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Advanced spectroscopic studies of nanosecond pulsed microplasmas

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14. ABSTRACT
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Accomplishments

- Research Objectives:
  1. **1.** Conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria.
  2. **2.** Conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties.
  3. **3.** Understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species including excited and ground state species.

- Accomplishments
  - Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air. i) We investigated the initiation of a guided helium streamer and its transition to a spark breakdown applying sub-microsecond voltage pulses. ii) We collaborated with Drs. Peng Zhang and John Verboncoeur at Michigan State University and developed a semi-analytic model to predict the breakdown voltage for direct current streamers. Based on Meek's criterion for streamer breakdown, the polarity dependence of the streamer breakdown process for a direct current condition was evaluated and the semi-analytical results agreed well with the experimental measurements.
  - Experimental studies of plasma properties including electron densities and mean energy of a nanosecond pulsed plasma jet were conducted in collaboration with the researchers at the Wright Patterson Air Force Research Laboratory. The electron density was measured on the order of 10^{13} cm^{-3}, in a distribution of ring-shaped profile, with the lower value in the center and higher at the outer edge of radius of 0.3 mm.
  - Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) Pulse duration: comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions; for the pulse duration of 200 – 2000 ns, the shortest pulse duration

corresponds to the highest energy efficiency for producing liquid phase OH, whereas the emission of OH(A-X), related the excited OH(A) production in gas phase, favors 800 ns pulse width. 2) Pulse risetime and repetition frequency: Use of fast rising voltage pulse for plasma ignition, the voltage amplitude required for combustion ignition can be reduced while keeping the same or even enhancing the combustion performance. Using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NOx emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

- Advanced spectroscopic techniques have been developed in the PI's laboratory, which facilitates the training for the next generation researchers to conduct low temperature plasma science research. These include spatiotemporally resolved optical emission spectroscopy, laser induced fluorescence to measure gas phase OH, Thomson laser scattering for electron property measurements for atmospheric pressure, weakly ionized plasmas. In addition, diagnostic techniques in liquid phase have also been explored including the high resolution respirometry-derived or the use of a chemical dye in combination with photospectrometer approaches to measure OH_{aq} production of ns-pulsed plasma jet impinging on water.

- How were the results disseminated to communities of interest?
  - Results from the related research were integrated in a senior design course (ECE 486/487), which was offered to senior undergraduate students from Fall 2021 to Spring 2022. Four electrical and computer engineering students including two females were signed up for the project. At the end of the project, the team participated the ODU College of Engineering and Technology's Engineering Student Projects Expo (ESPEX) and won the 2nd place out of total 26 undergraduate research projects across the college. All the team members stated that they have learned a lot through the project, and the research experience they gained from the course has positive impact on their future careers.
  - A lab tour for undergraduate students taking Electromagnetics (ECE 323) was hosted by the PI's group on April 22, 2022. Projects and results including streamer breakdown, compact pulse power system, and biomedical and environmental applications of cold plasmas were showcased to the junior undergraduate students. This will encourage their involvement for related research activities.

Impacts

This component is used to describe ways in which the work, findings, and specific products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as

a result of the project. You can report on the following impact categories, but you are not required to report on all categories. Please only report in the categories that are relevant to your project:

Development of the principal discipline(s) of the project
Outcome of this project such as understanding discharge breakdown problems in a non-uniform, transient field will have significant impact on the fundamental knowledge of discharge formation theory and are the bases for all related plasma applications.

Other disciplines:
Findings and diagnostic techniques developed in this project involving plasma chemistry will have significant impact on non-plasma disciplines including environmental science, health care, and agriculture.

Describe the impact in this reporting period on the development of human resources
This project provided opportunities for research and teaching in fundamental and applied research of non-thermal plasmas by including diverse research groups including female engineering students, students with special needs, and students from Africa.

Describe the impact on teaching and educational experiences
This project helped develope and disseminate new educational materials that benefit students in a long run. Examples were listed in one of the previous sections.

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.
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Impact on society beyond science and technology:
None.

Changes

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Changes in approach
No changes.

Problems or delays
None.

Expenditure Impacts
Delays in recruiting graduate students and in obtaining parts/components/equipment due to the pandemic of COVID-19.
Virtual conferences reduced the cost of travel expenses and enabled more participation of students to the conference, although at a less effective way.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
Not applicable.

Changes to the primary place of performance from that originally proposed
No changes.

Technical Updates

Summary:

The goal of this research is to advance the understanding of plasma physics and chemistry for highly non-equilibrium microplasmas, particularly in forms of transient streamers in microscopic scales, generated with mixed flow fields and nanosecond pulsed electric fields. The research objectives are 1) to conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria; 2) to conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties; and 3) to understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species such as excited and ground state species.

Selected research effort is listed below to emphasize the accomplishment of this program:

1) Streamer initiation and breakdown studies
   Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air.
   a. Under a direct condition, streamer breakdown of atmospheric air with non-uniform electric field in a needle-to-plate electrode configuration was studied using a semi-analytic model and experimental measurements. Empirical relations between the critical avalanche size for streamer breakdown and the gap distance

were proposed, and the semi-analytical results agreed well with the experimental measurements. It was found that for *pd* > 380 Torr·cm (or *d* > 0.5 cm at one atmosphere) streamer breakdown of ambient air occurred at a lower applied voltage for a positively biased needle compared to that with a negatively biased needle, referred as the polarity effect. For *pd* < 380 Torr·cm, breakdown was attained at a lower applied voltage with a negatively biased needle compared to that with a positively biased needle, and breakdown mode transits from the polarity effect to the so-called inverted polarity effect. [Iqubal, et al., 2022]

b. Under a pulsed condition, we investigated the initiation of a guided helium streamer and its transition to a spark breakdown using a hollow needle-to-plate configuration. The experimental results show that streamer initiation requires at least 4 mm interelectrode gap distance, and the spark breakdown occurs directly for shorter gap distances. Applying a lower PRF or a shorter pulse duration, higher voltages are required for the streamer initiation and breakdown; the streamer transitions to a highly conductively spark at a lower voltage for longer pulses or higher PRFs. [Rahman, et al., 2022]

2) Plasma property studies
   a) Impact of pulsed electric field on electron densities and mean energy of a 150-ns pulsed He plasma jet in air were conducted using Thomson laser scattering. The measurements revealed a ring-shaped electron density distribution (with a max. of 1×10^{14} cm^{-3}) at 1 mm above the electrode nozzle (Fig. 1) and the ring converged after 5 mm. The electron temperature at the radius of the ring varied from 2.8 eV to 0.8 eV. Importantly, the formation and development of the guided streamer was found strongly dependent on the external pulsed electric field and the maximum electron densities were associated with the rising and falling phases of the voltage pulse (Fig. 2). [Jiang, et al., 2019]

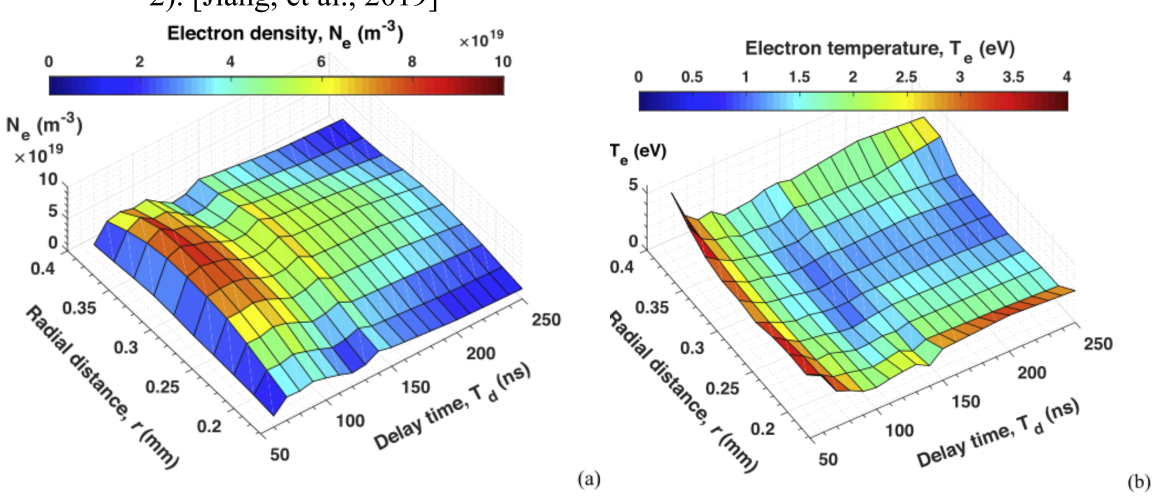

Fig. 1 Spatiotemporal development of the (a) electron density and (b) electron temperature of a 150-ns pulsed plasma jet at an axial distance of 1 mm from the nozzle surface

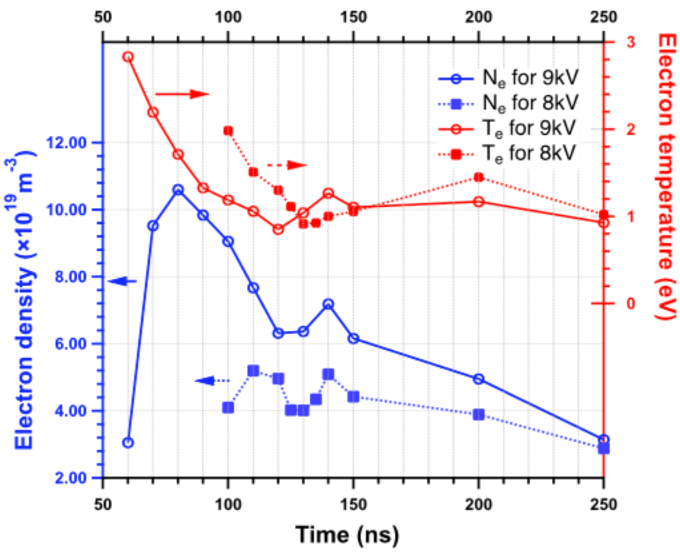

Fig. 2 Temporal development comparison of the peak electron density and corresponding temperature of the plasma jet driven by different voltages at 9 and 8 kV at the same axial distance, z =1 mm.

b) Impact of pulse duration and risetime on gas temperature were investigated by comparing a He microplasma jet excited by 5- or 164-ns 8-kV pulses at 500 Hz. Applying shorter and faster pulses resulted in higher energy per pulse (energy deposited in the plasma), more production of excited ions (e.g., N_2^+). The rotational temperature of the short and long ns-pulsed plasma jets was found comparable, both at 300 K, indicating that both plasma jets were under highly nonequilibrium conditions. [Song, et al., 2018]

3) Plasma chemistry studies

- Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) *Pulse duration*. Comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions [Song, et al., 2018]. For the pulse duration of 200 – 2000 ns, the shortest pulse duration corresponds to the highest energy efficiency for producing liquid phase OH_{aq}, whereas the 800-ns pulse width is associated with the highest emission of OH(A-X) or the production excited OH(A) in gas phase. [Song, et al., 2019]
2) *Pulse risetime and repetition frequency*. The use of fast rising voltage pulse in plasma ignition for combustion can reduce the voltage requirement needed to achieve successful ignition, while keeping the same or even enhancing the combustion performance. This was demonstrated with applying transient plasmas driven by 10-ns, 10 kV pulse bursts at 1-10 kHz repetition rates for igniting methane-dry air mixture in a static chamber at atmospheric pressure. Comparison of the plasmas powered by the same duration pulse bursts with different rise times, i.e., t_r = 5 ns and 10 ns, showed faster pulses benefit the combustion ignition with higher peak pressure, shorter

ignition delay and reduced energy needed to initiate combustion. In addition, there was a possible optimal PRF within 6–10 kHz, which was associated with the best combustion performance, i.e., the highest peak pressure and shortest ignition delay. [Alderman, et al., 2021]. More recently, using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NO_x emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

- Impact of target materials on the plasma formation and the associated chemistry are studied for applications of the plasma in medicine including cancer therapy and gene transfer. The presence of biological materials, especially as part of the electrode circuit, may change the plasma properties and impact on the production of reactive plasma species at the plasma-target interface. Using a needle-to-plate electrode configuration, the production of OH in a 200 ns, 7 kV pulses at 1 kHz, helium plasma jet impinging on water, phosphate-buffered saline (PBS) or pigskin were measured using both optical emission spectroscopy and laser induced fluorescence. The experimental results showed that the use of pigskin slowed down the streamer head propagation, whereas a more pronounced surface ionization wave was developed on the surface when water was used. The highest OH(A-X) emission above the biomaterial surface was observe using the PBS-covered electrode plate comparing to water or pigskin. Spatiotemporally resolved laser induced fluorescence showed that more OH was produced in regions near the needle electrode for both water and PBS and the use of pigskin resulted in the least OH production overall. [Lai, et al. 2022] In addition, the electric field at the plasma-target interface as well as in the biomaterial can vary significantly due to the use of different target, which results in different plasma properties and different biological effects, e.g., field-induced or reactive oxygen species-induced effects, during the plasma biological cell/tissue interactions. [Jiang, et al., 2021]

Archival publications during reporting period:

(The names of the graduate/undergraduate students under supervising are underlined, the names of postdocs under supervising are noted with * during the production of the publication.)

