

Mass spectrometer for measurements of relative ion concentrations in plasmas

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A mass spectrometer which can be used to measure relative ion concentrations in a multi-ion component plasma has been designed for use in a strong (1–4-kG) uniform magnetic field. The spectrometer features an acceleration region which accelerates thermal ions through a series of three tantalum electrodes at a 30° angle to the \mathbf{B} field, and a collection region in which ions are selectively collected, depending on the size of their gyroradii, by a cylindrical collector. Relative ion concentrations are determined from measurements of the collector current as a function of accelerating voltage. Results obtained using this instrument in a Q -machine device operated with a two-ion (Cs^+/K^+) component plasma are presented.

INTRODUCTION

A knowledge of the relative ion concentrations is required to characterize a multi-ion component plasma. Mass spectrometry is an effective technique for obtaining such information in both space and laboratory plasmas. Magnetic mass spectrometers provide a simple means of separating plasma ions according to their mass. Spectrometers of this type usually consist of an acceleration region in which monoenergetic ion populations are produced, and a collection region where ions of a given q/m ratio are separated in a known magnetic field. The magnetic field may be either the actual magnetic field used to confine the plasma¹ or a separate magnetic field system provided by current-carrying coils or permanent magnets.²

We report on the design of a magnetic mass spectrometer of the former type which is suitable for use in a relatively strong uniform field, in situations not requiring high mass resolution. The acceleration region consists of a series of tantalum electrodes and fine-mesh grids, while the collection region, where the ions of different masses are separated, consists of a cylindrical copper electrode. The use of a cylindrical collecting electrode greatly simplifies the construction of the spectrometer as compared with other possible designs (e.g., see Ref. 1) requiring precise positioning of the ion collector.

The details of the operating principle and construction of the spectrometer are given in Sec. I. The results and a discussion of the spectrometer's performance appear in Sec. II.

I. SPECTROMETER

The spectrometer was designed to operate in a single-ended alkali-metal Q machine.³ The Iowa Q machine⁴ produces a highly ionized cesium–potassium plasma through contact ionization of cesium and potassium neutral atoms on a hot ($\sim 2200\text{-K}$) tantalum plate. The Cs and K neutral atoms are produced by operating independent atomic beam ovens for each species. The plasma column is ~ 1 m in length, ~ 3 cm in diameter, and is confined by a variable 1–4-kG axial magnetic field. Typically, the plasma is character-

ized by a total density of $n_{\text{tot}} \sim 10^9\text{--}10^{11}\text{ cm}^{-3}$ and temperatures $T_e \cong T_{\text{Cs}^+} \cong T_{\text{K}^+} \cong 0.2\text{ eV}$. Since the constituents of the plasma are known, the function of the spectrometer is to determine the relative ion concentrations. High mass resolution is not required since the masses of the ions are in the ratio $m_{\text{Cs}^+}/m_{\text{K}^+} = 3.4$.

The Q -machine parameters define several of the design criteria for the spectrometer. For instance, one main consideration was that the entrance hole of the spectrometer be large enough to admit a measurable ion flux to the collection region. For 0.2-eV cesium ions with a density of 10^9 cm^{-3} , the ion flux is 2×10^{13} (particles/cm²)/s, which indicates that a reasonable ion current on the order of tenths of microamperes can be expected for an entrance hole diameter of 2 mm.

A. Operating principle

A schematic diagram of the spectrometer is shown in Fig. 1. The operation of the spectrometer relies on the mass dependence of an ion's gyroradius on the magnetic field. Thermal plasma ions enter the entrance hole in E1, and are accelerated through E2 and E3 at an angle α to a strong uniform magnetic field $\mathbf{B} = B\hat{z}$. E1 is unbiased and floats electrically, at a potential which is slightly negative relative to the plasma potential. This allows the thermal (0.2-eV) plasma ions to enter the spectrometer and also helps to shield the plasma from the potentials on E2 and E3. E2 acts as a preacceleration electrode and is biased a few volts more negative than E1. The ions are then drawn through E1 and E2 to E3, which is the main acceleration electrode. E3, in turn, is swept from $V_0 = 0\text{ V}$ to $V_0 = -250\text{ V}$ to accelerate ions into the collection cavity. Fine tungsten meshes (70 lines/cm) cover the entrance holes of E2 and E3 to improve the uniformity of the accelerating electric field.

