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Enhancement of Plasma Density in an Arc Discharge

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The amplification or generation of coherent signals by electron-beam–plasma interactions requires the creation of a high-density stable plasma. A plasma density of approximately 10^{15} particles/cm^3 is required to produce a plasma resonance frequency of 300 Gc/sec. The density in an arc-discharge plasma has been increased using mechanical and magnetic constriction methods with the result that $n_p = 7.5\times10^{14}$ particles/cm^3 is realized at a discharge current of 4 A in argon. Double Langmuir probe measurements on density and temperature in the plasma are presented and interpreted for zero and finite magnetic-field conditions.

INTRODUCTION

THE use of an ionized plasma column in electron-beam–plasma amplifiers and oscillators at short wavelengths (millimeter waves) requires high plasma particle densities since the operating frequency is approximately equal to the plasma resonance frequency. The plasma frequency and density are related by

$$f_p = 8980\sqrt{n}\ \text{cps}, \tag{1}$$

where n is the particle density (ions or electrons) per cm^3 and f_p is in cps. Thus densities in excess of 10^{15}/cm^3 are required for submillimetric operation. A large energy concentration is required to create such densities and as predicted by Lampert[1] is approximately 1 kW/cm^3 for $n = 10^{15}$/cm^3; the experimental work reported here supports this contention.

An enhanced plasma density may be achieved over limited regions of an arc discharge using the configuration illustrated in Fig. 1. The constriction of the electron stream between the cathode and anode electrodes results from the action of the conical conducting electrode, which assumes a negative potential, and from the convergence introduced by the spatially varying magnetic field, which creates cycloidal motion of the electrons and also decreases the rate of transverse diffusion to the walls.

There will be in general a variation of the plasma particle density in both the transverse and longitudinal directions, the degree being influenced by the following factors and processes: (1) discharge current density, (2) radial and longitudinal potential gradients, (3) frequency of ionizing collisions, (4) ambipolar diffusion coefficient transverse to the magnetic field, and (5) shape and type of plasma boundaries. In any practical situation factors (1) and (2) are balanced against processes (4) and (5). The conical conducting electrode is left floating and assumes a negative potential with respect to the anode; this results in an increase in the discharge current density, since the total current density is constant at all cross sections of the discharge. The volt–ampere characteristic of the conical electrode in the plasma tube is discussed in detail in the following section. As expected, the greatest constriction occurs between the end of the conical electrode and the anode. The plasma configuration bears some similarity to the work of von Ardenne[2] on the duoplasmatron which is used extensively as an ion source.

EXPERIMENTAL CONFIGURATION AND MEASUREMENT TECHNIQUES

A plasma tube constructed to obtain experimental information on the characteristics of geometric and magnetic constrictions is shown schematically in Fig. 2. For experimental operation the plasma tube is inserted in a set of solenoid coils whose currents are individually adjustable to produce the spatially varying magnetic field as illustrated in Fig. 1. The cathode consists of six oxide-coated nickel sleeves arranged in a cylindrical array. The array is surrounded by a heat shield in order to conserve heater power. The cathodes deliver up to 120 mA in a vacuum.

The anode electrode is provided with a Faraday cage so as to reduce the effects of secondary electron emission. The large end of the conical electrode has a diameter of approximately 5 cm and the smaller end a diameter of approximately 4 mm. The gas used was argon, with pressures in the range of 10–300 μHg. The discharge is initiated by connecting the intermediate electrode to the anode; thereafter it was left floating.

The current to the conical electrode as a function of the electrode potential relative to the anode is shown in Fig. 3 for a condition in which $B(z) = 0$. The net

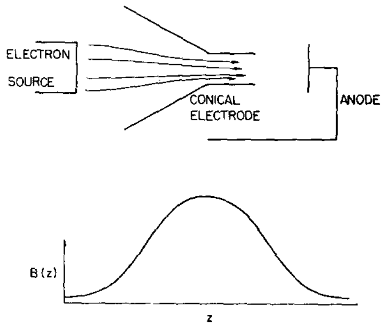

FIG. 1. Mechanical and magnetic convergence for plasma density enhancement.

