Surface ionization wave propagation in the nanosecond pulsed surface dielectric barrier discharge: the influence of dielectric material and pulse repetition rate

Bangdou Huang, Cheng Zhang, Igor Adamovich, Yuri Akishev and Tao Shao

1 Beijing International S&T Cooperation Base for Plasma Science and Energy Conversion, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, 100190, People’s Republic of China
2 University of Chinese Academy of Sciences, Beijing, 100049, People’s Republic of China
3 Nonequilibrium Thermodynamics Laboratories, Department of Mechanical and Aerospace Engineering, Ohio State University, Columbus, OH 43210, United States of America
4 State Research Center of Russian Federation TRINITI, 108840, Moscow, Troitsk, Pushkovykh Str., Vladeenie 12, Russia
5 NRN University MEPhI, 115409, Moscow, Kashirskoe Shosse 32, Russia

E-mail: zhangcheng@mail.iee.ac.cn and st@mail.iee.ac.cn

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Abstract

In this work, the propagation of the surface ionization wave (SIW) in the nanosecond pulsed surface dielectric barrier discharge with different dielectric materials and pulse repetition rates is investigated. The current waveforms at different locations along the route of the SIW propagation are obtained, based on a specially designed ground strip array geometry. The temporal evolution and spatial distribution of the electric field during the SIW propagation are measured by using the electric field induced second harmonic generation method. The distribution of the residual surface potential after the discharge is mapped with a Kelvin electrostatic probe, which verifies both the existence of the residual electric field and its opposite direction to that during the SIW propagation. It is found that with the dielectric material on which the surface charges decay faster, there are the well-pronounced primary and secondary SIWs with a higher velocity on the voltage rising edge and both the peak current and the peak electric field are also higher, with a less spatial attenuation along the SIW propagation route. It is demonstrated that the residual surface charges with the same polarity as the high-voltage pulse suppress the development of the SIW.

Keywords: nanosecond pulsed discharge, surface ionization wave, electric field

1. Introduction

Surface dielectric barrier discharge (SDBD) at atmospheric pressure driven by high-voltage (HV) nanosecond pulses has been a promising discharge form, which has its potential application in different fields, such as the plasma flow control [1–5] and the plasma assisted ignition and combustion [6–9].

The breakdown process of the nanosecond pulsed SDBD is generally accompanied by a discharge propagation along the dielectric surface, which is usually called the surface ionization wave (SIW) [10]. Except for the nanosecond pulsed SDBD, the phenomenon of SIW also widely exists in different kinds of atmospheric pressure discharge, such as the
plasma-liquid and the plasma-catalyst interaction [11–14]. An investigation of the SIW is valuable for both a deeper understanding of the atmospheric pressure discharge and an improvement of its plasma application.

As its name suggests, the SIW is one kind of discharge form with a strong coupling between the gas and the surface. The dielectric surface, as the boundary of a thin layer of plasma, and plasma-surface interaction processes can have a strong impact on the discharge evolution [15–17]. However, performing an on-line investigation on the plasma-surface interaction, especially at atmospheric pressure, is extremely challenging, as a non-intrusive diagnostic method with a spatial resolution down to micrometer and a temporal resolution down to nanosecond is needed. One example is using the electro-optical effect to measure the charge distribution on the dielectric in DBDs and the interaction between the atmospheric pressure plasma and the dielectric material has been investigated [18, 19]. Electric field induced second harmonic (EFISH) generation is a burgeoning diagnostic method for the electric field in the plasma and it has been applied to different form of discharges, such as the fast ionization wave and SIW [20–24]. As both the charges in the gas phase and those on the surface will contribute to the measured electric field in the plasma region, measuring the electric field using the EFISH method can provide an indirect route to investigate the plasma-surface interaction at an elevated pressure.

Except for the dielectric surface, another factor influencing the repetitively nanosecond pulsed SDBD is pulse repetition rate (PRR), which determines the time interval between the repetitive pulses and the initial condition of each pulse [25]. The impact of PRR on the nanosecond pulsed discharge and its gas-phase kinetics has been investigated in a quantitative way in our previous work [26, 27]. However, the effect of PRR on the SIW propagation is still needed to be explored.

In this work, the SIW driven by repetitive nanosecond HV pulses is generated in a specially designed SDBD geometry with the metal strip array as the ground electrode. Measuring the current flowing through the distributed ground electrode array, the SIW propagation process is monitored. The temporal evolution and spatial distribution of the electric field during the SIW propagation is also measured using the EFISH method. The distribution of the residual surface potential after the discharge is mapped, which is related to the residual electric field from the EFISH measurement. Moreover, the influence of the dielectric material and the PRR on the SIW propagation is illustrated.

2. Experimental methods

In this work, the SDBD geometry is constructed with the printed circuit board (PCB, as shown in figure 1). Both the flame-retardant-4 epoxy resin (ER, relative dielectric constant \( \varepsilon_r \approx 4.3 \)) and the polytetrafluoroethylene (PTFE, \( \varepsilon_r \approx 2.1 \)) are used as the PCB dielectric material with a thickness of 1 mm and a size of 6 cm × 6 cm. The electrodes are made of copper strips with a thickness of about 50 \( \mu \)m. In particular, the ground (GND) electrodes are made of copper strip array with a width of 1.5 mm and a length of 30 mm and the gap between two strips is 1 mm [28].

