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Confinement Properties of the Levitated Spherator*

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To eliminate the anomalous loss due to convective cells produced by the existence of the supports in the plasma volume, a levitated superconducting ring was installed in the Princeton spherator. The plasma decay time is increased from 10-15 msec in the supported version to a maximum of 150-220 msec for a helium discharge plasma. At $n_e = 2 \times 10^{11}$ cm^{-3} and $T_e = 1$-2 eV, this decay time is $\frac{1}{2}$ to $\frac{1}{4}$ of the calculated density decay time due to the classical diffusion process.

Anomalous plasma loss across the magnetic fields still persists in many azimuthally symmetric multipole plasma confinement systems,[1-4] even though the magnetohydrodynamic instabilities have been successfully stabilized by the large values of shear and/or the deep magnetic wells. Previous confinement studies in a supported version of the spherator led to the hypothesis that the supports for the internal ring were causing density inhomogeneities within a magnetic surface and, consequently, producing an anomalous particle loss across the magnetic field. A theoretical description of this anomalous particle loss in terms of support-induced nonuniformities of the plasma density successfully describes the observed dependence of the confinement time on the ion mass and neutral density.[2,5] Azimuthal nonuniformities of the plasma density and of the particle loss across the magnetic field were observed experimentally.[6,7] Even when the anomalous loss due to these support-induced density nonuniformities was minimized by lowering the neutral density, the confinement times were limited by the direct loss to the supports due to the flow along the magnetic field lines.[2] Thus, the conversion of the spherator to a levitated version has been of prime interest in the effort to eliminate the convective loss as well as the direct loss to the supports.

A schematic diagram of the levitated version of the spherator is shown in Fig. 1. The magnetic field configuration is similar to that in the previous version with a supported internal ring. In addition to the steady magnetic fields of the previous version, a steady magnetic field is used to levitate the superconducting ring, and time-varying magnetic fields are used to maintain the equilibrium position of the ring. The stabilizing magnetic fields are excited asymmetrically with a magnitude depending upon the displacement of the ring, as measured by the optical sensors. At present, the stabilizing magnetic fields are excited by 3-phase, 60-cycle ac power, causing magnetic perturbations as high as 100 G (10% of the main confining field). To avoid these excessive perturbations during the experiment, a gating (blanking) period, to cut

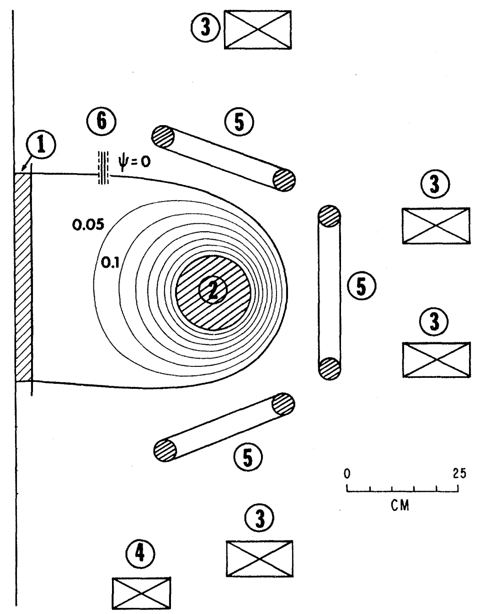

FIG. 1. Cross-sectional view of the levitated spherator: (1) toriodal field (TF) coil, (2) levitated superconducting ring, (3) external coils, (4) coil for levitating the ring, (5) stabilizing field coils, and (6) limiter.

off this stabilizing field for up to 40 msec, is used during the plasma production and the study of the subsequent plasma afterglow.

The base pressure was kept below 2×10^{-7} Torr (~ 50% H_2O and ~ 50% N_2). The working gases (H_2, D_2, He, A) were then introduced to 10^{-5}-10^{-6} Torr. The formation of the plasma was accomplished by using microwaves of 500-1000 W with a frequency close to the electron cyclotron resonance (2.5 GHz). The afterglow of the plasma was studied to determine the confinement properties of the plasma. The typical plasma parameters are as shown in Table I.

The density decay, the loss rate, and the electron temperature decay are shown in Fig. 2(a) for a helium afterglow plasma. The density decay is measured with a 4-mm microwave interferometer. The loss rate, $\Gamma_\perp$, which is measured by the particle-flux detectors, includes only the loss outwards from the plasma and not the loss to the levitated ring (previously in the supported version the loss to the ring was ~ 10% of the loss outwards[2]). These two quantities, the density decay and the loss rate, are analyzed, and their influences are compared in the following paragraph.

The density decay time τ_M measured from curve (1) of Fig. 2(a), is 150-220 msec during the blanking. The lifetime during the blanking

Table I. Typical plasma parameters.

