Collective Thomson Scattering Measurements of the Ion Acoustic Decay Instability

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K. Mizuno	UC Davis, and PPRI
J. S. DeGroot	UC Davis
R. P. Drake	PPRI
W. Seka	LLE

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I. INTRODUCTION

The Ion Acoustic Parametric Decay Instability (IADI)¹, in which an electromagnetic wave decays into an electron plasma wave (epw) and an ion acoustic wave (iaw) near the critical density n_c (where the electromagnetic wave frequency equals the plasma frequency), is a fundamentally important subject in plasma physics. It has been studied by numerous authors in laser plasma interactions²⁻¹⁴, as well as microwave experiments¹⁵, ionosphere studies¹⁶, and the theories and the computer simulations. The IADI was also studied by Thomson scattering radar in ionosphere¹⁶. However, all previous works (to our knowledge), including our works, measured the second harmonic (SH) emissions²⁻¹⁴ to study the IADI in laser produced plasma. For the conventional SH measurements, two (unknown) epws produce a signal. In addition, the SH emissions are integrated (in a complicated way) over wavenumber of electron plasma wave, k_{epw} , the propagation angle of epws, and also plasma density ($n/n_c \sim 0.7-1$), where the IADI is excited. The developments of the collective Thomson scattering diagnostic allow us to make drastic improvements over the conventional SH measurements in the understanding of the IADI in laser produced plasma.

One of the most important issues is to understand whether or not the IADI is important in large scale plasma relevant to laser fusion. Nevertheless, all previous experiments, including our previous works, have been carried out in relatively small scale plasma with maximum laser energy of about 100 Joul. In this letter, we present two important results: (1) the developments of the UV collective Thomson scattering (CTS) system to make direct measurements of the epw excited by the IADI. An important application of the UV CTS from the IADI is that it is a good diagnostic tool of the local electron temperature (T_e)

measurement near the critical surface of the interaction laser. It can be a large angle scattering, so the T_e is a sensitive function of the scattering angle. (2) the measurements of the IADI are made, for the first time, in a large scale, hot plasma that is directly relevant to high-gain, direct-drive laser fusion targets. The production of a large scale length, hot plasma requires a large laser energy. It was possible to produce such a large scale, hot plasma using the 24-beam, 1.5 kJ UV OMEGA laser system at the Laboratory for Laser Energetics. We have found that the IADI could be easily excited in the large scale, hot plasma. The collisional attenuation of the interaction laser is not strong enough to suppress the IADI, even in the large (mm) scale plasma, because the electron temperature is high (collisional frequency is low), and also the IADI threshold is low (which can be collisional threshold^{1, 11}). The IADI in a large scale plasma is important because significant hot and/or warm electron heating can occur even when it is relatively weak, if the unstable volume is large enough^{11, 15}.

II. DEVELOPMENTS OF MULTI-CHANNEL COLLECTIVE THOMSON SCATTERING SYSTEM

2.1 Thomson scattering from ion acoustic wave, and electron plasma wave

Collective Thomson scattering¹⁹ from plasma wave is a three wave process satisfying the k-matching conditions $\mathbf{k}_s = \mathbf{k}_o \pm (\mathbf{k}_{epw} \text{ or } \mathbf{k}_{iaw})$, and the energy conservation $\omega_s = \omega_o \pm (\omega_{epw} \text{ or } \Omega_{iaw})$. The $\mathbf{k}$'s and ω 's are the wave vectors and frequencies of the three waves; the subscripts o and s refer to the incident and scattered electromagnetic waves for a probe beam, and the subscript epw refers to electron plasma, and ion acoustic waves, which, in our case, are generated by the IADI instability. The scattering angle θ is given by

$$k_{epw}^2 = k_o^2 + k_s^2 - 2k_o k_s \cos\theta. \quad (1)$$

For the scattering from ion acoustic wave, since $\Omega_{iaw} \ll \omega_s$ or ω_o , we have $|\mathbf{k}_s| \approx |\mathbf{k}_o|$, so that

$$k_{iaw} \approx 2 k_o \sin(\theta/2). \quad (2)$$

In our experiments, $\omega_o = 3 \omega_L$, where ω_L is the interaction laser frequency with the wavelength of 1.06 μm . Therefor, for the up-shifted scattering from the electron plasma wave, we have, $\omega_s \sim 4/3 \omega_o$, and $|\mathbf{k}_s| \sim 4/3 |\mathbf{k}_o|$. The scattering angle θ is given by

