Topological effects of tokamak divertor geometry on particle transport in the presence of magnetic stochasticity

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The Resonant Magnetic Perturbations (RMP)[1] experiments have revealed that the electron and ion heat transport do not necessarily follow Gaussian process [1]. The edge particle and heat transport in stochastic magnetic field is studied by a guiding center orbit following calculation [2] in a concentric tokamak geometry. By further incorporating source and sink to sustain the equilibrium profile, shown below are the density and ion temperature evolution in the presence of magnetic stochasticity but with a prominent remaining island effect. In this work, the orbit calculation is extended to employ more realistic divertor geometry incorporating topologies of both the closed and the open magnetic field lines. The magnetic stochasticity allows particles to move from the closed field line region to open field line regions. Guiding center equation is derived by changing the flux coordinate to Cartesian to adopt the divertor geometry [3]. When the closed field lines are connected to the open filed lines, we expect to see particle and heat move along the field lines to the divertor plate and immediately disappear. The transport process then is no longer diffusive [4]. Computational model and numerical calculation results will be presented.

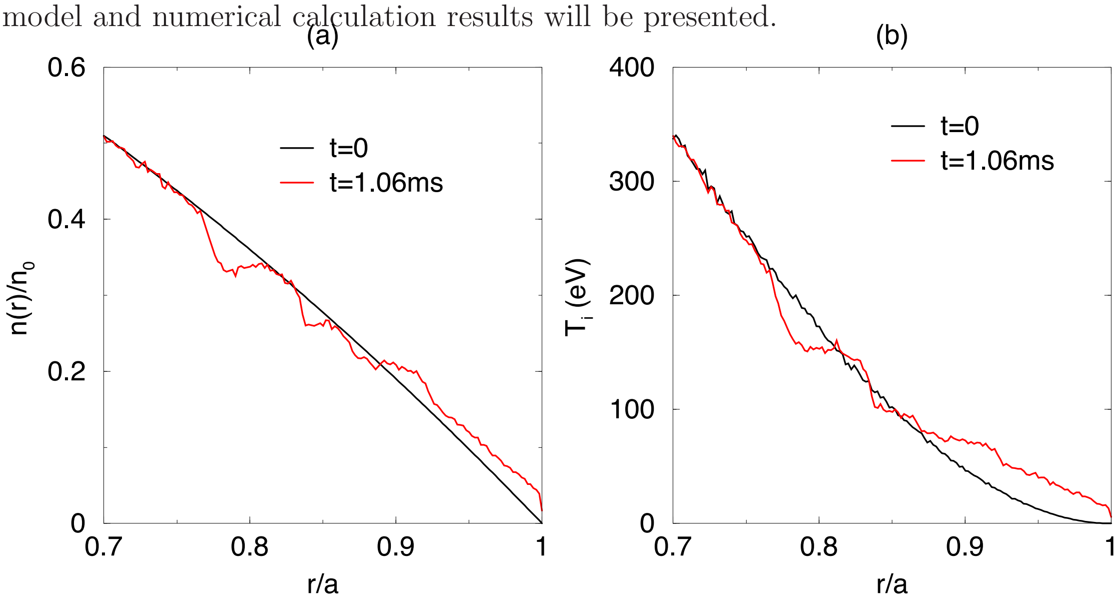

Figure 1: The radial profile of density and temperature evolution with source particles. (a) The density evolution and (b) the ion temperature evolution. Good flux surfaces inside the island cause particles to accumulate.

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Effects of magnetic islands on ECCD driven supra-thermal electron behaviors and current profiles in the tokamak plasma

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MHD instabilities such as tearing modes generate magnetic islands, which would enhance the heat and particle transport by breaking of magnetic flux surfaces due to the overlapping of magnetic islands. In the edge plasma, the transport related to the magnetic islands is one of the important issues.

ECCD is a reliable tool to drive current in plasma, and manage the toroidal current which can stabilize MHD instability and release bootstrap current in helical devices. It has been observed that the confinement-degrading islands can be reduced or completely suppressed by placing current inside the island by Electron Cyclotron Current Drive (ECCD)[1, 2]. However it has not yet been clearly understood the stabilization mechanism including the detail profile of the driven current. In order to make clear this point we have to solve the supra-thermal electron distribution by ECCD including the complex motion of supra-thermal electrons.

In this paper we study the ECCD driven supra-thermal electron behaviors including magnetic islands in tokamak plasma and evaluate the ECCD current profiles around the magnetic islands in the three dimensional space. We apply GNET code to simulate the supra-thermal electron distribution by ECCD, which can solve the drift kinetic equation including finite orbit effect in the 5D phase space[3].

Supra-thermal passing and trapped electrons are generated by the ECCD. Passing electrons almost follow the magnetic island structure, while trapped electrons are not sensitive to the magnetic island structure. We will make clear these electron behaviors with the magnetic islands and the effect on the current profile changing the heating points from O to X-point of the magnetic island.

As a next step we will assess the effect of obtained ECCD current profile on the MHD instabilities.

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Development of a drift-kinetic simulation code for estimating collisional transport affected by RMPs and radial electric field*

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To understand properties of collisional transport in a perturbed magnetic field is important for control of fusion plasma by employing resonant magnetic perturbations (RMPs) [1]. In recent tokamak experiments [2], RMPs are used to mitigate edge localized modes. It has been found simultaneously with the mitigation that theoretical estimates of the transport, which are based on the field line diffusion derived by Ref. [3], are too large compared to the experimental results [2]. The purpose of the present study is to reconsider the fundamental properties of the transport. For this purpose, we have started from a step of examining dependences of the ion thermal diffusivity on several important parameters (the strength of RMPs, collisionality, *etc.*) by using a δf simulation code, KEATS [4,5], which is developed to solve the drift-kinetic equation. In the simulation studies under an assumption of zero electric field [5], which is the same assumption as in Ref. [3], we have found that 1) the radial thermal diffusivity χ_r in the simulation is close to the diffusivity χ_r^{RR} derived by Ref. [3] if χ_r is evaluated in a temporary state of the guiding-center distribution function $f = f_{\mathrm{M}} + \delta f$, where f_{M} is a fixed Maxwellian background and the temporary state relaxes to a quasi-steady state of f after being sufficiently exposed to Coulomb scatterings; note that it is physically meaningful to evaluate χ_r in the quasi-steady state rather than the temporary state, which is the same as in the neoclassical theory; 2) the diffusivity χ_r evaluated in the quasi-steady state is extremely small compared with χ_r^{RR}; 3) the diffusivity χ_r has almost the same parameter-dependence as χ_r^{RR}; and 4) the effect of RMPs on χ_r is wiped out by the Coulomb collision in case of higher collisionality. At the present, the study is progressing for investigating effects of radial electric field on the transport. In this study, we further improve KEATS code for evaluating radial electric field and radial particle/energy fluxes of electron and ion in a perturbed region. We preliminary calculate the particle fluxes, and find that the electron particle flux is extremely larger than the ion particle flux when assuming zero electric field. We also find that the electron particle flux is reduced by radial electric field.

