Journal of the Korean Physical Society, Vol. 74, No. 6, March 2019, pp. 579∼583

Generation of Supersonic Plasma Flow by an Ion Extraction Electrode

In Je Kang,* Min-Keun Bae, In Sun Park, Seung-Hwa Lee, Seo Jin Jeong and Kyu-Sun Chung
Department of Electrical Engineering, Hanyang University, Seoul 04763, Korea

(Received 4 January 2019, in final form 1 February 2019)

A concept of ion extraction has been adopted to generate and analyze supersonic plasma flow ($M_\infty > 1$) in steady state condition. A capacitively coupled plasma (CCP) with weakly magnetic intensity ($B = 100$ G) was used as a plasma source along the axial direction and a cylindrical electrode was installed to generate negative potential within plasma by depleting ions. Characteristics of ion velocity distribution have been analyzed by equation of energy conservation from depletion ratio of ions within an ion extraction electrode. The normalized velocity ($M_\infty = v_\mathrm{i}/C_\mathrm{s}$) of flowing plasmas was deduced by using a Mach probe (MP) of parallel type using an exponential formula of the ratio of upstream and downstream ion saturation current densities. The first result on the measurement of ion velocity distribution with supersonic plasma flow ($M_\infty =\sim 1.1$–1.2) is obtained.

PACS numbers: 52.30.−q, 52.50.Dg, 52.70.−m
Keywords: Supersonic Plasma Flow, Mach Probe, Ion Extraction Electrode
DOI: 10.3938/jkps.74.579

I. INTRODUCTION

Supersonic plasma flow generates interesting problems of non-linear phenomena in space and astro-cosmological plasmas, which is also related to the sheath formation during plasma surface interaction in fusion devices [1–3]. Various kinetic and fluid models have been developed on plasma flow phenomena at fields of laboratory, astrophysical and fusion plasmas [4–6]. However, subsonic plasma flow has been mostly studied for verification of models, which requires further verification for supersonic plasmas. Also, the generation and measurements of supersonic plasma flow have been studied at pulsed plasma system or transient phenomena [7,8], which are still insufficient in steady state plasma conditions, even.

In fusion devices, flow measurements near X-points including $E \times B$ shear velocity and supersonic flow are still under debate [2, 9, 10], although the progress of edge plasma physics has been advanced in recent years. There is interest in determining the ion velocities in plasmas such as Mach probe (MP) [11], Laser induced fluorescence (LIF) [12] and gridded energy analyzer [13]. In case of LIF diagnostics, measurement of ion velocities for hydrogen plasmas in fusion devices is not possible and it is not easy even for hydrogen atoms due to the longest wavelength to the ground state of hydrogen, which is in the range of vacuum ultraviolet (121.6 nm) [10,14]. While the MP, which is an electric probe system to deduce the plasma flow velocity or Mach number (M_∞) from the measurement of ion saturation currents, is mostly used for plasma flow measurement [11]. Among several diagnostics to measure a plasma flow velocity, a MP is one of the most simple and useful tools for measurement of plasma flows [11,15].

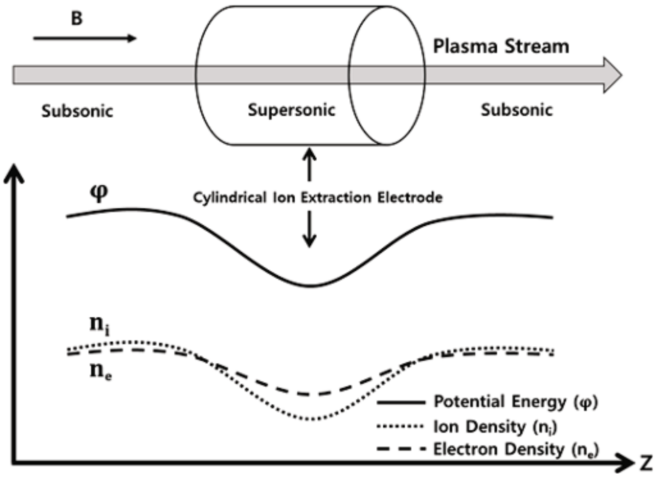

Fig. 1. Concept of a cylindrical ion extraction electrode to generate supersonic plasma flow ($M_\infty > 1$) in steady state condition. Z is axial position for horizontal axis and φ, n_i and n_e for vertical axis are potential energy, ion density and electron density, respectively.

