Rapid Communications

Influence of a nearby conductor on shape and length of a microwave plasma jet

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This Rapid Communication reports on the observation of an interesting phenomenon: the shape, especially the length, of a microwave plasma jet (MPJ) can be clearly influenced by simply placing a conductor near the plasma source, particularly when the nearby conductor is in contact with the external conductor of the coaxial microwave plasma generator, accompanied by a significant change in microwave reflection power from the terminal. To further investigate this discovery, the relationships between the length of the plume and some important factors, such as the conductivity and length of the nearby conductor, microwave input power, and gas flow velocity, are analyzed, and we find nonlinear rules of influence of these factors on the jet. Measurements of the electric potential around the jet reveal the nonuniform and non-neutral charge distribution inside the visible plasma plume, which plays a vital role in uncovering the mechanism underlying this phenomenon. The results are helpful for providing a deeper understanding of microwave plasma jet characteristics. More importantly, it provides guidelines to control the MPJ using simple structures.

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I. INTRODUCTION

Plasma jets have attracted substantial attention in recent years due to their huge potential in biomedicine, material processing and generation, artificial light source, and electromagnetic applications [1–9]. The microwave plasma jet (MPJ) is one of the most popular plasma sources due to its low source cost [10] and strong adaptability [11–15]. Corresponding research has also been conducted in various fields since the late 1960s [16–24]. In plasma jet applications, one particularly necessary area of exploration is techniques that can be used to lengthen or deform the plasma jet, especially when designing reconfigurable antennas based on MPJ. It has been reported that a small change in the shape or the length of a plasma antenna leads to a big difference in the radiation patterns, resulting in totally different application scenarios [25].

Various efforts, including the Thiene curved plasma arc using convection in his report [26], have been made in this direction. Konstantin *et al.* extended the propagation distance of plasma jets based on flexible plastic tubes that changed the airflow [27]. Liu *et al.* placed a pair of metal electrode plates subject to DC voltages around the plasma jet to deflect the jet and change its length [28]. Zheng *et al.* lengthened the plasma jet by placing folded copper plates inside a dielectric resonator for jet generation due to the increase in discharge intensity [29]. Previous studies have either employed external forces (Coulomb force of the charged electrode plates) or changed the ignition structure (adding flexible plastic tubes or inner metal plates) to make the plasma plume flexible. Nevertheless, no study found that merely conductors can influence the length of the plasma jet in open space, which corresponds to a recent study mentioned by Lee *et al.* that nearby metals have no effect on low-temperature microwave plasmas [30]. Lots of other microwave plasma generators and their applications have been investigated but no similar phenomena have been reported [31–48].

However, in recent experiments with our self-designed coaxial microwave plasma generator, we surprisingly found that the shape, especially the length, of the jet could be significantly affected by a conductor near the MPJ without any external forces. This phenomenon, accompanied by a change in the microwave reflection power in the system, is more obvious, particularly when the nearby metal is in contact with the external conductor of the coaxial generator within a certain range of microwave input power. The changes of the plasma jets with and without nearby conductors are described in detail through optical and thermal imagery. To conduct the mechanism investigation, the influence of some critical factors, such as the conductivity and length of the nearby conductors, on the jet is analyzed. Importantly, we present the potential distribution around the jet and indicate that the visible jet is both nonuniform and non-neutral and that the charge separation can be influenced by nearby conductors, which is the main cause of this phenomenon. The research in this work contributes to the interaction mechanism investigation of microwave and plasma. It provides an alternative simple method to control the shape or length of the MPJ and make it more adaptable in different situations, such as in medical applications.

II. EXPERIMENTAL SETUP

The schematic of the experimental system is shown in Fig. 1(a). The self-designed coaxial generator used to excite the plasma jet at 2.45 GHz is presented in Fig. 1(b). Its dimension details are provided in our previous work [49]. Microwave power propagates into the coaxial plasma generator through the circulator and waveguide-to-coax converter. The plasma jet is triggered and formed at the gas outlet of this apparatus under atmospheric pressure.