$$k_{epw}^2 = k_o^2 (25/9 - (8/3) \cos(\theta)) \quad (3)$$

To aid the design of the experiments, we can estimate the appropriate scattering angles for the electron temperatures expected in our experiments by using Eqs. (2) or (3) in conjunction with our past observations that the most prevalent values for k_{iaw} , and k_{epw} are found near the Landau damping cut-off, $k_{epw}\lambda_{De} \approx 0.23$. This value agrees with the theoretical maximum of the IADI growth rate. This yields a simple relationship

$$T_e = 1.4 \times 10^4 \times (k_{iaw}\lambda_{De})^2 / \sin^2(\theta/2) \quad (\text{eV}) \quad (4)$$

for scattering from ion acoustic wave, and

$$T_e = 5.7 \times 10^4 \times (k_{epw}\lambda_{De})^2 / (25/9 - (8/3) \cos(\theta)) \quad (\text{eV}) \quad (5)$$

for scattering from electron plasma wave. This relationship (Eqs. (4), and (5)) is plotted in Fig.1 which clearly shows that good electron temperature measurements can be expected for a large angle scattering of the probe beam. The optimum CTS will be around 90 degree scattering angle for the electron temperature of about 1 keV. Note that Eqs. (4), and (5) are used for the purpose of estimating the appropriate range of scattering angles, while the actual determination of the electron temperature is made by simultaneously measuring Ω_{iaw} or ω_{epw} , and the scattering angle θ , and using ion acoustic wave dispersion relation which is mentioned later. We can also verify that the measured plasma waves are excited by the IADI, if the values agree reasonably well with the above estimates. The refraction of the probe beam at the instability region is estimated using Snell's law. The refraction of the probe beam depends on the incident angle. It is about 10 (6) % for $\omega_0/\omega_L = 3$, and about 5 (3) % for $\omega_0/\omega_L = 4$, if the incident probe beam angle is 60 (40) degree.

2.2 Multi-channel UV Thomson Scattering System

Figure 2 shows the multi-channel UV Thomson scattering system for the measurements of the IADI in laser produced plasma. Scattered signal is focused into an optical fiber using a focusing mirror. The signals from the 6 channel detectors are fed to a spectrometer. By varying the length of the optical fiber, we can produce relative time delay between each channel. By using this method, we can measure 3 parameters (the multi-channel signals, the spectrum, and the time evolution) simultaneously. The signals from the spectrometer are fed to a streak camera, then measured, and analyzed using a CCD camera, and a computer.

The scattering geometry is shown in Fig. 2. The interaction laser incident normally onto a CH target. The ion acoustic wave, and the electron plasma wave are strongly excited along the electric field of the interaction laser. The growth rate decreases proportional to $\cos^2(\alpha)$, as the angle α between the propagation of the plasma wave, and the laser electric field increases. The Thomson scattering is set to measure ion acoustic wave, and electron plasma wave propagating nearly parallel to the laser electric field. Therefore, we measure plasma waves propagating nearly perpendicular to the density gradient, so that the plasma flow effect on the ion acoustic wave is minimized. Figure 2 shows that we also measure conventional second harmonic emission simultaneously to verify the excitation of the IADI.

III. ION ACOUSTIC DECAY INSTABILITIES IN LARGE SCALE PLASMA

3.1 The IADI decay conditions

The frequency of the scattering wave is determined from the IADI decay condition, and ion wave dispersion relation. In a large scale plasma⁴, the IADI dispersion relation is approximately given¹ by

$$(\omega^2 + i\omega\nu_i - \Omega_{ia}^2)[(\omega + \frac{i\nu_e}{2})^2 - \delta^2] + \omega_{pi}^2 \frac{k^2 v_{os}^2}{4} \frac{\delta}{\omega_L} = 0 \quad (6)$$

