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Towards Possible Control of Plasma Outflow in Fusion-Relevant Devices via Employing Virtual Terminating Surfaces

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ABSTRACT

High thermal-load and particle-bombardment damages, accompanied by increased plasma contamination in tokamaks, still remain intrinsically present and difficult to resolve, even with advanced configurations such as Snowflake or Super-X. Our idea is to definitely replace divertor plates with a immaterial, represented by double layer structures (DLs) in conjunction with a relaxer plasma capable of keeping the SOL ions trapped/confined sufficiently long for their energy to dissipates there via volume (rather than surface) processes. Possibilities of establishing a "virtual plate", as the main surface for outflow of ions are investigated via particle in cell (PIC) simulations.

1 INTRODUCTION

Plasma-boundary interaction can manifest via either "clean" and/or "impure" features and effects. The term "clean" here means that no new kind of atoms, ions or molecules appear near/at the boundaries, except those which primarily originate from the plasma. Some basic such effects (besides diverse particle-particle interactions) are particle-field-particle and particle-surface transfers of moments. Second "clean" effect is neutralisation of ions at the wall and their free reflection back to the plasma, and/or the ion absorption/implementation into the solid surface. Depending on plasma density, reflected neutrals can be again ionised, i.e., to become the "recycled" ions. In fusion devices increased recycling may lead to formation of a region of plasma located near the main ion outflow surface (divertor), well "detached" from the material, in which volume processes, start to dominate dissipation of kinetic ion energy at the surface. The recycling and detachment regimes are highly desirable in fusion devices, since the plates are better protected from damages (such as arcing and erosion), and the plasma is better protected against contamination, (e.g., sputtering and dilution originated from the material). Physics description related to the plasma-wall transition and interaction during low (sheath-limited – radially 1D) and high (conduction-limited – parallel to flow 1D) recycling, layer detachment (intense – parallel to flow 1D, conduction-limited, with strong parallel "cooling", i.e., energy detachment) and "flame"-detached (complete detachment, intrinsic 2D, complete momentum detachment with strong reduction of particle flux to plate) is extremely demanding (see e.g., Refs. [1, 2]). Simulations of tokamak SOLs via 2D codes such as SOLPS-B2 require additional CPU-expensive modules for properly simulate neutral transport represented by e.g., 3D Monte-Carlo EIRENE code (see e.g., Ref. [3] and references therein). Finally, engineering aspects appearing with installing divertor plates are very untrivial and become even more and more demanding with each new "movement" of the plates further from X-point (e.g., in very promising snowflake divertor geometry [4]). Therefore the idea emerges to get rid of the plasma-divertor interaction problems in fusion devices, and also to reduce contamination in e.g., technology plasmas via simple proposing a ”virtual plate”, i.e., a DL-structure, as the main surface for outflow of ions. Possibilities of establishing conditions for their formation are investigated. Present investigation is, in fact, aimed towards elaborating on H. Alfvéns ”first-principle’ statement ”that a double layer is a plasma formation by which a plasma in the physical meaning of this word protects itself from the environment...” [5], and at applying it to the scrape-off layer (SOL) plasma in a Tokamak device. For the present purposes we use the term double layer (DL) for a localised (within several Debye lengths) collisionless, steady electrostatic structure separating/joining two quasi-neutral plasmas at different potentials, such that ions from the low-potential plasma and electrons from the high-potential plasma can hardly cross the DL to the respective other side. Crudely speaking, this ”scenario” is similar to, e.g., quiescent H-modes which are characterised by the appearance of a sharp radial electric field between the core and SOL plasmas (see e.g., Refs. [2, 6]). The core plasma is thus ”safely protected” by a DL structure, being embedded in the SOL plasma, which hosts ”disobedient” (i.e., escaping) core ions rather than permitting them to hit the fusion-chamber walls. On the other hand, the SOL plasma is terminated on the far side by solid plates (divertors) which, when electrically biased, to a certain extent enable controlling recycling, impurity production [7] and energy transport [8], and reduce divertor heat load [9]. Anyway, high-thermal-load and particle-bombardment damages, accompanied by increased plasma contamination, still remain intrinsically present and difficult to resolve, even with advanced snowflake configurations [4]. Our idea is to definitely replace divertor plates with a DL in conjunction with a ”relaxer” plasma capable of keeping the SOL ions trapped/confined sufficiently long for their energy to dissipates there via volume (rather than surface) processes. This will require additional separate chamber(s) (relaxer(s)), probably with ”magnetic electrostatic plasma confinement” method (see e.g., Ref. [10] and references therein), together with some additional control of bulk-plasma parameters. Our idea is symbolically presented in Fig. 1 via two examples of a tokamak cross-section, each configuration consisting of two toroidal chambers located one above another. In configuration from Fig. 1(a) the inner and outer SOL branches are ”merged” while Fig. 1(b) shows a ”standard” scenario with X-point. In the configuration shown on the left, the SOL-plasma ions are expelled through just a single DL into the relaxation cage(s), while the right-hand option is a ”regular” (i.e., double-ended SOL) case with two such cages, ”mimicking” the standard divertor plates. In any case, within this proposal the cages walls and inner plates are equipped with independent DC sources (not shown in the right-hand option) for controlling the relaxation-plasmas potential. In the latter option, the advantage of asymmetric biasing and maintaining the poloidal SOL current is retained from the standard divertor-plate concept. Note, however, that the divertor plates in both options have been removed and replaced with DL-structures. Since their role is foreseen to ”trap” any kind of impurity

