PLASMA CONTAINMENT IN THE PRINCETON SPHERATOR USING A SUPPORTED SUPERCONDUCTING RING*

R. Freeman, M. Okabayashi, H. Pacher, G. Pacher, and S. Yoshikawa
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
(Received 8 July 1969)

Investigation of plasma confinement in the Princeton spherator by use of a supported superconducting ring shows that about 90 % of the total particles are lost to the supports, and thus the particle loss across the magnetic field is reduced to about 10 % of the total loss under the best operating conditions. An hypothesis—in terms of convective cells, which are established by the presence of supports—is proposed to explain the observed plasma loss.

Azimuthally symmetric, internal-conductor toroidal devices have strong plasma stability properties, as has been demonstrated both experimentally and theoretically.[1-5] In spite of the stability of these plasmas, a finite plasma loss across the magnetic field still persists and cannot be explained by classical diffusion processes. The subject of this Letter is a parametric study of this anomalous loss in a single-internal-ring device called the spherator.

The confining magnetic fields of the spherator are produced by essentially three conductors: first, a straight center coil producing a toroidal field (TF); second, a circular coil inside the plasma volume producing a poloidal field (PF); and third, a set of circular coils external to the plasma volume producing a vertical field (EF). A cross-sectional view of the spherator is shown in Fig. 1(a). The use of a supported, superconducting PF coil is a preliminary step in the conversion to a levitated ring device. This superconducting PF coil, with a major radius of 45 cm and a minor radius of 17.5 cm, is made of Nb_3Sn ribbon with 2275 turns and can be operated at currents up to 130 kA. It provides a higher poloidal magnetic field and a larger plasma confinement volume than did the previous version of the spherator, reported elsewhere.[5] The ring is suspended by three 0.1-cm-diam wires and three 0.4-cm-diam rods that are used for continuous filling and venting of the liquid helium. Magnetic surfaces similar to those of the previous version[5] are produced by choosing the appropriate combination of PF current, I_P, and EF coil current, I_E. The TF current, I_T, is variable up to 90 kA in steady-state operation, thus allowing variation of the shear and the magnetic well depth.

The confinement experiment is carried out using afterglow plasmas produced by electron-cyclotron-resonance heating (12-cm microwaves) and Ohmic heating. The base pressure is kept below 1×10^{-7} Torr, whereas the operating pres-

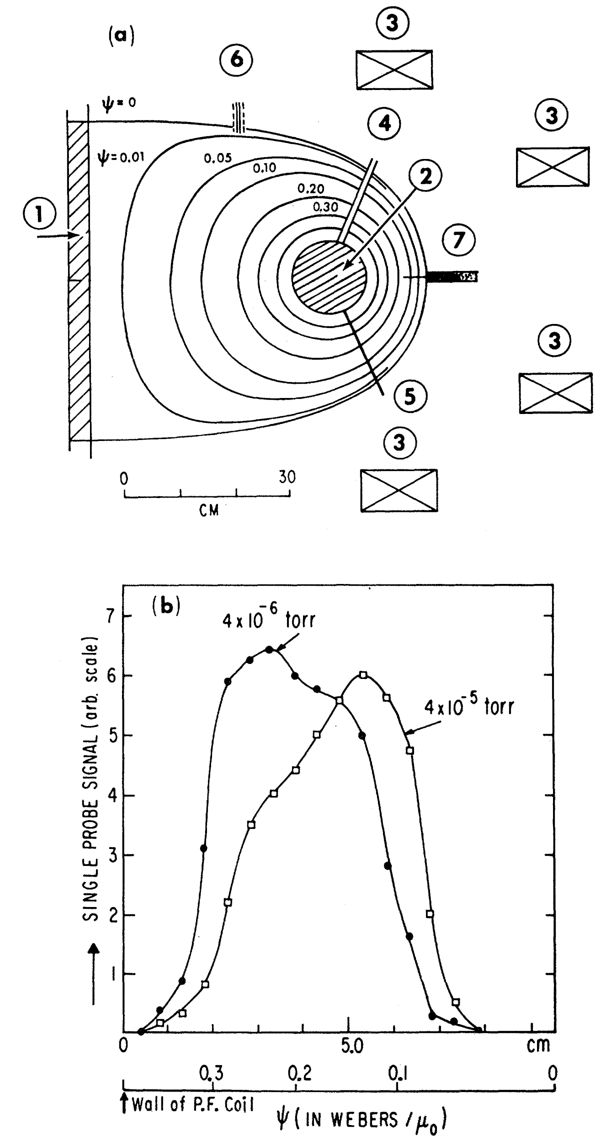

FIG. 1. (a) Cross-sectional view of the spherator: (1) TF coil, (2) PF coil, (3) a set of external coils, (4) support rod with a 4-mm diam, (5) support wire with a 1-mm diam, (6) limiter, and (7) single Langmuir probe. (b) Ion saturation current versus horizontal position for different neutral pressures at $T_e = 1$ eV.

