1-4. Theoretical Study

In order to comprehensively understand the physics mechanism of plasma confinement in LHD, theoretical and numerical researches related to LHD and pioneering theories of confinement plasmas are reported.

An MHD equilibrium solver HINT2, which is an improved version of HINT, is used for investigating 1) the relation between stochasticity of the magnetic field lines and the thermal diffusion in the peripheral region of LHD, and 2) effect of the Dynamic Ergodic Divertor (DED) to Edge Localized Mode (ELM) in TEXTOR tokamak with an external perturbed field. Also, the MHD equilibrium of the horizontally elongated LHD configuration will be examined by using HINT2 in order to study the MHD equilibrium β limit of LHD.

Sawtooth-like oscillations were observed by soft X-ray camera system in fairly high density LHD plasmas produced by pellet injection. The instability is localized around the magnetic axis and has an $m = 3$ mode structure. In order to explain this instability, non-resonant pressure-driven modes are investigated. It is reported that a large pressure gradient has a possibility to destabilize the non-resonant modes with infernal mode-like features. In order to examine properties of the magnetic island structure obtained in the nonlinear saturated state of resistive interchange modes, a new theoretical model is suggested.

On the re-heating stage in IDB-SDC discharge in LHD, an abrupt flushing of the central density, termed as "core density collapse (CDC)", occurs in some cases. To understand the physics mechanism, nonlinear MHD simulations have been done. The primarily induced linear instability is localized in the outer region, and so the crash of the structures is first seen in the barrier region, leading to a core crush through the stochastic magnetic field line in a whole plasma region.

A detailed comparison is made between moment-equation methods presented by Sugama-Nishimura and by Taguchi for calculating neoclassical transport coefficients in general toroidal plasmas including non-symmetric systems. Differences between two methods come from weight function to derive the moment equations. In a calculated axisymmetric case, the convergence of the moment of Sugama-Nishimura model is faster than that of Taguchi. To study the neoclassical transport including non-local nature by the finite orbit width effect, FORTEC-3D is under developing, which solves the drift kinetic equation and the time evolution of radial electric field in helical plasmas by using the δf Monte-Carlo method. Difficulties coming from multiple roots of the radial electric field and 3-D configuration have been resolved by using 1) a staggered-mesh scheme for evaluating electric field and particle flux, 2) filtering scheme for huge-weight markers, and 3) improvement of the conservation property of the Landau collision operator.

A new simulation code, KEATS, treating the neoclassical transport in the ergodic region with magnetic islands is under developing, where Monte-Carlo scheme based on the δf method is used. The energy flux of ions (protons) in the system with ergodic region is investigated as the first numerical study of the transport.

The treatment of the collision operator in the linear gyrokinetic eigenvalue problem is revisited, and the related numerical method - cyclic reduction method to solve block pentagonal matrix - is shown.

Ray tracing simulations for different mode-conversion scenarios leading to Bernstein wave heating in helical systems have been performed by using ART code. OXB and XB simulations in CHS have been shown to be in agreement with experimental results.

LHD experiments show that not only the

neoclassical transport but also the plasma confinement are improved in the inward-shifted LHD configurations. The link between these two is thought to be the zonal flow (ZF). Linear gyrokinetic Vlasov simulations have been performed in order to understand the geometrical effects on ITG growth rate and residual level of ZF. Comparing accurate descriptions of inward shifted and non-shifted LHD configurations, it has been found that a smaller difference in ITG growth rates is observed while the ZF level in the inward-shifted LHD configuration is larger than that of the non-shifted LHD configuration. Non-linear calculations of the appropriate numerical models identified through the linear calculations have shown compensation of the turbulence due to higher ZF level also exists in nonlinear phase in the inward-shifted LHD configuration.

Effects of equilibrium radial electric fields on ZF have been considered analytically. For helical systems, the label of field line α explicitly appears in the gyrokinetic equation in contrast to tokamak cases. Therefore, in helical configurations, $\mathrm{v}_E \cdot \nabla \delta f$ does not vanish generally, so that the zonal-flow response can be affected by the existence of the equilibrium electric field. In helical configurations such as the inward-shifted LHD configuration, which are optimized for reduction of neoclassical transport, the enhancement of zonal-flow response due to Er is expected to work more effectively than in the standard configuration because the neoclassical optimization reduces radial displacements of helically-trapped particles during their poloidal $\boldsymbol{E} \times \boldsymbol{B}$ rotation.

Nonlinear competition between zonal flows and geodesic acoustic modes has been investigated analytically. In order to study the competition between the ZFs and GAMs, the effect of the return flow along the magnetic field line must be taken into account. The coupling of the poloidal flow to the parallel flow enhances the effective inertia of plasma. The back interaction of the ZFs and GAMs on drift wave turbulence closes the set of coupled equations, which determines the level of turbulence and turbulent transport. The self-consistent solution of the microscopic fluctuations, ZFs and GAMs is obtained. The competition between ZFs and GAMs is summarized in the parameter space of the damping rates of ZFs and GAMs.

Model to analyze two-dimensional structures including poloidal shocks and geodesic acoustic modes in toroidal plasmas is proposed, where extensions of the previous 2-D model are carried out to investigate two effects on the structural formation, i.e., the deviation from the Boltzmann relation and the parallel flow dynamics. This model is used to research the poloidally-asymmetric structure in the edge transport barrier, where a large poloidal flow is generated, and poloidal shocks can be formed.

By developing a 3-D simulation code called 'Numerical Linear Device' (NLD), which describes the resistive drift wave turbulence in a linear device, a nonlinear simulation has been performed to examine the saturation mechanism of the resistive drift wave turbulence. A resistive drift wave can be excited with a small ion-neutral collision frequency. For small (large) collision frequency, turbulence with a zonal flow (streamer) has been obtained, and the formation mechanism of turbulent structures has been clarified.

Transport analysis of high density plasmas with internal diffusion barrier in toroidal helical plasmas has been performed by using transport code with a theoretical model for the IDB observed in LHD. The mechanism, which is based on the transport reduction due to the shear of the radial electric field, is newly examined in the formation of the IDB. In the case of the particle fuelling, the density rapidly increases. Therefore, the ion temperature temporally decreases and the positive gradient in the T_i profile is found to appear. From the ambipolar condition to determine the E_r profile, the positive E_r is found. As the result, the strong gradient of E_r and the reduction of the anomalous particle diffusivity can be shown.

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