On Edge Plasma, First Wall, and Dust Issues in Fusion Devices

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Abstract. The processes in the edge plasma and first wall play crucial role in both performance and design of any fusion reactor. Here we address some major issues related to the physics of the edge plasma, first wall, and dust in fusion devices: dynamics of mesoscale-structures (blobs and ELM filaments) in edge plasma; modeling of intermittent edge plasma transport; transport of hydrogenic species in wall material; the physics of coupled plasma-wall interactions; and the impact of dust on the performance of edge plasmas in both current tokamaks and ITER.

1. Introduction

Nowadays, crucial importance of the edge plasma transport and plasma-material interactions for the development of ITER and future magnetic fusion reactors is widely recognized (e.g. see review [1] and the references therein). This is not surprising, since physical processes in the plasma edge and wall material directly impact many of the most crucial issues of magnetic fusion science, such as: parameters of the edge plasma pedestal in H-mode (and, therefore, the confinement of core plasma), divertor detachment, formation of MARFE, impurity contamination, helium ash exhaust, plasma hydrogen isotope content and tritium retention in wall materials, material erosion/deposition/migration processes and surface morphology modification, transient and peak power load handling, the lifetime of plasma-facing components, and etc. Here we address some issues related to the multi-disciplinary physics of the edge plasma transport, first wall, and dust in fusion devices.

2. Edge Plasma Turbulence and Transport

Our main focus here was on 3D modeling of the dynamics of filamentary mesoscale structures (blobs and ELMs), ballistically propagating through the scrape-off-layer, and macroscopic modeling of edge plasma transport associated with these effects.

2.1. 3D modeling of mesoscale-structures (blobs) with BOUT++ code

The main 3D effects on plasma blobs that we have examined are the impact of resistive drift wave (RDW) instability and Boltzmann blob spinning [2]. Eq. (1) along with the sheath boundary conditions give the basic equations used in the modeling (the notations here are standard and we assume the cold ions and a constant electron temperature):
\[
\left( \partial_t + \bar{V}_e \cdot \nabla \right) h = 2\epsilon C_s \rho_s \left( \bar{b} \times \bar{\kappa} \right) \cdot \nabla n + \nabla \cdot j \approx \sigma_i^2 T_e / eC_e \left[ \ell (n) - \epsilon \Psi / T_e \right].
\]

The characteristic time scale of RDW instability can be estimated by the maximum growth rate \( \gamma_{\text{max}} \) from standard local linear analysis, while the convective time scale of the blob is the inverse of the flute mode frequency, \( 1/\omega_c \). As a result, an expression governing the importance of RDW is the ratio \( \gamma_{\text{max}} / \omega_c = 0.1 \sqrt{R_c / \delta} \), where \( R_c \) is the tokamak major radius and \( \delta \) is the characteristic size of the blob. Since the size of the most structurally stable (with respect to “fingering” and Kelvin-Helmholtz instabilities) blobs, \( \delta_s \), has a weak dependence on \( R_c \) [3]. Therefore one can expect that in future fusion reactors, like ITER, blobs will be more susceptible to RDW instability than in current tokamaks. The comparison of 2D and 3D simulations (performed with BOUT++ code [4]) for large-scale devices, shown in Fig.1, clearly demonstrate a strong blob dissipation caused by the onset of RDW turbulence for this case [2].

The sheath-connected plasma blobs may have a density and corresponding Boltzmann potential varying along the magnetic field. This potential, varying also radially (with respect to polar coordinates vs. the center of blob in the plane normal to magnetic field), will spin the blob and thereby mitigate the polarized charge, which drives the blob [4]. The relative importance of this Boltzmann spinning on blob dynamics is determined by the magnitudes of the Boltzmann and the conventional 2D driving potentials

\[
(\epsilon \Psi / T_e)_B = \ell (n / n_0), \quad (\epsilon \Psi / T_e)_{2D} = (\delta / \rho_s) \sqrt{2 \delta / R_c} . \tag{2}
\]

