Journal of Physics D: Applied Physics

PREFACE

Special issue on recent developments in plasma sources and new plasma regimes

To cite this article: Yuri Akishev *et al* 2019 *J. Phys. D: Appl. Phys.* **52** 130301

IOP Publishing

Journal of Physics D: Applied Physics

J. Phys. D: Appl. Phys. **52** (2019) 130301 (5pp)

https://doi.org/10.1088/1361-6463/ab0004

Preface

Special issue on recent developments in plasma sources and new plasma regimes

Guest Editors

Yuri Akishev
State Research Centre of Russian Federation TRINITI, Moscow, Russia
E-mail: akishev@triniti.ru

Zdenko Machala
Comenius University, Bratislava, Slovakia
E-mail: machala@fmph.uniba.sk

Nikolay Koval
High-Current Electronics Institute, Tomsk, Russia
E-mail: koval@hcei.tsc.ru

With great enthusiasm we present this special issue of *Journal of Physics D: Applied Physics*, which collects the best selection of the recent state-of-the-art in experimental and numerical research of non-thermal plasma sources and discharge regimes and their wide application possibilities. The research achievements and generation of such plasma discharges promote the advances in many areas of science and technology and open or stimulate new horizons and possibilities for their uses. The issue presents a wide spectrum of new approaches for pulsed generation of plasmas by the ultra-high electric field of nanosecond/sub-nanosecond duration, formation of discharges with runaway electrons, and generation of plasma by electromagnetic beams from microwave to terahertz diapason. New plasma regimes that were created by various plasma jets and multi-jets, dielectric barrier or other kinds of gas discharges operating in gases, as well as discharges interacting with or directly in liquids are also extensively addressed. Several contributions include modeling of some of these new plasma regimes, and most of them provide examples of applications that benefit from these plasma source designs, with a special focus on biomedical, agricultural, combustion, environmental, nanoparticle and diamond synthesis, and other emerging applications.

The special issue is launched with a topical review on low pressure discharges with hollow cathode and anode and their applications, by Korolev and Koval [1]. As historically plasma science started with low pressure electrical discharges and recently the focus moved to atmospheric pressure with a large variety of new applications, reviewing low pressure discharges with extremely small neutral particle density and electron free path in excess of the size of the discharge gap, where the discharge regimes are between the avalanche ionization and pure vacuum discharge in the cathode metal vapors, is still timely. New approaches to the interpretation of the discharge formation mechanism and sustaining are discussed and offer the possibility to obtain a uniform plasma in a large volume of the cathode or anode cavity, in the sources of electron and ion beams based on the plasma cathode and in the high-current pseudospark switches.

Several research papers in the issue deal with recent developments and new plasma regimes under low pressures. Burdovitsin *et al* [2] investigated the beam-plasma formed by an energetic electron beam at fore-vacuum pressure (1–10 Pa range). The maximum plasma density at the optimum collector potential can be much greater than the plasma density when the collector is at ground or at floating potential.

Bokhan *et al* [3] studied an open discharge with counter-propagating electron beams applicable in high voltage pulsed switches with a sub-nanosecond leading edge (kivotrons). It was shown that a fast current development arises when the discharge self-sustaining mode is caused by the photoemission from the cathodes due to the resonant radiation emitted by fast helium atoms with a large Doppler shift with respect to the line center. As a result, the emitted radiation reaches the cathode without absorption by the helium gas. They have shown that the radiative, collisional-radiative, and three-body collision recombination mechanisms significantly contribute to the afterglow decay only when the plasma density remains higher than 10^{12} cm^{-3}.

Runaway electrons with extremely high energy have been of great recent interest in plasma community. A reason of that runaway electrons form e-beam directly in the atmosphere of working gas without the use of additional vacuum equipment. Akishev *et al* [4] present a three-electrode open discharge in the pulsed overvoltage in low pressure deuterium as an effective source of the high-current beam of runaway electrons with energy up to 25 keV. Numerical calculations support their experiments to unveil the mechanisms

1361-6463/19/130301+5$33.00

responsible for the breakdown, sustaining and instability of the strongly overvoltage pulsed discharge in a narrow gap.

