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HIGH-TEMPERATURE ELECTRON COMPONENT IN A BEAM PLASMA INTERACTION

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We present the results of an investigation of the hot component of a plasma formed by an intense electron beam in a mirror device with a high mirror ratio. We have investigated the electron temperature and the total plasma energy as functions of the magnetic field, limiter radius, and heating time. The dependence of the turbulent diffusion coefficient on magnetic field has been obtained. A model is proposed for beam heating; this model is based on the assumption that the electron beam is the source of particles that are heated. The model is in good agreement with the data of the present experiment as well as earlier experimental work.

1. INTRODUCTION

AT the present time it is generally accepted that plasma heating in beam-plasma experiments[1-10] is due to the interaction of particles with waves, the driving mechanism being the beam that penetrates the cold plasma. Within the framework of this general idea one can consider two alternate theoretical models.

The first model is based on the notion that the beam acts only as a source of waves which propagate through the cold plasma and cause the heating of some fraction of the electrons in the plasma.

In the second model the beam serves not only as a source of waves, but also as a source of the particles that are entrained in the acceleration process. The qualitative pattern of effects corresponding to this models is the following: as a consequence of the development of the two-stream instability some fraction of the particles in the beam are "extracted" from it and fall into the region surrounding the beam; subsequently these particles interact with the waves (the source of which is also the beam) and diffuse away from the center of the trap toward the edge, acquiring energy in the process.

It will be evident that the difference between the two models indicated above lies in the origin of the accelerated particles. Whereas the first model considers heating of some fraction of the particles in the cold plasma, the second model assumes that the particles that are heated come from the beam itself and diffuse toward the edge of the trap. Obviously, intermediate situations are possible in actual systems. At the present time we lean toward the opinion that the conditions in the present experiment correspond to the second model which, as will be evident below, is in satisfactory agreement with most of the observed effects.

2. DESCRIPTION OF THE APPARATUS

A diagram of the apparatus is shown in Fig. 1. The basic elements are as follows: electron gun 1, plasma injector 2, vacuum chamber 3, coils for the main magnetic field 4, mirror coils 5. The electron gun is the same as that described in[9] but its parameters have been improved somewhat by some minor modifications. The acceleration voltage has now been increased to 35 kV and the beam current has been increased to 20 A at a pulse length of 250 μsec. The diameter of the electron beam at the center of the trap is 1.4 cm.

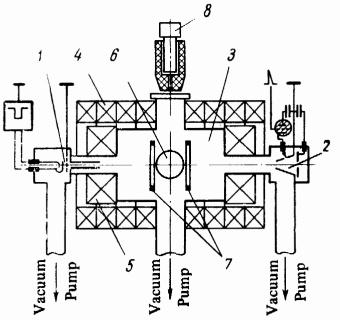


FIG. 1. Schematic diagram of the apparatus; 1 – electron gun, 2 – plasma injector, 3 – vacuum chamber, 4 – coil for the main magnetic field, 5 – mirror coils, 6 – diagnostic port, 7 – diamagnetic probe, 8 – FÉU-52 photomultiplier with NaI(T1).

The plasma injector consists of two electrodes made of titanium sheet 0.5 mm in thickness which are hydrogen saturated. One of the electrodes is in the form of a truncated cone while the other is a disc with an aperature at its center. The center of the disc lies on the axis of the cone and the plane of the disc is parallel to the base of the cone. The disc is located at some distance (approximately 1 cm) from the large base of the cone. A discharge is fired between the inner surface of the cone and the disc (in the direction of the magnetic field) by means of a low-inductance capacity. The plasma jet flows through the small base of the cone. The operation of the injector is initiated by a triggering device which can be fired with a controlled time delay with respect to the electron gun. The plasma injector and the electron gun are located beyond the mirrors on the axis of the system. The injection of the plasma jet and the electron beam takes place along the magnetic field in opposite directions. The injector fills the trap with cold plasma at a density of 10^{12} cm^{-3} and a temperature of 5–10 eV. During the injection of the electron beam the density of cold plasma remains essentially unchanged. The electron beam passes freely through the plasma injector, striking a massive end-plate in the chamber. It has been verified that the presence of the plasma does not lead to an appreciable change in beam diameter. The electron gun is isolated from the vacuum chamber by a long narrow channel and is pumped by a separate pumping system. For this reason the plasma jet has no effect on the gun operation.

