Ion-Beam Production using Thermionic Ion Emission from Sodium Silicate in a Plasma

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ionic impurities and electrohydrodynamic effects, which would be more prevalent in materials with large dielectric constants.

Response times were measured using 1-kHz excitation, and correspond to the time taken for the light transmitted through the sample to change from 10% to 90% of its initial value. Voltages up to 25 V rms were used, since these correspond to those anticipated for use in devices. From (2), one expects a linear relation between $1/\tau_r$ and V^2 for a given sample; such a relation was reported by Jakeman and Raynes[5] using voltages of 25–150 V. Some typical results given in Fig. 3 show an essentially linear relation except at the lowest voltages. The lowest rise time observed was about 3 msec. Although (3) predicts a decay time independent of applied voltage, Fig. 4 shows a small but consistent increase in τ_d with voltage. This could again be due to turbulence arising from ionic impurities, which would be more pronounced at higher voltages. More detailed studies of response times at various temperatures have recently been reported by Chang *et al.*[8]

The observed rise and decay times can be used to estimate changes in K, and hence to correct Fig. 2, in the following way. One assumes that Eqs. (2) and (3) can be used to describe the results for $1/\tau_r$ and τ_d; this means that changes in τ_d with concentration reflect changes in η/K, while changes in the slopes of the curves of Fig. 3 result from changes in $\Delta\epsilon/\eta$. Since the change in $\Delta\epsilon$ is known by independent measurement, the change of K with 1:1: 1 concentration can be estimated. By using the 10% sample as a reference point for these changes, the points of Fig. 2 were multiplied by the appropriate increases in K, and a good straight line was obtained. This confirms, in an indirect way, that the electrical threshold voltages can be described by Eq. (1)

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Ion-beam production using thermionic ion emission from sodium silicate in a plasma

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By using thermionic ion emission from a water glass (sodium silicate, $Na_2O \cdot 2SiO_2$) an ion beam is easily produced in a plasma. Possible applications of the ion emission to plasma diagnostics are also described.

Certain kinds of materials emit ions thermionically.[1] Aluminosilicates have often been used as good ion emitters.[2] Several papers have been published on ion-beam production and plasma synthesis using the thermionic ion emission from aluminosilicates.[3] A water glass (sodium silicate or potassium silicate solution) also emits ions thermionically. In this report, a nickel-chromium wire covered with a thin film of sodium silicate ($Na_2O \cdot 2SiO_2$) is used as an ion emitter, which emits Na ions at a temperature higher than about 1100 °K. This type of ion emitter was investigated previously by Hatta *et al.*,[4] who developed a pinhole detector for enamel wires, using thermionic ion emission in air. Here we try to employ this ion emitter in basic plasma experiments.

The emitter is made by smearing the water glass on a nickel-chromium wire being heated ohmically at 1400 °K or so in air. Thus, it is extremely easy to make ion emitters of various shapes. The emitter can be inserted at any position in a plasma. By applying a positive potential to the emitter heated enough to emit ions, we can produce a beam of Na ions in a plasma.

An experiment is carried out in a single-ended Q machine.[5] The plasma, about 4 cm in diameter and 80 cm long, is produced by surface ionization of Cs atoms on a hot tungsten plate of about 1800 °K and is confined radially by a uniform axial magnetic field of 3 kG. The background gas pressure is about 5×10^{-6} Torr. The machine is operated under a so-called "electron-rich" condition.[6] The plasma is terminated at a stainless-steel target 5 cm in diameter, biased negatively to reflect electrons. The plasma density is around 1×10^{8} cm^{-3}. The electron temperature, 2000–3000 °K, is a little higher than the hot-plate temperature. Ions are accelerated through the electron sheath in front of the hot plate, and thus the ion temperature is smaller than