In order to measure the current flowing through each ground strip, a shunt resistor \( (R_0 \approx 3 \, \Omega) \) is used and another resistor \( R_1 \) is used to achieve an impedance matching to the 50 \( \Omega \) coaxial cable, as shown in figure 1(a). The length of the coaxial cable connecting each shunt resistor and the oscilloscope is kept exactly the same (3 m). Attenuators (20 dB) are used to reduce the signal reflection. A large number of ferrite cores are clamped on the coaxial cables to suppress the common mode signal [28, 29]. The voltage waveform on the HV electrode is measured using a HV probe (Pintech, P6039A). The time synchronization between the voltage and the current measurement has been corrected as follows, which has been introduced in [28]. The HV electrode is extended with a square copper foil, which covers all ground strips. A pulsed voltage below the breakdown threshold is applied on the HV electrode and the time-deviation of the voltage waveform, which represents the displacement current in this case, and the measured current waveform are synchronized in time. By comparing the signal amplitudes from different shunt resistors in this case, their amplitude responses are also checked, which have a maximum variation of about 10% between different shunt resistors.

The discharge is generated using a homemade nanosecond HV generator (positive polarity) with a peak voltage of approximately 14 kV, a full width at half maximum of about 250 ns, and a rising edge (20%–80% of the peak value)
of about 200 ns. The PRR of the discharge is varied from 10 Hz to 500 Hz. In this work, argon is blown out from a nozzle (with a cross section of approximately 1 mm in height and 6 mm in width) attached to the HV electrode. The gas flow rate is 0.3 standard liter per minute. The purpose of introducing an argon flow is to extend the discharge length, as a result of which, the current when the SIW propagates can be measured by the ground strip array. In fact, it is very challenging to obtain the flow geometry and the gas component in our current experimental setup, even though the particle image velocimetry could be applied to visualize the flow geometry, which is already out of the main scope of this investigation. The influence of the gas component on the EFISH measurement will be discussed in detail below. Here, the Reynolds number of the argon flow \( Re = \rho_m v_f L_f / \nu \) is estimated to be 720, where \( \rho_m \) is the density of argon (\( \rho_m \approx 1.78 \text{ kg m}^{-3} \)), \( v_f \) is the flow velocity (\( v_f \approx 1 \text{ m s}^{-1} \)), \( L_f \) is the characteristic length of the flow (\( L_f \approx 1 \text{ cm} \)), and \( \nu \) is the viscosity of argon (22.9 \( \mu \text{ Pa s} \)). It can be seen that the argon flow from the nozzle is laminar flow in the discharge region.

An intensified charge coupled device (ICCD, Andor iStar sCMOS) camera is used to obtain both the single shot discharge image and the averaged image over multi-pulses. The gate width of the ICCD camera is 500 ns. The start time of the ICCD gate with respect to \( t = 0 \) (when the HV reaches its peak value) is set to be \(-280 \text{ ns} \) in the ER case and it is \(-210 \text{ ns} \) in the PTFE case, as the breakdown happens later in the PTFE case. With these settings, most of the discharge emission during both the voltage rising and falling edges can be captured. The length scale of the discharge images is calibrated using the distance between the ground strips, which can be seen in an image of the SDBD geometry without the discharge taken with the same optical setup.

Figures 2(a) and (b) show the single shot images of the SDBD using the ER dielectric with different grey scales and figure 2(c) shows the averaged image over 50 pulses, respectively. For comparison, those with the PTFE dielectric are also shown in figures 2(d)–(f). It can be seen that the emission intensity of the SDBD with the ER dielectric is stronger than that with the PTFE dielectric by one order of magnitude. This result is consistent with the measured current amplitude using these two kinds of dielectric materials (subsequently shown in figure 5). In addition, the discharge morphology with the ER dielectric is more filamentary, while that with the PTFE dielectric is more diffuse. Notice that, except for the main streamer in the argon flow region, there are also multi short streamers outside the argon flow with both dielectric materials, whose intensity is below 10% of the intensity of the main streamer.

In this work, the EFISH generation system is used to measure the temporal evolution and spatial distribution of the electric field. A detailed description of the EFISH method has been given in [20–24] and only a brief introduction of the experimental setup used in this work is given as follows (shown in figure 3).

The horizontally \( (x \text{ direction}) \) polarized 1064 nm fundamental output beam of a nanosecond Nd:YAG laser (Beamtech SGR-S400, pulse width 7–9 ns, 10 Hz) is focused to the discharge region (near the nozzle) using a plano-convex lens (with a focal length \( f \) of 55 cm). The laser energy is set as 15 mJ per pulse in this work. The \( 1/e^2 \) radius of the laser beam at the focus, measured by traversing a knife edge across the laser beam, is approximately 130 \( \mu \text{m} \). When using a shorter focal length lens, the beam radius around the focus will be less and the spatial resolution of the EFISH measurement will be improved [20]. However, as a nanosecond pulsed Nd:YAG laser is used in this work, the risk of the laser induced breakdown will increase with a short focal length lens. Therefore, we choose to use a relatively long focal length lens. After the laser beam passes through the discharge region, a prism is used to disperse the fundamental laser and the second harmonic light in space. A polarizer is used to select the horizontally polarized component of the second harmonic and a band pass filter (BPF) is used to select the wavelength of the second harmonic (532 nm). The intensities of the fundamental laser and the second harmonic light are detected with a photodiode (PD, Thorlabs, DET10A2) and a photomultiplier (PMT, Hamamatsu, R1828-01), respectively. The Nd:YAG laser and the nanosecond HV generator are synchronized with a delay generator (SRS, DG645), which determines the time interval between the laser output and the HV pulse. The frequency-division method is used when the SDBD has a higher repetition rate than the laser.