In the central region the vacuum chamber is 40 cm in diameter and the distance between mirror centers is 80 cm. The chamber is fabricated from stainless

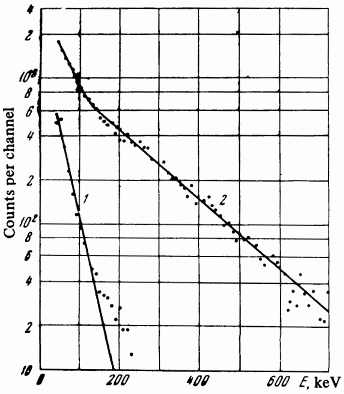


FIG. 2. Spectrum of the x-ray emission from the plasma. 1 – H = 0.5 kOe; 2 – H = 1.65 kOe. The acceleration voltage on the electron gun is 27 kV and the beam current is 10 A.

steel. The residual pressure in the chamber is 10^{-6} mm Hg. The maximum magnetic field at the center of the trap is 2 kG; the field at the mirrors is 10.5 kG.

The following diagnostic methods have been used to examine the plasma: 1) microwave measurements at wavelengths of 0.8 and 3 cm; 2) diamagnetic probes; 3) collimated x-ray detectors.

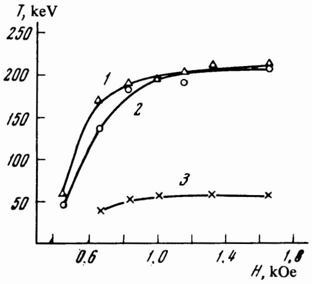
3. PLASMA TEMPERATURE

In earlier work[9] the present authors have observed a dependence of electron temperature of the hot component of the plasma on magnetic field. As the magnetic field is increased the electron temperature first increases and then reaches a steady value which is independent of magnetic field. In that same work it was observed that the diamagnetic signals increase monotonically during the time in which beam injection takes place (100 μsec). This increase can be due to the accumulation of hot electrons or to increasing electron energy. It is difficult to distinguish between the two effects. In order to resolve this question, in the present work we have investigated the x-ray spectra emitted from the plasma as a function of magnetic field and the length of the electron pulse.

The x-ray detector is an FÉU-52 photomultiplier with an NaI(Tl) crystal. A lead collimator is used to eliminate background x-ray radiation from the chamber walls. The spectra are recorded by means of a 100-channel analyzer. The analyzer operates in a slave mode and is switched on simultaneously with the initiation of the discharge (first 20 msec). Thus, the spectrum is averaged over this time period in each discharge. Approximately 200 discharges are used for one spectrum in order to obtain good statistics. The calibration is carried out by means of cesium 137 (E = 660 keV) and americium 241 (E = 60 keV).

In Fig. 2, on a semilogarithmic scale, we show the x-ray spectrum for limiting values of the magnetic field. It is evident that the spectral composition of the x-ray spectrum is very sensitive to the magnitude of the magnetic field. As the magnetic field increases the x-ray spectrum becomes harder, indicating that the electron energy is becoming higher. The electron temperature for H = 0.5 kOe is estimated to be 40 keV; for H = 1.65 kOe the estimated temperature is 200 keV. A large number of spectra have been taken with various values of the magnetic field H and electron-beam lifetime t. In Fig. 3 we show the temperature dependence for these spectra. The behavior of the electron temperature and its limiting level for t = 250 μsec and t = 130 μsec are essentially the same, but for t = 60 μsec the electron temperature is considerably lower. The dependence of electron energy on the lifetime of the electron beam shows that under the present experimental conditions there exists some optimum time beyond which there is no point in continuing the heating process. It will be shown below that this time is related to two effects: the escape of particles into the loss cone, and the diffusion of particles across the magnetic field.

