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EXPERIMENTS WITH PLASMA PRODUCED BY NEUTRAL INJECTION INTO A MAGNETIC MIRROR/WELL GEOMETRY

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ABSTRACT

In the PHOENIX IA experiment an 8 mA equivalent, 20 keV H^o beam is ionized by Lorentz $\underline{v} \times \underline{B}$ field to produce a plasma in simple mirror geometry. In the PHOENIX II experiment a beam of up to 35 mA equivalent at 20 keV is used to produce a plasma in magnetic well geometry formed by combining a mirror and $\ell = 2$ stabilising field.

The observations in simple mirror geometry are summarised. An $m = 1$ hydromagnetic drift instability limits the plasma density to about 3×10^8 particles/cc. In addition there are bursts of high frequency oscillation which begin at the ion cyclotron frequency corresponding to the central magnetic field and then drop both in amplitude and frequency, the latter falling by about 5% in a typical case. During these bursts, the ion energy is spread dramatically. The possibility of additional ion loss by scattering into the loss cones cannot be excluded.

In the magnetic well condition, the drift instability is absent and there is no evidence for plasma loss by processes other than charge exchange. A density an order of magnitude higher than that in the simple mirror case has been reached and appears to be limited only by technological considerations.

In the well condition the high frequency instability is smaller in amplitude and more intermittent. There is a scatter in frequency, the predominant emission being at the central field ion cyclotron frequency and a value 2.5 - 3.0 Mc/s above. Higher harmonics also appear and at the highest density achieved the emission is predominantly second harmonic. The ion energy spread is considerably less than that in the simple mirror geometry.

Complex phenomena occur during the transition from simple mirror to magnetic well geometry. These are discussed in terms of the changes of precessional drift behaviour of the ions.

The emission of fast neutral atoms from charge exchange of plasma ions is observed with a collimated detector in the median plane. This emission is found to be anomalously high at high plasma density. Several explanations of this effect are under investigation. One possibility is that ionization and consequent trapping of the incident beam by the plasma may be significant. The cross section for this process derived from the observed emission is not inconsistent with known data.

CONTENTS

1. INTRODUCTION

The observation of the hydromagnetic drift instability of plasma in mirror geometry has been well documented. This instability is driven by the negative radial gradient of magnetic field which produces differential drifts of ions and electrons. Gott et al(1) have shown that the addition of a 6-pole cusp field to the mirror field stabilises this instability and enables plasma to be retained for a considerably longer time than would otherwise be the case. This result has been confirmed recently by several experiments using $\ell = 3$,(2,3) and higher multipole fields(4). The stability of these complex magnetic field configurations has been investigated by Taylor(5), Andreoletti(6) and Furth(7) and the stability criteria are now well established. In particular, density distributions that decrease with radius confined by a magnetic field which increases outwards in all directions may be shown to be stable for perturbations that preserve the particle magnetic moments.

In addition to these low frequency instabilities, electric and magnetic fields have been observed at frequencies associated with the ion cyclotron frequency and it has been shown that in at least one experiment(8) these high frequency instabilities result in serious loss of plasma. In other experiments(9,10) there occur serious perturbations of the particle velocity distributions which may be associated with these phenomena. Since the first paper by Harris(11) many aspects of electrostatic velocity space instabilities have been treated and in particular Rosenbluth and Post(12) and more recently Galeev(13) have shown that these may cause serious loss of plasma from open ended containment systems.

In this paper we describe experiments carried out with the plasma formed by fast atom injection into a simple mirror magnetic field and into an $\ell = 2$ magnetic well and show the effect on the hydromagnetic drift instability and ion cyclotron instability of the transition from mirror to well geometry.

2. DESCRIPTION OF APPARATUS

For the work described in this paper the plasma is produced by ionization of pre-accelerated neutral atoms in a strong magnetic field. A basic description of a predecessor of the present experiment has been given elsewhere(14,9). The experiments on simple mirror geometry have been carried out with the PHOENIX IA apparatus in which a beam of maximum intensity 8 mA equivalent of 20 keV H^0 atoms is passed across the median plane of a simple mirror machine. The distance between mirrors is 30 cms and the mirror ratio 1.8 : 1. The maximum central magnetic field is 50 kG.

The experiments on magnetic well geometry were carried out with the PHOENIX II apparatus which is illustrated in Fig. 1. A maximum beam intensity of 35 mA equivalent of 20 keV H^0 is produced by dissociation of a beam of 40 keV H_2^+ ions in an organic vapour ($C_8 F_{16}$) chosen for its low vapour pressure at liquid nitrogen temperature and high molecular weight. The latter property assures a low thermal speed which enables the directed beam of vapour to be removed by a mechanical velocity filter.

The magnetic well is produced by a combination of two mirror coils, similar to those used in the PHOENIX IA experiment, and a quadrupole cusp configuration of four external oval coils. The mechanical arrangement is illustrated in Fig. 2. All coils are cooled to liquid nitrogen temperature, the temperature rising to approximately $-140^{\circ}C$ during a typical pulse. The current of 0.8 MA turns in the mirror windings is supplied by generators and a feedback arrangement maintains a field constant to ± 0.5% for five seconds. The peak power drawn during this period is 0.3 megawatts. The quadrupole current of 2.4 MA turns/coil is supplied by a 3 kilovolt battery bank and is pulsed on for several seconds, the maximum power drawn being 8 megawatts. A typical pulse shape is shown in Fig. 3.

Fig. 4 shows a plot of computed $|B|$ against radius in the median plane for various stabilising currents. Calculations have been made of the precessional drift surfaces in the zero gyro radius limit. It has been shown that these close around the axis for both small and large stabilising fields but that near zero radial gradient they allow particles to precess out of the apparatus.

3. SUMMARY OF CONDITIONS WITHOUT STABILISING FIELDS PRESENT

A number of experiments have been performed with the PHOENIX IA apparatus and also with the PHOENIX II apparatus without stabilising field. Some of the basic phenomena were described in a previous paper(9). A detailed summary of more recent experiments is being prepared and is to be published elsewhere(15).

The previous work showed that in the simple mirror geometry the principal limitation is the hydromagnetic drift or flute instability which prevents the density rising above about 3×10^8 cm^{-3}. This instability is identified by its associated electric field which has an $m = 1$ configuration and rotates at some fraction of the precessional drift rate of the fast ions in the magnetic field gradient. Increasing the neutral beam intensity or decreasing background gas pressure merely results in an increased electric field which transports plasma more rapidly across the magnetic field to maintain a constant density.

In addition regions of magnetic field and plasma density were determined in which an instability related to the cyclotron frequency of the ions occurred. This instability, when it occurs, is invariably accompanied by a modified form of the hydromagnetic drift instability which causes rapid transport of plasma across the magnetic field; this interdependence complicates observations on the PHOENIX IA apparatus.

In recent work, measurements have been made of the energy distribution of the fast neutral atoms emitted from the plasma. These measurements were made with a collimated energy analyser(16) both in the median plane and some distance off the median plane. A typical energy spectrum of an unstable plasma in mirror geometry is shown in Fig.5 where it is compared with an energy spectrum taken during a low density stable pulse. A very large energy spreading is observed during periods of H-F emission(17).

The spreading in ion energy has been correlated with the onset of emission at the ion cyclotron frequency as measured by a probe capacitively coupled to the plasma. Ions are accelerated to 70 keV within 2 milliseconds from the onset of H-F emission and in a typical case the distribution has reached equilibrium in about 20 milliseconds i.e. a time shorter than the length of the H-F burst, which at the lowest pressures may be 50 milliseconds or greater.

In some experiments an initial burst of H-F activity occurred at low magnetic field and the field was then raised to the point where the activity ceased. Particles were accelerated to several hundred kilovolts in the initial H-F burst and persisted for several seconds in spite of the continuation of the drift instability which gave an average lifetime for loss of 20 keV particles of 10 milliseconds. The precessional drift rate of the ions is proportional to energy and is much greater for high energy particles. They are therefore presumably out of resonance with the instability frequency. This essentially resonant nature of the drift instability has been observed in the well geometry and is commented on later.

Measurements have been made of the frequency spectrum of the H-F emission. A typical spectrum is shown in Fig.6. At the highest densities obtainable in mirror geometry the spectrum is predominantly 1st harmonic though higher harmonics up to the 6th are observed with lower amplitude. A characteristic feature is that the instability begins with an oscillation at the cyclotron frequency appropriate to the central magnetic field, followed by a steady drop in both amplitude and frequency, the latter falling by about 5%. All harmonics show simultaneous proportional changes in frequency. Measurements have been made of the phase of the wave using several probes. Signals observed at various azimuthal positions indicate a basic m = 1 charge configuration rotating at the ion cyclotron frequency. Probes placed in different axial positions at the same azimuthal setting show signals in phase to ± 2^{0}/cm between 10 and 15 kG, and ± 10^{0}/cm between 15 and 17 kG.