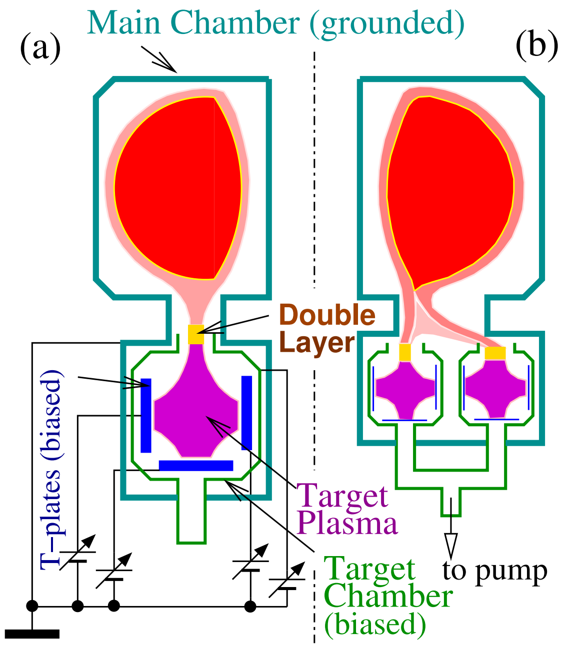

Figure 1: Two examples of a tokamak cross-section, each consisting of two toroidal chambers one above another.

arising from plasma-wall interaction, as well as the SOL-ions, without considerable acceleration of the last ones, the potential drop should be not stronger than necessary for assuring the trapping. This is a condition that can be probably easily achieved by trial and error method in a sufficiently versatile experimental non-magnetised double-plasma device, e.g., via tuning the relaxer plasma potential by help of additional beam electrons. However, at the moment one may not think about feasibility of a tokamak-device for such purposes, so that understanding of DLs in magnetised plasmas is a complex problem under permanent experimental investigations primarily in astrophysical plasmas (see e.g., Ref. [11] and references therein) which is hard to deal with theoretically or via numerical simulations, unless considerable simplifications about the problem geometry and particle velocity distributions have been made (see e.g., Ref. [12]). Still there is a huge number of free parameters entering the boundary conditions at the edges of a DL in present approaches, that might be reduced providing an integral plasma-DL-plasma-external circuit system is simulated. This approach is pursued bellow.

2 A BASIC SCENARIO LEADING TO DL FORMATION

Elementary considerations on a DL formation can be performed starting from the Tonks-Langmuir model [13] modified due to presence of electrons emitted from the wall with negligible initial velocity [14]. With increased their density such electrons can modify considerably the sheath potential profile $\Phi(z)$ in accordance with expression:

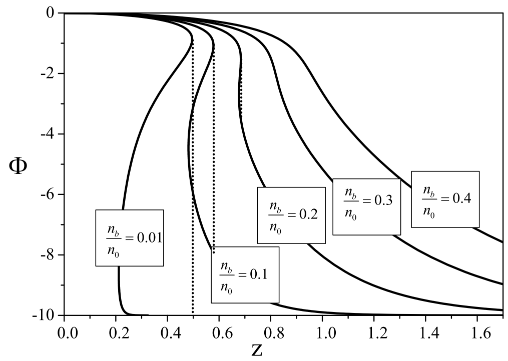

Figure 2: The potential profile in the Tonks-Langmuir model modified due to presence of "cold" electron "beam" with negligible initial velocity. Due to symmetry of the problem only the right-hand half of the discharge is shown.

