

MICROWAVE-ASSISTED FREEZE-DRYING: PHYSICAL LIMITATIONS AND PLASMA-AWARE SYSTEM ARCHITECTURE

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Abstract. Microwave-assisted freeze-drying represents a promising approach to overcome fundamental limitations of conventional sublimation processes, which are constrained by slow heat transfer through dry porous layers and significant energy losses. The integration of microwave energy enables volumetric heating of the product through direct interaction with water molecules, allowing accelerated sublimation and improved energy efficiency. However, the application of high-frequency electromagnetic fields in low-pressure environments introduces critical physical challenges associated with gas ionization and electrical discharge formation. In water vapour atmospheres typical of sublimation processes, reduced ionization energy, strong dipole interaction, and enhanced microwave absorption significantly lower the breakdown voltage, increasing the probability of glow discharge and arc formation. These phenomena can develop on microsecond timescales and pose a severe risk to power electronics, sensors, and vacuum components. This paper analyses the physical limitations of conventional freeze-drying, justifies the need for microwave-assisted approaches, and investigates the fundamental mechanisms of discharge formation under relevant operating conditions. Based on this analysis, a system-level engineering concept is proposed within the SubliMik project, integrating controlled microwave power delivery, real-time discharge risk mitigation, and microwave-compatible sensing. The presented approach demonstrates that successful implementation of microwave-assisted sublimation requires not only improved energy transfer methods but also a fundamentally new architecture combining plasma-aware design, fast control systems, and electromagnetic compatibility strategies.

Keywords: freeze-drying, microwave heating, gas discharge, vacuum systems, sublimation.

Introduction

Freeze-drying (lyophilisation) is widely used in food processing, pharmaceuticals, and biotechnology due to its ability to preserve structure, bioactive compounds, and product quality. The process is based on sublimation of ice under reduced pressure, requiring continuous heat input to sustain the phase transition from solid to vapour. In conventional systems, heat is supplied through conduction and radiation via heated shelves and trays. However, as sublimation progresses, a dry porous layer forms on the product surface, significantly reducing its thermal conductivity. This creates a fundamental limitation in heat transfer, resulting in long process durations and high energy consumption [1].

The slow propagation of heat through the dried layer leads to non-uniform temperature distribution and limits the rate of sublimation. As a result, typical industrial freeze-drying cycles may last tens of hours, making the process economically inefficient for many applications. These limitations have motivated the exploration of alternative heating methods capable of delivering energy directly to the sublimation front.

Microwave-assisted freeze-drying has emerged as a promising solution due to its ability to provide volumetric heating. Microwave radiation interacts directly with polar molecules, particularly water, enabling energy absorption within the product volume rather than only at its surface. This allows more efficient heating of the frozen core, reduces thermal gradients, and significantly increases drying rates while improving energy efficiency [1-3]. Previous studies have demonstrated that controlled microwave energy input can enhance process uniformity and reduce cycle duration, making this approach attractive for industrial implementation [2; 3].

Despite these advantages, the integration of microwave energy into vacuum sublimation systems introduces a fundamentally different physical regime. Under low-pressure conditions (typically 0.3-1.5 mbar), the presence of water vapour and organic compounds creates an environment highly susceptible to electrical discharge phenomena. According to gas discharge theory, the breakdown voltage of a gas depends on the product of pressure and electrode distance, as described by Paschen's law [5]. In water vapour, this breakdown voltage is significantly lower than in air due to reduced ionization energy and strong dipole interactions, increasing the probability of discharge initiation [6; 9].

Moreover, microwave electromagnetic fields introduce additional complexity compared to static electric fields. Oscillating fields at 2.45 GHz can produce localized field enhancement near dielectric interfaces, geometric discontinuities, and regions with elevated vapour density. These effects promote electron avalanches, glow discharge, and rapid transition to arc discharge, which can develop within microseconds and cause severe damage to power electronics, sensors, and vacuum components [6; 8].

