nonlinear interactions with matter.

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Particle Loss in the Levitated Spherator FM-1*

J. Sinnis, M. Okabayashi, J. Schmidt, and S. Yoshikawa
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
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The plasma confinement times were studied in the levitated spherator FM-1 as a function of the electron density and electron temperature. It was found that below approximately 1 eV, the plasma confinement time is proportional to T_e^m/n_e ($\frac{1}{2} \leq m \leq \frac{3}{4}$) with an absolute confinement time 4–6 times below the classical confinement time. Above 1 eV the confinement time decreases as T_e^{-1} with an absolute confinement of 300 times the so-called Bohm diffusion time.

Recent experiments[1-4] suggest that over a limited range of plasma parameters the plasma confinement time increases with increasing electron temperature and decreases with increasing density. This result is consistent with the scaling of classical diffusion, but the absolute value may differ by a factor of 1–10 (pseudoclassical diffusion).[5] In the LSP experiments,[1] the maximum plasma confinement time was about 200 msec, which was 260 times the so-called Bohm time.

The important question both from the basic plasma-physics point of view and for fusion application is whether there is any deviation from this scaling law as the electron temperature increases. Experiments to answer this question are reported here.

The experiments were carried out in the second-generation levitated spherator called FM-1.[6] The previous levitated ring experiments performed in the device called LSP have been reported elsewhere[1] and a detailed report is now in preparation. The spherator has a single levitated current-carrying ring which produces the poloidal magnetic field, and with the aid of external conductors provides an azimuthally symmetric, toroidal confinement configuration with strong magnetic shear.

Table I lists the parameters at which LSP was operated along with the parameters at which FM-1 is presently operated. The maximum design ring current (I_P) for FM-1 is 375 kAt; however, the data presented here were obtained at 150 kAt. FM-1 has not as yet been operated with Ohmic heating, a fact which the lower density and electron temperature reflect.

Electron-cyclotron resonant heating is used to form the plasma in FM-1. Nonresonant microwave heating (above resonant frequency) is used to control the electron temperature in the afterglow. The nonresonant microwaves produce resistive heating of very low efficiency. The $T_e^{-3/2}$ dependence of the heating efficiency due to the

TABLE I. Operating parameters for LSP and FM-1.

	LSP	FM-1
Magnetic field strength	~ 1 kΓ	~ 2 kΓ
Major diameter of ring	45 cm	75 cm
Shear length (L_s)	40 cm	50 cm
Plasma radius	5 cm	7 cm
Ring current	85 kAt	150 kAt
I_T/I_P	0.5 - 0.6	0.9 - 1.0
Base pressure	1×10^{-7}Torr	2×10^{-8}Torr
Neutral gas density	$0.5 - 2 \times 10^{11}cm^{-3}$	$0.5 - 2 \times 10^{11}cm^{-3}$
Plasma density	$1 - 30 \times 10^{11}cm^{-3}$	$0.1 - 10 \times 10^{11}cm^{-3}$
Electron temperature	0.1 - 100 eV	0.1 - 10 eV
Plasma volume	$2 \times 10^5 cm^3$	$7 \times 10^5 cm^3$
τ_{Bohm} (T_e = 1 eV)	2.9 msec	9 msec
τ_c(T_e = 1 eV; $n = 2 \times 10^{11}cm^{-3}$)	600 msec	2.5 sec

electron collision rate allows a very stable control of the electron temperature with maximum electron temperatures of the order of 2 eV.

The plasma cooling is dominated by two heat-loss mechanisms. For electron temperatures above 2 eV where ionization becomes important, the electrons lose energy directly to the background neutrals due to ionization and excitation. At all temperatures so far obtained in FM-1 the electron-ion coupling is strong with energy being lost from the ions through ion-neutral charge exchange. At very low electron temperatures where recombination occurs ($T_e < 0.2$ eV) some energy is returned to the electrons through collisions with excited neutrals. The electron temperature is determined from recombination light measurements for electron temperatures up to 0.2 eV, swept Langmuir probes are used between 0.1 and 5 eV, and the probe measurements are corroborated with excitation light measurements above 2 eV.

