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Faculty of Physics

Magnetized plasma diagnosis by experimental and numerical methods

Habilitation thesis
ABSTRACT

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In this habilitation thesis I have synthesized the most important scientific results that I obtained in the last 16 years, after defending the doctoral thesis. The general topic of my research was magnetized plasma diagnosis, with two directions: experimental studies and numerical simulations. The thesis contains four chapters in which I described my professional evolution, the results of my experimental and numerical research and the career development plan.

In the **first chapter** I sumarized my education, teaching, research and other related activities. I did my bachelor's, master's and doctoral studies at the Faculty of Physics of "Alexandru Ioan Cuza" University of Iași (UAIC), being specialized in Plasma Physics. From September 1999 until now I have been employed at the Faculty of Physics of UAIC, as associate assistant, lecturer and associate professor. I have carried out a large spectrum of teaching activities in the field of physics, from fundamental disciplines, with wide addressability, such as *General Physics* and *Mechanics* (seminars and practical works), to specialized disciplines, specific to master studies, such as *Plasma Sources and applications*, *Current Topics in Plasma Physics* and *Transfer Phenomena* (courses and practical works). In addition, I have also teached interdisciplinary courses, such as *Biomechanics* and *Ecosystem and the interaction of matter with living organisms*.

I have coordinated over 20 undergraduate thesis and over 25 dissertations, both on experimental studies and on numerical modeling / simulations. I have contributed to the development of international collaboration relations with laboratories from various teaching and research institutions in France, the Netherlands, the Czech Republic, Austria, the Republic of Belarus. I have been invited to give lectures on plasma physics in the Republic of Belarus, the Czech Republic, at summer schools and in the co-tutoring doctoral program between "Alexandru Ioan Cuza" University of Iași and Shizuoka University of Japan.

In numerical modeling / simulations, I developed several numerical codes based on the following simulation techniques: Monte Carlo, Monte Carlo Flux, Particle-In-Cell (PIC), fluid model and collisional radiative model. I used these numerical codes to study the electron distribution function in non-magnetized weakly ionized plasmas, to describe the magnetron discharge plasma, the dielectric barrier discharge, to study the interaction of an electrical probe with a magnetized plasma, etc.

I have also been involved in experimental studies of magnetized plasmas, either laboratory plasmas such as the magnetron discharge, or fusion relevant plasmas such as tokamaks (CASTOR and COMPASS) or linear devices with magnetic confinement (Pilot-PSI and Magnum-PSI). In these experiments, I mainly performed the electrical diagnosis of plasma using different types of probes. I had two post-doctoral research contracts in Romania and one in France. I actively participated in events to promote the Faculty of Physics and physics in general and I was involved in organizing different scientific events (conferences, summer schools, workshops).

In the **second chapter** I detailed the main results that I obtained in the experimental research activity. For the diagnosis of thermonuclear relevant plasmas, I have collaborated with the Institute of Plasma Physics of the Czech Academy of Sciences in Prague, Czech Republic, and I addressed three topics: the diffusion of charged particles, direct measurements of plasma potential and ion temperature measurements. All measurements have been performed in the CASTOR tokamak. The diffusion of charged particles has been studied with a new technique, based on an idea proposed by professor G. Popa, which uses ball-pen probe measurements and involves the analysis of the power spectrum of turbulence in a certain geometry. The plasma potential has been measured directly with a Katsumata probe, and the ion temperature with a segmented tunnel probe and a Katsumata probe. The main conclusion about temperature measurements is that electrons and ions have about the same temperature at the outer limit of the tokamak core, but they have different temperatures in the edge region of the tokamak.

I have also collaborated with FOM Institute for Plasma Physics Rijnhuizen (FOM-IPP) in Nieuwegein, the Netherlands, which later became the Dutch Institute for Fundamental Energy Research (DIFFER). Together, we performed the electrical diagnosis of the plasma column in linear devices with magnetic confinement (Pilot-PSI and Magnum-PSI), using systems with a large number of probes (over 60). The reported results are unique in terms of Magnum-PSI plasma diagnosis. We measured the distribution on the target surface of the floating potential and the fluxes of charged particles coming from the plasma column, for a wide range of working conditions. We showed that, in the central part of the plasma column, the local floating potential is more negative than the floating potential of the target and at the edge of the plasma column the situation is reversed. As a result, the floating target collects an electron-dominated flux in the center and an ion-dominated flux at the edge. For this reason, and for the conductive surface to preserve its equipotential nature, there must be an electron flow inside the floating target. We showed how the spatial distribution of ion and electron fluxes changes when the target is biased. We have also found a surprising property of Magnum-PSI device, in terms of plasma column parameters: for different combinations of discharge current and magnetic field, the same radial distribution of the floating potential can be obtained, but with different distributions of the ion saturation current, or almost similar distributions of the ion saturation current can be obtained, but with very different distributions of the floating potential. The cross-correlation analysis of the fluctuations of the ion currents measured by the probes revealed the rotation of the plasma column, which is determined by the electric drift $E \times B$, the results being in good agreement with the spatial distribution of the radial electric field in the plasma column. Thus, we provided essential information for Magnum-PSI device that must be the basis of any plasma-surface interaction study.