The SDBD structure is mounted on a three-dimensional displacement platform and the electric field at different locations can be obtained without changing the laser.
alignment. When performing the EFISH measurement, the SDBD structure is firstly adjusted using an air level. Next, the SDBD structure is raised until the laser is shot onto the side of the dielectric (and the laser is blocked by the dielectric). Then, the SDBD structure is moved lower-down slowly while the laser energy recovers to the value without blocking. The beam waist of the laser at the edge of the dielectric surface is approximately 0.15 mm (according to equation (7)), which is taken as the distance between the observation point and the dielectric surface. At each time point and at each position, signal average over 1000 pulses is performed.

In order to obtain the relationship between the intensity of the EFISH signal \((I(2\omega))\) and the electric field strength \((E)\), a calibration of the system is needed. When performing the EFISH calibration, both a static voltage and a nanosecond HV pulse are applied across the parallel-plate electrodes (34 mm by 12 mm, gap 2.5 mm) in order to obtain a known and uniform electric field. The laser beam passes through the parallel-plate electrodes along their short side (as shown in figure 3), i.e. in the calibration configuration, the interaction length between the laser and the electric field is 12 mm.

When the static voltage is larger than about 2.9 kV in argon, breakdown occurs between the parallel-plate electrodes, which means that an electric field larger than about 11.6 kV cm\(^{-1}\) cannot be obtained in this case. In order to extend the range of the electric field in the EFISH calibration, a nanosecond HV pulse with a peak voltage of 5.3 kV and a pulse width of 80 ns is applied, which does not induce a breakdown in argon (due to the pulsed breakdown delay effect [30, 31]), and a maximum electric field of 21 kV cm\(^{-1}\) is obtained in argon. Similarly, in air, a nanosecond HV pulse with a peak voltage of 8 kV is applied and a maximum electric field of 32 kV cm\(^{-1}\) is obtained.

Figures 4(a) and (b) show the relationship between the intensity of the second harmonic light \((I(2\omega))\) with the square of the electric field \((E^2)\) in argon and in air, respectively. It can be seen that the measured \(I(2\omega)/E^2\) relationship can be fitted well with a linear function, which agrees with the theoretical relationship [21]

\[
I(2\omega) \propto \left| N\chi_{ijkl}^{(3)}(-2\omega, 0, \omega, \omega)E_{0i}(\omega_0)E_{1j} \right|^2 \\
\times (\omega)E_{1i}(\omega)^2 L^2 \left[ \sin(\Delta k \cdot L/2) \right]^2.
\]

Here, \(N\) is the gas density, \(L\) is the interaction length between the laser and the external electric field, \(E_{0i}(\omega_0)\) represents the external electric field with a frequency of \(\omega_0\). \(E_{1i}(\omega)\) represents the electric field of the fundamental laser with a frequency of \(\omega\). The frequency of the laser electric field is much larger than that of the external electric field (\(\omega \gg \omega_0\)). \(\chi^{(3)}\) is the third-order nonlinear susceptibility (hyperpolarizability) and the ratio of \(\chi^{(3)}\) in air and \(\chi^{(3)}\) in argon \((\chi^{(3)}[\text{Air}]/\chi^{(3)}[\text{Ar}])\) is 0.79 from [32]. Note that a mixture fraction weighted hyperpolarizability for air is used in this work, i.e. \(\chi^{(3)}[\text{Air}] = 0.8 \chi^{(3)}[\text{N}_2] + 0.2 \chi^{(3)}[\text{O}_2]\), which has been done in [33]. \(\Delta k\) is the wavevector mismatch of the fundamental laser and its second harmonic, i.e. \(\Delta k = 2k_i - k_2\) and \(k_i = 2\pi n(\lambda_i)/\lambda_i\), where \(n(\lambda_i)\) is the refractive index of the light with a wavelength of \(\lambda_i\), \(c\) is the light velocity in vacuum. It has been
calculated that $\Delta k$ in argon ($\Delta k[\text{Ar}]$) is 0.47 cm$^{-1}$ and $\Delta k$ in air ($\Delta k[\text{Air}]$) is 0.50 cm$^{-1}$ [34, 35] and the coherence length $L_c = \pi / \Delta k$ is about 6 cm, which is much larger compared to the span of the HV electrode.

In the calibration of this work, the ratio of the slope of the $I(2\omega)-E^2$ relationship (i.e. the calibration coefficient) $S[\text{Air}]/S[\text{Ar}]$ is 0.8 from the fitting of the measured data and the square root of this ratio $(S[\text{Air}]/S[\text{Ar}])^{0.5}$ is 0.89, which is close to $\lambda^{(0)}[\text{Air}]/\lambda^{(0)}[\text{Ar}]$ of 0.79 from [32].

