ularly reflected laser waves mix in the plasma atmosphere in front of a target, the results provide a direct indication that at the higher powers encountered in such studies the effect of nonlinear electromotive forces will be significant.

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Observation of Non-Maxwellian Electron Distribution Functions in the Alcator Device by Means of Thomson Scattering and Their Interpretation*

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In the Alcator device incoherent Thomson scattering always gives Gaussian spectral profiles at low values of the ratio of electron drift velocity to thermal velocity ($v_D/v_{\rm th} \lesssim 0.1$). However, at higher values of $v_D/v_{\rm th}$ non-Gaussian profiles are observed and can be interpreted in terms of scattering from electrons with high toroidal velocity (low-energy runaways). This interpretation is supported by soft-x-ray and plasma-resistivity measurements and agrees with a previous theoretical analysis.

The Alcator device[1,2] can produce plasma discharges with high values of $v_D/v_{\rm th}$ even at relatively low toroidal current and high plasma density. Typically $v_D/v_{\rm th}=0.3$ for $I=100$ kA and $\bar{n}=2\times10^{13}$ cm^{-3}. In this machine incoherent 90° Thomson scattering is effected by sending in the laser beam vertically and collecting scattered radiation radially[3]; therefore, the scattering vector[4] $\vec{k}$ is in the meridian plane and only the distribution of transverse velocity is measured as shown in Fig. 1. Indeed, if v_k is the velocity component parallel to $\vec{k}$ and v_T and $v_\perp$ are the two other orthogonal velocity components and if the electron distribution function is $f(v_k, v_T, v_\perp)$,

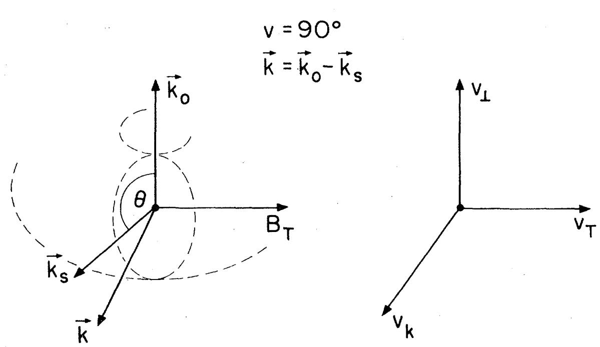

FIG. 1. Scattering geometry for the Alcator device ($\vec{k}_0$, incident light vector; $\vec{k}_\perp$, scattered light vector), and phase space.

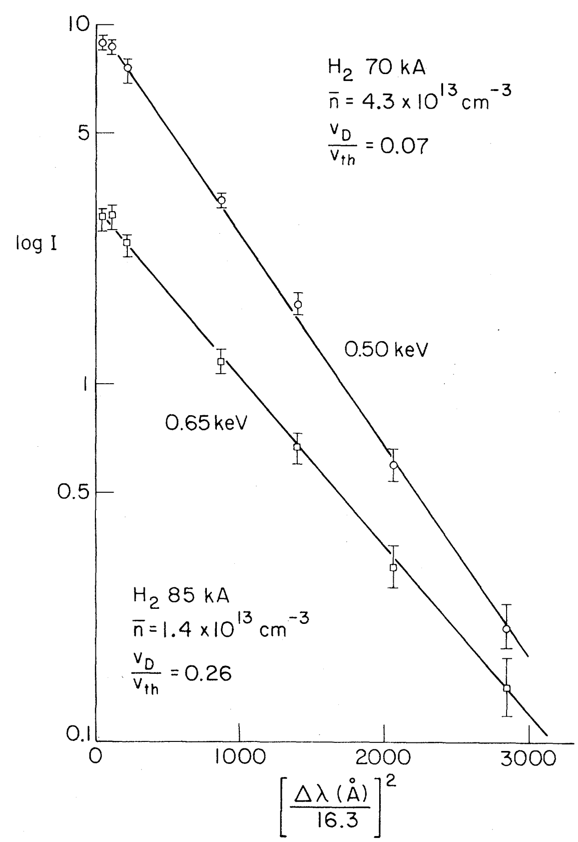

FIG. 2. Spectra of scattered radiation measured at times during the discharge ranging from 15 to 50 msec.