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[1] M. A. Lampert, J. Appl. Phys. 27, 5 (1956).

[2] M. von Ardenne, *Tabellen der Elecktronenphysik, Ionenphysik und Ubermikroskopie* (VEB Deutscher Verlag der Wissenschaften, Berlin, 1956), Vol. 1, p. 544.

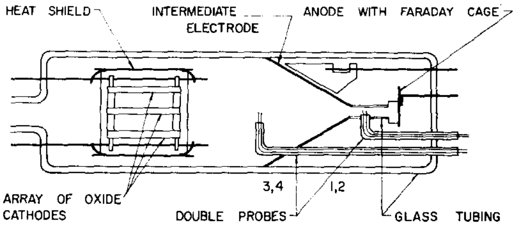

FIG. 2. Schematic diagram of experimental tube for study of plasma parameters.

current to the electrode is zero for a relative potential of −24.5 V. The current increases rapidly to positive values (random electron current) as the potential is made less negative, and, as expected, becomes negative (random ion current) for more negative potentials. Since the random ion current is considerably smaller than the random electron current, saturation is reached more quickly for the former.

The plasma particle density and temperature are determined using double Langmuir probe techniques in view of the presence of the magnetic fields. As illustrated in Fig. 2, two sets of double probes are used, one set in the large end of the conical electrode and the other pair in the constricted region where the plasma density is highest. Double Langmuir probes were used in preference to a single probe since they disturb the plasma to a lesser extent. The double probes consisted of tungsten wires of 0.25-mm diameter, separated by 1.5 mm, and they were insulated with a covering of glass. The bare portion of the probe wire was 2 mm in length for probes 1 and 2, and 3 mm in length for probes 3 and 4. The double probes were used to measure plasma ion density and the dimensions (length and separation) were chosen such that they were small in comparison to the ion Larmor radius. Both static and dynamic probe characteristics were taken and the results were in excellent agreement.

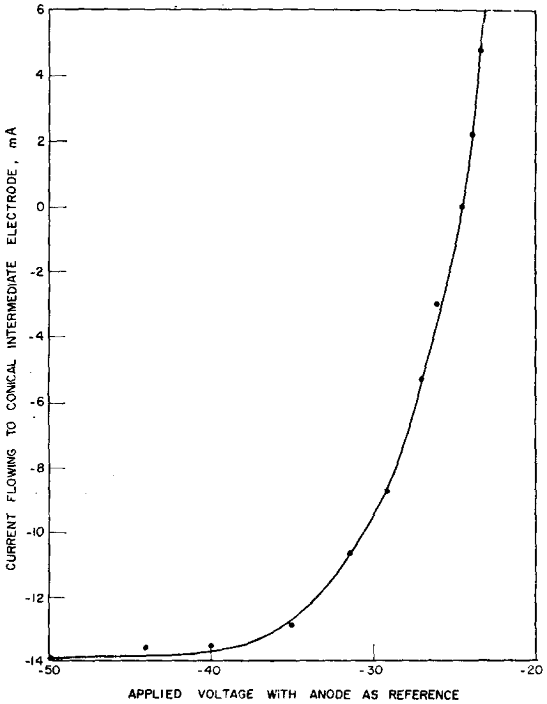

FIG. 3. Current–voltage characteristic for the conical electrode ($I_{\mathrm{dis}}=100$ mA, argon at 40 μHg).

The theory of the double Langmuir probe was developed by Johnson and Malter[3] and is used here to determine electron temperature and plasma particle density making use of the fact that the plasma is macroscopically neutral, i.e., $n_i=n_e$. The disturbing effect of the double probes on the plasma is much less than the single probe since as indicated by Kirchhoff's law the current to any probe can never exceed the random ion current, which is much smaller than the random electron current.

