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Gas breakdown in radio-frequency field within MHz range: a review of the state of the art

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Abstract

Low-temperature plasmas (LTPs) driven by 1–100 MHz radio-frequency (MRF) are essential for many industrial applications, and their breakdown characteristics are different to that of direct current (DC) breakdown. This review seeks to understand the state of the art of electric breakdown in the MRF field and provide references for related basic and applied research. We have given a brief history of research into MRF-driven breakdown, including Paschen curves, the corresponding discharge modes and parameter spaces, and the evolution of the parameters during the breakdown process. It is shown that the focus has been transferred from the breakdown voltage and *V-I* characteristics to the evolution of plasma parameters during the breakdown, both in experiments and simulations. It is shown that many fundamental and applied problems still need to be investigated, especially with the new global model and the incorporation of the external circuit model.

Keywords: gas breakdown, RF plasma, Paschen curve

(Some figures may appear in colour only in the online journal)

1. A brief history of gas breakdown

Gas breakdown is one of the most basic and common phenomena. From atmospheric lightning to fusion plasma in the laboratory, to industrial plasma for various applications, the gas breakdown process is an essential process. Nearly all laboratory and industrial plasma starts from gas breakdown [1]: when a weak voltage is applied across the gas gap, a small current flows through the gap. As the voltage increases, so does the current until it reaches a saturation value. When the voltage increases to a certain critical value, the electrons will be able to obtain high enough energy and generate a large amount of ionization, increasing the current rapidly, and the gas will be broken down to generate plasma.

The breakdown phenomenon has been known for centuries. As early as the end of the 19th century, before plasma physics became an independent discipline, gas breakdown has been studied by early experiments [2–4]. In 1889, Paschen systematically studied the breakdown phenomenon of air, hydrogen, CO_2, and other gases under direct current (DC) voltage, and gave the relationship between spark discharge and the voltage, air pressure, and discharge distance applied

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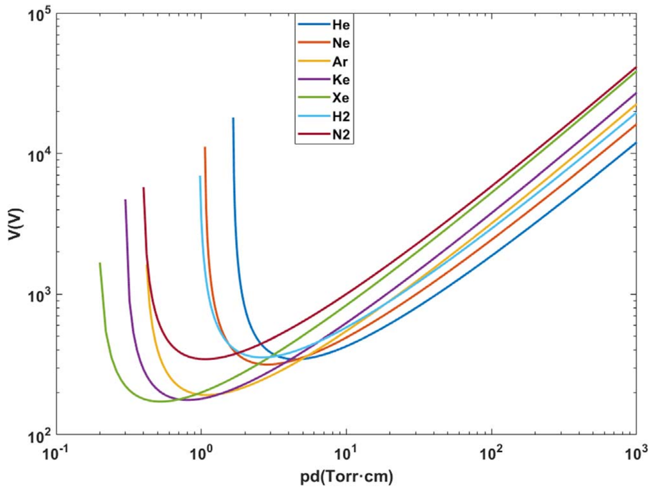

Figure 1. Paschen curves of He, Ne, Ar, Kr, Xe, H_2, N_2 driven by DC power, derived from Townsend discharge model in [6].

to the electrode [2]. Under a certain distance and gas pressure, when the voltage between electrodes is greater than a certain value, a gas breakdown can be achieved, and this voltage is called the breakdown voltage. The relationship between the breakdown voltage, the background gas pressure, and the discharge gap ($V-pd$) satisfies a certain law. In commemoration of Paschen's important discovery, this law is called Paschen's Law [5–7]. And the boundary of $V-pd$ where the gas can be broken down is called the Paschen curve.

At the beginning of the 20th century, the first gas discharge theory was proposed by Townsend [3], which can describe well the breakdown process of DC glow discharge. Through this theory, the Paschen curves can be directly derived.

According to the frequency of the driven power, the breakdown can be divided into DC breakdown, radio-frequency (RF) breakdown, microwave breakdown, and so on [6, 8, 9]. The Paschen curves of different gases under DC drive are shown in figure 1. In the high-pressure region, the breakdown voltage is basically linear with the product of the pressure and the distance. In the low-pressure region, the breakdown voltage suddenly increases as the value of *pd* decreases. The Paschen curve has a *pd* value that minimizes the breakdown voltage and makes the breakdown much easier. Paschen's Law can roughly describe the gas breakdown conditions under certain circumstances. Since the Paschen curve represents the breakdown range of the gas, it is of great significance for theoretical research and the practical application of gas discharge, and both theoretical and experimental research is easy to carry out. Therefore, the Paschen curve has always been the focus of gas discharge research.

Under different discharge environments, the gas breakdown voltages are also different, resulting in different Paschen curves. In 1954, Boyle discovered that the surface process is extremely important when the discharge gap is extremely short, and the field emission from the surface caused by the strong electric field will make the left branch of the Paschen curve approach zero [10]. In addition, space charge, dust, insulating materials, etc will make the Townsend model and traditional Paschen curve invalid [11].

RF breakdown is a breakdown phenomenon of gas discharge driven by RF power. Most low-temperature plasma sources are driven by RF power in the frequency range of 1–100 MHz. Thus, here we focused on the breakdown driven by MHz radio-frequency (MRF). Due to the oscillatory motion of electrons in the MRF field, the breakdown voltage corresponding to the Paschen curve changes significantly: when the amplitude of electron oscillation is less than half of the inter-electrode gap, the breakdown voltage decreases significantly compared with DC breakdown [12]; in lower pressure region, the same gas pressure may correspond to higher and lower breakdown voltage thresholds, and MRF breakdown can only occur within this interval [13]. In order to maximize the RF power absorption of the plasma, a matching circuit is usually applied between the RF power and the discharge chamber. So there are usually two 1–2 m long RF coaxial cables connected between the RF power, the matching circuit, and the discharge chamber [6], as figure 2 shows.

2. Significance of MRF breakdown research

The MRF breakdown process is not only an important fundamental research topic in the field of gas discharge and plasma physics but also an aspect of engineering research with important industrial application significance in applied research. Gases are more likely to be broken down by RF power. With the development of industry, more attention has been applied to MRF discharge. Most MRF plasma sources [6] are generated by low-pressure MRF breakdown, including capacitively coupled plasmas (CCPs), inductively coupled plasmas (ICPs), Helicon plasmas, etc. These plasma sources are now being widely used in etching and deposition processes in the semiconductor industry and in electric propulsion technology in the aerospace industry [14–17].

In these applications, the value of breakdown studies varies: on the one hand, many applications need to prevent MRF breakdown from occurring, such as CCP, which is widely used in etching and deposition equipment, where dielectric rings are usually placed at large radii of the electrodes to improve the radial homogeneity of the plasma, and gas breakdown at the dielectric rings can lead to unstable discharges and the generation of impurities, thus requiring the avoidance of breakdown [18, 19]. In addition, the reliable operation of MRF gas pedals also requires the avoidance of any gas or along-plane breakdown [20]; on the other hand, the MRF plasma widely used in industry is generated by low-pressure gas breakdown, and the breakdown voltage is usually higher than the steady-state voltage, and engineers must study how to break down the gas to generate plasma at low gas pressure and low RF voltage [20, 21]. For pulse-driven CCP in particular, the plasma will face a periodic breakdown and quenching process if the pulse duration is long, so the study of the MRF breakdown process is crucial for RF plasma-related applications.

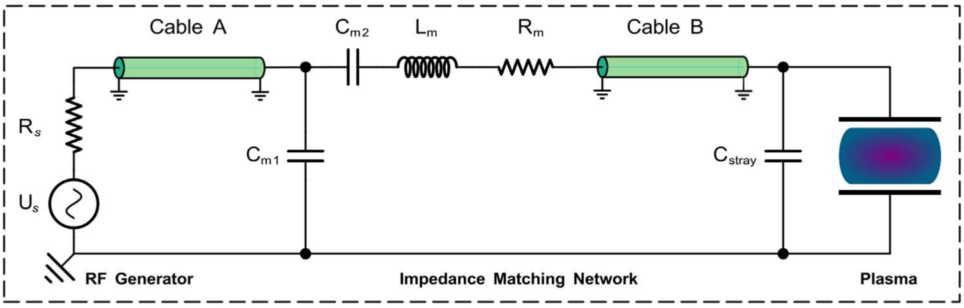

Figure 2. Circuit diagram of the discharge device.