Zubarev *et al* [5] numerically investigated the conditions under which runaway electrons are generated in a gas diode with a strongly nonuniform electric field created by electrodes of specific geometry. This electrode-shape conditions supplement the classical electron runaway condition according to which the field strength near the emitting edge of the cathode should exceed some value depending only on gas parameters. For a sharp-edged cathode, the new condition imposes more stringent requirements on the field strength compared with the classical one, which was also supported by experiments.

Generation and registration of runaway electron beams during the breakdown of highly overvoltaged gaps filled with dense gases (SF_6, CO_2, Ar, and N_2 at pressures of up to 1.2 MPa) is addressed in the article of Tarasenko *et al* [6]. They investigated the dynamics of plasma glow in the space between a sharp-ended tubular and a plane electrode during the prebreakdown stage of a nanosecond discharge. The generation of a runaway electron beam and fast electrons contributes to the formation of a discharge in a diffuse form and the time of runaway electron beam formation correlates with the maximum voltage in the gap.

Gas discharges in quasioptical beams of electromagnetic radiation of the THz frequency band are attractive for both fundamental and applied research, addressed here by Sidorov *et al* [7]. A significant difference of the THz discharge from that at lower frequencies, even in the dynamics of discharge glow was shown. The maximum of the discharge glow was observed after the end of the THz pulse and the afterglow duration was hundreds of microseconds. Their paper is devoted to the theoretical and experimental study of the breakdown thresholds of various gases by radiation at 263 and 670 GHz and the study of discharge dynamics in noble and molecular gases under 670 GHz radiation.

At slightly lower gyrotron frequencies (about 30 GHz), millimeter wave radiation induced microwave discharge is characterized by high plasma density and its size can be controlled by the wave beams, as reported by Vikharev *et al* [8]. Such discharges can be employed for advancing the technique of chemical vapor deposition of diamond films. Discharge characteristics at extreme values of power density up to 1000–1500 W cm^{-3} allow for the homoepitaxial growth of diamond.

Belevtsev *et al* [9] present comprehensive studies on a self-sustained volume discharge in SF_6-based working media for electrochemical non-chain hydrogen fluoride (deuterium fluoride) lasers at various gas pressures and the discharge gaps with a large interelectrode distance. A radically new mechanism of the ionization instability in SF_6-based mixtures at intermediate pressures has been first considered and they developed a relevant mathematical theory, explaining qualitatively break-up of the discharge current into separate filaments in a laser-heated SF_6-mixture.

Let us move to atmospheric pressure while staying with high frequencies. Krcma *et al* [10] developed a novel 2.45 GHz microwave micro torch, which produces a surface wave discharge operating at low power of 25 W by a surfatron resonator in argon (with admixtures of nitrogen and oxygen). Two different configurations were used and emission plasma parameters were determined. Such micro torch provides applicability for the surface treatment of biological objects and the torch conditions can be modified by molecular gases additions.

Non-thermal atmospheric pressure plasma jets are widely applicable in biomedical applications and surface modification for the removal and 3D-treatment of various subjects having low resistance against high temperature. Their penetration and propagation into volumes of sub-millimeter to micrometer sizes is demanded by practical needs in medicine, such as disinfection of the inside of catheter tubes, tooth cavities, skin pores and enhancement of plasma catalysis in porous catalysts. There are five papers in the issue dealing with plasma jets. Brahme *et al* [11] used a low voltage RF driven argon and helium plasma jets with the plasma generation outside a capillary tube with a large aspect ratio followed by its penetration and propagation inside the capillary and determine the limitations on the penetration diameter, and the underpinning mechanisms of the plasma propagation and penetration process.

Enhanced plasma jet setup based on a capacitively coupled discharge and adapted for endoscopic medical applications is described in the article by Winter *et al* [12]. The authors found that a combination of neon feed gas, CO_2 shielding gas and a current limited high voltage supply gives the best bactericidal results and, at the same time, reduces material erosion as well as patient leakage current.