In our typical experiments, ion acoustic frequency is larger than the damping rate, $\Omega_{iaw} \gg \nu_i, \nu_e$, where $\nu_i = 2\Gamma_i$ (Γ_i is ion wave Landau damping rate), and ν_e is collisional damping rate of the electron plasma wave. We have plotted the growth rate of the IADI and the ion wave frequency vs. $(\omega_L - \omega_{epw})/\Omega_{iaw}$ for the several intensities of the interaction laser in Fig. 3. If the laser intensity is less than 10 times of the threshold value, the growth rate peak happens at $\omega_L = \omega_{epw} + \Omega_{iaw}$, and ion wave frequency is $\omega = \Omega_{iaw}$. The IADI decay resonance condition is satisfied, and the normal mode of the ion acoustic wave is excited. It is also noted that the dipole approximation is valid in our experimental parameters: $k_L = k_{iaw} + k_{epw} \sim 0$, or $|k_{epw}| \sim |k_{iaw}|$. Therefore, ion acoustic wave frequency can also be obtained by measuring electron plasma wave, if the interaction laser intensity is not very high. When laser intensity is larger than 10 times of the threshold value, a driven ion wave is excited, and the frequency increases with the laser intensity.

3.2 Ion Acoustic waves in CH Plasma

Let's estimate ion acoustic wave in CH plasma. We have a slow, and a fast ion acoustic waves associated with C, and H ions. The ion wave dispersion relation in CH plasma is solved by previous authors²², which is given by

$$\frac{\omega^2}{k^2} = \frac{T_e}{M} \left\{ \left(\frac{2}{7(1+k^2\lambda_{De}^2)} + \frac{13}{8} \frac{T_i}{T_e} \right) \pm \frac{1}{2} \left[\left(\frac{4}{7(1+k^2\lambda_{De}^2)} - \frac{11}{4} \frac{T_i}{T_e} \right)^2 + \frac{11}{14(1+k^2\lambda_{De}^2)} \frac{T_i}{T_e} \right]^{1/2} \right\} \quad (7)$$

, where M is hydrogen mass, and we have made a reasonable assumption that plasma is fully ionized for the low ionic charge, CH target. Figure 4 shows the phase velocities (normalized by the electron thermal velocity) of the ion acoustic waves vs temperature ratio T_i/T_e obtained from the above equation (T_i is ion temperature). Williams et al²³ have calculated numerically the real and the imaginary parts of the ion acoustic waves. The real parts agree approximately with the results from the above equation. In typical laser produced plasma, the temperature ratio will be within $0.3 < T_i/T_e < 1$. In this regime, the damping rate of the fast wave is about $\Gamma_i/\Omega_{ia} \sim 0.8$, which is very strong damping. On the other hand slow wave damping rate is about $\Gamma_i/\Omega_{iaw} \sim 0.1$ in the regime of $0.3 < T_i/T_e < 1$. Slow wave has a moderate damping rate. The IADI threshold for the slow wave is 8 times smaller than the threshold value for the fast wave. Therefore, we are interested in the slow wave. Figure 4 indicates that the phase velocity of the slow wave is almost flat vs T_i/T_e in the regime of $0.3 < T_i/T_e < 1$. The slow wave phase velocity depends ion temperature very weakly. It is proportional to electron thermal velocity, if $0.3 < T_i/T_e < 1$. the phase velocity is approximately given by

$$\Omega_{iaw}/k_{iaw} \approx 1.87 \times 10^{-2} v_e \quad (8)$$

, where v_e is electron thermal velocity.

A good measure of the thermal electron temperature can thus be obtained from the simultaneous measurements of Ω_{iaw} and k_{iaw} by the Thomson scattering. We can measure either ion acoustic wave, or electron plasma wave, and use the IADI resonant decay condition mentioned above in order to estimate electron temperature. We can also estimate the plasma density using the Bohm-Gross equation. The electron temperature is measured for a local (selected) plasma density near the critical surface. It requires no averaging of the electron temperature over plasma density.

The ion acoustic dispersion relation is modified in a drifting plasma:

$$\Omega_{iaw} \approx k_{iaw} C_s + \mathbf{k}_{iaw} \cdot \mathbf{U} \quad (9)$$

where $\mathbf{U}$ is the plasma drift velocity, and C_s is sound speed. The plasma is drifting mainly normal to the target surface. The ion waves are mainly driven along the electric field of the interaction laser, which is perpendicular to the drift direction. Thus, the drifting plasma should not significantly perturb our measurements.

