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Collective scattering of CO₂-laser light from ion-acoustic turbulence

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The spectral density function $S(\mathbf{k}, \omega)$ associated with spontaneous turbulence in a current-driven plasma of medium density ($n_e = 10^{19} - 10^{20} \text{ m}^{-3}$) is measured with the scattering of the radiation of a cw low-power CO₂-laser ($P_i \approx 2 \text{ W}$, $\lambda_i = 10.6 \mu\text{m}$). Optical homodyne detection has been used. A remarkable result is that the level of fluctuations with wave vectors $\mathbf{k} \parallel \mathbf{B}$ is close to thermal; $\mathbf{B}$ is the magnetic field for plasma confinement. The level of fluctuations with $\mathbf{k} \perp \mathbf{B}$ is several orders of magnitude larger than the thermal level. The phase velocity of these fluctuations is equal to the ion-acoustic velocity. A power law spectrum of the form $\tilde{n}_e/n_e \sim \omega^{-2}$ has been found. It is consistent with the spectrum below 1 MHz as measured by optical probes.

I. INTRODUCTION

Although one of the main original objects of CO₂-laser light scattering, the determination of the ion temperature in tokamak plasmas, is not yet realized, collective scattering of CO₂-laser light with optical homodyne or heterodyne detection has become an important diagnostic.¹ It is ideal for the experimental study of turbulence in plasmas. In 1972 Surko *et al.*² first demonstrated heterodyne detection of CO₂-laser light scattered from small-band driven cyclotron harmonic waves with the aid of a cw 10 W laser. Most of the studies so far involve at least one of the following aspects: (1) detection of externally excited single frequency waves; (2) high-energy pulsed or medium to high-power cw CO₂-lasers; (3) high-electron density plasmas ($n_e \geq 10^{21} \text{ m}^{-3}$).²⁻¹³ Besides heterodyne or homodyne detection of scattered light, incoherent detection has also been used in CO₂-laser light scattering experiments.^{14,15} Such experiments require a high-energy pulsed or high-power cw laser.

Our purpose is the measurement of the spontaneously appearing turbulence down to the thermal level in the current-driven plasma of a hollow cathode discharge in argon with medium plasma density ($n_e = 10^{19} - 10^{20} \text{ m}^{-3}$) with the aid of a cw low-power CO₂-laser ($P_i \approx 2 \text{ W}$) using optical homodyne detection. This is not an easy task, because the thermal turbulence level is extremely low. Furthermore, the spontaneously appearing turbulence in a plasma is a relatively broad band both in frequency and in wavelength, and one has to cope with relatively large noise. So, we combine the problems associated with the detection of low level spontaneous turbulence, the use of a low-power cw laser, and a medium-density plasma. With scattering, we measure fluctuations with frequencies between 1 and 55 MHz and with wavelengths between 0.1 and 0.5 mm. We compare the fluctuation level measured by scattering with the level at frequencies below 1 MHz measured by op-

tical probes. With these optical probes the plasma light intensity fluctuations are measured.

II. PRINCIPLE OF THE METHOD

A. Plasma scattering of electromagnetic radiation

Collective scattering refers to scattering of electromagnetic radiation on electrons, for which the scattering parameter

$$\alpha = \frac{1}{k\lambda_D} = \frac{1}{|k_i|2\sin(\theta/2)\lambda_D} \quad (1)$$

is larger than unity.¹⁶ Here, $k = |\mathbf{k}| = |\mathbf{k}_s - \mathbf{k}_i|$, where $\mathbf{k}$ is the wave vector and s and i refer to scattered and incident, respectively, (cf., Fig. 1); λ_D is the Debye length; θ is the scattering angle, i.e., the angle between $\mathbf{k}_s$ and $\mathbf{k}_i$. At $n_e = 10^{20} \text{ m}^{-3}$, electron temperature $T_e = 3 \text{ eV}$, and $\lambda_i = 10.6 \mu\text{m}$ the scattering is collective for $\theta \leq 80^\circ$.

The scattered power observed at frequency ω_s in a band $\Delta\omega_s$ is equal to¹⁶

$$P_s(\mathbf{k}_s, \omega_s, \Delta\omega_s) = P_i n_e L \sigma_T \Delta\Omega \times \int_{\omega_s - \Delta\omega_s/2}^{\omega_s + \Delta\omega_s/2} S(\mathbf{k}_s - \mathbf{k}_i, \omega_s' - \omega_i) d\omega_s', \quad (2)$$

FIG. 1. Scattering geometry in $\mathbf{r}$ space and $\mathbf{k}$ space.

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where L is the observation length, $\sigma_T \approx 8 \times 10^{-30} \text{ m}^2/\text{sr}$ is the Thomson scattering cross section, and $\Delta\Omega$ is the solid angle of detection. $S(\mathbf{k}, \omega)$ is the spectral density function and represents the electron density fluctuations. It is defined as

$$S(\mathbf{k}, \omega) = \lim_{T, V \rightarrow \infty} \frac{1}{TV} \frac{\langle |n_e(\mathbf{k}, \omega)|^2 \rangle}{n_e}, \quad (3)$$

where T is the observation time, V is the scattering volume, and $n_e(\mathbf{k}, \omega)$ is the space-time Fourier transform of the electron density $n_e(\mathbf{r}, t)$. Formula (2) states that the scattered power contains information about the level of electron density fluctuations with wave vector $\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$ and angular frequency $\omega = \omega_s - \omega_i$. By varying the scattering angle θ and the frequency of observation ω_s , the function $S(\mathbf{k}, \omega)$ can be measured in various parts of $(\mathbf{k}, \omega)$ space.