Belevtsev *et al* [13] performed a spectral diagnostics of atmospheric pressure nitrogen plasma jet in the zone of its destructive interaction with heat-resistant graphite material. Changes in the concentration of emitting carbon atoms and CN near the surface of isotropic graphite occur in the process of intense and long (100–150 s) exposure of graphite to a nitrogen plasma jet. The analytical solution of the temperature change in a relaxing nitrogen plasma jet in the absence of graphite confirmed the experimentally observed slow cooling caused by a number of exothermic recombination processes.

Pei *et al* [14] investigated two discharge modes (a self-pulsing and 'true' DC discharge mode) that were observed for a plasma jet operated at atmospheric pressure with air or nitrogen by applying a DC high voltage to micro-hollow cathode geometry. These different modes can be controlled by gas flow rate and applied high voltage.

The helix plasma jet in a sealed quartz tube with/without a helical coil on the outer surface of the quartz tube was investigated by Liu *et al* [15]. They applied an additional high voltage pulsed DC power supply to the external helical coil to control the helix plasma inside the tube.

Simonchik and Kazak [16] characterized oscillations of DC atmospheric pressure glow discharge parameters caused by anode spots blinking. With the elements of chaos theory they demonstrated a mechanism, which allows controlling chaos state in a gas discharge.

The articles written by Babaeva *et al* [17] (computational study), and Bokhan *et al* [18] (experimental study) give the detailed information on the development of high-voltage pulsed discharges of nanosecond and sub-nanosecond duration at atmospheric and lower pressures. The conditions determining the domination either of conventional photoionization or preionization by fast electrons from the cathode in the precursor electron production under development of a negative streamer was established in [17]. The conditions under which the switching time of a new gas-discharge sharpener consisting of a series connection of open and capillary discharges in one device can be 100 ps have been determined in [18].

Dielectric barrier discharges (DBDs), most typically operated at atmospheric pressure, in many varieties of electrodes, geometries, gases etc are still very popular for various applications, e.g. plasma-assisted surface processing or gas phase chemical conversion. Liu *et al* [19] studied atmospheric-pressure diffuse DBDs obtained in Ar/O_2 gas mixtures using dual-frequency excitation at 200 kHz and 13.56 MHz radio frequency. The low frequency excitation results in a transient plasma with the formation of an electrode sheath and therefore a pronounced excitation near the substrate. The RF oscillation allows the electron trapping in the gas gap and helps to improve the plasma uniformity.

Klute *et al* [20] characterized dielectric barrier discharges that produce small, low temperature/power plasmas at atmospheric pressure that can be applied for the detection and quantification of analytes. DBDs can be used as fragmentation and excitation sources to detect elements via optical emission spectrometry, or as ionization sources of molecules for the detection via mass spectrometry. Their work summarizes the development from low pressure DBD implemented in diode laser atomic absorption spectrometry to atmospheric DBDs that can be used for ambient applications such as the trace detection of arsenic species or the soft ionization of molecular compounds.

Neretti *et al* [21] employed DBDs for annular plasma synthetic jet actuators that demonstrated their ability to produce a tubular flow normal to the surface where the DBD is ignited and enhance the delivery of reactive species towards the target to be treated. Their results show that the presence of charged particles in the jet flow outside the plasma could be an important factor to be accounted for when the plasma actuators are used for treatment purposes.

Non-thermal plasmas are rich sources of various reactive species (depending on the composition of the plasma forming gas) which can initiate or increase the intensity of the desired chemical or biochemical processes in the liquids, or can lead to modification of the electrode surfaces, or promote the formation of various nanoparticles in liquid. These are a few reasons why non-thermal plasmas are now widely used now for the treatment of liquids, either as gas discharge plasma interacting with liquids or plasma directly ignited in the liquid phase. Seven articles of this issue written by Ceriani *et al* [22], Kashapov *et al* [23], Hamdan and Cha [24], Burakov *et al* [25], Lebedev and Averin [26], Panov *et al* [27] and

Pongrac *et al* [28] are devoted to description of different plasma-liquid systems which use such liquids as water, electrolyte, crude oil, n-heptane, etc.

Ceriani *et al* [22] developed a versatile benchtop prototype plasma reactor for water treatment supporting different air discharge regimes: AC powered DBD and DC powered positive and negative corona discharge. They tested the reactor performance using phenol as model pollutant and determined the process energy efficiency, kinetics, nitrated byproducts and extent of mineralization to CO_2.