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Gyrokinetic model beyond the standard ordering

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Gyrokinetics is a common basis to study microturbulence in magnetized plasmas [1]. Recent local gyrokinetic simulations with realistic L-mode tokamak discharge parameters exhibit that turbulent ion heat diffusivities obtained from the simulations agree well with corresponding experimental results in an inner core region, but they deviate from each other in an outer core region [2,3]. The standard gyrokinetic model is formulated for perturbations with small amplitude and short wavelength. Since fluctuation amplitude tends to increase towards an edge region in L-mode tokamaks, it is anticipated that the standard gyrokinetic ordering fails there. Hence, several reduced kinetic models beyond the standard gyrokinetic ordering have been proposed for edge plasmas [4-8]. The limitation of small amplitude comes from the two-step phase space transformation in the standard formulation. Amplitude of electrostatic potential is used as a small parameter at the gyro-center transformation, the second step of the two-step phase space transformation. On the other hand, no assumption for wavelength is made at the phase space transformation stage. The assumption of short wavelength is used in deriving the gyrokinetic Poisson equation. This limitation can be relaxed by considering the high order displacement vector associated with the *guiding-center* transformation, the first step of the two-step transformation [9]. Although the original guiding-center transformation was constructed up to high order enough [10], the high order piece was not involved in the standard gyrokinetic formulation [11]. In this paper we consider a reduced kinetic model beyond both limitations on the basis of a reduced 1-form derived in Ref. [5].

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Self consistent turbulence response to RMPs and tearing modes

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The self consistent interplay of micro turbulence and magnetic islands in tokamak plasmas is compared for two different mechanisms of magnetic island generation, i.e. resonant magnetic perturbations (RMPs) and tearing modes. Numerical simulations are performed with EMEDGE3D [4], a three dimensional global fluid code in toroidal geometry using realistic plasma parameters. Concerning externally induced RMPs, previous results show that their penetration into the plasma is restricted by conditions on plasma rotation [1,3]. In presence of turbulence, a significant local reduction of the self- consistent plasma rotation governed by Reynolds and Maxwell stresses allows for RMPs penetration and also amplification [2,5]. Similarly, tearing modes have been shown to affect turbulent transport and zonal flows [6]. The aim of the present work is a comparative study and characterization of the interplay between RMPs and tearing modes, respectively, with plasma turbulence, transport and rotation.

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On Immediate Influence of Source Input on Edge-Core Coupling

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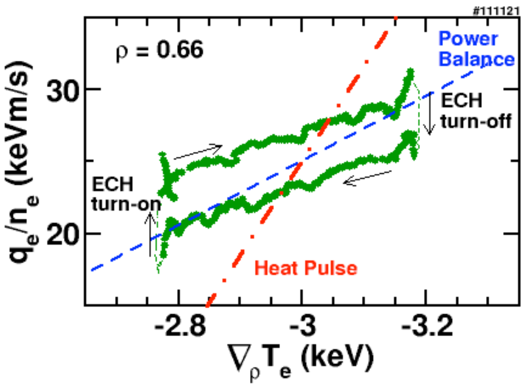

Recently, the radial heat flux and turbulence intensity were found to change immediately (within experimental time resolution) after the timing of heating power change [1]. The gradient-flux relation has hysteresis as is shown in the right figure. This is an essential element in observed violation of local closure in transport relations [2]. In order to understand the immediate influence of input source, the new thermodynamical force in phase space is introduced, and the enhancement of turbulence intensity I is predicted as

$$I = \frac{1}{1-\Gamma_h} I_0 , \quad \Gamma_h = \frac{\gamma_h}{\chi_N k_\perp^2} = \frac{\delta P}{\delta p} \frac{1}{\chi_N k_\perp^2}$$

where Γ_h indicates the direct effect of heating power, and other parameters are standard [3-5]. This result shows that the transport is immediately influenced by the source input, without waiting the changes of global plasma parameters. This mechanism is more effective for long-wavelength perturbations, so that this change of transport by source input is associated with the rapid core-edge coupling. The new insight of edge transport along this line of thought is explained.

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Particle simulation on the growth of plasma blob in an open system

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The implicit particle simulation was performed to research a flute instability under the gravitational acceleration $g(x)$, where there includes two regions of stable $[g(x) < 0]$ and unstable $[g(x) > 0]$ to a flute mode in the simulation system. The $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity shear is also included as an initial condition by introducing the excess electrons. It is found that the plasma blobs are born after the flute instability saturates as shown in Fig.3.

The centrifugal acceleration averaged over a magnetic field line in an open system such as GAMMA10 is given by $g_{eff} = \frac{T_{i,\perp}+T_{i,\parallel}}{2M_i}\nabla \ln U$. Here $U = \int[(\hat{p}_\perp + \hat{p}_\parallel)/B^2]d\chi$ is the effective magnetic specific volume, where $\hat{p}_{\perp,\parallel}$ is the pressure and the coordinate χ is defined by $\boldsymbol{B} = \nabla\chi$. Fig.1 is an example of radial profile of U of GAMMA10 in the case of a low anchor pressure. It is found that there is a unstable region to flute mode in $r/r_0 \gtrsim 0.6$ in Fig.1. Two-dimensional particle simulation ($x \times y = 256 \times 128$) is performed to research the flute instability in the case of $\mathbf{g}_{eff} = g(x)\hat{e}_x$, where $g(x = 64) = 0$ is assumed in Fig.2. Ions and electrons are distributed such that the density profile has a shape of $n(x) = -a_0 \tanh\{(x - x_h)/a_h\} + b_0$, where $x_h = 64$ and $a_h = 0.01 \times 256$ in Fig.2. The initial $E_x(x)\hat{e}_x \times B\hat{e}_z$ drift velocity shear is introduced with use of excess electrons, where $E_x(x) = -A_0 \tanh\{(x-X_h)/A_h\}+B_0$ with $X_h = 64$ and $A_h = 0.05\times256$.

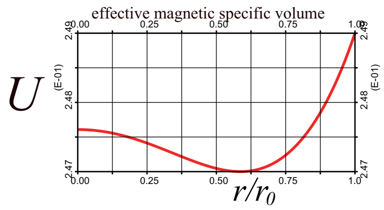

Fig.1 : Specific volume of GAMMA10

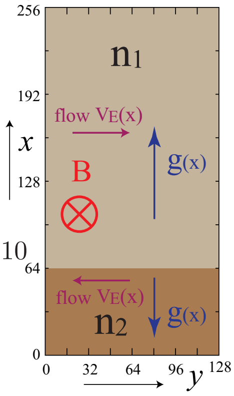

Fig.2 : Geometry of simulation

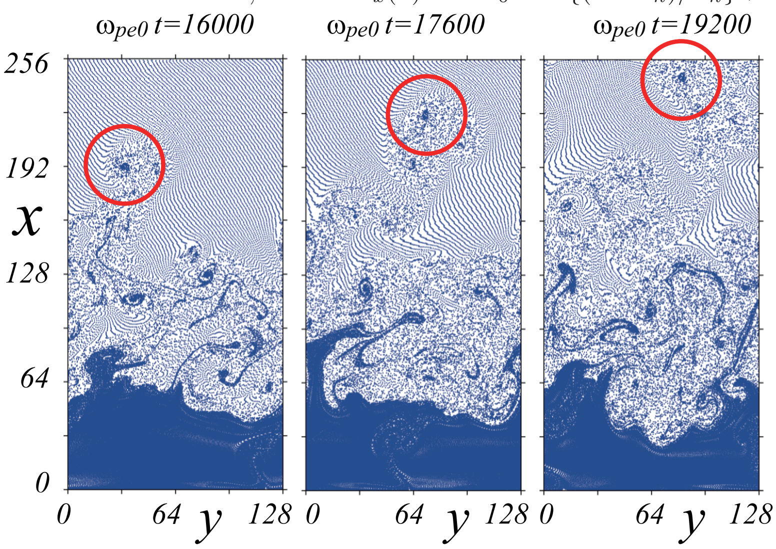

Fig.3 : Ion real space positions in x-y are plotted at each time.