Magnetic field strength (B)	~850 G
Ratio of toroidal current to poloidal current (I_T/I_P)	0.5-0.6
Background pressure	2×10^{-7} Torr
Neutral gas density	$(1-2)\times10^{11}$ cm^{-3}
Plasma density (n_e)	$(2-3)\times10^{11}$ cm^{-3}
Electron temperature (T_e)	0.5-4 eV
Plasma volume	2×10^5 cm^3
τ_M ($T_e \geq 0.8$ eV)	150-220 msec
$\tau_\perp$ ($T_e \geq 0.8$ eV)	120-180 msec
τ_B ($T_e = 1$ eV) (Bohm time)	2.9 msec

period is difficult to determine accurately since the time interval for the measurement is short compared to the decay time. However, decay times exceeding 140 msec were observed over long time intervals when the ring was in magnetic equilibrium before and after the blanking period (only a minimal response is required from the stabilization system). These lifetimes exceed by far the decay time of 15 msec obtained in the previous supported version.[2,4] The loss current [Fig. 2(a)] illustrates the increase in the loss rate when a large ring-stabilizing magnetic field is applied. The density decay time drops to 50-70 msec after the stabilizing magnetic fields are reintroduced. It is clear that the loss rate [curve (2) of Fig. 2(a)] increases as the ring-stabilizing magnetic field is applied. By knowing the plasma density and the loss rate $\Gamma_\perp(t)$ at a given time, and assuming that the loss to the ring is small, it is possible to calculate the plasma loss time by the formula

$$\tau_\perp = \int n_e(t)dV/\Gamma_\perp(t),$$

where $\int dV$ is the integral over the plasma volume and the density distribution is estimated from a Langmuir-probe measurement. The calculated value $\tau_\perp$ is 120-180 msec during the blanking and 60-80 msec after the stabilizing fields are reapplied. The decay times $\tau_\perp$ calculated from the loss rate are in good agreement with those measured with the microwave interferometer, τ_M. The largest discrepancy between these two methods occurs immediately after the plasma formation when the loss current is relaxing from its higher value during the heating. The agreement between the microwave-interferometer measurement with the loss rate collected by the flux detectors is illustrated by the dotted line in Fig. 2, which shows the loss rate

