Discharge from a high-intensity millimeter wave beam and its application to propulsion

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\textbf{ABSTRACT}

Many experimental and numerical studies have been conducted to elucidate the fascinating physics of plasma formation and shock wave propagation during millimeter wave beam irradiation outputted from a high average-power gyrotron. A microwave–rocket system for rocket launching was proposed as an engineering application using an intense millimeter wave beam. Flight demonstrations and thrust measurements were repeated while changing the ambient pressure, beam power density, beam profile, and vehicle shape. We reviewed reports of experimental and computational studies to assess information on plasma propagation and compressible fluid dynamics induced by the millimeter wave beam. Earlier experiments and simulations of rocket launching were also examined for this study.

\section{1. Introduction}

Studies of a coherent beam were born with Einstein’s proposed idea of stimulated radiation in 1917 \cite{1}. Based on the stimulated radiation proposed by Einstein, oscillation of microwave amplification by stimulated emission of radiation (maser) was conducted for the first time by Townes et al. in 1954 \cite{2}. Maiman decreased the oscillation wavelength of the coherent beam using ruby in 1960, thereby creating
light amplification by stimulated emission of radiation (laser) [3]. Development of the laser beam became active. Javan et al. succeeded in oscillating a continuous He–Ne laser [4]. However, in parallel with the advancement of laser beam technology, a gyrotron system was developed as a source of millimeter or sub-millimeter waves based on oscillation technique of the cyclotron-resonance maser [5,6]. In recent years, the laser oscillator and the gyrotron power are increasingly used in engineering fields related to nuclear fusion, material processing, medical treatment, and propulsion. New fields in gas breakdown physics were opened by irradiating atmospheric gas by a high-power beam. Plasma is generated by an atmospheric breakdown when the intense beam is focused in an atmospheric or lower pressure condition, while inducing a strong shock wave via energy transfer from the plasma to neutral particles. Breakdown experiments using intense beams have been conducted to observe dependence of the plasma and shock wave structures on various pressure, gas species, and incident beam power conditions. The plasma propagates toward the beam source at supersonic speed by absorbing the incident beam energy at the ionization front, forming a self-organized pattern when the beam wavelength is of approximately a millimeter. These structure dependencies on beam irradiation conditions can be explained using computational models that introduce plasma transport and electromagnetic wave propagation.

In addition to breakdown physics during beam irradiation, high-power beam irradiation is attracting attention for the launching of rockets from the earth to outer space. This innovative launching scheme using the intense beam irradiation, i.e. beamed energy propulsion, was proposed by Kantrowitz in 1972 [7]. In a beamed energy propulsion system, a rocket with a parabolic mirror receives electromagnetic waves transmitted from a ground-based beam oscillator. Dense plasma is formed behind the vehicle because the intense electric field focused by the mirror exceeds the breakdown threshold. The strong shock wave propagates from a focal point when the incident beam energy is transmitted to neutral particles via collision between the accelerated charged particles and neutral particles. The vehicle produces propulsive thrust through interaction between the shock wave and the thruster wall. The launch cost can be decreased because transmission of propulsive energy from the ground base to the flying rocket obviates on-board fuel. The beamed energy propulsion is categorized into laser and microwave propulsions, depending on the beam type. For laser propulsion, repeated laser pulses are used to create the blast wave. The thrust performance was measured when the repetitive laser pulses were irradiated to the vehicle with a focusing mirror. Flight demonstrations of a laser-boosted vehicle and numerical simulations to reproduce a beaming flight have been reported. We leave discussions related to laser propulsion to these many earlier reports [8–50].

This review describes recent experiments and numerical simulations conducted to elucidate the breakdown physics induced by intense beam irradiation. Beamed
energy propulsion technique is also explained as an engineering application of millimeter wave beams.

2. Experimental observations of plasma and shock wave structures driven by a millimeter wave beam

This section presents a review of experiments and the numerical simulations that have elucidated the breakdown physics that occurs during millimeter wave irradiation. The beam frequencies of 28–170 GHz were applied in various earlier experiments.

The breakdown experiments are classifiable as creating either overcritical or subcritical discharge depending on the local electric-field intensity in the breakdown volume. Progression of the gas discharge is determined mainly based on balances between the ionization and electron attachment processes, which determine the breakdown threshold. The number of the free electrons is important on the breakdown process, and the free electrons disappear when the electron attachment occurs. In an overcritical breakdown experiment, the local root-mean-square (rms) electric-field intensity exceeds the breakdown threshold electric field \( E_c \) for triggering the ionization. \( E_c \) is 2.4 MV/m at atmospheric pressure, which corresponds to a beam power density of 764 kW/cm\(^2\). Investigations for the breakdown physics induced by intense millimeter wave beams started in the 1980s because high-power gyrotrons were developed to heat the plasma and drive the current in nuclear fusion. Dense plasma was ignited by irradiation by the millimeter wave beam, while it propagated toward the beam source. In 1983, Brodskii et al. reported that the ionization front propagation speed was of approximately 10 m/s at atmospheric pressures when a 85-GHz beam with a power density of less than 20 kW/cm\(^2\) was irradiated to the breakdown volume [51]. This experiment was classified as a subcritical breakdown experiment because the local electric field in the discharge volume did not exceed \( E_c \). The ionization front propagation speed became supersonic at a beam power density of 12 kW/cm\(^2\). In 1984, Bykov et al. conducted a breakdown experiment to measure the gas temperature using laser spectroscopy [52]. In 1986, Bogatov et al. conducted subcritical breakdown experiments using a 85-GHz beam with a power density of less than 20 kW/cm\(^2\) [53]. The ionization front propagation speed increased with an increase of the incident beam power density. Propagation speed \( U_i \) was determined as 350S when beam power density \( S \) was less than \( S_c = 3 \) kW/cm\(^2\). Here, the units of \( U_i \), \( S \), and the factor of 350 are m/s, W/m\(^2\), and m\(^{-1}\) kg\(^{-1}\)s\(^2\). However, propagation speed \( U_i \) was determined as \( S^2 \) for beam power density higher than 3 kW/cm\(^2\) because the discharge properties change at \( S = 3 \) kW/cm\(^2\). Bogatov measured the gas temperature during the discharge. Results indicate that the gas temperatures were approximately 4000 and 1800 K when \( S < S_c \) and \( S > S_c \). Bogatov concluded that the breakdown at \( S < S_c \) was classifiable as an equilibrium discharge for which the photoionization was dominant for the plasma propagation. However, plasma
propagation at $S > S_c$ was classified as a non-equilibrium regime in which heat conduction mainly maintained the plasma propagation. Vikharev et al. observed the plasma light emission pattern of the helium and nitrogen plasmas by irradiating the 35 GHz subcritical beams in 1998, which revealed that a plasma pattern had a filamentary structure, resembling a fishbone, that extended perpendicular to the propagation direction [54]. Results of Vikharev’s breakdown experiment indicate that ambient pressure affected the breakdown structure. The clear fishbone structure was obtained at ambient pressure of more than 600 Torr in the helium discharge. The plasma slabs propagating in the parallel direction to the beam incident axis appeared at medium pressures of 5–600 Torr. The discrete structure disappeared completely at ambient pressure of less than 5 Torr in helium gas. The experiment revealed that the ambient pressure strongly affects the plasma structure. However, the mechanism of these pattern transitions was not identified in the breakdown experiment.