According to the method of Johnson and Malter,[3] since each probe of the pair has the same area exposed to the plasma, the electron temperature is given approximately by

$$T_e=5800V_p, \tag{2}$$

where V_p is the knee voltage of the double-probe volt-ampere characteristic. Under these same conditions the plasma ion density is given by

$$n_p=(i_p/Ae)(2\pi m_p/kT_p)^{\frac{1}{2}}\ \text{ions/cm}^3, \tag{3}$$

where i_p = the random positive ion current to the probe, A = effective sheath area (probe area) in cm^2, e = electron charge in coulombs, m_p = mass of the ion in grams, k = Boltzmann's constant, and T_p = positive ion temperature in °K. Since the ion density in Eq. (3) is not critically dependent upon the temperature T_p, it will be replaced by the gas temperature and taken as 400°K for these experiments. This approximation usually does not materially affect the results, i.e., less than an order of magnitude.

Double-probe measurements were obtained both by static and dynamic methods and these are illustrated in Figs. 4 and 5 for zero and finite magnetic field values. The results in Fig. 4 were taken at zero magnetic field and a low discharge current for a moderate gas pressure. Probes 1, 2 and 3, 4 refer to the probe locations illustrated in Fig. 2. Dynamic probe characteristics are shown in Fig. 5 for various discharge currents and a maximum magnetic field in the constricted region of the plasma of approximately 500 G; the curves are recorder tracings of actual dynamic probe characteristics. The double probes were well calibrated and checked against single-probe measurements for $B=0$, and since all probe dimensions were small compared to the ion Larmor radius the determined values of n_p are considered reliable. Since the V–I characteristics are generally symmetric about the origin the maximum error in the determination of T_e is considered to be 5–10%.

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[3] E. O. Johnson and L. Malter, Phys. Rev. 80, 58 (1960).

PHYSICAL THEORY

The plasma density dependence on discharge current, electron drift velocity, and the tube radius may be calculated following an analysis made by Engel and Steenbeck[4] for a positive column. The basis of this theory is that volume recombination processes are negligible compared to surface recombination processes and furthermore that the ion mean free path for the ion–neutral collision process is small (high degree of ionization) compared to the diameter of the constriction (small end of the conical electrode) since the collisions between ions and neutrals are more important in determining the diffusion rate than those between electrons and neutrals. The ionized gas diffuses to the wall under the electron pressure with a mobility determined by the rate of loss of momentum from ions to neutrals. The ion and electron concentrations are again considered equal. The result of this analysis, assuming an ambipolar diffusion process, is

$$n_p = (i_{\mathrm{dis}}/1.36evR^2)\mathrm{ions/cm}^3, \tag{4}$$

where i_{dis} = discharge current in amperes, e = electronic charge in coulombs, v = axial electron drift velocity in cm/sec, and R = internal radius in cm of the surrounding electrode at a particular displacement. The plasma density thus increases in direct proportion to the discharge current. Since the electron drift velocity increases as R decreases, the inverse square dependence of n_p on R is somewhat modified. It is important to note that there is no restriction on the cathode size and thus one may use relatively large electron sources for high-density plasmas. For a particular set of operating conditions the calculated plasma density on the axis of the system was 3.6×10^{13} ions/cm^3 from Eq. (3) and the corresponding experimental average value over the cross section was 1.0×10^{13} ions/cm^3, indicating excellent agreement.