(Journal publications)

1) S. Song, J. L. Lane* and C. Jiang, “Comparison study of spatiotemporally resolved emissions of nanosecond pulsed microplasma jets”, IEEE Transactions on Plasma Science, vol. 46, no. 3, pp. 587-593, March 2018, doi: 10.1109/TPS.2018.2795958.
2) S. Song, E. B. Sozer, and C. Jiang, “Effects of pulse width on He plasma jets in contact with water evaluated by OH(A–X) emission and OH_{aq} production,” Japanese Journal of Applied Physics, **58**, no. 6, 2019. https://iopscience.iop.org/article/10.7567/1347-4065/ab1e6d
3) C. Jiang, J. A. Miles, J. Hornef, C. Carter, and S. F. Adams, “Electron densities and temperatures of an atmospheric-pressure nanosecond pulsed helium plasma jet in air,” Plasma Sources Science and Technology, **28**, 085009, 2019. https://iopscience.iop.org/article/10.1088/1361-6595/ab2182
4) C. Jiang, E. B. Sozer, S. Song, N. Lai, P. T. Vernier, and S. Guo, "Modulation of ROS in nanosecond-pulsed plasma-activated media for dosage-dependent cancer cell inactivation *in vitro*," Physics of Plasmas, **27**(11), 2020, https://doi.org/10.1063/5.0020435, DOI: 10.1063/5.0020435. (This paper was selected as “Editor’s Pick” with Featured, Scilight.)
5) D. Alderman, C. Tremble, D. Singleton, J. Sanders, and C. Jiang, “Effects of pulse rise time and repetition frequency on nanosecond pulsed plasma ignition for combustion,” Plasma Research Express, **3**, 014001, (2021). https://iopscience.iop.org/article/10.1088/2516-1067/ab880a/meta.
6) C. Jiang, E. A. Oshin, S. Guo, M. Scott, X. Li, C. Mangiamele, and R. Heller, “Synergistic effects of an atmospheric pressure plasma jet and pulsed electric field on cells and skin," IEEE Transactions on Plasma Science, **49**(11), pp. 3317-3324, Nov. 2021, doi: 10.1109/TPS.2021.3113260.
7) M. Z. Rahman, E. A. Oshin and C. Jiang, "Initial Investigation of the Streamer to Spark Transition in a Hollow-Needle-to-Plate Configuration," IEEE Transactions on Plasma Science, vol. 50, no. 6, pp. 1942-1947, June 2022, doi: 10.1109/TPS.2022.3170346.
8) M. Lai*, S. Song, E. Oshin, L. Potter, N. Lai, and C. Jiang, “The production of OH in a nanosecond pulsed helium plasma jet impinging on water, saline, or pigskin,” Journal of Applied Physics, **131**(17), May, 2022, https://doi.org/10.1063/5.0083568
9) A. Iqbal+, D. Wozniak+, M. Z. Rahman, S. Banerjee, J. Verboncoeur, P. Zhang, and C. Jiang, "Influence of discharge polarity on streamer breakdown criterion of ambient air in a non-uniform electric field," Journal of Physics D: Applied Physics, vol. 56, no. 3, p. 035204, 2022/12/12 2022, doi: 10.1088/1361-6463/aca2b4. (+ Equal contributors)

(Conference publications)

10) D. Alderman, C. Tremble, C. Jiang, J. M. Sanders and D. Singleton, "Initial Evaluation of Pulse Risetime on Transient Plasma Ignition for Combustion," *2018 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2018, pp. 279-282, doi: 10.1109/IPMHVC.2018.8936811.

11) D. Alderman, C. Tremble, S. Song, J.M. Sanders, D. Singleton, and C. Jiang, "Plasma kinetics study of a repetitive 10-ns pulsed plasma ignition for combustion," *2019 IEEE Pulsed Power & Plasma Science (PPPS)*, 2019, pp. 1-3, doi: 10.1109/PPPS34859.2019.9009621.

12) X. Li, S. Song, D. Alderman, M. A. Malik, R. Heller, and C. Jiang, "Evaluation of electric field and charge on bio-substrates induced by nanosecond pulsed helium plasma jet," *2019 IEEE Pulsed Power & Plasma Science (PPPS)*, 2019, pp. 1-4, doi: 10.1109/PPPS34859.2019.9009897.

Students graduated during the performance period:
S. Song, Doctor of Philosophy (PhD), May 2020
Dissertation: "Diagnostic studies of non-thermal atmospheric pressure nanosecond plasma jets," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/c38j-st04, https://digitalcommons.odu.edu/ece_etds/217

D. Alderman, Master of Science (MS), Dec. 2019
Thesis: "Pulse power effects on transient plasma ignition for combustion," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/skjc-8882, https://digitalcommons.odu.edu/ece_etds/209

Thank you for your support in helping AFOSR discover, shape and champion basic science research that profoundly impacts that future of the Air and Space Forces!

Accomplishments

- Research Objectives:
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Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
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Technical Updates

Summary:

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were proposed, and the semi-analytical results agreed well with the experimental measurements. It was found that for *pd* > 380 Torr·cm (or *d* > 0.5 cm at one atmosphere) streamer breakdown of ambient air occurred at a lower applied voltage for a positively biased needle compared to that with a negatively biased needle, referred as the polarity effect. For *pd* < 380 Torr·cm, breakdown was attained at a lower applied voltage with a negatively biased needle compared to that with a positively biased needle, and breakdown mode transits from the polarity effect to the so-called inverted polarity effect. [Iqubal, et al., 2022]

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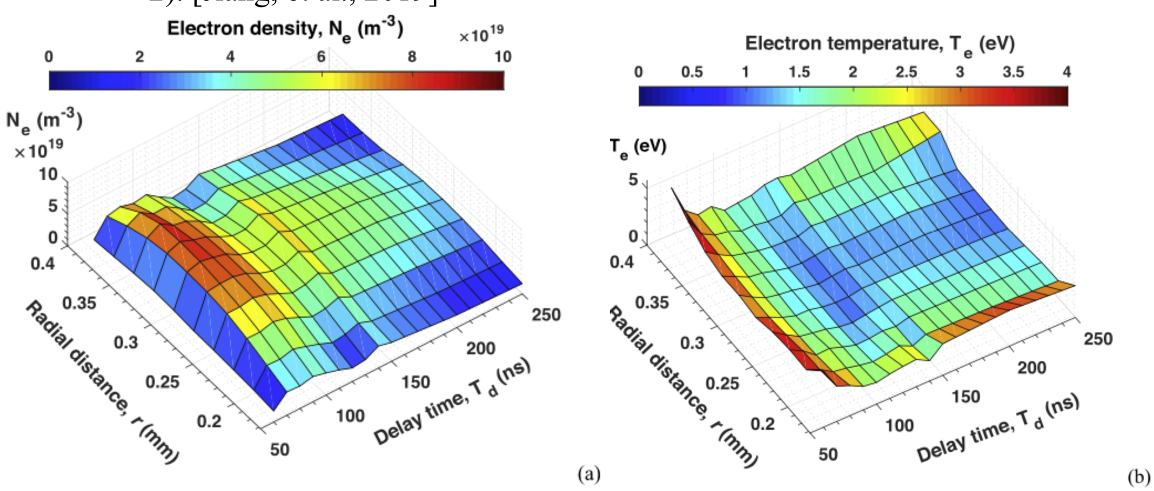

Fig. 1 Spatiotemporal development of the (a) electron density and (b) electron temperature of a 150-ns pulsed plasma jet at an axial distance of 1 mm from the nozzle surface

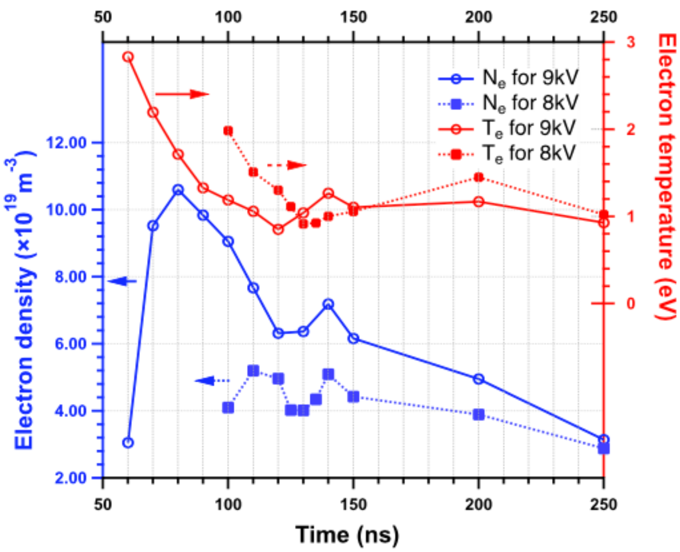

Fig. 2 Temporal development comparison of the peak electron density and corresponding temperature of the plasma jet driven by different voltages at 9 and 8 kV at the same axial distance, z =1 mm.

b) Impact of pulse duration and risetime on gas temperature were investigated by comparing a He microplasma jet excited by 5- or 164-ns 8-kV pulses at 500 Hz. Applying shorter and faster pulses resulted in higher energy per pulse (energy deposited in the plasma), more production of excited ions (e.g., N_2^+). The rotational temperature of the short and long ns-pulsed plasma jets was found comparable, both at 300 K, indicating that both plasma jets were under highly nonequilibrium conditions. [Song, et al., 2018]

3) Plasma chemistry studies

- Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) *Pulse duration*. Comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions [Song, et al., 2018]. For the pulse duration of 200 – 2000 ns, the shortest pulse duration corresponds to the highest energy efficiency for producing liquid phase OH_{aq}, whereas the 800-ns pulse width is associated with the highest emission of OH(A-X) or the production excited OH(A) in gas phase. [Song, et al., 2019]
  2) *Pulse risetime and repetition frequency*. The use of fast rising voltage pulse in plasma ignition for combustion can reduce the voltage requirement needed to achieve successful ignition, while keeping the same or even enhancing the combustion performance. This was demonstrated with applying transient plasmas driven by 10-ns, 10 kV pulse bursts at 1-10 kHz repetition rates for igniting methane-dry air mixture in a static chamber at atmospheric pressure. Comparison of the plasmas powered by the same duration pulse bursts with different rise times, i.e., t_r = 5 ns and 10 ns, showed faster pulses benefit the combustion ignition with higher peak pressure, shorter

ignition delay and reduced energy needed to initiate combustion. In addition, there was a possible optimal PRF within 6–10 kHz, which was associated with the best combustion performance, i.e., the highest peak pressure and shortest ignition delay. [Alderman, et al., 2021]. More recently, using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NO_x emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

- Impact of target materials on the plasma formation and the associated chemistry are studied for applications of the plasma in medicine including cancer therapy and gene transfer. The presence of biological materials, especially as part of the electrode circuit, may change the plasma properties and impact on the production of reactive plasma species at the plasma-target interface. Using a needle-to-plate electrode configuration, the production of OH in a 200 ns, 7 kV pulses at 1 kHz, helium plasma jet impinging on water, phosphate-buffered saline (PBS) or pigskin were measured using both optical emission spectroscopy and laser induced fluorescence. The experimental results showed that the use of pigskin slowed down the streamer head propagation, whereas a more pronounced surface ionization wave was developed on the surface when water was used. The highest OH(A-X) emission above the biomaterial surface was observe using the PBS-covered electrode plate comparing to water or pigskin. Spatiotemporally resolved laser induced fluorescence showed that more OH was produced in regions near the needle electrode for both water and PBS and the use of pigskin resulted in the least OH production overall. [Lai, et al. 2022] In addition, the electric field at the plasma-target interface as well as in the biomaterial can vary significantly due to the use of different target, which results in different plasma properties and different biological effects, e.g., field-induced or reactive oxygen species-induced effects, during the plasma biological cell/tissue interactions. [Jiang, et al., 2021]

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(The names of the graduate/undergraduate students under supervising are underlined, the names of postdocs under supervising are noted with * during the production of the publication.)

(Journal publications)

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Students graduated during the performance period:
S. Song, Doctor of Philosophy (PhD), May 2020
Dissertation: “Diagnostic studies of non-thermal atmospheric pressure nanosecond plasma jets,” Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/c38j-st04, https://digitalcommons.odu.edu/ece_etds/217

D. Alderman, Master of Science (MS), Dec. 2019
Thesis: “Pulse power effects on transient plasma ignition for combustion,” Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/skjc-8882, https://digitalcommons.odu.edu/ece_etds/209

Thank you for your support in helping AFOSR discover, shape and champion basic science research that profoundly impacts that future of the Air and Space Forces!

Accomplishments

- Research Objectives:
    1. Conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria.
    2. Conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties.
    3. Understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species including excited and ground state species.

- Accomplishments
    - Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air. i) We investigated the initiation of a guided helium streamer and its transition to a spark breakdown applying sub-microsecond voltage pulses. ii) We collaborated with Drs. Peng Zhang and John Verboncoeur at Michigan State University and developed a semi-analytic model to predict the breakdown voltage for direct current streamers. Based on Meek's criterion for streamer breakdown, the polarity dependence of the streamer breakdown process for a direct current condition was evaluated and the semi-analytical results agreed well with the experimental measurements.
    - Experimental studies of plasma properties including electron densities and mean energy of a nanosecond pulsed plasma jet were conducted in collaboration with the researchers at the Wright Patterson Air Force Research Laboratory. The electron density was measured on the order of 10^{13} cm^{-3}, in a distribution of ring-shaped profile, with the lower value in the center and higher at the outer edge of radius of 0.3 mm.
    - Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) Pulse duration: comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions; for the pulse duration of 200 – 2000 ns, the shortest pulse duration

corresponds to the highest energy efficiency for producing liquid phase OH, whereas the emission of OH(A-X), related the excited OH(A) production in gas phase, favors 800 ns pulse width. 2) Pulse risetime and repetition frequency: Use of fast rising voltage pulse for plasma ignition, the voltage amplitude required for combustion ignition can be reduced while keeping the same or even enhancing the combustion performance. Using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NOx emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

  - Advanced spectroscopic techniques have been developed in the PI's laboratory, which facilitates the training for the next generation researchers to conduct low temperature plasma science research. These include spatiotemporally resolved optical emission spectroscopy, laser induced fluorescence to measure gas phase OH, Thomson laser scattering for electron property measurements for atmospheric pressure, weakly ionized plasmas. In addition, diagnostic techniques in liquid phase have also been explored including the high resolution respirometry-derived or the use of a chemical dye in combination with photospectrometer approaches to measure OH_{aq} production of ns-pulsed plasma jet impinging on water.

- How were the results disseminated to communities of interest?
  - Results from the related research were integrated in a senior design course (ECE 486/487), which was offered to senior undergraduate students from Fall 2021 to Spring 2022. Four electrical and computer engineering students including two females were signed up for the project. At the end of the project, the team participated the ODU College of Engineering and Technology's Engineering Student Projects Expo (ESPEX) and won the 2nd place out of total 26 undergraduate research projects across the college. All the team members stated that they have learned a lot through the project, and the research experience they gained from the course has positive impact on their future careers.
  - A lab tour for undergraduate students taking Electromagnetics (ECE 323) was hosted by the PI's group on April 22, 2022. Projects and results including streamer breakdown, compact pulse power system, and biomedical and environmental applications of cold plasmas were showcased to the junior undergraduate students. This will encourage their involvement for related research activities.

Impacts

This component is used to describe ways in which the work, findings, and specific products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as

a result of the project. You can report on the following impact categories, but you are not required to report on all categories. Please only report in the categories that are relevant to your project:

Development of the principal discipline(s) of the project
Outcome of this project such as understanding discharge breakdown problems in a non-uniform, transient field will have significant impact on the fundamental knowledge of discharge formation theory and are the bases for all related plasma applications.

Other disciplines:
Findings and diagnostic techniques developed in this project involving plasma chemistry will have significant impact on non-plasma disciplines including environmental science, health care, and agriculture.