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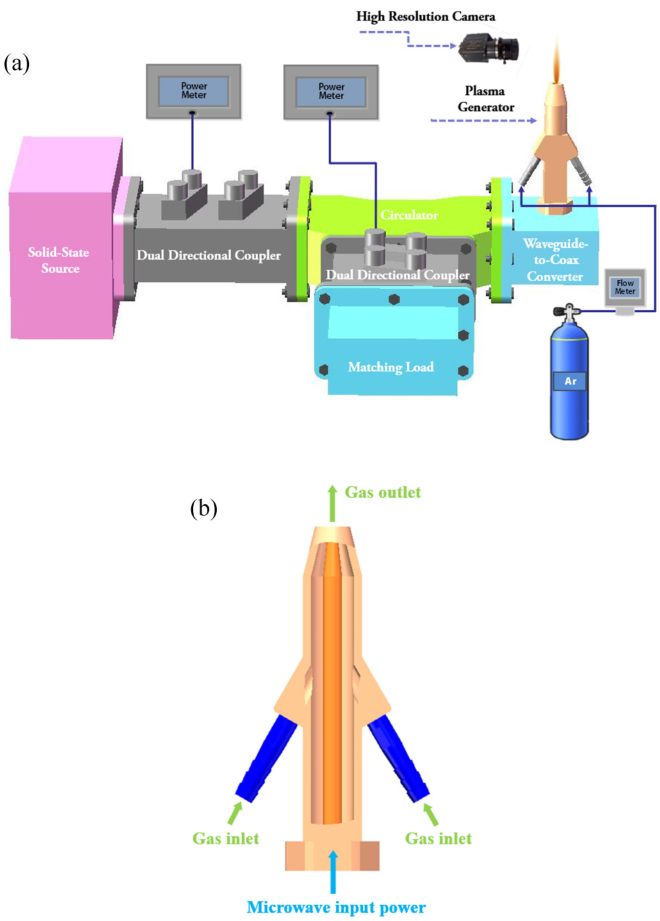

FIG. 1. (a) Schematic of the experimental system. (b) The coaxial plasma generator.

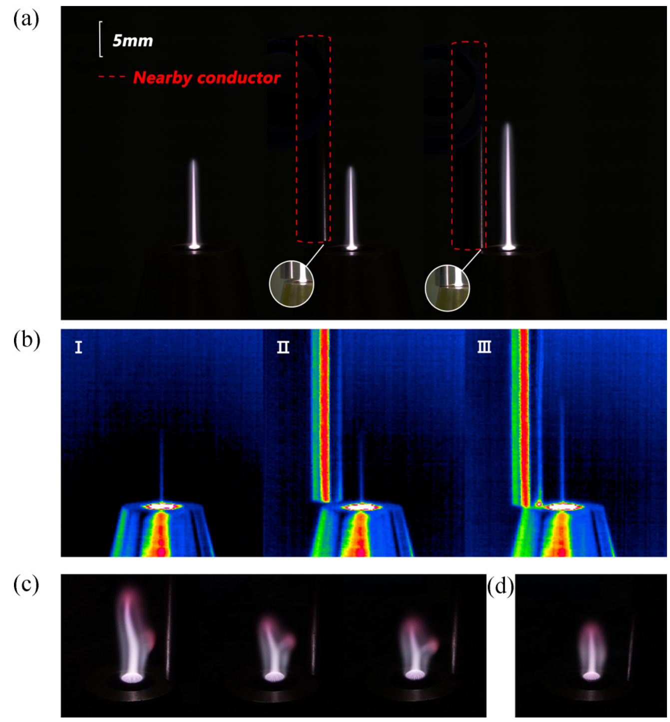

FIG. 2. Optical and thermal imagery of the influence of a nearby conductor on MPJ. (a) Optical images using a high-resolution camera. (b) Thermal images using a thermal imager. I, II, and III represent the cases in which there is no nearby conductor, the nearby conductor is not in contact with the plasma generator, and the nearby conductor contacts the plasma generator, respectively. (c) Bifurcation optical images with 34.9 W input power on the case of III. Flow rates are 2.5, 2, and 1.5 l/min, respectively, from left to right. (d) Contrastive image with the same 34.9 W power on the case of II, when the flow rate is 1.5 l/min.

