APPARENT HIGH-FREQUENCY STABILITY OF A HIGHLY ANISOTROPIC PLASMA*

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Many of the experiments designed for the production of energetic plasmas have exhibited intense rf emission at the ion-cyclotron frequency and its harmonics.[1] In most of the theoretical attempts to explain the origin of the associated electric fields, the anisotropy of the trapped-proton velocity distribution plays a significant role. In DCX-2 it has been determined that, under certain controllable operating conditions, a highly anisotropic plasma is produced as a result of an instability among the injected particles. This plasma may be used to test these theories. Recently, this plasma has been produced with gas dissociation, and is found to be free from rf radiation after the input beam has been turned off. The plasma density has been found to exceed significantly the highest instability threshold predictions of the theory of Soper and Harris[2] or that of Guest and Dory[3] which is more closely tailored to the experiment.

The plasma in DCX-2 is produced by injecting 540-keV molecular ions and accumulating the dissociated 270-keV protons between magnetic mirror coils spaced 164 inches apart.[4] The mirror ratio is 3.3:1. The intervening field is uniform at 11.4 kG except for a slight (but essential) depression in the central 60 inches, which traps the plasma to be discussed below. The beam current in these experiments averages 35 mA over the beam duration (~ 0.5 sec). The neutral hydrogen pressure required to produce the instability which results in the anisotropic plasma is $(1\text{-}5)\times 10^{-6}$ Torr.

Charge-exchange neutrals, from collisions of the trapped energetic protons with the particles of the background gas, are detected in energy-sensitive barrier detectors at the vacuum wall. The detectors are collimated to view particles emitted in a vertical fan of ±20° with a 0.1° horizontal (parallel to the field) acceptance angle. Horizontal angles to ±30° are scanned during successive beam-on intervals. In Fig. 1, we show the distribution of charge-exchange particles as a function of this angle, or equivalently, of the pitch angle of the helical trajectory of the protons. The strong central peak centered at 0° corresponds to a group of particles with an average density of $\sim 1\times 10^8$ ions/cm^3 (volume of 7.5×10^4 cm^3) trapped in a very shallow mirror (mirror ratio approximately 1.001) produced in the central region of the DCX-2 magnetic field. The energy distribution of these particles has been measured and is shown in Fig. 2. From the observed distribution, the ratio of the perpendicular to parallel "temperatures" is 10^3. The particles constitute a highly anisotropic plasma ("central-peak plasma") which, after the injected beam is off, is suprisingly stable against mi-

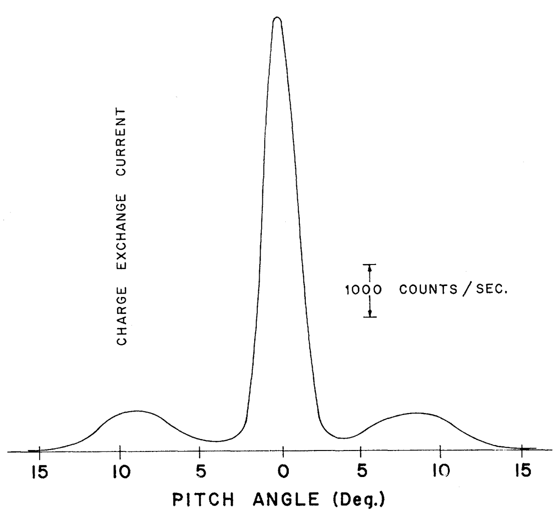

FIG. 1. Counting rate of charge-exchange neutral particles to a collimated silicon-barrier detector as a function of pitch angle of the trapped proton in its helical trajectory.

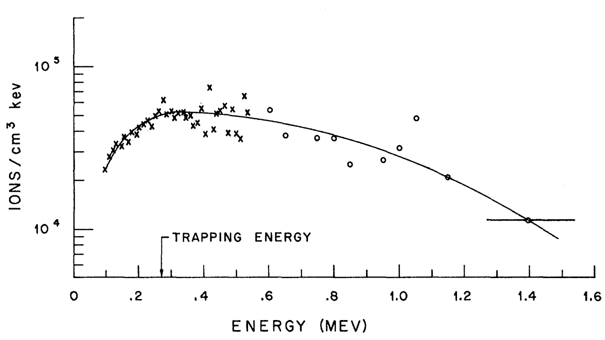

FIG. 2. Energy spectrum of trapped protons as determined from the charge-exchange neutral particles reaching the collimated detector scanned across the central-peak plasma. The points above 600 keV represent averages over a number of data values. Note the spread in energy about the trapping energy of 270 keV.

croinstabilities at ion cyclotron harmonics.

