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Simulation Tool for Dielectric Barrier Discharge Plasma Actuators at Atmospheric and Sub-Atmospheric Pressures

SBIR Phase I Final Report

Alexandre Likhanskii
Tech-X Corporation, Boulder, Colorado

February 2012

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Prepared under Contract NNX10CE78P

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Space Administration

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Project Summary

SBIR Phase I

Period of Performance January 29, 2010–July 29, 2010

Firm: Tech-X Corporation
Contract Number: NNX10CE78P
Project Title: Simulation Tool for Dielectric Barrier Discharge Plasma Actuators at Atmospheric and Sub-Atmospheric Pressures
Identification and Significance of Innovation:
Identification of Innovation:

- ✓ Simulation tool for dielectric barrier discharge (DBD) plasma actuator
- ✓ Analyzes and predicts DBD operation at wide range of ambient gas pressures

Significance of Innovation:

- ✓ Traditional DBD codes are limited to low-speed applications and have weak prediction capabilities
- ✓ Proposed tool allows DBD analysis/prediction for subsonic/hypersonic applications

Technical Objectives and Work Plan:
Objectives:

- Demonstrate VORPAL's capability of modeling DBD plasma actuator at low pressures using kinetic plasma modeling approach;
- Demonstrate VORPAL's capability of modeling DBD plasma actuator at moderate to atmospheric pressures using hydrodynamic plasma modeling approach;
- Validate developed DBD simulation tool by comparison between simulation results and experimental data.

Technical Accomplishments: (Limit 200 words or 2,000 characters whichever is less)

- Developed prototype DBD simulation tool using kinetic approach and demonstrated simulations of the DBD plasma actuator, driven by nanosecond pulses, at reduced and atmospheric pressures;
- Developed prototype DBD simulation tool using fluid approach and demonstrated simulations of the DBD plasma actuator, driven by nanosecond pulses, at atmospheric pressures;
- Demonstrated hybrid capabilities of the prototype DBD simulation tool;
- Integrated state-of-the-art numerical concepts, such as variable time step, parallel computing and variable weight particles into DBD simulation tool for increasing computational speed;
- Performed complex experimental study of the DBD, driven by nanosecond pulses;
- Qualitatively validated numerical results against experimental data.

NASA Application(s): The primary NASA applications of the proposed DBD simulation tool are active flow control concepts for both subsonic and hypersonic flights. Predictable active flow separation control, achieved using the proposed tool, will benefit many NASA Projects, such as Subsonic Fixed Wing Project, Subsonic Rotary Wing Project and Hypersonic Project. In addition to the flow separation application, DBD simulation tool can be used for a number of NASA problems, associated with gas discharges at different pressures. For example, DBD simulation tool can be used for the description plasma-assisted combustion for the reduction of carbon emissions.

Non-NASA Commercial Application(s): Proposed tool will be beneficial for subsonic/hypersonic programs which involve active flow separation control. These programs include, but are not limited to, flow separation control at commercial airplanes during take-off or landing, increase in lift for tiltrotor aircrafts, improvement of engine performance, active flow control at hypersonic vehicles. Besides the primary application for a description of DBD operation, DBD simulation tool can be used for a wide range of plasma aerodynamics applications, such as plasma-assisted combustion, flow control using different types of discharges, reduction of carbon emission, optimization of air vehicle operation, MHD and EHD application.

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Simulation Tool for Dielectric Barrier Discharge Plasma Actuators at Atmospheric and Sub-Atmospheric Pressures

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1. Introduction

Traditional approaches for active flow separation control using dielectric barrier discharge (DBD) plasma actuators are limited to relatively low-speed flows and atmospheric conditions. However, NASA missions target a number of applications, such as active flow control at turbine blades, fixed wings, rotary wings and hypersonic vehicles, which require a satisfactory performance of the DBD plasma actuators at wide range of conditions, including rarified flows and combustion mixtures.

A simulation tool that analyzes and predicts the DBD operation at particular conditions would benefit scientists involved in DBD research, allowing them optimizing DBD operation via simulations and reducing amount of work and cost of experimental equipment.

We proposed to develop a DBD plasma actuator simulation tool for a wide range of ambient gas pressures. At the completion of the Phase II of this work, scientists and engineers will be able to analyze and predict DBD operation at different flight regimes – from subsonic to hypersonic. The proposed tool will be validated by comparison with the experimental and numerical data on the DBD investigations.

In order to achieve maximum reliability and best performance, the proposed tool will utilize state-of-the-art numerical and theoretical approaches to the description of the DBD plasma actuator. The choice of these approaches will be dictated by the DBD projected applications.

Subsonic applications, such as active flow separation control at turbine blades or at airplane wings during take-off or landing, will require a comprehensive model of the DBD plasma actuator at atmospheric conditions. For these kinds of applications, DBD simulation tool will treat plasma as a multi-component fluid, consisting of neutral molecules, electrons and different types of positive and negative ions. The motion of the charged particles will be defined by the distribution of local electric field. The feasibility of this approach has been shown in numerous research efforts on discharge simulation at atmospheric conditions.

Hypersonic applications, such as flow separation control at scramjet vehicles, will require the ability to describe DBD at substantially reduced pressures. For this purposes, we will use kinetic approach for the discharge treatment. By utilizing kinetic approach, we will be able to develop the unique simulation tool for the DBD operation at sub-atmospheric pressures.

In order to achieve efficient performance of the proposed simulation tool at experimental scales, we will use modern numerical and theoretical concepts, including multiprocessor computing, non-uniform and adaptive meshes, and a concept of self-adjusting time step. Our previous experience with DBD modeling demonstrated up to two orders of magnitude increase in computational speed by using parallel simulations. Non-uniform and adaptive meshes will lead to another one/two orders of magnitude increase in computational speed, compared to traditionally-used uniform meshes. The concept of self-adjusting time step reduces the computational time between the breakdowns (most of the time) by three orders of magnitude. By utilizing these concepts, we anticipate high feasibility of the DBD simulation tool for a wide range of applications.

As an output of the DBD simulation tool, scientists will get the temporal and spatial distributions of the force, acting on the ambient gas and of rate of thermal energy deposition. By using these output data as an input file for 2D and 3D Navier-Stokes solvers, such as NASA developed code WIND-US or commercial code FLUENT, scientists will be able to simulate the DBD operation for different applications.

The validity of the proposed innovation will be confirmed by the comparing simulation results with available numerical and experimental data.

2. Technical Objectives

During Phase I project, we focused on the feasibility of the innovation. The objectives for the Phase I were:

Objective 1: *Demonstrate VORPAL's capability of modeling DBD plasma actuator at low using kinetic plasma modeling approach.*

Objective 2: *Demonstrate VORPAL's capability of modeling DBD plasma actuator at moderate to atmospheric pressures using hydrodynamic plasma modeling approach.*

Objective 3: *Validate developed DBD simulation tool by comparison between simulation results and experimental data.*

3. Technical Activities

3.1 Task 1: Develop prototype DBD simulation tool for low pressures

3.1.1 Incorporating dielectrics into VORPAL's Poisson Solver.

Before the start of the project, VORPAL's Poisson Solver included Dirichlet (constant potential), Neumann (constant electric field) and periodic boundary conditions. Dirichlet boundary conditions are to be applied at both grounded and exposed electrode, and Neumann boundary conditions are to be applied on the outer boundaries of the computational domain. In the case of an array of DBDs, periodic boundary conditions can be applied on left and right sides of the conventional simulation domain for DBD plasma actuators. In this subtask we successfully implemented boundary conditions for dielectrics. Now, user can specify the relative dielectric permittivity in the entire simulation domain. This implementation is beneficial not only for conventional DBD configuration, but also for recently proposed multilayer structures. Once the dielectrics were incorporated into the VORPAL's Poisson Solver, we were able to compute electric field distribution in the DBD configuration based on the geometry, applied voltages, dielectric permittivity and charged particle distribution.

3.1.2 Setup VORPAL simulation with air-like mixture, consisting of molecular nitrogen and oxygen as a neutral background gas.

3.1.2.1 Setup VORPAL simulation with nitrogen

The goal of this technical activity was to demonstrate the ability of PIC approach to resolve plasma phenomena observed in DBD simulations using fluid codes. It includes but not limited to sheath formation and streamer propagation. For the preliminary simulations, we limited the gas to nitrogen and included only inelastic collisions (ionization) in the model. The simulations started with seed background of positive ions and electrons. We have also included a constant rate of electron and ion production in the simulation domain in order to account for photoionization, which is not currently included into the model, but is crucial for resolving streamer formation. The solver for particle motion was coupled to the Poisson Solver.

Benchmark Results

In order to reproduce DBD physics and address the objectives of the project, we ran three different cases:

- DBD driven by positive nanosecond pulses at atmospheric conditions in 2D
- DBD driven by positive nanosecond pulses at reduced pressures (0.1 atm) in 2D
- DBD driven by positive nanosecond pulses at atmospheric conditions in 3D

We applied 3 kV 4 ns positive pulses for atmospheric conditions and 0.7 kV 4 ns positive pulses for reduced pressures.

Figure 1 shows the formation and propagation of the streamer above the dielectric surface at atmospheric pressure. In order to verify that the observed discharge is in streamer regime, we plotted electric potential distribution. The electric potential inside the streamer is the close to the one of the exposed electrode. This phenomenon is typical for streamer propagation and is also observed in fluid codes.