FIG. 3. The electron temperature as a function of magnetic field for various lifetimes of the electron beam: 1 – t = 250 μsec, 2 – t = 130 μsec, 3 – t = 60 μsec. The acceleration voltage on the electron gun is 27 kV and the beam current is 10 A.



In order to examine the role of diffusion in the plasma heating mechanism we have measured the electron temperature using various transverse dimensions for the plasma (the plasma was limited by an aperture). Measurements of the electron temperature for aperture radii of 12 cm and 6 cm in a magnetic field of 1.32 kOe and an electron-beam lifetime of 250 μsec yield values of 190 and 80 keV respectively. Quantitative temperature measurements were not carried out with smaller apertures; because of the reduction in the photon energy and the reduction in the total number of photons, in order to accumulate good statistics it is necessary to carry out the experiment for long time periods. However, the qualitative pattern of the x-ray spectra observed at smaller aperture dimensions indicate a further reduction in the energy of the hot electrons.

4. PLASMA DIAMAGNETISM

In principle, measurements of the plasma diamagnetism make it possible to determine the energy density associated with the transverse particle motion ($nT_\perp$). However, in computing the quantity $nT_\perp$ it is necessary to know the transverse cross-section of the plasma column S, a quantity which is generally now known. It is even more difficult to determine the plasma cross-section in pulsed experiments. Hence, one frequently deals with the quantity $Q = nT_\perp S$, which is proportional to the energy associated with the transverse particle motion in the plasma. This quantity, which will be called the energy confinement, can be directly computed from the signal obtained from the diamagnetic probe and fed to an RC integrating network through the use of the expression

$$Q = UHRC / 4\pi W,$$

where U is the measured voltage at the output of the RC network, H is the magnetic field at the center of the trap, and W is the number of turns on the probe.

In the experimental evaluation of the models that

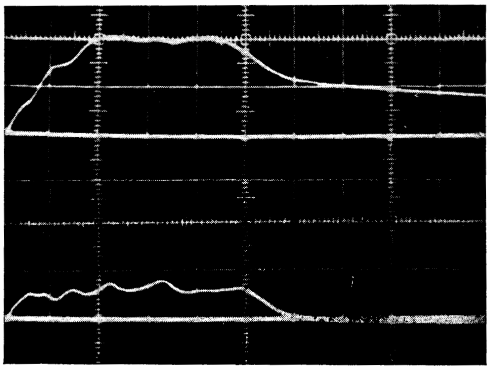


FIG. 4. Oscillograms of the diamagnetic signal for various radii of the plasma limiter. In the upper oscillogram r = 12 cm and in the lower oscillogram r = 4.5 cm. The acceleration voltage on the electron gun is 27 kV, the beam current is 13 A and the sweep width is 500 μsec.

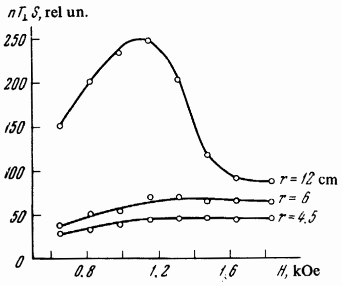


FIG. 5. The energy confinement in the plasma as a function of magnetic field. The acceleration voltage on the electron gun is 27 kV and the beam current is 10 A.

are proposed in the present work a very important element is the investigation of the dependence of the energy confinement on magnetic field and transverse plasma dimensions. The transverse dimensions of the plasma are determined by the apertures which are located at the center of the system. The diamagnetic probe itself serves as a large aperture (r = 12 cm); this probe is rigidly fastened inside the chamber. Two other limiters of sheet copper have aperture radii of 4.5 and 6 cm respectively. These limiters are located in perpendicular tubulations at the center of the chamber and can be moved individually to the axis of the system. The radii of the apertures in the limiters are considerably greater than the radius of the electron beam.

