The Stabilizing Effect of a Magnetic Field on the Plasma Production of a Vacuum-Discharge Rotating Plasma Gun

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A coaxial plasma gun which generates a rapidly rotating plasma in a magnetic field has been developed to improve the plasma centrifuge. It is demonstrated that a magnetic field stronger than a critical value is essential to stabilize the high-current vacuum discharge of the plasma gun and to make the plasma production and acceleration reproducible. For example, the critical field is 250 G for the discharge current of 13 kA and the anode-cathode spacing of 7.5 mm. A model is presented in which the critical field is assumed to be determined from the trapping of ionizing electrons in the annular anode-cathode gap. A qualitative agreement is achieved between the model and experiment.

Key words : Plasma centrifuge, Isotope separation, Plasma production, Electric discharges, High vacuum, Magnetic fields, Stability, Electron beams, Orbits

1. Introduction

Plasmas of metal elements have been used for many applications such as ion implantation and ion beam modification of materials⁽¹⁾, thin-film deposition⁽²⁾, heavy ion beam fusion⁽³⁾, and plasma isotope separation^{(4)~(6)}. In recent years, a vacuum discharge has received an interest as a means of producing metal plasmas, by reasons that the apparatus is simple and easy to construct; in addition, a number of solid elements and their alloys and compounds are available only by changing a cathode material⁽⁷⁾. A problem has also been pointed out, however, that the vacuum discharge tends to become unstable⁽⁸⁾: Cathode spots and current spokes often appear to move about on the electrode and in the glow region, respectively. This leads to the fluctuation in the voltage and plasma density. This result is attributable to the fact that the metal vapor as the source of plasma is provided by the vacuum discharge itself.

We have developed a coaxial, rotating plasma gun to explore the isotope separation by the plasma centrifuge, where rotating Cu, Cu/Zu, Al, Ag and Ta plasmas of densities $10^{14} \sim 10^{15} \text{ cm}^{-3}$ and rotation frequencies $10^5 \sim 10^6 \text{ rad/s}$ have been produced by the vacuum discharge

under a magnetic field of up to 3 kG⁽⁹⁾. The present paper reports that a magnetic field is essential not only to drive the plasma rotation but also to stabilize the vacuum discharge.

2. Experimental apparatus

Experimental arrangement is shown in Fig. 1. The plasma gun has a coaxial geometry where a rod cathode ($\phi 3 \sim 8 \text{ mm} \times 40 \text{ mm}$) which provides the metal vapor is placed inside the annular brass anode ($\phi 25 \text{ mm}$). The main vacuum discharge between the anode and cathode is triggered by a 8~10 kV impulse spark on a tungsten tip ($\phi 0.5 \text{ mm}$) inserted into the small bore of the cathode and is energized by a 12 kV, 40 μF capacitor bank. The plasma gun is attached to the end flange of the chamber where an axial magnetic field B_z of up to 3.0 kG is applied over the length of 40 cm. The voltage and current of the discharge are measured with a resistive divider and a Rogowski coil, respectively. The rotation frequency ω and the ion temperature T_i of the plasma are evaluated from doppler shift and doppler broadening of ion emission lines. An optical multichannel analyzer (OMA) which combines a MCP-intensified, 1,024-channel photodiode array with a 1 m spectrometer is

Fig. 1. Experimental setup.

used for this purpose. This system records the wavelength range of 20 nm with the resolution of 0.02 nm per channel by a single exposure. The light from the plasma is focused by a small lens ($\phi 1.8$ mm) to the end of a fiber cable and is transmitted to OMA. The micro-lens and the end of the fiber cable is introduced inside the vacuum chamber through a gauge port and is made movable along the radius over 5 cm and along the z axis over 30 cm. The chamber has been evacuated down to 6×10^{-6} Torr before the experiment.