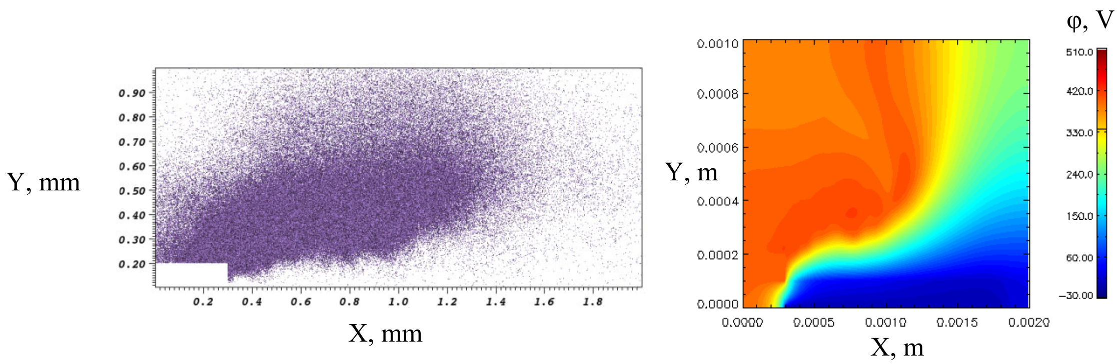


Figure 1. Distribution of positive ions during the streamer discharge (left) and potential propagation during the streamer discharge (right).

In the case of the reduced pressures, we observe much longer plasma formation (Figure 2) – cm scales compared to mm scales for atmospheric pressure.

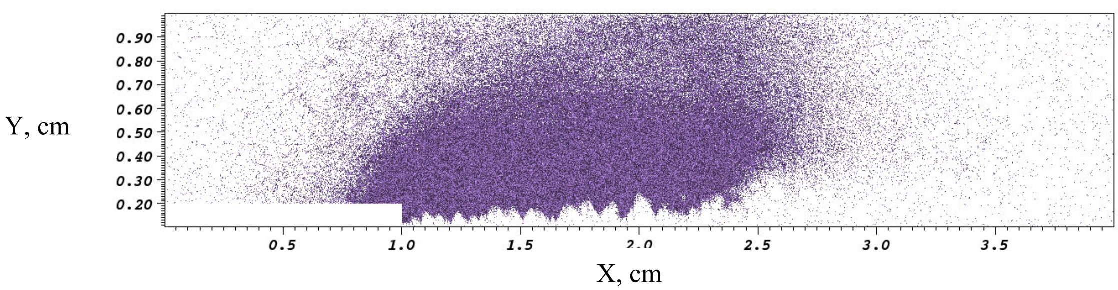


Figure 2. Distribution of positive ions during the breakdown at reduced pressure.

We also performed first 3D simulations of the DBD discharge using PIC method (Figure 3). We observed streamer propagation both in terms of generation new particles and associated streamer phenomena, such as transfer of maximum electric field region to the tip of the streamer.
One the open problem in DBD research is the description of an effect of 3D structures (filament formation) in the DBD operation. These structures were not resolved due to the absence of 3D DBD simulations. Figure 4 demonstrates the distinct structure in the z-direction (across the filaments) of the z-component of electric field. The ability to resolve 3D structures of the DBD will be beneficial to the community and will be able to provide insight on physics of the structures formation as well as quantify this structure.

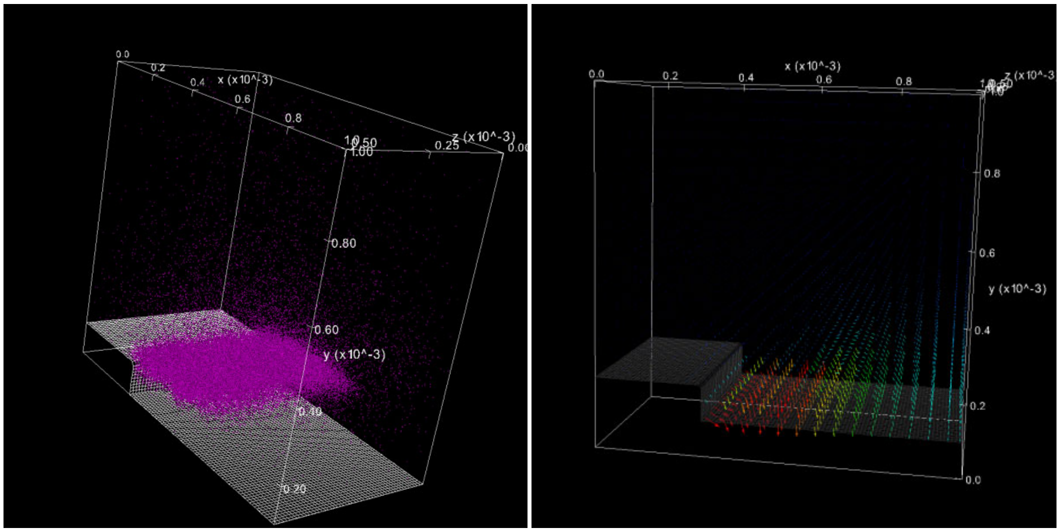


Figure 3. 3D distribution of the positive ions (left) and electric field (right) in the streamer discharge. Domain size is 1 mmX1 mmX0.5 mm.

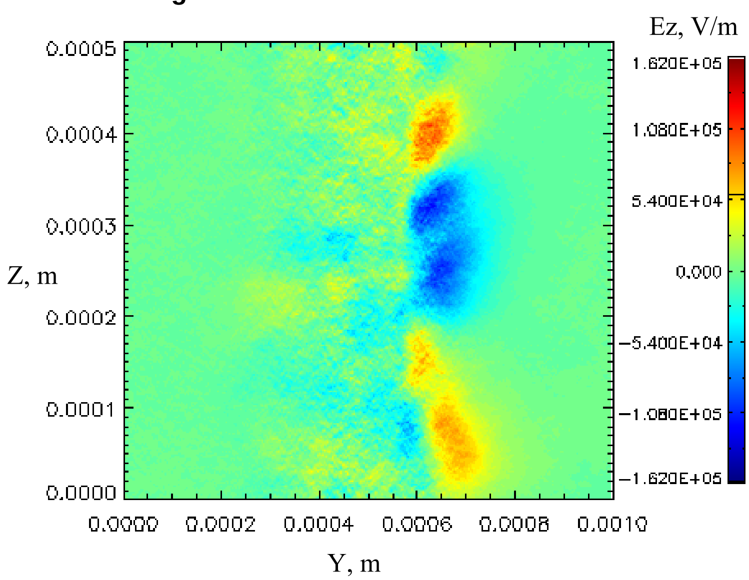


Figure 4. Distribution of z-component of electric field in the streamer discharge (top view on the DBD).

Note that running these demonstration simulations for code testing is also relevant to Task 4, resolution of anode breakdown stage for DBD operation.

3.1.2.2 Setup VORPAL simulation in air-like mixture

In this subtask we set up simulations in air-like mixture and demonstrated the applicability of variable weight particle concept for DBD simulations using PIC approach.

Air-like mixture.

We considered air as a mixture of molecular nitrogen and oxygen. Three major types of collisions were incorporated in VORPAL – ionization, excitation and elastic collisions. In the event of ionization, electron collision with neutral background gas led to generation of electron-ion pair. In the event of excitation or elastic collision, electron lost a portion of its kinetic energy.

Variable weight particles

First of all, let us briefly remind the physical concept behind PIC simulations. Ideal PIC simulation would consider the motion of each separate charged particle. This particle experiences collisions and gains energy in the electric field. If we consider sample plasma simulation, where the grid size is chosen in order to resolve typical plasma scales, we will observe, that each simulation cell contains lots of almost identical charged species. In order to reduce simulation time, the concept of macroparticles is introduced in PIC. The macroparticle is a collection of identical N charged particles, with the charge, equal to N times the charge of one particle and with the mass equal to N times the mass of one particle. With time evolution, one can observe the dynamics of macroparticles instead of observing dynamics of an ensemble of identical N particles. It leads to N-times increase in computational speed without loss of any physical phenomena. This concept works well for the quasi-steady state problems, when the “density” (number of real particles per macroparticle) of macroparticles can be chosen in advance.

However, the above described approach fails for the unsteady gas discharge problem. Gas discharge starts with relatively small density of charged particles. During the avalanche ionization stage, the density of charged particles increases several orders of magnitude. So, on one hand, one should choose relatively low “density” of macroparticles for the initial stage of the discharge in order to get correct physical representation. On the other hand, one does not need those low “density” macroparticles when the plasma is generated, because it would lead to significant slowdown of the simulations.

In order to tackle this problem, we used the concept of variable-weight particles. In this concept, macroparticle has two parameters – “nominal density” and “weight”. The “nominal density” of macroparticle is defined the similar way the “density” was defined before, i.e. the minimum (initially chosen) number of real particles in macroparticle. The “weight” of macroparticle defines the actual number of real particles in macroparticle. For example, if the “nominal density” of macroparticle is equal to 10, and the weight of macroparticle is equal to 5, there will be 5*10=50 real particles in macroparticle.

Now, let us consider the application of this concept to the DBD problem. Initially, when there is almost no plasma, we assign "nominal density" of macroparticles to be 10^5 particles per meter for 2D simulations. All initially generated macroparticles contain 10^5 real charged particles (electrons or ions) per meter distance. Once a discharge development starts, we end up with regions with 100-1000 macroparticles in one cell. These macroparticles behave similar way, but the solution of equation of motion for each macroparticle needs computational resources. So, we implemented the sorting algorithm in VORPAL to change the weight of the particles in order not to lose computational speed. If the number of particles in one cell exceeds predefined limit (10 in our case), we combine two macroparticles into one with the weight equal to the sum of the weights of initial two. In this case we don't lose any particle properties, but significantly reduce the simulation time (need to solve equation of motion for one particle instead of two, and so on).

