J. Coat. Technol. Res.
https://doi.org/10.1007/s11998-026-01304-x

Controlling electrode fouling in pulsed electric field (PEF)-based disinfection of spoiled E-coating paints

Christian Gusbeth, Georg Müller, Wolfgang Frey

Received: 9 October 2025 / Revised: 3 February 2026 / Accepted: 7 February 2026

Abstract The present study investigated the feasibility of applying pulsed electric field (PEF) treatment in anodic electrodeposition (AED) paints without inducing undesired paint deposition on electrode surfaces. PEF treatment is a promising non-thermal technique for microbial inactivation and control in E-coating lines. However, paint deposition on treatment electrodes can cause operational limitations. This study investigates paint stability, coating performance, and electrodeposition mechanisms during PEF treatment of industrial AED emulsions. Using both unipolar and bipolar square-wave pulses at varying durations and charge symmetry, deposition behavior and paint quality were evaluated under continuous flow for PEF treatments known to induce at least a 99% bacterial inactivation on bacteria isolated from E-coating lines. Intensive and repeated PEF treatment of AED paint did not impair the quality of the subsequent coating and did not change the properties of the paint. Paint quality remained unaffected across all trials. Regarding the coagulation and paint deposition on the PEF treatment electrodes, results show that unipolar pulses induce paint coagulation at the anode, even at short durations (when pulses are in the range of the double layer threshold time ≥ 1 µs). In contrast, bipolar pulses with nominal pulse durations ≤ 1.5 µs (0.75 + 0.75 µs) prevented electrode fouling and allowed uninterrupted treatment for over 10 h, without electrode fouling. Furthermore, the application of charge-symmetrical bipolar (CS-bipolar) pulses eliminated deposition entirely, even at nominal durations up to 2.9 µs (1.48 + 1.41 µs). Findings demonstrate that pulse polarity, charge balance, and field symmetry are critical for deposition-free PEF operation in AED systems. These insights provide a technical foundation for scaling PEF in industrial paint processing.

Keywords Pulsed electrical fields (PEF) treatment, E-coating, Electrodeposition, Paint disinfection, Spoiled paints, Bipolar pulses

Introduction

Electrophoretic coating (E-coating) is an essential process in industrial surface treatment due to its high efficiency, corrosion protection, and ability to coat complex geometries uniformly.[1,2] As the technology evolves, there has been a shift toward waterborne, environmentally friendly paint systems to comply with stricter environmental regulations. These low-temperature processes use large volumes of demineralised water, particularly in the pre-treatment and rinsing steps of both anodic and cathodic electrodeposition. However, the use of recirculated water and the increasing sensitivity of modern paints to microbial contamination have introduced new hygiene challenges.[3] Microorganisms enter the system via parts, air, or fresh water and proliferate in water tanks and pipelines, forming biofilms and leading to persistent contamination.[4] While older formulations contained solvents and heavy metals with inherent antimicrobial effects, newer formulations are more prone to microbial growth. Bacterial contamination not only deteriorates paint stability but also affects coating quality, leading to unnecessary rework to remove coating defects.[1,3] Thus, maintaining microbial control is essential for sustainable and reliable operation.

The current standard for controlling microbial growth in E-coating systems relies heavily on the application of chemical biocides. However, the effectiveness of biocides is highly dependent on precise

---

C. Gusbeth (✉), G. Müller, W. Frey
Institute for Pulsed Power and Microwave Technology (IHM), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
e-mail: christian.gusbeth@kit.edu

dosing and compatibility with the specific paint formulation. Not all biocides are suitable, and overuse can lead to the emergence of resistant strains. Additionally, legal restrictions on biocide types and concentrations are tightening, and new approvals are increasingly difficult to obtain. These limitations necessitate the development of alternative, non-chemical disinfection strategies that maintain both operational stability and environmental compliance.

One promising alternative is Pulsed Electric Field (PEF) treatment, a physical, non-thermal method that inactivates microorganisms by inducing electroporation.[5–7] High-voltage electric pulses permeabilize cell membranes, disrupting microbial viability. PEF has proven successful in food processing,[6] hospital wastewater disinfection,[7–9] and biorefinery applications,[10–15] showing high efficiency in microbial reduction without altering the chemical composition of the treated medium.[16,17]

Previous studies have shown that PEF treatment effectively reduces bacterial load in E-coating media. In particular, treatment with pulse durations longer than 1.0 µs, regardless of whether unipolar or bipolar pulses are used, achieves efficient microbial inactivation. Using bipolar pulses with field strengths of 40–50 kVcm^{-1} and treatment energy of 40 JmL^{-1}, reductions of over 2 $\log_{10}$ were achieved for both Gram-negative and Gram-positive bacteria. In addition, the study has shown that PEF treatment can be integrated into E-coating systems, e.g., in bypass or transfer flow setups, to ensure biocide-free, bacteriostatic operation.[4,5]

Despite its promise, a major obstacle to the application of PEF in E-coating systems is the tendency for electrode fouling and corrosion when high-voltage pulses are applied directly to the paint.[4] Conventional unipolar pulses can cause unwanted paint deposition on the electrodes and induce pH shifts, which affect coating quality and process consistency. Moreover, electrode fouling disrupts electric field uniformity and reduces treatment effectiveness. These electrochemical side effects limit long-term operation and reduce the efficiency of the treatment system.

To address this, the present study introduces a PEF treatment approach specifically designed to minimize electrode fouling while effectively inactivating bacteria in E-coating paints. To investigate the applicability of PEF treatment in E-coating media, a multi-step approach was developed, combining theoretical modelling with laboratory-scale experiments. The central aim was to find out whether PEF treatment could be performed on electrodeposition paints without resulting in the formation of unwanted paint deposits on the electrode surface.

Theoretical basis

Double layer model

When electrodes are immersed into an electrolyte, an electric double layer (EDL) forms instantaneously at the interface between the conductive electrode surface and the adjacent electrolyte.[18] This EDL comprises a layer of counter-ions in the electrolyte that compensates for the excess charge on the electrode surface. The two layers are separated by a monolayer of oriented dipolar solvent molecules (typically water) that adhere to the electrode surface, acting as a molecular dielectric.[19] The resulting charge separation behaves analogously to a conventional capacitor and is therefore referred to as the double-layer capacitor (C_{dl}).[20] As long as the applied potential across the electrodes remains below a critical threshold (the overpotential for Faradaic processes), the observed current is purely capacitive, corresponding to the charging and discharging of the EDL. Under these conditions, no net electrochemical (redox) reactions occur at the interface.[21]

In the case of PEF treatment, the treatment chamber, with its integrated electrodes, functions as an electrolytic cell.[21] Faradaic (redox) reactions are initiated only when both conditions are met: (1) the applied voltage exceeds the electrochemical threshold, and (2) the pulse duration is long enough for the double-layer capacitor to charge up to that threshold.[22–24] When these conditions are fulfilled, OH^- ions are generated at the cathode and H^+ ions at the anode, accompanied by gas evolution (H_2/O_2), potential formation of harmful by-products, and electrode corrosion.

The threshold time (t_{th}) can be calculated following Morren et al.[21] using the relation:

$$t_{th} = \frac{C_{dl} \cdot U_{th}}{J} \tag{1}$$

where t_{th} is the threshold time, U_{th} is the threshold voltage, and J is the current density. In our setup, assuming an EDL capacitance for stainless steel electrodes of $C_{dl} = 35\ \mu\text{F}\cdot\text{cm}^{-2}$ and a voltage across the double layer U_{th} between 1 and 2 V, the equation can be reformulated as:

$$t_{th} = R_S \cdot A \cdot \frac{C_{dl} \cdot U_{th}}{U} = \frac{d}{\kappa} \cdot \frac{C_{dl} \cdot U_{th}}{U} \tag{2}$$

Here, R_S is the resistance of the treated medium, with a conductivity R of 1.75 $\text{mS}\cdot\text{cm}^{-1}$, U (8 kV) is the applied voltage, d (m) electrode distance, and electrode area A (m^2). Based on the parameters used for PEF treatment, as shown in Table 1, the calculated threshold time ranges approximately between 0.5 and 1.0 µs.

$$J = \frac{U}{AR_S} \tag{3}$$

and

$$R_S = \frac{d}{\kappa A} \tag{4}$$

Table 1: Parameters values for PEF treatment by using the 8 kV solid-state pulse generator

