I. ACCOMPLISHMENTS:

1. The major goals of the project.

This major goal of the project is the creation of a scalable (volume and pressure) non-thermal plasma by controlling the space charge distribution to achieve a controllable large volume/surface dense plasma under ambient conditions. The specific objective of the proposed research to achieve the goal are**,**

1. Investigate by modeling and simulation the effect on space charge distribution in an electrical discharge due to a temporally and spatially varying electric field.
2. Create a large-volume uniform plasma with a spatially rotating electric field. This requires the design and implementation of a special power supply and electrode system.
3. Use plasma diagnostics to perform temporally and spatially resolved optical measurements to demonstrate uniformity and production of plasma chemical species and to measure the electron density to demonstrate the generation of dense plasma.

2. Accomplished under these goals.

Two major activities were carried out during performance period.

1. Multiphysics simulations of space charge transport and space charge electric field.
2. Design and implementation of a multi-phase power source and multi-electrode discharge chamber.

Previous theoretical work showed that it is possible to generate a spatially rotating electric field by exciting a set of electrodes with phase staggered sinusoidal waveforms. It was also shown that such a field is capable of producing a uniform plasma. We report the experimental proof of concept with an eight-electrode system in argon gas. Power measurements and spectral investigation show that the concept can be used to generate a uniform stable plasma. This plasma source has the potential of opening new applications of nonthermal plasma including combustion of carbon-free fuel. The current limitation of the proposed method in scaling to higher volume and pressure is the need for multiple high voltage amplifiers.

The lack of large volume atmospheric pressure glow-like discharges is due to the fundamental limitation of dimensional scaling which leads to instabilities due to local dense space charge generated at atmospheric pressure in large gaps. Since the current density in most uniform glow-like discharge scales as the square of the pressure, an increase in pressure for a constant discharge current leads to narrowing of the discharge and high-power densities. Therefore, as the pressure is increased the cross section of the discharge is reduced for a constant discharge current, creating a narrow discharge volume with high power densities which leads to instabilities [1, 2]. Below a pressure times gap distance (pd) of 200 Torr cm, the discharge mechanism is a glow like Townsend discharge corresponding to gaps below 3 mm at atmospheric pressure [3]. At larger gap distances the streamer mechanism of strong space charge dominated processes take over, leading to arc formation [3-6].

At pressures near atmosphere, the Dielectric Barrier Discharge (DBD) and pulsed nano second discharges have found applications. These types of discharges have a quenching mechanism to prevent the streamer like discharge turning into filamentary arc-like discharge. Some of these sources are finding application in the emerging field of plasma medicine but the requirements are very different for an industrial plasma [7]. Often to overcome the size limitation multiple sources are put together in various configuration to process larger surfaces. Most of the improvements proposed have been incremental.

For a given operating gas composition, the characteristics of a plasma can be primarily controlled by the electrode geometry and the power source, which can be DC, AC, or pulsed. Traditional methods of exciting electrodes are spatially fixed and temporarily varying. As a result, the space charge at atmospheric pressure tends to be spatially confined resulting in non-uniformity and localized electric field enhancement, which eventually leads to instability as the discharge gap distance is increased [8-10].

It has been theoretically shown that a spatially rotating electric field has the potential to control the spatial distribution of space charge which will lead to a large volume discharge near atmospheric pressure [11]. This is done by creating a rotating AC electric field. in a cylindrical geometry with a set of conformal azimuthal electrodes. This configuration does not require an inner concentric electrode to create an electric field. The excitation of the electrodes at a radius R is of the form [11]

$$V_R(\theta, t) = V_o \cos(\omega t + n\theta), \ 0 < \theta \leq 2\pi. \quad (1)$$

where V_o is the peak voltage of the sinusoid of frequency ω, and θ are the anticlockwise angle starting at the positive x-axis, and 'n' is the number of cycles of the excitation phase. An analytical solution of Equation 1 on a disk of radius R is given by [11],

$$V(r, \theta) = V_o \left(\frac{r}{R}\right)^n \cos(\omega t + n\theta). \quad (2)$$

The gradient of this electrostatic potential gives the electric field E,

$$E(r, \theta) = n \frac{V_o}{R} \left(\frac{r}{R}\right)^{n-1} [(-\cos(\omega t + n\theta)\, \overrightarrow{e_r} + \sin(\omega t + n\theta)\, \overrightarrow{e_\theta}]. \quad (3)$$