Describe the impact in this reporting period on the development of human resources
This project provided opportunities for research and teaching in fundamental and applied research of non-thermal plasmas by including diverse research groups including female engineering students, students with special needs, and students from Africa.

Describe the impact on teaching and educational experiences
This project helped develope and disseminate new educational materials that benefit students in a long run. Examples were listed in one of the previous sections.

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.
Advanced spectroscopic techniques have been developed in the PI's laboratory, which facilitates the training for the next generation researchers to conduct low temperature plasma science research. These include spatiotemporally resolved optical emission spectroscopy, laser induced fluorescence to measure gas phase OH, Thomson laser scattering for electron property measurements for atmospheric pressure, weakly ionized plasmas. In addition, diagnostic techniques in liquid phase have also been explored including the high resolution respirometry-derived or the use of a chemical dye in combination with photospectrometer approaches to measure OH_{aq} production of ns-pulsed plasma jet impinging on water.

Impact on society beyond science and technology:
None.

Changes

In this section, please incorporate any and all changes that you would like your program officers to know about the grant. The principal investigator is reminded that the recipient organization is required to obtain prior written approval from program officers whenever there are significant changes in the

project or its direction. Sections may include:

Changes in approach
No changes.

Problems or delays
None.

Expenditure Impacts
Delays in recruiting graduate students and in obtaining parts/components/equipment due to the pandemic of COVID-19.
Virtual conferences reduced the cost of travel expenses and enabled more participation of students to the conference, although at a less effective way.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
Not applicable.

Changes to the primary place of performance from that originally proposed
No changes.

Technical Updates

Summary:

The goal of this research is to advance the understanding of plasma physics and chemistry for highly non-equilibrium microplasmas, particularly in forms of transient streamers in microscopic scales, generated with mixed flow fields and nanosecond pulsed electric fields. The research objectives are 1) to conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria; 2) to conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties; and 3) to understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species such as excited and ground state species.

Selected research effort is listed below to emphasize the accomplishment of this program:

1) Streamer initiation and breakdown studies
   Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air.
   a. Under a direct condition, streamer breakdown of atmospheric air with non-uniform electric field in a needle-to-plate electrode configuration was studied using a semi-analytic model and experimental measurements. Empirical relations between the critical avalanche size for streamer breakdown and the gap distance

were proposed, and the semi-analytical results agreed well with the experimental measurements. It was found that for *pd* > 380 Torr·cm (or *d* > 0.5 cm at one atmosphere) streamer breakdown of ambient air occurred at a lower applied voltage for a positively biased needle compared to that with a negatively biased needle, referred as the polarity effect. For *pd* < 380 Torr·cm, breakdown was attained at a lower applied voltage with a negatively biased needle compared to that with a positively biased needle, and breakdown mode transits from the polarity effect to the so-called inverted polarity effect. [Iqubal, et al., 2022]

   b. Under a pulsed condition, we investigated the initiation of a guided helium streamer and its transition to a spark breakdown using a hollow needle-to-plate configuration. The experimental results show that streamer initiation requires at least 4 mm interelectrode gap distance, and the spark breakdown occurs directly for shorter gap distances. Applying a lower PRF or a shorter pulse duration, higher voltages are required for the streamer initiation and breakdown; the streamer transitions to a highly conductively spark at a lower voltage for longer pulses or higher PRFs. [Rahman, et al., 2022]

2) Plasma property studies
   a) Impact of pulsed electric field on electron densities and mean energy of a 150-ns pulsed He plasma jet in air were conducted using Thomson laser scattering. The measurements revealed a ring-shaped electron density distribution (with a max. of 1×10^{14} cm^{-3}) at 1 mm above the electrode nozzle (Fig. 1) and the ring converged after 5 mm. The electron temperature at the radius of the ring varied from 2.8 eV to 0.8 eV. Importantly, the formation and development of the guided streamer was found strongly dependent on the external pulsed electric field and the maximum electron densities were associated with the rising and falling phases of the voltage pulse (Fig. 2). [Jiang, et al., 2019]

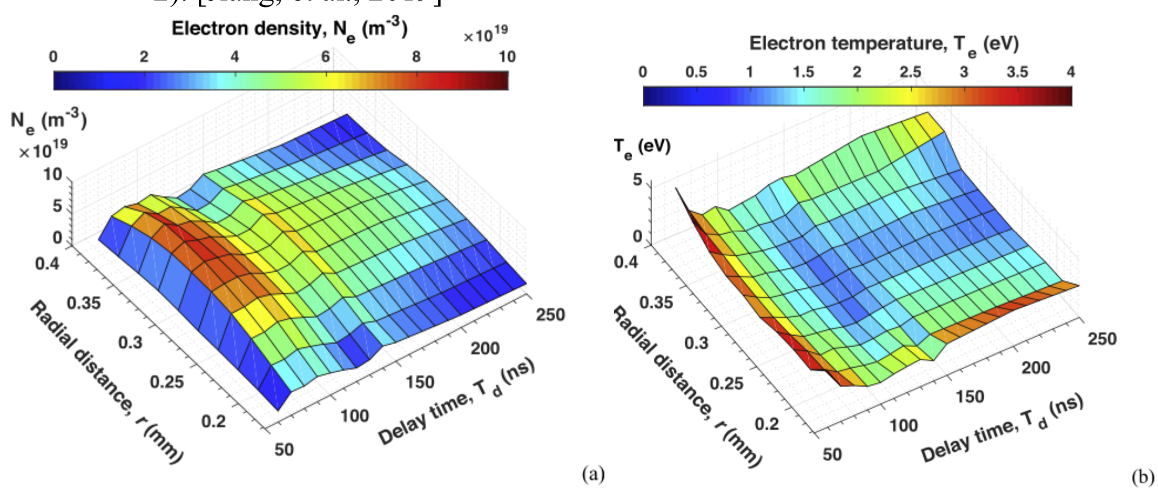

Fig. 1 Spatiotemporal development of the (a) electron density and (b) electron temperature of a 150-ns pulsed plasma jet at an axial distance of 1 mm from the nozzle surface

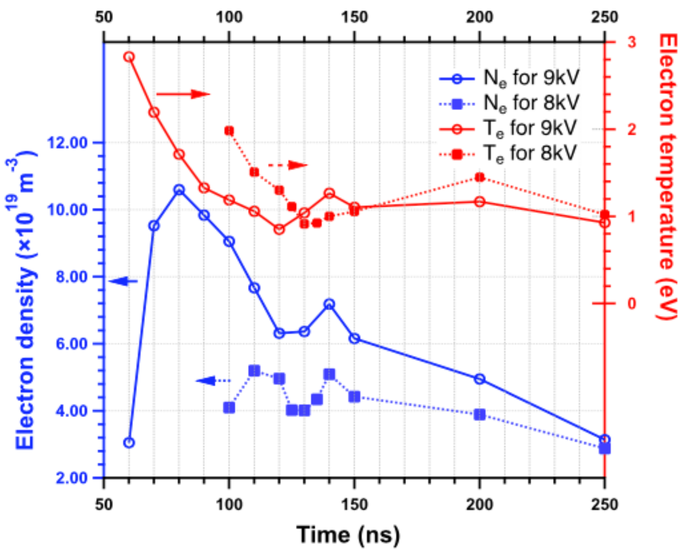

Fig. 2 Temporal development comparison of the peak electron density and corresponding temperature of the plasma jet driven by different voltages at 9 and 8 kV at the same axial distance, z =1 mm.

b) Impact of pulse duration and risetime on gas temperature were investigated by comparing a He microplasma jet excited by 5- or 164-ns 8-kV pulses at 500 Hz. Applying shorter and faster pulses resulted in higher energy per pulse (energy deposited in the plasma), more production of excited ions (e.g., N_2^+). The rotational temperature of the short and long ns-pulsed plasma jets was found comparable, both at 300 K, indicating that both plasma jets were under highly nonequilibrium conditions. [Song, et al., 2018]

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- Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications.
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- How were the results disseminated to communities of interest?
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Impacts

This component is used to describe ways in which the work, findings, and specific products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as

a result of the project. You can report on the following impact categories, but you are not required to report on all categories. Please only report in the categories that are relevant to your project:

Development of the principal discipline(s) of the project
Outcome of this project such as understanding discharge breakdown problems in a non-uniform, transient field will have significant impact on the fundamental knowledge of discharge formation theory and are the bases for all related plasma applications.

Other disciplines:
Findings and diagnostic techniques developed in this project involving plasma chemistry will have significant impact on non-plasma disciplines including environmental science, health care, and agriculture.

Describe the impact in this reporting period on the development of human resources
This project provided opportunities for research and teaching in fundamental and applied research of non-thermal plasmas by including diverse research groups including female engineering students, students with special needs, and students from Africa.

Describe the impact on teaching and educational experiences
This project helped develope and disseminate new educational materials that benefit students in a long run. Examples were listed in one of the previous sections.

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Impact on society beyond science and technology:
None.

Changes

In this section, please incorporate any and all changes that you would like your program officers to know about the grant. The principal investigator is reminded that the recipient organization is required to obtain prior written approval from program officers whenever there are significant changes in the

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No changes.

Problems or delays
None.

Expenditure Impacts
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Virtual conferences reduced the cost of travel expenses and enabled more participation of students to the conference, although at a less effective way.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
Not applicable.

Changes to the primary place of performance from that originally proposed
No changes.

Technical Updates

Summary:

The goal of this research is to advance the understanding of plasma physics and chemistry for highly non-equilibrium microplasmas, particularly in forms of transient streamers in microscopic scales, generated with mixed flow fields and nanosecond pulsed electric fields. The research objectives are 1) to conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria; 2) to conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties; and 3) to understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species such as excited and ground state species.

Selected research effort is listed below to emphasize the accomplishment of this program:

1) Streamer initiation and breakdown studies
   Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air.
   a. Under a direct condition, streamer breakdown of atmospheric air with non-uniform electric field in a needle-to-plate electrode configuration was studied using a semi-analytic model and experimental measurements. Empirical relations between the critical avalanche size for streamer breakdown and the gap distance

were proposed, and the semi-analytical results agreed well with the experimental measurements. It was found that for *pd* > 380 Torr·cm (or *d* > 0.5 cm at one atmosphere) streamer breakdown of ambient air occurred at a lower applied voltage for a positively biased needle compared to that with a negatively biased needle, referred as the polarity effect. For *pd* < 380 Torr·cm, breakdown was attained at a lower applied voltage with a negatively biased needle compared to that with a positively biased needle, and breakdown mode transits from the polarity effect to the so-called inverted polarity effect. [Iqubal, et al., 2022]

b. Under a pulsed condition, we investigated the initiation of a guided helium streamer and its transition to a spark breakdown using a hollow needle-to-plate configuration. The experimental results show that streamer initiation requires at least 4 mm interelectrode gap distance, and the spark breakdown occurs directly for shorter gap distances. Applying a lower PRF or a shorter pulse duration, higher voltages are required for the streamer initiation and breakdown; the streamer transitions to a highly conductively spark at a lower voltage for longer pulses or higher PRFs. [Rahman, et al., 2022]

2) Plasma property studies

   a) Impact of pulsed electric field on electron densities and mean energy of a 150-ns pulsed He plasma jet in air were conducted using Thomson laser scattering. The measurements revealed a ring-shaped electron density distribution (with a max. of 1×10^{14} cm^{-3}) at 1 mm above the electrode nozzle (Fig. 1) and the ring converged after 5 mm. The electron temperature at the radius of the ring varied from 2.8 eV to 0.8 eV. Importantly, the formation and development of the guided streamer was found strongly dependent on the external pulsed electric field and the maximum electron densities were associated with the rising and falling phases of the voltage pulse (Fig. 2). [Jiang, et al., 2019]

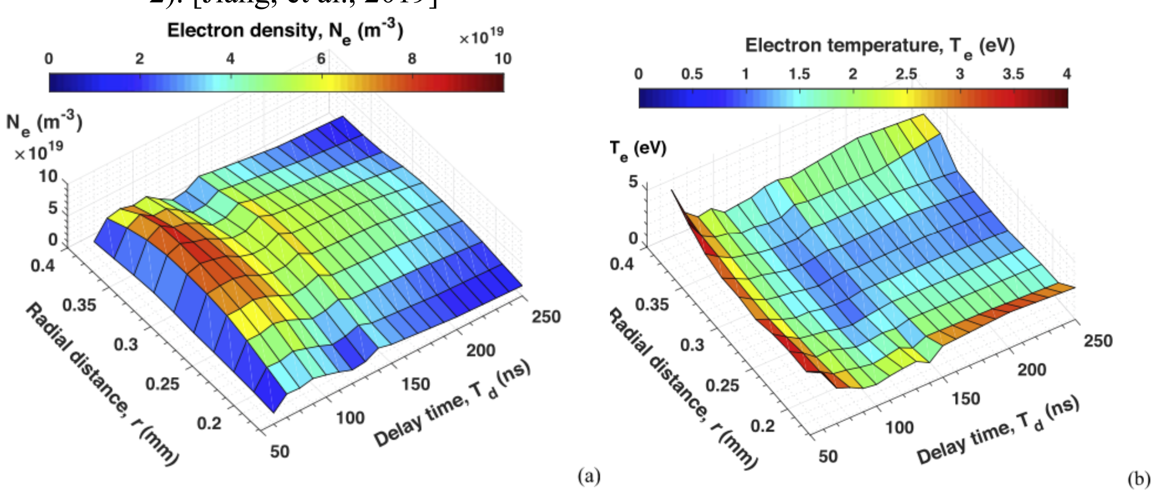

Fig. 1 Spatiotemporal development of the (a) electron density and (b) electron temperature of a 150-ns pulsed plasma jet at an axial distance of 1 mm from the nozzle surface

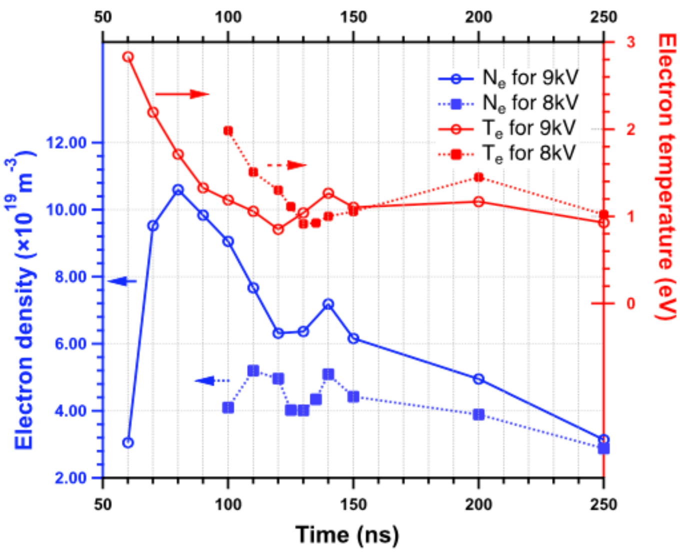

Fig. 2 Temporal development comparison of the peak electron density and corresponding temperature of the plasma jet driven by different voltages at 9 and 8 kV at the same axial distance, z =1 mm.