then the spectrum of scattered radiation is given by $g(\omega)=\int\int dv_\perp\, dv_T\, f(\omega/k,\, v_T,\, v_\perp)$. The measurements reported here were all made at the center of the discharge. The radiation is analyzed by means of a grating spectrograph and detected by a set of seven photomultipliers. Only the blue ring of the scattered spectra is measured. Stray laser light is negligible (< 5% at the lowest densities) for all channels and the plasma light intensity is small and is subtracted from each channel signal. The photomultipliers used are accurately calibrated[3] by a combination of a tungsten ribbon lamp and a red-light–emitting diode.

Typical measured spectra of the scattered radiation I are shown in Figs. 2, 3, and 4, where log$I$ is plotted as a function of the square of the wavelength shift, $\Delta\lambda^2$.[5] At small values of $v_D/v_{\rm th}$ ($v_D/v_{\rm th} \lesssim 0.1$) the spectrum is always Gaussian as in Fig. 1, indicating a Maxwellian distribution function. At larger $v_D/v_{\rm th}$ the spectrum is sometimes Gaussian (see Fig. 2), but on most discharges, even considering experimental errors, it is certainly not Gaussian. Typical spectra obtained at larger $v_D/v_{\rm th}$ are shown in Figs. 3 and 4. The spectra of Fig. 3 can be derived from the sum of two Maxwellian distribution functions with different transverse temperatures as is indicated in Fig. 5 for one of these spectra. The spectra of Fig. 4 can be derived from the sum of a low-transverse-temperature Maxwellian distribution function and a non-Maxwellian distribution function of higher average energy.

We interpret the low-transverse-temperature component to represent scattering from electrons with high toroidal velocity (energies of a few keV) and low transverse velocity, which are a large fraction of the total number. The presence of such mildly runaway (or slideaway) electrons at lower densities is suggested by the soft-x-ray measurements[2] which, at these densities, give electron "temperatures" about twice those obtained from Thomson scattering. Furthermore, measurements of resistivity show that, above a value of $v_D/v_{\rm th}$ of the order of 0.1, the ratio of measured resistivity to Spitzer resis-

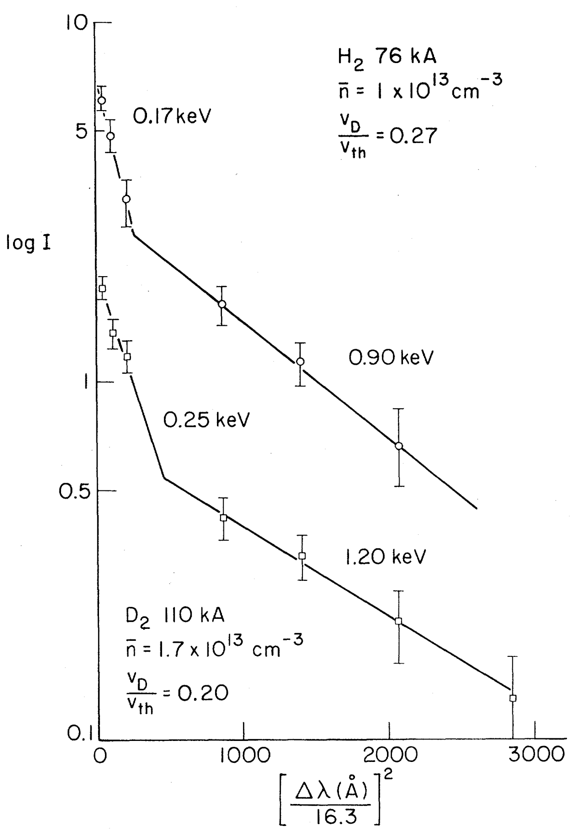

FIG. 3. Spectra of scattered radiation measured at times during the discharge ranging from 15 to 50 msec.

