Book of Abstracts

7th Asia Pacific Transport Working Group (APTWG2017) International Conference

Nagoya University

5 - 8 June, 2017

Special Talk

From Nagoya University

Interaction of vortices and waves in stably stratified turbulence

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In the atmosphere and oceans, flows are often stably stratified, and ongoing research seeks to understand the dynamics of stratification in geophysical turbulence. An important feature of stably stratified turbulence is the significant influence of internal gravity waves which makes stably stratified turbulence unique compared to homogeneous isotropic turbulence.
In this talk, we investigate the interaction of vortices and waves in stably stratified turbulence numerically using Direct Numerical Simulations (DNS) with 1024^3 grid points.
The simulation is done by solving the following non-dimensionalized 3D momentum and temperature fluctuation equations under the Boussinesq approximation pseudo-spectrally,

$$(\partial_t - \nu\nabla^2)\mathbf{u} = -\mathbf{u}\cdot\nabla\mathbf{u} - \nabla p + \theta\hat{\mathbf{z}} + \mathbf{f} \tag{1}$$

$$(\partial_t - \kappa\nabla^2)\theta = -N^2 w - \mathbf{u}\cdot\nabla\theta \tag{2}$$

$$\nabla\cdot\mathbf{u} = 0 \tag{3}$$

where $\mathbf{u} = (u, v, w)$ is velocity and θ is temperature fluctuations about the linear (stable) mean temperature profile $\mathrm{d}\overline{T}/\mathrm{d}z \equiv -N^2$, and $N = \sqrt{g\alpha(\partial\overline{T}/\partial z)/T_0}$ is the Brunt–Väisälä frequency. $\mathbf{f}$ is a stochastic forcing applied to the large horizontal velocity scales. In the wavenumber space, we set $\tilde{\mathbf{f}}(\mathbf{k}) = (\tilde{f}_x(k_x, k_y, 0), \tilde{f}_y(k_x, k_y, 0), 0)$ so that the forcing excites pure 2D velocity modes uniform in the z-direction and isotropic in (x,y). For the analysis of velocity field, we use the so-called Craya-Herring decomposition, which decomposes the velocity field into the vortex mode (ϕ_1) and the wave mode (ϕ_2) [1]. As an initial condition, we set all velocity components zero, and excite the velocity only by the forcing without coupling the temperature fluctuation. After the 2D velocity field is developed, the coupling between velocity and temperature fluctuations is switched on. We will demonstrate that strong horizontal layers develop quickly as the wave component grows comparable with the vortex mode.

[1] Y. Kimura & J. R. Herring, J. Fluid Mech. **698** (2012) 19–51.

Guest Talk

From US/EU TTF

Research Topics of the 2017 Joint US - EU Transport Task Force Workshop

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The US Transport Task Force (TTF) was established by the Department of Energy in 1989 to advance the predictive modeling of turbulence in magnetically confined plasmas. In 1994 the first joint EU and US TTF meeting was held in Goteborg Sweden. Since that time, the US and EU TTFs have held joint meetings alternating between the US and EU each year. The TTF workshops have encouraged experimentalist and theoreticians to collaborate on the validation of theoretical transport model predictions with data. The 2017 joint US-EU TTF was held April 25-28 in Williamsburg Virginia, USA. Highlights of this workshop will be presented in this talk. The focus areas were: Transport Prediction for Experimental Planning, Advances in Core Transport, Impact of 3D fields on Transport, Pedestal Structure and Dynamics, Transport Induced by Energetic Particle Instabilities, and Scrape of layer Transport. In each of these focus areas, the validation methodology was applied. Precision measurements were compared with theoretical predictions leading to refinement of the physics models. For some topics, the physics models have reached a sufficient level of accuracy to justify development of fast, reduced models suitable for integrated modeling. A new initiative in the US and EU TTFs is to begin routinely using these integrated models to predict the outcome of tokamak experiments as part of the planning process. International collaboration is essential in order to develop the integrated whole device models that are required to predict the path to optimized performance and confidently operate burning plasma class fusion devices within global stability and wall loading constraints. A large database of actual experience with predicting experimental outcomes is needed in order to quantify the accuracy of these models. The US and EU TTF research communities welcome participation in this long range mission by the APTWG members.

7th Asian Pacific Transport Working Group (APTWG2017)
http://www.p.phys.nagoya-u.ac.jp/APTWG2017/

Topic (A)

Turbulence and Blob at the boundary of magnetic topology (Edge and SOL)

What is a blob?

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Blobs are large-amplitude, coherent, field-aligned plasma filaments that have been observed in a myriad of plasma configurations including basic plasma physics devices, stellarators, and tokamaks. Our practical interest in blob dynamics stems, principally, from experimental observations that radial plasma transport driven by blobs can comprise 50% or more of the radial plasma flux in the tokamak scrape-off layer (SOL). The present talk discusses our present theoretical and experimental understanding of blob dynamics, with an emphasis on their role setting the tokamak scrape-off layer width. Experimental measurements have allowed an extensive characterization of spatial structure (amplitude, size, elongation, tilt) and propagation (velocity) dynamics of plasma filaments, as well as giving insights into the blob creation mechanism. Generally, the presence of blobs results in strongly skewed probability distribution functions for the perturbation amplitudes and fluxes, which is a result of the intermittent nature of filamentary transport. In an effort to quantify the radial transport driven by blobs, analytical theories have been developed to determine the blob propagation speed. Blobs are modeled as a plasma monopole associated to a dipolar vortex, which is in turn driven by toroidal curvature and radially propels the filament. The associated blob dynamics and resulting radial transport are largely dependent on parallel current transport closing the circuit along the magnetic field lines, giving rise to several translation regimes related to the filament size and the background plasma parameters. Thus, the predicted filamentary transport levels result from a complicated interaction of 3D effects, including mode filament parallel dynamics and coupling to the Bohm-Chodura sheath at the end of the magnetic field lines. Single-seeded blob dynamics have been simulated using 2D and 3D fluid models, giving much insight on the role of parallel dynamics. Indeed, 2D models can reproduce many of the experimentally observed features, such as the strongly skewed PDFs and the propagation velocities. Perhaps more surprisingly, blobs can propagate faster in 3D than in 2D models due to a reduction in strength of the parallel current response, which has been interpreted as an increased "sheath-drop factor". Recent advances in computational power now allow flux-driven simulations of tokamak SOL dynamics using realistic sizes and parameters. This enables a direct comparison between the simulations and state-of-the-art diagnostics, with the result that many of the blob structural properties are well reproduced by the simulations. The simulated plasma profiles display a two-decay length structure associated with a shear layer in the near-SOL, thus suggesting the possibility that blobs formed in the vicinity of the separatrix are responsible for setting the far-SOL decay length.

Work is supported by the U.S. DOE under contracts DE-FG02-95ER54309 and DE-FC02-04ER54698.

Fuelling Fuels Turbulence

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It has recently been pointed out that the plasma heating, which is one of the characteristic parameters that define nonequilibrium property of confined plasmas, is an origin of turbulence, in addition to plasma inhomogeneities that have been traditionally investigated [1]. That is, *heating directly heats turbulence*. This new degree of freedom for the drive of turbulence, may explain the hysteresis in gradient-flux relation [2]. This theory stimulates us to consider a possibility that the external source of particles can directly influence the turbulence intensity (i.e.,*fuelling fuels turbulence*).
We here discuss the process that the strong fluctuations in the SoL plasma penetrate into confined plasma via the fuelling of neutral [3]. The intensity of turbulence, which is driven by this process, is calculated. The ratio of this intensity to that of mixing-length estimate is given as

$$\frac{C}{\rho_i \Delta_n k^2} \left| \frac{\tilde{n}_e}{\langle n_e \rangle} \right|_{SOL}$$

where Δ_n is the penetration length of neutral particles and C is a numerical coefficient of the order unity. Considering that the fluctuation level of SoL is strong, this process can introduce substantially strong turbulence near the edge plasma. This driving mechanism is a candidate that explains experimentally-observed strong turbulence at the edge. Relation between this mechanism and the hydrogen isotope effect of confinement is also discussed.

Authors acknowledge discussions with Prof. S. Inagaki, Prof. K. Ida, Prof. H. Yamada, Dr. D. Kato, Dr. M. Kobayashi, Dr. T. Kobayashi, Dr. Y. Kamada. This work is partly supported by the Grant-in-Aid for Scientific Research of JSPS (JP15H02155, JP16H02442).

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First-Principle Simulations of Inward Particle Transport in the Inversed-density-gradient

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We here present simulation results on the particle transport in case that the density gradient is locally inversed. The locally inversed density profile appears in a hollow density profile when gas-puff or pellets are injected. Using a delfta-*f* electromagnetic gyrokinetic simulation code dFEFI [1], we investigate a local dynamics of particle transport in the inversed density region, as seen in Fig. 1. Other parameters are based on the typical edge ASDEX-Upgrade parameters.

We observe a linear mode with peaks at $k_y\rho_s$=0.2 and $k_y\rho_s$=0.8. The lower one rotates in the negative (ion diamagnetic) direction and the other rotates in the positive direction. In the nonlinear phase, the lower wave number mode becomes dominant. Here, we observe an inward particle flux.

As a candidate of the inward particle flux, we take into account of the ion-mixing-mode [2]. With a high electron collisionality, electron temperature fluctuations associated with the effects of finite electron thermal conductivity can produce a phase shift between the density and electrostatic potential fluctuations. The phase shift causes an inward pinch in the ITG-like mode. We analyze the obtained simulation results are consistent with the conditions for the ion-mixing-mode. Note that to satisfy the condition, the inversed density gradient is necessary. In Fig. 2, various ion temperature gradients are tested in the inversed density gradient, showing that more ion temperature gradient gives more inward particle fluxes. This can indicate that more ITG growth rates will gives more inward particle flux through a mixing-length theory.

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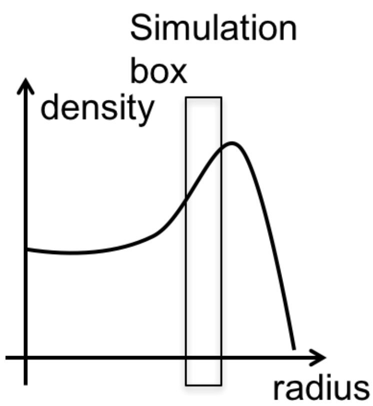

Fig. 1: A cartoon of the region in the inversed-density-gradient. The simulation targets on the inside of the peak of hollow density profile.

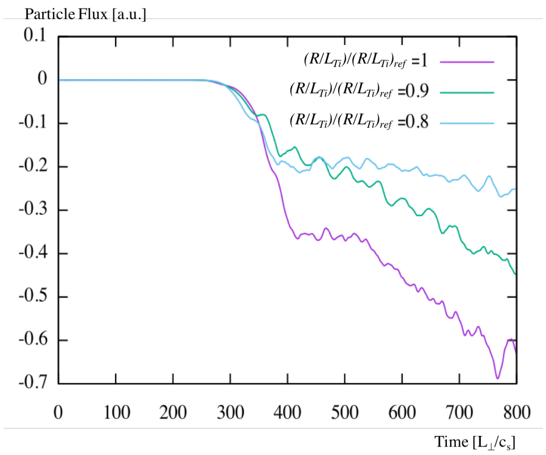

Fig. 2: Time evolution of particle flux with various temperature gradients. As the gradient increases, the inward particle flux increases.

Turbulent Particle Transport in Transport Barriers

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Experiments in tokamaks show that, in addition to neoclassical transport, small-scale turbulence induced by drift instabilities plays a significant role in particle transport. In recent H-mode experiments on HL-2A, it is found that the turbulent fluctuations induce inward particle flux and increases of density, pressure and their gradients. The particle transport in transport barriers is investigated with a gyrokinetic quasi-linear turbulent model for ion temperature gradient modes and trapped electron modes with impurity effects included. Detailed analyses of the particle flux dependence on plasma parameters, including the gradients of density and temperature, magnetic shear, safety factor, collision etc., were performed. The numerical simulation results are compared and shown reasonable agreement with the experimental observations. Moreover, for multiple ion temperature gradient modes in transport barriers, particle transport calculated from the gyrokinetic quasi-linear turbulent model compares with the result based on the quasi-linear mixing length estimations [1].

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Impact of pedestal plasma density and E_r on linear and nonlinear edge-localized mode simulations using BOUT++

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The BOUT++ simulations are used to study the linear and nonlinear characteristics of edge-localized mode at different collisionality and radial electric field via (pressure profiles are kept the same). By increasing collisionality, nonlinear simulations show that (a) power spectrum becomes broad and flat; (b) the dominant mode changes from $n = 6$ to $n = 35$. Bispectrum analysis shows that nonlinear mode coupling becomes stronger at high collisionality, especially for the high-n modes with $n > 20$, resulting in the lack of dominant filamentary structures and reduced ELM energy loss. The impact of radial electric field E_r on peeling and ballooning modes is different, as shown in Figure1. The increase E_r significantly enhances the linear growth rate of low-n peeling modes, while the linear growth rates of ballooning modes remain almost the same. Bispectrum analysis also indicates that the increase E_r can enhance the nonlinear coupling of all modes studied here, and shorten the phase coherence time of the linear growth stage, which is a key nonlinear criterion for the occurrence of ELM crash. Besides the collisionality, our simulations suggest a new way (E_r) to control the ELM size, which is proved by the suppression of ELM at larger $|E_r|$ and high collisionality case on EAST.