sure is usually kept between 2×10^{-6} and 4×10^{-5} Torr. The plasma density is about $(1\text{-}5)\times10^{10}$/cc, with a typical electron temperature range of 1 to 3 eV. The absolute value of the plasma density and its decay time are determined by the use of the microwave interferometer, the plasma flux detectors, and single probes. The electron temperature is measured at the peak of the density profile using single probes.

In order to estimate the particle flux to the supports, the surfaces of the three 0.4-cm-diam support rods are used as flux detectors by applying negative bias with respect to the vacuum vessel and the rest of the supports. Particle loss across the magnetic field is measured by the limiter flux detector and by biasing the surfaces of the TF and PF coils. (Since field lines near the stagnation surface, ψ_s, intersect either the limiter or the TF coil, plasma lost radially across the magnetic field will be collected at these surfaces, and also at the surface of the PF coil.)

Previous experimental results[5] in the spherator have shown that approximately half of the particles were lost across the magnetic field under the best operating conditions. The neutral pressure range in the previous experiments was between 1.2×10^{-5} and 8×10^{-5} Torr. In this new experiment, it is observed that about 90% of the total particles are lost to the supports if the neutral pressure is reduced from that of the previous case. It is now possible to ionize the gas at much lower neutral pressures than before because the present use of a steady magnetic field permits a much faster pulse repetition rate of the microwave heating.

Investigations of the neutral pressure dependence show that the ratio of the flux of particles lost across the magnetic field, $\Gamma_\perp$, to the flux of particles lost to the supports, Γ_s, decreased with a decrease of the neutral pressure; $\Gamma_\perp/\Gamma_s$ is 2.3 at 4×10^{-5} Torr and 0.12 at 4×10^{-6} Torr. The ratio $\Gamma_\perp/\Gamma_s$ is equated to the fundamental parameter $\tau_s/\tau_\perp$, where τ_s is a density decay constant if all particles are lost only to the support, and $\tau_\perp$ is a density decay constant if all particles are lost only across the magnetic field; that is,

$$\tau_s = \int n dV/\Gamma_s, \quad (1)$$

$$\tau_\perp = \int n dV/\Gamma_\perp. \quad (2)$$

Typical results with the present experiment are presented in Table I for microwave-produced deuterium plasmas. The PF current, I_P, is 75 kA and the TF current, I_T, to I_P is 0.72. The magnetic field configuration is such that the stagnation point appears at $z = \pm30$ cm on the major axis.

Table I. Confinement results for microwave-produced deuterium plasmas evaluated at $T_e = 1$ eV.

	Low pressure	High pressure
Neutral pressure (Torr)	4×10^{-6}	4×10^{-5}
Ratio of particle loss ($\Gamma_\perp/\Gamma_s$)	0.12	2.3
Confinement times (msec)		
τ_{mw}	12	5.0
τ_{probe}	10	5.4
τ_{flux}	11	6.4
$\tau_\perp$	110	9.2
τ_B	2.9	2.9
τ_s	13	21
$\tau_{\text{theo},s}$	17	19

The Bohm confinement time shown in Table I was calculated by Goeler et al.,[6] and the theoretical support confinement time, $\tau_{\text{theo},s}$, is estimated from the plasma-sheath condition. τ_{flux}, $\tau_\perp$, and τ_s are calculated by integrating the ion saturation current to the particle flux detectors over time, and τ_{mw} is determined from the decay of the microwave interferometer signal. For a given neutral pressure the ratio of the particle loss, $\Gamma_\perp/\Gamma_s$, changes by less than a factor of 3 over the range of electron temperatures and plasma densities investigated. Experiments to investigate a wide range of magnetic field strengths and different magnetic field configurations have not yet been carried out. However, it is noted that $\Gamma_\perp/\Gamma_s$ is a function of the current ratio I_T/I_P with its minimum at about $I_T/I_P = 0.24$. On the other hand, the minimum amplitude of the fluctuations appears at $I_T/I_P = 0.72$. It was reported previously that fluctuations do not appear to play an important role in determining the particle loss.[7]

These results raise a question about the physical process responsible for the decrease of $\Gamma_\perp/\Gamma_s$ when the neutral pressure is reduced. Table I shows that the change in $\tau_\perp$ is much larger than the change in τ_s; so the change in $\Gamma_\perp = \int D_\perp \nabla_\perp n d\vec{S}$ is thus due to a change in the density gradient or a change in the absolute value of the diffusion coefficient.