A zero-dimensional computer code is used to compute the electron and ion temperature variation from the known ionization, charge exchange, recombination, and electron-ion collisional-rate coefficients. Also taken into account in the computer code is the resistive heating by nonresonant microwaves and the collisions with excited neutrals. Figure 1 shows a comparison between the measured electron temperature and the calculated temperature variation for cases with and without nonresonant heating. Two computed curves are

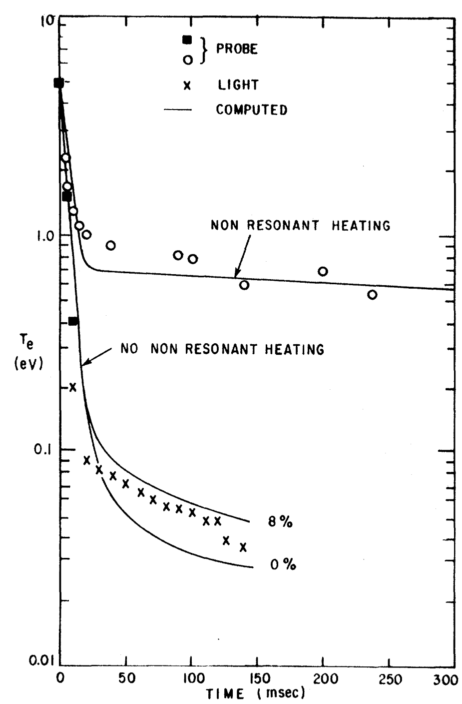

FIG. 1. Electron temperature as a function of time as measured with Langmuir probes and recombination light detectors with and without nonresonant microwave heating. These are compared to the computed values assuming classical rate coefficients.

shown without nonresonant heating: one for no superelastic collisions (0%) and one with 8% of the recombination energy being returned to the electrons via electron-neutral collisions. A return of 4% of the recombination energy gives a best fit to the measured temperature decay. The temperature variation with nonresonant heating was computed using classical resistivity and assuming the microwave Q value for the vacuum vessel. The importance of nonresonant heating in the confinement experiments is apparent in Fig. 1. Without heating, the temperature cools in 25 msec to 0.1 eV. With nonresonant heating the electron temperature is maintained relatively constant for more than 1 sec while measured confinement times exceed 1 sec.

The temperature and density dependence of the particle confinement time was measured for electron temperatures between 0.1 and 10 eV, and densities between $(0.2-2)\times 10^{11}$ cm^{-3}. The results of these measurements are shown in Fig. 2. Nonresonant heating was used in these measurements to maintain the electron temperature during the afterglow. The primary diagnostic used to determine the particle containment time was the density decay rate measured with 4- and 8-mm microwave interferometers. For electron temperatures above 2 eV, ionization becomes important and was corrected for by measuring the excitation light. Near 5 eV, steady-state discharges occur with the ionization rate equal to the loss rate. Although the efficiency of particle collection in the divertor is not well determined as yet, the particle loss to the divertor gave a good relative confirmation of the density decay rates measured with the microwave interferometers.

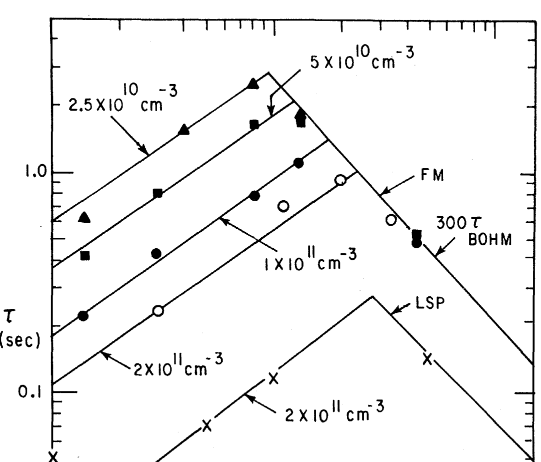

FIG. 2. Plasma confinement time as a function of electron temperature for LSP and FM-1. The parametric dependence on plasma density is shown for FM-1. At low electron temperature the confinement time improves with electron temperature as $T_e^{3/4}$. At higher electron temperature the confinement time decreases as T_e^{-1} with an absolute confinement time of 300 times the so-called Bohm time.

