Reentrant cavity as a low-power plasma source

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A low-power source of plasma employing ECRH microwave breakdown in a reentrant cavity is described. The cavity has the following features: its dimensions can be made much smaller than its resonant wavelength, cavity Q values of several hundred are not difficult to achieve, and the vacuum rf electric field is uniform near its center. The plasma density to power ratio is roughly 10^9 cm^{-3} per watt for powers up to about 10 W. A smooth radial profile and a temperature of 5–10 eV are observed, and the plasma is very quiescent ($\delta n/n$ is less than 1%). The cavity's construction and performance is described and compared to the performance of a simple loop antenna in a nonresonant structure.

INTRODUCTION

Hot cathode discharges typically require heater powers of about a kilowatt in the case of tungsten filaments,[1] or several kilowatts for lanthanum hexaboride (LaB_6) emitters.[2] Standard microwave breakdown discharges typically require about 50 W of power.[3,4] Other low-power rf sources use cavity modes with vanishing electric field on axis thereby creating nonuniform, or even hollow, plasmas.[5]

In every rf plasma source input power is converted to an oscillating electric field which in turn breaks down a neutral gas. At each neutral gas density there is a minimum electric field required to achieve breakdown. Once breakdown is achieved, a much smaller oscillating electric field is required to maintain the discharge. The threshold for breakdown is significantly reduced if the driver frequency is resonant with the cyclotron motion of electrons in an imposed magnetic field. With an unenclosed antenna, input power is simply launched as a propagating wave into the chamber, in which case the oscillating electric field is proportional to the square root of the amplitude of the Poynting vector, since $\mathbf{S} = (1/\mu_0)(\mathbf{E}\times\mathbf{B})$, so $|\mathbf{S}| = E^2/c\mu_0$. There are a number of ways to increase the electric field for a given power. Enclosing the antenna with a reflective structure affords some enhancement of the electric field because of multiple incoherent reflections. A resonant structure affords much higher electric field strength per unit input power because the energy is stored for roughly Q oscillation periods, where Q is the quality factor of the cavity. In other words, reflected waves are added coherently. A reentrant cavity affords still higher electric field strengths per unit power since the electric field is concentrated at its center (see Fig. 1). The result of this is that breakdown can be initiated with very little power; we are able to make a plasma with as little as 1-mW peak power. At very low densities, the presence of plasma can be measured by a slight decrease in reflected microwave power. This diagnostic is more sensitive than either the Langmuir probe or the resonance shift in the density measuring cavity. We are able to use this method effectively because at the low powers we employ, the reflected signal is small, and thus differences in reflected power are easy to resolve. At higher powers, the cavity still acts as an efficient plasma source. After the initial breakdown, plasma production is primarily around the antenna.

This paper will discuss the performance of a reentrant microwave cavity as a source of magnetized plasmas. We are interested in quiet, moderate density plasmas for distribution function measurements[6] and double layer experiments which require $\delta n/n \leqslant 1\%$. Using standard low-power rf oscillators, quiet plasmas with densities of up to 10^{10} cm^{-3} are easily attained with this technique.

I. THEORY AND CAVITY CHARACTERISTICS

A reentrant cavity can be viewed as a capacitor, in parallel with an inductor, terminating a transmission line.[7] The reentrant disks form the capacitor and cylindrical walls form the inductor (see Fig. 1). Using this model we may approximate the resonant wavelength in the limit of small gap thickness[8]:

$$\lambda_0 = r_1\sqrt{2\pi(L/d)\ln(r_2/r_1)}.$$

Using more precise numerical methods, families of curves of constant resonant frequency were obtained as a function of cavity length and gap thickness.[9] Using such curves, we constructed an aluminum cavity with a vacuum resonant frequency of 1.5 GHz ($\lambda_0 = 20$ cm). Using standard procedures and tolerances, we were able to build a cavity to within 1% of the design value. The cavity Q was measured to be about 500. The cavity was driven by means of a semicircular loop antenna located at the cavity wall, which coupled to the rf magnetic field. The rf electric field in the cavity is perpendicular to a uniform axial magnetic field, and the electron cyclotron frequency is tuned to the resonant

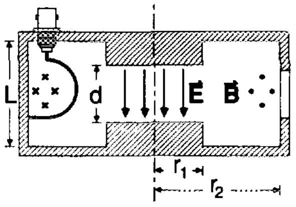

FIG. 1. Schematic of reentrant microwave cavity indicating location of rf fields and dimensions, $d = 1.25$ in., $L = 2.2$ in., $r_1 = 1$ in., and $r_2 = 2.75$ in.