The Kelvin-Helmholtz instability is driven by the velocity shear at first, so that ions and electrons in the high density region ($x < 64$) come into the unstable region ($x \gtrsim 64$) to the flute mode, so that the flute instabilities are driven near $x \simeq 64$. But the instabilities are localized around $x \simeq 64$ and saturate at a low amplitude because of a small amount of ions and electrons which contribute to a flute instability. A mass of particles inside the instability is broken into several blobs of particles, some of which begin to move upward in Fig.3. Fig.3 shows the ion real space positions observed in the simulation. The deep color means that the particle density is high. It is found that the blob (deep color) surrounded by circle clearly moves upward in time. The region around $x \simeq 64$ has changed into a turbulence flow state and many masses of ions are observed to be born repeatedly in time.

Turbulence dynamics with the coupling of density gradient and parallel velocity gradient in the edge plasmas

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Recently, the coupled dynamics of particle transport and parallel flow momentum was observed in a basic experiment on linear plasma device, PANTA [1,2]. In these experiment, the 2D flow structure with the inversion of flow direction, as well as density peaking behavior were reported. As a possible mechanism behind these behavior, we proposed a model for coupled dynamics of ∇n driven drift waves and ∇v_z driven D'Angelo modes. The theory[3] predicts the resultant transport flux as

$$\frac{\Gamma_n}{n_0 c_s} = \sum_{\mathbf{k}} k_y \rho_s \frac{-\omega + \omega_{*e}}{k_\parallel^2 D_\parallel} \left| \frac{e\tilde{\phi}_{\mathbf{k}}}{T_e} \right|^2 + \sum_{\mathbf{k}} k_y \rho_s \frac{c_s^2 k_\parallel^2 - c_s k_\parallel \rho_s k_y \langle v_z \rangle'}{k_\parallel^2 D_\parallel \omega} \left| \frac{e\tilde{\phi}_{\mathbf{k}}}{T_e} \right|^2, \tag{1}$$

$$\frac{\Pi_{rz}}{c_s^2} = \sum_{\mathbf{k}} k_y \rho_s \frac{(-\omega + \omega_{*e}) c_s k_\parallel}{k_\parallel^2 D_\parallel \omega} \left| \frac{e\tilde{\phi}_{\mathbf{k}}}{T_e} \right|^2 + \sum_{\mathbf{k}} k_y \rho_s \frac{c_s k_\parallel - \rho_s k_y \langle v_z \rangle'}{\gamma_{KH}} \left| \frac{e\tilde{\phi}_{\mathbf{k}}}{T_e} \right|^2 \Theta(\gamma_{KH}). \tag{2}$$

Here Γ_n is the particle flux, Π_{rz} is the momentum flux per unit mass density, and $\Theta(\gamma_{KH})$ is the step function. Others follow standard notations. The last term of Eq.(1) describes the interference of the particle transport and the parallel flow shear. If the parallel flow shear becomes strong enough, the net particle flux can be inward to peak the profile. In this work, we address the application of these ideas on the edge turbulence, where the parallel flow shear becomes strong. For typical plasma parameters, the particle flux can invert for $\langle v_z \rangle' L_n / c_s \gtrsim O(1)$. This condition may be satisfied for SOL turbulence, where ion thermal Mach number $\sim O(1)$ and/or the narrow layer width are reported. We also argue that once excited, D'Angelo modes may spread from the SOL region into the main plasma and could impact transport process.

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Edge plasma turbulence interaction with transport barriers generated by forced and self-consistent mechanisms

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Despite its essential role for present and future tokamaks, the generation of transport barriers as observed in H-mode regime remains not yet fully understood as well as its self-organization with turbulence. The shearing of radial turbulent structures by large-scale poloidal flows appears to be one of the key mechanisms of the turbulence reduction induced by a transport barrier at the pedestal [1]. Understanding such interaction between turbulence and transport barrier could also pave the way for turbulence control in the Scrape-Off-Layer, for instance by a local biasing of the divertor plates, as experimented on NSTX [2].

In this work, a flux-driven 2D fluid code, TOKAM-2D [3], based on the interchange instability is used to analyze the properties of transport barriers in the edge plasma. These barriers are generated either artificially with different forcing approaches or self-consistently by target plates biasing or at the transition between closed and open field lines.

Transport barriers are analyzed statistically, showing the existence of two kinds of barriers as reported in [4]. Strong barriers are characterized by a low-frequency emission of large amplitude relaxation events whereas leaky barriers exhibit small amplitude bursts with a large occurrence. The ratio between the turbulent flux and the total flux (including both turbulent and diffusive fluxes) appears to be the key parameter to identify the barrier localization. We also focus on the impact of the barrier width and stiffness on the barrier stopping capability.

Two stabilizing mechanisms, a nonlinear one driven by the shear of the ExB velocity (second radial derivative of the electrostatic potential) [5] and a linear one involving the third radial derivative of the mean electrostatic potential, are identified. These mechanisms are then artificially forced in dedicated simulations to analyze their differences and their impacts on the turbulent transport. We show for instance that they have opposite impacts on large amplitude events. These are filtered by the linear mechanism, which leads to a decrease of the density skewness from 1 to 0.5. On the contrary, the non-linear mechanism tends to enhance the level of density fluctuations, associated with a typical increase of the skewness by a factor of 2.

Finally, we analyze which of these two mechanisms is dominant in two self-consistent phenomena: a transport barrier driven by local biasing of the target plates and the spontaneous plasma response to the transition between open and closed field lines.

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Flux-driven turbulence simulation of L-H transition with BOUT++ code

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Understanding the L-H transition dynamics [1] is one of the key issues for predicting the confinement performance of the core plasma and controlling the heat load on the plasma facing materials in magnetically confined fusion devices. In JAEA, an Integrated Transport Simulation Framework (ITSF) for the L-H transition has been therefore developed and the qualitative evaluation of the L-H transition was obtained such as the spontaneous quench of the thermal diffusion [2]. The quantitative evaluations such as the prediction of the pressure at the pedestal top and the power threshold of the L-H transition, however, have been still an open issue so that improvement of the turbulent transport model and the development of a simulation framework closer to first-principles theory than the ITSF are required.
Recently 3-dimensional First-principles Transport Simulation Frameworks (FTSFs) of the L-H transition by 2-field reduced magnetohydrodynamic (RMHD) models have been reported [3, 4] incorporating the following three key components; (1) the resistive ballooning mode (RBM) turbulence based on the 2-field RMHD model, (2) the strongly sheared radial electric field due to the neoclassical force balance, (3) the flux-driven pressure evolution. If the FTSF is extended to the 3-field current diffusive ballooning mode (CDBM) RMHD model, it also provides a new procedure to improve the CDBM turbulent transport model [7] employed in ref [2] through the comparison between the L-H transition simulations by ITSF and FTSF. In this study, we have been developing a FTSF for the L-H transition based on the nonlinear 3-dimensional edge turbulence/MHD code BOUT++ [5, 6] for improving the CDBM transport model. We will present nonlinear flux-driven simulations of the L-H transition with the RBM and the drift-wave turbulence modeling in toroidal geometry with a circular cross-section. We utilize a Hasegawa-Wakatani-like 2-field RMHD model consisting of the vorticity equation and the energy transport equation as a preliminary step for the L-H transition simulation with the CDBM turbulence.