III. OBSERVATION OF PHENOMENA

The plasma plume shape or length variations produced with the nearby conductor is recorded by optical and thermal imaging and shown in Fig. 2. From the images in Figs. 2(a) and 2(b), it was observed that the plasma jet increases significantly when the nearby conductor contacts the outer conductor of the microwave coaxial plasma generator. However, the plume length became shortest when the nearby conductor was not in contact with the outer conductor of the plasma generator. It is also noteworthy that, as shown in Fig 2(c), during the experiments, the plasma plume was found to be drawn and bifurcated obviously toward the contacting nearby conductor with a high enough power and a low argon flow rate. The smaller the gas flow rate, the more obvious this bifurcate phenomenon. Nevertheless, if the nearby conductor did not contact the outer conductor of the plasma generator, no branches were observed on the plasma jet even though under the same working conditions [Fig. 2(d)].

IV. EFFECTS OF PIVOTAL FACTORS ON PHENOMENA

According to this phenomenon, adjustment of the shape, especially the length, of the jet by using a nearby simple metal structure contacting the outer conductor of the plasma generator can be implemented. It is worth exploring some pivotal influencing factors of this phenomenon to obtain a deeper understanding. Investigations on the effects of the nearby conductor length L_c, nonmetal length L_n, conductivity σ, relative permittivity ε_r, microwave input power P_i, and gas flow velocity R_{Ar} on the jet length L_j were conducted. The corresponding results are presented in Figs. 3 and 5. The influences of these factors on the microwave reflected power were also explored, as demonstrated in Fig. 4.

From Fig. 3(a), it is obvious that the conductivity of the metal has an impact on the plasma jet length L_j. The higher the conductivity, the stronger the influence. It should also be noted that the conductor's length L_c plays an important role in the jet length L_j. Generally, when L_c is less than 70 mm, increasing the length of the contacted nearby conductor increases the length of the plasma jet. The jet length starts to shorten slightly when L_c further increases above 70 mm. The impact trend is much the same when the rods are nonmetallic instead of metal [Fig. 3(b)]. Logically, rods such as quartz with conductivity close to zero have no impact on L_j. However, the curve of the jet length L_j does not increase monotonously with L_n but rather fluctuates with a tiny decrease when L_n is approximately 5 and 30 mm. It is also worth noting that when the nearby rod is shorter than the plasma jet, the top of the rod strongly attracts the jet, causing bifurcation, widening the jet and decreasing the jet length L_j.

