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AN ALPHA PARTICLE DIAGNOSTIC BASED ON MEASUREMENTS OF LOWER HYBRID WAVE FLUCTUATIONS

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Abstract

It is shown that the one-dimensional alpha particle velocity distribution function can be determined from the fluctuation-dissipation theorem based on measurements of lower hybrid wave fluctuations in an equilibrium plasma. This method uses collective Thomson scattering data with large signal-to-noise ratio, but it is applicable only when the alpha particles have an isotropic velocity distribution.

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As present tokamak parameters approach the reactor regime, the interest in fusion research starts to focus on alpha particle behavior [1] in ignited plasmas. While new machines are being designed for this purpose, it is noticed that the diagnostic for alpha particles is one major item which needs to be developed. In order to study alpha particle physics, one would like to measure the alpha particle distribution function $f_{\alpha}(\vec{r}, \vec{v}, t)$ with good resolution in space, velocity, and time. Many schemes have been proposed recently, and each one has its own difficulties [2]. One method that is being seriously investigated is collective Thomson scattering [3]. This process has a very small cross section that is characterized by the classical electron radius ($r_e = e^2/mc^2 = 2.82 \times 10^{-13}$ cm). Therefore, high incident beam power is necessary. A 100 MW CO₂ laser (10.6 μ m) has been proposed. Because of the short wavelength, the scattering angle is very small ($\theta \leq 1^\circ$), which gives rise to very poor spatial resolution. Such a high power laser must be operated in a pulsed mode and can only take measurements at one point in time. The power requirement is substantially reduced when one uses 1 - 2 mm microwave sources. A few hundred kilowatts of microwave power would be sufficient [4]. At these long wavelengths, wave refraction inside the plasma will introduce complications, but this is not an unsurmountable difficulty. The scattering angle will be large enough to provide good spatial resolution. Calculations [5,6] of the spectral function $S(\vec{k}, \omega)$ show that if $k_z/k_{\perp}$ (k_z is the component of $\vec{k}$ parallel to the magnetic field and $k_{\perp}$ is the component perpendicular to the magnetic field) is not too small, the alpha particle feature in S can become dominant and the one-dimensional alpha particle distribution function can be obtained from the frequency spectrum of $S(\vec{k}, \omega)$ at one fixed value of $\vec{k}$. Large enhancement of $S(\vec{k}, \omega)$ was noticed due to lower hybrid waves at small values of $k_z/k_{\perp}$. The scattering signal can be three orders of magnitude higher [7]. This large signal is discarded because of the difficulty in data interpretation. In this paper, we investigate the possibility of using this large signal to extract information about the alpha particle distribution function. If successful, we may be able to increase the signal-to-noise ratio by three orders of magnitude, or reduce the incident power requirement by three orders of magnitude so that steady-state operation of the diagnostic can be easily realized.

It has been shown that lower hybrid waves can be strongly damped by energetic alpha particles in a tokamak reactor [8]. Therefore, the fluctuation level of lower hybrid waves is sensitive to the velocity distribution function of the alpha particles $f_\alpha(\vec{v})$. A lower hybrid wave is an electrostatic wave in the frequency range $\omega_{ci} \ll \omega \ll \omega_{ce}$, and it is a common practice to assume magnetized electrons and unmagnetized ions for the wave dispersion relation. Suppose the plasma is at equilibrium. The spectral power density of electrostatic fluctuations in the plasma can be estimated from the fluctuation-dissipation theorem [9] as follows:

$$\begin{aligned}
 P(\vec{k}, \omega) = & \frac{n_e e^2}{k^2 \epsilon_0^2 |K_L(\vec{k}, \omega)|^2} \int d^3v \sum_n J_n \left(\frac{k_\perp v_\perp}{\omega_{ce}} \right) \delta(\omega - n\omega_{ce} - k_z v_z) f_e(\vec{v}) \\
 & + \frac{n_i e_i^2}{k^2 \epsilon_0^2 |K_L(\vec{k}, \omega)|^2} \int d^3v f_i(\vec{v}) \delta(\omega - \vec{k} \cdot \vec{v}) \\
 & + \frac{n_\alpha e_\alpha^2}{k^2 \epsilon_0^2 |K_L(\vec{k}, \omega)|^2} \int d^3v f_\alpha(\vec{v}) \delta(\omega - \vec{k} \cdot \vec{v}) \quad , \quad (1)
 \end{aligned}$$

where n_j = particle density of the j-species
 e_j = electric charge of the j-species
 ω_{ce} = electron cyclotron frequency
 K_L = $\vec{k} \cdot \vec{K} \cdot \vec{k} / k^2$ is the longitudinal dielectric function ($\vec{K}$ is the dielectric tensor).

The magnetic field is along the $\hat{z}$ -axis. The three terms in Eq. (1) correspond to those in the spectral function [5,6] $S(\vec{k}, \omega)$ which determines the electron density fluctuation $\tilde{n}_e(\vec{k}, \omega)$. From $\tilde{n}_e(\vec{k}, \omega)$, one can easily calculate the electric

fluctuation $\tilde{E}(\vec{k}, \omega)$ and $P(\vec{k}, \omega)$. Hence, $P(\vec{k}, \omega)$ is treated as a quantity measured in the experiment.

Lower hybrid waves with wave number $\vec{k}$ and wave frequency ω are normal modes of the plasma. The real part of $K_L(\vec{k}, \omega)$ vanishes, which causes significant enhancement in $P(\vec{k}, \omega)$ and $S(\vec{k}, \omega)$. When $\omega \gg \omega_{pi}$, (ω_{pi} is the ion plasma frequency), the wave dispersion relation is:

$$\frac{k_z^2}{k^2} = \frac{\omega^2}{\omega_{pe}^2} \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} \right) \ll 1 \quad (2)$$

When $\omega \sim \omega_{pi}$, the ion dynamics becomes important. If one neglects finite Larmor radius effects, there is a lower hybrid resonance ($k_\perp \rightarrow \infty$) when

$$\omega = \omega_{LH} = \left(\frac{1}{\omega_{ci}^2 + \omega_{pi}^2} + \frac{1}{\omega_{ci}\omega_{ce}} \right)^{-1/2} \quad (3)$$

This resonance is removed by ion finite Larmor radius effects [10,11]. Nevertheless, when $\omega \sim \omega_{pi}$, k_z/k is even smaller than that given in Eq. (2). Therefore, $P(\vec{k}, \omega)$ and $S(\vec{k}, \omega)$ are significantly larger at small values of k_z/k in the lower hybrid frequency range, as was noted in previous calculations [5,6]. Since we know that lower hybrid waves can be absorbed by energetic alpha particles, the imaginary part of $K_L(\vec{k}, \omega)$ contains information on the alpha particle velocity distribution function $f_\alpha(\vec{v})$. We will show that under certain conditions, the large values of $P(\vec{k}, \omega)$ or $S(\vec{k}, \omega)$ due to lower hybrid waves can be used to obtain information on $f_\alpha(\vec{v})$.

Let $v_{\parallel}$ and $v_{\perp}$ be the velocity components parallel and perpendicular to $\vec{k}$, respectively. The one-dimensional distribution function [12] is defined as:

$$F(u) = \int f_{\alpha}(\vec{v}) \delta(u - \frac{\vec{k} \cdot \vec{v}}{k}) d^3v = \int_{-\infty}^{\infty} dv_{\parallel} \delta(u - v_{\parallel}) \int_0^{\infty} f_{\alpha}(\vec{v}) 2\pi v_{\perp} dv_{\perp} \quad (4)$$

