm using a 10-μm resolution x-ray pin-hole camera with the help of the usual Abel inversion technique. The pin-hole camera measurements did not show any profile steepening. This is expected because, for a 5-nsec Nd:glass laser, radiation pressure becomes much greater than the local plasma pressure only at laser intensities greater than 10^{16} W/cm^2.[8–10] Thus one notes that the density scale length is nearly the same as the focal spot diameter. This is in agreement with the expansion model discussed by Mora,[11] where he states that for laser-plasma experiments such that $C_s\tau > R$, the plasma expansion is spherical instead of planar, where C_s and τ are ion-acoustic velocity and pulse duration. In that case, L is expected to be of the order of R for planar target experiments, irrespective of the target material. It has been checked that the above inequality is well satisfied in our experimental conditions.

The second-harmonic emissions were recorded in the wavelength domain of 5310–5400 Å. We observed two peaks, one known as the primary peak arising due to resonance absorption and the other red-shifted sideband recognized as the parametrically excited second-harmonic emissions arising due to the combination of the plasmons produced by the PDI process, as reported earlier by Tanaka *et al.*[1] and Sinha and Kumbhare.[2] The primary peak occurs at about 5325.0 Å and is Doppler shifted by 4.5 Å from the exact $2\omega_0$ harmonic (5320.5 Å). The sideband peak which is expected to be shifted by twice the ion-acoustic frequency from the exact $2\omega_0$ harmonic occurs at 5347.5 Å, thus shifted by 22.5 Å from the primary peak. It was observed that the primary peak did not have a threshold and the signals were checked and observed up to a laser intensity of 3×10^{12} W/cm^{-2}, whereas the secondary peak had a threshold in the vicinity of laser intensity predicted by the theory of the PDI process. Moreover, it was observed that the peak shift of the sideband was independent of the electron temperature and the target material. It is important to note that the experimental irradiation threshold for PDI is inferred as the laser intensity at which the parametrically excited $2\omega_0$ sideband signal first appears over the background radiation emitted by the plasma itself.

Figure 1 shows the variation of parametrically excited $2\omega_0$ sideband peak intensity as a function of incident laser intensity for carbon, aluminum, and copper targets. The laser intensity scale for carbon is different from that for aluminum and copper. Within experimental errors we note that the irradiation threshold for PDI for all the three cases comes to approximately $(2.0\pm0.5)\times10^{13}$ W/cm^2. We further note that these $2\omega_0$ emissions show saturation behavior beyond a laser intensity of 10^{14} W/cm^2. It may also be seen that the dependence of the nonsaturated $2\omega_0$ intensity on the irradiation intensity ϕ for all the three materials follows approximately a square law and varies more accurately as $\phi^{(1.7\pm0.3)}$, which is expected from theoretical considerations. The detailed theoretical investigation of the saturation behavior will be reported elsewhere. Presently, we confine our attention to the investigation of the PDI threshold problem. In theoretical analysis of the threshold it is important to know the plasma temperature at threshold. These temperatures were estimated, using the two foil ratio technique,[12,13] to be 350±40 eV for carbon and 600±60 eV for aluminum and copper. The estimation of higher temperature for aluminum and copper, at the same laser intensity, is in agreement with the observations of Turner *et al.*[14] where they reported that the underdense plasma temperature is higher for high-Z targets, due mainly to their lower thermal conductivity and lower hydrodynamic losses.

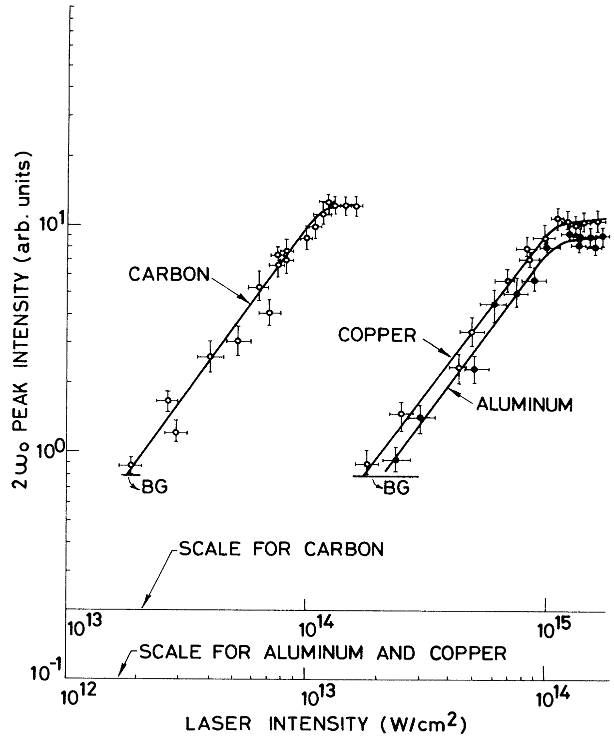

FIG. 1. Variation of the peak intensity of parametrically excited second-harmonic emissions for carbon, aluminum, and copper as a function of p-polarized laser intensity, incident on the target surface. BG is the background radiation level.