Oscillograms of the diamagnetic signals (Fig. 4) obtained with all other experimental conditions the same indicate that the diamagnetic signal increases (as does the quantity Q) to some fixed level in a time shorter than the lifetime of the electron beam. It is also evident that the time for saturation of the signal becomes smaller, the smaller the radius of the aperture in the limiter. The plateau in the diamagnetic signal is due to the fact that the plasma expands across the magnetic field and comes into contact with the limiter. This contact inhibits further increases in the energy confinement of the plasma. Using the steady-state signal from the diamagnetic probe and the area of the corresponding limiter it is possible to compute the mean value of $nT_\perp$. This quantity is found to be approximately the same for all the limiters that have been used. Thus, the accumulation of hot plasma proceeds with an increase of its volume, in which case the energy density remains essentially constant with the possible exception of a small region around the beam itself.

From oscillograms of the diamagnetic-probe signals obtained for different values of the magnetic field and limiter radii we have plotted the dependence of plasma energy confinement on magnetic field for limiters of different dimension. The results are shown in Fig. 5. For the limiters with aperture radii of 4.5 cm and 6 cm the curve showing the dependence of the energy confinement on magnetic field are essentially the same in shape. In both cases, as the field increases one first observes an increase in the energy confinement of the plasma which is followed by a leveling; beyond this point the energy confinement remains essentially constant. However, the pattern is very different in the case of the large radius limiter (r = 12 cm, Fig. 5). The curve showing the dependence of plasma energy confinement on magnetic field is bell-shaped with a clearly defined maximum at H = 1.15 kOe. For magnetic fields to the right of the maximum (H > 1.15 kOe) there is a considerable reduction in the energy confinement of the plasma although the temperature remains essentially the same for these values of magnetic field. We conclude that the reduction in energy confinement is a consequence of the reduction of the total number of hot electrons. The initial part of the curves in Fig. 5 correlate well with the rise in electron temperature in weak magnetic fields (Fig. 3).

5. DIFFUSION OF HOT PLASMA ACROSS THE MAGNETIC FIELD

Many authors[3,5,8,9] have indicated effects associated with increases in the transverse dimensions of the plasma as compared with the diameter of the electron beam, a result that is found to be a characteristic feature of beam-plasma experiments. This "bulging" of the plasma is to be associated with an anomalously high rate of diffusion across the magnetic field. In order to determine the rate of transport of the boundaries of the hot plasma we have made use of an x-ray method which can be summarized as follows. If the hot plasma encounters some obstacle in its expansion (the wall or any other target) the result of the deceleration of the electrons leads to intense x-ray radiation. By establishing a target at some known distance from the axis of the trap (more precisely at a known distance from the boundary of the beam) and by measuring the delay time for the appearance of the x-ray radiation from the target with respect to the time at which the electron beam is switched on, one can determine the rate of expansion of the plasma. In the present experiments the target is a tungsten needle which can be moved along a radius of the chamber. The x-ray detector is enclosed in a lead container and the radiation from the point of the needle can reach the crystal only through a long narrow channel in a lead collimator. In order to verify that the detector recorded radiation from the target only the latter was removed from the field of view of the collimator. The radiation from the volume of the plasma subtended through by collimator was found to be at least two orders of magnitude lower in

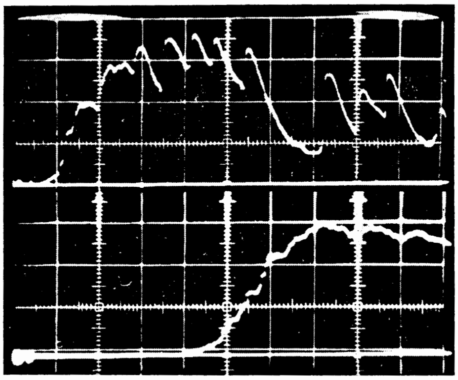


FIG. 6. Oscillograms of the x-ray signal with the target located at a distance of 9 cm from the axis of the trap. In the upper oscillogram H = 0.66 kOe and in the lower oscillogram H = 1.65 kOe. The acceleration voltage on the electron gun is 27 kV, the beam current is 10 A and the sweep width is 200 μsec.