Parameter	Symbol	Unit	Value
Applied voltage	U	V	≤ 8,000
Electrode area	A	m^2	0.0005
Resistance, R_S	R_S	Ω	22.85
Electrode gap	d	m	0.002
Conductivity	κ	$S{\cdot}m^{-1}$	0.175

Anodic electro-deposition

Anodic electrodeposition (AED) is an electrochemical process used for the controlled deposition of negatively charged paint particles, typically polymeric resins or oxide precursors, onto a conductive substrate serving as the anode in an electrolytic cell.[25] In contrast to cathodic electrodeposition (CED), AED relies on the migration of anionic species under an applied electric field towards the positively charged electrode, where a localized pH shift initiates precipitation of the paint.[26] Upon application of a direct current, water oxidation occurs at the anode interface, generating oxygen gas and protons according to the reaction:[21]

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^{-2}$$

This reaction causes local acidification in the diffusion layer adjacent to the electrode. The protonation of ionizable functional groups on the resin particles (e.g., carboxylates) reduces their water solubility and leads to film formation:[26]

$$R - COO^- + H^+ \rightarrow R - COOH$$

As a result, the resin coagulates and deposits on the anode surface, forming a coherent, continuous film. The process is inherently self-limiting: as the deposited layer thickens, it acts as an electrical insulator, reducing charge transfer and slowing down further deposition.[27]

In applications where AED-based emulsions must be treated for microbial inactivation or stabilization using PEF treatment, the inherent deposition mechanism presents a major challenge. The high field strengths applied during PEF treatment can unintentionally induce electrodeposition at the treatment electrodes. Preventing this undesired deposition requires a detailed understanding of the electrochemical mechanisms, specifically the kinetics of ion accumulation and the conditions under which deposition initiates.

The electrodeposition process and water electrolysis can be modelled as a two-step, pseudo–first-order process. A critical ion concentration, primarily $[H^+]$ for AED or $[OH^-]$ for CED, must be reached near the electrode surface to initiate deposition. The time required to reach this threshold is referred to as the induction time (τ_i). Suppressing electrodeposition under PEF conditions is theoretically possible if the pulse duration remains shorter than τ_i. The induction time can be described by a modified Sand and Cottrell [28] equation that relates τ_i to the current density (J) and electrochemical parameters:[1]

$$\tau_i = \pi D \left(\frac{zFC_{H+}}{2}\right)^2 \frac{1}{J^2} \tag{5}$$

where D is the diffusion coefficient ($m^2{\cdot}s^{-1}$), z the ion valence, F the Faraday constant ($C{\cdot}mol^{-1}$), C_{H+} the critical coagulation concentration ($mol{\cdot}m^{-3}$) given as $C_{H+} = 10^{-pH}$ and J the current density ($A{\cdot}m^{-2}$), which depends on applied voltage U (V), electrode distance d (m), conductivity R ($S{\cdot}m^{-1}$), and electrode area A (m^2).

The induction time τ_i is thus sensitive to the applied voltage, electrode gap, and medium conductivity, while being independent of the absolute electrode area if current density is held constant.

Strategy for suppressing the electrodeposition on electrodes during PEF treatment

Sub–threshold and Sub–induction time pulsing

According to EDL theory, undesirable redox reactions at the electrode surface can be avoided if the pulse duration remains below a critical threshold time, which, as shown previously,[21,22] lies in the range of 0.5 to 1.0 µs. Since electrodeposition does not begin immediately but only after an induction time,[26,29,30] associated with the generation and accumulation of H^+ and OH^- ions, paint deposition on the electrodes during PEF treatment can be prevented if the pulse duration remains shorter than the sum of the threshold time and the induction time, i.e.,

$$t_{pulse} \leq \tau_{th} + \tau_i \tag{6}$$

For typical carboxylic acid groups (R–COOH), the coagulation occurs at pH values of ~2–3. [25,29,30] The corresponding C_{H+} can be estimated using the relation $[H^+] = 10^{-pH}$ At pH 2, this result in $[H^+] = 10$ $mol{\cdot}m^{-3}$, and at pH in $[H^+] = 1$ $mol{\cdot}m^{-3}$. The diffusion coefficient of H^+ in water at 25 °C is typically $D_{H+} = 9.3 \times 10^{-9}$ m^2s^{-1}.[31–33] In the present analysis, the diffusion coefficient of H^+ in water was used as an upper-bound approximation to compare the characteristic time scales of electrochemical processes under industrial AED conditions and PEF treatment conditions. Although direct experimental diffusion data for H^+ in AED paints are not available, it should be noted that established AED deposition models reported in the literature similarly employ the diffusion coefficient of H^+ in water.[33] Furthermore, studies on diffusion of H^+ in hydrogels and polymer/silicate gels have shown that the effective diffusion coefficients can be close to value characteristic of an aqueous solutions.[34,35] Under typical industrial AED conditions ($J \leq 3$ mA·cm^{-2}), the calculated induction time lies in s-range (≤ 8 s).[29,30] In contrast, based on the parameters of the 8 kV solid-state pulse generator prototype used for PEF treatment (Table 1 and 2), τ_i falls within ns-range ($\leq$ 14 ns).

For the present application, these considerations indicate that, during PEF treatment, the onset of undesirable redox reactions at the electrode surface is primarily governed by the electrical double-layer threshold time. The induction time depends strongly on the effective diffusion coefficient and may therefore range from negligible nanosecond values to values comparable to the threshold time. Nevertheless, the characteristic time scale for the onset of redox and deposition reactions at the electrodes can be reasonably assumed to be on the order of 1 µs. Consequently, high-voltage pulses should be shorter than, or at most comparable to, this time scale (Eq. (6)).

Bipolar pulses

This treatment approach builds on the same hypothesis discussed earlier: that electrodeposition of paint requires the local accumulation of a critical concentration of OH^- or H^+ ions at the electrode interface. As previously shown, the onset of undesirable redox reactions at the electrode surface is governed by the double-layer threshold time. By applying short bipolar pulses (µs-range) with instantaneous polarity reversal, the ions generated during one half-wave can be neutralized in the subsequent half-wave by their respective counterions (i.e., OH^- neutralized by H^+ and vice versa). This mechanism effectively suppresses pH shifts at the electrode surface, thereby preventing the local chemical conditions required for resin coagulation and paint deposition. In addition, for the same nominal pulse duration, the electric field in bipolar pulses persists only half as long as in unipolar pulses, further reducing the probability of ion accumulation and faradaic reactions.

Materials and methods

Experimental setup

A modular laboratory system (Fig. 1) was developed for the controlled treatment of AED paint in a bypass configuration. The core component was a polycarbonate PEF treatment cell[15,36] equipped with stainless steel electrodes, with an electrode gap of 0.2 cm and a surface area of 5 cm^2. The AED emulsion was circulated using a micro annular gear pump (mzr-7245, HNP Mikrosysteme GmbH, Germany), allowing pressure regulation up to 2 bar. Flow rates were maintained between 0.1 and 2.0 L h^{-1} using a mini CORI-FLOW mass flow controller (Bronkhorst, UK), ensuring stable flow conditions and preventing gas accumulation.

The system operated in a closed-loop configuration and was equipped with a microfiltration unit and magnetic stirring to prevent pigment sedimentation. During PEF treatment, a minimum system pressure of 1 bar was maintained to avoid dielectric breakdown caused by gas bubble formation. The test paint samples consisted of a white AED paint (VEA61036-1-02, FreiLacke – Emil Frei GmbH & Co. KG, Germany) with a conductivity of 1.75 mS cm^{-1}. Prior to each experiment, the pulse generator and all experimental components in contact with the paint were thoroughly cleaned according to a manufacturer-specific procedure provided by FreiLacke – Emil Frei GmbH & Co. KG, Germany. Briefly, the following steps were performed. The electrodes and the treatment chamber were cleaned using Kimtech Science Precision Wipes (No. 05511, Kimberly-Clark Professional, USA) soaked in a ‘‘cleaning solution’’ consisting of 690 g deionised water, 10 g Freiotherm-ATL-pH-Korrektur (2-dimethylaminoethanol, 50–100%, item number 300048, FreiLacke, Germany), and 300 g Freiotherm Th (2-butoxyethanol, 50–90%, item number 400910, FreiLacke, Germany). After reassembly of the treatment chamber, the system was flushed with the

Table 2: Parameter values for AED and the calculated induction time (using equation 5) under industrial conditions (E-coating line) and PEF treatment