b) Impact of pulse duration and risetime on gas temperature were investigated by comparing a He microplasma jet excited by 5- or 164-ns 8-kV pulses at 500 Hz. Applying shorter and faster pulses resulted in higher energy per pulse (energy deposited in the plasma), more production of excited ions (e.g., N_2^+). The rotational temperature of the short and long ns-pulsed plasma jets was found comparable, both at 300 K, indicating that both plasma jets were under highly nonequilibrium conditions. [Song, et al., 2018]

3) Plasma chemistry studies
   - Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) *Pulse duration*. Comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions [Song, et al., 2018]. For the pulse duration of 200 – 2000 ns, the shortest pulse duration corresponds to the highest energy efficiency for producing liquid phase OH_{aq}, whereas the 800-ns pulse width is associated with the highest emission of OH(A-X) or the production excited OH(A) in gas phase. [Song, et al., 2019]
     2) *Pulse risetime and repetition frequency*. The use of fast rising voltage pulse in plasma ignition for combustion can reduce the voltage requirement needed to achieve successful ignition, while keeping the same or even enhancing the combustion performance. This was demonstrated with applying transient plasmas driven by 10-ns, 10 kV pulse bursts at 1-10 kHz repetition rates for igniting methane-dry air mixture in a static chamber at atmospheric pressure. Comparison of the plasmas powered by the same duration pulse bursts with different rise times, i.e., t_r = 5 ns and 10 ns, showed faster pulses benefit the combustion ignition with higher peak pressure, shorter

ignition delay and reduced energy needed to initiate combustion. In addition, there was a possible optimal PRF within 6–10 kHz, which was associated with the best combustion performance, i.e., the highest peak pressure and shortest ignition delay. [Alderman, et al., 2021]. More recently, using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NO_x emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

- Impact of target materials on the plasma formation and the associated chemistry are studied for applications of the plasma in medicine including cancer therapy and gene transfer. The presence of biological materials, especially as part of the electrode circuit, may change the plasma properties and impact on the production of reactive plasma species at the plasma-target interface. Using a needle-to-plate electrode configuration, the production of OH in a 200 ns, 7 kV pulses at 1 kHz, helium plasma jet impinging on water, phosphate-buffered saline (PBS) or pigskin were measured using both optical emission spectroscopy and laser induced fluorescence. The experimental results showed that the use of pigskin slowed down the streamer head propagation, whereas a more pronounced surface ionization wave was developed on the surface when water was used. The highest OH(A-X) emission above the biomaterial surface was observe using the PBS-covered electrode plate comparing to water or pigskin. Spatiotemporally resolved laser induced fluorescence showed that more OH was produced in regions near the needle electrode for both water and PBS and the use of pigskin resulted in the least OH production overall. [Lai, et al. 2022] In addition, the electric field at the plasma-target interface as well as in the biomaterial can vary significantly due to the use of different target, which results in different plasma properties and different biological effects, e.g., field-induced or reactive oxygen species-induced effects, during the plasma biological cell/tissue interactions. [Jiang, et al., 2021]

Archival publications during reporting period:

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(Journal publications)

1) S. Song, J. L. Lane* and C. Jiang, "Comparison study of spatiotemporally resolved emissions of nanosecond pulsed microplasma jets", IEEE Transactions on Plasma Science, vol. 46, no. 3, pp. 587-593, March 2018, doi: 10.1109/TPS.2018.2795958.
2) S. Song, E. B. Sozer, and C. Jiang, "Effects of pulse width on He plasma jets in contact with water evaluated by OH(A–X) emission and OH_{aq} production," Japanese Journal of Applied Physics, **58**, no. 6, 2019. https://iopscience.iop.org/article/10.7567/1347-4065/ab1e6d
3) C. Jiang, J. A. Miles, J. Hornef, C. Carter, and S. F. Adams, "Electron densities and temperatures of an atmospheric-pressure nanosecond pulsed helium plasma jet in air," Plasma Sources Science and Technology, **28**, 085009, 2019. https://iopscience.iop.org/article/10.1088/1361-6595/ab2182
4) C. Jiang, E. B. Sozer, S. Song, N. Lai, P. T. Vernier, and S. Guo, "Modulation of ROS in nanosecond-pulsed plasma-activated media for dosage-dependent cancer cell inactivation *in vitro*," Physics of Plasmas, **27**(11), 2020, https://doi.org/10.1063/5.0020435, DOI: 10.1063/5.0020435. (This paper was selected as "Editor's Pick" with Featured, Scilight.)
5) D. Alderman, C. Tremble, D. Singleton, J. Sanders, and C. Jiang, "Effects of pulse rise time and repetition frequency on nanosecond pulsed plasma ignition for combustion," Plasma Research Express, **3**, 014001, (2021). https://iopscience.iop.org/article/10.1088/2516-1067/ab880a/meta.
6) C. Jiang, E. A. Oshin, S. Guo, M. Scott, X. Li, C. Mangiamele, and R. Heller, "Synergistic effects of an atmospheric pressure plasma jet and pulsed electric field on cells and skin," IEEE Transactions on Plasma Science, **49**(11), pp. 3317-3324, Nov. 2021, doi: 10.1109/TPS.2021.3113260.
7) M. Z. Rahman, E. A. Oshin and C. Jiang, "Initial Investigation of the Streamer to Spark Transition in a Hollow-Needle-to-Plate Configuration," IEEE Transactions on Plasma Science, vol. 50, no. 6, pp. 1942-1947, June 2022, doi: 10.1109/TPS.2022.3170346.
8) M. Lai*, S. Song, E. Oshin, L. Potter, N. Lai, and C. Jiang, "The production of OH in a nanosecond pulsed helium plasma jet impinging on water, saline, or pigskin," Journal of Applied Physics, **131**(17), May, 2022, https://doi.org/10.1063/5.0083568
9) A. Iqbal+, D. Wozniak+, M. Z. Rahman, S. Banerjee, J. Verboncoeur, P. Zhang, and C. Jiang, "Influence of discharge polarity on streamer breakdown criterion of ambient air in a non-uniform electric field," Journal of Physics D: Applied Physics, vol. 56, no. 3, p. 035204, 2022/12/12 2022, doi: 10.1088/1361-6463/aca2b4. (+ Equal contributors)

(Conference publications)

10) D. Alderman, C. Tremble, C. Jiang, J. M. Sanders and D. Singleton, "Initial Evaluation of Pulse Risetime on Transient Plasma Ignition for Combustion," *2018 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2018, pp. 279-282, doi: 10.1109/IPMHVC.2018.8936811.

11) D. Alderman, C. Tremble, S. Song, J.M. Sanders, D. Singleton, and C. Jiang, "Plasma kinetics study of a repetitive 10-ns pulsed plasma ignition for combustion," *2019 IEEE Pulsed Power & Plasma Science (PPPS)*, 2019, pp. 1-3, doi: 10.1109/PPPS34859.2019.9009621.

12) X. Li, S. Song, D. Alderman, M. A. Malik, R. Heller, and C. Jiang, "Evaluation of electric field and charge on bio-substrates induced by nanosecond pulsed helium plasma jet," *2019 IEEE Pulsed Power & Plasma Science (PPPS)*, 2019, pp. 1-4, doi: 10.1109/PPPS34859.2019.9009897.

Students graduated during the performance period:
S. Song, Doctor of Philosophy (PhD), May 2020
Dissertation: "Diagnostic studies of non-thermal atmospheric pressure nanosecond plasma jets," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/c38j-st04, https://digitalcommons.odu.edu/ece_etds/217

D. Alderman, Master of Science (MS), Dec. 2019
Thesis: "Pulse power effects on transient plasma ignition for combustion," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/skjc-8882, https://digitalcommons.odu.edu/ece_etds/209

Thank you for your support in helping AFOSR discover, shape and champion basic science research that profoundly impacts that future of the Air and Space Forces!

Accomplishments

- Research Objectives:
  1. **1.** Conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria.
  2. **2.** Conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties.
  3. **3.** Understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species including excited and ground state species.

- Accomplishments
  - Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air. i) We investigated the initiation of a guided helium streamer and its transition to a spark breakdown applying sub-microsecond voltage pulses. ii) We collaborated with Drs. Peng Zhang and John Verboncoeur at Michigan State University and developed a semi-analytic model to predict the breakdown voltage for direct current streamers. Based on Meek's criterion for streamer breakdown, the polarity dependence of the streamer breakdown process for a direct current condition was evaluated and the semi-analytical results agreed well with the experimental measurements.
  - Experimental studies of plasma properties including electron densities and mean energy of a nanosecond pulsed plasma jet were conducted in collaboration with the researchers at the Wright Patterson Air Force Research Laboratory. The electron density was measured on the order of 10^{13} cm^{-3}, in a distribution of ring-shaped profile, with the lower value in the center and higher at the outer edge of radius of 0.3 mm.
  - Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) Pulse duration: comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions; for the pulse duration of 200 – 2000 ns, the shortest pulse duration

corresponds to the highest energy efficiency for producing liquid phase OH, whereas the emission of OH(A-X), related the excited OH(A) production in gas phase, favors 800 ns pulse width. 2) Pulse risetime and repetition frequency: Use of fast rising voltage pulse for plasma ignition, the voltage amplitude required for combustion ignition can be reduced while keeping the same or even enhancing the combustion performance. Using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NOx emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

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Technical Updates

Summary:

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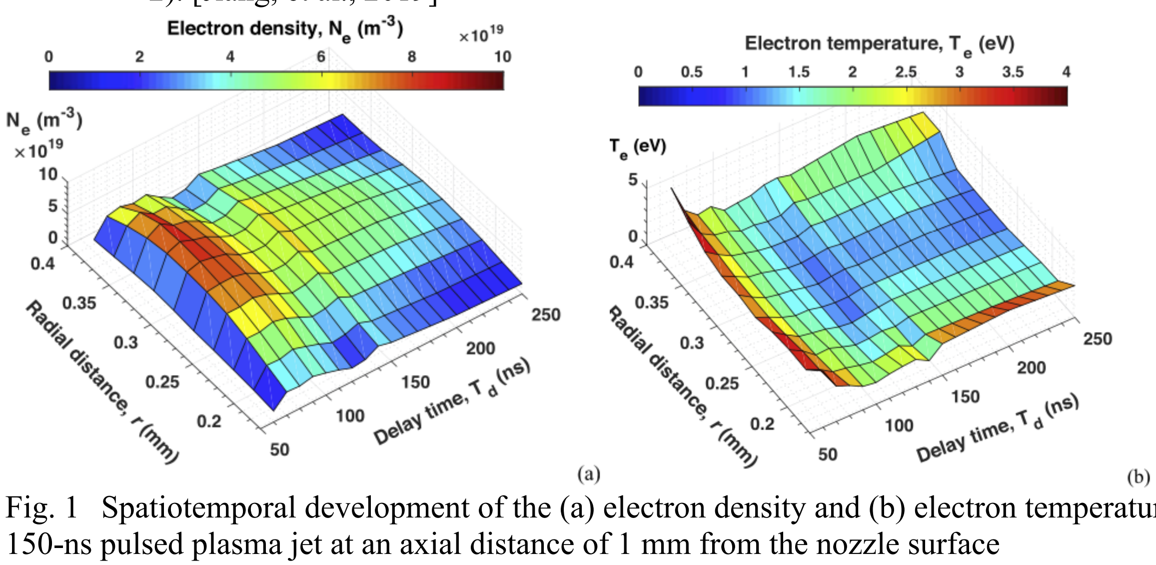
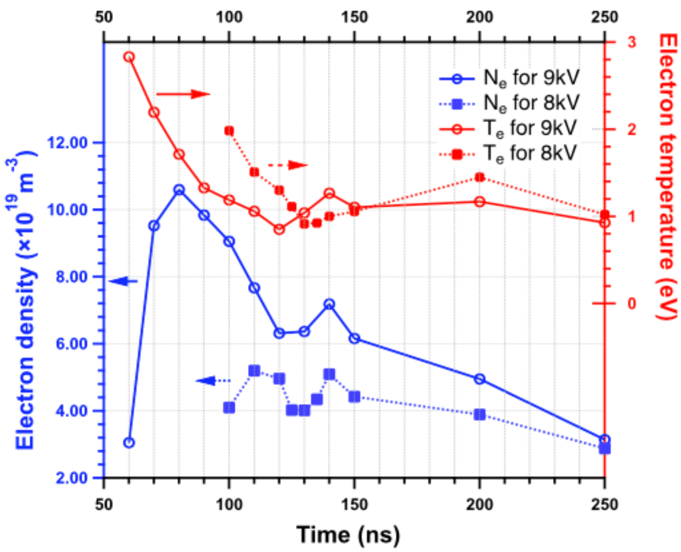


Fig. 1 Spatiotemporal development of the (a) electron density and (b) electron temperature of a 150-ns pulsed plasma jet at an axial distance of 1 mm from the nozzle surface



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5) D. Alderman, C. Tremble, D. Singleton, J. Sanders, and C. Jiang, "Effects of pulse rise time and repetition frequency on nanosecond pulsed plasma ignition for combustion," Plasma Research Express, **3**, 014001, (2021). https://iopscience.iop.org/article/10.1088/2516-1067/ab880a/meta.
6) C. Jiang, E. A. Oshin, S. Guo, M. Scott, X. Li, C. Mangiamele, and R. Heller, "Synergistic effects of an atmospheric pressure plasma jet and pulsed electric field on cells and skin," IEEE Transactions on Plasma Science, **49**(11), pp. 3317-3324, Nov. 2021, doi: 10.1109/TPS.2021.3113260.
7) M. Z. Rahman, E. A. Oshin and C. Jiang, "Initial Investigation of the Streamer to Spark Transition in a Hollow-Needle-to-Plate Configuration," IEEE Transactions on Plasma Science, vol. 50, no. 6, pp. 1942-1947, June 2022, doi: 10.1109/TPS.2022.3170346.
8) M. Lai*, S. Song, E. Oshin, L. Potter, N. Lai, and C. Jiang, "The production of OH in a nanosecond pulsed helium plasma jet impinging on water, saline, or pigskin," Journal of Applied Physics, **131**(17), May, 2022, https://doi.org/10.1063/5.0083568
9) A. Iqbal+, D. Wozniak+, M. Z. Rahman, S. Banerjee, J. Verboncoeur, P. Zhang, and C. Jiang, "Influence of discharge polarity on streamer breakdown criterion of ambient air in a non-uniform electric field," Journal of Physics D: Applied Physics, vol. 56, no. 3, p. 035204, 2022/12/12 2022, doi: 10.1088/1361-6463/aca2b4. (+ Equal contributors)

(Conference publications)

10) D. Alderman, C. Tremble, C. Jiang, J. M. Sanders and D. Singleton, "Initial Evaluation of Pulse Risetime on Transient Plasma Ignition for Combustion," *2018 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2018, pp. 279-282, doi: 10.1109/IPMHVC.2018.8936811.