In industrial discharge, most low-temperature plasma sources (LTPs) work under a stable discharge state, so previous research also focused on steady-state discharge [22–26], and this makes the study of the stable discharge relatively mature. In fact, the breakdown process is indispensable for all LTPs, which makes the breakdown process also an essential process for the plasma sources. Thus, it is of great significance to study the breakdown of MRF-driven plasmas:

(i) The evolution process of breakdown can further deepen people's understanding of the plasma formation process, the gas breakdown conditions, and the breakdown process. The detailed parameter evolution of the plasma can further optimize the gas discharge theory;
(ii) As an indispensable process of CCP and other plasma sources to form plasma, in the actual process, each material processing will experience breakdown discharge, and whether there will be favorable or unfavorable phenomena for the semiconductor or other industrial process during the breakdown process is still unknown. Therefore, the study of CCP breakdown is also of great significance for optimizing the plasma source and controlling the gas breakdown;
(iii) For some special discharges, such as pulse CCPs driven by MRF, the plasma will continuously experience the process of breakdown and extinction. The study of CCP breakdown is also of great reference significance for understanding and controlling such discharges.

3. Fundamental problems of MRF breakdown research

The theoretical study of gas breakdown has a history of more than 100 years, even longer than plasma physics as an independent discipline. For different discharge conditions, a variety of models have been proposed, including Townsend discharge, flow injection discharge, discharge along the surface, and other theories, which can explain the DC high-pressure breakdown process with relatively large E/p (electric field/gas pressure) values. However, for more complex cases such as MRF discharge, only simple models such as single-particle approximation are available [27], and there is still no better analytical or semi-analytical global model that can qualitatively explain the relevant experimental phenomena, and quantitative PIC/MC simulations also have many unsolved problems. With the improvement of computer performance and the rapid development of algorithms [28, 29], it is possible to simulate plasma evolution on large timescales and large orders of parameter magnitude, while the study of MRF breakdown processes through numerical simulations can further improve the MRF breakdown theory. Except for fundamental theoretical studies, the study of MRF breakdown processes by numerical simulations can also be used for optimizing RF plasma sources in industrial applications.

The most significant in terms of applied research is to give the discharge patterns and parameter space required by industry to give simulations of Paschen curves [30–32]. Usually, MRF plasma sources operate in a steady-state or quasi-steady state, i.e. the plasma parameters do not change with time or change only periodically. Previous experimental studies have mainly focused on steady-state discharges, with less attention to the breakdown process. The gas breakdown is affected by a variety of factors, including different working gases, gas pressure, etc, the driving frequency and voltage of the power supply, as well as the gap and electrode material and shape, which will correspond to a variety of discharge modes and a huge parameter space, with long experimental study periods and high costs. In practical applications, in most cases, the plasma can be first broken down by adjusting various controllable parameters to the working mode [1]. The discharge mode and parameter space given by quantitative simulations can provide important reference values for optimizing and expanding MRF plasma applications and can reduce the workload and cost of related R&D.

3.1. Experimental research into MRF breakdown

Compared with DC discharge, MRF is easier to start. However, the periodic oscillation of the MRF complicates the gas breakdown. For nearly a century, people have continuously studied gas breakdown driven by MRF power through experiments, analytical theory, numerical simulation, etc, and obtained relatively rich research results.

In terms of experimental research, as early as 1925, Kirchner measured the gas breakdown curve driven by MRF [33]. Due to the limitation of the experimental conditions of that age, only a few points are got that made the shape of the breakdown curve difficult to distinguish, as shown in

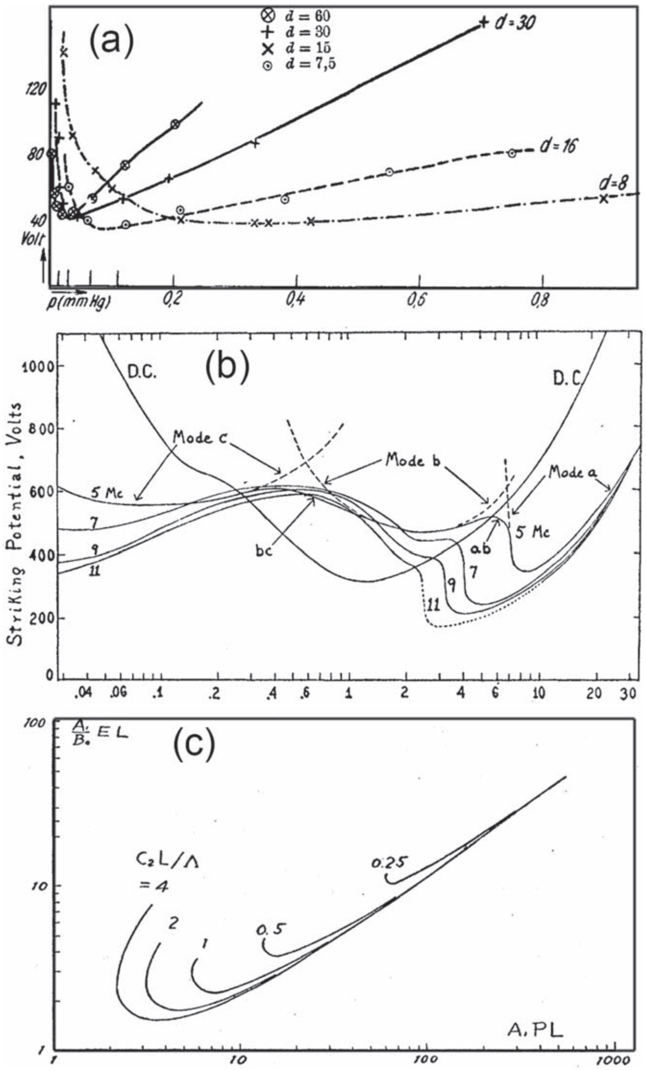

Figure 3. (a) Gas breakdown curve measured by Kirchner [33], used with permission of John Wiley & Sons—Books (from Über die Glimmentladung bei schnell wechselndem Feld, F.Kirchner, Annalen der Physik. 382(11): 287–301, 1925); permission conveyed through Copyright Clearance Center, Inc. (b) Hydrogen breakdown curve obtained by Githens in 1940, in which they made a more precise measurement of the MRF breakdown. Reprinted (figure 1) with permission from [34], Copyright (2022) by the American Physical Society. (c) Breakdown curve obtained by Kihara through the Boltzmann equation. Reprinted (figure 17) with permission from [36], Copyright (2022) by the American Physical Society.

figure 3(a). Githens [34] made a more precise measurement of the MRF breakdown of hydrogen. It is found that the curve is similar to the traditional Paschen curve in the higher-pressure region, but there are multiple discharge patterns in the low-pressure region. Levitskii experimentally and theoretically studied the multivalued property on the left hand side of the breakdown curve [35].

In the 1990s, Lisovsky found that secondary electron emission (SEE) is the main reason for the downward anomalous curvature of the left side of *pd* [30]. In 1998, Lisovsky studied the breakdown curves of argon with an experiment, using hydrogen and air in the pressure range of 0.2–20 Torr [31], as shown in figure 4. Lisovsky analyzed in detail the reasons for the turning point of the breakdown curve and found that when the discharge distance is greater than 1 mm, the drift-diffusion branch caused by ion-induced secondary electron emission (ISEE) is more obvious, and when the discharge distance is less than 1 mm, it shows a basic Paschen curve. Later works on the studies of breakdown curves are mostly based on this work. In addition, Lisovsky also studied the effect of different discharge chamber diameters on the breakdown [31], and found that when the diameter is reduced, the electron loss increases, resulting in the not obvious drift-diffusion branch. The breakdown curves of CF_4 and SF_6 were also studied, in which a method to determine the electron drift velocity by the breakdown curves was given [37].