Figure 4(c) shows the temporal evolution of the electric field between the parallel-plate electrodes from both the EFISH signal and the voltage over the electrode gap ($V/d$), when a HV pulse is applied in argon. It can be seen that if a calibration coefficient obtained in air, $S[\text{Air}]$, is used, there is an overprediction of the electric field by about 10% compared with the $V/d$, illustrating the difference between the hyperpolarizabilities of argon and air. However, when $S[\text{Ar}]$ is used, the EFISH data fall on the $V/d$ curve. This observation agrees with the effect of varying gas species on the EFISH signal in [33]. Notice that even small variations of the $V/d$ pulse shape are reproduced by the EFISH measurements.

In addition, a Kelvin electrostatic probe (Trek-6000B-6) and an electrostatic voltmeter (Trek 347) are used to measure the surface potential distribution on the PTFE dielectric after the discharge, by mounting the SDBD structure on a two-dimensional displacement platform, as has been performed in [36, 37]. The distance between the tip of the electrostatic probe and the dielectric surface is approximately 5 mm. This definitely limits the spatial resolution of the surface potential measurement, which is estimated to be at least 5 mm, based on the measurement of the spatial distribution of the potential generated by applying a static voltage on a metal plate with a sharp edge [26, 29].

3. Results and discussion

3.1. The current flowing through the ground strip array

Figure 5(a) shows the voltage waveform on the HV electrode and the current waveforms flowing through each ground strip with the ER dielectric. The peak voltage is 14 kV and the PRR is 100 Hz. The zero point of time is set at when the voltage reaches its peak value.

It can be seen that on the voltage rising edge, the current waveform through the first three ground electrode strips presents a two-peak feature, indicating the primary and the secondary SIWs [21]. The peak value of the current through a ground strip further away from the HV electrode is reached later, as a result of the SIW propagation. The velocities of the primary and the secondary SIWs are estimated to be about 0.29 mm ns$^{-1}$ and 0.25 mm ns$^{-1}$, respectively, obtained from the relationship between the location of different ground strips and the time when the peak current through each strip is reached.

It can also be seen that the peak current of the secondary SIW is 3 times higher than that of the primary SIW. This is due to the fact that the secondary SIW propagates in the conductive channel left over by the primary SIW. The current attenuation during the propagation of the secondary SIW is also less than that of the primary SIW. The current waveform through the fourth ground strip, located at where the SIW extends to its maximum length, presents only one peak during the period of the secondary SIW propagation, which means that the primary SIW hardly reaches this position.

On the voltage falling edge, the current through each ground strip turns to be negative, indicating a reverse discharge. Note that, during this period, the negative current through the first ground strip is much larger than that through strips further away from the HV electrode. This means that there are residual positive charges left far away from the HV electrode (which may be like an isolated island). This effect will also be proved by the measured electric field as well as
the distribution of the residual surface potential after the discharge (shown below).

Figure 5(b) shows the HV waveform and the current waveforms flowing through each ground strip using the PTFE dielectric with a peak voltage of 14 kV and a PRR of 100 Hz. Differing from the case with the ER dielectric, the current waveform with the PTFE dielectric presents much less pronounced two-peak feature on the voltage rising edge, which means that there may not be well-distinguished primary and secondary SIW propagation processes. The velocity of the SIW propagation on PTFE is estimated to be about 0.08 mm ns\(^{-1}\), which is much slower than that on ER. The peak current with PTFE is much smaller than that with ER by one order of magnitude, which agrees with the huge difference in the emission intensity shown in figure 2. The peak current through each ground strip with PTFE also attenuates significantly away from the HV electrode, in contrast with the almost constant (second) peak current in the ER case.

Figure 6(a) shows the current waveform through the first ground strip using the ER dielectric with different PRRs of 10, 100, and 500 Hz. The peak voltage is kept at the same value of 14 kV. It can be seen that the two-peak feature on the current waveform is less obvious with a high value of PRR (500 Hz) compared with that with a low PRR (10 and 100 Hz), which means that the primary and the secondary SIWs are less distinguished with a high PRR. This feature agrees with what has been observed in the fast ionization wave propagating in a shielded dielectric tube, which shows a lesser difference between the peak electric field and that after the breakdown with a high value of PRR [26].

Figure 6(b) shows the current waveform through the first ground strip using the PTFE dielectric with different PRRs and with the same peak voltage of 14 kV. Similar as the case with the ER dielectric, the two-peak feature of the current waveform is slightly more obvious with a low PRR of 10 Hz. Other than this, the current waveform is almost the same with different values of PRR.

The following estimation is performed, trying to give an interpretation about the influence of dielectric material on the current during the SIW propagation \((I(t))\), which can roughly
be given as follows [38, 39]:

$$I(t) = \frac{d(C(t) \cdot U(t))}{dt} = C(t) \cdot \frac{dU(t)}{dt} + \frac{dC(t)}{dt} \cdot U(t).$$  \hspace{1cm} (2)

Here, $U(t)$ is the voltage waveform. $C(t)$ is the capacitance between the plasma slide and the ground electrode, which changes with time due to the SIW propagation and the extension of the plasma slide. $C(t)$ and $dC(t)/dt$ can be written as:

$$C(t) = \frac{\varepsilon_0 W_p L_p(t)}{d_e}, \quad \frac{dC(t)}{dt} = \frac{\varepsilon_r \varepsilon_0 W_p}{d_e} \cdot \frac{dL_p(t)}{dt} = \frac{\varepsilon_r \varepsilon_0 W_p}{d_e} \cdot V_{SIW}.$$ \hspace{1cm} (3)

Here, $\varepsilon_0$ is the vacuum permeability and $\varepsilon_r$ is the relative dielectric constant of the dielectric material. $d_e$ is the thickness of the dielectric. $W_p$ and $L_p$ are the width and the length of the plasma slide, respectively. Here, $W_p$ is assumed to be a constant during the SIW propagation, while $L_p$ extends with a velocity of $V_{SIW}$.

