Applied Physics Letters

Comment on “Electric field measurements under DC corona discharges in ambient air by electric field induced second harmonic generation” [Appl. Phys. Lett. 115, 244101 (2019)]

Cite as: Appl. Phys. Lett. **117**, 026101 (2020); https://doi.org/10.1063/5.0007572
Submitted: 14 March 2020 • Accepted: 19 June 2020 • Published Online: 16 July 2020

N. G. C. Ferreira, P. G. C. Almeida, M. S. Benilov, et al.

Applied Physics Letters COMMENT scitation.org/journal/apl

Comment on "Electric field measurements under DC corona discharges in ambient air by electric field induced second harmonic generation" [Appl. Phys. Lett. 115, 244101 (2019)]

Cite as: Appl. Phys. Lett. **117**, 026101 (2020); doi: 10.1063/5.0007572
Submitted: 14 March 2020 · Accepted: 19 June 2020 ·
Published Online: 16 July 2020

View Online Export Citation CrossMark

N. G. C. Ferreira,[1,2] P. G. C. Almeida,[1,2] M. S. Benilov,[1,2,a)] and G. V. Naidis[3]

AFFILIATIONS

[1]Departamento de Física, Universidade da Madeira, 9000 Funchal, Portugal
[2]Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, 1041 Lisbon, Portugal
[3]Joint Institute for High Temperatures RAS, 125412 Moscow, Russia

[a)]Author to whom correspondence should be addressed: benilov@staff.uma.pt

https://doi.org/10.1063/5.0007572

Recently, Cui *et al.* reported results of the measurement of the electric field inside negative corona discharges in an axially symmetric wire-cylinder gap, performed using the modern electric field-induced second harmonic (E-FISH) diagnostics.[1] Based on these results, it was concluded that the electric field at the wire surface is proportional to the current density of the corona discharge with a negative constant of proportionality or, in other words, appreciably decreases with increasing current, contrary to the classic Kaptzov assumption, which states that the steady state electric field at the conductor surface remains at the corona onset value. Note that this assumption can be traced back to the foundational work of Townsend of 1914[2] and is a cornerstone of the corona discharge theory.

In this comment, we do not question the importance of the experiment,[1] which constitutes a significant advance and may be used, in particular, for validation of various corona discharge models. Moreover, the distribution of the electric field in the drift region, given by numerical modeling in the framework of a steady-state one-dimensional (1D) model, is in good agreement with experimental values,[1] which shows that this model provides a reasonably accurate averaged description of a negative wire-cylinder corona and, in particular, justifies the use of this model for the interpretation of experiment as done in Ref. 1. However, we show that the conclusion that the electric field at the wire surface decreases with increasing current stems from a misinterpretation and there are no reasons to doubt the validity of the Townsend–Kaptzov assumption.

Values of the electric field reported in Ref. 1 have been measured in the range of axial distances r from 0.25 cm to 2.5 cm, while the wire radius was $r_0 = 0.1$ cm. In order to estimate the electric field value at the surface of the wire, the measurements were extrapolated with the use of the well-known approximate equation (e.g., Ref. 3) describing the distribution of the electric field in coaxial wire-cylinder corona discharge gaps,

$$E^2(r) = \frac{I_l}{2\pi\varepsilon_0\mu}\left(1 - \frac{r_0^2}{r^2}\right) + \left(\frac{E_0 r_0}{r}\right)^2. \quad (1)$$

Here, I_l is the corona current per unit length, μ is the mobility of the ions that are believed to dominate current transfer in the drift region (mobility of the negative ions was assumed in Ref. 1), and $E_0 = E(r_0)$ is the electric field at the wire surface. Based on this extrapolation, the authors[1] estimated E_0. For example, the value of E_0 obtained for $I = 0.45$ mA, which was the highest discharge current reported in Ref. 1, was approximately 44 kV/cm. The distribution of the electric field in the discharge gap calculated by means of Eq. (1) with the use of this value and μ equal to 2.2 cm^2 V^{-1} s^{-1} is depicted by the dashed line in Fig. 1.

There is a grave problem with these data, which can be explained as follows. The value of E_0 at inception, given in Ref. 1, is approximately 63 kV/cm, and the corresponding value of the ionization integral K (that is, the integral of the effective ionization coefficient over the ionization region), evaluated in terms of the Laplacian distribution of the electric field, is 9.58. For $I = 0.45$ mA, the value of K, evaluated with the use of Eq. (1) with the above-mentioned value $E_0 = 44$ kV/cm, is 1.85, i.e., much lower, and hence, the condition of reproducibility of charges in the ionization region is grossly violated; such discharge would not be self-sustained.

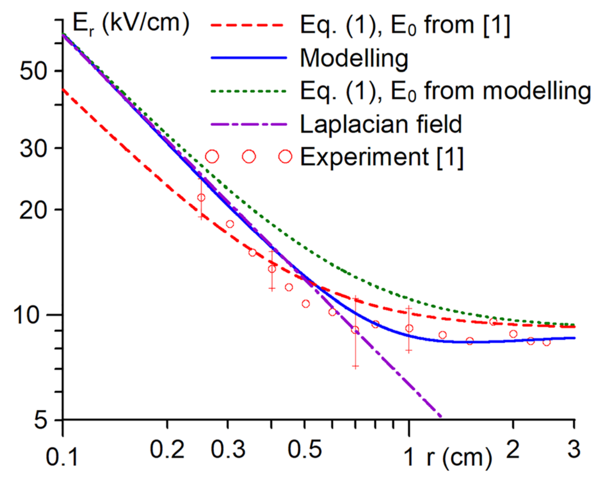

FIG. 1. Electric field distributions in the gap evaluated under various approximations, I = 0.45 mA.

