ENERGETIC PLASMA LOSSES DUE TO MICROINSTABILITIES*

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With flute instabilities apparently under control,[1,2] microinstabilities at ion gyrofrequency and above remain as a major threat to magnetic mirror confinement of thermonuclear plasmas. Such instabilities have long been observed in hot plasmas,[2-4] and one recent experiment[2] reported particle losses possibly associated with them. Here we shall report the definite observation of significant particle losses attributable to microinstabilities in a hot-ion plasma. We detect radio-frequency signals at $\omega \geqslant \omega_{ci}$. We detect energetic ion ejection radially and axially, and the radio-frequency signals and ion losses are correlated. Furthermore, the effect is gross, for the losses depress the ion density an order of magnitude. We have excluded other explanations for the observations, such as flutes, which are absent, and certain possibilities not associated with instability.

The basic experimental apparatus, the DCX-1 facility, has been described in detail elsewhere.[4] Briefly, a plasma with a volume of 2-10 liters and a very energetic (≈300 keV) proton component is formed by dissociation of part of a 600-keV H_2^+ beam that makes a single transit through a 2:1 magnetic mirror field. The central field value is 10 kG, the proton equilibrium orbit radius is 3.25 in., and the closest approach of the molecular ion beam to the magnetic axis is also 3.25 in. The radius of the fast-proton plasma (R) is determined by the position of the closest radial obstruction and is usually 8 to 9 in. Titanium evaporation onto liquid-nitrogen-cooled surfaces permits operation at pressures in the plasma chamber down to 1×10^{-9} Torr.

In these experiments, the plasmas were established by Lorentz-force dissociation of the molecular ion beam.[5] For this trapping mechanism, the initial radial hot-ion density distribution varies smoothly from a peak near $r = 0$ to zero at R. This distribution is quite unlike the proton ring of earlier experiments in which an arc discharge was used for dissociation.[6]

Since instability losses are observed, we first want to make it clear that flute instabilities are not present and thus that flutes cannot be blamed for the ion losses. At pressures $<1\times10^{-8}$ Torr there is a low-frequency disturbance, 3 to 200 kc/sec, most prominent on electrostatic probes and also observed on slow-plasma collectors located outside the mirrors. The disturbance occurs in the absence of instability losses, and the level of these losses varies in response to microinstabilities though the level of low-frequency disturbance remains about constant. Observations of the low-frequency disturbance are complex and are given in detail elsewhere.[7] It is probably a cold-plasma phenomenon, for an interpretation as flutes involving hot ions is ruled out by at least two observations. First, the phase relations between azimuthally displaced electrostatic probes and also between azimuthally displaced slow-plasma collectors do not permit interpretation as a disturbance in simple azimuthal rotation. Secondly, the prominent low-frequency signal at the electrostatic probe is almost surely due to charge fluctuations in cold plasma near the probe and not to energetic protons. These protons are several inches away from the probe. If they were responsible for the low-frequency signals, under conditions of maximum signal amplitude the corresponding potential fluctuations in the hot-plasma region would be hundreds of volts. This value is grossly inconsistent with potential measurements made in the hot-ion region with a lithium-ion-beam probe.[8] For under these conditions of maximum low-frequency signal amplitude, the lithium-ion beam shows the fluctuations of plasma potential to be less than 20 volts.

As in other hot-ion plasmas, electron-capture collisions of trapped protons with background gas provides a natural diagnostic system. These charge-exchange losses are monitored by a longitudinal array of fast atom detectors (foil-covered Faraday cups and/or secondary-emission detectors) mounted at intervals in Z outside the periphery of the plasma so as to yield the Z distribution of charge-exchange losses. The time for the charge-exchange current to decay to $1/e$ of the steady state value after molecular ion injection ceases is defined as the charge-exchange decay time (τ_d). The integral of the decaying charge-exchange current over Z, θ, and t gives a minimum value for the total number of protons trapped in steady state.

If losses other than charge exchange are insignificant during the decay interval, the minimum value from the Z, θ, t integral is the actual value of the total number trapped, and τ_d is the mean lifetime for steady-state confinement against charge-exchange losses.[9] Fortunately, our experiment meets this condition, for even with significant microinstability-driven losses in steady state, the instabilities persist only very briefly after injection ceases and charge-enchange losses completely dominate during the decay.

Microinstability losses result in a trapped proton population significantly less than that expected for charge exchange alone. The magnitude of these losses is the difference between the number of protons actually accumulated (from the Z, θ, t integral) and that permitted by charge exchange (the product of the proton input current and τ_d). With a fixed molecular ion current, the latter varies as τ_d since Lorentz-force dissociation then provides a constant proton input current.[5] A number of ancillary experiments have excluded other explanations for the difference (such as axial scattering beyond the neutral detector array) not associated with instability losses.

The results of a typical experimental run are given in Fig. 1, which shows the number of protons accumulated (N) as a function of τ_d, the latter being controlled by a helium gas leak. The accumulation up to about 1×10^{12} is limited by charge exchange (N varies as τ_d), but instability losses then set in and N saturates at less than 2×10^{12}, about 20% of the value permitted by the charge-exchange limitation. The saturation value has consistently been $(1\times2)\times10^{12}$, and in some cases has been only 10% of the number permitted by charge exchange.

