Integration of Global Stability into the Simulation of a Burning Plasma Experiment

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Burning-plasma magnetic fusion experiments necessarily operate with parameters that lead to a wide separation of time scales. In the foreseeable future, the only possibility for an "integrated simulation" of a burning plasma experiment is to use a number of different codes that are capable of exchanging information with one another, and that solve successively different sets of reduced plasma equations. The "transport timescale" code solves a set of equations obtained by averaging over all Alfven-wave and faster activity. It evolves a sequence of 2D equilibrium though time by alternatively integrating the surface averaged transport equations and solving an elliptic equation that enforces 2D force balance. These equilibrium need to be monitored against linear stability criteria, and as one is approached, the same equilibrium needs to be passed to a non-linear MHD code to calculate the nonlinear evolution of that instability, and it's effect on modifying that equilibrium.

The need for a nonlinear global 3D MHD calculation arises from many separate but related phenomena. These are: sawtooth oscillations, neoclassical tearing modes (NTMs), disruptions caused by short wavelength modes interacting with long wavelength modes, pellet injection, TAE modes, edge localized modes (ELMs) and the need to calculate vessel forces and heat loads during a major disruption and vertical displacement event. There may also be a need to calculate the evolution of resistive wall modes (RWM) in advanced operating scenarios. These modes are well described by extended MHD equations utilizing either a two-fluid or a hybrid particle/fluid closure. Nonlinear 3D MHD codes addressing these issues need to deal with the computational problems of multiple timescales, multiple space scales, extreme anisotropy, and the modeling of essential kinetic effects.

The Center for Extended MHD Modeling (CEMM) is a SciDAC project that has joined together the efforts and capabilities of the M3D and NIMROD codes and code-development teams, and has developed a new adaptive mesh refinement MHD code (AMRMHD). We have made much progress in addressing many of these numerical difficulties by using implicit methods, adaptive meshing, unstructured meshes, high-order finite elements, and hybrid particle/fluid models. One current focus is to perform realistic modeling of a small tokamak, CDX-U, to demonstrate benchmarking of an integrated model against real experimental data.

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Kinetic MHD Simulation in Tokamaks

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Kinetic modifications of MHD modes introduce new paradigms in MHD theory. Previous studies of the (collisionless) m=1/n=1 kinetic internal kink mode withelectron diamagnetic effects revealed that there is a weakly unstable mode even in the region in which theory predicts complete stabilization [1,2]. The mode pattern has m=1 sheared poloidal flow which generates vortices due to the Kelvin-Helmholz instability [3]. These studies have been carried out in cylindrical geometry using the gyro-reduced-MHD(GRM) code. The relevance to toroidal geometry is quite critical to the theory of the sawtooth crash because the mode-coupling due to toroidal effects may dominate the nonlinear development of the instability. A modified version of the FAR code including kinetic effects is being developed to study the effect of vortex generation on the internal kink mode. In the cylindrical limit, the linear mode pattern and the complex frequency obtained with the modified FAR code coincide with the results obtained with the GRM code. Nonlinear calculations in toroidal geometry has been started and results will be reported as available.

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Recent progress in simulations of kinetic-MHD instabilities

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Recent progress in simulations of kinetic-MHD instabilities, toroidicity-induced Alfvén eigenmode (TAE) bursts, fast frequency sweeping (fast FS) mode in the JT-60U experiments, and precessional fishbone instability, is reported.

Recurrent bursts of TAE were studied using a self-consistent simulation model [1]. Bursts of beam ion losses observed in the neutral beam injection experiment at the Tokamak Fusion Test Reactor are reproduced using experimental parameters. Surface of section plots demonstrate that both the resonance overlap of different eigenmodes and the dissapearance of KAM surfaces in phase space due to overlap of higher-order islands created by a single eigenmode lead to particle loss. Only co-injected beam ions build up to a significant stored energy even though their distribution is flattened in the plasma center. They are not directly lost as their orbits extend beyond the outer plasma edge when the core plasma leans on a high field side limiter.

Particle-magnetohydrodynamic hybrid simulations of the fast FS mode in the JT-60U experiments were carried out [2]. For a JT-60U experiment a new kind of energetic particle mode (EPM) was found near the plasma center at frequency close to the central frequency of the fast FS mode. The new EPM is a nonlocal mode destabilized by passing energetic ions in monotonic magnetic shear plasma. Two types of nonlinear evolution take place depending on the initial energetic ion pressure. When a classical distribution is taken for the initial condition, frequency shifts only downward after saturation and large redistribution of the energetic ions occurs. On the other hand, when reduced distributions are considered for the initial condition, frequency shifts both upward and downward at a rate of frequency sweeping close to that of the fast FS mode.

For the precessional fishbone instability, linear and nonlinear evolution is investigated for the initial conditions with parameters similar to those of the PDX experiments [3]. It is demonstrated that the spatial profile of the fishbone mode is different from the kink mode, and frequency shifts downward at saturation of the fishbone instability.