Axial and radial density distribution both with and without the presence of the ion cyclotron instability were measured. Unfortunately, the simultaneous occurrence of the low frequency drift instability, which produces a strong radial flow of plasma, prevented a detailed balance of energy being made, and it is not possible from this data alone to say whether there is particle loss due specifically to the ion cyclotron instability. However, measurements of the energy spectrum of the ions near the median plane showed spreading upwards in energy from 20 keV but not downwards. At the same time the neutral particle detector showed that the total energy emitted was reduced. Since the driving energy of the instability is derived from the ions, clearly some ions must have been decelerated. A search was made for such low energy particles and some indications were obtained that these particles existed and formed a group with velocity components along the field such that they travelled deep into the mirrors. Evidence has been obtained for fast particle loss through the mirrors though quantitative measurements are difficult because of the confusion with slow ions produced by charge exchange and ionization of background gas which are accelerated axially by the plasma potential.

In summary, the ion cyclotron instability causes an extensive redistribution in velocity space which appears as a spreading upwards in energy for particles near the median plane and may produce lower energy particles near the mirrors. The possibility of serious loss of particles due to this instability cannot be excluded.

4. TRANSITION TO MAGNETIC WELL GEOMETRY

In the PHOENIX II experiment the current in the mirror windings is held constant and the current through the stabilising coils rises and falls as indicated in Fig.3. The effect of this additional field is to cause tilting of the field lines relative to the axis and initially to reduce the precessional drift rate of the ions around the axis. It is convenient to define a 'Compensation Ratio' (C_R) as the ratio of the stabilising current to that required to produce zero gradient at the centre. The radial field distributions for several values of C_R are shown in Fig.4.

Measurements have been made of the slow ion current through the mirrors during the transition to well geometry. Two systems were used for these measurements: one consisting of a plate about 13 cm diameter which filled the throat of the mirror and in front of which were situated three biased grids, and another consisting of a set of small plates 0.4 cm × 1.0 cm at different radii again preceded by three biased electrodes. Suitable voltages on the electrode system enabled the detection and energy analysis of ions or electrons. Slow ions arise from ionization of the background gas by plasma particles. Electrons arise from ionization of the injected atom beam and by ionization of the background gas by the plasma particles.

Experiments in mirror geometry have shown that the plasma acquires a positive space charge potential sufficient to retain the comparatively cold electrons in the apparatus. Cold ions produced in the plasma are therefore accelerated along the field lines and acquire an energy equal to the local potential at the point of creation. By applying a negative potential of 300 volts to the third electrode, and varying positive potentials to the second electrode, ions with energies greater than the potential of the second electrode were selected.

Results of measurements of the slow ion current, without energy selection are shown in Fig.7c. A high background gas pressure was used so that the fast ion density was sufficiently low to give essentially single particle behaviour. The slow ion current through the central region refers to the current collected on the central small collector plate and is, in the absence of changes in electron temperature, essentially proportional to the line density of fast ions near the axis. The 'line density' is here defined as the number of ions in a flux tube of unit area at the median plane. As may be seen from the graph the line density remains constant at the simple mirror value up to a compensation ratio of 0.8, drops to essentially zero at $C_R = 1$ and is fully established again at $C_R = 1.3$.

This loss of particles near a flat radial field is understandable in terms of single particle precessional drift motion. Calculations have been made which show that near this condition the drift surfaces do not close around the axis but go out to the walls. This occurs at $C_R = 1$ for particles trapped at small radii and moves to higher values of C_R for particles trapped at higher radii. Fig.7d shows the slow ion current to the large end collector which accepts a larger range of radii. As expected this indicates a less pronounced loss of particles over the range $C_R = 0.8$ to 1.35. Beyond $C_R = 1.5$ all relevant precessional drift surfaces close around the axis. The loss of total end collector signal in the well geometry condition is accounted for by the changing angle of field lines which, in the magnetic well case, deposits much of the slow ion current on the vessel wall.

The change in anisotropy of the plasma may be derived from measurements of fast neutral particle emission due to charge exchange of plasma ions. This was measured using collimated Cs I(Tℓ) scintillation counters. Observations were made through diagnostic ports at 45° to the cusp lines (i.e. through the stabilising winding) both on the mirror median plane and at 6 cms above and below it. These diagnostic ports are essentially normal to the field lines and accept particles which would traverse the median plane with angles 0° and 26° respectively, independent of radius.

Figs.7a and 7b show the emission on the median plane and 6 cm from the median plane as a function of compensation ratio. Quite small values of C_R tilt field lines relative to the magnetic axis so that particles trapped at outer radii have appreciable $v_{\parallel}$. Thus the median plane emission drops and the emission at 6 cms rises. For large C_R the median plane emission reflects the density near $r = 0$ (all particles trapped on large r have been given $v_{\parallel}$) and the 6 cm emission represents particles trapped at some large radius. Particles trapped near $r = 0$ are lost completely from the apparatus at $C_R = 1$ and particles trapped at high r are lost at $C_R = 1.3$.

It is clear from the above measurements and from computation of precessional drift surfaces that in PHOENIX II a C_R of 1.5 or more is required to ensure correct precessional drift behaviour over the whole plasma.

All the graphs in Fig.7 refer to low density behaviour. We now consider the behaviour at high density. Fig.8 illustrates the effect of the stabilising field on the drift instability. The rotating electric field associated with this instability was detected by a probe capacitatively coupled to the plasma. In the upper photograph the amplitude of this oscillation, the frequency, and the centre end plate current, are compared and correlated with the compensation ratio.

During the initial part of the pulse (with mirror field only) the beam intensity and gas pressure were such as to give a plasma density limited by the drift instability; hence the low value of end plate current. As the stabilising field rises, the initial effect is to reduce the precessional drift rate and so drop the frequency of oscillation. It was shown in a previous paper(9) that the plasma density for the onset of the drift instability is proportional to the precessional drift frequency. Consequently the density drops below that of the simple mirror, in marked contrast to the low density behaviour of Fig.7c where the density remained constant up to $C_R = 0.8$.

The small changes of frequency and the low value of the amplitude of the electrostatic signals during the simple mirror period are due to the presence of the ion cyclotron instability. This instability in its gross form is quenched at quite small values of C_R.

The line density, however, is beginning to drop below the unstabilised value in this region. This is indicated in the lower photograph of Fig.8. It is not yet clear whether the loss of high frequency activity is due to this loss of density or the change in average anisotropy of the plasma produced by trapping on the tilted field lines.

At a value of C_R near unity the frequency of the drift instability oscillations increases. This is now believed to be due to an increase of precessional drift rate at outer radii which computations show occurs at this value of C_R.

At $C_R \sim 1.1$ continuous low frequency oscillations disappear. However a closer examination on an expanded time scale shows that small damped oscillations may occur with C_R as high as 1.2. These are associated with loss of particles from the outer radii only and it is believed that this is a drift instability occurring in a group of particles at high radii (which have precessional drift in the unstable direction) even though the central core of the plasma is stable. This appears to be another example of the specific nature of the drift instability which interacts only with those particles that have drift frequencies broadly resonant with the oscillation frequency.

At values of C_R above 1.2, low frequency oscillations are no longer detected by the electrostatic probe and the ion current to the end plate reaches its saturation value appropriate to the magnetic well condition. The increased line density compared with that for the simple mirror case is illustrated by these photographs.

5. PHENOMENA IN MAGNETIC WELL GEOMETRY

The measurements described in this section were carried out at a compensation ratio of between 1.5 and 1.6. This produces a well with closed constant $|B|$ surfaces out to a radius of about 5 cms. Under these conditions the calculated precessional drift rates of fast ions are comparable with those in the simple mirror geometry, but in the reverse direction. Appreciably lower values of compensation ratio introduce the complex precessional drift behaviour and other phenomena described in Section 4.

In the deep well condition, where the precessional drift surfaces are well behaved, the dominant fast ion loss process is apparently charge exchange with the background gas. Under these conditions the plasma density is dependent on the neutral beam intensity and the time constant for charge exchange loss. The exact dependence is discussed in more detail in Section 6. In this section we discuss the phenomena that occur in plasma of line density up to 6×10^9 particles/cm^2.

As was mentioned in Section 4 no low frequency phenomena associated with the drift instability were detectable in the deep magnetic well condition. High frequency activity is however observed. The normal H-F activity in simple mirror geometry at 10-20 kG is continuous for periods of up to 50 msec. In contrast, in the well condition, short bursts of H-F activity occur which last from 0.1 to 5 msec. As the density is increased to the maximum at present obtainable the bursts of activity occur more frequently.

Detailed measurements have been made of the frequency spectrum as a function of time. A Hewlett-Packard spectrum analyser was used and was modified so that the complete spectrum was swept in 1 msec. The spectrum as a function of time is shown in Fig.6 where the behaviour in well geometry is contrasted with that in simple mirror geometry at a lower density. A characteristic feature of the behaviour is the emission at the cyclotron frequency corresponding to the central magnetic field (25.4 Mc/s), a frequency 2.5 - 3.0 Mc/s higher, and harmonics of these. As the density is raised the harmonics become more intense until, at the highest density reached, the emission is predominantly 2nd harmonic. This is illustrated more clearly in Fig.9 where the upper photograph shows the frequency spectrum over a complete pulse. The lower photograph shows the behaviour on an expanded time scale where it is seen that the two neighbouring frequencies rarely occur simultaneously. Harmonics higher than the 2nd are present but with greatly reduced amplitude. In the simple mirror case the 1st harmonic is predominant and intensity falls rapidly with harmonic number, though harmonics up to the 7th have been detected.