For \( (\epsilon \Psi / T_e)_B > (\epsilon \Psi / T_e)_{2D} \), the standard 2D theory does not hold and the blob will actually slowly move more in the poloidal direction rather than in the radial one. Fig. 2 shows the time slices of blob density contours for no (top) and large (bottom) variation of blob density along the magnetic field found from numerical simulations. The potential contours in the first time slices, show change from a dipolar at the top to almost completely Boltzmann at the bottom. These features are somewhat similar to that found for 2D blob dynamics assuming the radially inhomogeneous electron temperature [3]. The coherency of the blob is eventually may be destroyed by either a 2D rotational instability or the 3D drift wave instability. Our study of the effect of resistive drift waves on blob dynamics was done under the assumptions of highly collisional electrons with constant temperature and cold ions. To address these limitations, we derived a linear dispersion relation [5] by treating the ions with the full collisionless kinetic equation and considered the electrons to be governed by the drift kinetic equation with a BGK-like collision operator to represent the momentum loss due to collisions with the ions. The main results of this work was that both collisionless drift waves driven Landau resonances and electron-ion collisions yield a maximum growth rate that are practically the same, however the parallel mode number at which the maximum growth rate corresponds changes. The maximum growth rate is shown to decrease by about a factor of two when \( T_i \) is an order of
magnitude larger than $T_e$. This study suggests that the fluid equations used to simulate the effect of RDW on blob dynamics may not capture the appropriate parallel wavenumber, but the main conclusion on the blob dissipation effects should still be valid.

2.2. Modeling of intermittent edge plasma transport with UEDGE

The plasma transport equations used in UEDGE are based on the usage of averaged plasma parameters, whereas large spatiotemporal fluctuations inherent to the intermittent blobby transport are ignored. As a result, some important parameters inferred from the modeling significantly differ from those measured in experiments [3]. In order to resolve this issue, we developed a novel “Macro-Blob” (MB) approach [6] using a coherent spatiotemporal variation of anomalous cross-field convective plasma velocity in a way to reproduce the ballistic motion of spatially localized plasma fluid elements from the vicinity of separatrix to the wall. Intermittent transport is simulated as a sequence of MBs appropriately seeded in edge plasma according to experimental statistics. Extensive calculations with new version of the code, UEDGE-MB [6], demonstrate its capability to simulate simultaneously $\sim 10^4$ s plasma bursts due to blobs and 2-D fluid transport on $\sim 0.1$ s scale with sophisticated UEDGE model, which includes plasma dynamics, plasma-wall interactions, neutral gas transport, plasma radiation, impurities, and atomic physics (note that running the 3-D edge turbulence codes on 100 ms scale to dynamic equilibrium is extremely time-consuming, if possible.). As an example of MB dynamics, the spatiotemporal evolution of plasma parameter profiles due to ballistic propagation of the MB with advection speed 1 km/s is shown in Fig.3. While the ion temperature and plasma density propagate with the MB rather coherently, the electron temperature in the MB degrades significantly due to fast parallel electron heat conduction (similar to experimental observations [3]). The main particle loss from MB is the parallel transport (Mach~1 is reached at the MB edges). Ion energy is lost mainly via parallel convection. Significant fraction of initial particle inventory ($\sim 50\%$) and stored energy ($\sim 20\%$) of the MB reaches the chamber wall causing an enhanced plasma-wall interaction.

To obtain time-averaged characteristics in the fluctuating edge plasma we simulated periodic sequences of many macro-blobs (PSMB) where the sequence period is $1/f_{MB}$, which we take as a parameter. In Ref. [6] we show that the resulting plasma evolves to dynamic equilibrium with the characteristic equilibration time $\sim 0.1$ s. We also found that this time is connected with establishing the return plasma flows. In the PSMB modeling, it requires a sequence consisting of hundreds of macro-blobs to reach the dynamic equilibrium. The modeling of plasma characteristics with UEDGE-MB was performed for L-mode shot #105517 on DIII-D. Even in simple PSMB modeling, we were able to match experimental data from various diagnostics (see [8] for the details) by adjusting mainly the frequency $f_{MB}$ of macro-blob generation in the core-edge region. In Fig. 4, we compare experimental profiles of plasma density and the corresponding time-average profiles
calculated with the PSMB model for $f_{MB} = 1$ kHz. Note that there is an increasing scatter of experimental data with radius, which is due to the impact of large density blobs.