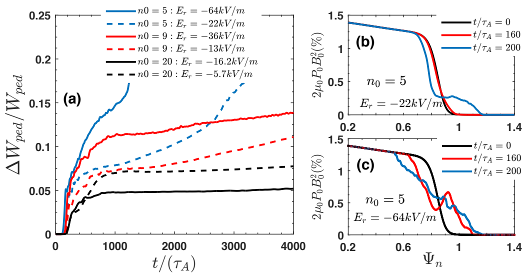

Figure 1: *(a) The time history of the plasma ELM loss fraction ($\Delta W_{ped}/W_{ped}$). Profile evolution of pressure at different time for (b) $n_0 = 5\times10^{19}m^{-3}$ and (c) $n_0 = 20\times10^{19}m^{-3}$.*

This work was performed under the auspices of the U.S. DOE by LLNL under Contract No. DE-AC52-7NA27344 and is supported by the NSFC under Grant No. 11405214, No. 11275234, No. 11305208, No. 11305215, No. 11505221, the China National Fusion Project for ITER under Grant No. 2014GB106000 and No.2014GB106003.

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Vacuum ultraviolet imaging of the edge plasma on EAST

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For long-pulse ELMy H mode discharge, it is a big challenge for the divertor plate to hold the high-level transient heat flux due to the quasi-periodic ELM event. Therefore, ELM control is necessary to realize steady state operation. It is known that ELMs are strongly related with the dynamics of the so-called pedestal region, where steep pressure gradient exists. But the mechanism is still an open topic in fusion research. Experimental studies on the pedestal may be helpful on the understanding of the related physics and benefit the development of efficient method on ELM control. Dedicated diagnostics are essential tools for such experimental studies.

On EAST tokamak, a high-speed vacuum ultraviolet (VUV) imaging system is being developed. It aims to measure the evolution of the spatial structures of the pedestal, by selectively measuring emission of 13.5 nm in wavelength, which mainly comes from C VI (one of the intrinsic impurities in EAST). ELM dynamics can be studied by the combination of VUV imaging and the existing visible imaging system, which mainly monitors the bottom of the pedestal and SOL region on EAST. The key optics consists of an inverse Schwarzschild telescope, a Micro-channel plate (MCP) and a high-speed camera. At present, it is installed to monitor the plasma perpendicularly from the low field side, and the major optical axis is parallel to the major radius. In the 2016 EAST campaign, it has been commissioned and lots of VUV imaging data have been obtained under different discharge conditions, such as ELM event, MHD instabilities, etc. In this work, the hardware of the VUV imaging system, the first results from the VUV imaging data and the VUV imaging of ELMy H mode plasma in the EAST high-betaN discharges will be presented. In addition, the upgrade of the optics is scheduled for the next campaign, which aims to view the plasma tangentially. The proposals of the upgrade will be discussed as well.

Acknowledgement:
This work is supported by the Natural Science Foundation of China under Contract No. 11605244 and the National Magnetic Confinement Fusion Science Program of China under Contract No. 2014GB106000, 2014GB106001 and 2013GB106000.

Capture of the enhanced cross-field transport localized in the recombining linear plasma

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Sufficient reduction of huge heat and particle fluxes flowing into the divertor plate is essential in future fusion machines such as ITER and DEMO. The detached divertor is the most promised solution to reduce the divertor loads; however, any simulation code cannot reproduce a great reduction of the ion flux that is experimentally observed [1]. One of the candidates of the ion-flux reducing mechanism is a cross-field transport. Enhancement of the cross-field transport in the detached divertor condition is reported in several devices [2–4]. In the linear device NAGDIS-II, radially-elongated spiraling plasma structures surrounding the plasma column [5] was clearly observed in the recombining plasma. Additionally, axial localizations of $m = 0$ [6] and peripheral strong fluctuations [7] were independently detected near the recombination front.

In this study, we have investigated the relationship between $m = 0$ and spiraling structures in the three-dimensional space by using a radially and azimuthally segmented electrode and a microwave interferometer. The segmented electrode consisting of 12 pieces was installed in the plasma column. By biasing –100 V, ion saturation current fluctuations were simultaneously measured at a sampling frequency of 500 kHz. In order to capture the enhanced phenomenon near the recombination front, detached and attached divertor conditions were continuously varied by changing the neutral gas pressure, as if the measurement position was swept against the recombination front. We also measured an upstream fluctuation with the interferometer without disturbance in order to determine whether a detected event was axially localized or not. As a result, it was found that the $m = 0$ fluctuation at $f < 8$ kHz abruptly appeared at the radial center in the transient state. At the same time, the radial profile of the ion saturation current broadened and positive spikes significantly appeared in the periphery. Conditional averaging and proper orthogonal decomposition techniques reveal existences of rotating spiraling structures in the periphery with a few-kilohertz negative $m = 0$ fluctuation at the center region. Further, the envelope analysis indicates that the spiraling plasma ejection correlated with low-frequency $m = 0$ fluctuation of the order of milliseconds. Understanding of the low-frequency fluctuation is necessary to clarify the enhancement mechanism of the cross-field transport. This work was supported by KAKENHI (16H06139, 16H02440, 25820440), NIFS collaboration research program (NIFS16KUGM108, NIFS17KUGM120), and NIFS/NINS under the project of Formation of International Network for Scientific Collaborations.

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Turbulence Characterization in 2D Forced Drift Wave-Zonal Flow Systems

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From nonlinear simulations of the two-dimensional forced Hasegawa-Mima equation, we show that a Reynolds number-like parameter, Re_w, can characterize the energy spectrum in fully developed wave turbulence. Re_w is defined as the ratio of the convective nonlinear term to dissipation terms. For a given Re_w, the power law exponent in the inertial range is shown to be universally determined regardless of forcing and dissipation conditions. At high Re_w, we show the power law exponent approaches to -7, which is consistent with a recent theoretical prediction based on the shell model [1], as shown in Figure 1.

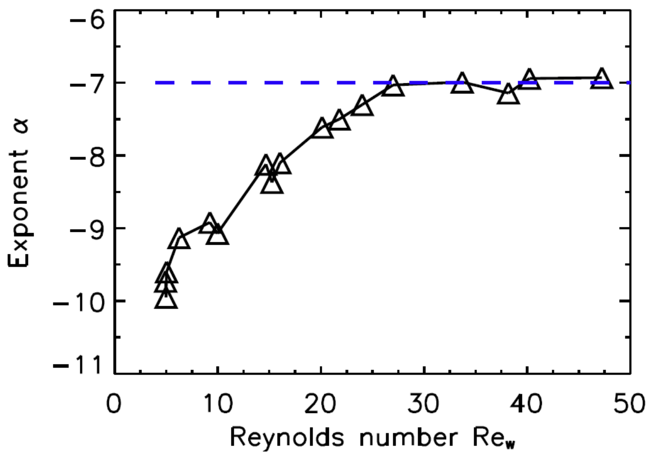

Figure 1. Exponent α in inertial range of power spectrum as a function of average Reynolds number Re_w.

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Study of Ion Thermal Internal Transport Barrier Formation in Reversed Shear Plasmas : Role of Localized Heating

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Previous experiments show that location of electron cyclone heating has important role for internal transport barrier formation [1]. To analyze the role of localized heating on ITB formation, we use gyrofluid equation developed by M.Yagi which takes into account of the ion poloidal flow damping due to the neoclassical effect was applied [2]. This model equation, however, didn't consider the quasilinear modification of neoclassical viscosity as well as the offset ion poloidal flow damping in the neoclassical viscosity [3,4], since the ion heat flow velocity is comparable to diamagnetic velocity [5] for edge transport barrier formation. For neoclassical viscosity coefficients, we adopted the interpolation formula derived by Callen [6] for the ion poloidal flow damping term and by Hinton and Hazeltine [7] for the offset ion poloidal flow damping term. We investigate these effects on ion temperature gradient(ITG) driven drift wave turbulence in the reversed shear plasma. In addition, we introduce the local heat source to clarify the effects of neoclassical viscosity on ITB formation. Finally, optimum location of local heat source for ITB formation has been found.
This work was supported in part by the collaboration research between SNU and QST.

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Measurement of electron density profile and turbulence with comb microwave reflectometer in linear magnetized plasma

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Cross-field heat and particle transport is important in the open field line region to mitigate localization of heat load on divertor plate. A comb microwave reflectometer is developed for turbulence and transport study in the linear device PANTA. The plasma in the PANTA is produced by the helicon wave (plasma length of 4 m, plasma radius of 0.06 m, $n_e \sim 10^{19}$ m^{-3}, $T_e \sim 3$ eV, B = 0.09-0.15 T) [1]. To realize multi-point simultaneous measurement of plasma turbulence, a microwave frequency comb reflectometer ranging from 12-26 GHz with intervals of 0.5GHz is developed. Radial profile of electron density and density fluctuation are reconstructed according to the phase delay of reflected wave [2]. Low frequency turbulence is observed with this reflectometer, and radial structure of the turbulence is estimated. Doppler shift of reflected signal is also measured by oblique injection of microwave, and azimuthal rotation of plasma and its fluctuation are obtained. These contribute to further study on plasma transport and turbulence in the SOL region of tokamaks.

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Axial momentum transport driven by turbulence in linear magnetized plasma

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Controlling of ion flows parallel to magnetic field, e.g. toroidal flow in closed field line region of tokamak and flow toward walls in boundary plasma, is a key issue for the development of fusion power. Here we report results of experimental investigations of axial flow from a linear magnetic device with a strong vacuum pumping system. Cylindrical argon plasma (radius of 6 cm and axial length of 4 m) is generated by 3-6 kW rf (7 MHz) power and radially confined by homogeneous axial magnetic field (0.09 T). Typical parameters measured by YAG-Thomson scattering and laser induced fluorescence are $n_{e0} \sim 1.0 \mathrm{x} 10^{19}$ m^{-3}, $T_{e0} \sim 3$ eV and $T_{i0} \sim 3$ eV. By means of Langmuir probe and Mach probe, the spatial structure of axial flow and turbulent fluctuation are measured and excitation of D'Angelo mode and strong axial flow shear formation are observed. Axial Reynolds stress evaluated from the axial and radial flow fluctuations clearly indicated that axial flow in the steady-state is determined by a balance between Reynolds force and collisional neutral drag [1]. The axial flow structure and spectral of fluctuations are changed by controlling of axial flow velocity of neutral Ar. Slow mass flow condition of Ar gas (realized by low injection velocity and low pumping velocity) makes the axial flow shear stronger. The neutral gas can contribute both to the drag of axial flow and excitation of instabilities. Effect of neutrals on the axial flow will be determined by competition between such processes. Understanding of interactions between axial flow, turbulence and neutrals will contribute to further study on divertor plasma control.

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Observation of Streamer as a Trigger for ELMs on HL-2A Tokamak

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The dynamic features of the trigger for edge-localized-modes (ELMs) on HL-2A tokamak are presented. Detailed analyses of the dynamic evolutions of plasma parameters, including density, temperature, pressure, particle flux, shear flow and their gradients, in pedestal were performed in recent HL-2A H-mode plasma. As a precursor to ELM onset, a pedestal coherent mode (PCM) was observed in the edge transport barrier of H-mode plasmas in inter-ELM phases. The mode interacts with and modulates ambient turbulence and induces inward particle flux and increases of density, pressure and their gradients. It transits into streamers, that stretches in the radial direction near the mid-plane at the low field side, and induces almost instantaneous collapse of plasma energy in the outer region ~ 0.3 of the plasma column and onset of ELMs within a few tens of microseconds without global MHD instabilities. The path of the onset is identified and a clue to the trigger problem of violent events in wider circumstances of high temperature plasmas is discussed.

Nonlinear Interaction between Low-Frequency Fluctuations and Turbulence in the Scrape-Off Layer of ASDEX Upgrade

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Understanding and controlling the Scrape-Off Layer (SOL) plasma is of prime importance for a future reactor, since most of the plasma heat flux and transport is along open magnetic field lines to the divertor plates. Therefore, a substantial number of researchers have investigated the SOL physics by measuring the edge plasma parameters in detail [1-3], however, there still are many open questions. For example, even though there is no large plasma gradient in the SOL, significant plasma fluctuations and irregular radial plasma profiles are observed in the SOL [2]. On the other hand, the nonlinear interaction among disparate fluctuations has been considered as the basis for understanding the plasma transport [4]. Therefore, we have investigated the disparate scale nonlinear couplings in the SOL for an in-depth understanding of the nature of edge turbulent transport.

Recently, we have observed a coherent large scale low-frequency (~2 kHz) fluctuation (CLF) which is enhanced via nonlinear couplings with the background turbulence (10-500 kHz) in the separatrix of ASDEX Upgrade. The CLF is localized at the safety factor $q \sim 5$, which is determined by using the lithium beam emission spectroscopy and the electron cyclotron emission diagnostics. The CLF propagates in the electron diamagnetic direction, and is characterized by a toroidal mode number of $n = 2$. Furthermore, the CLF has significant coherence with the magnetic signal, the divertor fluctuations, and the envelope of the turbulence, which propagates across the SOL with the radial phase velocity of approximately 100 m/s. The radial structure of the SOL turbulence is locally influenced by the sign of the CLF amplitude through the disparate scale nonlinear interactions.

Authors acknowledge discussions with K. Itoh, K. Ida and T. Kobayashi, and partial support by JSPS KAKENHI Grant Number 16H02442.

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Divertor detachment in LHD with edge stochastic layer and comparison with 3D numerical simulations

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Divertor detachment in LHD with edge stochastic layer is reported. Change of divertor plasma parameters at the detachment transition has been characterized as follows by Langmuir probe measurements. The peak values of divertor particle and power fluxes are reduced by a factor of 5 and 10, respectively, after the detachment transition. Plasma temperature at the divertor plate stays around 5 eV before and after the detachment transition, while the divertor density decreases by a factor of 10. Particle flux broadening towards private flux region during the detachment is also observed.

