Change of plasma propagation state due to force balance with collision

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ABSTRACT

The main findings of this study are that the plasma propagation state changes with the force equilibrium relationship between the driving force due to the electromagnetic field and neutral gas flow. The plasma propagation transitions from a continuous state to a discontinuous state when plasma emission light intensity changes. The plasma emission light intensity changes suddenly as the applied voltage frequency varies. The frequency at which plasma emission light changes is inversely proportional to the dynamic pressure with the flow velocity of neutral gas. The plasma with strong light emission at high frequency propagates continuously, while that with weak light emission at low frequency propagates discontinuously. Because the plasma current with strong light emission is larger than that with weak light emission, the plasma charge quantity—the amount of plasma generated—increases. Consequently, when the plasma quantity is enough to exist continuously as a group, the plasma group propagates in space with time variations like a stationary wave. However, when the plasma quantity is inadequate to exist continuously, the plasma group propagates through the space discontinuously like a bullet state.

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I. INTRODUCTION

The four states of matter comprise solid, liquid, gas, and plasma. These are decided in each state because energy is balanced. Thus, the state of matter is decided by equilibration of the inertial force from the input energy by driving force and output energy by restricting force. The state of plasma generation and loss is determined by equilibrating the driving and restricting forces applied to the plasma and neutral particles (gas). The spatial distributions of electrons, ions, and neutral particles are determined by the balance between the driving and restricting forces. When plasma generation exceeds losses, a plasma flow (propagation) occurs to satisfy the force balance. The spatial distributions of each density and temperature are determined by plasma flow. Electron acceleration with a relativistic plasma wave causes plasma breaking. The phenomenon of plasma breaking is plasma traveling discontinuously. The flows of electrons, ions, and neutral particles are important to determine the plasma property. Because the plasma flow is determined by the plasma spatial distribution, the plasma flow state changes by varying spatial distributions. If the density of the plasma is low, the plasma flow will be discontinuous. Consequently, the state of plasma flow is determined by the force balance. It has been expected that the plasma propagation state would change by the effect of ponderomotive wave–particle interactions. The transition phenomenon in the plasma would be related not only to the plasma propagation state but also to the plasma density and temperature states. The streamer, which is a kind of plasma propagation due to electron energy transport, is observed in the tokamak of the fusion plasma apparatus. Additionally, the H-mode, in which the plasma density and the confinement characteristics are improved, is also observed in the tokamak. The model of L- to H-mode transition in the tokamak is related to the collision and electric field. Electrons are confined by magnetic field pressure, and ions are confined by an electric field. The driving of current with electron traps caused by a magnetic field pressure occurs in the torus devices. In a hollow cathode discharge of a glow plasma, a transition phenomenon (change in discharge mode) due to an increase in plasma density with potential oscillation occurs. The increase in plasma density is caused by the enhanced impact ionization due to electron traps accompanying potential oscillation. Such a density increase is also caused by RF discharge, and the plasma thermal pressure is increased by increasing the plasma density. Therefore, the cyclic frequency of electron gen-
eration would be an important factor that causes a plasma transition phenomenon. Additionally, the generated plasma density depends on the electron collision cross section. The flow involves collisions between particles. The collision between a nonionized gas and a magnetized plasma is expected to be important in astrophysics studies in which a low-density plasma is hit by a continuous stream of neutral gas. Although the plasma drift velocity and neutral particle flow velocity in the flow field differ greatly, the plasma density increases in proportion to the flow velocity of the neutral particles. The plasma travel distance depends on the plasma charge and varies depending not only on the plasma drift velocity but also on the flow velocity of the neutral particles. Electromagnetic forces act on electrons and ions, but forces on neutral particles are also related to plasma generation and loss. Thus, the plasma current, which comprises density and drift velocity, is determined as the balance between the electromagnetic force and the drag force with collision of gas flow in the local micro-field. Because the plasma charge is the plasma’s electric energy and the flow of neutral particles is the kinetic energy, the plasma travel distance, which is the plasma’s potential energy, is determined from the energy conservation law. Consequently, by observing the plasma, which is one state of the substance, it is possible to examine the substance state based on the energy conservation law.