In 2006, Oda et al. conducted a breakdown experiment using a subcritical beam with electric field intensity in a breakdown volume of less than 1.3 MV/m with frequency of 170 GHz [55–58]. The plasma pattern had a branching structure that did not change depending on the observation angle (Figure 1). Oda et al. measured the propagation front of the ionization front based on an imaging technique. The ionization front propagation speed became supersonic when the 85-GHz beam was at an average power density of 12 kW/cm$^2$, as shown by Brodskii’s experiment [51]. However, when using a 170-GHz gyrotron, the propagation speed became

![Figure 1. Image of plasma propagation during irradiation by a 170-GHz, 930-kW beam [55].](image)
supersonic when the average power density of the beam exceeded 75 kW/cm². These results indicate that the ionization front propagation speed became higher when the lower frequency beam was selected. However, the beam frequency affected the propagation speed for reasons that remain unknown. Oda et al. investigated the relation between the shock wave propagation speed and the ionization front propagation speed during beam irradiation of the 170-GHz gyrotron [59]. The respective propagation speeds of the shock wave and the plasma front were measured by changing the power density of the 170-GHz beam irradiated to a tube with a conical end. The shock wave propagation speed \( U_s \) was higher than that of the plasma front \( U_i \) when the propagation speed of the plasma front was transonic \( 0.8 < M_i = U_i/a < 1.5 \), where \( a \) stands for the speed of sound (Figure 2).

However, \( U_i \) was equal to \( U_s \) when \( S/S^* > 1.5 \) and \( M_i > 1.5 \), which differed from combustion wave propagation, where the propagation of the ionization front exceeded supersonic speed when \( S^* = 75 \) kW/cm². Therefore, the shock wave and plasma front propagation modes changed from deflagration to detonation modes when crossing \( S/S^* = 1.5 \). Here, deflagration and detonation modes are analogous to chemical deflagration and detonation. The pressure was measured at the tube end during shock wave propagation using a pressure gauge. The pressure became constant before the expansion wave arrived at the tube end. Theoretical prediction of the pressure at the tube end was also accomplished using relations between the normal shock wave, isobaric gas heating, and expansion wave propagation, which showed good agreement with the experimentally obtained results. The pressure at the tube end increased with an increase of the incident beam power when \( S/S^* < 1.5 \). However, the pressure was saturated when the plasma front propagation speed became supersonic. In 2011, shadowgraph imaging of shock

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**Figure 2.** Propagation speeds of the shock wave and ionization front for the normalized power density [59].

Note: The propagation of the ionization front exceeded supersonic speed when \( S^* = 75 \) kW/cm².
wave propagation was conducted by Oda et al. using a 170-GHz beam [60]. Figure 3 portrays shadowgraph images of the shock wave driven by the 170-GHz beam irradiation with power density of 95 kW/cm². The beam was irradiated from the right side; the plasma was induced by a parabolic mirror focusing at the left side of the tube. The shock wave and the plasma front propagated toward the millimeter wave source while absorbing the beam energy. A one-dimensional shock wave structure propagating at constant velocity was captured in the tube. A region of turbulence was observed behind the shock wave because of the plasma region non-uniformity. The shock wave velocity was evaluated as 480 m/s. The plasma front velocity was evaluated as 453 m/s when the beam power density was 95 kW/cm². The distance between the plasma front and the shock wave increased with the time evolution because of the speed difference. The shock wave velocity was 401 m/s, which was much higher than the plasma front velocity of 175 m/s when a beam with 42 kW/cm² was irradiated. The distance between the plasma front and the shock wave lengthened, becoming greater than that obtained by the 95 kW/cm² beam. The pressure in the tube was measured using the pressure sensor. The peak pressure of 95 kW/cm² was higher than that of 42 kW/cm² because of the greater gas heating. In the 95 kW/cm² case, the pressure decreased rapidly over time because a strong rarefaction wave propagated after the shock wave. The plateau pressure of 42 kW/cm² lasted longer than that of 95 kW/cm² because of the longer distance between the shock wave and the gas heating region. The rarefaction wave became weaker because less gas heating occurred in the 42 kW/cm² case.

In 2008, Hidaka et al. first reported observations of overcritical breakdown using a 110 GHz, 1.5 MW gyrotron at 3-μs pulse [61]. In that experiment, the local electric field in the breakdown volume was stronger than 4.4 MV/m, which exceeded the breakdown threshold of about 2.4 MV/m. The breakdown structure captured by Hidaka et al. differed depending on the observation angle. The discrete structure was obtained in the E-plane of the incident beam, although it propagated toward the incident beam source. The distance between filaments was about λ/4, but the grained plasma spots were alternately formed on the axis and non-axis in the H-plane. These plasma structures differed from the breakdown structure described by Oda et al. because the breakdown structure was

![Figure 3. Shadowgraph images of shock wave during 170-GHz beam irradiation [60].](image-url)
not changed depending on the observation angle in Oda’s experiment. These breakdown experiments revealed that the discharge physics varied according to whether the incident microwave field was higher or lower than the breakdown threshold. The transition mechanism of the plasma structure between the overcritical and subcritical conditions was not clear. Actually, development of numerical models must be done to explain the breakdown pattern transition mechanism because the breakdown experiment with the subcritical beam is unable to capture sufficient information to explain the plasma pattern transition. In addition, pressure dependency and gas species dependency of the breakdown pattern were observed using air, nitrogen, SF₆, and helium gases by 110-GHz beam irradiation [62]. Well-defined plasma arrays were obtained in air and nitrogen when the ambient pressure was 760 Torr. However, the plasma pattern changed with a decrease in ambient pressure. In order, from the downstream to upstream regions, diffusive plasma, sheet-like plasma, and discrete plasma were formed in nitrogen at 360 Torr. This result indicates that the breakdown structure depends on the local electric field and on the ambient pressure because the local electric field decreased from the focal spot (downstream) to the upstream region during beam irradiation. In the helium breakdown, a second plasma appeared from the downstream region after the first plasma arrays propagated toward the upstream region. That phenomenon differed from those found for other gas species. The ionization front propagation speed was measured in air and nitrogen by tracing the ionization front captured using an intensified charge-coupled device camera and a photodiode array. Under nitrogen and air, the propagation speeds were evaluated as 12–14 km/s at 760 Torr when the incident power density was about 3 MW/cm². The ionization front propagation speed increased with a decrease in an ambient pressure, although it showed almost equal speeds in nitrogen and in air. The propagation speed finally achieved about 20 km/s at ambient pressure of 420 Torr. Nevertheless, the mechanism of this second plasma evolution was not explained from the breakdown experiment results. It is necessary to use a numerical model that can reproduce the gas species and electric field intensity dependence of the breakdown structure to understand the breakdown physics during the millimeter wave beam irradiation.