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Energetic Particles and Burning Plasma Physics

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Energetic particle physics can have an effect on stability, transport, heating and current drive, edge physics, etc. Therefore it is important to develop integrated simulation, along with theory-based modeling, for energetic particle physics in a burning plasma. This talk will describe several related issues: (1) predictive capabilities, (2) Alfven cascades, (3) nonlinear fishbone modes, and (4) convective/diffusive transport.

Nonlinear Tearing Modes in Finite-Beta Tokamaks with Noncircular-Cross Sections

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The numerical calculations have been performed for nonlinear interactions of tearing modes in finite-beta tokamaks and we have investigated effects of finite beta and triangularity of the plasma poloidal cross section on them. In tokamaks it is observed that these modes are destabilized in a pre-disruption phase and believed to form ergodic magnetic fields that often lead to major disruptions. Typically finite-beta effects lower the growth rate of tearing modes. However, when the beta value increases, the shift of magnetic axis can decrease the distance between magnetic islands, which can enhance their nonlinear interactions and result in ergodic magnetic fields. In the present work, we have evaluated these effects by varying beta values and the shape of the plasma poloidal cross section, using a three-dimensional code to solve reduced MHD equations in toroidal geometry. The code is based on the finite-element method (FEM) with unstructured triangular elements in the poloidal plane and the fourier decomposition in the toroidal direction.

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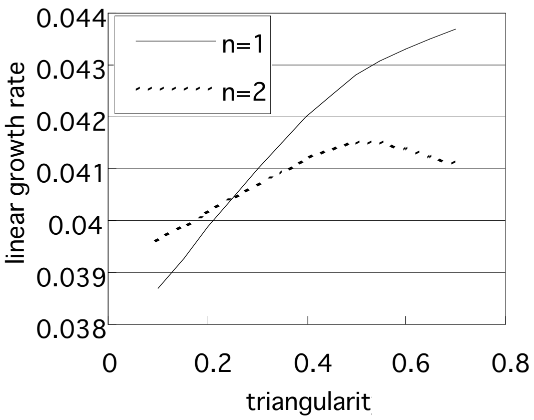

Fig.1

The linear growth rates for the n=1 and n=2 modes vs. triangularity.

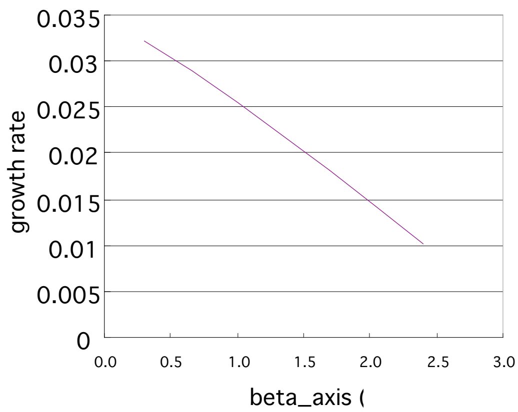

Fig.2

The linear growth rate for the n=1 mode vs. .

Integrated modeling of wave-plasma interactions in fusion systems

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There is great potential for electromagnetic wave techniques to provide control of fusion plasmas by means of localized heating, current drive, flow drive and energetic particle production. With support from the Scientific Discovery Through Advanced Computation (SciDAC) program, we have established a multi-institutional partnership between plasma physicists and computational scientists, the overarching goal being to obtain quantitatively accurate predictive understanding of electromagnetic wave processes important for heating, current drive, stability and transport applications in fusion-relevant plasmas. Activities during the first two years of the project have focused on massive parallelization and acceleration of computer-intensive full-wave RF field solver codes, extension of all-orders methods to two- and three-dimensional plasmas, increasing the physics detail contained in the RF conductivity operator, inclusion of non-Maxwellian distributions, linking to Fokker-Planck solvers, benchmarking and code comparison, and application to wave propagation problems in Alcator C-Mod, NSTX and LHD.

Full-Wave Maxwell Simulations for ECRH

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The standard method studying electron cyclotron resonance heating (ECRH) in magnetically confined plasmas is ray-tracing method based on the geometrical optics. This method describe wave absorption due to wave-particle resonances, however, cannot take into account wave diffraction, wave tunneling across the wave-evanescent region between cutoff and resonance, and mode conversion.

We here study full-wave Maxwell simulations for fundamental ECRH of magnetically confined plasmas. We solve numerically Maxwell equations for electromagnetic wave fields (***E***, ***B***) and the equation of motion for induced plasma current ***J*** with the use of a finite difference and time domain (FDTD) method. These basic equations can describe O and X (or, R and L) modes being correct under the approximation of infinite ion mass. We emphasize that our numerical scheme can take into account wave diffraction, wave tunneling across the wave-evanescent region between cutoff and resonance, and also mode conversion, since it solves full Maxwell equations directly. The wave absorption mechanism in the present scheme can be taken into account as follows: The collisional damping of electromagnetic waves can be introduced by adding term to the equation of motion for induced plasma current ***J***, on the other hand, the wave dissipations due to wave-particle resonances such as cyclotron resonance can be introduced by adding term to the Ampere's equation. This artificial conductivity tensor is determined so that our basic equations can reproduce the local dispersion relation with wave-particle resonance terms in the limit of , where is the wavenumber perpendicular to a magnetic field, where the parallel wavenumber appeared in is approximately determined from the local dispersion relation in the numerical calculations. Unfortunately, the present numerical scheme cannot treat harmonic resonances such as second harmonic ECRH, as this basically depends on the fluid theory.