More recently, Walsh and Zhang *et al* [38] studied the breakdown curve between parallel plate electrodes of 2–100 MHz under atmospheric pressure, helium environment by experimental method. It was found that the voltage decreases first and then increases with the increase in frequency. Lisovsky [39] studied the gas breakdown curve of CCP driven by low-pressure DC and MRF power, and found that adding another component to the electrical signal component would significantly change the breakdown curve. Limited by the diagnostic technology, most of the early experimental work can only give the Paschen curve of the breakdown voltage, or the volt-ampere characteristic, and rarely give the information about the plasma. By using electrodes of different materials, Dakhov *et al* [40, 41] proved that the higher electron-induced secondary electron emission (ESEE) coefficient expands the breakdown zone of the low-pressure region and makes the left-hand multi-valued Paschen curve more prominent.

After 2014, the rapid development of diagnostic techniques such as high-time-resolution spectroscopy has made it possible to observe the evolution of plasma, which has significantly improved the MRF breakdown research [42]. In 2015, Lisovsky *et al* [43] used a combination of experiments and Monte Carlo simulations to study the breakdown voltage curves of hydrogen under DC and RF conditions, and the results showed that SEE had a significant impact on the breakdown curves. In 2018, Ding *et al* [44] used a voltage-current probe and a fast camera to study the radio frequency breakdown process under atmospheric pressure in micro-spacing, which clearly demonstrated the processes of plasma filamentation, splitting, and expansion. In 2019, Aponte *et al* [45] studied the breakdown characteristics of air under DC and RF conditions for plasma antennas. The Paschen curve given by the experiment is consistent with the results given by the Monte Carlo simulation.

Since 2020, Liu *et al* [21, 46, 47] used advanced diagnostic methods such as time-resolved spectral diagnosis to study the breakdown process driven by pulsed MRF power, and obtained the evolution of plasma parameters during the breakdown process, as shown in figure 5. Combined with experiments, they studied the breakdown process of MRF plasma driven by pulses with analytical models and simulations and found that the breakdown can be divided into three stages: pre-breakdown, breakdown, and post-

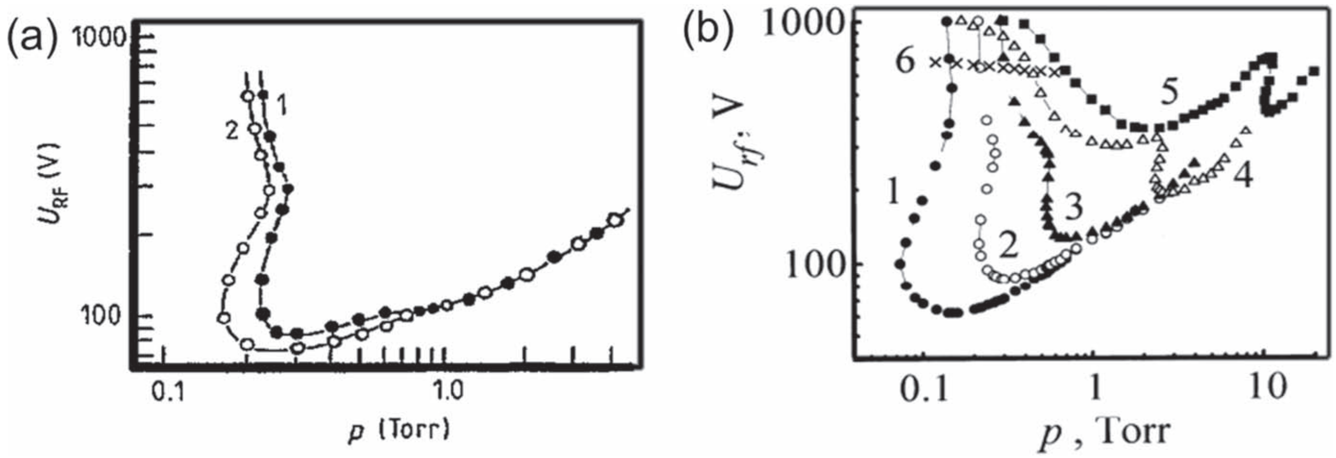

Figure 4. (a) MRF breakdown curve under different electrodes. Reproduced from [30]. (b) MRF breakdown curve of air under different discharge gaps. Reproduced from [31],

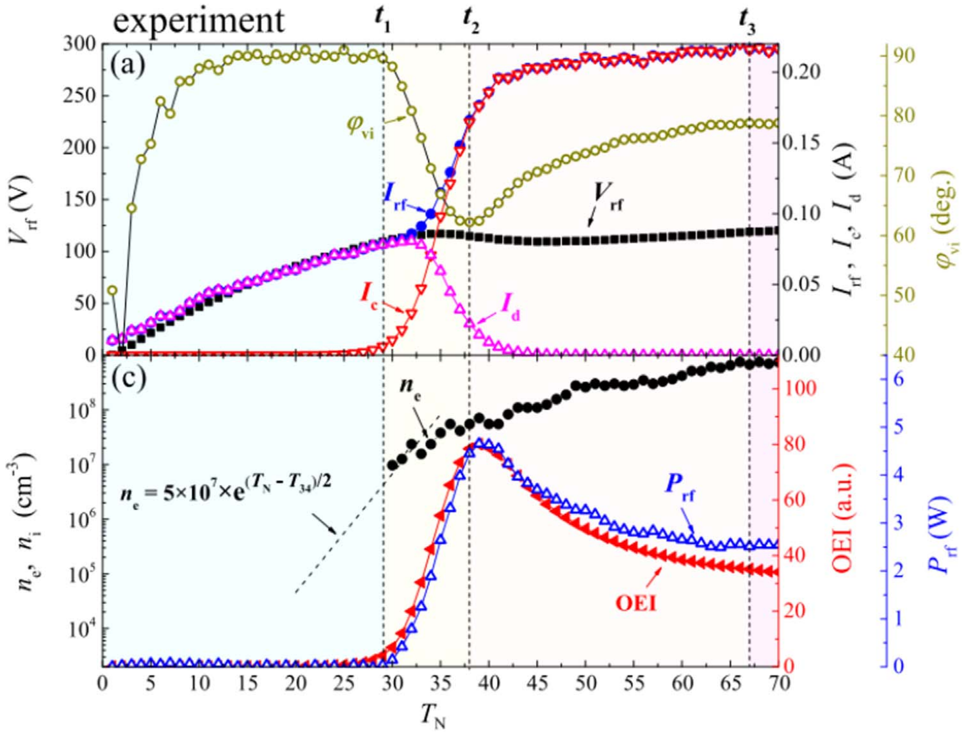

Figure 5. Plasma parameter evolution of MRF-driven CCP breakdown process obtained by periodic pulse MRF discharge. Reproduced from [46],

breakdown. There are significant changes in plasma parameters during those three processes [46]. They further studied the breakdown process of MRF pulsed driven Ar gas discharge on electrodes with a diameter of 300 mm using various diagnostic methods such as spectroscopy and probes, and the results also showed that the evolution of plasma parameters during those three processes was significantly different.

3.2. Theoretical and numerical research into MRF breakdown

In terms of analytical theory, as early as 1948, Hale gave a simple model describing the MRF breakdown curve based on the relationship between ionization threshold, electric field, and free path [48]. Pim [49, 50] studied the discharge under the atmospheric pressure micro-spacing and found that the MRF breakdown voltage was 10%–15% lower than that of DC Kihara analyzed the MRF-driven discharge based on the Boltzmann equation [36], and the results show that the process of electron emission from the surface will also make the breakdown curve more complicated. Based on the Boltzmann equation, Kihara proposed a relatively complete MRF-driven breakdown theory in 1952 [36].