11) D. Alderman, C. Tremble, S. Song, J.M. Sanders, D. Singleton, and C. Jiang, "Plasma kinetics study of a repetitive 10-ns pulsed plasma ignition for combustion," *2019 IEEE Pulsed Power & Plasma Science (PPPS)*, 2019, pp. 1-3, doi: 10.1109/PPPS34859.2019.9009621.

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Students graduated during the performance period:
S. Song, Doctor of Philosophy (PhD), May 2020
Dissertation: "Diagnostic studies of non-thermal atmospheric pressure nanosecond plasma jets," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/c38j-st04, https://digitalcommons.odu.edu/ece_etds/217

D. Alderman, Master of Science (MS), Dec. 2019
Thesis: "Pulse power effects on transient plasma ignition for combustion," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/skjc-8882, https://digitalcommons.odu.edu/ece_etds/209

Thank you for your support in helping AFOSR discover, shape and champion basic science research that profoundly impacts that future of the Air and Space Forces!

Accomplishments

- Research Objectives:
  1. **1.** Conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria.
  2. **2.** Conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties.
  3. **3.** Understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species including excited and ground state species.

- Accomplishments
  - Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air. i) We investigated the initiation of a guided helium streamer and its transition to a spark breakdown applying sub-microsecond voltage pulses. ii) We collaborated with Drs. Peng Zhang and John Verboncoeur at Michigan State University and developed a semi-analytic model to predict the breakdown voltage for direct current streamers. Based on Meek's criterion for streamer breakdown, the polarity dependence of the streamer breakdown process for a direct current condition was evaluated and the semi-analytical results agreed well with the experimental measurements.
  - Experimental studies of plasma properties including electron densities and mean energy of a nanosecond pulsed plasma jet were conducted in collaboration with the researchers at the Wright Patterson Air Force Research Laboratory. The electron density was measured on the order of 10^{13} cm^{-3}, in a distribution of ring-shaped profile, with the lower value in the center and higher at the outer edge of radius of 0.3 mm.
  - Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) Pulse duration: comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions; for the pulse duration of 200 – 2000 ns, the shortest pulse duration

corresponds to the highest energy efficiency for producing liquid phase OH, whereas the emission of OH(A-X), related the excited OH(A) production in gas phase, favors 800 ns pulse width. 2) Pulse risetime and repetition frequency: Use of fast rising voltage pulse for plasma ignition, the voltage amplitude required for combustion ignition can be reduced while keeping the same or even enhancing the combustion performance. Using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NOx emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

- Advanced spectroscopic techniques have been developed in the PI's laboratory, which facilitates the training for the next generation researchers to conduct low temperature plasma science research. These include spatiotemporally resolved optical emission spectroscopy, laser induced fluorescence to measure gas phase OH, Thomson laser scattering for electron property measurements for atmospheric pressure, weakly ionized plasmas. In addition, diagnostic techniques in liquid phase have also been explored including the high resolution respirometry-derived or the use of a chemical dye in combination with photospectrometer approaches to measure OH_{aq} production of ns-pulsed plasma jet impinging on water.

- How were the results disseminated to communities of interest?
  - Results from the related research were integrated in a senior design course (ECE 486/487), which was offered to senior undergraduate students from Fall 2021 to Spring 2022. Four electrical and computer engineering students including two females were signed up for the project. At the end of the project, the team participated the ODU College of Engineering and Technology's Engineering Student Projects Expo (ESPEX) and won the 2nd place out of total 26 undergraduate research projects across the college. All the team members stated that they have learned a lot through the project, and the research experience they gained from the course has positive impact on their future careers.
  - A lab tour for undergraduate students taking Electromagnetics (ECE 323) was hosted by the PI's group on April 22, 2022. Projects and results including streamer breakdown, compact pulse power system, and biomedical and environmental applications of cold plasmas were showcased to the junior undergraduate students. This will encourage their involvement for related research activities.

Impacts

This component is used to describe ways in which the work, findings, and specific products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as

a result of the project. You can report on the following impact categories, but you are not required to report on all categories. Please only report in the categories that are relevant to your project:

Development of the principal discipline(s) of the project
Outcome of this project such as understanding discharge breakdown problems in a non-uniform, transient field will have significant impact on the fundamental knowledge of discharge formation theory and are the bases for all related plasma applications.

Other disciplines:
Findings and diagnostic techniques developed in this project involving plasma chemistry will have significant impact on non-plasma disciplines including environmental science, health care, and agriculture.

Describe the impact in this reporting period on the development of human resources
This project provided opportunities for research and teaching in fundamental and applied research of non-thermal plasmas by including diverse research groups including female engineering students, students with special needs, and students from Africa.

Describe the impact on teaching and educational experiences
This project helped develope and disseminate new educational materials that benefit students in a long run. Examples were listed in one of the previous sections.

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.
Advanced spectroscopic techniques have been developed in the PI's laboratory, which facilitates the training for the next generation researchers to conduct low temperature plasma science research. These include spatiotemporally resolved optical emission spectroscopy, laser induced fluorescence to measure gas phase OH, Thomson laser scattering for electron property measurements for atmospheric pressure, weakly ionized plasmas. In addition, diagnostic techniques in liquid phase have also been explored including the high resolution respirometry-derived or the use of a chemical dye in combination with photospectrometer approaches to measure OH_{aq} production of ns-pulsed plasma jet impinging on water.

Impact on society beyond science and technology:
None.

Changes

In this section, please incorporate any and all changes that you would like your program officers to know about the grant. The principal investigator is reminded that the recipient organization is required to obtain prior written approval from program officers whenever there are significant changes in the

project or its direction. Sections may include:

Changes in approach
No changes.

Problems or delays
None.

Expenditure Impacts
Delays in recruiting graduate students and in obtaining parts/components/equipment due to the pandemic of COVID-19.
Virtual conferences reduced the cost of travel expenses and enabled more participation of students to the conference, although at a less effective way.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
Not applicable.

Changes to the primary place of performance from that originally proposed
No changes.

Technical Updates

Summary:

The goal of this research is to advance the understanding of plasma physics and chemistry for highly non-equilibrium microplasmas, particularly in forms of transient streamers in microscopic scales, generated with mixed flow fields and nanosecond pulsed electric fields. The research objectives are 1) to conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria; 2) to conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties; and 3) to understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species such as excited and ground state species.

Selected research effort is listed below to emphasize the accomplishment of this program:

1) Streamer initiation and breakdown studies
   Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air.
   a. Under a direct condition, streamer breakdown of atmospheric air with non-uniform electric field in a needle-to-plate electrode configuration was studied using a semi-analytic model and experimental measurements. Empirical relations between the critical avalanche size for streamer breakdown and the gap distance

were proposed, and the semi-analytical results agreed well with the experimental measurements. It was found that for *pd* > 380 Torr·cm (or *d* > 0.5 cm at one atmosphere) streamer breakdown of ambient air occurred at a lower applied voltage for a positively biased needle compared to that with a negatively biased needle, referred as the polarity effect. For *pd* < 380 Torr·cm, breakdown was attained at a lower applied voltage with a negatively biased needle compared to that with a positively biased needle, and breakdown mode transits from the polarity effect to the so-called inverted polarity effect. [Iqubal, et al., 2022]

b. Under a pulsed condition, we investigated the initiation of a guided helium streamer and its transition to a spark breakdown using a hollow needle-to-plate configuration. The experimental results show that streamer initiation requires at least 4 mm interelectrode gap distance, and the spark breakdown occurs directly for shorter gap distances. Applying a lower PRF or a shorter pulse duration, higher voltages are required for the streamer initiation and breakdown; the streamer transitions to a highly conductively spark at a lower voltage for longer pulses or higher PRFs. [Rahman, et al., 2022]

2) Plasma property studies
   a) Impact of pulsed electric field on electron densities and mean energy of a 150-ns pulsed He plasma jet in air were conducted using Thomson laser scattering. The measurements revealed a ring-shaped electron density distribution (with a max. of 1×10^{14} cm^{-3}) at 1 mm above the electrode nozzle (Fig. 1) and the ring converged after 5 mm. The electron temperature at the radius of the ring varied from 2.8 eV to 0.8 eV. Importantly, the formation and development of the guided streamer was found strongly dependent on the external pulsed electric field and the maximum electron densities were associated with the rising and falling phases of the voltage pulse (Fig. 2). [Jiang, et al., 2019]

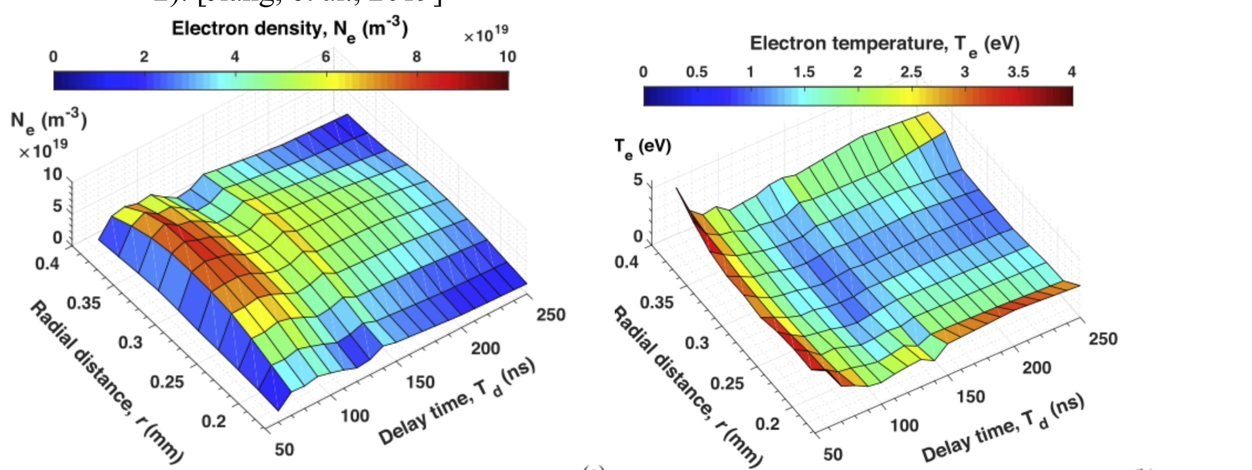

Fig. 1 Spatiotemporal development of the (a) electron density and (b) electron temperature of a 150-ns pulsed plasma jet at an axial distance of 1 mm from the nozzle surface

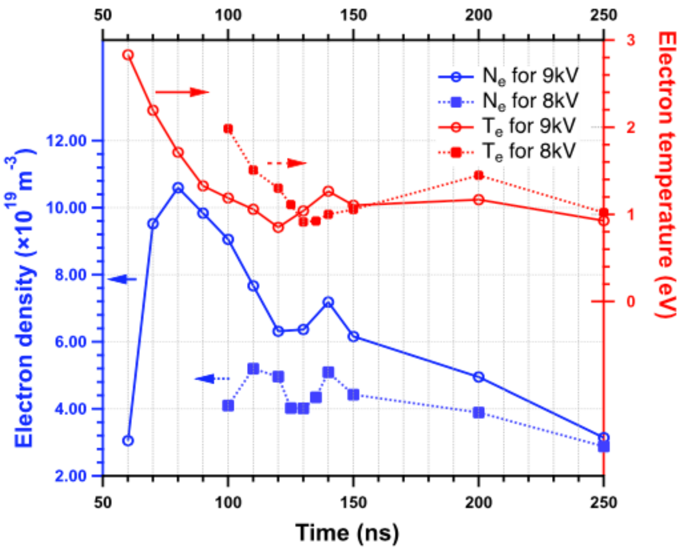

Fig. 2 Temporal development comparison of the peak electron density and corresponding temperature of the plasma jet driven by different voltages at 9 and 8 kV at the same axial distance, z =1 mm.

b) Impact of pulse duration and risetime on gas temperature were investigated by comparing a He microplasma jet excited by 5- or 164-ns 8-kV pulses at 500 Hz. Applying shorter and faster pulses resulted in higher energy per pulse (energy deposited in the plasma), more production of excited ions (e.g., N_2^+). The rotational temperature of the short and long ns-pulsed plasma jets was found comparable, both at 300 K, indicating that both plasma jets were under highly nonequilibrium conditions. [Song, et al., 2018]

3) Plasma chemistry studies

- Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) *Pulse duration*. Comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions [Song, et al., 2018]. For the pulse duration of 200 – 2000 ns, the shortest pulse duration corresponds to the highest energy efficiency for producing liquid phase OH_{aq}, whereas the 800-ns pulse width is associated with the highest emission of OH(A-X) or the production excited OH(A) in gas phase. [Song, et al., 2019]
  2) *Pulse risetime and repetition frequency*. The use of fast rising voltage pulse in plasma ignition for combustion can reduce the voltage requirement needed to achieve successful ignition, while keeping the same or even enhancing the combustion performance. This was demonstrated with applying transient plasmas driven by 10-ns, 10 kV pulse bursts at 1-10 kHz repetition rates for igniting methane-dry air mixture in a static chamber at atmospheric pressure. Comparison of the plasmas powered by the same duration pulse bursts with different rise times, i.e., t_r = 5 ns and 10 ns, showed faster pulses benefit the combustion ignition with higher peak pressure, shorter

ignition delay and reduced energy needed to initiate combustion. In addition, there was a possible optimal PRF within 6–10 kHz, which was associated with the best combustion performance, i.e., the highest peak pressure and shortest ignition delay. [Alderman, et al., 2021]. More recently, using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NO_x emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

- Impact of target materials on the plasma formation and the associated chemistry are studied for applications of the plasma in medicine including cancer therapy and gene transfer. The presence of biological materials, especially as part of the electrode circuit, may change the plasma properties and impact on the production of reactive plasma species at the plasma-target interface. Using a needle-to-plate electrode configuration, the production of OH in a 200 ns, 7 kV pulses at 1 kHz, helium plasma jet impinging on water, phosphate-buffered saline (PBS) or pigskin were measured using both optical emission spectroscopy and laser induced fluorescence. The experimental results showed that the use of pigskin slowed down the streamer head propagation, whereas a more pronounced surface ionization wave was developed on the surface when water was used. The highest OH(A-X) emission above the biomaterial surface was observe using the PBS-covered electrode plate comparing to water or pigskin. Spatiotemporally resolved laser induced fluorescence showed that more OH was produced in regions near the needle electrode for both water and PBS and the use of pigskin resulted in the least OH production overall. [Lai, et al. 2022] In addition, the electric field at the plasma-target interface as well as in the biomaterial can vary significantly due to the use of different target, which results in different plasma properties and different biological effects, e.g., field-induced or reactive oxygen species-induced effects, during the plasma biological cell/tissue interactions. [Jiang, et al., 2021]

Archival publications during reporting period:

(The names of the graduate/undergraduate students under supervising are underlined, the names of postdocs under supervising are noted with * during the production of the publication.)