Combining equations (2) and (3), the following relationship can be obtained,

$$I(t) = \frac{\varepsilon_r \varepsilon_0 W_p L_p(t)}{d_e} \cdot \frac{dU(t)}{dt} + \frac{\varepsilon_r \varepsilon_0 W_p}{d_e} \cdot V_{SIW} \cdot U(t).$$ \hspace{1cm} (4)

The first term on the right side of equation (4) is the classical displacement current due to the variation of the voltage across a capacitor, while the second term is due to the extension of the conductive plasma slide and the variation of the capacitance, which is called the dynamic displacement current in [38].

It can be estimated that for the ER dielectric case when the SIW has a relatively high velocity (about 0.3 mm ns$^{-1}$), the first term on the right side of equation (4) contributes a current on the order of 0.2 A, while the second term contributes a current on the order of 1 A. However, for the PTFE dielectric case when the SIW has a relatively low velocity (about 0.08 mm ns$^{-1}$), both terms contribute to a current on the order of 0.1 A. As one can see, the velocity of the SIW propagation and the dynamic displacement current help to explain the huge difference in the measured current (by one order of magnitude) when different dielectric materials are used, which goes beyond the influence of the relative dielectric constant ($\varepsilon_r \approx 4.3$ for ER versus $\varepsilon_r \approx 2.1$ for PTFE).

It is worth to notice that in the above estimation, we ignore the voltage drop across the plasma slide, which has a certain resistance and is not a perfectly conductive medium [40, 41]. Even so, the purpose of this estimation is to give a qualitative explanation on the huge difference in the measured current with different dielectric materials. Further detailed analysis considering the spatial distribution of $U(t)$ based on the measured electric field distribution will be given in the appendix.

3.2. The electric field: temporal evolution and spatial distribution

Figures 7(a) and (b) shows the measured temporal evolution of the horizontal electric field ($E_x$) at different locations using the EFISH method with the ER and the PTFE dielectrics, respectively. The peak voltage is 14 kV and the PRR is 100 Hz.

Note that there is already a non-zero electric field before the HV pulse, which is due to the existence of residual surface charges from the previous pulse. The direction of the electric field is inverted when it reaches a local minimum point (the same as what has been done in [21]).

It can be seen in figure 7(a) that as the voltage starts to rise, $E_x$ near the HV electrode starts to increase firstly, while $E_x$ at locations further away from the HV remains more or less unchanged. This means that before the breakdown happens, the electric field near the HV electrode is a superposition of the Laplacian field and the field due to the residual surface charges.

When $E_x$ near the HV electrode reaches a peak value of 26 kV cm$^{-1}$, it starts to drop and a local minimum value is
formed, which indicates the breakdown happens. This is accompanied by the sudden rise of $E_x$ at 2.5 mm and 5 mm, which happens later at a position further away from the HV electrode, indicating the SIW propagation. These phenomena happen during a time period roughly corresponding to the primary SIW period indicated by the first peak of the current waveform in figure 5(a). However, due to the limited temporal resolution of the EFISH system, no exact matching between the current waveform and the electric field evolution can be achieved. Afterwards, $E_x$ near the HV increases again and reaches a second peak, while $E_x$ at 2.5 mm and 5 mm keeps increasing and reaches its positive maximum, which also happen in time sequence and correspond to the secondary SIW.

On the voltage falling edge, $E_x$ near the HV electrode and that at 2.5 and 5 mm reverses and reaches their negative maximum in time sequence, which is consistent with the negative current shown in figure 5(a). This is explained by the fact that the residual positive charge on the dielectric surface generates a negative horizontal electric field and a reverse breakdown process.

It is worth noticing that $E_x$ at 7.5 mm, where the SIW reaches its maximum length, experiences a dull rise during the voltage rising period, followed by a slow decay during the voltage falling period and it presents no reverse process. This is explained by that this location is affected by the electric field at the SIW front, which rises as the wave front of the SIW approaches and drops as the SIW decays, and no plasma slide is formed across this location.

Comparing figures 7(a) and (b), it can be found that $E_x$ near the HV electrode with the PTFE dielectric has only one peak (without the two-peak feature in the ER case). With the PTFE dielectric, the peak $E_x$ near the HV electrode is slightly lower than that with ER (23 kV with PTFE versus 26 kV with ER). Even so, the time when the peak value is reached is later ($-170$ ns with PTFE versus $-193$ ns with ER), which is due to a larger negative residual $E_x$ with the PTFE dielectric ($-18$ kV with PTFE versus $-14$ kV with ER). With the PTFE dielectric, $E_x$ also attenuates faster away from the HV electrode (for example, $E_x$ at 2.5 mm is 15 kV cm$^{-1}$ with PTFE, while it is 24 kV cm$^{-1}$ with ER). This feature is consistent with its faster current attenuation during the SIW propagation (shown in figure 5).

Figures 8(a) and (b) show the temporal evolution of the horizontal electric field at 2.5 mm with different PRRs using the ER dielectric and the PTFE dielectric, respectively.

