Spatially Resolved Measurement of Impurities and the Effective Charge $\bar{Z}$ in a Tokamak Plasma

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(Received 1 April 1974)

Laser-radiation scattering is proposed as a method for measuring impurities in tokamak or toroidal pinch plasmas. A direct measurement of the effective charge for momentum transfer, $\bar{Z}$, appears feasible by this technique.

The importance of plasma impurities to the outcome and interpretation of experiments on magnetically confined plasmas of the tokamak or toroidal pinch types is widely recognized. A large fraction of the energy input can be lost through radiation by impurity ions, while the increase in the plasma effective charge $\bar{Z}$ incurred by the addition of high-Z ions results in enhanced resistivity, and the impurity concentration affects the particle containment time.[1,2] Moreover, the possibility that heavy impurities will tend to diffuse inwards and collect on the axis of the discharge[3] has a critical effect upon the steady-state reactor concept, and emphasized the exceptional significance of a detailed study of impurity behavior. In this Letter we draw attention to the feasibility of performing a sensitive, spatially resolved measurement of impurity concentration which relies upon the influence of a small fraction of heavy, $Z > 1$ material on the frequency spectrum of laser radiation scattered by a plasma.[4]

Tokamak plasmas acquire heavy-ion impurities by evaporating limiter and wall material, giving rise to populations of, for example, molybdenum ($M=96$, $Z=42$) or tungsten ($M=184$, $Z=74$). These appear in the plasma as highly charged or even, at temperatures of several keV, as fully stripped ions.

The expression for the frequency distributions of collective fluctuations in a contaminated plasma, given in Ref. 4, has been evaluated for cases where the principal ion is deuterium and the impurity is fully stripped molybdenum or tungsten. Results of this calculation are shown in Fig. 1, where the abscissa x is the frequency shift $\Delta\omega$ normalized to the thermal spectrum width of the deuterium, kv_{deut}, and the parameter α is the usual ratio of scattering scale length to plasma Debye length. The heavy ions manifest themselves at the center of the ion feature as a narrow peak which remains detectable at levels of contamination as low as ten heavy ions per million deuterons.

It appears to be impossible to identify different species from their simultaneous contributions to a composite fluctuation spectrum. However, it turns out that the very important effective charge of the plasma for momentum transfer $\bar{Z}$, where

$$\bar{Z} = \sum Z_j^2 N_j / \sum Z_i N_i,$$

is susceptible to direct measurement in a scattering experiment. An examination of Eq. (3) of

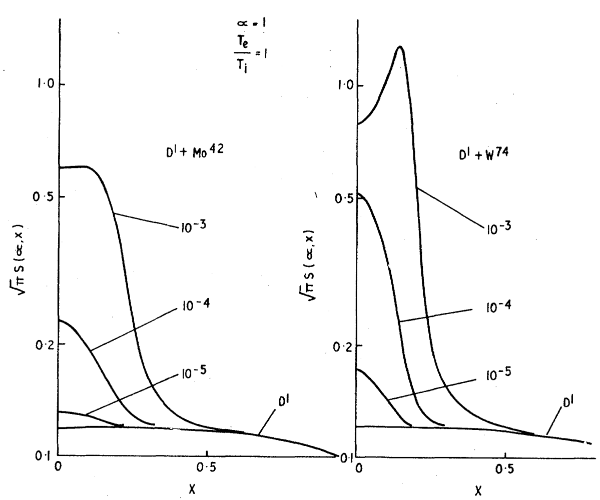

FIG. 1. Computed frequency distribution of collective electron fluctuations in deuterium plasmas containing fully stripped molybdenum or tungsten at concentrations 10^{-3}, 10^{-4}, and 10^{-5} times the deuterium particle density. Curves labeled D^1 refer to pure deuterium. $x = \Delta\omega / kv_{\text{deut}}$.