$$z \equiv \frac{z}{L} = -\frac{1}{L}\frac{1}{m_i}\int_0^{e\Phi} \frac{f_i(\Phi')d\Phi'}{s_i(\Phi')} = \frac{1}{s_{i0}L}\Gamma_i(\Phi)$$

where the ion flux is given by

$$\Gamma_i = n_0\sqrt{\frac{kT_e}{m_i}}\frac{2\sqrt{2}}{\pi}\left[N\sqrt{\Phi_b}\ln\frac{\sqrt{\Phi_b}+\sqrt{\Phi}}{\sqrt{\Phi_b-\Phi}} + D(\sqrt{\Phi})\right],$$

$D(y)$ is the Dawson function, L is the system length, m_i the ion mas, s_i the ionization source strength, $N \equiv n_b/n_0$ the ratio of beam and bulk electrons at the centre of discharge, k the Boltzmann constant T_e the electron (Boltzmann distributed) temperature and $e(\Phi_b - \Phi)$ is the (local) electron-"beam" energy acquired due to self-consistent electric field. The potential profiles obtained for various density ratios N are shown in Fig. 2 apparently showing formation of a DL of variable potential drop of which strength depends on N. Closer inspection of the ion velocity distribution function (VDF), however, shows that it is a rather artificial, uniquely defined (mathematical) expression [14] (consisting of a "bulk" population plus a sharp spike), which is a result of mathematical self-consistency of the Vlasov-Poison problem. In nature and practice one does not need either of particular potential-profiles and such VDFs but rather two "flat" plasma regions separated/joined with a DL structure. That means that one has to adjust the parameters of the low-potential plasma with additional *producing* ion and/or electron populations, in order to really provide the "missing" bulk-ions from the model, and/or to control the electron beam density and also the DL potential drop in a predictable manner. Thus it turns out that a DL problem should be modelled and solved in an integral manner together with adjacent plasmas, as follows.

3 SIMULATIONS

In Fig. 3 we illustrate the "conventional" principle of terminating a SOL-plasma ion-outflow by solid divertor plates (Fig. 3-a) in comparison with the proposed method of "hosting" the outflowing ions in another plasma (relaxer) (Fig. 3-b) Simulating scrape of layer is, usually, performed via fluid codes such as SOLPS-B2, (see e.g., Ref. [3]), which are based on solving the Braginskii-equations [15] in toroidal coordinates. The problem with applicability of fluid approach appears at the SOL boundaries, i.e., in the vicinity inner and outer plates, where thermodynamic equilibrium fails. Therefore the boundary conditions could not be defined at the plates but rather at a characteristic point (surface) inside the quasi-neutral plasma, known as the plasma-sheath boundary, which is conventionally formulated as the point along the ion-outflow after which no ion-sound (low-frequency –long wavelength perturbation) can propagate from the sheath region into the quasineutral plasma. Determining this (sonic) point is an intrinsically kinetic task which requires theoretical calculation of an "exotic" quantity $\int v^{-1}\partial f_i(v)/\partial v$, the ion velocity distribution (VDF) $f_i(v)$ has to be either calculated self-consistently for the discharge under consideration, or known from experimental and/or numerical simulation data. The task remains, how to link this quantity with an experimental observable such as the *directional* ion mean (fluid) velocity. From the theoretical point of view, this is an almost one century old task, that has been solved for so-called Tonks-Langmuir (TL) model only under considerable simplifications, leading to the explicit directional ion velocity only recently in both "cold" [16, 17] and "warm" [18, 19] ion-models, which are applicable only in direction of ion flow aligned to magnetic field lines. The key quantity of interest for quantitative description of the plasma-sheath boundary, entering the ion-sound velocity c_S, or equivalently, the ion directional velocity $u_i^2 \equiv c_S = (kT_e^2 + \gamma_i kT_i)/m_i$ turned out to be the *local* polytropic coefficient function $\gamma_i = d(\ln T_i)/d(\ln n)$, (with $T_{i,e}$ the ion and electron temperature, k the Boltzmann constant and $n = n_i = n_e$ the plasma density at the plasma-sheath boundary, and m_i the ion mas) which, before the seminal work from Ref. [16], in standard plasma textbooks and applications has been by rule considered to be a constant ($\gamma = 1$, $\gamma_P = 5/3$ and $\gamma_P = 3$ for isothermal flow, adiabatic flow with isotropic pressure and for adiabatic one-dimensional flow, respectively). Situation with a simple sheath ("single layer") is usually complicated by deviations of the electron VDFs from Maxwellian, so that the electron temperature in the Bohm criterion should be replaced with so called "screening temperature" $kT_e^* \equiv en_e\left(\frac{dn_e}{d\varphi}\right)^{-1}$ i.e., $m_i u_i^2 = en_e\left(\frac{dn_e}{d\varphi}\right)^{-1} + \gamma_P kT_i$. Furthermore, electron VDFs in fusion plasmas are by rule, characterised with e.g., presence of high energy electron "tails", secondary electrons, and a variety of ion species, making the theoretical plasma-boundary problem enough complicated even without presence of any double layer and/or a magnetic field. From this point of view 2D SOL-simulations with fluid codes could be performed with the present state of the art equally successful/unsuccessful

