TEST OF THE PREDICTIVE CAPABILITY OF B2-EIRENE ON ASDEX-UPGRADE

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Abstract

Based on validated B2-Eirene results for the previous divertor of ASDEX Upgrade, the modelling predictions for the new divertor are compared with the actual experimental results. For the same experimental scenarios (L-mode) in both divertors the predictions are robust and in agreement with experimental results. For a full quantative agreement in H-mode both the carbon chemical sputtering yield and the radial transport had to be adjusted. The new divertor has a reduced power load due to larger radiation losses. These are caused by larger hydrogen losses, enhancement of carbon radiation due to radial transport and convective energy transport into the radiation zone, and larger radial energy transport in the divertor.

1. INTRODUCTION

For optimization of divertor operation, e.g. for ITER, 2D scrape-off layer (SOL) simulation codes are used to study different target plate and baffle geometries and their effect on power and particle exhaust and SOL characteristics.

Starting from validated results for the previous divertor (Div I) of ASDEX Upgrade [1,2], the modelling predictions for the new divertor (Div II or Lyra) are compared with the actual experimental results.

2D multifluid simulations for the experiments are done using the coupled B2-Eirene code package in a fully time-dependent mode [3,4] including deuterium and carbon. Carbon is produced at the target plates and side walls by physical and chemical sputtering, where the physical sputtering data are taken from TRIM calculations [5]. The chemically sputtered carbon is started as carbon atoms with 1 eV. A comparison with a more complete model starting methane and following the whole dissociation chain showed that this simplification (resulting in reduced run-time) is applicable. The chemical sputtering coefficient for this study is taken to be constant, neglecting for simplicity the dependence on flux, impact energy and surface temperature.

2. RECOMBINING PLASMAS

To test the predictive capability of the B2-Eirene modelling one starts with comparison of results for L-mode conditions, which have been analysed in detail already for Div-I [2]. As already seen from the modelling of Div I, a proper description of the detachment process requires the inclusion of volume recombination [6,2]. In the original predictive calculation [7] this process was missing. Therefore, the B2-Eirene calculations for the new Div II were redone with the inclusion of this process, which becomes important at temperatures of about 1-2 eV.

This recombining phase is determined by the formation of a recombination ionization double layer, where in the net recombining zone close to the target plates the plasma is neutralized forming a kind of virtual target below a temperature of about 1 eV in agreement with spectroscopy [8]. These neutrals then travel upstream in a 2-D way by leaving the zone sidewards and getting through multiple reflections at the side walls and the plasma into a hotter upstream regions where they are ionized (5 - 7 eV) [6]. In this ionization front zone one drives quite large Mach flows even up to or above Mach equal 1 due to the large neutral sources there as confirmed by a fast movable Langmuir divertor probe [9]. In contrast, the net recombination zone is characterized in the modelling by quite small flow velocities (confirmed with a sophisticated toroidally viewing spectroscopy system [10]) giving the plasma enough time to recombine.

3. DETACHMENT PROPERTIES

The different divertor geometry and the reflection of neutrals into the hot zone close to the separatrix in the LYRA divertor causes quite different detachment properties. In Div I detachment as defined by a drop of the total ion saturation current by at least one order of magnitude developed rather uniformly and rather close to the density limit. In Div II one observes an earlier detachment at the separatrix associated with an earlier onset of strong volume recombination [11] and an earlier drop of the separatrix ion saturation current.

Detachment in Div II progresses from the separatrix to the outer scrape-off layer, which stays attached up to the global density limit. The modelling shows also that the earlier drop of the separatrix ion saturation current in Div II is not seen in the total integrated particle flux, because in Div II the outer scrape-off layer stays attached due to inverted temperature profiles up to a global detachment of the target plates.

4. IMPURITY PHYSICS

The analysis of impurity transport in the scrape-off layer is one of the most challenging topics, both for experiments and for modelling, due to the complexity of the problem, because motion of neutrals and ions are at least two dimensional. Also, understanding the important aspects of the impurity transport means the need for a validated model accounting for the impurity generation at the plates and side-walls, and a proper description of the transport process (including atomic/molecular processes).

The detailed spectroscopic divertor diagnostics allow a quantative check of the predicted losses as measured with bolometry, H_α, CII and CIII lines. One gets good agreement with the bolometry results and enhanced losses compared to coronal values due to limited residence time of impurities close to the plate and radial transport resulting in a larger radiation volume [12]. The agreement with the specific spectroscopic lines is within a factor of 2 in absolute values and very good agreement of spatial profiles. The experimental measurement of flow velocities of neutrals and ions allows the checking of rather subtle details like flow patterns [9]. Here, an experimental confirmation of the predicted flow reversal of impurities was possible [10].