Parameter	Symbol	Unit	Industrial AED conditions	PEF treatment
Current density	J	A·m^{-2}	30	700,000
Diffusion coefficient of H^+	D_{H+}	m^{2}s^{-1}	9.3×10^{-9}	9.3×10^{-9}
Ion valence (H^+)	Z	—	1	1
Faraday constant	F	C mol^{-1}	96,485	96,485
Critical coagulation concentration (H^+)	C_{H+}	mol m^{-3}	$\leq$ 10	$\leq$ 10
Calculated induction time	τ_i	s	**$\leq$ 8 s**	**$\leq$ 14 ns**

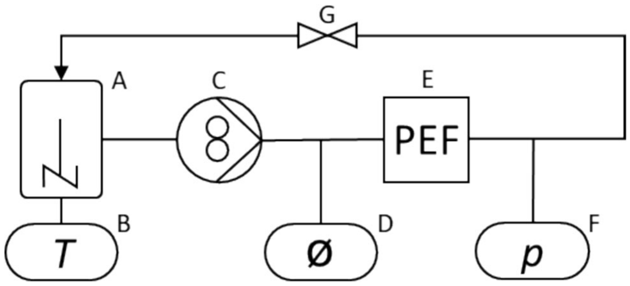


Fig. 1: Schematic of the modular laboratory paint circulation system, consisting of a 3L vessel with magnetic stirrer containing 2L of AED paint (A) and external water bath for temperature control (B), micro annular gear pump (C), flow meter (D), PEF treatment cell (E), pressure sensor (F), and membrane valve (G)

cleaning solution for 1 h. Subsequently, the system was evacuated and flushed overnight at a flow rate of 500 mL h^{-1} using a "storage solution" consisting of 1 L deionised water and 5 mL Freiotherm-ATL-pH-Korrektur. Finally, the system was filled with AED paint, discarding the first 500 mL to ensure that only uncontaminated paint remained in the system.

This cleaning procedure was applied to eliminate traces of insulating materials commonly used in high-voltage equipment, such as silicone- or mineral oil-based substances, that could cause coating defects due to paint-wetting impairments. These conditions, commonly referred to as LABS-free (free of substances impairing paint wetting), were verified before each PEF experiment using a control paint (sham) sample provided by the manufacturer for coating validation.

All experiments were conducted in duplicate, and the results shown are representative of repeated trials. The experiments were intentionally performed under closed-loop conditions with multiple recirculation passes through the PEF treatment chamber, representing a worst-case scenario. Any adverse effects on paint stability or coating performance would therefore be expected to accumulate and become evident.

Continuous flow PEF treatment

Two types of in-house-built pulse generators were used: (i) a transmission line pulse generator[7] equipped with an SF_6 gas spark-gap switch, capable of delivering square-wave unipolar pulses with durations ranging from 0.1 to 10 µs and a maximum output voltage of 25 kV. A modified version of this setup, a bi-directional transmission line generator,[37] was used to deliver bipolar pulses within the same parameter range; (ii) an 8 kV solid-state pulse generator consisting of eight 1-kV full-bridge modules, designed to generate square-wave pulses in both unipolar and charge-symmetric bipolar (CS-bipolar) modes, providing high temporal precision and reproducible current profiles. Pulse monitoring was performed using a Rogowski coil (Pearson Current Monitor, Model 410, Pearson Electronics, Palo Alto, CA, USA) for time-resolved current measurement. For data acquisition and processing, a 1 GHz, 12 bit, Teledyne LeCroy oscilloscope was utilized (HDO6104A, Teledyne LeCroy, Chestnut Ridge, NY, USA). For calculating the transferred charge Q, the measured current was instantaneously integrated over time by using the integration mathematics function INT[i(t)dt] of the oscilloscope.

The pulse parameters used in this study were systematically varied as summarized in Table 3. The combination of pulse duration, pulse shape, and amplitude was selected to achieve a bacterial reduction of at least 99%, as demonstrated in a previous study.[5] Accordingly, the specific treatment energy was ≥ 40 kJ L^{-1}, which has been shown to be sufficient for achieving the required inactivation efficiency. All PEF treatments were conducted in 2L batches of AED emulsion contained within 3L glass vessels under continuous magnetic stirring. The PEF process was operated in bypass mode: the paint was drawn from the bottom of the vessel, passed through a 10 µm stainless steel microfilter, treated in the PEF cell, and returned to the upper third of the beaker. The vessel was temperature-controlled at 20 ± 2 °C using an external water bath. Each batch of paint was circulated twice through the system, which corresponds to a total treatment time of 2 to 4 h, depending on the selected parameter settings. To control for non-electrical influences, each experiment began with a sham treatment, in which the paint sample was processed under identical hydraulic and thermal conditions, but with the pulse generator switched off.

Determination of dielectric strength in AED paint under PEF conditions

To determine the dielectric strength and define a discharge-free operating window for PEF treatment of AED paint, the electric field strength was incrementally increased in steps of 10 kV cm^{-1}. Each field strength was tested at defined pulse durations (1 µs, 2 µs, and 5 µs) and media overpressures ranging from 100 to 2000 mbar. Each condition was maintained for 10 min, during which the occurrence of dielectric breakdown or partial discharges was monitored visually. The initial system pressure was set to 100 mbar above ambient. If discharge events were observed, the media pressure was increased stepwise and the test repeated until either a discharge-free condition was achieved or the maximum pressure of 2 bar was reached. This procedure was repeated for all pulse durations to establish the dielectric strength threshold as a function of pulse duration. Breakdown events were assessed via direct visual observation during pulse application.

Table 3: Pulse parameters for treating the AED paints with unipolar, bipolar square-wave pulses, and charge-symmetrical bipolar pulses (CS-bipolar)

Pulse Generator	Square-waves pulses	Field strength [kV cm^{-1}]	Pulse duration [μs]
Transmission-line	unipolar	≤ 80	1.0
	unipolar	≤ 80	2.0
	unipolar	≤ 65	5.0
Bidirectional transmission-line	bipolar	60	0.75 + 0.75
	bipolar	55	1.0 + 1.0
	bipolar	45	2.5 + 2.5
8 kV solid-state	CS-bipolar	40	1.5 + 1.5
	CS-bipolar	40	2.5 + 2.5
	CS-bipolar	40	5.0 + 5.0

Quality assessment of PEF treated AED sample

PEF treated samples were systematically compared with sham-treated controls that were subjected to identical handling conditions, except for the application of the specific PEF treatment under investigation. The analysis included key parameters such as film thickness, gloss, edge coverage, and crater formation and were performed by the paint manufacturer. To identify coating defects (e.g., craters), the applied paint films were examined using infrared microscopy. Additionally, electrochemical and physicochemical parameters, including conductivity, solids content (dry matter), and solvent ratio, were measured and compared to untreated reference samples to identify any alterations induced by PEF treatment. The integrity of the polymeric binder was assessed via Fourier-transform infrared spectroscopy (FTIR) to detect potential degradation or chemical modifications. This comprehensive evaluation provided critical insight into the applicability of PEF treatment in electrodeposition media, ensuring that microbial decontamination could be achieved without compromising coating quality.

Assessment of paint deposition on the electrodes

Immediately after PEF treatment, the electrodes were carefully removed from the chamber, rinsed with a gentle stream of deionized water, avoiding any mechanical cleaning, then dried using compressed air and photographed for documentation. To evaluate potential paint deposition, electrode surfaces were imaged using a digital camera (DMC-FZ28, Panasonic Entertainment & Communication Co., Ltd., Japan). For more detailed structural analysis of residual coatings, a stereo zoom microscope (Leica MZ6) equipped with a digital camera (FLEXCAM C1, Leica Mikrosysteme Vertrieb GmbH, Germany) was used, providing magnifications of up to 40 ×. Surface topography and layer thickness were quantified using a laser profilometer (μScan, NanoFocus AG, Oberhausen, Germany). Thickness measurements were performed along multiple profile lines oriented perpendicular to the flow direction, enabling identification of both localized and uniform deposition patterns.

Results

Discharge-free operating window for PEF treatment of AED paint

The primary aim was to determine field strength thresholds that prevent dielectric breakdown in AED paint under practical PEF conditions. Fig. 2A summarizes the results of these investigations. For a pulse duration of 1 μs, dielectric breakdown was avoided at field strengths exceeding 60 kV cm^{-1} when a media overpressure of at least 1 bar was applied. In contrast, the permissible field strength decreased with increasing pulse duration, dropping to approximately 30 kV cm^{-1} for 5 μs pulses. This inverse relationship between pulse duration and dielectric strength confirms the time-dependent nature of breakdown phenomena in water-based paint systems. Representative unipolar voltage waveforms used in the tests are shown in Fig. 2B. The specific energy per pulse is denoted by W, illustrating the link between pulse amplitude, duration, and energy input. The filled region in Fig. 2A indicates the discharge-free operating range for PEF treatment using unipolar pulses, at a minimum overpressure of 1 bar. Outside this range, either partial discharges, visible as localized luminescent events, or full dielectric breakdowns were observed. This effect was particularly evident at lower overpressures and longer pulse durations, where the dielectric strength of the medium was insufficient to suppress breakdown.