The effects of this instability on the plasma properties have been investigated and are described in the following sections.

ELECTRON LOSS RATE AND PLASMA POTENTIAL CHANGES

Electrons are lost through the mirrors simultaneously with H-F bursts. This is illustrated in Fig.10. One of the grids in front of the end collector was biased to + 300 volts so as to exclude ions. Under these conditions the observed electron current fluctuates, presumably because of slight changes in plasma properties which allow electrons to 'spill out' of the electrostatic well which contains them. Superimposed on these fluctuations are large electron currents which are correlated with the H-F bursts as shown in Fig.10.

The energy of the electrons emitted during an H-F burst was estimated. Most of these were below 10 eV but some 20% had energy between 10 and 50 eV. Since the energy gained per transit must be of the same order, this suggests that the acceleration process requires several transits to reach electron energies compatible with the plasma potentials discussed below.

By negatively biasing one of the grids, only slow ions were collected on the receiving plate. The energy spectrum of these slow ions was measured by applying a suitable positive bias to the second grid. The energy of the slow ions gives a measure of the positive plasma potential at the point of ionization. The results showed that this potential normally remains at 10 volts or lower but during H-F bursts it typically increases to some tens of volts and occasionally reaches 200 volts. The recovery time is compatible with the electron replacement time.

Changes in the surface plasma potential are recorded on the electrostatic probes near the plasma. These show positive signals characteristic of a rise in surface potential of the order of 100 volts which are correlated with the H-F bursts. The behaviour of one such probe is shown also in Fig.10.

ION ENERGY SPECTRA

The energy spectrum of the ions has been measured both for low density, stable conditions and for high density, unstable conditions.

The spectra were taken using the electrostatic deflection analyser described elsewhere(16). This accepts neutral particles emitted by charge exchange of plasma ions and is collimated to receive only those from a 1 cm diameter region aligned along the mirror median plane. The spectra are time averaged over a period of about 1 second and are corrected for instrumental effects and for the charge exchange cross section in the neutral to charged particle conversion cell. They are not corrected for the variation with energy of the charge exchange cross section in the plasma i.e. the spectra represent the energy spectra of the neutral particles emitted.

Fig.5 shows typical energy spectra. The instrumental resolution is 6.5% and is indicated by the stable pulse at low density. As has been reported previously, spectra taken at high density with simple mirror field only, show considerable broadening of the distribution. In the magnetic well condition the energy spreading is much reduced even though the line density is considerably higher. Up to a line density of 6×9^9 particles/cm^2 very few particles achieve energy greater than 30 keV or less than 12 keV, whereas in the simple mirror case, at a line density of 1×10^9 particles/cm^2, some 5% of particles have an energy greater than 40 keV.

Time resolved spectra in the magnetic well condition show an essentially continuous spread of energy which is consistent with the ion replacement time of about 50 msec. During the simple mirror period the H-F bursts last about an ion replacement time and there is appreciable fluctuation in theenergy spectrum. Thus the mirror spectrum displayed above shows a distinct 20 keV peak which is almost absent from the instantaneous spectra taken in the middle of an H-F burst.

EMISSION OF FAST NEUTRAL ATOMS

The emission of fast neutral particles both in the mirror median plane and 6 cms above and below it shows no fluctuation detectable above that expected statistically (i.e. $< 5\%$) during H-F bursts. It may be concluded therefore that an individual burst of H-F activity causes little perturbation of the ion velocity distribution. At high densities there are, however, changes in the neutral emission both on the median plane and 6 cms from it. These are discussed in more detail in Section 6.

6. TRAPPING AND LOSS PROCESSES

In previous experiments the dominant process for trapping of incident beam atoms has been ionization by the Lorentz $\underline{v} \times \underline{B}$ electric field. At low plasma density the dominant fast ion loss process has been charge exchange, and at high density the drift instability. A number of experiments have been performed to discover the situation in well geometry.

The emission of fast neutral atoms collimated in the median plane has been correlated with the time constant for decay of the plasma after beam switch off. The gas pressure, and hence the decay time, were varied by admitting helium gas to the system. The beam intensity (I_0) was held approximately constant. The ion density in the region of velocity and real space observed by the neutral atom collimator is proportional to (neutral atom emission) x τ, where τ is the decay time. Fig.11 shows a plot of this product against $I_0\tau$.

Over most of the pressure range Lorentz trapping is the dominant process. For this trapping process, and loss by charge exchange, the density is proportional to $I_0\tau$. At high gas pressure (low τ) trapping by ionization on gas atoms contributes. At low gas pressure (high τ) the points are seen to deviate by as much as a factor of two from the value expected on the basis of Lorentz trapping alone.

The explanation of this rise is not yet clear. A small contribution to the neutral emission should occur at low gas pressure due to charge exchange with beam atoms. This contribution may be determined by observation of its fast decay as the beam is switched off. At the highest densities it never accounts for more than 10% of the observed rise. Observations of the slow ion current through the mirrors show a large scatter from pulse to pulse but no significant rise at high values of τ. Several alternative explanations are being investigated:

(a) The rise may be due to a change in the energy distribution of the ions. Since the Cs I crystals used for fast neutral particle detection are energy sensitive, changes in the energy distribution may cause increased output. The energy distribution measurements made so far indicate that this is unlikely to account for such a large rise.

(b) The rise may be due to a very local background gas jet which causes neutral emission in a preferred direction at low gas pressure. This possibility is being investigated by correlating neutral emission in two perpendicular directions.

(c) A change of spatial distribution of the fast ions may be occurring at the highest densities which increases the output of the central neutral emission detectors. This explanation at first seems unlikely but is supported by recent evidence of a reduction in the neutral emission seen through the collimator 6 cm from the median plane.

(d) Ionization of the incident beam by the plasma may be occurring. This process is expected to occur near the centre at first and spread outwards as the density is raised. It is easy to show that this contribution should enhance the beam trapping by a factor $1/(1 - A\sigma_p I_0\tau)$ where σ_p is the cross section for ionization of the beam by the plasma, and A is a constant which depends on the beam size, the aperture of the neutral particle collimator, and the spatial distribution of plasma. When $I_0\tau$ reaches the critical value $1/A\sigma_p$, the density should rise exponentially to a value limited only by ion-ion collisions. Thus a knowledge of the cross section σ_p is most important for predicting the behaviour of neutral injection experiments(14).

On the assumption that plasma trapping is the explanation of the increased particle emission, a plot of normalised fast neutral emission against $I_0\tau$ has been fitted with a curve of the above form and is shown in Fig. 12. By comparing the rise due to gas trapping at high helium pressure with that supposedly due to plasma trapping at low pressure, σ_p may be estimated in terms of known helium cross sections and many of the collimator geometrical factors may be eliminated. The cross section calculated on this basis is $1.3 \pm 0.7 \times 10^{-15}$ cm^2/plasma ion. The measured cross section for ground state 20 keV beam atoms colliding with stationary protons is 1.4×10^{-16} cm^2. Only estimates are available for the contribution from excited beam atoms but these suggest that the effective corss section (per beam particle) may be of the order 7×10^{-16} cm^2 for ionization from the $n = 10$ state. If, as Hiskes suggests(20), cascading plays a significant role, then more than one excited state may contribute and the effective cross section will be correspondingly enhanced. In view of this the above cross section does not seem unreasonable.

Work is underway to discover the explanation of the rise in neutral emission. Meanwhile, it may be taken as evidence that at the densities achieved there is little loss of plasma from the central regions by processes other than charge exchange.

7. DISCUSSION

We have shown that for a line density of up to 6×10^9 cm^{-2} the addition of sufficient $\ell = 2$ stabilising field to the simple mirror field quenches the hydromagnetic drift instability. The addition of a small field, sufficient to reduce but not reverse the precessional drift of the ions, has a destabilising effect and reduces the achievable density, in agreement with theoretical predictions(9).

The phenomena associated with the transition from mirror to well geometry, as well as the behaviour of very high energy particles in mirror geometry, suggest that under steady state conditions of injection the drift instability should be regarded essentially as broadly resonant. It drives out particles with precessional drift rates near the instability frequency but leaves essentially unperturbed those with appreciably faster drift rates. Such behaviour is not of course characteristic of extremely non-linear versions of the instability found in some plasma injection experiments where the $\underline{E} \times \underline{B}$ motion clearly dominates over the $\underline{\nabla B} \times \underline{B}$ motion.

Changes in plasma distribution induced by a relatively small stabilising field quench the long high intensity bursts of H-F associated with the ion cyclotron frequency. However the instability reappears in a less harmful form at the high densities in the well geometry.

It is not yet clear what is the precise origin of this H-F instability. Its appearance at low β suggests an electrostatic origin and it is clearly associated with the ion cyclotron frequency. Possibilities include the negative mass instability(18), the instability first suggested by Harris(11), which draws its energy essentially from the anisotropy of the plasma ions, and the Rosenbluth-Post instability(12) which relies on the peak in the $v_\perp$ distribution of the ions.

