SAND2024-08437C

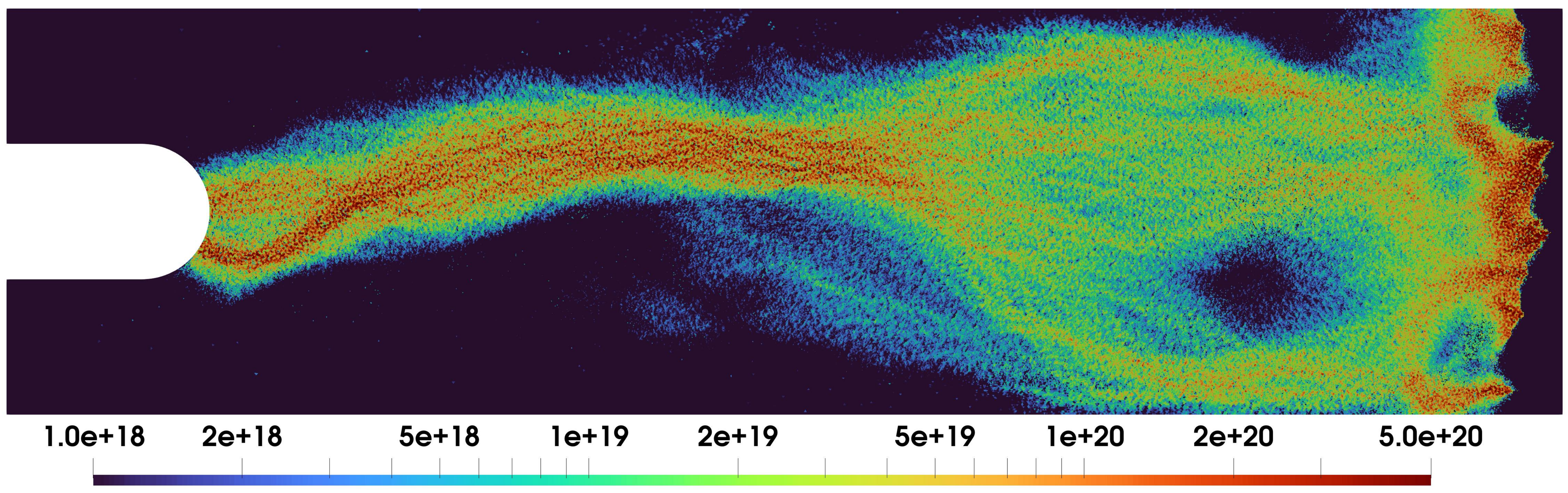
Simulations of centimeter-scale, atmospheric pressure, positive streamer discharges using EMPIRE-PIC

D.Nikic[1], A. Fierro[1], J. Lehr[1], C.Moore[2]

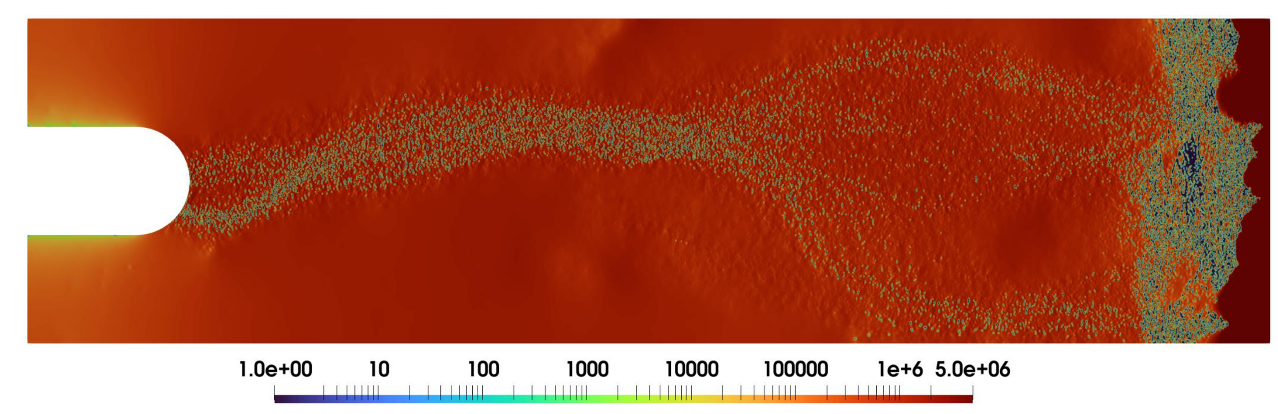
[1]Electrical and Computer Engineering, University of New Mexico [2]Sandia National Laboratories