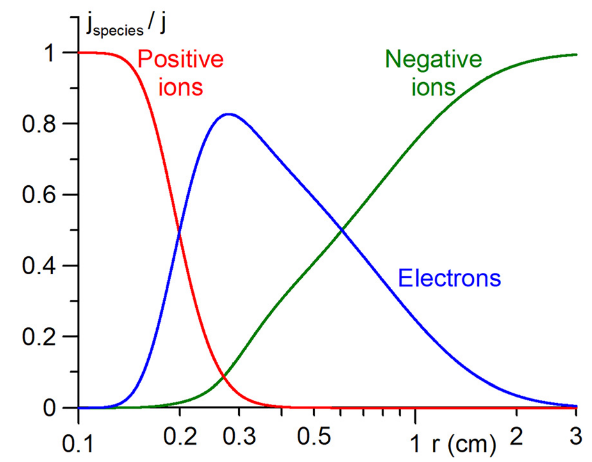

FIG. 2. Contributions of various charged species to the current transport, I = 0.45 mA.

One should suspect that Eq. (1) cannot be used for extrapolation in these conditions. Another indication in the same direction is suggested in Fig. 1: the slope of the electric field distribution, given by Eq. (1), is different from that revealed by the experimental data.

Equation (1) is an approximate relation obtained from the ion transport equation coupled with the Poisson equation, and in order to analyze its validity, one should resort to a more accurate theoretical model, comprising these and other relevant equations. A number of such models are described in the literature. In this work, the model described in Ref. 4 was used. The results below refer to $r_0 = 0.1$ cm, the inner radius of the cylinder is equal to 3 cm, and the secondary electron emission coefficient is equal to 10^{-5}. The computed distribution of the electric field in the gap is in good agreement with the experimental data,[1] as exemplified by the solid line in Fig. 1, and the computed values of the inception field and discharge voltages for different currents conform to the experimental values, given in Ref. 1, to the accuracy within approximately 3%. This attests to the suitability of the model[4] for the discharge conditions considered.

In Fig. 2, the computed contributions to the current transport of the electrons, positive ions, and negative ions are shown for $I = 0.45$ mA. It is seen that the main contribution in the range of $r = 0.2$–0.6 cm is made by the electrons, with their mobility being by several orders of magnitude higher than that of the ions. It follows that Eq. (1) with the negative ion mobility does not describe correctly the electric field distribution in the region $r \geq 0.2$ cm. The latter is indeed the case, as shown in Fig. 1: the distribution of the electric field given by Eq. (1) and depicted by the dotted line deviates for $r \geq 0.2$ cm from the solid line, which represents the modeling results. It is unsurprising that, therefore, no choice of E_0 allows bringing Eq. (1) into agreement with experimental data obtained over a wide range of r values, as exemplified by the dashed line in Fig. 1.

This explains why Eq. (1) cannot be used for the extrapolation of the experimental data to the wire surface. In fact, such extrapolation gives values of the surface electric field that are significantly lower than those given by the modeling, as exemplified in Fig. 1. Note that the field at the wire surface, given by the modeling, varies by not more than approximately 1% over the whole current range considered. In other words, the electric field at the wire remains at the corona inception level, in agreement with the Townsend–Kaptzov assumption. This is consistent with the fact that the computed electric field in the ionization region is very close to the Laplacian field at the inception (dotted-dashed line in Fig. 1), i.e., is not perturbed by the space charge.

It is well known that the negative DC corona in air frequently operates in a pulsed regime: the current waveform reveals the so-called Trichel pulses. Moreover, negative wire coronas are in many cases three-dimensional: bright spots appear on the wire surface. These spots, which are sometimes called 'tufts', represent a self-organization phenomenon and do not necessarily appear on the whole wire, e.g., Fig. 10 in Ref. 5 and its discussion. Neither the images of the negative corona wire nor the waveforms of the corona current are given in Ref. 1, and it is possible that the Trichel pulses and tufts were present in these experiments. If the latter is the case, the agreement between the modeling and experimental data seen in Fig. 1 shows that a steady-state 1D model provides a reasonably accurate averaged description of current transfer in the drift region of a pulsed negative wire-cylinder corona, sufficiently far away from the highly transient near-cathode layer. In particular, this justifies the use of the steady-state 1D model for the interpretation of measurements performed in the drift region, as done in Ref. 1.

It is useful to emphasize that while the dependence of the wire surface field on the DC corona discharge current in axially symmetric wire-cylinder gaps is weak, in other corona configurations, e.g., in point-plane gaps, the field at the stressed electrode can vary substantially with the current due to a redistribution of the current density over the electrode surface with the increase in the applied voltage. This topic requires special consideration.

This work was supported by the European Regional Development Fund through the program Madeira 2014–2020 under project PlasMa-M1420-01-0145-FEDER-000016, by FCT of

Portugal under project UIDP/50010/2020 (UMa), and by RFBR Grant No. 20-02-00320 (JIHT).

REFERENCES

[1] Y. Cui, C. Zhuang, and R. Zeng, Appl. Phys. Lett. **115**, 244101 (2019).
[2] J. S. Townsend, Philos. Mag. **28**, 83 (1914).
[3] Y. P. Raizer, *Gas Discharge Physics* (Springer, New York, 1991).
[4] N. G. C. Ferreira, D. F. N. Santos, P. G. C. Almeida, G. V. Naidis, and M. S. Benilov, J. Phys. D **52**, 355206 (2019).
[5] M. S. Benilov, Plasma Sources Sci. Technol. **23**, 054019 (2014).