Plasma Studies in a Low Pressure High Frequency Discharge

By A. J. Hatch*

The utilization of high frequency electromagnetic fields for the containment and heating of thermonuclear plasmas appears to present attractive possibilities. The exploitation of these possibilities, however, depends on the solving of many formidable problems. One phase of an attack on these problems is the experimental investigation of basic phenomena related to thermonuclear containment and heating in low pressure high frequency plasmas. This paper presents a description of such experimental work in progress at Argonne National Laboratory.

THE MULTIPACTING PLASMA MECHANISM

Density requirements for a thermonuclear plasma indicate that the pressure range of 10^{-2} to 10^{-5} mm Hg is of interest for basic studies of relatively cool plasmas. High frequency plasmas in this pressure range are usually produced by the multipacting mechanism.[1-9] Multipacting is also known as the secondary electron resonance mechanism, as "electrodeless discharge," and as "Pendelvervielfachung der Sekundärelektronen." Multipacting plasmas are sufficiently well understood to be a useful research tool. Furthermore, recently observed phenomena in multipacting plasmas appear to have possible significance for the understanding of high frequency thermonuclear plasmas. Most of the experimental work described in this paper is being done with plasmas produced by the multipacting mechanism.

The principal features of the multipacting mechanism are as follows. The mechanism is operative when the electron mean free path exceeds the electrode separation. The mechanism is controlled mainly by the parameters of frequency, electrode separation and applied voltage, and by the secondary emission characteristics of the electrode surfaces. Electron transit time between electrodes is nominally $\frac{1}{2}$ cycle in the fundamental mode. Higher order modes of $\frac{3}{2}$, $\frac{5}{2}$ and $\frac{7}{2}$ cycle transit times can be excited under appropriate conditions. Electron multiplication is mainly by secondary emission at the electrode surfaces. At the upper pressure limit of multipacting, the contribution of gaseous ionization to electron population can be comparable to that of secondary emission. This contribution decreases with decreasing pressure. Electrons traversing the inter-electrode gap are well bunched in space, time and energy. Electron energies are typically of the order of tens and hundreds of electron volts. The energy distribution of ions in the plasma, however, is not known.

A useful generalized parameter for multipacting is fd, the product of frequency f times electrode separation d.[9] The fundamental $\frac{1}{2}$ cycle mode is dominant from cutoff at about 100 Mc cm/sec to about 450 Mc cm/sec. The $\frac{3}{2}$ cycle mode is dominant from 450 to about 650 Mc cm/sec. The higher order modes usually overlap and are resolvable only under special conditions.

EXPERIMENTAL APPARATUS

The demountable discharge tube assembly being used at present is shown in Fig. 1. Rubber gaskets and "O" rings are used throughout. A tubulated glass cylinder 30 cm in diameter and 45 cm long is mounted between a pair of 40 cm diameter metal base plates. Plane parallel metal electrodes 22.5 cm in diameter are mounted inside the cylinder. They are supported by metal tubes which pass through a sliding "O" ring seal in each base plate. The position of each electrode can be axially adjusted over a range of 25 cm. The three tubulations on the top and front of the discharge tube are probe ports. Two of these, A and C, are in the center plane of the discharge tube. Probe port B is axially displaced from A and C by 5 cm. The probes are radially adjustable through sliding "O" ring seals. Fine position adjustment is provided for by the metal bellows. The combined flexibility of the electrode and probe positions permits location of the probes at any desired point in the plasma. Various probes are to be used, including single and double probes. Provision is made for the mounting of electron and ion energy analyzers behind small apertures in the discharge electrode surfaces. Electrode temperature and secondary emission ratio of the electrode surfaces can also be measured. The large tubulation on the bottom of the discharge tube is connected to the vacuum system (not shown). The vacuum system includes a 300 liter/sec oil diffusion pump, a 10 cm diameter throttling valve and a liquid nitrogen baffle. The source of high frequency energy (not shown) is a 1 kw continuously

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tunable continuous wave generator covering the range of 3 to 50 Mc. The output terminals of the high frequency generator are connected to the base plates of the discharge tube assembly.

EXPERIMENTAL PROGRAM

Three experiments now being performed or planned for the immediate future will be described briefly:

The first experiment is an exploration of the characteristics and fundamental nature of a type of high frequency plasmoid† originally observed by R. W. Wood.[10, 11] The experimental conditions under which these observations were made appear to be those of multipacting. Wood has hypothesized that this type of plasmoid is associated with the longitudinal electron plasma oscillations studied by L. Tonks and I. Langmuir.[12] It is well known that plasma oscillations constitute one of the principal mechanisms whereby a plasma can be shielded from an applied high frequency field. Furthermore, the plasma density limitations inherent in plasma oscillations are generally too low for thermonuclear applications. Hence an understanding of plasmoids and plasma oscillations can be considered as an essential first step in order to overcome these limitations to high frequency methods of plasma heating.