It can be seen in figure 8(a) that with the ER dielectric, the absolute value of the residual $E_x$ before the breakdown deceases with the PRR, i.e. it decreases from $-14.5$ kV cm$^{-1}$ with 500 Hz to $-10.5$ kV cm$^{-1}$ with 10 Hz, which is also shown in figure 8(c). This indicates the decay of the residual surface charges on the ER dielectric, as the pulse interval increases from 2 ms to 0.1 s. Other than this, the temporal evolution of $E_x$ is almost the same with different PRRs.

In figure 8(b), when PRR changes from 10 to 500 Hz, the evolution process of $E_x$ with PTFE coincides with each other and the residual $E_x$ before the breakdown remains the same. This indicates that the residual surface charges on the PTFE dielectric hardly decay within a time period of 0.1 s. Indeed, it has been verified the residual $E_x$ with PTFE remains unchanged for more than one hour after the HV generator is turned off. This fact provides the possibility to perform an
off-line measurement on residual surface potential (as well as the residual electric field) due to the surface charge accumulation using the Kelvin electrostatic probe, which will be shown in the next section.

Indeed, the characteristic time for the charge decay $\tau_V$ through the volume resistivity $\rho_V$ is given by [42],

$$\tau_V = \varepsilon_0 \rho_V. \quad (5)$$

ER has a volume resistivity on the order of $10^{10}$ $\Omega \cdot m$ (according to the datasheet of the dielectric material used) and its characteristic charge decay time is approximately 0.4 s obtained from equation (5), which can partially explain the decay of the residual electric field when the pulse interval increases from 2 ms to 0.1 s. However, PTFE has a much higher $\rho_V$ ($>10^{16}$ $\Omega \cdot m$) and a much longer charge time ($\tau_V > 2 \times 10^5$ s). Therefore, it is hard to observe a variation of the residual electric field within the pulse interval range in this work ($<0.1$ s). Other factors influencing the decay of the surface charges include the electric conduction along the dielectric surface and the neutralization by the charge in the gas phase [42]. Currently, we do not perform a detailed analysis of these effects, as it is already beyond the main topic of this work.

3.3. The residual surface potential distribution after the discharge

As mentioned above, the residual electric field with the PTFE dielectric remains unchanged for a long time period ($>1$ h), which allows us to measure its residual surface potential distribution after the discharge using the Kelvin electrostatic probe (shown in figure 9 with the contour-plot). From the gradient of the surface potential distribution, the electric field in $x$ and $z$ directions ($E_x$ and $E_z$) can be obtained, which is presented by the arrows, together with the surface potential in figure 9. The HV electrode locates at 0 mm in the $x$ direction and the middle point of the nozzle is set as the zeros point of the $z$ axis.

It can be seen that the residual surface potential increases away from the HV electrode, which is due to the positive residual surface charges after the discharge and agrees with that observed in [36]. Near the nozzle region, the contour-line of the surface potential bulges away from the HV electrode, as the SIW mainly happens in the argon flow blown out from the nozzle. Two almost symmetric plateaus of the surface potential are formed at the coordinates of $(x \approx 10$ mm, $z \approx 13$ mm) and $(x \approx 10$ mm, $z \approx -13$ mm). The electric field is directed outside from these two plateaus and it is directed toward the HV electrode. This verifies that the residual $E_x$ before the breakdown and the $E_z$ during the SIW propagation are in the opposite direction, the latter of which is directed outward the HV electrode when a positive HV is applied. Therefore, it is reasonable to perform an inversion of the measured $E_z$ when it reaches a local minimum during both the voltage rising and falling edges.

It worth to notice that the distance between the tip of the Kelvin electrostatic probe and the dielectric surface ($\approx$5 mm) limits the spatial resolution of the measured surface potential and that of the electric field from its gradient, especially at locations where their distribution is extremely non-uniform. For example, the residual $E_x$ near the HV electrode is quite strong (as shown in figure 7(b)), while $E_z$ inside the HV electrode, which is in parallel with the metal surface, should be zero. However, $E_x$ from the gradient of the surface potential will be smooth out this feature. Therefore, no quantitative agreement between the electric field from the EFISH method and that from the surface potential could be obtained in this work.

3.4. Analysis of EFISH signal accumulation along the beam path

It is already known that the EFISH method detects a line-of-sight signal integration along the laser propagation path and former investigations have prominently contributed to the influence of the measurement length [20, 33]. In this work, especially, as the SIW has an extremely non-uniform electric field distribution and both the charge on the dielectric surface and that in the plasma slide will contribute to the EFISH signal, it is desirable to analyze the distribution of the EFISH signal along the laser beam path.

According to [43, 44], when both the external electric field $E_0$ and the electric field of the fundamental laser $E_1$ have a non-uniform spatial profile, the electric field of the second harmonic can be given as follows,

$$E_2(2\omega, z) \propto \int_{-\infty}^{z} N\chi^{(3)}(\omega_0, z')E_0^2(\omega) \times (1 + i2\omega'/\beta_1)^{-1} \exp(i\Delta k z')dz'.$$ \quad (6)

Here, $\beta_1$ is the confocal parameter of the fundamental laser beam, and $\beta_1/2$ indicates the distance (along the laser path) between the focus to the position where the beam radius has increased by $\sqrt{2}$. 