In this magnetic configuration with thick stochastic layer, it is observed that the detached plasma becomes stable with application of m/n=1/1 RMP field, which create magnetic island in the edge stochastic layer. Te profile becomes flat at the island position, and is kept at ~ 10 eV during detached phase. This temperature range is favorable for emission of carbon impurity, which is divertor materials in LHD. Imaging bolometer and AXUV measurements show enhanced radiation at the X-point of the edge island during detached phase, indicating selective cooling of plasma there. Divertor particle flux is modulated in toroidal direction according to the mode number of RMP field, i.e. n=1.

Saddle loop coil measurements show that during attached phase the RMP is tend to be shielded by plasma, while after the detachment transtion the plasma tends to enlarge the RMP.

These observation are compared with 3D edge transport simulation with EMC3-EIRENE, and validity of the transport model is discussed.

Particle-in-cell simulation of non-diffusive plasma transport in scrape-off layer

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Intermittent filamentary coherent structures which are called “blob” or ”hole” are thought to play an important role in the radial transport in the scrape-off layer (SOL) in magnetic confinement devices [1, 2]. The size of such structures on the cross-section is in meso-scale, that is, the size of small one is slightly larger than the ion Larmor radius. Since the kinetic effects should be considered in such a situation, we have developed the three-dimensional (3D) electrostatic particle-in-cell (PIC) simulation code named “p3bd” (particle-in-cell 3-dimensional simulation code for boundary layer plasma dynamics) to investigate the kinetic effects on blob and hole dynamics [3, 4]. Using the p3bd code, we have shown the self-consistent current system and the temperature structure in a blob [5]. Furthermore, the dynamics between a blob / a hole and impurity ions have been analyzed [6]. This analysis has shown that the dipolar profile of impurity ion density in a blob / a hole is formed by the polarization drift as shown in Fig. 1. We will discuss not only the effect of impurity ions on blob / hole dynamics but also the impurity ion transport by a blob / a hole.

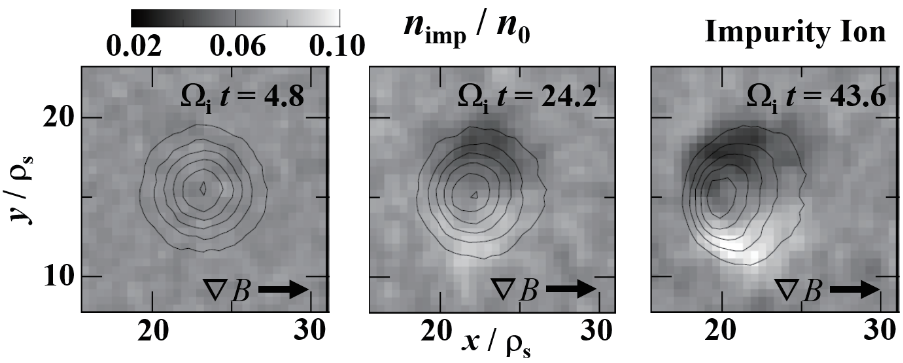

Figure 1: Impurity ion density distributions in poloidal cross-section at various times. Here, the contour lines in each panel represent the electron density distributions.

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Topic (B)

Model reduction and experiments for validation

Flux-driven global transport simulations based on joint approach with gyrokinetic and transport solvers

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Understandings of turbulent transport mechanisms and the accurate prediction of the transport levels and steady profiles are crucially important for realizing self-ignited burning plasmas in ITER and DEMO reactor. Gyrokinetic turbulence simulations are powerful tools to address them, and recently the quantitative validations of the local fluxtube simulations based on the experimental measurements have been performed[1]. In addition to the local analyses with delta-f gyrokinetic model[2], global analyses of the profile evolution under the auxiliary heating with full-f approaches have extensively been carried out[3-5]. However, the heating conditions were rather limited there due to the huge numerical costs on the full-f gyrokinetic simulations.

In this study, we investigate the global heat transport processes and profile formations in ITG-TEM unstable plasmas by using a newly developed 1D global transport solver coupled with multiple local fluxtube gyrokinetic calculations, TRESS+GKV[6]. The time evolutions of the ion and electron temperature profiles towards a power balanced steady state are simultaneously solved, where a fixed density profile is assumed. The neoclassical and anomalous heat fluxes are calculated by using the matrix inversion method and the quasilinear approximation, respectively. An example of the steady profiles in a tokamak plasma is shown in Fig. 1, where the auxiliary heating power of ~10MW in total is imposed in the core region. It is also found that the adaptive source/sink, which is imposed on the transport solver, successfully accelerate the temporal convergence to the steady power balanced state. Statistical properties of the front propagations in the heat flux and temperature gradient profiles are also discussed.

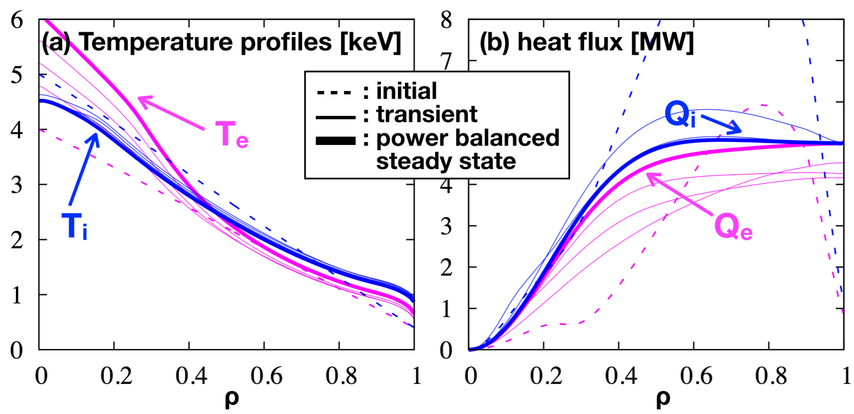

Fig. 1 Radial profiles of (a) the ion and electron temperature, and of (b) the heat flux calculated by TRESS+GKV, where the power balanced steady profiles are shown by thick lines.

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Turbulent particle flux suppression by radial electric field non-uniformity at edge transport barrier in JFT-2M tokamak

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After the discovery of L-H transition in ASDEX, modeling works for turbulent transport suppression across the L-H transition have been intensively promoted. Focusing on shear decorrelation effect, a possible model explaining the high confinement regime was proposed [1], which is nowadays subject to experimental validation [2,3]. More recently, not only sheared ExB flow but also curvature of the radial electric field is regarded as an important player to suppress the turbulence transport [3,4]. At the radius of the radial electric field well, confinement improvement owing to the radial electric field curvature, possibly via a modulational coupling between turbulence and flow, was confirmed [4]. In this paper, we analyze a turbulence data set obtained with a heavy ion beam probe (HIBP) in order to investigate how the radial electric field shear and curvature affect the turbulent particle transport across the L-H transition in JFT-2M tokamak.

With the HIBP system, the electron density fluctuation and the electrostatic potential fluctuation are simultaneously and directly measured with a high time resolution. In L-mode, in which the edge radial electric field is weak, turbulence is characterized by resistive drift wave like properties, i.e., the relative electron density fluctuation amplitude and the relative potential fluctuation amplitude are almost same. Turbulent particle flux is directed toward the edge. After emergence of the radial electric field in H-mode, the outward particle flux is significantly reduced. The particle flux is suppressed predominantly by reducing the density fluctuation amplitude and the cross phase between the density fluctuation and the potential fluctuation. Both the shear and the curvature are found to play an important role to reduce the particle flux. Amplitude reduction of the potential fluctuation is not as large as that of the density fluctuation. The turbulence property in H-mode significantly differs from that in L-mode. Different time scale of changes in the density fluctuation amplitude and the cross phase between the density fluctuation and the potential fluctuation is also observed.

This work is partly supported by a grant-in-aid for scientific research of JSPS Japan (17K14898, 15H02155, 16H02442), the collaboration programs of QST and of the RIAM of Kyushu University, and Asada Science foundation.

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Preliminary plasma core transport analysis of optimized internal inductance steady-state H-mode discharges in EAST

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The optimized internal inductance advanced tokamak scenario has been developed both theoretically [1] and experimentally [2] motivated by previous confinement improvement studies of high internal inductance plasmas [3-6].In the last EAST campaign, a class of moderately high internal inductance steady state H-mode discharges with fully non-inductive current drive has been achieved using pure radio-frequency heating. The energy confinement enhancement factor H89 is observed to increase with the internal inductance. This kind of plasmas has peaked electron density and temperature profile in plasma core and q profile flat in the near-axis region with $q_0 > 1$. Thermal transport analysis in plasma core has been performed by using of TRANSP code, which uses EFIT reconstructed equilibria constrained by current profile from an 11-channel far infrared laser polarimeter interferometer and kinetic profiles from a Thomson scattering system (T_e, n_e) and a tangential X-ray crystal spectrometer (T_i). Preliminary results from TRANSP give very low electron thermal diffusion coefficient in the plasma core. Besides, role of ECRH/CD on the formation of the plasma current profile is also investigated. Preliminary TRANSP simulation shows that ECR power deposited at $\rho = 0.1$, which raise up the electron temperature in plasma core to help LHW deposit also near plasma center and therefore enhance core heating. Simulation of a discharge with ECRH shut down during the plasma current flat top supports that the confinement improvement in plasma core is due to higher poloidal field in the plasma core and larger magnetic shear in the outer half of the plasma when the internal inductance is relatively high. Investigation on possible underlying mechanisms of turbulence suppression reducing the anomalous transport in plasma core can be seen in Dr. Siye Ding's report ["Gyrokinetic Simulations on the Optimized Internal Inductance Steady-State Plasmas on EAST", this conference].

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Electron thermal fluctuation and transport in the ITB and L-mode plasmas without the large scale MHD instabilities

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Preliminary observations and analysis of electron thermal fluctuations and transport in the ITB and L-mode plasmas will be presented. The ITB and L-mode plasmas both are limited plasmas heated by similar NBI power (above the H-mode threshold power for the diverted plasma), and the auxiliary ECRH is applied in the L-mode plasma to suppress the m/n=2/1 tearing mode. Periods without the large scale MHD instabilities such as sawtooth or tearing modes are compared. In the ITB plasmas the electron temperature profile evolves in time slowly to have a more peaked profile, whereas it does not change in time in the L-mode plasmas unless the ECRH vertical target position is changed. The strong electron temperature fluctuation over the broad frequency band (0~130 kHz) is observed with the increased electron temperature gradient in the L-mode plasma, but the only weak 60 kHz fluctuation is detected in the ITB plasmas. In addition, the intermittent electron heat transport event across the q=2 flux surface is observed both in the ITB and L-mode plasmas (more clearly in the ITB plasmas). Note that in the ITB plasmas the electron temperature profile, the 60 kHz fluctuation amplitude, and the intermittent transport event size are found to be related.

Optimization for long pulse high β_N operation on EAST

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Abstract. High normalized beta (β_N = 1.5~2) discharges have been studied on the EAST tokamak [1, 2]. The stable high power heating is required essentially, and the control of impurity radiation is also critical issue for the maintenance of high β_N discharges on EAST. Additionally, the Internal Transport Barrier (ITB) was observed recently at ELMy H mode discharges on EAST [1]. The ITB dynamics is a key issue for the EAST high β_N plasmas. Optimization of plasma towards long pulse high β_N operation is performed in 2016 campaign on the EAST tokamak.

Keywords: Optimization, high normalized beta, long pulse

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Gyrokinetic Simulations on the Optimized Internal Inductance Steady-State Plasmas on EAST

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In the last EAST experiments in 2016 campaign, efforts had been paid on achieving high performance and steady-state plasma in long pulse. The recent statistic data analysis shows the proportional relation between global confinement and internal inductance. The experimental analysis can be seen in Dr. Hongfei Du's report ["Preliminary plasma core transport analysis of optimized internal inductance H-mode discharges in EAST", this conference]. This work is focused on the gyrokinetic simulations on physical mechanisms leading to the high confinement in high internal inductance plasmas on EAST. The simulations use GYRO code for linear analysis to identify the most unstable modes (and the sub-dominant modes as well, if necessary) in different radial regions (i.e. confinement region: ρ~0.2-0.5; no-man's land near pedestal top: ρ~0.8-0.85). TEM-like modes are dominant in the near-axis confinement region, like ρ~0.2, 0.3. The highest growth rate appears at $k_y\rho_s$~0.5. The growth rate of this mode decays towards short wavelength. It also decays when the collisionality is artificially scaled up. The simulation results confirm that the growth rate of most unstable mode becomes lower in the radii closed to magnetic axis, which has higher pressure gradient and lower thermal diffusivity. This is consistent with the experimental observation of central peaking electron temperature profile. The transition of dominant mode from TEM-like to ETG in the confinement region is identified as the radii increases. In the no-man's land near pedestal top, the dominant unstable mode is found to be ITG. Further analysis will focus on the parametric dependence of the mode features on major physical quantities, e.g. the local magnetic shear. A comparison between optimized (high) l_i case and normal (relatively low) l_i case will also be discussed.

Reduced transport models for the dynamical simulation by the gyro-kinetic analysis with kinetic electrons in helical plasmas

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Turbulent transport is one of the most critical issues for plasma confinement in magnetic fusion devices. Recently, a large number of the gyro-kinetic simulations which are applied to the turbulent transport have been done in toroidal plasmas. The gyro-kinetic simulation results in tokamak and helical plasmas have been studied with the experimental observations. Gyro-kinetic simulations of helical plasmas need a large number of mesh points along the field line to catch the helical ripple structure. Therefore, the gyro-kinetic simulation in helical plasmas consumes the larger computer resources in most cases than for tokamaks. The reduced transport model, which reproduces the nonlinear gyro-kinetic simulation results, is needed especially for the dynamical transport simulation in helical plasmas.