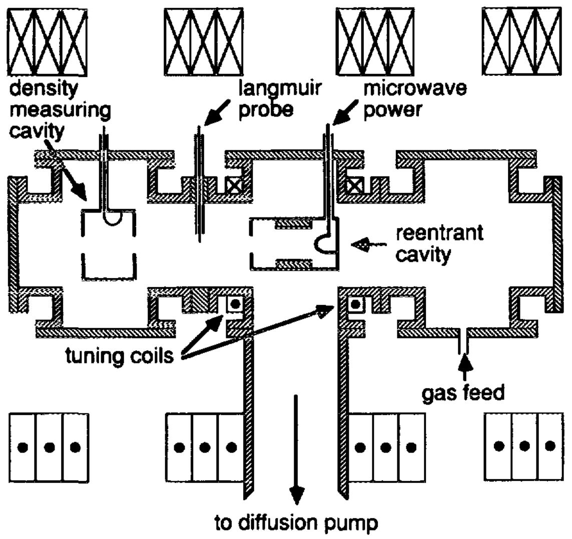

FIG. 2. Schematic of experiment indicating locations of the reentrant cavity, the density measuring cavity, and tuning coils.

frequency of the cavity by means of a set of small coils (see Fig. 2).

In order to allow plasma to exit the cavity it was necessary to bore a 1-in. hole through the cavity wall opposite the antenna. This had a minimal effect on the cavity Q. In fact there was no change in Q to the accuracy of our measurement technique (about 10%). The vacuum resonant wavelength increased less than 1% after the hole was bored.

II. PLASMA CHARACTERISTICS

Typically, peak microwave powers between 1 and 10 W were applied to the cavity during a 400-μs pulse. The driver frequency was 1.5 GHz, corresponding to the electron cyclotron frequency at about 540 G. Neutral argon densities were varied between 10^{-5} and 10^{-3} Torr. Electron density was measured by Langmuir probe ion saturation current calibrated with resonance shifts of a 2.3-GHz microwave cavity[10] located downstream from the source (see Fig. 2). Plasma potential was measured with emmisive probes[11] and found to be between + 5 and + 10 V.

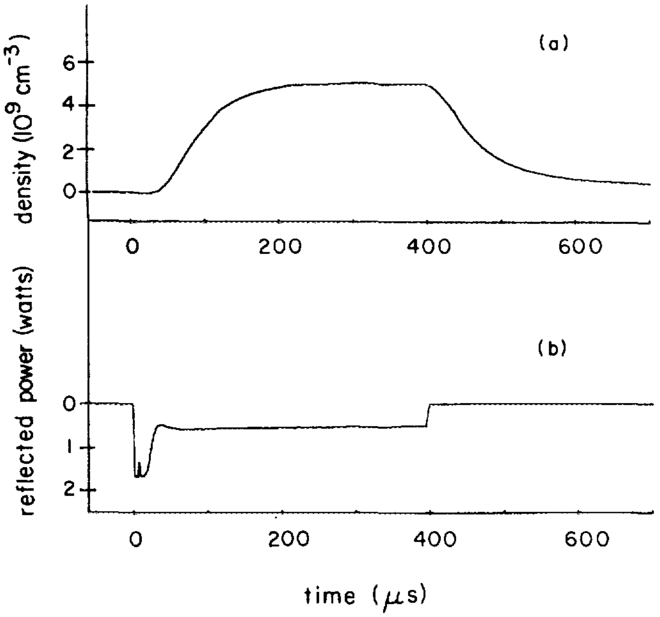

FIG. 3. Data from a typical shot, with 1.6 W of peak microwave power applied to the cavity and with a fill pressure of 1.5×10^{-4} Torr of argon, (a) time evolution of plasma density as measured by ion saturation current, and (b) reflected microwave power as a function of time where reflected power increases downward in the figure. Note the small, sharp decrease in reflected power early in the pulse which indicates initial plasma production.