Quality of paint and coating after PEF treatment

The aim of these experimental investigations was to evaluate the impact of PEF treatment on paint integrity (e.g., polymer coagulation) and overall coating quality. All experiments were consistently conducted at a specific treatment energy of 150 kJ L^{-1}

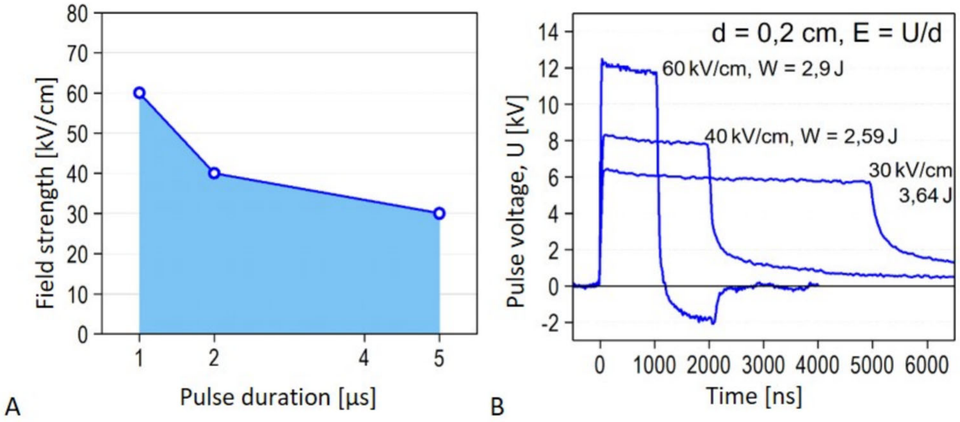


Fig. 2: (A) Dielectric strength thresholds of AED paint as a function of pulse duration. The filled area in the diagram indicates the breakdown-free operating range for PEF treatment of AED paint at a system overpressure of ≥ 1 bar. (B) Representative unipolar voltage waveforms during PEF treatment. The specific energy input per pulse is denoted by *W*

using pulse durations of 1, 2, and 5 µs. Although bacterial inactivation tests using strains isolated from E-coating lines demonstrated that 80 kJ L^{-1} or less is sufficient to achieve effective inactivation for bypass operation (> 99% bacterial reduction) [Ref], the electrochemical impact of PEF on paint was assessed using nearly double the energy input and two treatment passes. This approach was chosen to better evaluate the operational limits of the process under elevated electrical and thermal stress. The investigations were performed exclusively with unipolar pulses, as this pulse shape maintains the electric field across the cell's plasma membrane for a longer continuous duration than bipolar pulses (at equal nominal pulse durations), thereby increasing the probability of redox reactions at the electrode interface. Analysis of the PEF treated AED samples revealed no impairments in either paint properties or coating performance. Even at extended pulse durations of up to 5 µs, subsequent coating trials conducted by the paint manufacturer showed no signs of LABS or any degradation in coating quality.

Paint deposition on electrodes during PEF treatment

Unipolar pulses

Experiments using unipolar pulses with a duration of 1 µs initially showed no significant paint deposition on the electrode surfaces, supporting the hypothesis that short pulses can prevent resin coagulation. However, these results were not consistently reproducible. In repeated trials under identical conditions, paint layers with thicknesses between 8 and 12 µm were detected on the electrodes, as measured by laser profilometry (Fig. 3).

At longer pulse durations of 2 µs and 5 µs, substantial paint deposition was observed on the anode, frequently forming distinct structures such as "nail file" or tubular morphologies, as illustrated in Fig. 4.

Bipolar pulses

The results of paint deposition following PEF treatment using bipolar pulses generated by a bidirectional transmission line pulse generator are shown in Fig. 5. The treatment was applied continuously over 2.5 h (2 passes) using nominal pulse durations of 1.5 µs, 2.0 µs, and 5.0 µs at field strengths of 60, 55, and 45 kV cm^{-1}, respectively. For short bipolar pulses (1.5 µs), no paint deposition was observed on the electrode surfaces. The dark shadows visible in Fig. 5A result from loosely adhering, non-crosslinked AED paint, which could be removed by gentle wiping. In contrast, deposits from previous experiments using unipolar pulses were resistant to wiping and required solvent application for removal, indicating actual resin coagulation and electrodeposition. To verify the suppression of electrode fouling at short pulse durations, the treatment was repeated under more stringent conditions by increasing the number of passes to 8, extending the total PEF exposure time to 10 h. Even under these extended conditions, no firmly adherent paint was detected on either electrode.

Similarly, bipolar pulses with a nominal duration of 2.0 µs (1.0 + 1.0 µs) also prevented paint deposition. However, with a nominal pulse duration of 5.0 µs (2.5 + 2.5 µs), the onset of paint deposition was observed, with film thicknesses ranging from 2 to 6 µm and clear accumulation on the electrodes (Fig. 5C). This unexpected electrodeposition behavior is attributed to pulse asymmetry. Voltage traces (Figs. 5A–C) revealed that the amplitude of the second

Unipolar Pulses

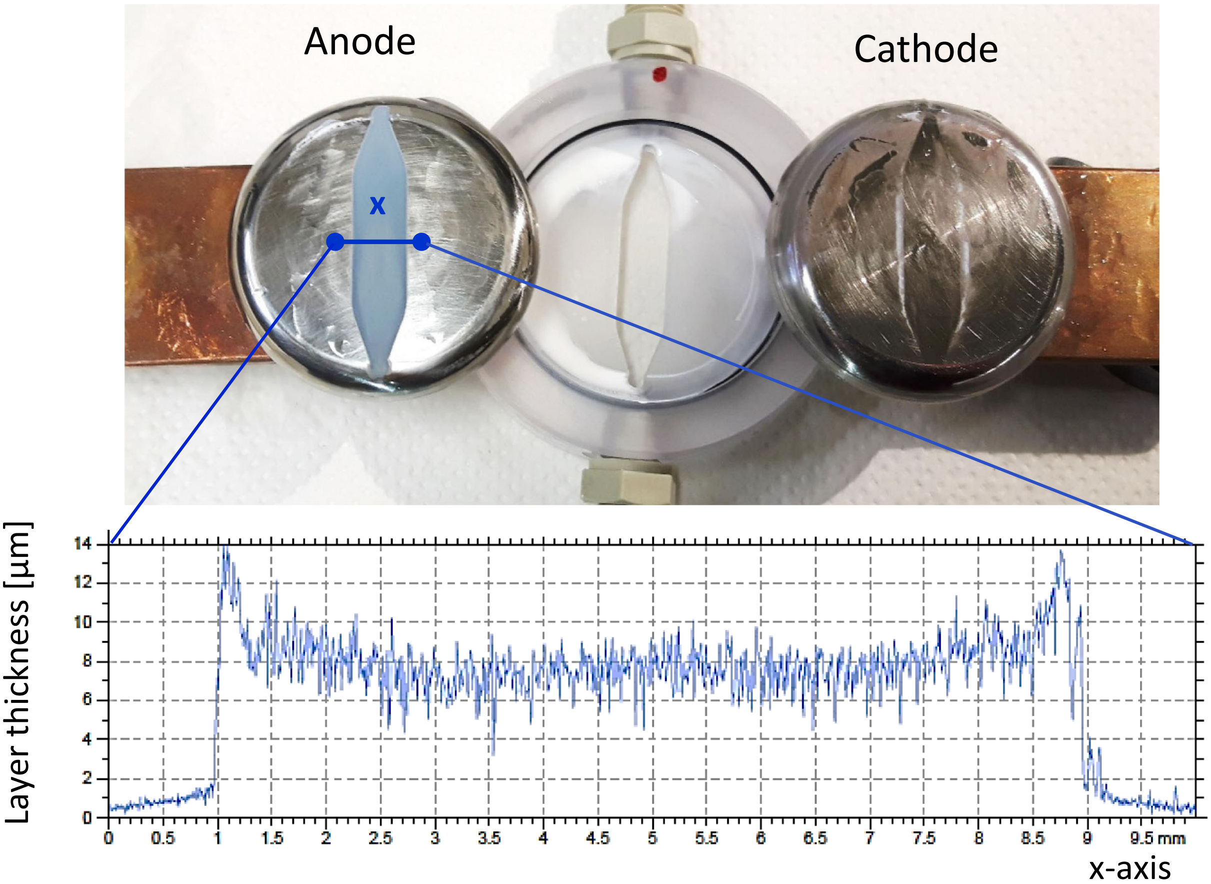


Fig. 3: Paint deposition on the anode (grey-bluish surface, left electrode) following PEF treatment with unipolar pulses of 1 µs duration at an average field strength of 63 ± 2 kV cm^{-1}. The total treatment time was approximately 2.5 h. The polycarbonate treatment chamber is visible in the centre. The thickness profile of the deposited paint layer, shown in the lower diagram, corresponds to the horizontal blue line across the deposited area (measured perpendicular to the flow direction). The coating exhibited a thickness of approximately 8 ± 2 µm. Experiments were conducted in duplicate, and the results shown are representative of repeated trials