The guiding centers of electrons tend to follow the magnetic lines of force.[5] Thus, in a converging magnetic field, the electron trajectories would also tend to converge towards the axis as the electrons move into regions of higher magnetic field. From this factor alone, the electron density would be approximately proportional to the number of magnetic lines of force per unit area or, in other words, to the magnetic flux density. If the variation in magnetic field takes place over distances that are large in comparison with the Larmor radius the magnetic moment associated with the orbiting electron may be considered as an invariant. In other words, since $\mu = w_\perp/B$ (where μ is the magnetic moment, $w_\perp$ the kinetic energy of the electron due to the component of velocity transverse to the magnetic field, and B the magnetic flux density), $w_\perp$ increases as B increases. The magnetic field does not change the total kinetic energy and thus $w_\parallel$, which is the kinetic energy due to the component of velocity parallel to the magnetic field, has to decrease. As a consequence, for a given current flowing through an arc discharge, the decrease of drift velocity has to be compensated for by an increase in plasma density. In both of the above phenomena collisions would modify the simple behavior outlined. These collisions result in diffusion transverse to the magnetic field.

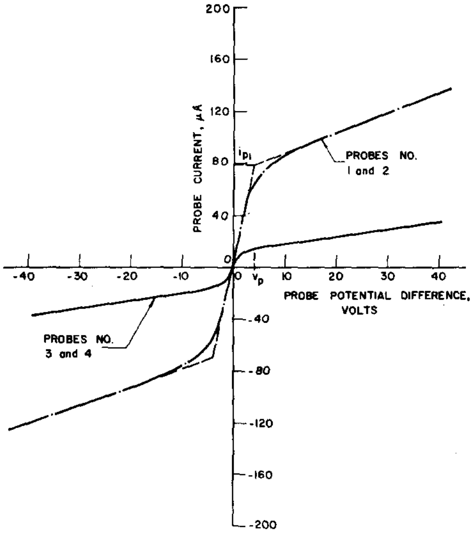

FIG. 4. Double-probe volt–ampere characteristic (I_{dis} = 67 mA, B = 0, argon pressure = 77 μHg).

An analysis of the transverse diffusion process can be given[6] in terms of a "random walk" of the guiding centers as a result of collisions. Such an analysis indicates that the diffusion coefficient transverse to the magnetic field is inversely proportional to the square of the magnetic field. Analyses[7] which take into account the possibilities of turbulence in the plasma yield a diffusion constant inversely proportional to the magnetic field for the case in which the effects of turbulence predominate over those of collision. In either case, with

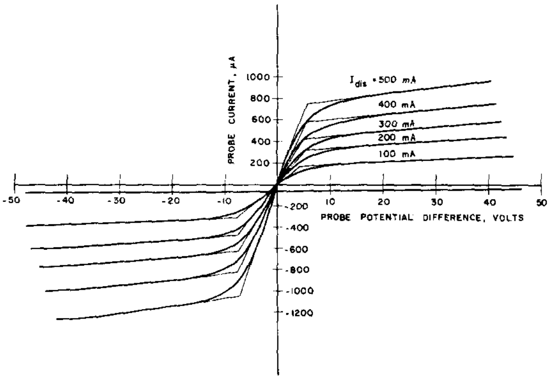

FIG. 5. Double-probe volt–ampere characteristic for probes 1 and 2 ($B_{\max} \approx 500$ G, argon pressure = 260 μHg).

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[4] A. V. Engel and M. Steenbeck, Ihre Physik und Technik 1, 184, 236 (1932); 2, 83 (1934).

[5] L. Spitzer, *Physics of Fully Ionized Gases* (Interscience Publishers, Inc., New York, 1956).

[6] S. Chandrasekhar, *Plasma Physics* (The University of Chicago Press, Chicago, 1960).

[7] S. Yoshikawa and D. J. Rose, Phys. Fluids 5, 334 (1962).

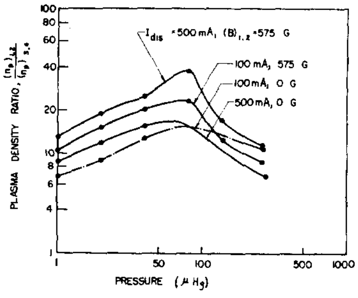

FIG. 6. Plasma density enhancement dependence on pressure, discharge current, and magnetic field.

higher magnetic fields, the transverse diffusion is slower.

