PIC-MC SIMULATIONS FOR MICROPLASMAPROPAGATION IN PARALLEL MULTI CAVITY ARRANGEMENTS AT ATMOSPHERIC PRESSURE CONDITIONS

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ABSTRACT

Porous materials instead of solid ones are planned to be used as high voltage insulations to reduce weight. Due to non-ideal compositions cavities inside the insulation material may lead to discharges. These discharges are called microplasmas or partial discharges.

Analytic approximation for modelling of the discharge processes can be very complex even in simple cavities. Thus, for detailed analysis numerical simulations are required. In this work a three dimensional plasma simulation tool based on the Particle-in-Cell Monte-Carlo method (PIC-MC) is used. The applicability of PIC-MC simulations for small single cavities at atmospheric pressure has been shown previously [1,2]. Subsequently, asymmetric propagation behaviour was revealed by PIC-MC for multiple cavities, aligned in series with respect to the field vector [3].

In contrast, this work analyses the microplasma-propagation in multi cavity arrangements, which are aligned in parallel. Two scenarios are investigated: One with two separated cavities and one with an opening allowing particle transfer. Thus, the interactions between two cavities solely by electric field influence and via additional charge transfer are compared.

1. INTRODUCTION

Electric fields e.g. in high-voltage applications get stronger due to miniaturisation. Non-ideal production processes may create voids inside the insulations. Depending on their size and alignment, these microcavities may cause so-called partial discharges leading to accelerated device degradation. Furthermore, for plasma surface modification discharges are ignited intentionally and are called microplasmas [4-6]

In many applications a good compromise between weight and functionality of electrical insulations is aimed for. Thus, porous materials, so called foams, are used instead of solid insulations. Herein, more cavities exist and are not distributed regularly. The cavities can be connected or encapsulated which is referred to as “open-cell foam” or “closed-cell foam”, respectively. [7]

Modelling of discharge processes with analytical calculations in foams is very complex and requires numerical simulations for description and optimization of applications. In this project a Particle-in-Cell Monte Carlo simulation tool (PIC-MC) is used [8,9]. Thereby, the microplasmapropagation processes observable during measurements are simulated.

2. PIC-MC SIMULATION TOOL

The simulations are done with a PIC-MC simulation software, which formally was developed by Fraunhofer IST for low pressure plasma processes [9]. This tool uses an efficient parallelisation method and is compatible with high performance computing clusters. The use of a parallel iterative field solver in combination with parallelized DSMC (Direct Simulation Monte Carlo) code enables even three dimensional plasma simulations. Arbitrary geometric models can be handled via a mesh interface. High resolution simulations of gas discharges are possible with the particle-based PIC-MC simulation model, which calculates gas and plasma dynamics by means of representative macroparticles. The averaged particle states deliver temporally and spatially macroscopic state variables [2,9]. The PIC-MC tool calculates the discharge processes basing on the Townsend criterion. Thus, UV radiation or photons are not considered. Regarding to dimensions and pressure used for microcavity conditions the Townsend criterion is a reasonable approach [10]. PIC-MC is typically feasible for simulations with high Knudsen numbers, which is typical for rarefied gas flow conditions [11,12]. In this project atmospheric pressure conditions are possible due to the small cavity diameters. The applicability of this PIC-MC tool was already shown in [1-3].

3. SIMULATION MODELL

In this work two multiple microcavity arrangements were tested with the PIC-MC software. Two single cavities from [1] were assembled to parallel arrangements as shown in ***Fig. 1***. The single cavities have a height of 300 µm and width of 500 µm. Simulations are done in quasi 2D, where the third spatial direction has a depth of 1 µm with periodic boundary conditions.

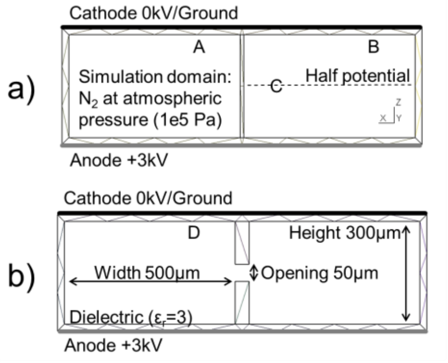

Fig. 1 Simulation models with characteristics and places of start electrons (A, B, C, D),
a) separated multi cavity, b) connected multi cavity

Two different scenarios were simulated: The first one consists of two separated microcavities oriented in parallel with respect to the field vector (***Fig. 1*** a). In the second model, the separating insulation barrier was build up thicker and the cavities are connected via a small opening (***Fig. 1*** b). Both model arrangements are completely surrounded by an insulating dielectric boundary ($\varepsilon_r = 3$). The simulations are done with the cathode (top) as ground electrode and a high voltage of 3 kV potential at the anode (bottom). Due to the fast discharge process within a few ns, we assume constant applied voltage (DC) and thus constant electric field strength of approximately 10 kV/mm during the whole simulation run. The simulation domains are filled with pure Nitrogen (N_2) at atmospheric pressure (10^5 Pa) at ambient temperatures. Electron- and ion-densities are applied as under typical ambient conditions [13]. This leads to a negligible number of charged particles (averaged under 0.1 particles) in the observed domain. Thus, for initiation of the avalanche process one or more electrons are introduced selectively. The description of the gas discharge is done by simulation of electron-, ion- and neutral particle densities of the gas species. Reactions of N_2, N_2^+ and e are considered. The temporal development of the electric potential in the microcavity arrangements is also observed.