In this paper, to experimentally investigate characteristics of supersonic plasma flow ($M_\infty > 1$) at steady state conditions by using the MP, the system of plasma flow generation in capacitively coupled plasma (CCP) was designed with a cylindrical ion extraction electrode, which we called as Supersonic tube (ST). Concept of plasma

*E-mail: calmkang@hanyang.ac.kr

 ©2019 The Korean Physical Society

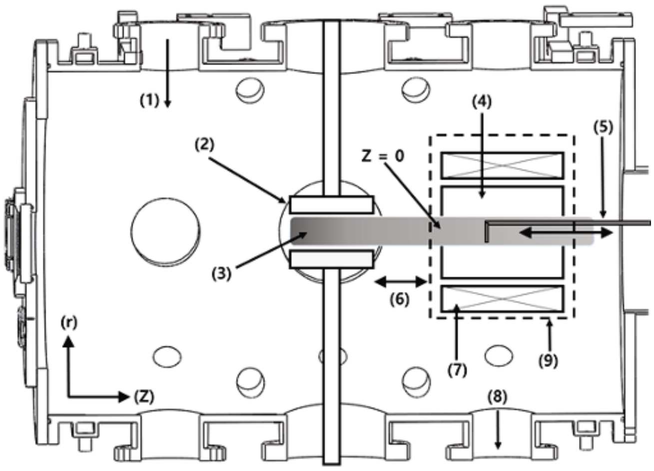

Fig. 2. A simplified schematic view of the experimental set-up: (1) gas injection, (2) electrode for a capacitively coupled plasma (CCP), (3) plasma, (4) cylindrical ion extraction electrode, (5) Mach probe, (6) distance (= 7 cm) between electrodes of CCP and supersonic tube (ST), (7) electro-magnet, (8) gas pumping and (9) ST.

flow generation has been adopted as shown in Fig. 1. A cylindrical ion extraction electrode was developed for observation classical analogue to the Hawking radiation by Shoji [16]. Supersonic plasma flow can be formed by externally applied electric field with weakly magnetic fields. Also, gradient of flow velocity at the sonic point can be controlled by external electric or magnetic fields.

II. EXPERIMENT

A simplified schematic view of the experimental set-up is shown in Fig. 2 for generation of supersonic plasma flow in CCP with ST and measurements of its characteristics by using a MP. Cylindrical plasma chamber has a diameter of 50 cm and an axial length of 80 cm. The parallel plates (a diameter = 5 cm) of stainless steels were used as electrodes of CCP, which were excited with 13.56 MHz RF power. A cylindrical ion extraction electrode of stainless steel, which has a diameter = 5 cm and an axial length = 4 cm, was used to generate supersonic flow. Distance between electrodes of CCP and ST is 7 cm. For formation of electrons and ions gyro-motions, electromagnets were installed at the outside of a cylindrical electrode. Figure 3 shows geometry and circuit of MP. The z-axial plasma flow profiles were measured by the MP of parallel type, consisted of two molybdenum tips (collective area: 1.5 mm^2) and ceramic insulator between tips as shown in Fig. 3. By using a bipolar operational power supply (KEPCO), negative bias = -100 V was introduced to probe tips for collection of ion saturation currents (I_{sat}). To reduce uncertainty of data acquisition, conversion factors (α_1 and α_2 as shown in Fig. 3) were introduced for calibration of BNC cables