We perform the full-wave Maxwell simulations for fundamental ECRH in a simple magnetic beach configuration, and show the numerical results on the wave absorption by ECRH and wave tunneling across the wave-evanescent region between cutoff and resonance.

ICRF heating Simulation in 3D Magnetic Field Configuration

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Radial transport of energetic particles due to the ripple trapped particle is one of important issues in the development of a reactor based on the helical system. The behaviors of trapped particles are complicated and have relatively large orbit size in the radial direction in helical systems. These radial motions of trapped particle would enhance the radial transport of energetic ions. Thus, a detail study of energetic ion confinement is necessary for the helical system.

In LHD, the experiment for energetic ion confinement has been successfully done. ICRF heating experiments have shown significant performance of this heating method and up to 400keV of energetic tail ions have been observed by fast neutral analysis. Also, confined energetic beam ions are observed in the NBI heating experiment. These measured results indicate a good property of energetic ion confinement in LHD. However, the measured information is obtained as an integrated value along a line of sight and we need a reliable theoretical model for reproducing the energetic ion distribution to discuss the confinement of energetic ions.

In this paper we study the complex behavior and radial transport of energetic ions during ICRF heating using a global transport simulation code (GNET)[1,2] in LHD. This code solves a linearized drift kinetic equation for energetic ions including complex behavior of trapped particles in 5-D phase space. We make clear the characteristics of energetic ions distribution in the phase space and show the confinement property of LHD configurations by comparing the simulation and experimentally observed results.

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Modeling of Neutral Beam Ion Absorption of High Harmonic ICRF Waves in the DIII-D Tokamak

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The absorption of ion cyclotron radio frequency (ICRF) wave by neutral beam injected ion species at high ion cyclotron harmonics ($\omega = n\Omega$, $n \geq 2$) has been observed experimentally in the DIII-D tokamak during the 1999 experimental campaign. Anomalously peaked pressure profile was reported in the central region of plasma with a significant enhancement of the measured neutron rate when rf pulses were applied to neutral beam (NB) heated discharges. Energy spectrum from neutral particles analyzer showed a strong enhancement of the tail energy above the NB injected energy. To understand and quantify this phenomenon of energetic beam ion species-wave interaction, a Monte-Carlo rf orbit code, ORBIT-RF, has been upgraded to treat steady-state NB injection and ICRF absorption at higher harmonics. The first ORBIT-RF results for the interaction study of 80 keV D beam ion and 60 MHz ICRF wave at 4th harmonic resonance surface show that several experimental observations are reproduced in the simulations within reasonable agreement using an estimated magnitude of $|E_+|$ based on a simple model: (1) the extended tail energies of beam ions above the injected beam energy are found in the central region of plasma, and (2) about 20%-30% enhanced D-D reaction rate is also calculated due to the interaction of ICRF and beam ions. Additional DIII-D experimental results on the damping of wave on $H(He^3)$ beam ion at 2nd(3rd) harmonic resonance are being simulated and will be reported at the meeting. For quantitative comparisons and predictions, a more accurate wave model will be implemented to estimate the magnitude of $|E_+|$.

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*In collaboration with M. Choi, J. Candy, C.C. Petty, R.I. Pinsker (General Atomics), S.C. Chiu (Sunrise Inc.), W.W. Heidbrink (UC-Irvine).

Recent Gyrokinetic Simulations with GYRO: Bohm Transport in DIII-D, the Local Limit of Global Simulations, and Transport Across a Minimum-q Surface*

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Abstract

In this presentation we summarize results from three major transport studies carried out with the global Eulerian gyrokinetic code, GYRO.[1] First, and most importantly, we discuss comprehensive simulations[2] which match, within experimental error bounds, the turbulent transport levels observed in DIII-D L-mode discharges 101381 and 101391. The experimentally-observed Bohm-like scaling of ion transport in these discharges was recovered, and the sensitive dependence of both electron and ion transport on ion temperature gradient was also explored. These were full-physics simulations which included trapped and passing electrons with pitch angle collisions, finite-β fluctuations, real DIII-D flux-surface shape, linear and nonlinear $\mathbf{E} \times \mathbf{B}$ rotation, parallel flow shear, and radial variation of all equilibrium quantities.

