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ENERGY SPREADING AND STABILISATION OF PLASMA BY APPLICATION OF A HIGH FREQUENCY ELECTRIC FIELD

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ENERGY SPREADING AND STABILISATION OF PLASMA BY APPLICATION OF A HIGH FREQUENCY ELECTRIC FIELD

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A B S T R A C T

The ion cyclotron instabilities in the PHOENIX high energy injection mirror machine have been suppressed by applying oscillating electric fields. Two instabilities appear to be present. One is suppressed by energy spreading and the suppression of the other appears to be due to the effect of the applied electric fields on the electrons.

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Even though the very serious flute instability has been successfully eliminated in mirror systems by the introduction of magnetic well geometry, most of the high energy injection mirror machines are still suffering from microinstabilities characterised by electric and magnetic field fluctuations at frequencies at or above the ion gyrofrequency ω_i. These are expected to arise from deviations of the velocity distribution function, $f(v_\perp, v_\parallel)$, from the Maxwellian. In general, when a plasma is formed by Lorentz trapping of neutral beams, it is highly anisotropic in that $\langle v_\perp^2 \rangle \gg \langle v_\parallel^2 \rangle$ where $\langle v_\perp^2 \rangle$ and $\langle v_\parallel^2 \rangle$ denote average perpendicular and parallel energy respectively relative to the magnetic field. Such a distribution is expected to give rise to the Harris instability(1). If the injected beam is monoenergetic, the velocity distribution function can be highly peaked in $v_\perp$ at least for $v_\parallel = 0$. The consequent positive slope $\left(\frac{\partial f}{\partial v_\perp^2}\right)_{v_\parallel} > 0$ can give rise to further instabilities such as the type A ion-electron instability of Hall et al.(2), and the ion cyclotron drift instability(3). Even in collisional equilibrium, the presence of a loss cone in the mirror system means that $f(0, v_\parallel) = 0$ and $\frac{\partial f}{\partial v_\perp^2}$ is necessarily positive for a region near $v_\perp = 0$(4). In addition, the monoenergetic injection combined with the radial decrease of the magnetic field in simple mirror geometry make a negative mass type of instability(5) possible. Although all these instabilities differ in their growth rates, wave numbers, and frequencies, the absolute values are not accurately known for finite systems and therefore cannot serve as a reliable basis of identification. However, they all arise from some features of the ion velocity distribution and by varying these independently one can determine the dominant feature. In this experiment we varied the width of the energy distribution by the application of an external high frequency electric field without affecting the anisotropy considerably. A similar method of energy spreading was used on DCX1(6).

The plasma was formed in the Phoenix IA(7) device by Lorentz trapping of a 20 kV neutral H^0 beam injected perpendicular to the axis of the simple mirror field. The resulting plasma was highly anisotropic with $\langle v_\perp^2 \rangle / \langle v_\parallel^2 \rangle \approx 75$ and $f(v_\perp, v_\parallel)$ having a maximum at $v_\perp = 2.0 \times 10^8$ cm sec^{-1}. The flute instability limited the density to 3×10^8 cm^{-3}; the radial density distribution decreased slowly from the axis to 7 cm, where it was mechanically limited by a probe. The axial extent of the plasma was $\pm$ 4 cm with a full width at half maximum of about 2 cm. The oscillating electric fields were produced by applying a filtered noise signal to a copper electrode at 8 cm radius. The electric field was mainly transverse to the magnetic axis although some parallel component could not be avoided. However, the effect of the parallel field on ion motion was small as the applied frequency ($\approx$ 20 MHz) was much larger than the axial oscillation frequency ($\approx$ 3 MHz).

The microinstability in Phoenix IA[8,9] is characterised by signals at the ion-cyclotron frequency and its harmonics received on a pair of loop antennae[10]. The strongest signals are generated by azimuthal currents (θ-mode) which occur in repetitive bursts lasting 10 to 100 msec and starting at a frequency ω_{oi} corresponding to the ion gyro-frequency on the magnetic axis in the median plane. The frequency decreases monotonically in time until it corresponds to the ion gyro-frequency at 5 cm radius (a drop of 10%). Considerable energy spreading of the trapped protons has been observed to coincide with the high frequency signals[11].