IV. EXPERIMENTS

4.1 Experimental Arrangements

The experiments are carried out using a large ($\sim$ mm) scale, hot ($\sim$ keV) plasma¹⁷. The 24-beam, 1.5 kJ UV OMEGA laser at the LLE has been used to produce the hot, long-scale-length plasma. Two sets of four opposing beams are used to explode the CH foil of $6\mu\text{m}$ thickness with the diameter of either $400\mu\text{m}$ and $600\mu\text{m}$ at a relative timing, $t = 0$ nsec. Four beams are used as secondary heating beams, which are incident at 0.6 nsec after the primary beams. The on-target laser energy is typically 50-60 J per beam with a pulse duration of 0.60 – 0.65 nsec at a wavelength of 351 nm. The typical plasma has a center density $1 - 2 \times 10^{21} \text{ cm}^{-3}$, and is maintained within a factor of two of this density, and at electron temperature $T_e \sim 1$ keV for approximately 1 nsec, with a scale length of the order of 1 mm, at about $t = 2.2$ nsec.

The experimental set up is shown in Fig. 5. We used a $1.05\mu\text{m}$, interaction (pump) laser to excite the IADI (applied through the port 5-1). A random phase plate was used to minimize the non uniform irradiation. One UV ($0.35\mu\text{m}$) laser beam is used for Thomson scattering (through the port 4-3). The CTS signal is collected by a focusing mirror (placed at the port 124). The signal reflected from the mirror is focused on to the detector system (at the opposite port 115), with UV streak camera, (one meter) spectrometer, CCD camera, and computer data acquisition system. Simultaneously, we have measured the time-resolved second harmonic spectrum (through the port 4-3), using the SH detector with streak camera, (one-third meter) spectrometer, CCD camera, and computer system. The locations of the important ports in our experiments are 2-3 (elevation angle= 111° , Azimuth angle= 157.5°), 5-1 ($111, 22.5$), 4-3 ($150, 45$), and 124 ($112.5, 180$).

4.1 SAGE computer simulation results

Our experiments are guided by the SAGE computer calculations²⁰. Figure 6 shows the typical plasma parameters (the spatial profiles of n_e and T_e along the center axis) at a timing of 2.2 nsec. We choose this timing, so the center plasma density is slightly higher than the critical density $n_c \sim 10^{21} \text{ cm}^{-3}$ of the pump laser. The plasma scale length is very large, which is of the order of mm. When the pump laser is applied to the preformed plasma, there is no significant change on the plasma density, but the electrons are heated by classical collision as is shown by the hump at the right hand side of the T_e curve. The T_e is of the order of 1 keV. The SAGE calculation result indicates that about 20 ~ 70 % of the pump laser energy reaches the instability region depending on the laser intensity (or T_e). Notice that the collisional attenuation of the interaction laser is rather weak even in the large (mm) scale plasma because of the high electron temperature.

4.3 Experimental Results

The pump laser excites the IADI when the intensity is above the threshold. We have measured the epw excited by the IADI with the Thomson scattering. The up-shifted CTS is measured to minimize the refraction effect, so the frequency is about 4 times of the pump frequency (4ω). Several features are checked to verify that the measured signals are indeed due to the CTS from the epw excited by the IADI; (1) the 4ω signal intensity decreases as the pump laser intensity, and the signal disappears when it is below the threshold of the IADI (determined by the conventional SH measurements), (2) when we turned off the probe beam, no 4ω signal was observed, (3) the intensity of the 4ω signal

varied drastically (decreased about 10 times) when we changed the probe beam polarization from the out-of plane to the in-plane as is expected from the factor $f(\theta, \phi)$ (the results are shown in Fig. 7), and (4) the measured phase velocity of the epw, and the frequency shift $\Delta\Omega$ are consistent with the theories, which will be discussed later.