Next, we revisit the issue of gyroBohm scaling (and the breaking thereof) in the context of a certain adiabatic-electron test case favoured by the GTC code.[3] For this case, we have shown that transport levels from local and global GYRO simulations are perfectly matched in the limit of small $\rho_* = \rho_i/a$. We also show that this limiting value is identical to the local value obtained by Dimits.[4] The confluence of local and global results, which we observe repeatedly and robustly, has been previously noted[5] in a more general context. For this particular case, we show that the transition point in ρ_*, where gyroBohm gives way to worse-than-gyroBohm scaling, is strongly dependent on the temperature-gradient profile. In particular, use of the original "humped" GTC profile leads to the requirement $\rho_* \lesssim 1/375$ for gyroBohm scaling, whereas the use of a more physical temperature-gradient profile in the same scenario gives rise to gyroBohm scaling and recovers the local limit at the much larger value $\rho_* \lesssim 1/150$.

Finally, we examine a conjecture regarding ion transport barrier formation in the vicinity of a minimum-q surface.[6] The validity of the conjecture relies, ostensibly, on the absence of ITG modes in the minimum-q region. Indeed, fluid transport simulations[7] have shown that when so-called nonresonant modes are ignored, a minimum-q region can give rise to a barrier. However, a series of linear and nonlinear, as well as local and global, GYRO simulations show no evidence of mode suppression or of transport reduction in the minimum-q region. Instead, we find that transport is smoothly increasing across a minimum-q surface, and that this region is populated by nonresonant ITG modes characteristic of the low-shear regime. We also observe that as $\rho_* \to 0$, transport computed via a global simulation agrees with that from local simulations, even at the point where $s = 0$.

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Local and non-local Gyro-Fluid Simulation of ITG and ETG turbulence and the statistical properties

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The turbulent-zonal flow system due to micro-scale electron and meso-scale ion temperature gradient mode turbulence is studied based on our gyro-fluid model in order to understand various prominent structure formations in magnetically confinement plasma. Here, we investigate the possible mechanism regulating the zonal flow and resultant turbulent dynamics from various view points, i.e. secondary and higher order instabilities and saturation mechanism, control of zonal flow instability including enhancement and diminishment, electromagnetic effect, toroidal coupling effect due to Stringer-Winsor term and GAM, non-local and/or global effect, etc. Specifically, it is found that the electromagnetic effect plays an important role for the zonal flow and resultant transport dynamics in ETG turbulence. The coupling between zonal mode and poloidal pressure anisotropy through Stringer-Winsor term is found to lead to a new energy transfer channel that regulates the zonal flow level. We also study the turbulent dynamics by introducing statistical approaches such as fractal dimension and probability distribution function. A significant dimensionality lowing and coherent transport characteristics are obtained for the transport dominated by zonal flows.

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Transport Model with Global Flow

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Anomalous transport in high temperature plasmas is an important issue for nuclear fusion research. This phenomenon is complicated due to the synergetic effect of the fluctuating density or temperature and the flows. To understand the transport in a system with flow, the conventional approaches are not enough and the more consistent approach is necessary. In this study, a transport model with flow is proposed, taking the fluctuating electrostatic field into account. This system consists of three components: transport, flow and turbulence. The flux-surface-averaged density and pressure evolve according to the conventional 1D transport equation with anomalous particle and heat fluxes. Then the neoclassical parallel flows are determined by the parallel momentum and the heat balance equations with turbulence source[1,2]. These neoclassical flows affect the saturation level of turbulence, hence change the anomalous particle and heat fluxes. The radial electric field which gives rise to zonal flow is determined by turbulence. As the first step, we investigate the linear stability of ideal and/or resistive ballooning mode with given neoclassical (global) flows solving the 2D eigenvalue problem and estimate the quasi-linear flux. The next step is to develop a global 3D turbulence code with equilibrium flows and evaluate the radial electric field and the anomalous fluxes. Simultaneously, impacts of spatially long-range fluctuations are also discussed[3]. The final goal is to couple the 3D code with the transport equations.

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Intermittent oscillations generated by ITG-driven turbulence

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In order to understand the mechanisms of anomalous transport due to micro-instabilities and transport barrier formation related to generation of sheared plasma flows, we have studied transport regimes of ion-temperature gradient (ITG)-driven turbulence using a low degree-of-freedom model composed of 18 ODEs [1]. When the system is close to the threshold of ITG instability, an L-H-like transition and periodic oscillations are observed in the kinetic energy and convective flux fluctuations. As the ion temperature gradient 'Ki' is increased further, the system bifurcates to turbulent regimes. In the strongly turbulent regime, intermittent bursts (so-called avalanches) are observed, which contrasts with the report that no such intermittency was observed in simulations of the previously proposed low degree-of-freedom model based on 11 ODEs [2]. This intermittency is caused by the competition of the following 3 factors; (1) generation of sheared flows due to nonlinear coupling among higher harmonics and suppression of ITG turbulence by the sheared flows,
(2) gradual reduction of the sheared flows due to viscosity, and (3) rapid re-growth of ITG modes due to the reduction of stabilizing effects by the sheared flows. We also obtained a scaling law between time average of the Nusselt number and the ion pressure gradient Ki. The obtained scaling law shows that, in the case of large Ki where sheared flows become dominant and intermittency occurs, the Nusselt number is significantly lower than its value that we would expect if it were not for intermittency. We have demonstrated that essential nonlinear behaviour of the ITG turbulence can be at least qualitatively accounted for by nonlinear interaction of several low order harmonics.

