SHEATH PROPERTIES AND RELATED PHENOMENA OF THE PLASMA WALL INTERACTION IN MAGNETIZED PLASMAS. APPLICATION TO ITER

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1. Introduction

The activity covered two main parts: i) experiments and data processing; ii) modelling.

Experiments and data processing. Experiments were made on Pilot-PSI machine at FOM-Institute for Plasma Physics "Rijnhuizen", The Netherlands and in Plasma Laboratory of the "Alexandru Ioan Cuza" University (UAIC), Iasi, Romania. Moreover, the main components used for plasma diagnostics were designed and manufactured at UAIC, Iasi.

Modelling. It should be mentioned that the modelling activity was carried out mainly at UAIC, Iasi but almost permanent contact and exchange of information were realized with our partners from the University of Innsbruck, FOM and IPP Prague, respectively.

2. Plasma diagnostics

2.1 Ion multi-channel analyser measurements in magnetised plasmas as Pilot-PSI

A new multi-channel analyzer with multi-collector system has been realized in order to measure time resolved distribution of the ion fluxes in the cross section of the plasma column of Pilot-PSI machine. The analyzer faces the plasma with a carbon plate of 26 mm diameter and 4 mm thickness in which 61 holes have been drilled. The holes are arranged in a concentric regular form, each hole having 0.5 mm in diameter. A ceramic plate fixes 61 collectors behind the carbon plate. Each collector is a 0.6 mm tungsten wire and is placed to correspond to a hole of the analyser carbon plate. The analyzer will be placed on the axis as target of the Pilot-PSI plasma column. It will provide 2D spatial distribution (polar-plane coordinates) of the ion flux as well as information about instabilities and rotation process of the plasma column. Measurements with the ion analyser are planned to be later performed also in Magnum-PSI. A period of documentation was considered to find good solutions for both a new data acquisition system and the corresponding software for simultaneously registering the 61 electrical signals provided by the analyzer.

Moreover, the microwave generator (2.56 GHz frequency and 1.5 kW power) has been considered for designing and manufacturing, at the Plasma Laboratory of the UAIC Iasi, a magnetized plasma device to produce a rather dense plasma column for testing the multi-channel analyser. The device will also be exploited for testing a new data acquisition system envisaged to be used for measuring the plasma parameters of the Pilot-Psi machine.

2.2 Experiments and results concerning diffusion model for Katsumata type probe and validation of the theoretical model

At the beginning of 2007 Castor Tokamak was decommissioned. Nevertheless, we have continued to analyse the large amount of data that were already taken in collaboration with IPP Prague and Innsbruck University groups to conclude if one can speak about diffusion process of the plasma particles inside the Katsumata type probe. The results were presented at the *7th International Workshop on Electrical Probes in Magnetized Plasmas*, Prague, Czech Republic, 22-25 July 2007 and later published within Contribution to Plasma Physics Journal. We also transferred the new Katsumata probe to Pilot-PSI to perform similar measurements concerning the diffusion model. The probe was used either as cylindrical probe (when the collector of the probe is outside the ceramic tube) or as Katsumata probe (when the collector is inside the ceramic tube). The interest is to measure the plasma potential and to compare the results with those obtained by a cold cylindrical probe and/or an emissive one.

Before performing Katsumata probe measurements, a cold cylindrical probe and an emissive one were used to obtain preliminary results on plasma parameters as: plasma potential, radial distribution of the electric field and ion density. The plasma source of Pilot-PSI (a cascaded arc) was operated in argon, hydrogen or argon-hydrogen mixture with a gas flow rate of 1 or 2slm (1slm ~ 4.48×10^{20}molec/s) and a total discharge current I_d of 80 to 150 A. The target was positioned at 56 cm from the nozzle of the arc source, the gas pressure in the vessel was in the range of 3 to 5 Pa and the magnetic field strength was 0.4 T for all measurements.

The cylindrical probe made of tungsten wire of 9 mm length was introduced at 3.5 cm in front of the target. The probe was movable in the radial direction with its axis parallel to the magnetic field lines. A linear ramp voltage of ±28 V sets the probe bias and the probe current was measured as a function of voltage across a 10 or 100 Ω resistor in the probe circuit.

At present there is no satisfactory model of the probe characteristic obtained in such experimental conditions, but ion saturation current I_{si}, floating potential V_f and plasma potential V_p might be obtained from these characteristics at least as relative values. These parameters can be used to evaluate, within the simplest model, at least two rotational drift velocities of the plasma beam: the electric drift velocity (calculated as $v_E = E_r/B$) and the diamagnetic drift velocity (calculated as $v_n = (kT/eB)*\nabla_r n/n$).