Benchmark Results

In order to test the above described concepts, we performed 2D PIC simulation of the DBD in air-like mixture at atmospheric pressure. 3 kV 4 ns Gaussian positive pulse was applied in order to initiate the discharge. Figures 5 show the distribution of positive molecular nitrogen and oxygen ions during the streamer propagation (3 ns after the start of the pulse). Figure 6 shows distribution of electric potential and x-component of electric field at the same moment of time. After the air-like mixture was added to VORPAL capabilities, the discharge characteristic (breakdown electric field, plasma number density) became much closer to one observed experimentally, compared to simulations in nitrogen with only ionization included. Figure 7 shows the evolution of macroparticle weight distribution. Initially, all macroparticles had weight equal to 1 (which is the same to the case with constant weight macroparticles). Once the breakdown starts, and number of macroparticles in the cell exceeds the threshold limit (10 for this particular simulation), macroparticles start to combine, and their weight increases.

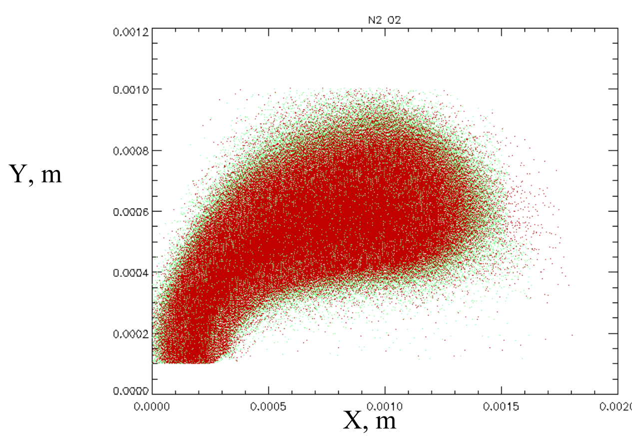


Figure 5. Distribution of N_2^+ (red) and O_2^+ (green) ions during the streamer discharge in air. Positive 3 kV, 4 ns Gaussian pulse, 3 ns after the start of the pulse.

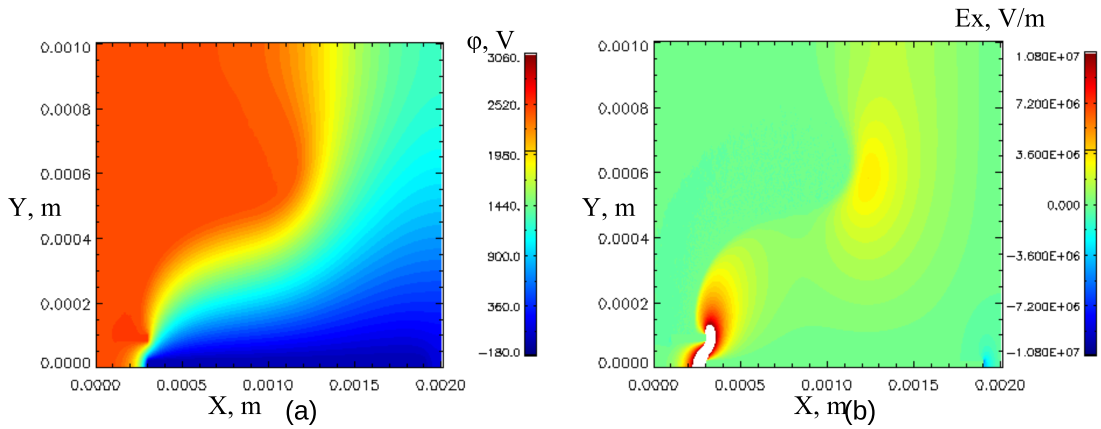
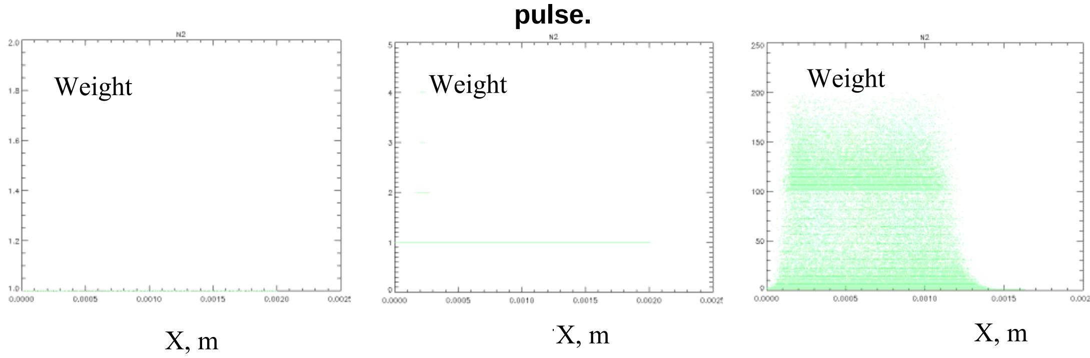


Figure 6. Distribution of electric potential (a) and x-component of electric field (b) during the streamer discharge in air. Positive 3 kV, 4 ns Gaussian pulse, 3 ns after the start of the pulse.



(a) (b) (c)

Figure 7. Concept of variable-weight particles during the gas discharge. Plots show the particles with corresponding weight and x-coordinate during the breakdown. (a) corresponds to 0.3 ns after the start of the pulse – breakdown has not started. (b) corresponds to 1.5 ns after the start of the pulse – initial stage of the breakdown, macroparticles start to combine near the edge of the exposed electrode. (c) – corresponds to 3 ns after the start of the breakdown – many macroparticles are combined to particles with “weights” from 2 to 200.

3.2 Task 2: Develop prototype DBD simulation tool for moderate to atmospheric pressures

3.2.1 Prototype rate equation model in VORPAL.

The goal of this technical activity was to develop a fluid plasma model for DBD simulations based on the drift-diffusion approximation. We started the implementation with the choice of appropriate infrastructure based on the discussions with COTR for adding the hybrid capabilities of the DBD simulation tool (see discussion in Additional Activities section). The chosen infrastructure was Multifields concept in VORPAL. Its benefits are as follows. The Multifield infrastructure allows user defining the field of variables (such as number densities, plasma parameters, etc) and apply finite-difference schemes at each time step. This infrastructure also includes messaging between processors, making it easy to run parallel simulations without extra code development. Finally, this infrastructure has a communication with the PIC part of the VORPAL, making the development of hybrid model possible. The developed fluid code consists of 5 major blocks – Poisson Solver for electric potential distribution (same as for PIC simulations), definition of initial conditions, calculation of all plasma parameters based on local electric field, gas number density and temperature, block for boundary conditions and solver for continuity equations for all charged species. The model is developed both in 2D and 3D.

Benchmark Results

In order to verify the developed model, we ran simulations for DBD, driven by positive nanosecond pulses (3 kV and 4 ns). At the beginning of the pulse, since there is only background (very low density) electrons and ions present in the simulation domain, we observed standard potential distribution between two electrodes (Figure 8 (left)). After the plasma was generated (peak of the pulse), we observed the propagation of the electric potential above the dielectric (Figure 8 (right)). The potential in highly conductive streamer is the same to the potential of the exposed electrode. We observed the same phenomena in PIC simulation. Figure 9 shows the distribution of the positive ions in linear and decibel (20*log) scale. Figure 10 demonstrates the effect of transfer of maximum electric field region to the tip of the head of the streamer.

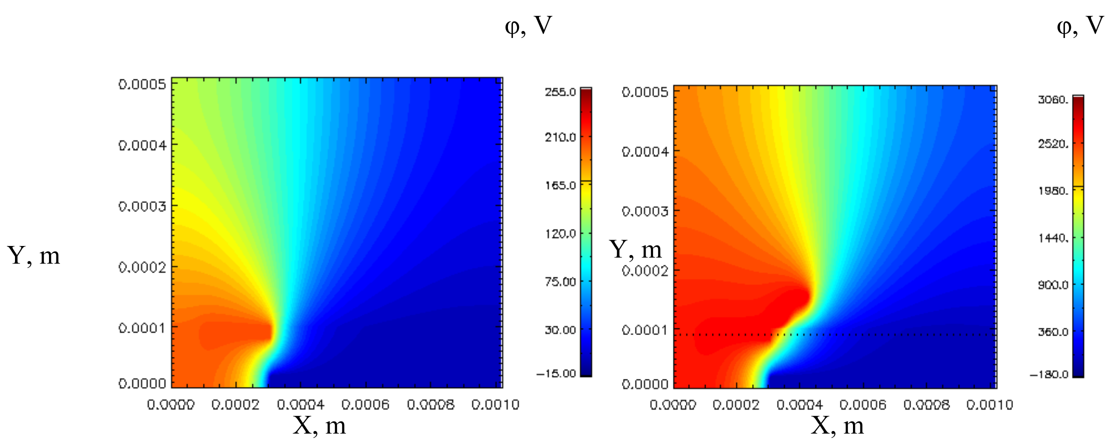


Figure 8. Electric potential distribution at the beginning of the pulse (no plasma) and at the peak of the pulse (streamer is generated).

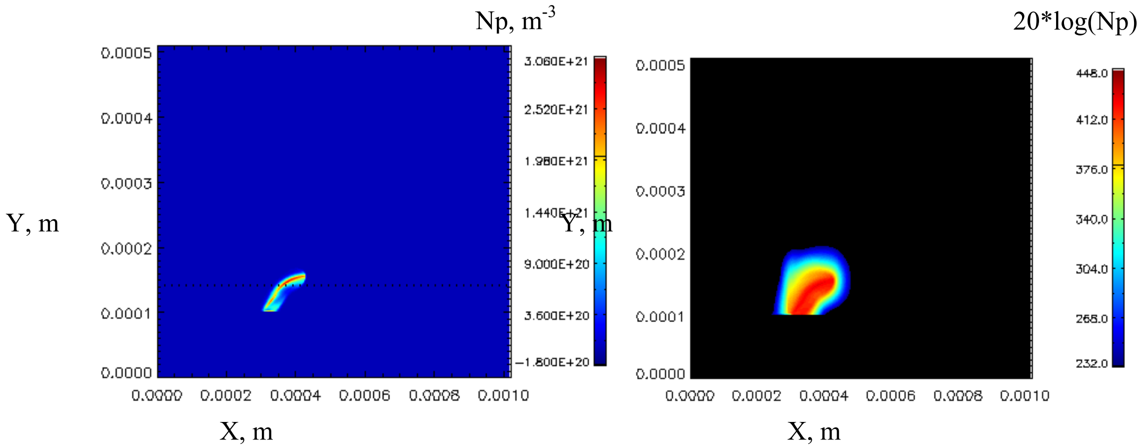


Figure 9. Distribution of positive ions in linear scale (left) and decibel scale (right).