Figure 9. The contour-plot of the residual surface potential distribution on the PTFE dielectric after the discharge measured using the Kelvin electrostatic probe. The electric field in the $x$ and $z$ directions is presented by the arrows.
The beam radius along the laser path \( w(z) \) is given by [45],

\[
w^2(z) = w_0^2 [1 + (2z/b_1)^2].
\]

(7)

Here, \( w_0 \) is the \( 1/e^2 \) beam radius at the focus (\( w_0 \approx 130 \mu m \)). \( b_1 \) can be obtained from,

\[
b_1 = w_0^2 \cdot k_1 = w_0^2 \cdot 2\pi n(\lambda_i) / \lambda_i
\]

and it is calculated to be about 10 cm.

The spatial distribution of the laser intensity \( I(z, \lambda) \) and the relationship between the laser intensity and the electric field are given by [45],

\[
I(z, \lambda) = 0.5n(\lambda)c\varepsilon_0 \left| E(r, \lambda) \right|^2 \propto |E|^2 w_0^2 / w^2 \times \exp\left( -\frac{2r^2}{w^2} \right).
\]

(9)

By moving the parallel-plate calibration electrodes along the laser path, the distribution of the square root of the EFISH signal \( I(2\omega)^{0.5} \) in the \( z \) direction is obtained, which is shown in figure 10. In the same figure, the calculated \( I(2\omega)^{0.5} \) distribution in the \( z \) direction corresponding to the uniform electric field generated by the parallel-plate electrodes is also shown. It can be seen that the calculated \( I(2\omega)^{0.5} \) curve agrees well with the measured one, demonstrating the validation of the analysis on the EFISH signal accumulation along the beam path.

As for the SDBD, the analysis on the EFISH signal accumulation is performed based on the residual electric field distribution in \( z \) direction on the PTFE dielectric (shown in figure 11(a)). As it is very challenging to obtain the real gas component in the discharge region in this work, a step wise multiplicative factor accounting for the different hyperpolarizabilities, \( \chi^{(3)} \), and wavevector mismatch, \( \Delta k \), of argon and air is included, i.e. the gas component in the region with \(-3 \text{ mm} < z < 3 \text{ mm} \) is taken as argon and that in the other region is taken as air. This simplifying assumption introduces an upper bound uncertainty of approximately 20%, since \( \chi^{(3)}[\text{Air}] / \chi^{(3)}[\text{Ar}] = 0.79 \), while \( \Delta k[\text{Ar}] \) and \( \Delta k[\text{Air}] \) are very close to each other, \( \Delta k[\text{Ar}] = 0.47 \text{ cm}^{-1} \) versus \( \Delta k[\text{Air}] = 0.50 \text{ cm}^{-1} \).

As mentioned above, the argon flow from the nozzle leads to the bend of the contour-line of surface potential. As a consequence, the \( z \) direction distribution of \( E_z \) around the HV electrode has a dip near the nozzle region, which partially cancels the effect of the larger \( \chi^{(3)}[\text{Ar}] \) than \( \chi^{(3)}[\text{Air}] \) and leads to an almost linear increase of the electric field of the second harmonic \( |E_2| \), as shown in figure 11(b). On the contrary, \( E_z \) away from the HV electrode by 7.5 mm has a peak in the region of the argon flow, where \( |E_2| \) has a drastic increase.

4. Limitations

First and foremost, the SDBD under investigation in this work is extremely inhomogeneous, while the EFISH method
captures a line-of-sight integration of the electric field along the laser path, i.e. both the electric field around the main streamer channel in the argon flow region and that away from the main streamer will contribute to the EFISH signal. In fact, the effect of the laser-electric field interaction length $L$ can be taken into account based on the relationship $(2a)^{0.5} \sim E \cdot L$ according to equation (1), i.e. there is an inverse relationship between the electric field and the laser-electric field interaction length for the same EFISH signal. However, the choice of the $L$ value is somewhat arbitrary for an extremely inhomogeneous SDBD, and the electric field distribution inference may be uncertain. Therefore, no attempt to infer the electric field distribution in the discharge is performed. The line-of-sight integration may result in an underestimation of the peak electric field during the SIW propagation, as the SIW in this work is quite filamentary and a strong electric field may exist near the wave front region (i.e. near the thin streamer head). On the other hand, the residual electric field near the HV electrode may be overestimated, as it spans over the whole HV electrode region (as shown in figures 9 and 11(a)). Indeed, the peak electric field in the nanosecond pulsed discharges obtained from the widely adapted line-ratio method can be much higher (up to 1000 Td, i.e. 260 kV cm$^{-1}$ bar$^{-1}$) [46–49]. This can be explained by the fact that the excited species emitting optical light are mainly generated by the impact of high energy electrons ($> 10$ eV, depending on the excitation threshold energy), which are concentrated in the region where the electric field is the strongest [2, 26, 50, 51].