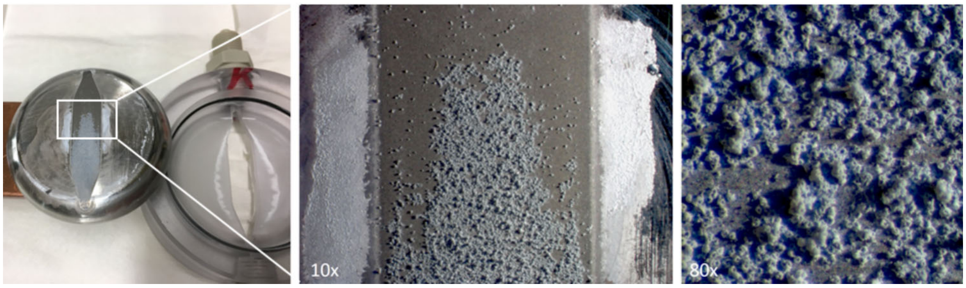


Fig. 4: Paint deposition on the exposed electrode surface following PEF treatment with unipolar pulses of 5 µs duration. The applied electric field strength was 30 kV cm^{-1}, and the specific treatment energy was 120 kJ L^{-1}. A total paint volume of 2L was treated twice over a continuous operating period of 4 h. Experiments were conducted in duplicate, and the results shown are representative of repeated trials

half-wave was consistently lower than that of the first. Assuming constant load conditions, this suggests that transmission line and switching losses in the pulse generator reduce the charge transfer during the second half-wave. As a result, a net charge imbalance develops

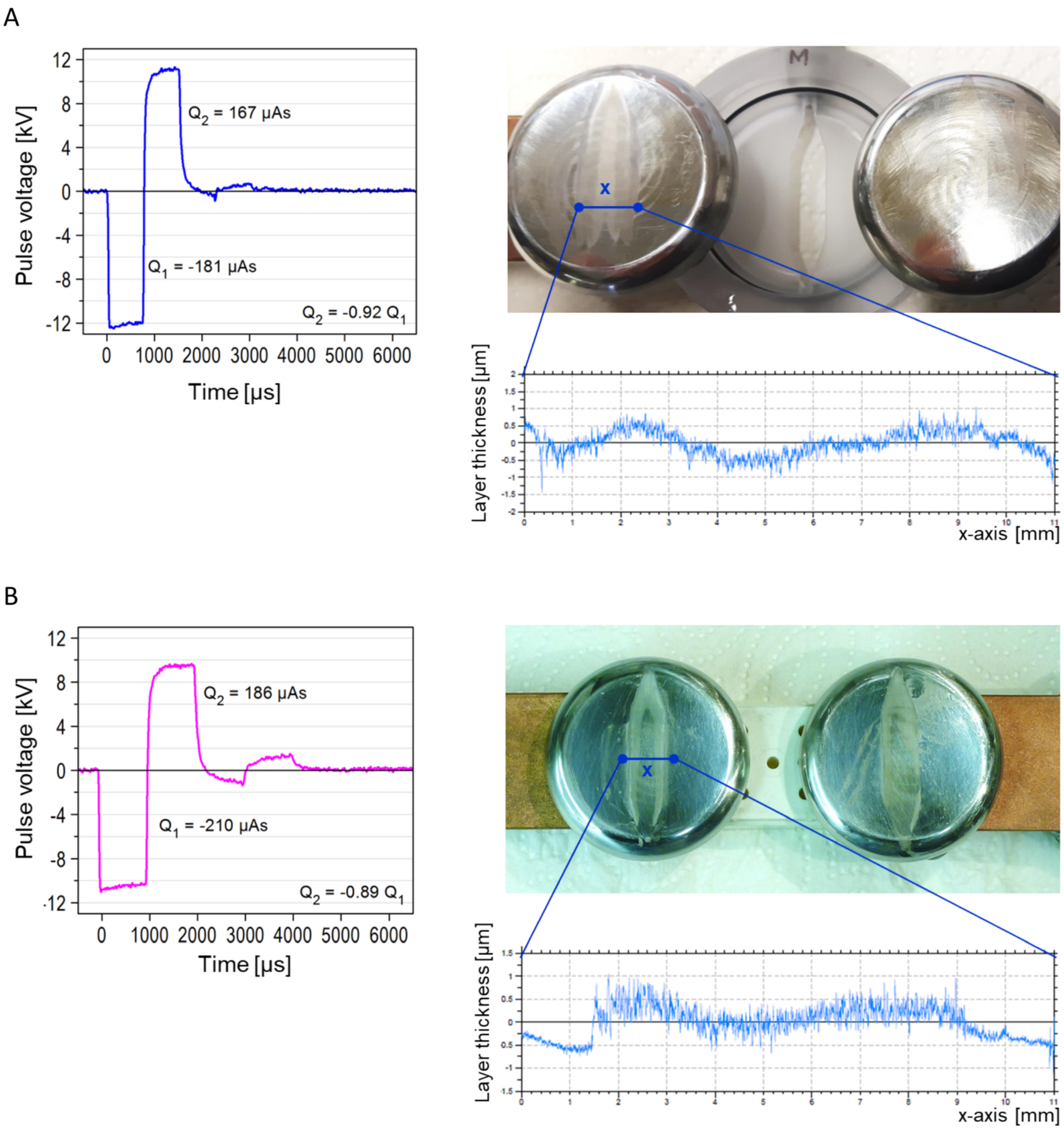


Fig. 5: Results of paint deposition following PEF treatment using bipolar pulses generated by a bi-directional transmission line pulse generator, with half-wave durations of 0.75 µs (A), 1.0 µs (B), and 2.5 µs (C), corresponding to nominal total pulse durations of 1.5, 2.0, and 5.0 µs, respectively, applied at field strengths of 60, 55, and 45 kV·cm^{-1}, respectively. Q_1 and Q_2 denote the charge transported during the first and second half-wave of each bipolar pulse. The surface profiles show the thickness distribution of the deposited paint layer across the electrode surface, measured along the blue line indicated in each image. Experiments were conducted in duplicate, and the results shown are representative of repeated trials

($Q_1 > Q_2$), which promotes ion accumulation and subsequently paint deposition on the electrode.