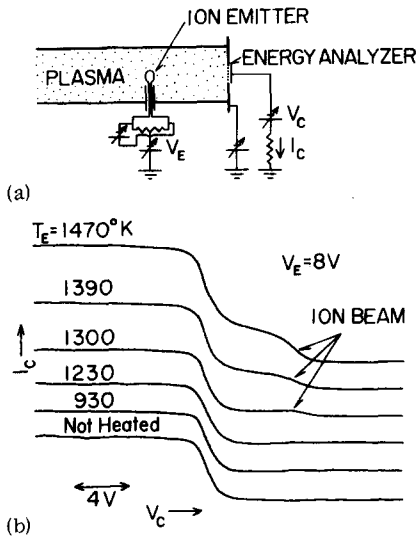

FIG. 1. (a) Schematic diagram of experimental apparatus. (b) Characteristics (I_c-V_c curves) of energy analyzer, with emitter temperature T_E as a parameter, at emitter bias V_E = 8 V. The curves are shifted upwards with an increase in T_E. For each curve, the zero point of I_c corresponds to the flat region on the right hand.

the hot-plate temperature. There is a negligibly small axial electric field ($\simeq 10^{-3}$ V/cm) in the direction of ion acceleration.[7] The target has a 8-mm-diam hole covered with a grid (made of 45-μ-diam wires spaced at 100 μ) at the center. Ions passing through this grid are picked up by a collector situated behind it. An ion energy analyzer consists of this grid and collector (their separation is 1 mm). Some details of the machine and the analyzer were described previously in Refs. 5 and 7.

In this experiment, an ion emitter of ring shape is especially adopted. It is made of 0.9-mm-diam nickel-chromium wire covered with a thin film ($\simeq$ 0.05 mm) of $Na_2O{\cdot}2SiO_2$. The emitter is situated at the center of the plasma cross section at 43 mm from the hot tungsten plate of the Q Machine, with the normal of the ring parallel to the magnetic field. Its inner diameter ($\simeq$ 4 mm) is larger than the ion Larmor radius ($\simeq$ 1 mm). The plasma flow is not disturbed appreciably by the ring emitter. In order to heat the emitter, a dc current of 10 A or so is fed to the nickel-chromium wire through a current-feed line which is in a ceramic sleeve to avoid direct contact with a plasma. The voltage drop across the emitter itself is lower than 0.2 V and the drop across the current-feed line can be neglected. A bias voltage V_E is applied to the emitter with respect to the hot plate which is kept at earth potential, as shown in Fig. 1(a). When the plasma space potential is lower than the potential of the heated emitter, a beam of Na ions is produced along the magnetic field in a plasma. The energy analyzer picks up the ion beam flowing downstream, in addition to Cs ions in a plasma.

Figure 1(b) shows typical characteristics of the energy analyzer, i.e., the collector current I_c versus the voltage applied to the collector with respect to the hot plate, V_c, with the emitter temperature T_E as a parameter, at V_E = 8 V. When there is no ion beam of Na ions in a plasma, the I_c-V curve gives only one peak of the derivative dI_c/dV_c whose shape is the same as an ion energy distribution parallel to the magnetic field.[7] For $T_E \gtrsim 1300$ °K, however, the curve gives another peak of dI_c/dV_c, ascribed to an ion beam flowing along the magnetic field. The beam intensity increases with an increase in T_E. Since the nickel-chromium wire melts to break for $T_E \gtrsim 1600$ °K, T_E is kept to be lower than 1600 °K. In our case, the beam energy eV_b is not equal to eV_E, because the sheath is in front of the hot plate and the work function of the emitter differs from that of the hot plate. Figure 2 shows the variation of the I_c-V_c curve with an increase in V_E at T_E = 1470 °K. These curves maintain the same shapes along the plasma flow even if the analyzer is moved axially, except for a little decrease in I_c. Thus, the beam energy does not change along the plasma column.[8] It is, however, impossible to know V_b from the I_c-V_c curves. This is because the analyzer gives no information on the plasma space potential V_s in this experiment.[7] If it is possible to mark V_s on the abscissa of the I_c-V_c curves, the beam energy can be easily obtained from the relation $V_b = V_{cb} - V_s$, where V_{cb} is the collector voltage at the peak of dI_c/dV_c corresponding to the ion beam. Even if the Langmuir probe were used to determine V_s, it would not be easy to mark V_s correctly on the abscissa of the I_c-V_c curves because the work functions of the probe and the analyzer cannot be given definitely, especially in a Q machine.