In this paper, we consider the force balance equation with collisions among electrons, ions, and neutral particles. The plasma is generated by applying high-voltage AC under low-pressure in a vacuum vessel with flowing neutral gas. Plasma emission light intensity and plasma current are measured. The factor that

### II. FORCE BALANCE EQUATIONS

From the energy conservation law, force balance is examined by the spatial distribution of total pressure, \( \nabla p_{\text{tot}} = \nabla p_{\text{stat}} + \nabla p_{\text{dyn}} \), which is the sum of static pressure, \( \nabla p_{\text{stat}} \), and dynamic pressure, \( \nabla p_{\text{dyn}} \). The plasma comprises electrons, ions, and neutral particles. Electrons and ions are accelerated by the electric field and magnetic field and are decelerated by collisions between different species. The momentum transfers between the same species are dynamic pressure with a velocity change due to perfect elastic collision. When the electric field varies with temporally, spatially, and periodically alternating current \( \{e.g., g(t) = \frac{\omega_0}{2 \omega} \text{sine} \} \), the driving force with electric field \( F_D \) is expressed as

\[
F_D = e n E \cos \omega t, \quad (2)
\]

where \( \omega \) is the angular frequency of the applied electric field. The time-averaged effective driving force is written as

\[
F_D = \pm e n E - \frac{\varepsilon_0}{2} \nabla \left( \frac{E^2}{\omega^2} \right) = \mp e n E, \quad (3)
\]

where \( \varepsilon_0 \) is the permittivity of free space and \( \omega_p \) is the plasma’s angular frequency. The second term on the right side of Eq. (3) is the dynamic gravitational force (ponderomotive force). Because the sign on the first term on the right side changes with respect to electrons or ions, the second remains because of bipolar diffusion. Because electrons move faster than ions, the first term of the effective ambipolar diffusion field is ignored by time averaging. Here, a sine wave is a continuous voltage wave; however, when the impulse wave, which is a discontinuous (intermittent) voltage wave, is related to the voltage application period, \( t_{ap} \), and duty ratio, the time-averaged electric field depends on the frequency of the applied voltage, \( f(=\omega/2\pi) \) (i.e., \( X = X_{\text{max}} t_{ap} / \sqrt{2} \)); and the effective driving force is rewritten as

\[
F_D = -\frac{\varepsilon_0 \omega_0^2}{4} \nabla \left( \frac{E_{\text{max}}^2}{\omega^2} \right), \quad (4)
\]

The intensity of the driving force with the impulse wave depends on the frequency of the applied electric field. When the frequency is high, ions barely move compared with the electrons (i.e., \( v_i = 0 \)) because the mass of ion is heavier than that of electron. For simplicity, the force balance equations without a magnetic field are written as

\[
-\varepsilon n e (E + v_e \times B) - R_{e} - R_{en} = \nabla p_{\text{stat}}^e + \nabla p_{\text{dyn}}^e = \nabla n_e kT_e + m_e n_e v_e \nabla v_e, \quad (1a)
\]

\[
en (E + v_i \times B) - R_e - R_{en} = \nabla p_{\text{stat}}^i + \nabla p_{\text{dyn}}^i = \nabla n_i kT_i + m_i n_i v_i \nabla v_i, \quad (1b)
\]

\[
(0) - R_n - R_{ni} = \nabla p_{\text{stat}}^n + \nabla p_{\text{dyn}}^n = \nabla n_n kT_n + m_n n_n v_n \nabla v_n, \quad (1c)
\]

where the superscript and subscript “e,” “i,” and “n” designate the electron, the ion and the neutral particle, respectively; \( e \) is the elementary electric charge; \( n \) is the density; \( E \) is the electric field; \( v \) is the drift velocity; \( B \) is the magnetic field; \( R \) is the momentum gained by electron-, ion-, and neutral particle collisions; \( k \) is the Boltzmann constant; \( T \) is the temperature; and \( m \) is the mass. The momentum transfer between the same species due to collisions is dynamic pressure and conserves in its specie. The momentum transfers between different species because of collisions acting as the drag force. The balance between the electromagnetic force and the drag force due to collision with gas flow determines the spatial distribution of electrons, ions, and neutral particles.