Our aim is the measurement of the spectral density function. The dispersion of the fluctuations found from these $S(\mathbf{k}, \omega)$ measurements will be compared with dispersion predicted by linear theory. Since the plasma equilibrium is complicated and the plasma contains several sources of free energy, it is not possible to predict the absolute level of the fluctuations from non-linear theory. For a thermal plasma, $S(\mathbf{k}, \omega)$ can be calculated and compared with experimental observations. For a thermal plasma with $\alpha \gg 1$ and $T_e \geq T_i$, $S(\mathbf{k}, \omega)$ peaks at the dispersion that corresponds to the ion-acoustic velocity (T_i is the ion temperature). For a thermal plasma $S(\mathbf{k}) = \int S(\mathbf{k}, \omega) d\omega \approx 1$. For a turbulent plasma $S(\mathbf{k}) \gg 1$ is possible.

B. Optical mixing detection

Often optical homodyne or heterodyne detection is used in CO_2 -laser light scattering experiments. In our case, the scattered radiation (signal beam) is mixed optically with a fraction of the original laser beam, called local oscillator LO, its power denoted by P_{10} . We call this homodyne detection.¹⁷ There is confusion in the literature on homodyne-heterodyne labeling. Some would call the present scheme heterodyne since an "independent" beam is used as LO. For our purpose, incoherent detection cannot be used because small scattering angles ($\theta \leq 8^\circ$), a medium-density plasma with low temperatures ($T_e = 2.5\text{--}10 \text{ eV}$, $T_i = 0.2\text{--}20 \text{ eV}$), and a low-power cw laser are involved. Consequently, stray light, spectral analysis (e.g., with a Fabry-Pérot interferometer), and the responsivity of infrared detectors present insurmountable problems. For optical homodyne detection, these problems are circumvented because of the following facts:

- (1) selective reduction of laser stray light due to a high resolution in both ω and $\mathbf{k}$;
- (2) the frequency spectrum of the scattered radiation is shifted from the optical to the rf range, so that no optical dispersive element is needed; the observed rf frequencies are the frequencies of the turbulence phenomena;
- (3) the voltage level is enhanced by a factor of the order $(P_{10}/P_s)^{1/2}$ as compared with incoherent detection.

Homodyne mixing of a signal beam of power P_s with an LO beam on the surface of a square law detector yields the following root mean square (rms) voltage across a load resistor R_l

$$V_m = 2^{1/2} m (\eta e G / h \nu) (P_{10} P_s)^{1/2} R_l, \quad (4)$$

where η is the quantum efficiency of the detector, G is its gain, and $h\nu$ is the photon energy. The mixing efficiency m can take values close to unity if LO and signal beams are properly matched.¹⁸

The most important contribution to the noise is the white shot noise of the LO; its rms voltage for the case of a photoconductor is equal to

$$V_n = (4eGR_d P_{10} \Delta\omega_s / 2\pi)^{1/2} R_l, \quad (5)$$

where $R_d = \eta e G / h \nu$ is the responsivity of the detector. Besides the shot noise of the LO, white thermal noise of the load and amplifier, and $1/f$ -noise of the detector also contribute.

An important quantity is the signal-to-noise ratio. The ideal signal-to-noise ratio can be written as

$$S/N = [P_s / (P_s + P_{sn})] (\Delta\nu \tau)^{1/2}, \quad (6)$$

where $P_{sn} = 2h\nu\Delta\nu/\eta$ is the power associated with the LO shot noise (noise equivalent power times bandwidth), $\Delta\nu$ is the if band of detection, and τ is the post detection integration time. In practice, degradations Δ_j ($j = 1, 2, \dots$) are present, which tend to deteriorate the signal-to-noise ratio. The most important degradations are $\Delta_m = m^2$ due to losses in mixing efficiency and Δ_{th} due to thermal noise. Including these degradations and noting that we deal with low scattered powers, i.e., $P_s \ll P_{sn}$, the signal-to-noise ratio can be rewritten as

$$S/N = (\eta P_s / 2h\nu\Delta\nu) (\Delta\nu \tau)^{1/2} \Pi_j \Delta_j. \quad (7)$$

For $m = 1$, the ideal signal-to-noise ratio can be approached when the shot noise of the LO is the dominant noise contribution, which can be achieved for a sufficiently large value of P_{10} , so that $\Delta_{th} = 1$.

According to the antenna theorem,¹⁹ the solid angle of detection $\Delta\Omega$ (homodyne field of view) is limited to

$$\Delta\Omega = \lambda_i^2 / A, \quad (8)$$

because coherence requires that the LO and signal wave fronts are matched within one wavelength over the effective source area A . The measurement of $S(\mathbf{k}, \omega)$ refers to an averaged value of $S(\mathbf{k}, \omega)$ over the observational $\mathbf{k}$ volume (cf., Fig. 1) with the dimensions¹⁸

$$\Delta k_x \approx 2\pi/l_x, \quad \Delta k_y \approx 2\pi/l_y, \quad \Delta k_z \approx 2\pi/l_z, \quad (9)$$

where l_x , l_y , and l_z are the dimensions of the scattering volume. Equation (9) describes the $\mathbf{k}$ resolution.