Several candidates for the plasma loss mechanisms have been investigated. Experiments have demonstrated that impurities in the neutral base pressure (H_2O, N_2, CO_2, etc.) have a detrimental effect on plasma confinement.[2,7] The confinement as a function of electron temperature was measured for several background pressures above our best operating conditions. The reduction in particle confinement time produced by background impurities was only weakly if at all dependent on electron temperature, consistent with experiments reported in Ref. 7. The impurity effect extrapolated to our best conditions under which the data on Fig. 2 were measured gave at most a 20% correction to the confinement time for impurity effects. The weak overall effect of impurities coupled with the weak temperature dependence of their effect eliminate impurities as a factor responsible for the temperature and density variation of plasma confinement in FM-1 under good vacuum conditions.

Recombination light measurements show that recombination of electrons and atomic ions is only important below 0.15 eV. At 0.1 eV the recombination rate represents 30% of the total particle decay rate.

The possible effect of ionization by high-energy electrons produced during the resonant microwave discharge was checked by several methods: (1) During the afterglow containment measurements, excitation light was monitored. The lack of observable excitation light indicated an ionization time per electron in excess of 7 sec. (2) A particle (6-mm-diam ball) was dropped through the plasma with a traverse time of about 200 msec to collect a large fraction of any hot electrons present with no observable effect on the particle decay time.

At low electron temperatures the particle confinement time measured on FM-1 shows an improvement with electron temperature as observed on LSP. The measurements indicate an electron temperature dependence which is slightly stronger than $T_e^{1/2}$. The density dependence of confinement has been well documented showing a confinement time inversely proportional to density. This parametric dependence of the confinement time suggests classical confinement; however, the observed confinement times fall short of the calculated classical confinement time by about a factor of 5. This factor is consistent with "pseudoclassical diffusion."[5] The containment times measured for LSP at a density of 2×10^{11} cm^{-3} are also plotted in Fig. 2.[1] If the low-temperature results scale as classical diffusion, the two devices should differ by a factor of 4.2 in confinement time at the same density and temperature. This is in good agreement with the observations, although the individual plasma thickness and poloidal field dependence have not been determined because of restrictions imposed by ring levitation.

At higher electron temperatures the measured confinement time on both devices decreases with increasing electron temperature. The confinement time at these temperatures goes approximately as T_e^{-1} and appeared independent of n_e. This temperature dependence suggests Bohm-like diffusion. The scaling between the two devices reflects an a^2B dependence which is not inconsistent with the characteristics associated with Bohm diffusion although the magnitude of the diffusion rate is about 300 times less than Bohm diffusion.

On LSP it was necessary to use Ohmic heating to raise the electron temperature into the Bohm-like region. The question arose whether the turbulence or nonuniformities caused by the Ohmic heating were responsible for the deterioration of confinement with temperature. The scaling of the pseudoclassical and Bohm-like containment regions in FM-1 has moved the region of maximum containment to lower electron temperatures where it is accessible with nonresonant microwave heating. The data were obtained by continuously varying the nonresonant microwave heating power. Some question still remains as to whether the microwave power could be affecting the containment. The density and temperature profiles may not be in a normal-mode configuration. However, the density profiles do not change appreciably as a function of electron temperature, suggesting that the dependence of the confinement time on electron temperature reflects a more fundamental effect.

Loss mechanisms which may be responsible for the reduction in containment at higher electron temperatures are magnetic-field errors and density fluctuations. Field errors were shown to effect the containment on LSP at higher temperatures but it remains to be seen whether this is the dominant effect on FM-1. Small density fluctuations are observed in the higher electron temperature region on both devices ($\delta n/n \sim 1\%$). Experiments are planned to determine the nature and effects of these fluctuations.