The central fast-proton density, the average density in the vicinity of the median plane, saturates at $(1\text{-}2)\times10^{8}$ cm^{-3}. By way of comparison, the central density expected for loss charge exchange at the longest τ_d point of Fig. 1 was 2×10^{9} cm^{-3}. Part of this depression of central density results from instability-driven axial expansion of the plasma.

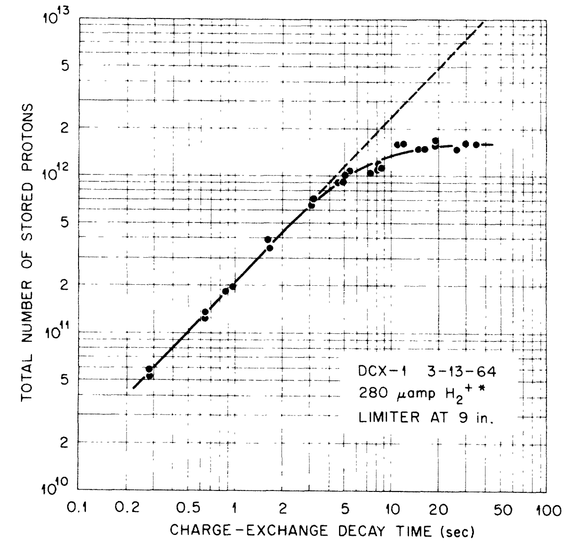

FIG. 1. Total number of stored protons as a function of charge-exchange decay time. The broken line represents the number expected for loss only by charge exchange. The plasma was established by Lorentz dissociation of a 280-μA H_2^+ beam and had a radius of 9 in.

Radial and axial losses of protons are correlated with radio-frequency signals from microinstabilities. Present data indicate that radial losses dominate by about an order of magnitude. Radial losses are observed with fast-proton current detectors mounted in the median plane so as to constitute the obstruc-

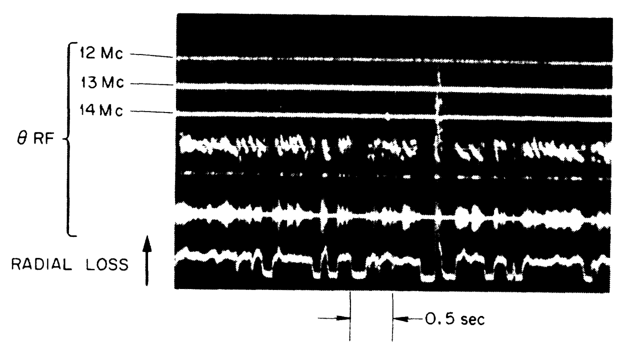

FIG. 2. Simultaneous recordings of the magnetic probe signal (dB_Z/dt) from the microinstability and radial fast-proton losses. The time-resolved frequency spectrum of the rf signal is given (in the upper 4 cm) with marker frequencies at 12, 13, and 14 Mc/sec. The diminished frequency mode occurred only once in this exposure, at 6 cm. The trace 5 cm from the top is the oscilloscope display of the rf signal. The plasma was established by Lorentz dissociation of a 460-μA H_2^+ beam at a pressure which gave $\tau_d = 6\frac{1}{2}$ sec.

tion that determines the radius of the fast-proton plasma. Figure 2 is an example of the correlation of these losses with magnetic-probe signals (dB_Z/dt) near the proton-cyclotron frequency.

The magnetic probe signals are dominated by a microinstability having two distinct modes. One, termed the gyrofrequency mode, generates signals at frequencies (≈15 Mc/sec) appropriate for proton-cyclotron rotation near the equilibrium orbit. The radio-frequency signals from the second mode, termed the diminished frequency mode, are lower by 1-2 Mc/sec. Most of the losses are due to the gyrofrequency mode.

We have not been able to make unique mode assignments for the microinstabilities. The negative mass,[10] drift cyclotron ($k_{11} \neq 0$),[11] maser ($k_{11} \neq 0$),[12] and Harris[13] ($k_{11} \neq 0$) instabilities are the theoretically recognized possibilities.

A complete report of the microinstability limitations of this plasma is in preparation.

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PHASE COHERENCE AND STABILITY OF HELIUM II IN NARROW CHANNELS*

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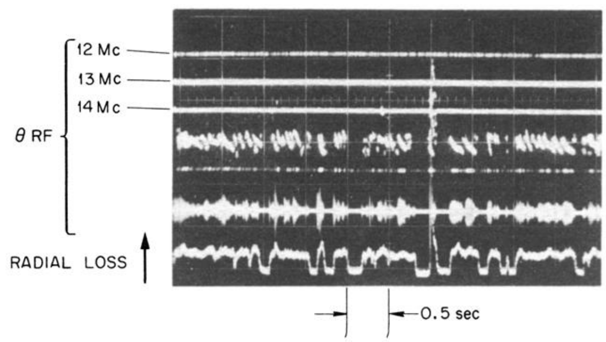
There has been considerable interest recently in exploring analogies between superconductivity and superfluidity. In particular, Richards and Anderson[1] have been able to observe the analog of the ac Josephson effect at a small orifice connecting two baths of helium II. The purpose of this communication is to study the flow of superfluid through narrow channels, narrow in the sense that the normal fluid is effectively clamped by its viscosity.

Consider first the situation illustrated in Fig. 1 where the flow of the saturated film is considered as one example of a narrow channel. Beliaev[2] has shown that the order parameter for



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