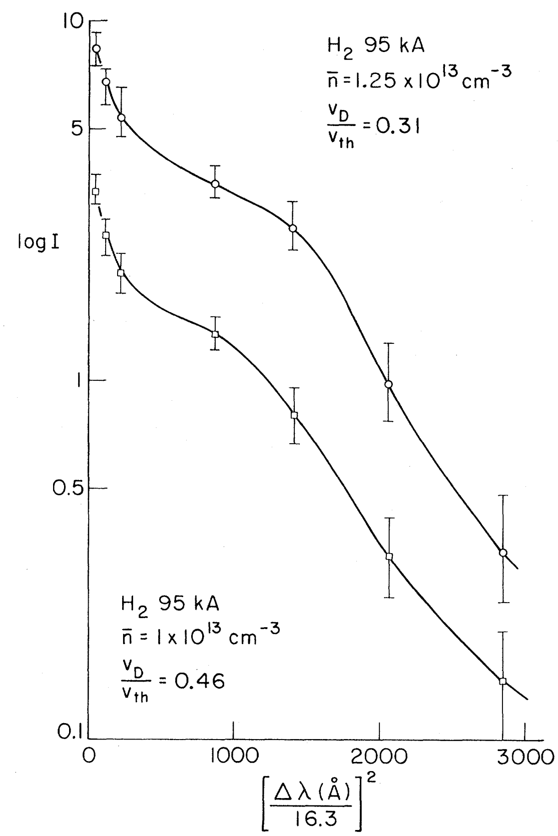

FIG. 4. Spectra of scattered radiation measured at times during the discharge ranging from 15 to 50 msec.

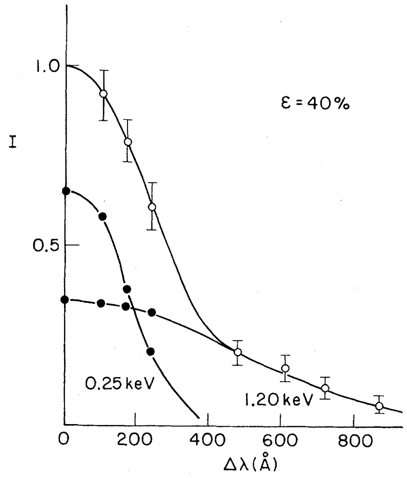

FIG. 5. Linear representation of one of the spectra shown in Fig. 3, assuming that the scattered radiation is due to electrons belonging to two Maxwellian distribution functions.

tivity for H_2 and D_2 deviates from unity, indicating a modification in the number and average energy of current-carrying electrons.[6]

The existence of such a slideaway regime for large values of v_D/v_{th} has been discussed theoretically at some length.[7] It is to be expected that the spread in transverse velocities and hence the transverse temperature of the slideaway electrons should be small since they originate from preferential acceleration of those electrons from the bulk of the plasma which already have higher toroidal velocities (untrapped electrons) and hence are less affected by collisions.

By integrating the curves for the two components of Fig. 4, we can determine the fraction ϵ of slideaway electrons to be 40%. For $0.2 < v_D/v_{th} < 0.5$ we find values in the range $25\% < \epsilon < 40\%$. This confirms the theoretical expectation[7] that a large fraction of the electrons should be affected.

The fact that the high-"transverse"-energy components of Figs. 3 and 4 are, respectively, Maxwellian and non-Maxwellian shows that when the slideaway regime occurs, the bulk of the plasma electrons may also deviate strongly from a Maxwellian distribution.

Finally, we wish to point out that, while Thomson scattering with $\vec{k}$ in the toroidal direction gives complete information on the toroidal velocity distribution, even with $\vec{k}$ in the meridian plane, as this Letter shows, information can be obtained on electrons not belonging to the main Maxwellian.

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