In Fig. 3, data from a single typical shot are shown. Figure 3(a) depicts the time evolution of plasma density as measured by ion saturation current and Fig. 3(b) shows a plot of reflected microwave power as a function of time. Close examination of Fig. 3(b) reveals a sharp transient decrease in reflected microwave power early in the pulse. Visual observations with the cavity turned sideways and with holes cut at ± 90° with respect to the antenna correlate this feature with plasma production between the pads (this feature was not observed during plasma production with the bottom of the cavity removed). Plasma production does not

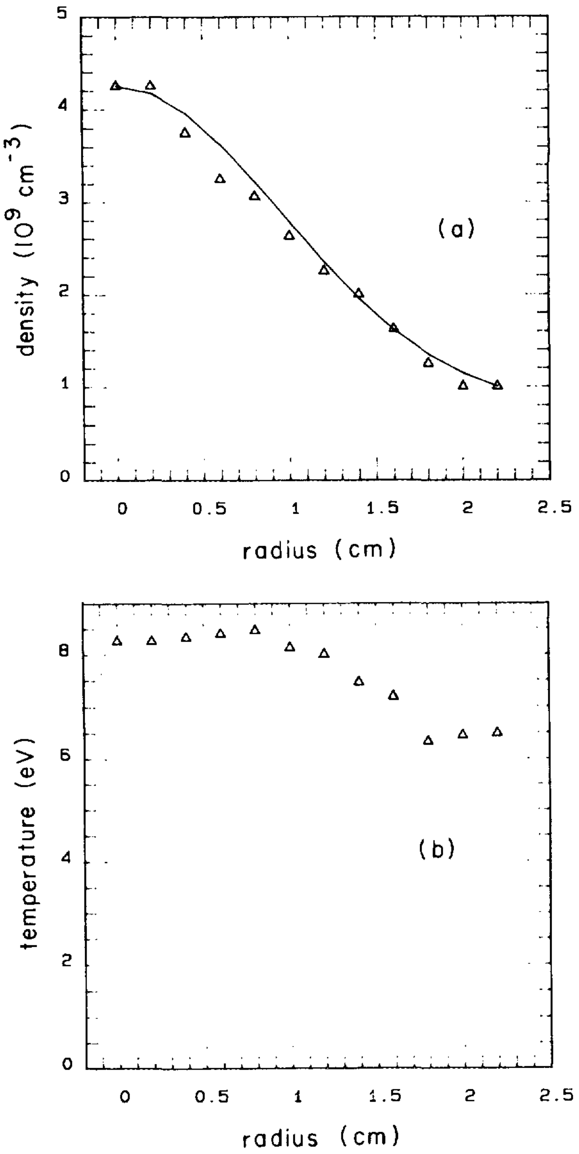

FIG. 4. Radial distributions of (a) electron density and (b) electron temperature.

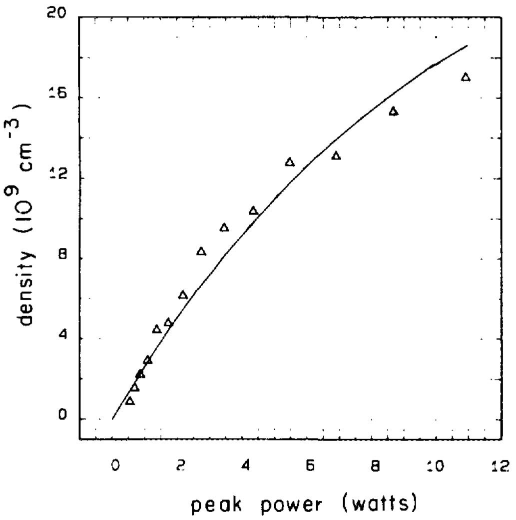

FIG. 5. Central electron density as a function of peak microwave power. The data are fit to $n_{1.5}(1 - e^{-P/10})$, where $n_{1.5}$ is the density corresponding to 1.5 GHz (2.8×10^{10} cm^{-3}) and P is the peak power in watts.

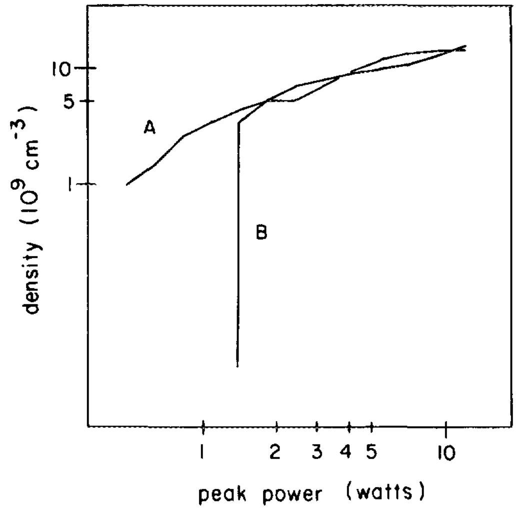

FIG. 6. Electron density as a function of peak microwave power for (A) the reentrant cavity and (B) a nonresonant cylindrical cavity.