More recently, Lieberman *et al* [18] used an analytical model to study the relationship between the breakdown voltage and the gap near the dielectric ring in a CCP chamber driven at 27 MHz in the presence of a dielectric ring, and the results showed that two-dimension has a significant impact on the Paschen curve. Garner *et al* [12] proposed a relatively simple analytical model for DC, RF, and microwave breakdown, which can qualitatively explain the characteristics of breakdown curves under different frequencies.

With the rapid development of computers, numerical simulations are gradually being used for breakdown research. The common numerical simulation methods used in breakdown include the Monte-Carlo method, fluid method, and PIC/MCC method. Simulation of MRF breakdown is always a challenge [51–53], especially when considering that the plasma parameters evolve rapidly during breakdown. In 2021, Fu *et al* [54] studied the similarity law of MRF-driven discharge, and proved three nonlinear transition processes, namely $\alpha - \gamma$ mode conversion, random-ohmic heating, and other mode conversion processes.

Monte Carlo simulation is easier to implement and requires less computation, which is very suitable for simulating breakdown conditions to obtain the breakdown curve. However, since the electric field is not self-consistent, this method is only suitable for simulating the avalanche process in the early stage of breakdown. Korolov *et al* studied the RF- and DC-driven breakdown curves by experiments and Monte Carlo methods [32], which are similar to the breakdown curves obtained by Lisovskiy [31] experiments, and proved that different SEE coefficients have obvious effects on the breakdown curve. Petrović *et al* [55] also developed a Monte Carlo simulation method. The relationship between breakdown voltage and frequency in the MRF range was obtained by his code. Puač *et al* [56, 57] also used the Monte Carlo method to study the breakdown characteristics of argon and oxygen driven by 13.56 MHz RF power, and the corresponding Paschen curve is simulated. Qiu *et al* [58] found that the role of photon-emission processes is shown to be important for large-area electrode configurations of air atmospherics with Monte Carlo simulation and experiment.

In 2008, Deng *et al* [59] used a fluid model to study the MRF breakdown of argon at a higher pressure, and the Ohmic heating process in the discharge gap is analyzed in this work. In 2021, Zhang *et al* [60] used a fluid model to study the pulsed MRF-driven plasma under atmospheric pressure. The simulation results show that a strong electric field with the same polarity as that near the cathode can be formed near the anode. Electrons near the anode can be re-accelerated. Therefore, short pulse discharge can effectively enhance the ignition process of MRF discharge.

Another well-known simulation method is now widely used in low-temperature plasma, and is called the PIC/MCC algorithm [29, 61–65]. This method is based on the assumption of particle resolution in the dynamics in which the interaction between particles and electromagnetic field in the discharge process can be self-consistently simulated.

In 1996, Vender *et al* [27] used the PIC/MCC method to study the evolution of MRF breakdown for the first time and provided important parameters such as plasma density and temperature in the breakdown process under MRF drive. The simulation results also prove that ESEE has an important influence on breakdown. In 2003, Smith *et al* [66] used experiments and the PIC/MCC model to study the MRF breakdown curve of argon and found that ESEE can significantly affect the left branch of the breakdown curve, and has little effect on the right branch of the breakdown curve. Radmilović *et al* [67] used the PIC/MCC code to study the breakdown curve when both ESEE and ISEE existed and found that the multi-value on the left side of the breakdown curve was significantly affected by SEE. Dakhov *et al* [40, 41] also used a method based on PIC kinetic simulation to analyze the significant effect of ESEE on MRF breakdown in low-pressure regions. Lee *et al* [68] used the single-particle approximation and the one-dimensional PIC/MCC model to study the MRF breakdown curve of the atmospheric pressure micro-gap.

In recent years, we have studied the capacitive low-pressure Ar/CF_4 breakdown driven by MRF power [69, 70], in which the spatio-temporal evolution of critical parameters during the breakdown process is given in detail by the PIC/MCC code, and the balance of particle number and powers is also given and analyzed in detail, as shown in figure 6.

No matter whether it is for laboratory plasma or reactive plasma in industry, there must be an external circuit connected between the rf power supply and the discharge chamber. Many works have shown that the external circuit plays an important role in protecting the power cabinet and adjusting the power matching. In previous theoretical studies, by simplifying the external circuit [16, 71–73], the plasma properties can be studied, but the effect of the plasma on the complex matching circuit cannot be studied; by simplifying the plasma as a network of capacitors, resistors and inductors [74–77], the characteristics of power matching under complex matching circuits can be studied, but the effects of matching circuits on plasma cannot be studied self-consistently.

The devices of the external circuits can also affect the process of gas breakdown driven by MRF power. By simplifying the matching circuit to a blocking capacitor, the effect of the external circuit on MRF breakdown has also been analyzed in our recent work [69, 70]. However, a single blocking capacitor can never replace the matching circuit in real discharge. Thus, based on the work of Verboncoeur [71], we studied the whole MRF breakdown process under the commonly-used L-type matching circuit [78]. The different matching devices can significantly affect breakdown and even change the direction of the evolution and breakdown curve (shown in figure 7).

In 2021, Cary *et al* [79] of Tech-X Company successfully calculated the Paschen curve of Ar gas in the range of 0.1–10 Torr centimeters using the 1D speed-limited PIC/MCC simulation method. With the same accuracy, Cary's method is 200 times faster.

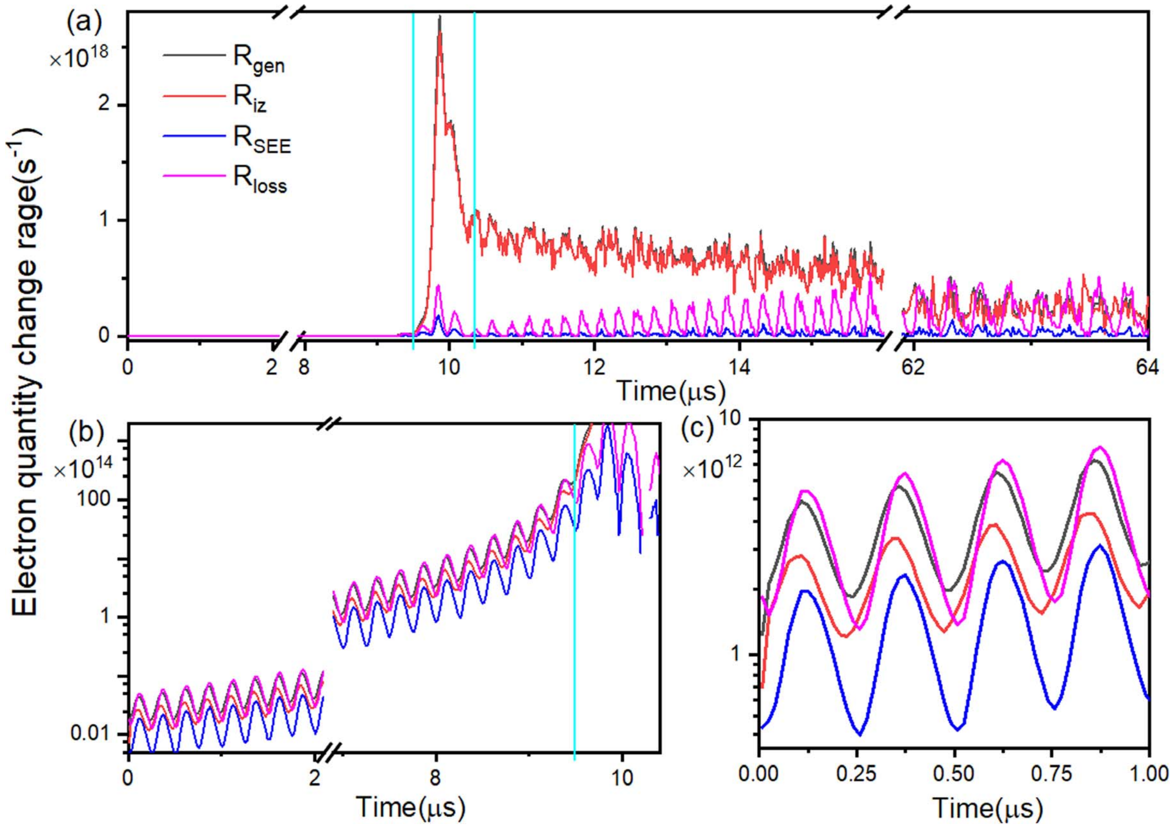

Figure 6. Temporal evolution of electron quantity change rate under time averaged over 1/60 MHz: (a) 0–64 μs in linear coordinates, (b) 0–10.4 μs in logarithmic coordinates, (c) part of (b) from 0 to 1 μs. Reproduced from [69], © IOP Publishing Ltd. All rights reserved.