The alpha particle contribution to $K_L(\vec{k}, \omega)$ is:

$$\chi_{\alpha} = -\frac{\omega_{p\alpha}^2}{k^2} \int_L \frac{dF/du}{u - (\omega/k)} du = -\frac{\omega_{p\alpha}^2}{k^2} \left[P \int_{-\infty}^{\infty} \frac{dF/du}{u - (\omega/k)} du + i\pi \frac{dF}{du} \right]_{\omega/k} \equiv \chi_{\alpha R} + i\chi_{\alpha I} \quad (5)$$

In the above expression, L denotes the Landau contour and P denotes the principal value of the integral. In the case of $\omega \gg \omega_{pi}$, we have

$$\begin{aligned} K_L(\vec{k}, \omega) &= \frac{k_{\perp}^2}{k^2} \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2} \right) + \frac{k_z^2}{k^2} \left(1 - \frac{\omega_{pe}^2}{\omega^2} \right) + \chi_{\alpha R} + \frac{i\sqrt{\pi}}{k \lambda_{de}^2} \frac{\omega}{k_z v_z} \exp\left(-\frac{\omega^2}{k_z^2 v_e^2}\right) \\ &+ \frac{i\sqrt{\pi}}{k \lambda_{di}^2} \frac{\omega}{k v_i} \exp\left(-\frac{\omega^2}{k^2 v_i^2}\right) - i\pi \frac{\omega_{p\alpha}^2}{k^2} \frac{dF}{du} \Big|_{\omega/k} = K_R(\vec{k}, \omega) + i K_I(\vec{k}, \omega) \end{aligned} \quad (6)$$

We have assumed Maxwellian distribution for the plasma electrons (v_e = electron thermal velocity) and ions (v_i = ion thermal velocity). $\lambda_{dj} = \omega_{pj}/v_j$ is the Debye length of the j -species. The three terms in $K_L(\vec{k}, \omega)$ correspond to wave damping due to electrons, ions, and alpha particles. The spectral power density of lower hybrid waves, which have the dispersion relation $\zeta_R(\vec{k}, \omega) = 0$, can be calculated from Eq. (1):

$$\begin{aligned}
P(\vec{k}, \omega) = & \frac{n_e e^2}{k_z k_\perp^2 \epsilon_0^2 \sqrt{\pi} v_e} \frac{\exp\left(-\omega^2/k_z^2 v_e^2\right)}{\left|K_1(\vec{k}, \omega)\right|^2} + \frac{n_i e_i^2}{k_\perp^3 \epsilon_0^2 \sqrt{\pi} v_i} \frac{\exp\left(-\omega^2/k_\perp^2 v_i^2\right)}{\left|K_1(\vec{k}, \omega)\right|^2} \\
& + \frac{n_\alpha e_\alpha^2}{k_\perp^3 \epsilon_0^2} \frac{F(u)|_{\omega/k}}{\left|K_1(\vec{k}, \omega)\right|^2} \quad (7)
\end{aligned}$$

In the parameter regime where $\omega/k_z v_e \gg 1$ and $\omega/k v_i \gg 1$, the electron and ion contributions to $P(\vec{k}, \omega)$ are exponentially small, and the alpha particle contribution can be dominant. Let us assume that the alpha particles have a slowing-down distribution, namely,

$$\begin{aligned}
f_\alpha(\vec{v}) = & \frac{F_0}{v^3 + v_c^3} \equiv \frac{F_0}{\left(v_\perp^2 + v_\parallel^2\right)^{3/2} + v_c^3}, \text{ when } 0 \leq v \leq v_\alpha \\
= & 0, \text{ otherwise}
\end{aligned}$$

v_α = velocity of 3.5 MeV alpha particles

$$v_c = \left(\frac{3\sqrt{\pi} m_e Z_1}{4 m_\alpha} \right)^{1/3} v_e, \quad Z_1 = \frac{n_i Z_i^2 m_\alpha}{n_e m_i} + \frac{n_\alpha Z_\alpha^2}{n_e}$$