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Nonlinear oscillations in a Reaction-Diffusion model with $E \times B$ frequency shear: a paradigm for type-III ELMs

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We derive and study a 1D Partial-Differential-Equation (PDE) of the Reaction-Diffusion type describing the nonlinear oscillations of a transport barrier in a prescribed finite $E \times B$ shear-layer of width $d << a$ (a is the plasma minor radius). It is based on a 1D reduced model previously derived to explain nonlinear barrier oscillations in 3D turbulence simulations [1]. We show that this single nonlinear equation describes well the physics of the barrier relaxations [Fig. 1]. The nonlinear oscillations have common characteristics with type-III Edge Localized Modes (ELMs), such as a repetition frequency which decreases with increasing power [2]. In addition to the flow-shear, the shear-layer width is predicted to control the nature of the oscillations. This model sheds some light on the basic mechanism responsible for the fast-burst of the ELM-cycle. In between bursts, the phase of the mode increases approximately linearly with time [Fig. 1]. This reflects the fact that the local frequency is locked to the local $E \times B$ frequency: $\omega \sim \omega_E(x)$, i.e. the mode is locally advected by the flow. In contrast, at the time of the burst, our model shows a *phase-jump*, with a much faster timescale. This jump in the mode phase α corresponds to a burst in the local frequency -$\partial\alpha/\partial t$ of the mode. Experimental data from KSTAR (although on type-I ELMs) shows evidence of such a burst in frequency, at the ELM crash.

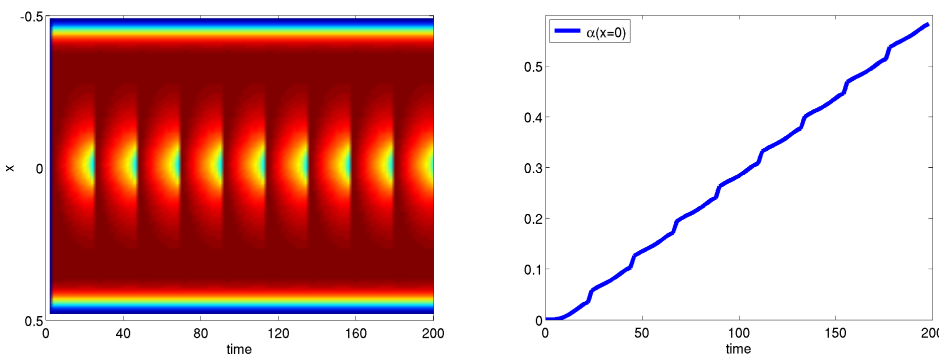

Figure 1: Spatiotemporal evolution of the mode amplitude (left) and dynamics of the mode phase (right)

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Fluid neutral model for use in hybrid simulations of a detached ITER case

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Most current plasma edge codes use a kinetic neutral particle description solved with a Monte Carlo code. This leads to exacerbated run-times and high statistical noise in high recycling and detached regimes, hampering the design of next generation fusion reactors.
Because of the high number of charge-exchange collisions between ions and neutrals in these regimes, a continuum approximation might be valid in at least part of the simulation domain, bringing the perspective of efficient hybrid neutral modeling. In this paper, we deduce a fluid model assuming dominant neutral-ion collisions. This leads, fully consistently with the kinetic equation, to a pressure diffusion and an energy equation. The model also includes the reflection of the neutrals at the target plate by using a diffusion approximation to estimate the flux of neutrals impinging on the target plate.
Next, we investigate this neutral model within a 1D (parallel) context concentrating on the region just upstream the divertor target. The neutral model represents the physics present in the EIRENE code [1] as much as possible, but only purely mono-atomic Deuterium is modeled. The TRIM code database [1] is used to model the reflection of the neutrals reaching the target plates and fits for the microscopic cross-sections and the rate coefficients from the AMJUEL-HYDHEL databases [2,3] are incorporated. As a result, the boundary conditions are fully consistent with the kinetic model, and no artificial fitting parameters are introduced. To enforce similarity of the neutral-ion interactions to those of a detached regime, fixed typical ion and electron temperature profiles are imposed. The plasma continuity and momentum equations and the neutral model are solved for a flux tube along the separatrix. The fluid neutral model and its related boundary conditions are assessed by comparing with a kinetic description of the neutral transport. To solve the kinetic Boltzmann equation with a finite volume approach, it is reduced to two independent variables (the poloidal position and particle velocity). Thus, the influence of Monte Carlo noise is avoided.
The simulation results with the fluid model match well with the kinetic reference solution. Already with the pressure diffusion equation only, plasma properties are predicted with a relative error of 30%. Adding a neutral energy equation further reduces plasma property deviations to values lower than 3%. This neutral model is therefore expected to perform efficiently in hybrid approaches for neutral transport modeling as envisaged in future work.

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Parameter scan study of impurity transport model in comparison with EUV emission measurements in the stochastic layer of LHD: effects of first wall recycling and transport coefficients

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The transport behavior and line emissions of the intrinsic carbon in the stochastic layer of Large Helical Device (LHD) have been simulated by the three-dimensional (3D) edge transport code EMC3-EIRENE [1-2] in order to validate the trace impurity transport model adopted in the 3D code. The cross-field particle and energy transport coefficients, $D_\perp$ and $\chi_\perp$, are determined by fitting the electron density and temperature profiles measured at the mid-plane. Based on these cross-field transport coefficients, 2D distribution of carbon line emission is simulated and compared with the emission distribution in the poloidal and toroidal directions measured by a space-resolved EUV spectrometer. Several parameters in the calculations are surveyed to explain the measured carbon emissions, i.e. the perpendicular diffusivity, coefficients of each term in the impurity parallel momentum transport equation, the injection energy of impurity and impurity source distribution at divertor and first wall. A discrepancy of the carbon line emission between the measurement and simulation can be discussed with the ion thermal force and the friction force in the impurity transport model. It is also found that the first wall impurity source, in particular, the impurity production at which the space between the first wall and plasma edge is smallest, plays an important role to determine the emission distribution. The result indicates a substantial effect of the plasma-wall interaction on the edge impurity transport in LHD in addition to the impurity generation at the divertor region.

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Extended Numerical Modeling of Impurity Neoclassical Transport in Tokamak Edge Plasmas

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Understanding of impurity transport in tokamaks is an important issue in order to reduce the impurity contamination in fusion core plasmas. Recently, a new kinetic numerical scheme of impurity classical/neoclassical transport[1,2] has been developed. This numerical scheme makes it possible to reproduce collisional self-diffusion (SD), inward pinch (IWP), and temperature screening effect (TSE) of impurity ions. However, impurity neoclassical transport has been modeled only in a case where background plasmas are in the Pfirsch-Schluter (PS) regime. The purpose of this study is to extend our previous model to wider range of collisionality regimes, i.e., not only PS regime, but also Plateau regime.

In this study, a kinetic model[1,2] with the Binary Collision Monte-Carlo Model (BCM)[3] has been adopted. Trajectory of each test impurity ion in the magnetic field is followed by the Boris-Buneman algorithm[4]. We focus on the modeling of the SD and the IWP in this paper. In order to simulate the neoclassical transport with the BCM, velocity distribution of background plasma ions has been modeled as a deformed Maxwellian distribution which includes plasma density gradient.

By using this scheme, some test calculations with a simple torus magnetic configuration have been done. Some parameter dependences of SD and IWP have been checked. Figure 1 and 2 show the dependence of IWP velocity on safety factor q in cases of $\nu^* \approx 14$ (in PS regime) and $\nu^* \approx 3$ (in Plateau regime) respectively, where ν^* is the collisionality parameter of background plasmas which is defined as the effective collision frequency divided by the bounce frequency. The IWP velocity increases almost in proportion to q^2. Other parameter dependences of IWP velocity (e.g., the dependence on the impurity charge state) have been studied and will be discussed in the presentation.

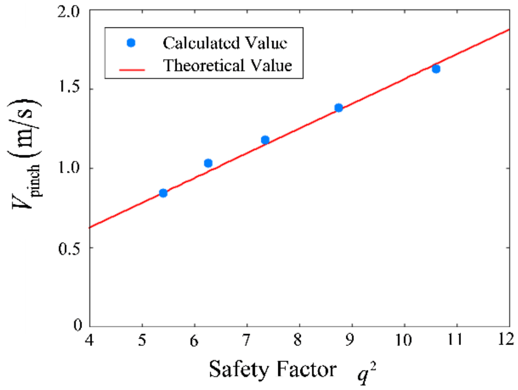

Fig. 1 Dependence of IWP on safety factor (in PS regime).