In 2010, Cook et al. measured the breakdown threshold as a function of pressure in air and argon using a linearly polarized (LP) Gaussian beam with incident powers of 10 kW–1.3 MW and a frequency of 110 GHz [63,64]. The ambient gas pressures were changed in the range of 5–700 Torr in air and argon. The breakdown structures in the $E$-plane and $H$-plane of the incident microwave were classified by irradiating a beam with output power nearly equal to the breakdown threshold for each gas pressure. The plasma structure became diffusive in air at less than 10 Torr. At 125 and 180 Torr, the three plasma columns extending parallel to the propagation direction were observed in the $E$-plane: a result that was obtained also from Vikharev’s breakdown experiment. The reason why the plasma columns were induced in Cook’s experiment remains unknown. The well-defined
filamentary structure, which had $\lambda/4$ pattern, appeared in the $E$-plane at pressures greater than 250 Torr. The grained plasma spots were obtained in the $H$-plane at pressures greater than 180 Torr in air. Well-defined grained plasmas were obtained at above 250 Torr in the $H$-plane, which was classified as the collisional dominant breakdown regime. However, unlike the air breakdown, an argon plasma had a tree-branching structure with a triangular array at pressures greater than 40 Torr. The branching structure formation mechanism in argon remains unclear. Neutral gas expansion by Joule heating might affect plasma branching when the incident beam power is near the breakdown threshold because the time scale of the plasma propagation might be comparable with that of the neutral gas expansion. Development of a numerical model that includes interactions between the plasma and the neutral gas expansion is necessary to explain the tree-branching formation in the argon breakdown.

In 2015, Yamaguchi et al. conducted breakdown experiments using a 28-GHz beam with output power of 250–350 kW to examine the beam frequency dependence of the breakdown structure and the plasma propagation speed by comparing the experimentally obtained results with those reported by Oda [65]. The typical power density was 40 kW/cm$^2$ in the breakdown region, which corresponds to electric field intensity of 0.4 MV/m. Therefore, Yamaguchi’s experiment was classified as examining subcritical breakdown, similar to Oda’s experiment. A parabolic mirror focused the millimeter wave beam. The ionization front propagated toward the millimeter wave source. Plasma structures in the $E$-plane and $H$-plane for the incident electromagnetic wave were observed simultaneously using the mirror. In contrast with Oda’s experiment using the 170-GHz beam, filamentary plasma like that of Hidaka’s overcritical breakdown experiment was captured in the $E$-plane (Figure 4(a)). The distance between filaments was $\lambda/4$. The grained plasma spots like those of the overcritical condition were also observed in the $H$-plane. The propagation speeds of the ionization front were measured using imaging by a high-speed camera (Figure 4(b)). The propagation speed at 28 GHz was higher than that at 170 GHz; actually, it became supersonic at the power density of 0.4 GW/m$^2$, which was lower than when beam power of 170 GHz was used. A classical theory of power absorption by electrons holds that the rate of energy absorption by electrons increases with decreased beam frequency. Therefore, the electron temperature might be increased by a decrease in the beam frequency. It is possible that the discrete structure like overcritical breakdown appeared because the ionization process became dominant over electron diffusion when the electron temperature increased. In addition to the structure transition, the propagation speed became higher because the electron temperature increased with a decrease in the beam frequency. More concrete discussion of the frequency dependence can be conducted using the computational model. It is left as a subject for future investigation.

In 2016, Schaub et al. conducted a breakdown experiment using 110-GHz and 124.5-GHz beams to examine the electron number density and neutral gas
heating dynamics occurring during plasma propagation [66]. The beam powers were set as 1.4 and 1 MW for the LP beams of 110 and 124.5 GHz, which satisfied the overcritical breakdown condition. The peak electron density during beam irradiation was measured using optical emission spectroscopy. The peak

Figure 4. Images of plasma self-emission during the 28-GHz breakdown, and propagation speeds of the ionization front [65]. (a) Images of self-emission (top, E-plane; bottom, H-plane). Yellow arrows described elongation direction of the plasma filaments. Yellow circles meant that granular plasma spots were generated in the H-plane. (b) Propagation speeds of the ionization front.
electron density measured by the experiment increased with increased ambient pressure, which shows good agreement with the theoretical cut-off plasma density in collisional plasma. The plasma energy was transmitted to the neutral particle energy during the plasma propagation. The neutral gas expands because of the gas heating. Schaub et al. measured the neutral gas density because the neutral gas dynamics is an important property of the atmospheric plasma [67,68]. The gas heating peaked at the tips of the filamentary plasmas because of the strong electric field at the filament tips. The neutral gas density changed drastically. However, Schaub et al. concluded that the plasma transport and reaction were unaffected by the neutral gas dynamics because the time scale of the plasma propagation toward the beam source was much shorter than that of the neutral gas expansion during the overcritical beam irradiation. Interactions between the neutral gas and the plasma are small in the overcritical breakdown condition. However, the neutral gas dynamics might change the plasma dynamics at the subcritical breakdown condition because the plasma propagation is slower and because the gas expansion time scale is comparable to that of the plasma propagation time scale.

3. Numerical simulations for plasma propagations driven by a millimeter wave beam

3.1. Breakdown physics during overcritical beam irradiation

Numerical studies have been conducted to explain the plasma filamentation mechanism when the overcritical beam was irradiated to the breakdown volume. In 2009, to reproduce the plasma filamentation obtained by Hidaka’s experiment, Nam and Verboncoeur numerically solved a one-dimensional (1D) electron continuity equation under a drift–diffusion approximation while integrating an electron energy equation in argon gas [69]. The Helmholtz equation was solved numerically to reproduce the electromagnetic wave propagation of electric field intensity of 5 MV/m and a frequency of 110 GHz. Nam’s simulation is classifiable as the overcritical incident condition because the electric field at the breakdown volume exceeded the breakdown threshold. A quasi-standing wave was induced in front of the plasma because the incident electromagnetic wave was reflected by the dense plasma; then the reflected wave overlapped the incident wave. A strong electric field region was formed at a distance of $\lambda/4$ from the edge of the bulk plasma, which corresponds to an antinode of the standing wave. The electrons diffused from the bulk plasma to an antinode of the quasi-standing wave with the strong electric field. The next plasma filament with the $\lambda/4$ structure was formed because the electron-impact ionization occurred quickly at the position with the enhanced electric field. However, the plasma density obtained using their simulation reached $4.5 \times 10^{23} \text{ m}^{-3}$, which was too high for the atmospheric plasma with the 110-GHz electromagnetic wave. Increase of the plasma density normally stops at the cut-off density for the collisional plasma [70]. The cut-off density was on the order of $10^{21} \text{ m}^{-3}$ for the 110-GHz beam, but their simulation
did not capture the cut-off physics of the plasma because the current density driven in the collisional plasma was not reproduced correctly.