To quantify this asymmetry, the charge transported during each half-wave (Q_1 with i={1; 2}) was calculated, assuming a constant characteristic transmission lin impendence (Z_0=50 Ω) and the fact, that current and voltage along a transmission line are coupled via the characteristic impedance Z_0, using the equation:

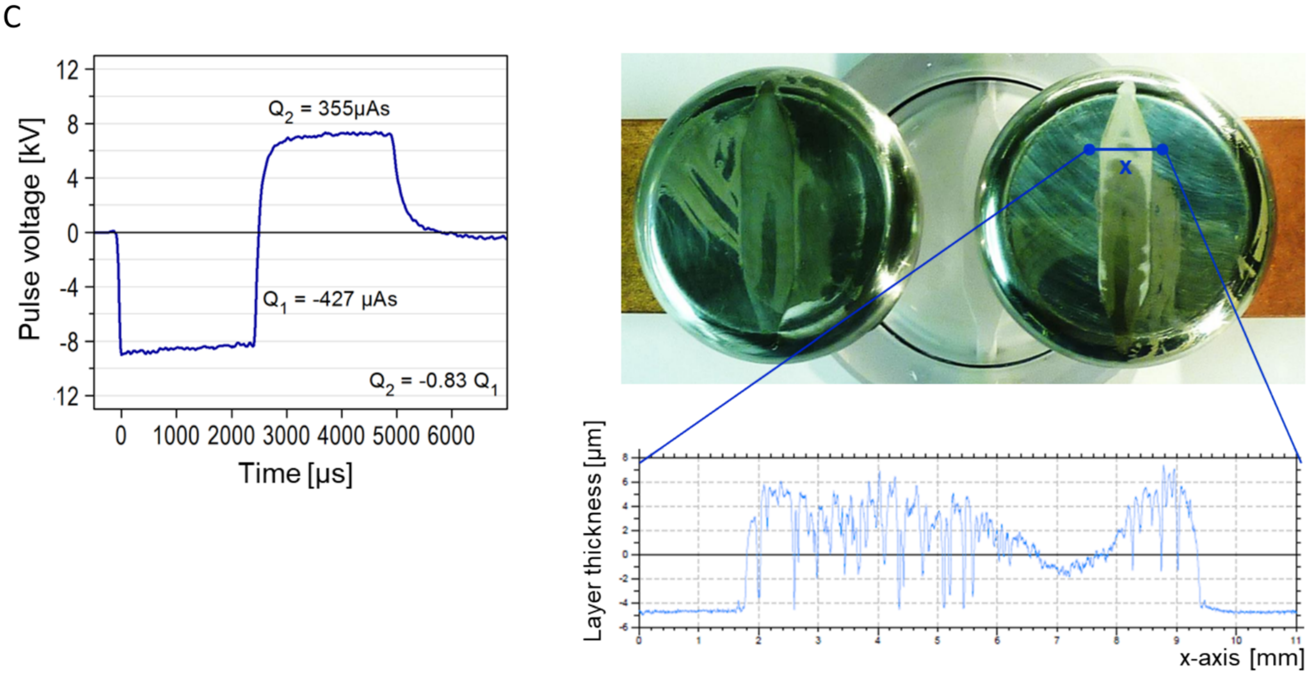


Fig. 5: continued

$$Q_i = I(t)\cdot t_i = \frac{V_i(t)}{Z_0}\cdot t_i, \quad i = \{1, 2\} \tag{7}$$

where $V_\mathrm{i}(t)$ is the voltage of each half-wave measured at the load, $I(t)$ is the corresponding current, and t_i is the duration of each half-wave.

The calculations show that Q_2 was consistently lower than Q_1, resulting in a net positive charge at the electrode interface. This imbalance increased with nominal pulse duration (Fig. 5), indicating a correlation between increasing pulse asymmetry and the likelihood of electrodeposition. For instance, at a half-wave duration of 2.5 µs, a charge imbalance of approximately 17% was observed. This imbalance likely caused localized pH shifts at the electrode interface, ultimately triggering resin coagulation and visible paint deposition.

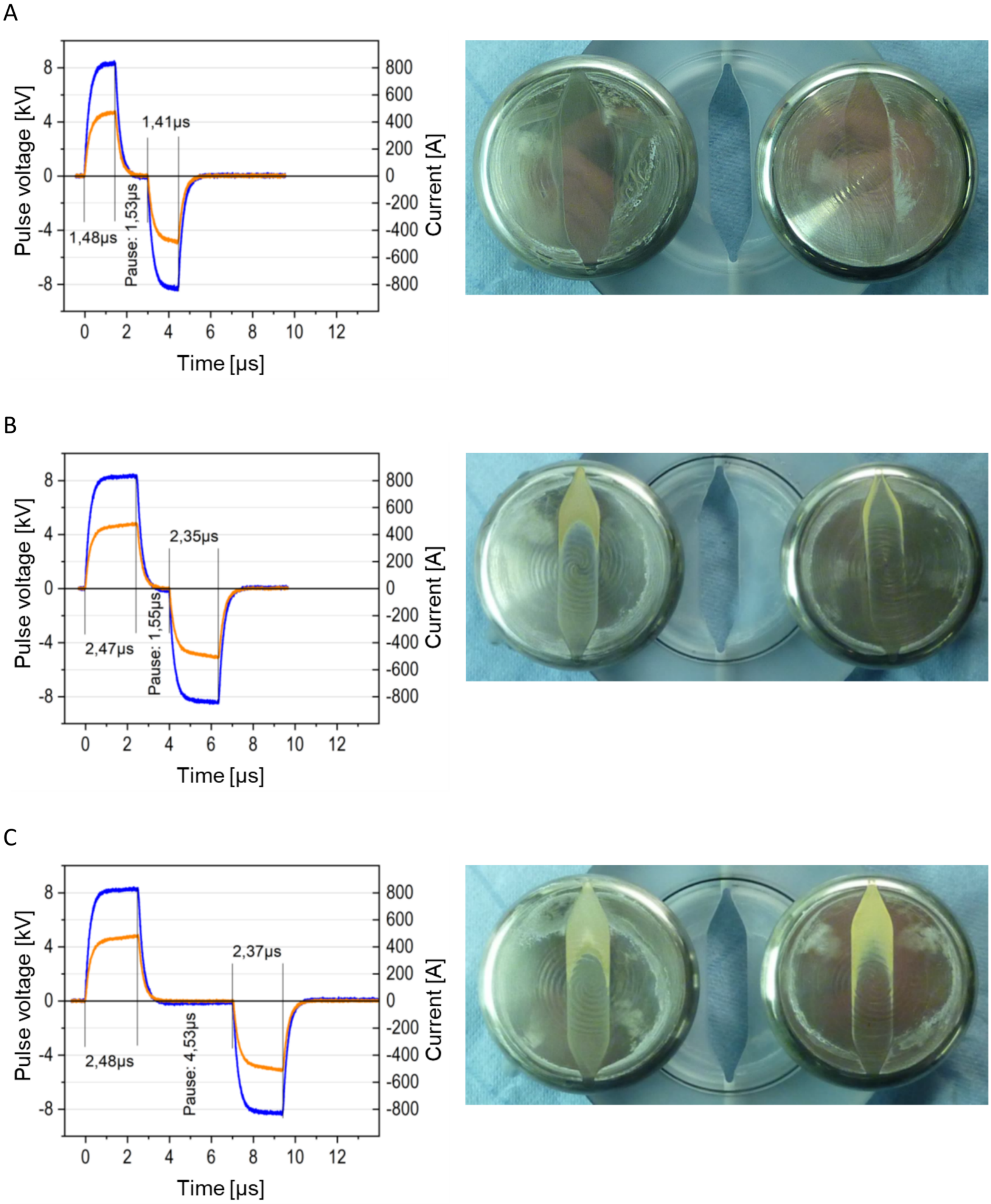
To verify this assumption, treatments were carried out for comparison by utilizing the 8 kV solid-state pulse generator [Ref M Sack], which, unlike transmission line–based systems, enables the generation of bipolar pulses with a precisely symmetrical charge distribution.

Bipolar pulses with symmetrical charge distribution

In this setup, the duration of the second half-wave was adjusted based on the analysis of previously applied, non-adjusted bipolar pulses to ensure that the net charge transferred over both half-waves was effectively zero ($Q(t) = |Q_1| - |Q_2| \approx 0$). Bipolar pulses with half-wave durations of 1.5 µs, 2.5 µs, and 5.0 µs (corresponding to nominal pulse durations of 3, 5, and 10 µs, respectively) were applied. The associated electric field strength was approximately 40 kV cm^{-1}, resulting in specific treatment energies of 85, 88, and 96 kJ L^{-1} for a total treatment period of 2 h (2 passes).

Following the analysis of current and voltage waveforms from the initial pulses (recorded using the Pearson current monitor 410 and a Tektronix P6015A voltage probe), the duration of the second half-wave was fine-tuned, for example, adjusted to 1.41 µs for the 1.5 µs half-wave pulse (Fig. 6A), to compensate for thermally induced conductivity changes in the paint medium that slightly affected current symmetry. These adjustments were guided by calculations of the transported charge (via integration of $I(t)$), ensuring charge balance between the two half-waves. The oscilloscope's built-in integration function was used to quantify Q_i for each half-cycle.

No paint deposition was observed on the treatment electrodes when short CS-bipolar pulses (1.5 + 1.5 µs) were applied, as shown in Fig. 6A. In contrast, treatment with longer CS-bipolar pulses (≥ 2.5 + 2.5 µs) resulted in localized paint deposition, particularly in regions with low flow velocity and elevated temperature (Fig. 6B). This effect was further intensified when the treatment temperature exceeded 40 °C or when the delay between the first and second half-wave was extended, e.g., from 1.55 µs to 4.53 µs, resulting in visible deposition on the electrode surface (Fig. 6C). When CS-bipolar pulses with half-wave durations of 5.0 µs were applied, strong paint deposition was observed on both electrodes.