Water vapour plays a particularly critical role in this process. Its polar molecular structure and high microwave absorption cross-section lead to enhanced coupling with electromagnetic fields and localized energy deposition. In addition, the presence of volatile organic compounds released during sublimation further reduces the effective ionization threshold, increasing discharge probability [9; 10]. As a result, the operating conditions of microwave-assisted freeze-drying systems often coincide with the region of minimum breakdown voltage, making discharge prevention a primary design challenge.

Therefore, the successful implementation of microwave-assisted freeze-drying requires not only improved energy transfer mechanisms but also a comprehensive understanding of plasma-related phenomena and their interaction with system components. This necessitates a system-level approach combining physical modelling of discharge processes with engineering solutions for power control, sensing, and electromagnetic compatibility.

A survey of the available scientific literature indicates that, although several hundred publications can be identified using keywords related to microwave-assisted freeze-drying, the majority of these works consist of review articles, theoretical analyses, mathematical modelling studies, patent descriptions, or laboratory-scale proof-of-concept investigations focused primarily on drying kinetics and energy efficiency.

After excluding general review papers, conceptual publications without experimental validation, studies not operating under true sublimation conditions (below 0 °C and pressures around 0.3-1.5 mbar), and publications lacking detailed system-level implementation analysis, the number of experimentally validated microwave-assisted sublimation systems described in the open scientific literature remains very limited.

Furthermore, publications addressing coupled problems of microwave field distribution, discharge formation, electromagnetic compatibility, high-voltage stability, and integrated process control under low-pressure water vapour conditions are extremely rare.

This imbalance between theoretical interest and practical implementation strongly suggests that the principal difficulty of microwave-assisted sublimation lies not in the individual physical principles themselves, but in their simultaneous realization within a technically stable, controllable, and economically feasible industrial system.

Practical industrial implementation of such systems remains extremely limited. Although several manufacturers, including EnWave Corporation, PÜSCHNER GmbH + Co KG, and Jinan Talin Tech Co., Ltd., offer microwave-assisted vacuum drying systems, these installations operate mainly above 0 °C and are intended for vacuum drying rather than true sublimation drying under freeze-drying conditions.

At present, no widely available commercial industrial system is known to the authors that performs stable microwave-assisted sublimation at product temperatures below 0 °C and pressures around 0.3-1.5 mbar, which are typical for freeze-drying processes. This suggests that the principal barriers are not associated with microwave heating itself, but with the complexity of implementing stable technical solutions for discharge prevention, electromagnetic compatibility, vacuum stability, microwave field control, and integrated process management under low-pressure water vapour conditions at a cost acceptable for industrial application.

One of the very few publicly documented advanced developments toward practical realization is a prototype microwave-assisted freeze-drying system developed by a consortium involving the Technical University of Munich and GEA Group AG for pharmaceutical applications (Fig. 1). However, this prototype is characterized by relatively large dimensions and high system complexity. The installation does not include active cooling of product samples, but instead uses a nitrogen trapping system installed before the vacuum pump. The estimated cost of such a system is approximately 1 million EUR, and the technology is not currently offered as a standard industrial solution, but rather as part of specialized development activities for specific customer applications.

Although this prototype demonstrates the technical feasibility of microwave-assisted sublimation, its applicability to economically viable large-scale food industry processing remains uncertain without substantial simplification of system architecture and significant reduction of implementation costs.



Fig. 1. Technical University of Munich and GEA Group AG prototype of microwave-assisted freeze-drying system for pharmaceutical applications

The SubliMik project addresses these challenges by developing a new generation of sublimation equipment with integrated microwave heating, focusing on both process efficiency and operational safety. The objective of this paper is to justify the need for microwave-assisted sublimation, analyse the key physical and technical challenges associated with this approach, and present a system-level architecture that enables reliable operation under discharge-prone conditions.