In 2010, Boeuf et al. developed the two-dimensional (2D) plasma fluid model coupled with the current density driven in the collisional plasma to reproduce the 2D filamentary structure obtained during the overcritical beam irradiation [71]. In the plasma fluid model, the free diffusion coefficient was suitable at the plasma front because the Debye length was much greater than the electron's scale length, but the ambipolar diffusion coefficient should be used in the bulk region because quasi-neutrality holds. The transition of the electron diffusion coefficient could be captured if Poisson's equation, the electron's drift–diffusion equation, and the ion's drift–diffusion equation were solved simultaneously. However, the computational cost becomes huge if Poisson's equation is solved. Instead of solving these three equations, Boeuf numerically integrated only the electron reaction–diffusion equation by introducing an effective diffusion coefficient to capture the transition between the free and ambipolar diffusion processes, while saving the computational cost by avoiding the process of solving Poisson’s equation. The effective diffusion coefficient was designed based on Poisson's equation, the electron's drift–diffusion equation, and the ion's drift–diffusion equation without assuming quasi-neutrality. By substituting the electron and ion drift–diffusion equations into Poisson's equation, the derivative equation for the space–charge electric field was obtained. When the plasma propagation velocity was assumed by

$$U_i = 2(D_e v_i)^{(1/2)},$$

and the scale length for the space–charge electric field was assumed by $2L$, the derivative term of the electric field was approximated, where $D_e$ is the electron free diffusion coefficient, $v_i$ stands for the ionization frequency, and $L$ denotes the scale length of the electron. By substituting the approximated electric field into the electron drift–diffusion equation, the effective diffusion coefficient was obtained as

$$D_{\text{eff}} = (\alpha D_e + D_a)/(\alpha + 1),$$

where $D_a$ represents the ambipolar diffusion coefficient, $\alpha = \lambda_D^2/L^2$ represents the transition parameter, and $\lambda_D$ denotes the Debye length. Using the effective diffusion coefficient, the diffusion coefficient was changed automatically from ambipolar to free diffusions when the Debye length was much greater than the electron scale length. The electron reaction–diffusion equation using the effective diffusion coefficient was solved numerically when it was coupled with Maxwell's equation. Maxwell's equation was integrated using the finite-difference time-domain (FDTD) method. To capture interactions between the electromagnetic wave and the plasma, the current density was evaluated by integrating the electron equation of motion with the elastic collision term. The current density was fed back to Maxwell's equation to reproduce the electromagnetic wave reflection and damping by the plasma. The transport coefficients of the electron reaction–diffusion equation were evaluated from Bolsig+ [72] using the local effective field $E_{\text{eff}} = E_{\text{rms}}/(1 + \sigma^2/n^2)^{1/2}$, where $E_{\text{rms}}$ stands for the local rms.
electric field, $\omega$ represents the angular frequency of the incident beam, and $\nu_m$ signifies the elastic collision frequency. The 2D breakdown pattern, with off-axis and on-axis plasma arrays, was reproduced in the $H$-plane using the effective diffusion model coupled with the electromagnetic wave propagation. The electric fields at two off-axis points were enhanced when the electromagnetic field was scattered by the front plasma, which generated two off-axis filaments. These structures reflected the incident electromagnetic field and enhanced the electric field at the on-axis point, forming the on-axis filament when the electrons diffused from the bulk plasma. The discrete structure elongating perpendicular to the propagation direction was also reproduced in the $E$-plane. The ionization front propagation speed was modeled as Equation (1) based on an analogy of the streamer propagation theory under the direct current voltage, which showed good agreement with those obtained using the numerical simulations and the breakdown experiments reported by Hidaka et al. [61,62]. The effective diffusion model proposed by Boeuf et al. was validated through comparison with a more accurate model using the electron and ion drift–diffusion equations coupled with Poisson’s equation [73]. In the 1D drift–diffusion–Poisson model, the electron and ion mass conservations were integrated without a quasi-neutrality assumption. The space–charge electric field was calculated from Poisson’s equation. Transition from the ambipolar to free diffusions was considered by introducing the space–charge electric field obtained from Poisson’s equation into the electron and ion drift–diffusion equations. The electron and ion drift–diffusion equations were solved using the Scharfetter–Gummel method. Poisson’s equation was solved using a semi-implicit method [74] to obtain the breakdown structure during the overcritical beam irradiation, which has intensity of 6 MV/m and a frequency of 110 GHz, following Hidaka’s experiment. The semi-implicit method was effective to save computational time in solving Poisson’s equation. The filamentary structure obtained using the effective diffusion model showed good agreement with that obtained using the drift–diffusion–Poisson model at atmospheric pressure. The validity and usability of the effective diffusion model were demonstrated by the agreement between the effective diffusion and drift–diffusion–Poisson models. However, approximation of the space–charge electric field when introducing the effective diffusion coefficient can be violated when the ionization front propagation speed deviates from the propagation velocity (Equation (1)) estimated from an analogy of the direct current discharge. The propagation speed can be different from Equation (1) when the alternate current effect becomes dominant in conditions such as lower pressure and higher wave frequency because the relaxation time of the electrons becomes comparable to a single period of the beam frequency. Upgrading of the effective diffusion model might be necessary when one attempts to capture the accurate plasma dynamics in lower pressure or higher beam frequency conditions. In 2010, Chaudhury et al. conducted a 2D computational simulation using the effective diffusion model for plasma transports to compare the numerical results with the overcritical breakdown experiment conducted by Hidaka et al. while
particularly addressing the ambient pressure dependence of the plasma structure and the plasma propagation speed when the breakdown was induced by 110-GHz wave irradiation [75]. The filamentary plasma was obtained at atmospheric pressure in a manner similar to that reported for Boeuf’s simulation. However, the plasma structure transitioned from discrete to diffusive patterns with a decrease in ambient pressure because the density peak was smeared out by the rapid electron diffusion. The ionization front propagation speed became higher with a decrease in the ambient pressure because the electron quickly diffused from the bulk plasma to the position with the strong electric field. The propagation speed reproduced by the numerical simulation for the 1.5 MW/cm² beam irradiation showed good agreement with the experimentally obtained results reported by Hidaka et al. [61,62]. The theoretical prediction of Equation (1) also showed good agreement with the simulation results at widely various ambient pressures. In 2011, Zhou and Dong conducted a 2D fluid simulation using the effective diffusion model to reproduce the breakdown structure obtained by Cook et al. [76]. The incident beam intensity was set as $E_{\text{rms}}/E_c = 1.6$. Breakdown simulations using 100, 200, and 400 Torr revealed that the two off-axis plasma columns propagated toward the incident beam source in the $E$-plane because strong electric fields were induced at the two off-axis positions attributable to wave diffraction by the main plasma column. Ionization was induced at the enhanced field regions of the off-axis when the electrons diffused from the main plasma, which formed the two off-axis plasma columns. The off-axis plasma structure closely resembled that of the breakdown experiment conducted by Cook et al. [63,64].

In 2014, Kourtzanidis et al. used a three-dimensional (3D) simulation to compare the plasma structure with that obtained using a 2D simulation based on the effective diffusion model for plasma transports when it was coupled with Maxwell’s equation [77]. The overcritical microwave irradiation and wave reflection were reproduced numerically using the alternative direction implicit (ADI) FDTD method coupled with a Crank–Nicholson formulation for the electron’s momentum equation. The LP electromagnetic wave with intensity of 6 MV/m and a frequency of 110 GHz was irradiated in the computational domain. The elongation speed of each filament became higher than that obtained in the 2D simulation because stronger electric field enhancement was obtained around the edges of the plasma filament. Shorter plasma filaments were formed in the 2D simulation because the electromagnetic waves were blocked by the next plasma filament. However, the filament elongation was maintained in the 3D simulation because the incident electromagnetic waves were diffracted by the subsequent plasma filament and reached the former plasma filament. Kourtzanidis et al. also specifically examined the time evolution of the neutral gas density during the microwave discharge [78]. The transverse electric waves were injected to the computational domain from the left and right boundaries to induce the standing wave and thereby examine the gas heating effect during the atmospheric discharge. The ADI–FDTD simulation was coupled with the effective diffusion model to
reproduce the standing wave. The Euler equation was numerically integrated to capture the neutral gas dynamics during microwave heating. Joule heating was evaluated in the coupling simulation between the plasma and Maxwell’s equation. It was used to model a source term in the Euler equation. The neutral gas expanded because of the Joule heating created when the standing wave was induced. The elongation length of the plasma with gas heating was shorter than that without considering gas heating because the transport coefficient of the plasma was changed by the neutral gas expansion. Results show that the neutral gas dynamics affected the plasma because a standing plasma, not a propagating plasma, was obtained and the time scale of the plasma elongation was comparable with that of the neutral gas expansion. The neutral gas dynamics can affect the plasma traveling toward the microwave source when the ionization front propagation speed is lower than that maintained by the overcritical beam.