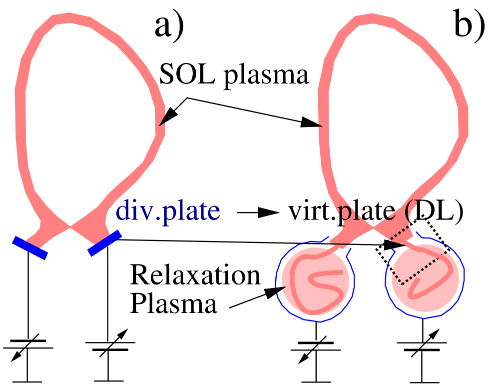

Figure 3: Illustration of the "conventional" principle of terminating a SOL-plasma ion-outflow by solid divertor plates (a) in comparison with the proposed method of "hosting" the outflowing ions in another plasma (relaxer) (b). Note that in (b) the terminating divertor-plate surfaces of (a) have been replaced with immaterial, namely the DL structures preventing the transmitted/relaxed and bulk ions in the relaxation plasma (RP) chambers (relaxers) from flowing back into the SOL region.

irrespective of weather a DL is present or not. Namely, the SOL-plasma could not be influenced in a dramatically different manner in either of scenarios from Fig. 3, since the main parameter, which could influence the Bohm velocity, is the rate of ”secondary” electrons originating either from secondary emission or from the low-potential (relaxer) plasma. In fact, replacing the solid boundary with a DL, is expected to be advantageous from the point of view of decreased number of various ion species (originated from plasma-wall interaction when a solid material is present).

Thus, providing that the SOL boundary conditions (BCs) have been prepared with a known rate of ”beam” electrons originated from either solid or immaterial plate (DL) with a ”standard” method, such as kinetic particle in cell (PIC) simulation [20], the central problem shifts to the low-potential side of the boundary, i.e., to the relaxer plasma. The first question there arises what is the ”counterpart” of the Bohm criterion in the presence of a positively biased object. A ”standard” approach is to model the electron VDF with a cutoff Maxwellian [21]. This scenario can hold in a limited (local) area (pre-sheath) near an electron-absorbing boundary, otherwise, excessive loss of electrons carried with such a distribution could cause fast plasma potential jump, i.e., transition from the electron ion-rich to the ”standard” ion-rich sheath, i.e., destruction of a DL, if any. Assuring sufficiently low electron-loss rate naturally suggests either a large volume relaxer plasma (with a small area of its surface covered by an electron-absorbing boundary as estimated in Ref. [22], or injecting external additional electrons for the purpose of compensating excessive loss of the ”bulk” population. In addition, the ”missing” bulk-ions discussed in previous Section should be supplied either from additional volume production or simple from properly ”configuring” in the engineering sense of this the *phase*-space such that bulk electrons will be permanently populated (i.e., via surface magnetic field-aided randomisation and/or volume collisional processes). Unfortunately, pursuing a variety of possible such realisations is strongly limited within both of analytic and numerical simulation method available capabilities for both geometrical (dimensionality) reasons and level of physics currently implemented into the existing codes. Anyway, it is quite natural to start investigations of DLs (to be possibly ”installed” in our still hypothetical relaxer plasma/chamber) under rather simplified plasma production and outflow conditions, in a 1D/3v (one-dimensional in configuration-space and three-dimensional velocity-space) PIC code, such as BIT1 (see e.g., Ref. [23] and references therein) which is well suited for calculating the local VDFs at arbitrary point and spatial profiles of all their relevant moments, with an additional advantage of implemented artificial ”heating” of particles (similarly as by rule occur with electrons in experimental plasmas due to e.g., fluctuations). The code flowchart is presented in Fig. 4, where it should be noted that in practice, the self-consistent contribution to the total magnetic field (originated from internal currents) not calculated (electrostatic code). The relevant (poloidal) spatial coordinate is here denoted with x while the computational domain is usually divided into several hundred of cells. Each super-particle consists of a sufficient number of real particles so that plasma densities comparable with those at SOL edges can be achieved, and