The GKV code [1] solving the gyro-kinetic equation has been used to examine the ion temperature gradient (ITG) mode and zonal flows in the Large Helical Device (LHD). The gyro-kinetic simulation with the adiabatic electron is performed for the high-T_i LHD discharge (# 88343). The ion heat flux by the ITG mode instability agrees with the experimental results. The reduced model for the ion heat diffusivity is proposed [2] using the GKV code with the adiabatic electrons for the transport simulation. This reduced model is the function of the linear growth rate for the ITG mode and the zonal flow decay time. How to apply the reduced model of the turbulent ion heat diffusivity derived from the gyro-kinetic simulation with the adiabatic approximations for the electron motion to the transport code has been shown in helical plasmas with a low computational cost [3]. The transport simulation results using the gyro-kinetic simulation with the adiabatic electron for the T_i profile do not contradict with the experimental observation [3]. The simulation with the kinetic electrons shows the larger ion heat flux than the experimental results in the LHD [4]. To compare the turbulent ion heat diffusivity of the gyro-kinetic simulation results with that of the experimental results, the effect of the kinetic electrons should be included to construct the reduced model of the diffusion coefficients.

In this study, the reduced model for the diffusion coefficient is constructed by solving the gyro-kinetic equation in terms of the electron in addition to the ion to examine the effect of the kinetic electrons. At first, the ITG mode is studied in the region of the low poloidal wavenumber to reduce the computational cost, when the small number of the Fourier mode is taken. Next, the plasma instability is investigated in the wide wavenumber region when the larger number of the Fourier mode is taken. The nonlinear gyro-kinetic simulation with the kinetic electrons is performed to derive the diffusivity value. The linear gyro-kinetic simulation with the kinetic electrons is also done to show the reduced model to reproduce the value of the diffusivity by the nonlinear gyro-kinetic simulation. The same method with the gyro-kinetic analysis using the adiabatic electrons [2] is adopted.

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Turbulence Spreading and Transport Events in Tokamak Plasmas

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Transport in tokamak plasmas is usually modeled by diffusive process caused by linearly unstable local turbulence. However, there exists a variety of phenomena from experiments and simulations which cannot be described by those simple models [1]. Outstanding examples include turbulence spreading from linearly unstable zone to stable zone [2,3] and avalanche-like transport events which possess characteristics of self-organized-critical systems [4]. This topical overview presentation will cover direct numerical simulation results, simple theoretical models, and their need for interpretation of experimental results.

This work was supported by R&D Program through the National Fusion Research Institute of Korea(NFRI) funded by the Government funds.

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Gyrokinetic modeling of the quasilinear particle flux

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A highly peaked density profile is favorable to increase fusion power, because fusion power is proportional to the square of the density and it is empirically known that the density has a upper limit in the peripheral region. In tokamak plasmas, particle transport is governed by turbulence. The turbulent particle flux is usually a nonlinear function of the thermodynamic forces such as the density and the temperature gradients, and the diagonal and the off-diagonal components in the transport matrix are defined in the quasilinear limit. The off-diagonal component sometimes generates the inward flux, which is essential for the highly peaked density profile. However, existing particle transport models do not deal with these components separately. This paper proposes the method to estimate these components. Since this method consumes relatively little computational resources, it is realistic to construct a table of the relationship between the plasma parameters and these components. Using the table enables us to predict the particle flux with further little computational resources.

For the estimate of the diagonal and off-diagonal terms, we use the JT-60U H-mode plasma [1], which is heated by neutral beam injection (NBI), and assess particle transport with the flux-tube gyrokinetic code GKV [2]. We assume the quasilinear electron particle flux in the form: $\Gamma_\mathrm{e} = \frac{n_\mathrm{e}}{R} D\,(R/L_{n_\mathrm{e}} + C_\mathrm{T} R/L_{T_\mathrm{e}} + C_\mathrm{P})$, where R is the major radius and n_e, R/L_{n_e}, R/L_{T_e} and D are the density, the density gradient, the temperature gradient and the diffusivity for electrons, respectively. The off-diagonal contributions appear through the thermodiffusive ($C_\mathrm{T} R/L_{T_\mathrm{e}}$) and another pinch ($C_\mathrm{P}$) mechanisms. Here, the positive (negative) value in each term indicates the outward (inward) flux. Adopting the method of trace particle species [3], the linear calculations are performed to compute the factors C_T and C_P (figure 1). After obtaining C_T and C_P, D is estimated to match the experimental particle flux, assuming that the particle flux is balanced with the particle source due to NBI. As shown in figure 1, C_T, C_P and D can be estimated in the above semi-empirical way. In this paper, we apply the semi-empirical method to plasmas with different density profiles.

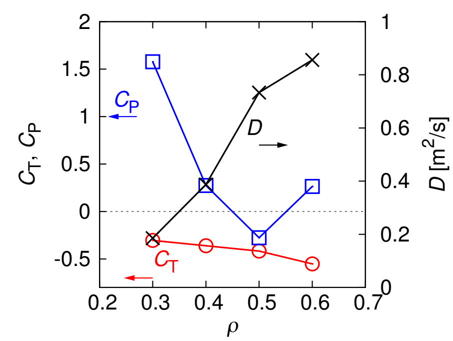

Figure 1: Profiles of factors for the thermodiffusive term, C_T, and for another pinch term, C_P, and the electron diffusivity D.

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Correlation between nonlinear time of pressure fluctuations and Kubo number of stochastic magnetic fields in BOUT++ simulation

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Nonlinear convection through stochastic magnetic fields is considered as a possible mechanism causing transport of density, momentum and heat during an edge localized mode crash. In the presence of stochastic fields, the characteristic of the transport process strongly depends on the magnetic Kubo number (MKN). Thus, identification of MKN in experiments is of special importance in elucidation of the transport processes in stochastic fields. MKNs have not been measured experimentally in tokamaks, and we demonstrate how one might estimate them based on BOUT++ simulation data. We calculate correlation functions of fluctuating magnetic fields and pressure obtained from an edge pedestal collapse simulation. With the correlation functions, we estimate and compare MKNs and nonlinear time of pressure fluctuations. We discuss our preparation on experimental measurements of the Kubo numbers in a DC multi-dipole chamber.

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Turbulent transport in LHD and Heliotron J plasmas

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We have investigated drift-wave instability and nonlinear turbulent transport in two configurations with different magnetic field structures by means of electromagnetic gyrokinetic simulations [1]. Here, one is the neoclassically optimized Large Helical Device (LHD) plasma and the other is the Heliotron J (HJ) plasma. First, we show that the validation against the turbulent transport in the LHD plasma is successful, and that the neoclassically optimized configuration has smaller turbulent transport. Second, the neoclassical optimization through an enhanced toroidal mirror ratio, which is a capability of non-axisymmetric plasma, is found to improve the turbulent transport in the HJ plasma, which is qualitatively consistent with the observation in the HJ. Hence, the neoclassical optimization reduces the turbulent transport in both the LHD and HJ plasmas. Third, as a trial in evaluating the performance of a helical system designed with different concepts for stability, we compared turbulent transport in these plasmas and found that both the mixing-length-estimated diffusion and nonlinear turbulent transport of the HJ plasma are smaller than those of the LHD plasma in gyro-Bohm units. The significant difference is stronger zonal flows in the HJ plasma than in the LHD plasma.

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Comparative study of characteristics of ion-gyroscale fluctuations between measurements and gyrokinetic simulations in KSTAR

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We have studied characteristics of electron density fluctuations measured using the microwave imaging reflectometer [1] in a core region of stationary NBI L-mode plasmas on KSTAR [2]. The fluctuations are found to be broad-band (∼200 kHz) from a cross-coherence analysis between multiple poloidal channels and their local coherence peaks place in the range of ∼150 to ∼400 kHz. Poloidal wavenumbers of the unstable modes, deduced from the frequencies and poloidal rotation velocities of the fluctuations in the laboratory frame [3], are comparable with those from linear gyrokinetic simulations with the GYRO code. The values of about $2-4$ cm^{-1} from both the measurements and simulations suggest that the unstable modes can be ion-gyroscale micro-instabilities such as the ITG modes or TEMs. Although direct measurement (or deduction from measurements of other quantities) of the phase velocities of the unstable modes in the plasma frame, where the equilibrium $E \times B$ flow velocity is zero, is almost impossible, the group velocities in the plasma frame can be estimated from a cross-phase analysis of the fluctuations in the laboratory frame. The estimated group velocities are all in the ion diamagnetic drift direction and this agrees well with the linear simulation results.

This work was supported by the Ministry of Science, ICT, and Future Planning under the KSTAR project and the National Research Foundation of Korea under contract No. NRF-2014M1A7A1A03029865, and partly supported by the JSPS-NRF-NSFC A3 Foresight Program in the field of Plasma Physics (NSFC: No. 11261140328, NRF: No. 2012K2A2A6000443).

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Turbulence Bistability-a Mechanism for Avalanching and L-mode Heat Flux Hysteresis

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We report on a new theoretical model which explains the remarkable observations of heat flux and fluctuation intensity hysteresis in MECH L-mode experiments on LHD , in the absence of a discernable transport barrier (c.f., S. Inagaki et al Nucl. Fusion 53, 113006 (2013)). This study also strikes at the fundamental questions of “WHAT IS AN AVALANCHE ? and what is the essential PHYSICS thereof?”. Avalanching is a fundamental process in flux driven transport. Thus, a reduced model of avalanching is of significant interest, and is absolutely necessary to illuminate the physics behind the color VG from large simulations.The principal results of this study are:

1. an avalanche is seen as a propagating “reaction-diffusion” pulse in the “ excitable medium” of the plasma. Avalanching includes turbulence spreading plus additional physics.

2.hysteresis is a consequence of fluctuation bistability, which results from “multiplicative noise”, due mesoscale grad T corrugations. The avalanche excitation mechanism thus is seen as a noise -induced phase transition.

3.the variance of the mesoscopic grad T corrugations is obtained from a generalization of the Zeldovich Theorem,which includes the mesoscale flux of fluctuation intensity.

4.hysteresis strength and pulse (avalanche) speed are calculated, explicitly, by solving the stochastic nonlinear pde for intensity, using the statistics of mesoscale grad T, obtained as above. Corrections to the dimensional analysis result-ie the diamagnetic speed- have been obtained

5.the probability distribution function of the fluctuation intensity was calculated, and is a stretched exponential, with an exponential tail for high intensity.

Starting from the conventional hypothesis that there exists a critical temperature gradient for the excitation of the turbulence, we show that mesoscopic fluctuations in temperature gradients-such as those due to profile corrugations- trigger an local exceedance of the critical threshold and so induce bistability of turbulence and system state bifurcation. The corrugations may be related to the presence of an ExB staircase ,which consists of a lattice of shear layers and temperature corrugations. The critical effect is multiplicative noise in the fluctuation intensity equation, due to the mesoscale temperature gradient corrugations. If the heat flux exceeds a ‘forward’ threshold, the system transitions from a ‘laminar’ state to a turbulent state. Correspondingly, the effective thermal conductivity jumps from a value close to the neoclassical value to an anomalous value. Once below a ‘backward’ threshold, the turbulent state returns to the laminar one. The back threshold differs from the forward threshold–manifesting hysteresis. For a locally excited state, a stable front of turbulence intensity is formed. This ‘connects’ the turbulent, and laminar states, and propagates as an avalanche. Thus, L-mode hysteresis and turbulence intensity avalanching are addressed in a unified theoretical framework.

Microinstability and Turbulent Transport of Multi-ion-species Plasmas in Helical System

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Understanding of the transport phenomena in the mixed plasma consists of multi-ion species is strongly demanded for burning plasma studies in the ITER, future fusion reactors, and the deuterium experiments in the Large Helical Device (LHD). In this work, we investigate the ion scale microinstability and turbulent transport of multi-ion-species plasmas in helical system such as LHD by gyrokinetic simulations. Quantitative evaluations of anomalous transport fluxes of heat and particle in magnetically confined plasmas are critical issues to design the fusion reactors, and the gyrokinetic simulation is one of the most powerful tools to analyze the transport phenomena driven by the drift-wave plasma turbulences. In the present work, we focused on the LHD experiment with the multi-ion-species including hydrogen, helium, and impurity carbon ions. In the experiments, it was found that the ion temperature increases with the decreases of the ratio of hydrogen density to helium density [1]. The gyrokinetic simulations with the real-mass kinetic electrons and multi-ion-species in the LHD plasmas show that the linear growth rates of the ion temperature gradient mode are reduced for the helium-dominated plasma compared with the hydrogen-dominated plasma [2]. As shown in Figure 1, the mixing length estimates obtained from the gyrokinetic simulations show smaller ion thermal diffusivity for the helium-dominated plasma than the hydrogen-dominated one in the hydrogen gyro-Bohm unit, due to the differences of the plasma profiles of the temperatures, densities and the temperature ratio between the hydrogen- and helium-dominated plasmas. In this work, we also discuss the resultant transport levels and the effects of the mass number and the electric charge of the mixed ion species.