The spatial distribution of the electric field depends very strongly on 'n'. To illustrate the controllability of the electric field, the normalized electric field along the radial direction is shown in Figure 1. The magnitude is independent of the azimuthal angle, θ, but the radial and tangential components are functions of θ. For n=1 (dipole field) the magnitude of the field is constant throughout the volume of the cylinder and as 'n' increases the electric field shifts towards the outer surface. The magnitude of the field is linear in the radial direction for n=2 (quadrupole) and increasing value of 'n' produces n-times the uniform dipole field at the boundary. This suggests a unique method of initiating a discharge with high 'n' and subsequently reducing 'n' to the uniform dipole field to obtain a uniform plasma. The value of "n" can be changed in real time using digitally synthesized waveforms, and the

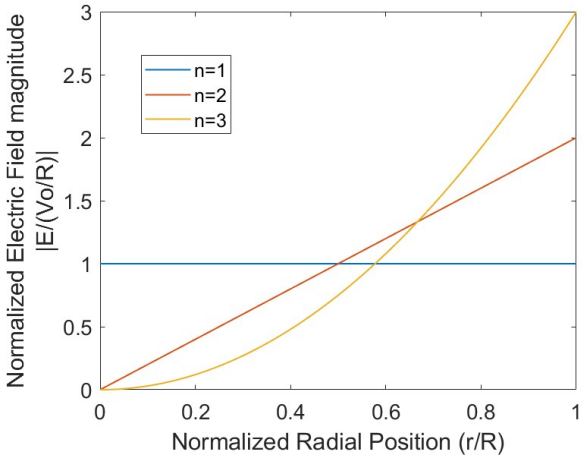

Figure 1. The normalized electric filed showing the spatial distribution along the radial direction for different 'n'.

spatial field profile can be modified. The tangential component of the electric field keeps the ions within the discharge volume which can also be manipulated by changing the frequency of waveform as shown by the path of an argon ion in Figure 2 for two different frequencies.

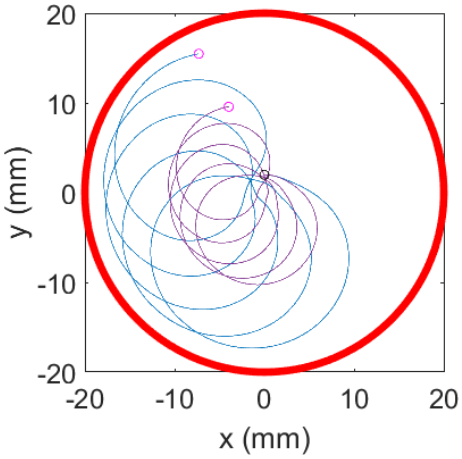

Figure 2: Particle trajectory of an argon ion for two different frequencies (blue 35,000Hz and purple is 70,000 Hz).

This report shows the experimental results to demonstrate the proof of concept of generating a plasma using such a rotating electric field created by the application of phase staggered sinusoidal voltages. This was done for an eight-electrode system in argon gas. The signals were synthesized digitally using an Arduino uno and converted to analog sinusoidal waveforms with analog to digital converters [12]. The waveform sequence of the eight phase shifted signals is shown in Figure 3. These signals were applied to eight high voltage operational amplifiers capable of producing sinewaves with peak amplitude of 1350 V. The type of experiments we could perform were limited by the voltage and bandwidth of the voltage amplifiers. We used argon below atmospheric pressure for this study due to its relatively low static breakdown voltage.

The discharge chamber has a cylindrical geometry, and eight discharge electrodes are positioned at 0, 45, 90, 135, 180, 225, 270, and 315 degrees around the circumference of the chamber. The electrode spacing is at a 4 mm distance from the electrode opposite to it. Due to the limitation of the voltage source, to get a discharge, pin electrodes were used instead of conformal plane electrodes. Shown in Fig.4 is the discharge in argon gas at 100 Torr pressure. This image was taken with a camera with large exposure time (about a fraction of a second). So, the image is time integrated, and any spatial features are smoothed out. The image does suggest that the combined effect of all electrodes results in a dense plasma in the inter electrode gap.