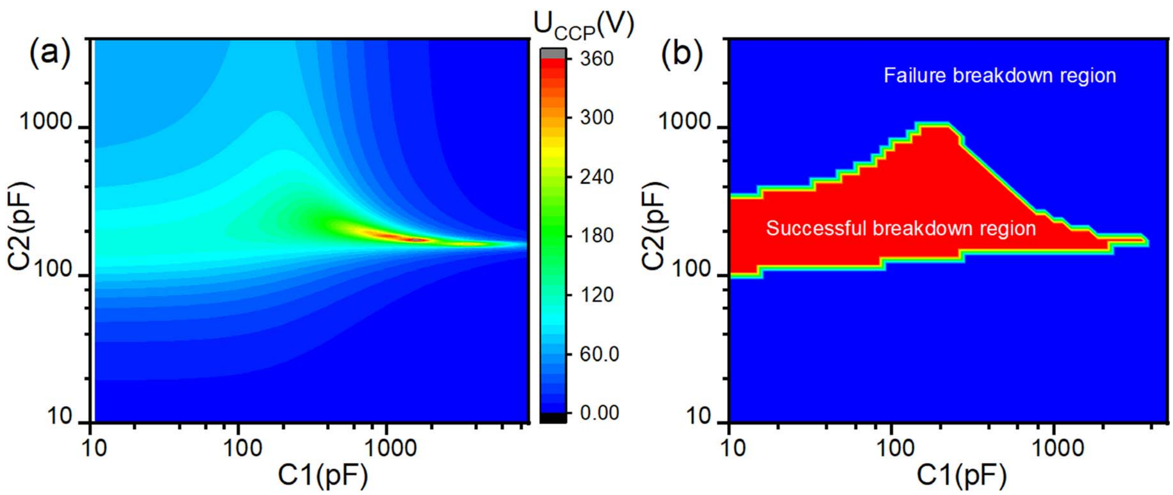

Figure 7. (a) Relationship between the stabilized voltage amplitude of CCP in a vacuum and the external capacitor of C_1 and C_2, (b) the region of successful breakdown (red region) and failure breakdown region (blue region). Reprinted with permission from [78]. Copyright (2022), AIP Publishing LLC.

4. Future trends of MRF breakdown research

4.1. Deficiencies of previous MRF breakdown models

Previous research on the breakdown of CCP is mainly divided into breakdown conditions and parameter evolution during breakdown. The research on breakdown conditions mainly determines whether the gas can be broken down under the conditions by changing the discharge conditions, so as to obtain the breakdown curve. Since it is easy to determine whether the gas is broken down experimentally, the research on the breakdown in the academic community has always focused on the breakdown conditions. People have obtained the breakdown curves of CCP under various conditions through experiments and simulations [30–32, 37, 39, 66, 67], the experimental study is more detailed. However, compared with more studies on CCP breakdown conditions, there are

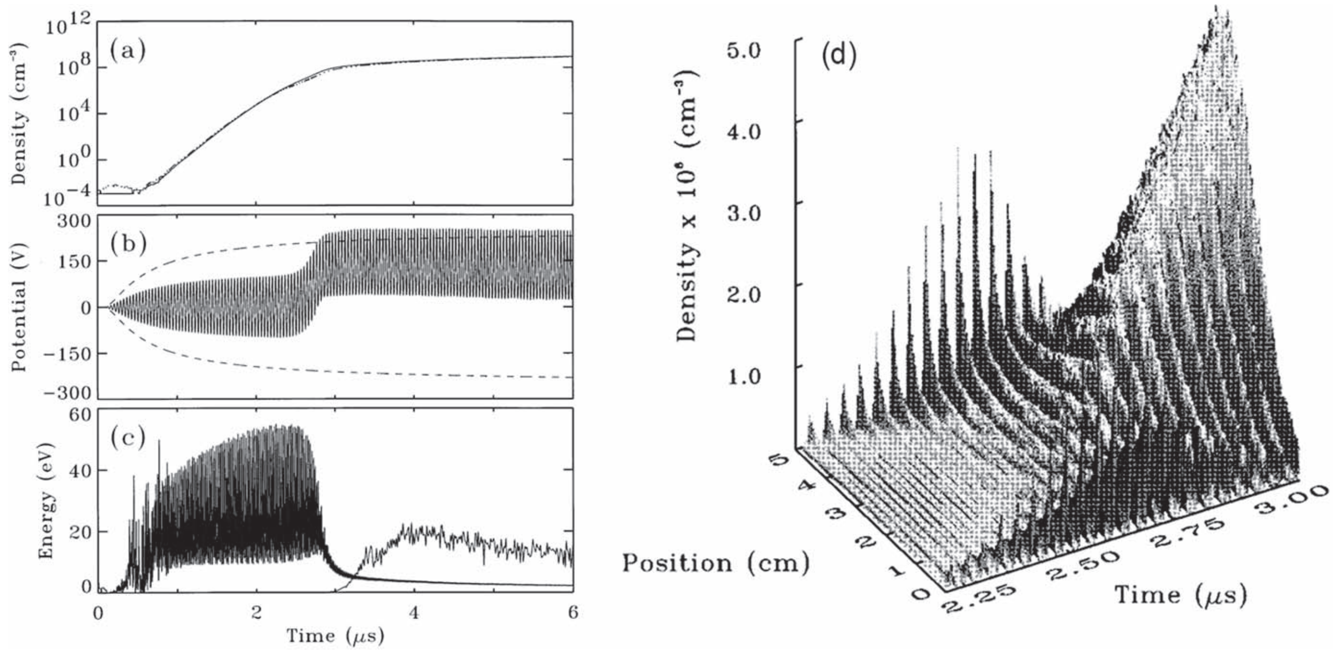

Figure 8. Evolution key parameters during breakdown driven by 25 MHz, 250 V, RF power, (a) electron and ion density, (b) center potential, (c) mean electron energy in the discharge gap and the energy of ion bombarding the electrode. (d) Spatio-temporal evolution of electron density during breakdown. Reprinted with permission from [27]. Copyright (2022), AIP Publishing LLC.

few studies on the evolution of plasma parameters during CCP breakdown. The main reasons are as follows:

(i) In experimental or real industrial applications, the CCP always operates in a steady-state. In most cases, the gas can be broken down in advance by adjusting various controllable parameters and then adjusted to the working mode. In practice, the discharge-sustaining condition is often lower than the breakdown condition. Therefore, the breakdown process of the CCP is often neglected relative to the stable discharge. On the contrary, in the field of high voltage and insulation, more attention has been applied to the breakdown conditions, which caused more research works on breakdown condition [1, 80].

On the other hand, over past decades, carbon tetrafluoride (CF_4) or other fluoride mixtures have been widely studied in experiments [81–84] and simulations [22, 85–91], as it is widely used in the etching of silicon, silicon-dioxide [6], silicon carbide [92]. The steady-state discharge of CF_4 like gases is quite different with argon [87–91], and the breakdown process will also different, this has been presented until recently [70].