In this work, the temporal resolution of the EFISH measurement is limited by the laser pulse width (about 7–9 ns), which could smear out the electric field evolution on the shorter time scales, and reduce the peak electric field during the SIW propagation. This effect could be significant especially for the SIW propagating on the ER dielectric, which has a velocity $V_{SW}$ of about 0.3 mm ns$^{-1}$. Considering the laser radius of about 130 $\mu$m around the focal point and the characteristic length scale for atmospheric pressure plasma of the order of hundred micrometers, a sub-nanosecond time resolution is needed to well resolve the electric field evolution, i.e. a picosecond laser may be required in the further investigation. Note, however, that nanosecond EFISH measurements can provide a temporal resolution shorter than the laser pulse duration, by using a detector with a shorter response time [52]. Although the field reversal has been detected, when the electric field at a certain position passes though zero during the SIW propagation, only a local minimum value is obtained in the experiment. This is also due to the limited temporal resolution of the EFISH system, which induces an averaging effect.

5. Conclusions

In this work, the propagation of the SIW in the nanosecond pulsed SDBDs with different dielectric materials (ER and PTFE) and different PRRs (from 10 to 500 Hz) is investigated. With a specially designed ground strip array structure, the current waveform at different locations along the route of the SIW propagation is obtained. Using the EFISH method, the temporal evolution and spatial distribution of the horizontal electric field during the SIW propagation are measured with different dielectric materials and PRRs. The distribution of the residual surface potential after the discharge is mapped with a Kelvin electrostatic probe, which verifies both the existence and the direction of the residual electric field from the EFISH measurement.

By comparing the results using the dielectric materials with different charge decay rates and by changing the PRR (i.e. the pulse interval), the effect of the residual surface charges on the SIW propagation is illustrated. It is found that with the ER dielectric, on which the residual surface charges decay faster, there are the well-pronounced primary and secondary SIW propagation processes with a higher velocity on the voltage rising edge. Both the peak current and the peak electric field during the SIW propagation on the ER dielectric are higher, with a less spatial attenuation of both parameters along the SIW route. A higher PRR tends to smear out the feature of the primary and secondary SIWs. The residual electric field increases with the PRR in the ER dielectric case, which has a characteristic charge decay time comparable with the pulse interval used in this work. However, when the PRR changes, the residual electric field is nearly a constant with the PTFE dielectric, whose characteristic charge decay time is much longer than the pulse interval in this work. It is...
demonstrated that the residual surface charges with the same polarity as the HV pulse tend to suppress the development of the SIW.

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Appendix

According to [40, 41] and based on the Kirchhoff equations, the current in a SDBD is described as follows:

$$I(t) = \varepsilon_0 W_p \frac{\partial}{\partial t} \int U(x, t) dx.$$  \hfill (A1)

Here, $U(x, t)$ describes the potential at different locations along the route of the SIW propagation and its temporal evolution. $U(x, t)$ can be obtained combining the HV waveform $U(0, t)$ and the horizontal electric field $E_x(x, t)$ from the EFISH measurement:

$$U(x, t) = U(0, t) - \int_0^x E_x(x', t) dx'$$  \hfill (A2)

which is shown in figures A1(a) and (b), corresponding to the case with ER and PTFE dielectrics, respectively.

Combining equations (A1) and (A2), the current in a SDBD can be obtained, which is shown in figure A2, together with the spatial integration of the potential $\int U(x, t) dx$.

It can be seen in figure A1 that before the HV is applied, the potential rises away from the HV electrode, which is due to the existence of the residual surface charges and the negative residual $E_x$. This feature is consistent with the measured surface potential distribution using the Kelvin electrostatic probe. The SIW propagation process is accompanied with a drop and a following fast rise of the potential at each position. After the discharge, the potential recovers to a similar value as that before the breakdown. Note that the overshoot of $U(x \approx 5 \text{ mm})$ and $U(x \approx 7.5 \text{ mm})$ compared with the peak value of HV waveform can be explained by the uncertainty of the absolute value of $E_x$ from the EFISH measurement. This is due to the fact that the laser-plasma interaction length has a strong impact on the EFISH signal [21].

In figure A2, it can be seen that the current obtained from equation (A1) has a negative dip before its main positive peak, which is not observed in the measured current waveform using the shunt resistor. Indeed, this dip is due to the non-accuracy in the $E_x$ measurement especially when $E_x$ passes through the zero point during the SIW propagation. As mentioned above, $E_x$ will be over-estimated due to the nanosecond pulse width of the laser used in this work. This effect is even more obvious in the ER dielectric case, when the SIW has a much faster propagation velocity. Furthermore, the long laser pulse will also over-estimate the electric field after the wave front of the SIW passes due to the averaging effect, as a result of which, the voltage drop across the plasma slide will also be over-estimated. Taking these factors into consideration, it is reasonable to argue that there is no full agreement between the measured current waveform and that obtained using equations (A1) and (A2). Based on an $E_x$ measurement with a better temporal resolution and perhaps a denser spatial sampling, one can expect a better agreement between the results from these methods.

Figure A1. The temporal evolution of the potential at different locations $U(x, t)$ obtained using the HV waveform and the measured horizontal electric field $E_x$ with the EFISH method. (a) ER dielectric, (b) PTFE dielectric.
Figure A2. The temporal evolution of the spatial integration of the potential $\int U(x,t) dx$ and the current obtained from equation (A1). (a) ER dielectric, (b) PTFE dielectric.

ORCID iDs
Bangdou Huang https://orcid.org/0000-0002-1523-7380
Cheng Zhang https://orcid.org/0000-0003-1512-2820
Igor Adamovich https://orcid.org/0000-0001-6311-3940
Yuri Akishev https://orcid.org/0000-0001-8379-5782
Tao Shao https://orcid.org/0000-0002-5738-1241

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