3. Results

3.1 Vacuum discharge in a transverse magnetic field

Fig. 2 indicates the trigger characteristics of the plasma gun; the probability of stimulated vacuum breakdown between the anode (A) and cathode (K) is plotted as a function of B_z and a capacitor charging voltage V_c for a fixed triggering voltage of 10 kV. The inner diameter of the anode is 23 mm while the cathode has the diameter of 8 mm and is made of brass (Cu 60%/Zn 40%), so that the A-K gap spacing is 7.5 mm. Five trigger sparks have been tested for each set of B_z and V_c . The breakdown becomes more difficult to occur with increasing B_z in the range $V_c \leq 7$ kV. This is probably because the breakdown is promoted by the injection of charged particles and UV photons into the A-K gap while the charged particles are easily blocked by the transverse field B_z .

It is found that the magnetic field B_z which traverses the annular A-K gap plays a role of stabilizing vacuum discharge as well as driving the plasma rotation. Typical oscillograms of the diode voltage taken at $V_c = 9$ kV and at different B_z are given in Fig. 3. Data are for the brass cathode but similar results have been obtained for Cu, Al, Ag and Ta cathodes. The lower trace shows

Fig. 2. Trigger characteristics of the plasma gun.

the diode current detected by the Rogowski coil. The diode current rises to a peak value of 13 kA ($V_c = 9$ kV) in $8 \mu\text{s}$ and falls to zero in $30 \mu\text{s}$; the waveform is the same for different B_z because the effective plasma impedance of 0.02Ω is much smaller than the driver circuit impedance of 0.67Ω . For $B_z = 2$ and 3 kG, waveforms are quite smooth and reproducible and any difference can not be identified between them. On the other hand, the fluctuation of the voltage at about 1 MHz grows rapidly with decreasing B_z to less than 1.5 kG and the relative voltage fluctuation $\tilde{V}_d/V_d$ reaches as high as 100% at $B_z = 0$, implying destabilization of the discharge. The shot-to-shot variation in the waveform becomes quite large in this range.

Fig. 4 shows typical examples of end-on framing photographs. When $B_z = 2.5$ kG is applied, the vacuum discharge which first started at a local position on the cathode expands over the whole gap in a time of about $1 \mu\text{s}$ with increasing its luminosity and appears to form an annular glow region surrounding the cathode surface. This observation suggests that electrons are accelerated by the cathode fall up to the energy $eV_c \approx eV_d$ and the anode fall is negligible, so that the ionization of the metal vapor occurs predominantly near the cathode surface. On the other hand, the discharge looks very

 Fig. 3. Waveforms of the diode voltage at different B_z .

 Fig. 4. End-on framing photographs of the vacuum discharge for (a) $B_z = 2.5$ kG and (b) $B_z = 0$ kG. The sequence is from the bottom left to the top right. The framing speed is $0.5 \mu\text{s}/\text{frame}$.

 Fig. 5. Diode voltage, relative voltage fluctuation and visible light intensity as a function of B_z .

irregular at $B_z = 0$ as demonstrated by some pieces of moving spokes. These behaviors are well correlated with voltage waveforms in Fig. 3.

In Fig. 5, (a) the diode voltage V_d (DC component), (b) the relative voltage fluctuation $\tilde{V}_d/V_d$ and (c) the visible light intensity I_{ph} detected by a PIN diode are plotted as a function of B_z . These data demonstrate the existence of a critical magnetic field strength $B_c \approx 0.3$ kG for stabilizing the intense vacuum discharge: In the range $B_z > B_c$, V_d is kept constant at about 280 V

independent of B_z and the voltage fluctuation $\tilde{V}_d/V_d$ is negligibly small there, while $B_z < B_c$, V_d rapidly increases up to 1,000 V with decreasing B_z to 0 G and $\tilde{V}_d/V_d$ increases up to about 1.0 in the same manner. This clearly indicates that a transverse magnetic field in excess of a critical strength is essential for stabilizing the intense vacuum discharge and for producing the dense metal plasma efficiently. Note that I_{ph} shows the same B_z dependence as V_d . This result is also reasonable because I_{ph} should be proportional to the plasma

density n while $n \propto V_d I_d \propto V_d$ for I_d fixed at 13 kA. A model to derive B_c will be discussed in the next chapter.