A
Pulse voltage [kV]
Current [A]
Time [µs]
1,48µs
Pause: 1,53µs
1,41µs
B
Pulse voltage [kV]
Current [A]
Time [µs]
2,47µs
Pause: 1,55µs
2,35µs
C
Pulse voltage [kV]
Current [A]
Time [µs]
2,48µs
Pause: 4,53µs
2,37µs
8
4
0
-4
-8
800
600
400
200
0
-200
-400
-600
-800
0
2
4
6
8
10
12

◀**Fig. 6: Voltage and current waveforms of charge symmetrical bipolar pulses (CS-bipolar) and corresponding paint deposition results following PEF treatment with: (A) 1.5 µs half-waves at 85 kJ L^{-1}; (B) 2.5 µs half-waves at 88 kJ L^{-1}; and (C) 2.5 µs half-waves at 88 kJ L^{-1}, with an extended interval of 4.53 µs between the first and second half-wave. The applied field strength was 40 kV·cm^{-1}, and the total treatment time was 2 h. The temperature was maintained below 40 °C. Experiments were conducted in duplicate, and the results shown are representative of repeated trials**

Discussion

Our results indicate that, under appropriately selected pulse conditions, PEF treatment can be applied to AED paint formulations without inducing observable processing-related changes and while preventing AED deposition on the PEF treatment electrodes. While unipolar pulses led to visible paint deposition on the PEF treatment electrodes, particularly at pulse durations ≥ 1 µs, no adverse effects on paint quality were detected in subsequent coating trials. This suggests that coagulation, driven by local pH shifts, was confined to the electrode interface, while the bulk paint matrix remained unaffected. Our findings align with the double-layer model described by Morren et al.[21], which states that redox reactions at electrode surfaces can be effectively suppressed by applying pulses shorter than the double-layer threshold time ($\tau_{th} \approx 0.5$–1.0 µs). In addition, cumulative charge build-up must be avoided either by removing residual charge between pulses or by applying bipolar pulses to achieve charge cancellation. Our results confirm that both pulse duration and shape (unipolar vs bipolar) are critical parameters influencing paint coagulation during PEF treatment.

A key finding of this study is the central role of pulse characteristics in controlling electrode fouling. Unipolar and asymmetric bipolar pulses caused net charge transfer to the electrodes, resulting in local OH^- or H^+ accumulation and subsequent resin coagulation. This behavior is consistent with the observations of Morren et al.,[21] who showed that interfacial pH gradients and redox processes significantly influence corrosion and deposition under electric field exposure.

Temperature rise during PEF treatment is another relevant factor. A specific energy input of 150 kJ L^{-1} raised paint temperature by approximately 30 °C, with outlet temperatures approaching 50 °C. Although the manufacturer advises against operation at elevated temperatures, short-term exposure did not affect coating performance. However, electrodeposition clearly increased at temperatures exceeding 40 °C, especially in zones of low flow velocity or where local electric field inhomogeneities may exist (Fig. 6B–C). A better understanding of the influence of temperature requires further investigation to define safe thermal limits under prolonged and intensified PEF operating conditions.

In long-term trials, bipolar pulses with nominal durations of 1.5 µs (0.75 + 0.75 µs) enabled continuous paint treatment for over 10 h without detectable paint deposition on the PEF treatment electrodes. Using CS-bipolar pulses, even longer nominal pulse durations of 2.89 µs (1.48 + 1.41 µs) could be applied without inducing paint deposition, as demonstrated in 2 h treatments at a specific energy of 88 kJ L^{-1} (Fig. 6A). When comparing pulse conditions that do not cause paint coagulation or deposition, CS-bipolar pulses (2.89 µs nominal) deliver higher energy per pulse due to their longer duration than 0.75 + 0.75 µs bipolar pulses (1.5 µs nominal), thereby offering a clear advantage for operation at higher flow rates.

The antimicrobial efficacy of such pulse regimes has been confirmed by Gusbeth et al.,[5] who demonstrated > 99% reduction in bacterial load in E-coating media using bipolar pulses ≥ 2 µs at specific energies of ~ 40 kJ·L^{-1}. In contrast, shorter pulses (≤ 1 µs) showed markedly reduced efficacy. This provides a rationale for excluding sub-µs CS-bipolar pulses in the present study and underscores the dual functionality of these treatments for microbial control and paint stability.

Interestingly, we observed that paint deposition occurs when the time interval between the two half-waves of CS-bipolar pulse exceeds ~ 1.5 µs. This suggests that each half-wave behaves electrochemically as an independent unipolar pulse. This behavior can be explained by the fact that redox reactions have already progressed substantially at such longer delays, which is consistent with the threshold time estimated from equation (2) using Morren et al.'s [21] model to lie in the range of 0.5–1.0 µs. Although this critical time interval is an important observation, we did not determine its exact value experimentally. Nevertheless, a time interval of 1.5 µs or more is sufficient for the redox reactions to reach completion, making subsequent neutralisation of the generated ions by the second half-wave unlikely.

This highlights the importance of precise pulse timing: net charge balance must be achieved within a narrow temporal window to prevent boundary layer destabilisation. Fine-tuning of inter–wave intervals may enable the application of even longer nominal pulses without initiating deposition.

The ability to precisely adjust pulse symmetry using solid-state pulse generators was essential for achieving stable long-term operation at extended pulse durations without paint deposition on electrodes. Altogether, these findings demonstrate that CS-bipolar pulsing is a robust strategy for deposition-free PEF treatment of AED paints without compromising coating performance.[38] This enables the safe integration of PEF technology into bypass treatment modules for microbial control in industrial E-coating processes.

Conclusions

This study demonstrates that CS-bipolar pulsing provides an effective strategy for long-term, deposition-free PEF treatment of AED paints. By applying symmetrically alternating half-waves, electrochemical gradients at the electrode surface are minimized, thereby suppressing local pH shifts and preventing resin coagulation. The findings confirm that pulse duration, field strength, and pulse symmetry are critical parameters that must be precisely controlled to maintain paint stability and avoid electrode fouling. In addition, our results suggest that the time interval between the two half-waves of CS-bipolar pulses is a critical parameter, as longer intervals may result in paint deposition. This is consistent with the theoretically estimated redox reaction threshold of 0.5–1.0 µs, as well as with our observation that deposition occurs at intervals exceeding ~ 1.5 µs. Further experiments are required to confirm this critical interval and align it with the theoretical model. The successful integration of CS-bipolar pulses into the PEF process opens a new pathway for safe microbial control in sensitive coating systems, particularly in bypass modules of industrial E-coating lines.

Funding Open Access funding enabled and organized by Projekt DEAL.