Since the electron temperature is generally constant over the confinement region, the spatial variation of the ion saturation current should reflect the plasma density profile. Figure 1(b) shows this profile for two different neutral pressures at an electron temperature of 1 eV. Since most of the plasma that is lost across the magnetic field is collected by the limiter and the TF coil, the density gradient on the outside should be the most important part; however, the difference in the profiles at this position does not seem to be large enough to account for the difference by a factor of 10 in $\Gamma_\perp$ for these two cases. Also, when the limiter is moved further into the confinement region for the high-neutral-pressure case the peak of the profile is shifted and the gradient changes, but the value of $\Gamma_\perp$ changes by less than a factor of 2. These results indicate that the change of the density gradient is not the most important effect of the neutral gas; so the possibility that the magnitude of the diffusion coefficient is modified by the presence of the neutral gas must be considered.

One possibility is that the magnitude of the diffusion coefficient depends on the electron- or ion-neutral collision frequency, and thus these collisions are important for determining the particle loss across the magnetic field. In order to investigate this possibility neutral gas is injected by a pulsed gas feed into the afterglow of a plasma produced in lower neutral pressure; the number of neutral particles and the timing of the injection relative to the start of the afterglow are varied. The neutral density becomes comparable with the higher neutral-discharge case within a few milliseconds after the pulsed gas feed is opened. The observed change of the ratio $\Gamma_\perp/\Gamma_S$ is less than a factor of 1.5. However, after a subsequent application of a short heating pulse the ratio then becomes similar to the higher neutral-pressure case. The above results indicate that the increased neutral density is not the only important parameter, and that the heating process must also influence the confinement.

The most interesting question is what happens to the plasma loss if the neutral pressure is reduced to zero. Deuterium gas is injected by a pulsed gas valve and then the microwave heating is left on for 7 sec so that the neutral pressure is reduced to approximately 4×10^{-7} Torr. Even for this condition the ratio $\Gamma_\perp/\Gamma_S$ remains 0.1, which is about the same that can be achieved with neutral pressure of 4×10^{-6} Torr. Although this experiment may not be typical because the impurity concentration is certainly increased, the inference is that the radial loss appears to remain finite even if all the neutral gas is eliminated.

The neutral-pressure dependence of the ratio $\Gamma_\perp/\Gamma_S$ can be explained by a simple model that introduces the mechanical supports of the PF coil as a boundary condition on the plasma diffusion along a magnetic field line. Since the magnetic field lines are connected to the supports, a density gradient can develop along the field lines. The strength of this gradient depends upon the rate at which the ions flow to the supports; at low neutral densities the flow rate along the magnetic field is determined by the ion inertia, but at higher neutral densities the ion-neutral collisions retard the ion flow. In the spherator the presence of rotational transform and shear in magnetic field lines causes an azimuthal variation of plasma density due to this gradient parallel to the magnetic field. Thus the surfaces of constant pressure no longer coincide with the magnetic surfaces, and an electric field must exist in the surface. A particle loss across the magnetic field then can be caused by the resulting $\vec{E}\times\vec{B}$ motion. Because of the similarity to a Benard cell, this may be called convective motion. The particle loss across the magnetic field $\Gamma_\perp$, due to the nonuniformity in the density, is estimated in a somewhat arbitrary fashion:

$$\Gamma_\perp = \int D_\perp \nabla_\perp n d\vec{S} = \left(\frac{\delta n}{n}\right)^2 \frac{kT_e}{eB}\frac{n}{a}S, \qquad (3)$$

where a is the plasma radius, S is the surface area of the confinement region, and $\delta n/n$ is obtained by a self-consistent solution of the diffusion equation for the model described above. Details of the treatment will be published in another article. Figure 2 shows a comparison between the results of this calculation and the experimental results for different deuterium neutral gas densities. The theoretical curve is calculated for $T_e = 1$ eV and $\sigma v = 2.3\times10^{-9}$ cm^3/sec. The theoretical predictions of the particle loss due to the nonuniformity of the density can be summarized in terms of a Bohm diffusion coefficient:

higher neutral densities, $D_\perp = \frac{1}{2}D_B$,

lower neutral densities, $D_\perp = (1/8\pi^2)D_B$,

where

$$D_B = \tfrac{1}{16}kT_e/eB.$$

Thus the perpendicular losses remain finite even for the "collisionless" case.