3.2 Production of rotating plasmas

Rotating metal plasmas have been produced with brass and Al cathodes to explore the isotope separation by the plasma centrifuge. The plasma rotation has been driven by the $\mathbf{J} \times \mathbf{B}$ Lorentz force where $\mathbf{J}$ is the radial current density of the discharge and $\mathbf{B}$ is the applied field. Since $\mathbf{J}$ produces an azimuthal magnetic field B_θ , the plasma also is accelerated outward along the axis as is the case of conventional, coaxial-plasma-accelerators.

Typical plasma parameters for Cu/Zn plasmas⁽⁹⁾ ($I_d = 13$ kA/ $B_z = 2.5$ kG) are: The electron temperature remains 10~12 eV independent of I_d and B_z . The ion temperature is in the range 10~30 eV. The plasma density is the order of 10^{15} cm⁻³ (single-charged ions are assumed) and further increases in proportion to I_d^2 since $V_d \propto I_d$ experimentally. The axial flow velocity is about 2×10^4 m/s.

Emission spectra have been measured by OMA over the wavelength from 290 to 610 nm. An example for the Cu/Zn plasma is given in Fig. 6 where the wavelength is from 489 to 509 nm. The detection of impurities, C and O implies that they have been sputtered from polymer and glass surfaces inside the plasma gun by the

Fig. 6. Emission spectra of the Cu/Zn plasma.

Fig. 7. Rotational velocity profiles for (a) Zn⁺ and (b) O⁺ ions.

bombardment of Cu⁺ and Zn⁺ ions. Since spectral intensities of CuII and ZnII are superior in the UV range (<300 nm), they appear rather weak compared with CII and OII in this visible range. Representative two lines, ZnII 491.16 nm and OII 492.46 nm have been chosen to measure profiles of the rotational velocity from the spectroscopic doppler shift. The results are given in Fig. 7. Error bars on data points show shot-to-shot variations. We will derive the following features from the figure:

(1) Roughly speaking, velocity profiles for Zn⁺ and O⁺ ions are the same.

(2) The plasma core within the diameter of about 1 cm is in rigid rotation at $\omega \approx 2.5 \times 10^6$ rad/s.

(3) On the other hand, the plasma outside rotates at a constant velocity of about 1×10^4 m/s; that is, a shear flow is formed around the plasma core.

The mass separation factor α for the plasma centrifuge in the rigid-rotor equilibrium is given by

$$\alpha = \exp\left\{\left(\frac{\Delta M}{M}\right)\Theta\right\} \quad (1)$$

where, $\Delta M/M = 2(M_H - M_L)/(M_H + M_L)$ is the relative mass difference between heavier (M_H) and lighter (M_L) ion species and $\Theta = Mr^2\omega^2/2T_i$. The rotation frequency observed here is quite large compared with those in earlier experiments⁽⁵⁾. Thus, a considerable improvement in the separation factor can be expected according to Eq.(1)

4. Discussion

Here, we derive the critical field strength B_c for stabilizing the vacuum discharge from a simple consideration. Suppose a coaxial diode with the anode radius r_a , the cathode radius r_k and the AK spacing $d \equiv r_a - r_k$ as shown in Fig. 8. An electron from the cathode is accelerated in the positive sheath in front of the cathode (d_s in thickness) up to an energy eV_c and enters the plasma-filled gap under the uniform B_z . The diode

Fig. 8. Orbit of an electron in the diode gap.

