Analysis of Breakdown Mechanisms in Heated Short Air Gaps During Contact Opening in Compact DC Circuit Breakers

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***Abstract*—DC commutative circuit breakers, characterised by their compact size and rapid commutation capabilities, are increasingly recognised for their potential in DC circuit interruption. However, challenges such as arc re-ignition significantly hinder their scalability. This paper reviews traditional predictive models for breakdown behaviours, particularly Paschen's Law and Critical Field Theory, to explore their adequacy in explaining the mechanisms behind re-ignition post-commutation. This research addresses the observed discrepancies between theoretical predictions and experimental results in compact LC commutative circuit breakers, particularly in scenarios involving rapid contact separation and the presence of hot gas in the gap. It proposes that the Critical Field Theory, due to the remaining noticeable background ionisation, more accurately describes the breakdown mechanism during contact opening. The proposed study integrates detailed modelling of temperature distribution, electrical phenomena associated with the arc, and airflow effects within the air gap, supported by experimental validations. The findings enhance our understanding of the electrical breakdown dynamics and provide insights into improving the design and reliability of DC circuit breakers.**

***Index Terms*—DC Circuit Breakers, Arc Re-ignition, Paschen's Law, Critical Field Theory, Air Breakdown**

I. Introduction

DC commutative circuit breakers, noted for their compact size and rapid switching capabilities, have emerged as a promising technology for interrupting DC power flows. Despite these advantages, their widespread application is hindered by persistent issues related to arc re-ignition [1], [2]. In experiments [1], [3], it was observed that the arcing between contacts and the current disappears briefly but then reappears, causing the arc to continue burning. Arc re-ignition is often associated with thermal runaway, which occurs when low conductivity, warm air is further heated by a low current [4]. This phenomenon remains poorly understood, particularly whether it occurs due to voltage levels exceeding the critical breakdown field, or as proposed in [1] current interruption criteria does not mach experiments in [1], indicating an arc re-ignition just after 10 μs from the current commutation. Conventional models like Paschen's Law and Critical Field Theory have historically been utilised to predict breakdown voltages [5]. Paschen's Law, an empirical formula, dictates the necessary voltage to initiate a discharge within a uniform electric field, considering the product of pressure and electrode distance (pd) as the key variable. This law reveals a minimum voltage threshold required to break a gap of any size [5], [6]. The theory primarily relies on Townsend's avalanche theory, which posits that pd is the controlling variable in discharge phenomena [7]. However, this model does not fully encompass the various factors contributing to gas ionisation under applied voltage conditions [5]. Recent studies have proposed modifications to this law by incorporating thermal effects to better predict breakdown scenarios under varying conditions [8]. Research by Loveless et al. [9] and Jang et al. [10] indicates that in gaps up to the few micrometres scale, the breakdown mechanism transitions from Townsend's avalanche to field emission [11]. This shift marks a pivotal change; the breakdown becomes predominantly dependent on the critical field strength, which varies significantly with temperature due to its impact on gas component density and the ionisation process involving attachment and detachment. This critical field is highly temperature-sensitive and becomes the primary determinant in such scenarios.

Despite the theoretical frameworks provided by both Paschen's Law and Critical Field Theory, there is a noticeable discrepancy in breakdown behaviours observed in experiments, as shown in Figure 1 and Figure 2, the gap distance variable and temperature significantly impacts the observed breakdown voltage. Even at ambient temperature, the experimental data sometimes aligns with the Critical Field Theory, as seen in Dandaron's data [8], while at other times, it follows Paschen's Law, as indicated by Toshiro's group testing [12]. Particularly for small distances under 100 micrometers, the majority of experimental breakdown voltage data falls between the two theoretical prediction lines. Therefore, the research question arises: which mechanism should be followed in explaining the re-ignition mechanisms post-commutation for LC commutator-based circuit breakers? The observed discrepancies challenge the theoretical frameworks provided by both Paschen's Law and Critical Field Theory, making it difficult to definitively explain the re-ignition process in such systems.