(Journal publications)

1) S. Song, J. L. Lane* and C. Jiang, "Comparison study of spatiotemporally resolved emissions of nanosecond pulsed microplasma jets", IEEE Transactions on Plasma Science, vol. 46, no. 3, pp. 587-593, March 2018, doi: 10.1109/TPS.2018.2795958.
2) S. Song, E. B. Sozer, and C. Jiang, "Effects of pulse width on He plasma jets in contact with water evaluated by OH(A–X) emission and OH_{aq} production," Japanese Journal of Applied Physics, **58**, no. 6, 2019. https://iopscience.iop.org/article/10.7567/1347-4065/ab1e6d
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Outcome of this project such as understanding discharge breakdown problems in a non-uniform, transient field will have significant impact on the fundamental knowledge of discharge formation theory and are the bases for all related plasma applications.

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Findings and diagnostic techniques developed in this project involving plasma chemistry will have significant impact on non-plasma disciplines including environmental science, health care, and agriculture.

Describe the impact in this reporting period on the development of human resources
This project provided opportunities for research and teaching in fundamental and applied research of non-thermal plasmas by including diverse research groups including female engineering students, students with special needs, and students from Africa.

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Impact on society beyond science and technology:
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Changes

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Delays in recruiting graduate students and in obtaining parts/components/equipment due to the pandemic of COVID-19.
Virtual conferences reduced the cost of travel expenses and enabled more participation of students to the conference, although at a less effective way.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
Not applicable.

Changes to the primary place of performance from that originally proposed
No changes.

Technical Updates

Summary:

The goal of this research is to advance the understanding of plasma physics and chemistry for highly non-equilibrium microplasmas, particularly in forms of transient streamers in microscopic scales, generated with mixed flow fields and nanosecond pulsed electric fields. The research objectives are 1) to conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria; 2) to conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties; and 3) to understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species such as excited and ground state species.

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   Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air.
   a. Under a direct condition, streamer breakdown of atmospheric air with non-uniform electric field in a needle-to-plate electrode configuration was studied using a semi-analytic model and experimental measurements. Empirical relations between the critical avalanche size for streamer breakdown and the gap distance

were proposed, and the semi-analytical results agreed well with the experimental measurements. It was found that for *pd* > 380 Torr·cm (or *d* > 0.5 cm at one atmosphere) streamer breakdown of ambient air occurred at a lower applied voltage for a positively biased needle compared to that with a negatively biased needle, referred as the polarity effect. For *pd* < 380 Torr·cm, breakdown was attained at a lower applied voltage with a negatively biased needle compared to that with a positively biased needle, and breakdown mode transits from the polarity effect to the so-called inverted polarity effect. [Iqubal, et al., 2022]

b. Under a pulsed condition, we investigated the initiation of a guided helium streamer and its transition to a spark breakdown using a hollow needle-to-plate configuration. The experimental results show that streamer initiation requires at least 4 mm interelectrode gap distance, and the spark breakdown occurs directly for shorter gap distances. Applying a lower PRF or a shorter pulse duration, higher voltages are required for the streamer initiation and breakdown; the streamer transitions to a highly conductively spark at a lower voltage for longer pulses or higher PRFs. [Rahman, et al., 2022]

2) Plasma property studies

   a) Impact of pulsed electric field on electron densities and mean energy of a 150-ns pulsed He plasma jet in air were conducted using Thomson laser scattering. The measurements revealed a ring-shaped electron density distribution (with a max. of 1×10^{14} cm^{-3}) at 1 mm above the electrode nozzle (Fig. 1) and the ring converged after 5 mm. The electron temperature at the radius of the ring varied from 2.8 eV to 0.8 eV. Importantly, the formation and development of the guided streamer was found strongly dependent on the external pulsed electric field and the maximum electron densities were associated with the rising and falling phases of the voltage pulse (Fig. 2). [Jiang, et al., 2019]

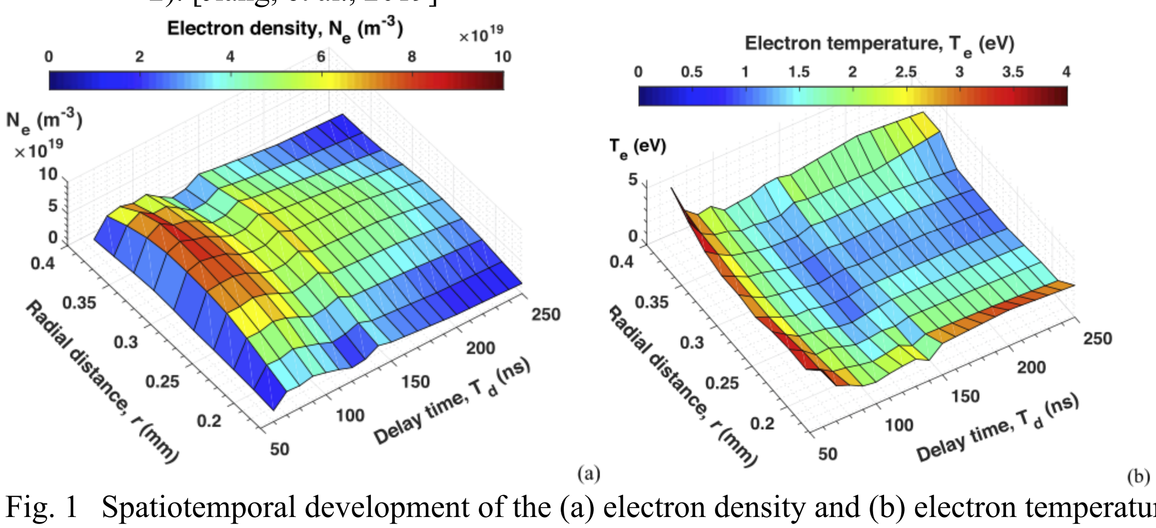

Fig. 1 Spatiotemporal development of the (a) electron density and (b) electron temperature of a 150-ns pulsed plasma jet at an axial distance of 1 mm from the nozzle surface

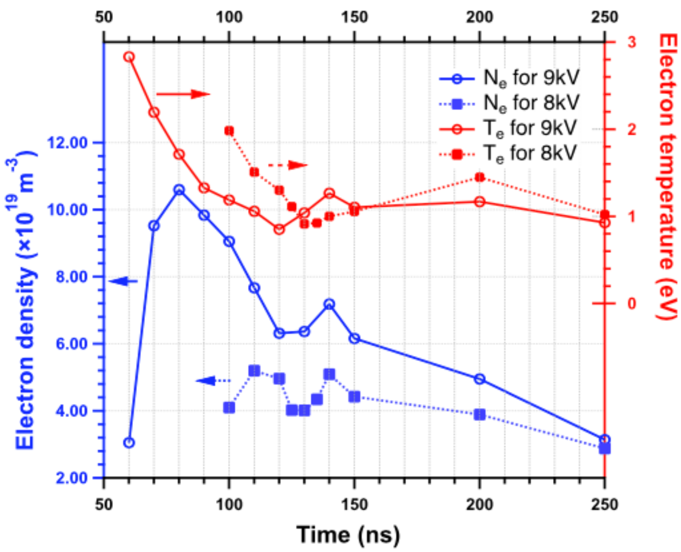

Fig. 2 Temporal development comparison of the peak electron density and corresponding temperature of the plasma jet driven by different voltages at 9 and 8 kV at the same axial distance, z =1 mm.

b) Impact of pulse duration and risetime on gas temperature were investigated by comparing a He microplasma jet excited by 5- or 164-ns 8-kV pulses at 500 Hz. Applying shorter and faster pulses resulted in higher energy per pulse (energy deposited in the plasma), more production of excited ions (e.g., N_2^+). The rotational temperature of the short and long ns-pulsed plasma jets was found comparable, both at 300 K, indicating that both plasma jets were under highly nonequilibrium conditions. [Song, et al., 2018]

3) Plasma chemistry studies

- Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) *Pulse duration*. Comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions [Song, et al., 2018]. For the pulse duration of 200 – 2000 ns, the shortest pulse duration corresponds to the highest energy efficiency for producing liquid phase OH_{aq}, whereas the 800-ns pulse width is associated with the highest emission of OH(A-X) or the production excited OH(A) in gas phase. [Song, et al., 2019]
  2) *Pulse risetime and repetition frequency*. The use of fast rising voltage pulse in plasma ignition for combustion can reduce the voltage requirement needed to achieve successful ignition, while keeping the same or even enhancing the combustion performance. This was demonstrated with applying transient plasmas driven by 10-ns, 10 kV pulse bursts at 1-10 kHz repetition rates for igniting methane-dry air mixture in a static chamber at atmospheric pressure. Comparison of the plasmas powered by the same duration pulse bursts with different rise times, i.e., t_r = 5 ns and 10 ns, showed faster pulses benefit the combustion ignition with higher peak pressure, shorter

ignition delay and reduced energy needed to initiate combustion. In addition, there was a possible optimal PRF within 6–10 kHz, which was associated with the best combustion performance, i.e., the highest peak pressure and shortest ignition delay. [Alderman, et al., 2021]. More recently, using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NO_x emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

- Impact of target materials on the plasma formation and the associated chemistry are studied for applications of the plasma in medicine including cancer therapy and gene transfer. The presence of biological materials, especially as part of the electrode circuit, may change the plasma properties and impact on the production of reactive plasma species at the plasma-target interface. Using a needle-to-plate electrode configuration, the production of OH in a 200 ns, 7 kV pulses at 1 kHz, helium plasma jet impinging on water, phosphate-buffered saline (PBS) or pigskin were measured using both optical emission spectroscopy and laser induced fluorescence. The experimental results showed that the use of pigskin slowed down the streamer head propagation, whereas a more pronounced surface ionization wave was developed on the surface when water was used. The highest OH(A-X) emission above the biomaterial surface was observe using the PBS-covered electrode plate comparing to water or pigskin. Spatiotemporally resolved laser induced fluorescence showed that more OH was produced in regions near the needle electrode for both water and PBS and the use of pigskin resulted in the least OH production overall. [Lai, et al. 2022] In addition, the electric field at the plasma-target interface as well as in the biomaterial can vary significantly due to the use of different target, which results in different plasma properties and different biological effects, e.g., field-induced or reactive oxygen species-induced effects, during the plasma biological cell/tissue interactions. [Jiang, et al., 2021]

Archival publications during reporting period:

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(Journal publications)

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3) C. Jiang, J. A. Miles, J. Hornef, C. Carter, and S. F. Adams, "Electron densities and temperatures of an atmospheric-pressure nanosecond pulsed helium plasma jet in air," Plasma Sources Science and Technology, **28**, 085009, 2019. https://iopscience.iop.org/article/10.1088/1361-6595/ab2182
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8) M. Lai*, S. Song, E. Oshin, L. Potter, N. Lai, and C. Jiang, "The production of OH in a nanosecond pulsed helium plasma jet impinging on water, saline, or pigskin," Journal of Applied Physics, **131**(17), May, 2022, https://doi.org/10.1063/5.0083568
9) A. Iqbal+, D. Wozniak+, M. Z. Rahman, S. Banerjee, J. Verboncoeur, P. Zhang, and C. Jiang, "Influence of discharge polarity on streamer breakdown criterion of ambient air in a non-uniform electric field," Journal of Physics D: Applied Physics, vol. 56, no. 3, p. 035204, 2022/12/12 2022, doi: 10.1088/1361-6463/aca2b4. (+ Equal contributors)

(Conference publications)

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Students graduated during the performance period:
S. Song, Doctor of Philosophy (PhD), May 2020
Dissertation: "Diagnostic studies of non-thermal atmospheric pressure nanosecond plasma jets," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/c38j-st04, https://digitalcommons.odu.edu/ece_etds/217

D. Alderman, Master of Science (MS), Dec. 2019
Thesis: "Pulse power effects on transient plasma ignition for combustion," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/skjc-8882, https://digitalcommons.odu.edu/ece_etds/209

Thank you for your support in helping AFOSR discover, shape and champion basic science research that profoundly impacts that future of the Air and Space Forces!

Accomplishments

- Research Objectives:
  1. **1.** Conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria.
  2. **2.** Conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties.
  3. **3.** Understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species including excited and ground state species.

- Accomplishments
  - Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air. i) We investigated the initiation of a guided helium streamer and its transition to a spark breakdown applying sub-microsecond voltage pulses. ii) We collaborated with Drs. Peng Zhang and John Verboncoeur at Michigan State University and developed a semi-analytic model to predict the breakdown voltage for direct current streamers. Based on Meek's criterion for streamer breakdown, the polarity dependence of the streamer breakdown process for a direct current condition was evaluated and the semi-analytical results agreed well with the experimental measurements.
  - Experimental studies of plasma properties including electron densities and mean energy of a nanosecond pulsed plasma jet were conducted in collaboration with the researchers at the Wright Patterson Air Force Research Laboratory. The electron density was measured on the order of 10^{13} cm^{-3}, in a distribution of ring-shaped profile, with the lower value in the center and higher at the outer edge of radius of 0.3 mm.
  - Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) Pulse duration: comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions; for the pulse duration of 200 – 2000 ns, the shortest pulse duration

corresponds to the highest energy efficiency for producing liquid phase OH, whereas the emission of OH(A-X), related the excited OH(A) production in gas phase, favors 800 ns pulse width. 2) Pulse risetime and repetition frequency: Use of fast rising voltage pulse for plasma ignition, the voltage amplitude required for combustion ignition can be reduced while keeping the same or even enhancing the combustion performance. Using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NOx emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

  - Advanced spectroscopic techniques have been developed in the PI's laboratory, which facilitates the training for the next generation researchers to conduct low temperature plasma science research. These include spatiotemporally resolved optical emission spectroscopy, laser induced fluorescence to measure gas phase OH, Thomson laser scattering for electron property measurements for atmospheric pressure, weakly ionized plasmas. In addition, diagnostic techniques in liquid phase have also been explored including the high resolution respirometry-derived or the use of a chemical dye in combination with photospectrometer approaches to measure OH_{aq} production of ns-pulsed plasma jet impinging on water.