Simultaneously with the start of the θ-mode there was usually a Z-mode corresponding to axial currents, the Z-activity was of shorter duration and had a correspondingly smaller frequency sweep.

Applying the oscillating electric field, with a centre frequency $\omega_{ext} = \omega_{oi}$ and a full width at half maximum of 5%, suppressed the θ-activity when the peak to peak voltage exceeded a threshold of 100 V. The resonant nature of the suppression is shown in Fig.1(a) where it can be seen that the θ-mode is suppressed only at frequencies within a narrow band around the applied frequency. The local nature of the instability is illustrated by the single frequency character of the activity at any instant and is further emphasised by the curtailment of the frequency sweeps when they approach the applied frequency band.

With an applied amplitude of 1000 V, it was possible to suppress the θ-mode in other bands above and below ω_{oi} without appreciably changing the energy spread and anisotropy. A and B on Fig.1(b) are examples of such bands.

Over limited regimes of gas pressure and applied frequency, θ-activity was induced in an otherwise stable plasma.

Suppression of the Z-activity was investigated and it was found that it could be quenched over a wide range of frequencies (3 MHz to 22 MHz were used).

Information on the energy distribution of ions was inferred from measurements on charge exchange neutrals. An electrostatic energy analyser[12] in the median plane was collimated to accept particles with $v_{\parallel} \approx 0$. This yielded the energy distribution $v_{\perp}f(v_{\perp},0)$ against $v_{\perp}^2$, where $f(v_{\perp},v_{\parallel})$ is defined in the usual way so that particle density is $2\pi \int_{-\infty}^{+\infty}\int_{0}^{+\infty} f(v_{\perp},v_{\parallel})\, v_{\perp}dv_{\perp}dv_{\parallel}$. Fig.2 shows such energy spectra for one low density stable case 2(a), and three high density cases with different amplitudes of external electric field at a frequency $\omega_{ext} = \omega_{oi} = 22$ MHz. Each spectrum is integrated over 3 seconds at constant magnetic field. Fig.2(c) shows the naturally unstable case with no applied field; the energy spread is three times that of the stable case. From 2(d) it can be seen that when the amplitude of the applied high frequency field has just reached the threshold for suppression the resultant induced energy spread equals that normally produced by the instability. It appears therefore that energy spreading is a significant factor in limiting the growth of the instability. Furthermore, experiments with stable and unstable plasma using various frequencies of applied field show that it is the energy spreading at the centre of the plasma that is important.

Although the evidence seems to indicate strongly that the mechanism of suppression of the instability is spreading of $v_{\perp}$, it is necessary to examine the changes in other plasma parameters when the external field is applied. These include changes in the ion velocity anisotropy and the electron energy distribution. Changes in anisotropy were measured using an array of collimated neutral particle detectors. In no case did the anisotropy deviate from the mean value $\langle v_{\perp}^2\rangle/\langle v_{\parallel}^2\rangle = 75$ by more than 15%. There was no obvious correlation between stabilisation and the small anisotropy changes.

Whenever electric fields are applied there are changes in the electron energy distribution as evidenced for instance by changes in plasma potential. Although this may account for suppression of the Z-mode the strongly resonant character of θ-mode suppression suggests rather an association with changes in the ion velocity distribution.

Finally measurement of plasma density (using the slow ion current collected at an end plate) showed that there was no particle loss due to the applied field and that the flute instability remained the sole limitation on density. It was also established that there was no particle loss due to the external field from a low density stable plasma produced by lowering the injection current.

The likely candidates for the observed instabilities are the Hall et al.[2] type (A) instability due to $\left(\frac{\partial f}{\partial v_\perp^2}\right) > 0$, the type (B) (Harris) instability due to anisotropy, and the negative mass instability. The first two are of the electron-ion type and rely on electrons for creation of electric fields while the third one does not. A large electron contribution requires the instability frequency to be close to the longitudinal electron frequency. In mirror geometry the latter will be a combination of a modified plasma frequency and the natural frequency in the magnetic and electrostatic potentials. Such an instability should then be sensitive to changes in the plasma potential and electron temperature.