continue between the pads, presumably because the presence of plasma between the pads alters the resonant frequency of the cavity. This initial spark of plasma production is, however, sufficient to initiate production around the antenna, if the cavity is oriented such that the region between the pads and the antenna are connected by field lines. Later in the pulse, as plasma production around the antenna begins, we note a sustained decrease in reflected power. After an initial buildup of plasma density, there is a long period of quiet, steady-state operation. After the microwave pulse ends, the plasma density decays with a time constant of about $50\,\mu$s, at the neutral pressure used (1.5×10^{-4} Torr). This corresponds to about an ion acoustic transit time from the cavity to the nearest ground plane along magnetic field lines. At higher neutral pressures, decay times are somewhat longer. During the steady-state phase, noise levels at ion acoustic frequencies, measured from peak to peak fluctuations of ion current, show $\delta n/n \approx 5 \times 10^{-3}$. Noise was peaked at about 20 kHz, which is well below both the typical ion plasma frequency (about 1 MHz) and the high-frequency roll-off of our data-acquisition system (5 MHz). The lowest noise levels are observed for the highest neutral pressures.

Figure 4 shows the radial distributions of various plasma parameters during the steady-state phase averaged over many shots. A radial density profile is shown in Fig. 4(a) and a radial temperature profile is shown in Fig. 4(b). The density profile has been fit to a Gaussian with a half-width of a centimeter. This is commensurate with the 1-in. aperture in the cavity, which acts as a limiter. The temperature profile, however, is fairly flat on axis at around 8 eV.

In Fig. 5 we plot central plasma density as measured by ion saturation current, calibrated with the resonance shift in a 2.3-GHz cavity, versus peak microwave power. There is apparently a limitation on the maximum plasma density we can efficiently produce with this source. This limit corresponds to plasma with central density of a few times 10^{10} cm^{-3} at the highest microwave powers and neutral pressures. The plasma frequency at these densities approaches the frequency of our driver (1.5 GHz). We have fit the data to $n_{1.5}(1 - e^{-P/P_0})$, where $n_{1.5}$ is the density corresponding to a plasma frequency of 1.5 GHz (2.8×10^{10} cm^{-3}) and P_0 is 10 W, to emphasize this upper limit. We are able to produce plasma at densities well below the resolution of our density measuring cavity (about 10^8 cm^{-3}). From ion saturation current measurements, we estimate that the lowest density plasmas are about 10^6 cm^{-3}. This suggests that we have a dynamic range in density of about 4 orders of magnitude.

In order to provide a basis for comparison, we removed the reentrant pads of the cavity and measured the performance of this nonresonant plasma source. In Fig. 6 we again plot density versus peak power, this time on a log–log scale, for both the reentrant cavity (A) and nonresonant cavity (B) as sources of plasma. We found that below a threshold of about 1-W peak, we cannot make a plasma unless we have a localized, resonant vacuum electric field to initiate breakdown. The density on axis at this threshold is about 4×10^9 cm^{-3}. With the reentrant pads installed, we were able to use the reflected microwave power signal to detect the presence of plasma at powers down to a milliwatt. It is noteworthy that the minimum power necessary to initiate breakdown without the pads is roughly Q times the minimum power necessary with the pads.

We also attempted to make plasma with the bottom of the cavity removed. In this open structure we had intermittent success. On one occasion we created a plasma with several watts, on another we were unable to create a plasma at any power level or neutral pressure available. We speculate that our initial success was due to a fortuitous overmoded resonance between the open cavity and the tank wall. From the above results it appears that at low powers the localized, resonant electric field is necessary to initiate breakdown while at higher powers breakdown is easily initiated.

III. OPERATIONAL ADVANTAGES AND LIMITATIONS

One distinct advantage of the reentrant cavity plasma source over hot cathode discharges and other microwave breakdown sources is the small power requirement. Plasmas can be made with as little as 1 mW of peak power. One watt of peak power produced plasma densities over 10^9 cm^{-3} and broke down gas at less than 5×10^{-5} Torr. Higher Q cavities could be used to produce low-density plasma with even less power. Because of the low powers used and because the electric fields are localized, ensuring microwave safety becomes an easy task. Other advantages, of particular interest for our experiments, include very low noise, and a uniform radial profile, with the absence of small scale transverse structure such as could result from the use of filaments in a strongly magnetized plasma. There is an upper limit on the plasma density which we are able to produce. At this density, the plasma frequency approaches the frequency of our rf oscillator. There is no apparent lower density limit for reproducible plasma production, so long as a vacuum resonant structure is employed; without vacuum resonance, plasmas with densities smaller than about 4×10^9 cm^{-3} could not be produced.

ACKNOWLEDGMENTS

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