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Linear Stability of Electrostatic Drift Waves in Helical plasmas

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The linear gyrokinetic mode equation is numerically solved to investigate the stability properties of the electrostatic drift waves in helical plasmas. The mode equation is rather exact except for the ballooning representation, and is 1D in the space and 2D in the velocity space, as is FULL code [1]. The circulating and trapped particles are correctly treated, and in the electrostatic regime, ion temperature gradient mode (ITG) and trapped electron mode (TEM) are expected to be unstable with k_perp*rho_i<~1. The electron temperature gradient mode (ETG) can also become unstable with k_perp*rho_e<~1.0. As a model of helical plasmas, LHD [2] is considered, whose MHD equilibria are obtained by VMEC code [3].

The non-axisymmetric equilibrium properties of helical plasmas are expected to affect the stability, through the curvature of field line, which is mainly determined by the magnetic field strength B, and the perpendicular wave number k_perp, which is strongly depending on the geometry (R, Z). These local effects on the stability can be investigated by the local parameter dependence of the growth rate in the ballooning formalism, and in fact, the local growth rate was found to be sensitive to the field line label (alpha) as well as the theta_k in the helical systems in the MHD case [4]. However it is found that in the drift wave case, their dependence is very weak. The local parameter dependence is investigated and the destabilizing mechanism is discussed.

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Control of Turbulent Transport and Dynamics of Transport Barriers in Edge Tokamak Plasmas

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Control of turbulent transport in edge tokamak plasmas is an important issue for the realization of fusion reactors. The most promising operational regime of future reactors is characterized by the existence of a transport barrier at the plasma edge. This barrier is not stable but relaxes quasiperiodically. It is thus important to investigate the physical mechanisms underlying the dynamics of such barriers in order to use them as control tools of the turbulent transport in fusion machines. We will review in this paper different aspects of such dynamics and show their implications on turbulent transport.

On dust dynamics in tokamak edge plasmas

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It has been suggested long time ago [1] that dust particles might be a source of plasma impurities in the early stages of a tokamak discharge. Later on the presence of significant amounts of dust has been observed in the chambers of fusion devices (see for example the review paper [2], and the references therein). The dust particle impact on the performance of current fusion devices has still not been adequately understood [3, 4]. The existence of dust particles in next -step fusion devices, however, may potentially pose a significant safety threat due to the accumulation of hardly containable toxic and radioactive materials retaining tritium [2].

In this paper we consider some aspects of the dust dynamics in tokamak plasmas, and show that transport of dust particles can be an important mechanism of core plasma contamination with impurities. We assume that dust density in a tokamak plasma is rather small so that our consideration is based on a single dust particle motion. Therefore, we ignore the collective phenomena associated with the dust [5].

Similarly as in the studies of dust behavior on the devices with weakly ionized plasmas (see [6], and references therein), a dust particle in a tokamak edge plasma can be confined in an effective potential well formed in the sheath region by the perpendicular components of plasma friction and electrostatic forces. However, unlike those studies, dust particles in a tokamak edge plasma are subject of acceleration by unbalanced large parallel components of the plasma friction force, which appear due to: a) the plasma flow along the shallow magnetic field lines and b) diamagnetic and $\mathbf{E}\times\mathbf{B}$ flows within the magnetized sheath. Therefore, dust particles in tokamak divertor region can be quickly (for ~1 ms) accelerated to the speed $\sim 3\times10^3$ cm/s, which can explain some of the puzzles in Ref. [4].

In the present study we have found that the motion of a dust particle along the wall surface, having micro-inhomogeneities, is subject to resonance interactions with particle oscillations in the potential well. As a result, the oscillation amplitude can grow drastically and dust particle can leave the sheath region and fly outside it and, being pushed back by the plasma flow to the wall, bouncing time to time off the surface and further gaining speed by plasma flow acceleration. Finally, the amplitude of particle excursions becomes too large to be pushed back so that dust particle moves to another location at the wall, or flies toward the core plasma.

Assessment of dust impact on core plasma contamination by impurities shows that: It is unlikely that dust formation on the main chamber wall due to first wall recycling processes can strongly contribute to core contamination. It is, however, quite likely that dust formation in the divertor region, with further dust transport into main chamber, can play significant role in core contamination.

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Edge Plasma Modeling Using PARASOL Code

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In magnetic confinement systems, not only open systems like a mirror but also closed systems like a tokamak, there exist the regions of open-field plasmas. An open-field plasma surrounding a closed-field plasma is called a scrape-off-layer (SOL) plasma or a divertor plasma. Since the open-field plasma attaches walls of a device directly, plasma particles and heat escape to the walls mainly along magnetic field lines. Utilizing this nature, we expect divertor functions for the heat removal, ash exhaust, and impurity shielding in fusion reactors, such as ITER. Analyses of experiments on the above functions in present devices and predictions of their performances in future reactors have been carried out by using comprehensive simulation codes with the fluid model. In the fluid model for SOL/divertor plasmas, however, various physics models are introduced, i.e., boundary conditions at the plasma-wall boundary, heat conductivity, viscosity and so on. Kinetic approach is required to examine the validity of such physics models. One of the most powerful kinetic models is the particle simulation. The particle simulation, in which particle motions and the electrostatic potential are computed self-consistently, can describe accurately the sheath formation.