The CTS system is designed to measure the optimum IADI (the optimum propagation angle, and wave number of the epw). The measured wave number k_{epw} is $2.9 \times 10^5 \text{ cm}^{-1}$. The propagation angle of the measured epw is nearly parallel (perpendicular) to the pump electric field (density gradient). The threshold laser energy of the most unstable epw ($k_{epw} = 2.9 \times 10^5 \text{ cm}^{-1}$), is about 5 J. Taking into account the collisional attenuation, and the refraction estimated from SAGE calculation, the threshold pump intensity I_{th} is about $3 \times 10^{12} \text{ W/cm}^2$ at the instability region of $n/n_c \approx 0.86$. The theoretical local threshold¹ of the IADI for the ion acoustic slow wave in a large scale plasma is about $2 \times 10^{12} \text{ W/cm}^2$ for $T_e = 0.6 \text{ keV}$ (the slow wave will be discussed later). As T_e increases, the threshold decreases. This threshold value correspond to $v_{osc}/v_e \sim 0.06$ (the value includes the swelling of the laser electric field at the instability region), where v_{osc} , and v_e are the quiver velocity, and the electron thermal velocity. The threshold is quite low, the IADI is easily excited, and the I_{th} agrees favorably with the theoretical value.

Figure 8 (A) shows two dimensional, time and wavelength, intensity plots of the CTS signal. We can clearly see the red shift of the CTS signal relative to the $4\omega_L$ wavelength. We have measured the epw due to the prime IADI decay process. IN our experiments, where the pump laser energy is less than 50 J, no cascade decay process²¹ is observed near the Landau cut-off, $k_{epw}\lambda_{De} \sim 0.23$. The solid curve in Fig. 8 (B) presents the CTS spectral intensity vs frequency $(\omega_L - \omega_{epw})/\Omega_{iaw}$ at the time of the peak pump intensity.

The dotted curve presents the IADI growth rate calculated using our experimental parameters. The growth rate peak happens at $\omega_L - \omega_{epw} = \Omega_{iaw}$; the IADI decay resonance condition is satisfied, and the normal mode of the ion acoustic wave will be excited. The measured CTS spectral width agrees reasonably with the growth rate curve. On the other hand, if the interaction laser intensity is much larger than 10 times of the threshold, the growth rate peak shifts towards higher frequency, and the ion acoustic wave frequency increases with the laser intensity (driven mode).

The phase velocity ω_{epw}/k_{epw} of the epw is 6.19×10^9 cm/sec, which is 4.7 times of the thermal electron velocity with $T_e = 1$ keV. We can also estimate the phase velocity of the ion acoustic wave. In our experiments, dipole approximation is valid, $k_L \sim k_{epw} + k_{iaw} \sim 0$, or $|k_{epw}| \sim |k_{iaw}|$. Using the IADI resonance condition, we can estimate the ion acoustic wave frequency, $\Omega_{iaw} = 2\pi c \Delta\lambda / \lambda_4 \omega^2 \approx 9 \times 10^{12}$ Hz ($\Delta\lambda$ is the wavelength shift of the CTS signal). Therefore, the phase velocity Ω_{iaw}/k_{iaw} of the ion acoustic wave is about 3.1×10^7 cm/sec. The theoretical value of the phase velocity of the ion acoustic slow wave is about 2.5×10^7 cm/sec, and 3×10^7 cm/sec for $T_e = 1$, and 1.5 keV.

We have also measured the conventional SH signal (where two epws couple to produce a SH emission) simultaneously with the CTS measurements to confirm the presence of the IADI. The low threshold value support the CTS measurements. The measured Stokes signal is spread over large wave length, and decreases gradually without a distinct peak as shown in Fig. 9. This indicates that the intensity of the epw spreads over a wide range of the wave number in the large scale plasma.

The CTS from the IADI is a good diagnostic to estimate the local electron temperature near the critical density. Because we are measuring a large angle scattering, the T_e is a sensitive function of the scattering angle. Let's estimate