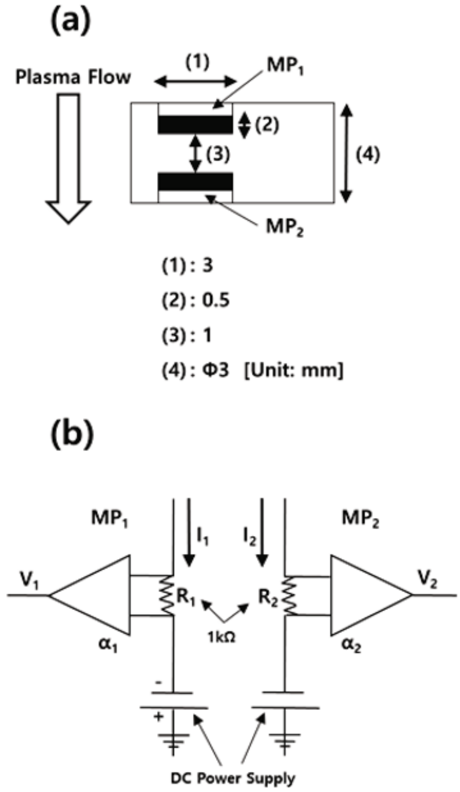

Fig. 3. (a) Geometry and (b) circuit of Mach probe. MP_1 and MP_2 are for measurement of upstream and downstream ion saturation current densities, respectively. Measured voltage from each probe is $V_1 = \alpha_1 I_1 R_1$ for upstream current (MP_1) and $V_2 = \alpha_2 I_2 R_3$ for downstream current (MP_2) where α, I, and R are conversion factors, ion saturation currents and resistors (1 kΩ), respectively.

and two power supplies. For MP data, measured voltage from each probe is given as $V_1 = \alpha_1 I_1 R_1$ for upstream current (MP1) and $V_2 = \alpha_2 I_2 R_3$ for downstream current (MP2), respectively. Detail schematic diagram of data collection system and operating control system is shown in Fig. 4.

To generate plasmas, helium gas was used. Base pressure was 7×10^{-6} Torr and operating pressure was 8×10^{-2} Torr when helium gas with 500 sccm was injected to plasma chamber. With RF power = 150 W and gas flow rate = 500 sccm for helium, plasmas generated by CCP have electron temperature (T_e) $\sim$ 1–2 eV and plasma density (n_e) $\sim 10^8$ cm^{-3} deduced from measurement of IV characteristics by a single probe.

III. RESULTS

During moving along the cylindrical electrode in weakly magnetized plasmas, ions have larger gyro-radii than electrons calculated by $r_L \equiv mv/|q|B$ [17] where, m, v, q and B are mass of charged particles, drift velocity,

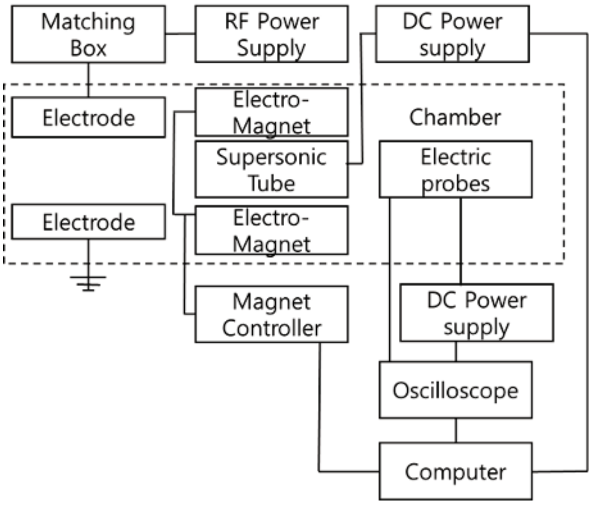

Fig. 4. Detail schematic diagram of data collection system and operating control system.

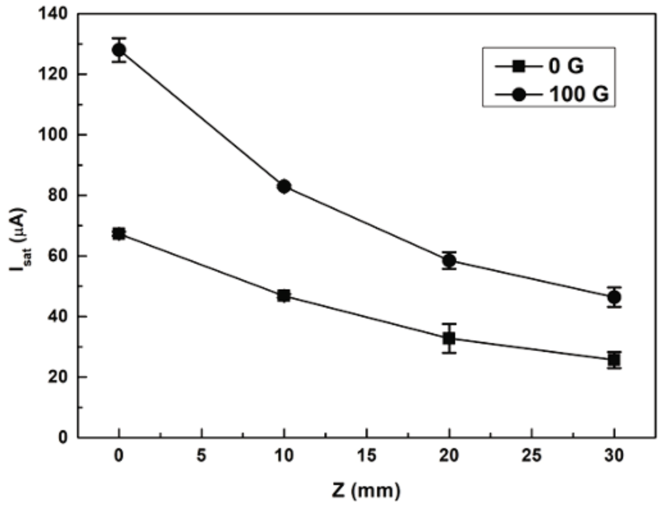

Fig. 5. Results for measurement of $I_{\rm sat}$ in supersonic tube (ST) as function of Z-axis. Experimental conditions: RF power = 150 W, helium gas flow rate = 500 sccm (8×10^{-2} Torr).