Once accelerated, the ions enter the collection cavity with a kinetic energy of eV_0 and gyroradius

$$\begin{aligned} \rho_i &= v_{\perp} / \Omega_{ci} \\ &= (\sin \alpha / B) \sqrt{2V_0 m_i / e}, \end{aligned} \quad (1)$$

where v_{\perp} is the postacceleration ion velocity perpendicular

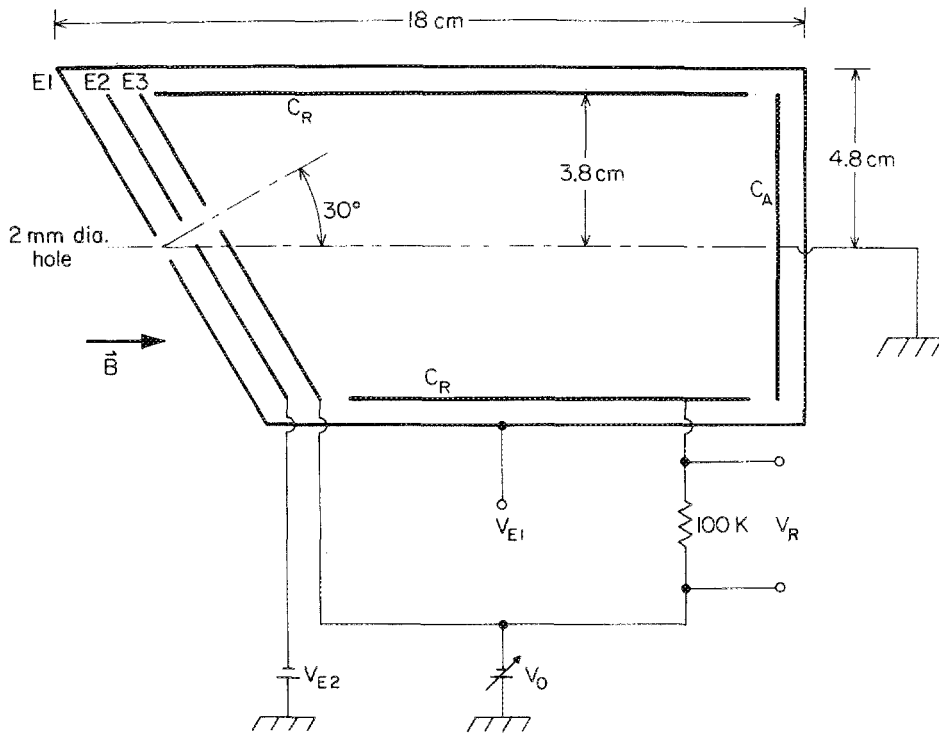


FIG. 1. Schematic of the spectrometer and biasing circuitry used for measurements of the relative ion concentrations.

to the \mathbf{B} field, Ω_{ci} is the cyclotron frequency of the ions, V_0 is the accelerating potential, and m_i is the mass of ion species i . The projection of such an ion orbit onto a plane perpendicular to the magnetic field is shown in Fig. 2. Here, ρ_i is just large enough for radial collection to take place. In fact, collection will occur as long as $\rho_i \geq R/2$, R being the radius of the radial collector (C_R). If $\rho_i < R/2$, the ions cannot reach C_R . For a critical V_0 of

$$V_{c,i} = eB^2 R^2 / 8m_i \sin^2 \alpha, \quad (2)$$

that is, when $\rho_i = R/2$, ions of mass m_i begin being collected radially. Figure 3 indicates the relationship between ρ_i and V_0 for both cesium and potassium, and defines the threshold voltage for each species, $V_{c,i}$, as the accelerating potential at which $\rho_i = R/2$ (dashed line).

The relative ion concentrations are determined from a

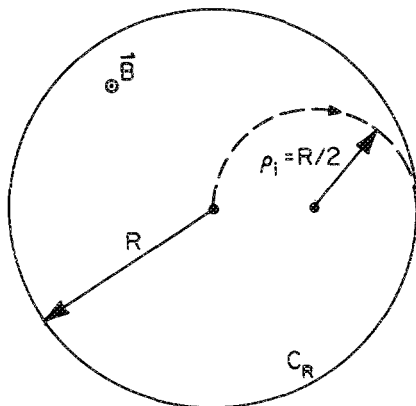


FIG. 2. Projection of an ion orbit inside the collector cavity onto a plane perpendicular to \mathbf{B} . Since $\rho_i = R/2$, the ions just reach C_R in this case.

spectrometer characteristic curve of the radial collector current I_R vs V_0 . As V_0 is increased, the radial current increases in a series of two steps for a two-ion component plasma. The first step corresponds, in our case, to V_{c,Cs^+} , the threshold voltage of the cesium ions, and is followed by a constant current until the threshold voltage of the potassium ions, V_{c,K^+} , is reached. In this way, each "steplike" increase in the collected ion current can be attributed to the additional flux of a new ion species being collected by the radial collector. The determination of the relative concentrations from the I_R -vs- V_0 curve is discussed in Sec. II.