Materials and methods

The methodological approach of this study is based on a combined physical and engineering analysis of microwave-assisted freeze-drying under low-pressure conditions. The investigation focuses on identifying fundamental limitations of conventional sublimation, analysing the interaction between microwave electromagnetic fields and water vapour, and formulating system-level design principles that enable safe and efficient operation.

Physical basis of sublimation and heat transfer limitations. Freeze-drying is governed by coupled heat and mass transfer processes. It is an endothermic process in which ice sublimates directly into vapour under reduced pressure. Equation (1) shows, that the rate of sublimation is governed by the heat flux delivered to the sublimation front and the mass transfer of vapour away from the product:

$$\dot{m} = \frac{q}{L_s}, \quad (1)$$

where \dot{m} - sublimation rate, $\text{kg}\cdot\text{s}^{-1}$;
 q – heat flux to the sublimation front, W;
 L_s – latent heat of sublimation, $\text{J}\cdot\text{kg}^{-1}$.

As shown in the equation (2), in conventional systems, heat is transferred by conduction from heated shelves through the dry porous layer:

$$q = -k_{eff}\nabla T, \quad (2)$$

where k_{eff} – effective thermal conductivity of the dried product, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$;
 ∇T – temperature gradient.

As drying progresses, k_{eff} decreases significantly due to porosity, leading to increased thermal resistance and reduced heat flux, i.e. reducing effective heat transfer to the frozen core. This creates a fundamental bottleneck in conventional freeze-drying systems, limiting process speed and efficiency [1]. This limitation can be expressed qualitatively by the decrease in effective thermal conductivity of the product, resulting in a temperature gradient between the surface and the sublimation interface. Consequently, the drying rate becomes controlled by heat diffusion through the dry layer, leading to long process durations and inefficient energy utilization (Fig. 2).

In practical industrial processing, this limitation is often compensated by increasing product temperature, which partially destroys thermally sensitive nutritional compounds and effectively transforms the process into hot vacuum drying rather than true freeze-drying.

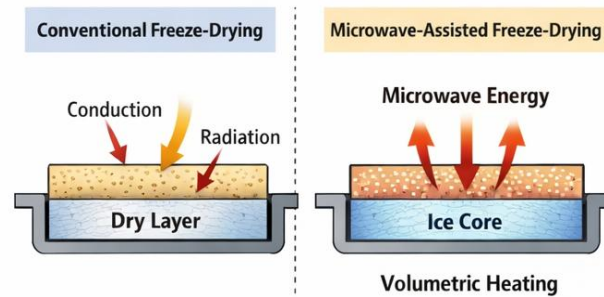


Fig. 2. Heat transfer mechanisms in conventional and microwave-assisted freeze-drying

Microwave energy interaction with product and vapour phase. Microwave-assisted freeze-drying introduces volumetric heating, where electromagnetic energy at 2.45 GHz is absorbed directly by polar molecules, primarily water. The interaction is governed by dielectric heating mechanisms, in which oscillating electric fields induce rotation of molecular dipoles and generate internal heat within the material. The equation (3) describes this process:

$$P_v = 2\pi f \epsilon_0 \epsilon'' E^2, \quad (3)$$

where P_v – volumetric power density, $\text{W}\cdot\text{m}^{-3}$;
 f – microwave frequency (2.45 GHz);
 ϵ_0 – vacuum permittivity;
 ϵ'' – dielectric loss factor;
 E – electric field strength.

Unlike conductive heating, this mechanism allows direct energy deposition within the product volume, microwave energy is delivered directly to the frozen core, reducing thermal gradients and bypassing thermal resistance of the dry layer and increasing sublimation efficiency [1-3].

However, dielectric properties depend strongly on moisture content and vapour distribution, and non-uniform field distribution arises, due to variations in dielectric properties, product geometry, and vapour concentration resulting in spatially non-uniform power absorption and localized field intensification.

In the vapour phase, water molecules exhibit strong microwave absorption due to their permanent dipole moment. This results in localized energy deposition, particularly in regions of high vapour density near the product surface. The combined effect of volumetric heating and vapour-phase interaction creates spatially non-uniform electromagnetic fields, which can lead to arc discharge and must therefore be considered in system design.