v_c is the critical alpha particle velocity at which electron drag equals ion drag [13], and $F_0 = 3/[4\pi \ln(1 + v_\alpha^3/v_c^3)]$ is the normalization constant. The one-dimensional velocity distribution function can then be calculated from Eq. (4), which yields:

$$F(u) = -\frac{2\pi}{3} \frac{F_0}{v_c} \left\{ \frac{3}{2} \ln \left[\frac{(v_\alpha + v_c)/(v_\alpha^3 + v_c^3)^{1/3}}{(|u| + v_c)/(|u|^3 + v_c^3)^{1/3}} \right] + \sqrt{3} \tan^{-1} \left(\frac{\sqrt{3} v_\alpha}{v_\alpha - 2 v_c} \right) \right. \\ \left. - \sqrt{3} \tan^{-1} \left(\frac{\sqrt{3} |u|}{|u| - 2 v_c} \right) \right\} \quad (8)$$

It should be noted here that Eq. (8) is different from previously published results [6,14]. For the benefit of those who are interested in checking the algebra, the detailed steps are outlined in the Appendix. The spectral power density can be obtained by substitution of Eq. (8) into Eq. (7).

The purpose of the alpha particle diagnostic is to measure $f_\alpha(\vec{v})$ or its related quantities, for example, the alpha particle density, or other moments of $f_\alpha(\vec{v})$. It has been shown [5,6] that the one-dimensional alpha particle distribution function $F(u)$ can be obtained from the frequency spectrum of $S(\vec{k}, \omega)$ at one fixed value of $\vec{k}$ provided that k_z/k is large enough to avoid signals from lower hybrid wave fluctuations, which are much larger signals at small values of k_z/k . Here, we will show that these large signals can be used to obtain the same information provided that $f_\alpha(\vec{v})$ is isotropic. In a large reactor, $f_\alpha(\vec{v})$ is expected to be isotropic in the region where prompt orbit loss is not important, and the one-dimensional distribution function $F(u)$ would be independent of the direction of $\vec{k}$. Let us consider a schematic setup as shown in Fig. 1. The scattering angle θ is kept fixed while the scattered wave number $\vec{k}_s$ moves on a conical surface. The magnitude of $\vec{k}$ is kept fixed; this is realized experimentally by placing detectors on the circle shown in Fig. 1. Signals from different detectors correspond to different values of k_z/k while k is held fixed. With these values of k_z and k , the lower hybrid wave frequency ω can be calculated from the dispersion relation $K_R(\vec{k}, \omega) = 0$, and the signal from the detector measures the value of $P(\vec{k}, \omega)$ at a particular value of $u = \omega/k$. The array of detectors on the circle shown in Fig. 1 will determine $P(\vec{k}, \omega)$ over a range of u . Let us put $P(u) = P(\vec{k}, \omega)$ as a known function of u , then the one-dimensional distribution function $F(u)$ can be determined from Eq. (7). For the

general case in which lower hybrid wave damping by the bulk plasma is not entirely negligible, we have

$$K_I(\vec{k}, \omega) = \frac{\sqrt{\pi}}{k^2 \lambda_{de}^2} \frac{\omega}{k_z v_e} \exp\left(-\frac{\omega^2}{k_z^2 v_e^2}\right) + \frac{\sqrt{\pi}}{k^2 \lambda_{di}^2} \frac{\omega}{k v_i} \exp\left(-\frac{\omega^2}{k^2 v_i^2}\right) - \pi \frac{\omega_{p\alpha}^2}{k^2} \frac{dF}{du}$$

From the dispersion relation $K_R(\vec{k}, \omega) = 0$, ω/k_z and k_z can be expressed in terms of $\omega/k \equiv u$, and we can write $K_I(k, \omega)$ in the following form:

$$K_I(\vec{k}, \omega) = L_1(u) - \pi \frac{\omega_{p\alpha}^2}{k^2} \frac{dF}{du} \quad (9)$$