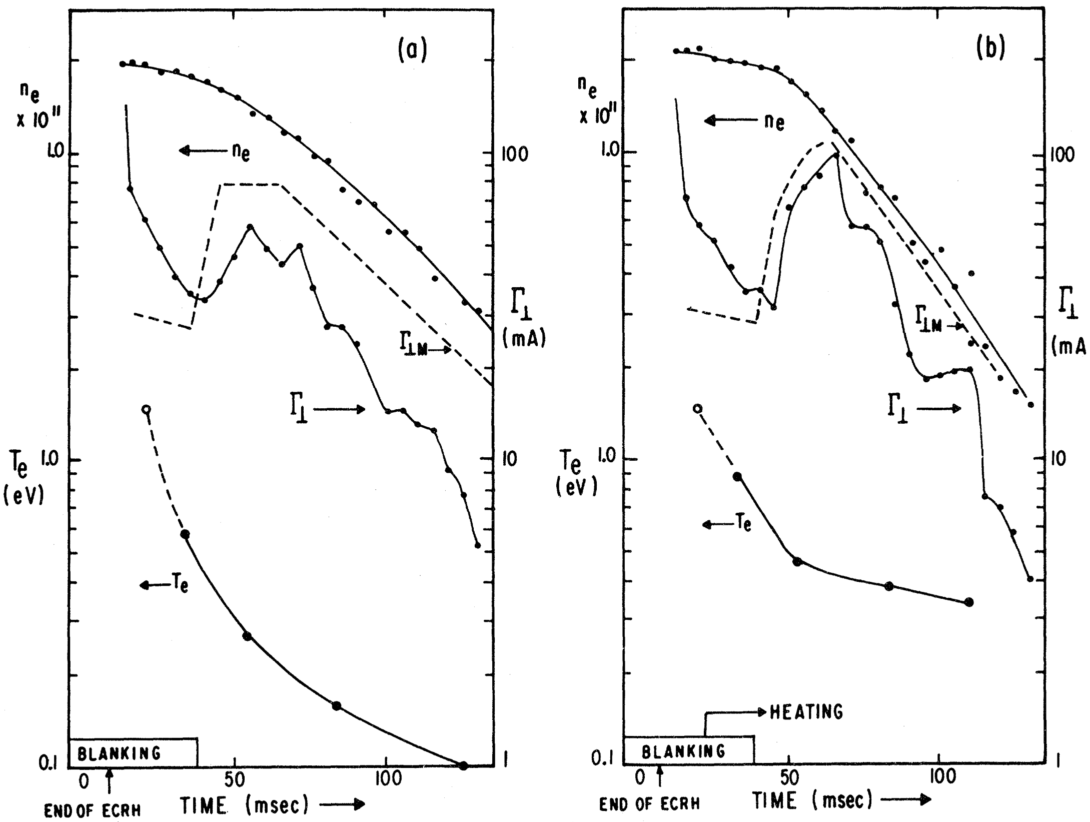

FIG. 2. Density decay n_e, plasma loss rate, and the electron temperature T_e (the dotted portion of the line is from the previous data); (a) without additional heating, and (b) with additional heating.

$\Gamma_{\perp M}$ expected from the interferometer decay:

$$\Gamma_{\perp M} = \int n(t) dV / \tau_M(t).$$

The electron temperatures were measured by a swept Langmuir probe. The decay of electron temperature in the afterglow is slower than that calculated for atomic processes (primarily neutral charge exchange), assuming that the neutral atoms are at room temperature. We will consider this problem later. An absolute intensity measurement of the excitation and recombination light was performed as an additional determination of the electron temperature. This measurement and those of the Langmuir probes agree within a factor of 2. This spectroscopic measurement also establishes that recombination is not the dominant process in reducing the electron density.

In order to maintain the electron temperature near 1 eV, a nonresonant low-power ($\lesssim 40$ W) microwave at 5 GHz was applied during the afterglow. The effect of the heating on the electron temperature, density decay, and loss rate is shown in Fig. 2(b). The density decay during the blanking period is similar to that without the heating; however, the plasma loss rate increases substantially after the stabilizing field is reapplied. The loss to the flux detectors integrated over time does not show any significant difference, with or without heating. Thus, the effect of the ionization due to the additional heating seems to be small.

It was found that argon plasmas gave approximately the same confinement time (within a factor of 1.5) as deuterium plasmas. This is in marked contrast to the data obtained in the supported version, where the difference in the confinement time between deuterium and argon reaches a factor of $\gtrsim 5$.[2,4]

The plasma decay times are found to be very sensitive to the amount of impurity gases (chiefly H_2O) present. When the background pressure of H_2O could not be reduced to less than 5×10^{-6} Torr, the decay time was as short as 5 msec, which was, in fact, shorter than the decay times in the supported-ring version. Reduction of the impurity pressure has resulted in an approximately linear increase in the plasma decay times down to the present best operating pressure of 1.5×10^{-7} Torr. The physical mechanism that causes this effect is still unknown.

The electron-temperature decay without heating, as shown in Fig. 2(a), can be explained by atomic processes (chiefly excitation) down to ~0.5 eV. The decay of the electron temperature after 20 msec is somewhat slower than would be expected from the electron-ion cooling and the subsequent ion-neutral cooling via charge exchange, assuming that the neutral gas is at room temperature. One possibility is that neutrals created by charge exchange do not thermalize upon hitting the vacuum wall, and thereby return to the confinement region with a high temperature. Another possibility is that high-energy (runaway) electrons are trapped in the mirror sections and are feeding the energy to the plasma electrons.

Although no direct experimental evidence of runaway electrons exists, it is necessary to be cautious about the possibility that the plasma decay time appears longer because of the presence of high-energy electrons that are continuously ionizing the background neutral gas. The direct loss measurement appears to discount this possibility, since the loss to the flux dectectors integrated over time does not exceed the number present at the beginning of the afterglow discharge. Even if we assume the existence of runaway electrons with an energy of 10 keV and a density of 10^9 cm^{-3} to explain the slow decay of the electron temperature, the plasma-density confinement time (150-220 msec) would only be reduced to 100-150 msec. These experimental results indicate that the measured plasma decay time probably represents the plasma-density confinement time.

The compare the observed plasma-density decay with that expected from the classical processes, we calculated the decay time numerically by using the observed initial density profile and the diffusion coefficient of Johnson and von Goeler[8]

$$\frac{\partial n(\psi)}{\partial t}\oint\frac{d\chi}{B_p^2}=4\pi^2\frac{\partial}{\partial\psi}D\frac{\partial n(\psi)}{\partial\psi},$$

$$D=k(T_e+T_i)n(\psi)\eta_\perp(1+\alpha)\oint(R^2/B^2)d\chi,$$

and

$$\alpha=\frac{\eta_\parallel}{\eta_\perp}\left[\oint\frac{d\chi}{B^2B_p^2}-\frac{\oint d\chi\, B_p^{-2}}{\oint(B^2/B_p^2)d\chi}\right]\left[\oint\frac{d\chi}{B^2B_T^2}\right]^{-1},$$