charge and intensity of magnetic fields, respectively. As the results, compared with fast electrons, ion density relatively reduced due to frequent interaction with cylindrical wall. It makes potential gradient to accelerate ions as shown in Fig. 1. For example, when $q = 1.6 \times 10^{-19}$ C, $B = 100$ G and $m_{\rm i} = 6.6 \times 10^{-27}$ kg for helium and ion temperature ($T_{\rm i}$) $= 0.1T_{\rm e}$ assumed for thermal velocity, r_L is obtained as ~ 1 cm. From this result, when radial length ~ 1 cm of ST which has similar scales of r_L is assumed, potential gradient from depletion of ions could be induced. Therefore, radius = 2.5 cm was designed for the ST. B = 100 G was applied for plasma extraction from CCP to ST and confinement of plasmas.

Results for measurement of $I_{\rm sat}$ in ST is shown in Fig. 5. By increasing magnetic fields, the measured $I_{\rm sat}$ was increased. Compared with $B = 0$ G, plasmas at $B = 100$ G was more confined in ST because of increasing ion collection rates as shown in Fig. 5. In case of $B = 100$ G, higher gradient of $I_{\rm sat}$ profiles according to Z-axis than $B = 0$ was found due to a lack of ions while generating gyro-motion with magnetic fields. When the formation of gradient plasma potential from depletion of ions within ST due to large r_L of ions, the expected plasma density, assuming $n_{\rm i} \sim n_{\rm e}$, can be described by the Boltzmann relation:

$$n_1 = n_0 \exp\left[\frac{e\varphi_1}{T_{\rm e}}\right], \quad n_2 = n_0 \exp\left[\frac{e\varphi_2}{T_{\rm e}}\right] \tag{1}$$

where n_1, n_2 and φ are plasma densities before and after depletion of ions and potential energy, respectively. For potential difference, it can be rewritten as:

$$\frac{n_2}{n_1} = \exp\left[\frac{e(\varphi_2 - \varphi_1)}{T_{\rm e}}\right] = \exp\left[\frac{e\Delta\varphi}{T_{\rm e}}\right] \tag{2}$$

If $n_2/n_1 = 0.9$ is assumed for 10% reduction of ions, $e\Delta\varphi = T_{\rm e} \ln 0.9 \approx 0.1T_{\rm e}$ could be obtained. From Eq. (2) with $e\Delta\varphi \sim (m_{\rm i}\Delta v^2)/2$ for energy convservation, the expected ion drift velocity ($\Delta v_{\rm i}$) could be calculated as:

$$\Delta v_{\rm i} = \sqrt{\frac{2T_{\rm e}\Delta\varphi}{m_{\rm i}}}. \tag{3}$$

For example, assuming $n_2/n_1 = 0.6$ for 40% reduction of ions, $T_{\rm i} = 0.1T_{\rm e}$ and $C_{\rm s} = \sqrt{(T_{\rm e} + T_{\rm i})/m_{\rm i}}$ as Bohm velocity [11], the expected $M_\infty \sim 1$ could be deduced as $M_\infty = \Delta v_{\rm i}/C_{\rm s}$. To simply calculate M_∞, $I_a/I_b \approx n_2/n_1$ is assumed for this study, where I_b and I_a are ion saturation currents before and after depletion of ions, respectively. Since plasma density is strongly dependent on the mean free path (λ_n), it would be decreased as $n(Z) \approx n_0 \exp[-Z/\lambda_n]$, axially. Therefore, ion current ratio (δ) was calculated by comparing two cases $B = 0$ and 100 G as:

$$\delta = I_a/I_b = [(I_{a100} - I_{a0})/(I_{b100} - I_{b0})], \tag{4}$$

where I_{b100}, I_{b0}, I_{a100} and I_{a0} are ion saturation currents with magnetic intensities of 100 G and 0 G before and after depletion of ions, respectively. Figure 6 shows the results of δ as function of Z-axis calculated by Eq. (4) for the expected ion drift velocity. δ decreased by entering the inside of ST was found as shown in Fig. 6.