Confinement times well in excess of 1 sec have been obtained on FM-1 at electron temperatures of the order of 1 eV. At electron temperatures less than 1 eV, the containment time has a classical dependence on electron temperature and density although falling short of the classical confinement time by about a factor of 5. Above 1 eV the containment has a Bohm-like dependence on electron temperature and density. The two containment regions scale from earlier results on LSP as a^2B^2 and a^2B, respectively, which is consistent with the pseudoclassical and Bohm-like character of these regions. Although the density and electron temperature dependence of the confinement time at low electron temperatures (T_e < 1 eV) reflects a pseudoclassical behavior, the important poloidal field dependence has not been determined. The scaling of the diffusion rate from LSP to the higher field FM-1 has moved the transition region downward to where it is accessible to nonresonant microwave heating. The accessibility of the transition region will facilitate future studies and comparisons of the two types of plasma diffusion.

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Observation of a Parametric Instability near the Lower Hybrid-Resonance Frequency*

W. M. Hooke and S. Bernabei
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
(Received 29 June 1972)

A parametric instability is observed at frequencies close to and above the lower hybrid-resonance frequency. The threshold occurs when the electron drift velocity is of the order of the plasma sound speed. At pump-power levels well above threshold the energy in the decay waves is comparable to that associated with the pump wave.

The possibility of heating plasma at frequencies near the lower hybrid resonance has been stressed for many years.[1] Experimental evidence of ion and electron heating at this frequency has been reported recently.[2] The nature of the heating process, however, remains unclear. According to linear theory,[3,4] near the lower hybrid resonance these waves will convert into a very short-wavelength electrostatic mode, which can heat plasma, for example, through ion Landau damping.

We wish to show in this Letter that nonlinear processes are likely to play an important, if not a dominant, role in the plasma heating processes.

The waves in question here are all primarily electrostatic with the main component of the rf electric field $\vec{E}$ perpendicular to the plasma-confining magnetic field $\vec{B}_0$. At frequencies near the lower hybrid resonance the drift velocity of the ions, $\vec{V}_i \cong e\vec{E}/m_i\omega$, is much smaller than the electron drift $\vec{V}_e \cong c\vec{E}\times\vec{B}_0/B_0^2$. At the power levels used in typical plasma-heating experiments the electron drift velocity near the lower hybrid resonance becomes comparable to, or greater than, the plasma sound speed, so that an instability appears possible. Kindel, Okuda, and Dawson[5] have, in fact, predicted theoretically and observed in numerical simulation experiments a parametric instability which leads to ion and electron heating. They find the threshold drift velocity to be given by

$$\frac{V_e}{V_s} = 4\frac{\omega_p}{\omega_0}\left(\frac{\gamma_L\gamma_H}{\omega_L\omega_H}\right)^{1/2}, \qquad (1)$$

where V_s is the plasma sound speed, ω_p is the frequency of the pump wave, ω_0 is the lower hybrid frequency, and $\gamma_{L,H}$ and $\omega_{L,H}$ are the damping rates and frequencies, respectively, of the low- and high-frequency "daughters" of the decay process.

The low-frequency decay wave is an ion-acoustic mode propagating nearly parallel to the direction of $\vec{V}_e$, and the high-frequency decay wave is similar in nature to the pump wave but has a different frequency and wave number. For the experiments described below $\omega_p \gtrsim \omega_{ip} \approx \omega_0$. If the daughter waves of the decay are weakly damped, the term under the radical in Eq. (1) becomes much less than unity, and the threshold for this process can occur for values of V_e of the order of the sound speed or even smaller.

In an experiment designed to study waves propagating near the lower hybrid-resonance frequency we have discovered a parametric instability with characteristics similar to those described above. A schematic diagram of the experimental arrangement is shown in Fig. 1. Waves are coupled to the plasma with 70-cm-long plates which are driven electrostatically by a balanced rf system. A doubly shielded rf probe travels in the radial direction and is used to detect the plasma oscillations. Not shown is a rotary probe which is capable of moving 360° in the $\hat{\theta}$ direction at a fixed radius in the vicinity of the radial probe. Wavelengths are measured with an amplitude-insensitive rf interferometer. The magnetic field is typically 1000 G, the electron density is approximately 10^{10} cm^{-3}, and the electron tempera-