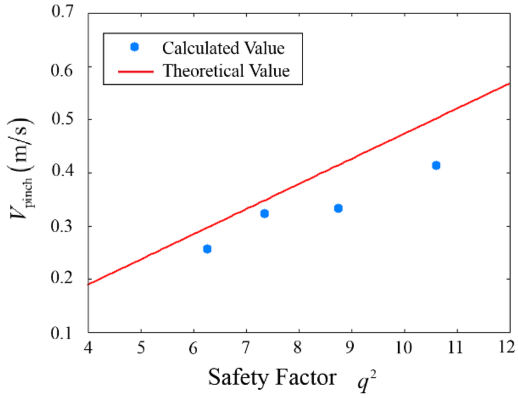

Fig. 2 Dependence of IWP on safety factor (in Plateau regime).

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Study on molecular ion production during detached plasma formation in divertor simulator TPD-SheetIV

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In the design of fusion reactors for high power and long pulse operation, vast heat flux($>$ 10[MW/m^2]) is expected to flow onto divertor target plates. In order to reduce this heat load, the divertor design on stable detached plasma formation must be realized. Experimental simulation on the V-shaped target for gas divertor has been conducted in a linear divertor plasma simulator TPD-SheetIV. [1] Recently advanced divertor concept such as V–shaped divertor or long leg divertor has been proposed for ITER design and its optimization with detail information on charged and neutral particles has been conducted.
In order to understand the basic physical process of detached plasma,[2] many kinds of ion must be detected separately. In our experiment, the hydrogen atomic and molecular ion currents (H^+, H_2^+, H_3^+) are measured by omegatron type mass analyzer located behind target. The ionization and recombination events are discussed using the collisional-radiative (CR) model. When long duct is connected to V–shaped divertor, signal of H_3^+ is increase even in low gas puff case. This means the evidence of detachment plasma with little neutral back flow.
Experimental data is, however, still limited due to the difficulty of 2 dimensional measurement and numerical simulation study must be developed. Study on neutral particle behavior with DEGAS 2 Monte Carlo code [3] has already launched and preliminary result is reported.[4] Although qualitative effect of the divertor design on neutral behavior is confirmed, quantitative agreement with omegatron data has not achieved yet.
In this work, collisional radiative model which determine the molecular ion density is improved with detail atomic process data, realistic plasma parameter, and neutral source modeling. New divertor configuration with baffle structure is also studied for more serious heat handling problem in DEMO design.
In the conference, these detail experiment results and improved simulation results will be presented. This work is partially performed with the support and under the auspices of the NIFS Collaborative Research Program. (NIFS12KOBF024)

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On divertor detachment and detachment stability

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Detached or semi-detached diverter operation is the primary operational scenario for the ITER diverter (e.g. see Ref. 1 and the references therein). Here we define a diverter detachment as a "roll over" of plasma flux which in experiment is often observed with increasing plasma density [2].

However, detached diverter conditions should be compatible with a good core plasma confinement, which is often accompanied with large ELMs which "burn through" detached diverter and release a large amount energy in diverter target, which can lead to erosion of diverter targets. In addition, detached diverter conditions should be stable and not cause thermal instability resulting in the MARFE formation, which, potentially, can cause disruption of the discharge. Finally, often inner and outer diverter detach at different plasma conditions, which can lead to detachment instability and core confinement degradation.

Here we discuss basic physics of diverter detachment, detachment stability, and an impact of ELMs on detachment. We consider an impact of different magnetic and diverter geometries on detachment onset, stability, in- out- asymmetry, and tolerance to the ELMs. Based on available scalings of the width of the heat flux to the target we derive the scalings for the onset of detachment for different magnetic and diverter geometries. We also discuss possible mechanisms of the impact of diverter detachment on core plasma confinement and the role of plasma facing material in diverter detachment.

Acknowledgements. This material is based upon work supported by the U.S. Department of Energy Office of Science, Office of Fusion Energy Sciences under Award Number DE-DE-FG02-04ER54739 at UCSD.

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Detailed Analysis of Plasma Resistivity in Detached Plasmas

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Detached plasmas can be used to reduce the heat load on plasma-facing components in nuclear fusion devices and the understanding of characteristics of the detached plasmas is one of the important issues. Langmuir probe is popular measurement method to obtain electron temperature and density in plasmas. However, anomaly of probe characteristics leads to, high electron temperature in detached plasmas compared with that determined with the spectroscopic methods[1]. In this study, the influence of plasma resistivity on the probe characteristics in detached plasma is investigated in the linear plasma device NAGDIS-II. Based on the experiment results, the cause to induce larger plasma resistivity in detached plasmas is also discussed.

In a conventional double probe method, the electron temperature T_e can be determined from the following equation:

$$\left.\frac{dI_\mathrm{p}}{dV_\mathrm{p}}\right|_{V_\mathrm{p}=0} = \frac{e}{2kT_\mathrm{e}} I_\mathrm{is}\,, \tag{1}$$

where I_p is probe current, V_p is probe voltage, I_is is ion saturation current, k is Boltzmann constant, e is the elementary charge. By taking the plasma resistance between electrodes, R_p, into account, eq. (1) is modified to be

$$\left.\frac{dI_\mathrm{p}}{dV_\mathrm{p}}\right|_{\substack{I_\mathrm{p}=0\\ V_\mathrm{p}=0}} = \frac{\frac{e}{2kT_\mathrm{e}} I_\mathrm{is}}{1 + R_\mathrm{p}\frac{e}{2kT_\mathrm{e}} I_\mathrm{is}}. \tag{2}$$

Eq.(2) makes it possible to evaluate the influence of plasma resistivity on the probe characteristics.

A comparison between the the meshed double probe measurement and spectroscope method in the detached plasmas was made in NAGDIS-II. Eq. (1) gave us a considerably high electron temperature compared with the spectroscopic method.

The plasma resistivity is estimated to be 0.36 Ωm to match T_e from the probe method to that with the spectroscopic method in eq. (2). The estimated plasma resistivity is much larger than both Spitzer resistivity and resistivity caused by electron - neutral collision.

To discuss the cause of larger plasma resistivity in the detached plasma, the resistivities induced by electron collision to highly excited neutrals, so-called Rydberg atom, which are produced by volumetric plasma recombination and by plasma turbulence were calculated. However, the calculation results also became smaller values more than an order of magnitude compared to the experimental ones. So, further physical mechanism in detached recombining plasmas should be considered.

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Modeling of ELMs in detached divertor plasmas with UEDGE-MB-W

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In this study we used the UEGDE-MB-W code (the newest version of 2-D edge plasma transport code UEDGE, which incorporates Macro-Blob (MB) approach to simulate non-diffusive filamentary transport and various "Wall" (W) models for time-dependent wall recycling [1-2]) to simulate the dynamics of boundary plasma and impurities over a sequence of many type-I ELM events under detached divertor plasma conditions in DIII-D tokamak. We present the results of parametric analysis on the impact of the size and frequency of ELMs on the divertor plasma parameters where we vary the Macro-Blob characteristics under different pedestal plasma conditions.