III. PLASMA FACILITY AND AUXILIARY DIAGNOSTICS

A. Plasma facility

For our investigations, we use the argon plasma of the positive column of a large size hollow cathode discharge (cf., Fig. 2). The most important features are a hot hollow cathode with a large thermionic emission,

FIG. 2. Sketch of the hollow cathode discharge. TS=Thomson scattering diagnostic, OS=optical spectroscopy, FI=Fabry-Pérot interferometry, OP=optical probes, CS=collective scattering diagnostic.

a continuous gas feed through the hollow cathode, a continuous pumping of the gas, and the confinement of the plasma column by an external axial static magnetic field. A stationary, highly ionized and magnetized plasma is formed with electron densities between 10^{18} and 10^{21} m^{-3} . For an argon plasma, the electron temperature is between 2.5 and 10 eV. The hollow cathode discharge consists of a large stainless steel vacuum vessel connected to two oil diffusion pumps, with four observational sections giving access to the diagnostics and surrounded by coils to provide for the magnetic field needed for plasma confinement. The electrode supports for the anode and the cathode are movable in the axial direction, so that the same plasma volume can be diagnosed with the diagnostics located at various ports (cf., Fig. 2). We verified that for several plasma conditions an axial displacement of the plasma, whereby the value of the magnetic field at the cathode location was left unchanged, did not influence the values of the plasma quantities by more than 10–20%. The visual appearance of the plasma is a bright blue transparent column that runs from the inside of the cathode to the anode. The diameter of the column at the cathode is approximately the cathode diameter. It increases to several centimeters toward the anode. The blue light stems mainly from argon II lines. The independent variables of the hollow cathode discharge are the plas-

ma current, denoted by I_{pl} , the confining magnetic field B_z , the gas flow Q or pressure p_a , the length of the arc L_{pl} , and the cathode diameter d_c . In Table I, relevant data of our hollow cathode discharge are given.

The electron density and electron temperature are measured using Thomson scattering. The temperatures of ions and neutrals are measured by Fabry-Pérot interferometry. The neutral density is determined from experimental line intensities and collisional radiative models for the argon I and II spectral systems.²⁰ Besides collective scattering, the plasma turbulence is measured by optical probes. Since one of the purposes of this paper is to make a comparison between the results of the optical probes and the scattering, we discuss these probes in the next section.

B. Optical probes

Plasma light emission is a powerful source for the experimental study of a plasma. With an optical probe, a voltage proportional to the plasma light intensity is measured. We are interested in the relative voltage fluctuation level $\tilde{V}(\nu, \Delta\nu)/\bar{V}$, i.e., the ratio of the rms voltage $\tilde{V}(\nu, \Delta\nu)$ in a band $\Delta\nu$ around an adjustable frequency ν to the average voltage $\bar{V}$. The ac voltage $\tilde{V}$ is a measure of the plasma light intensity fluctuations and the dc voltage $\bar{V}$ of the average plasma light inten-

TABLE I. A review of the relevant data of the hollow cathode discharge.

	gas	argon	
$n_e = n_i^+$	electron density	$10^{18}-10^{21}$	m^{-3}
n_a	neutral particle density	$10^{18}-10^{20}$	m^{-3}
T_e	electron temperature	2.5–10	eV
T_i	ion temperature	0.2–20	eV
T_a	neutral particle temperature	0.03–1	eV
B_z	magnetic field	≤ 0.5	T
I_{pl}	plasma current	10–250	A
V_{ac}	anode-cathode voltage	30–100	V
p_a	pressure	$10^{-4}-10^{-2}$	Torr
Q	gas flow	1–10	$\text{cm}^3 \text{ NTP/sec}$
L_{pl}	length plasma column	0–2.5	m
R_{pl}	radius plasma column	10–20	mm
d_c	cathode inner diameter	2–8	mm

sity level. The relative voltage fluctuation level is related to the relative plasma density fluctuation level. An extended description of the optical probe diagnostic can be found in Ref. 20. We note that we use photodiodes since these are superior to photomultipliers for the detection of light intensity fluctuations. With photodiodes, detection of relative plasma light intensity fluctuation levels of 10^{-6} per $\text{Hz}^{1/2}$ is possible for a photon rate of 10^{13} photons/sec up to 1 MHz.

It appears that the argon plasma of a hollow cathode discharge generates turbulence phenomena over the whole frequency range of the optical probe diagnostic (few kHz $< \nu < 1$ MHz). Here we will focus on those results which are of relevance in our discussion of the turbulence measured with scattering. For details with respect to the optical probe measurements and interpretations, we refer to Ref. 20.

(1) The total relative plasma light intensity fluctuation level, i.e., the level integrated over the frequency is typically 10% at the lateral position $y=0$. The level is maximal in the periphery of the plasma, that is, at $r \approx 1-2 \text{ cm} \approx \Lambda$, where Λ is the electron density gradient length. In Fig. 3, the light intensity level of our hollow cathode discharge plasma during a time interval of 1 msec is compared with that of a tungsten ribbon lamp emitting the same average amount of photons per unit time. It illustrates that the plasma light is afflicted with relatively large fluctuations as compared with the light of a tungsten ribbon lamp.