The electric drift velocity v_E was estimated using the radial electric field E_r derived from the radial distribution of the measured floating potential of the cold and hot probes. This velocity (E_r/B) characterizes the azimuthal drift of a collisionless or weakly-collisional plasma for which the ion collision frequency is much smaller than the ion cyclotron frequency. Assuming that the ion saturation current of the probe is proportional with the plasma density, one can write $\nabla_r n/n = \nabla_r I_{si}/I_{si}$ and the diamagnetic drift velocity v_n can also be evaluated. Comparing the radial profile of the calculated v_E with the plasma jet rotation velocity profiles measured by optical methods in hydrogen learns that the magnitude, the radial position of the maximum velocity and the profile width are similar, but the electric drift velocity is greater. The latter result appears because several effects as collisionality, viscosity, particles density and electric field gradients are not considered when calculating v_E. The diamagnetic drift velocity has the same order of magnitude as v_E in argon, while it is one order of magnitude lower for hydrogen plasma.

The fluctuations of the current intensity measured either on the probe or on the target can be associated with possible instabilities of the drift motion previously described. Also, the fundamental frequencies in the power spectrum of the current fluctuations (approximately 6.5 MHz for H_2 and approximately 80 kHz for Ar) are comparable to the ion-cyclotron frequency.

The emissive probe (tungsten wire of 0.35 mm diameter) in form of a rectangular loop is also radially moveable and it was inserted into the vessel at about half the distance between the arc-source and the target. The active part of the loop, of 3 mm length, was oriented parallel to the magnetic field lines. The experiments showed that inside the plasma column ($r \leq 5$ mm), both emissive and cold probe measure the same floating potential, which is approximately equal to the plasma one. This result proves that in such dense plasmas (approx. 10^{20} m^{-3}) even a cold probe becomes emissive under charged particles bombardment and the measured floating potential can be a good approximation of the plasma potential. The effect of what we called "self-heated" (or "self-emissive") probe-plasma system was investigated in Plasma Laboratory of UAIC, Iasi using dense and magnetised plasma of a magnetron discharge. The results were used for designing and manufacturing the system for the diagnostic of the plasma potential of the Pilot-PSI experiment.

Electrical measurements in Pilot-PSI allow the estimation of the power density transferred from the plasma to the target. The obtained power values (approx. 0.6 MW/m^2) confirm that Magnum-PSI will be able to operate at ITER relevant parameters for plasma surface interaction at the divertor. Probe measurements show that plasma parameters are significantly different for Ar and H_2. The presence of the radial electric field determines the appearance of a drift instability, which may enhance radial particle losses and consequently diminish the energy transferred from the plasma to the target.

The Katsumata probe realized within the UAIC has been installed in the same plasma region as the emissive probe. This time the collector of the Katsumata probe was placed inside the ceramic tube, so that two series of measurements have been realized: the first series was related to the plasma instability and the second one to the plasma potential. The former data are used within our proposed diffusion model, while the latter data are related to radial distribution of the plasma potential. These data are under evaluation.

2.3 Secondary electron emission at the probe (and wall) surface. Final form of the experimental model and device using multi-polar confinement system

The final form of the experimental device for the investigation of the secondary electron emission (SEE) induced by electron bombardment was finished in 2006. The performances of the data acquisition system have been expanded at the beginning of 2007, by using a new acquisition board and by enlarging the range limits for data registering. The secondary electron emission was studied on the current-voltage (I-V) characteristics of a plane probe bombarded by a mono-energetic electron beam. The beam energy was adjustable in the range of 50 to 400 eV. The contribution of the secondary electron emission was evidenced by the increase of the probe current intensity in the ion branch of the I-V characteristics. The electrons bombarding the probe with low energy (less than the threshold energy of the primary electrons that may produce SEE) could not be relieved on the I-V characteristics. This is due to an electrostatic mirror effect that appears between the electron gun exit and the strongly negative probe surface, which has to be considered in the quantitative estimation of the SEE effect on the probe characteristic.

On the purpose of exceeding this experimental inconvenient, the next step is to modify the construction of the electron gun to obtain a better collimated primary electron beam. The experiments were realized in residual gas (no gas inserted in the vessel). Further measurements will be realized in the presence of argon or helium plasma.

