KINETIC MODELING OF H-MODE PEDESTAL WITH EFFECTS FROM ANOMALOUS TRANSPORT AND MHD STABILITY

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Scaling of the H-mode pedestal in tokamak plasmas with type I ELMs and dependence of the pedestal properties and the resulting divertor head load width with the plasma elongation and plasma current are investigated using the kinetic neoclassical XGC0 code for DIII-D and Alcator C-Mod tokamaks. The simulations in this study use realistic diverted geometry and are self-consistent with the inclusion of kinetic neoclassical physics, theory-based anomalous transport models with the E×B flow shearing effects, as well as an MHD ELM triggering criterion. Scalings for the pedestal width and height are developed as a function of the scanned plasma parameters. The nonlinear interplay between anomalous and neoclassical effects motivates the development of a self-consistent simulation model that includes neoclassical and anomalous effects simultaneously. It is demonstrated that the divertor heat load width depend on the plasma currents. In the development of this dependence, effects of neutral collisions and anomalous transport are taken into account. Changes in the neoclassical divertor heat load fluxes associated with the introduction of the neutral collision and anomalous transport effects are described.
PACS: 52.25.Xz, 52.35.Ra, 52.55.Fa, 52.65.Tt

1. INTRODUCTION

For the basic kinetic neoclassical behavior, the XGC0 kinetic guiding-center code [1] is used with a realistic diverted geometry. For the anomalous transport, a radial random-walk is superposed in the Lagrangian neoclassical particle motion, using the FMCFM interface to the theory-based MMM95 and GLF23 models. These anomalous models include transport driven by drift-wave instabilities, such as the electron and ion temperature gradient driven modes and trapped electron modes. The MMM95 model includes a resistive ballooning component that is particularly important near the plasma edge. The sheared E×B flows result in a reduction of anomalous transport, which leads to the formation of an edge transport barrier and the transition to the H-mode improved confinement in tokamaks. The effect of E×B flow shear quenching is implemented through a flow shear suppression factor [2]: $F_s=1/(1+(\tau_c\,\omega_{\mathbf{E}\times\mathbf{B}})^2)$, where τ_c is the correlation time of fluctuations for the case without flow and $\omega_{\mathbf{E}\times\mathbf{B}}$ is the normalized E×B flow shear rate: $\omega_{\mathbf{E}\times\mathbf{B}}\equiv|R\,B_\theta/B_\varphi\,\partial/\partial r\,(E_r/R\,B_\theta)|$. Growth of the pedestal by neutral penetration and ionization is limited by an ELM instability criterion computed by the ELITE MHD stability code [3]. H-mode pedestal profiles for DIII-D and Alcator C-Mod tokamaks are considered: DIII-D for low B-field, low-density, high temperature plasmas; and Alcator C-Mod for a high B-field, high-density plasmas.

2. STUDY OF H-MODE PEDESTAL WIDTH AND HEIGHT SCALING

The study of DIII-D discharges includes a scan with respect to plasma shaping. Three DIII-D discharges are analyzed in this section. The DIII-D discharge 136674 has high elongation, $\kappa\approx1.7$, which is typical for most DIII-D discharges, but rather low triangularity $\delta\approx0.1$. The DIII-D discharge 136693 has almost circular geometry with the elongation $\kappa\approx1.2$ and triangularity $\delta\approx0.03$. The third DIII-D discharges studied in this section, DIII-D discharge 136705, has very small elongation, $\kappa\approx1.3$, but relatively high triangularity, $\delta\approx0.3$. Thus, the elongation is been varied by a factor of 1.4 and the triangularity is being varied by a factor of 10 in this study.

These simulations do not include the effects associated with the anomalous transport. The anomalous transport was selected at small residual level through the whole edge region for all DIII-D discharges that are investigated in this section. The electron and ion thermal diffusivity have been selected to be 0.02 m^2/s in the pedestal region and 0.4 m^2/s in the SOL region and the particle diffusivity has been selected to be 0.01 m^2/s in the pedestal region and 0.05 m^2/s in the SOL region. Motivation of the selection of anomalous transport coefficients at a small residual level is that the focus of this study is the neoclassical and MHD effects on the H-mode pedestal structure. However, a residual anomalous transport was still necessary in these simulations. Without the anomalous transport, the plasma density becomes too low in the near outer separatrix region. The plasma density depletion leads to unrealistic ion and electron temperature profiles. These changes to the plasma profiles might occur before the H-mode pedestal develops enough to trigger the peeling or ballooning instabilities that would lead to an ELM crash.