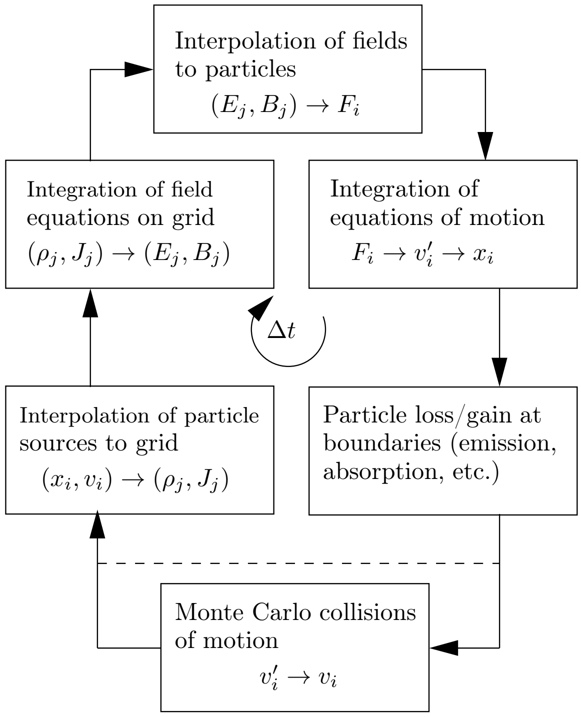

Figure 4: The typical flowchart of PIC codes employed within present investigation.

simulation performed fairly fast with several million of super-particles, providing the system volume is sufficiently small. In Fig. 5 we present the results obtained in a system bounded with two terminating plates which, in principle, are electrically biased with respect to each other and serve here as hypothetical inner "walls" of inner and outer relaxer chambers (see Figs. 1-b and 3-b).

The default situation corresponds to a homogeneously distributed either over the first third of the discharge ("supposed" to come there from a perpendicular to x direction represented by a hypothetical tokamak-core and/or originate from self-ionization) or over the whole region, a source of ion and electron pairs. Collision particle-particle processes are completely neglected. Transition from ion-rich to electron-rich sheath at the left side (black curves at Fig. 5-a is achieved via virtually changing the size of left plate (by applying the particle transmission/reflection rates there). No DL-structure has been obtained unless the second plasma-source with different electron temperature is introduced, such that an internal electron acceleration can appear. The typical profiles with different sheath regimes at the left plate, both with a double layer formed between the two plasmas, are presented in red and blue colours in Fig. 5-a. It should noted that in our simulations the electric circuit bias does not play any significant role in a DL scenario appearance, but this is the problem of the limitations regarding the physics that can be implemented in a 1D code. On the other hand the source strengths and temperatures need strong imbalance, obtained in simulations quite similarly as, by rule, done in laboratory experiments on DLs – via trial and error "method". After a huge number of simulations performed by this method, a common conclusion is that characterising the final state can be hardly correlated in a systematic manner with a "scheduled" one, at least regarding the applied imbalance in the source strengths. This is illustrated in Fig. 5-b where, in spite that the SOL plasma production rate is for two order of magnitude stronger than in the relaxer-plasma, the resultant densities differ only for a factor of two. On one hand, this observation is quite clear having in mind that the density of SOL-ions, after their acceleration within a weak DL such as achieved in present simulations could not decrease considerable, but the question is, in