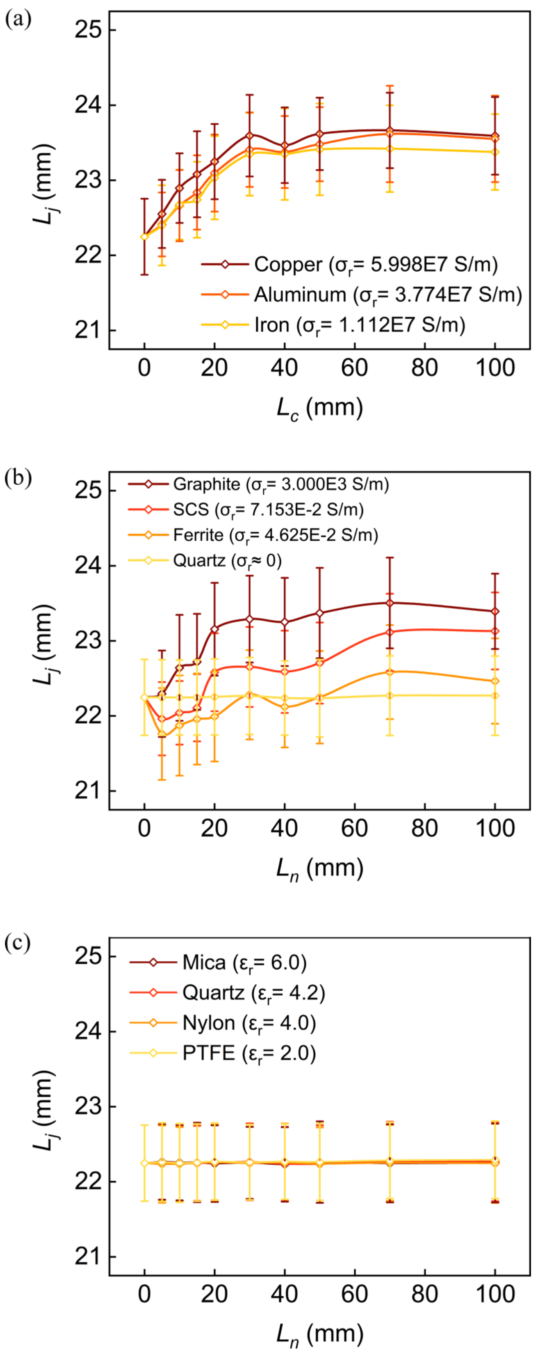

FIG. 3. The influence of nearby conductors and dielectrics with different lengths, conductivity, and relative permittivity on MPJ. (a) MPJ lengths with different metals. (b) MPJ lengths with different conductivity of nonmetals. (c) MPJ lengths with different relative permittivity of nonmetals. Data are connected by B-spline curves. Error bars represent the standard deviation of the measurements.

The influence of dielectric's permittivity has been explored. As the experimental result shows [Fig. 3(c)], electrical insulators ($\sigma_i = 0$) have no influence on the jet, although it possesses non-negligible relative permittivity and will cause changes of electrical field distribution around the plasma jet. This phenomenon reveals that electric field change caused by permittivity variation around the jet negligibly influences the jet.

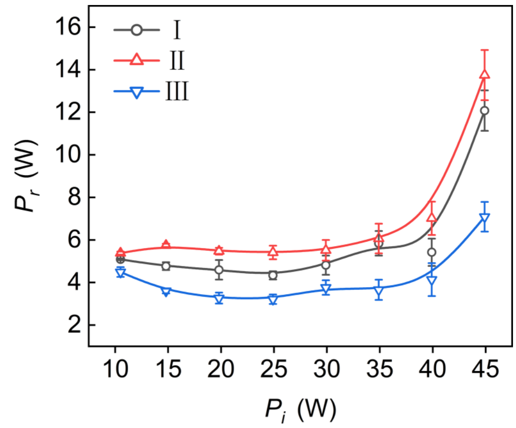

FIG. 4. The influence of nearby conductors on the microwave reflection power P_r of the system. I, II, and III represent the same cases as those in Fig. 2. Data are connected by *B*-spline curves. Error bars represent the standard deviation of the measurements.

The variations in P_r acquired from microwave power meters (shown in Fig. 4) indicate that the reflected powers P_r decrease obviously when the nearby conductor contacts the outer conductor of the plasma generator. The higher the input power P_i is, generally, the larger the differences in P_r among the three situations.

To further study this phenomenon, the effects of working condition changes (input power P_i, gas flow rate R_{Ar}, and metal conductor length L_c) on the plasma jet length with the contacted nearby conductor were investigated. The jet length evolutions with changes in P_i and R_{Ar} are displayed in Figs. 5(a) and 5(b), respectively. The influence of nearby conductor rods with different lengths is also shown in Fig. 5. The solid blue line represents the curve of the maximum value of the plasma length change rate R_j in the upper figures. Specifically, the case without a nearby conductor is expressed by the red dotted line. The yellow-orange background area, where the maximum R_j is higher than that without a nearby conductor, is defined as the jet increase area. Analogously, the yellowish background area indicates the jet decrease area, while the blue background area indicates the stable area, where the maximum value of R_j is close to zero.