In order to measure the beam energy directly, we modulate the beam velocity by superposing a small oscillating voltage (0.1—1 V peak to peak) to the emitter bias. Measuring perturbed ion currents along the plasma column with the interferometer method using a lock-in amplifier (PAR model 121),[9] we can determine the beam velocity v_b [$= (2eV_b/M)^{1/2}$]. Typical output variations of the lock-in amplifier along the plasma flow are demonstrated in Fig. 3(a), where the modulating frequency f is 110 kHz and the perturbed ion currents are detected by a movable coarse grid. Their

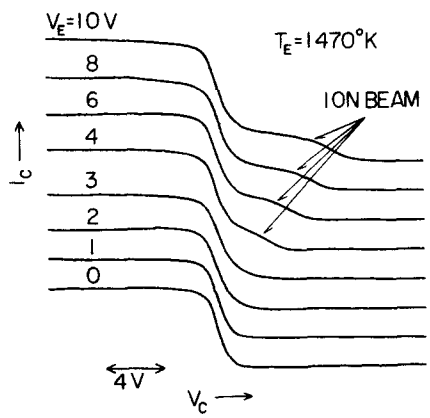

FIG. 2. Characteristics of energy analyzer, with emitter bias V_E as a parameter, at emitter temperature T_E = 1470 °K. The curves are shifted upwards with an increase in V_E. For each curve, the zero point of I_c corresponds to the flat region on the right-hand side.

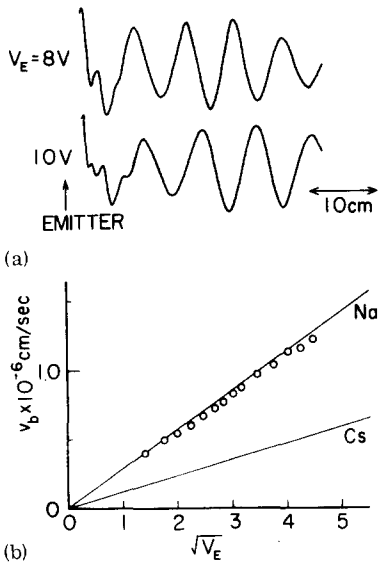

FIG. 3. (a) Modulated ion-beam currents measured along the plasma column with the interferometer method. Modulating frequency f is 110 kHz. The patterns do not depend on the modulating voltage in the range 0.1—1 V peak to peak. The arrow shows the position of the emitter. (b) Beam velocity v_b given by the relation $v_b = f\lambda$ as a function of emitter bias V_E, where λ is the pitch at which the modulated ion-beam current oscillates along the plasma column. The values of $(2eV_E/M)^{1/2}$ for Na and Cs ions are shown by solid lines.

pitches λ give the values of v_b $(=f\lambda)$, as shown in Fig. 3(b), where the solid lines show the values of $(2eV_E/M)^{1/2}$ for Na and Cs ions. The measured values of v_b are plotted a little lower than $(2eV_E/M)^{1/2}$ for Na ions. Thus, the beam energy is a little smaller than eV_E in this experiment.

As an extension of the above-mentioned procedure, we can estimate the drift velocity v_0 of Cs ions in a plasma. Since V_b is known, it is possible to mark V_s on the abscissa of the I_c-V_c curves by using the relation $V_b = V_{cb} - V_s$. The energy of the ion drift is given by $e(V_{cp} - V_s)$, where V_{cp} is the value of V_c at the peak of dI_c/dV_c corresponding to Cs ions. In our case, v_0 is estimated to be $(0.5-1.0)\times10^5$/sec, which is quite reasonable under our conditions in a single-ended Q machine.[5]

To our knowledge, our method is the simplest among various methods producing an ion beam in a plasma. Up to the present, an ion beam of density 10^6-10^8 cm^{-3} and energy 0.5—100 eV is obtained without any trouble. The lifetime of the emitter is longer than a 100 h. The values of V_s and v_0 can also be determined with the method employed by Andersen *et al.*,[10] using charge exchange in a single-ended Q machine. But their method cannot be applied directly to discharge plasmas. Our experiment is much simpler and can be easily applied to other plasmas. Production of more intense ion beam and plasma synthesis using the thermionic ion emission from a water glass will be described in future. Applications of our emitter to experiments on ion-beam-plasma interaction would be also fruitful.

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