ion acoustic wave in CH plasma. We have a slow, and a fast ion acoustic waves associated with C, and H ions. The ion wave dispersion relation in CH plasma is shown in the previous section. In typical laser produced plasma, the temperature ratio will be within $0.3 < T_i/T_e < 1$. Figure 6 shows that the temperature ratio is about 0.7 at the instability region. In this regime, the damping rate of the fast wave is about $\Gamma_i/\Omega_{iaw} \sim 0.8$, which is very strong damping. On the other hand slow wave damping rate is about $\Gamma_i/\Omega_{iaw} \sim 0.1$ in the regime of $0.3 < T_i/T_e < 1$. Slow wave has a moderate damping rate. The IADI threshold for the slow wave is 8 times smaller than the threshold value for the fast wave. Therefore, if the interaction laser intensity is not very high, only slow wave is excited. Figure 4 indicates that the phase velocity of the slow wave is almost flat vs T_i/T_e , if $0.3 < T_i/T_e < 1$, which is the case of typical laser produced plasma. The slow wave phase velocity depends ion temperature very weakly. It is proportional to electron thermal velocity, if $0.3 < T_i/T_e < 1$. The phase velocity is approximately given by $\Omega_{iaw}/k_{iaw} \approx 1.87 \times 10^{-2} v_e$ (or $v_e \approx 53 \times \Omega_{iaw}/k_{iaw}$). Since, we have measured the phase velocity, the electron thermal velocity v_e (or T_e) is about 1.6×10^9 cm/sec (or 1.5 keV) using the above equation at the plasma density of 8.6×10^{21} cm⁻³. The theoretical values ($v_e = 1.4 \times 10^9$ cm/sec, and $T_e = 1.1$ keV) given by SAGE calculation (Fig. 6) are somewhat lower than the experimental values (about 13 % for v_e , and 27 % for T_e). However, taking into account the complicated nature of the large scale plasma produced, and heated by multi laser beams, these may be rather good agreements. The plasma density is estimated using the Bohm-Gross equation of epw. The electron temperature is measured for a local (selected) plasma density (in our experiments $n/n_c \sim 0.86$) near the critical surface. For this diagnostic purpose, we have a good laser intensity window; $I_{th} < I_L < 8 \times I_{th}$, so normal mode of the ion acoustic slow wave is excited, and no fast wave is

excited. The refraction of the probe beam is less than 7 % for our experiments. The detection vector $(\mathbf{k}_s - \mathbf{k}_i)$ is perpendicular to the radial axis of the plasma expansion, indicating that the flow effect is small: $k_{epw} c_s \gg (\mathbf{k}_s - \mathbf{k}_i) \cdot \mathbf{v}_f$, where $\mathbf{v}_f$ is the velocity vector of the plasma flow.

V. SUMMARIES

In summary, we have developed an UV collective Thomson scattering system for plasma produced by a short wavelength laser. The Ion Acoustic Decay Instabilities are studied in a large ($\sim$ mm) scale, hot ($\sim$ keV) plasma, which is relevant to a direct-driven laser fusion plasma. The IADI primary decay process is measured by the CTS. We used a random phase plate to minimize the non uniform irradiation of the interaction laser. Nevertheless, the threshold of the most unstable mode driven by the IADI is quite low. The measured threshold value agrees favorably with the theoretical value of the large scale plasma. We have also shown that the CTS from the IADI can be a good tool for measuring a local electron temperature. The measured results agree reasonably with the SAGE computer calculations. We used the real part of the wave (frequency) to estimate T_e . The real part is, in general, reliable compared to the imaginary part such as the damping, and the growth rates.

We have shown that the IADI can be easily excited in a large scale, hot plasma. The IADI has potentially important applications to direct drive laser fusion, and also critical surface diagnostic.

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FIGURE CAPTIONS

Fig. 1. Estimated electron temperature vs scattering angle for several values of $k\lambda_{De}$. The solid and the dotted curves are ion acoustic wave, and electron plasma wave. From the left to right, $k\lambda_{De} = 0.15, 0.23$ (most unstable), 0.3 . Interaction laser wavelength is $1.06 \mu\text{m}$, and probe beam wave length is $1.06/3 \mu\text{m}$.

Fig. 2. Schematic of the experimental geometry, and the multi-channel Thomson scattering detector system.

Fig. 3. Frequency, and growth rate of the IADI are plotted for several α , where $\alpha = I_L/I_{th}$; interaction laser intensity divided by the IADI threshold intensity.

Fig. 4. Phase velocity of the ion acoustic wave vs temperature ratio T_i/T_e in CH plasma. The solid, and the dotted curves are slow wave, and fast wave.

Fig. 5 Experimental set up.

Fig. 6 SAGE computersimulation results.

Fig.7 CTS signal with the polarization of the probe beam (in & out).

Fig. 8 (A) The two-dimensional intensity plots of the CTS signals.

8 (B) The solid line shows the frequency spectrum of the epw with $k_{epw} = 2.9 \times 10^5 \text{ cm}^{-1}$ at $t = 2.2 \text{ nsec}$. The dotted line is the IADI growth rate.

Fig. 9 Spectrum of the second harmonic signal.

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