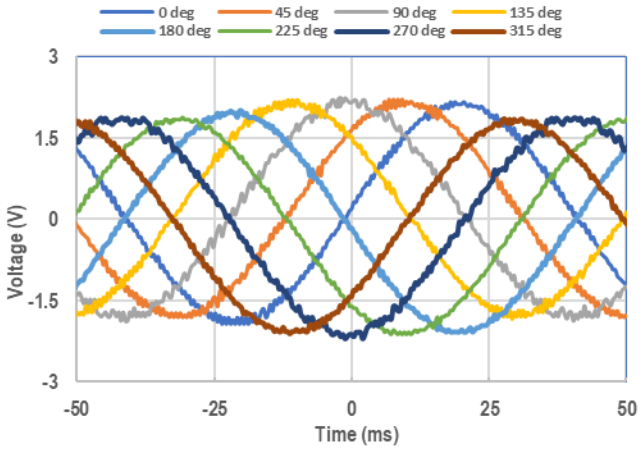

Figure 3: The voltage waveforms for the eight electrodes

The expected electric field magnitude obtained from Equation 1, for Vo= 1350 V and a radius of 0.004 m is 34 kV/m and at a pressure of 50 Torr gives a reduced electric field E/N of 20 Td. Using the BOLSIG+ Boltzmann solver, the ionization frequency in argon at the range of reduced electric field of interest is given by [13],

$$\upsilon_i = 1.3 \times 10^{-40} e^{(.0077\mathcal{E}_n{}^3 - 0.39\mathcal{E}_n{}^2 + 7.5\mathcal{E}_n)}\ m^3/s \qquad (4)$$

where $\mathcal{E}_n$ is the reduced electric field in Td. The ionization frequency shows an exponential increase with $\mathcal{E}_n$, so small changes in the electric field can change the ionization rate significantly. In this discharge, as the applied voltage (V_A) is increased, the discharge current increases. However, the discharge voltage (V_D) will remain nearly constant and change by small amounts. Therefore, for a ballast resistor, R (47 kΩ), connected in series with the discharge, the expected discharge power, $P = V_D(V_A - V_D)/R$. This is consistent with the experimental result shown in Figure 5 which shows a linear dependence of the power with the applied voltage.

Figure 4 – Image of a discharge in argon at a pressure of 100 Torr and applied voltage of .1350 V at 7.6 kHz.

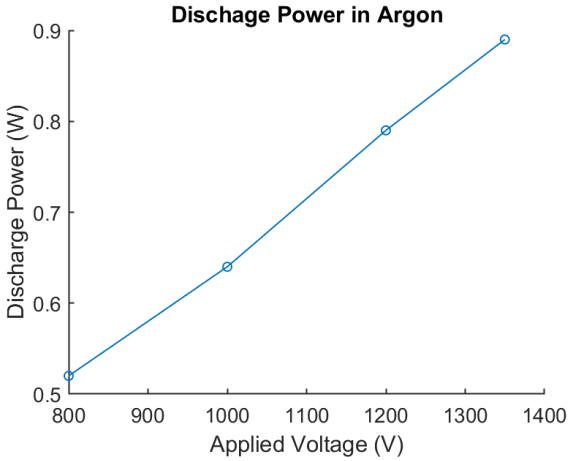

Figure 5: Voltage versus Power of one phase of the discharge system. Pressure: 100Torr; Frequency: 7.5 kHz

The spectrum in the visible region of the argon plasma is shown in Figure 6. The peaks are consistent with the known spectral lines of argon I [14]. Figure7 shows the intensity of the spectral peaks of the argon plasma as a function of applied voltage. The plot shows that as the applied voltage to the gap increases, the intensity of each species of the plasma also increases almost linearly. The relative intensities of the lines with increasing applied voltage are fairly constant. The change in the applied voltage does not impact the electron energy distribution but increases the electron density due

to increase in current. This would suggest that the voltage across the discharge does not change significantly with increase in applied voltage.