where B is the absolute value of the magnetic field strength, B_T is the toroidal field component, B_p is the poloidal component, and $\eta_\parallel$ and $\eta_\perp$ are the resistivities parallel and perpendicular, respectively, to the magnetic field. The boundary condition used in the calculation is that of zero density at the internal conductor and at the limiter. For a peak density of 2×10^{11} cm^{-3} and an electron temperature of 1 eV, the predicted classical decay time is 560 msec assuming a flat temperature profile. If it is assumed that the density and temperature have the same profile shapes, the decay time is reduced to 450 msec. The Pfirsch-Schluter factor α was included in the calculations, but this enhancement factor is small for our experimental condition (the ratio of the toroidal current to the poloidal current is 0.54).

The observed confinement times are approximately $\frac{1}{2}$ to $\frac{1}{4}$ of the calculated classical confinement time during the blanking. When the stabilization fields are present, the asymmetries caused by these fields appear to be the predominant source of the plasma loss. During the blanking, the increase over the classical loss rate may be attributable to (1) convective cells (due to nonuniformity and/or field errors), (2) atomic processes, (3) fluctuations, and (4) field error resulting from the misalignment of the internal ring. The existence of convective cells is unlikely, since the azimuthal distribution of plasma loss, as measured by a segmented limiter, was uniform within the reproducibility of the experiment, and, in addition, the plasma decay times did not show noticeable dependence on the ion mass for a change by a factor of 40. The optical measurement rules out atomic recombination as a major source of plasma loss. However, the unknown process which yields the observed dependence of decay time on impurity pressure may cause some residual loss, even under our best operating conditions. Further investigation will clarify this point. Neither fluctuations nor field errors can be eliminated as a possible loss mechanism during the blanking, because the loss rate in the levitated spherator is quite small. Field errors resulting from misalignment of the ring (~1%) or small-amplitude fluctuations (~0.5%) may be sufficient to cause the observed loss.

In summary, the best decay times observed at present in the levitated spherator have been about 200 msec, which is an order of magnitude better than the decay times in the supported version. These results agree with the previously conceived hypothesis that the existence of supports in the plasma volume was responsible for most of the perpendicular loss. Numerical calculations show that the present observed decay times are $\frac{1}{2}$ to $\frac{1}{4}$ of the expected classical decay time; thus, anomalous loss may exist. The most likely cause of any additional loss seems to be a combination of the existence of magnetic field errors and fluctuations. Although our parameter range is still small, indications are that a small increase of the electron temperature does not change the decay times when the large magnetic field errors are absent. These preliminary results are quite encouraging; but, in order to decide whether an anomalous loss mechanism is still present in this levitated version of the spherator, a wider range of plasma parameters must be investigated.

*Work performed under the auspices of the U. S. Atomic Energy Commission, Contract No. AT(30-1)-1238. Use was made of computer facilities supported in part by National Science Foundation Grant No. NSF-GP579.

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Mechanism of Excess Electron Transport in Liquid Hydrocarbons

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Stable excess electrons have been recently observed in liquid hydrocarbons after suitable purification, but the mobilities indicated the existence of short-lived electron traps in the liquids. We have measured electron mobilities in mixtures of n-hexane and neopentane and find that the mobility is given accurately by an expression of the form

$$\mu = \mu_n \exp(-x_h E/kT),$$

where x_h is the mole fraction of hexane. It is concluded that the trap cannot be a negative-ion state of a single molecule, but is instead a collective trap involving several fluid molecules.

It has been observed that after suitable purification, stable excess electrons can be produced in the rare-gas liquids[1,2] and in many nonpolar hydrocarbon liquids.[3,4] Lekner[5] has shown that a kinetic theory proposed by Cohen and Lekner[6] (based on the single-scattering approximation and the Boltzmann equation) provides a quantitative explanation of electron mobilities in the rare-gas liquids. In the low-field limit, the theory yields the following expression for the mobility:

$$\mu = \tfrac{2}{3}(2/\pi mkT)^{1/2}[e/n4\pi a^2 S(0)], \qquad (1)$$

where a is the electron-atom scattering length and $S(0)$ is the long-wavelength limit of the structure factor [$S(0) = nkT\kappa_T$, where κ_T is the isothermal compressibility]. The charge carriers in the hydrocarbons, while undoubtedly electronic, generally exhibited much lower mobilities than predicted by Eq. (1) and exhibited large variations between different hydrocarbons. (At 300°K electrons in n-hexane and neopentane have mobilities of 0.07 and 70 cm^2/V sec, respectively.) Possible explanations[3] for this behavior are (1) an increased effective cross section arising from incoherent scattering in polyatomic fluids,