The effect of the applied fields on the two observed modes (Z and θ) is very different. The first one is easily suppressed over a range of frequencies without necessarily affecting the ion velocity distribution significantly. Since the large axial currents accompanying it can be plausibly attributed to electrons, the suppression is probably due to changes in plasma potential. All this suggests an electron-ion instability for the Z-mode.

The θ-mode, on the other hand, can exist without measurable Z-currents, and requires a spread in perpendicular energy for suppression; recent measurements have shown that this mode disappears in magnetic well geometry[13]. The principal candidate for this mode is therefore the negative mass instability.

Though it does not rely on electrons, it could conceivably be affected by them under conditions of resonance and this may explain the suppression of θ-activity in bands above and below ω_{oi}.

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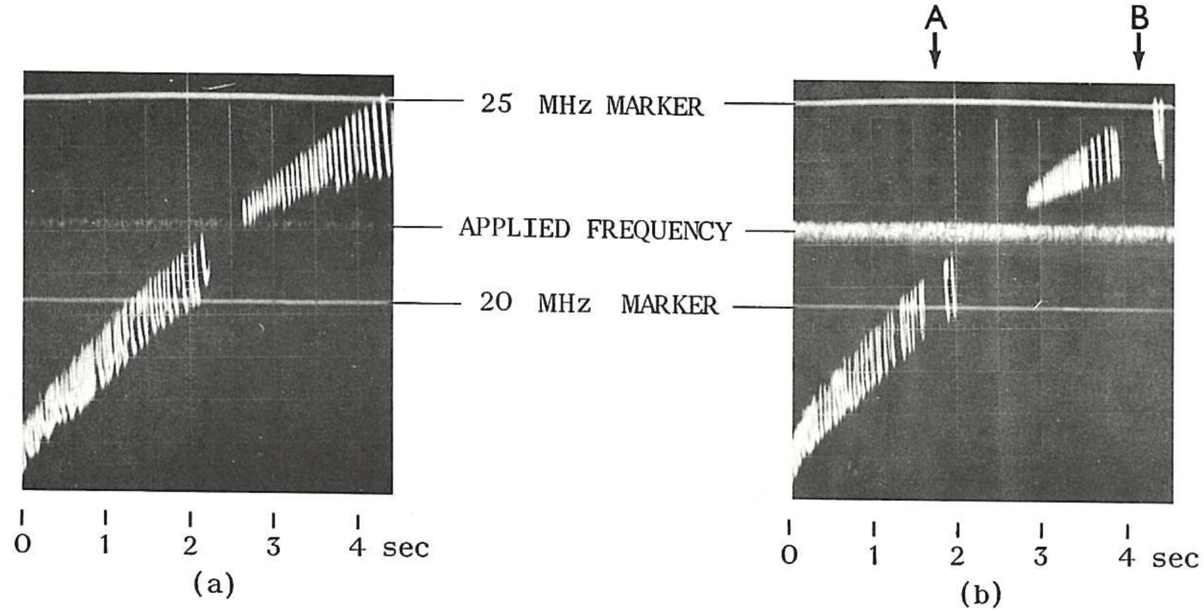

Fig. 1

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Time resolved frequency spectra of theta-activity. Magnetic field (and ω_i) increases with time. The applied frequency is constant. (a) Applied amplitude = 100 V; (b) Applied amplitude = 1000 V.