intensity and could not be measured. In the chamber wall opposite the collimator there is an aperture used for pumping; at this point the wall is far-removed from the nominal position of the chamber wall and does not generate x-ray radiation. The radiation from the remaining surface of the plasma does not fall into the field of view of the collimator.

In Fig. 6 we show oscillograms of the x-ray signals for two values of the magnetic field for a case in which the target is located at a distance of 9 cm from the axis of the trap. It is clear that the rate of transport of the plasma boundary is a sensitive function of magnetic field. The pulse shape for the weak magnetic field (H = 0.66 kOe, upper oscillogram) shows an oscillatory structure which is evidently due to pulsations or rotation of the plasma. In the strong magnetic field (H = 1.65 kOe, lower oscillogram) the large scale pulsations disappear and the plasma boundary appears to be smeared out.

The time of arrival of the hot plasma at the target, as a function of magnetic field, is shown in Fig. 7 (curve 1). These results allow us to establish the dependence of the effective diffusion coefficient on magnetic field; this effective diffusion coefficient is defined by the relation $D_{eff} = r^2/\tau_D$ where r is the distance from the target to the axis of the trap and τ_D is the time required for the hot plasma to reach the target. The dependence of D_{eff} on magnetic field is approximately H^{-2}. It should be noted that D_{eff} is appreciably greater than the classical diffusion coefficient computed on the basis of Coulomb collisions. This is probably a consequence of the turbulence of the plasma.[11]

Similar experiments have been carried out with the target removed up to distances of 12 cm from the axis of the trap. In the weak field region (H < 1.15 kOe) the nature of the dependence of the arrival time of the hot plasma on magnetic field is found to be unchanged. In going to higher magnetic fields one observes a qualitatively new effect: specifically, when H > 1.15 kOe the hot plasma does not generally reach the target. This result indicates a reduction in the diameter of the hot plasma at high magnetic fields.

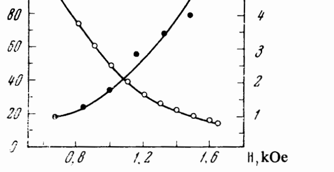


FIG. 7. Time required for the boundary of the hot plasma to reach the target as a function of magnetic field-curve 1; curve 2 is the effective diffusion coefficient. The accelerating voltage on the electron gun is 27 kV and the beam current is 10 A.

6. DISCUSSION OF THE RESULTS

In interpreting the experimental results we will start with the model of heating based on the assumption that the electron beam itself is the source of accelerated particles (cf. Introduction). If this assumption corresponds to reality, the filling of the trap with hot plasma can occur only through diffusion of fast electrons from the axis of the trap to the edge. Hence, we will call this the diffusion-heating model.

Assuming the validity of the diffusion model we first examine what conclusions the diffusion mechanism and electron acceleration mechanism lead to in connection with the experimental data. As we have shown above, the trap is filled with hot plasma in a time of 50—100 μsec while the decay extends over several tens of milliseconds.[9] Thus, it is reasonable to assume that when the beam is switched on the diffusion of fast electrons is due to their interaction with the oscillations excited by the beam. The point here is that if diffusion is due to other causes, not associated with the presence of the "working" beam,[1] the time required for filling the trap with hot plasma would be comparable with the time required for decay of the hot plasma after the beam is switched off, in contrast with the experimental results.