III. THEORETICAL FORMULATIONS AND RESULTS

With a view to interpreting the experimentally observed threshold values, we consider the existing theoretical formulations for PDI threshold in detail. It is generally understood that in the PDI process an incident intense laser beam of frequency ω_0 decays into an electron plasma wave of frequency $\approx\omega_p\approx\omega_0$ and an ion-acoustic wave of frequency $\omega_a\approx(\omega_0-\omega_p)$.[1,2] The PDI process occurs beyond a certain intensity threshold and at about $0.8n_c$ plasma density. Different expressions for the threshold intensity for PDI are given depending on whether the plasma produced by laser is homogeneous or inhomogeneous, isothermal or nonisothermal, and whether the ion-acoustic wave is weakly or heavily damped. Moreover, the existing theoretical expressions are given for a plasma with only singly ionized ions. We generalize these expressions by considering the ions in the plasma having an average ionization state Z_a in rewriting them here. As the criterion for applicability of these expressions is obtained from a comparison of electron and ion pressures, one replaces T_e by Z_aT_e in these original expressions given for $Z_a=1$. The threshold for PDI for weakly damped ion-acoustic waves in an inhomogeneous plasma of density scale length L is obtained by Perkins and Flick[3] and is expressed as

$$\frac{E_0^2}{4\pi n_e k_B T_e} = \frac{1.6A\gamma}{k_y L}\left[\frac{2\Gamma_a}{\omega_a}\right]^{1/2} + 3.2\left[\frac{2\Gamma_a}{\omega_a}\right]\left[\frac{2\Gamma_p}{\omega_p}\right], \tag{1}$$

where $A=5$, $\gamma=1+3T_i/Z_aT_e$, E_0 is the incident laser electric field, T_e and T_i are the electron and ion temperatures, k_y is the wave number of the excited wave in the direction of the pump electric field, Γ_a and ω_a are the temporal damping rate and frequency of the ion-acoustic wave, and Γ_p is the temporal damping rate of the electron plasma wave. The symbol k_B represents the Boltzmann constant. As seen from the wave-number matching condition, the wave number of the electron plasma wave is approximately the same as that of the ion-acoustic wave in the PDI process. The condition that a plasma is homogeneous is determined by the inequality[3]

$$L > \lambda_F(2.5/k_y\lambda_D)(\omega_a/2\Gamma_a)^{1/2}, \tag{2}$$

where λ_F and λ_D are mean free path and Debye length, respectively. Thus, when the density scale length is much larger than the mean free path, the homogeneous consideration is valid. In strongly inhomogeneous plasma where L is smaller or approximately equal to λ_F, the first term on the right-hand side of Eq. (1) is dominant. In the mildly inhomogeneous plasma it is safer to consider both the terms on the right-hand side of Eq. (1). Expressing E_0 in terms of the rms laser intensity in a medium with refractive index μ as $I=(c\mu E_0^2/4\pi)$, the threshold intensity I_{th}, from Eq. (1), can be written as

$$I_{\text{th}} = \frac{8c\mu n_e k_B T_e}{k_y\lambda_D}\left[\frac{\lambda_D}{L}\right]\left[\frac{2\Gamma_a}{\omega_a}\right]^{1/2}\gamma + 3.2c\mu n_e k_B T_e\left[\frac{2\Gamma_a}{\omega_a}\right]\left[\frac{2\Gamma_p}{\omega_p}\right]. \tag{3}$$

It is relevant to note that Tanaka *et al.*[1] have deduced an expression from Eq. (1) by considering some particular values of λ_D, γ, and Γ_a in a strongly inhomogeneous plasma with $\mu \approx 1$ and written it as

$$I_{\text{th}} = 3\times10^{11}(T_{\text{eV}}/\lambda_\mu^2 L_\mu)\ \text{W/cm}^2, \tag{4}$$

where T_{eV} is the electron temperature in electron volts; λ_μ, the pump wavelength in μm; and L_μ, the density scale length in μm. This is not applicable to a general case of laser-produced plasma with μ changing significantly from 1, whereas Eq. (3) is the general expression for inhomogeneous plasma. It should be further noted that Eq. (1) is derived on the assumption of weakly damped ion-acoustic wave which is the case in a plasma with $Z_aT_e > T_i$. Hence Eq. (1) or Eq. (3) is applicable to plasmas with $Z_aT_e > T_i$.