By modeling the L-mode discharge #105517 on DIII-D with a set of periodic sequences of macro-blobs (PSMB) with different frequencies of MB generation $f_{MB}$ (ranging from 0.4 to 1.8 kHz), all reaching a dynamic equilibrium (see Fig. 5), we found that the PSMB model predicts significantly larger average energy flux to the first wall and average sputtering yield due to the higher ion temperature in comparison with what one can infer from a standard convective-diffusion model. For each sequence, we calculated the corresponding profile of time-average convective velocity and then use it in the calculations with usual time-average convective transport (TACT) model.

We also found that the advection of MBs toward the wall promotes the backflow of background plasma, so that the impurity low ionization states are moved from the near-wall region toward the separatrix, which enhances impurity radiation loss [6]. As an example, in Fig. 6 we show carbon charge state density profiles before and after single blob propagation. One sees that while the profiles of $C^{+1}$-$C^{+4}$ ions are advanced towards the core, the $C^{+5}$-$C^{+6}$ ions, which are entertained by the blob, move toward the wall and deposited into it.

3. Wall Physics

The main focus of our research in this field was on hydrogen retention in and outgassing from the first wall material, dynamic response of the wall to plasma bursts associated with ELMs, and on the physics of “fuzz” growth.

3.1 Hydrogen retention in Beryllium

Substantial amount of experimental data on hydrogen interactions with ITER wall materials (e.g. beryllium) under various plasma and wall operational regimes has been accumulated [7]. Among the issues requiring better understanding are the depth profiles and temperature dependence of the retained hydrogen. For example, experimental data show that a significant amount of H is retained in the material, well beyond the implantation layer [7]. We approached these issues with recently newly developed First wAll simulation CodE (FACE) code [8] which is based on the reaction-diffusion equations for different species of interest (including interstitials and vacancies produced by plasma ion bombardment and creating the traps for hydrogen, free and trapped hydrogen).
To define the diffusion coefficients and the reaction rate constants we are using the data from Ref. 9 and some fitting parameters. We find the steady-state solutions of the reaction-diffusion equations for different plasma fluxes and sample temperatures and then compare our simulation results on both the depth profiles of trapped hydrogen (Fig. 7) and overall trapped hydrogen content (Fig. 8) with experimental data from [7]. We found that the shoulder on trapped hydrogen depth profile in Fig. 7 is determined by the transport of interstitials and vacancies and that depending on sample temperature either interstitials or vacancies can play a dominant role in the formation of the tail distribution of trapped hydrogen. We were able to reproduce available experimental results rather well (see Figs. 7, 8) with exception of room temperature range.

3.2 On the Hydrogen outgassing from co-deposits

In fusion devices majority of retained hydrogen is accumulated in co-deposited material, which can contain traps with, potentially, a broad spectrum of activation energy, which can be sensitive to the wall temperature at which co-deposits were formed and is not known a priori. As a result, the set of limited number of reaction-diffusion equations, which often used for the TDS analysis, becomes ill defined. In this case a more appropriate way for the description of hydrogen transport in the first wall material could be based on a continuum kinetic model of the population of traps over activation energy, E, assuming that de-trapping energy spectrum, $P_E(\epsilon)$, is known (here $\epsilon = E / T$, T is the wall temperature). Such kinetic model can be analyzed with the theory of random walk with varying waiting time, $\tau$, given by the probability function, $P_\tau(\tau)$, (e.g. see Ref. 10 and the references therein). This probability function can be expressed in terms of $P_E(\epsilon)$ as follows:

$$P_\tau(\tau) = \int_0^\infty f(\tau / \tau_E) P_E(\epsilon) d\epsilon,$$

where $\tau_E = \tau_0 \exp(\epsilon)$, $\tau_0$ is the normalization constant, and the function $f(\xi)$ describes the contribution to the waiting time distribution from one kind of traps with energy E: $P_\tau(\tau_E) = f(\tau / \tau_E / \tau_E)$. For $P_E(\epsilon) = \alpha \exp(-\alpha \epsilon)$ we find $P_\tau(\tau \rightarrow \infty) \propto \tau^{-(1+\alpha)}$, which for $0 < \alpha \leq 1$ corresponds to the sub-diffusion process, $\partial_t \rho = 0.5(\partial_x^{2/\alpha} + \partial_x^{2/(\alpha+1)})$, [10] resulting in a power-law time dependence of the outgassing flux: $j_{\text{out}}(t) \propto t^{-(1-\alpha/2)}$. Recalling recent results on the outgassing dynamics in JET and TS showing $j_{\text{out}}(t) \propto t^{-0.7}$ [11], we can conclude that within our approach these experimental results can be explained with exponential trapping spectrum for $\alpha = 0.6$ [12].

3.3 Dynamic response of the wall

The H-mode, which is a primary candidate for the operation of ITER, is a subject of ELM bursts accompanied by a fast degradation of H-mode plasma pedestal. It is widely assumed that the pedestal recovery is determined solely by plasma transport processes. However, the reduction of total amount of hydrogen in tokamak after the ELM crash is due to accumulation of hydrogen in the first wall. Our study of the wall outgassing process during ELM with simplified 0-D model shows that for some cases the pedestal recovery can be strongly impacted by hydrogen retention [13]. To verify these qualitative results we performed
simulation of the first wall response to ELM bursts using FACE code taking into account wall temperature variation, transport and interaction between solute hydrogen, vacancies, and interstitial atoms of the wall material [8]. Parameters of these interactions were taken corresponding to those of beryllium. The impact of ELMs was mimicked by periodic plasma influx, $\Gamma_p(t)$, having rectangular-like shape with maximum value $\Gamma_{in}$. The plasma heat flux to the wall was taken in the form $Q(t)= \Gamma_p(t)E_p + R$, where $E_p$ is the averaged particle energy coming to the wall with plasma flux and $R$ is the radiation flux to the wall, which is assumed to be constant.

The simulation results are shown in Fig. 9, where the ratio of the outgassing flux, $\Gamma_{out}(t)$, to $\Gamma_{in}$, is plotted against time (left) and the ratio of cumulative amount of hydrogen atoms outgassed to the corresponding number of hydrogen hitting the wall during ELM burst is shown as an averaged wall surface temperature (right). The results for six sets of parameters are presented for the averaged surface temperature 400 and 600 K. However, averaged plasma particle flux and radiation power $R$ were chosen in such a way, that the surface wall temperature is controlled either by particle flux or by radiation (correspondingly labeled “flux” and “radiation” in Fig. 9). In all case we assume that $E_p=1000$ eV, the wall thickness 1 cm, and the backside wall temperature 300 K. From Fig. 9 one sees that the wall outgassing can make the most pronounced impact on the pedestal recovery for 400 K surface temperature where about of 50% of hydrogen implanted during the ELM burst is released with large time-delay. Comparison with the criterion of the impact of the wall outgassing on the pedestal recovery found with 0-D model [13] shows good agreement with simulation results after incorporation of 1-D features of hydrogen transport in the wall material.