In conclusion, an experimental proof of concept was demonstrated based on the theoretical results reported earlier [11]. The electrical and optical measurements demonstrated a stable discharge and a steady plasma in the pressure range of 50-200 Torr. With increase in applied voltage, the discharge voltage stays nearly constant while there is an increase in the discharge current. Due to the limitation of amplifiers needed to power each phase, the discharge was operated below atmospheric

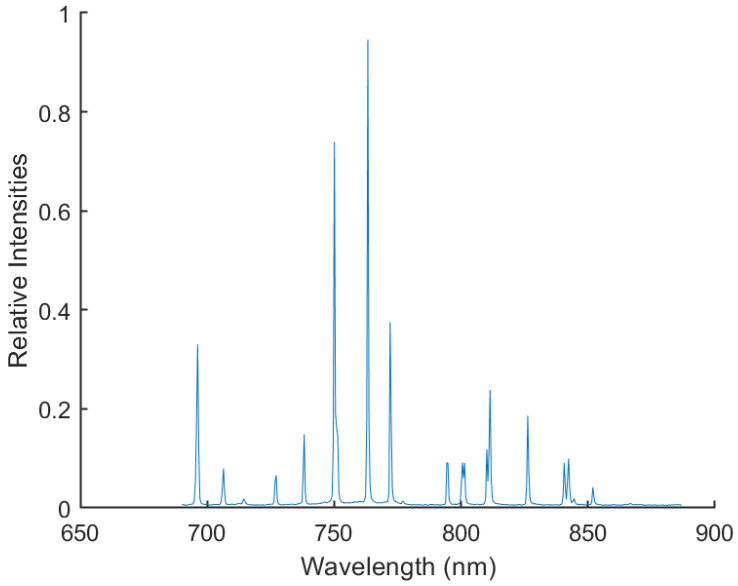

Figure 6: Argon spectra in the visible range for at a pressure of 100 Torr and applied voltage of .1350 V

pressure. Work is underway to build MOSFET power amplifiers to extend the range of pressure to atmospheric pressures. An application of considerable interest is the plasma-assisted combustion of ammonia and hydrogen. This particular plasma source conforms with the geometry of combustors unlike more conventional nano-second pulsed discharges or the dielectric barrier discharge.

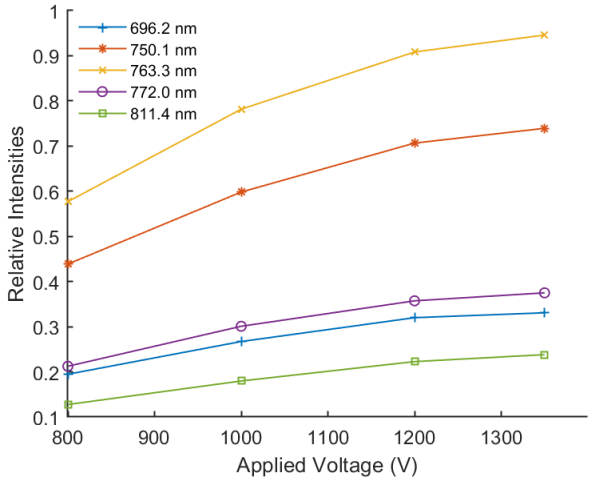

Figure 7. Relative intensity of the spectral peaks of the Argon plasma as a function of discharge voltage at a pressure of 100 Torr and applied voltage of .1350 V.

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3. Opportunities for training and professional development

Two conference presentation: ICOPS and GEC 2020

Department seminar for graduate students

Presentation to researchers at WPAFB

4. Disseminated to communities of interest.

The PI visited in January 2020 the laboratory of Dr. Steven Adams at Electrical Systems Branch, AFRL/RQQE, Wright Patterson Air Force Base and presented the results of the project. This group has expertise in electron densities measurements and PI plans to spend a part of summer 2020 to use their facility.

II. PRODUCTS:

1. Publications

i. Journal publications. (Acknowledged DoE support)

- S K Dhali , Transient behavior of drift and ionization in atmospheric nitrogen discharge. Plasma Sources Sci. Technol. Vol 31, 025014 (2022) https://doi.org/10.1088/1361-6595/ac43c6.
- Y. Bezawada and S. K. Dhali, "8-Plate Multi-Resonant Coupling Using a Class-E^2 Power Converter for Misalignments in Capacitive Wireless Power Transfer," Electronics, 11(4) 635 (2022), https://doi.org/10.3390/electronics11040635
- Dhali S. K. "Generation of excited species in a streamer discharge," AIP Advances **11**, 015247 (2021); https://doi.org/10.1063/5.0033110..
- Dhali S. K. "Generation of Large Volume Plasma using spatially and temporally rotating electric fields," AIP Advances **10**, 035002, https://doi.org/10.1063/1.5143923. (2020).