4. RESULTS AND DISCUSSIONS

The discharge process in a single microcavity is shown in [1]. In this work the interaction through electric field and plasma coupling between two adjacent cavities in field direction parallel oriented is determined (***Fig. 1***). In both arrangements the electric potential is homogeneous at the beginning.

4.1. SEPARATED MULTI CAVITY

At first a simulation with two separated cavities is analysed (***Fig. 1*** a). One start electron is introduced in the left cavity near the cathode (***Fig. 1*** a place A) and one in the middle (at half potential; ***Fig. 1*** a, place C) in the right cavity. The discharge process appears similar to single cavities: After initialisation of the start electrons at 0 ns a primary avalanche starts which reaches the anode within approximately one nanosecond. The electric density remains for some ten nanoseconds (***Fig. 2***) until secondary avalanche.

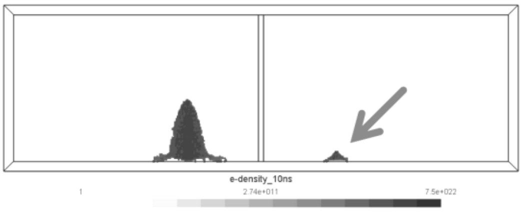

Fig. 2 Electron density in separated cavities at 10 ns by start-electrons in both cavities (Fig. 1 a , places A, C)

The generated positive ions may create secondary avalanches through electrons which start at the cathode. As in single cavity arrangements, secondary avalanches are only generated by start-electron initialisation near the cathode. Initialisation of start-electrons at half potential doesn't lead to discharges. Thus, in the left cavity a discharge channel is build up and in the right cavity the electrons are absorbed (see arrow ***Fig. 3*** compared to ***Fig. 2***).

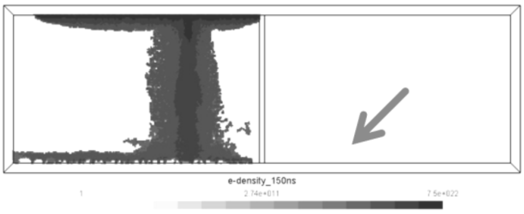

Fig. 3 Electron density in left cavity and without electrons in right cavity at 150 ns

The field distortion in the left cavity is too far away to trigger a discharge in the right cavity by field enhancement (see arrow ***Fig. 4***). No field coupled streamer propagation at these parameters occurs.

Fig. 4 Electric potential during secondary avalanche in left cavity at 150 ns

To determine if avalanches are suppressed by discharge channel, behaviour of two separated cavities with a start-electron near cathode in each cavity was tested (***Fig. 1*** a, places A, B). Both cavities show discharge channels and are field free after discharge (***Fig. 5***).

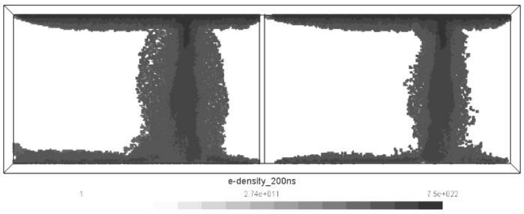

Fig. 5 Electron density at 200 ns in both separated cavities with start-electrons in both cavities (Fig. 1 a, places A, B)

4.2. CONNECTED MULTI CAVITY

An arrangement with two connected cavities was simulated (see ***Fig. 1*** b). Both cavities are connected with an opening outside the fall regions. Only one start electron was placed in the left cavity near the cathode (***Fig. 1*** b, place D).

We can see the electron density during secondary avalanche and growing of the discharge channel (***Fig. 6***). The electric potential (***Fig. 7***) shows negligible field distortion in the right cavity during discharge in the left one.

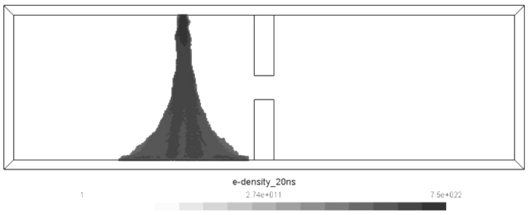

Fig. 6 Electron density during build-up of discharge channel in connected cavities at 20 ns by start-electron in the left cavity (Fig. 1 b, place D)

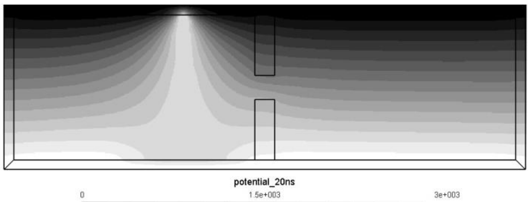

Fig. 7 Electric potential at 20 ns regarding to Fig. 6

As usually, the electrons form the anode and cathode fall region. In the anode fall region the electrons flow up to the opening between the cavities (***Fig. 8***) but do not get through it and are absorbed in the insulation wall between the cavities (see arrow ***Fig. 9*** compared to ***Fig. 8***).