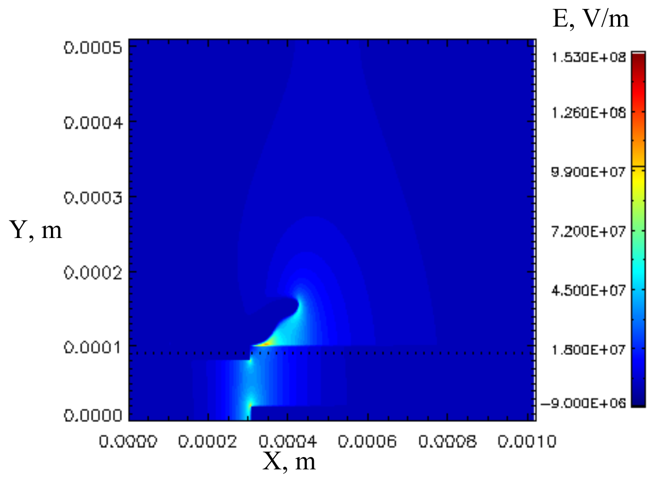


Figure 10. Transfer of maximum electric field region to the tip of the streamer head during streamer propagation.

3.2.2 Prototype a post processor for DBD relevant parameters.

Typical DBD relevant parameters are: spatial distribution of instant body force; spatial distribution of instant rate of thermal energy; spatial distribution of the momentum, transferred to the gas; spatial distribution of thermal energy, released to the gas; total gas momentum due induced by the DBD; total energy, released by DBD plasma. We computed these parameters according to the following expressions:

Instant force distribution: $\vec{F} = e(n_+ - n_- - n_e)\vec{E}$

Rate of thermal energy release distribution: $P = \vec{E}\vec{j}$, where *j* is the discharge current.

Momentum distribution: $Momentum = \int \vec{F} dt$

Energy release distribution: $Energy = \int P dt$

Total momentum: $TMomentum = \iint \vec{F} * dV * dt$

Total Energy: $TEnergy = \iint P * dV * dt$

Benchmark Results

In order to demonstrate post-processing capabilities and experimental scale simulation capabilities for short times, we set up the following simulation. The simulation domain was 5x0.5 milllimeters. The grid size was 1x1 microns. Dielectric thickness was 100 microns. Lengths of exposed and grounded electrodes were 200 microns and 4.6 millimeters. Applied voltage profile, which is typical for experimental DBD studies, is shown in Figure 11. The results of the simulation 12 ns after the start of the pulse are presented in Figures 12-14. These results demonstrate developed post-processing capabilities of the DBD simulation tool. Figure 12 shows distribution of x-component of instant force, acting on the gas, during the streamer breakdown (a) and spatial distribution of the x-component of the momentum, transferred to the gas (b). Figure 13 shows distribution of instant rate of thermal energy release (a) and distribution of energy release (b). Figure 14 shows time evolution of average (within the domain) x-component of instant force, acting on the gas, and average (within the domain) x-component of the momentum, transferred to the gas. During last two months of the projects we implement the time evolution of spatially integrated instant force, acting on the gas, and spatially integrated momentum, transferred to the gas. The results on this development are presented in technical activities for Task 4.

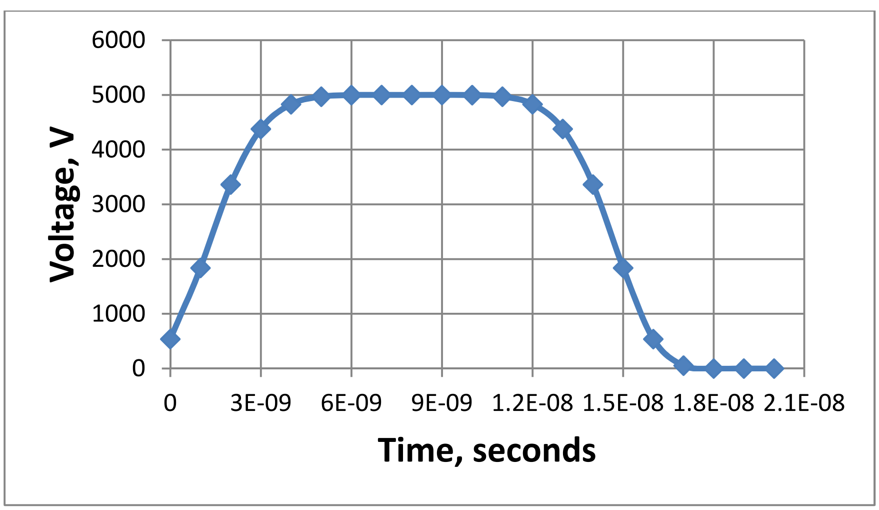


Figure 11. Positive pulse profile.

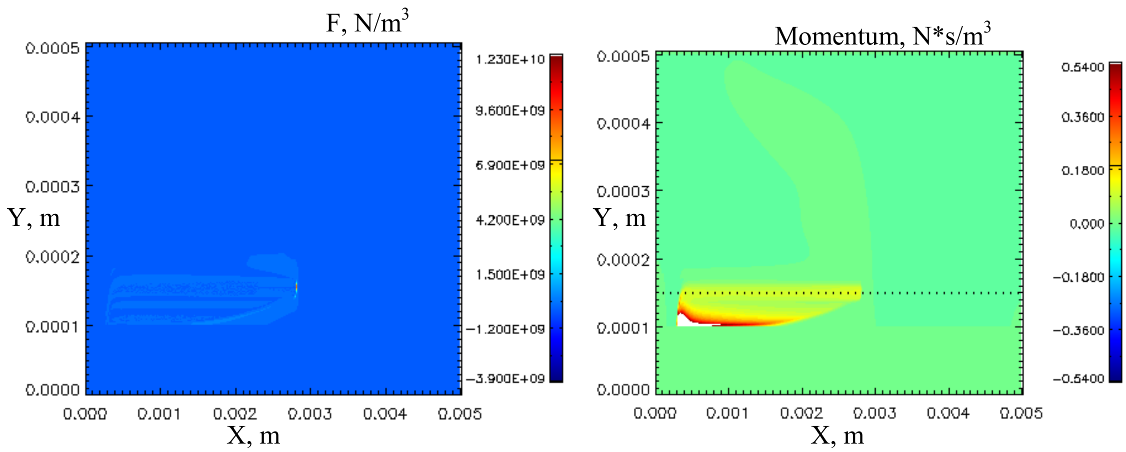


Figure 12. Distribution of the instant force and time-integrated force, acting on the gas during the breakdown.

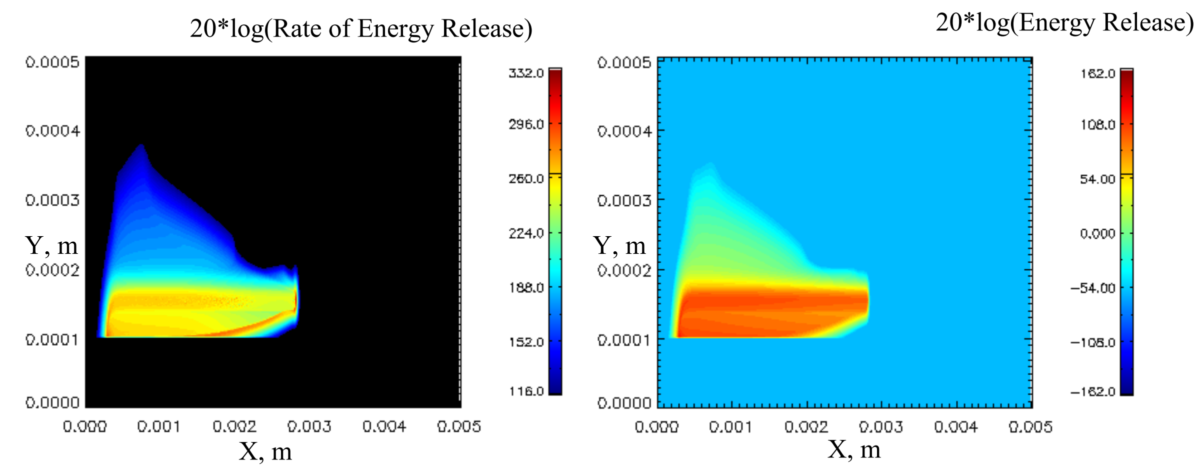


Figure 13. Distribution of instant rate of thermal energy release (left, in dB scale) and distribution of thermal energy release (right, in dB scale).