Ref. 4 modified to take account of electron drift and magnetic field reveals that, provided all ions have the same temperature T_i, the analytic expression for the scattering form factor of a plasma composed of a mixture of ionic species contains the effective charge $\bar{Z}$ explicitly when evaluated at the spectrum center ($x=0$):

$$\sqrt{\pi}\, S(\alpha, 0) = \left[a_e\left(\frac{g}{\cos\theta}\right)\left(\frac{1}{\alpha^2} + \frac{T_e}{T_i}\bar{Z}\right)^2 + \Gamma\right] \times \left[1 + \frac{1}{\alpha^2} + \frac{T_e}{T_i}\bar{Z}\right]^{-2},$$

where a_e is the ratio of thermal speeds of ions of the most abundant kind and the electrons,

$$g = \exp[-(\omega_{pe}/\omega_{ce})^2]\sin^2\theta/\alpha^2,$$

θ is the angle between the scattering vector $\vec{k}$ and the magnetic field $\vec{B}$, T_e is the electron temperature, and Γ is independent of α. Two scattering experiments performed at different values of α, i.e., at different scattering angles in the same plasma, eliminate Γ and allow the solution of the above equation for $\bar{Z}$ in terms of α_1, α_2, $S(\alpha_1, 0)$, and $S(\alpha_2, 0)$. Figure 2 shows spectra calculated for the contaminants reported for the hydrogen plasma of the Princeton University ST tokamak[5] at scattering angles corresponding to $\alpha_1 = 1.0$ and $\alpha_2 = 10$. The field factor $g/\cos\theta$ was set equal to unity. The effective charge is calculated from these distributions to be $\bar{Z} = 3.30$, in good agreement with the Princeton value.

The possibility that electron drift current may obscure the influence of impurity ions on the frequency spectrum has been investigated, as far as is possible within the linear theory of plasma density fluctuations, by introducing multiple ion species into the equation given by Boyd, Evans, and Gardner[6] for the dynamic form factor incorporating electron drift and magnetized electrons. Because the electron drift velocity v_D in a tokamak is not expected to exceed the ion thermal velocity v_i, and because the electron gyro frequency ω_{ce} is comparable with the plasma frequency ω_{pe}, the distortion of the spectrum by drift can be approximated, to first order in v_D/v_e (the drift velocity normalized to the electron thermal speed), by the expression

$$\frac{S(y)}{S(y=0)} \cong 1 + \frac{2\sqrt{\pi}D(v_D/v_e)}{(\cos\theta/g)[(A+1)^2 + D^2 + D^2] + 2\sqrt{\pi}a_e Dx},$$

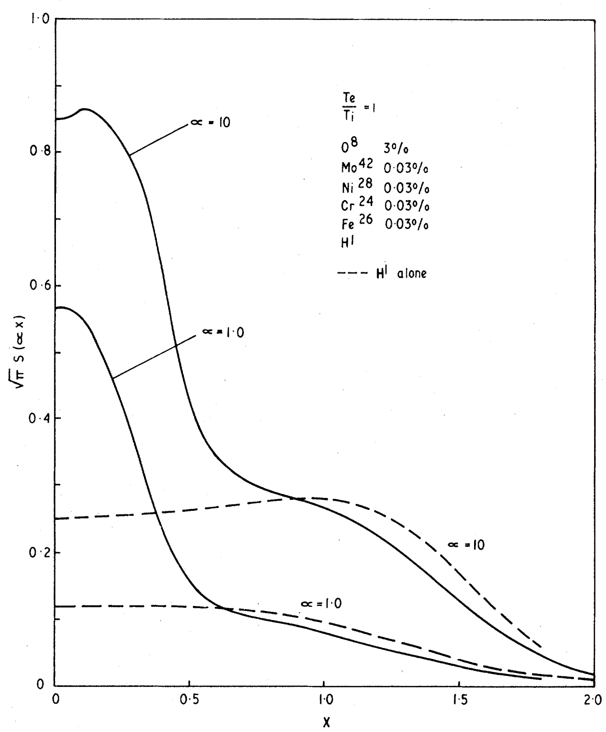

FIG. 2. Computed frequency distributions of collective electron fluctuations in hydrogen plasma with contaminants found in the Princeton University ST tokamak (Ref. 5). Concentrations given as fraction of hydrogen number density. Ions are assumed fully stripped. $\bar{Z} = 3.30$. Here $x = \Delta\omega/kv_{\text{hydro}}$.

