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Some remarks on stochastic collective oscillations in ECRIS plasmas

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14

Abstract

It is proposed that the thermal fluctuations in plasmas in general and in ECRIS plasmas in particular create rather strong stochastic electrical fields affecting both confinement and heating of an ECRIS plasma.

The amplitude, range and characteristic frequency of the stochastic fields as well as the perpendicular diffusion coefficient and the upper density limit for the mirror confinement are determined on the level of the approximate evaluations. Some aspects of the ECRIS plasma's peculiarities due to the stochastic electrical fields are discussed.

(submitted to Plasma Sources Science & Technology)

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I. Introduction

Plasma confinement and heating are the key processes in ECRIS devoted to producing positive single and multiply charged or negative ions. In each case plasma parameters such as electron density and temperature, which depend on energy and particle confinement times, should be maintained in some well defined limits in order to promote the desired atomic and molecular processes and prevent undesired ones.

Both confinement and heating in ECRIS plasmas are traditionally discussed in the literature in terms of single particle models taking into account various kinds of binary collisions. This approach is quite adequate in the case of rarefied plasma where the collective interactions play a secondary role. However, as the plasma density increases approaching levels typical for each kind of ECRIS, the collective effects begin to play an important and often a determinant role in the ECRIS plasma dynamics.

As an example (see Fig. 1) the standard 10 GHz ECRIS plasmas are classified in three categories depending on the density level. The density range below 10^9 cm^{-3} corresponds to a deep underdense plasma where the Debye length r_d is larger or comparable to the plasma radius d, and the plasma frequency ω_p is much smaller than the microwave frequency ω. The individual particle dynamics is in fact applicable only to this kind of plasma which is of limited interest for ECRIS. The density range 10^9 cm^{-3} $< n_e < 10^{12}$cm^{-3} is typical for multiply charged and negative ion ECRIS and is classified here as an underdense plasma. In this case the Debye length is shorter than the plasma radius but the plasma frequency remains smaller than the microwave frequency. Finally, the range $n_e > 10^{12}$cm^{-3} corresponds to the overdense plasmas which are of interest in the single charged positive ions ECRIS and in highly efficient ionizers in particular for short lived radioactive elements. The Debye length is this case is negligible as compared to the plasma radius and the plasma frequency generally surpasses the microwave frequency. As one observes in this diagram, in the ECRIS plasmas which are of practical interest, the collective approach is unavoidable.

One such trial has recently been made in analyzing collective mechanisms of energizing electrons in ECRIS plasmas[1]. In the present article such universal collective phenomenon as fluctuating electrical fields and their effect on plasma confinement in a magnetic mirror configuration (cusped or non-cusped) is discussed on a level of numerical evaluations.

II. Fluctuating electrical fields in plasmas

Although macroscopically the plasmas are usually regarded as electrically neutral media (which means that the macroscopic electrical fields are null), the microscopic electrical fields seen by every individual charged particle are quite significant, in particular in ECRIS plasmas.

To have an idea about the actual level of the microscopic electrical field's strength affecting the electron motion between two successive collisions with other particles, let's remember that if one applies the virial theorem of Causius to a plasma, one should recognize that the average kinetic energy of plasma electrons is equal to the average potential energy of the electrical fields seen by electrons.

$$\overline{W}_{\rm kin} = \overline{W}_{\rm pot} \ . \qquad (1)$$

This principle has been successfully applied by Artsimovich and Sagdeev[2] to analyze Langmuir waves in plasmas. In particular they have found that the kinetic energy of electrons in a Langmuir wave electrical field is

$$\overline{W}_{\text{kin}} = \frac{n m u_e^2}{2} \tag{2}$$

while the Langmuir wave potential energy is

$$\overline{W}_{\text{pot}} = \frac{E^2}{8\pi} \, . \tag{3}$$

Here n is the electron density, m is the electron mass, u_e is the oscillatory electron velocity, E is the electrical field amplitude*.

In fact, the equality in average between the potential and the kinetic energie's densities in plasma waves, which follows from the virial theorem, becomes more evident if one imagines a plasma not as a mixture of charged particles only, but as a mixture of charged particles (electrons and ions) and quasi-particles (plasmons and phonons) as it is generally accepted in modern plasma physics[6]. In this more general model an equilibrium between the particles (kinetic energy carriers) and quasi-particles of fields (potential energy carriers) becomes a natural manifestation of the virial theorem and any type of plasma instability appears as desequilibrium between the kinetic and the potential energies' densities, which finally leads to an equilibrium state.