We have been developing a particle simulation code PARASOL (PARticle Advanced simulation for SOL and divertor plasmas), and studying the edge modeling. This code treats various kind of situations; one-dimensional (1D) steady state, 1D dynamic state (such as ELM behavior), slab 2D configuration, and 2D configuration with separatrix like a tokamak divertor configuration. The magnetic field is given. The electrostatic field inside a system is calculated self-consistently with a usual PIC method. Coulomb collisions play very important role in open-field plasmas. For instance, the collisional diffusion in the velocity space is the main mechanism to supply high-energy electrons. These electrons can escape to the divertor plate, while low energy electrons are trapped in a SOL plasma by the sheath potential. The collisional effect is simulated by a binary collision model.

Simple Core-SOL-Divertor Model To Investigate Plasma Operational Space

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To understand operational SOL-Divertor conditions is the critical issue to realize a fusion power plant. Those conditions should be investigated consistently with core plasma conditions. Recently, the core plasma performance required to generate net electric power is roughly revealed [1]. According to that study, we have to increase the ratio of greenwald density limit (fn_{GW}) together with normalized beta value (β_N), and fn_{GW} required to generate net electric power depends on the core plasma temperature. The core plasma temperature will be restricted by the divertor operation of detateched plasma. Consequently, the relationship between the core plasma temperature and the divertor operation condition has a great impact on fn_{GW} required for a fusion power plant. To understand such relationship between core and SOL-divertor plasma, we integrated 0D core plasma model and two-point model into a simple Core-SOL-Divertor (C-S-D) model.

The 0D core plasma model is based on ITER physics design guideline [3] and the LH transiton condition is installed by the same fashion as in ref. [4]. The two-point model[5,6] is basically applied to SOL-divertor analysis. The SOL density, which is usually a given parameter, has to be calculated including the core plasma conditions such as particle and heat flux across the separatrix. In the present study, we solve the particle balance with a simple neutral transport model[2,6].

We compare this C-S-D model with B2-EIRENE analysis results for the attached divertor of JT-60U[9], and the following good agreement is obtained; $T_{sol} = 51.4\ \mathrm{eV} (T_{sol}^{B2} \approx 50\ \mathrm{eV})$, $T_{div} = 10.1\ \mathrm{eV} (T_{div}^{B2} \approx 12.0\ \mathrm{eV})$, $n_{sol} = 0.9\times10^{19}\ \mathrm{m}^{-3} (n_{sol}^{B2} \approx 1.0\times10^{19}\mathrm{m}^{-3})$, $n_{div} = 2.3\times10^{19}\ \mathrm{m}^{-3} (n_{sol}^{B2} \approx 3.0\times10^{19}\mathrm{m}^{-3})$, where those inside brackets are B2-EIRENE results. With this C-S-D model, we also reproduce the transition phenomenon from Low to High recycling state as reported in ref.[7,8]. We apply this C-S-D model to the HT-7U(EAST) operational space. In the first phase of HT-7U, the plasma current will be driven with LH current driving method, where low density is preferable. In contrast, High recycling state of divertor is required to decrease heat load on the divertor plate. We carry out the preliminary analysis for the operation space for both core and divertor plasma. We also apply this model to ITER LH transition phase and find the possibility of the divertor density oscillation during the LH transition, which may makes it difficult to control divertor plasma[2]. The modelling of the detached plasma condition remains to be done. This work is partly supported by JSPS-CAS Core-University Program on Plasma and Nuclear Fusion.

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Non-local Transport of Strongly Coupled Plasmas

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Collective motion of charged meso-scopic particles (i.e., particulates) immersed in a plasma (i.e., dusty plasmas) is of great interest with regard to improving our understanding of the fundamental nature of strongly coupled Coulomb systems. Observable phenomena in most laboratory dusty plasma experiments are often macroscopic in nature, i.e., phenomena whose scale lengths are significantly larger than the average interparticle distance and time scale much longer than the plasma frequency of charged particulates. In order to understand the relation between the dynamics of charged particulates in the meso-scopic level and such observable macroscopic phenomena, one needs a theoretical framework in which statistical properties of particulates are directly incorporated in the dynamical equations governing the macroscopic motion of the system. One of such models is hydrodynamic equations, where statistical properties of constituent particles are incorporated in their transport and thermodynamical coefficients.

In the case of moderately or strongly coupled dusty plasmas, one is also often interested in "less macroscopic" phenomena whose typical space scales are several times larger than or almost the same as the average interparticle distance, and equally whose typical time scales are several larger than or almost the same as the particulate plasma frequency. The hydrodynamics equations can also describe such phenomena approximately if one includes memory effects in their transport coefficients.