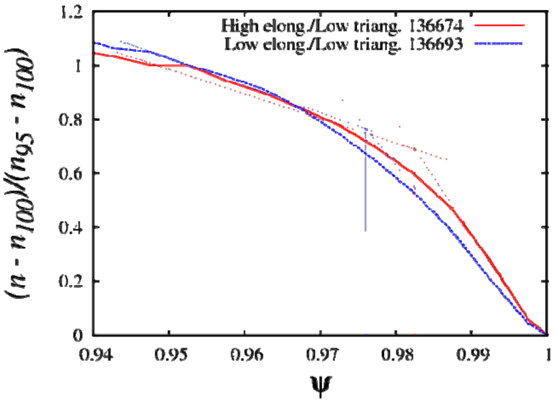

Fig. 1. Normalized plasma density profiles as a function of normalized poloidal flux for DIII-D discharges with different elongations and similar triangularities. Here, n_{100} and n_{95} are the plasma densities at the separatrix and at 95% of the normalized poloidal flux, respectively

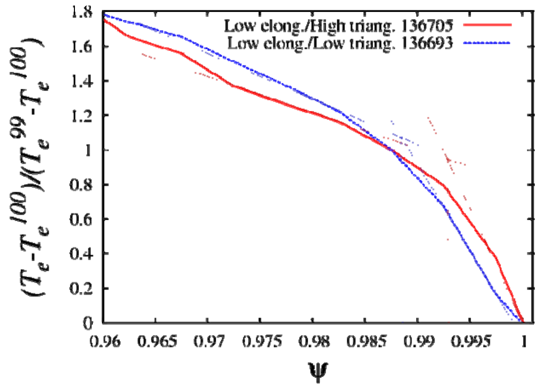

Fig. 2. Normalized electron temperature profiles as a function of normalized poloidal flux for DIII-D discharges with different triangularities and similar elongations. Here, T_e^{100} and T_e^{99} are the electron temperatures at the separatrix and at 98.8% of the normalized poloidal flux, respectively

The simulation results illustrate a scaling that is qualitatively similar to some experimental observations. Fig. 1 shows the normalized plasma density profiles as a function of the normalized poloidal flux for high and low elongation DIII-D discharges. Fig. 2 shows the normalized electron temperature profiles for low and high trinagularity DIII-D discharges. In XGC-0 kinetic simulations, it has been found that the pedestal width is smaller for high elongation and high triangularity discharges. In the discharges considered in this study, the effect of increased elongation manifests itself in the plasma density profiles first, while the effect of increased triangularity manifests itself in the electron temperature profiles first. It has also been found that the pedestal width for the ion temperature profile is much wider than the pedestal width for the electron temperature and plasma density profiles. The pedestal height is found to be significantly larger in the discharges with larger elongation.

While the neoclassical effect together with the MHD stability conditions can explain some experimental trends, the question about the contributions of the anomalous transport in the pedestal and SOL regions remains. This question will be partially addressed in the next section.