where

$$A = \frac{1}{\alpha^2} + \frac{\sum_j Z_j^2 N_j}{\sum Z_i N_i}\frac{T_e}{T_j}R(a_j x),$$

$$D = \frac{\sum_j Z_j^2 N_j}{\sum Z_i N_i}\frac{T_e}{T_j}I(a_j x),$$

$$a_j = [(M_j/M_1)(T_1/T_j)]^{1/2}, \quad x = \omega/kv_i,$$

and eZ_j, M_j, N_j, and T_j are charge, mass, number density, and temperature of ions of the jth kind, respectively. $R(a_j x)$ and $I(a_j x)$ are real and imaginary parts of the plasma dispersion function.

This shows that, at least to first order in v_D/v_e, electron drift produces no distortion at the spectrum center ($x=0$) since $D(\arg = 0) = 0$, and also that drift distortion is asymmetric with respect to the center in contrast to the symmetric enhancement expected for impurity ions. Decreasing the magnetic field, or making the angle between the scattering vector $\vec{k}$ and magnetic field $\vec{B}$ depart from perpendicular, increases the field factor $\cos\theta/g$ and diminishes the enhancement produced by a fixed drift. Numerical examples demonstrate that the comparatively weak drift current expected in a tokamak has almost no effect unless $\vec{k}$ and $\vec{B}$ are nearly perpendicular. Thus with $v_D = v_i$ and $\theta = 0$, $S(y)/S(y=0) - 1 = 10^{-4}$ near the maximum ($x = 0.18$) of the spectrum of the deuterium plasma containing 10^{-3} Mo^{42} ions per deuteron shown in Fig. 1. Enhancement as large as 1% is achieved only when θ reaches 89.7°. Similarly, the drift perturbation of the ST tokamak spectrum illustrated in Fig. 2 was computed at $x = 0.2$ to be less than 2% if θ was less than 60°. So, provided $\vec{k}$ and $\vec{B}$ are far enough from perpendicular, the influence of electron drift on the ion feature expected for a tokamak plasma appears to be negligible compared with impurity effects.

Since the Debye length in a tokamak plasma is 75 to 100 μm, the laser needed to reach the required α values at scattering angles large enough to retain the spatial resolution inherent in scattered-light experiments might be either HCN, operating at 337 μm for which a pulsed power of 1 kW has been reported,[7] or CO_2-pumped methyl fluoride at 496 μm at a pulsed power of 30 kW.[8] In either case, heterodyne detection[9] would be obligatory.

We conclude that contamination of a hydrogen plasma by heavy, high-Z ions can be measured by collective scattering of laser radiation down to about 10 ppm. In contrast to conventional spectroscopy, fully stripped ions are detectable. Moreover, a correctly designed scattering experiment could measure the effective charge $\bar{Z}$ of the plasma directly. Within the approximations of the linear theory of fluctuations, electron drift of the strength expected in a tokamak has negligible effect on these conclusions, provided that the angle between the magnetic field and the scattering vector is sufficiently far from perpendicular. Spatial resolution, without recourse to Abel inversion, is a feature inherent in the scattering technique.

We are indebted to Dr. J. Sheffield for drawing our attention to this problem, and to Dr. A. Wootton for valuable comment.

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Ion Heating at Twice the Ion-Cyclotron Frequency in Reactor-Oriented Machines

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(Received 18 March 1974)

A systematic study is made of the efficiency of first-harmonic ion-cyclotron heating in hot, dense, large plasmas. Promising heating times are derived when the imposed axial wavelength satisfies the rather restrictive high-temperature, high-density limitation $k_z \geq \omega_{pi}^2 V_i \omega_{ci}^{-1} c^{-2}$.

Heating at the first harmonic of the ion-cyclotron frequency ($\omega = 2\omega_{ci}$) is considered to be one of the more attractive supplementary heating schemes for reaching ignition in large tori. As is well known,[1-3] this heating method depends upon the excitation of the fast hydromagnetic wave, whose electric field at $\omega = 2\omega_{ci}$ has an appreciable left-hand polarized component, i.e., in the