3. <u>Modelling of the formation of the space charge sheath in front of a conductive wall</u>

3.1 Computer set-up for plasma numerical simulation

A dual processor computer was installed at UAIC, Iasi for plasma numerical simulations. This computer is able to support remote access and handling from all over the world using a secure Internet network for all registered users. A parallel compiler named LAM/MPI, a high-quality open-source implementation of the Message Passing Interface specification (http://www.lam-mpi.org/), was implemented for future plasma simulation codes. Kinetic (PIC) simulations algorithms, based on **Bit1** PIC-MCC code developed at the Institute for Theoretical Physics, University of Innsbruck, were written in C for Unix/Linux platforms aiming the code parallelisation. The Unified Modelling Language (UML) will be used to identify within the algorithms further possible locations where parallel programming can improve the computation time.

3.2 Numerical investigation on the formation of the floating space-charge sheath in the Pilot-PSI plasma and obtaining the floating potential of the target

Kinetic (PIC) studies of plasma-wall interaction in the Pilot–PSI machine working with H_2 plasma were performed. The previous linear 1D-PIC-MCC code was written only for atomic hydrogen plasma, so the main aim of this task was to complete the code with elementary processes specific for molecular hydrogen plasma. Fourteen new elementary processes involving H_2 were implemented in the Monte-Carlo collision routine.

For the initial investigations, the model included a floating solid conductive target interacting with a plasma column having similar parameters to the above-mentioned experimental device: plasma density $n_0 = 4\times10^{19}$ m^{-3}, electron temperature T_e = 12 eV, ion temperature T_i = 2 eV, H_2 neutral density $n_n = 10^{21}$ m^{-3} and magnetic field B = 0.4 T.

The injection conditions corresponding to Pilot-PSI plasma source are imposed to one boundary of the modified PIC 1D-code while the floating space-charge sheath is investigated at the second boundary. The calculated value of the steady-state floating potential is about -50 V with respect to the plasma potential. Other numerical simulations were performed considering the secondary electron emission at the floating boundary as an additional process.

A parallel code that can run on multiprocessor machines is envisaged in order to improve the numerical performances. The first step has been prepared by recompiling the old code with a parallel compiling tool to support multiple CPUs. This work is in progress and preliminary tests give a reduction of the computing time of about 20% on 2 dual core processors machine (total of 4 CPUs) from Iasi.

3.3 Kinetic (PIC) in the process of floating space-charge sheath formation

The plasma parameters used for the numerical modelling correspond to SOL (Scrape of Layer) region of a tokamak device ($T_e = T_i$ = 20 eV, $n_e = n_i = 10^{18}$ m^{-3}). The magnetic field strength B varied between 0 and 1T. The Φ angle between the magnetic field direction and the normal to the conductor surface varied from 0 to 90 degrees. Additionally, simulations for Pilot-PSI plasma parameters were also conducted.

Three different cases have been considered: (a) B = 0 T; (b) B = 1 T and Φ = 0 deg and (c) B = 1 T, Φ = 45 deg. The case without magnetic field and the one with magnetic field perpendicular to the wall are similar. In contrast, the potential distributions within the sheath are considerably perturbed in the case of a magnetic field inclined at 45 deg. This is due to the fact that the plasma flow is no longer in the direction of the observation. During sheath formation different types of waves are excited, crossing the magnetic field lines. The spectrum of these waves reveals the electron plasma oscillation. In the case of the inclined magnetic field, two frequencies are evidenced: the lower and the upper hybrid frequency. The results of the PIC simulation and the analytic computation of these frequencies agree up to the third digit.

The observations and conclusions resulted from our floating-sheath formation investigations are applicable for a large variety of plasma parameters. Currently we investigate more complex models that include other collisions and surface processes.

4. Development of a 2D fluid model for Pilot-PSI

4.1 Writing and solving the fluid equations for electrons, positive ions and neutrals

The numerical code is first applied for argon. Three types of particles are considered in the model: neutrals, electrons and positive ions (Ar^+). Fluid equations were written for electrons and ions, considering that the neutrals spatial distribution is homogeneous in the vessel. This first approach neglects the neutrals flow. The discharge is supposed to be azimuthally symmetric, thus only radial and axial treatment is considered.

The solving of the fluid equations requires proper choice of the boundary conditions (in our case for potential and for particle fluxes). The spatial domain chosen for modelling has four types of boundary: the chamber walls, the target, the entrance of the gas and plasma in the vessel which corresponds with the exit of the cascaded-arc source and the gas exit to the pumping system. While the conditions for the first two boundaries are clear, the conditions for the last two boundaries had to be investigated.