(2) The propagation of all observed waves is perpendicular to the applied magnetic field. No axially propagating waves are found, even for the ion Hall parameter $\Omega_{ci} \tau_{ii} \approx 1$ and for parameter sets of the hollow cathode discharge that refer to points close to the stability boundary of the current-driven ion-acoustic instability (Ω_{ci} is the ion cyclotron angular frequency and τ_{ii} is the ion-ion collision time). It is noted that the presence of a poloidal field B_θ , caused by the plasma current I_{p1} , allows for a finite $k_\parallel$ ($k_\parallel$ is the component of k parallel to B).

(3) The highest relative plasma light intensity fluctuation levels are measured at $r \approx \Lambda$. Most of the level is related to a low-frequency rotational instability ($\omega \ll \Omega_{ci}, \tau_{ii}^{-1}$). From detailed measurements (optical probes, streak photographs, and time-resolved Doppler shifts), it appears that the instability can be described by an eccentric rotation of the entire plasma column. The frequency of this instability is between 5 and 20 kHz.

FIG. 3. Comparison of light levels of a tungsten ribbon lamp and the hollow cathode discharge plasma, both emitting the same average amounts of photons per unit time.

(4) Collisional drift waves ($\omega < \Omega_{ci}, \tau_{ii}^{-1}$) and collisional ion cyclotron waves are found ($\omega \approx n\Omega_{ci} < \tau_{ii}^{-1}$, $n=1, 2, 3, 4$). Near the axis of the plasma column, the relative plasma light intensity fluctuation level due to these instabilities is maximal at 5%.

(5) A perpendicular ion-acoustic instability ($\omega > \Omega_{ci}, \tau_{ii}^{-1}$) is found for relatively large values of the ion Hall parameter, that is, $\Omega_{ci} \tau_{ii} \approx 1$, at frequencies close to the ion-ion collision frequency (see Fig. 4). Cross correlation measurements of the signals of two optical probes yield phase velocities equal to the ion-acoustic velocity.

(6) Finally, a background spectrum is found with the form of a ω^{-2} -power law.

It is noted that the identification of the fluctuations is based on the dispersion found experimentally (frequency and wavelength). We will come back on identification in Sec. VC.

IV. COLLECTIVE SCATTERING EXPERIMENT

A. Optical arrangement and k selection

Plasma waves are characterized by a wave vector k and a frequency ω . The laser wavelength λ_i and the scattering angle θ determine the wave vector k and consequently, the wavelength λ of the observed fluctuations. For scattering angles $\theta \leq 30^\circ$ and $\lambda_i = 10.6 \mu\text{m}$, we get $k = k_i 2 \sin(\theta/2) \approx k_i \theta \approx 10^4 \hat{\theta} (^\circ)$. The range of scattering angles θ is limited. A lower limit of 0.3° is set by diffraction of the primary laser beam, that is, $\theta_d = \lambda_i/d$, where $d \approx 2 \text{ mm}$ is the laser beam diameter. In practice, the lower limit is about 1° due to the finite sizes of our optical components. An upper limit of 80° is set by the condition $\alpha = 1$ [cf., Eq. (1)]. In practice, the upper limit is about 8° due to the restricted dimensions of the plasma vessel observation ports. These limits imply that wavelengths can be observed between 0.1 and 0.5 mm. The maximum wavenumber that can be observed is about one tenth of the Debye wavenumber. Besides variation of the scattering angle between 1° and

FIG. 4. Spectra of the hollow cathode discharge plasma for the interval 50 to 1000 kHz as a function of the plasma current. Resolution of 500 Hz. Parameter set: gas=argon, $B_z=0.4 \text{ T}$, $Q=2.5 \text{ cm}^3 \text{ NTP/sec}$, $L_{p1}=1.5 \text{ m}$, $d_c=6 \text{ mm}$, $z=0.75 \text{ m}$, and $y=0$.

FIG. 5. Experimental arrangement for collective scattering of CO_2 -laser light for $k//B$. L = lens, SH = shutter, CH = chopper, D = diaphragm, M = mirror, BS = beamsplitter, CF = cold filter, MO = monitor, W = window.

8° , the direction of k can be chosen parallel or perpendicular to the magnetic field B .

In Fig. 5, the experimental arrangement is sketched. Our CO_2 -laser is focused in the plasma to a spot with a diameter of 2 mm. Here, scattering follows as a consequence of electron density fluctuations. Via mirror M_1 , beamsplitter BS, lens L_2 , and mirror M_2 , the scattered radiation is focused on an infrared-sensitive detector. The scattered radiation is chopped for phase sensitive detection purposes. Blocking of the signal is possible with the shutter SH. The scattering angle can be varied by translation of the mirror M_1 . A fraction of the incident laser beam is used as LO and via beamsplitter BS, the LO power is mixed optically with the signal beam (scattered beam). The LO power can be adjusted by diaphragm D_1 . A laser monitor MO is used for the determination of the laser power and also acts as a laser dump. The windows, beamsplitter, and lenses are made all of sodium chloride. We use a photoconductive Ge:Cu detector with an active area of $1 \times 1 \text{ mm}^2$. Its sensitivity is determined with the aid of a black body radiator. The quantum efficiency $\eta \approx 10\%$. The detector is mounted on the cold surface of a Dewar with liquid helium (4 K). A BaF_2 -window is used for optical access, in front of which an optional cold filter can be placed.

