Self-consistent particle-in-cell simulations of a collisional magnetized plasma-wall transition

D. Tskhakaya* and S. Kuhn

Plasma and Energy Physics Group, Department of Theoretical Physics, University of Innsbruck, Innsbruck, Austria

**Permanent address: Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia*

In recent years, significant efforts have been made towards the investigation of the plasma-wall transition (PWT) region (see [1], [2] and references there). The PWT is present in practically all plasma devices, extending from the bulk plasma to the material wall. This region, which controls the particle and energy fluxes to the wall, plays an extremely important role in fusion plasmas, where these fluxes can determine the impurity release rate from the wall and the lifetime of the wall components. Generally speaking, a magnetized PWT consists of three subregions (Fig.1): a collisional presheath (CPS), a collisionless magnetic presheath (MPS), and a collisionless non-neutral Debye sheath (DS). In each of these regions, the plasma behavior is governed by different physical processes, resulting in different characteristic scale lengths of these subregions and making practically impossible the complete analytical treatment of the PWT. Typically, these scale lengths are the charged-neutral collision mean free path l_c for the CPS (here we do not consider the case when the CPS is influenced by strong anomalous diffusion [3], or device geometry [1]), a few ion Larmor radii ρ_i for the MPS, and a few Debye lengths λ_D for the DS. Fortunately, at least in the fusion plasmas these scales differ strongly and the PWT subregions can be treated separately to some extent [1], [2]. To match the corresponding solutions together, the marginal forms of the well-known Bohm condition [4] (associated with the DS edge),

$$V^i_{Dse} = C_s \ , \tag{1}$$

and of the Bohm-Chodura condition [5] (associated with the MPS edge),

$$V^i_{mpse} = C_s \sin\theta \ , \tag{2}$$

are used. Here, V^i_{Dse} and V^i_{mpse} are normal (to the wall) components of the ion fluid velocity at the DS and the MPS edges, respectively, and $C_s = \sqrt{(T_i + T_e)/m_i}$ is the ion sound speed.

In contrast to the unmagnetized plasma, where the Bohm condition can be derived using kinetic analysis [6], conditions (1) and (2) for the magnetized plasma were obtained from fluid models which makes them questionable. Strictly speaking, these conditions have to be obtained from a complete kinetic model of the PWT.

The aim of the present work is to simulate a one-dimensional magnetized electrostatic PWT including all subregions self-consistently. Special attention is paid to the Bohm and

Bohm-Chodura conditions. For this purpose we use the 1d3v particle-in-cell (PIC) code BIT1, developed on the basis of the XPDP1 [7] code from the University of California at Berkeley.

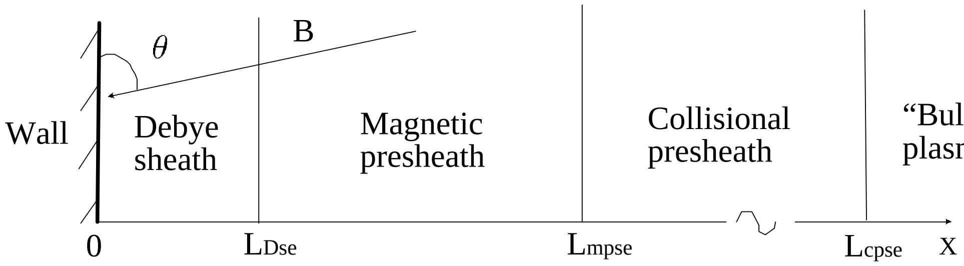

Figure 1: Structure of the magnetized electostatic PWT. The x axis is normal to the wall surface. The points L_{Dse} ($\simeq 5\lambda_D$), L_{mpse} ($\simeq 10\rho_i$) and L_{cpse} ($\simeq l_c \sin\theta$) denote the Debye-sheath, the magnetic-presheath, and the collisional-presheath edges, respectively. We consider the case $L_{Dse} \ll L_{mpse} \ll L_{cpse}$.

We consider a hydrogen plasma, taking into account elastic and charge-exchange collisions between ionic and atomic hydrogen. The plasma parameters at the CPS edge are chosen so as to be relevant to tokamak conditions: magnetic field strength $B = 1\,T$, angle between the magnetic field and the wall $\theta = 5^\circ$, plasma density $n_{cpse} \approx 10^{18}\ m^{-3}$, electron temperature $T^e_{cpse} = 30\ eV$, and ion temperature $T^i_{cpse} = 15\ eV$. In order to ensure high accuracy, a very large number of simulation particles is used, ~ 1600 per spatial grid cell. The total number of spatial grid cells is 400. During the simulation, the electron and ion motions are fully resolved. The atomic-hydrogen fraction represents a fixed background. In order to shorten the simulation region and, accordingly, to speed up the simulation, a high atomic-hydrogen density of $2\times 10^{19}\ m^{-3}$ is assumed. The simulation region extends from the wall ($x = 0$) to the CPS edge ($x = L_{cpse} = 1.2\ cm$ Fig.1).