In the present work, we model dusty plasmas by the Yukawa system, i.e., the system of particles interacting through Yukawa potentials, and evaluate its memory effects and the relaxation time (i.e., time scale of memory effects) in the shear viscosity, using molecular dynamics (MD) simulations. We have found a phenomenological scaling of the relaxation time as a function of the system parameters. These results are used to construct the hydrodynamics equations (i.e., generalized hydrodynamics equations) applicable to moderately or strongly coupled dusty plasmas.

Predictive Integrated Modeling Simulations Using a Combination of NTCC H-mode Pedestal and Core Models

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Predictive integrated modeling (frequently referred to as predictive transport modeling) of tokamak plasmas involves the interaction between transport, sources, sinks, equilibrium, and large scale instabilities, to predict temperature, density, and other profiles. Integrated modeling simulations are used to understand the physics of confinement, to optimize the performance of tokamaks, and to predict the expected fusion power production in planned burning plasma experiments. Before the development of predictive boundary conditions, the temperatures and densities at the edge of the simulations were taken from experimental data. The simulations yielded core plasma profiles that were consistent with experimental data within measurement errors. As a first step in developing predictive boundary conditions for simulations of H-mode discharges, static models (without the effect of periodic ELM crashes) were developed for the height of the H-mode pedestal. These pedestal models were combined with models for the plasma core, such as the Multi-Mode, GLF23, and mixed-Bohm/gyro-Bohm anomalous transport models, to predict the temperature and density profiles in H-mode discharges. In more recent simulations, dynamic models for the pedestal and ELMs at the edge of H-mode plasmas are used to produce time-dependent simulations of plasma profiles from the magnetic axis to the separatrix. MHD stability codes are used to calibrate the models that trigger ELM crashes within the integrated modeling code. A geographically distributed collaboration developed the NTCC project, which has explored the use of modern computer software engineering to produce Web-invocable, community-owned integrated modeling codes. The NTCC module library (which is available at http://w3.pppl.gov/NTCC) was established in order to facilitate the development of integrated modeling codes. A review process is in place to ensure that modules conform to the Module Library standards. The exchange between the author of each module and the reviewer often results in improvements to the module and its documentation. Currently, there are 44 modules in the Module Library, including modules for transport, plasma heating, equilibrium and MHD stability, H-mode pedestal, neutral gas, atomic and nuclear reaction rates, and numerical and visualization tools.

Real-time control of internal transport barriers in JET : Experiments and simulations

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Real-time control of the plasma profiles (current, pressure and flows) is a key issue to sustain steady state discharges with internal transport barriers (ITB) and a large bootstrap current fraction. In order to simultaneously control the current and pressure profiles in JET ITB discharges, a multi-variable model-based technique has been proposed. It is based on a truncated singular value decomposition (TSVD) of an integral model operator and retains the distributed nature of the plasma parameter profiles. The related algorithms have been implemented in the JET control system, and applied to the control of the current profile in reversed shear plasmas using three actuators (neutral beam injection, ion cyclotron heating and lower hybrid current drive). Successful control of the q-profile has been achieved in quasi steady state conditions with a significant fraction of bootstrap current. In these experiments the strength of the ITB's was marginal during the control phase, due to the chosen q-profile setpoints and to the moderate heating power which was requested by the controller. Hence, further experiments aiming at the simultaneous control of the current profile and of the normalized ITB temperature gradient are being pursued and first results will possibly be reported. Integrated modelling of the proposed control algorithms is also being attempted using transport codes (JETTO, CRONOS). Preliminary results will be shown concerning interpretative modelling of past experiments as well as predictive modelling for future experiments with the complete algorithms. In particular, the way the control matrix is determined from open loop experiments can be mocked up with simulations. The application of the TSVD in closed loop can then be tested in order to assess the capability of the model-based (linear) algorithms in achieving adequate control and the effect of transport non-linearities on the closed loop response. This can be very valuable in optimizing the proposed method and the characteristics of the controller in parallel with the experiments.

Invited talk at the Joint Meeting of US-Japan JIFT Workshop on Theory-Based Modeling and Integrated Simulation of Burning Plasmas, and 21COE Workshop on Plasma Theory.
Kyoto (Japan) 15-17 Dec. 2003

Integrated Simulation Based on TASK Code

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In order to predict the behavior of burning plasmas and to develop a scheme to control them, a simulation code system which integrates various theory-based models and large-scale simulations is strongly desired. For this purpose, we have started the activity of "Burning Plasma Simulation Initiative" which stimulates the collaboration among universities, NIFS and JAERI. One of the first targets of this activity is to propose a common data-interface between the existing and coming simulation codes and to develop a reference core code based on the TASK code which has been developed in Kyoto University and will be available as an open source code.

The TASK code is composed of several modules for equilibrium (EQ), transport (TR), Fokker-Planck (FP), ray-tracing (WR), full wave (WM), wave dispersion (DP), data interface (PL), and common libraries. Each module works now, but the data interface is under reconstruction. Some of recent results of the TASK code, such as dependence of the internal transport barrier formation on the bootstrap current models, evaluation of electron cyclotron current drive for neoclassical tearing mode stabilization, and analysis of Alfven eigenmodes in a reversed configuration.