When the electric field varies with temporally, spatially, and periodically alternating current \( \{e.g., g(t) = \frac{\omega_0}{2 \omega} \text{sine} \} \), the driving force with electric field \( F_D \) is expressed as

\[
F_D = en E \cos \omega t, \quad (2)
\]

where \( \omega \) is the angular frequency of the applied electric field. The time-averaged effective driving force is written as

\[
F_D = \pm en E - \frac{\varepsilon_0 \omega_0^2}{2} \nabla (E^2) = \mp en E, \quad (3)
\]

where \( \varepsilon_0 \) is the permittivity of free space and \( \omega_p \) is the plasma’s angular frequency. The second term on the right side of Eq. (3) is the dynamic gravitational force (ponderomotive force). Because the sign on the first term on the right side changes with respect to electrons or ions, the second remains because of bipolar diffusion. Because electrons move faster than ions, the first term of the effective ambipolar diffusion field is ignored by time averaging. Here, a sine wave is a continuous voltage wave; however, when the impulse wave, which is a discontinuous (intermittent) voltage wave, is related to the voltage application period, \( t_{ap} \), and duty ratio, the time-averaged electric field depends on the frequency of the applied voltage, \( f(=\omega/2\pi) \) (i.e., \( X = X_{\text{max}} t_{ap} / \sqrt{2} \)); and the effective driving force is rewritten as

\[
F_D = -\frac{\varepsilon_0 \omega_0^2}{4} \nabla \left( \frac{E_{\text{max}}^2}{\omega^2} \right), \quad (4)
\]

The intensity of the driving force with the impulse wave depends on the frequency of the applied electric field. When the frequency is high, ions barely move compared with the electrons (i.e., \( v_i = 0 \)) because the mass of ion is heavier than that of electron. For simplicity, the force balance equations without a magnetic field are written as

\[
-\varepsilon n e E - R_{e} - R_{en} = \nabla n_e kT_e + m_n n_e v_e \nabla v_e, \quad (5a)
\]

\[
- R_{en} - R_{en} = \nabla n_e kT_e, \quad (5b)
\]

\[
- R_{ni} - R_{ni} = \nabla n_i kT_i + m_n n_i v_i \nabla v_i. \quad (5c)
\]

The single fluid equation is obtained by considering the momentum transfers between different species. We therefore obtain

\[
-\varepsilon n e E - m_n n_i v_i \nabla v_i (= F_i) = \nabla n_e kT_e + \nabla n_i kT_i + \nabla n_n kT_n + m_n n_i v_i \nabla v_e. \quad (6)
\]
The inertial force to the plasma, \( F_i \), is determined by the relationship between the electromagnetic (driving) and drag (restricting) forces. From the spatial (line) integral of the inertial force along a path of length, \( L \) (that is axial direction, \( \partial / \partial z \)), we obtain

\[
\int F_i(\lambda) \, d\lambda = F_{i,\text{plu}} = p_c + p_n + n_e m_e v_{\text{plu}}^2 \quad \text{and} \quad p_n = n_e k T_n + m_n v_n^2/2,
\]

where \( L_{\text{plu}} \) is the plasma length, which is equivalent to the travel distance from the power source in the axial direction. The dynamic pressure of neutral particles is related to the flow velocity of neutral gas with perfect elastic collision, \( v_{\text{gas}} \). Before the collision, the neutral particle moves at the gas flow velocity and another is thermal motion. The neutral particle after the collision stops and moves thermally, while the other particle moves at the gas flow velocity. Consequently, the entire gas flow is regarded as a continuous flow with the gas flow velocity because collisions occur repeatedly. Therefore, the flow velocity of the entire gas is equivalent to the individual gas flow velocity. We therefore obtain

\[
\nabla n_e k T_n + m_n n_e v_n \nabla n = \nabla n_e k T_n + m_n n_e v_{\text{gas}} \nabla n_{\text{gas}}.
\]

The frequency of neutral particles’ collisions with the dynamic pressure due to neutral gas flow velocity is written as

\[
f_{\text{coll}} = \frac{\langle v \rangle}{\lambda_0} = \frac{\sqrt{8 k T_n / \pi m_n}}{\sqrt{2 \pi \sigma_0^2 p_{\text{dyn}}}},
\]

where \( \langle v \rangle \) is the averaged thermal velocity, \( \lambda_0 \) is the mean free path of neutral particles, and \( \sigma_0 \) is the diameter of neutral particles.