By the same token, Eq. (7) can be written as

$$P(u) = L_2(u) + \frac{n_\alpha e_\alpha^2}{k^3 \epsilon_0^2} \frac{F(u)}{[L_1(u) - \pi (\omega_{p\alpha}^2/k^2)(dF/du)]^2}$$

or

$$\pi \frac{\omega_{p\alpha}^2}{k^2} \frac{dF}{du} = L_1(u) - \left[\frac{n_\alpha e_\alpha^2}{k^3 \epsilon_0^2} \frac{F(u)}{P(u) - L_2(u)} \right]^{1/2} \quad (10)$$

Since $P(u)$, $L_1(u)$, and $L_2(u)$ are known functions of u , $F(u)$ can be solved by numerical methods.

As an illustration of the above scheme, let us consider the simple case where $\omega/k_z v_e \gg 1$ and $\omega/k v_i \gg 1$ such that Landau damping of the bulk plasma is negligible, then $L_1(u) \simeq 0$, $L_2(u) \simeq 0$, and Eq. (10) is reduced to

$$\pi \frac{\omega_{p\alpha}^2}{k^2} \frac{dF}{du} = - \left[\frac{n_\alpha e_\alpha^2}{k^2 \epsilon_0} \frac{F(u)}{P(u)} \right]^{1/2} \quad (11)$$

Equation (11) is integrable, and the solution is:

$$F(u) = \frac{C_1}{4} \left[\int \frac{du}{[P(u)]^{1/2}} + C_2 \right]^2,$$

where $C_1 = km_\alpha^2/\pi^2 n_\alpha e_\alpha^2$, and C_2 is the integration constant determined from the condition that $F(u) = 0$ for $u \geq v_\alpha$. Normalization of $F(u)$ will determine C_1 and n_α .

In summary, we have discovered a method to determine the one-dimensional alpha particle distribution function from collective scattering of lower hybrid wave fluctuations in the plasma. This method has the potential of substantial improvement in the signal-to-noise ratio, but it is applicable only when $f_\alpha(\vec{v})$ is isotropic, and it involves more complicated data analysis. Since this method employs the natural fluctuation of lower hybrid waves in the plasma interior, it should be better than the method of measuring the damping of externally launched lower hybrid waves [15] whose power spectrum can be altered by density fluctuations along the path of wave propagation. The spatial resolution should be comparable to the absorption length of lower hybrid waves, which is much less than the minor radius for tokamak plasmas close to thermonuclear ignition [8].

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APPENDIX

By putting the slow-down distribution function into Eq. (4), we obtain

$$\begin{aligned}
 F(u) &= \int_{-\infty}^{\infty} dv_{\parallel} \delta(u - v_{\parallel}) \int_0^{v_{\alpha}^2 + v_{\parallel}^2} \frac{\pi F_0 d (v_{\perp}^2)}{(v_{\perp}^2 + v_{\parallel}^2)^{3/2} + v_c^3} \\
 &= \int_{-\infty}^{\infty} dv_{\parallel} \delta(u - v_{\parallel}) \cdot \left(\frac{2}{3} \pi F_0 \right) \int_{|v_{\parallel}|^3 + v_c^3}^{v_{\alpha}^3 + v_c^3} \frac{dy}{y(y - v_c^3)^{1/3}} ,
 \end{aligned}$$

where $y = (v_{\perp}^2 + v_{\parallel}^2)^{3/2} + v_c^3$. From the integral table by Gradshteyn and Ryzhik [16], the integral over y can be carried out, and yield