(ii) The process of CCP is a fast evolution process, because of the extremely short time (in the order of hundreds of nanoseconds to tens of microseconds), and the plasma parameters will change greatly during this period. For example, the electron density can be changed from 10^8 m^{-3} to 10^{16} m^{-3}) by many order [27, 69, 70]. In experiments, most of the diagnostic devices are designed for steady-state discharge, so it is difficult to diagnose the breakdown process experimentally. Especially for the initial stage of breakdown, due to the extremely low electron density, common devices such as probes and spectroscopy cannot work properly. However, whether the gas can be broken down under certain discharge conditions can be well verified by experiments and theory. Because of this, the previous theoretical and simulation work mainly focused on predicting or measuring the Paschen curve, and few scholars have studied the whole MRF breakdown process, which means we still know little about the parameter's evolution during the MRF breakdown.

Compared with the limitations of experimental studies, numerical methods based on computer simulations can give a detailed evolution of plasma parameters during breakdown. For example, in the above work, Vender *et al* used the PIC/MCC algorithm to study the parameter evolution process of the plasma in the process of MRF breakdown [27], and obtained the evolution of important parameters in the process of CCP breakdown, as shown in figure 8.

In general, although many magnificent works have been applied on the breakdown process of CCPs before, they are still insufficient or not comprehensive enough. The shortcomings of the previous work are mainly manifested in the failure to give a detailed parameter evolution of the plasma during the breakdown process. The incompleteness of previous work is mainly reflected in the following four points:

(i) Multiple-frequency-driven CCPs have become mainstream plasma sources [22, 93, 94], while previous breakdown studies have focused on single-frequency-driven CCPs, and there are few studies on the breakdown process of CCPs driven by other MRF sources; the commonly used gases in the actual industry are generally electronegative gases. For the electronegative gas, the previous work has almost only studied its breakdown conditions, and few studies have given the plasma parameter evolution of the electronegative gas breakdown process in the CCP;

(ii) Many previous works have given the breakdown curves of CCP under different conditions and proved that SEE has a great influence on the low-pressure region of the breakdown curve [27, 30, 40]. However, few works have analyzed the specific effects of electron- or ion-induced SEE on the breakdown curves systematically. In the low-pressure region close to the breakdown curve, the surface effect is more pronounced. At this time, the characteristics of the discharge and breakdown inside and outside the breakdown curve still need further study;

(iii) In order to protect the power supply, a matching circuit is usually connected between the CCP and the RF power [71, 75, 95]. Gas breakdown can instantaneously change the electrical properties of the CCP, which is likely to cause drastic changes in matching characteristics. Whether and how this change affects discharge has been poorly studied. RF coaxial cables also have a significant effect on the breakdown process. The coaxial cable in the RF isotropic drive power supply has essentially no effect on the well-matched steady-state operating conditions. However, since the breakdown process is only on the order of nanoseconds to microseconds, the transmission time of the electrical signal in the cable is on the order of tens of nanoseconds, the propagation time of the RF voltage on the cable is comparable to the breakdown time. Therefore, for the MRF breakdown process, a suitable transmission line model must also be developed to consider the effect of coaxial cables.

For the breakdown process, the initial breakdown stage is noteworthy. Due to the extremely low particle density in the initial stage, it is difficult for most experimental diagnostic equipment to work [46], and it is even more difficult to perform spatio-temporal resolution of each physical quantity on the nanosecond and microsecond scales. In addition, at lower gas pressures, the discharge system before breakdown has obvious nonlocal thermal equilibrium characteristics, and the fluid model at this time is likely to fail.

4.2. Future trends of previous MRF breakdown models

In recent decades, many works have been applied to the study of MRF breakdown, both experimental and theoretical [46, 54, 69, 70], but there are still many fundamental and applied problems that need to be investigated. In order to better study the MRF breakdown process, we need both to improve existing models and to develop new ones. The improvement of existing models, that is breakdown evolution simulation based on PIC/MC models, and the development of a new model MRF breakdown, must take into account the interaction of external circuits and coaxial cables with the plasma.

(i) The global model [6, 96, 97] (also known as the zero-dimensional model) can be used to qualitatively give the evolution of the plasma parameters during the breakdown process, which is a useful complement to analytical models such as the single-particle approximation and can also be used to compare with PIC/MC models and experimental results. The main idea is to ignore the spatial variation of physical quantities, directly solve the density and energy conservation equations for electrons and ions, respectively, and combine the neutral gas conservation equation and the external circuit equation to derive the time evolution of density, temperature, plasma current, and other parameters by solving the set of ordinary differential equations, which is an extension of the commonly used steady-state holonomic model. Most holonomic models used for low-temperature plasma simulations are designed to simulate steady-state discharges and give steady-state solutions, but the breakdown is dynamic, nonlinear, and significantly deviating from the thermal equilibrium process, and the density-temperature evolves rapidly with time, so the holonomic model for simulating breakdown must be modified with the corresponding model and algorithm. For the tokamak initiation process, there are good global model [98–101], which can explain the experimental results of tokamak initiation in a semi-quantitative form for the three cases of pure ohmic, electron cyclotron resonance and electron beam injection, proving that the model is a powerful tool for studying the breakdown process. The physical processes of tokamak initiation and MRF breakdown in low-temperature plasma are close to each other, and the main difference is the different expressions of plasma parameters, ionization terms, heating terms, etc. The holistic model should be modified for the qualitative study of the low-pressure MRF breakdown process in the future.

At low pressure (<1 Torr), the electron-free path and device size are comparable, and the plasma generated by the MRF breakdown process is nonlocal thermal equilibrium, so the fluid approach is usually invalid, a PIC/MC model of kinetics is required for accurate description. However, to simulate MRF breakdown through the PIC/MC algorithm, the code must be modified accordingly, including control of the macro-particle number [27], implicit methods [28], surface process models [102], and diagnosis of evolutionary simulations [69]. In particular, most of the current MRF plasma simulations are based on steady-state discharges, while the breakdown process must consider the evolutionary process, so the evolutionary simulation is more complex than the steady-state simulation.

(ii) Previous theoretical and numerical simulations have been performed with a given voltage or considering only the presence of the simplest spacer capacitance, and in the simulations compared with experiments [46], the voltage

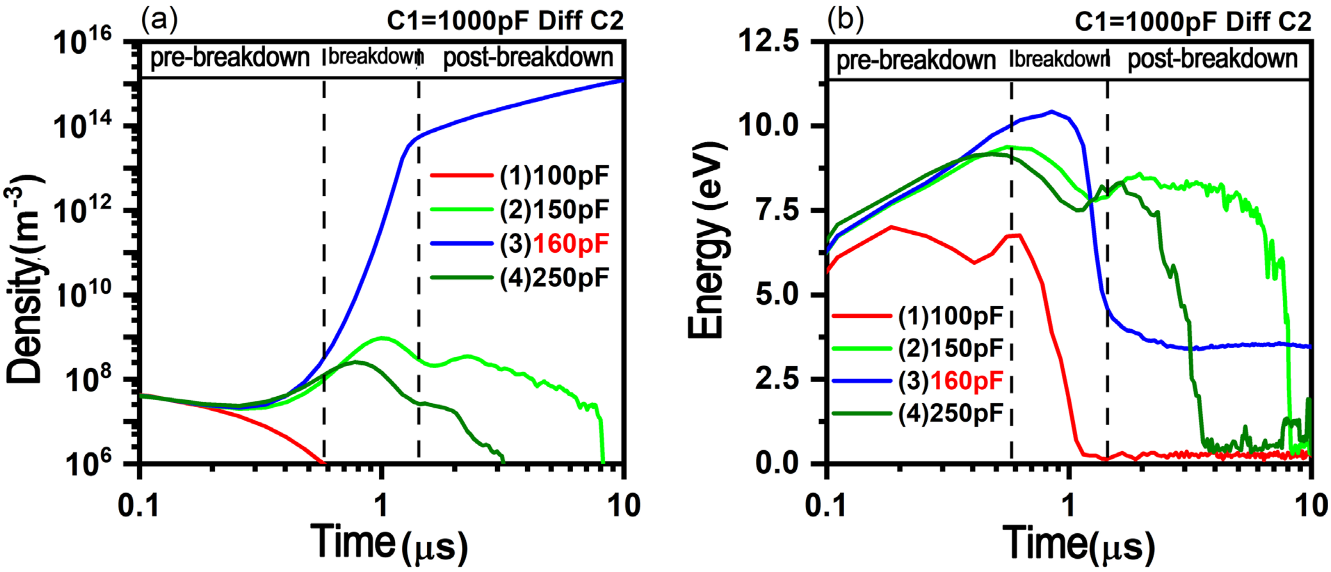

Figure 9. Effect of external circuit parameters on the breakdown process of MRF capacitively coupled plasma. Reprinted with permission from [78]. Copyright (2022), AIP Publishing LLC.