Gas discharge mechanisms in low-pressure water vapour. At the operating pressures typical for freeze-drying (0.3-1.5 mbar), the gas environment is highly susceptible to electrical breakdown. The breakdown voltage is described by Paschen's law, which relates the voltage required for discharge initiation to the product of gas pressure and electrode distance [5]. In this pressure range, the system often operates near the Paschen minimum, where breakdown voltage is lowest. Paschen's law, given by Eq. (4), describes the relationship between breakdown voltage, pressure, electrode gap, and secondary electron emission.

$$V_b = \frac{Bpd}{\ln(Apd) - \ln(\ln(1 + \gamma^{-1}))}, \quad (4)$$

where A – Townsend ionization coefficient constant, $\text{Torr}^{-1}\cdot\text{cm}^{-1}$;
 B – breakdown constant, $\text{V}\cdot\text{Torr}^{-1}\cdot\text{cm}^{-1}$;
 p – pressure, Pa;
 d – electrode gap, m;
 γ – secondary electron emission coefficient.

The equation (4) for the case of water vapor is illustrated in Fig. 3.

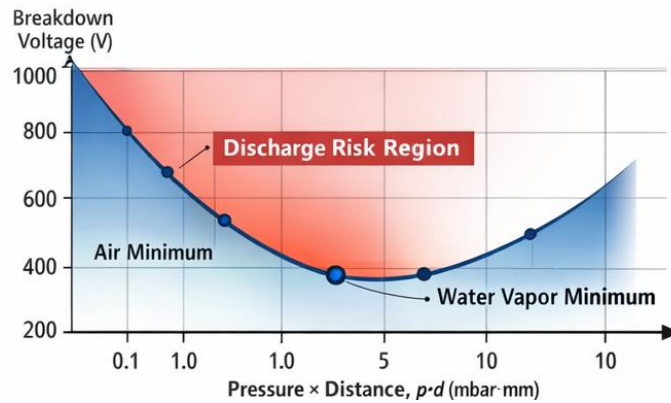


Fig. 3. Paschen curve for water vapour indicating the discharge risk region in typical sublimation conditions

Water vapour significantly alters discharge behaviour compared to air. Due to its lower ionization energy and polar molecular structure, water vapour facilitates electron-impact ionization and enhances energy coupling with electromagnetic fields [6; 9]. As a result, even moderate electric field strengths can initiate ionization processes. For water vapour constants A and B are significantly lower than for air, resulting in breakdown voltages as low as 300-480 V in the relevant pressure range.

Electron avalanche and plasma development. The discharge development follows a sequence of physical stages: initial electron generation, Townsend avalanche multiplication, transition to glow discharge, and eventual formation of a thermal arc. The transition between these regimes is governed by ionization rate, electron density, and local electric field strength [6; 8]. In microwave fields, these processes are further accelerated by oscillating electric fields, allowing discharge development on microsecond timescales.

Additional factors influencing discharge formation include the presence of volatile organic compounds released during sublimation, surface irregularities, and dielectric interfaces. These factors reduce the effective breakdown threshold and create localized regions of field enhancement, increasing the probability of discharge initiation [9; 10].

The initial stage of discharge is governed by the Townsend avalanche development mechanism, which is described by the equation (5):

$$n(x) = n_0 e^{Ax}, \quad (5)$$

where $n(x)$ – electron density;
 n_0 – initial electron density;
 x – distance in the electric field direction.

The transition to self-sustained discharge occurs when:

$$\gamma(e^{Ad} - 1) = 1, \quad (6)$$

The condition defined by Eq. (6) determines the onset of glow discharge, which can rapidly evolve into arc discharge if energy input continues [6; 8].

Mean free path and pressure regime analysis. Electron and ion motion in low-pressure gas is characterized by the mean free path:

$$\lambda = \frac{k_B T}{\sqrt{2} \pi d_m^2 p}, \quad (7)$$

where k_B – Boltzmann constant;
 d_m – molecular diameter, m.