The model also provides a qualitative explanation of the experimental results discussed above

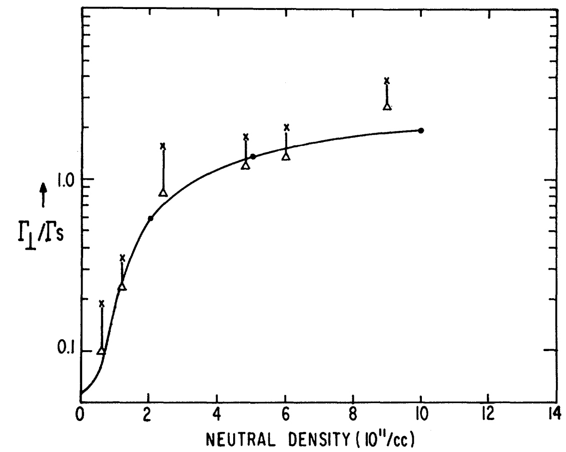

FIG. 2. The ratio of $\Gamma_\perp/\Gamma_s$ versus neutral pressure for deuterium plasma at $T_e = 1$ eV.

for the case when neutral gas was injected into the afterglow and then heated. The role of the heating process in this case is related to the fact that the time required to establish an equilibrium is determined by the support loss time, τ_s. Therefore, when the neutral gas is pulsed into the afterglow, the value of $\Gamma_\perp/\Gamma_s$ does not change appreciably before a time of the order of τ_s; however, when the plasma is also heated, the support loss time is decreased and the change in $\Gamma_\perp/\Gamma_s$ takes place within the observation interval since the equilibrium is established faster.

Other possibilities do not appear to explain the observed phenomena. (1) Since the electron temperature is about 1 eV, the recombination coefficient is quite small and this process has a negligible influence on the confinement. (2) The maximum value of the flux predicted by classical diffusion due to collisions with the neutrals or plasma particles would give a perpendicular loss approximately two orders of magnitude smaller than the minimum value of the observed loss. (3) In order for the Simon-type,[8] short-circuit diffusion to be operative, it is important that the perpendicular-flux detector (such as the limiter) is connected electrically to the supports. (Simon diffusion assumes that the electrons flow parallel to the magnetic field lines, whereas the ions flow across the magnetic field lines by their own diffusion coefficient. Thus, the electrons must flow through the conducting end plate to meet the ions.) Experimentally there is no significant difference when the collectors are electrically connected. Incidentally, the diffusion coefficient of ions due to ion-neutral collisions should be strongly mass dependent, and for deuterium, the calculated diffusion coefficient predicts a perpendicular flux of 1/100 of the minimum value observed (for neutral density of $10^{11}/cm^3$). (4) The fluctuation level does not seem to be related to the mechanism of the plasma loss.[7] (5) At present, it is not possible to definitely eliminate imperfections in the magnetic surfaces as being responsible for this perpendicular loss. However, a fairly extensive study[9] has shown that introducing a deliberate imperfection changed the perpendicular loss by less than a factor of 2.

In summary, it is found that the plasma loss across the magnetic field can be reduced to about 10% of the total by operating at low neutral densities. The plasma loss appears to be unconnected with fluctuations, and present experimental evidence is consistent with that of a loss process due to convective cells established by the presence of supports. This picture presents an optimistic outlook for the levitated conductor experiment. However, historically—even after the elimination of the mechanisms which were thought to be the causes of the particle losses—it was found in several confinement devices that the anomalous loss still persisted due to other causes.[2,4,5,10] Therefore, the decisive test of the implications of the above discussion must await the results of the experiment with a levitated ring.

We are grateful to Dr. S. von Goeler and Dr. M. Sadowski for many helpful discussions and to B. Chianese and his staff for technical assistance.

*Work performed under the auspices of the U. S. Atomic Energy Commission, Contract No. AT(30-1)-1238.

[1]T. Ohkawa et al., Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. I, p. 329.

[2]H. Forsen et al., Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. I, p. 313.

[3]S. Yoshikawa and U. Christensen, Phys. Fluids 9, 2295 (1966).

[4]M. Roberts et al., Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. I, p. 351.

[5]S Yoshikawa et al., Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. I, p. 403.

[6]S. von Goeler et al., Princeton Plasma Physics Laboratory Report No. MATT-607, 1968 (unpublished).