The negative mass instability relies on $\delta^2 B/\delta r^2$ being negative and becomes a 'positive mass' stabilising term in well geometry. Calculations suggest that, for the PHOENIX operating conditions, these terms are weak and give growth rates, or stabilising terms, of less than $10^{-3}\ \omega_{ci}$ (where ω_{ci} is the ion cyclotron frequency). They may, however, stabilise very slow growing instabilities in well geometry.

A considerable literature exists on the theory of instabilities which electrostatically couple the ion gyro motion to electron plasma oscillations. The necessary condition for onset is $\omega_{pe} \geqslant \omega_{ci}$ and for plasma densities near this lower limit, the wave vector is nearly parallel to the magnetic field. As the density is raised the angle of the wave moves round until it is more nearly at right angles to the magnetic field and for $\omega_{pi} > \omega_{ci}$ the frequency moves up to the higher harmonics of the ion gyro frequency.

At low densities where $\omega_{pi} < \omega_{ci}$ the detailed treatment used by Harris and other workers is necessary. At high density it is sufficient to use the simplified treatment of Rosenbluth and Post. The highest plasma densities described in this paper represent an intermediate stage. Near the centre of the plasma $\omega_{pi} \simeq \frac{1}{2} \omega_{ci}$. It is perhaps significant that the H-F emission is predominantly in the second harmonic of ω_{ci}.

Clearly in the experiments the predominant effect of the instability is to spread $v_{\perp}$. It cannot however be argued that the electric vector is therefore nearly normal to the magnetic field, since it may be shown quite simply that $v_{\perp}$ is spread more than $v_{\parallel}$ even when $k_{\perp} < k_{\parallel}$. The direction of the wave vector is not determinable from present information.

The instability of Rosenbluth and Post is essentially convective in nature and requires a reasonable length in which to grow. For non-reflecting ends Rosenbluth and Post suggest as a reasonable length $L > 10^4 a(m/M)^{\frac{1}{2}}$ which, for the PHOENIX parameters, gives $L > 300$ cm. If this is indeed the Rosnebluth-Post instability, its appearance in such a short plasma ($L \sim 15$ cms) suggests either that highly reflecting ends and a standing wave behaviour are more appropriate, or that, because of the near δ-function nature of the $v_{\perp}$ distribution, the growth rate is considerably greater than that calculated.

In the well condition two frequencies occur, one at the central gyro frequency and one 2.5 - 3.0 Mc/s above. The reason for this is not fully understood. The frequency of oscillation of the ions between their mirror turning points is calculated to be 3 Mc/s and an explanation might be sought in terms of betatron oscillations which couple this frequency with the ion gyromotion. This mechanism has been used to explain some of the behaviour in the DCX-1 experiment. Difficulties arise with this explanation however. It is difficult to account for the lack of a difference frequency below the central gyro frequency; and the behaviour of the second harmonics, in which each frequency is doubled separately, suggest that the explanation should be sought elsewhere. That the two frequencies occur simultaneously is also surprising. The highest frequency is not inconsistent with the average gyro frequency of ions at higher radii with comparatively large $v_{\parallel}$. The unique value of this frequency is however surprising in view of the continuum of different radii of injection. A convincing explanation must await further experiments.

The curious increase of intensity of emission of fast charge exchange neutrals at high density described in Section 6 is certainly of interest. It may represent the effect of some spatial redistribution of the fast ions or may be the initial stages of the much sought after build-up process. In either case, clearly no major loss processes other than charge exchange are occurring at the highest plasma densities reached in these experiments. It remains to be seen whether this will still be true as the base pressure and beam intensity are improved.

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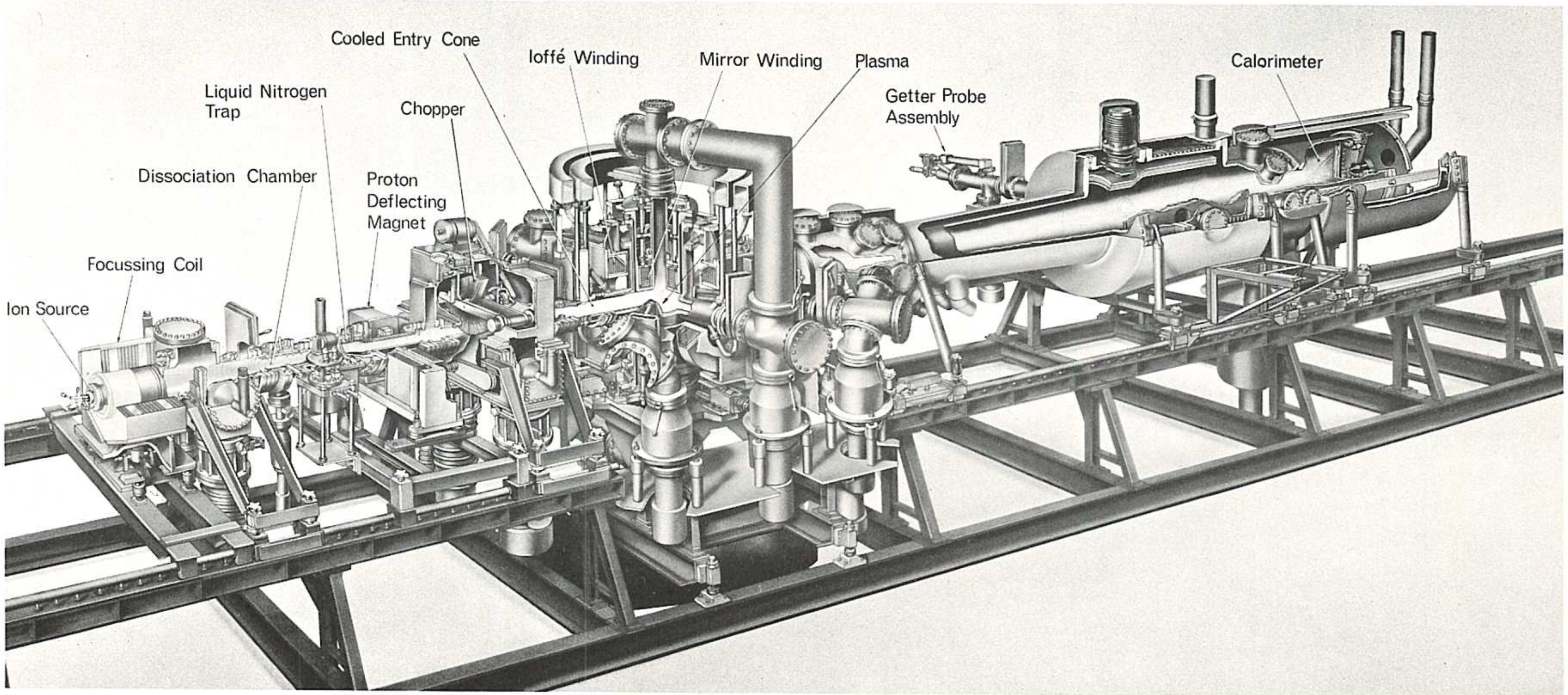


Fig. 1 **PHOENIX II** (CLM-P91)