As follows from the equation (7), at pressures of 0.3-1.5 mbar, the mean free path becomes comparable to system geometries (sub-millimeter scale), enabling efficient electron acceleration and ionization, which enhances discharge probability.

Microwave field effects and plasma coupling. Unlike static fields, microwave fields oscillate at high frequency, modifying electron trajectories and energy gain. The effective ionization condition depends on the ratio E/p , which determines the energy gained between collisions. In water vapour, strong dipole interaction and high dielectric loss increase local electric field coupling, especially near dielectric interfaces [9].

Additionally, localized increases in relative permittivity lead to field enhancement, as shown in the equation (8):

$$E_{local} \approx \varepsilon_r E_{avg}, \quad (8)$$

where ε_r – relative permittivity, resulting in hot spots and increased discharge risk.

Engineering methodology for discharge-aware system design. Based on the described physical mechanisms, the engineering methodology focuses on preventing transition from pre-breakdown ionization to arc discharge. The key design principles include:

- maintaining operating conditions outside critical $p \cdot d$ regions where breakdown voltage is minimal;
- controlling electric field intensity and spatial distribution within the chamber;
- detecting early-stage ionization through indirect indicators of plasma formation;
- implementing rapid interruption of microwave power to suppress avalanche growth;
- ensuring electromagnetic compatibility of sensors and control systems.

System-level modelling approach. The SubliMik system is modelled as a coupled multi-physics system integrating:

- heat transfer and sublimation kinetics;
- electromagnetic field distribution;
- gas discharge dynamics.

The system architecture is represented as a closed-loop control system, where feedback from pressure, temperature, and discharge indicators is used to regulate microwave power and maintain stable operation.

In addition to theoretical analysis, the SubliMik project includes laboratory-scale realization and validation of critical technological subsystems at TRL4 level (Fig. 4).



Fig. 4. Laboratory-scale model of microwave-assisted sublimation system developed within the SubliMik project

An experimental microwave-assisted sublimation platform was developed, integrating:

- vacuum chamber with microwave-transparent product container;
- four magnetrons with rectangular waveguides;
- controlled high-voltage PWM power supply;
- rotating product support system;
- automatic vacuum pressure regulation system;

- microwave field redistribution reflector;
- infrastructure for arc sensor integration.

During laboratory experiments, several engineering limitations specific to microwave-assisted sublimation under vacuum conditions were experimentally identified and analysed, including:

- reflected microwave power causing magnetron overheating;
- instability of high-voltage switching regimes;
- deformation of dielectric structural materials under microwave exposure;
- vacuum sealing and waveguide integration problems;
- electromagnetic interaction between rotating structures and microwave fields.

These experimental investigations were used to refine the proposed plasma-aware system architecture and validate the necessity of integrated control strategies.

This integrated methodology enables the transition from purely thermal process design to plasma-aware system engineering, which is essential for reliable microwave-assisted freeze-drying.

Results and discussion

Necessity and advantages of microwave-assisted freeze-drying. The analysis of heat transfer limitations in conventional freeze-drying demonstrates that the process is fundamentally constrained by the low thermal conductivity of the dry porous layer. As sublimation progresses, the effective thermal resistance increases, leading to reduced heat flux and prolonged drying times. This results in inefficient energy utilization and limits industrial scalability [1].

Microwave-assisted freeze-drying overcomes this limitation by introducing volumetric heating, enabling direct energy delivery to the sublimation front. As shown by the volumetric power density relation, energy absorption occurs within the product volume rather than only at its surface. This significantly reduces temperature gradients and enhances sublimation rates [1-3].

From a physical perspective, the key advantage lies in decoupling heat transfer from thermal conductivity limitations. The ability of microwave radiation to penetrate the dry layer allows continuous energy supply to the frozen core, which leads to:

- accelerated sublimation kinetics;
- reduced process duration (potentially several times shorter);
- improved energy efficiency;
- better preservation of temperature-sensitive compounds.