INTRODUCTION

Development of a new particle-in-cell (PIC) code EMPIRE-PIC has enabled simulations of high pressure discharges over wide electrode gaps. This is primarily due to implementation of scalable solvers allowing for 100's of millions of elements, sub-Debye length mesh sizes, and 10's of billions of macro-particles. EMPIRE-PIC allows an unlimited number of species and practically unlimited number of interactions, making it suitable for complex plasmas and plasma chemistry. Furthermore, code allows for spontaneous emission which enables random behavior due to random emission events occurring anywhere within the volume. This is particularly important for positive streamer discharges where photo-ionization is a primary streamer propagation mechanism. In this instance it is the photons that photo-ionize secondary species in the gas which in turn generates additional charged particles to be created at random location within the electrode gap. Each of these locations is a source of a new electron avalanche formation and growth of a streamer branch that may or may not connect with the primary branch.

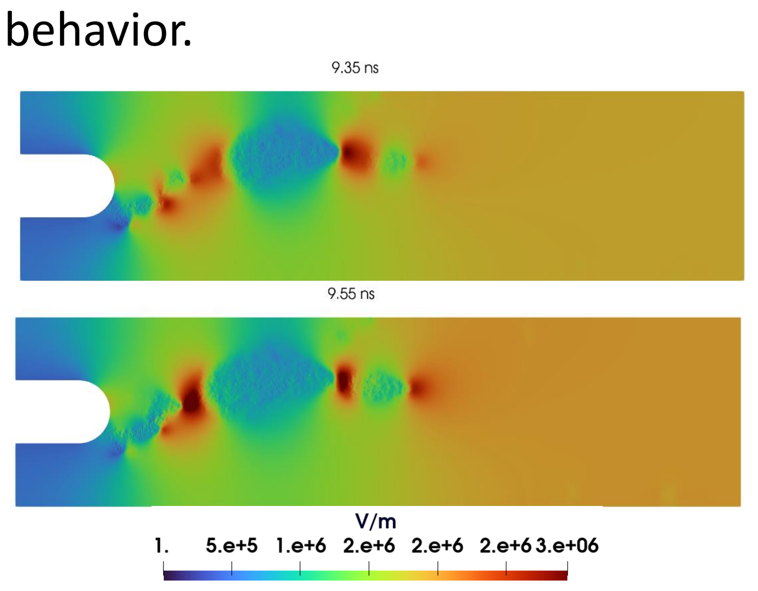


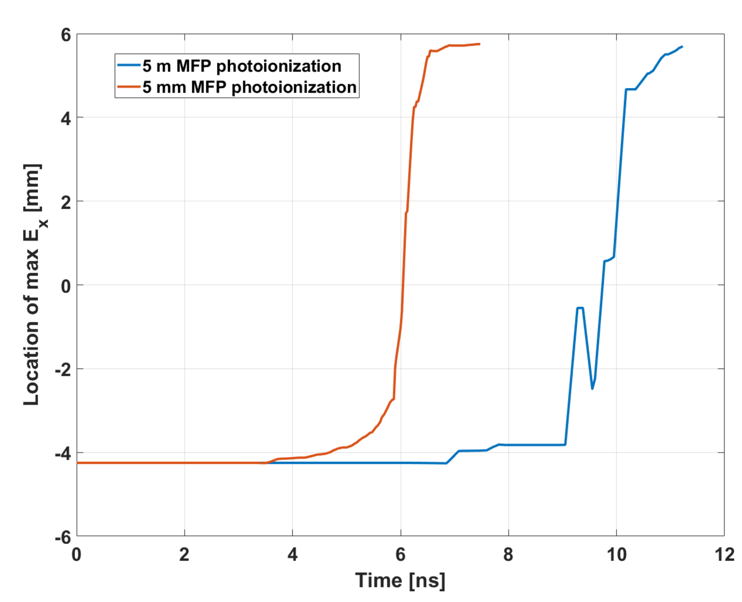
Example of a fully developed streamer utilizing long (5 m) photoionization mean-free-path. Electron density plotted is in m^{-3}. Note the creation of multiple filaments and stochastic branching between anode and cathode. E_x field plotted below in units V/m.