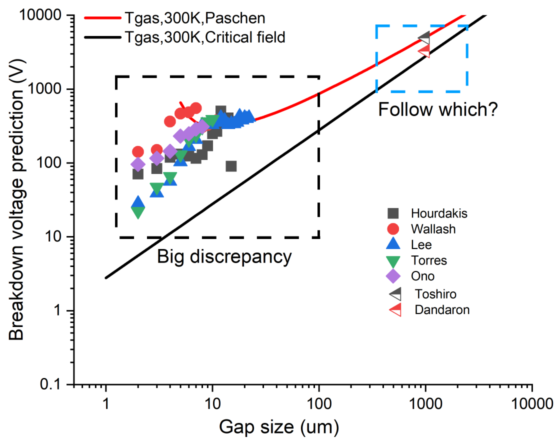

Fig. 1. Breakdown voltage predictions for 300K air using Paschen's Law and Critical Field Theory versus experimental data from [5], showing significant discrepancies in the micrometre gap size range

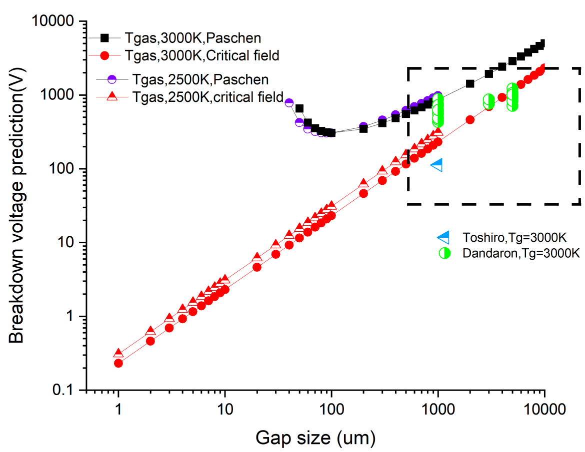

Fig. 2. Breakdown voltage predictions for 3000K and 2500K air using Paschen's Law and Critical Field Theory versus experimental data from [8] and [12], showing significant discrepancies in the millimetre gap size range

Our research seeks to understand whether the re-ignition phenomena in compact circuit breakers adhere to the expected theoretical pathways, particularly under conditions of rapid contact separation where hot gas mixed with metal vapour dominates the gap. This paper hypothesises that the presence of hot air significantly contributes to an average background electron density due to electrons' high diffusion coefficient, despite the presence of a colder boundary layer. We propose that the critical field theory is more applicable to the conditions within compact circuit breakers, particularly due to noticeable background ionisation shortly after contact separation.

This paper investigates these discrepancies by exploring the breakdown mechanisms in short air gaps during contact opening processes. The research incorporates a detailed modelling approach that accounts for the temperature distribution within the air gap and the electrical phenomena associated with the arc. Also, our model integrates the effect of airflow initiated upon contact opening, which cools the arc and potentially influences the breakdown process. The model was supported through experimental validations, and the findings demonstrate a promising alignment between model prediction with observed experimental data, offering new insights into the complex dynamics of electrical breakdowns in air gaps.

II. Model Formulation

A. Modified Paschen's Law

For a basic configuration involving two electrodes separated by a gas, Paschen's law that describes the electrical breakdown voltage V_B of a gas as a function of its pressure P in $[Torr]$, the distance d in $[cm]$ between two electrodes, and the gas composition [6], [11].

$$V_B = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]} \tag{1}$$

In Equation 1, γ_{se} represents the secondary electron emission influenced by ions from the electrode's material. Constants A and B are derived empirically for individual gases. For Air, A=15 $[1/cm/Torr]$, B=365 $[V/cm/Torr]$, γ_{se}=0.01 [13]. With increased gap distances and pressure, there's an approximate proportionality between the breakdown voltage and the product of pressure and gap distance. At extremely low pd values, Paschen's law suggests that initiating a discharge could be impossible. But contrary to this indication, a discharge can still happen, as its initial considerations overlook the certain effects of the surface field emission as well as temperature effect [14], as in Figure 1 and Figure 2. Hence, the first modification we took modified Paschen's law by linking the thermal effects.

$$V_{B_1} = \frac{Bpd\frac{T_0}{T_g}}{\ln(Apd\frac{T_0}{T_g}) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]} \tag{2}$$

Here, the reference temperature T_0 is 300K and T_g represents the temperature of the air gap. However, the experimental test results illustrate that Paschen's law is only applicable at 2200K [8]. Because the temperature in the gap remains higher than 2200K even after the current is commutated to the LC branch, it is necessary to investigate another mechanism to evaluate the breakdown voltage for the given temperature. The accurate prediction of gas breakdown in millimetre-scale gaps is crucial for post-commutating stages, the conventional method of predicting the breakdown voltage through Paschen's law fails in millimetre-scale gaps, the discrepancy arises because the mechanism driving the breakdown shifts from the Townsend avalanche to the field emission as highlighted by [9].