3. STUDY OF THE EFFECTS ASSOCIATED WITH THE ANOMALOUS TRANSPORT

The anomalous transport in the plasma edge region has been previously analyzed in a number of studies. In particular, it has been pointed out that particle pinches might play an important role in the pedestal region [4,5]. Experimental observations and some analytical models suggest that anomalous transport in SOL can be significantly larger than in the pedestal region and intermittent. Studies of the anomalous transport in the plasma edge region are typically based on the analysis of experimental data that should include a robust model for the neoclassical transport. Particle and thermal fluxes obtained from analysis of experimental data include contributions from both the anomalous and neoclassical transport so that the neoclassical transport needs to be deducted to get the correct anomalous fluxes and effective diffusivities. Effects associated with neutral collisions and recycling are other factors that can affect the total particle fluxes and should be carefully taken into consideration. The kinetic XGC0 code is designed for the first-principle neoclassical computations and includes several advanced models for neutral collisions including the DEGAS2 model. Also, the XGC0 code takes into consideration the recycling and other particle effects that contribute to the total particle fluxes. Thus, the XGC0 code can be used for the analysis of experimental fluxes in order to derive the effective diffusivities. These anomalous effective diffusivities can be also used for comparisons with the analytical models for anomalous transport. In particular, it is important to understand the origin of particle and thermal pinches in the pedestal region. While the origin of particle and thermal pinches is not studied in this work, it is worth mentioning that there are several physical effects that can be associated with the pinches in the pedestal area such as curvature effects and parallel compression. The purpose of the study described in this section is to derive the anomalous effective diffusivities that can reproduce the experimental profiles when they are used in the neoclassical kinetic XGC0 code. These profiles will be used in the next section of this paper for the computation of the divertor heat load fluxes. There are three regions of constant diffusivites that are separated by two narrow transitional regions that use *tanh*-fit. The levels of anomalous transport in all three regions, locations of transitional regions and their widths are adjustable parameters. The diffusivity profiles are adjusted to find a steady state solution that reproduces the experimental profiles. A series of four DIII-D discharges that represent plasma current scan [6] is analyzed in this study. In this series of DIII-D discharges, the total plasma current is varied from 0.51 to 1.50 MA with an approximately fixed toroidal magnetic field (B_T≈2.1 T), plasma shape (δ≈0.55), and normalized toroidal beta (β_n≈2.1…2.4). The discharges differ by total plasma current, and auxiliary heating power that are given in the Table below. The plasma density is also different in these discharges. The plasma density at the top of the pedestal varies in the ranges from approximately $4.5 \times 10^{19}\,m^{-3}$ for the high plasma density DIII-D discharge 132016 to $2.3 \times 10^{19}\,m^{-3}$ for the low plasma density DIII-D discharge 132018.

DIII-D discharges analyzed in this study and their parameters

Discharge #	EFIT time, ms	Plasma current, MA	Auxiliary heating power, MW
132016	3023	1.50	8.12
132014	3023	1.17	7.36
132017	2998	0.85	8.50
132018	1948	0.51	7.10

The anomalous diffusivity profiles are selected so that the resulting profiles remains close to the experimental profiles at least up to eight ion transit periods (see Fig. 3).

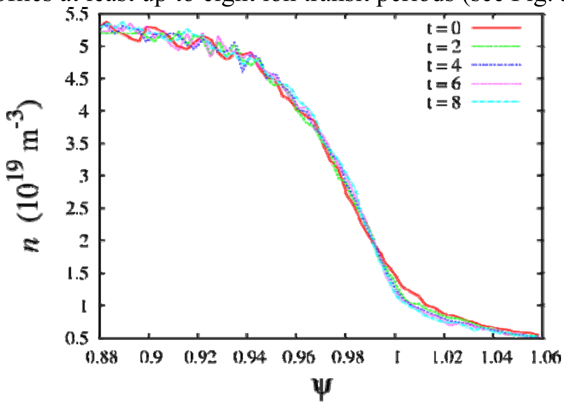

Fig. 3. Simulation results of the plasma density profile in the DIII-D discharge 132016 for the first eight ion transit periods. The experimental plasma density profile is shown in red

There is a clear evidence of strong pinches in the particle and thermal channels of anomalous transport. While the mechanisms that result in these pinches are not the subject of this study, we have analyzed the anomalous transport in the DIII-D discharges, which are described in the Table, with the drift wave anomalous transport model MMM95 that is implemented in the XGC0 code.

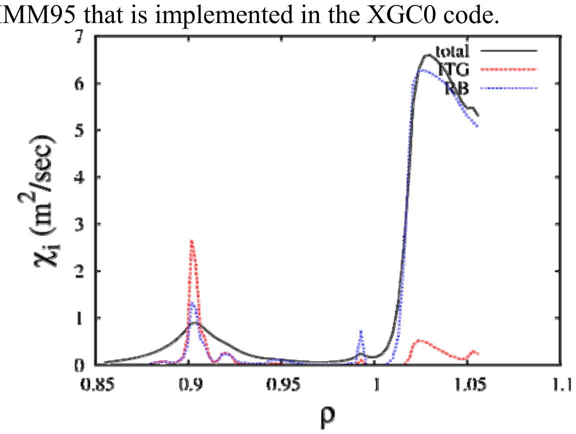

Fig. 4. Ion thermal diffusivity profiles predicted with drift-wave transport model MMM95 for the DIII-D discharge 132016 at five ion transit periods. Contributions to the anomalous thermal transport from ITG and RB modes are shown in red and in blue correspondingly. The smoothed total ion thermal diffusivity that is used in the XGC0 simulations is shown in black

It has been found that the largest contribution to the anomalous transport in the outer pedestal region comes from the turbulence driven by the resistive-ballooning instabilities (see Fig. 4). The resistive-ballooning model gives somewhat larger contribution for the lower plasma current and lower plasma density discharges 132017 and 132018 comparing to the contributions to the anomalous transport for the higher plasma current and higher density discharges 132014 and 132016.