B. Construction

The spectrometer (Fig. 1) was constructed using a coaxial geometry of an outer aluminum housing and an inner copper cylinder as the radial collector. The accelerating

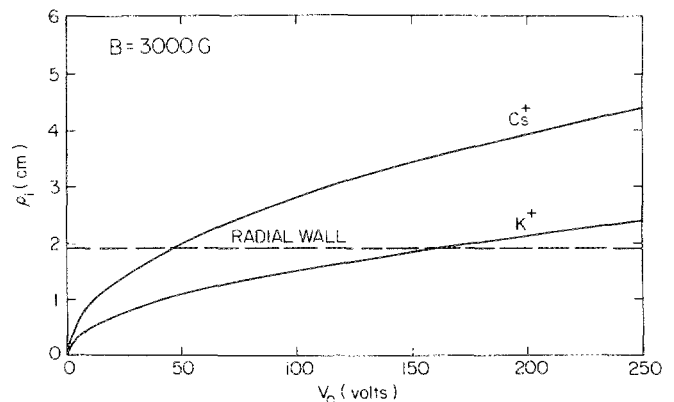


FIG. 3. Relationship between ρ_i and V_0 for both cesium and potassium ions as calculated from Eq. (1). The dotted line ($\rho_i = R/2$) defines the wall of the radial collector.

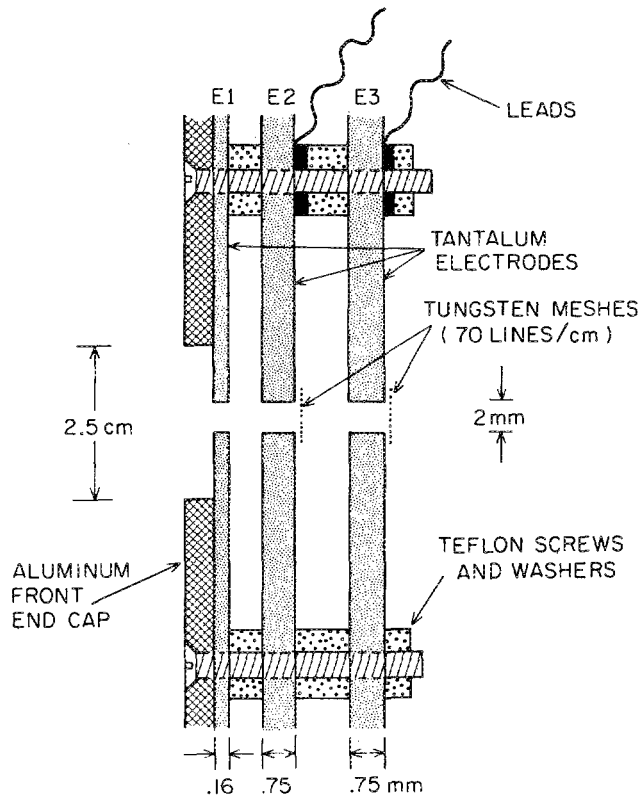


FIG. 4. Electrode assembly of the spectrometer (not to scale).

electrodes and collectors are contained in the 9.6-cm-diam cylindrical aluminum housing. The front endcap, with a 2-mm-diam entrance hole and three tantalum electrodes (E1, E2, E3), is mounted to the aluminum cylinder at a 30° angle, as shown in Fig. 1. The copper radial collecting cylinder (C_R) of radius $R = 3.8$ cm is concentric with the aluminum housing and is supported and insulated from the aluminum housing by six nylon screws. The collection cavity is terminated by a grounded plate (C_A), which is electrically isolated from the aluminum housing and the radial collector by nylon spacers. A 1.5-cm-diam hole was drilled into each cylinder and covered with a coarse mesh to allow for pumping of the spectrometer cavity.

Figure 4 details the electrode assembly. The three tantalum electrodes are attached to the front endcap using Teflon washers and nylon screws. The spacing between E1 and E2 is 0.5 mm, while that between E2 and E3 is 1 mm. Tungsten meshes (70 lines/cm) are spot welded onto the backsides of E2 and E3, and wire leads with stainless-steel washers are attached to each electrode for biasing purposes.