Our calculations show that in the case of relatively small-sized and frequent type-I ELMs on DIII-D typical for high-power H-mode discharges with very strong deuterium gas puff, the ELMs are not "burning" through the formed detached divertor plasma. In this case, the inner and outer divertors are filled by sub-eV, highly-recombining, impure plasma. The change in the total inventory of impurity particles over the ELM cycle is relatively small, whereas the distribution of carbon ions over ionization states and, hence, the plasma radiation pattern change dramatically in the ELM. In response to strong enhancement of plasma radiation, the degree of divertor plasma detachment increases during the ELM. The UEDGE-MB-W modelling results will be compared to the experimental data available on DIII-D.

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Statistical analysis of particle flux flowing into the end-target in between attached and detached states in the linear divertor plasma simulator NAGDIS-II

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In the edge region of magnetically confined plasma devices, there are several types of frequent-occurring phenomena accompanying positive and/or negative spikes, such as ELMs and blobs/holes. In this study, we have found similar event during the transient phase between attached and detached states of the end-target in the linear divertor plasma simulator NAGDIS-II. By rapidly increasing the neutral gas pressure, negative and positive spikes of the particle flux flowing into the end-target were observed in sequence. This would reflect spatial behavior of the ionization front and is important to understand stability of the detached plasma. To analyze the particle flux measured by the end-target, we applied a new method which clarifies the statistics of amplitude and frequency characteristics simultaneously. This method could also be useful for analyses of similar fluctuations.

Typically, fluctuation ($\tilde{x} \equiv x - \langle x \rangle$) having positive/negative spikes is often characterized by the skewness (S) that is defined by the third-order central moment ($m_3 \equiv \langle \tilde{x}^3 \rangle$) normalized by the standard deviation ($\sigma \equiv \langle \tilde{x}^2 \rangle^{1/2}$), $S \equiv m_3/\sigma^3$. If positive spikes are dominant in the signal, S becomes positive. Thus, $m_3 = S\sigma^3$ indicates the sign of the dominant spikes and the fluctuation intensity. On the other hand, frequency range information of the positive/negative spikes is important for access to the phenomenon. We are suggesting the analysis method to expand the m_3 to the frequency domain.

Firstly, substituting $y \equiv \tilde{x}^2$ to m_3, $m_3 = \langle \tilde{x} \cdot \tilde{x}^2 \rangle = \langle \tilde{x} \cdot y \rangle = \langle \tilde{x} \cdot (\tilde{y} + \langle y \rangle) \rangle = \langle \tilde{x} \cdot \tilde{y} \rangle + \langle \tilde{x} \rangle \langle y \rangle = \langle \tilde{x} \cdot \tilde{y} \rangle$. Therefore, an integration of one-sided cross-spectrum ($S_{\tilde{x}\tilde{y}}$) of $\tilde{x}$ and $\tilde{y}$ corresponds to m_3 as follows:

$$m_3 = \int_0^\infty S_{\tilde{x}\tilde{y}}(f)\mathrm{d}f = \int_0^\infty K_{\tilde{x}\tilde{y}}(f)\mathrm{d}f, \tag{1}$$

where $K_{\tilde{x}\tilde{y}}$ means the co-spectrum. To calculate $K_{\tilde{x}\tilde{y}}$, we can select the Fourier technique and the wavelet analysis with the mother wavelet (ψ) as

$$K_{\tilde{x}\tilde{y}}(f) = \frac{1}{T f_\mathrm{c} C_\psi} \int_0^T \mathrm{Re}\left[W_1(a,b) W_2^*(a,b)\right] \mathrm{d}b, \tag{2}$$

where $W_1(a,b) = (1/a)\int_0^T \tilde{x}(t)\psi^*\left[(t-b)/a\right]\mathrm{d}t$ and $W_2(a,b) = (1/a)\int_0^T \tilde{x}^2(t)\psi^*\left[(t-b)/a\right]\mathrm{d}t$. By applying this method, we obtained the sign of the spikes and its frequency characteristic.

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An analytical expression for the electric field and particle tracing in plasma-wall interaction experiments at the JET ITER-like wall

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For a successful realization of the ITER project it is important to study the plasma-surface interaction (PSI) processes. PSI is determined to a large extent by the Debye sheath (DS) and the magnetic pre-sheath (MPS). Therefore, it is necessary for calculating ions movement correctly to describe these sheaths including the electric field distribution in the presence of the oblique magnetic field there.

For detailed studies of erosion and deposition of shaped wall components in fusion experiments the simplified analytical expression for the electromagnetic field is suggested which mimics the potential dependence on magnetic field angle, however allowing to avoid solving of the complex integral equations as in [1-2]. It describes the distribution of the electric field in the DS and MPS for wide range inclination angles between magnetic field and the surface including small angles $1° \leq \alpha \leq 5°$ that are typical for limiter tips and over critical locations of plasma-facing components in fusion devices. The resulting sheath electric field is in a good agreement with the Chodura and Stangeby solutions [1, 2] and also with respective particle-in-cell (PIC) simulations carried out using the SPICE2 code [3].

In the 3D local plasma impurity transport and PSI code ERO [5] a purely numerical approach was used previously for calculating of the traced particle trajectories. A second analytical solution, using the one for the E-field variation in the sheath, is suggested for the very last part of the trajectory just before the surface impact. The angular distributions of impinging ions obtained from suggested analytical solutions and PIC simulations [3, 4] are in good agreement. These analytical solutions then were introduced into the code ERO. The updated code was used to simulate the energy and angular distributions of impinging ions which determine the physical sputtering. The earlier ERO simulations [5] for the erosion Be limiter at JET ITER-like wall were revised (up to 30% increase). The related comparison of the ERO-simulated Be emission with the experimental observations is presented.

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Accuracy and convergence of coupled finite-volume / Monte-Carlo codes for plasma edge simulations

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The physics of the plasma edge in nuclear fusion reactors is simulated using computationally expensive coupled finite-volume / Monte-Carlo (FV/MC) codes, such as a.o. B2-EIRENE (SOLPS) [1]. In future reactors, such as ITER [2] and DEMO, so-called high recycling and detached regimes are targeted. These regimes heavily rely on increased plasma-neutral interactions to reduce the heat load and erosion of plasma-facing components to acceptable levels, a major issue compared to present-day experiments. As a result, plasma-neutral interactions become so strong that achieving accurate simulations within an affordable computational time becomes a challenging task.
To improve the computational performance of these FV/MC systems, we first asses numerical error contributions with a simplified 1D model. In this model, the plasma is described by fluid equations discretized numerically with the FV approach. Neutral transport is governed by a simplified kinetic equation solved with both a MC and a FV code. This allows comparing the FV/MC result with a deterministic FV/FV solution. We examined the accuracy and convergence for several coupling techniques: correlated sampling, random noise and Robbins-Monro [3]. For each coupling technique, a procedure is formulated to estimate the errors from statistical noise, discretisation, finite sampling and incomplete convergence.
The aim is to apply this error framework to B2-EIRENE simulations of ITER regimes. We follow two tracks. On the one hand, a simple 2D test case of a slab geometry is run with B2-EIRENE. On the other hand, the 1D model is extended with additional terms to mimic radial transport and additional physics under ITER-relevant conditions. To this end, B2-EIRENE simulation results under partially detached ITER conditions are used. For both approaches, an error assessment is performed and the major contributions to the numerical error are analysed.
This work is complementary to the work of Marandet et al. (this conference) where the noise is artificially induced - for analysis purposes - in an otherwise deterministic set of equations.

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Effects of classical and neo-classical cross-field transport of tungsten impurity in realistic tokamak geometry

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Due to its high melting point and high thermal conductivity, tungsten has been considered as one of the most promising candidate materials for divertor plates and first wall material for the ITER and DEMO reactors. However, the atomic number of tungsten is so high that the strong radiation cooling affects the main plasma performance even if a small amount of tungsten penetrates the main plasma. Therefore, it is important to understand tungsten impurity transport processes from their birth point towards the main plasma.