As the LO passes through the plasma also "small- k " scattering with $\theta \lesssim \theta_d = \lambda_i/d$ will be detected in addition to the scattering at angle θ . It is discriminated by phase sensitive detection and measured separately by blocking the signal beam. It yields information about $S(k, \omega)$ in the small wave vector region, however, without k resolution.

The scattering volume is the intersectional volume of (1) the incident laser beam, (2) the view volume of detection, and (3) the "effective" plasma volume, that is, the plasma volume where fluctuation phenomena of the kind under investigation are present. Referring to Fig. 1, it means that the maximum dimensions are: l_x is the diameter of the plasma $\approx 2 \text{ cm}$ and $l_y = l_z \approx$ the neck

diameter of the laser spot, $d \approx 2 \text{ mm}$. Note that in the x direction local measurements are hardly possible since the observation length is equal to $L = d/\sin\theta \approx 10^{-1}/\hat{\theta}(\text{rad}) \text{ m}$ for $\theta \lesssim 30^\circ$. This length is larger than the plasma diameter for $\theta \lesssim 5^\circ$.

Lateral plasma scanning, i.e., scanning in the y direction, is achieved by moving the plasma through the fixed scattering volume by moving the cathode of the hollow cathode discharge vertically. Axial plasma scanning, i.e., scanning in the z direction, is achieved by moving both electrodes of the hollow cathode discharge in the axial direction.

Proper optical alignment is crucial in optical mixing and small signal detection. Rough alignment is achieved with the aid of a He-Ne laser. In the final alignment, Rayleigh scattering on high-level acoustic waves is used.²¹ These acoustic waves are generated by ceramic crystals in argon gas at 1 atm. For that purpose a crystal (disk of BaTiO_3 material) is placed close to the scattering volume, where during the actual measurement the plasma is present. Although a monochromatic, directed acoustic wave is used, small misalignments with respect to the desired k direction are allowed (e.g., $k||B, k \perp B$) due to the finite k resolution ($\pm 4^\circ$). It has been verified that, by turning the crystal, the measured k resolution is consistent with the anticipated k resolution [Eq. (9)].

B. Electronic arrangement and ω selection

In the case of optical mixing, the frequency spectrum of the scattered radiation is shifted from the optical to the rf range. The spectral analysis is achieved electronically after detection instead of optically before detection.

The electronic arrangement is sketched in Fig. 5. The photocurrent is measured across a load resistor of 600Ω and impedance transformation to 50Ω is applied. A high-pass filter (1 MHz, 12 dB/octave) is used in order to eliminate $1/f$ -noise contributions. The signal is amplified by broad-band, low-noise Avan-

FIG. 6. Transmission of passive band pass filters (—) and total gain (---) of hf part of electronic system.

tek AWL-500M amplifiers (0–500 MHz, total gain 50 dB). Home-made, passive, broad-band pass filters are used for the spectral analysis. In Fig. 6, the transmissions of the filters and the gain of the rf part of the system are given. The fall of the gain above 15 MHz is caused by RC-integration of the parasitic capacitance of about 20 pF of the detector and leads, and the load resistor. An HP 8471-A squarer is used for rf detection. The low frequency part of the system consists of a Krohn-Hite variable band pass filter adjusted at 0.2–1 kHz, a Brookdeal amplifier with variable gain (30–100 dB), and a Brookdeal phase sensitive detector (integration time $\tau < 10$ sec). A PDP 11/20 process computer is used if integration times longer than 10 sec are required.

C. Optimization of the signal-to-noise ratio

One of our aims is the detection of plasma fluctuations close to the thermal level. In terms of the scattered power it means $P_s \approx 3 \times 10^{-16}$ W for $P_i = 2$ W, $n_e = 10^{20}$ m $^{-3}$, $L = 2$ cm, $\Delta\Omega = 3.6 \times 10^{-5}$ sr, $S(k) = 0.5$, and an optical system transmission of 50%. The scattered power is 16 orders of magnitude lower than the value of the incident laser power. Optimization of the signal-to-noise ratio is therefore crucial for the experiment.

The mixing efficiency can be optimized independently by optimum focusing and colinearity of the LO and signal beams. As stated, the quantum limit is approached when the shot noise of the LO is dominant. The influence of thermal noise can be reduced by: (1) large LO power or; (2) a large load R_L . However, low detector dissipation asks for low LO power (bias power + $P_{10} \leq 100$ mW). Therefore, we choose a high load of 600 Ω and impedance transformation to 50 Ω . The transformer is placed as close as possible to the helium Dewar in order to minimize the parasitic stray capacitance. Moreover, ultra-low noise components are used (noise figure 5 dB). In this arrangement an LO power of $P_{10} \approx 10$ mW suffices in order to obtain $\Delta_{th} \approx 0.5$ (bias voltage detector approximately 100 V and current approximately 1 mA). An additional advantage of low LO power is that noise introduced by “small- k ” scattering is reduced.