III. EXPERIMENTAL SETUP

The dependence due to the neutral particle flow is examined experimentally. The schematic diagram of the plasma device is shown in Fig. 1. The neutral particle gas flows from the small diameter (1.5 mm) quartz tube to the large one (50 mm). The large quartz tube is 150 mm long. The small quartz tube inside the large quartz tube is 30 mm long. The quartz tube is sealed with an insulating flange on the top and a stainless-steel flange on the bottom. Helium gas as working gas is supplied from 0.035 slm to 0.65 slm by using a mass flow controller. The supplied gas is exhausted by a vacuum pump through a diaphragm valve. The gas static pressure is controlled by the balance between the supply and exhaust volumes and is monitored using a gas pressure gauge. The gas dynamic pressure is estimated from the gas flow rate and helium gas density at room temperature. The powered electrode comprises 20-×20-mm copper foils with a thickness of 0.1 mm and is located upstream. The helium plasma is generated using an AC power supply (Haiden PHP2-KH) that provides a peak voltage of +9 kV and frequency from 1 kHz to 100 kHz. The waveform is an impulse wave. The applied voltage between the powered and grounded electrodes is measured using a high-voltage probe. The power- and ground-line currents are measured using a current monitor. The plasma emission light is measured using a photodetector through an optical fiber. The measurement points are set 10 mm and 15 mm from the edge of the powered electrode inside the small quartz tube on the downstream side. In the experimental condition, the plasma density, electron, and ion temperatures are estimated to be about \( 10^{19} \text{ m}^{-3} \), a few electronvolts, and \( \sim 0.1 \text{ eV} \), respectively.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

We confirmed that the plasma emission light intensity changes suddenly depending on the frequency of the applied voltage at a gas flow rate of 0.095 slm (Fig. 2). The plasma length with the strong light emission gets longer compared with that with weak light emission. As the frequency of the applied voltage increases, the intensity of plasma emission light suddenly increases and vice versa. The emission intensity changes nonlinearly with respect to the change in frequency. To clarify the factor, the plasma current in each state is examined. The time evolution characteristics of the applied voltage, the power- and ground-line currents, and the plasma current are shown in Fig. 3. Each curve was obtained from the moving time average (a duration of 72 ns). The plasma current is estimated by subtracting the ground-line current from the power-line current using the difference current method. The negative plasma current is generated by moving electrons first, and the positive plasma current is generated moving ions later. In both states, the time during which the negative and positive currents are generated hardly changes. Thus, the current generation time is determined by the voltage application time. The plasma current during strong light emission is larger than during weak light emission. The photodetector signal’s time evolutions are shown in Fig. 4. Each curve was obtained from the moving time average (18 ns duration). Although the measurement points are 10 mm and 15 mm from the edge of the powered electrode inside the small quartz tube on the down-
stream side, the photodetector signal in the state of the strong light emission changes simultaneously. Thus, the plasma propagates continuously in space with time variations like a stationary wave inside the small quartz tube. Conversely, the plasma propagates through the space discontinuously like a bullet state because the signal in the state of the weak light emission changes with time difference. Consequently, we confirmed a transition phenomenon in which the plasma emission light intensity changes suddenly depending on the plasma propagation state. Such a change in the plasma propagation state has been reported under atmospheric pressure conditions, but the generation mechanism remains unclear and no change in emission intensity has been reported. In each plasma propagation state, the case of continuous propagation is called a continuous transmission mode (CTM) and the case of discontinuous propagation is called a discontinuous transmission mode (DTM).

To elucidate the factors that change the plasma propagation state, the relationship between the frequency at which the state change occurs and the static and dynamic pressures of the gas, which are controlled by the balance between the supply and exhaust volumes, is investigated. The dependences of the applied voltage frequency at which propagation state changes dynamic pressure because of gas flow are shown in Fig. 5. Each value is averaged from three sets of analyses; the error bars denote the maximum and minimum values, and the curve is a smoothing spline. The change from discontinuous to continuous transmission states with increasing the frequency is expressed as CTM, and the change from continuous to discontinuous transmission states with decreasing the frequency is expressed as DTM. For each gas dynamic pressure,
the gas static pressure is changed by controlling the exhaust volume with the diaphragm valve. When the gas static pressure is controlled to be constant and the gas dynamic pressure due to the gas flow rate is increased, the applied voltage frequency at which the plasma emission light intensity changes decreases. If the gas static pressure is different, but the gas dynamic pressure is the same, the state change occurs at the same applied voltage frequency. When gas does not flow and its gas dynamic pressure is zero, no transition phenomenon occurs. The frequency at which the state change occurs does not depend on the gas static pressure but depends on the gas dynamic pressure. The gas flow is in a direction along the small quartz tube, and the gas flow is one-dimensional dynamic pressure. The gas dynamic pressure is an equilibrium thermal pressure, so it is three-dimensional. Thus, dynamic and static pressures must be treated separately. Because the plasma formation is mainly in the direction along the quartz tube, the electromagnetic force and gas dynamic pressure are applied in the same direction. The waveform of the applied voltage is an impulse wave, and the plasma is generated intermittently and periodically. Thus, the frequency of applied voltage is equal to the frequency of plasma generation. The plasma propagation state is changed by the frequency of plasma generation. Because the plasma is generated intermittently and periodically, it is necessary to consider the ratio between the generation and non-generation periods (duty ratio). From Eqs. (4), (6), and (8), the inertial force applied to the plasma is written as