voltage can be expressed as $V_d = V_c + \Delta V$ and from measurements can be approximated to $V_d \approx V_c$, where ΔV denotes the potential drop due to the plasma rotation, $(r_a^2 - r_k^2)\omega B_z/2$. The sheath potential due to the uniform ion space-charge of density n is given by

$$V_c = \frac{en}{2\epsilon_0} d_s^2 \dots \dots \dots (2)$$

The sheath is very thin since $d_s \approx 4.7 \times 10^{-3} \text{ mm} \ll d = 7.5 \text{ mm}$ is calculated from measured values, $n \sim 10^{15} \text{ cm}^{-3}$ and $V_c \approx 200 \text{ V}$. The electron of mass m first moves toward the anode along a circular orbit of radius

$$\rho_e = \sqrt{2mV_c/eB_z^2} \dots \dots \dots (3)$$

If a maximum traveling distance, $\Delta r_m < d$, the electron turns at Δr_m and re-enters the sheath at right angle to the surface, where it is again reflected back to the anode. As a result, the electron continues to drift around the axis until it is scattered by collision with plasma ions, plasma electrons and neutral atoms as illustrated in Fig. 8. On the other hand, if $\Delta r_m > d$, the electron is lost to the anode in a time shorter than the electron gyroperiod, $2\pi\Omega_e^{-1}$. The good electron confinement will improve the efficiency and uniformity of ionization of vapor atoms and will result in a considerable reduction in the diode voltage. Here, we have assumed $\Omega_e\tau_e \gg 1$ reasonably where τ_e is the electron collision time. This assumption is valid because $\Omega_e\tau_e \approx \Omega_e\tau_{en} \sim 10 \gg 1$ has been estimated from experimental parameters, where τ_{en} is the electron-neutral collision time. If $\Omega_e\tau_e \ll 1$ was the case, the effect of B_z would not appear or would be obscure in the experimental results.

From Fig. 8. Δr_m is given by

$$\Delta r_m = \sqrt{\rho_e^2 + r_k^2} + \rho_e - r_k \dots \dots \dots (4)$$

The critical strength B_c for the stable discharge is therefore derived by solving the equation $\Delta r_m = d$ as

$$B_c = \left(\frac{1+\delta}{1+2\delta} \right) \sqrt{\frac{8mV_c}{ed^2}} \dots \dots \dots (5)$$

where $\delta \equiv r_k/d$.

Fig. 9 shows V_c as a function of B_z measured, together

Fig. 9. Derivation of the critical field strength.

with the theoretical V_c - B_c curve [Eq. (5)] for $d = 7.5 \text{ mm}$ and $\delta = 0.53$ of the present experiment. The theoretical value, B_c (model) is evaluated from the intersection A between two curves. This yields B_c (model) $\approx 170 \text{ G}$. On the other hand, the inflection point B on the V_c - B_z data curve will give B_c (exp) $\approx 250 \text{ G}$. Agreement between B_c (exp) and B_c (model) seems good. Comparison between B_c (exp) and B_c (model) has been carried out for $I_d = 7$ and 13 kA and $d = 3.0$ and 7.5 mm ; the difference was within a factor of 2. Thus, the present model is sufficient to explain the observation.

5. Conclusion

The stabilizing effect of a transverse magnetic field B_z has been investigated on the intense vacuum discharge of the coaxial plasma gun which has been developed to generate rotating metal plasmas for the plasma centrifuge. In typical, the experiment was carried out at the diode current I_d of 13 kA ($20 \mu\text{s}$ duration) and B_z of up to 3.0 kG . A quite stable and uniform discharge was found to be established even in the high power when B_z in excess of a critical value of 250 G was applied; otherwise, the discharge became unstable. A model which considers the trapping of ionizing, beam electrons in the annular A-K gap was found to predict the critical field strength qualitatively.

Rotating Cu/Zn plasmas have been produced at $I_d = 13 \text{ kA}$ and $B_z = 2.5 \text{ kG}$. Spectroscopic doppler measurements revealed that Zn^+ ions within the core region of a diameter of 1 cm rotate rigidly, while the velocity of them appears to be saturated outside. The plasma density was the order of 10^{15} cm^{-3} and the rotation frequency was about $2.5 \times 10^6 \text{ rad/s}$.

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