Semenov et al. conducted a 1D plasma fluid simulation coupled with Maxwell’s equation to examine the effects of the incident electromagnetic wave intensity, incident microwave frequency, and the background plasma profile on the microwave plasma formation [79,80]. A 1D plasma diffusion equation was numerically integrated using a simple diffusion coefficient instead of using the effective diffusion coefficient. The electromagnetic wave propagation was numerically reproduced by solving Maxwell’s equation with the current–density feedback evaluated using the Drude model. In Semenov’s simulation, the higher frequency microwave (670 GHz) was irradiated to the breakdown volume to ascertain the incident wave frequency dependence of the breakdown structure. The quasi-monochromatic approximation for the microwave field was applied to reduce the computational cost when the higher frequency microwave was irradiated. Then the plasma diffusion equation was rewritten using the dimensionless length and time. Based on the non-dimensional reaction diffusion equation, neglecting the electric field dependence of the diffusion coefficient and the recombination coefficient, the plasma propagation during the millimeter wave beam irradiation was determined using only two parameters: the ratio of the elastic collision frequency and the incident beam frequency, and the incident electromagnetic wave amplitude. The plasma structure became diffusive when the higher frequency beam was irradiated at the atmospheric pressure. The plasma structure driven by the lower frequency beam became the same at the lower pressure when the ratio of the elastic collision frequency and the incident beam frequency was the same. The plasma dynamics was roughly captured when the ratio of the elastic collision frequency and the beam frequency was changed in Semenov’s model. Nevertheless, a more accurate plasma model must be used to assess the beam frequency and ambient pressure dependence of the plasma structure because Semenov’s model was over-simplified. To evaluate the beam frequency dependence of the plasma propagation speed, the maximum electron density, and the reflectivity of the incident wave, Zhao et al. simulated the 1D plasma structure using the effective diffusion model by changing the beam frequency in the range of 2.85–17 GHz at the ambient pressure
of 0.01 atm [81]. However, the fluid model cannot supply the correct solution of the plasma structure at the lower pressure. Kinetic modeling might be necessary to elucidate the lower pressure discharge.

Takahashi and Ohnishi conducted a 1D particle-in-cell with Monte Carlo collision (PIC–MCC) simulation to investigate microwave filamentation that occurs at lower pressures and an external magnetic field, based on a request for the engineering application such as a rocket propelled by the millimeter wave beam [82]. An external magnetic field was applied to the breakdown volume obtained using microwave irradiation to control the ionization front propagation speed and the plasma energy absorption rate. In Takahashi's computation, the electric field was oscillated in the $y$-direction, the charged particles diffused in the $x$-direction, and the external magnetic field was applied in the $z$-direction. Microwaves with intensity of 5 MV/m and a frequency of 110 GHz were irradiated from the left boundary ($x = 0$ m) to the right boundary. The microwave propagation was numerically reproduced using the FDTD method. The current density was evaluated by the weighting in the PIC simulation. Then, it was fed back to the FDTD simulation to assess interactions between the dense plasma and the electromagnetic wave propagation. The discrete plasma structure was obtained at the higher pressure because of the standing wave induced by the wave reflection when the plasma density reached the cut-off value of the collisional plasma. The diffusive plasma was obtained at ambient pressure of 0.006 atm because of the rapid electron diffusion. However, the discrete structure appeared even at the low ambient pressure when the external magnetic field of 1 T was applied because the electron was trapped by the magnetic field and because the electron-impact ionization was induced before the electrons diffused (Figure 5). The plasma propagation speed became lower when the external magnetic field was applied because magnetic field trapping suppressed the electron diffusion. The theoretical prediction of

![Figure 5](image-url)  

**Figure 5.** Electron number densities and electric fields at 0.006 atm with an external magnetic field of 1 T [82].
the plasma propagation speed was modified as $2(D_{\perp}v_i)^{1/2}$, which shows good agreement with the propagation speeds obtained using the PIC–MCC simulation under a magnetic field, where $D_{\perp} = D_e/(1 + \omega_c^2/\nu_m^2)$. $\omega_c$ denotes the electron cyclotron frequency. The ionization frequency becomes higher when an electron cyclotron resonance (ECR) heating condition is satisfied by selecting $\omega_c^2 = \omega^2$, which accelerates the ionization front propagation speed because the time scale of the new plasma formation is shortened. At this condition, the electrons are steadily accelerated by synchronizing the electron cyclotron motion in the $x$–$y$ plane with electromagnetic wave oscillation in the $y$-direction. Therefore, the electron energy was increased drastically, thereby inducing rapid ionization. Results of Takahashi’s simulation indicate that controlling the ionization propagation speed was achieved by the magnetic field, which is useful in engineering applications such as microwave rocketry. In 2016, Takahashi and Ohnishi investigated the beam frequency dependence of the plasma structure and the propagation speed during overcritical microwave irradiation with an intensity of 5 MV/m using the 1D PIC–MCC model when it was coupled with Maxwell’s equation [83]. The ambient pressure was changed in the range of 0.003–1 atm. The beam frequency was changed in the range of 25–110 GHz. Results of earlier experiments conducted by Vikharev and Oda revealed that the filamentary plasma remained at the lower pressure if the lower frequency beam was used. The diffusive plasma pattern was obtained at 0.006 atm with beam irradiation of 110 GHz. However, as in past experiments, plasma filamentation was induced even at the low ambient pressure of 0.006 atm when the lower frequency microwaves of 25 and 50 GHz were irradiated to the plasma spot with intensity of 5 MV/m (Figure 6). The energy absorption rate by the plasma, which was described by $P_{abs} \approx e^2E_0^2n_e\nu_m/(2m_e\sigma^2) \propto \sigma^{-2}$ at the lower pressure, increased with a decrease in the microwave frequency, where $e$ signifies the elementary charge, $E_0$ represents the incident beam intensity, $n_e$ stands for the electron number density, and $m_e$ denotes the electron mass (Figure 7(a)). The electron temperature increased with a decrease in the microwave frequency because of an increase of the energy absorption rate by the electrons. The plasma filamentation was accelerated by irradiation with lower frequency microwaves because the ionization process became dominant rather than the electron diffusion when the electron temperature increased (Figure 7(b)). The ionization front propagation speed increased with a decrease in the incident microwave frequency because the electron-impact ionization was enhanced by an increase in the energy absorption rate at the plasma front. The external magnetic field was also applied to the lower frequency breakdown to suppress plasma propagation and enhance the energy absorption rate by satisfying the ECR and second-harmonic ECR conditions. The energy absorption rates were improved when the magnetic field of 0.893 T was coupled with microwaves of 25 and 50 GHz because the fundamental ECR and second-harmonic ECR conditions were satisfied, respectively. The PIC–MCC simulation revealed that lower frequency microwaves were beneficial for gas heating because the energy absorption rate with the fundamental ECR heating at
25 GHz was higher than that with the second-harmonic ECR heating at 50 GHz (Figure 8(a)). However, the propagation speed at 25 GHz was higher than that at 50 GHz (Figure 8(b)). The total gas heating performance was determined by the trade-off between an increase in the energy absorption rate and speeding up of the propagation speed.

