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Report

on the dissertation presented by Aleksei Vladimirovich Siasko
Titled "The influence of thermal, kinetic, and radiation effects on constriction of a glow discharge in inert gases" submitted for the degree of candidate of physical and mathematical sciences, specialization 01.04.08 – "Plasma Physics"

In this thesis Mr. Siasko presents a very detailed and comprehensive study of the constriction phenomenon of the positive column plasma of glow discharges in the rare gases helium, neon and argon. Special emphasis is placed on the different impact of thermal, kinetic and radiation transport effects in these three gases. Experimental investigations are coupled with state-of-the-art theoretical approaches.

The topic is very attractive in view of the broad applications of glow discharges as light and radiation sources, where the constriction should be prevented in the operation in most applications. Moreover, the constriction effect also occurs in other low temperature plasmas, in atmospheric pressure non-thermal plasmas in particular, with an additional application range and a great potential for future applications e.g. for surface modification, thin coating and gas treatment at atmospheric pressure. Therefore, a more detailed inside into the constriction mechanism is highly desired.

The dissertation of Mr. Siasko is well written with clear and informative figures.

Mr. Siasko gives in chapter 1 of the thesis an appropriate introduction including a comprehensive literature review about the study and the present findings with respect to the constriction phenomenon in glow discharges. It has to be pointed out, that the review comprises studies starting with the pioneer work of Stark in 1902 and also a thorough summary of important works from the 1960s and 1970s.

In chapter 2 the experimental methods are explained. This comprises CCD imaging of the radiation intensities and the application of a Michelson interferometer for the determination of the radial gas temperature profile. In addition, optical emission spectroscopy is used to determine the radial electron density profile from bremsstrahlung continuum radiation and the radial profile of the rotational temperature of He molecules from molecular band spectra.

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The theoretical approaches applied in the work are explained in chapter 3. The electron kinetic equation is treated with two-term approximation in a local approach, and the resulting integro-differential equation is solved with applying some appropriate simplifications. A simple analytical expression for the excitation number is deduced. Finally, a model including the coupled solution of a simplified electron energy balance and the heat equation for neutral atoms.

Mr. Siasko presents the results of the experimental studies in chapter 4 with the focus on a comparison of the constriction phenomena in the rare gases neon, argon and helium. Important results concern the proof of the so-called optical constriction in helium in contrast to the constriction of the current path in neon and argon. The synchronous appearance of constriction and moving striations (ionization waves) is studied in neon in a pulsed regime. The measurements of the gas temperature behaviour in pulsed and stationary regime are compared with calculations, and a very good agreement of the time behaviour as well as of the radial profile has been obtained. The comparison of the temporal behaviour in neon and argon reveals the important role of the conversion of molecular atoms into molecular ions. The strong impact of heat convection in the constricted regime in argon has been investigated by the solution of a fluid equation system, and a good agreement with the measurements has been obtained here too. Finally, a helium glow discharge is studied with the interesting approach to compare the normal operation (in the free convection regime and with inhomogeneous heating) with a thermostatic regime in a water bath. Mr. Siasko could demonstrate that no constriction occurs in helium in the absence of inhomogeneous heating, whereas it occurs in argon and neon also without heating e.g. in the pulsed regime.

Chapter 5 is aimed at the discussion of the constriction mechanism applying the theoretical approaches from chapter 3. Mr. Siasko could prove the dominant kinetic effects in argon and neon by showing the strong differences in the rate of dissociative recombination and in the energy dependence of the cross section of elastic electron-atom collision, which lead to remarkable differences in the electron energy distribution and the excitation frequency. In contrast, for helium a theoretical description of the thermal constriction mechanism was deduced. With the help of a simplified balance equation system for excited levels and ions Mr. Siasko could successfully reveal the radial profiles of line radiation corresponding well to the measurements.

In chapter 6 Mr. Siasko presents a theoretical study of the impact of resonance radiation transport on the constriction phenomenon. He compares the Holstein effective lifetime approximation with a correct consideration of resonance radiation transport by a matrix method. In addition, the impact of higher diffusion and radiation modes is discussed. The coupled solution of equations for the ambipolar diffusion and the radiation transport have to be highlighted as an important step in the theoretical modelling of constricted discharges.

Altogether, in spite of the comprehensive preceding studies of the constriction in a glow discharge over many decades, Mr. Siasko could obtain a number of important and orginal results, which express the novelty of the work. It should be mentioned in particular:

- the experimental proof of the optical constriction mechanism in helium which occurs in the presence of inhomogeneous gas heating only and can be prevented by a thermostatic operation,
- the theoretical explanation of the optical constriction in helium by the description of the redistribution of neutral particles and an appropriate treatment of the excitation and ionization balance,
- the experimental proof and the theoretical explanation of the dominance of kinetic effects for the constriction in neon and argon by studies of stationary and pulsed regimes and by showing the specific features of the electron energy distribution, and
- the strict proof of the impact of resonance radiation transport on the constriction mechanism by solving a coupled system of the diffusion and radiation transport equations for the first time.

An impressive number of 6 papers in reviewed journals about the topic of the dissertation, co-authored by Mr. Siasko, verifies the high scientific level of the work and the international acceptance of the thesis results. It should be pointed out that 3 of these papers have been published in the journal Plasma Sources, Science and Technology, which is the journal with the highest impact factor among the journals for low-temperature plasma physics and technology.

A considerable benefit of the work is the strict coupling of experimental and theoretical approaches, and the high degree of agreement of the results verifying the applied simplifications. The application of state-of-the-art modelling approaches as well as complex measurement methods proves the high experience level of Mr. Siasko.

Despite of the imposing results, I have three remarks:

1. There is obviously a limited stability of a constricted column. How the changes in space and time have been treated in the experimental observations? What was the limitation for the acquisition time in CCD imaging, and what was the reproducibility, among others in the Michelson interferometry and in the spectroscopy?
2. What is the typical measurement uncertainty in the radial profiles of line intensity, continuum radiation and gas temperature? (Error bars are given in Figs. 4.15, 4.22. and 4.24 for the gas temperature – Are they representative for the other measurements of gas temperature too?)
3. The models allow the determination of the radial electron density profile. The approach of ambipolar diffusion can be used to calculate also the radial electric field. Is there any possibility in the presented theory to deduce the radial electric potential? And what have to be added to estimate the distribution of space charges in case of the constriction?

Altogether, this thesis deserves to be positively evaluated, and I propose granting of the candidate with the Degree of Candidate of Physical and Mathematical Sciences.

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