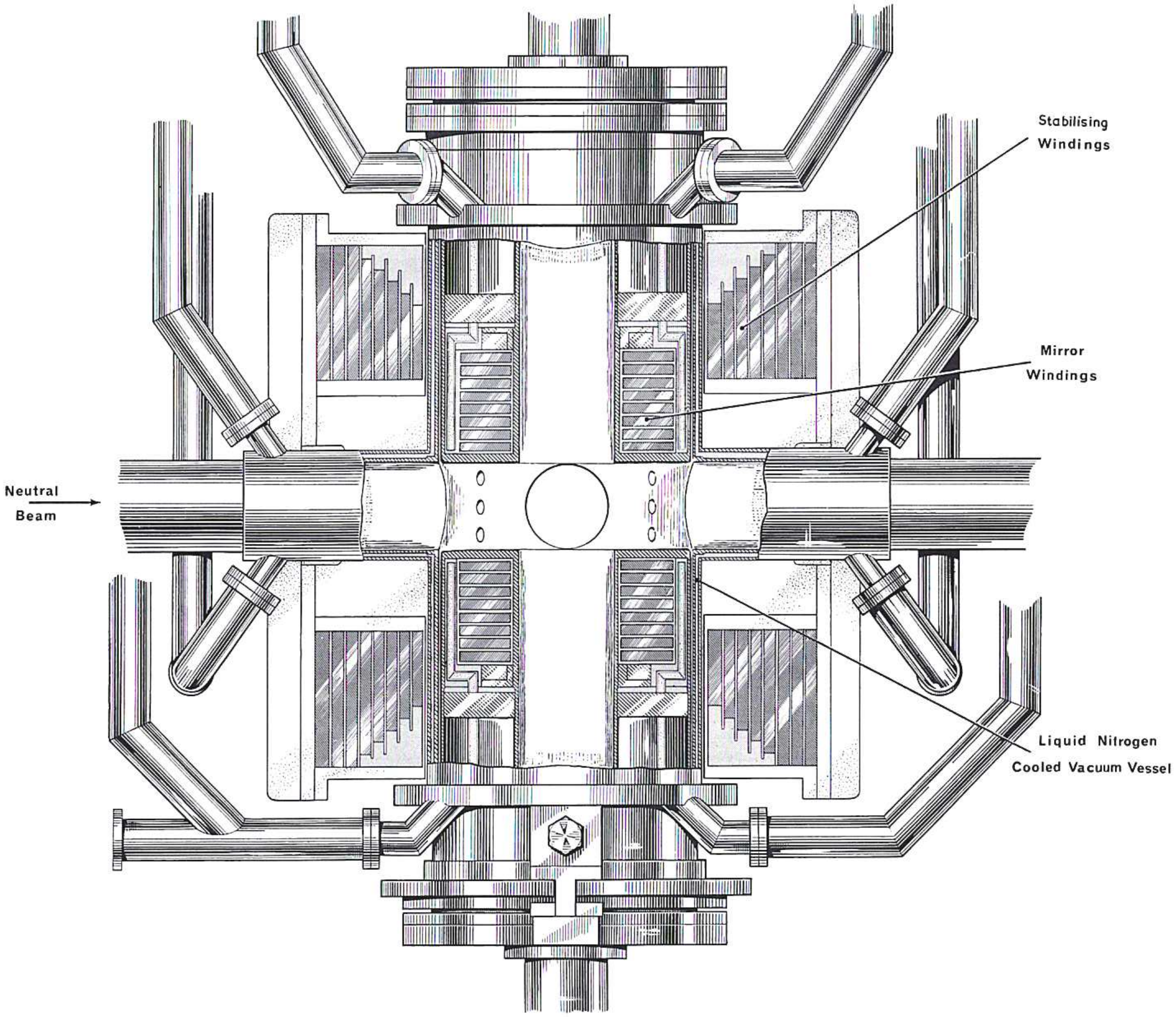


Fig. 2 (CLM-P91)
PHOENIX II. Centre chamber and coils

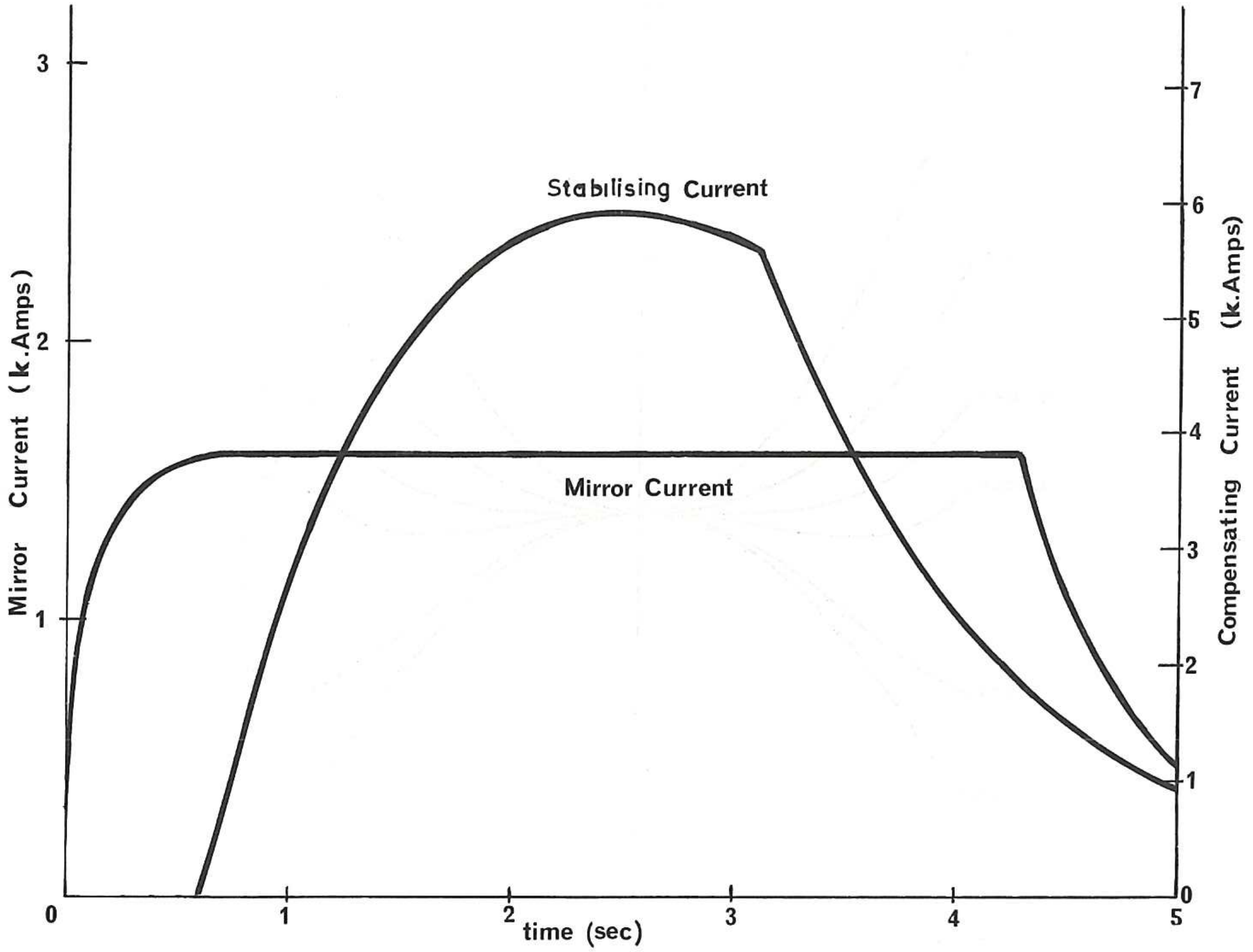


Fig. 3 (CLM-P 91)
Current profiles for mirror and magnetic well configuration

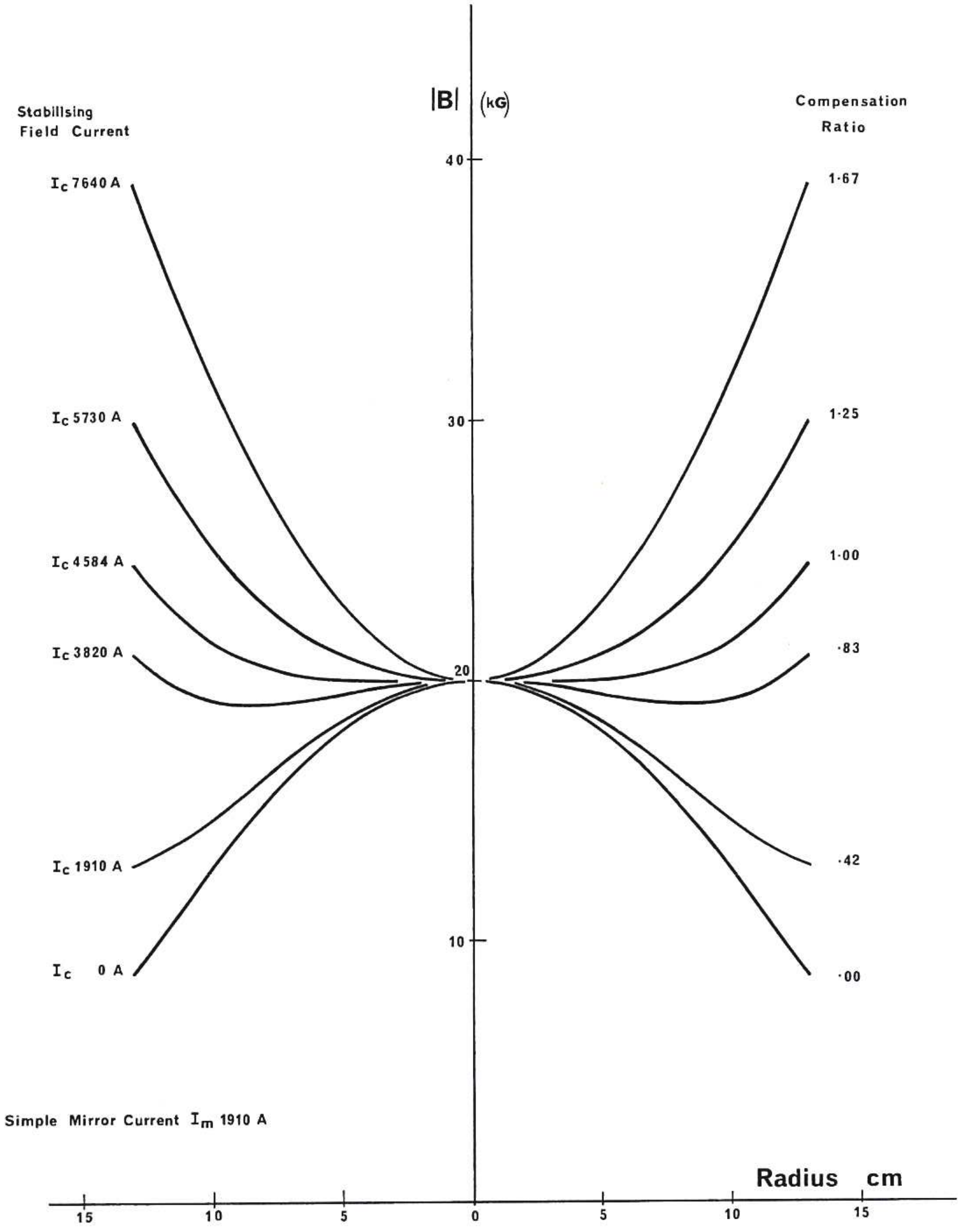


Fig.4 (CLM-P91)
PHOENIX II. Magnetic field intensity in the median plane as a function of radius