FIELD BEHAVIOR

Normally, streamer propagation can be tracked with electric field, with the expectation that the maximum electric field is at the head of the streamer. In the case where photoionization MFP is long there are pockets of charge created well ahead of the streamer which at times can generate higher electric fields than the streamer head itself. An example of such case is shown below as well as the comparison of maximum electric field location as a function of time. Note that short photoionization MFP streamer exhibits smooth behavior while long photoionization MFP has a more erratic behavior.

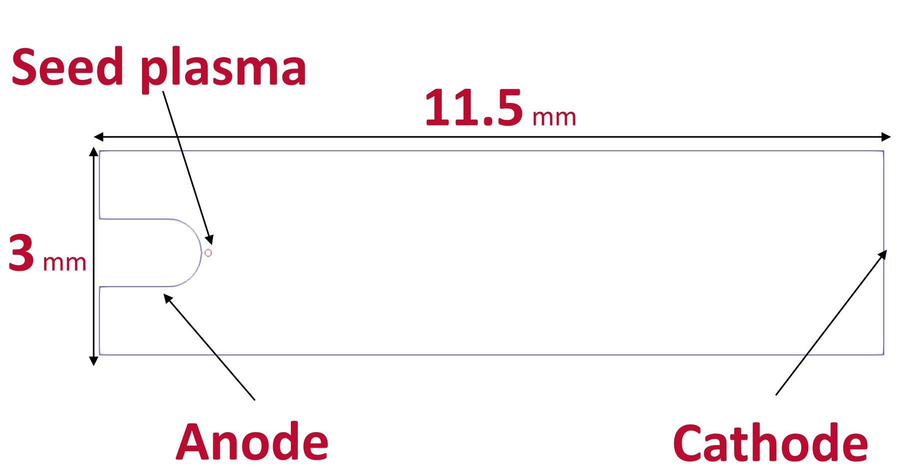




SIMULATION SETUP

Pin to plate geometry in 2D is chosen to study atmospheric streamer discharges between two electrodes. Figure below shows the representative geometry where two electrodes are placed 10 mm apart with gas at atmospheric pressure completely filling the gap. Some of the basic parameters are:

- Electrostatic formulation
- Mesh size = 10 µm
- Time step size = 0.05 ps
- Gap = 10 mm
- Applied voltage = 15 kV
- IC = atmospheric pressure (2.68×10^{25} m^{-3}), temperature (300 K)
- Seed plasma placed at tip of anode pin (see below) n = 1 x 10^{15} m^{-3}