D. Sensitivity and calibration of the homodyne system

The absolute sensitivity is of interest since it allows for the determination of the absolute value of the level of plasma fluctuations. Rayleigh scattering on a gas sample is not possible in view of the small cross section at 10.6 μ m. Calibrations within a factor of two are possible with other methods. We applied three, more or less independent methods, which yield a relation between the voltage V_{psd} at the phase sensitive detector and the scattered power P_s at the detector. The results are given in Fig. 7, which refers to the flat part of the transmission curve of the system (cf. Fig. 6). Indicated are: (1) the result of a calculation of the relation $V_{psd}(P_s)$ on the basis of data of the components of the system, assuming a mixing efficiency $m = 1$; (2) the results of calibrations with the aid of Rayleigh scattering on acoustic waves generated by the ceramic crystals, which allows for coherent as well as for incoherent detection in case of high-level waves; (3) the results of calibrations with a black body (1000 K), which is also pre-eminently suitable for the calibration of the various frequency bands because a white spectrum is involved. One may gather from Fig. 7 a large dynamic range of our homodyne system and a good agreement between the various methods. The results with the ceramic crystal indicate a mixing efficiency $\Delta_m \approx 0.5$. We also show in the figure the measured signal-to-noise ratio referring to the Rayleigh scattering on acoustic waves. Good agreement exists with the calculated signal-to-noise ratio, including a total degradation of a factor of one tenth (note that the use of a chopper introduces an extra degradation $\Delta_{ch} = 0.5$).

We calculate the spectral density function $S(k, \omega)$ from the measured scattered power P_s with the aid of formula (2), assuming an observation length of $L = 0.02$

FIG. 7. Calibration plot of the homodyne detection system. The voltage V_{psd} is normalized to 100 dB gain of the lf amplifier. The figure refers to the flat part of the hf transmission curve (cf., Fig. 6). The calculated signal-to-noise ratio refers to $\tau = 1$ sec, $\Delta\nu = 10$ MHz, and a total degradation factor of 0.1. The measurements with the ceramic crystal have been performed at $\theta = 2^\circ$.

m. A calculated optical transmission of 50% is taken into account.

V. EXPERIMENTAL RESULTS AND DISCUSSION

A. Introduction

We use two scattering geometries; one with wave vector $\mathbf{k} \parallel \mathbf{B}$ and one with $\mathbf{k} \perp \mathbf{B}$. The results presented in this section refer to a plasma length $L_{pl} = 1.8$ m and a cathode with a diameter $d_c = 6$ mm. Most results refer to argon. In Sec. V E, a measurement with helium will be mentioned.

B. $\mathbf{k} \parallel \mathbf{B}$ geometry

For the orientation $\mathbf{k} \parallel \mathbf{B}$, extremely small signals are measured for all parameter sets of the hollow cathode discharge. The fluctuation level is close to or slightly higher (factor of three) than the thermal level, i.e., $S(\mathbf{k} \parallel \mathbf{B}) \approx 0.5$ (cf. Fig. 13). Spectral analysis, although difficult, indicates a maximum of the level around the ion-acoustic velocity. The signal is too small to allow for detailed $S(\mathbf{k}, \omega)$ diagrams as will be possible for $\mathbf{k} \perp \mathbf{B}$.

The observation of a level close to thermal for $\mathbf{k} \parallel \mathbf{B}$ is a remarkable result, especially so because in our case a current-driven plasma is involved. Current-driven ion-acoustic turbulence may be expected and although the criterion for instability has not quite been reached, a higher level than thermal was anticipated.²²

C. $\mathbf{k} \perp \mathbf{B}$ geometry

As contrasted with the case $\mathbf{k} \parallel \mathbf{B}$, for $\mathbf{k} \perp \mathbf{B}$ high fluctuation levels of the electron density are measured. These levels can reach values 10^4 to 10^5 times the thermal level.

1. Lateral scanning

In Fig. 8, we show the spectral density function $S(\mathbf{k}, \omega)$ for $k_1 = 2 \times 10^4 \text{ m}^{-1}$ as a function of the frequency for various lateral positions y . The figure demonstrates a clear change of spectral structure as a function of y . An inverse power law spectrum is observed at the periphery of the plasma, whereas, for the center, hf phenomena are observed with a peak around 15 MHz. Here, we note an interpretation problem. The collective scattering diagnostic observes fixed $\mathbf{k}$'s. Fluctuations of a cylindrical plasma can be thought of as the superposition of radial and azimuthal waves (cf., Fig. 9). A wave vector of an azimuthal wave matches the wave vector $\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$ if the scattering is performed at a lateral position which corresponds to the middle of the plasma. A wave vector of a radial wave matches the wave vector $\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$ if scattering is performed at the periphery of the plasma. Consequently, at the middle of the plasma azimuthal waves and at the periphery radial waves are observed. Although we will not treat the low-frequency phenomena at the periphery of the plasma, we note that they can be explained by (radial) macroscopic motion of the plasma through the observation volume rather than by small scale fluctuations; such motion can be due to the rotational instability mentioned in Sec. III B. The observed spectra at the peri-

FIG. 8. $S(\mathbf{k}, \omega)$ at fixed $k_1 = 2 \times 10^4 \text{ m}^{-1}$ as a function of the frequency for various lateral positions. Hollow cathode discharge parameter set: $I_{p1} = 50$ A, $B_z = 0.2$ T, $p_a = 0.5$ mTorr, and $z = 0.25$ m.

phery are consistent with this macroscopic motion, since both the frequencies and fluctuation level are consistent with it. Since we are not interested in measuring macroscopic motion with scattering, we restrict our attention to the middle of the plasma, i.e., only azimuthal waves related to small scale fluctuations are considered.