In this context there are no obvious reasons why the electron density fluctuations having a thermal origin cannot be treated as a plasmon gas which is nothing other than a stochastic Langmuir oscillatory thermal background. If one were to put oneself in this position, one can replace the kinetic energy density in the form of eq. (2) by the thermal energy density:

$$\overline{W}_{\text{kin}} = nkT_e \tag{4}$$

k being the Boltzmann constant.

Then, using eq. (1), (3) and (4) one immediately obtains the fluctuating electrical field amplitude (which is of thermal origin and therefore is unavoidable):

$$E_{\text{fl}} = (8\pi n k T_e)^{\frac{1}{2}} \tag{5}$$

or

$$E_{\text{fl}}, \text{kV/cm} = 2.10^{-6} (n T_e)^{\frac{1}{2}} \tag{6}$$

T_e being expressed in electron-volts, n in cm^{-3}.

In Fig. 2 eq. (6) is represented graphically and the typical parameter ranges for three kinds of ECRIS are approximately located. As one observes in Fig. 2, the typical fluctuating microscopic electrical field amplitudes range around 2 kV/cm in negative ion ECRIS, between 5 kV/cm and 10 kV/cm in single charged overdense ECRIS and between 20 kV/cm and 50 kV/cm in multiply charged ECRIS.

*Here and further the CGSE units are used if not stipulated.

These quite remarkable field strengths are the result of a local disturbance of the plasma neutrality. Due to the thermal character of this disturbance, the averaged local potential energy of electrons in the steady state condition is equal to their average kinetic (thermal) energy so that

$$kT_e = eU_{\text{fl}} \tag{7}$$

where e is the electron charge, U_{fl} is the fluctuating potential. Using eq. (7) and eq. (5) one can easily convince oneself that the range of fluctuating electrical fields E_{fl} is of the order of the Debye length. Indeed, according to eq. (7) and eq. (5), the range is

$$r_{\text{fl}} \simeq \frac{U_{\text{fl}}}{E_{\text{fl}}} = (kT_e/8\pi e^2 n)^{\frac{1}{2}} = 0.7 \cdot r_d \tag{8}$$

where r_d is the Debye length.

The typical time of the field fluctuations can be evaluated dividing the range r_{fl} (eq. (8)) by the thermal electron velocity $v = (2\ kT_e/m)^{\frac{1}{2}}$:

$$\tau_{\text{fl}} \simeq (m/16\pi e^2 n)^{\frac{1}{2}} = 0.5 \cdot \omega_p^{-1} \tag{9}$$

i.e. τ_{fl} is a half-period of Langmuir oscillations.

So the characteristic frequency of fluctuations is the plasma frequency. This is in agreement with the initial basic suggestion that the thermal fluctuations can be seen as a Langmuir oscillation's thermal background.

Figures 3 and 4 show respectively the range r_{fl} and the time τ_{fl} of the stochastic electrical fields provided by thermal fluctuations. As one concludes from Fig. 3 the electrical field is localized in the cells of small diameter, ranging between ~0.5 mm for multiple charged ECRIS and ~ 0.02 mm for single charged ECRIS. The typical range for negative ion ECRIS is around ~ 0.2 mm being in the middle between the single and multiply positive ion ECRIS cases.

The typical time for stochastic electrical field ranges between 5 psec in single charged ECRIS and 50 psec in negative ion ECRIS, the multiply charged ECRIS ranging somewhere around 15 psec.

The above consideration gives an unusual picture of an ECRIS plasma which, although macroscopically neutral, is still filled by extremely intense stochastic electrical background. According to this model, the plasma electrons are seeing around them a rather violent electrical 'tempest' and are not freely flying from one collision to another, as one imagines from a classical kinetic model. This very strong stochastic noise is not a result of some kind of plasma instability but is a thermal effect. For this reason it cannot be regarded as a plasma turbulence which commonly is a result of degeneration of some kind of initially coherent plasma instability having in its turn the origin in the kinetic non-equilibrium. The stochastic electrical noise discussed in this article exists in any kind of plasma, even in those which are in the thermal equilibrium.