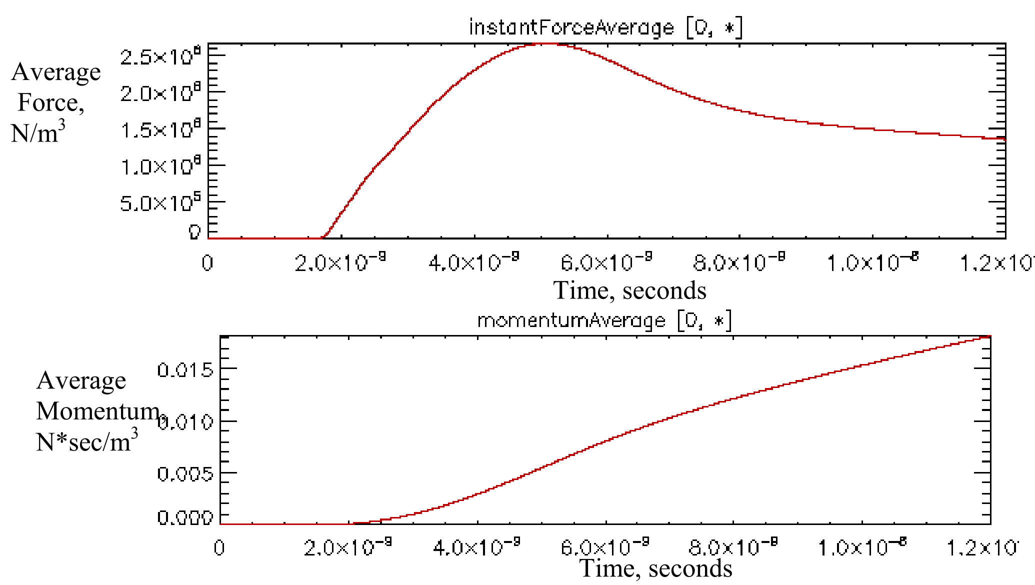


Figure 14. Time evolution of the averaged (over the domain) x-component of the instant force, acting on the gas (top), and averaged (over the domain) x-component of the momentum, transferred to the gas (bottom).

3.2.3 Enabling variable time steps in VORPAL.

An idea of using variable time step for reducing simulation time for the proposed tool comes from the fact, that most of the DBD operation time electron number density is much less than negative ion density. Electrons are important only during the breakdown stage of the DBD operation (several nanoseconds). After the breakdown, electrons are rapidly attached to the molecular oxygen, forming negative ions. If electrons are present in the system, they define time step in the simulations, since they are the fastest particles in the system. In order to take advantage of the fact that between the breakdowns plasma is ion-ion, we artificially attach all electrons after the breakdown to molecular oxygen. This process results in getting pure ion-ion plasma. After all electrons are attached, we compute only ion dynamics using the time step, defined by ion drift velocity. Figure 15 shows the evolution of positive ion number density for DBD, driven by a combination of positive nanosecond pulse and positive bias. After pulse ends, we artificially attach electron, and compute plasma dynamics based on ion time. Using this concept, we reduced simulation time between breakdowns by a factor of 20 and got stable correct results.

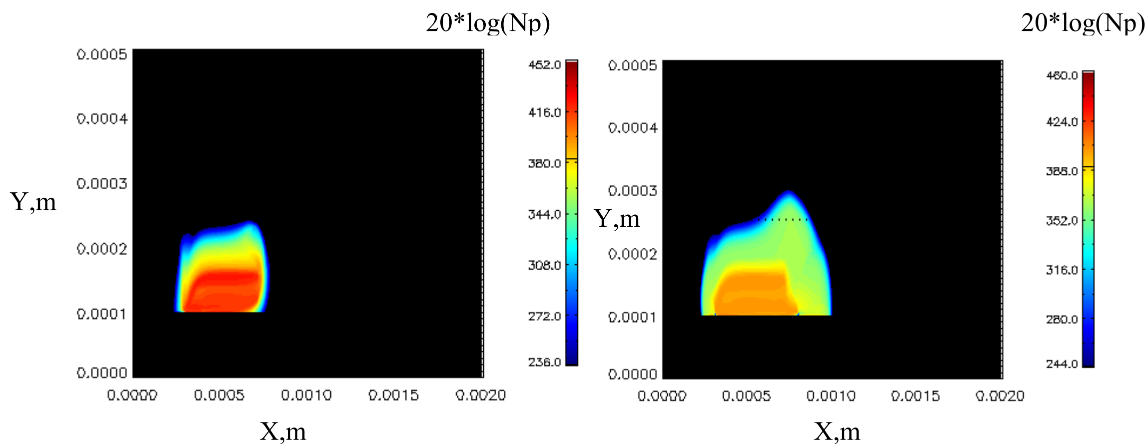


Figure 15. Distribution of positive ions in decibel scale right after the breakdown and 200 ns after the breakdown. Applied voltage is 3 kV 4 ns positive pulse and 1 kV dc bias.

3.3 Task 3: Perform experimental study of the Pulses+Bias DBD configuration

The experiments were conducted at Princeton University (D. Opaits and M. Shneider) via subcontract.

3.3.1 Power measurements in pulsed DBD's

Voltage and current profile measurements have been performed to quantify power consumption in DBD plasma actuators. The profiles were measured using LeCroy PPE20kV, 100 MHz high voltage probe and LeCroy CP031, 100MHz current probe connected to a LeCroy WavePro 7300A, 3GHz, 20GS/s oscilloscope. The nanosecond pulses were produced by FID Technology FPG 25-200MC4 pulser. The schematic of the electric circuit is shown at Figure 16. The DBD plasma actuator was made of 100 micron thick kapton tape and copper tape electrodes. The length of the actuator was 75 mm. The high voltage pulse was applied to the top electrode at frequency 10 Hz while the encapsulated one was grounded. To reduce the noise the scope was averaging over 10 profiles. The profiles were measured for both positive and negative polarities, the entire range of peak values allowed by the pulser and various length of the applied pulse voltage (5.5, 10, 17 ns FWHM). A typical voltage and current profiles are presented at Figure 17. Also, experiments were done with the top electrode encapsulated. Corona dope was used to cover the electrode and avoid the plasma formation. This approach allows estimation of plasma's contribution to the power consumption and separate it from radiative and dielectric losses.

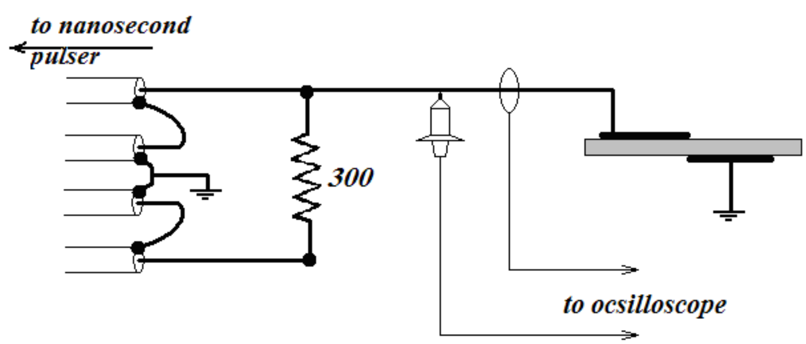


Figure 16. Schematic of the electric circuit.

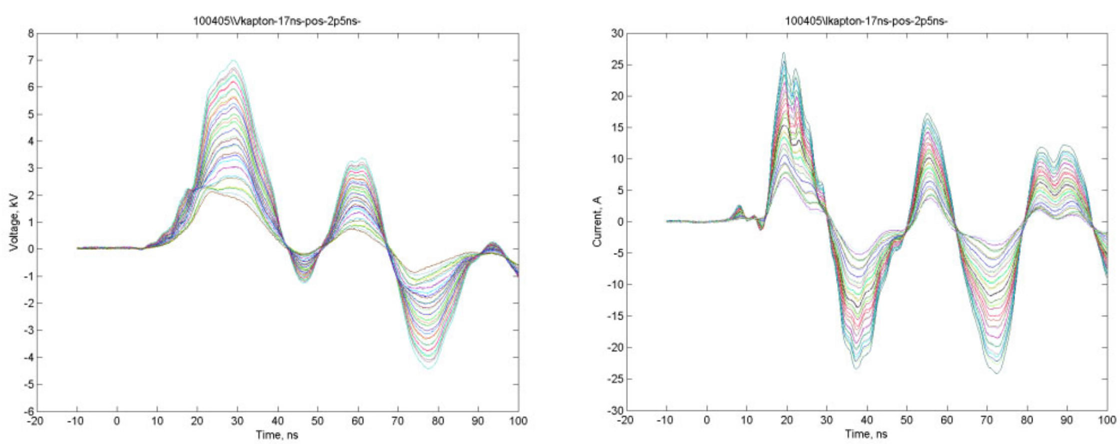


Figure 17. Typical voltage (right) and current (left) profiles.

By multiplying the voltage and current profile one will get instantaneous power consumption which can be integrated to find total energy dissipation. The difficulty is that due to very short periods of time involved the profiles should be synchronized with a high accuracy. Since the time which it takes for a signal to travel from the probes to the scope is unknown the difference can reach a few nanoseconds which will have a significant effect on the power calculations. The calibration was done using a non-inductive resistor. Both voltage and current pulses measured at this load had the same shape and were shifted in time by 2.5 ns. This value of the time shift was used to adjust the experimental data.

Figure 18 shows calculated energy dissipated in a single pulse in DBD. First of all, the results show that if the plasma is absent (the top electrode is covered with corona dope) power losses are still significant. It means that a big part of the energy consumed by DBD is lost due to dielectric and radiative losses. Second result is that the pulse duration has very little effect on the power consumption, at least in kapton made DBD's. Third, negative pulses dissipate significantly higher energy than the positive ones. Overall the power consumption is low and equals to about 10-20 mJ per meter per pulse.