2. $S(\mathbf{k}, \omega)$ diagrams

In Figs. 10 and 11, we show examples of $S(\mathbf{k}, \omega)$ diagrams for various hollow cathode discharge parameter sets. In Fig. 10(b), we have added the values of "small- k " scattering. The reduced optical transmission for this kind of scattering is taken into account. We have projected the maximum of the spectral density function in ω at each measured k_1 on the (k_1, ω) plane. It yields the dispersion of the fluctuations and a phase velocity can be determined.

FIG. 9. Illustration of the matching of wave vector $\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$ with the wave vector $\mathbf{k}_r$ of radial waves and the wave vector $\mathbf{k}_\theta$ of azimuthal waves.

FIG. 10. $S(k, \omega)$ diagrams for three different axial positions, i.e., $z = 0.10$ m, $z = 0.25$ m, and $z = 0.50$ m. Hollow cathode discharge parameters: $I_{p1} = 100$ A, $B_p = 0.4$ T and $p_a = 0.5$ mTorr. (b): electron density $n_e = 1.4 \times 10^{20}$ m $^{-3}$, electron temperature $T_e = 7$ eV, and ion temperature $T_i = 20$ eV; "small- k " scattering values are indicated; note change in scale. Insert shows dispersions.

3. Discussion

(1) The spectral structure changes with the change in the parameter set of the hollow cathode discharge. The phase velocity and fluctuation level increase toward the cathode (cf., Fig. 10). Moreover, phase velocity and level increase with increasing plasma current, increasing magnetic field, and decreasing pressure.

(2) The fluctuations are broad band, i.e., the relative width is about $\Delta\nu/\nu = 1$.

(3) There is one main dispersion curve, which is approximately linear. In some of the diagrams a low frequency dispersion branch with a lower level than the main branch is observed.

(4) The spectra have the form of inverse power laws in both $k_{\perp}$ and ω . In two of the diagrams a peak is observed around the lower hybrid frequency $\omega_{lh} \approx (\Omega_{ce}\Omega_{ce})^{1/2} \approx 40$ MHz.

(5) The fluctuation level is high and may reach values

FIG. 11. $S(k, \omega)$ diagram. Parameter set: $I_{p1} = 150$ A, $B_z = 0.4$ T, $p_a = 0.5$ mTorr, and $z = 0.25$ m.

of 10^4 to 10^5 times the thermal level. It means that there exists a large anisotropy in k space; for $k \parallel B$ the level is thermal, for $k \perp B$ the level is several orders of magnitude above thermal. This proves the selectivity of CO_2 -laser light scattering with optical homodyne detection.

(6) The level decreases with increasing axial position and the dispersion is determined by local plasma parameters.

(7) The "small- k " scattering joins the rest of the $S(k, \omega)$ diagram referring to the nature of the power law and dispersion.

4. Dispersion and identification

We first note another difficulty in interpretation. In our case, the observed frequencies are Doppler-shifted due to the $\mathbf{E} \times \mathbf{B}$ drift. Therefore, we have measured the ion rotation of the plasma with Fabry-Pérot interferometry. We find at $r \approx \Lambda$, ion rotational velocities that are about one fifth of the measured phase velocities of the fluctuations [$\omega_{i\theta}(\Lambda) \approx 1.5 \times 10^3$ m/sec]. The rotation is in the direction of the $\mathbf{E} \times \mathbf{B}$ drift. Consequently, no frozen structures at $r \approx \Lambda$ are involved, which rotate together with the plasma. However, as the $\mathbf{E} \times \mathbf{B}$ drift is directed oppositely to the ion diamagnetic drift, the actual $\mathbf{E} \times \mathbf{B}$ drift is the sum of the measured ion rota-

tion plus the ion diamagnetic drift, which can be determined from the measured temperatures and densities. Since we use homodyne detection, the direction of propagation of the observed fluctuations is unknown. However, taking the propagation in the direction of the electron diamagnetic drift yields phase velocities, that are close to the ion-acoustic velocity $c_s = [(kT_e + 3kT_i)/m_i]^{1/2}$ (Ref. 23). Consequently, perpendicularly propagating ion-acoustic turbulence is involved.

Although the electron diamagnetic drift velocity v_{de} is smaller than c_s , sometimes it is not that much different from c_s . Consequently, there may be a gradual transition from ion-acoustic waves to drift waves or a (nonlinear) mixture of these two. Further, various sources of free energy may contribute to the observed turbulence (e.g., gradients, plasma current, plasma rotation). In fact, an unambiguous identification is not possible. Despite the fact that the physical situation is more complicated than the name suggests, we call the main branch in the $S(k, \omega)$ diagrams of argon, which is probably a conglomerate of wave modes more than a pure wave mode, perpendicularly propagating ion-acoustic turbulence. The strongest argument for this name is the agreement between the experimental dispersion and the anticipated (linear) dispersion of ion-acoustic waves.

That among others, hf drift waves may play a role is illustrated by the observation at $B_z = 0.4$ T of an instability that resembles the lower hybrid drift instability.²⁴ Lower hybrid drift waves are confluences of lower hybrid waves and drift waves. An increase in the plasma current from 100 to 150 A, stabilizes the instability [cf., Figs 10(b) and 11]. It can be explained by the stabilizing effect of finite shear on the waves, i.e., finite $k_{\parallel}/k_{\perp} \sim I_{p1}/B_z$.