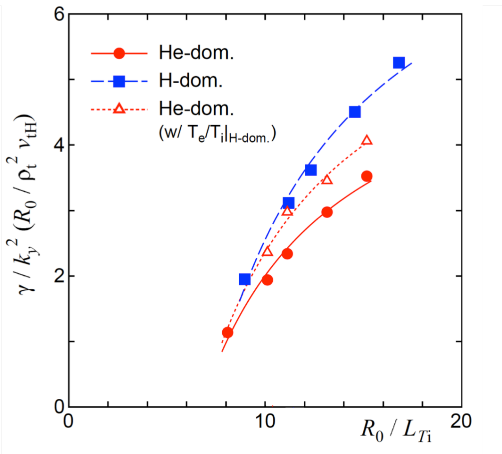

Figure 1: Ion temperature gradient dependences of the mixing length diffusivities in the helium-dominated plasma (red solid curve) and the hydrogen-dom. case (blue dotted curve) at $\rho = 0.48$ and $k_y \rho_t = 0.407$. The red dotted curve with the triangles shows the results in the helium-dominated case with same T_e/T_i in the hydrogen-dominated

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Extraction of nonlinear waveform in turbulent plasma

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Structure and propagation of nonlinear waves have been studied widely [1, 2]. One of the interesting characteristics of nonlinear wave is their localization. As known widely, the localization is influenced by the competition between dispersion and steepening, i.e. nonlinear effect, which increases with wave amplitude. In magnetized plasma, inhomogeneity generates turbulence and several types of nonlinear waves form. In particular, a streamer is important class of nonlinear waves [3, 4]. A streamer has radially elongated structure and thus enhances transport. Therefore its behavior is important for the plasma confinement. The streamer was found as an azimuthally localized nonlinear wave, coupled with ambient drift wave fluctuations [5]. Nonlinear wave of streamer is extracted by convolution method. A phase of the wave of a specific frequency is used as clock for the conditional averaging. Obtained waveform contains the nonlinear components of the wave. To quantify the localization of the streamer, anharmonicity, which implies the difference form the sinusoidal wave, is defined. Relation between the anharmonicity and the amplitude of the wave indicates that the localization becomes stronger for larger fluctuation amplitude. The result is also compared with theoretical prediction of streamer waveform [3] and confirmed the theoretical prediction on the amplitude dependence.

This work is partly supported by a grant-in-aid for scientific research of JSPS Japan (15H02335, 15H02155, 15K14282, 15K14283, 16H02442), the collaboration programs of NIFS (NIFS15KLPH024), JSPS Research Fellow (16J00560) and Asada Science foundation.

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Stability and error analysis of a moment extract approach to the toroidal gyrokinetic simulation with finite collision effect

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Numerical analyses of plasma instabilities which are closely related to the turbulent transport are important for deeper our understandings on properties of the magnetic fusion confinement. When we use an explicit time integration scheme for the gyrokinetic equation with ions and electrons such as the Runge-Kutta scheme, the time step size is severely restricted by the Courant-Friedrich-Lewy condition for the fast electron motion or the dispersive Alfven wave (DAW) propagation. In order to overcome this difficulty, we have proposed the moment extract approach where the drift kinetic equation (DKE) for electrons is divided into the 0^{th} and the 1^{st} order moment equations, and the remnant kinetic equation. With this technique, the stiff terms of DAW propagation appear only in the fluid equations, which enables us to apply an semi-implicit integration to the gyrokinetic equation straight forwardly.

In this study, we further extend the moment-extract approach for application to the non-uniform magnetic field and finite collisionality. The DKE

$$\frac{\partial f_e}{\partial t} + v_\parallel \frac{\partial f_e}{\partial z} = -\frac{q_e}{T_{e0}} v_\parallel F_M \left(\frac{\partial \varphi}{\partial z} + \frac{1}{c}\frac{\partial A_\parallel}{\partial t}\right) + \frac{\mu}{m_e}\frac{\partial B}{\partial z}\frac{\partial f_e}{\partial v_\parallel} + C_L(f_e)$$

is separated into the 0^{th} moment, the 1^{st} moment, and the remnant kinetic equations, such that

$$\frac{\partial n_e}{\partial t} = -n_0\left(\frac{\partial U_\parallel}{\partial z} - \frac{1}{B}\frac{\partial B}{\partial z}U_\parallel\right),$$

$$n_0 m_e \frac{\partial U_\parallel}{\partial t} = -q_e n_0\left(\frac{\partial \varphi}{\partial z} + \frac{1}{c}\frac{\partial A_\parallel}{\partial t}\right) - \frac{\partial}{\partial z}(n_e T_0 + n_0 T_\parallel) + \frac{1}{B}\frac{\partial B}{\partial z} n_0 (T_\parallel - T_\perp),$$

and

$$\begin{aligned}\frac{\partial h_e}{\partial t} + v_\parallel \frac{\partial h_e}{\partial z} - \frac{\mu}{m_e}\frac{\partial B}{\partial z}\frac{\partial h_e}{\partial v_\parallel} \\ = \left[\left(1 - \frac{m_e v_\parallel^2}{T_{e0}}\right)\frac{\partial U_\parallel}{\partial z} + \frac{v_\parallel}{T_{e0}}\frac{\partial T_\parallel}{\partial z} + \left(\frac{\mu_e}{T_{e0}}U_\parallel - \frac{U_\parallel}{B} - \frac{v_\parallel}{B}\frac{T_\parallel - T_\perp}{T_{e0}}\right)\frac{\partial B}{\partial z}\right] F_M + C_L(h_e)\end{aligned}$$

where $h_e = f_e - (n_e/n_0)F_M - (m_e/T_{e0})v_\parallel U_\parallel F_M$.

Here, we examine the two types of semi-implicit schemes, the 2^{nd} order Adams-Bashforth and Crank-Nicolson (ABCN) scheme and the 2^{nd} order Additive Semi-Implicit Runge-Kutta (A-SIRK) scheme for analysis of the electrostatic potential oscillation. Our benchmark test shows that the A-SIRK scheme successfully provides the stable solution of Courant number $C_L \sim 10$, while the AB-CN scheme yields unfavourable growth oscillation. We have also carried out a detailed stability and error analysis and convergence tests of which details will be reported at the meeting.

The Predict First Initiative

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The next generation of tokamaks, including ITER, will have a very low tolerance for large transient increases in heat and force loading of the plasma facing first wall. Due to these limitations, the exploration and optimization of regimes in burning plasma class devices will be done primarily with whole device modeling simulations. Developing a predictive whole device modeling capability, with high accuracy and a quantified statistical confidence, requires a long record of experience with predictive modeling. The "predict first initiative" calls for the use of a predict first, run discharge, validate results methodology in order to gain experience, and evolve the tools, towards the goal of producing the predictive, validated whole device modeling capability that is needed for the future of fusion energy. Present tokamaks are exquisitely diagnosed for validation and can more safely challenge operational limits so it is important to begin this predict first methodology now. Predicting the outcome of experiments on present machines, as part of the planning process, will also enhance the rate of successful outcomes.

Exciting developments are making it possible to begin this predict first methodology now. Standardized workflows for data processing and theoretical model verification, validation, and uncertainty quantification are rapidly being written using the OMFIT framework. These workflows are improving the efficiency of the validation-model development cycle across all plasma physics domains. Some examples will be presented. An OMFIT workflow [1] that iterates predictive models of core transport, pedestal pressure and MHD equilibrium to calculate steady state profiles of plasma density, temperatures, and rotation has recently been built. These predicted profiles can be used to predict diagnostic signals like density and temperature fluctuations, MHD instabilities, and fast ion losses. Fast neural networks, trained on the core and pedestal theoretical models, and simplified source and MHD models, can be used in this workflow to make fast predictions of plasma profiles without experimental data. Routine use of this workflow for predictive experimental design is now possible. Including scrape-off layer and plasma wall interaction models is the next stage in the evolution towards whole device modeling.

[1] O. Meneghini, P. B. Snyder, S. P. Smith, J. Candy, G. M. Staebler, et al., Phys. Plasmas 23 (2016) 042507

Acknowledgement: DOE contracts DE-FG02-95ER54309 and DE-FC02-04ER54698

Topic (C)

Mode competition in turbulence and MHD driven by energetic particle

On the presence of GAM-ZF competition en route to tokamak turbulence transitions

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Turbulence has long been known to dominate cross-field transport in toroidal magnetic confinement devices. As such, the ubiquitously observed regimes of global confinement are various states of turbulence. Phase transitions between these are inherently interesting from the perspective of understanding turbulence, but also carry a crucial significance for making fusion viable. The longest known and most obvious of such transitions is the low- to high-confinement (L-H) transition. High confinement (the "H-mode") is characterized by large temperature and density gradients at the plasma surface, providing a much higher core pressure and hence fusion power. Access to the H-mode is tied to a threshold heating power P_{LH} above which the transition can occur. The parametric dependences of P_{LH} are vitally important for the design of future plasmas, with several – such as those on main species isotope, method of auxiliary heating, plasma rotation, etc – still unaccounted for in theory or scaling laws. Among these, one of the largest effects is the up-down asymmetry of magnetic configurations with a single poloidal null. The power threshold in an equilibrium in which the ion grad-B drift points toward the poloidal null (X-point) is approximately half as high as in the opposite case. Since the discovery of the H-mode, some intermediate regimes have also been found. One remarkable feature of the asymmetry of magnetic geometry is the difference in the intermediate regimes to which each configuration leads, with limit-cycle oscillating (LCO) regimes typical of H-mode-favoring geometries, and the "I-mode" of the opposite. The I-mode is an intriguing alternative regime combining high heat confinement with strong mass transport.
New results [1] address the up-down asymmetry and offer an insight into the background of the range of plasma parameters in which I-modes can be maintained (the "I-mode window") as one of nonlinear dynamics. Interactions between turbulent structures and between turbulence and mesoscale flows are discussed and their dependence on geometry addressed.
For this purpose, edge fluctuations are studied in and near I-mode regimes with a focus on the nonlinear interaction between the broadband turbulence and edge flows. In particular, ZF structures are studied in I-mode for the first time and their role in triggering the I-H transition is addressed. Since the damping, and thus the existence, of GAM in the plasma edge strongly depends on collision frequency, and therefore plasma density, the role of GAM-ZF competition or interaction is directly addressed in high magnetic field I-modes.
Work performed in partial support by the U.S. Department of Energy under Award Numbers DE-SC-0008689 and DE-FC02-99ER54512.

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Mode Competition ,Saturation Mechanisms ,and Spatial Patterns in Multi-Scale Turbulence

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The problem of interacting disparate scale populations of turbulence is a classic in plasma physics, dating from the work on Langmuir Turbulence by Zakharov . Recently, large simulations have suggested that multiscale interaction may be relevant to explaining the shortfall in transport predictions. However, depth of understanding has not kept pace with computation size. Here we describe a simple reduced model which enables both discovery and understanding relevant to multi-scale systems. Initial results are presented, along with some predictions to guide future analysis.The model SIGNIFICANTLY extends previous work on multi-scale interaction by Holland and Diamond (PoP 2004), and builds on the theory of envelope patterns by Ashourvan and Diamond (PRE Rap Comm 2016, PoP 2017).

The model is based on the primitive system of ion scale electron drift waves (DW) driven by grad Te, coupled to electron scale ETG turbulence. This naturally leads to a reduced model consisting of four equations in radius and time for evolution of :
1.mean Te , due to DW and ETG fluxes, which compete to balance the source
2. ExB flow , due to DW and ETG stresses. Care is taken to account for enhanced ETG inertia due to the role of adiabatic ions.
3.the ETG energy field, which evolves by mean gradient coupling, flow Reynolds work , dissipation by inverse cascade to ion scales and self-spreading. Cross scale coupling enters via straining and spatial scattering (ie spreading) by ion scales.
4.the DW energy field, evolving by mean gradient coupling, Reynolds work, NL dissipation, self-spreading, and nonlinear DRIVE due to the influx of energy from ion scales.
Here, shearing effects on scales for DW and ITG are included . Also, grad Te evolves self-consistently ,so the two turbulence populations compete to carry the flux driven by the heat source.

Analysis of the model is ongoing, though several interesting results have already been obtained. These include:
1. a new “Dimits shift” like state, where ETG energy condenses to ION scale zonal flows. The mechanism is inverse cascade from electron to ion scales,and Reynolds work on the flow. Linear DW instability is not essential ,and DW excitation serves only to couple the incoming (from small scales) ETG energy to zonal flows via stresses. This interaction defines a mechanism whereby ETGs can inhibit or suppress DW turbulence and transport.
2. Multi-scale interaction is manifested in REAL SPACE, as well as k-space. One example is multiscale patterning and staircases, in which ETG staircases form in the jumps (ie steep gradient regions) between steps in the DW staircase. Note that ion scale turbulence is necessarily suppressed in the staircase jumps, so there will be no straining effect or spreading driven locally in that region. Multi-scale, multi-step staircase gradients are limited by mode competition to carry the heat flux.
Further manifestations of inverse cascade physics are under study and will be discussed.