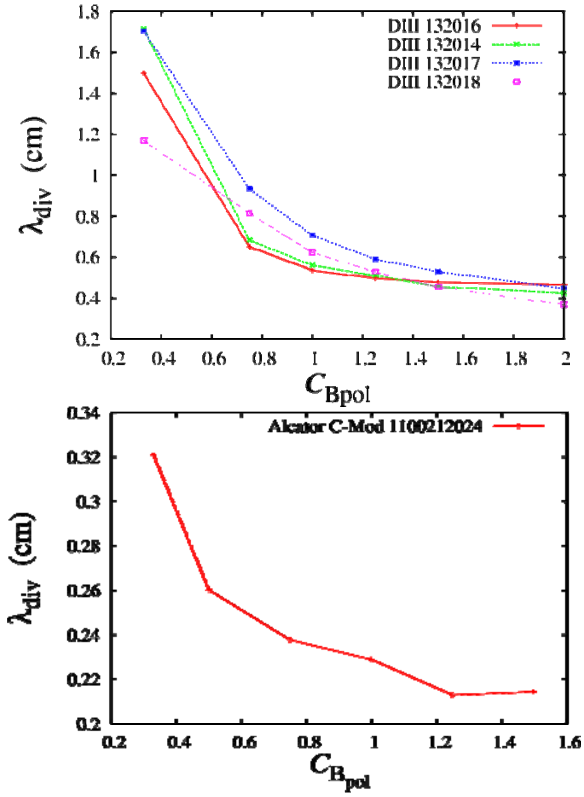

Fig. 5. The heat load widths for four DIII-D discharges (first panel) and one Alcator C-Mod discharge (second panel) as functions of plasma current scaling factor

There are no physical effects in the resistive-ballooning model that can explain the particle and thermal pinches that are found to be important in the analyzed discharges. As result, the effective diffusivities computed with the MMM95 model are found to be overpredicted and the corresponding plasma profiles are found to be under-predicted compared to the experimental profiles and profiles computed with the diffusivities derived in the analysis mode. The computations of the divertor heat fluxes that are presented in the next section of this report use the diffusivities obtained in the analysis mode. It should be pointed out that the theory-based reduced model for the resistive-ballooning modes might need a significant revision that would extend its validity to the SOL and near separatrix regions.