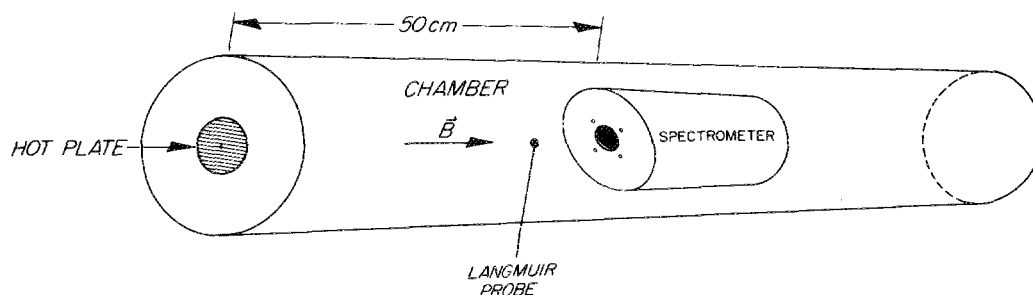


FIG. 5. Location and orientation of the spectrometer in the Q machine.

II. RESULTS AND DISCUSSION

The spectrometer was located in the plasma column of the Q machine 50 cm downstream from the hot plate (Fig. 5). The device⁴ provided a plasma environment with a steady two-component ion flux parallel to a strong uniform magnetic field. The potassium and cesium ion densities were controlled by independently varying the neutral flux from the atomic beam ovens (not shown). The first electrode of the spectrometer, E1, served as the floating cold endplate for the plasma.

The circuit for biasing the various electrodes and measuring the current to the radial collector is also shown in Fig. 1. The accelerating voltage V_0 is applied directly to E3 and also to the radial collector through a 100-k Ω resistor. The voltage drop V_R across this resistor is then a measure of the radial ion current. Biasing E3 and C_R at the same potential ensures that there are no stray electric fields in the forward postacceleration region of the spectrometer, where radial collection takes place. We found that the sharpest characteristic curves (I_R vs V_0) were obtained when the endplate C_A was grounded. The electric field introduced by the grounded endplate is negligible in the forward postacceleration region, since this electric field falls off exponentially with distance from C_A .⁵

Some typical data obtained with the spectrometer are shown in Fig. 6. Here, I_R vs V_0 curves are shown for three values of the magnetic field. For small values of V_0 , the ion gyroradii are small and no radial current is measured. The first current plateau is reached when the heavy species, Cs^+ , having the larger gyroradius, is collected at a voltage of about 30 V for a magnetic field of 2.7 kG. At around 100 V, the gyroradii of the light ion species, K^+ , becomes large enough so that K^+ ions are collected. The contributions to the radial current due to Cs^+ (I_{Cs^+}) and K^+ (I_{K^+}) are indicated. From these currents the relative ion concentrations can be computed since the current can be related directly to the ion flux $n_i v_i$ at the entrance hole by

$$I_i = e \alpha_i n_i v_i, \quad (3)$$

where I_i is the radial current, n_i is the density, and v_i is the thermal velocity of species i . The parameter α_i is a factor which takes into account the area of the entrance hole and the spectrometer collection efficiency for species i . The relative concentration of, e.g., Cs^+ can then be found from

$$\frac{n_{Cs^+}}{n_{Cs^+} + n_{K^+}} = I_{Cs^+} / \left[I_{Cs^+} + \frac{\alpha_{Cs^+}}{\alpha_{K^+}} \left(\frac{m_{K^+}}{m_{Cs^+}} \right)^{1/2} I_{K^+} \right], \quad (4)$$