3.4 Enhanced plasticity of tungsten with large amount of dissolved helium

Recent experiments on tungsten irradiation with hydrogen/helium plasma similar to that expected in ITER, demonstrated dramatic change in both surface morphology and near surface material structure. For sample temperature range 1000-2000 K a long (mm-scale) and thin (nm-scale) fiber-like structures (“fuzz”) filled with nano-bubbles start to grow [14]. In Ref. [15] a “visco-elastic” model of “fuzz” growth was suggested. This model is based on the assumption of enhanced tungsten’s plasticity in the presence of large amount of dissolved helium. Then, under the stresses caused by growing bubbles tungsten can move (“flow”) eventually forming the nano-fiber structures. Although this “fuzz” model reproduces all major experimental observations until our recent work there were neither experimental nor theoretical results directly supporting the enhanced tungsten plasticity in the presence of large amount of dissolved helium. In Ref. [16] we addressed the tungsten plasticity issue with Molecular Dynamic (MD)

![Fig. 9.](image)

![Fig. 10.](image)
simulations. To find the transition to plastic deformation we consider a slab of mono-
crystalline tungsten of size of 10 unit cells in each of the three dimensions with periodic
boundary conditions and different crystal orientations corresponding to free surfaces \{010\}
and \{110\} of tungsten crystallographic planes. A number of helium atoms are initially
randomly distributed in the slab volume and equilibrated. The shear stress in the sample was
produced by applying anti-parallel forces at the two free surfaces along the X-axis chosen as
\(<100>\) crystallographic direction in \{010\} plane and \(<111>\) direction in the \{110\} plane. The
magnitude of the forces on each affected atom was linearly ramped up from zero to material
failure point with the rate 1 eV/(Å ns). In Fig. 10 the dependencies of the simulated shear yield
strength, \(\tau_Y\), on temperature are plotted for different helium content. For pure tungsten at
300K \(\tau_Y\) is found to be in a good agreement with experimental data. However, \(\tau_Y\) significantly
decreases with increased He concentration. The simulated \(\tau_Y\) at 1000 K and He content >10
at.% is \(\approx 5\) GPa, which in a ballpark consistent with the pressure created in the helium bubbles.
Thus the results of MD simulation support the idea of enhancement of plasticity of tungsten
containing significant fraction of helium atoms and clusters. In addition, MD simulations
show that the “flow” of tungsten strongly facilitates coagulation of helium clusters (otherwise
practically immobile) and the formation of nano-bubbles (see Fig. 11).

4. Dust in fusion devices

Dust inside vacuum vessel and in fusion plasmas has been observed on most
current tokamaks [17]. Dust can be deliberately injected to plasma. For
example, by modeling of lithium dust injection in NSTX with the
DUSTT/UEdge coupled code [18] we demonstrated that the dust injection rates
\(\approx 10\) mg/s can lead to edge plasma cooling and significant reduction of heat
load on the outer target. It can also cause significant reduction of the radial plasma
pressure gradient in the edge, which may suppresses ELMs. Here we model injection with
various rates of carbon dust in ITER-like discharge [19]. The grain radius was 10\(\mu\)m radius
and dust was injected at poloidal positions from midplane to \(\approx 7\) cm below the midplane and at
the outer edge of the outer divertor plate with the initial radial speed of 100m/s.

For comparison purposes we also simulate injection of dust material in
atomic vapor form with the same
rates and at the same poloidal locations as for dust injection. We
have found that dust injection is
more effective in reduction of the
peak heat load to outer divertor plate
as compared to gas impurity seeding
in both divertor and midplane
injection scenarios due to targeted
delivery of impurities to near separatrix plasma regions (see Fig. 12). It also has been shown
(see Fig. 13) that radiation of impurities seeded by dust injection in divertor region tends to
saturate at a level below one leading to development of divertor thermal instability, while all
other simulated impurity seeding scenarios led to the instability development and discharge termination when ~10g/s of impurities was injected in ITER-like plasmas [19]. The development of detached divertor operational regimes shortly before the instability development in these injection scenarios was observed. The saturation of impurity radiation and stabilization of divertor operation in case of dust injection in divertor region may be attributed to reduction of availability of dust originated impurities as the divertor temperature drops and/or non-coronal effects in radiation of impurities delivered by dust to hot plasmas near the separatrix.

The further studies of impurity seeding with dust injection are required in order to explain the observed saturation of impurity radiation power and divertor thermal stabilization, and to envisage an optimal strategy to mitigate divertor heat load in ITER.

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