- How were the results disseminated to communities of interest?
  - Results from the related research were integrated in a senior design course (ECE 486/487), which was offered to senior undergraduate students from Fall 2021 to Spring 2022. Four electrical and computer engineering students including two females were signed up for the project. At the end of the project, the team participated the ODU College of Engineering and Technology's Engineering Student Projects Expo (ESPEX) and won the 2nd place out of total 26 undergraduate research projects across the college. All the team members stated that they have learned a lot through the project, and the research experience they gained from the course has positive impact on their future careers.
  - A lab tour for undergraduate students taking Electromagnetics (ECE 323) was hosted by the PI's group on April 22, 2022. Projects and results including streamer breakdown, compact pulse power system, and biomedical and environmental applications of cold plasmas were showcased to the junior undergraduate students. This will encourage their involvement for related research activities.

Impacts

This component is used to describe ways in which the work, findings, and specific products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as

a result of the project. You can report on the following impact categories, but you are not required to report on all categories. Please only report in the categories that are relevant to your project:

Development of the principal discipline(s) of the project
Outcome of this project such as understanding discharge breakdown problems in a non-uniform, transient field will have significant impact on the fundamental knowledge of discharge formation theory and are the bases for all related plasma applications.

Other disciplines:
Findings and diagnostic techniques developed in this project involving plasma chemistry will have significant impact on non-plasma disciplines including environmental science, health care, and agriculture.

Describe the impact in this reporting period on the development of human resources
This project provided opportunities for research and teaching in fundamental and applied research of non-thermal plasmas by including diverse research groups including female engineering students, students with special needs, and students from Africa.

Describe the impact on teaching and educational experiences
This project helped develope and disseminate new educational materials that benefit students in a long run. Examples were listed in one of the previous sections.

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.
Advanced spectroscopic techniques have been developed in the PI's laboratory, which facilitates the training for the next generation researchers to conduct low temperature plasma science research. These include spatiotemporally resolved optical emission spectroscopy, laser induced fluorescence to measure gas phase OH, Thomson laser scattering for electron property measurements for atmospheric pressure, weakly ionized plasmas. In addition, diagnostic techniques in liquid phase have also been explored including the high resolution respirometry-derived or the use of a chemical dye in combination with photospectrometer approaches to measure OH_{aq} production of ns-pulsed plasma jet impinging on water.

Impact on society beyond science and technology:
None.

Changes

In this section, please incorporate any and all changes that you would like your program officers to know about the grant. The principal investigator is reminded that the recipient organization is required to obtain prior written approval from program officers whenever there are significant changes in the

project or its direction. Sections may include:

Changes in approach
No changes.

Problems or delays
None.

Expenditure Impacts
Delays in recruiting graduate students and in obtaining parts/components/equipment due to the pandemic of COVID-19.
Virtual conferences reduced the cost of travel expenses and enabled more participation of students to the conference, although at a less effective way.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
Not applicable.

Changes to the primary place of performance from that originally proposed
No changes.

Technical Updates

Summary:

The goal of this research is to advance the understanding of plasma physics and chemistry for highly non-equilibrium microplasmas, particularly in forms of transient streamers in microscopic scales, generated with mixed flow fields and nanosecond pulsed electric fields. The research objectives are 1) to conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria; 2) to conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties; and 3) to understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species such as excited and ground state species.

Selected research effort is listed below to emphasize the accomplishment of this program:

1) Streamer initiation and breakdown studies
   Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air.
   a. Under a direct condition, streamer breakdown of atmospheric air with non-uniform electric field in a needle-to-plate electrode configuration was studied using a semi-analytic model and experimental measurements. Empirical relations between the critical avalanche size for streamer breakdown and the gap distance

were proposed, and the semi-analytical results agreed well with the experimental measurements. It was found that for *pd* > 380 Torr·cm (or *d* > 0.5 cm at one atmosphere) streamer breakdown of ambient air occurred at a lower applied voltage for a positively biased needle compared to that with a negatively biased needle, referred as the polarity effect. For *pd* < 380 Torr·cm, breakdown was attained at a lower applied voltage with a negatively biased needle compared to that with a positively biased needle, and breakdown mode transits from the polarity effect to the so-called inverted polarity effect. [Iqubal, et al., 2022]

b. Under a pulsed condition, we investigated the initiation of a guided helium streamer and its transition to a spark breakdown using a hollow needle-to-plate configuration. The experimental results show that streamer initiation requires at least 4 mm interelectrode gap distance, and the spark breakdown occurs directly for shorter gap distances. Applying a lower PRF or a shorter pulse duration, higher voltages are required for the streamer initiation and breakdown; the streamer transitions to a highly conductively spark at a lower voltage for longer pulses or higher PRFs. [Rahman, et al., 2022]

2) Plasma property studies
   a) Impact of pulsed electric field on electron densities and mean energy of a 150-ns pulsed He plasma jet in air were conducted using Thomson laser scattering. The measurements revealed a ring-shaped electron density distribution (with a max. of 1×10^{14} cm^{-3}) at 1 mm above the electrode nozzle (Fig. 1) and the ring converged after 5 mm. The electron temperature at the radius of the ring varied from 2.8 eV to 0.8 eV. Importantly, the formation and development of the guided streamer was found strongly dependent on the external pulsed electric field and the maximum electron densities were associated with the rising and falling phases of the voltage pulse (Fig. 2). [Jiang, et al., 2019]

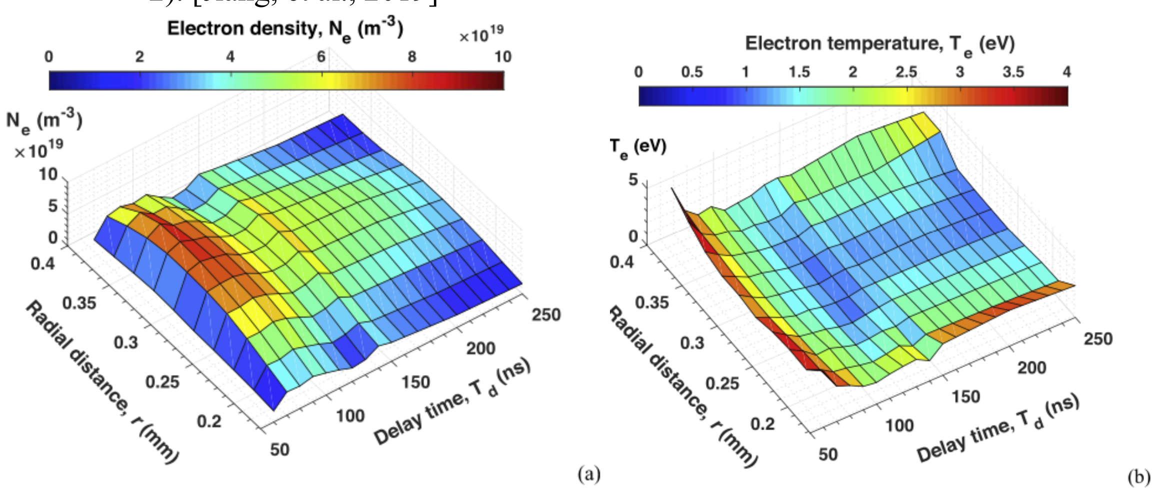

Fig. 1 Spatiotemporal development of the (a) electron density and (b) electron temperature of a 150-ns pulsed plasma jet at an axial distance of 1 mm from the nozzle surface

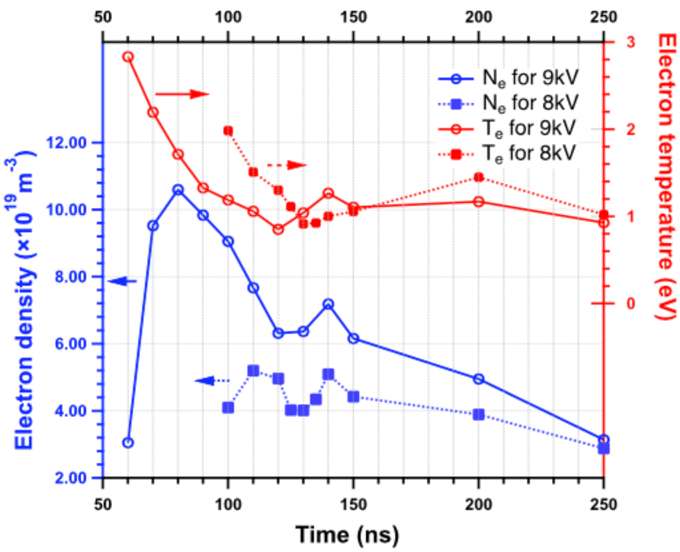

Fig. 2 Temporal development comparison of the peak electron density and corresponding temperature of the plasma jet driven by different voltages at 9 and 8 kV at the same axial distance, z =1 mm.

b) Impact of pulse duration and risetime on gas temperature were investigated by comparing a He microplasma jet excited by 5- or 164-ns 8-kV pulses at 500 Hz. Applying shorter and faster pulses resulted in higher energy per pulse (energy deposited in the plasma), more production of excited ions (e.g., N_2^+). The rotational temperature of the short and long ns-pulsed plasma jets was found comparable, both at 300 K, indicating that both plasma jets were under highly nonequilibrium conditions. [Song, et al., 2018]

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- Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) *Pulse duration*. Comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions [Song, et al., 2018]. For the pulse duration of 200 – 2000 ns, the shortest pulse duration corresponds to the highest energy efficiency for producing liquid phase OH_{aq}, whereas the 800-ns pulse width is associated with the highest emission of OH(A-X) or the production excited OH(A) in gas phase. [Song, et al., 2019]
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Dissertation: “Diagnostic studies of non-thermal atmospheric pressure nanosecond plasma jets,” Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/c38j-st04, https://digitalcommons.odu.edu/ece_etds/217

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    - Experimental studies of plasma properties including electron densities and mean energy of a nanosecond pulsed plasma jet were conducted in collaboration with the researchers at the Wright Patterson Air Force Research Laboratory. The electron density was measured on the order of 10^{13} cm^{-3}, in a distribution of ring-shaped profile, with the lower value in the center and higher at the outer edge of radius of 0.3 mm.
    - Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) Pulse duration: comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions; for the pulse duration of 200 – 2000 ns, the shortest pulse duration

corresponds to the highest energy efficiency for producing liquid phase OH, whereas the emission of OH(A-X), related the excited OH(A) production in gas phase, favors 800 ns pulse width. 2) Pulse risetime and repetition frequency: Use of fast rising voltage pulse for plasma ignition, the voltage amplitude required for combustion ignition can be reduced while keeping the same or even enhancing the combustion performance. Using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NOx emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

- Advanced spectroscopic techniques have been developed in the PI's laboratory, which facilitates the training for the next generation researchers to conduct low temperature plasma science research. These include spatiotemporally resolved optical emission spectroscopy, laser induced fluorescence to measure gas phase OH, Thomson laser scattering for electron property measurements for atmospheric pressure, weakly ionized plasmas. In addition, diagnostic techniques in liquid phase have also been explored including the high resolution respirometry-derived or the use of a chemical dye in combination with photospectrometer approaches to measure OH_{aq} production of ns-pulsed plasma jet impinging on water.

- How were the results disseminated to communities of interest?
  - Results from the related research were integrated in a senior design course (ECE 486/487), which was offered to senior undergraduate students from Fall 2021 to Spring 2022. Four electrical and computer engineering students including two females were signed up for the project. At the end of the project, the team participated the ODU College of Engineering and Technology's Engineering Student Projects Expo (ESPEX) and won the 2nd place out of total 26 undergraduate research projects across the college. All the team members stated that they have learned a lot through the project, and the research experience they gained from the course has positive impact on their future careers.
  - A lab tour for undergraduate students taking Electromagnetics (ECE 323) was hosted by the PI's group on April 22, 2022. Projects and results including streamer breakdown, compact pulse power system, and biomedical and environmental applications of cold plasmas were showcased to the junior undergraduate students. This will encourage their involvement for related research activities.

Impacts

This component is used to describe ways in which the work, findings, and specific products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as

a result of the project. You can report on the following impact categories, but you are not required to report on all categories. Please only report in the categories that are relevant to your project:

Development of the principal discipline(s) of the project
Outcome of this project such as understanding discharge breakdown problems in a non-uniform, transient field will have significant impact on the fundamental knowledge of discharge formation theory and are the bases for all related plasma applications.

Other disciplines:
Findings and diagnostic techniques developed in this project involving plasma chemistry will have significant impact on non-plasma disciplines including environmental science, health care, and agriculture.

Describe the impact in this reporting period on the development of human resources
This project provided opportunities for research and teaching in fundamental and applied research of non-thermal plasmas by including diverse research groups including female engineering students, students with special needs, and students from Africa.

Describe the impact on teaching and educational experiences
This project helped develope and disseminate new educational materials that benefit students in a long run. Examples were listed in one of the previous sections.

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.
Advanced spectroscopic techniques have been developed in the PI's laboratory, which facilitates the training for the next generation researchers to conduct low temperature plasma science research. These include spatiotemporally resolved optical emission spectroscopy, laser induced fluorescence to measure gas phase OH, Thomson laser scattering for electron property measurements for atmospheric pressure, weakly ionized plasmas. In addition, diagnostic techniques in liquid phase have also been explored including the high resolution respirometry-derived or the use of a chemical dye in combination with photospectrometer approaches to measure OH_{aq} production of ns-pulsed plasma jet impinging on water.

Impact on society beyond science and technology:
None.

Changes

In this section, please incorporate any and all changes that you would like your program officers to know about the grant. The principal investigator is reminded that the recipient organization is required to obtain prior written approval from program officers whenever there are significant changes in the

project or its direction. Sections may include:

Changes in approach
No changes.

Problems or delays
None.

Expenditure Impacts
Delays in recruiting graduate students and in obtaining parts/components/equipment due to the pandemic of COVID-19.
Virtual conferences reduced the cost of travel expenses and enabled more participation of students to the conference, although at a less effective way.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
Not applicable.

Changes to the primary place of performance from that originally proposed
No changes.