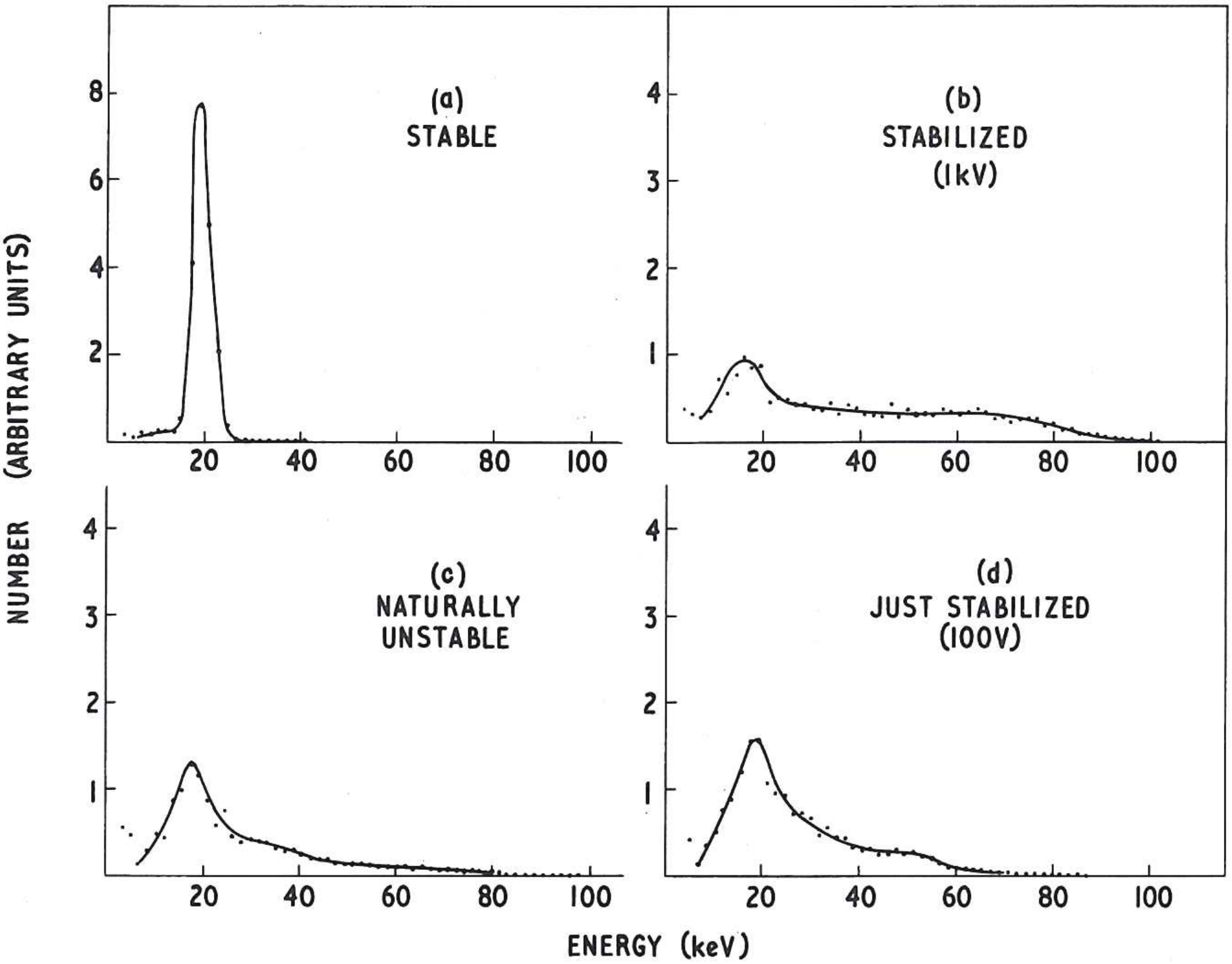

Fig. 2 (CLM - P 108)

Energy spectra of protons in the plasma as measured by the energy analyser in the median plane *

(a) Low density ($\approx 5 \times 10^7$ cm^{-3}) stable plasma

(b) High density ($\approx 3 \times 10^8$ cm^{-3}) stabilised plasma with 1 kV applied high frequency potential at $\omega_{ext} = \omega_{oi}$. Note that the average energy of the confined particles as seen by the analyser has increased to 38 keV.

(c) Energy spectrum integrated over many instability bursts from a high density naturally unstable plasma.

(d) High density stable plasma with an applied potential of 100 V (just sufficient to stabilise the plasma) and $\omega_{ext} = \omega_{oi}$

* Since the solid angle subtended by the energy analyser is very small (0.9×10^{-5} sterad.) and $v_\perp \approx v$, $v_{||} \approx 0$ in our case, the graphs are essentially $v_\perp f(v_\perp, v_{||} \approx 0)$ vs $v_\perp^2$.