Transition from MHD mode to tongue deformation before the collapse events in LHD

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The tongue deformation is characterized by toroidally, poloidally, and radially localized plasma displacement which triggers the plasma minor collapse[1]. Transition from stationary (non-rotating) m/n=1/1 MHD mode to the tongue deformation is observed in the Large Helical Device (LHD). The displacement of plasma, ξ, during the deformation is evaluated from the high frequency (1 – 10 kHz) change in temperature, δT_e, and quasi-state temperature gradient ∇T_e (<1 kHz) as $\delta T_e / \nabla T_e$. The stationary m/n=1/1 MHD mode is localized near the rational surface of q = 1. When the tongue deformation appears at the non low-order-rational surface (well inner side of q = 1 surface), the m/n=1/1 MHD mode disappears. The plasma displacement due to the deformation increases to 2 cm and expands outwards in 100 μs. The perturbation of poloidal magnetic field is toroidally localized near the port where the neutral beam is injected and poloidally localized upward in the $B \times \nabla B$ direction. This is in contrast to that the perturbations of poloidal magnetic fields at 180 degree apart of the n/m =1 MHD mode have always odd parity both in toroidal and poloidal direction. The transition from stationary MHD mode to tongue is within 100 μs. After the tongue deformation, the plasma has minor collapse and rotating m/n=1/1 MHD mode starts. This rotating mode lasts only 2 ms and stops rotations associated the appearance of stationary m/n=1/1 MHD mode. These observation shows that there are three phases (stationary m/n=1/1 MHD mode, tongue, and rotating m/n=1/1 MHD mode). Moment analysis of the ion velocity distribution measured with charge exchange spectroscopy is applied in this experiment in order to investigate the impact of crash triggered by tongue on ion velocity distribution. A clear 3rd and 4th moments of ion velocity distribution in the epithermal region (within the three times of thermal velocity) is observed after the tongue event as well as 1st and 2nd moments. The finite 3rd moments observed indicates a clear evidence of the distortion of ion velocity distribution from Maxwell-Boltzmann distribution. This distortion from Maxwell-Boltzmann distribution is observed in the outer region of the tongue deformation up to the plasma edge and disappears in the ion-ion collision time scale.

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Energetic particle modes of $q=1$ high order harmonics in tokamak plasmas with monotonic weak magnetic shear

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Energetic particle physics is a key issue in burning plasma experiments of advanced tokamaks. Instabilities driven by energetic particles, such as fishbones, long lived modes and various Alfvén eigenmodes, are commonly observed in many tokamaks with Neutral Beam Injection (NBI) heating, which can significantly degrade energetic particle confinement and alpha particle heating. Recently, the weak magnetic shear is recommended for high-performance tokamak operations. However, some instabilities, such as ballooning, infernal and long lived modes, can be excited in the weak magnetic shear configuration. The phenomena that the high-order harmonics are stronger than the $m/n=1/1$ component in the low magnetic shear configuration have been observed in some devices, such as HL-2A and HT-7.

In this work, we use a particle/MHD hybrid code M3D-K to study the linear and nonlinear characteristics of the high-order harmonics EPMs driven by trapped fast ions in weak magnetic shear tokamak plasmas. It is found that with a flat safety factor profile in the core region, the linear growth rate of high-order harmonics ($m=n>1$) driven by energetic trapped particles can be higher than the $m/n=1/1$ component. The high $m=n>1$ modes become more unstable when the pressure of energetic particles becomes higher. And there are multiple resonant conditions for high n components in the different resonant locations. In the nonlinear phase, the nonlinearity effects of both energetic particles and fluid are analyzed by comparing the time evolutions of kinetic energy with and without fluid nonlinearity. The frequency of these modes does not chirp significantly, especially for high n components, comparing with the typical fishbone driven by trapped particles. In addition, the flattening region of energetic particle distribution due to high-order harmonics excitation is wider than that due to $m/n=1/1$ component, although the $m/n=1/1$ component has higher saturation amplitude.

Energetic-Ion-Driven Instabilities and Transport: Simulation Methods, Benchmark, Validation and Predictions

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Using the MHD-PIC hybrid code MEGA [1, 2], the transport of fast ions in a beam-driven tokamak plasmas subject to resonant magnetohydrodynamic (MHD) mode activity is simulated. The simulation includes realistic beam ion sources and beam-bulk collisions [3]. In order to able to cover the evolution of the fast ion distribution on the slowing-down time scale (several 100 ms), the so-called multi-phase method [4, 5] is employed, where 4 ms intervals of classical Monte-Carlo simulations (without MHD) are interlaced with 1 ms intervals of hybrid simulations (with MHD). This method has allowed us to reproduce multiple cycles of so-called abrupt large events (ALE) [6], which were seen in JT-60U experiments and cause avalanche-like relaxations of the fast ion density profile [7, 8, 9]. In this presentation, the simulation methods are reviewed, and results of recent benchmark, validation and physics studies are presented. Possible implications for the construction of reduced models for fast ion transport are also discussed.

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Observation of reverse-sheared Alfvén eigenmodes (RSAEs) in ELMy H-mode plasma on EAST tokamak

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Reverse-sheared Alfvén eigenmodes (RSAEs) have been observed by using interferometer and ECE diagnostics in NBI heated ELMy H-mode plasma on EAST tokamak. A typical feature of these modes is with a fast frequency sweeping upward from ~80 kHz to ~110 kHz in hundred milliseconds during which the plasma temperature, density and rotation keeps no change. Only core channels of interferometer can observed these modes, implying a core localized mode. The ECE measurement further shows that these modes just located at about ρ_{tor}=0.37 – 0.46. Although these modes are very week in the magnetic fluctuations measured by mirnov probes mounted at the machine wall, the coherence analysis between ECE signals and mirnov signals still distinguish two bands of these RSAEs. A multiple frequency fluctuation components, seemingly the so-called 'grand cascades', was also clearly observed on ECE signal at ρ_{tor}=0.46. During the phase, a transit internal transport barrier (ITB) in ion temperature and toroidal rotation was observed while it seems that the formation time of ITB is some earlier than the observation of 'grand cascades'.

Energetic particle driven geodesic acoustic mode in a toroidally rotating tokamak plasma

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Energetic particle (EP) driven geodesic acoustic modes (EGAMs) in toroidally rotating tokamak plasmas are analytically investigated using the hybrid kinetic-fluid model and gyrokinetic equations. By ignoring high-order terms and ion Landau damping, the kinetic dispersion relation is reduced to the hybrid one in the large safety factor limit. There is one high-frequency branch with a frequency larger than the transit frequency of EPs with initial energy, which is always stable. Two low-frequency solutions with a frequency smaller than the transit frequency are complex conjugates in the hybrid limit. In the presence of ion Landau damping, the growth rate of the unstable branch is decreased and the damping rate of the damped branch is increased. The toroidal Mach number is shown to increase the normalized real frequency of both branches. Although not affecting the instability critical condition, the Mach number decreases the growth rate when the real frequency is larger than a critical value and enlarges the growth rate when the real frequency is less than the critical value. The ion Landau damping effect is negligible for large M. But the discrepancy between the kinetic dispersion relation and the hybrid one becomes ignorable only when the safety factor is about larger than 7.

Keywords: geodesic acoustic mode, energetic particles, toroidal rotation, tokamak

Enhancement and suppression of turbulence by energetic-particle-driven geodesic acoustic modes

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Energetic particle driven geodesic acoustic modes (EGAMs), which are oscillatory zonal flows, have attracted much attention [1]. Recently, large amplitude EGAMs have been observed in experiments, and the impact on the background plasma and turbulence could be significant [2]. On the one hand, GAMs have velocity shear, and the suppression of turbulence transport by GAMs has been reported [3]. Experimental study has shown that the formation of a transport barrier can be accompanied by GAMs [4]. On the other hand, the enhancement of turbulence by EGAMs has been observed in turbulence simulations [5]. In these simulations, EGAM destroys a transport barrier, and the turbulence increases in the turbulence stable region. In this way, EGAMs can either mitigate or enhance the turbulence. This dual effect of the EGAMs on turbulence requires theoretical investigation.

In this study, we investigate the phase-space dynamics of spatially inhomogeneous turbulence with a transport barrier in the presence of EGAMs. The phase-space dynamics results in trapping of turbulence wave-packets by EGAMs. We found that the trapped turbulence wave-packets leak across the transport barrier. As a result, turbulence is enhanced by EGAMs in the stable region, while turbulence suppression is obtained in the unstable region. The propagation of the turbulence is ballistic, with the phase velocity of the EGAM [6]. Hence, there appear a new global characteristic velocity for turbulence dynamics, in addition to the local group velocity and that of the turbulence spreading [7]. Thus, turbulence carried by the EGAMs shows non-Fickian transport properties. The propagation of trapped turbulence is different from processes such as turbulence spreading and avalanches.

Keywords: EGAM, turbulence transport, nonlocal transport, turbulence spreading

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Hydrogen Isotope Effect on Confinement

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The energy confinement in tokamaks is known better for heavier hydrogen isotope [1]. However, the conventional model of transport coefficient with gyro-Bohm dependence (e.g., [2]), has an opposite dependence on the hydrogen mass number A. Essential roles of zonal flow [3] are widely known, but do not fully explain the isotope effect [4]. Recently, it has been pointed out that the plasma heating directly drives turbulence [5]. This new driving mechanism may explain the hysteresis in gradient-flux relation [6]. These results stimulate us to consider the relation between transport hysteresis and hydrogen isotope effect [7]. Owing to the heating, the turbulence intensity I is enhanced as [5]

$$I = \frac{1}{1-\Gamma_h} I_0$$

where $\Gamma_h = \gamma_h \chi_0^{-1} k_\perp^{-2}$ represents the competition between drive by heating and decay by background turbulence, and I_0 is the level with out this effect. If the decay rate by turbulence is proportional to $A^{0.5}$ like the gyro-Bohm dependence, a dependence like $\Gamma_h \sim A^{-0.5}$ is deduced, if other parameters are unchanged. That is, the jump of hysteresis at the onset of heating is smaller for the plasmas with heavier hydrogen isotope. This indicates that need to extend the theoretical framework of transport, in order to understand the hydrogen isotope effect on plasma confinement.

The experimental study of the isotope effect on the transport hysteresis is in progress on LHD. The implication of new experimental observation is also discussed.

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This work is partly supported by the Grant-in-Aid for Scientific Research of JSPS (JP15H02155, JP16H02442).

Turbulence Simulation Taking Account of Inhomogeneity of Neutral Density in Linear Devices

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Elementary processes of mode competition have been studied in linear devices to clarify the transport mechanism in turbulence of magnetically confined plasmas [1]. It is important to consider combination of multiple inhomogeneities, which affect properties of instabilities, even in this simple magnetic configuration [2]. Numerical simulations have shown a bifurcation diagram for turbulent structures with ion-neutral collision frequency ν_{in} as the control parameter [3], and experimental investigations have been also made [4]. Here we take account of the inhomogeneity of neutral particle density. The importance of the existence of neutrals is not limited to basic plasmas. Interaction with neutrals are utilized for particle and heat control in the divertor region of fusion plasmas [5].
Two kinds of simulations are combined in this research. One is a simulation for 2-D profiles of neutral particles [6], and the other is that for resistive drift wave turbulence [3]. Radial and axial profiles of neutral particles are calculated by the Monte Carlo method with a configuration of linear device PANTA [2]. The ratio for ionization of neutrals depends on the electron temperature, and the higher temperature in the operation range makes the neutral density smaller near the center of the plasma. Then next the radial profile of ν_{in} is set introducing these neutral density profiles into turbulence simulations. Smaller ν_{in} makes the instabilities more unstable. In addition, it is found that the inhomogeneous ν_{in} profile enhances the potential formation. The azimuthal flow shear near the center of the plasma is generated with the convective derivative nonlinearity in this potential formation. Not only a dominant unstable drift-wave mode but also a nonlinearly-excited mode affects the nonlinear structural formation, whose mechanism will be discussed.

Keywords: drift-wave turbulence, bifurcation, inhomogeneity, neutral particle, potential

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Control and measurement of distribution function of fast ions for deeper understanding of nonlinear interaction of fast ions and Alfvén eigenmodes

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Stability and nonlinear phenomena of energetic-particle-driven Alfvén eigenmodes are fundamental and challenging subjects of plasma physics, and kinetic consideration is required. In the experimental study, control and measurement of distribution function of fast ions are key issues to understand behaviors of Alfvén eigenmodes. In this paper, two experimental studies are discussed: one is control of fast-ion profile and the other is measurement of response of velocity distribution function of fast ions interacting with Alfvén eigenmodes.

<Control> In the Large Helical Device (LHD), the experimental study of Alfvén eigenmodes was carried out with peaked, flat and hollow profiles of tangentially injected fast ions. Two ion sources (ISs) are mounted on tangential beam injectors (NBI#1, #2, #3) and the tangential radius are different (3.63m for IS1B, 2B, 3.77m for IS1A, 2A, 3.58m for IS3B, 3.72m for IS3A). The combination of IS operation enables us to investigate AE stability with different fast-ion profile with the same magnetic configuration of R_{ax}=3.60m. It was observed that some Alfvén eigenmodes were excited depending on the fast ions profiles.

<Measurement> In order to resolve fast-ion detection time on the wave frame, pulse signals of fast-ion detector such as Si-based fast neutral analyzer (Si-FNA), compact neutral particle analyzer (CNPA) was digitized with sampling rate of 50 MHz, and the information of the particle energy, detection time were recorded. The detection time of fast-ion was converted to the phase of the Alfvén eigenmode and the wave-particle interaction was investigated by the histogram of fast-ion as a function of the phase. The procedure of the wave-particle interaction analysis is identical to wave-particle interaction analyzer (WPIA) developed for Arase satellite project. The developed system was applied to the plasma experiments in LHD, Heliotron J and TJ-II for experimental measurement of the responses of distribution function of fast ions interacting with Alfvén eigenmode. The preliminary results will be discussed in the conference. These experimental approaches are new challenges to understand the nonlinear phenomena caused by kinetic effects of fast ions and the related discussions in the conference seem to be fruitful, while the results are still preliminary.