At pressures where the mean free path of the electrons is small in comparison with the tube dimensions, the transverse diffusion process would be dominant; otherwise one may think solely in terms of particle motion along the guiding centers.

EXPERIMENTAL RESULTS

Following the experimental procedure outlined above for determining plasma density and electron temperature from double-probe characteristics, the influence of such parameters as discharge current, gas pressure, and magnetic field on plasma ion density is investigated. Some of the representative results are shown and discussed below.

The variation of plasma density at both the wide and narrow ends of the cone was investigated over a wide range of discharge current in argon, at various pressures, and for a range of applied magnetic field. The increase in density between the two locations was clearly evident and also it is noted that the density varies linearly with discharge current, which is the expected behavior outlined in connection with Eq. (3).

Figure 6 indicates the effect of pressure and magnetic field variations on the plasma density enhancement ratio. These data did indicate the following trends:

(a) The application of a converging magnetic field results in two or more orders of magnitude increase in plasma density.

(b) At elevated magnetic fields the plasma density tends to saturate and become independent of the magnetic field. As the pressure is lowered, the saturation effect occurs at lower magnetic fields. This independence of n_p on magnetic field is expected since the effect of the magnetic field on particle trajectories is more ordered if the mean free path is large in comparison with the Larmor radius.

(c) The ion density, in general, decreased with increasing pressure for a wide range of magnetic fields.

The density enhancement ratio is maximum at a pressure of approximately 80 μHg for moderate discharge currents and this optimum pressure is relatively independent of both magnetic field and discharge current, indicating that the effect is apparently associated with the constriction of the column. Much larger enhancement ratios occur at high discharge currents. The plasma density is related to the pressure and the diameter of the constriction through the drift velocity of the electrons, as discussed in relation to Eq. (3). The dependence is complex in view of the fact that the drift velocity of the electrons is dependent on the tunnel radius R. The maximum enhancement factor, shown in Fig. 6, is 38 and the minimum approximately 7. Note that at 500 mA of discharge current and an argon pressure of 80 μHg the enhancement due to the geometric constriction is 15, while that due to the magnetic field is approximately $38/15=2.54$.

The plasma density at the throat of the cone depends quite linearly on the discharge current and it thus is worthwhile to investigate the variation of n_p for an extended range of the discharge current. The results for ion density in the constricted region $(n_p)_{1,2}$ at an argon pressure of 40 μHg and $B_{\max}\approx 575$ G are shown in Fig. 7. The linear dependence of ion density on discharge current is preserved up to quite high current levels with some saturation effects apparently setting in at around 4 A. The density of 7.5×10^{14} particles/cm^3 at $I_{dis}=4$ A corresponds to a plasma frequency of 246 Gc/sec. The enhancement ratio is well in excess of 100 times under these conditions and there is no apparent reason why this technique could not yield densities greater than 10^{15} per cm^3. We were not able to operate the present apparatus at higher discharge currents continuously due to the high power density in the column (approx. 1 kW/cm^3), which produced excessive heating of the conical electrode and damage to the Langmuir probes. Operation at higher currents could be done on a pulsed basis if one wanted to use Langmuir probes, or the densities could be measured using microwave methods if the discharge were operated continuously.

The electron temperature vs argon pressure at the two probe locations is shown in Fig. 8 for a discharge current of 500 mA and a magnetic field of 575 G. It was noted that T_e was quite insensitive to both discharge current and magnetic field.

The double-probe characteristics were also observed on an oscilloscope and revealed that plasma oscillations were occasionally present, particularly at low values of magnetic field. The frequency of these oscillations was not well defined under all conditions, although some periodicity was observable in the range of 20 kc/sec,

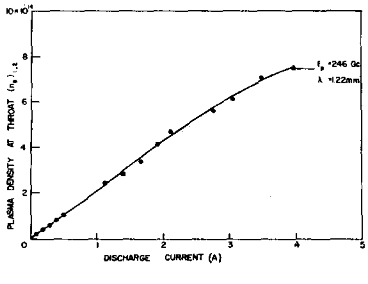

FIG. 7. Plasma density at the throat of the cone vs discharge current.