In 2016, Takahashi and Ohnishi examined the gas species dependence of the breakdown structure and the plasma propagation speed by simulating the breakdown processes under nitrogen and argon gases when overcritical microwaves of 5 MV/m were irradiated to the breakdown volume [84]. The fluid model with the effective diffusion coefficient was coupled with Maxwell’s equation to reproduce the plasma structure. The transport coefficients in the fluid model, such
M. TAKAHASHI AND K. KOMURASAKI

as the ionization frequency, elastic collision frequency, and electron diffusion coefficient, were evaluated using 1D PIC–MCC simulation without using Bolsig+. The effective field concept was not justified in the argon breakdown because the elastic collision frequency showed strong correlation for the local electric field. A data map of the transport coefficient for the rms electric field was made using results of the PIC–MCC simulation coupled with the electromagnetic wave propagation. Instead of using the effective field concept, the local rms electric fields were calculated in the plasma fluid and FDTD coupling code and were used to deduce the local transport coefficient for more precise modeling of the breakdown physics. Comparison between the PIC–MCC and fluid simulations revealed that

Figure 7. Ambient pressure and beam frequency dependence of energy absorption rates, and the ratio of electron diffusion coefficient and ionization frequency \[83\]. Transport coefficients were evaluated using PIC–MCC simulation. The vertical axis was normalized using values evaluated at 110 GHz. (a) Energy absorption rates. (b) Ratio of electron diffusion coefficient and ionization frequency.

![Graphs showing energy absorption rates and ratio of electron diffusion coefficient and ionization frequency](image-url)
the electron density profile obtained using the fluid model was almost identical to that obtained from the PIC–MCC simulation (Figure 9(a)). Consistency between the particle and fluid models was maintained by introducing the transport coefficients, which were evaluated by the PIC–MCC simulation, into the fluid model. Results of Takahashi’s simulation indicated that the ionization front propagation speed in argon was higher than that in nitrogen because of the higher ionization frequency and the faster electron diffusion. The elongation width of the plasma filament in argon was larger than that obtained in nitrogen because of the quick electron diffusion. The trigger of the tree-branching structure, which was observed by Cook’s experiment in argon [63], was obtained numerically at the edge of the argon plasma filament because of the wave diffraction (Figure 9(b)).

**Figure 8.** Energy absorption rates and propagation speeds under external magnetic fields [83]. (a) Energy absorption rates. (b) Propagation speeds.
3.2. Breakdown physics during a subcritical beam irradiation

Many numerical models well captured the breakdown physics under the over-critical condition such as Hidaka’s experiment. However, these models cannot explain the plasma propagation during subcritical beam irradiation because the ionization frequency became zero. The plasma just diffused in the conventional coupling model between the plasma and the electromagnetic wave propagation. In 2002, by combining the plasma fluid model, the Helmholtz equation, and the Euler equation for describing the neutral gas dynamics, Voskoboinikova et al. numerically investigated the gas heating effect on the plasma propagation during subcritical beam irradiation [85]. The incident electric field was set as $0.5E_c$ to reproduce the breakdown structures during the subcritical beam irradiation. Joule heating was induced at the plasma front, which formed the shock wave and

![Graph](image-url)

(a) results obtained from PIC-MCC and fluid models

![Graph](image-url)

(b) electron number density in argon

**Figure 9.** Comparison between PIC–MCC and fluid models, and electron number density in argon [84]. (a) Results obtained from PIC–MCC and fluid models. (b) Electron number density in argon.
the rarefaction wave. The local reduced electric field $E/N$ increased at the plasma front because the neutral gas density decreased as a result of the gas heating. The local $E/N$ exceeded the breakdown threshold value of $(E/N)_c$ at the plasma front, which formed the ionization region, where $N$ was the neutral gas density. Therefore, the ionization front propagated toward the beam source by repeating the gas expansion, increase in the local reduced electric field, electron diffusion, and electron-impact ionization. In contrast to the overcritical breakdown, the neutral gas dynamics affected the plasma dynamics because the time scale of plasma propagation with the subcritical beam was smaller than that with the overcritical beam. The diffusion coefficient was simply changed depending on the local electric field to capture the transition between the free and ambipolar diffusions in Voskoboinikova’s plasma fluid model. A more accurate diffusion model is necessary to discuss the plasma structure during the subcritical beam irradiation because Voskoboinikova’s diffusion model has not been validated. In addition, a 2D simulation is necessary to reproduce the breakdown structure with a branching plasma captured by Oda et al. because Voskoboinikova’s work is 2D axisymmetric computation.

In 2015, Nakamura et al. conducted a numerical simulation to reproduce the subcritical breakdown structure observed by Oda [86]. The effective diffusion model proposed by Boeuf et al. was coupled with Maxwell’s equation. Instead of solving the neutral gas dynamics, the breakdown threshold electric field was decreased artificially from 2.4 to 0.31 MV/m to sustain the plasma propagation under the subcritical electric field. Change of the breakdown threshold was not validated. However, the rough dynamics of the plasma propagation was captured in Nakamura’s model. The several plasma spots were initially set on the computational domain to reproduce a comb structure captured by Oda et al. Plasma columns with the comb structure propagated toward the beam source. Parameter studies reported by Nakamura revealed that the plasma structures were classified using the non-dimensional parameter of $\nu_i \lambda^2 / D_e$. The plasma pattern became diffusive when $\nu_i \lambda^2 / D_e$ was small. However, the discrete structure was induced when $\nu_i \lambda^2 / D_e$ was large. Irrespective of the initial plasma distribution, plasmoids having the same interval propagated toward the beam source because of the self-organization physics [87]. The interval of each plasmoid was 0.9$\lambda$, which showed good agreement with the experimentally obtained results reported by Oda et al. [55,59,60]. However, the correct propagation physics of the ionization front was not captured by Nakamura’s model because the change of the breakdown threshold was not validated.