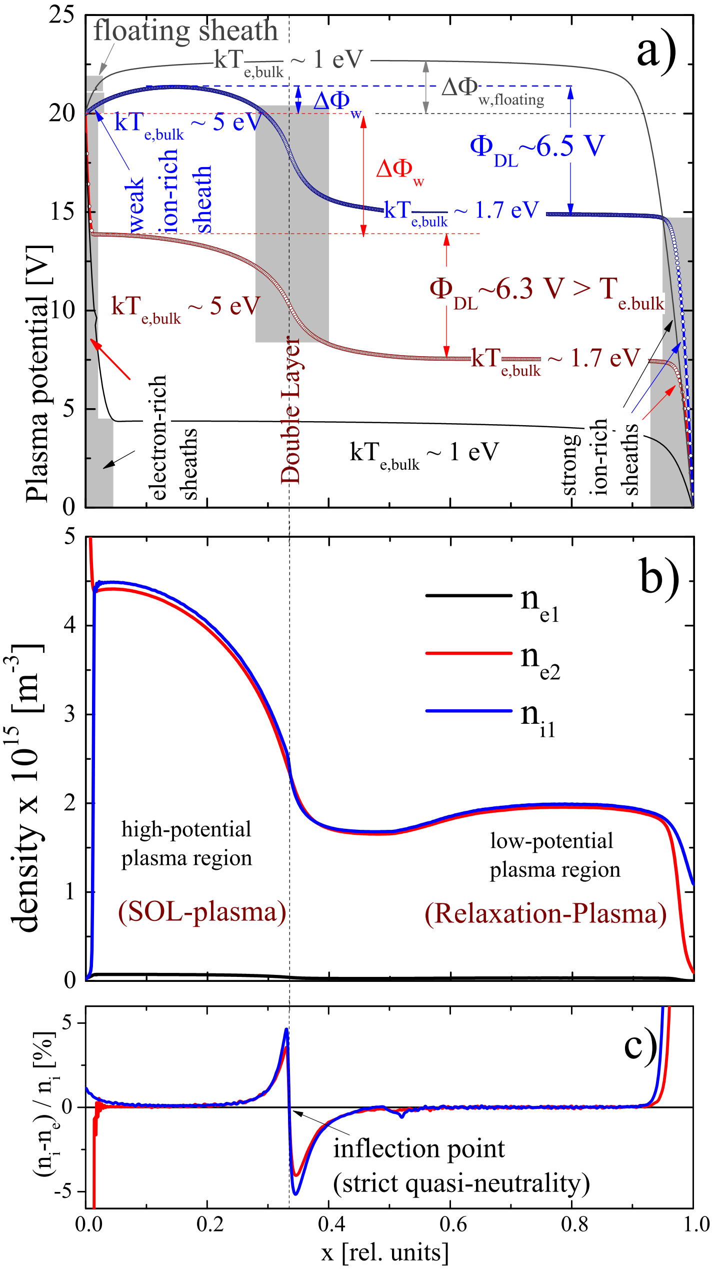

Figure 5: The potential profiles under various plasma production scenarios (a), together with the density profile corresponding to a case with established double layer (b) and corresponding density imbalance profile (c).

