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GENERATION AND MEASUREMENT OF HIGHLY IONIZED QUIESCENT PLASMAS IN STEADY STATE

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The purpose of the experiments described in this Letter is to perfect techniques for generating highly ionized quiescent plasmas of useful density in steady state, and to use such plasmas for a systematic and conclusive investigation of the properties of fully ionized quiescent plasmas. Thermionic electron emission combined with resonance ionization (or contact ionization) of cesium vapor is a most suitable process for producing plasmas of this type. This technique was recognized a number of years ago[1]; more recently, it has found new favor in a number of laboratories.[2-5] The experimental results obtained to date in our Laboratory by means of this technique are summarized below and will be reported more extensively at a later date in papers under preparation.

A quiescent highly ionized cesium plasma is generated and sustained in steady state in the apparatus sketched on Fig. 1. This apparatus consists of two plasma emitters facing one another and immersed in a homogeneous axial dc magnetic field (shown by H_0 on Fig. 1). Each plasma emitter consists of a tungsten plate heated to thermionic emission temperature by electron bombardment from an auxiliary cathode. The whole device, including the hot tungsten plates, is placed in a vacuum-tight and thoroughly outgassed enclosure. The pressure of background gases different from cesium vapor is kept at all times of the order of 10^{-8} mm of Hg or less, in order to keep the effect of these gases negligible. The cesium vapor pressure is controlled by admitting an excess of cesium metal into the apparatus, and accurately controlling the temperature of the enclosure walls. A direct measurement of the cesium vapor pressure by means of saturation ion emission from a hot tungsten filament indicated that this method of control of cesium vapor pressure is, with due care, quite reliable.

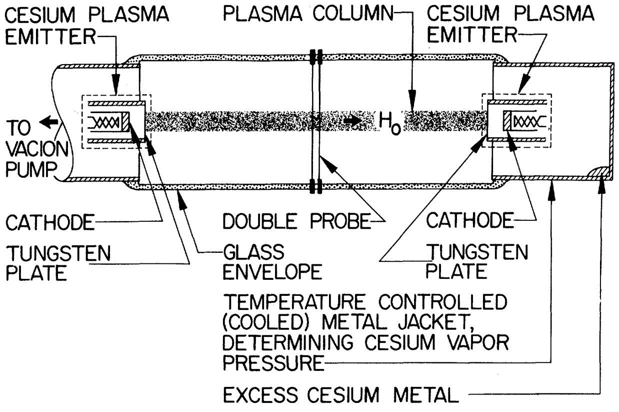

FIG. 1. Apparatus for generation of a highly ionized cesium plasma column in a homogeneous dc magnetic field H_0.

In the apparatus of Fig. 1, ions are emitted by contact ionization of the cesium on the hot tungsten plates; electrons are emitted thermionically on the central hot part of the tungsten plates. Plasma thus is continuously generated at both ends of the plasma column at a rate controlled by the neutral cesium vapor pressure. A relatively modest dc magnetic field (of the order of a few hundred oersteds) is found sufficient to make plasma diffusion in the radial direction negligible. This technique results in a well-defined quiescent cesium plasma column, as indicated in Fig. 1. The first-order cause for plasma loss in this plasma column is volume recombination, together with plasma loss on the small probes used to measure the plasma density and temperature. (The plasma loss on the probes is readily taken into account and its effect on the degree of ionization of the plasma is, to a first order approximation, independent of plasma density.) The degree of ionization of the plasma then is determined by the condition that the rate of cesium ion generation on the plasma emitters be equal to the rate of cesium ion loss by volume recombination and on the probes. The rate of volume recombination being, by definition, proportional to the recombination coefficient, the latter is found directly from the measurement of the degree of ionization as a function of plasma density.

By means of such a plasma, in an apparatus of the type sketched on Fig. 1, the following experimental results have been obtained:

(a) Validity of double-probe measurements in dc magnetic field. Because of its simplicity, the double-probe method of measurement of plasma density and temperature has been used. Because of the presence of a dc magnetic field, the validity and interpretation of this method of measurement could be subject to question. Our experimental results did, however, substantiate our theoretical expectation that double-probe measurements, even in the presence of a dc magnetic field, are completely reliable under the conditions of our measurements (probe dimensions, spacing, and sheath thickness small compared to the ion cyclotron radius). Comparison of the double-probe measurements of plasma density with microwave cavity plasma density measurements showed excellent agreement (within 30%) over the whole range of magnetic fields investigated (300 to 1500 oersteds). Comparison of the plasma electron temperature evaluated by double probes in the same magnetic fields with pyrometric measurements of the plasma emitter temperature (hot tungsten plates) showed agreement within 10% to 15%. Prior comparison of the plasma electron temperatures with the plasma emitter temperature by measurements of the mean electron cyclotron radius had shown these two temperatures to be the same within measuring accuracy for the conditions of our experiments.[6] We thus conclude that, within the limits stated above, double-probe measurements of both plasma density and temperature in the presence of a magnetic field remain reliable and are not appreciably affected by the presence of the magnetic field.