For the check of plasma flow velocity, $I_{\rm sat}$ profiles with up ($J_{\rm up}$) and down ($J_{\rm dn}$) streams were measured by MP. $M_\infty = \ln[R]/k$ could be calculated where R and k are ratio of upstream and downstream of ion saturation current densities, $R = J_{\rm up}/J_{\rm dn}$, and calibration factor for MP, respectively [11]. In case of B $\lesssim$ 100 G, $r_L > a$ is satisfied where a is probe tip area. Therefore, unmagnetized probe model for k was used for calculation of M_∞. Even though recent results from Hutchinson [5], for a spherical probe using a particle-in-cell (PIC) code

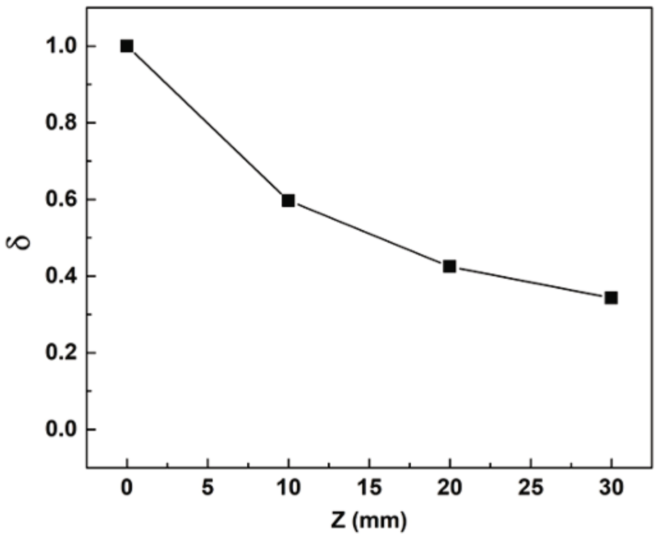

Fig. 6. Ion saturation current ratio (δ) before (I_b) and after (I_a) depletion of ions in supersonic tube (ST) as function of Z-axis.

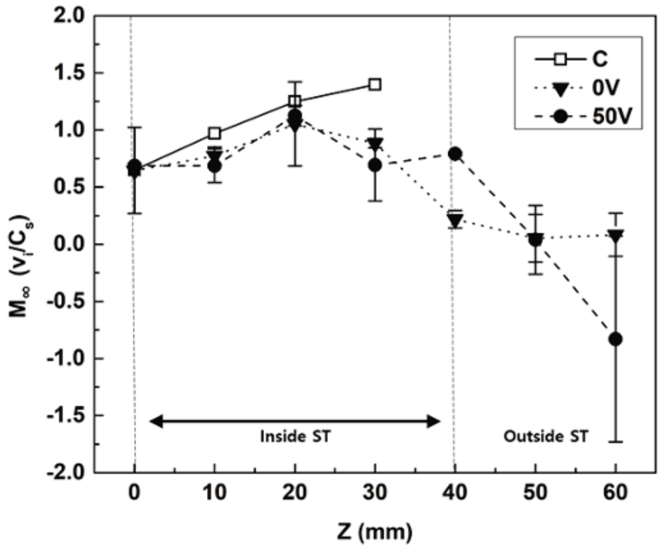

Fig. 7. Characteristics of ion velocity distribution as function of Z-axis. C = calculation values from energy conservation, 0 V = measurement data by a Mach probe (MP) without bias to ST, −50 V = measurement data by a MP with negative bias 50 V to ST. ST = Supersonic tube. Experimental conditions: RF power = 150 W, helium gas flow rate = 500 sccm (8×10^{-2} Torr), Magnetic intensity = 100 G.

and previous result from Chung [6] for a planar probe using a kinetic analysis produce similar ion velocities in unmagnetized plasmas with subsonic plasma flow at low ion temperatures [11], further verifications of MP results would be necessary for detailed supersonic plasma flow. Therefore, as the calibration factor of MP for analysis of current plasma flow, $k = (k_{\rm h} + k_{\rm c})/2 \approx 1.16$ was adopted by average of Hutchinsons PIC model ($k_{\rm h}$) and Chungs kinetic model ($k_{\rm c}$).