The stochastic electrical background is not easy to directly observe experimentally because of very short characteristic time and range of the 'Langmuir cells'. On the

other hand such a strong electromagnetic noise should significantly affect the transport phenomena which in turn are determinant in the energy and particle confinement so important in each type of ECRIS.

In the following sections the effect of stochastic Langmuir fluctuations will be applied to the magnetic confinement in order to see how much the physical predictions made on this basis are consistent with the well known experimental results.

III. Diffusion across the magnetic lines

The diffusion as a transport phenomenon which is controlled by collisions should be affected by the stochastic electrical fields of thermal Langmuir fluctuations. To evaluate this effect, let's start with the most general definition of the diffusion coefficient coming from the kinetic theory of the gases:

$$D = \lambda \cdot v/3 \tag{10}$$

where λ is the characteristic length, v is the characteristic velocity. In the classical diffusion theory λ is the mean free path between two successive collisions, v is the thermal velocity. In our case both quantities, λ and v, are not so transparent in physical nature. Indeed, since in this section we are interested in the transverse to the magnetic lines motion, the thermal velocity is no longer characteristic because without collisions a charged particle with any thermal velocity doesn't move across magnetic field being in rotation around a given magnetic line (we suppose for simplicity the magnetic field to be homogeneous). The only mechanism propelling a particle across the magnetic lines is the drift in the crossed fluctuating electrical field $\vec{E}_{\text{fl}}$ and the static magnetic field $\vec{B}$. So, in our case we can write

$$v = c(E_{\text{fl}}/B) \tag{11}$$

c being the speed of light in the free space.

As for the characteristic length, we will define it later, writing it now in an implicit form using the Debye length:

$$\lambda = A \cdot r_d \tag{12}$$

where A is an unknown constant which will be determined below.

Then we obtain from eq. (10), (11) and (12):

$$D = 0.47 \cdot A \cdot (c/B)(kT_e/e) \ . \tag{13}$$

This expression is very similar to the diffusion coefficient of Bohm who postulated that

$$D_B = 0.06 \cdot (c/B)(kT_e/e) \ . \tag{14}$$

This last expression has been experimentally found to be universal in a very large band of plasma parameters from the thermal alkaline plasmas to the ECR or ohmic heated Tokamak plasmas [3].

The fact, that the stochastic Langmuir fluctuation concept results in a coefficient of the perpendicular diffusion which has been experimentally confirmed many times in

various plasma condition, is an indirect justification of the above proposed stochastic collective fields model. Comparing numerical coefficients in eq. (13) and (14) we found that A=0.13 so that the 'mean free path' takes an explicit form:

$$\lambda = 0.13 r_d \ . \tag{15}$$

As follows from eq. (15) a notion of 'collisions' with fluctuating electrical fields is very conditional. Since the 'free path' is shorter than the Debye length, an electron is in fact in a kind of permanent collision with a large number of surrounding charged particles which produce in each point an extremely intense stochastic electrical field. These 10 kV/cm range stochastic fields are a natural environment in which the charged particles move.

IV. Confinement along the magnetic lines (magnetic mirrors)

Macroscopically, the plasma confinement by the magnetic mirrors is due to the diamagnetic properties of a plasma. Microscopically, the diamagnetism is a result of the magnetic force effect on the trajectory of a moving charged particle. An isolated single charged particle whose velocity $\vec{v}$ is not strictly collinear to the magnetic induction vector $\vec{B}$ acquires a perpendicular energy and loses the same amount of parallel energy due to the non-working fraction of the Lorentz force:

$$F_L = (e/c)[\vec{v} \times \vec{B}] \tag{16}$$

being responsible for the confinement effect.

However, according to the above model, a particle in a plasma is subjected not only to the magnetic force but also to a fluctuating electrical force:

$$F = F_{\text{fl}} + F_L \ . \tag{17}$$

In contrast to the case of perpendicular confinement, the magnetic and electrical effects as seen in eq. (17) are additive and not multiplicative as in eq. (11). It means that two extreme cases exist:

$$\text{case} \quad F_{\text{fl}} \ll F_L \tag{18}$$

when particles are not interacting between them (single particle approximation is valid in this case) and

$$\text{case} \quad F_{\text{fl}} \gg F_L \tag{19}$$

in which the mirror effect can be neglected.

