Structural Change of Plasma at Various Ambient Pressures in 28 GHz Millimeter-Wave Discharges

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Abstract

Millimeter-wave discharges generated by a 28 GHz gyrotron were observed using a high-speed camera. Detail structures has never observed far below the breakdown threshold while plasma structures were observed at various frequency. Ambient pressure was changed from atmospheric to 15 kPa. Resulting ionization front propagation velocity was found higher than those in 170 GHz experiment at all pressures. Clear quarter-wavelength filamentary plasma structure identical to those generated using a 110 GHz gyrotron was observed at the beam intensity slightly lower than breakdown threshold. However, neither quarter-wavelength structure nor discharge front propagation was observed at the intensity lower than 0.51 GW/m^2.

Keywords: Millimeter-wave, Gyrotron, Breakdown, Microwave rocket.

1. Introduction

Microwave Rocket is expected to drastically reduce space transportation cost in future.[1] The rocket has a detonation tube to produce thrust. A millimeter-wave beam is focused at the top of the tube, and then millimeter-wave discharge is ignited and extends in the beam at a supersonic speed driving a detonation wave in the tube. For optimum rocket design, it is necessary to understand discharge mechanism and to predict the propagation speed of discharge by observing discharge structure.

Direct current and low frequency discharge phenomena have been well understood, whereas millimeter-wave discharge experiments have hardly been performed. However, recent development of gyrotron technology enabled us to generate a high power millimeter-wave and to investigate millimeter-wave discharge phenomena. Oda *et al.*[2] observed atmospheric discharge generated by a 170 GHz gyrotron and reported the unique filamentary plasma structure, as shown in **Fig. 1,** propagating toward the direction opposite to the beam incidence. Hidaka *et al.*[3),4)] conducted a similar experiment using a 110 GHz gyrotron and observed a quarter-wavelength plasma structure as shown in **Fig. 2,** in which filamentary plasmas extended in the electric field direction at a pitch of quarter-wavelength. Cook *et al.*[5] decreased the ambient pressure to 5 Torr in a vacuum chamber and observed a diffusive structure, as shown in **Fig. 3,** having no such discrete structure.

Experimental and theoretical air breakdown thresholds are plotted for 110 GHz and 24.1 GHz in **Fig. 4**. The breakdown threshold field is defined as minimum electric field where electron receives enough

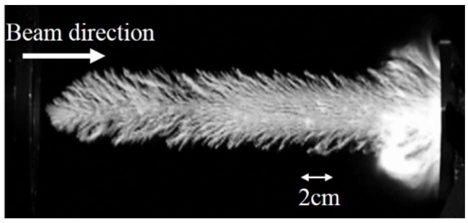

Fig. 1 Filamentary structure at 170 GHz, Oda.[2]

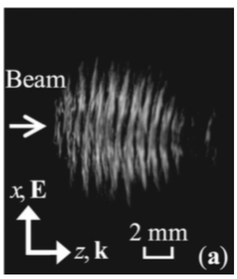

Fig. 2 Filamentary structure at 110 GHz, Hidaka.[3]

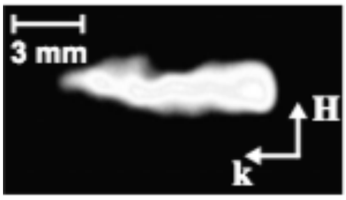

Fig. 3 Diffusive structure at 110 GHz, 5 Torr, Cook.[5)]

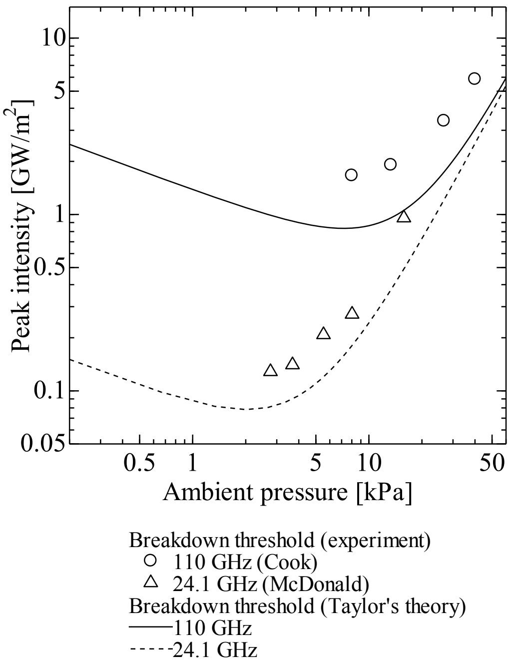

Fig. 4 Breakdown threshold.[5-7)]