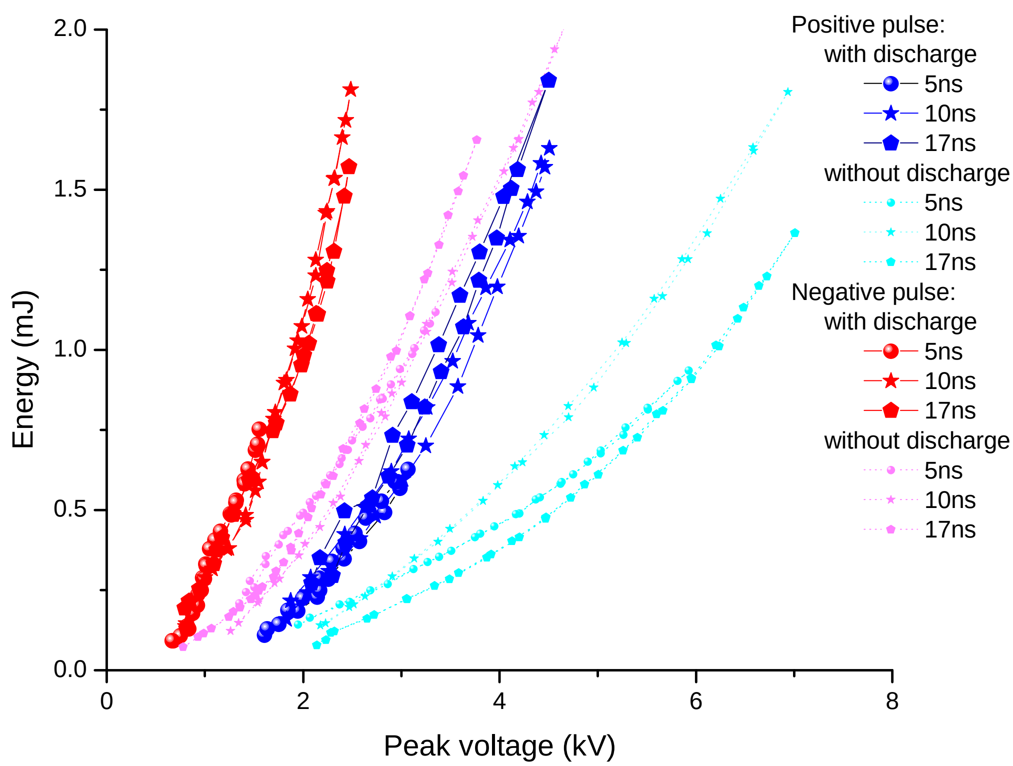


Figure 18. Power consumption in pulsed DBD.

Discharge dimensions

Images of plasma were acquired to study dimensions of pulsed surface dielectric barrier discharge. The plasma actuator was made of two copper electrodes 100 micron thick and a kapton tape of the same thickness as the dielectric barrier. The actuator was pulsed by FID

Technology pulser FPG 25-200MC4 at frequency about 1 Hz. Pulses of both polarities and three different durations were applied to the top electrode, the lower one was grounded. Intensified CCD Princeton Instruments camera was used to capture images of the discharge. Exposure time was equal to 1 microsecond, field of 12 by 6 mm, resolution 512x256 pixels, i.e. 23 microns/pixel. The experiments were conducted in room air.

Typical results of the discharge appearance (top view) along with the pulse voltage profile are shown in Figures 19 and 20. The top 1/3 part of the image is the top electrode; the lower 2/3 of the image is the dielectric and the bottom electrode under it. Note, the contrast and brightness of the images were changed for best appearance. It can be seen that positive discharge (especially at longer pulses) consists of uniformly distributed streamer, whereas the negative pulses produce more uniform glow. Still some irregular filamentation can be observed in negative polarity at higher peak voltages.

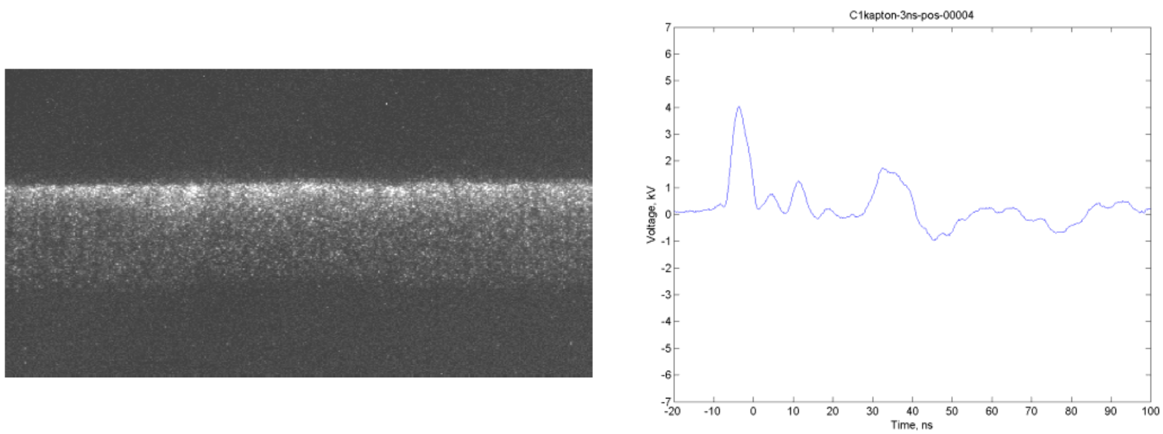


Figure 19. Plasma appearance, top view, image size 12x6 mm.
Voltage profile – 5.5 ns, 4 kV positive pulse, shown on the right.

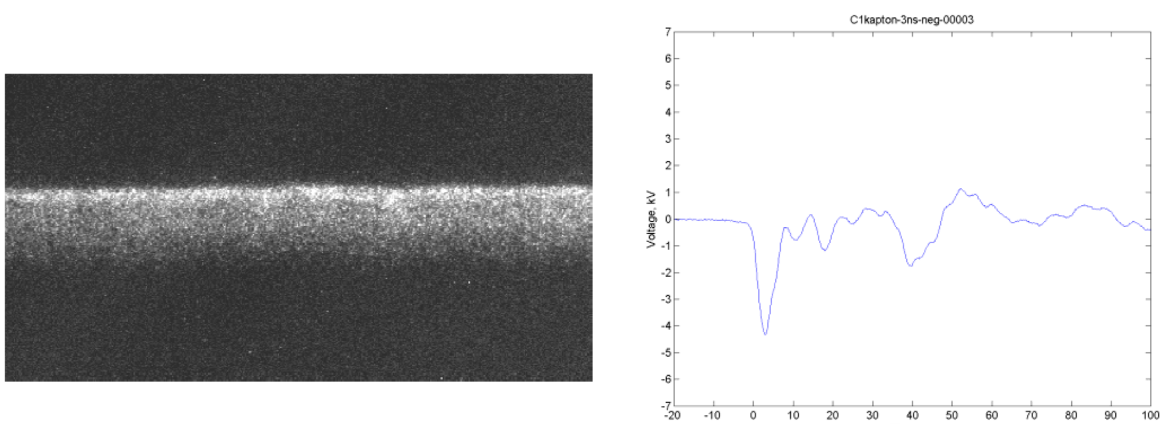


Figure 20. Plasma appearance, top view, image size 12x6 mm.
Voltage profile – 5.5 ns, 4 kV negative pulse, shown on the right.

Profiles of the intensity distribution in DBD along the distance downstream is shown in Figure 21. Relative intensity in all plots is the same which makes possible comparison of the effect of the pulse polarity and duration on the intensity distribution. The intensity profiles demonstrate higher radiation close to the electrode edge. The intensity is higher for pulses of higher peak voltage and duration. Pulse polarity, although has some effect of the profile shape, does not make a big difference.

Figure 22 shows the dependence of the discharge maximum intensity, total radiation (which was found by integration of the intensity over distance), and length as functions of the pulse voltage. The length of the discharge is defined as size of the region where the plasma radiation exceeds 10% of its maximum value. Sometimes this definition of the discharge length may lead to confusion. For example, the size of the discharge created by 10 ns positive pulse increases with peak voltage as we can see from the intensity profiles. However the length measurements show that the discharge length suddenly decreases around 4 kV of the pulse voltage, see Figure 22.

It can be seen from the plots that the maximum intensity, total emitted radiation, and the length of the discharge go up with the pulse voltage and duration.

Thickness of the discharge

Images of the discharge were acquired to measure its thickness. The actuator was 75 mm long and was made of 100 micron thick kapton tape and copper electrodes. The camera was placed downstream of the actuator as shown at Figure 23. The reason for that was to make sure that the entire discharge stays within the focal depth of the optical system (about 1 cm in this particular case). If the camera was taking side images of the discharge than the parts of the plasma which stick out of the focal plane of the optical system by more 5 mm would be out of focus and come out blurry. It can be misinterpreted as a thicker discharge. If the images are taken from the downstream this problem does not arise.