Fig. 8 Electron density and rising up electrons at 110 ns

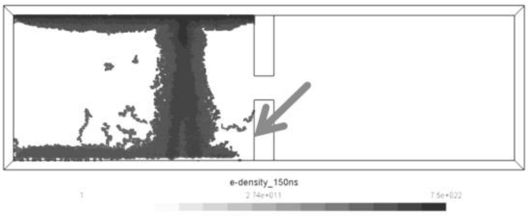

Fig. 9 Electron density at 150 ns with absorbed electrons compared to Fig. 8

Thus, no discharge in the right cavity is triggered. The left cavity is field free after discharge process but the right cavity shows still a nearly homogenous electric field (***Fig. 10***). This results in no plasma coupled streamer propagation with this parameters.

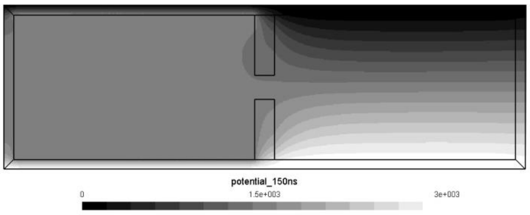

Fig. 10 Electric potential after discharge process at 150 ns in left cavity field free and in right cavity nearly homogeneous

5. CONCLUSIONS

PIC-MC simulations with connected and encapsulated microcavities aligned in parallel with respect to the electric field direction are investigated to specify mechanisms of experimentally observable findings. For this purpose, simulations of single discharges are done. At the chosen parameters in the encapsulated cavities no field coupled streamer propagation can be seen. Also, at the chosen parameters in the connected cavities no field coupled streamer propagation can be observed by an opening outside the fall regions. Further investigations are planned e.g. with parallel multi cavities and connections near the fall regions.

6. ACKNOWLEDGEMENT

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REFERENCES

[1] M. Hilbert, M. Kurrat, “PIC-MC Simulation-Model for Microplasma-Propagation at Atmospheric Pressure in Cavities”, 19th International Conference on Gas Discharges and Their Applications, September 2nd – 7th 2012, Beijing, China

[2] M. Hilbert, M. Siemers, A. Pflug, M. Kurrat, “PIC-MC Simulations for Microplasma-propagation on Surfaces at Atmospheric Pressure Conditions”, 4. ETG-Fachtagung Grenzflächen in elektrischen Isoliersystemen, November 12th – 13th. 2013, Dresden, Germany

[3] M. Hilbert, M. Siemers, A. Pflug, M. Kurrat, “PIC-MC Simulations for Microplasma-propagation in Multiple Cavity Arrangements at Atmospheric Pressure Conditions”, 31st International Conference on Phenomena in Ionized Gases, July 14th -19th, 2013, Granada, Spain

[4] D. Koenig, Y. N. Rao, *Partial Discharges in Electrical Power Apparatus*, VDE Verlag, p. 79, 1993

[5] A. Dziubek, *Mikroplasmen in Kanälen bei Atmosphärendruck*, Cuvillier Verlag Göttingen, Dissertation, Braunschweig, 2009

[6] N. Lucas, *Microplasma Stamps – An Atmospheric-Pressure Plasma Source for the Area-Selective Modification of Surfaces*, Shaker Verlag, Dissertation, Braunschweig, 2009

[7] C. Roggendorf, M. Kessler, A. Schnettler, “Modification of the mechanical properties of epoxy resin with polymeric microspheres”, International. Symposium on High Voltage Engineering (ISH), Hannover, Germany, Paper, No. E-024, 2011

[8] C. K. Birdsall, “Particle-in-Cell Charged-Particle Simulations, Plus Monte Carlo Collisions with Neutral Atoms, PIC-MCC”, Trans. on plasma science, Vol. 19, No. 2, p. 65, 1991

[9] C. Schwanke, A. Pflug, M. Siemers & B. Szyszka, “Parallel Particle-in-Cell Monte-Carlo Algorithm for Simulation of Gas Discharges under PVM and MPI”, Lecture Notes in Computer Science 7133 (2012), p. 213-219

[10] K. H. Becker, U. Kogelschatz, et al. *Non-Equilibrium Air Plasmas at Atmospheric Pressure*, Institute of Physics Publishing, p. 247, 2005

[11] D. Benyoucef, M. Yousfi et. al., “PIC MC Using Free Path for the Simulation of Low-Pressure RF Discharge in Argon”, IEEE Trans. on plasma science, Vol. 38, No. 4, p. 902, 2010

[12] A. Cenian, A. Chernukho, C. Leys, “Particle-in-cell Monte Carlo (PIC-MC) simulations of plasma–wall interactions in low-pressure AR plasma”, Radiation Physics and Chemistry 68, p. 109, 2003

[13] D. Meschede, *Gerthsen Physik*, Springer, p. 466, 2006