We are planning several extensions of the modules. One is a new transport module, TX, which solves the flux averaged fluid equation and describes the toroidal and poloidal plasma rotation and the radial electric field. The analysis of edge transport barrier formation is also in the scope of this module. Another is the full wave analysis of global stability, WA. Preliminary results will be presented. Extension to the analysis of helical system will be also discussed.

1-D Transport Simulation for a 3-D MHD Equilibrium

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Several 1-D transport code simulation studies have been done for non-axisymmetric toroidal plasmas such as stellarators (or helical systems). Many of these studies adopted the cylindrical approximation similar to the circular tokamak cases. Transport simulations for non-circular tokamak plasmas can be done by a combination of the 1-D transport code and the 2-D MHD equilibrium code, so called 1.5-D transport code. In the same sense, several 1D transport simulations combined with a 3-D MHD equilibrium code have been performed in helical systems. Most of these studies use the specific volume and neoclassical ripple transport coefficients calculated from the data obtained by the VMEC 3-D MHD equilibrium code, which is a 3-D inverse solver based on the variational principle.

In this talk, we will briefly review 3-D MHD equilibrium calculations and 1-D transport simulations for helical systems, and will discuss some difficulties and problems to be resolved. As an example, Fig.1 shows an MHD equilibrium of an L=1 helical-axis heliotron, Heliotron J (H-J) calculated by the PIES code, which can calculate a 3-D MHD equilibrium without assuming the existence of nested flux surfaces. It is shown in Fig. 1 that magnetic islands can exist in 3-D MHD equilibria of stellarator plasmas and they will affect transport like NTMs in tokamaks.

Not only for the helical systems, ripple loss or diffusion of alpha particles is one of the important issues on tokamak fusion reactors. It has been pointed out from the 3-D MHD equilibrium calculation for the rippled tokamak that ripple structure can be changed in the finite beta plasmas. Finite beta effects on the alpha ripple loss will also discussed.

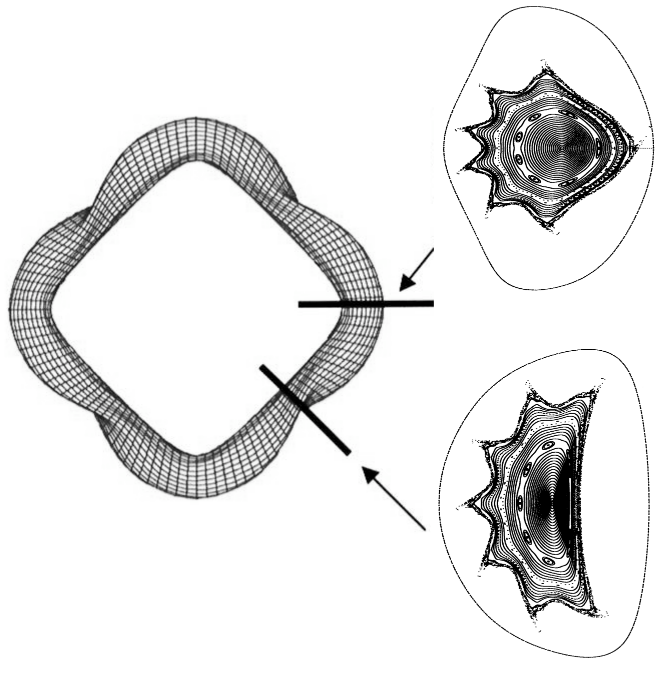

Fig.1 Top view and puncture plots of an MHD equilibrium in the Heliotron J calculated by the PIES code

Remote Collaboration Environment on the Grid

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In the visualization group of the VizGrid project, we plan to develop a tele-immersive environment using volume communication technologies, which mean a suite of technologies for communicating using volume datasets. The volume communication make the best of volume graphics technologies, where a volume data is represented as a three-dimensional array of voxels. The term voxel is used to characterize a volume element. It is a generalization of the notion of pixel that stands for a picture element. Today, widely used 3D computer graphics first extracts geometry data from volume data, and then uses polygonal meshes to represent an object by its surface. Volume rendering-based graphics, that is, volume graphics uses voxels - 3D or volumetric pixels - as basic element to represent not only the surface but also the entire inner part of an object. The volume graphics visualization is superior to polygon based 3D graphics in means of image quality and performance when we visualize highly complex objects that our project has to handle with finest details. In this project, we will develop a volume communication suite, that is an infrastructure that makes a remote collaborative environment, and it is composed of a series of techniques that are applied on a volume dataset generated from real scenes and computer simulations. These techniques include volume creation, volume compression/decompression, volume transmission, volume display, and volume search., We will describe three accomplishments, which were completed in 2002, a streaming-based and a CPG-based visualization techniques, and an ongoing development of a portable tele-immersive system which uses multi-viewpoint display system and a 3D pointing device with a perspective of the finalized system.

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