Effects of electron-scale turbulence on micro-tearing modes

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Plasma turbulence is inherently multi-scale physics containing both of electron/ion-scale micro-instabilities. Thanks to advances of supercomputers and of high performance computing algorithms, gyrokinetic simulations are now powerful tools to investigate the multi-scale turbulence. Multi-scale turbulence studies by means of gyrokinetic simulations clarified the existence of cross-scale interactions between electron and ion scales [1-3], and its necessity for explaining experimental transport levels in Alcator C-mod [4, 5]. Experimental study on DIII-D discharge with ITER baseline parameters also ensures that cross-scale interactions are relevant for ITER, and its understanding is required for accurate predictions of ITER performance [6]. Our recent works revealed a part of mechanisms of the cross-scale interactions in multi-scale electron/ion temperature gradient mode (ETG/ITG) driven turbulence via intermediate (sub-ion-scale) structures: shearing of ETG by ITG turbulent eddies, and damping of ITG-driven short-wave-length zonal flows by ETG turbulence [7, 8]. However, multi-scale turbulence analyses are until now limited to the case between ETG and ITG in the world. The application of multi-scale turbulence analysis to another instabilities is a critical step to extend the understanding of multi-scale nature of plasma turbulence.

We here apply the multi-scale turbulence analysis for the cross-scale interactions between ETG and micro-tearing modes (MTM). Although a typical poloidal wave number of MTM in tokamak is of the order of ion gyroradius, its linear eigen-function also has a radially localized current sheet structure much shorter than ion gyroradius. Therefore, our finding in multi-scale ETG/ITG turbulence, “electron-scale turbulence effectively interacts with short-wave-length structures”, motivates us to investigate whether ETG turbulence can affect MTM turbulence. The understanding of ETG and MTM is, not only a disciplinary interest, one of the critical problems in ITER performance prediction [9]. Multi-scale ETG/MTM turbulence simulations revealed that ETG suppresses MTM by distorting radially localized current sheets, which may have significant impact on electron heat transport.

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RF radiation as an indicator of fast ion loss by instabilities

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Fast ions in magnetically confined plasmas can collectively excite RF radiation in the MHz to GHz range, spanning ion cyclotron emission (ICE), whistler waves, and lower hybrid waves. This radiation reflects the physical characteristics of the fast ion populations, especially their loss from the plasma, hence RF measurements have potential as diagnostics of the fast ions. This is highly topical: RF radiation data is being collected and analyzed worldwide to verify its feasibility for fast ion diagnostics on ITER [1].

RF radiation measurement involves relatively simple diagnostic assemblies which essentially comprise an in-vessel antenna, an RF spectrometer (filter bank) and an ADC. In LHD, a dipole antenna has been installed 2 m away from plasma, and the RF spectrum is measured in two ways. One is direct measurement by a fast ADC with a sampling frequency of 1.25 GHz. The other is an intensity measurement in each frequency range partitioned by a spectrometer. The measurement frequency range of the spectrometer is up to 2.8 GHz. With perpendicular neutral beam injection (NBI) in LHD, ICE from promptly lost beam ions has been observed, similar to JET, ASDEX-Upgrade, and DIII-D. In addition to ICE, a broad-band RF spectrum without harmonic structure is observed in LHD. Intense RF radiation, which combines both broadband and harmonic spectral structure, is observed coinciding with abrupt instabilities [2, 3]. These phenomena can be interpreted in terms of the expulsion of fast ions from the plasma core to the edge, due to the instabilities, giving rise to RF radiation.

The LHD RF radiation measurement system benefits from good availability and simplicity, with its antenna recessed from the plasma, and it provides a sensitive diagnostic of the fast ion losses. In this presentation, observations of instabilities and the consequent RF radiation will be presented.

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Entropy transfer function and zonal flow shearing in ion temperature gradient turbulence

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It is important to clarify the mechanism of turbulent transport in magnetically confined plasmas, in order to improve plasma confinement performance. Gyrokinetic simulations have widely been carried out for the evaluation of the ion heat transport driven by ion temperature gradient (ITG) instability. In a recent work [1], the entropy transfer analysis clearly captures nonlinear interactions of the ITG turbulence and the zonal flows. It is pointed out that there exists successive entropy transfer of turbulent modes through the coupling with zonal modes.

A purpose of this study is to deepen our physical understandings on entropy transfer process through a parameter survey and comparisons with the zonal flow shearing model [2]. As the ion temperature gradient decrease, the field energy ratio of zonal modes to turbulent modes increases, and the entropy variable is transferred to high-k_x modes. This suggests the entropy transfer function is related to the strength of zonal modes. Here we focused on the shearing process of zonal flows and defined the entropy transfer rate (ETR) for the modes driving the heat flux. The entropy transfer function consists of two parts, that is the transfer through the zonal modes (zf) and that among turbulent modes (trb). It is found that the entropy transfer rate corresponding to the coupling with zonal modes is in good agreement with the shearing rate of zonal flows for cases with low ion temperature gradient region ($R_0/L_T \leq 6.92$) (FIG. 1). In high ion temperature gradient region, however, turbulence interactions with zonal flows becomes subdominant. We will further discuss a relation to Dimits shift regime.

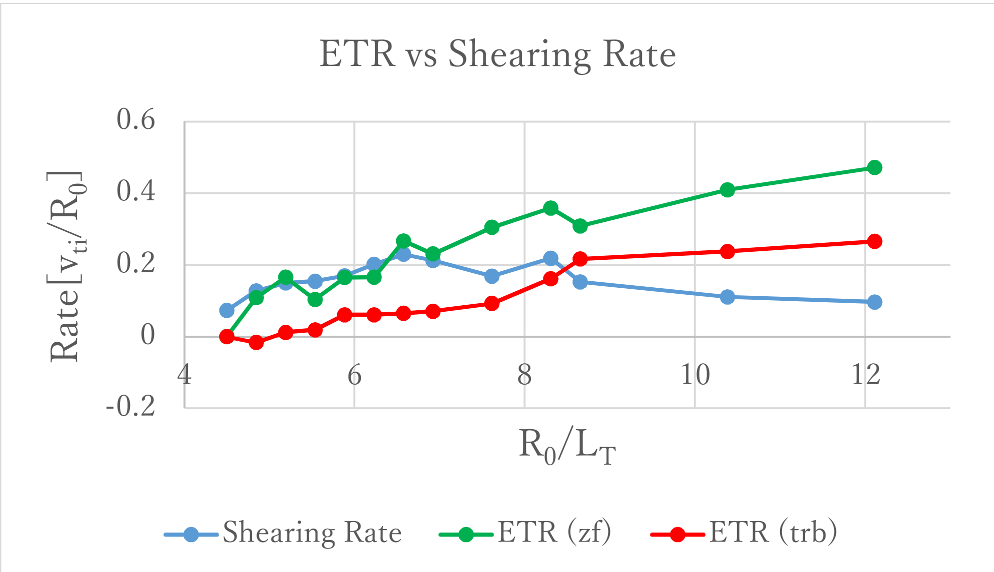

FIG. 1 Entropy transfer rate and shearing rate under various ion temperature gradient

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Zonal flows and geodesic acoustic modes in the evolution of energetic particle driven instabilities

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Zonal flows and geodesic acoustic modes that appear in the evolution of energetic particle driven instabilities, and their effects on the instabilities are discussed based on the results of the kinetic-magnetohydrodynamic (MHD) hybrid simulations. It was found that zonal flows and sidebands with higher mode numbers are generated in the nonlinear evolution of toroidal Alfvén eigenmode (TAE) [1,2]. The generation of zonal flows and sidebands increases the dissipation leading to the reduction of the saturation level of TAE. The increased dissipation due to the sidebans with higher mode numbers is attributed to the continuum damping. In the Large Helical Device experiments, it was observed that the secondary energetic-particle driven geodesic acoustic mode (EGAM) is suddenly excited during the upward frequency chirping of the primary EGAM [3]. The frequency of the secondary EGAM is a half of that of the primary EGAM. The frequency chirping of the primary EGAM and the excitation of the secondary EGAM are successfully reproduced with a kinetic-MHD hybrid simulation [4]. The properties and the excitation mechanism of the secondary EGAM will be discussed.

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Energetic particle-driven GAM in deuterium plasma in LHD

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Geodesic acoustic mode(GAM) is a branch of zonal flow in toroidal plasmas, and driven by not only turbulence but also energetic particles (EPs)[1]. Since the EP driven GAM (EGAM) may affect transport of thermal plasmas and EPs, understanding the EGAM is necessary for better prediction of behaviors of fusion plasma. EGAM is widely observed in toroidal plasmas such as JET, DIII-D, LHD, JT-60U, ASDEX-Upgrade, and HL-2A. In LHD, heretofore, the basic characteristics of EGAM[2] have been observed, and excitation of a subcritical instability of the EGAM[3-5] was discovered[6,7] in hydrogen plasmas.

In the present experiment campaign in LHD, deuterium experiment successfully started, and the EGAM is also being investigated in the deuterium plasmas with a focus on the mass dependence of the characteristics of the EGAM. At present, there seems to be no much difference in the excitation location and the radial profiles between hydrogen plasmas and deuterium plasmas. The observed frequency of the EGAM in deuterium plasma is smaller than that in hydrogen plasma. The result seems to correspond to the mass dependence of the GAM frequency and suggests a possibility of estimation of mass density, though the contribution of the EP should be taken into account.

In addition, another chirping mode with the toroidal mode of 0 or 10, which correspond to the toroidal periodicity of the helical coil, has been found near the edge region. The characteristics of the mode will be discussed.

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Topic (D)

Mechanism determining plasma flows and their impact on transport and MHD

Abstract Submitted for the 7th Asia Pacific Transport Working Group June 5th to June 8th, 2017

The Influence of Plasma Rotation on Burning Plasma Performance in Tokamaks*

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Plasma rotation is essential to the description of tokamak dynamics. Rotation affects MHD stability, impurity transport, and, through its influence on the radial electric field, suppression of turbulent transport and access to certain plasma regimes. Plasma rotation is governed by the conservation of momentum, and its vector nature makes momentum transport more complicated than particle or energy transport. The need to account for toroidal and poloidal rotation is a complication that becomes increasingly important when external momentum input is small compared to the moment of inertia, as it will be for a large tokamak like ITER. Experiments are important for gaining understanding of the transport and source of momentum in a tokamak. Dimensionless parameter scan experiments provide a path for gaining basic understanding of the underlying complex phenomenon. Intrinsic torque and rotation have been investigated with scans of normalized gyroradius and collisionality, yielding predictions for ITER of 33 Nm of intrinsic torque (nearly equal to the available neutral beam torque). Similar momentum transport experiments have shown incremental momentum transport consistent with turbulence suppression due to ExB shear. Recent progress has enabled the prediction of toroidal rotation for ITER based on simulated momentum transport and predicted intrinsic torque. The results demonstrate the importance of even moderate ExB shear for fusion performance as well as the potential effect of poloidal rotation in large tokamaks.

*Work supported by the US Department of Energy under DE-FC02-04ER54698

ITB formation by toroidal momentum injection in flux-driven gyrokinetic turbulence

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Profile stiffness is a long standing problem, which may limit the overall performance of H-mode plasmas. In the JET experiment, while strong ion temperature profile stiffness is observed around the nonlinear threshold of ion temperature gradient, it can be greatly reduced by co-current Neutral Beam Injections (NBIs) in weak magnetic shear plasma [1]. NBIs can provide two possible stabilization mechanism of toroidal Ion Temperature Gradient (ITG) mode. One is the electromagnetic stabilization by fast ions and the other is the stabilization by toroidal rotation shear. Indeed, the latter can be decomposed into stabilizing effect of $\mathbf{E}\times\mathbf{B}$ flow shear and destabilizing effect of parallel velocity shear, which often cancel with each other. However, most previous studies are based on local gyrokinetic theory, in which global effects such as radial mean electric field and profile shear effects are not fully taken into account.

For the comprehensive study of such toroidal rotation effects, we performed global gyrokinetic ITG simulation with heat and momentum sources by means of our full-*f* toroidal gyrokinetic code GKNET. We found that toroidal momentum injection can change the mean E_r through the radial force balance, leading to Internal Transport Barrier (ITB) formation in which the ion thermal diffusivity decreases to the neoclassical transport level [2].

In this study, we investigate the impact of weak or reversed magnetic shear on ITB formation by toroidal momentum injection. Figure 1 shows the radial ion temperature profile at different times in reversed magnetic shear plasma. It is found that ITB is not created around momentum source region $(0 < r < 0.4a)$, because the momentum diffusion is enhanced in negative magnetic shear region $(0 < r < 0.6a)$ according to the momentum transport theory [3]. On the other hand, once momentum diffusion reaches to q_{min} surface $(r = 0.6a)$, it is blocked by momentum pinch from positive magnetic shear region $(r = 0.6a)$. As a result, steep $U_{\parallel}$ and E_r shears are formed around q_{min}, which is considered to trigger ITB formation (see Fig. 1).

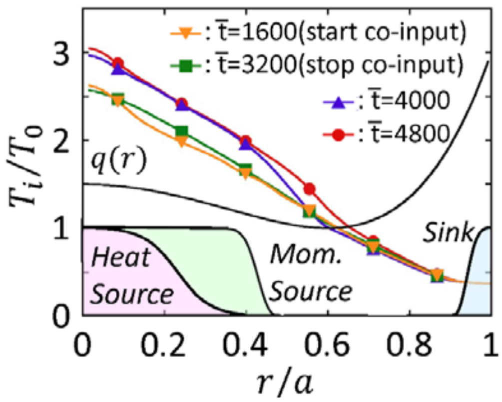

Fig. 1: *Radial ion temperature profile at different four times in reversed magnetic shear plasma.*

From the modulation test for momentum injection, it is also found that there exists a hysteresis nature with counter-clockwise in gradient-flux relation. This indicates that the turbulence intensity and turbulent flux can respond without waiting for the changes of temperature gradient and mean E_r shear, showing a kind of bifurcation phenomena.

This work was supported by Grants-in-Aid from JSPS with No. 25800304, 16K17844.