on the pole plate is not calculated self-consistently but comes from experimental measurements. The actual drive circuit has a complex matching circuit and coaxial cable (figure 2), the circuit has processes such as capacitive charging, the plasma has a significant change in impedance before and after breakdown, and the MRF voltage may be reflected on the coaxial cable, so the breakdown model must include the complete external circuit and transmission-line model.

The breakdown model must include a complete external circuit model [71, 72, 74, 78, 103–105]. In the case of a capacitively coupled plasma, for example, the circuit is linear before breakdown and the pole plate can be considered as a vacuum capacitor, while the plasma has both capacitive and resistive components and is nonlinear due to the presence of the plasma and sheath layer after a breakdown.

Recently, a generalized method to simulate CCP and external matching networks together is proposed by Schmidt [76, 104]. The voltage across the electrode usually changes significantly, so the simulation of the breakdown process must be coupled to an external circuit model, as has been demonstrated by previous results of others and our preliminary results. Our simulations of self-consistently coupled external circuits and plasmas found that the external circuit parameters have a significant effect on the MRF breakdown process [78], as shown in figure 9. It can be seen that the plasma is able to break down normally only for $C_2 = 160$ pF in the matched circuit; while $C_2 = 100$ pF the avalanche process does not occur due to the low pole plate voltage, and this failure breakdown mode, which occurs in the initial stage, can be studied with conventional Monte Carlo simulations, fluid or PIC/MC models without the external circuit; while $C_2 = 150$ pF and $C_2 = 250$ pF, the avalanche process can occur, but the breakdown does not occur because the plasma density increases and then decreases due to the load voltage change caused by the load impedance change, and this breakdown failure mode that occurs during the sheath formation process cannot be studied by previous models. Only by considering the external circuit can give the correct voltage waveform and voltammetric characteristics for a complete description of the breakdown characteristics.

Coaxial cables also have a significant impact on the breakdown process. The coaxial cable in the MRF plasma drive power supply has essentially no effect on the well-matched steady-state operating conditions, but since the breakdown process is only on the order of nanoseconds to microseconds, the transmission time of the electrical signal in the cable is on the order of tens of nanoseconds, and the propagation time of the MRF voltage on the cable is comparable to the breakdown time. Therefore, for the MRF breakdown process, it is also necessary to establish a suitable transmission line model [106–109] to consider the impact of coaxial cables.

5. Conclusion

A brief introduction to the research history of MRF-driven breakdown has been presented in this article. Compared to the breakdown driven by DC power that has been studied already by many researchers, works, methods, and models, for its more complicated driven methods and later appearance, even though there are many plasma sources based on MRF-driven breakdowns, it is rare that works have applied to MRF-driven breakdown research, and many works have been directed from the experiment and concentrate on the breakdown condition. Few works have been applied to the evolution of plasma parameters during breakdown. With the development of diagnostic devices and computers, in recent years, several breakthrough works have been applied to the parameter evolution of MRF-driven gas breakdown, including experiments and simulation, which has also attracted the attention of academics industry.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

[1] Raizer Y P and Allen J E 1997 *Gas Discharge Physics* vol 2 (Berlin: Springer)
[2] Paschen F 1889 *Ueber die Zum Funkenübergang in Luft: Wasserstoff und Kohlensäure Bei Verschiedenen Drucken Erforderliche Potentialdifferenz* (Berlin: JA Barth)
[3] Townsend J S 1915 *Electricity in Gases* (Oxford: Clarendon)
[4] Pejovic M M, Ristic G S and Karamarkovic J P 2002 *J. Phys. D: Appl. Phys.* **35** R91
[5] Graf R F 1999 *Modern Dictionary of Electronics* (Woburn: Newnes)
[6] Lieberman M A and Lichtenberg A J 2005 *Principles of Plasma Discharges and Materials Processing* (New York: Wiley)
[7] Naidu M S 2013 *High Voltage Engineering* (New York: McGraw-Hill)
[8] Raizer Y P and Allen J E 1991 *Gas Discharge Physics* vol 1 (Berlin: Springer)
[9] Bogaerts A *et al* 2002 *Spectrochim. Acta, Part B: Atomic Spectroscopy* **57** 609
[10] Boyle W and Kisliuk P 1955 *Phys. Rev.* **97** 255
[11] Cookson A H 1970 Electrical breakdown for uniform fields in compressed gases *Proc. of the Institution of Electrical Engineers* (London: IET), vol 117, 269
[12] Loveless A M and Garner A L 2017 *Phys. Plasmas* **24** 104501
[13] Savic M *et al* 2011 *IEEE Trans. Plasma Sci.* **39** 2556
[14] Chabert P and Braithwaite N 2011 *Physics of Radio-Frequency Plasmas* (Cambridge: Cambridge University Press)
[15] Al Bastami A *et al* 2020 Comparison of radio-frequency power architectures for plasma generation *2020 IEEE XXI Workshop on Control and Modeling for Power Electronics (COMPEL)* (Piscataway, NJ: IEEE) pp 1–8
[16] Verma A K and Venkattraman A 2021 *Comput. Phys. Commun.* **263** 107855
[17] Tolpygo S K *et al* 2016 *IEEE Trans. Appl. Supercond.* **26** 1
[18] Lieberman M A *et al* 2006 *Plasma Sources Sci. Technol.* **15** 276
[19] Chang H W and Hsu C C 2010 *Jpn. J. Appl. Phys.* **49** 016101
[20] Obermair C *et al* 2022 *Phys. Rev. Accel. Beam.* **25** 104601
[21] Su Z X *et al* 2021 *Plasma Sources Sci. Technol.* **30** 125013
[22] Donkó Z and Petrović Z L 2006 *Japan. J. Appl. Phys.* **45** 8151
[23] Delattre P A *et al* 2013 *J. Phys. D: Appl. Phys.* **46** 235201
[24] Lafleur T and Chabert P 2015 *Plasma Sources Sci. Technol.* **24** 044002
[25] Yang S *et al* 2017 *J. Vacuum Sci. Technol. A: Vacuum, Surfaces, and Films* **35** 061311
[26] Wu H *et al* 2022 *Plasma Sources Sci. Technol.* **31** 047001
[27] Vender D, Smith H and Boswell R 1996 *J. Appl. Phys.* **80** 4292
[28] Kawamura E, Birdsall C K and Vahedi V 2000 *Plasma Sources Sci. Technol.* **9** 413
[29] Wang H Y, Jiang W and Wang Y N 2010 *Plasma Sources Sci. Technol.* **19** 045023
[30] Lisovsky V and Yegorenkov V 1994 *J. Phys. D: Appl. Phys.* **27** 2340
[31] Lisovskiy V and Yegorenkov V 1998 *J. Phys. D: Appl. Phys.* **31** 3349
[32] Korolov I, Derzsi A and Donkó Z 2014 *J. Phys. D: Appl. Phys.* **47** 475202
[33] Kirchner F 1925 *Annalen der Phys.* **382** 287
[34] Githens S Jr 1940 *Phys. Rev.* **57** 822
[35] Levitskii S 1957 *Sov. Phys. Tech. Phys.* **2** 887
[36] Kihara T 1952 *Rev. Mod. Phys.* **24** 45
[37] Lisovskiy V A and Yegorenkov V D 1999 *J. Phys. D: Appl. Phys.* **32** 2645
[38] Walsh J L *et al* 2008 *Appl. Phys. Lett.* **93** 221505
[39] Lisovskiy V, Kharchenko N and Yegorenkov V 2010 *J. Phys. D: Appl. Phys.* **43** 425202
[40] Dudin S *et al* 2012 *Questions of Atomic Science and Technology* (in Russian)
[41] Dakhov A and Dudin S 2013 *Questions of Atomic Science and Technology* (in Russian)
[42] Petrović Z L *et al* 2014 *J. Phys. Conf. Ser.* **514** 012043
[43] Lisovskiy V A, Derevianko V A and Yegorenkov V D 2015 *J. Phys. D: Appl. Phys.* **48** 475201
[44] Huo W *et al* 2018 *IEEE Trans. Plasma Sci.* **46** 8
[45] Aponte I A *et al* 2019 *Phys. Plasmas* **26** 123512
[46] Liu Y X *et al* 2020 *Plasma Sources Sci. Technol.* **29** 12LT03
[47] Wang X Y *et al* 2021 *Plasma Sources Sci. Technol.* **30** 075011
[48] Hale D H 1948 *Phys. Rev.* **73** 1046
[49] Pim J 1949 *Proc. of the IEE-Part III: Radio and Communication Engineering* **96** 117
[50] Pim J 1948 *Nature* **161** 683
[51] Dosopoulos S and Lee J F 2010 *J. Comput. Phys.* **229** 8521
[52] Verma A K and Venkattraman A 2021 *Comput. Phys. Commun.* **263** 107855
[53] Kühn C and Groll R 2021 *Comput. Phys. Commun.* **262** 107853