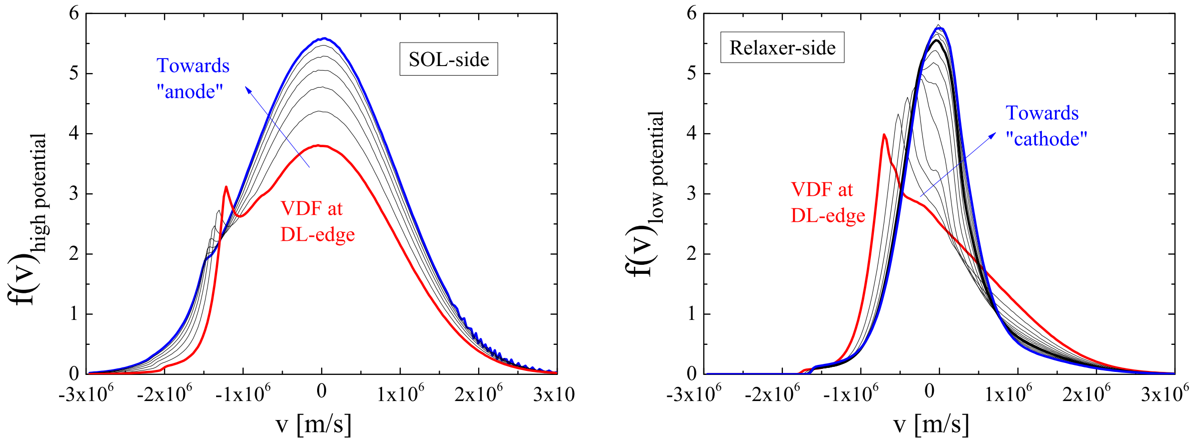

Figure 6: Total electron velocity distribution of the present model both left and right from a DL.

fact, why the DL is so weak, i.e., slightly higher but still close to that one of particle temperatures which dominates (in our particular example 6.5 V in comparison with $T_{e,SOL} = 5eV$)? A general answer is that the 1D geometry does not offer enough flexibility regarding the relaxer plasma potential, neither in a laboratory nor in numerical-simulation experiments, i.e., that an expanding-plasma configuration with, e.g., an additional external electron population is needed. This does not mean that our DL is too weak, but just that such a potential drop as obtained under present conditions is too strongly constrained, i.e., out of a full control. In this context we show in Fig. 6 the total electron VDFs of the present model both left and right from a DL, i.e., in the SOL and hypothetical relaxer sides respectively. While far from DL (blue lines) in both region they are nearly non-shifted Maxwellian, at the edges (red lines) they are mixed and microscopically unstable, especially at the SOL side. However, in practice (especially in the presence of an external magnetic field), DLs are rich in a variety of micro and macro instabilities which develop depending in a self-consistent manner together with the VDFs. In our investigations, however, both electron and in VDFs are chosen just for demonstrating appearance of a DL, whole in fusion plasmas they are much more complicated, at least regarding a common feature of electron VDFs in the SOL, being populated with high energetic tail, which is known to play extremely important role in DLs formations.

4 DISCUSSION AND CONCLUSION

The "standard" approach in investigating the conditions for a DL formation is, by rule, based on expressing the directional particle velocities in terms of so called generalised Bohm criteria $n_i(\Phi_1) = n_e(\Phi_1)$, $n_i(\Phi_2) = n_e(\Phi_2)$, $dn_i/d\Phi|_{\Phi_1} = dn_e/d\Phi|_{\Phi_1}$, $dn_i/d\Phi|_{\Phi_2} = dn_e/d\Phi|_{\Phi_1}$, holding at each of DL's sides in a self-consistent manner. In mathematical sense these conditions represent a demanding system of four non-linear equations, with several free parameters of the problem [24], supported by the total pressure balance condition $\frac{\epsilon_0}{2}\left(\frac{d\Phi}{dz}\right)^2 - \int[m_i^2 v^2 f_i(v) + m_e^2 v^2 f_e(v)]dv = \text{const.}$, which due to vanishing electric fields at the double layer boundaries ($\Phi_{1,2}$) may be expressed in the kinetic-balance form $\sum_{i,e}[n_{i,e}m_{i,e}u_{i,e} + n_{i,e}kT_{i,e}]_{\Phi_1} = \sum_{i,e}[n_{i,e}m_{i,e}u_{i,e} + n_{i,e}kT_{i,e}]_{\Phi_2}$. The present approach is, however, an attempt to obtain DLs with boundary conditions at the plates of a diode-like system, supported with assumption about inhomogeneous ionisation source and particular electron VDFs, aiming towards reducing the number of free parameters in possible applications of DLs towards a plasma-relaxer fusion reactor conceptual design. As noted above, these assumptions have been made for demonstration purposes. As emerges from presented results, the proposed configuration may be considered as a feasible one, at least in principle. In practice, both VDFs and fields establish in a self-consistent manner, which depend on particular physical scenario i.e., experimental setup, where the number of free parameters is much smaller than in available models of DLs (with their own BCs). Henceforth, once a particular experimental device/setup has been ready it will be much easier and cost-effective to understand and interpret the plasma-DL-plasma-circuit behaviour than performing theoretical investigations and simulation experiments. At the moment the only such ”devices” has been created by Nature, so intense mutual transfer of knowledge between fusion and space plasma communities is of high priority, at least within the present plasma reactor-relaxer context.

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