4.2 Testing different boundary conditions for the potential at the gas entrance

Regarding the potential boundary conditions, the chamber walls are grounded and the target can be biased with respect to the ground. The cascaded-arc plasma source fixes the discharge current by adjusting the applied voltage. The radial distribution of the potential at the source exit is unknown (no experimental data are available) and thus a boundary condition had to be found for the model. For that, a stationary plasma beam was considered in the discharge chamber (corresponding to the imposed discharge current) and different potential distributions were tested for the exit of the cascaded-arc source. The general conclusion is that the spatial distribution of the potential in the discharge chamber strongly depends on the charged particles distribution. The latter one is related with both charged particle fluxes and the potential boundary condition at the plasma source exit.

4.3 Testing different boundary conditions for the particle fluxes

By neglecting the neutrals flow, as a first approach, no boundary conditions have to be imposed for the neutrals flux. Electron and ion fluxes have to be chosen at the gas entrance with respect to the discharge current. Knowing that the plasma expands from the source into the vessel, it is expected that both electron and ion fluxes are inward directed. Yet, two different conditions can be imposed: (1) equal electron and ion fluxes; (2) different electron and ion fluxes. At the gas exit both electron and ion fluxes are outward directed. A first approach is to write both electron and ion fluxes as they are for the case of a wall: each flux has two components, a drift and a thermal one. This task is under development.

5. Collaborative actions

The research topics described in the sub-paragraph 2.2 and in the paragraph 4 were realised in collaboration with FOM-Institute for Plasma Physics "Rijnhuizen", The Netherlands, Association EURATOM/FOM. The experimental results and some numerical developments were obtained during our team member missions/mobilities at FOM.

A part of the research topics described in the sub-paragraphs 3.2 and 3.3 were realised during our team member mobilities at Theoretical Plasma Physics Group, Innsbruck University, Austria, Association EURATOM-ÖAW.

Publications

[1] **J. Brotankova, E. Martines, J. Adamek, J. Stockel, G. Popa, C. Costin, C. Ionita, R. Schrittwieser, G. Van Oost,** "*Novel Technique for Direct Measurement of the Plasma Diffusion Coefficient in Magnetized Plasma*", *Contributions to Plasma Physics* **48**(5-7) (2008), pp. 418-423

[2] **J. Adamek, M. Kocan, R. Panek, J. P. Gunn, E. Martines, J. Stöckel, C. Ionita, G. Popa, C. Costin, J. Brotankova, R. Schrittwieser, G. Van Oost,** "*Simultaneous Measurements of Ion Temperature by Katsumata and Segmented Tunnel Probe*", *Contributions to Plasma Physics* **48**(5-7) (2008), pp. 395-399

[3] **M. L. Solomon, Steluta Teodoru, G. Popa, "***Secondary electron emission at Langmuir probe surface***",** *Journal of Optoelectronics and Advanced Materials* **10**(8) (2008), pp. 2011–2014

Conferences

[1] **C. Costin, V. Anita, R. S. Al, B. de Groot, W. Goedheer, A. W. Kleyn, W. R. Koppers, N. J. Lopes Cardozo, H. J. van der Meiden, R. J. E. van de Peppel, R. P. Prins, G. J. van Rooij, A. E. Shumack, M. L. Solomon, W. A. J. Vijvers, J. Westerhout, G. Popa,** "*On the power balance at the end plate of the plasma column in Pilot-PSI*", 34th EPS Conference on Plasma Physics, Warsaw, Poland, 2-6 July 2007

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[4] **M. L. Solomon, R. S. Al, V. Anita, C. Costin, B. de Groot, W. Goedheer, A. W. Kleyn, W. R. Koppers, N. J. Lopes Cardozo, H. J. van der Meiden, R. J. E. van de Peppel, R. P. Prins, G. J. van Rooij, A. E. Shumack, W. A. J. Vijvers, J. Westerhout, G. Popa,** "*On the self excited instabilities in the plasma column of Pilot-PSI*", 14th International Conference on Plasma Physics and Applications (CPPA), Brasov, Romania, 14 – 18 September 2007

[5] **M. Solomon, V. Titon, C. Andrei, G. Popa,** "*High density magnetised plasmas by self emissive probe*", 14th International Conference on Plasma Physics and Applications (CPPA), Brasov, Romania, 14 – 18 September 2007

[6] **C. Lupu, C. Agheorghiesei, D. Tskhakaya, S. Kuhn, G.Popa,** *"Modelling by PIC code the time evolution of the floating potential of the plate electrode ending a high density and magnetized plasma column",* 14th International Conference on Plasma Physics and Applications (CPPA), Brasov, Romania, 14 – 18 September 2007

[7] **M. L. Solomon, Steluta Theodoru, G. Popa,** "*Secondary electron emission at Langmuir probe surface*", 14th International Conference on Plasma Physics and Applications (CPPA), Brasov, Romania, 14 – 18 September 2007.