Kashapov *et al* [23] applied low-voltage (0–350 V) gas discharge with a liquid electrolytic NaOH cathode at various temperatures of the electrolyte to study the influence of the electrolytic cathode temperature on the self-sustaining mechanism of such plasma-electrolyte discharge. The change in the discharge structure with increasing temperature is demonstrated, in particular, the transition from the bulk diffuse discharge to the leader discharge.

Hamdan and Cha [24] established nanosecond discharges at the interface of two immiscible liquids: *n*-heptane and water (with very different relative dielectric permittivities of 2 and 80, respectively), which could significantly intensify the electric field intensity to enable the synthesis of carbon-based nanomaterials. The synthesized material is a mixture of two carbon-based phases: a crystalline phase (graphite like) embedded into a phase of hydrogenated amorphous carbon.

Plasmas both inside and in contact with liquid for synthesis and surface engineering of carbon and silicon nanoparticles were investigated by Burakov *et al* [25]. The high-voltage discharge between two electrodes submerged into liquid is used for the synthesis of carbon and silicon nanoparticles (NPs). The gas–liquid interfacial discharge plasma generated between a capillary (hollow needle) with flowing argon and the liquid surface is used for surface modification of as-prepared NPs directly in solution.

Plasma discharges in the liquids were further studied by Lebedev and Averin [26], who applied microwave discharges in crude oil at atmospheric pressure in order to separate metals (Al, Co, Cu, Fe, Mo, Ni, V, and Zn). Panov *et al* [27] studied the slow 'thermal' (with the average speed of plasma channel propagation of 5 m s^{-1}) and fast 'streamer-leader' (up to 7 km s^{-1}) breakdown modes in conductive water at conductivity of 90 μS cm^{-1} in the range of applied voltage from 9 to 27 kV in 1 cm gap with pin anode. Finally, Pongrac *et al* [28] characterized time-resolved emission spectra of $H\alpha/O^{I}$ atomic lines generated by nanosecond pulsed corona-like discharge ignited by fast rise-time high-voltage pulses (duration 6 ns and amplitude + 100 kV) in a point-to-plane electrode geometry submerged in deionized water. The electron densities calculated from the $H\alpha$ profile fit were estimated to be of the order of 10^{18}–10^{19} cm^{-3}. Their results indicate that the discharges generated due to the reflected high voltage pulses were very likely generated in the non-relaxed environment.

The guest editors congratulate and thank all the authors for their excellent contributions. We hope they will inspire future investigations of novel plasma sources and discharge regimes in the broad plasma community that may not only tackle the existing needs but also create new plasma applications for various technological/environmental/biomedical challenges.

ORCID iDs

Yuri Akishev https://orcid.org/0000-0001-8379-5782
Zdenko Machala https://orcid.org/0000-0003-1424-1350

References

[1] Korolev Y D and Koval N N 2018 Low-pressure discharges with hollow cathode and hollow anode and their applications *J. Phys. D: Appl. Phys.* **51** 323001
[2] Burdovitsin V A *et al* 2018 Effect of collector potential on the beam-plasma formed by a forevacuum-pressure plasma-cathode electron beam source *J. Phys. D: Appl. Phys.* **51** 304006
[3] Bokhan P A *et al* 2018 Limit characteristics of switches based on planar open discharge *J. Phys. D: Appl. Phys.* **51** 404002

[4] Akishev Y S *et al* 2018 Three-electrode strongly overvoltage open discharge in D_2 as an effective source of the high-current beam of runaway electrons with energy up to 25 keV *J. Phys. D: Appl. Phys.* **51** 394003

[5] Zubarev N M *et al* 2018 Experimental and theoretical investigations of the conditions for the generation of runaway electrons in a gas diode with a strongly nonuniform electric field *J. Phys. D: Appl. Phys.* **51** 284003

[6] Tarasenko V F *et al* 2018 Generation and registration of runaway electron beams during the breakdown of highly overvoltaged gaps filled with dense gases *J. Phys. D: Appl. Phys.* **51** 424001

[7] Sidorov A V *et al* 2018 Gas discharge powered by the focused beam of the high-intensive electromagnetic waves of the terahertz frequency band *J. Phys. D: Appl. Phys.* **51** 464002