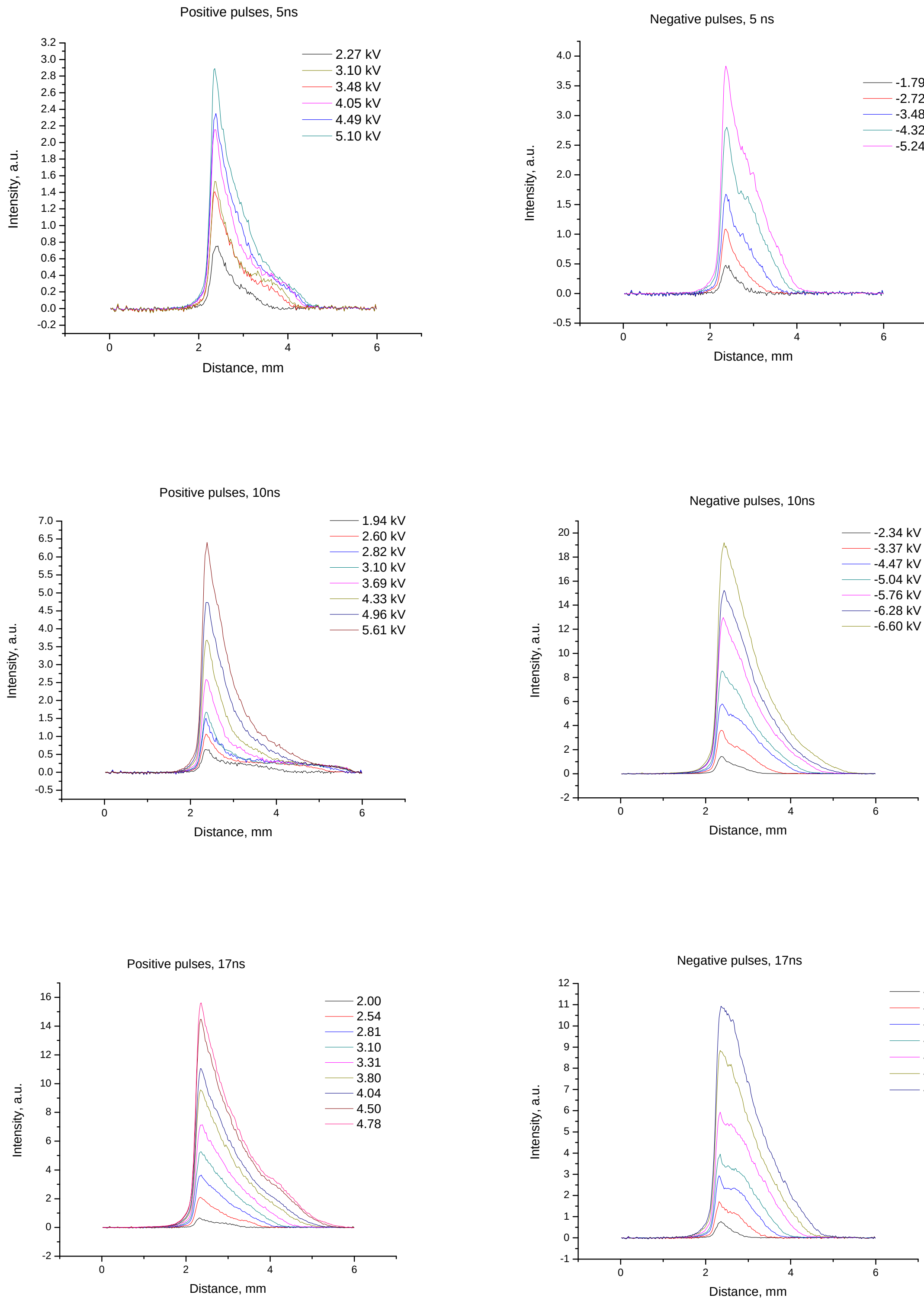


Figure 21. Intensity distribution in DBD along the distance downstream. Relative intensity in all plots is the same. Electrodes edge located at 2 mm.

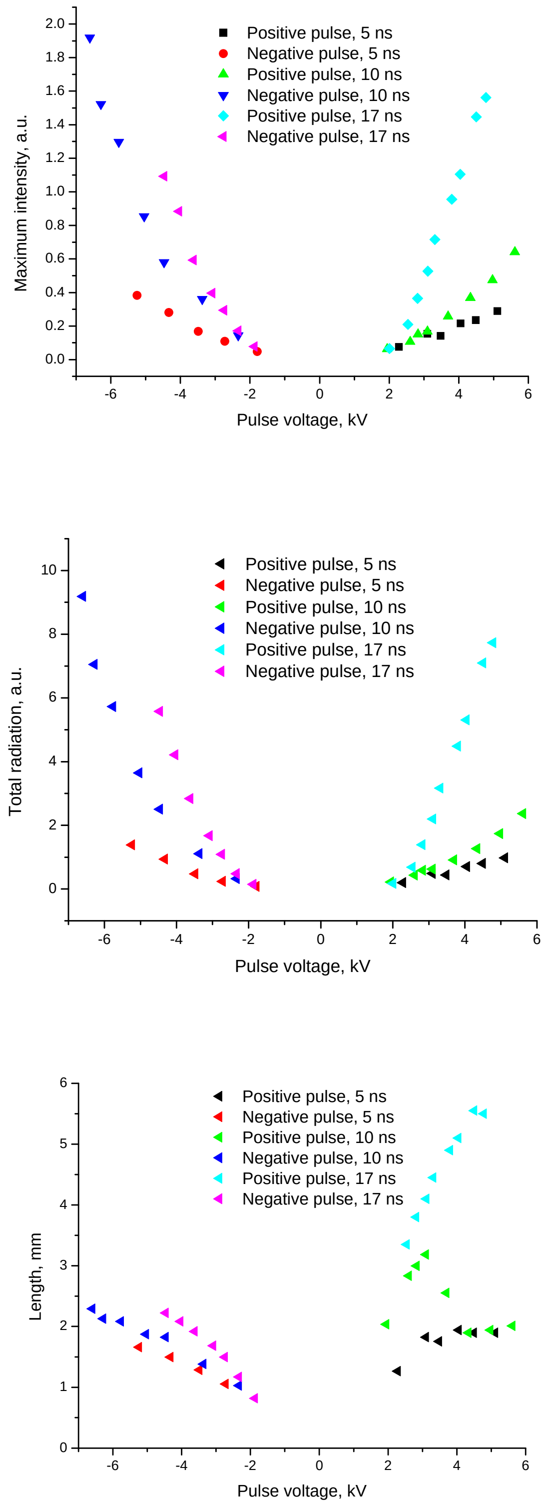


Figure 22. The discharge maximum intensity, total radiation, and length measured at 10% of peak intensity versus pulse voltage.

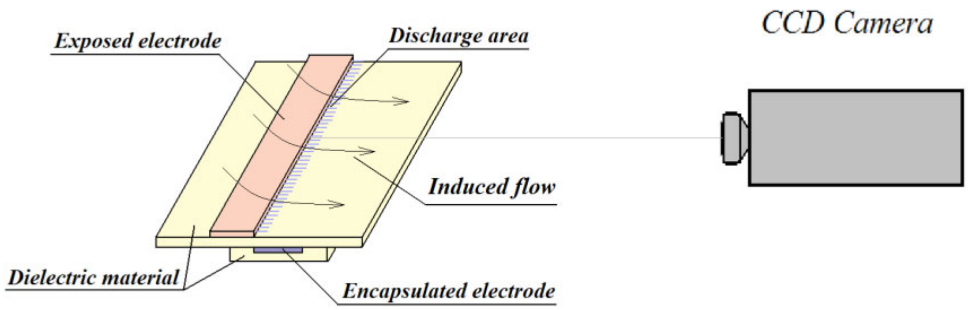
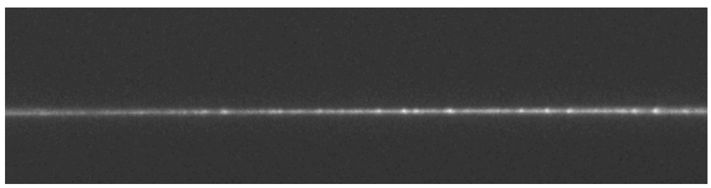
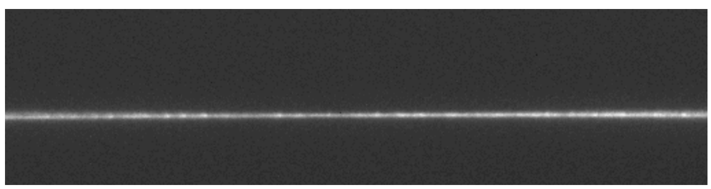


Figure 23. Experimental layout.

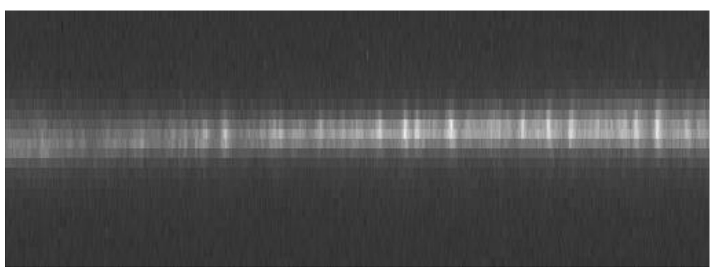
The image resolution was 512 by 512 pixel and the field of view was 40 by 40 mm. This corresponds to resolution 78 micron per pixel. Typical images for both polarities of the pulses are shown in Figure 24. It can be seen that the thickness of the discharge in the picture was only 2-3 pixel what corresponds to about 150-200 microns. The thickness does not vary noticeably in the given range of pulse voltages (3-7 kV) and is similar for both polarities. A better optical system, namely a microscope, is required to perform exact plasma thickness measurements.



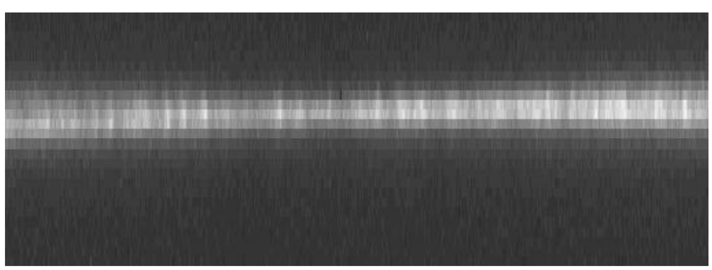
Negative pulse 40x10 mm



Positive pulse 40x10 mm



Negative pulse 40x2 mm



Positive pulse 40x2 mm

Figure 24: Images of the discharge, front view, single pulse.

3.4 Task 4: Validate developed prototypes by comparing simulation and experimental results

3.4.1 The anode breakdown stage of the DBD discharge.

The goal of this technical activity was to demonstrate that developed prototype of DBD simulation tool can resolve all essential physical phenomena. We have accomplished this subtask during the testing of the developed prototype in Task 1 and 2 technical activities. We have studied DBD plasma actuator, driven by positive nanosecond pulses, and observed all phenomena, corresponding streamer propagation, such as transfer of region of maximum electric field to the tip of the streamer head, same potentials of the exposed electrode and streamer body, longer streamers at lower pressures. Besides it, we observed for the first time 3D structure in DBD discharge using 3D PIC simulations. These results are unique and show the high potential of the proposed DBD simulation tool for correct description of the DBD physical phenomena.