B. Critical Field Approximation

The calculations reveal that the reduced critical field of dry air remains relatively constant up to temperatures of 2000K, and decays linearly up to around 4000K, then reaches the constant value at the higher temperature as shown in Figure 3. The critical field is lower than the dielectric strength: the former allows ionisation to overcome attachment raising current conduction in the gas, and the latter is affected by electron losses mainly due to diffusion to the areas around the streamer head [13]. In the case of significant background ionisation, the diffusion losses play a smaller role and the breakdown happens at the critical field. This observation is grounded in data from published experiments as [15]. Beyond 2000K, we have extrapolated the critical reduced breakdown field values using simple mathematical interpolation to predict their behaviour. The reduced electric field strength is denoted

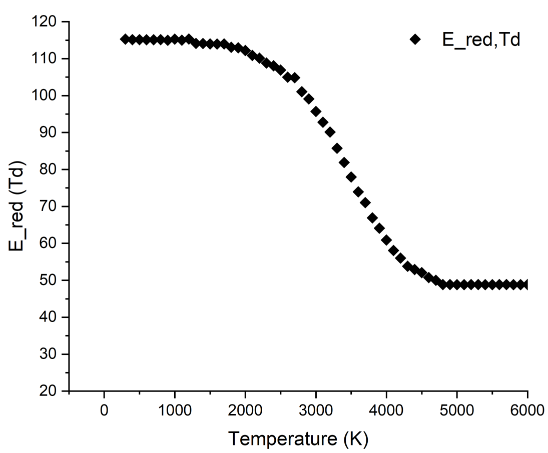

Fig. 3. The relationship between critical field and temperature adapted from [15]

as E_{red}, signifies the net electric field effect resulting from the attachment and detachment processes of charged particles within air during electrical breakdown. This field strength is typically measured in Townsend Td, with one Townsend $1Td$ being equivalent to $1 \times 10^{-21} \left[V \cdot m^2\right]$ [15].

Consequently, the critical electric field for breakdown, E_{critical}, can be calculated using the following equation:

$$E_{\text{critical}} = E_{\text{red}} \cdot N(T_g) \cdot Td \tag{3}$$

where E_{red} represents the reduced electric field, $N(T_g)$ is the number density of particles at temperature T_g.

The number density $N(T_g)$ can be determined by:

$$N(T_g) = \frac{P}{K_b \cdot T_g} \quad [1/m^3] \tag{4}$$

where P is the pressure, K_b is the Boltzmann constant, and T_g is the gas temperature.

By combining the equations for the reduced electric field and the number density, the breakdown field can be accurately calculated. To calculate the breakdown voltage in the uniform electric field across the electrode gap, the equation is formalised as:

$$V_{B_2} = E_{\text{critical}} \cdot d \tag{5}$$

where d signifies the total gap distance in m. This calculation provides a more accurate estimation of the breakdown voltage by accounting for the temperature distribution between the electrodes.

III. Model Implementation

A. Modelling of Thermal Plasma

Our research utilises established plasma simulation methods governed by Magnetohydrodynamic (MHD) principles, with the system dynamics derived from the fundamental conservation laws for mass, momentum, and energy as detailed work in [16]. These are expressed through fluid flow differential equations and supplemented by Maxwell's equations to capture electromagnetic phenomena including electrical potential, current density, and magnetic flux density [17]. To estimate radiation-induced energy losses, we employ the Net Emission Coefficient (NEC) method [18]. The simulated geometry features two symmetric cylindrical electrodes, set within a cylindrical air domain, maintaining consistency with the detailed thermal plasma model settings from previous publication [19], the computational domain are detailed as Figure 4. Notable adjustments in this model include the gap size between the two electrodes, which starts at $40\mu m$, and a modified sheath layer thickness, reduced to $0.01mm$ in response to the decreased gap size. These refinements are designed to verified the model by the experimental data from [1], [2].

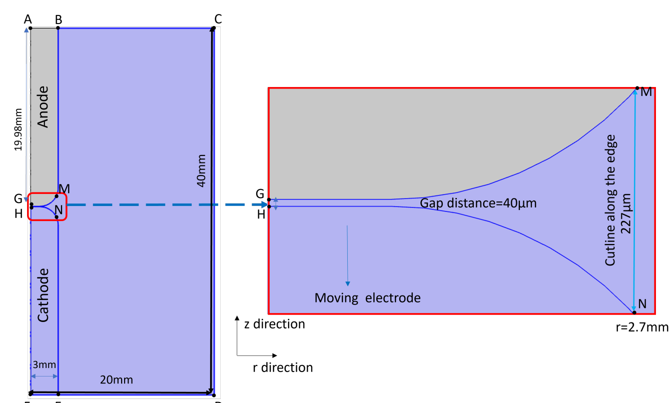

Fig. 4. Details of computational domain of two cylindrical electrode circuit breakers, anode and cathode are made by copper, remain is air domain, the initial gap size is $40\mu m$, and one example of a defined 2D cut-line is marked as $227\mu m$ when electrodes radius is 2.7mm