During the simulation, Maxwell-distributed electrons and ions are injected at $x = L_{cpse}$ ("injection plane"). The related fluxes are adjusted so as to ensure quasineutrality and to avoid an artificial source sheath at the injection plane. After a few ion transit times $L_{cpse}/\sin\theta\sqrt{T_i/m_i}$, the system reaches a stationary state. The profiles found for the plasma parameters, averaged over a few plasma oscillation periods, are given in the Fig. 2. The fluctuations of the averaged values are about $2 \div 3\%$ (and do not exceed 5%). In Fig. 3, particle distributions at different spatial locations are shown. As expected, the PWT is seem to consist of three subregions (Fig. 2). The smallest one is the DS with strong gradients of the plasma parameters (except the temperature). The DS edge (L_{Dse}) can be recognized as the end of the quasineutral region (Fig. 2d), and the width of the DS is about $5\lambda_D$. The next subregion, the MPS, is practically isotermal (Fig. 2g) and characterized by an electric field that is still strong (Fig. 2b). In contrast to the DS-MPS transition, the transition between the MPS and the CPS is smooth and there exists no clear boundary. We *propose* to define the MPS edge (L_{mpse}) as the point where the Bohm-Chodura condition is marginally satisfied. The width of the MPS is about $9\rho_i$. The last subregion is the CPS with a weak electric field and a strong ion-temperature gradient.

The fact that the electron temperature is practically constant across the PWT is in agreement with our assumption of collisionless electrons. Moreover, as shown in Figs. 3a)-c), the electron distribution can be well approximated by a Maxwellian. Also, the ion distribution at the MPS edge can be approximated with a shifted Maxwellian (Fig. 3d).

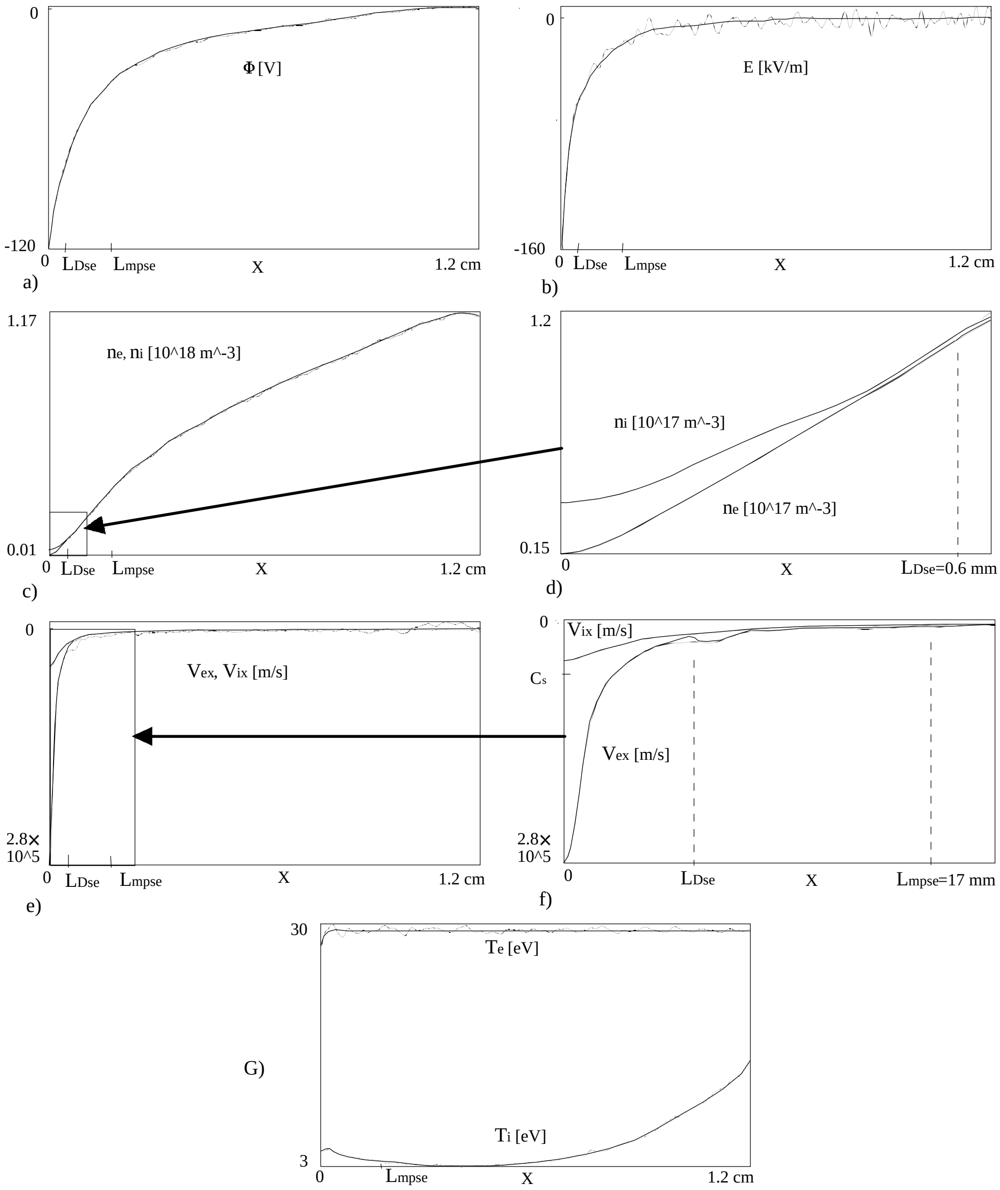

Figure 2: Profiles of different plasma parameters in the PWT region: a) potential Φ, b) electric field E, c) and d) particle densities n_e and n_i, e) and f) normal components of the fluid velocity V_{ex} and V_{ix} , and g) Temperatures T_e, T_i.