The frontier separating these two extreme cases is, obviously, at

$$F_{\text{fl}} = F_L \tag{20}$$

To digitize the condition eq. (20) let's replace the right side by the maximal value of F_L:

$$F_L^{\max} = \frac{e}{c} v \cdot B \tag{21}$$

v being the thermal velocity

$$v = (2kT_e/m)^{\frac{1}{2}} \ . \tag{22}$$

Then, using eq. (5) and (16) we obtain eq. (20) in the form

$$B = (4\pi nmc^2)^{\frac{1}{2}} \tag{23}$$

or

$$B_{(\text{kilogauss})} = 3.2 \times 10^{-6} n^{\frac{1}{2}} \tag{24}$$

where n is expressed in cm^{-3}.

Equation (24) is represented graphically in Fig. 5. It is seen that at the mirror field ranging around 1 kG which is typical for 2.45 GHz plasma sources only densities $\ll 10^{11}$ cm^{-3} can be well confined by magnetic mirrors so that the widely used overdense 2.45 GHz plasmas are freely flowing through the mirrors following magnetic lines without being reflected by the magnetic gradient.

As for 10 GHz ECR plasmas, there the typical peak magnetic field in the mirrors ranges around 5 kG and therefore, according to Fig. 5, the confined density should be $\ll 2 \times 10^{12}$ cm^{-3}. The typically reported value of the confined density in such ECRIS for multiply charged ions doesn't exceed 3×10^{11} cm $^{-3}$ which is in good agreement with the above limitation.

It is entertaining that multiplying both sides of eq. (23) by the factor of e/mc, one obtains the condition (eq. (23)) in the form

$$\omega_c = \omega_p \tag{25}$$

ω_c being the cyclotron frequency $\omega_c = eB/mc$. In these terms the condition of a normal parallel mirror confinement is

$$\omega_c \gg \omega_p \ . \tag{26}$$

In the case when one desires to transport a dense plasma along a magnetic canal with an increasing magnetic field without reflection, one should satisfy an opposite condition

$$\omega_c \ll \omega_p \ . \tag{27}$$

The cessation of the mirror confinement, when the density becomes as high as the plasma frequency is close or higher than the cyclotron frequency, is in good quantitative agreement with the experimental observations[4].

V. Discussion

As one could see, the adopted model in which a plasma is permanently filled by quite strong stochastic collective electrical fields gives adequate physical conclusions which are in agreement with independently obtained experimental results.

If one accepts this model, one should recognize that an electromagnetic field introduced into a plasma from outside can affect the plasma state only in the case that the strength of this field considerably surpasses the electrical noise, i.e. when it ranges at several tens of kilovolts or more. It is known, nevertheless, that an ECR plasma can be sustained by a very weak microwave power (few watts and even less[5]) at which the vacuum electrical field amplitude is several orders of magnitude less than the stochastic plasma fields. This seeming contradiction between the model and reality is easily eliminated if one remembers that at the resonance (ECR or Upper Hybrid Resonance) the energy compression takes place and, due to this effect, the electrical field amplitude drastically grows[1]. Such an energy densification can occur not only at resonances but also at cut-off conditions, for example in a non-magnetized microwave plasma or in laser produced plasmas. In this case, although the phase velocity of the incident electromagnetic wave

$$v_{\text{phase}} = c(1 - \omega_p^2/\omega^2)^{-\frac{1}{2}} \tag{28}$$

infinitely increases at ω_p approaching to ω, the group velocity

$$v_{\text{group}} = c(1 - \omega_p^2/\omega^2)^{\frac{1}{2}} \tag{29}$$

becomes zero at $\omega_p = \omega$ providing conditions for the energy densification[1].

In view of this, if one excludes from consideration the microwave discharges fed by exceptionally high power microwave supplies providing electrical field amplitudes of the order of 10^5 V/cm or more, the conventionally used microwave sources can sustain a plasma if a strong deceleration of the incident e.m. wave occurs somewhere inside the plasma due to a resonance or a cut off. In this case a strongly enhanced electromagnetic wave transfers its energy to the plasma via linear and/or non-linear resonant mechanisms of coupling with the collective degrees of freedom as discussed recently in detail elsewhere[1].

As one could see from the above analysis, both parallel and perpendicular confinements are highly dependent on the stochastic fields. The value of the confinement time is particularly important in ECRIS for multiply charged ions. Let us for this reason analyze some more in detail this particular case.