Figure 7 shows results of measurement by MP, compared with calculation values from energy conservation by Eq. (5). The initial velocity of plasma flow from CCP source is $M_\infty \sim 0.6$ (subsonic flow = $M_\infty < 1$). Plasma flow velocity was slightly increased by supersonic flow inside ST. Peak velocity which has $M_\infty \sim 1.1$ (supersonic flow = $M_\infty > 1$) was obtained in the center of ST (Z = 20 mm). After going through ST, plasma flow velocity returned to subsonic flow was found. For more acceleration of ions, negative bias = −50 V was applied to ST to effectively generate higher potential gradients between those of outside and inside ST. However, the effects of negative bias to ST with −50 V was not enough to increase peak velocity of $M_\infty \sim 1.2$. Calculation values has agreement with measurements results by MP except for data at Z = 30 mm. Results showed uncertainty of data as shown in Fig. 7. It seems further investigation of the discrepancy should be warranted by additional diagnostics such as LIF system with MP calibration.

IV. CONCLUSION

Supersonic plasma flow has been generated by applying a cylindrical ion extraction electrode in the CCP. To investigate characteristics of ion velocity distribution as function along the axial direction, plasma velocities were measured by a Mach probe, and compared with those by equation of energy conservation. In steady state conditions, the initial plasma flow ($M_\infty \sim 0.6$) from a CCP source was slightly increased by supersonic plasma flow ($M_\infty =\sim 1.1$–1.2) inside ST was found.

For future work on supersonic plasma flow by the designed ST, plasma potential and ion velocity distribution should be investigated by an emissive probe and LIF system, included with MP data at various experimental conditions such as magnetic intensity bias voltages to ion extraction electrode and *etc.* Also, gridded acceleration system would be helpful after ST to increase plasma flow velocity further.

ACKNOWLEDGMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education(2017R1D1A1B03033076).

REFERENCES

[1] F. Melandsø and J. Goree, Phys. Rev. E **52**, 5312 (1995).
[2] Y. Nishimura, K. Borrass, D. Coster and B. Scott, Contrib. Plasma Phys. **44**, 194 (2004).

[3] I. J. Kang, M-K. Bae, T. Lho and K-S. Chung, Curr. Appl. Phys. **17**, 358 (2017).
[4] L. Oksuz and N. Hershkowitz, Plasma Sources Sci. Technol. **13**, 263 (2004).
[5] I. H. Hutchinson, Plasma Phys. Control. Fusion **44**, 1953 (2002).
[6] K-S. Chung, J. Appl. Phys. **69**, 3451 (1991).
[7] S. P. Kuo and D. Bivolaru, Phys. Plasma **8**, 3258 (2001).
[8] L. A. Dorf, T. Intrator, X. Sun, J. Hendryx, G. A. Wurden, I. Furno and G. Lapenta, Phys. Plasma **17**, 102101 (2010).
[9] N. Asakura and ITPA SOL and Divertor Topical Group, J. Nucl. Mater. **363**, 41 (2007).
[10] Y-S. Choi, H-J. Woo, K-S. Chung, M-J. Lee, D. Zimmerman and R. McWilliams, Jpn. J. Appl. Phys. **45**, 5945 (2006).
[11] K-S. Chung, Plasma Sources Sci. Technol. **21**, 063001 (2012).
[12] I. J. Kang, K. Y. Lee, K. I. Lee, Y-S. Choi, S. G. Cho, M-K. Bae, D-H. Lee, S. H. Hong, T. Lho and K-S. Chung, JINST **10**, C12019 (2015).
[13] Z. Harvey, S. C. Thakur, A. Hansen, R. Hardin, W. S. Przybysz and E. E. Scime, Rev. Sci. Instrum. **79**, 10F314 (2008).
[14] I. H. Hutchinson, *Principles of Plasma Diagnostics 2nd ed.* (Cambridge University Press, New York, 2002), Chap. 6.
[15] K-S. Chung, Jpn. J. Appl. Phys. **45**, 7914 (2006).
[16] Y. Nambu, H. Iwayama, H. Saida and T. Shoji, J. Plasma Fusion Res. SERIES **8**, 920 (2009).
[17] F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion 2nd ed.* (Plenum Press, New York, 1974), p. 20.