energy for ionization and the electron density n increases exponentially to its initial value n_0 ($n/n_0 = 10^{12}$).[8)] When the intensity exceeds the breakdown threshold, breakdown occurs just at the waveguide exit window and no discharge is observed in a beam. Electric field cannot exceed this breakdown threshold in air. In Fig. 4, experimental thresholds were taken from Cook's[5)] and MacDonald's[6)] experiments, whereas theoretical thresholds were calculated using Taylor's formula[7)] which was referred by Cook *et al.* Experimental thresholds were higher than Taylor's one in this range of condition.

At 170 GHz experiment, the experimental condition was far from the breakdown threshold and each structure was too small to observe detail structures. Although the frequency dependency of the plasma structure has not been understood, the structure is supposed to be proportional to the wavelength. Then, when the frequency is changed from 170 GHz to 28 GHz, the structure on a photograph is expected to be magnified six times. The experimental condition also became near the breakdown threshold by reducing ambient pressure.

In this study, plasma structure change both near and far from the breakdown threshold at 28 GHz was observed by changing the ambient air pressure.

2. Experimental Method

The experimental setup is shown in **Fig. 5**. Ambient pressure inside a chamber was changed in the range from 15 kPa to atmospheric pressure. The chamber diameter and the length were 190 mm and 240 mm, respectively. The pressure was monitored by a pressure gauge (AP-C30, Keyence).

28 GHz millimeter-waves generated by the gyrotron were transmitted through a corrugated waveguide whose diameter was 63.5mm, and irradiated at the waveguide exit as a Gaussian beam whose beam waist radius was 20.4 mm. When the millimeter-wave was focused by a focusing mirror, discharge was initiated near the focal point. Beam power was variable from 300 kW to 420 kW: Corresponding peak intensity in the Gaussian beam was from 0.43 GW/m^2 to 0.59 GW/m^2 and the electric field was from 0.40 MV/m to 0.47 MV/m.

A high-speed camera (Ultra cam, nac Image Technology Inc., Resolution: 410 pixel by 360 pixel) was placed close to the waveguide exit as shown in **Fig. 5**. The exposure time and frame rate were set at

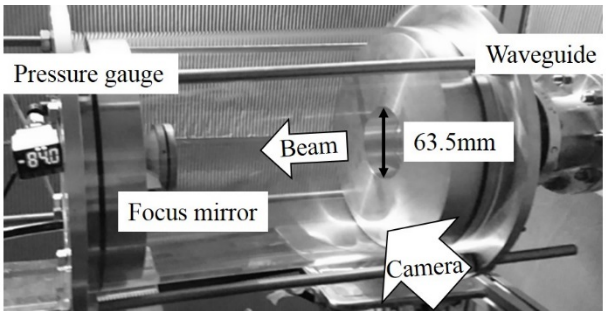

Fig. 5 Experimental setup.

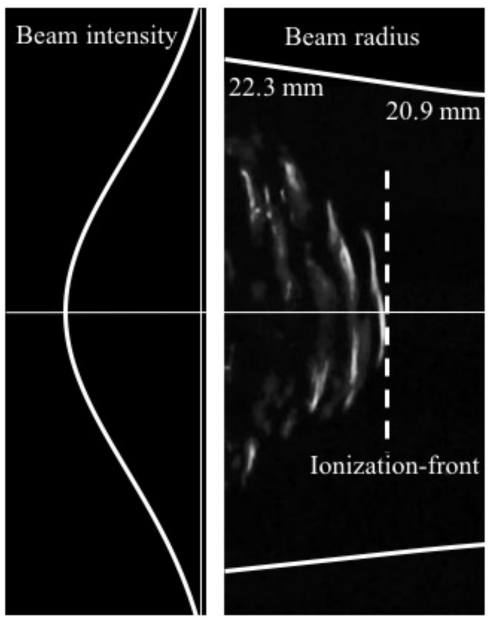

Fig. 6 Beam intensity distribution and divergence.