In multicharged ECRIS the plasma is underdense so that the condition eq. (26) is satisfied and the mirrors work well. In these conditions the electron confinement is limited by the stochastic fluctuation diffusion displayed with the Bohm diffusion coefficient D_B given by eq. (14). Note that in the metallic chambers the perpendicular diffusion of ions and electrons is independent because of the short-circuiting of the ambipolar fields by the end plates (so-called Simon diffusion regime). For this reason the electron confinement time τ_e can be estimated using a classical relationship

$$\tau_e = \frac{\Lambda^2}{D_B} \tag{30}$$

Λ being the diffusion length which is of the order of the chamber radius R. Taking into account eq. (14) and replacing Λ by R we obtain an approximate expression for an electron confinement time in multiply charged ECRIS

$$\tau_e \simeq 1.7 \times 10^{-4} \times R^2\,(\text{centimeter}) \frac{B(\text{kilogauss})}{T_e(\text{electron} - \text{volts})} \ . \tag{31}$$

For a typical 10 GHz multicharged ECRIS we can put $R = 3$ cm B=3 kG, $T_e = 500$ eV which gives $\tau_e = 9$ μsec. At the typical plasma density of $n = 3 \times 10^{11}$cm^{-3} and the core plasma volume $V = 10$ cm^3 the total electron loss current is

$$I_e^{(\text{loss})} = enV/\tau_e = 50 \text{ mA} . \tag{32}$$

The energy flux leaving the plasma due to these losses is 25 W which is quite a reasonable value.

To maintain the negative potential, which is necessary to provide the ion confinement, an equivalent electron current should be injected into the plasma from outside in addition to the electrons from the ionization 'in situ'. The dc electron current coming from the lateral walls which has indeed been measured in [7] ranged at 13.5 mA. This value is of the same order of magnitude that gives an approximate estimation (eq. (32)) if one takes into account the 'in situ' ionization. It is also stated in [7] that an artificial cut-off of this current resulted in an immediate collapse of the plasma, i.e. an external electron injection into a multiply charged ECRIS plasma is proved to be of vital importance for it. The necessity of supporting the core ECRIS plasma by an external electron injection is a direct indication on a quite short confinement time of electrons. To explain this very poor electron confinement the concept of stochastic collective fields, which gives the quantitatively reasonable estimation of the confinement time and related parameters, seems to be adequate.

The direct detection of the stochastic electrical fields in the case of a low density, low temperature plasma can be provided by a simple probe sized smaller than the Debye length and maintained at optimized potential in order to reduce the plasma sheath effect. For example a plasma with $n = 1 \times 10^8$ cm^{-3} and $T_e = 5$ eV has the Debye length $r_d = 1.7$ mm so that a spherical probe of 0.2 to 0.3 mm in diameter immersed in such a plasma would be appropriate to receive a signal from fluctuations with the amplitude of about 5 V in the frequency range around 90 MHz. The electrical field strength in this case is about 45 V/cm.

The high density and/or high temperature plasmas are much more difficult for such experiments because the probe should be very small and should support very high energy fluxes. In this case an analysis of the optical spectral lines' shape seems to be a hopeful way to detect high amplitude, high frequency stochastic electrical fields affecting atomic and ionic quantum states. It is likely that at the stochastic fields amplitude of several tens of kV/cm the Stark effect will give the results similar to those in a strong microwave field: the appearance of satellites around the fundamental spectral lines. In the case when the stochastic electrical fields become of the order of the atomic fields ($\sim 10^9$ V/cm) the atomic spectral lines should disappear, being replaced by continuous spectrum. According to (6) in this case the (nT_e) - parameter should be of the order of $5 \cdot 10^{23}$ eV/cm^3 to reach such high field amplitudes. Such conditions are realized in a laser plasma, for example at $n \simeq 5 \cdot 10^{20}$ cm^{-3} and $T_e \simeq 1$ keV.

VI. Conclusions

It is proposed that the thermal fluctuations in a plasma produce intense stochastic electrical fields affecting the magnetic confinement and the rf heating. In ECRIS the typical values of these fields range between 1 kV/cm and 50 kV/cm. The characteristic range and frequency of these stochastic fields are the Debye length and the

Langmuir frequency. The stochastic electrical fields are not a result of some kind of plasma instability but are a thermal effect so that they are present in any kind of the equilibrium or non-equilibrium plasma and are unavoidable.