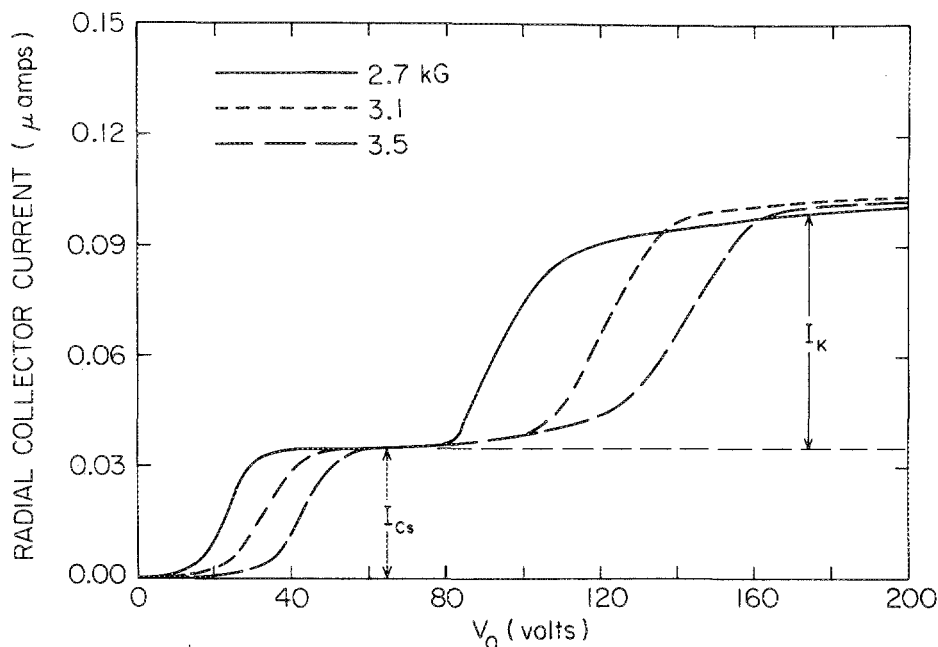


FIG. 6. Radial collector current as a function of V_0 for several values of the magnetic field; $V_{i2} = -9$ V. The current contributions due to Cs^+ and K^+ are indicated.

where we have taken $T_{\text{Cs}^+} \cong T_{\text{K}^+}$.

The ratio of the relative calibration factors, $\alpha_{\text{Cs}^+}/\alpha_{\text{K}^+}$, is determined by comparing the radial current with the plasma density obtained from a Langmuir probe, in a pure Cs^+ plasma and then in a pure K^+ plasma.

The data in Fig. 6 also show the expected shift of the characteristic curves predicted by Eq. (2) as B is varied. In Fig. 7 we present results from a more extended series of measurements of the type shown in Fig. 6. The solid lines exhibit the variation of the observed threshold voltages $V_{c,i}$ with B^2 , while the dashed lines show the theoretical values computed from Eq. (2). The ratio of the slopes of the experimental

curves for the K^+ and Cs^+ thresholds is in good agreement with the mass ratio $m_{\text{Cs}^+}/m_{\text{K}^+} = 3.4$. The measured threshold voltages are also in reasonable agreement with the theoretical values, although the rounding-off of the characteristic curves (Fig. 6) near the threshold edges makes an accurate determination of the $V_{c,i}$'s somewhat difficult. Any misalignment of the radial collector, or uncertainty in the measurement of the magnetic field strength, will also lead to differences between the measured threshold voltages and the theoretical values.

The relatively good agreement between the observed characteristics and the theoretical expectations indicates that this spectrometer can be a useful instrument for measurements of relative ion concentrations. This instrument is now being used in an experiment studying the excitation of electrostatic ion-cyclotron waves in a two-ion species (Cs^+/K^+) plasma.

ACKNOWLEDGMENTS

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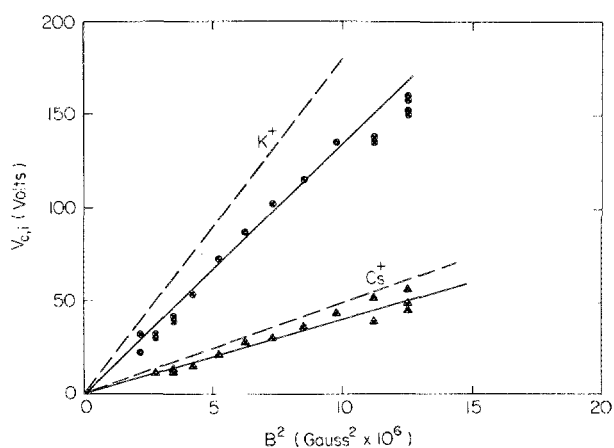


FIG. 7. Threshold voltages for both cesium and potassium as a function of B^2 . The solid lines are best fits to the data points, while dashed lines are the values computed from Eq. (2).

¹See, for example, S. von Goeler, T. Ohe, and N. D'Angelo, in *Proceedings of the Seventh International Conference on Phenomena in Ionized Gases*, Belgrade, August 1965, edited by B. Perović and D. Tasić (Građevinska Knjiga, Belgrade, 1966), Vol. 1, p. 260; *J. Appl. Phys.* **37**, 2519 (1966).

²See, for example, D. L. Reasoner, C. R. Chappell, S. A. Fields, and W. J. Lewter, *Rev. Sci. Instrum.* **53**, 441 (1982).

³R. W. Motley, *Q-Machines* (Academic, Orlando, FL, 1975).

⁴S. L. Cartier, N. D'Angelo, and R. L. Merlino, *Phys. Fluids* **28**, 3066 (1985).

⁵See, for example, J. D. Jackson, *Classical Electrodynamics*, 2nd ed. (Wiley, New York, 1975), pp. 108–110.