References

1. Streitberger, H-J, Karl-Friedrich, D, *Automotive Paints and Coatings*. Wiley-VCH Verlag GmbH & C. KGaA, Weinheim, Germany, John Wiley (2008)
2. Brock, T, Groteklaes, M, Mischke, Peter, *European Coatings Handbook 2nd*, Revised Vincentz Network, Hannover, Germany (2014)
3. Gühring, IK, *Mikrobieller Befall von Elektrotauchlack in der Automobilindustrie*. Universität Stuttgart, Stuttgart (2000)
4. Entwicklung eines ressourceneffizienten Wassermanagement- und Anlagenkonzepts für Vorbehandlungs- und Tauchlackieranlagen unter Nutzung der Elektroimpulstechnologie zur Dekontamination von industriellen Wässern und Lacken DiWaL: Abschlussbericht. Karlsruher Institut für Technologie, KIT. Preprint 2020. https://doi.org/10.2314/KXP:1778016480
5. Gusbeth, C, Krolla, P, Bruchmann, J, Schwartz, T, Müller, G, Frey, W, "Bacterial decontamination of process liquids and paints in E-coating lines by pulsed electric field treatment." *J. Coat. Technol. Res.*, **21** (4) 1385–1398. https://doi.org/10.1007/s11998-023-00901-4 (2024)
6. Gusbeth, C, Frey, W, "Processing liquid food with hundreds of hertz and tens of kilovolts. Comment on "Advances in pulsed electric stimuli as a physical method for treating liquid foods." *Phys. Life. Rev.*, **48** 201–202. https://doi.org/10.1016/j.plrev.2024.02.001 (2024)
7. Frey, W, Gusbeth, C, Schwartz, T, "Inactivation of pseudomonas putida by pulsed electric field treatment: A study on the correlation of treatment parameters and inactivation efficiency in the short-pulse range." *J. Membr. Biol.*, https://doi.org/10.1007/s00232-013-9547-6 (2013)
8. Gusbeth, C, Frey, W, Schwartz, T, Rieder, A, "Critical comparison between the pulsed electric field and thermal decontamination methods of hospital wastewater." *Acta Phys. Pol. A.*, https://doi.org/10.12693/APhysPolA.115.1092 (2009)
9. Gusbeth, C, Frey, W, Volkmann, H, Schwartz, T, Bluhm, H, "Pulsed electric field treatment for bacteria reduction and its impact on hospital wastewater." *Chemosphere*, https://doi.org/10.1016/j.chemosphere.2008.11.066 (2009)
10. Scherer, D, Krust, D, Frey, W, Mueller, G, Nick, P, Gusbeth, C, "Pulsed electric field (PEF)-assisted protein recovery from *Chlorella vulgaris* is mediated by an enzymatic process after cell death." *Algal Res.*, https://doi.org/10.1016/j.algal.2019.101536 (2019)
11. Krust, D, Gusbeth, C, Müller, ASK, "Biological signalling supports biotechnology – Pulsed electric fields extract a cell-death inducing factor from *Chlorella vulgaris*." *Bioelectrochemistry*, **143** 107991. https://doi.org/10.1016/j.bioelechem.2021.107991 (2022)
12. Gusbeth, C, Eing, C, Göttel, M, Straessner, R, Frey, W, "Fluorescence diagnostics for lipid status monitoring of microalgae during cultivation." *Int. J. Renew. Energy Biofuels*, https://doi.org/10.5171/2016.899698 (2016)
13. Jaeschke, DP, Mercali, GD, Marczak, LDF, Müller, G, Frey, W, Gusbeth, C, "Extraction of valuable compounds from *Arthrospira platensis* using pulsed electric field treatment." *Bioresour. Technol.*, https://doi.org/10.1016/j.biortech.2019.03.035 (2019)
14. Eing, C, Goettel, M, Straessner, R, Gusbeth, C, Frey, W, "Pulsed electric field treatment of microalgae - Benefits for microalgae biomass processing." *IEEE Trans. Plasma Sci.*, https://doi.org/10.1109/TPS.2013.2274805 (2013)
15. Goettel, M, Eing, C, Gusbeth, C, Straessner, R, Frey, W, "Pulsed electric field assisted extraction of intracellular valuables from microalgae." *Algal Res.*, https://doi.org/10.1016/j.algal.2013.07.004 (2013)
16. Rivas, A, Rodrigo, D, Martínez, A, Barbosa-Cánovas, GV, Rodrigo, M, "Effect of PEF and heat pasteurization on the physical–chemical characteristics of blended orange and carrot juice." *LWT Food Sci. Technol.*, **39** (10) 1163–1170. https://doi.org/10.1016/J.LWT.2005.07.002 (2006)
17. Grimi, N, Lebovka, NI, Vorobiev, E, Vaxelaire, J, "Effect of a pulsed electric field treatment on expression behavior and

juice quality of chardonnay grape.'' *Food Biophys.*, **4** 191–198. https://doi.org/10.1007/s11483-009-9117-8 (2009)

18. Breitkopf, C, Swider-Lyons, K, ''Modern electrochemistry.'' In: Breitkopf, C, Swider-Lyons, K (eds.) *Handbook of Electrochemical Energy*. Springer, Heidelberg (2017)
19. Brett, CMA, Brett, AMO, *Electrochemistry: Principles, Methods, and Applications*. Oxford University Press (2005)
20. Bockris, JO, Reddy, AKN, *Modern Electrochemistry*. Springer, Cham (1970)
21. Morren, J, Roodenburg, B, de Haan, SWH, ''Electrochemical reactions and electrode corrosion in pulsed electric field (PEF) treatment chambers.'' *Innov. Food Sci. Emerg. Technol.*, **4** (3) 285–295. https://doi.org/10.1016/S1466-8564(03)00041-9 (2003)
22. Roodenburg, B, Morren, J, Berg, HE, de Haan, SWH, ''Metal release in a stainless steel Pulsed Electric Field (PEF) system: Part I. Effect of different pulse shapes; theory and experimental method.'' *Innov. Food Sci. Emerg. Technol.*, **6** (3) 327–336. https://doi.org/10.1016/J.IFSET.2005.04.006 (2005)
23. Pataro, G, Donsì, G, Ferrari, G, ''Modeling of electrochemical reactions during pulsed electric field treatment.'' In: Miklavčič, D (ed.) *Handbook of Electroporation*. Springer, Cham (2017)
24. Pataro, G, Ferrari, G, ''Electrochemical reactions in pulsed electric fields treatment.'' In: Raso, J, Heinz, V, Alvarez, I, Toepfl, S (eds.) *Pulsed Electric Fields Technology for the Food Industry: Fundamentals and Applications*. Springer, Cham (2022)
25. Doerre, M, Hibbitts, L, Patrick, G, Akafuah, NK, ''Advances in automotive conversion coatings during pretreatment of the body structure: A review.'' *Coatings*, https://doi.org/10.3390/COATINGS8110405 (2018)
26. Beck, F, ''Electrodeposition of polymer coatings.'' *Electrochim. Acta*, **33** (7) 839–850. https://doi.org/10.1016/0013-4686(88)80080-X (1988)
27. Hamdy Makhlouf, AS, *Handbook of Smart Coatings for Materials Protection*. Woodhead Publishing Limited, Cambridge (2014)
28. Britz, D, ''History of the Sand equation in electrochemistry.'' *J. Electroanal. Chem.*, **996** 119364. https://doi.org/10.1016/J.JELECHEM.2025.119364 (2025)
29. Beck, F, Guder, H, ''Potentiodynamic electrodeposition of paint (EDP).'' *J. Appl. Electrochem.*, **15** 825–836. https://doi.org/10.1007/BF00614359 (1985)
30. Padash, F, Dorff, B, Liu, W, et al. ''Characterization of initial film formation during cathodic electrodeposition of coatings.'' *Prog. Org. Coat.*, **133** 395–405. https://doi.org/10.1016/J.PORGCOAT.2019.04.061 (2019)
31. Rajska, D, Brzózka, A, Hnida-Gut, KE, Sulka, GD, ''Investigation of electrodeposition kinetics of In, Sb, and Zn for advanced designing of InSb and ZnSb thin films.'' *J. Electroanal. Chem.*, https://doi.org/10.1016/J.JELECHEM.2020.114967 (2021)
32. Gellings, PJ, Ekama, HC, ''The change of pH under a paint film due to cathodic protection.'' *Corros. Sci.*, **15** (6–12) 529–535. https://doi.org/10.1016/0010-938X(75)90018-9 (1975)
33. Beck, F, ''Elektrotauchlackierung an der rotierenden Scheibenelektrode.'' *Chemie Ingenieur Technik*, **40** (12) 575–581. https://doi.org/10.1002/cite.330401206 (1968)
34. Schuszter, G, Gehér-Herczegh, T, Szucs, A, Tóth, A, Harvath, D, ''Determination of the diffusion coefficient of hydrogen ion in hydrogels.'' *Phys. Chem. Chem. Phys.*, **1213** 19–12136. https://doi.org/10.1039/c7cp00986k (2017)
35. Lakatos, I, Lakatos-Szabó, J, ''Diffusion of H^+, H_2O and D_2O in polymer/silicate gels.'' *Colloids Surf. A. Physicochem. Eng. Asp.*, **246** 9–19. https://doi.org/10.1016/j.colsurfa.2004.06.035 (2004)
36. Straessner, R, Eing, C, Goettel, M, Gusbeth, C, Frey, W, ''Monitoring of pulsed electric field-induced abiotic stress on microalgae by chlorophyll fluorescence diagnostic.'' *IEEE Trans. Plasma Sci.* https://doi.org/10.1109/TPS.2013.2281082 (2013)
37. Smith, PW, *Transient Electronics: Pulsed Circuit Technology*. John Wiley & Sons, LTD, The Atrium, Southern Gate, Chichester, West Sussex (2011)
38. Frey, W, Gusbeth, C, ''Method for the microbial disinfection of water-based dispersions with liquid and/or solid ingredients using high voltage pulses.'' EU Patent EP000003822231B1 (2020)