[8] Vikharev A L *et al* 2019 Physics and application of gas discharge in millimeter wave beams *J. Phys. D: Appl. Phys.* **52** 014001

[9] Belevtsev A A *et al* 2018 Self-sustained volume discharge in mixtures of SF_6 with hydrocarbons, hydrogen and deuterium for non-chain HF(DF) lasers *J. Phys. D: Appl. Phys.* **51** 384003

[10] Krčma F *et al* 2018 Microwave micro torch generated in argon based mixtures for biomedical applications *J. Phys. D: Appl. Phys.* **51** 414001

[11] Brahme A *et al* 2018 Penetration of Ar and He RF-driven plasma jets into micrometer-sized capillary tubes *J. Phys. D: Appl. Phys.* **51** 414002

[12] Winter J *et al* 2019 Enhanced atmospheric pressure plasma jet setup for endoscopic applications *J. Phys. D: Appl. Phys.* **52** 024005

[13] Belevtsev A A *et al* 2018 Spectral diagnostics of plasma in the zone of its destructive interaction with heat-resistant materials *J. Phys. D: Appl. Phys.* **51** 484002

[14] Pei X *et al* 2018 Discharge modes of atmospheric pressure DC plasma jets operated with air or nitrogen *J. Phys. D: Appl. Phys.* **51** 384001

[15] Liu F *et al* 2018 Effect of external electric field on helix plasma plume *J. Phys. D: Appl. Phys.* **51** 294003

[16] Simonchik L V and Kazak A V 2019 Characterization of oscillations of DC atmospheric pressure glow discharge parameters caused by anode spots blinking *J. Phys. D: Appl. Phys.* **52** 024004

[17] Babaeva N Y *et al* 2018 Development of nanosecond discharges in atmospheric pressure air: two competing mechanisms of precursor electrons production *J. Phys. D: Appl. Phys.* **51** 434002

[18] Bokhan P A *et al* 2018 A high-voltage subnanosecond sharpener based on a combination of 'open' and capillary discharges *J. Phys. D: Appl. Phys.* **51** 364001

[19] Liu Y *et al* 2018 Atmospheric-pressure diffuse dielectric barrier discharges in Ar/O_2 gas mixture using 200 kHz/13.56 MHz dual frequency excitation *J. Phys. D: Appl. Phys.* **51** 114002

[20] Klute F D *et al* 2018 Characterization of dielectric barrier discharges for analytical chemistry *J. Phys. D: Appl. Phys.* **51** 314003

[21] Neretti G *et al* 2018 Measurement of the charge distribution deposited by an *annular* plasma synthetic jet actuator over a target surface *J. Phys. D: Appl. Phys.* **51** 324004

[22] Ceriani E *et al* 2018 A versatile prototype plasma reactor for water treatment supporting different discharge regimes *J. Phys. D: Appl. Phys.* **51** 274001

[23] Kashapov N *et al* 2018 Influence of the electrolytic cathode temperature on the self-sustaining mechanism of plasma-electrolyte discharge *J. Phys. D: Appl. Phys.* **51** 494003

[24] Hamdan A and Cha M S 2018 Carbon-based nanomaterial synthesis using nanosecond electrical discharges in immiscible layered liquids: n-heptane and water *J. Phys. D: Appl. Phys.* **51** 244003

[25] Burakov V *et al* 2018 Plasmas in and in contact with liquid for synthesis and surface engineering of carbon and silicon nanoparticles *J. Phys. D: Appl. Phys.* **51** 484001

[26] Lebedev Y A and Averin K A 2018 Extraction of valuable metals by microwave discharge in crude oil *J. Phys. D: Appl. Phys.* **51** 214005

[27] Panov V A *et al* 2018 Slow 'thermal' and fast 'streamer-leader' breakdown modes in conductive water *J. Phys. D: Appl. Phys.* **51** 354003

[28] Pongrác B *et al* 2018 Spectroscopic characteristics of $H\alpha/O^{I}$ atomic lines generated by nanosecond pulsed corona-like discharge in deionized water *J. Phys. D: Appl. Phys.* **51** 124001