We wish to note that the self-consistent results presented here confirm some well-accepted properties of the PWT which were obtained from theoretical analysis or from numerical simulations that were not completely self-consistent ([1], [2]). Nevertheless, we found out one important new property: the normal component of the ion fluid velocity is subsonic everywhere inside the PWT (Fig. 2f). Hence, the Bohm condition is not satisfied at all. This result is also confirmed by the ion velocity distribution at the DS edge (Fig.

3e): The distribution function does not vanish at zero velocity as required by Bohm's condition in its kinetic form [6]. It seems that in general the influence of the magnetic field on the DS cannot be neglected and the Bohm condition, which was obtained for unmagnetized plasma, is not well applicable in the magnetized case.

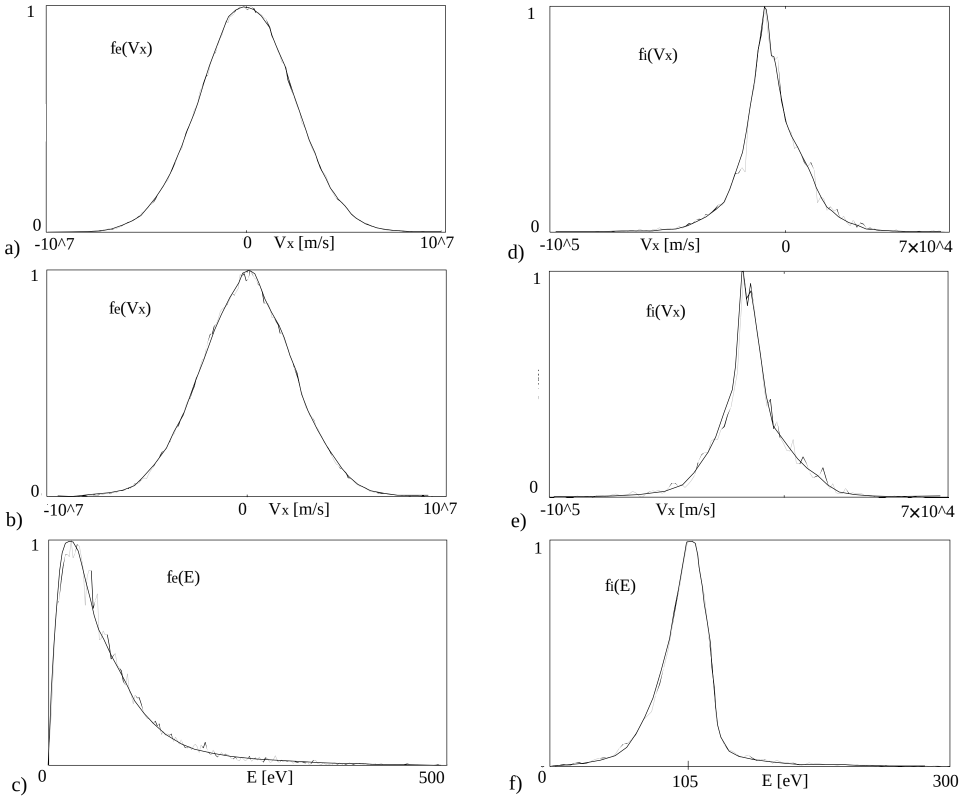

Figure 3: Electron (ion) velocity distribution at the magnetic presheath a) (d)) and Debye sheath b) (e)) edges. Energy distribution of electrons c) and ions f) absorbed at the wall.

This work was performed within the Association EURATOM-ÖAW and supported by Austrian Research Fund (FWF) contract P12477-TPH.

[1] P.C. Stangeby, The Plasma Boundary of Magnetic Fusion Devices, IOP, Bristol and Philadelphia, 2000.

[2] K.-U. Riemann, J. Tech. Phys. **41** (1), 89 (2000).

[3] I.H. Hutchinson, Phys. Fluids, **3** (3), 847 (1991).

[4] D. Bohm, Characteristics of Electrical Discharges in Magnetic Fields, edited by A. Guthrie and R. Wakeling, McGraw-Hill (1949).

[5] R. Chodura, Phys. Fluids 25, 1628 (1982).

[6] E.R. Harrison and W.B. Thompson, Proc. Phys. Soc. London, 74 145 (1959).

[7] J.P. Verboncoeur, M.V. Alves, V. Vahedi, and C.K. Birdsall, J. Comput. Phys. **104** (2), 321 (1993).