These advantages make microwave-assisted sublimation a highly attractive approach for advanced food and pharmaceutical processing. However, the benefits are intrinsically linked with new physical challenges that do not appear in conventional systems.

Discharge-related limitations as the primary constraint. The most critical limitation of microwave-assisted freeze-drying is the high probability of gas discharge formation under operating conditions. The analysis of Paschen's law indicates that the typical pressure range of sublimation (0.3–1.5 mbar) coincides with the region of minimum breakdown voltage [5; 6]. This creates conditions where even moderate electric fields can initiate ionization.

The presence of water vapour further exacerbates this effect. Due to its lower ionization energy and strong dipole moment, water vapour enhances electron impact ionization and increases microwave energy absorption. As a result, the effective breakdown threshold is reduced compared to air, making the system highly susceptible to discharge initiation [6; 9].

In microwave fields, the situation becomes more complex due to:

- oscillating electric fields that continuously accelerate electrons;
- spatial non-uniformity of electromagnetic field distribution;
- localized field enhancement near dielectric interfaces and geometric discontinuities;
- vapour density gradients near the product surface.

These factors lead to rapid development of electron avalanches, which can transit from pre-breakdown ionization to glow discharge and further to arc discharge within microseconds. The characteristic timescale of this transition makes conventional control approaches ineffective.

Experimental observations in microwave vacuum systems confirm that discharge events are most likely to occur near regions of field concentration, such as feedthroughs, antenna interfaces, and sharp edges. These regions act as initiation points where local electric field strength exceeds the breakdown threshold.

The occurrence of arc discharge has severe consequences, including:

- destruction of dielectric components and vacuum feedthroughs;
- damage to magnetron and power electronics;
- interference with sensor signals;
- degradation of process stability.

Therefore, discharge formation represents the primary barrier to industrial implementation of microwave-assisted freeze-drying.

Experimental observations from laboratory-scale implementation. Laboratory-scale experiments performed within the SubliMik project confirmed that implementation of microwave-assisted sublimation under vacuum conditions introduces several coupled engineering and plasma-related challenges that are not encountered in conventional freeze-drying systems.

Experimental tests with magnetron PWM control systems demonstrated the appearance of high-voltage transient processes during switching operation. Measurements showed voltage peaks reaching approximately 3.78 kV on closed switching elements, resulting in repeated breakdown of high-voltage driver circuits despite operation within nominal voltage limits specified by the manufacturer. The laboratory installation for controlled magnetron high voltage power supply experiments is shown in Fig. 5. Analysis indicated the presence of resonant phenomena associated with high-frequency switching processes and interaction between microwave load conditions and power electronics.



Fig. 5. Laboratory setup for experiments with controlled magnetron power supplies

Experimental investigations also revealed strong sensitivity of dielectric structural materials to microwave radiation. Initial tests using PVDF-based structural components demonstrated local overheating and deformation under intensive microwave exposure, despite nominal microwave compatibility specified by the material supplier. This required redesign of the product support structure using alternative microwave-transparent materials.

Additional experiments identified problems associated with reflected microwave power inside the vacuum chamber. Significant reverse microwave flux entering waveguide channels caused magnetron overheating and unstable operation. To mitigate this effect, a specially shaped reflector geometry was developed and experimentally validated, improving electromagnetic field redistribution inside the chamber.

The obtained experimental results demonstrate that stable microwave-assisted sublimation requires simultaneous management of electromagnetic field distribution, high-voltage switching behaviour, vacuum stability, material compatibility, and discharge prevention mechanisms.

System-level solution in the SubliMik concept. The analysis demonstrates that the integration of microwave heating into sublimation systems cannot be achieved by simply adding a microwave source.

Instead, it requires a fundamentally new system architecture that accounts for plasma-related phenomena.