$e^- + A \rightarrow e^- + A^+ + e^-$ → Ionization

$e^- + A \rightarrow e^- + A$ → Elastic

$A^+ + A \rightarrow A^+ + A$ → Elastic

$A^+ + A \rightarrow A + A^+$ → Charge exchange

$e^- + A \rightarrow e^- + A^*$ → Excitation

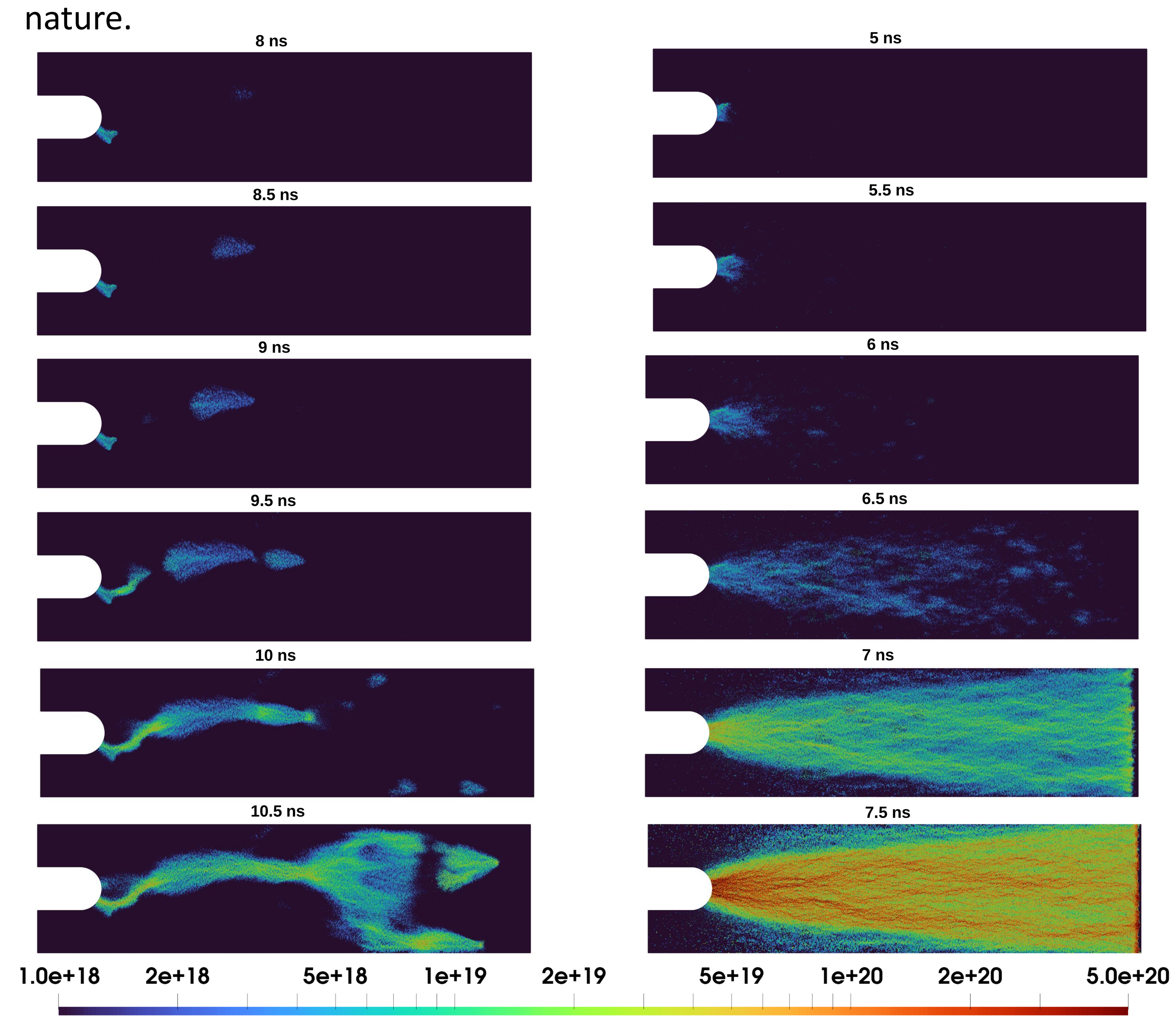
$A^* \rightarrow A + \gamma$ → Emission

$\gamma + B \rightarrow B^+ + e^-$ → Photo-ionization

For these studies we used two artificial gases labeled A and B. Gas A is an Argon-like gas with well defined reaction cross-sections. Furthermore, gas A excited states are allowed to emit 15 eV photons. Gas B serves as a photo-ionizing species which reacts with photons to ionize. Concentration of gas B is varied 0.001-1% to characterize the effects of photoionization mean-free-path on the streamer behavior. A full list of reactions used in simulations is shown above.

STREAMER PROPAGATION

Propagation of a streamer with long photoionization MFP (5 m) is shown on **left**, while a streamer with short photoionization MFP (5 mm) is shown on **right**. Plotted is electron density (m^{-3}). Note that streamer growth rate is significantly faster for short photoionization MFP streamer and growth is more uniform through out the volume, while long photoionization MFP streamer exhibits filamentary behavior and generally a more stochastic nature.



CONCLUSIONS

We have demonstrated the importance of the photo-ionization on positive streamer propagation over centimeter-scale gaps. Furthermore, effects of increased photo-ionization rates have shown that propagation of the streamer can vary from filamentary propagation mode to volumetric propagation as photo-ionization rate is increased. Additionally, electric field has been shown to vary along the streamer, in particular for the case where photo-ionization is low allowing for creation of high localized charge density. This can lead to, in some cases, to erratic propagation of the streamer with electric field forcing the streamer propagation between the head of the stream and areas of local high charge density. This behavior allows the streamer to propagate quicker than what would've been possible if photo-ionization was not present.

ESCAMPIG XXVI Brno, Czech Republic - 2024

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.