[54] Fu Y *et al* 2021 *Phys. Rev. Appl.* **16** 054016
[55] Petrović Z L *et al* 2017 *Plasma Processes Polym.* **14** 1600124
[56] Puač M *et al* 2018 *Plasma Sources Sci. Technol.* **27** 075013
[57] Puač M, Đorđević A and Petrović Z L 2020 *Eur. Phys. J.* D **74** 1
[58] Qiu X *et al* 2022 *IEEE Transactions on Plasma Science* (Piscataway, NJ: IEEE) pp 1–8
[59] Deng Y *et al* 2008 *Phys. Plasmas* **15** 053507
[60] Gao S H, Wang X L and Zhang Y T 2021 *Phys. Plasmas* **28** 113501
[61] Birdsall C K 1991 *IEEE Trans. Plasma Sci.* **19** 65
[62] Vahedi V *et al* 1993 *Plasma Sources Sci. Technol.* **2** 261
[63] Vahedi V and Surendra M 1995 *Comput. Phys. Commun.* **87** 179
[64] Nanbu K 2000 *IEEE Trans. Plasma Sci.* **28** 971
[65] Wen D Q *et al* 2017 *J. Phys. D: Appl. Phys.* **50** 495201
[66] Smith H, Charles C and Boswell R 2003 *Phys. Plasmas* **10** 875
[67] Radmilović-Radjenović M and Lee J 2005 *Phys. Plasmas* **12** 063501
[68] Lee M U *et al* 2017 *Plasma Sources Sci. Technol.* **26** 034003
[69] Wu H *et al* 2021 *Plasma Sources Sci. Technol.* **30** 065029
[70] Wu H *et al* 2022 *J. Phys. D: Appl. Phys.* **55** 255203
[71] Verboncoeur J P *et al* 1993 *J. Comput. Phys.* **104** 321
[72] Vahedi V and DiPeso G 1997 *J. Comput. Phys.* **131** 149
[73] Jiang M *et al* 2020 *Plasma Sources Sci. Technol.* **29** 015020
[74] Rauf S and Kushner M J 1998 *J. Appl. Phys.* **83** 5087
[75] Schmidt F, Mussenbrock T and Trieschmann J 2018 *Plasma Sources Sci. Technol.* **27** 105017
[76] Schmidt F *et al* 2019 *J. Appl. Phys.* **125** 173106
[77] Qu C *et al* 2020 *J. Appl. Phys.* **127** 133302
[78] Wu H *et al* 2022 *J. Appl. Phys.* **131** 153301
[79] Theis J G *et al* 2021 *Phys. Plasmas* **28** 063513
[80] Xiao D 2016 *Gas Discharge and Gas Insulation* (Berlin: Springer)
[81] Jauberteau J *et al* 1991 *J. Phys. D: Appl. Phys.* **24** 261
[82] Haverlag M *et al* 1991 *J. Appl. Phys.* **70** 3472
[83] Rauf S and Kushner M J 1997 *J. Appl. Phys.* **82** 2805
[84] Booth J *et al* 1999 *J. Appl. Phys.* **85** 3097
[85] Gogolides E, Stathakopoulos M and Boudouvis A 1994 *J. Phys. D: Appl. Phys.* **27** 1878
[86] Denpoh K and Nanbu K 1998 *J. Vacuum Sci. Technol. A: Vacuum, Surfaces, and Films* **16** 1201
[87] Denpoh K and Nanbu K 2000 *Jpn. J. Appl. Phys.* **39** 2804
[88] Proshina O *et al* 2010 *Plasma Sources Sci. Technol.* **19** 065013
[89] Schulze J *et al* 2011 *Phys. Rev. Lett.* **107** 275001
[90] Liu G H *et al* 2015 *Plasma Sources Sci. Technol.* **24** 034006
[91] Liu Y X *et al* 2019 *Plasma Sources Sci. Technol.* **28** 075005
[92] Jin C *et al* 2015 *Plasma Processes Polym.* **12** 1061
[93] Georgieva V, Bogaerts A and Gijbels R 2004 *Phys. Rev.* E **69** 026406
[94] Georgieva V and Bogaerts A 2005 *J. Appl. Phys.* **98** 023308
[95] Kushner M J 2009 *J. Phys. D: Appl. Phys.* **42** 194013
[96] Lee C *et al* 1994 *J. Electrochem. Soc.* **141** 1546
[97] Lee C and Lieberman M 1995 *J. Vacuum Sci. Technol. A: Vacuum, Surfaces, and Films* **13** 368
[98] Lloyd B, Carolan P and Warrick C 1996 *Plasma Phys. Controlled Fusion* **38** 1627
[99] Kim H T 2013 Physics and computational simulations of plasma burn-through for tokamak start-up *Ph.D. Thesis* Imperial College London
[100] Kim H T *et al* 2013 *Plasma Phys. Controlled Fusion* **55** 124032
[101] Hada K *et al* 2015 *Fusion Sci. Technol.* **67** 693
[102] Horváth B *et al* 2017 *Plasma Sources Sci. Technol.* **26** 124001
[103] Lin M C, Zhou C and Smithe D N 2014 *IEEE Trans. Electron Devices* **61** 1742
[104] Schmidt F, Mussenbrock T and Trieschmann J 2018 *Plasma Sources Sci. Technol.* **27** 105017
[105] Yu S *et al* 2023 *Comput. Phys. Commun.* **282** 108468
[106] Liu J K *et al* 2022 *Phys. Plasmas* **29** 013508
[107] Chabert P 2007 *J. Phys. D: Appl. Phys.* **40** R63
[108] Chabert P *et al* 2004 *Phys. Plasmas* **11** 1775
[109] Chabert P *et al* 2004 *Phys. Plasmas* **11** 4081