$$\begin{aligned}
 F(u) &= \int_{-\infty}^{\infty} dv_{\parallel} \delta(u - v_{\parallel}) \left(-\frac{2\pi}{3} F_0 \right) \frac{1}{v_c} \left\{ \frac{3}{2} \ln \left[\frac{(y - v_c^3)^{1/3} + v_c}{y^{1/3}} \right] \right. \\
 &\quad \left. + \sqrt{3} \tan^{-1} \left[\frac{\sqrt{3}(y - v_c^3)^{1/3}}{(y - v_c^3)^{1/3} - 2v_c} \right] \right\} \bigg|_{|v_{\parallel}|^3 + v_c^3}^{v_{\alpha}^3 + v_c^3} \\
 &= -\frac{2\pi}{3} \frac{F_0}{v_c} \left\{ \frac{3}{2} \ln \left[\frac{(v_{\alpha} + v_c)/(v_{\alpha}^3 + v_c^3)^{1/3}}{(|u| + v_c)/(|u|^3 + v_c^3)^{1/3}} \right] \right. \\
 &\quad \left. + \sqrt{3} \tan^{-1} \left(\frac{\sqrt{3} v_{\alpha}}{v_{\alpha} - 2v_c} \right) - \sqrt{3} \tan^{-1} \left(\frac{\sqrt{3} |u|}{|u| - 2v_c} \right) \right\} .
 \end{aligned}$$

This differs from previous results apparently obtained by using a slow-down distribution for $v_{\perp}$ rather than v , which is incorrect. It should also be pointed out that there is a minor error in Gradshteyn and Ryzhik's integral table, formula (2.235). The first factor on the right-hand side should read $a^{-1/3}$ instead of $a^{-2/3}$.

REFERENCES

- [1] H. P. Furth, Bull. Am. Phys. Soc. 33 (1988) 1861.
- [2] S. J. Zweben, Rev. Sci. Instrum. 57 (1986) 1723.
- [3] D. P. Hutchinson, K. L. Vander Sluis, J. Sheffield, and D. J. Sigmar, Rev. Sci. Instrum. 56 (1985) 1075.
- [4] P. P. Woskov, J. S. Machuzak, R. C. Myer, D. Y. Rhee, D. R. Cohn, N. L. Bretz, P. C. Efthimion, and J. L. Doane, Bull. Am. Phys. Soc. 33 (1988) 2098.
- [5] L. Vahala, G. Vahala, and D. J. Sigmar, Nucl. Fusion 28 (1988) 1595.
- [6] T. P. Hughes and S. R. P. Smith, Nucl. Fusion 28 (1988) 1451.
- [7] I. H. Hutchinson, JET Joint Undertaking Report JET-R(87)07, Abingdon, Oxon, OX143 EA, UK.
- [8] K. L. Wong and M. Ono, Nucl. Fusion 24 (1984) 615.
- [9] G. Bekefi, Radiation Processes in Plasmas, John Wiley and Sons, Inc. (1966), p. 128.
- [10] T. H. Stix, Phys. Rev. Lett. 15 (1965) 878.
- [11] G. A. Wurden, K. L. Wong, F. Skiff, and M. Ono, Phys. Rev. Lett 50 (1983) 1779.
- [12] N. A. Krall and A. W. Trivelpiece, Principles of Plasma Physics, McGraw Hill, Inc. (1973), p. 382.
- [13] John D. Gaffey, Jr., J. Plasma Phys. 16 (1976) 149.
- [14] L. Vahala, G. Vahala, and D. J. Sigmar, Nucl. Fusion 26 (1986) 51.
- [15] K. L. Wong, Rev. Sci. Instrum. 56 (1985) 1073.
- [16] I. S. Gradshteyn and I. M. Ryzhik, Table of Integrals, Series and Products — Corrected and Enlarged Edition, Academic Press (1980), p. 75.

FIGURE CAPTION

Fig. 1. Schematic diagram of the scattering geometry. The incident beam has wave number $\vec{k}$ pointing vertically upward. The scattered beam has wave number $\vec{k}_s$ lying on a conical surface, i.e., the scattered angle θ and the magnitude of $\vec{k}$ ($k = k_s - k_i$) are held fixed.

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Figure 1

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