The perpendicular electron diffusion displays as a result of the stochastic electrical fields with the enhanced rate characterized by the Bohm diffusion coefficient. Due to the stochastic electrical fields the mirror confinement becomes inefficient if the plasma frequency is of the order of or higher than the cyclotron frequency in the mirror. These quantitative conclusions of the stochastic electrical fields' concept are in good agreement with the independent experimental data obtained elsewhere.

The application of the stochastic electrical fields concept to the multi-charged ECRIS plasmas results in prediction of the fundamental importance of the external electron injection into the core ECRIS plasma as a consequence of the stochastic fields enhanced perpendicular diffusion.

VII. REFERENCES

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Figure Captions

1. Ranges of densities where the individual or the collective models are valid in the case of 10 GHz ECRIS.

2. Fluctuating electrical field amplitude as a function of plasma density of three values of the electron temperature. Typical conditions for various kinds of sources range inside the ellypses: 1) negative ion ECRIS, 2) multiply charged ion ECRIS, 3) single charged positive ion ECRIS.

3. Range of fluctuations at 10 eV, 100 eV and 1000 eV electron temperatures: 1) negative ion ECRIS, 2) multiply charged ECRIS, 3) single charged ECRIS.

4. Characteristic time of fluctuations as a function of the plasma density: 1) negative ion ECRIS, 2) multiply charged ECRIS, 3) single charged ECRIS.

5. The thermal fluctuations caused density limit for the mirror confinement as a function of the magnetic induction in the mirror.

6. Thermal fluctuations controlled perpendicular electron confinement time as a function of the magnetic field for three different electron temperatures.