As a complement to the work of Perkins and Flick,[3] Liu[5] analyzed the PDI process having a heavily damped ion-acoustic mode in an inhomogeneous plasma and gave the following expression for threshold under the assumption that Γ_p is negligible in comparison to ω_a:

$$\frac{E_0^2}{4\pi n_e k_B T_e} = \frac{3\pi}{\sqrt{2}}\left[\frac{\lambda_D}{L}\right]\left[\frac{\Gamma_a}{\omega_{pi}}\right](k_y\lambda_D)^{-3/2}, \tag{5a}$$

where ω_{pi} is the ion plasma frequency. Expressing this in terms of rms laser intensity in a medium, the threshold intensity is obtained as

$$I_{\text{th}} = (3\pi/\sqrt{2})(c\mu n_e k_B T_e)(\lambda_D/L) \times(\Gamma_a/\omega_{pi})(k_y\lambda_D)^{-3/2}. \tag{5b}$$

The applicability of Eq. (5a) or Eq. (5b) is limited to plasmas with $Z_aT_e \approx T_i$ and with Γ_p negligible as compared to ω_a.

The threshold for PDI involving a weakly damped ion-acoustic wave in a homogeneous plasma is given by Liu and Kaw[4] as

$$E_0^2/(16\pi n_e k_B T_e) = (\Gamma_a/\omega_a)(\Gamma_p/\omega_p). \tag{6a}$$

The corresponding threshold intensity is expressed as[15]

$$I_{\text{th}} = 4c\mu n_e k_B T_e(\Gamma_a/\omega_a)(\Gamma_p/\omega_p). \tag{6b}$$

Equation (6a) or (6b) is valid for plasmas with $Z_aT_e > T_i$ and having L very much greater than the mean free path. In order to estimate the threshold intensity one requires the damping rates of electron plasma and ion-acoustic waves. The temporal collisional damping rate $(\Gamma_p)_c$ of electron plasma waves is expressed[16] as $(\Gamma_p)_c = (\nu_{ei}/2)$, where ν_{ei} is the electron-ion collision frequency. The collision frequency ν_{ei} (in sec^{-1}) is expressed as[17]

$$\nu_{ei} = 5.2\times10^{-6} Z_a n_e T_e^{-3/2}\ln\Lambda, \tag{7a}$$

$$\Lambda = 1.24\times10^7 T_e^{3/2}/(Z_a^{3/2} n_e^{1/2}), \tag{7b}$$

where Z_a is the average ionization state, T_e the electron temperature in K, n_e the electron density in m^{-3}, and $\ln\Lambda$ is the usual Coulomb logarithm. The temporal Landau damping rate $(\Gamma_p)_L$ of the plasma wave is given as[16]

$$(\Gamma_p)_L = (\pi/8)^{1/2} e^{-3/2}(\omega_p/k_y^3\lambda_D^3)e^{-1/(2k_y^2\lambda_D^2)}. \tag{8}$$

The damping of ion-acoustic wave is primarily due to Landau effect. The temporal Landau damping rate Γ_a of ion-acoustic waves in a nonisothermal plasma with $Z_aT_e > T_i$ is given by Shafranov[18] as

$$\Gamma_a = (\pi/8)^{1/2}\omega_a[(Z_a m_e/m_i)^{1/2} + (Z_aT_e/T_i)^{3/2} e^{-Z_aT_e/2T_i}], \tag{9}$$

where m_e and m_i are electron and ion masses. The ion-acoustic wave frequency ω_a is given as