Obviously, R_j is approximately maximized with a relatively low P_i and a large R_{Ar} in a certain range according to the above studies. It is worth mentioning that there is still substantial room to improve R_j because the nearby conductors are somewhat far from the jet to avoid the influence of nearby conductors on the airflow as best as possible in these experiments.

V. PHENOMENA MECHANISM EXPLORATION

As mentioned above, whether the nearby conductor is contacting the external conductor leads to tremendous discrepancy in the plasma jet, even though the other working conditions are exactly the same. For these two cases, the only difference may be the potential distributions of the nearby conductors. The equipotential surfaces and lines of the potential distribution fitted by a polynomial function are provided in Fig. 6, respectively. From the measurements, one

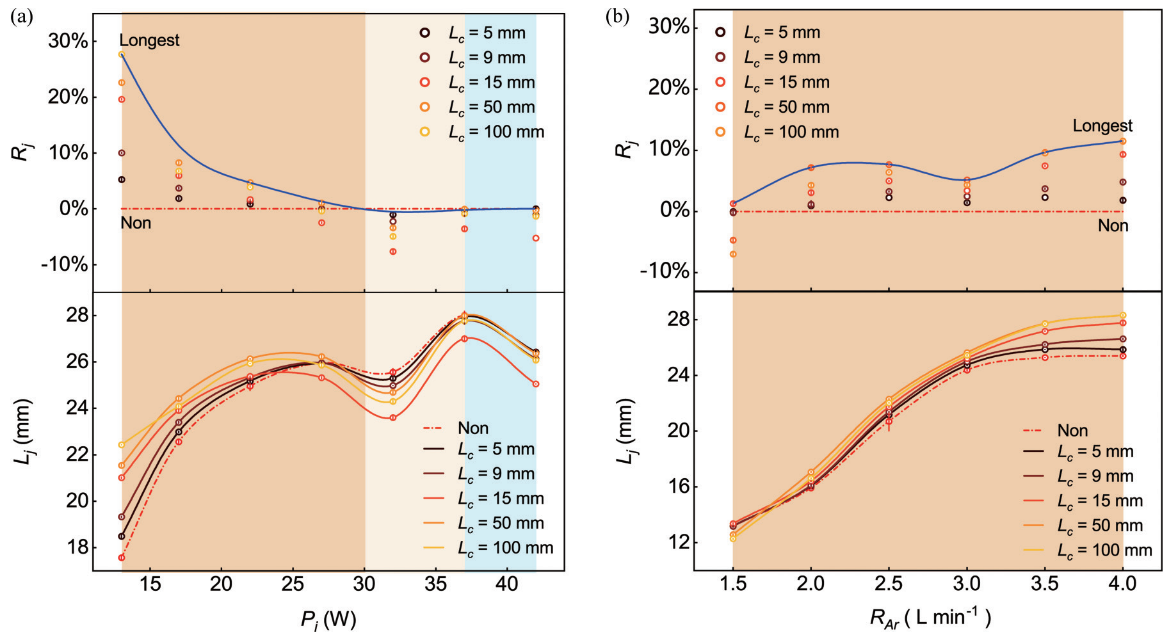

FIG. 5. The influence of microwave input power and input flow on MPJ when the nearby conductor contacts the outer conductor of the plasma generator. (a) The influence of P_i on MPJ length with different L_c when $R_{Ar} = 3.15\,\mathrm{l/min^{-1}}$. (b) The influence of R_{Ar} on MPJ length with different L_c when $P_i = 17.2$ W. Data are connected by modified Bezier curves. Error bars represent the standard deviation of the measurements.

can obviously observe that the potential around the plasma jet is positive, which indicates that this MPJ is non-neutral. In addition, the water-drop-shaped potential distribution evidences the nonuniform distribution of the charged particles in the jet. These discoveries are, at first glance, in conflict with the definition of plasma because it is commonly believed that the plasma is electrically neutral macroscopically in the absence of external forces; however, they are explicable.