B. Moving Contacts Coupling

This model is designed to simulate the dynamics of electrode movement during contact separation in a circuit breaker. The separation process is characterised by applying a specific velocity to the cathode, and the moving mesh method is utilised to manage this dynamic interaction. In Figure 4, the domain undergoing deformation is highlighted in purple, indicating the area affected by the motion. Despite the movement, the overall computational domain remains fixed, with changes in the area of the cathode effectively representing the electrode's motion. Boundary conditions are set as follows:

- Symmetry/Roller condition is set to HG, HF, NE.
- Prescribed mesh displacement: $dr = 0$ in r direction, $z(t) = z_0 + V_e \times t$, in this case, z_0 is 40 μm as initial gap size and the V_e is moving velocity and specify to top surface of cathode boundary HN.
- Fixed boundary is specified to anode surface boundary BMG and the whole external boundary BC,CD,DE,EF.

C. Commutation Circuit Description

The thermal plasma model is integrated with an external LC commutation circuit to accurately simulate the DC interruption process in commutative circuit breakers as shown in Figure 5. The schematic diagram features three branches: The main

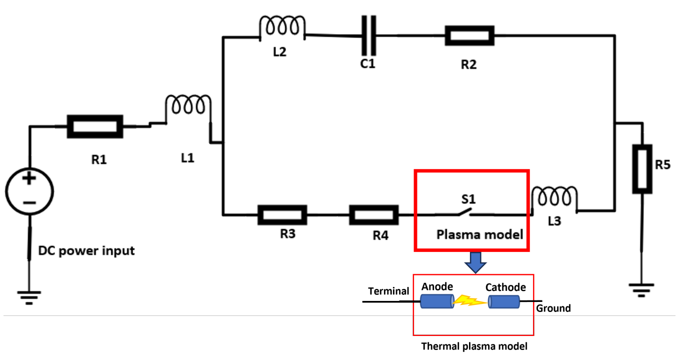

Fig. 5. Schematic of the equivalent electric circuit of circuit breaker coupled with physical thermal plasma model

branch includes a DC power supply, a transmission line resistance R_1, an inductance L_1, and a small resistance R_5 that represents the connecting wire resistance. The commutation branch contains a smaller inductance L_2 and a capacitor C_1 forming an oscillatory circuit designed to transfer the fault current into this branch. It also includes R_2, which represents the line resistance of the LC branch. The circuit breaker branch consists of three components—connecting wires, an arc sheath, and an arc core—represented by R_3, R_4, and the terminal coupled with a thermal plasma model (R_{gap}), respectively. A small inductance L_3 is included in this branch to enhance the model's stability by emulating the inductance of this branch. The circuit parameters are detailed in the study [19].

In this updated approach, the arc sheath effect in R_4 is monitored by measuring the interface surface temperature between the hot plasma and the electrodes, utilising two probes at Point G and Point H in Figure 4. An approximation is devised to establish a more realistic dependence of sheath voltage on arc current with a model voltage V_b(I). This setup accounts for the real circuit behaviours, where, the voltage drop across the sheath increases for small currents. Consequently, the voltage in the sheath, calculated as $I \times R_{\text{gap}}$, cannot exceed a specified 'breakdown' voltage V_b. Any arc voltage exceeding V_b leads to current rise and associated reduction in arc voltage.

IV. Results Discussion and Verification

A. Results for larger air gaps with moving electrodes

According to the experimental test data from [2], the experiments indicate a failed current breaking at 1.4 kV DC. The results demonstrate that once the gap is opened, it takes approximately 30 to 40 μs to complete the current commutation process putting the arc current to zero. During this short time a hot air is formed in a small gap. However, re-ignition is observed 200 μs later, with the re-ignition voltage approximately 700 V. In our model, the v_e contacts separation velocity is set as $5m/s$ to the bottom electrodes as the experiment setting.