The SubliMik concept addresses this challenge through a system-level approach that combines physical understanding of discharge processes with real-time control and monitoring. The architecture is based on coordinated interaction between several subsystems:

- microwave power modulation subsystem;
- vacuum pressure control subsystem;
- sensor subsystem for temperature and pressure;
- discharge risk monitoring subsystem;
- central control unit.

The key principle of the system is to maintain operation within a safe region of the parameter space defined by pressure, electric field strength, and vapour composition. This is achieved through dynamic control of microwave power and process conditions.

A conceptual representation of the system architecture is shown in Fig. 6.

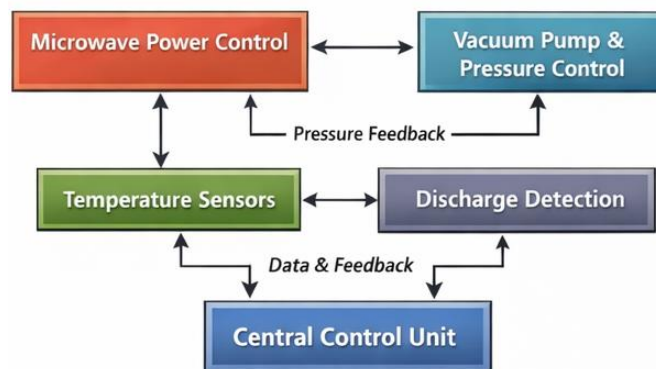


Fig. 6. Conceptual architecture of the SubliMik microwave-assisted freeze-drying system

Control strategy and discharge prevention. The central control unit plays a critical role in coordinating system operation. It processes real-time data from sensors and adjusts microwave power accordingly. The control strategy is based on:

- continuous monitoring of process parameters;
- detection of early-stage ionization phenomena;
- rapid response to prevent transition to arc discharge;
- adaptive regulation of microwave power.

From a physical standpoint, the goal is to interrupt the avalanche process before it reaches the self-sustaining condition. This requires response times on the order of microseconds, which defines strict requirements for system design.

Another important aspect is pressure control. Since breakdown voltage depends on the product $p \cdot d$, maintaining pressure outside critical regions reduces discharge probability. This introduces an additional control dimension, where vacuum conditions are actively managed to ensure safe operation.

Electromagnetic field management. Uniform distribution of microwave energy is essential for both process efficiency and safety. Non-uniform fields lead to localized overheating and increased discharge risk. Therefore, the system must minimize:

- standing wave formation;
- field concentration at sharp edges;
- dielectric discontinuities.

This can be achieved through appropriate design of antenna systems, waveguides, and chamber geometry. Non-uniform fields lead to localized overheating and increased discharge risk, as illustrated in Fig. 7.

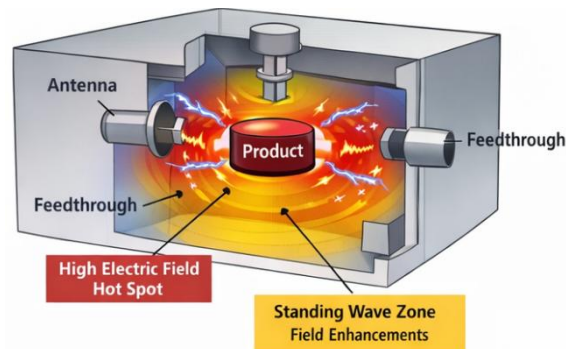


Fig. 7. Non-uniform electromagnetic field distribution and typical discharge initiation zones in a microwave vacuum chamber

Integration of physics and engineering constraints. The results of this study demonstrate that microwave-assisted freeze-drying is governed by a complex interaction between thermal, electromagnetic, and plasma processes. The key challenge is not only to improve heat transfer but also to manage the transition between different discharge regimes.

From an engineering perspective, this leads to several critical design requirements:

- fast-response control systems capable of interrupting energy input;
- plasma-aware system architecture;
- microwave-compatible sensors;
- optimized electromagnetic field distribution.

The SubliMik concept integrates these requirements into a unified system, enabling stable operation in conditions where conventional approaches would fail.