In 2017, Takahashi et al. numerically reproduced the plasma filamentation and branching structure during subcritical microwave beam irradiation based on the effective diffusion model proposed by Boeuf et al. when it was coupled with a compressible fluid dynamics simulation for neutral particles and Maxwell’s equation [88]. Coupling simulation between the plasma and the neutral particles can capture changes of the electron’s transport coefficient induced by variation
of the neutral particle density. The subcritical microwave irradiation such as that of Oda’s experiment was reproduced numerically by irradiation with microwaves of 170 GHz and intensity \( E_{0,\text{rms}} < E_c \) where \( E_{0,\text{rms}} \) is the rms electric field of the incident microwave. Here, \( E_{0,\text{rms}} \) is different from \( E_{\text{rms}}, E_{0,\text{rms}} \) is the rms electric field of the beam source, but \( E_{\text{rms}} \) is the local rms electric field at the particular place. The 2D simulation was conducted in the \( H \)-plane for the incident wave. Boeuf’s model [71] cannot explain plasma propagation during the subcritical microwave irradiation because the ionization was not maintained using the local electric field satisfying \( E_{\text{rms}} < E_c \). However, in a similar fashion to that used for Voskoboinikova’s simulation, Takahashi’s model revealed that the plasma propagation was sustained during the subcritical beam irradiation using neutral gas heating because the reduced field \( E_{\text{eff}}/N \) was increased locally by a decrease of the neutral particle density and the local \( E_{\text{eff}}/N \) exceeded the breakdown threshold value of \( (E/N)_c \), where \( E_{\text{eff}} \) is the effective electric field. The discrete plasma was induced when the incident beam intensity was set as \( 0.69 \leq E_{0,\text{rms}}/E_c < 1 \) because strong gas heating decreased the elastic collision frequency and increased the reflectivity at the plasma front (Figure 10(a)). The overcritical electric field was locally formed at a point on the on-axis away from the off-axis plasma, which induced the discrete plasma structure. However, the diffusive plasma with a branching structure was formed when the incident beam intensity of \( E_{0,\text{rms}}/E_c < 0.69 \) was irradiated to the breakdown volume because the gas heating was weaker (Figure 10(b)). The wave reflection did not form an overcritical field region distant from the plasma front because the reflectivity was smaller. The continual plasma structure was induced because the distance between the plasma front and the overcritical field region became zero. The maximum interval of the branching structure was about 0.8\( \lambda \) in Takahashi’s simulation, which showed good agreement with the subcritical beam experiment conducted by Oda et al. [55,59,60]. The ionization front propagation speed increased with an increase in the incident electric field (Figure 10(c)). The slope of the propagation speed increase was larger at \( 0.69 \leq E_{0,\text{rms}}/E_c \) because an increase of the reflectivity at the plasma front was easily obtained. Using Takahashi’s model, it is necessary to simulate the plasma structures by changing the incident beam frequency to elucidate the beam frequency dependence of the plasma propagation obtained from Yamaguchi’s subcritical breakdown experiment.

4. Applications to rocketry

Microwave rockets were proposed as an engineering application of intense millimeter waves. This section presents a review of the experiments and numerical investigations used to elucidate the impulse generation mechanisms of the microwave rocket. Ideas to improve the microwave rocket thrust performance were also reviewed.

In 2004, the microwave rocket concept was first proposed by Nakagawa et al. by irradiating rocket models with 1 MW, 110-GHz microwaves [89]. To a microwave
rocket, intense beams of microwaves are irradiated with a parabolic mirror from a ground-based beam oscillator to a flying rocket. The gas breakdown is induced by focusing the incident microwaves using the parabolic mirror. The plasma propagates toward the microwave source while inducing a strong shock wave through the rapidly heating gas. The high pressures of the shock wave interact with the thruster wall, thereby creating an impulsive thrust in the rocket. Note that the microwave rocket discussed in this paper is different from a microwave-absorbing heat exchanger type. Three thruster models were tested in Nakagawa’s launch experiment to examine the vehicle shape and vehicle rigidity dependencies of thrust performance: (a) a duralumin parabolic thruster, (b) a polymer parabolic thruster, and (c) a duralumin cone–cylinder thruster. The overcritical electric field was induced only at the focal point of the mirror. The steady plasma and shock wave propagations inside the rocket nozzle were maintained using the subcritical electric field of the incident beam. Therefore, Nakagawa’s launch experiment was classified as the subcritical condition. The microwave rocket thrust performance
M. TAKAHASHI AND K. KOMURASAKI

was evaluated with three methods using horizontal and vertical setups for the beam irradiation. The propulsive impulses were estimated using the vehicle flight altitude or velocity. The momentum-coupling coefficient \( C_m \) was evaluated by \( C_m = I/(P\tau) \), where \( P \) stands for the microwave power, \( I \) signifies the impulse, and \( \tau \) denotes the microwave irradiation duration. A \( C_m \) of the polymer vehicle was half that of the duralumin model because the rigidity of the polymer membrane thruster was lesser than that of the duralumin vehicle and an inelastic reflection of the shock wave was created on the vehicle surface. The \( C_m \) of the parabolic thruster decreased with increased \( \tau \) because the incident microwave energy was absorbed outside of the rocket nozzle and the beam energy was not converted to the propulsive impulse. The \( C_m \) of the cone–cylinder thruster was evaluated to assess the relation between the nozzle length and the pulse duration. The \( C_m \) increased monotonically with an increase in the cylinder part length \( L \) because the energy-absorbing region at the plasma front remained inside the rocket nozzle and the microwave energy was converted to the propulsive force effectively. The maximum \( C_m \) of 395 \( \text{N/MW} \) was achieved with 0.175-ms pulse duration, 1-MW beam power, and 120-mm nozzle length in Nakagawa’s experiment, which was comparable with the rocket launched by the laser pulses [8–50].

In 2006, Oda et al. measured the microwave rocket thrust performance to ascertain the relation between the normalized heating length and the propulsive thrust, while examining the plasma structure and the plasma propagation speed [55,90]. Cone–cylinder rockets with total lengths of 180 and 380 mm and 60 mm radius were used to measure the \( C_m \). A 170 GHz, 1 MW gyrotron was used to induce the gas breakdown at atmospheric pressures. The beam profile was set as Gaussian distribution with a beam waist of 40 mm. The microwave pulse duration was changed from 0.1 to 1 ms to evaluate the pulse duration dependence of the thrust performance. The thrust performance was measured for beam power of 230–850 kW. Non-dimensional heating length \( l \) was defined as the ratio of the propagation distance of the ionization front \( U_i\tau \) to the total nozzle length \( l \). The \( C_m \) reached a maximal value at \( l = 0.6–0.8 \) because too small \( l \) induced insufficient pressure restoration from an open end of the nozzle and overly large \( l \) decreased the conversion rate from the beam power to the propulsive thrust (Figure 11). The ionization front propagation speed was measured based on side view photographs of the plasma evolution. The propagation speed exceeded Mach 1 at the power density \( S > 75 \text{ kW/cm}^2 \). The shock wave inside the rocket nozzle was enhanced through isometric heating when the plasma propagation became supersonic, which supplied higher \( C_m \). In 2009, Oda et al. explained the thrust generation mechanism of the microwave rocket based on an analogy to a pulse detonation engine [91]. The thrust performance was measured when the repetitive pulses were irradiated to the rocket nozzle. The microwave power was 1 MW, the microwave frequency was 170 GHz, the pulse duration was 1.7–3.4 ms, the beam profile was Gaussian with a waist of 20 mm, and the repetitive pulse frequency was 20–50 Hz. The total lengths of the nozzles were changed in the range of
190–590 mm. The vehicle diameter was 60 mm. A forced breathing system was equipped on the nozzle head to supply fresh air inside the rocket nozzle with flow velocities of 2.5 m/s–10 m/s. The generated impulse decreased with time evolution. A steady impulse was obtained after the second pulse. The impulse without air breathing was less than that with air breathing because the hot gas remained inside the rocket nozzle. The shock wave velocity obtained using the experiment showed good agreement with the theoretical prediction based on the relations of the normal shock wave, isobaric heating, and gas expansion. The impulse was normalized using the single-pulse impulse; it was shown for the partial filling rate $u/Lf$. The normalized impulse became unity when the partial filling rate became unity, which revealed that the sufficient partial filling rate was necessary for thrust generation during repetitive pulse operation. Oda et al. also measured the thrust performance at low ambient pressures because the microwave rocket can fly at higher altitudes [92]. The plasma structure became diffusive at ambient pressure of less than 0.1 atm for the 170-GHz beam. The ionization front propagation speed increased with decreased ambient pressure. The thrust performance of the microwave rocket decreases with a decrease in the ambient pressure (Figure 12(a)). However, the performance decrease mechanism was not identified from Oda’s experiment. Takahashi and Ohnishi conducted a fully kinetic simulation and the computational fluid dynamics simulation to elucidate the thrust performance decrease that occurs at lower pressures [83]. The ionization front propagation speed increased with a decrease in the ambient pressure, which increased the energy loss of the incident beam. In addition, to speed up the plasma propagation, the energy absorption rate by the plasma decreased with a decrease in the

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**Figure 11.** Momentum coupling coefficients for dimensionless heating length [55].