FIG. 12. Relative density fluctuation level as a function of the frequency. Same parameter set as in Fig. 10(b). Note that extrapolation of the spectrum to the ion plasma frequency yields a fluctuation level that is approximately equal to the thermal fluctuation level.

FIG. 13. Relative density fluctuation level as a function of the frequency. Parameter set: $I_{p1}=50$ A, $B_z=0.2$ T, $p_a=0.5$ mTorr, and $z=0.25$ m. Electron density $n_e=9 \times 10^{19} \text{ m}^{-3}$, electron temperature $T_e=3.0$ eV and ion temperature $T_i=5.5$ eV. The level for $k \parallel B$ is also shown in the figure.

D. Comparison with optical probes

In this section, we compare the results of scattering with the results of the optical probes. For that purpose, we calculate the relative density fluctuation level $\tilde{n}_e/n_e$ for both cases.

The density fluctuation level can be calculated from the measured $S(k, \omega)$ as

$$\tilde{n}_e/n_e = \left(\frac{\int d^3k}{(2\pi)^3} \cdot \frac{S(k, \omega)}{n_e} \right)^{1/2}, \quad (10)$$

where the integration refers to the whole k space. We now make the reasonable assumption that only the observed dispersion branch around c_s is present, although we did not investigate the entire (k, ω) space. Furthermore, we have corrected for the fact, that at higher frequencies, not the entire Δk -width of the observed spectrum around $\omega = kc_s$ fits in the observational k volume. This leads to minor corrections only at higher frequencies. For the optical probes, the density fluctuation level is determined from the measured photo-voltage fluctuation level $\tilde{V}/V$. Taking a frequency of 500 kHz and a phase velocity of 5×10^3 m/sec [cf., $S(k, \omega)$ diagrams] yields wavelengths that are of the order of the density gradient length and we find $\tilde{n}_e/n_e \approx \tilde{V}/V$. In Figs. 12 and 13, examples are given and they are typical for other parameter sets. The level $\tilde{n}_e/n_e$ per $\text{Hz}^{1/2}$ is shown as a function of the frequency.

It appears that the results of the scattering experiment are consistent with those obtained from optical probes. A power law spectrum has now been proved over a large frequency interval. The overall behavior agrees with a ω^{-2} spectrum. We note that the relative fluctuation level $\tilde{n}_e/n_e$ extrapolated to ω_{pi} , thus $k=1/\lambda_D$, is approximately equal to the thermal level, as is to be expected because of strong Landau damping. It is of interest to note that most of the fluctuation activity is con-

centrated at low frequencies and consequently, only low frequency phenomena contribute significantly to the total level. We estimate the total relative density fluctuation level above 1 MHz to be less than 1% for all parameter sets of the hollow cathode discharge.

E. Measurement with helium

We have also measured the $S(k, \omega)$ diagram for one parameter set of a helium discharge. This is shown in Fig. 14. It is comparable to those of argon. The fluctuation level is of the same order of magnitude as for argon. However, recognizably two dispersion curves are involved. The measurements indicate one branch with a phase velocity close to the electron diamagnetic drift velocity $v_{de} = (\rho_c/\Lambda)c_s$, and one branch with a phase velocity close to the ion-acoustic velocity (ρ_c is the ion cyclotron radius evaluated at the electron temperature). We note that for argon often $\rho_c \approx \Lambda$, so that $v_{de} \approx c_s$ and therefore the two branches may coincide.

VI. CONCLUSIONS

We proved the possibility of measuring plasma turbulence in terms of the spectral density function $S(k, \omega)$ down to about the thermal level in a medium density plasma by the scattering of electromagnetic radiation with the aid of a low-power cw CO_2 laser. As a consequence of special attention to the optimization of the signal-to-noise ratio, relative density fluctuation levels of 10^{-9} – 10^{-10} per $\text{Hz}^{1/2}$ are detectable.

FIG. 14. $S(k, \omega)$ diagram for helium. Parameter set: $I_{p1}=50$ A, $B_z=0.2$ T, $p_a=0.5$ mTorr, and $z=0.25$ m.

Further improvement of the signal-to-noise ratio is possible by mounting the impedance transformer into the Dewar. Our measurements refer to absolute plasma density fluctuation levels. The method can be applied to tokamak plasmas.^{5,20}

We have determined the spectrum, dispersion, and level of fluctuations in the plasma of a hollow cathode discharge in the range $1 < \omega/2\pi < 55$ MHz and $10^4 < k < 8 \times 10^4$ m⁻¹. The most striking result is the observation of a thermal level for fluctuations with $k \parallel B$. For $k \perp B$, the fluctuation level can be several orders of magnitude above thermal. Two types of fluctuations are observed: (1) perpendicularly propagating ion-acoustic turbulence; and (2) a lower hybrid drift instability. The identification has been based on the experimental dispersion. It is not possible to indicate the driving source of free energy. The measurements are consistent with the results of optical probes and, although locally in (k, ω) space the level may be several orders of magnitude above thermal, the total level above 1 MHz is less than 1%. A power law spectrum of the form $\tilde{n}_e/n_e \sim \omega^{-2}$ has been found.

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