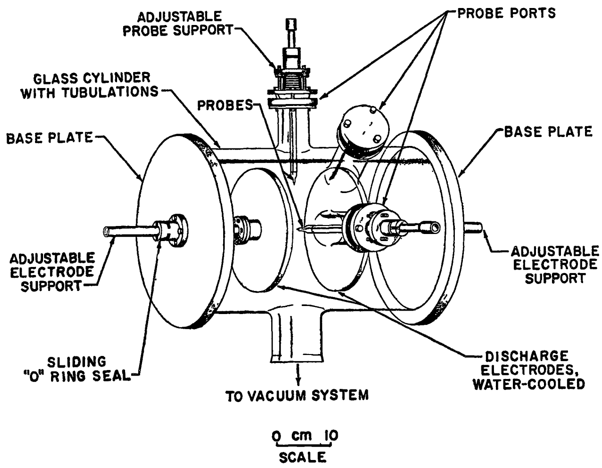

Figure 1. Discharge tube

The second experiment is an investigation of a possible containment mechanism in a multipacting plasma. It has been pointed out by C. F. Robinson[13] and by H. B. Williams[14] that the time-average force exerted on a positive ion in a multipacting plasma by the oscillating cloud of electrons is directed toward the center of the plasma volume. Thus, a three dimensional well or trap for ions can be established. This containment mechanism is illustrated schematically in Fig. 2. Although the temperature and density capabilities of this mechanism are estimated to be fairly high, the possible limitations due to effects such as plasma oscillations is not known. A further aspect of the mechanism is that it may be associated with the high frequency plasmoid discussed in the preceding paragraph. Studies of the characteristics of the multipacting containment mechanism are expected to contribute to an understanding of the general problem of high frequency (or dynamic) containment mechanisms.

The third experiment is an investigation of the penetration of a plasma by high frequency fields in the presence of transverse static magnetic fields. Theoretical studies by M. H. Johnson[15] indicate the possibility of greatly enhanced high frequency field penetration of the plasma in such systems. In a simple experimental geometry such as that of the discharge tube shown in Fig. 1 the longitudinal or axial plasma oscillations are converted to transverse plasma oscillations by the transverse magnetic field. This conversion is shown schematically in Fig. 3A. Although this modification provides a substantial enhancement of field penetration, the transverse plasma oscillations still constitute a serious barrier. The transverse plasma oscillations arise from charge separation at the edges of the plasma perpendicular to the electron trajectories. A method of overcoming both the longitudinal and transverse plasma oscillation limitations on high frequency field penetration as proposed by Johnson is illustrated in Fig. 3B. In this coaxial cylindrical geometry, the high frequency electric field is radial and the static magnetic field is axial. There is now no