An important experimental fact is the presence of a strong dependence of the hot-electron temperature on the radius of the aperture used to limit the plasma. It is clear that the characteristic energy of the electrons "expelled" from the beam is determined by processes that occur in the beam itself and that these would not depend on the radius of the limiter.[2] Hence we are led to the conclusion that the energy acquired by the fast electrons outside the beam is much greater than their initial energy, the energy they have directly upon leaving the beam (if this were not the case the temperature of the hot plasma would be determined by the initial energy of the electrons and would be independent of the limiter radius).

Thus we have obtained two important results: first, the electrons "expelled" from the beam diffuse to the edge of the trap as a consequence of their interaction with oscillations excited by the beam; second, in the region outside the beam these electrons undergo a strong acceleration mechanism which leads to a significant increase in their energy.

We now consider the question of which oscillations are responsible for the diffusion and heating of the

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[1] For example, the development of instabilities excited by virtue of the inhomogeneity in the density of hot electrons.

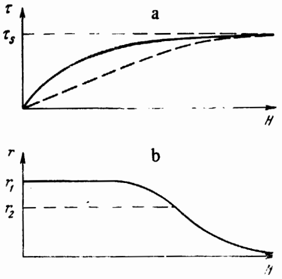
[2] The radii of the apertures in the limiters in the present experiments were all appreciably greater than the radius of the electron beam and thus do not have an effect on processes occurring within the beam.

fast electrons. First of all, we can eliminate from consideration all kinds of oscillations whose existence require the presence of streams of charged particles (cf. for example[12,13]) since these oscillations can only exist within the beam itself. It is important, furthermore, that in the present experiments the density of hot electrons is small compared with the density of cold electrons, that is to say, the dispersion properties of the plasma are determined by the cold electrons. For this reason we need consider only those modes of oscillation which can propagate in a cold electron plasma with no beams. The problem can be simplified still further if one recalls that in the present experiments the electron plasma frequency $\omega_{\rm pe}$ computed from the density of the cold electrons, considerably (3—10 times) exceeds the electron cyclotron frequency $\omega_{\rm He}$. Under these conditions, as is well known from theory, the electron beam will primarily excite plasma oscillations.[3)] [12] The latter conclusion is in agreement with the results of experiments[5] in which microwave oscillations of the plasma were observed and in which it was established that when $\omega_{\rm pe} > \omega_{\rm He}$ the oscillations are concentrated near the electron plasma frequency. These considerations indicate that the basic role in the diffusion and heating is that of plasma oscillations which propagate from the axis of the trap to the edge.

It follows from the expressions for the growth rate for the two-stream instability[14] that the beam will primarily excite waves with wave vector parallel to its axis, that is to say, the spectrum of plasma oscillations in the present system is highly anisotropic. The interaction of the fast electrons with the plasma waves, which are characterized by a high degree of anisotropy, leads to diffusion and heating of the fast electrons. In order to evaluate these effects quantitatively it would be necessary to know the energy of the plasma waves excited in the system. Unfortunately, the determination of the energy of these waves would require a complete analysis of the processes that occur in the beam and, at the present time, such an analysis is not possible. However, one can introduce some general considerations which indicate that when $\omega_{\rm pe} \gg \omega_{\rm He}$ the energy of the waves in the system is independent of magnetic field. On the basis of this result we can find the dependence of the diffusion coefficient and rate of increase of electron energy on magnetic field. It turns out that the diffusion coefficient is inversely proportional to the square of the magnetic field and that the rate of increase of the energy is independent of the magnetic field.

During the diffusion and heating process the fast electrons, as a consequence of their interaction with the waves, can be scattered into the loss cone and escape from the trap. Calculations show that the characteristic scattering time is independent of magnetic field and limiter radius. In addition, the time for scattering into the loss cone is a sensitive function of the mirror ratio. This dependence is of a threshold nature, that is to say, the scattering time falls off sharply when the mirror ratio becomes smaller than some critical value, and is due to the anisotropic spectrum of the waves.

FIG. 8. Diagram referring to the theoretical interpretation of the experimental results.