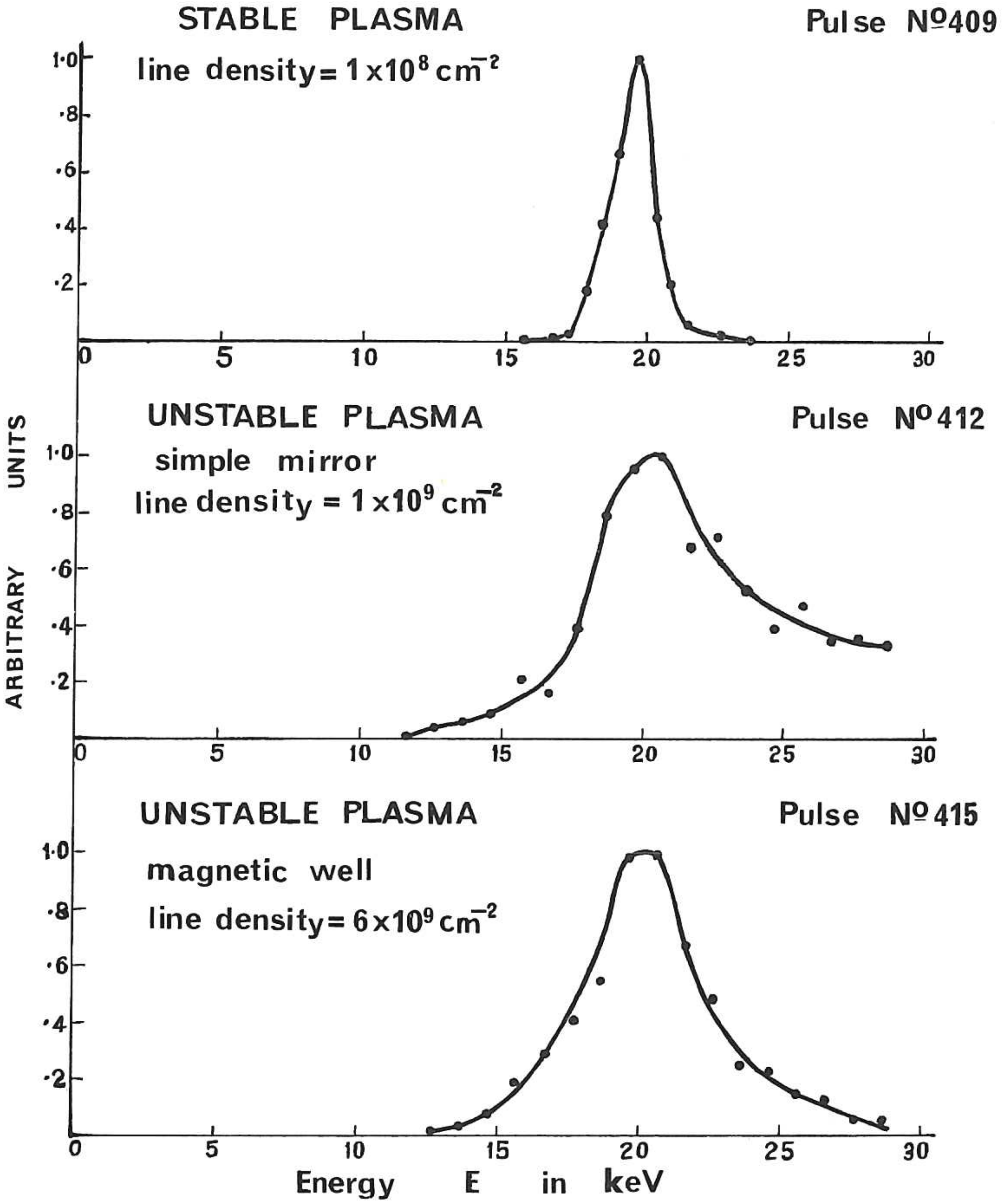


Fig.5 (CLM-P 91)
Energy spectra of neutrals emitted in the median plane

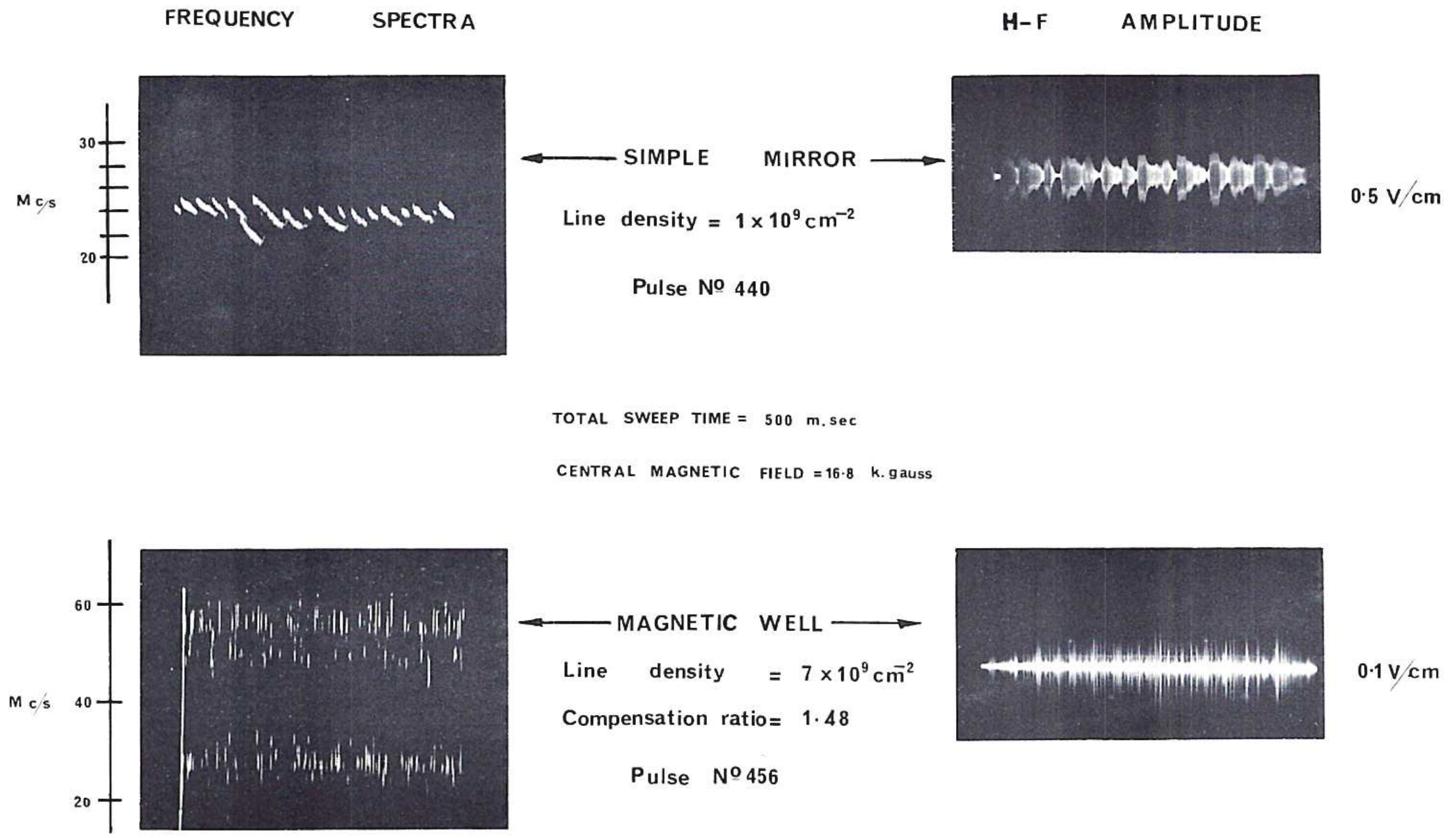


Fig.6 (CLM-P91)
H-F amplitude and frequency observed in simple mirror and magnetic well geometry