\[ F_s = -\frac{e_0}{16\pi^2} \nabla \left( E_{max}^2 \right)_{pl} - m_n n_0 v_{gas} \nabla v_{gas}, \] (10)

where \( t_{pl} \) is the period of plasma generation and is equivalent to the voltage application period. When the inertial force is balanced and the plasma state is sustained, the inertial force can be regarded as substantially zero so that the first term and the second term can be regarded as equal. Thus, the frequency of plasma generation is inversely proportional to the gas dynamic pressure due to the gas flow rate. The collision frequency of neutral particles due to gas dynamic pressure in Eq. (8) is shown in Fig. 5. The collision frequency of neutral particles intersects with the frequency at which the transition phenomenon occurs. In the region of low collision frequency, the frequency difference with which the transition phenomenon occurs is wide, but in the high region, the frequency difference is narrow. Because the density of the generated plasma depends on the electron collision, the density and amount of plasma generated are related to the transition phenomenon. The plasma current is related to the density and generated amount of plasma charge. The dependences of the time-averaged plasma current on the dynamic pressure due to gas flow are shown in Fig. 6. The negative and positive currents on the plasma current are generated with the large pulse of the applied voltage (Fig. 3). The time-averaged plasma current is estimated from the negative current because it becomes zero when the positive and negative currents are combined. The time-averaged plasma current does not depend on the dynamic pressure due to the neutral gas flow. Because the plasma current in CTM with strong light emission is larger than that in DTM with weak light emission, the cyclic frequency of plasma generation is related to the transition phenomenon. Assuming that the second term of the neutral particle is the same in each state in Eq. (10), we obtain

\[ \left[ -\frac{e_0}{16\pi^2} \frac{\omega_p^2}{f} \nabla \left( E_{max}^2 \right)_{pl} \right]_{CTM} (\approx m_n n_0 v_{gas} \nabla v_{gas}) = \left[ -\frac{e_0}{16\pi^2} \frac{\omega_p^2}{f} \nabla \left( E_{max}^2 \right)_{pl} \right]_{DTM}, \] (11)

If the period of plasma generation and the strength of electric field (voltage) are the same in each state, we obtain

\[ \left[ \frac{\omega_p^2}{f} \right]_{CTM} = \left[ \frac{\omega_p^2}{f} \right]_{DTM}. \] (12)

The plasma’s angular frequency, \( \omega_p \), depends on the plasma density. From the relationships among the plasma current, density, and drift velocity, we obtain

\[ \frac{n_{CTM}}{n_{DTM}} \approx \frac{I_{CTM} \nu_{CTM} S_{CTM}}{I_{DTM} \nu_{DTM} S_{DTM}} = \frac{I_{CTM}}{I_{DTM}} \frac{\nu_{CTM}}{\nu_{DTM}} = \frac{f_{CTM}}{f_{DTM}}, \] (13)

where \( S \) is the cross section of the plasma inside the small quartz tube and \( I \) is the plasma current. Because the drift velocity in a continuous propagation state cannot be measured, it is expressed as plasma current amplification assuming that the drift velocity hardly changes before and after the transition. To elucidate the influence of amount and cyclic frequency of plasma generation, the dependences of the plasma current amplifications and the cyclic frequency of plasma generation (the applied voltage frequency) on the dynamic pressure due to gas flow are calculated (Fig. 7). Each value is averaged from three sets of analyses; the error bars denote the maximum and minimum CTM values, and the line shows a linear fit. The plasma current amplification in CTM is about twice that in DTM, which is almost the same as the amplification of the frequency of plasma generation. Neither amplification depends on the gas dynamic pressure. In the state of the strong light emission, the plasma density is high and the plasma amount is larger than that in the state of the weak
light emission. Because the amount of plasma generated by collision in the region of low collision frequency is low, it is necessary to have a large amount of high-density plasma to sustain the continuous propagation state. However, in the high collision frequency region, the amount of plasma generated by collision is sufficient to sustain continuous propagation and the transition occurs at a low plasma generation frequency.