We can now consider qualitatively the entire complex of effects that occurs in the trap. The electrons are "expelled" from the beam and undergo an acceleration process, acquiring energy and diffusing from the beam to the outer wall of the trap. The energy acquired by the electron, which is determined by its lifetime in the trap τ, can be written in the form

$$\tau \sim \left(\frac{1}{\tau_D} + \frac{1}{\tau_S}\right)^{-1},$$

where $\tau_{\rm S}$ is the time for scattering into the loss cone while $\tau_{\rm D}$ is the time for the electron to diffuse to the outer boundary of the plasma ($\tau_{\rm D} \sim r^2/D_{\rm eff}$). The quantity $\tau_{\rm D}$ is proportional to H^2 while $\tau_{\rm S}$, as indicated above, is independent of H. At small magnetic fields, in which case $\tau_{\rm D} < \tau_{\rm S}$, the lifetime is determined by the diffusion and increases in proportion to H^2. At some value of H the diffusion time becomes comparable with the scattering time. A further increase in H then means that the lifetime is determined by $\tau_{\rm S}$, being independent of H (Figure 8-a). It is clear that the temperature of the hot plasma is an increasing function of the lifetime so that the curve T(H) must qualitatively reproduce the behavior of the curve τ(H). This conclusion is found to be in accordance with the experimental results (cf. Fig. 8-a and Fig. 3).

A reduction in the radius of the limiter leads to a reduction in the diffusion time $\tau_{\rm D}$; as a consequence the curve τ(H) changes in the way indicated by the dashed curve in Figure 8-a. It is evident that from the figure at low fields the lifetime τ will be reduced. This reduction corresponds to the dependence of electrons on temperature on limiter radius for weak magnetic fields as described in Section 3 and which is observed in the present experiments.

We now wish to consider the way in which the plasma radius ρ depends on the magnetic field. So long as the magnetic field is small so that $\tau_{\rm D} < \tau_{\rm S}$, the plasma reaches the limiter and its radius is equal to r. When the magnetic field is increased to a value such that $\tau_{\rm D} > \tau_{\rm S}$, the plasma does not reach the limiter and its radius is determined by the relation $\rho \sim \sqrt{D_{\rm eff}\tau_{\rm S}} < r$. This effect is observed experimentally, as we have indicated above. Since $D_{\rm eff} \propto H^{-2}$, the dependence of ρ on H at strong fields is given by $\rho \propto H^{-1}$ (cf. Fig. 8-b). On the basis of Figs. 8-a and 8-b we can now explain the dependence of the energy confinement Q on magnetic field. The quantity Q is proportional to the cross-sectional area of the plasma and the temperature of the hot electrons $Q \propto \rho^2 T$. At low fields, such

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[3)] In the present experiments the condition $\alpha \gg V_0/\omega_{\rm pe}$ is satisfied where α and V_0 are the radius and velocity of the beam. Hence, in determining the growth rates it is permissible to use the model of an infinite beam.

that $\tau_D < \tau_S$, the plasma radius ρ is equal to the limiter radius and does not depend on H while the temperature T is an increasing function of H. Hence, at weak fields Q will be an increasing function of H. In strong fields, for which $\tau_D \sim \tau_S$, the temperature is constant while the plasma radius falls off. Consequently, in this region Q will be a diminishing function of H. In the intermediate region, where $\tau_D \sim \tau_S$ the quantity Q will have a maximum.

We now wish to consider the threshold dependence of the energy contribution on the mirror ratio R which has been reported by us earlier.[7] Within the framework of the model adopted here this effect can be explained by the corresponding threshold dependence of the scattering time τ_S on R, which is due to the anisotropic wave spectrum.

In conclusion we wish to introduce other points of comparison of the theory (based on the diffusion model) with the experimental results. First of all the theory gives the correct dependence of diffusion coefficient on magnetic field. Second, it yields a natural and reasonable explanation for the dependence of energy confinement on mirror ratio, which has been observed earlier. Finally, the theory allows us to understand the dependence of energy confinement and hot electron temperature on magnetic field and transverse plasma dimensions.

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