Recently, Refs. [1-3] pointed out that the effects of Inward Pinch (IWP) and Temperature Screening Effect (TSE) to impurity particles may be comparable with anomalous diffusion while these effects are not considered in existing kinetic impurity transport simulations in the SOL/Divertor plasma of tokamak. So far, these effects have been examined only in the slab and simple torus geometry. Due to the existence of steep perpendicular gradient of plasma temperature and density in the SOL, IWP and TSE may also be non-negligible in the realistic tokamak geometry. The effects of classical and neo-classical IWP and TSE to tungsten impurity transport processes should be examined in SOL/divertor plasma.

The purpose of this paper is to examine the effects of classical and neo-classical cross-field transport processes, namely, IWP and TSE, in a model geometry of JT-60U tungsten tile experiment[4]. Prior to the impurity transport simulations, classical and neo-classical TSE model [2] and IWP model [3] have been implemented into the tungsten impurity transport code IMPGYRO [5]. Background plasma parameters have been calculated by SOLPS5.0 code package [6]. Tungsten impurity transport has been calculated by the IMPGYRO based on the obtained background parameter above. The effects of classical and neo-classical cross-field transport to tungsten are examined in several characteristic regions of tokamak plasma such as the SOL region, the pedestal region, and the private region.

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Basic Consideration of Monte-Carlo Algorithm to Solve Fluid Equations for SOL/Divetror Plasmas

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Understanding of plasma transport in SOL/Divertor region is one of the most important issues in order to reduce heat and particle loads to the divertor plate in future fusion reactors. For this purpose, several numerical codes[1-5] based on the fluid plasma equation, so called Braginskii equation, have been developed so far. Among them, from the aspect of calculation cost and convergence, Monte Carlo method is thought to be more appropriate than the usual finite difference method for “3D” simulation. That’s why it has been applied and improved in recent years[3-5]. With the maximum use of characteristic features of Monte-Carlo algorithm, extensive “3D” simulation studies have been successfully done[3,4].

In this study, some basic considerations have been given for the application of the Monte-Carlo algorithm to highly nonlinear fluid equations for SOL/divertor plasma transport. For the first practice, we focus on the following simple equation for the electron energy balance parallel to the magnetic field:

$$\frac{\partial}{\partial s}\left(\frac{5}{2}n_e u_{//} k_B T_e - \kappa_{//}\frac{\partial T_e}{\partial s}\right) = Q_E \ , \qquad \kappa_{//} = \kappa_0 T_e^{5/2} \ , \tag{1}$$

where s is the distance along the magnetic field, and the symbols $n_e,\ T_e,\ u,\ k_B,\ \kappa_{//}$ and Q_E are the electron density, temperature, flow velocity, Boltzmann constant, parallel thermal conductivity and energy source/sink, respectively. Since the parallel conductivity $\kappa_{//}$ depends on T_e like above, equation(1) is highly nonlinear problem. In the case where $u_{//}=0,\ Q_e=0$, we can strictly check our numerical scheme by comparing to the analytic solution as follows:

$$T_e^{7/2}(s) = T_e^{7/2}(0) - \frac{7Q_E}{4\kappa_0}s^2 + Cs \ , \quad C = \frac{T_e^{7/2}(L) - T_e^{7/2}(0)}{L} + \frac{7Q_E}{4\kappa_0}L \ . \tag{2}$$

The boundary conditions, $T_e(s=0)=T_e(0)$ and $T_e(s=L)=T_e(L)$ have to be given. The locations of $s=0$ and $s=L$ correspond to the stagnation point in the SOL upstream and the divertor plate, respectively. Several numerical iteration algorithms to solve nonlinear equation(1) are now being checked for their convergence property, and for the numerical parameters, e.g., the number of Monte Carlo test particles N_T and the time step Δt. The treatment of the boundary conditions and its effect on the numerical results will be discussed as well. After these basic considerations, coupling of particle, momentum and energy balance equations and their iteration schemes will be discussed.

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Simulation of radiative divertor plasmas by *Ar* seeding with the full *W* wall in JT-60SA

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Experimental study on the metal first wall such as tungsten (*W*) will be planned on JT-60SA (duration ≤ 100s and heating power ≤ 41 MW) [1] at the later phase of high current (I_p ≤5.5 MA) steady state operation to contribute the ITER/DEMO metal wall.
The SONIC code [2] simulation on JT-60SA is being carried out to find the required condition for SOL/Div. on the *W* wall with introducing the *W* non-coronal model with combination of the non-coronal or the Monte Carlo (IMPMC) code as the *Ar* impurity model.
Present simulation indicates that a large D_2 gas puff Γ_p (≥ $3.0\text{x}10^{22}$ s^{-1}) and *Ar* ratio n_{Ar}/n_i (≥1.0 x 10^{-3}) are needed to obtain the required SOL/Div. conditions (divertor heat load q_t ≤10 MW/m^2, mid-plane SOL electron density $n_{e\text{-mid}}$ =3~$8\text{x}10^{19}$ m^{-3}, radiation loss power P_{rad}~20 MW) at uniformly *W* ratio (n_W/n_i=1.0 x 10^{-5}) in the SOL/Div. space. Considering the distributed n_W/n_i from10^{-5} to 10^{-3} in SOL/Div. space suitably, regions for the required condition are expanded but *Ar* injection is essential. It is also obtained that recycling enhancement is not avoided at the *W* wall operation.
The IMPMC simulation to analyse the *Ar* transport on the *W* wall indicates that higher ionized *Ar* concentrates typically on the bottom of core edge regions, where n_{Ar}/n_i and P_{rad} are also enhanced.

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Self-consistent turbulence-recycling modeling for PISCES-relevant linear plasma device conditions

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The PISCES linear plasma devices (San Diego, USA) are widely used in investigating plasma turbulence (PISCES-A) as well as in investigating plasma interaction with materials (PISCES-B). One feature of PISCES is good experimental access to plasma conditions which may also be relevant for the boundary and divertor plasma in tokamaks. In the present work the plasma turbulence under PISCES relevant conditions is modeled using the resistive drift fluid code BOUT++ (flux-driven turbulence) [1,2]. In order to provide consistent particle, momentum and energy source/losses caused by the surrounding atomic and molecular neutral gas to the plasma, the turbulence code BOUT++ has been recently coupled to the kinetic neutral particle transport code EIRENE [3].

Distinct from other existing coupled plasma-neutral particle codes (e.g. SOLEDGE2D-EIRENE, see H. Bufferand, inv. talk at this workshop) for our application it is essential that the full time dependent EIRENE mode is used in order to capture the microscale turbulence behavior evolving on the ions gyrofrequency time scale, together with the short lifetime of released molecules and sputtered impurities (Mo). This allows us to understand how neutrals, atoms, molecules and sputtered impurities react on plasma density/temperature fluctuations, as well as the turbulence stabilization mechanism due to the transfer of parallel momentum to neutral particles. This mechanism is expected to be important close to the neutralizer plate, and in the case of puffed gas (He), due to the non-zero difference of average momentum between ions and recycled neutrals.

In particular, there is a strong analytical indication that the transport of slow neutrals in high amplitude and large scale turbulence can be enhanced, compared to their transport in the corresponding time-average plasma profile [4]. This result, but now with fully self-consistent feedback between neutrals and turbulent plasma will be used in the interpretation of the relation between puffed He and sputtered Mo density fluctuations and plasma density turbulence in PISCES plasma is presented.