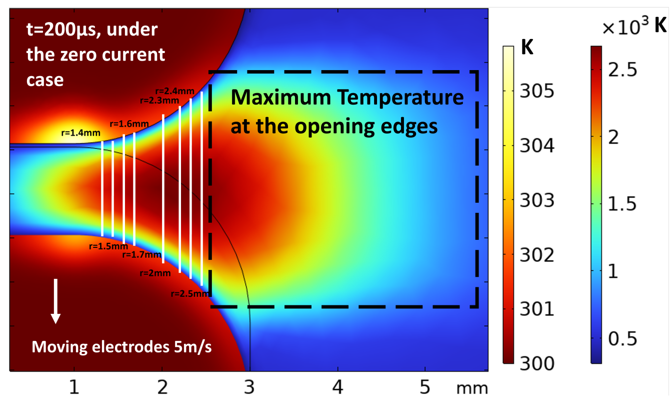

Fig. 6. Temperature distribution in Kelvin (K) between 1mm gap size with moving velocity is $5m/s$, t=200μs, illustrating the maximum temperature at the opening edges, the first color bar represents the temperature of the electrodes, and the second color bar represents the temperature of the plasma.

In our model, we observed that after the circuit disconnection, the gap between the two electrodes remains relatively cold, while the hottest part concentrates around the curved edges of the electrodes as Figure 6. To evaluate the maximum voltage that this region can withstand, we defined several cut lines across the air gap for assessment as shown in Figure 6. The temperature distribution across different cut-lines is illustrated in Figure 7. After circuit disconnection, the gas temperature in the gap remains below 2500K. The bottom electrodes exhibit lower temperatures because the movement of the electrodes draws cold surrounding air into the gap. The hottest position is identified at cutline 6 (r=2.5mm). Upon determining the temperature of the gas, and in combination with Equation 4 and Equation 3, then the breakdown voltage across the gap could be calculated as Equation 6.

$$V_{br} = \int_0^{\text{Gap size}} E_{\text{critical}}(T(z))\, dz \tag{6}$$

The predicted breakdown voltages are listed in the figure 8 according to various prediction mechanisms. Our results

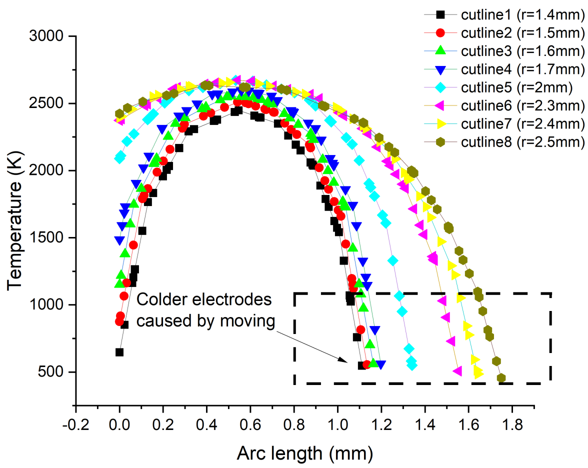

Fig. 7. Temperature distribution along the cut-line across the hottest part of gap, colder electrodes are observed because of moving

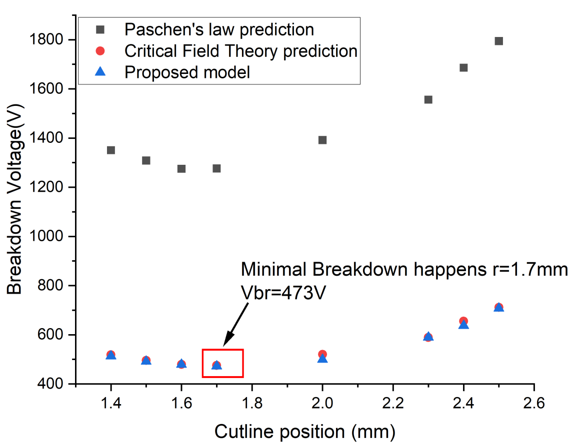

Fig. 8. Predicted Breakdown Voltage across the different cut-line for large gap size, illustrating the minimal breakdown happens at r=1.7mm and the breakdown voltage is around 473V, both Paschen Law and Critical Field models use an average temperature, whereas the proposed model takes into account variation in the gap

indicate that the minimal breakdown occurs at r=1.7mm, with a breakdown voltage of 473V in our model. We find that the breakdown is highly dependent on the position of the cutline. Experimentally, the breakdown occurs at 700V, which deviates significantly from the predictions of Paschen's law. However, the critical field theory provides a plausible explanation for the breakdown occurrence, though some discrepancies remain.

One potential cause for this discrepancy is that, in our simulation, the electrode geometry is different from the experiment and also our modelling domain is quite small with strong effects of the boundary conditions. This is discussed further in the analysis section.