I worked on the diagnosis of the magnetron discharge operated in high power pulses, a discharge known in the literature as High Power Impulse Magnetron Sputtering (HiPIMS). This technology has opened new perspectives in the production of advanced materials, in the form of thin layers, due to a high degree of ionization of the sputtered material in the discharge. We have investigated the pulsed magnetron discharge by the fast-imaging method. Unlike optical emission measurements, the fast-imaging technique allows distinguishing between the spatial and temporal dynamics of the local density of the excited species in the discharge. In order to increase the deposition rate in HiPIMS mode, we replaced the single pulse mode with a multi-pulse mode, obtaining very good results.

For plasma diagnosis with electric probes, I proposed two methods to obtain the current-voltage characteristic of an electrical probe by measuring a single time-dependent parameter, either the electric current collected by the probe or the potential of the probe. The second signal is obtained by calculation. The methods are called *integral* and *differential*, depending on the calculation formula. The two proposed methods were validated by experimental measurements, both in fusion-relevant magnetized discharges and in non-magnetized laboratory discharges. Both methods have the advantage of measuring a single signal, but they have the disadvantage of obtaining the characteristic in two steps. The proposed methods are suitable for experiments with a large number of probes as the required number of acquisition channels is equal to the number of probes. Also, the methods are very promising for fusion devices in which plasma is magnetically confined and only the ion branch of the probe characteristic is used for plasma diagnosis. In such cases, the proposed methods will be applied in one step.

In the **third chapter** I discussed the results of my numerical studies. Numerical simulation has become an important component of the scientific research, sometimes being as useful as the experimental or theoretical methods. I studied the process of sputtering of a metal target in a direct current magnetron discharge, using the fluid model developed during my PhD. The radial profile of the energy flux of the gas ions bombarding the target, calculated from the fluid model, was correlated with the erosion profile of the target and with the profile of the global light intensity emitted by the plasma. Also with the fluid model, I studied the influence of the working gas pressure on the spatial distribution of the neutral oxygen species in a magnetron discharge produced in the argon-oxygen gas mixture. At high pressures (3-4 Pa), the density of oxygen molecules in the ground state has a well-defined minimum located in the dense plasma zone (the region of the plasma ring corresponding to the negative light), where the density of excited oxygen species has a maximum. At lower pressures (~1 Pa), oxygen species exhibit a non-local behavior, losing the memory of the term source consisting in electronic collisions that are precisely located in the dense plasma zone.

In order to simulate the pulsed magnetron discharge plasma (HiPIMS), together with prof. T. Minea, I developed a two-dimensional PIC-MCC code. This was the first space-time simulation of a HiPIMS discharge reported in the literature, describing the evolution of plasma parameters during an ultra-short pulse (approx. 2 μs): plasma potential, electron and ion density, electron energy distribution function etc.

To understand the origin and evolution of spokes rotational phenomena, I have used the *a posteriori* Monte Carlo technique. The term spoke refers to a dense plasma structure that rotates azimuthally in discharges characterized by the presence of the electric drift $E\times B$. The simulation results support the theory that inside the spoke structures develops both an azimuthal electric field that prevents elongation of the structure in azimuthal direction and an axial electric field that helps reducing the electric field created by the plasma, resulting in decreased azimuthal drift velocity. The same *a posteriori* Monte Carlo technique allowed me to study the transport of electrons in a pulsed magnetron discharge, calculating two transport coefficients: the drift velocity and the diffusion coefficient.

I developed a Monte Carlo code to study the role of the ceramic holder on the probe current, when the probe is placed in a magnetized plasma and the probe characteristic exhibits a negative slope. The idea came out from the fact that the region with negative slope appears on the characteristic from a certain threshold of the magnetic field. The negative slope region appears due to an additional increase in the electron current when the probe is biased to a positive potential relative to the plasma potential. The probe captures the electrons reflected by the negative floating potential of the ceramic holder (dielectric material) surrounding the probe. The presence of the ceramic holder of the probe and the collisions with neutral atoms explain the additional increase of the electron current compared to the saturation current, but it does not explain the region with negative slope of the probe characteristic in which the electron current returns to the saturation current value. The subject is open to future investigations.

I performed a study on the distribution functions frequently used in the literature when simulating particles coming from a boundary surface of a plasma. I defined the isotropic and cosine angular distributions and I indicated the algorithms for their generation. I combined the angular distributions with three types of energy distributions and I compared the resulting distribution functions. I have also given examples of distribution functions that are incorrectly defined in the literature.

To fill in the gap in the literature, I studied the process of secondary electron emission in an oblique magnetic field. Using the Monte Carlo simulation method, I have analyzed the influence on the relative coefficient of the secondary electron emission of: the magnitude and tilt of the magnetic field, electric field in front of the surface, electron reflection, secondary electrons emission energy and angular distribution. Based on the analysis of the numerical results, I proposed an analytical formula for the relative coefficient of the secondary electron emission.

In the **fourth chapter** I described the objectives of my career development plan. The list of teaching objectives contains: updating electronic support materials for courses and practical works; writing a guide for plasma physics practical works in English; continuous guidance of undergraduate and master students; supervising doctoral students; updating the plasma physics laboratory; carrying out tutoring activities; compiling a collection of solved problems for plasma physics. Concerning the research activity, I have the following goals: creating a modeling / simulation group in plasma physics; simulation of the deposition process of nano-structured patterns; simulation of the pulsed magnetron discharge; thorough understanding of theoretical and experimental aspects of magnetized plasma diagnosis using electrical probes; optical diagnosis of fusion relevant plasmas; investigation of transport phenomena in fusion relevant plasmas; development of new tools for the diagnosis of dense plasmas; strengthening international collaborations.