The transition phenomenon occurs because of the relationship between the electromagnetic force and the force of collision due to the neutral gas flow. The transition phenomenon occurs in the entire region including the region where the collision frequency is extremely low and can be ignored. Additionally, when gas does not flow and its gas dynamic pressure is zero, no transition phenomenon occurs. If the collision term is ignored on the assumption that the collision frequency is extremely low in the relationship equation, the equilibrium relationship of the equation is not established and Eq. (11) cannot be derived. The plasma that is not completely ionized comprises electrons, ions, and neutral particles. However, collisions that occur because plasma generation and loss occur even in the completely ionized plasma, so the collision term cannot be ignored. Thus, in the force balance equation, the plasma state changes because of the restricting force of collision between particles in a local micro-field. This may possibly indicate that energy dissipation is always caused by collisions, unlike energy dissipation without collisions, such as Landau damping. The transition phenomenon would be related not only to the plasma propagation state but also to the plasma density and temperature states. The H-mode in which the plasma density and the confinement characteristics are improved in the tokamak is likely a wave state as a continuum in which the density condition in the change of the plasma state is sufficiently satisfied. Therefore, the occurrence of a continuous propagation state accompanying an increase in density with the cyclic frequency of electron generation is an important factor that causes a plasma transition phenomenon. In the discontinuous propagation state, energy propagation is discontinuous, so energy propagation is inefficient and energy loss occurs. However, in the continuous propagation state, energy propagation is continuous, so heating due to the continuous state increases in plasma pressure (density and temperature). The state of matter is determined by force balance; the propagation state changes according to the field flow. When the plasma particle is regarded as a photon, the wave and particle states of the light are observed by the force balance relationship. Thus, because of the balance of the forces applied to the photons, the light shows characteristics of waves and particles. A wave state occurs when conditions with the continuous existence of density or quantity are sufficiently satisfied. When the density or quantity is insufficient, it occurs intermittently and discontinuously and exists as a particle state. Furthermore, when light acts through a diffraction grating or a filter, the photon receives a restricting force from the object (field). The force applied to the photons is balanced by the state of the spatial field, and the light exhibits wave and particle characteristics. The same applies not only to photons but also to other substances. For example, when a large amount of water comes out from a faucet, the water flows continuously. When the amount is small, the water flows intermittently. Thus, the atmospheric space field acts as a restricting force against water, and the state of continuous propagation is determined. Consequently, wave characteristics are observed when photons act as a group and particle characteristics are observed when they act individually.

V. CONCLUSION

We considered the force balance equations with collision. The plasma transition phenomenon was observed with changing plasma emission light and propagation state. The intensity of plasma emission light changed suddenly as the applied voltage frequency varied. The plasma propagates continuously in space with time variations like a stationary wave state with strong emission light at high frequency. However, it propagates discontinuously like a bullet state with weak emission light at low frequency. The change in the propagation state of the plasma was observed as the plasma’s light emission state changed. The frequency at which plasma propagation changes was inversely proportional to the dynamic pressure with the neutral gas flow. The static pressure of the neutral gas was independent of the plasma transition phenomenon. The plasma current in both propagation states and current amplification were examined. The plasma current amplification in CTM was about twice that in DTM, which was almost the same as the amplification of the applied voltage frequency. The applied voltage frequency is equal to the cyclic frequency of the plasma generation. Neither amplification depended on the gas dynamic pressure. The plasma transition phenomenon is related to the collision due to the neutral gas flow. In the state of the strong light emission, the plasma density is high and the plasma amount is large compared with the state of the weak light emission. Because the amount of plasma generated by collision in the low collision frequency region is low, it is necessary to have a high density and large amount of plasma to sustain the continuous propagation state. However, in the high collision frequency region, the amount of plasma generated by collision is sufficient to sustain the continuous propagation state and the transition occurs at a low plasma generation frequency.
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