Electrostatic probes sensitive to radial electric fields are used to determine the frequency spectrum of electric fields seen at the walls of the vacuum chamber. Intense radiation is seen at the H_2^+ and H^+ cyclotron harmonics when the beam is on. However, these fields decay rapidly to noise (a change of more than 40 dB) in about a millisecond after the beam is cut off although the energetic ion plasma has not changed appreciably in this time. The density decay indicates that half of the particles remain after 0.25 sec. The measurement of density from the energy spectrum during equilibrium yields the same value as the integral of the charge-exchange flux after the beam is shut off implying that all of the losses during the decay are by charge exchange. An array of neutral-particle detectors gives no evidence for spread of the fast protons along the field after the beam is off.[5]

The velocity-space distribution of the central-peak plasma is rather closely modeled by the theory of Guest and Dory. This theory predicts that in an infinite homogeneous plasma of anisotropic fast ions and cold (less than 100 eV) plasma, waves at the Nth harmonic of the ion gyrofrequency will grow if $(T_{\parallel}/T_{\perp})_{\text{ions}}$ is sufficiently low and $\omega_{pe}/\omega_{ci}>N$. The observed anisotropy is enough to permit ~500 harmonics to grow; the density should limit this number to ~5. The absence of all rf fields implies that the actual threshold density is at least 40 times greater than that predicted from infinite-medium theory.

For a more plausible comparison with experiment, one can attempt to simulate the effect of the finite size of the laboratory plasma[2,3,6] by setting lower bounds on the components of the wave vector k, and using the infinite-medium theory. Thus we require $k_{\perp}R \gtrsim \pi$ and $k_{\parallel}L \gtrsim \pi$, where R and L are the radius and length of the plasma. For $R \approx 15$ cm the criterion for instability becomes $(\omega_{pe}/\omega_{ci})_{\text{threshold}} > 2$ for $N = 1$. The length of the central-peak plasma in DCX-2 is ≈100 cm, which is about 5 times the minimum length required for a standing wave at the fundamental frequency. The experimental value of ω_{pe}/ω_{ci} is greater than 7, assuming the electron density equals the total ion density. There is experimental evidence that this value is a considerable underestimate.

This result shows that the finite size of the plasma has a strong effect on threshold densities; the corrections just discussed change the predictions by a factor of 4. The apparent stability at densities approximately an order of magnitude greater than the amended predictions may reflect either the approximate nature of the simulation above or the influence of additional effects of the finite size. In particular, the instabilities discussed in the theory are likely to be convective so that reflection, transmission, or damping processes at boundaries of the plasma may substantially alter the stability.

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[1]See, for example, Proceedings of the International Conference on Controlled Thermonuclear Reactions, Culham, 1965 (to be published).

[2]G. K. Soper and E. G. Harris, Phys. Fluids 8, 984 (1965).

[3]G. E. Guest and R. A. Dory, Phys. Fluids 8, 1853 (1965).

[4]P. R. Bell et al., Thermonuclear Division Semiannual Progress Report, Oak Ridge National Laboratory Report No. ORNL-3908, 31 October 1965 (unpublished); Nucl. Fusion, Suppl. I, 251 (1961); Proceedings of the International Conference on Controlled Thermonuclear Reactions, Culham, CN 21/112, 1965 (to be published).

[5]Similar stability after beam cutoff has been observed in DCX-1 [cf. J. L. Dunlap et al., Phys. Fluids 9, 199 (1966)], but in that case the stability is in accord with theory, in view of the relatively short length of the plasma.

[6]Laurence S. Hall, Warren Heckrotte, and Terry Kammash, Phys. Rev. 139, A1117 (1965).