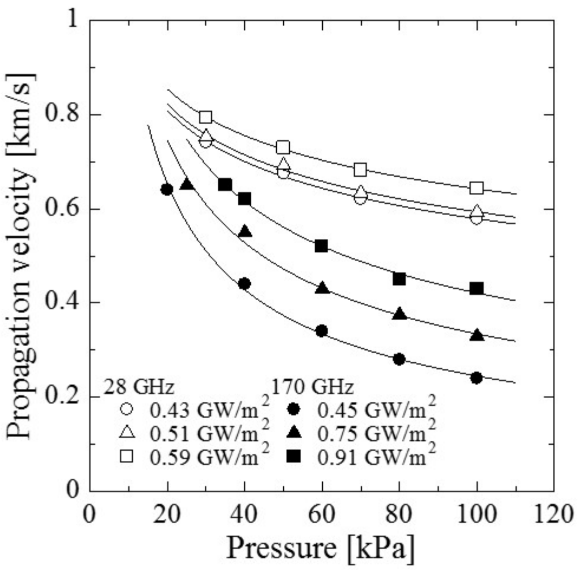

Fig. 7 Propagation velocity in 28 GHz and 170 GHz beams.

0.9 μs and 500,000 fps, respectively. The discharge was photographed on the ***E-k*** and ***B-k*** planes where the incident beam direction vector was denoted by ***k***, and the electric and magnetic field vectors were by ***E*** and ***B***, respectively. Beam intensity distribution and divergence are shown in **Fig. 6**.

3. Results and Discussion

3.1 Ionization front propagation velocity

The ionization-front propagation velocity deduced from high-speed camera images is plotted in **Fig. 7**, along with those in the 170 GHz experiment. Propagation velocity increased with the peak intensity and decreased with the ambient pressure at both frequencies. However, the velocity at 28 GHz was about twice or three times higher than those at 170 GHz when the peak intensity was around 0.43 GW/cm^2.

3.2 Plasma structures

Plasma structures photographed on the ***E-k*** and ***B-k*** planes at the peak intensity of 0.59 GW/m^2 are shown in **Fig. 8**. At high ambient pressure conditions, plasmoids overlapped each other and showed a complex structure as shown in Fig. 8(a) and (b), whereas at the low pressure conditions from 16 kPa to 20 kPa, a clear filamentary structure extending in the ***E*** direction at a pitch of quarter wavelength was observed as seen in Fig. 8(c). This structure was identical to the one observed in the 110 GHz experiment.[3] Diffusive structures as shown in Fig. 3 were not observed in this experiment.

Observed plasma structures are plotted in an operational map in **Fig. 9,** in which experimental breakdown thresholds at 110 GHz[5] and at 24.1 GHz[6] are shown using broken lines. In Region A, a clear quarter-wavelength filamentary structure was observed in the limited pressure range from 16 kPa to 21 kPa and only at 0.59 GW/m^2. Formation mechanism of this structure has been explained as follows: Electric field at the antinode of a standing wave generated by an incident and a reflect wave locally exceeds the breakdown threshold ahead of the ionization front and creates a new plasma filament there.[9)-11)] At lower pressure than 15 kPa, propagation was not observed.

In Region B, the intensity was much lower than the breakdown threshold. The structure was not clear and but complex. The electric field intensity of the