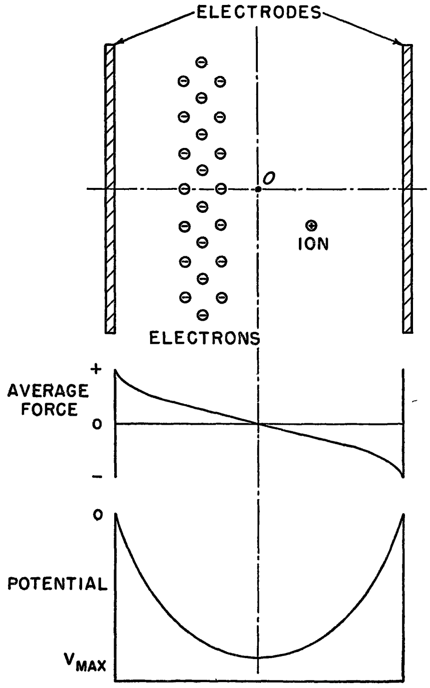

Figure 2. Schematic representation of multipacting potential well

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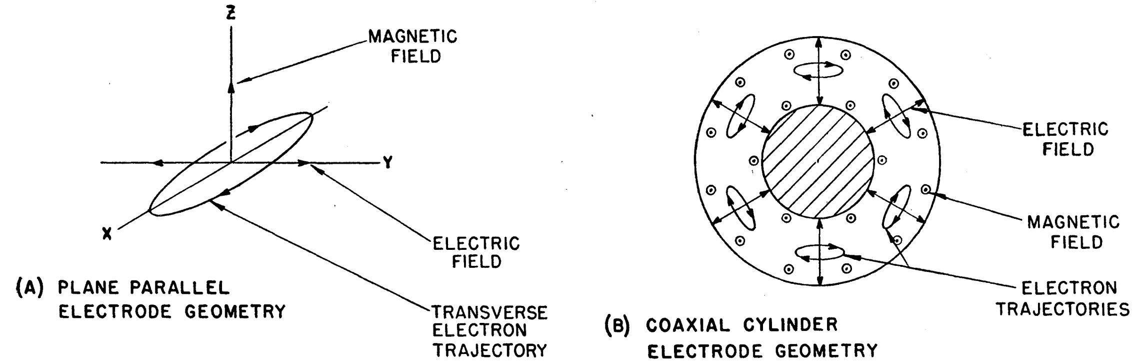
† The term "Plasmoid" was originally suggested by R. W. Wood (Ref. 10). He applied the term to the luminous balls, spindles, etc., observed in certain low pressure high frequency plasmas. W. H. Bostick has more recently generalized the term to include any well defined plasma-magnetic entity or compact geometrical configuration, independent of the method of production (see Ref. 11).



(A) PLANE PARALLEL ELECTRODE GEOMETRY

(B) COAXIAL CYLINDER ELECTRODE GEOMETRY

Figure 3. Electron trajectories in transverse plasma oscillations

azimuthal boundary at which charge separation due to the azimuthal (transverse) motion of the electrons can occur. Charge neutrality can now be maintained throughout the plasma. The resulting high frequency field penetration is now adequate to enable the plasma to accept energy efficiently by the ion cyclotron resonance mechanism. This experiment will be performed in two parts, one using the plane parallel electrode geometry of Fig. 1, the other using the cylindrical geometry of Fig. 3.

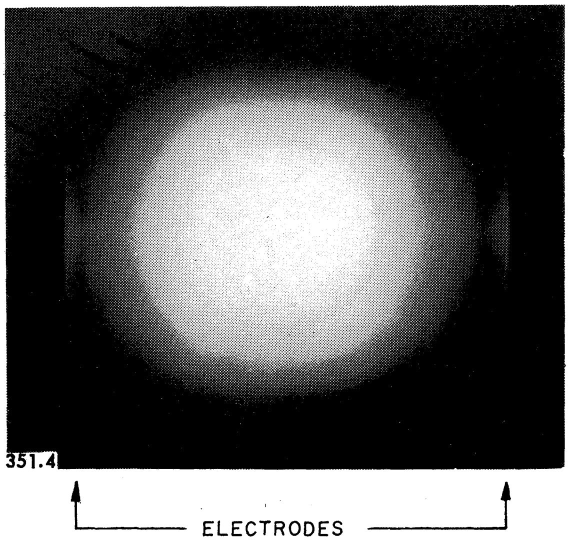


Figure 4. Photograph of high-frequency plasmoid

EXPERIMENTAL RESULTS

A photograph of a typical high frequency plasmoid is shown in Fig. 4. This plasmoid was formed between the plane parallel electrodes of the apparatus shown in Fig. 1. The electrodes were on the left and right hand sides of Fig. 4. The frequency was 15 Mc and the electrode separation was 25 cm, corresponding to $\frac{1}{2}$ cycle multipacting at 375 Mc cm/sec. The plasmoid was formed in air at a pressure of 0.3×10^{-3} mm Hg. Both the plasmoid and the surrounding plasma were white. A prominent feature of the plasmoid is the dark boundary which completely surrounds it. The plasmoid thus defined is approximately a spheroid of diameter 12 cm. The plasmoid exists in various forms from about 3×10^{-3} mm Hg to about 0.1×10^{-3} mm Hg. At pressures above 0.3×10^{-3} mm Hg the plasmoid enlarges, becomes more cylindrical in form, and the dark boundary becomes less distinct. At pressures below 0.3×10^{-3} mm Hg the plasmoid becomes ellipsoidal. At a pressure of about 0.1×10^{-3} mm Hg both the plasmoid and surrounding plasma sometimes suddenly disappear. At other times the plasmoid suddenly becomes quite flat, like a thin double convex lens which tapers off to a thin tenuous edge, and the dark boundary extends all the way to the confining edges of the discharge tube and electrodes. This latter plasmoid configuration is usually quite unstable; it either reverts quickly to the ellipsoidal plasmoid with the narrow dark boundary, or both the plasmoid and plasma suddenly disappear.

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