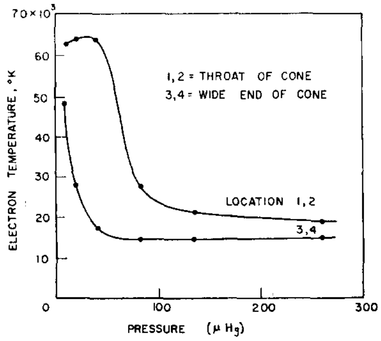

FIG. 8. Variation of electron temperature with pressure at the two probe locations ($I_{\text{dis}}=500$ mA, $B\approx 575$ G).

suggesting the presence of ion plasma oscillations. At high values of magnetic field, above 500 G, the oscillations generally disappeared.

CONCLUSIONS

A configuration well suited to the objective of achieving high plasma particle densities has been studied. Its main features are a conical intermediate electrode between the anode and the hot cathode of an arc discharge, and a converging magnetic field in the same region.

An analysis of the important physical phenomena has been given. The plasma density was found to vary nearly linearly with current and was increased by more than an order of magnitude at the narrow end of the cone (conical electrode) over that at the broad end, at zero magnetic field. When a converging magnetic field was applied, the density in the narrow region could be increased by at least another order of magnitude. The ratio of plasma density in the narrow region to that at the broad region went through a maximum at a pressure of 80 μHg in argon, which appeared to be an optimum pressure for all magnetic field and current values.

As the magnetic field increases, the plasma density increases at first, but reaches a saturation at a value which is a function of the pressure. Saturation comes at lower magnetic fields for lower pressures.

The electron temperature increases with decreasing pressure and is relatively independent of the discharge current and the magnetic field.

At ion densities near $7\times10^{14}/\text{cm}^3$ the power density in the constricted region of the discharge has been estimated at 800–1000 W/cm³. It was noted that the basic technique appears well suited for achieving plasma particle densities in excess of $10^{15}/\text{cm}^3$.

ACKNOWLEDGMENT

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Incorporation of a Laser into the Arm of an Interferometer for Measurement of Transient Phase Changes*

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An interferometer is described in which a He–Ne laser has been introduced into one of the arms to act as a coherent light source, eliminating the use of a beam splitter and making more efficient use of available light. The interferometer has been used with 0.63-μ laser light to observe the fringe shift produced in a small transient plasma with submicrosecond time resolution. Electron densities of the order of $10^{15}/\text{cm}^3$ over a path length of 15 cm were measured, close to the sensitivity limit for the unrefined experimental setup. The use of a laser source with long light paths and narrow beam width gave good discrimination against plasma light.

INTERFEROMETRIC methods provide a very sensitive means of detecting small displacements or changes in refractive index, and one use of these techniques is in measuring the electron density in transient plasmas in which the presence of ionization results in a change in refractive index. The upper limit to the electron density which can be measured is determined by the criterion that the frequency of the probing signal be greater than the plasma frequency. This sets an upper limit of the order of 10^{13} cm^{-3} for millimeter microwaves and 10^{21} cm^{-3} for visible radiation.

The use of microwaves to measure the spatially integrated phase change is a well-established technique,[1] but in many instances it is desirable to measure higher electron densities, as high as 10^{18} cm^{-3}, for which it is necessary to use infrared or visible radiation. In this region the main problem is in obtaining a light source of sufficient intensity to override the intense plasma light associated with high ionization, and a secondary problem is in obtaining fast detectors in the infrared for transient plasmas.

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* Work sponsored by IIT Research Institute.

[1] R. F. Whitmer, Phys. Rev. **104**, 572 (1956).