According to research on the microwave plasma torch conducted by Zhang *et al.*, a microwave plasma torch bounded by a quartz tube is positively charged inside but electrically neutral on a macroscopic scale [50] because many electrons accumulate on the wall of the tube to form the plasma sheath. In our case, because the plasma jet is exposed to open space and lacks external boundaries, the lightweight electrons escape the plasma bulk faster into the nearby space and form a sheath, resulting in a concentration of positive ions in the plasma bulk and positive potential around the plasma plume.

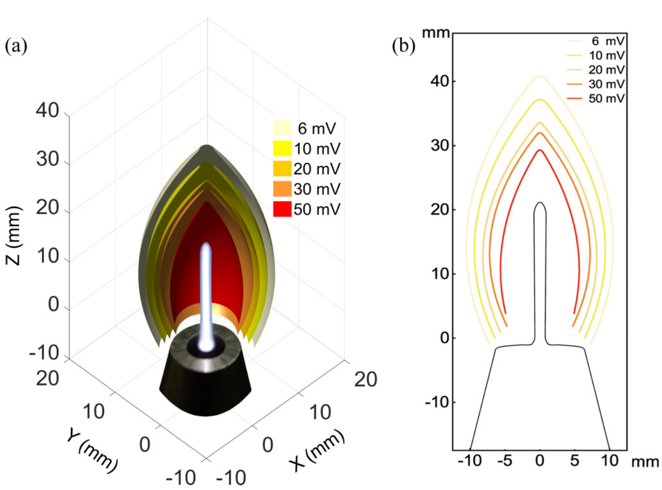

FIG. 6. Measured potential distribution around the MPJ. (a) Three-dimensional equipotential surface of potential. (b) Corresponding two-dimensional equipotential line of potential.

On the other hand, the shape of the potential distribution is also explicable. Compared to the electrons, the ions tend to move downward and make the particles denser in the lower part of the plasma jet due to the influence of gravity. Moreover, the microwave energy and gas volume decrease further away from the excitation port, leading to a lower ionization degree and charge density. These results indicate why the potential distribution forms the water-drop shape.

Returning to the phenomenon mechanism, as shown in Figs. 6 and 7(a), potential around the jet is positive. When a conductor is placed near the plasma jet while touching the outer conductor of the coaxial generator, which has lower potential and can be regarded as the ground in our experimental system, sufficient electrons are attracted via this ground and accumulate on this conductor due to the potential difference between the nearby conductor and the space around it, which repels the electrons and attracts the argon ions in the jet [Fig. 7(b)]. This will enhance the separation of positive and negative charges, decreasing the possibility of recombination of electrons and ions. A lower chance of recombination of particles results in more effective collision and the generation of a longer plasma plume. More plasma can absorb more microwave energy and decrease the reflected power. Increasing the input power in a certain range can also excite more plasma. These observations explain the phenomenon presented in Fig. 4.

The higher the conductivity of the conductor, the better the ability of attracting and guiding electrons. However, when the contacted metal rod is too long, too many electrons are guided