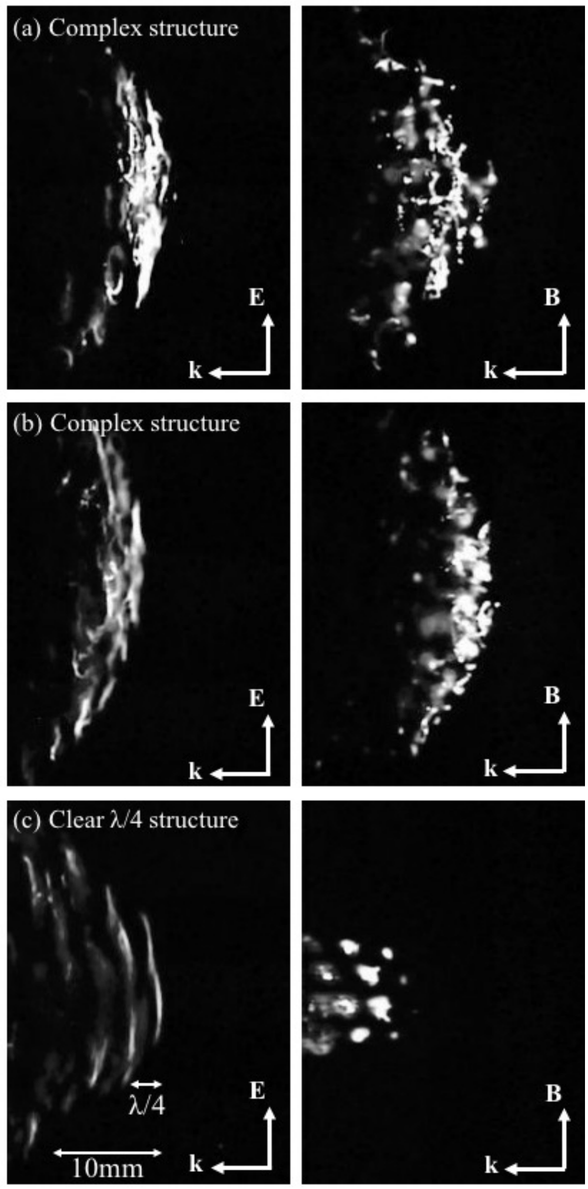

Fig. 8 Plasma structures at the peak intensity of 0.59 GW/m^2. Ambient pressure: (a) 100 kPa, (b) 50 kPa, and (c) 20kPa.

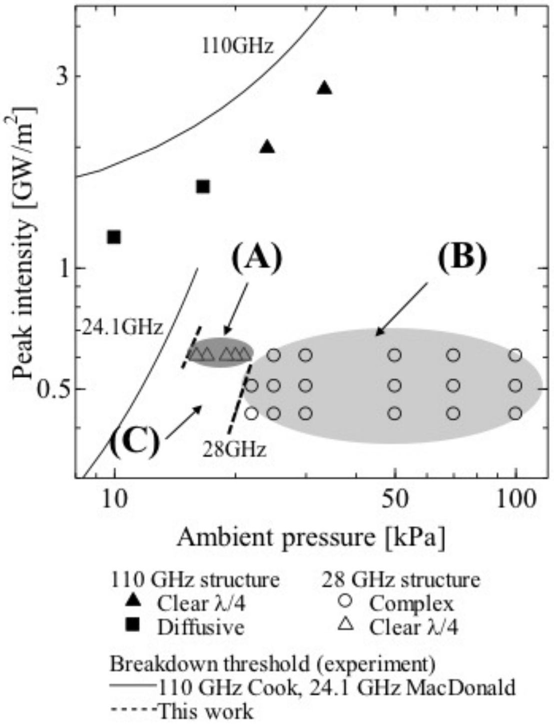

Fig. 9 Observed plasma structures and experimental breakdown thresholds for 24.1 GHz and 110 GHz experiments.

associated wave never exceeds the breakdown threshold. The propagation mechanism has not been understood yet.

Although, in the 110 GHz experiment, the structure changed from clear λ/4 filamentary one (denoted by closed triangles) to diffusive one (denoted by closed squares) with a decrease in ambient pressure, at 28 GHz, diffusive structure was not observed. In Region C, when the peak intensity was lower than 0.51 GW/m^2 and the ambient pressure was down to 20 kPa, plasma was extinguished without propagation just after the breakdown despite that the peak intensity was still lower than the threshold. This result implies the existence of propagation limit at low intensity and low ambient pressure. Experimental breakdown threshold at 28GHz is shown as a broken line in Fig. 9.

4. Conclusion

(1) Ionization-front propagation velocity was increased with the peak intensity and decreased with the ambient pressure. The velocity at 28 GHz was about twice or three times higher than those at 170 GHz.

(2) A clear quarter-wavelength filamentary structure was observed in the limited pressure range from 16 kPa to 21 kPa and only at 0.59 GW/m^2. This structure was identical to the one observed at 110 GHz.

(3) Even when the intensity was much lower than the breakdown threshold, the ionization front propagated, showing complex plasma structures. This propagation mechanism has not been understood yet.

(4) Diffusive structure as observed in 110 GHz experiments was not seen at 28 GHz.

Acknowledgment

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