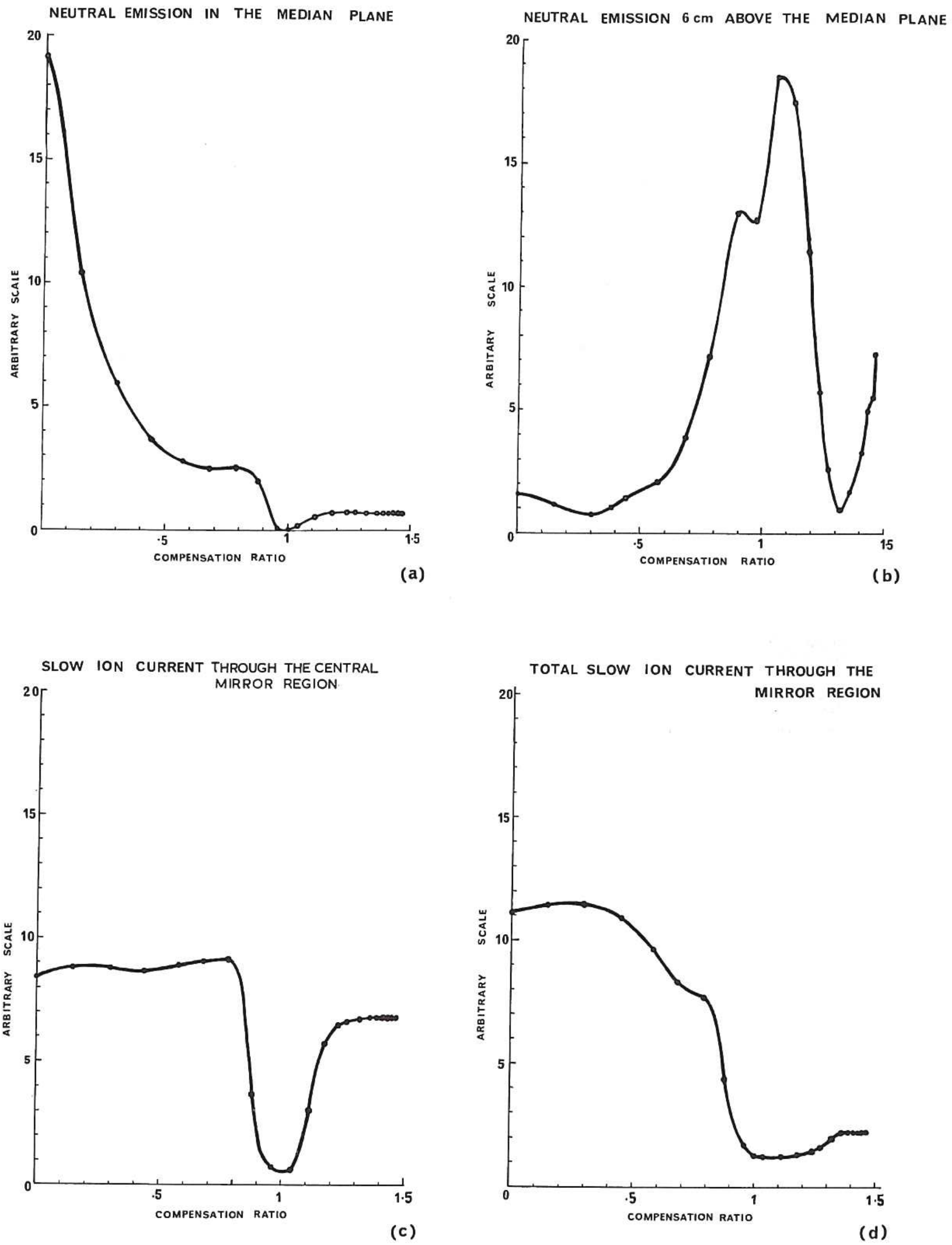
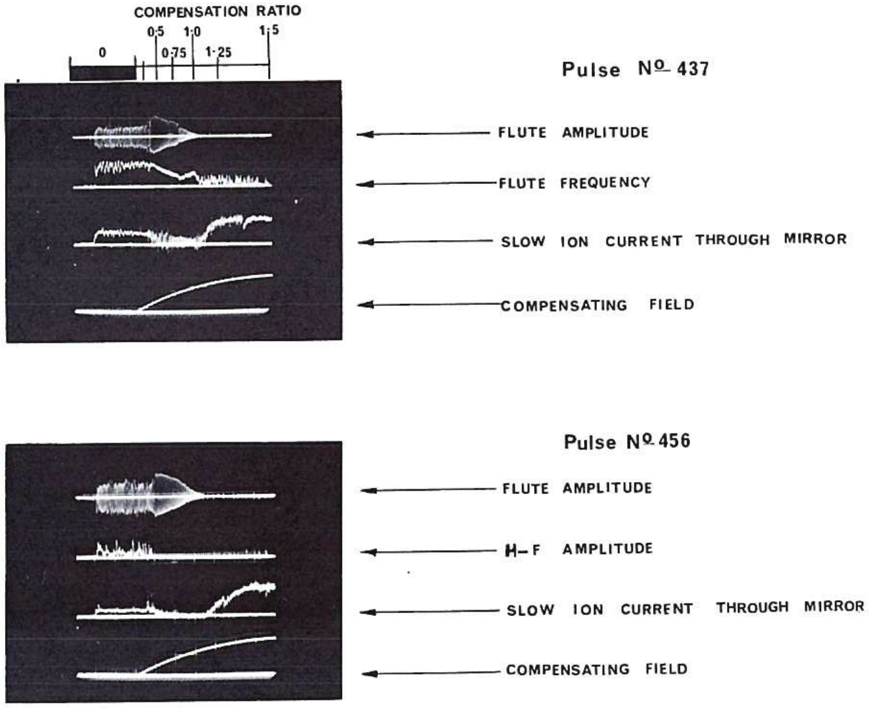


Fig. 7 (CLM-P91)

Variation of neutral emission and cold ion currents with compensation ratio



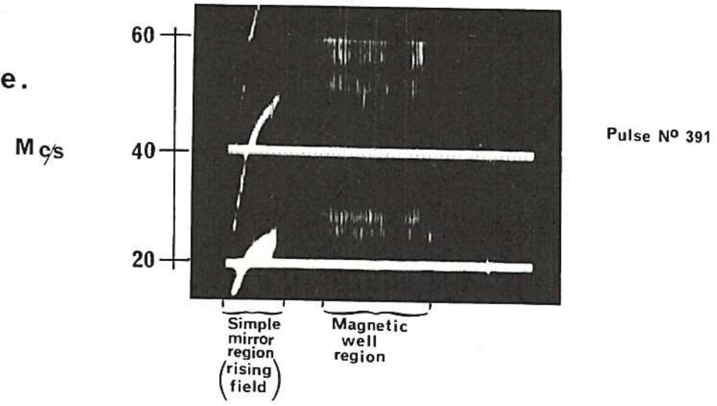
SWEEP SPEED = 0·2 sec/cm

CENTRAL MAGNETIC FIELD = 16·8 k.gauss

Fig.8 (CLM-P91)
Phenomena in the transition region

Frequency Spectra of H-F over a Complete Pulse.

Time scale. 500 m sec/cm



Frequency Spectra of H-F in Magnetic Well Region.

On Expanded Time Scale. 20 m sec/cm

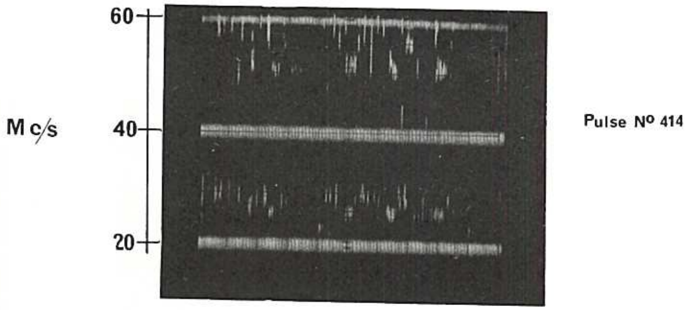


Fig.9 (CLM-P91)
Frequency spectra of H-F (a) over a complete pulse (Time scale: 500 msec/cm); (b) in magnetic well region (On expanded time scale: 20 msec/cm)

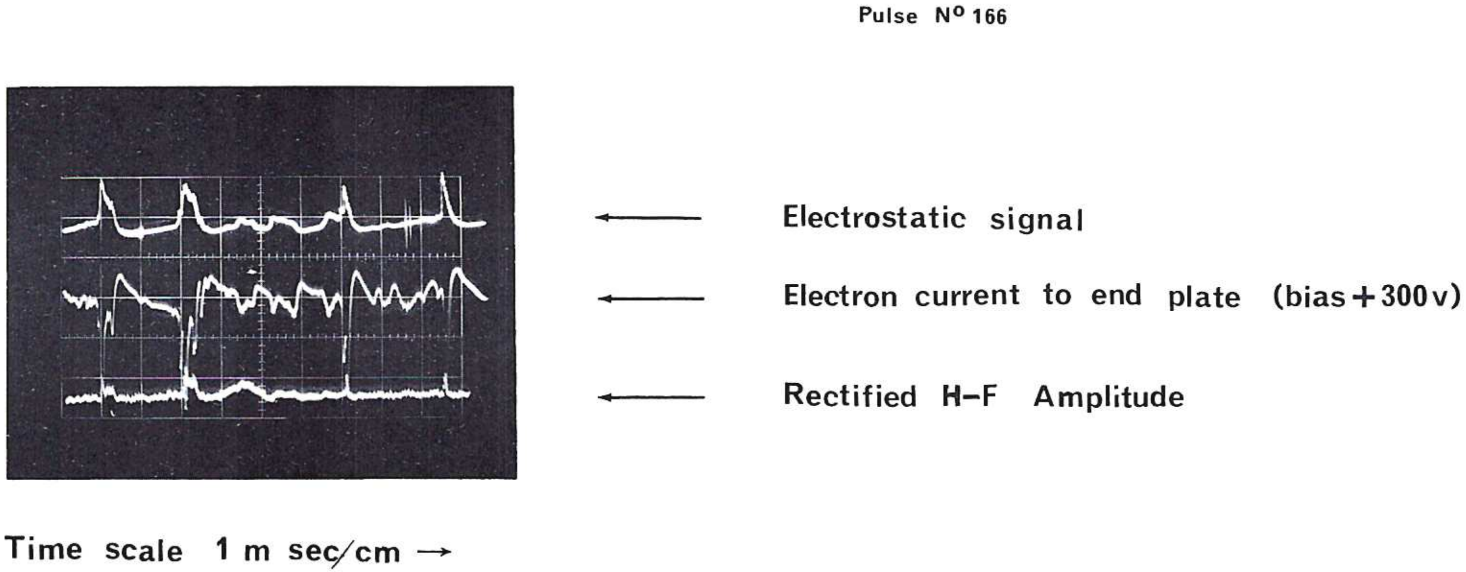


Fig.10 (CLM-P91)
The dependence of plasma potential and electron current through the mirror on H-F activity in the magnetic well