3.4.2 Pulses+bias configuration

The goal of this technical activity was qualitative comparison between experimental and numerical results of the project and demonstration of potential of using DBD simulation tool for modeling experimental configurations.

<u>Qualitative comparison between experimental and numerical data</u>

In order to demonstrate feasibility of the proposed DBD simulation tool, we performed qualitative comparison between the results of prototype model, developed during Phase I project and experimental results. Since detailed air-chemistry, photoionization and electric circuit models will be implemented during Phase II project, we anticipated getting only qualitative agreement. We have compared four plasma characteristics – plasma length, plasma thickness, general plasma appearance and power consumption. The comparison has been made for 3 kV 4 ns + 1 kV DC bias simulated positive pulses and 3 kV 5 ns experimental pulses. The numerical results on plasma length and plasma appearance for both PIC and fluid DBD simulations are taken from section 3.1.2 and 3.2.2 and experimental results are taken from section 3.3.1. As was mentioned in Task 3 Technical activities, we have also implemented a number of post-processing capabilities for DBD simulation tool in VORPAL. One of them is energy, deposited into plasma. Figure 25 shows the computed energy, deposited by nanosecond pulse, per DBD length.

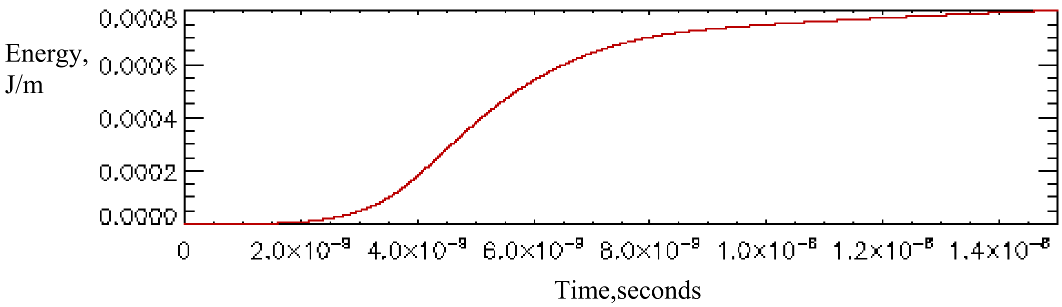


Figure 25. Energy consumed by DBD as a function of DBD operational time.

By comparing the results of simulations and experiments, we observe that qualitative plasma properties are similar and the results are in good agreement. Despite we observe the expected discrepancy in the quantitative comparison of the results, the values of the differences between numerical and simulations results are quite low. Once the detailed air chemistry, photoionization and electric circuit models are included into DBD simulation tool during Phase II project, we expect to get excellent quantitative agreement between the results. Table 1 summarizes the comparison between numerical and experimental results.

DBD Property	Experimental Results (3 kV, 5 ns)	Numerical Results (3 kV, 4 ns)	Qualitative Comparison Result
Plasma length	~ 2 mm	~ 0.5 mm	Good agreement
Plasma thickness	150-200 microns	• 100 microns for fluid approach • 250 microns for kinetic approach	Good agreement
Consumed Energy per plasma volume	~20 kJ/m^3	~18 kJ/m^3	Excellent agreement
Plasma appearance	Starts from edge of exposed electrode and propagates along dielectric	Starts from edge of exposed electrode and propagates along dielectric	Excellent agreement

Table 1. Results of comparison between DBD simulations and experiments.

3.5 Additional Technical Activities

3.5.1 Demonstration of speedup for parallel simulations

One of the key elements for the successful development of the commercial parallel simulation codes is the demonstration of the speedup with number of processors. Ee have performed such study for 1, 2, 4, 8, 16, 32 and 64 processors. We ran same sample simulation and measured the time, required for execution. Based on the measured time, we have computed the speedup, which is the ratio of simulation times for 1 processor and N processors. The results are presented in Figure 26. We observe very good scaling of the speedup with the number of processors.

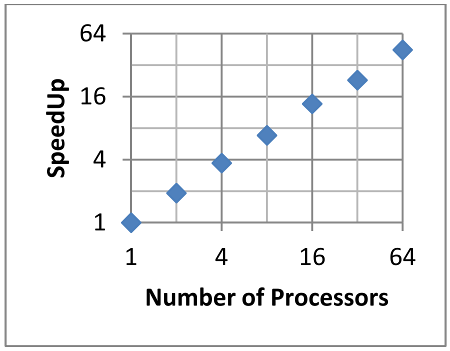


Figure 26. Speedup of parallel simulations.

3.5.2 Demonstration of hybrid capabilities for DBD simulations for single processor

Besides demonstration of PIC and fluid approaches for DBD plasma simulations, projected in Phase I proposal, we have also set up a simulation to show hybrid capabilities of the DBD simulation tool. For the demonstration purposes, we considered DBD in nitrogen with ionization collisions only. User was allowed to choose the time frames for PIC simulations and fluid simulations. In the following example, initial stage of the breakdown was computed using PIC approach. In order to proceed with fluid approach, the DBD simulation tool converted data on particle distribution to the distributions of number densities. This concept was successfully implemented for the single processor in VORPAL. Figure 27 shows the conversion of the nitrogen ion distribution in PIC approach (a) to the number density of nitrogen ions (b). The same applies to the electrons. Once the number densities are converted, simulations can continue using fluid approach.

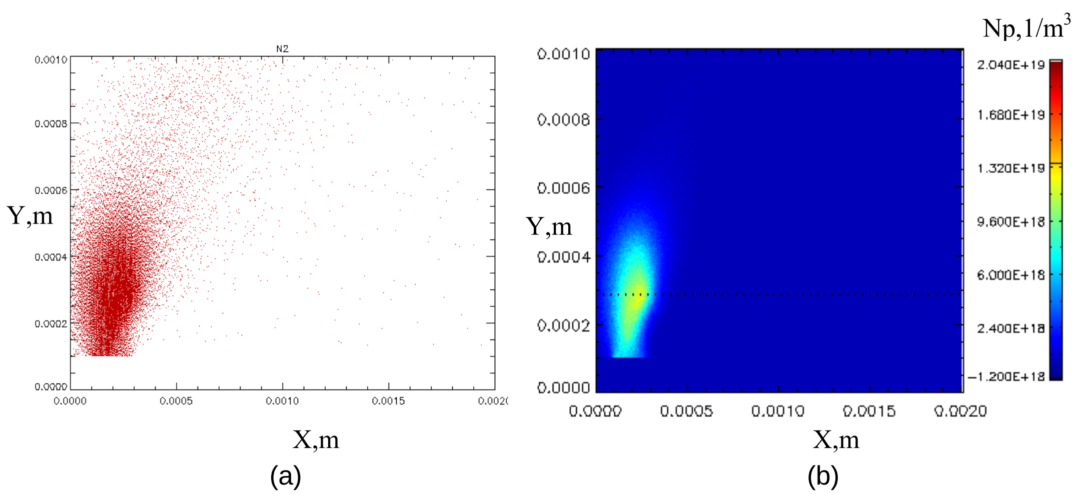


Figure 27. 2D distribution of positive ions at the beginning of streamer formation, obtained using PIC code (a). 2D distribution of positive ion number density at the beginning of streamer formation, converted into fluid code (b).

4. Potential Applications

4.1 Potential NASA applications

The primary NASA applications of the proposed DBD simulation tool are active flow control concepts for both subsonic and hypersonic flights. Predictable active flow separation control, achieved using the proposed tool, will benefit many NASA Projects, such as Subsonic Fixed Wing Project, Subsonic Rotary Wing Project and Hypersonic Project. In addition to the flow separation application, DBD simulation tool can be used for a number of NASA problems, associated with gas discharges at different pressures. For example, DBD simulation tool can be used for the description plasma-assisted combustion for the reduction of carbon emissions.

4.2 Potential non-NASA applications

Active flow control using DBD plasma actuators is of interest to a number of government agencies, private industry and universities. Proposed tool will be beneficial for subsonic/hypersonic programs which involve active flow separation control. These programs include, but are not limited to, flow separation control at commercial airplanes during take-off or landing, increase in lift for tiltrotor aircrafts, improvement of engine performance, active flow control at hypersonic vehicles. Besides the primary application for a description of DBD operation, DBD simulation tool can be used for a wide range of plasma aerodynamics applications, such as plasma-assisted combustion, flow control using different types of discharges, reduction of carbon emission, optimization of air vehicle operation, MHD and EHD application.

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13. SUPPLEMENTARY NOTES
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14. ABSTRACT
This report is the final report of a SBIR Phase I project. It is identical to the final report submitted, after some proprietary information of administrative nature has been removed. The development of a numerical simulation tool for dielectric barrier discharge (DBD) plasma actuator is reported. The objectives of the project were to analyze and predict DBD operation at wide range of ambient gas pressures. It overcomes the limitations of traditional DBD codes which are limited to low-speed applications and have weak prediction capabilities. The software tool allows DBD actuator analysis and prediction for subsonic to hypersonic flow regime. The simulation tool is based on the VORPAL code developed by Tech-X Corporation. VORPAL's capability of modeling DBD plasma actuator at low pressures (0.1 to 10 torr) using kinetic plasma modeling approach, and at moderate to atmospheric pressures (1 to 10 atm) using hydrodynamic plasma modeling approach, were demonstrated. In addition, results of experiments with pulsed+bias DBD configuration that were performed for validation purposes are reported.

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Jet engines; Aeropropulsion; Turbomachinery; Plasma; Dielectric barrier discharge; Flow control

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