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Observation of solitary and mono-cycle shaped flow structure associated with the TESPEL injection

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The temporal shapes of the responded velocity change are different in the location and have a variety such as a solitary shape and a mono-cycle one, etc. by a multi-channel Doppler reflectometer.

As for studying the behavior of the turbulence affecting transport, the multi-scale interaction of turbulence between micro-, meso-, and macro-scale structures is receiving much attention at present. For this aim, higher spatial and temporal resolution diagnostics have been developed and applied in several devices [1]. In LHD, such the precise spatio-temporal behavior of turbulence flow velocity and intensity has been measured by the several channel microwave Doppler reflectometer system [2, 3]. Recently, we succeeded in increasing the radial observation points of this Doppler reflectometer system up to 20 (or especially up to 40).

Such a high resolution observation shows the interesting phenomena in the small pellet (TESPEL [4]) injection experiments. When the TESPEL travels from the low field side of the plasma edge, the perpendicular velocity, which is measured by the Doppler shift of probing microwave frequency, responded from edge to core in turn.

In the conference, we report the detail of experimental results and try to explain the considerable model in this phenomenon.

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The present study was supported in part by KAKENHI (Nos. 15H02335, 15H02336, 26630474 and 25289342), by a budgetary Grant-in-Aid from the NIFS LHD project under the auspices of the NIFS Collaboration Research Program, and by Collaborative Research Program of RIAM of Kyushu University. Additional support was provided by Japan/U.S. Cooperation in Fusion Research and Development.

Finite orbit width effect on the neoclassical toroidal viscosity in the superbanana-plateau regime

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The toroidal rotation determined by the radial transport of the toroidal momentum is an important issue in tokamaks for the prediction and/or control of the plasma performance and stabilities. Since tokamak plasmas are sensitive to non-axisymmetric perturbations, even small non-axisymmetric magnetic field perturbations can change the toroidal rotation by the neoclassical toroidal viscosity (NTV), which is induced by the non-axisymmetric perturbations.

According to theoretical NTV studies based on the bounce-averaged model [1], the NTV in the zero radial electric field ($E_{\mathrm{r}} = 0$) limit becomes independent of ν in a low collisional plasma (the so-called superbanana-plateau regime), where ν is the plasma collisionality. Recently, however, the global drift-kinetic code, FORTEC-3D, shows that the NTV is much smaller than that predicted by the superbanana-plateau theory and depends on the collisionality [2]. Clarifying the cause of the discrepancy is of importance to establish a reliable basis for the precise NTV prediction.

In this study, we examine the NTV in a low collisional plasma by two global kinetic simulations. One is a global full-f gyrokinetic Eulerian code, GT5D [3], and the other is the aforementioned code, FORTEC-3D, which is based on the δf Monte Carlo approach. As the first numerical verification, it is demonstrated that the NTV of both simulations shows similar ν-dependency over a wide range of collisionalities. The non-axisymmetric parts of the distribution functions from both global kinetic simulations also show a good agreement, showing a clear large structure in the deeply-trapped region. The structure is not expected from the superbanana-plateau theory based on the resonance of the toroidal precession of an unperturbed orbit.

By examining the unperturbed particle orbit, it is found that the barely-trapped particles subject to the unperturbed orbit resonance in the superbanana-plateau theory are actually no longer resonant due to the large banana width. The absence of the resonance in the global kinetic simulations leads to the smaller NTV of the global kinetic simulations than the superbanana-plateau theory. Then, the finite banana width of the trapped particles also generates the finite-$k_{\parallel}$ mode structure along the bounce motion, leading to the phase mixing in the trapped region of the velocity space. Fine scale structures caused by the phase mixing in the velocity space results in the smaller NTV in lower collisionality.

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Empirical investigation of spontaneous rotation under co- and counter-NBI heated H-mode plasma in KSTAR*

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The ion temperature, toroidal rotation, and density pedestal profiles have been investigated during LH transition in both co- and counter-NBI heated KSTAR H-mode plasmas. Recently the pedestal structures are observed in counter-NBI heating plasma both with and without non-axisymmetric magnetic field. A clear disparity between the width of the toroidal rotation pedestal and that of the ion temperature pedestal was observed in co-NBI heated plasma [1] while it is not in counter-NBI heated plasma. Also, toroidal rotation pedestal is observed to form ahead of temperature pedestal in both co- and counter-NBI-heated H-mode plasmas with and without non-axisymmetric magnetic field.
Ion temperature increases almost linearly from the very plasma edge in L-mode while rotation shows a modest pedestal structure in all plasma except the case with non-axisymmetric field. In H-mode, ion temperature profile develops a strong edge gradient with pedestal width ($\Delta_i^{ped} \sim 2$ cm), due to transport barrier formation and the core ion temperature increases correspondingly while rotation has a stronger pedestal gradient from $\Delta_i^{ped} \sim 5$ cm in co-NBI plasma to $\Delta_i^{ped} \sim 2$ cm in counter-NBI plasma and rotation pedestal width is fixed to 3 cm in both co- and counter-NBI heated plasma with non-axisymmetric field. Moreover, the plasma can be stationary against its spontaneous rotation by applying a torque in the co-current direction in KSTAR. Both core and pedestal rotation are saturated when stored energy increased in counter-NBI heated H-mode for “Rice scaling” while pedestal rotation is only saturated in co-NBI heated H-mode plasma.

*This work was supported by the Korean Ministry of Science, ICT and Future Planning of Republic of Korea.

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Helical electric potential modulation via Zonal-Flow coupling to Resonant Magnetic Perturbations

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Controlling Edge Localized Modes (ELMs) is very important for ITER, and a well-tested way to achieve this is by using external coils to generate Resonant Magnetic Perturbations (RMPs), demonstrated on several tokamaks [1-4]. The working hypothesis for the origin of ELM stabilization is that RMPs increase transport in the pedestal, thus lowering the pressure-gradient below the ideal-MHD threshold. Helical modulations of the electric potential were observed in several devices during application of Resonant Magnetic Perturbations [5,6]. To address the implication of the helical modulation on RMP-induced transport, we derive a system of 1D equations for Zonal Flows (ZFs) and helical potential in the presence of RMPs. This finding clarifies the theory of RMP-induced Zonal Flow damping [7]. As Zonal Flows are turbulence-driven, turbulence plays a major role in this plasma self-organization towards a quasi-equilibrium with 3D helical potential. The model reveals how RMPs modify an initially given saturated-state of coexisting turbulence and Zonal Flows. It is shown that RMPs trigger a transport bifurcation by allowing energy-transfer out of turbulence-driven Zonal Flows into ZF-driven helical potential [8,9].

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How turbulence fronts induce plasma spin-up

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Toroidal flows play an important role in magnetically confined plasmas, as they regulate transport by shear and stabilize harmful MHD instabilities. Recent researches have revealed that toroidal flows can accelerate in the absence of apparent external flow drive[1]. In order to account for its generation mechanism, extensive research is in progress both theoretically[2] and experimentally[1]. In particular, recent experiments report the importance of the triplet term, $\langle \tilde{n}\widetilde{v_r}\widetilde{v_\phi}\rangle$, in the parallel (toroidal) momentum flux[3]. Since this term describes the spatial transfer of fluctuation momentum, this observation indicates that the radial propagation of turbulence (with finite parallel momentum)[4] plays an important role in flow generation. The purpose of this work is then i.) to analyze this triplet term and seek for an implication on the spatial transport of fluctuation momentum, and ii.) to discuss how the triplet term impact toroidal flow phenomenology reported from experiments. We perform a closure calculation based on the two-scale direct interaction approximation[5]. This leads to the convective-diffusion form of the spatial flux of fluctuation momentum. The result indicates that fluctuation momentum can spatially propagate at the speed $V_{NL} \approx v_*(L_n^2/(\rho_s L_I))|\hat{\phi}|^2$, where L_I is the intensity scale length, and the other notation is standard. The direction is down the intensity gradient, which is typically from the edge to the core. This is much faster than the inward pinch velocity, thus a fast core response is expected. Implications on edge-core coupling of toroidal flows[6] are discussed as well.

We acknowledge stimulating discussion with Drs. Lu Wang, S. Inagaki, T. Kobayashi, M. Sasaki. This work is partly supported by the Grants-in-Aid for Scientific Research of JSPF of Japan (JP15K17799, JP15H02155, JP16H02442), Asada Science Foundation, Kyushu University Interdisciplinary Programs in Education and Projects in Research Development.

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Residual zonal flows with finite radial wavenumber revisited, and effects of initial parallel flow and electromagnetic potentials in tokamaks

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Finite radial wavenumber dependence of the residual zonal flows in tokamaks are revisited by means of the collisionless gyrokinetic simulations of Rosenbluth-Hinton test and semi-analytical approach using an analytical solution of gyrokinetic equation [1]. The well-known level~ $O[1/(1+1.6q^2/(r/R)^{1/2})]$ is obtained for ion Larmor radius scale, $k_r << 1/\rho_i$ while the level is O(1) for electron Larmor radius scale, $1/\rho_i << k_r << 1/\rho_e$, if physically same assumptions are assumed for these cases. In the intermediate scale between the ion and electron Larmor radius scale, it seems not trivial to determine the level uniquely. In addition to the initial ExB flows in the usual Rosenbluth-Hinton test, effects of initial parallel flow on the residual flows are investigated. Realization of the toroidal momentum conservation in the Rosenbluth-Hinton test is not easily checked for the finite radial wavenumber. The reason is discussed. Effects of electromagnetic potentials is also investigated. When electromagnetic potentials are applied initially, fast oscillations which are associated with the Alfven modes, are introduced in the decay phase of the geodesic acoustic modes. Although the residual level in the long time limit is not modified, this makes the time reaching to the stationary zonal flows longer and may weaken the effectiveness of the turbulent transport suppression by the zonal flows.

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Effects of parallel flow fluctuation on zonal flow generation: A gyrokinetic simulation study

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When drift waves are coupled to ion acoustic waves in a three-dimensional system, it is expected that perpendicular zonal flow is driven by the compression of fluctuating parallel flow [1,2]. In this work, we show that parallel flow fluctuation indeed contribute to ZF generation in ion temperature gradient turbulence. By using gyrokinetic simulations, we examine characteristics of the zonal flow generated by different levels of parallel flow fluctuations, which are obtained by varying the equilibrium parallel flow shear. Radial structures of zonal flow show clear differences in the cases with and without the equilibrium parallel flow shear. We perform an analysis of poloidal momentum transport in the framework of a kinetic version of the potential vorticity (PV) mixing theory [3]. We estimate the total PV flux and a portion caused by the fluctuating parallel flow compression, which are found to be consistent with the zonal flow evolutions. The change of zonal flow radial structure in the presence of the equilibrium parallel flow shear is accounted for by the parallel flow compression contribution. This manifests the fluctuating parallel flow compression coupling drive of zonal flow.

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Impact of end-plate biasing on plasma fluctuations in PANTA

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Study on plasma turbulence is one of the most important studies for controlling plasma transport and for realizing fusion plasma. In recent years, observation and analysis of plasma turbulence have significantly progressed in toroidal and basic plasma experiments. As a next step study, development of method for turbulence control could be required. Electric biasing is one of the well-known experiments for fluctuation control. In a cylindrical linear plasma device Plasma Assembly for Nonlinear Turbulence Analysis (PANTA), end-plate biasing experiments have been performed, and change in fluctuation properties is observed between with and without the biasing. Other than electric biasing experiments in toroidal plasmas, in the end-plate biasing experiment, radial and axial electric fields application is considered, where the radial direction indicate the radial direction in cylindrical coordinate, and the axial direction means the direction of the magnetic field. Application of the radial electric field may affect turbulence Reynolds stress $\langle \tilde{v}_\theta \tilde{v}_r \rangle$, therefore, we have measured spatiotemporal impact of the electric biasing on turbulence Reynolds stress, and have tried to clarify mechanisms behind the change in the plasma fluctuations by the biasing. To measure the spatiotemporal impact on the plasma fluctuation in the vicinity of trigger timing for the biasing, large number of ensemble averaging for obtaining statistical values is required because Turbulence Reynolds stress has large variance. We performed conditional averaging based on a number of triggers for the biasing. A number of reproducible experiments with the discharge duration time of 0.5 s are performed, and 50 Hz triggers for the biasing are input during stationary period in a discharge. The turbulence Reynolds stress is measured with Reynolds stress probe [1]. In the experiment, several experimental findings were discovered. First, change in the floating potential is very fast, within order of μs just after the trigger. However, change in the turbulence Reynolds stress is relatively slow, order of 100 μs just after the trigger. The time scale is similar to order of one cycle period of drift-wave oscillation. In addition, we also found spatial variation of the response time of the turbulence Reynolds stress from the triggering [2]. In the presentation, a number of experimental findings will be shown. This work is supported by Grant-in-Aid for Specially Promoted Research (JP17H06089) and Grants-in-Aid for Scientific Research (JP26420852, JP15H02335, JP15H02155)

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Gyrokinetic formulation to derive conservation laws for collisional and turbulent transport of particles, energy, and toroidal momentum

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A novel gyrokinetic formulation [1] is presented by including collisional effects into the Lagrangian variational principle to yield the governing equations for background and turbulent electromagnetic fields and gyrocenter distribution functions, which can simultaneously describe classical, neoclassical, and turbulent transport processes in toroidal plasmas with large toroidal flows on the order of the ion thermal velocity. Noether's theorem modified for collisional systems and the collision operator given in terms of Poisson brackets are applied to derivation of the particle, energy, and toroidal momentum balance equations in the conservative forms, which are desirable properties for long-time global transport simulation.

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