B. Results for short air gaps within fixed electrode

Another re-ignition scenario was examined by [1], which documents a failed commutation at 430A and C_1=208μF. Their observations indicated that although the switch current decreased rapidly, reached zero for a short time and continued to oscillate. Based on the test results the re-ignition happens at 21μs, which contains 14μs for switching and 7μs for arc cooling. Therefore, their setup's calculated breakdown voltage for the 430A scenario is approximately 43V. In our model, we

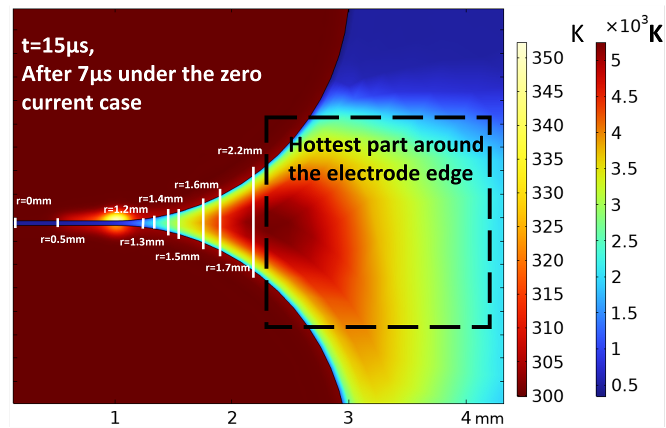

Fig. 9. Temperature distribution in Kelvin (K) between 40μm, t=20μs, showing the very fast cooling between two electrodes, the first color bar represents the temperature of the electrodes, and the second color bar represents the temperature of the plasma.

trace the voltage and current behaviours and the switching finished within 8μs, hence, we select t=15μs to discuss thermal phenomena after 7μs cooling as the experimental setup in [1]. Also, several cut-lines with different r positions are marked in Figure 9, the air gap along the axis cools down very quickly. This rapid cooling suggests that for small gaps, typically on the micrometre scale, arc formation is highly influenced by the geometry of the electrodes. Our model captures the behaviour of arc ignition and its subsequent motion, starting with the spark formation in the middle of the air gap. The arc then shifts to the edge of the electrodes where is either decay or re-ignition. And after re-ignition arc moves back to the center between the two electrodes. This behaviour aligns with experimental observations, which report that arcing often occurs on the sides of the contacts [20].

Modelling results of the temperature distributions along the axial symmetry line and at the hottest cut-line are depicted in Figure 10. The calculated breakdown voltages are shown in Figure 11. The results show that the minimum breakdown occurs at r=1.2mm with a breakdown voltage of around 42.7V. This finding indicates that the breakdown does not happen at either the hottest or coldest part of the gap. The breakdown voltage along the axis is quite similar at r=2.2mm, which can be attributed to several factors. Although the symmetry line has a cooler average temperature resulting in a higher critical field, the breakdown voltage is also influenced by the small 40μm gap distance. Conversely, the hottest part exhibits a

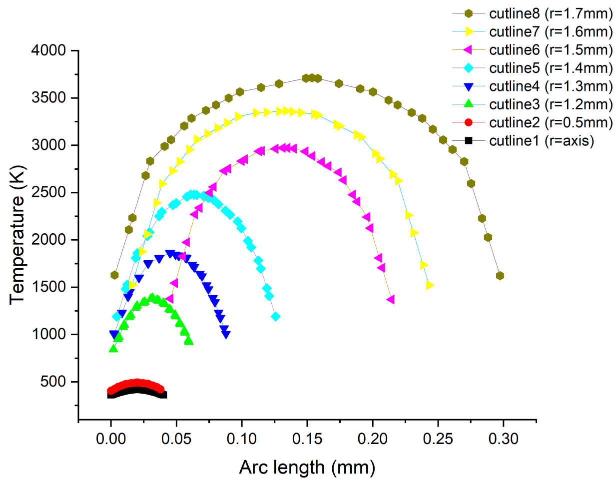

Fig. 10. Temperature distribution along the cut-line across, illustrating that the coldest air is between electrodes, the hottest part is around the electrode edge