$$\omega_a = k_a C_S, \quad C_S = (Z_a k_B T_e/m_i)^{1/2}. \tag{10}$$

The ion-acoustic wave in a plasma with $Z_aT_e \approx T_i$ is heavily Landau damped by the ions. In this case the temporal Landau damping rate of ion-acoustic wave has been approximately considered by Shearer *et al.*[15] as $\Gamma_a \approx \omega_a$. On the basis of the above equations we have made theoretical estimates of the PDI threshold and have displayed them in Table I. At threshold the experimental values of T_e for carbon as well as aluminum and copper have been estimated to be 350±40 eV and 600±60 eV, respectively. The average ionization states at these temperatures for carbon, aluminum, and copper have been taken as 6, 11, and 16 from the works of Mosher.[19] In Table I the threshold values where $\Gamma_a/\omega_a \neq 1$ are obtained by using the actual values of Γ_a calculated from Eq. (9). Although Shearer *et al.*[15] used $\Gamma_a/\omega_a = 1$ for $T_e \approx T_i$ in a plasma with ions of finite Z_a, its use is justified only when $Z_a T_e \approx T_i$. It overestimates the damping rate for ion-acoustic waves when $Z_a T_e > T_i$ with $T_e \approx T_i$. The refractive index μ of the plasma is obtained from the relation $\mu = (1 - n_e/n_c)^{1/2}$ and is 0.447 at $n_e = 0.8 n_c$. The threshold values obtained from the expression of Tanaka *et al.*[1] have also been multiplied by μ to obtain the values in the fifth column of Table I with a view to estimating the threshold intensity at $n_e = 0.8 n_c$.

From damping calculations of electron plasma waves we have found that Landau damping is negligible below a certain wave number which corresponds to $k_y \lambda_D \approx 0.2$ and strongly increases, thereafter, with increase in k_y. Only the collisional damping is dominant for plasma waves with wave numbers corresponding to $k_y \lambda_D \lesssim 0.2$. From the phase matching conditions and the dispersion relations for electromagnetic, electron plasma (p), and ion-acoustic (a) waves, it is observed that $k_p \approx k_a \gg k_0$, where k_0 is the local pump wave number. As one gets the lowest threshold when the growth rate is maximum, which occurs for decay waves propagating along $\mathbf{E}_0$ and having the largest value of k_y consistent with negligible Landau damping of electron plasma waves, one sets $k_y \lambda_D \approx 0.2$ for the most unstable decay waves.[20] Hence only the collisional damping rate is taken for electron plasma waves in estimating the threshold. Regarding the ion-acoustic wave damping one should first assess the isothermal or nonisothermal nature of the plasma. This is established from the consideration of the equilibration time τ_{ei} for exchange of energy from electrons to ions, which is given by Stacey[17] as (in sec)

$$\tau_{ei} = (m_i/m_e)\nu_{ei}^{-1} . \quad (11)$$

We estimate τ_{ei} to be 1.3 nsec for carbon at $T_e = 350$ eV and 3.7 and 6.7 nsec for aluminum and copper plasmas at $T_e = 600$ eV. Since our laser pulse duration [full width at half maximum (FWHM)] is of 5 nsec, the electrons and ions thermalize to form plasmas with $T_e = T_i$ on carbon and aluminum targets, whereas T_e is approximately equal to T_i in copper plasma. Thus the plasmas formed on all the three targets are considered isothermal ($T_e \approx T_i$). As $Z_a T_e > T_i$ in all the three cases, Liu's expansion [Eq. (5)] for the threshold is not applicable here and has not been used.

The effective threshold intensity which prevails at the $0.8 n_c$ layer, given in the third column of Table I, is obtained from the incident laser intensity threshold shown in the second column, 2 which decreases owing mainly to the inverse bremsstrahlung process as discussed below. If the intensity of a laser beam normally incident in the z direction on the solid target is I_0, the effective laser intensity I_R available for the PDI at $n_e = 0.8 n_c$ is given by

$$I_R = I_0 \exp\left[-\int_{n_e=0}^{n_e=0.8n_c} \alpha(z) dz \right] , \quad (12)$$

where $\alpha(z)$ is the linear absorption coefficient given as[21]

$$\alpha(z) = \frac{\nu_{ei}}{\mu c} \frac{n_e(z)}{n_c} . \quad (13)$$

Following Hughes,[21] the expression for I_R in an isothermal plasma with linear density gradient of scale length L is obtained as

TABLE I. Experimental and theoretical values of threshold for parametrically excited second-harmonic emissions.