After the successful test for L-mode conditions a detailed analysis was done for H-mode conditions (ELM averaged). To be able to get a reasonable fit of the outer divertor profiles - especially those of the thermography - a critical parameter is the value of the chemical sputtering coefficient for carbon Y_C. The variation of this coefficient from 2% to 3% changed the outer target peak value of the total power load from 3.0 MW/m^2 to 0.8 MW/m^2. The best description of the experimentally measured profile for a high power H-mode reference discharge is obtained with a chemical sputtering coefficient for carbon Y_C of 2.5% resulting in outer target peak value of the total power load of 1.8 MW/m^2 as in experiment.

5. RADIAL TRANSPORT

The largest uncertainty in the predictions is the unknown scaling of the radial anomalous transport. As expected one needs for the analysis of the H-mode discharges also a change of the radial transport compared with the L-mode conditions. Doing a detailed comparison with experiment for a high power H-mode reference discharge one gets a better fit of both experimental midplane and divertor profiles by introducing an outward pinch velocity rising with distance from the separatrix to values of about 20 m/s. The outward pinch models the region of enhanced turbulent transport seen as shoulders in the experimental profiles, possibly due to the loss of line tying in a low temperature, low density plasma (flute mode turbulence).

In contrast to local variations one also has to account for global transport changes. Starting from the reference case with 2% chemical sputtering the same variations as in experiment [13] were done. For higher densities and for lower current it was necessary to increase the radial transport at least by a factor of 2. Especially the lower current operation is of specific interest, because here the detachment is not driven by radiation losses but just by the large radial transport. By using a fast version of B2-Eirene for fitting the scrape-off layer profiles one should be able to get scalings of the anomalous transport coefficients correcting already for divertor effects like profile broadening close to detachment.

6. REDUCED TARGET POWER LOAD

Measurements reveals a reduction of the maximum heat flux in the LYRA divertor by about a factor of two compared to the open Div I [13]. For relatively low power cases (total input power below about 2 MW), the effect of the preferential reflection of neutrals towards the separatrix with maximized losses there can already explain for pure plasma conditions a factor of 2 reduction at high densities.

However, the experimental results of thermography, calorimetry and Langmuir measurements show this power load reduction also for attached conditions. That this effect has to be related to changes of the radial transport in the divertor region and not to changes of the upstream transport is experimentally confirmed because there is no indication for a large change of the midplane energy fall-off length from Div I to Div II [14].

In the code predictions the larger compression of the flux surfaces in the deeper Div II results in larger anomalous radial fluxes when they are assumed to be described as a diffusion process determined by the local gradient in real space. This produces already for attached conditions a considerable broadening of the profile and by this a reduction of the power load maximum. If the diffusion process is assumed to be constant in flux-coordinates, this effect disappears.

Comparing the spectroscopically measured impurity production, e.g. by measurements of the CD bands [11], for Div I and Div II the larger divertor radiation in Div II cannot be understood by larger impurity production. The large values for the total radiation losses in Div II can be explained by the higher electron densities compared with Div I (target inclination effect), the radial transport (enhancing the radiation volume [12]) and the transport of energy into the radiation zone not only by conduction but predominantly by convection in the cold divertor region as already discussed by DIII-D [15].

Also, the carbon residence time in the separatrix-near region is large, because the carbon ion mass flow pattern shows a flow reversal zone due to the ion thermal force with small flow velocities close to the separatrix and a forward flow in the outer scrape-off layer with relatively fast flow [10].

7. PARTICLE EXHAUST

A check of the predictive capability for divertor impurity compression and pumping is important, because the removal of the helium ash is a critcial issue for any reactor. B2-Eirene was able to describe the compression of deuterium, helium and neon qualitatively and quantatively for the Div I [16,1]. The predicted improved compression of helium and hydrogen pumping for Div II [17] was confirmed experimentally [18].

8. CONCLUSIONS

B2-Eirene calculations for the new Div II based on validated results (L-mode) for the Div I are able to predict successfully details of recombining plasmas, detachment properties, impurity transport of carbon and even flow pattern. Also, impurity compression and pumping properties, mainly dominated by classical neutral transport, are correctly predicted.

To get a quantative agreement in different experimental scenarios (H-mode) one needs to adjust the chemical sputter yield and the perpendicular transport coefficient. Using these calculations one gets an insight into the physical mechanisms responsible for the increase of the divertor radiation.

Overall, the predictive quality of B2-Eirene is quite good for geometry variations in scenarios where the radial transport has already been adjusted. Robust results are also obtained for effects, where the classical neutral transport is dominant, e.g. pumping. To extend the predictive capablity further SOL transport scaling studies are needed allowing the derivation of scaling laws of the radial transport coefficients. For this, a fast version of B2-Eirene for a SOL transport interpretation code is under development.

All results presented here are for the ion drift direction towards the outer divertor. Reversing the toroidal magnetic field changes the results, indicating the importance of drifts. Analysing this using a multifluid B2 version with drifts and currents, the main effect is the change of the impurity transport by drifts, whereas the effect of drifts and currents on the pure plasma is relatively weak.

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