[7]S. von Goeler and S. Yoshikawa, Bull. Am. Phys. Soc. 13, 1502 (1968).

[8]A. Simon, Phys. Rev. 98, 317 (1955).
[9]M. Okabayashi and S. Yoshikawa, Bull. Am. Phys. Soc. 13, 1502 (1968).
[10]D. J. Grove et al., Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. I, p. 479.

SUPPRESSION AND ENHANCEMENT OF AN ION-SOUND INSTABILITY BY NONLINEAR RESONANCE EFFECTS IN A PLASMA

B. E. Keen and W. H. W. Fletcher
United Kingdom Atomic Energy Authority, Research Group, Culham Laboratory, Abingdon, England
(Received 18 August 1969)

Results are presented which show the classical anharmonic resonance effects (including hysteresis) on a marginal ion sound instability, when forcing at the fundamental and the subharmonic frequencies. Also, when the instability is well defined it appears to behave as a classical Van der Pol oscillator for drive frequencies near the fundamental and the subharmonics.

There has been considerable interest in the last few years[1-4] in the nonlinear mechanisms which determine the saturation level of a self-excited oscillation (or instability) present in a plasma. Anharmonic effects,[5] mode-mode coupling,[2,3] and wave-particle scattering[6] have been proposed as possible mechanisms in various cases. In particular, the mode-mode coupling approach appears to give rise to the plasma instability behaving as a classical Van der Pol[7] oscillator. We have obtained further experimental evidence that for an ion-sound instability in two different regions the instability behaves (a) as a classical anharmonic oscillator and (b) as a classical Van der Pol oscillator.

Theory. — The instability considered in this case was an $m=0$ ion-sound instability, and the problem has been investigated using the two-fluid approach in slab geometry. The axial magnetic field B_0 is taken along the z direction, and only spatial variations of the form $e^{ik_z z}$ are considered, where k_z is the axial wavelength of the sound instability. The density n is considered of the form $n=n_0+n_1$, where n_0 is the zero-order density and n_1 the perturbed value, and φ_1 and v_1 are taken as the potential and ion-velocity perturbations, respectively. The z component of the electron equation of motion reduces to the form $n_1/n_0=\varphi_1(kT_e/e)$. The ion equation of motion gives

$$\frac{d\vec{v}_1}{dt}=-\frac{e}{M_i}\nabla\varphi_1-\vec{v}_1\nu+\frac{e}{M_i}[\vec{v}_1\times\vec{B}_0], \tag{1}$$

where ν is the ion-neutral collision time and M_i the ion mass. The equation of continuity is given by

$$(dn/dt)+\nabla\cdot(n\vec{v}_1)=S_i, \tag{2}$$

where S_i is a source term due to ionization, etc. caused by large-amplitude oscillations present in the plasma. This source term is taken to be of the form

$$S_i=\alpha n_1-\beta n_1^2-\gamma n_1^3, \tag{3}$$

where $\gamma n_1^2 \ll \beta n_1 \ll \alpha \ll \omega_0=k_z c_s$, and $c_s=(kT_e/M_i)^{1/2}$ is the ion-sound velocity. After eliminating v_1 between (1) and (2), substituting for S_i from (3), and including an external drive term of the form $A\sin\omega t$, the equation reduces to

$$\frac{d^2n_1}{dt^2}+\frac{dn_1}{dt}[\nu-\alpha+2\beta n_1+3\gamma n_1^2]+\omega_0^2 n_1 =\omega_0^2 A\sin\omega t-\nu\beta n_1^2-\nu\gamma n_1^3. \tag{4}$$

This equation may be considered in two situations:

Case (a). — When $\nu>\alpha$, that is, when the self-excited instability is damped out, then the equation is of a standard anharmonic forced-resonance type,[8] which can be written as

$$\frac{d^2n_1}{dt^2}+\omega_0^2 n_1=f\left(n_1,\frac{dn_1}{dt}\right)+\omega_0^2 A\sin\omega t, \tag{5}$$

where

$$f\left(n_1,\frac{dn_1}{dt}\right)=-\left(\frac{dn_1}{dt}\right)[(\nu-\alpha)+2\beta n_1+3\gamma n_1^2]-\nu\beta n_1^2-\gamma\nu n_1^3.$$

A trial solution is assumed of the form $n_1=b\times\cos(\omega t+\psi)$, where ψ is a phase angle and ω is close to ω_0, and upon substitution Eq. (5) reduces to a cubic equation in b^2 correct to second order. Let $\omega=(\omega_0+\epsilon)$, where $\epsilon\ll\omega_0$, and con-