Technical Updates

Summary:

The goal of this research is to advance the understanding of plasma physics and chemistry for highly non-equilibrium microplasmas, particularly in forms of transient streamers in microscopic scales, generated with mixed flow fields and nanosecond pulsed electric fields. The research objectives are 1) to conduct both theoretical and experimental studies of the initiation process of non-equilibrium pulsed microplasmas and understand the plasma initiation criteria; 2) to conduct experimental studies and understand the impact of nanosecond pulsed power parameters on the transient plasma properties; and 3) to understand the impact of pulse power parameters on the direct and indirect electronic processes and their impact on the production of reactive plasma species such as excited and ground state species.

Selected research effort is listed below to emphasize the accomplishment of this program:

1) Streamer initiation and breakdown studies
   Systematic breakdown and streamer initiation were evaluated for a non-uniform electric field distribution using a hollow needle-to-plate geometry in ambient air.
   a. Under a direct condition, streamer breakdown of atmospheric air with non-uniform electric field in a needle-to-plate electrode configuration was studied using a semi-analytic model and experimental measurements. Empirical relations between the critical avalanche size for streamer breakdown and the gap distance

were proposed, and the semi-analytical results agreed well with the experimental measurements. It was found that for *pd* > 380 Torr·cm (or *d* > 0.5 cm at one atmosphere) streamer breakdown of ambient air occurred at a lower applied voltage for a positively biased needle compared to that with a negatively biased needle, referred as the polarity effect. For *pd* < 380 Torr·cm, breakdown was attained at a lower applied voltage with a negatively biased needle compared to that with a positively biased needle, and breakdown mode transits from the polarity effect to the so-called inverted polarity effect. [Iqubal, et al., 2022]

b. Under a pulsed condition, we investigated the initiation of a guided helium streamer and its transition to a spark breakdown using a hollow needle-to-plate configuration. The experimental results show that streamer initiation requires at least 4 mm interelectrode gap distance, and the spark breakdown occurs directly for shorter gap distances. Applying a lower PRF or a shorter pulse duration, higher voltages are required for the streamer initiation and breakdown; the streamer transitions to a highly conductively spark at a lower voltage for longer pulses or higher PRFs. [Rahman, et al., 2022]

2) Plasma property studies

a) Impact of pulsed electric field on electron densities and mean energy of a 150-ns pulsed He plasma jet in air were conducted using Thomson laser scattering. The measurements revealed a ring-shaped electron density distribution (with a max. of 1×10^{14} cm^{-3}) at 1 mm above the electrode nozzle (Fig. 1) and the ring converged after 5 mm. The electron temperature at the radius of the ring varied from 2.8 eV to 0.8 eV. Importantly, the formation and development of the guided streamer was found strongly dependent on the external pulsed electric field and the maximum electron densities were associated with the rising and falling phases of the voltage pulse (Fig. 2). [Jiang, et al., 2019]

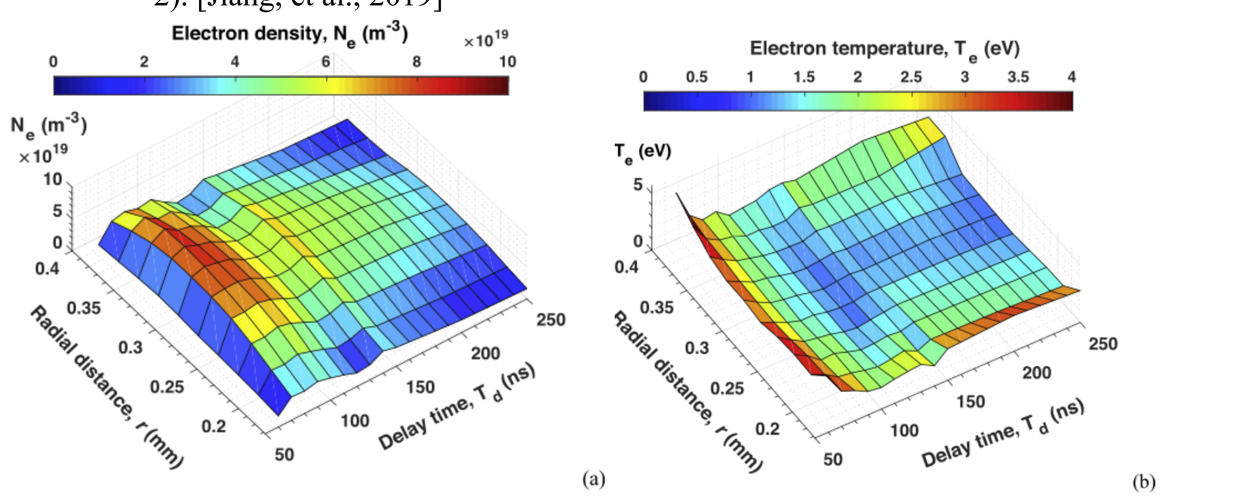

Fig. 1 Spatiotemporal development of the (a) electron density and (b) electron temperature of a 150-ns pulsed plasma jet at an axial distance of 1 mm from the nozzle surface

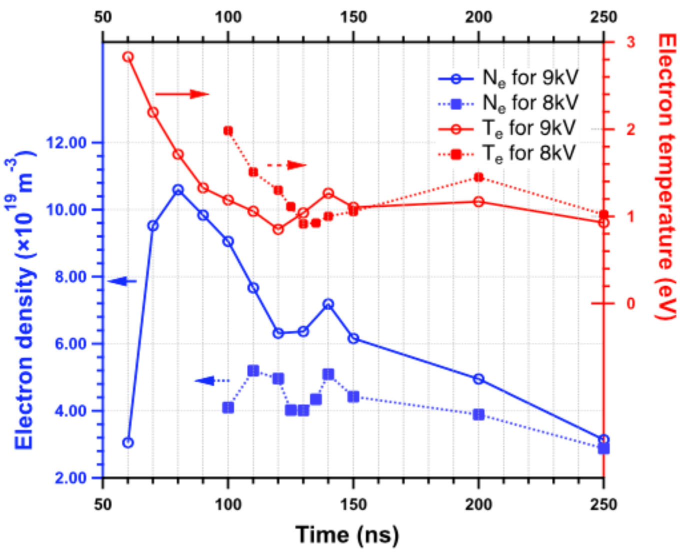

Fig. 2 Temporal development comparison of the peak electron density and corresponding temperature of the plasma jet driven by different voltages at 9 and 8 kV at the same axial distance, z =1 mm.

b) Impact of pulse duration and risetime on gas temperature were investigated by comparing a He microplasma jet excited by 5- or 164-ns 8-kV pulses at 500 Hz. Applying shorter and faster pulses resulted in higher energy per pulse (energy deposited in the plasma), more production of excited ions (e.g., N_2^+). The rotational temperature of the short and long ns-pulsed plasma jets was found comparable, both at 300 K, indicating that both plasma jets were under highly nonequilibrium conditions. [Song, et al., 2018]

3) Plasma chemistry studies

- Impact of pulsed power parameters (i.e., pulse rising time, pulse duration, and pulse repetition rate) were studied for different ns pulsed plasmas for different applications. 1) *Pulse duration*. Comparison of 5 ns and 164 ns pulsed helium microplasma jets in one atmospheric air showed shorter pulses with faster pulse rising increased the plasma conductivity during the discharge initiation, and enhanced the excited ion productions [Song, et al., 2018]. For the pulse duration of 200 – 2000 ns, the shortest pulse duration corresponds to the highest energy efficiency for producing liquid phase OH_{aq}, whereas the 800-ns pulse width is associated with the highest emission of OH(A-X) or the production excited OH(A) in gas phase. [Song, et al., 2019]
2) *Pulse risetime and repetition frequency*. The use of fast rising voltage pulse in plasma ignition for combustion can reduce the voltage requirement needed to achieve successful ignition, while keeping the same or even enhancing the combustion performance. This was demonstrated with applying transient plasmas driven by 10-ns, 10 kV pulse bursts at 1-10 kHz repetition rates for igniting methane-dry air mixture in a static chamber at atmospheric pressure. Comparison of the plasmas powered by the same duration pulse bursts with different rise times, i.e., t_r = 5 ns and 10 ns, showed faster pulses benefit the combustion ignition with higher peak pressure, shorter

ignition delay and reduced energy needed to initiate combustion. In addition, there was a possible optimal PRF within 6–10 kHz, which was associated with the best combustion performance, i.e., the highest peak pressure and shortest ignition delay. [Alderman, et al., 2021]. More recently, using a surface-discharge spark plug, we demonstrated that the use of multiple short pulses at high PRFs (e.g., 10 kHz) allowed lean combustion, reduced NO_x emission at a relatively low voltages, which is crucial to the successful application of compact and economic high voltage pulse power for plasma ignition.

- Impact of target materials on the plasma formation and the associated chemistry are studied for applications of the plasma in medicine including cancer therapy and gene transfer. The presence of biological materials, especially as part of the electrode circuit, may change the plasma properties and impact on the production of reactive plasma species at the plasma-target interface. Using a needle-to-plate electrode configuration, the production of OH in a 200 ns, 7 kV pulses at 1 kHz, helium plasma jet impinging on water, phosphate-buffered saline (PBS) or pigskin were measured using both optical emission spectroscopy and laser induced fluorescence. The experimental results showed that the use of pigskin slowed down the streamer head propagation, whereas a more pronounced surface ionization wave was developed on the surface when water was used. The highest OH(A-X) emission above the biomaterial surface was observe using the PBS-covered electrode plate comparing to water or pigskin. Spatiotemporally resolved laser induced fluorescence showed that more OH was produced in regions near the needle electrode for both water and PBS and the use of pigskin resulted in the least OH production overall. [Lai, et al. 2022] In addition, the electric field at the plasma-target interface as well as in the biomaterial can vary significantly due to the use of different target, which results in different plasma properties and different biological effects, e.g., field-induced or reactive oxygen species-induced effects, during the plasma biological cell/tissue interactions. [Jiang, et al., 2021]

Archival publications during reporting period:

(The names of the graduate/undergraduate students under supervising are underlined, the names of postdocs under supervising are noted with * during the production of the publication.)

(Journal publications)

1) S. Song, J. L. Lane* and C. Jiang, "Comparison study of spatiotemporally resolved emissions of nanosecond pulsed microplasma jets", IEEE Transactions on Plasma Science, vol. 46, no. 3, pp. 587-593, March 2018, doi: 10.1109/TPS.2018.2795958.
2) S. Song, E. B. Sozer, and C. Jiang, "Effects of pulse width on He plasma jets in contact with water evaluated by OH(A–X) emission and OH_{aq} production," Japanese Journal of Applied Physics, **58**, no. 6, 2019. https://iopscience.iop.org/article/10.7567/1347-4065/ab1e6d
3) C. Jiang, J. A. Miles, J. Hornef, C. Carter, and S. F. Adams, "Electron densities and temperatures of an atmospheric-pressure nanosecond pulsed helium plasma jet in air," Plasma Sources Science and Technology, **28**, 085009, 2019. https://iopscience.iop.org/article/10.1088/1361-6595/ab2182
4) C. Jiang, E. B. Sozer, S. Song, N. Lai, P. T. Vernier, and S. Guo, "Modulation of ROS in nanosecond-pulsed plasma-activated media for dosage-dependent cancer cell inactivation *in vitro*," Physics of Plasmas, **27**(11), 2020, https://doi.org/10.1063/5.0020435, DOI: 10.1063/5.0020435. (This paper was selected as "Editor's Pick" with Featured, Scilight.)
5) D. Alderman, C. Tremble, D. Singleton, J. Sanders, and C. Jiang, "Effects of pulse rise time and repetition frequency on nanosecond pulsed plasma ignition for combustion," Plasma Research Express, **3**, 014001, (2021). https://iopscience.iop.org/article/10.1088/2516-1067/ab880a/meta.
6) C. Jiang, E. A. Oshin, S. Guo, M. Scott, X. Li, C. Mangiamele, and R. Heller, "Synergistic effects of an atmospheric pressure plasma jet and pulsed electric field on cells and skin," IEEE Transactions on Plasma Science, **49**(11), pp. 3317-3324, Nov. 2021, doi: 10.1109/TPS.2021.3113260.
7) M. Z. Rahman, E. A. Oshin and C. Jiang, "Initial Investigation of the Streamer to Spark Transition in a Hollow-Needle-to-Plate Configuration," IEEE Transactions on Plasma Science, vol. 50, no. 6, pp. 1942-1947, June 2022, doi: 10.1109/TPS.2022.3170346.
8) M. Lai*, S. Song, E. Oshin, L. Potter, N. Lai, and C. Jiang, "The production of OH in a nanosecond pulsed helium plasma jet impinging on water, saline, or pigskin," Journal of Applied Physics, **131**(17), May, 2022, https://doi.org/10.1063/5.0083568
9) A. Iqbal[+], D. Wozniak[+], M. Z. Rahman, S. Banerjee, J. Verboncoeur, P. Zhang, and C. Jiang, "Influence of discharge polarity on streamer breakdown criterion of ambient air in a non-uniform electric field," Journal of Physics D: Applied Physics, vol. 56, no. 3, p. 035204, 2022/12/12 2022, doi: 10.1088/1361-6463/aca2b4. ([+] Equal contributors)

(Conference publications)

10) D. Alderman, C. Tremble, C. Jiang, J. M. Sanders and D. Singleton, "Initial Evaluation of Pulse Risetime on Transient Plasma Ignition for Combustion," *2018 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2018, pp. 279-282, doi: 10.1109/IPMHVC.2018.8936811.

11) D. Alderman, C. Tremble, S. Song, J.M. Sanders, D. Singleton, and C. Jiang, "Plasma kinetics study of a repetitive 10-ns pulsed plasma ignition for combustion," *2019 IEEE Pulsed Power & Plasma Science (PPPS)*, 2019, pp. 1-3, doi: 10.1109/PPPS34859.2019.9009621.

12) X. Li, S. Song, D. Alderman, M. A. Malik, R. Heller, and C. Jiang, "Evaluation of electric field and charge on bio-substrates induced by nanosecond pulsed helium plasma jet," *2019 IEEE Pulsed Power & Plasma Science (PPPS)*, 2019, pp. 1-4, doi: 10.1109/PPPS34859.2019.9009897.

Students graduated during the performance period:
S. Song, Doctor of Philosophy (PhD), May 2020
Dissertation: "Diagnostic studies of non-thermal atmospheric pressure nanosecond plasma jets," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/c38j-st04, https://digitalcommons.odu.edu/ece_etds/217

D. Alderman, Master of Science (MS), Dec. 2019
Thesis: "Pulse power effects on transient plasma ignition for combustion," Electrical & Computer Engineering, Old Dominion University, DOI: 10.25777/skjc-8882, https://digitalcommons.odu.edu/ece_etds/209

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