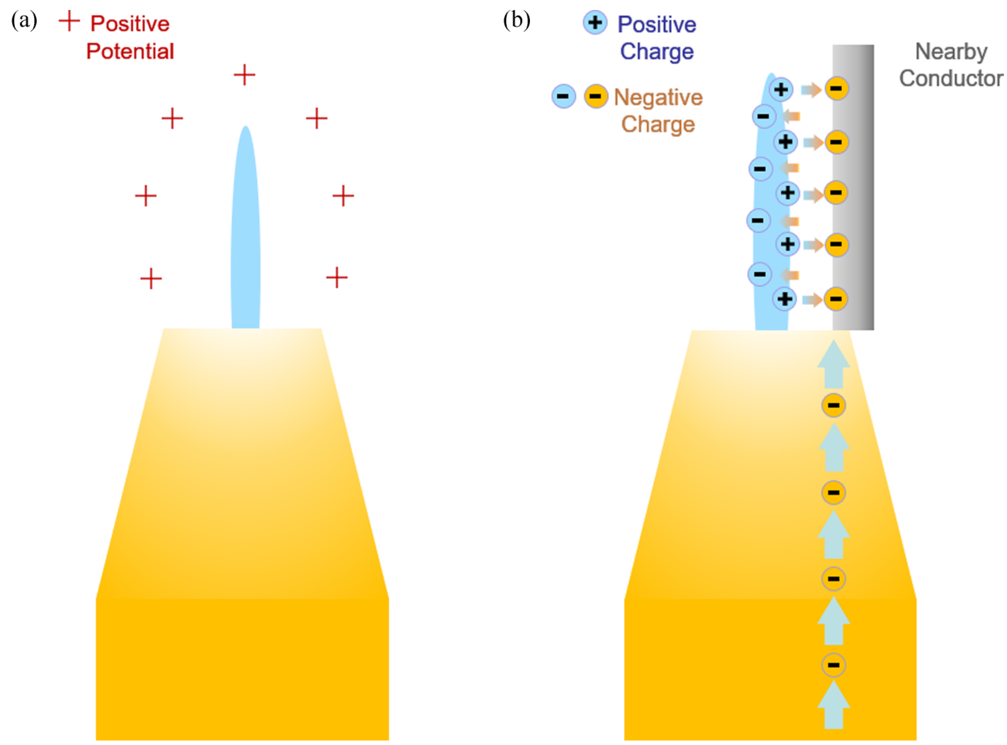

FIG. 7. Schematic of phenomena mechanism. (a) Case with no nearby conductor. (b) Case with a nearby conductor contacting the external conductor of the plasma generator.

away, which makes the collision probability of high-energy electrons and argon atoms lower and the plasma jet shorter. Therefore, the plasma jet length becomes smaller when the metal rod is longer than 70 mm (Fig. 3).

It has been reported that the electrical field (input power) and gas flow rate can also influence the shape and length of the plasma plume [33]. The plasma length showed a wavy tendency with increasing input power and gas flow rate. Normally, the plasma length will increase with increasing input power and gas flow rate. However, further enhancing these two factors will make the plasma initiation area larger and the plasma jet fatter rather than longer. In our cases, the gas flow rate change range is small, making the plasma length increase with it (Fig. 5).

In particular, when the flow rate is sufficiently low and the input microwave power is high enough, the high microwave energy will almost ionize the working gas and generate more electrons and ions. Since the gas flow rate is small, all the particles, especially the argon ions, in the plasma move with sufficiently low longitudinal velocities as well. As shown in Fig. 6 and expressed above, the point a little bit below the plasma center presents the maximum potential, which indicates that the largest number of electrons accumulated at the corresponding point of the contacted metal rod. When the horizontal Coulomb force by the electrons on the nearby metal rod is capable of competing with the longitudinal momentum, the particles propagate toward the metal rod. That is why the plasma with the contacted nearby metal rod branches at low gas flow rate and high microwave input power. It also provides the reason why the bifurcation phenomena always emerge at the point a little bit below the plasma center.

VI. CONCLUSIONS

In conclusion, this Rapid Communication reports the phenomenon that a nearby conductor could significantly influence microwave plasma jet shape in open space. A nearby conductor enables the length extension and bifurcation with warp of the plasma jet when it contacts the outer conductor of the microwave coaxial generator. However, the plasma jet would become shorter once the nearby conductor did not contact the plasma generator, whose related deeper investigations were then conducted to explore the mechanism underlying this phenomenon. The results demonstrate that the MPJ in open space is nonuniform and non-neutral. The potential of the contacted nearby conductor affects the charge motion in the plasma jet and thus leads to the jet length change. However, further investigations on reasons which cause the phenomenon with the noncontacted conductor are still needed and will be conducted in the future. These findings and mechanism investigations in this Rapid Communication should be helpful in achieving a deeper understanding of the MPJ and realizing the control of the MPJ by a simple conductor to enhance its adaptability for various applications.

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