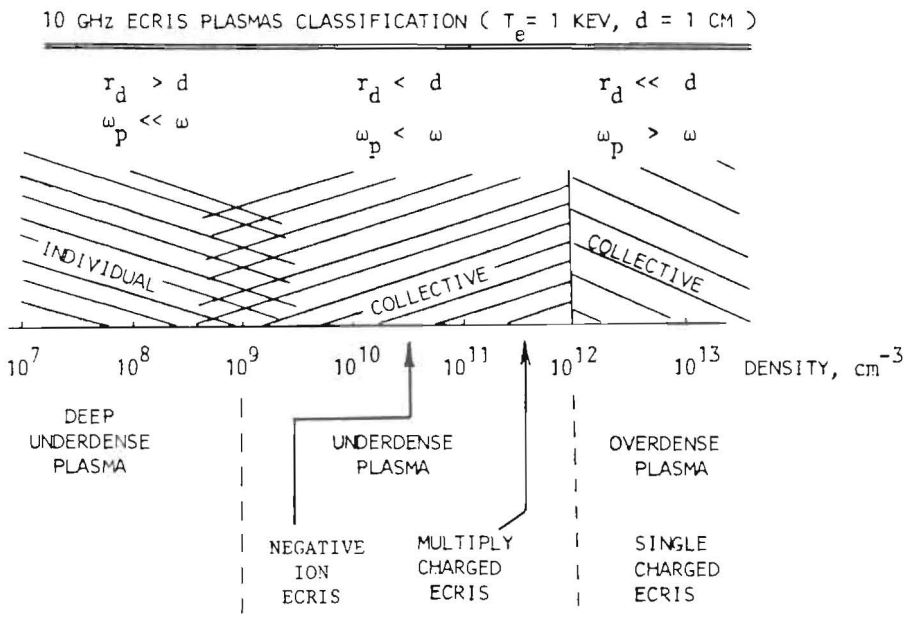

Fig. 1

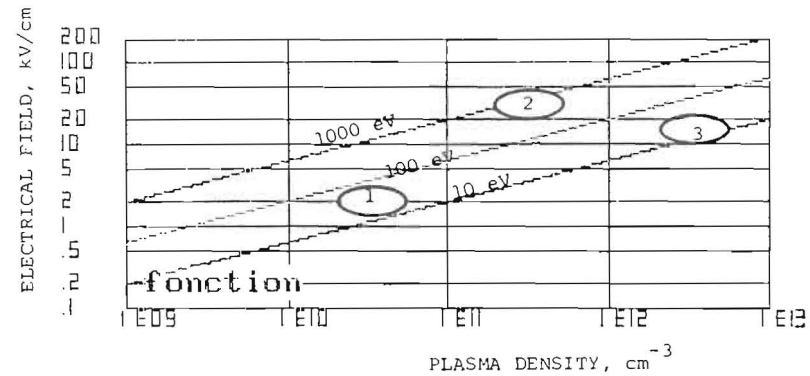

Fig. 2

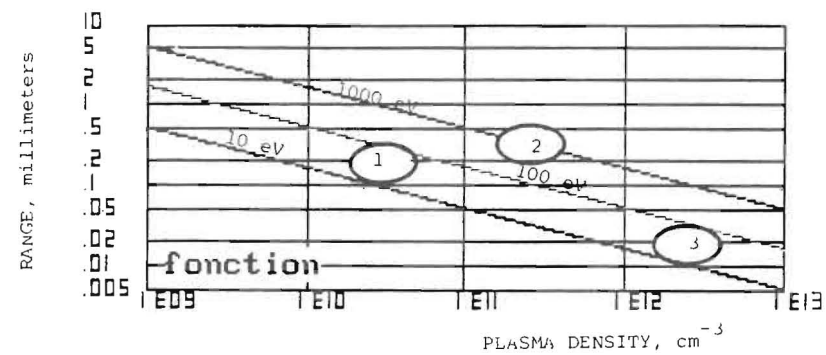

Fig. 3

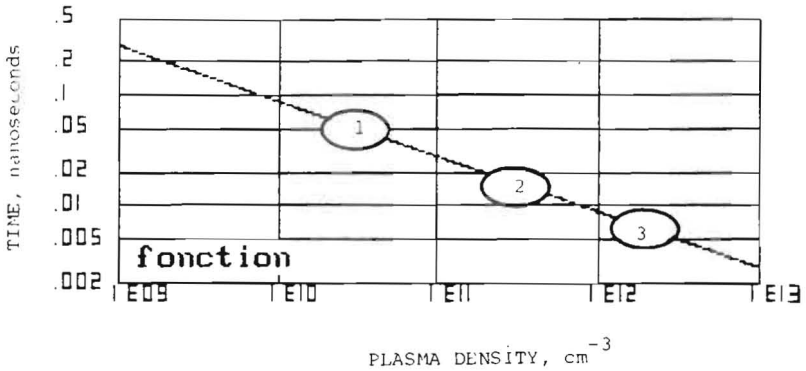

Fig. 4

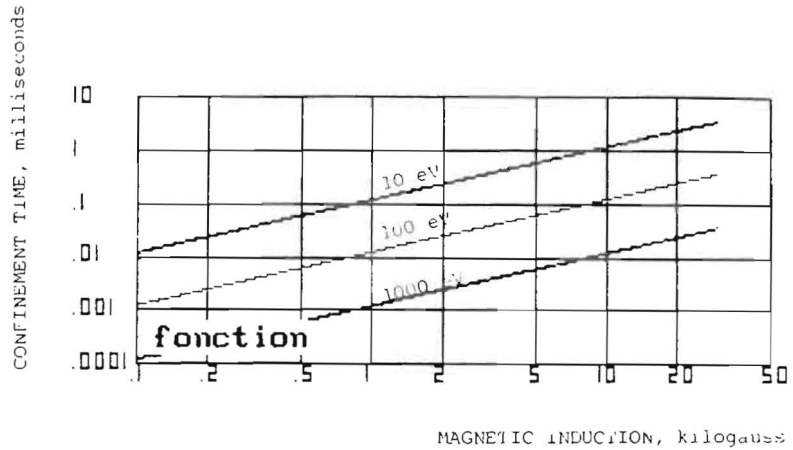

Fig. 6

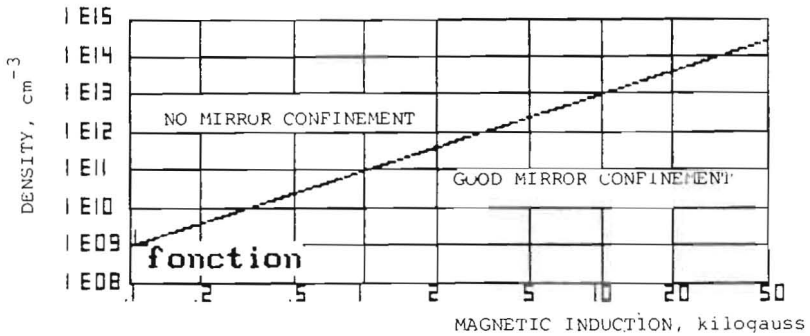

Fig. 5