2. Other publications, conference papers and presentations.

- S. K. Dhali, and P. Mosley, Controlled combustion by spatiotemporal control of plasma kinetics, IEEE ICOPS, Santa Fe, NM, June 2023.
- S. K. Dhali, Dependence of macro-kinetic paraments on the local electric field and mean energy in Nitrogen. 74th Annual Gaseous Electronics Conference, Oct., 2021, Huntsville Alabama, Abstract: DT22.00002, 2021.

- Dhali S. K.(2020) SCALING OF NON-THERMAL PLASMA BY USING A TRAVELING ELECTRIC FIELD, IEEE International Conference on Plasma Science, December 2020
- Dhali S. K. and Boothpur N., (2020) "Generation of active species in a streamer discharge," Abstract submitted to the Gaseous Electronics Conference, October 2020.

3. Intellectual Property

Provisional Invention Disclosure E20198QC16084950, August 2019, A Method and Apparatus for Producing Uniform Large Volume Dense Atmospheric Pressure Non-thermal Plasma

III. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS:

1. Participants

- **Name:** Shirshak K. Dhali
  - **Project Role:** Principle Investigator
  - **Nearest person month worked:** 5
  - **Contribution to Project:** Modeling and Simulation; Supervision of graduate and undergraduate students.

- **Name:** Nikhil Boothpur
  - **Project Role:** Graduate Student
  - **Nearest person month worked:** 9
  - **Contribution to Project:** Experimental investigation: Power supply, chamber.
  - **Funding Support:** Supported by the Electrical and Computer Engineering Department at Old Dominion University.
- Name: Franklin Price Mosely
  - **Project Role:** Graduate Student
  - **Nearest person month worked:** 12
  - **Contribution to Project:** Experimental investigation: Power supply, chamber.
  - **Funding Support:** Supported by employer (Newport News Shibuilding)

2. Other Collaborators

Have other collaborators or contacts been involved?

None

V. IMPACT:

1. The impact on the development of the principal discipline(s) of the project

There was a concerted effort to advance the understanding of non-equilibrium air plasma at atmospheric pressure. However the progress in this area has only been incremental. Achieving a large-volume glow-like discharge at atmospheric pressure has been challenging. Any attempt to scale pressure and volume of nonthermal plasma usually leads to instabilities due to formation of localized space charge. The control of the plasma is limited by the discharge geometry, type of excitation, and gas composition. This research systematically (modeling and experimentation) investigates the control of the space charge in a discharge with a spatially and temporally varying electric field. It is shown that a phase-staggered sinusoidal excitation to a set of conformal azimuthal electrodes in a cylindrical geometry leads to a traveling electric field. Simulations show that in space charge dominated transport, the charged species are dispersed both in the radial and azimuthal directions. This will lead to better control of the space charge and stable discharges near atmospheric pressures.

2. The impact on other disciplines

Non-thermal plasma at atmospheric pressure is a rich source of reactive species. It is an unique source for plasma chemistry under ambient conditions. This research will lead to development of devices which can used for manufacturing, pollution control and

disinfection of surfaces, fabric and breathing air to minimize the infection due pandemic such as COVID-19**.**

3. **The impact on the development of human resources**

   Training of a graduate student in plasma science and engineering. Student senior design projects in electronics and testing.

4. **The impact on physical, institutional, and information resources that form infrastructure**

   The funding has resulted in a plasma laboratory with power sources and diagnostics. This will be used by both undergraduate and graduate students past the end date of this project.

5. **The impact on technology transfer**

   An invention disclosure has been filed. The project results will aid in the design and implementation of an ambient non-thermal device which is efficient and cost effective for use in manufacturing of composites and pollution abetment.

6. **The impact on society beyond science and technology**

   This research will lead to technology which can be used to sterilize personal protective equipment (PPE) and disinfect surfaces and fabrics. This is also suitable for breathing air cleaning for ventilators and enclosed spaces.

7. **Foreign Spending: Dollar amount of the award's budget is being spent in foreign country(ies)**
   NA

VI. DEMOGRAPHIC INFORMATION: Mandatory (providing email addresses)

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Franklin Price Mosely, Graduate Student, fmose001@odu.edu