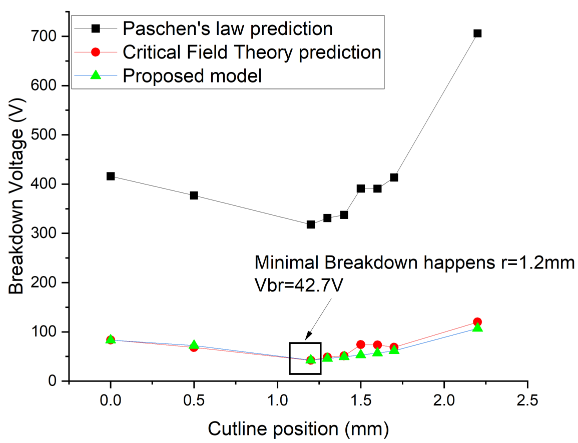

Fig. 11. Predicted Breakdown Voltage across the different cut-line for large gap size, illustrating the minimal breakdown happens at r=1.2mm and the breakdown voltage is around 42.7V, both Paschen Law and Critical Field models use an average temperature, whereas the proposed model takes into account temperature variation in the gap

much higher temperature and a lower critical field, but the length of the cut-line extends to 227μm due to the filleted shape of the electrodes, effectively increasing the breakdown voltage despite the lower critical field. These observations highlight the complexity of the breakdown process, where multiple factors, including temperature distribution and gap geometry, interplay to determine the breakdown voltage.

C. Comparison for model prediction with experimental data

Based on the comparison results presented in the Table I, it is evident that the Critical Field Theory is the primary mechanism driving the breakdown in the observed phenomena. Our model, which integrates Vbr(T(z)), has demonstrated relative accuracy in predicting the breakdown voltages. For small air gaps, the model shows good agreement with experimental data. Although there are some discrepancies between our model's predictions and the experimental data for large air gaps, the observed breakdown occurs between the predictions of Paschen's Law and the Critical Field Theory. The dominant mechanism driving the breakdown for large gap sizes remains unclear. These discrepancies are likely due to differences in the geometry of the experimental device; the model is axis-symmetrical, whereas the real device is three-dimensional. Specifically, the experimental setup uses the shape of the rectangular electrodes for a smooth sliding as shown in Figure12, which may affect the cooling rate and subsequently the breakdown characteristics. Another observation is that the minimum breakdown voltage is dependent on both temperature and distance. The position of the breakdown path varies, highlighting the importance of modelling due to temperature variations. While experiments can indicate the breakdown characteristics in a particular setup, for modified geometry accurate modelling can yield more precise breakdown voltage values.

Despite the limitations, our model provides a plausible explanation for the behaviour observed in compact circuit breakers, particularly the re-ignition phenomena. The data shows that the re-ignition is mainly driven by the Critical Field Theory, whereas Paschen's Law predictions are significantly off from the experimental results. We hypothesise that the effectiveness of Critical Field Theory during these short time intervals after current commutation can be attributed to the noticeable remaining background ionisation that occurs shortly after contact separation. It takes some time for electrons to be attached to the atoms and high temperature slows down the process. This high background ionisation facilitates the breakdown process, making Critical Field Theory a more accurate predictor in these scenarios.

The final verification was conducted using the published data on failed current interruption [1]. Unfortunately, the data only include max possible interrupted current for a given circuit parameter. The Critical Field model allows us to calculate the average gas temperature at which the breakdown was observed and compare it with MHD simulations. The failed commutation experimental data for maximum commutation current, according to different capacitance, could be replicated as shown in Table II. This replication is a strong indicator that our model can be used for circuit breaker design and supports the conclusion that the breakdown mechanism for compact circuit breakers with short gaps is driven by the Critical Field Theory.

But at the initial opening stage, it is worth noting that the Critical Field model works very well for short times/small gaps, with the gap increases we can see the increase in the breakdown voltage towards Paschen Law predictions, but still the breakdown voltages are much lower. As time progresses, the background ionisation reduces and a higher voltage is needed for the breakdown. Eventually, for large gaps after longer opening, the breakdown voltages are going to approach

TABLE I
EXPERIMENTAL OBSERVATIONS AND MODEL PREDICTIONS COMPARISON

Breakdown Prediction Methods	**Paschen's Law Prediction (VB_1) at average temperature**	**Critical Field Theory Prediction (VB_2) at average temperature**	**Our Model Integration Vbr(T(z)), minimal value**
Experimental Observation			
Case 1: 200µs, 1.4kA current, 1mm gap, 700V, re-ignition			
Model Prediction Results	T average = 2080K VB_1 = 1276.3V	T average = 2080K VB_2 = 475V	Vbr = 472.58V
Case 2: 21µs, 430A current, re-ignition, breakdown at 43V			
Model Prediction Results	T average = 1177K VB_1 = 318V	T average = 1177K VB_2 = 42.3V	Vbr = 42.668V

the Paschen Law values. The critical Field Theory effectively explains the breakdown and re-ignition phenomena in compact circuit breakers, especially for small air gaps within a sub-millimetre scale. Our model, despite minor discrepancies due to geometric differences, aligns well with experimental observations and supports the dominance of Critical Field Theory in these events. Conversely, Paschen's Law predictions are far removed from the observed reality, highlighting the need for models that consider the electron recombination dynamics in predicting breakdown behaviours.