Target	Observed threshold intensity at the surface (W/cm²)	Effective threshold at $0.8n_c$ (W/cm²)	T_e/T_i	Theoretical threshold W/cm² from different expressions: Inhomogeneous plasma, Tanaka *et al.*	Inhomogeneous plasma, Perkins and Flick, valid for $Z_a T_e > T_i$	Homogeneous plasma, Liu and Kaw valid for $Z_a T_e > T_i$
Carbon	$(2.0 \pm 0.5)\times 10^{13}$	$8.4\times 2.8)\times 10^{12}$	1	9.4×10^{11}	4.6×10^{13} ($\Gamma_a/\omega_a = 1$) 2.0×10^{13} ($\Gamma_a/\omega_a \neq 1$)	1.3×10^{13} ($\Gamma_a/\omega_a = 1$) 5.9×10^{12} ($\Gamma_a/\omega_a \neq 1$)
Copper	$(2.0 \pm 0.5)\times 10^{13}$	$(8.0 \pm 2.7)\times 10^{12}$	1	1.6×10^{12}	2.5×10^{13} ($\Gamma_a/\omega_a = 1$) 3.0×10^{12} ($\Gamma_a/\omega_a \neq 1$)	2.3×10^{13} ($\Gamma_a/\omega_a = 1$) 4.7×10^{11} ($\Gamma_a/\omega_a \neq 1$)
Aluminum	$(2.0 \pm 0.5)\times 10^{13}$	$(1.0 \pm 0.3)\times 10^{13}$	1	1.6×10^{12}	2.1×10^{13} ($\Gamma_a/\omega_a = 1$) 9.0×10^{12} ($\Gamma_a/\omega_a \neq 1$)	1.7×10^{13} ($\Gamma_a/\omega_a = 1$) 1.8×10^{12} ($\Gamma_a/\omega_a \neq 1$)

$$I_R = I_0 \exp\left[-\frac{\nu_{ei}(n_c)L}{c} \int_0^{0.8} z^2(1-z)^{-1/2} dz \right], \tag{14}$$

where $\nu_{ei}(n_c)$ is the collision frequency at critical density n_c. Using Eqs. (14) and (7), we have obtained for our laser-plasma experiments the values of I_R/I_0, at threshold, equal to 0.42, 0.40, and 0.50 for C, Cu, and Al, respectively.

IV. DISCUSSION

At this stage it is useful to infer the region of the second-harmonic emissions. From energy and momentum conservation and the dispersion relations, one obtains the expression to estimate the wavelength shift of the sideband of $2\omega_0$ emissions due to PDI as[1,2]

$$\frac{\Delta\lambda}{\lambda_{2\omega_0}} = \frac{1}{\sqrt{3}} \frac{C_s}{V_e} \left[1 - \frac{n_e}{n_c} \right]^{1/2}, \tag{15}$$

where $V_e = (k_B T_e / m_e)^{1/2}$ is the electron thermal speed. By comparing the theoretical and experimental wavelength shifts, we have concluded that PDI occurs at approximately $0.8n_c$.

Now, we consider the theoretical estimates of PDI thresholds under different formulations. The approximation relation given in Eq. (4) by Tanaka *et al.*[1] cannot be used for a general case as they have ignored the homogeneous term of the complete relation given by Perkins and Flick[3] as given by Eq. (1). Moreover, they have not discussed the role of damping constants Γ_a and Γ_p as well as that of γ, which strongly determine the threshold value. Equation (4) gives a rather low estimate of the threshold. As is well known, the theoretical estimate of the threshold value for an inhomogeneous plasma has to be greater than that of the homogeneous expression where L is considered to be very large. The thresholds given by the expression of Perkins and Flick [Eqs. (1) and (3)] are larger than those given by the homogeneous theory. Hence the theory seems to be in order. Now it is interesting to pay some more attention to the results obtained from Eq. (3) and shown in the sixth column of Table I. As discussed earlier, $T_e \approx T_i$ in all the three plasmas with the ions having different values of Z_a. Following Shearer *et al.*,[15] if we use $\Gamma_a = \omega_a$ irrespective of Z_a in Eq. (3), the theoretical estimate is observed to be higher than the effective threshold intensity at $n_e = 0.8n_c$. This is owing to the fact that this equality overestimates the damping rate for ion-acoustic waves resulting in higher threshold when $Z_a T_e > T_i$. However, if we use the values of $\Gamma_a(\neq\omega_a)$ calculated using Eq. (9) appropriate for $Z_a T_e > T_i$, the threshold intensity estimated from Eq. (3) is observed to reasonably agree with the experimental estimate of threshold at $n_e = 0.8n_c$ within experimental errors. Thus we conclude that the theoretical estimates from the expression given by Perkins and Flick,[3] and expressed in Eqs. (1) and (3), with the damping rate of ion-acoustic waves calculated using Eq. (9) reasonably agree with the experimental estimates of threshold for carbon, and aluminum, as well as copper.

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