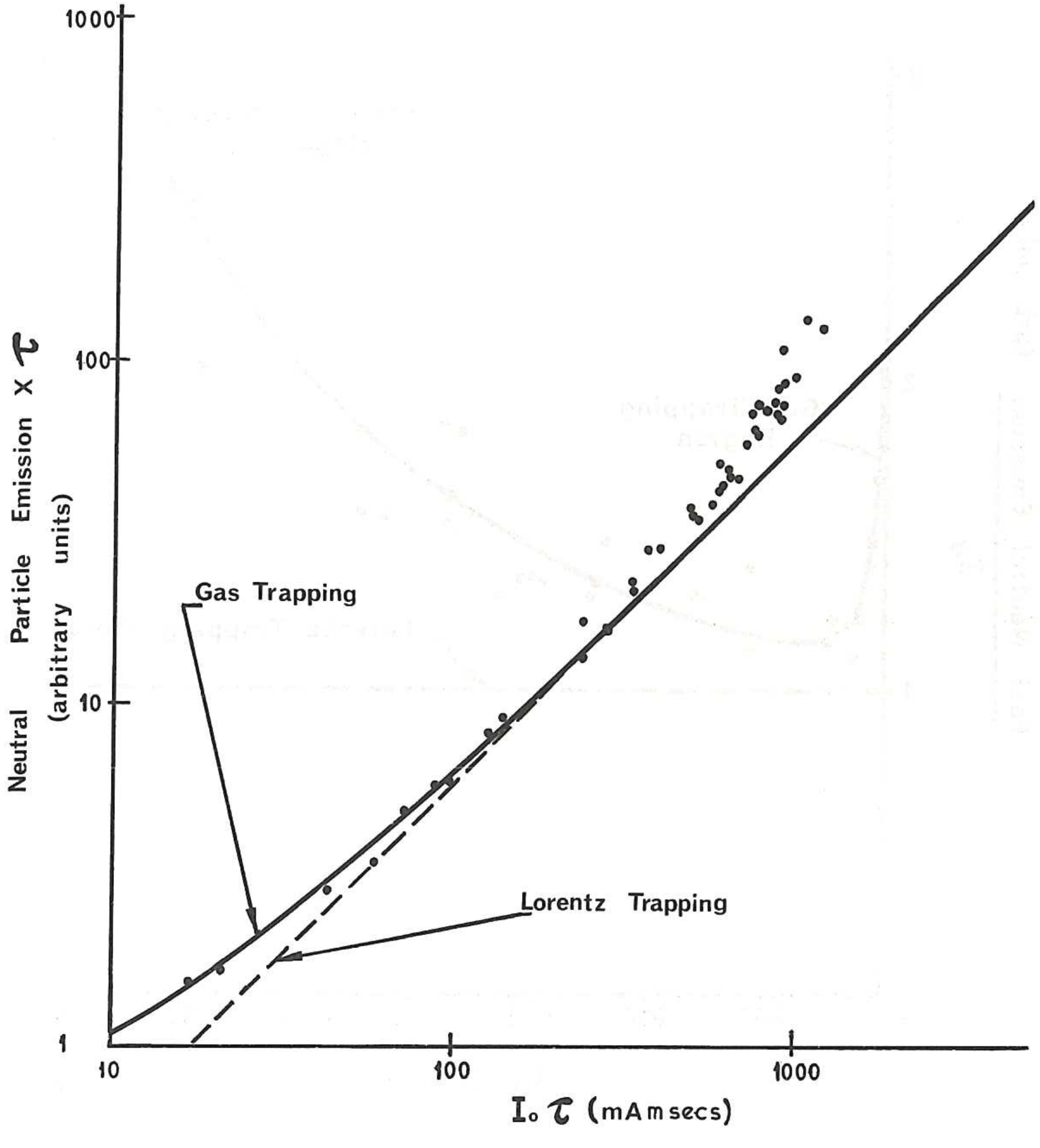


Fig. 11 (CLM-P91)

Neutral particle emission × τ as a function $I_0 \tau$

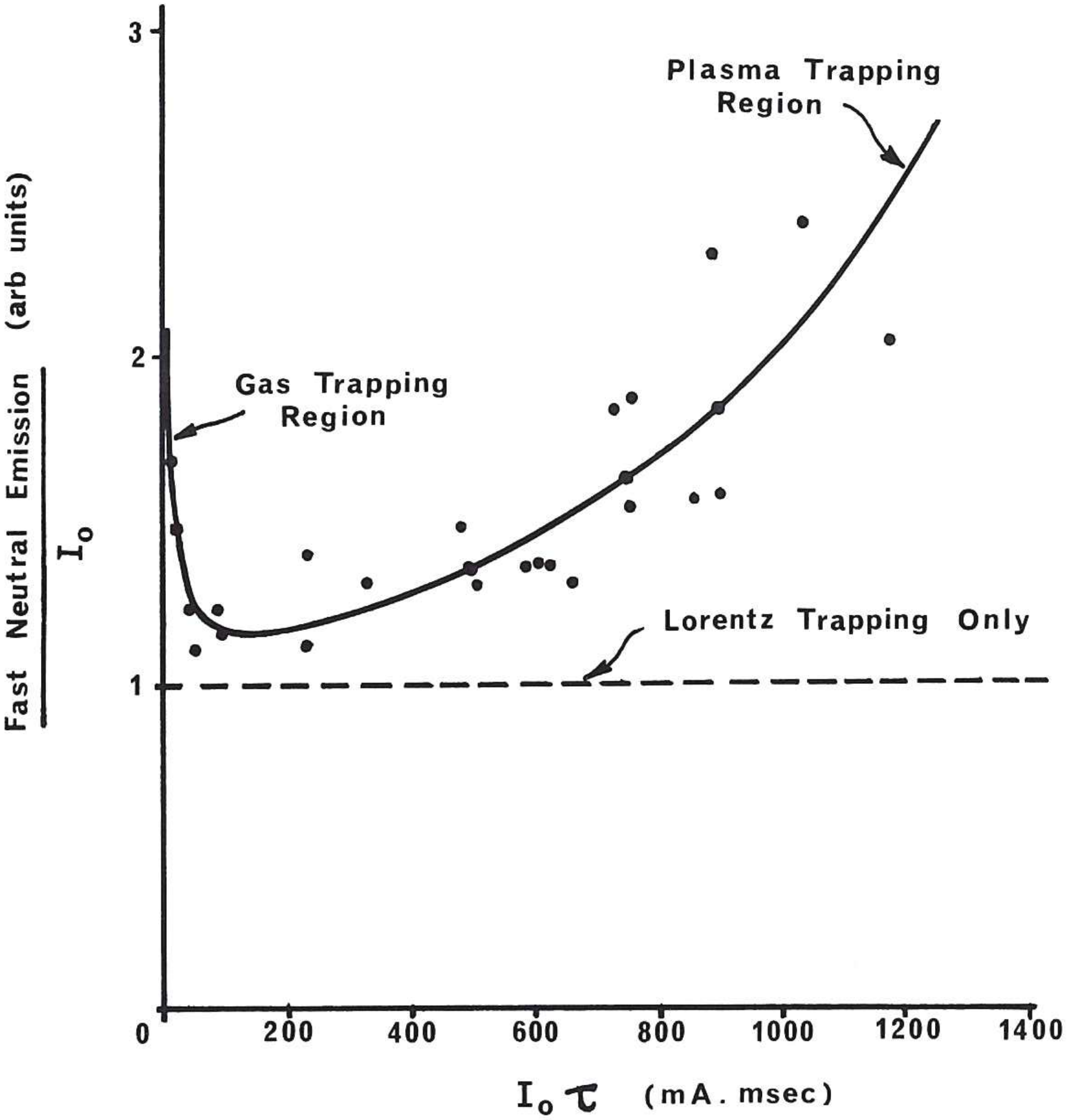


Fig. 12 (CLM-P91)
Normalised neutral particle emission as a function of $I_0 \tau$