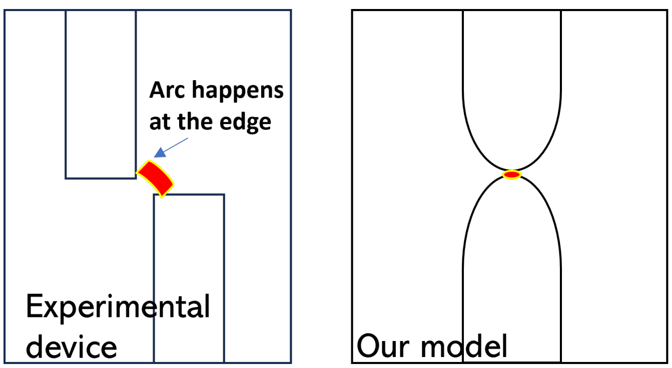

Fig. 12. Comparison of geometry differences between the experimental device and our model, simplified 2D model with symmetrical contacts was used for efficiency and stability.

V. Conclusion

This paper revisits the application of electrical breakdown theory for short gaps filled with hot ionised air. Our study focused on two widely used theories: the adjusted Paschen's law for elevated temperatures and the Critical Field Theory. By contrasting modelling and experimental data, our analysis indicates that the Critical Field Theory is more applicable in describing the phenomena of contact openings in short air gaps within the 1 mm distance frame. We hypotheses that the effectiveness of Critical Field Theory during these short time intervals and small gaps is likely due to significant background ionisation shortly after contact separation. While our findings validate the Critical Field Theory for short durations, the potential applicability of Paschen's Law for longer intervals and times remains uncertain and warrants further exploration. Additionally, the breakdown behaviour is highly dependent on

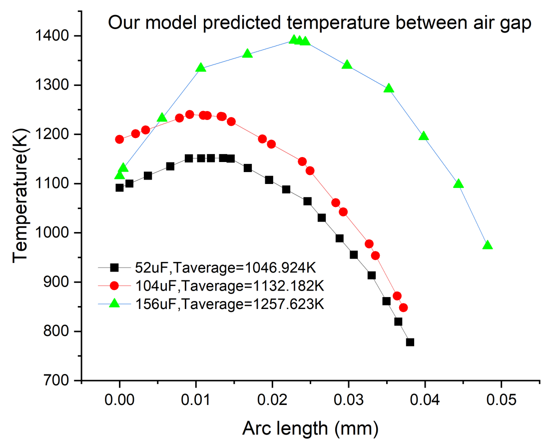

Fig. 13. The model temperature prediction in the air gap demonstrating close alignment with Table II and validating the model's predictive capability

the temperature distribution in the vicinity of the electrodes, combining the effects of the variations in temperature and breakdown path length. The proposed model qualitatively agrees with the experiments. To address the transition law between the Paschen curve and critical field theory, a more complex plasma model is required. This advanced model should account for the remaining electron density in the hot air gap and its interaction with the electric field, which may lead to ionisation avalanches. It should also include the dynamics of ionisation, recombination, electrons attachment and avalanches development in high electric fields and consider non-uniform initial electron densities due to temperature variations in the gap. This comprehensive approach will help us better understand the transition between critical field theory, which is predictable over short timescales, and Paschen's law, which applies to larger gaps.

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TABLE II
COMPARISON OF MODEL PREDICTION BASED ON BREAKDOWN MECHANISM OF CRITICAL FIELD THEORY VERSUS EXPERIMENTAL DATA FOR MAXIMUM COMMUTATION CURRENT COMPARED WITH TEMPERATURE PREDICTION IN FIGURE 13

Capacitance (uF)	**Current (A)**	**Temperature (K)**	**Our model prediction, time selection**	**Breaking point**
Experimental data Failed commutation		**Expected Average Temperature at Breaking Point**		
52	125.5	1050	$2\mu s$ commutation, $7\mu s$ cooling, t=$9\mu s$	r=0.9mm
104	239	1100	$3\mu s$ commutation, $7\mu s$ cooling, t=$10\mu s$	r=0.95mm
156	319	1250	$4\mu s$ commutation, $7\mu s$ cooling, t=$11\mu s$	r=1mm
208	417.5	1250	$7\mu s$ commutation, $7\mu s$ cooling, t=$15\mu s$	r=1.2mm

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