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Coupled core and edge tokamak simulations using gyrokinetic full f particle-in-cell approach

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To capture a full picture of plasma dynamics in a tokamak simulations, the core and edge physics needs to be included in a coupled simulation. This is due to the reliant nature of each on the other. The core plasma is determined by the material boundary at the edge, while the edge plasma is determined by the cross-field transport in the core. Despite the continuous progress being made in the development of gyrokinetic codes, they are mostly restricted to either the edge or the core plasma region with closed magnetic flux surfaces, thus reducing the accuracy of the solution.

ELMFIRE [1] is a full f 5D gyrokinetic particle-in-cell code used for particle simulation of tokamak transport. The code has been used to investigate turbulent transport and geodesic acoustic mode (GAM) in the edge pedestal region. A parametric study shows that the density gradient drives trapped electron mode turbulence and through it also GAMs. Both radial and temporal correlation of turbulent transport and electric field oscillations is seen in the simulations, supporting the picture of GAMs as a self-regulating mechanism of turbulence [2].

Recently the code has been extended to the plasma center and limiter scrape-off-layer [3]. The latter is found important for describing edge plasma transport in limited plasmas. The introduction of scrape-off-layer region in ELMFIRE enables also the study of parallel flows, electric potential and radial plasma transport and their poloidal asymmetries from first principles.

Currently we have had good success with comparing simulation results to experimental measurements from the FT2 Tokamak [4]. To capitalize on the recent advances and to study larger machines, a 3D domain decomposition approach is being applied on ELMFIRE. Optimization of the code will allow more highly resolved turbulence and also simulations of larger tokamak devices. A higher resolution is especially crucial for the the edge and scrape-off layer physics. The upgrade will provide a link and allow the further study between core and edge physics in JET sized machines.

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Effects of multi-species ions on sheath and presheath in a magnetic field decreasing toward a wall

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The detached divertor plasma is characterized by the reduction of heat load and ion influx toward the divertor plate through the volume recombination process. In the divertor region, the plasma contains deuterium (D) and tritium (T) in an open magnetic field. In a study of magnetically confined plasma, it is important to understand the profile of the electric potential near the wall in magnetized plasma in order to examine the plasma behavior near the wall. For unmagnetized plasma, Emmert *et al*. investigated formation of the electric potential considering both the plasma and the sheath regions self-consistently by using a plasma-sheath equation [1]. Sato *et al*. extended the method of Emmert *et al*. to a case of magnetized plasma with the open magnetic field [2]. However the effect of D ion and T ion on the electric potential near the wall in the open magnetic field has not been understood.

The distributions of the electric potential and the particle near the wall with the open magnetic field decreasing toward the wall will be studied analytically, where D ion and T ion are considered. The analytical model is shown in Fig. 1. The electric potential $\phi(z)$ and the magnetic field $B(z)$ are assumed to be symmetric about z=0 and decreases monotonically toward the walls, and $\phi(z)=0$ and $B(z)=B_0$ at z=0, respectively. The problem is treated as one-dimensional model in z-direction. The distribution functions are obtained by integrating the kinetic equations in the phase space for D ion and T ion for each particle trajectory with the boundary conditions. The particle densities are obtained by integrating the distribution functions for the each energy space and the magnetic moment, respectively. As the electron density a Maxwell-Boltzmann distribution is used. By substituting the densities of D ion, T ion, and the electron into Poisson’s equation, the plasma-sheath equation is derived. The distributions of the electric potential and the particle are obtained by solving the plasma-sheath equation numerically. The result will indicate the effect of the multi-species ions on the distributions of the potential and the particle. In addition, the effect of negative ion species produced by MAR (the molecular activated recombination) process will be also studied.

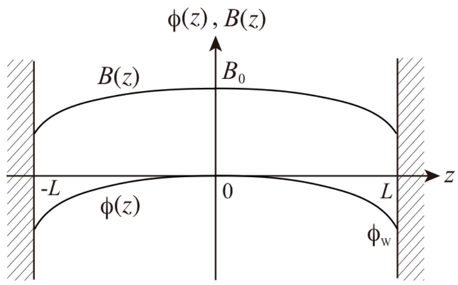

Fig. 1 Geometry of potential and magnetic field in the analysis mdel.

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Kinetic modelling of the detached divertor plasma

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The detached plasma regime is one of the most promising candidates for reducing divertor heat loads in large tokamaks to the acceptable level [1]. Typically, plasma detachment is reached at sufficiently high upstream SOL densities, leading to electron cooling in front of the divertor plates and to so called "roll over" of the divertor ion flux [2]. Physics of the plasma detachment is not yet well understood and there are number of experimental observations, which can not be reproduced by SOL simulating large fluid codes [3-6]. One of the possible explanations is the influence of kinetic effects, which are not included in these simulations, but might play dominant role in the detachment [7, 8]. Existing kinetic models of the detached plasmas are too simplified: the detachment is reached by artificially applied radial electric field and/or random removing of plasma particles in the divertor region, mimicking the plasma recombination (e.g. see [9, 10]).
The aim of the present work is to perform a self-consistent kinetic modelling of the plasma detachment and to study the characteristics of the detached plasma sheath. For the simulations we use the PIC code BIT1 [11]. Plasma recycling and recombination, as well as the impurity (carbon) sputtering and transport in the SOL are included in the model. In order to avoid artificial effects, which might result from applying of (in principle unknown) boundary conditions at the divertor plasma, we simulate the entire SOL. We consider detached plasma characteristics for different upstream SOL parameters and impurity sputtering rates.
Our simulations indicate that (i) plasma profiles in the detached plasma are not monotonic, (ii) particle velocity and energy distribution functions are far from the Maxwellian, and (iii) sheath classical boundary conditions can not be applied there.

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Simulation Study of Detached Plasmas by Using One-Dimensional SOL-Divertor Fluid Code with Virtual Divertor Model

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Reduction of divertor heat load is one of the most important issues for developing tokamak fusion reactors [1]. Detachment of divertor plasma is considered to be essential to reduce particle and heat fluxes to the divertor plates drastically. Detached plasmas have been investigated experimentally, theoretically and numerically. The physics of them, however, is still not fully been understood, and the control methods of them have not satisfactory been developed so far.

Simulation studies of SOL-divertor plasmas generally adopt the fluid model [2]. Conventional SOL-divertor plasma fluid codes assume that the Mach number at the sheath entrance just in front of the divertor plate is unity based on the Bohm criterion. The Bohm criterion, however, imposes only the lower limit of the Mach number. It is pointed out by kinetic simulations that supersonic plasma flows are generated by the effect of particle diffusive loss and radiative energy loss [3]. Under the supersonic condition, the plasma density near the divertor plate is kept low, the high-recycling mechanism is suppressed, and the particle-flux reduction (a sign of the detachment) could be achieved easier.

A generalized SOL-divertor plasma fluid model, taking account of the anisotropy of ion temperature, the parallel momentum transport is described by the first-order differential equation [4]. In conventional SOL-divertor plasma fluid codes on the other hand, the effect of anisotropic temperature is approximated by the second-order-differential viscosity term in the momentum equation, which requires the boundary condition of a fixed Mach number at the sheath entrance. We developed a one-dimensional SOL-divertor plasma simulation code based on the generalized fluid equations [5]. We devised a virtual divertor (VD) model, which sets artificial sinks for particle, momentum and energy in artificial region beyond the divertor plates along the image of a 'waterfall'. It simulates the effect of divertor plate and accompanying sheath instead of the boundary condition of a fixed Mach number. In our code directly introducing anisotropic ion temperatures, the Mach number at the sheath entrance is determined only by the upstream conditions.

A neutral fluid model, which matches the VD modeling, is also incorporated to our code. We have been successfully obtaining solutions of detached divertor plasma. In the presentation, we will discuss how the anisotropic temperature affects the feature of detached plasmas, and whether the supersonic flow alters or not the condition of detached plasma formation.

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