Notes: Triangles show $S = 98$ kW/cm$^2$ and $L = 180$ mm, open circles show $S = 98$ kW/cm$^2$ and $L = 380$ mm, and filled circles show $S = 50$ kW/cm$^2$ and $L = 380$ mm.
ambient pressure because of infrequent elastic collision. The thrust performance was decreased at the lower pressure because the shock wave strength inside the rocket nozzle became weaker. Takahashi and Ohnishi proposed application of the external magnetic field to the rocket nozzle to suppress the ionization front propagation speed. The ECR heating condition was also satisfied to improve the energy absorption rate by the plasma. The stronger shock wave was induced inside the rocket nozzle, which improved the thrust performance at lower pressures (Figure 12(b)).

**Figure 12.** Ambient pressure dependence of the momentum coupling coefficients \([92]\). Circles show \(U\tau/L = 2.0\), triangles represent \(U\tau/L = 3.0\), and squares show \(U\tau/L = 4.0\). Results of the numerical simulation conducted by Takahashi and Ohnishi revealed that the thrust performance at lower pressures can be improved by an external magnetic field \([83]\). (a) Momentum coupling coefficients for ambient pressure. (b) Momentum coupling coefficient evaluated by Takahashi’s simulation.
Yamaguchi et al. conducted a breakdown experiment to examine the beam profile dependence of the plasma structure and the thrust performance of the microwave rocket [93]. For the experiment, 1 MW, 170-GHz beams with the Gaussian, ring-shaped, and flat-top profiles were irradiated to the thruster. The Gaussian beam profile was converted to a ring-shaped or flat-top beam profile through the phase correcting mirror system. An acrylic tube was used for clear observation of the plasma structure propagating toward the beam source during beam irradiation. The filamentary structure of the plasma was not observed because the beam power density was low. The hollow plasma was obtained during the ring-shaped beam irradiation. However, the wider plasma was induced by irradiating the flat-top beam. The propagation speeds of the ionization front were evaluated as 140 and 68 m/s for the Gaussian beam of 33 kW/cm² and the flat-top beam of 16 kW/cm². The flat-top beam propagation speed was lower than that of the Gaussian beam because of the lower peak power density. The pressure sensor was installed in the tube to capture the pressure history during the Gaussian and flat-top beam irradiations. The plateau pressure duration driven by the flat-top beam was longer than that driven by the Gaussian beam because of the lower propagation speed. The momentum coupling coefficients $C_m$ were estimated as 93 and 199 N/MW for the Gaussian and flat-top beams by integrating the pressure histories. The larger $C_m$ was obtained using the flat-top beam because the slower plasma propagation increased the conversion rate from the beam power to the impulse. The slower propagation of the ionization front was beneficial for thrust generation.

In 2013, Fukunari et al. proposed a reed valve system to improve the thrust performance under repetitive pulse operation by increasing the partial filling rate of the rocket nozzle [94]. A launch experiment using the reed valves was conducted by irradiating 170 GHz, 1.16-MW microwaves to the rocket nozzle [95,96]. The 16 reed valves were installed on the thruster wall to improve the refilling performance. However, sufficient refilling was not found in this experiment. It is necessary to redesign the reed valve system on the thruster wall to obtain sufficient air refilling under repetitive pulse operation. In 2014, Fukunari et al. conducted a cost study of the microwave launch based on the flight trajectory analysis [97]. A thrust model was analytically constructed. Then, the flight trajectory was evaluated by solving the equation of motion for the vertical rocket launch. The development cost of the beam oscillator was found to be huge, but this initial cost is expected to be repaid by repeated launches of inexpensive rockets. Results of Fukunari’s analysis indicate that the launch cost became lower than that of a conventional chemical rocket at 42 launches. The initial cost of the beam oscillator was fully amortized at 2000 launches. The microwave rocket launch cost is lower than that of laser propulsion because development costs of the initial beam oscillator are low.
5. Conclusion

Experimental and computational investigations were conducted to understand the breakdown physics occurring during the millimeter wave irradiation with frequencies of 3–600 GHz. Experimental observations revealed the characteristic plasma structure with a discrete filament. It was affected by the ambient pressure, ambient gas species, beam frequency, and beam power. The computational model was proposed to reproduce the breakdown structure during beam irradiation, while solving Maxwell’s equation, plasma transport, and neutral gas dynamics. The wave reflection process formed a standing wave in front of the plasma, which induced the filamentary plasma under the overcritical condition. Plasma propagation with a branching structure was also reproduced under the subcritical condition when the neutral gas expansion was captured while solving the electromagnetic wave propagation and the plasma transport. Interactions between the plasma and the neutral gas became important when the time scale of the plasma propagation became comparable with that of the neutral gas dynamics.

The rocket launch technique was proposed using a shock wave induced during beam irradiation. A flight demonstration of the microwave rocket was conducted, during which the thrust performance was measured experimentally by changing the beam power density, ambient pressure, vehicle shape, and beam profile. The thrust performance with the single microwave beam pulse was comparable to that of the laser-boosted propulsion system. The thrust performance decreased when the ionization front propagation speed was too high because the energy conversion rate from the microwave power to the impulse decreased. Using subcritical beam irradiation is better than overcritical beam irradiation because slower propagation was obtained with the subcritical beam irradiation. The thrust performance with the repetitive pulses decreased with increased pulse frequency because the hot gas cannot be exhausted from the nozzle inside. A gas refilling technique using a reed valve was proposed. However, no performance improvement was obtained by repetitive pulse operation. It is necessary to assess the refilling process inside the rocket nozzle using computational simulations and redesign of the refilling technique to improve the thrust performance with repetitive pulses. The thrust performance decreased with decreased ambient pressure because of the increase in propagation speed and a decrease in the energy absorption rate by the plasma. Results of numerical simulation revealed that the thrust performance at the lower pressure can be improved by application of the external magnetic field. However, no experimental demonstration was conducted. Some combination of launch experiments and numerical simulation is necessary to achieve rocket launches using a high average-power beam.

In the future, it could be effective to use microwave rockets to develop a space-based solar power because transportation of $10^4$ tons material requires about 355 billion US dollars when a conventional rocket is utilized for development.
of a 1-GW class system [98]. Further investigation is required to realize a rocket system propelled by intense beams.

Acknowledgments

The authors appreciate fruitful discussions with Dr Yasuhisa Oda and Dr Keishi Sakamoto of The National Institutes for Quantum and Radiological Science and Technology, Prof. Naofumi Ohnishi of Tohoku University, and Dr Masafumi Fukunari of University of Fukui.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Japan Society for the Promotion of Science (JSPS KAKENHI) [grant number 15H05770].

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