Novelty and scientific contribution of the SubliMik approach. The individual physical phenomena involved in microwave-assisted freeze-drying are well known. Sublimation under reduced pressure has been extensively applied in food and pharmaceutical technologies, microwave dielectric heating is a mature industrial method, and gas discharge behaviour in low-pressure environments has been described by classical plasma physics and Paschen's law for more than a century [5].

However, practical industrial implementation of microwave-assisted sublimation systems remains extremely limited. This indicates that the principal challenge is not the isolated physical processes themselves, but their simultaneous integration into a stable, controllable, and economically feasible industrial system.

The novelty of the SubliMik approach therefore lies not in the separate application of sublimation, microwave heating, or plasma physics principles, but in their system-level integration under conditions where all these effects interact simultaneously. Based on the authors' analysis of the available scientific literature, no previously published work has presented an experimentally validated plasma-aware control architecture specifically intended for microwave-assisted sublimation under low-pressure food-processing conditions. The proposed concept addresses the coupled interaction between:

- low-pressure sublimation conditions;
- water vapour with enhanced microwave absorption;
- discharge-prone electromagnetic field environments;
- rapid plasma formation mechanisms;
- high-voltage pulsed power systems;
- industrial process stability requirements;
- food-industry cost and reliability constraints.

Under such conditions, the system can no longer be considered a purely thermal drying process. Instead, it becomes a coupled thermo-electromagnetic-plasma system requiring coordinated management of microwave power delivery, pressure conditions, electromagnetic field distribution, vacuum stability, and discharge mitigation mechanisms.

The scientific contribution of this work is therefore the formulation and preliminary laboratory validation of a plasma-aware system architecture for microwave-assisted freeze-drying, in which discharge prevention is integrated directly into the process control philosophy rather than treated as an isolated protection function.

Conclusions

1. Conventional freeze-drying is fundamentally limited by heat transfer resistance within the dry porous layer, resulting in long processing times and low energy efficiency.
2. Microwave-assisted freeze-drying enables volumetric heating of the product, significantly improving energy transfer to the sublimation front and reducing process duration while preserving product quality.
3. The primary limitation of microwave-assisted sublimation is the high probability of gas discharge formation under operating conditions, particularly in water vapour environments within the Paschen minimum region.
4. The combination of low ionization energy, strong dipole interaction, and high microwave absorption of water vapour significantly increases susceptibility to electron avalanche, glow discharge, and arc formation.
5. Successful implementation of microwave-assisted freeze-drying requires a system-level approach integrating plasma-aware design, fast-response control systems, and electromagnetic field management.
6. The SubliMik project achieved preliminary laboratory-scale realization of a plasma-aware microwave-assisted sublimation platform at TRL4 level, confirming that stable operation requires coordinated management of microwave power delivery, vacuum conditions, electromagnetic field distribution, and discharge-related phenomena.

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Author contributions

Conceptualization, S. Kravčenko, V. Kravchenko, N. Kuļešovs, K. Carjova and N. Kravčenko; methodology, S. Kravčenko, N. Kuļešovs, V. Kravchenko, N. Kravčenko and K. Carjova; software, validation, V. Kravchenko, S. Kravčenko and N. Kuļešovs; formal analysis, N. Kravčenko, K. Carjova, D. Panova, N. Kuļešovs and S. Kravčenko; investigation, S. Kravčenko, N. Kuļešovs, N. Kravčenko, K. Carjova, V. Kravchenko, and D. Panova; data curation, N. Kuļešovs, N. Kravčenko, V. Kravchenko, and D. Panova; writing - original draft preparation, S. Kravčenko; writing - review and editing, S. Kravčenko, N. Kravčenko, N. Kuļešovs and K. Carjova; visualization, N. Kravčenko, K. Carjova and D. Panova; project administration, N. Kravčenko; funding acquisition, N. Kravčenko. All authors have read and agreed to the published version of the manuscript.

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