4. DIVERTOR HEAT LOAD STUDIES FOR THE DIII-D AND ALCATOR C-MOD TOKAMAKS

Understanding physical effects that contribute to divertor heat load fluxes is important for experiment planning, design of future tokamaks, and development of new models for the SOL region. In this study, the neoclassical effects and effects related to neutral collisions and anomalous transport are investigated. Four DIII-D discharges described in the Table above are analyzed here. In addition, one Alcator C-Mod discharge 1100212024 that was a part of Alcator C-Mod/DIII-D similarity campaign is analyzed. The divertor heat load widths, $\lambda_{div} \equiv \int q_{\|} d\rho / q_{\|}^{max}$, for four DIII-D discharges and one Alcator C-Mod discharge as functions of the poloidal magnetic field amplification factor C_{Bp} are shown on Fig. 5. This scaling factor is an internal numerical multiplier introduced in the XGC0 code in order to alter the initial equilibrium by scaling the poloidal flux. If the toroidal flux is not modified, $I_{pl} \propto B_p \propto \partial\psi/\partial\rho$, where ψ is the normalized poloidal flux. Thus, the amplification factor C_{Bp} can be also considered as a scaling factor for the total plasma current I_{pl}. It has been found that the neoclassical heat load width for all four DIII-D discharges follows approximately the $1/I_p$ dependence. There is neither anomalous transport nor neutral effects included in these simulations. The difference in the slopes of divertor heat load widths for different DIII-D discharges might be attributed to different collisionality in these discharges. The difference in slopes is especially noticeable if two set of discharges with lower (DIII-D discharges 132017 and 132018) and higher plasma densities (DIII-D discharges 132014 and 132016) are compared. This computational result on the effect of collisionality on divertor heat fluxes still needs to be confirmed in further computational and analytical analysis. Meantime, there is no doubt that the neoclassical divertor heat load width is decreasing with increasing plasma current for all DIII-D discharges studied in this research. Simulation results that are shown on Fig. 6 demonstrate the effects of neutral collisions and anomalous transport. The dependence of the divertor heat load width is weakly affected by neutral collisions, but it can be completely modified when the anomalous transport is introduced and is applied uniformly for all poloidal angles. Changes to the divertor heat load width scaling related to the ballooning nature of resistive-ballooning modes, that are likely to be major players in the region near the separatrix, are shown as purple curve on Fig. 6. In these simulations, the anomalous transport is applied in the region within 45° from the midplane. The neoclassical dependence of the divertor heat load width on the total plasma current is preserved for the high-density DIII-D discharge 132016 and is almost vanished for the low-density DIII-D discharge 132018 (not shown on Fig. 6). The dependence of divertor heat load width on the current density was weakest for the DIII-D discharge 132018 among discharges studied in this research (see Fig. 5). The introduction of anomalous transport effects typically widens the divertor heat load width. This observation becomes evident, when red and purple plots on Fig. 6 are compared.

5. CONCLUSIONS

The dependence of H-mode pedestal width and height on plasma shaping is investigated in coupled XGC0-ELITE simulations. The initial plasma profiles from equilibria reconstructed from three DIII-D experiments, where the elongation and triangularity have been significantly varied, are evolved in the kinetic neoclassical XGC0 code.

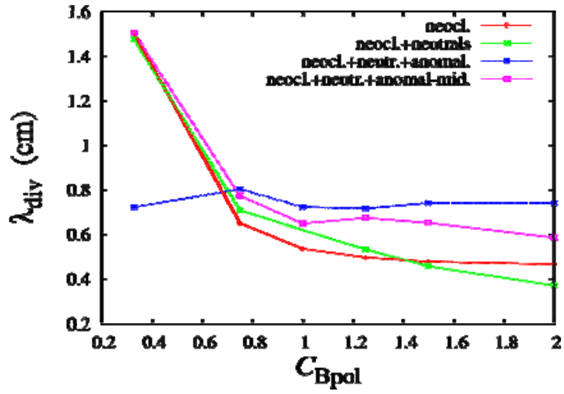

Fig. 6. Effects of neutral collisions and anomalous transport on the divertor heat load width scaling in the XGC0 simulations of the DIII-D discharge 132016. The red curve shows the neoclassical scaling that does not include the effects of neutral collision and anomalous transport. The green curve shows the effect of neutral collisions. The anomalous transport that is applied uniformly for all poloidal angles in used in the simulations resulted in the blue curve. The purple curve shows the divertor heat load width scaling when the anomalous transport is applied within 45° from the midplane

As plasma profiles evolve, the ideal MHD stability ELITE code is used to check if peeling-ballooning stability conditions are violated. These conditions set maximum H-mode pedestal height. In this research, it has been found that the neoclassical effects and MHD stability conditions alone can explain some experimentally observed trends. In particular, it has been found that the pedestal height is the largest in the DIII-D discharges with the largest elongation. The effect of triangularity is found to be somewhat weaker comparing to the effect of elongation. As result, it might be more difficult to reach specific pedestal height and width by altering the triangularity and keeping the elongation fixed. It has been also found that the H-mode pedestal width for electron temperature and plasma density is affected differently by elongation and triangularity. The effect of elongation reveals itself on the plasma density profiles first, while the effect of triangularity reveals itself on the electron temperature profiles first. Pedestal width for the plasma density profiles decreases with the elongation and is almost independent of triangularity, while the pedestal width for the electron temperature profiles decreases with the triangularity and is almost independent of elongation. It should be pointed out that these conclusions might change if the anomalous transport is included in this analysis. The theory-based MMM95 model has been tested for several DIII-D discharges that represent plasma current scan. The anomalous transport driven by the resistive ballooning modes is found to be one of the major contributors to the total anomalous transport in the near separatrix region. However, it is also found that the resistive-ballooning component of MMM95 produces too much transport if compared with effective diffusivites computed in the analysis mode using the XGC0 code. In addition, there are strong indications of particle and thermal pinches in the pedestal regions of Alcator C-Mod and DIII-D discharges, while the resistive-ballooning model does not predict particle and thermal pinches in these plasma regions. There is an urgent need for an improved resistive-ballooning model that can be applied for predictive modeling in the H-mode pedestal and SOL regions.