(b) Plasma diffusion and profile of plasma columns. For a preliminary estimate of the profile of the plasma column and of the nature of diffusion of a quiescent plasma in a dc magnetic field, the apparatus of Fig. 1 was used with only one plasma emitter operating, the other being kept cold. The orientation of the dc magnetic field was then continuously changed so as to sweep the plasma column across the probes (3 fixed probes at different radial positions were used in this experiment). Recording of the plasma density measured by the probes as a function of magnetic field orientation yielded the well-defined profile shown on Fig. 2 for the plasma column. Although more detailed and extensive measurements now being prepared are needed to reach final conclusions, preliminary indications are that plasma diffusion is purely ambipolar, even in the presence of the dc magnetic field. This seems consistent with the results obtained independently and at about the same time as ours by Rynn and D'Angelo.[5]

(c) Measurement of degree of ionization. The results of a typical set of measurements of cesium plasma density and neutral cesium density are shown in Fig. 3. The corresponding values of the degree of ionization ν of the plasma are shown on the same figure. It may be observed that up to a density higher than $n_+ = 10^{12}$ ions/cm^3 a plasma with a degree of ionization

$$\nu = 90\%$$

has been obtained. It is particularly interesting

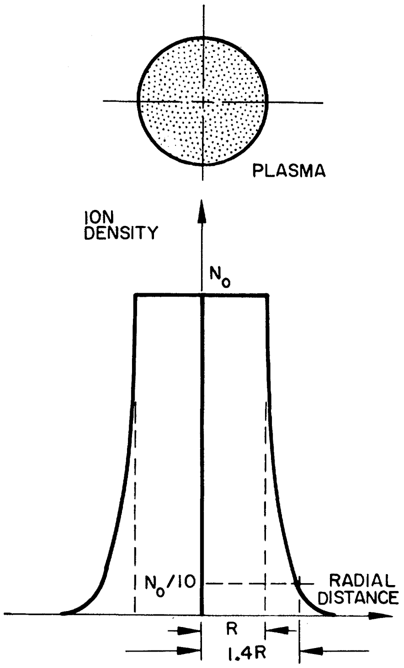

FIG. 2. Profile of cesium plasma column.

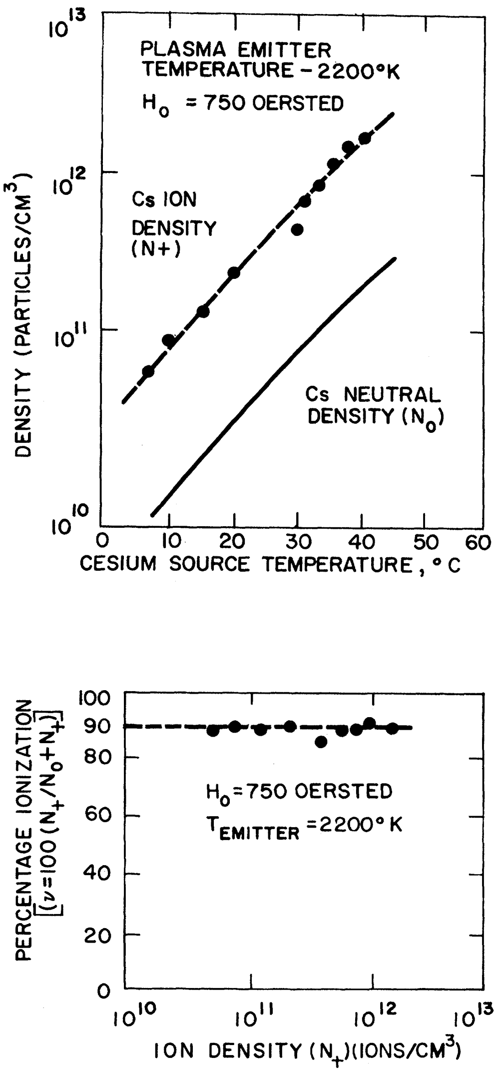

FIG. 3. Ion density, neutral density, and degree of ionization in cesium plasma column.

to mention that the value $\nu = 90\%$ corresponds rather well to the degree of ionization expected from the plasma loss on the probes as long as volume recombination is negligible.

(d) Estimate of recombination coefficient. From the data of Fig. 3 it follows that volume recombination is negligible up to plasma densities exceeding 10^{12} ions/cm^3. This, together with the known dimensions of the plasma column (length $L = 10$ cm), leads to the following upper limit for the recombination coefficient:

$$\alpha < 10^{-10}\ \text{cm}^3\ \text{sec}^{-1}.$$

This value is substantially lower than the values reported to date in the literature.[7,8] Our result, however, is not too surprising because of the low probability of formation of molecular ions leading to dissociative recombination. A determination of the actual value of α rather than of its upper limit requires measurements at higher plasma densities, in the apparatus of Fig. 1. This apparatus is presently being modified to make such measurements possible. It will be interesting to observe how close the actual value of α is to radiative recombination. Alternatively, our experiments may provide a verification of the theory recently proposed by D'Angelo[9] for the electron-ion recombination in highly ionized plasmas. It may also be observed that because of the apparently very low value of α, it is reasonable to expect to be able to generate highly ionized quiescent plasmas in steady state by the type of apparatus shown on Fig. 1 up to densities of the order of 10^{14} electrons and ions/cm^3 over appreciable volumes and even higher densities over small volumes.

In conclusion it may be stated that we have demonstrated the usefulness of a very simple technique for generating highly ionized quiescent plasmas in steady state up to relatively high densities, that we have verified the validity of double-probe measurements in the presence of dc magnetic fields, that we have found preliminary evidence that the diffusion of quiescent plasmas in homogeneous dc magnetic fields appears purely ambipolar, that we have established a direct technique for the measurement of the recombination coefficient of cesium plasmas, and that we have found so far this coefficient to be below 10^{-10} cm^3 sec^{-1}.

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