The neoclassical scaling of divertor heat load width with the plasma current in DIII-D and Alcator C-Mod discharges is studied in this report. It has been found that the divertor heat load width is broader for lower plasma currents for all discharges simulated in this work. The effect of neutral collisions does not significantly modify this dependence, while the inclusion of anomalous transport is typically widen the divertor heat load width and enhances the heat load fluxes on the divertor.

ACKNOWLEDGEMENTS

This work supported by the U.S. Department of Energy under grants DE-SC0000692, DE-FC02-08ER54985, DE-FG02-06ER54845, DE-FG02-92ER54141, DE-FG03-98ER54461, DE-FG02-94ER54084, DE-FC02-04ER54698, DE-FC02-99ER54512.

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Article received 29.09.10

КИНЕТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПЬЕДЕСТАЛА В РЕЖИМЕ УЛУЧШЕННОГО УДЕРЖАНИЯ ПЛАЗМЫ С ЭФФЕКТАМИ АНОМАЛЬНОГО ТРАНСПОРТА И МГД-УСТОЙЧИВОСТИ

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С помощью кинетического неоклассического кода XGC0 для разрядов в токамаках DIII-D и Alcator C-Mod исследованы скэйлинг пьедестала в плазме, находящейся в режиме улучшенного удержания, с приграничными локализованными модами (ПЛМ) первого типа, и зависимость свойств пьедестала и потока тепла на дивертор от вытянутости плазмы и тока плазмы. В расчетах используются: реалистичная геометрия дивертора, кинетическая модель для неоклассических эффектов, модель аномального транспорта, которая учитывает эффекты шира (ExB)-потоков, и условия возбуждения ПЛМ-неустойчивостей. В результате расчетов получены скэйлинги для ширины и высоты пьедестала как функции параметров плазмы. Нелинейное взаимодействие неоклассических эффектов и эффектов, связанных с аномальным транспортом, является мотивацией разработки самосогласованной численной модели, которая одновременно включает эффекты аномального и неоклассического транспорта. Показано, что потоки тепла на дивертор зависят от плазменных токов. Также представлены результаты исследования зависимости полуширины профилей тепла на дивертор от эффектов, связанных с аномальным транспортом и столкновениями с нейтральными частицами.

КІНЕТИЧНЕ МОДЕЛЮВАННЯ П’ЄДЕСТАЛУ В РЕЖИМІ ПОЛІПШЕНОГО УТРИМАННЯ ПЛАЗМИ З ЕФЕКТАМИ АНОМАЛЬНОГО ТРАНСПОРТУ І МГД- СТІЙКОСТІ

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За допомогою кінетичного неокласичного коду XGC0 для розрядів в токамаках DIII-D і Alcator C-Mod досліджено скейлінг п’єдесталу в плазмі, що перебуває в режимі поліпшеного утримання, з прикордонними локалізованими модами (ПЛМ) першого типу, властивості п’єдесталу і потоку тепла на дивертор в залежності від витягнутості плазми та струму плазми. У розрахунках використовуються: реалістична геометрія дивертора, кінетична модель для неокласичних ефектів, модель аномального транспорту, яка враховує ефекти шира (ExB)-потоків, і умови збудження ПЛМ-нестійкостей. У результаті розрахунків отримані скейлінгі для ширини і висоти п’єдесталу як функції параметрів плазми. Нелінійна взаємодія неокласичних ефектів і ефектів, пов'язаних з аномальним транспортом, є мотивацією для розробки самоузгодженої чисельної моделі, яка одночасно включає ефекти аномального і неокласичного транспорту. Показано, що потоки тепла на дивертор залежать від плазмових струмів. Також представлено результати дослідження залежності напівширини профілів тепла на дивертор від ефектів, пов'язаних з аномальним транспортом і зіткненнями з нейтральними частинками.