3. Numerical Simulation Research Project

Based on the past two-decades activities at the Theory and Computer Simulation Center and the Department of Simulation Science in the National Institute for Fusion Science (NIFS), Numerical Simulation Research Project (NSRP) has been launched to continue the tasks in the theory and simulation research activities at NIFS, and evolve them in more systematic way on the occasion of the re-organization of NIFS in 2010. Under intensive international and domestic collaborations on large-scale numerical simulation, the NSRP is aiming to understand and systemize physical mechanisms in fusion plasmas and to realize ultimately the numerical test reactor (NTR) which will be an integrated predictive modeling for plasma behaviors in a whole machine range.

In order to make this approach effective, nine research groups responsible for each task in the NSRP were set up in 2010, which cover a wide range of simulation subjects including 3D equilibrium of core plasmas and its stability, high energy particle physics, plasma heating, plasma transport, micro and macro turbulence, burning plasma physics, fueling, periphery plasmas, plasma-wall interaction, other basic plasma physics supporting fusion science, and simulation methodology such as multi-scale simulation modeling, scientific visualization. In 2013, two of the nine groups, “Fluid turbulence transport simulation group” and “Kinetic transport simulation group”, were unified with one task group “Neoclassical and turbulent transport simulation group”.

We have promoted the NSRP activities to develop and improve various simulation codes required for the construction of the NTR, covering fluid, kinetic, hybrid, multi-scale, integral transport codes and so on. By effective use of the Plasma Simulator upgraded in 2012, we applied them to magnetic fusion plasmas including the Large Helical Device (LHD) plasmas, and clarified new physical pictures on three-dimensional equilibria, transports, instabilities, and nonlinear evolutions. The tasks and the typical examples of their simulation results of eight research task groups are as follows.

“Plasma fluid equilibrium stability group” studies macroscopic physics of core plasmas using nonlinear MHD and extended MHD models. MHD numerical simulation was carried out to analyze the interaction between the pressure driven modes and the magnetic islands in the LHD plasma with a resonant magnetic perturbation (RMP) and revealed that the mode was localized around the X-point like a ballooning mode in contrast to the case of no RMP. A system of magnetic flux coordinates were constructed from an analytic solution for the reduced MHD equations for high-beta toroidal equilibria in the presence of poloidal flow comparable to the poloidal sound velocity.

“Energetic particle group” investigates physics issues related to energetic-particles in toroidal plasmas such as Alfven eigenmodes, neoclassical transport of alpha particles in burning plasmas, and NBI/ICRF heating. A multi-phase simulation model, that was a combination of classical and hybrid simulations for energetic particles interacting with an MHD fluid, have been developed to simulate the nonlinear dynamics on slowing down time scales of the energetic particles. An application of the multi-phase simulation to DIII-D discharge clarified that the stored fast ion energy was saturated due to Alfvén eigenmodes at a level lower than in the classical simulation.

“Integrated transport simulation group” works on the development of core transport code in 3D configuration (TASK3D) and its application towards prediction of the overall time evolution of observable physics quantities in the core plasma. Integrated transport analysis suite, TASK3D-a (Analysis version), has been developed for conducting automated energy confinement analyses for NBI plasmas in LHD. The capability of TASK3D-a has been gradually increasing from its first version TASK3D-a01 by implementing modules such as for neoclassical transport, international Stellarator-Heliotron Confinement Database, and neutral penetration from the plasma periphery and so on.

“Neoclassical and turbulent transport simulation group” aims to investigate anomalous transport mechanisms, collisional transport mechanisms and multi-scale physics of transport, and predicts the transport level for achieving efficient confinement of high-temperature plasmas based on kinetic and fluid modeling. A reduced model for ion temperature gradient (ITG) turbulent transport in helical plasmas has been developed based on nonlinear gyrokinetic simulations, and succeeded in reproducing the nonlinear simulation results in the LHD high ion temperature plasma. Electromagnetic gyrokinetic simulation studies identified a new saturation process of the kinetic ballooning mode (KBM) turbulence originating from the spatial structure of the KBM instabilities in a finite-beta LHD plasma. FORTEC-3Dcode, which solved the drift-kinetic equation in 3-dimensional magnetic configuration, was incorporated with TOPICS to evaluate the NTV caused by toroidal field ripples. The meso-scale structural formation and turbulent transport have been investigated using the Turbulent Diagnostic Simulator for the helical, tokamak and cylindrical configuration.

"Peripheral plasma transport research group" studies impurity transport process near a plasma-facing wall in LHD based on the model of boundary plasma between scrape-off layer (SOL) and divertor plate. The calculation mesh of EMC3-EIRENE code has been extended to cover the divertor legs of Large Helical Device (LHD). A series of simulations were carried out to investigate parallel and perpendicular plasma transport with neutrals in the open and close divertor configurations. Comparisons of the simulation results with measurements showed a good agreement on scaling of neutral gas pressure to the electron density when the heating power was fixed.

"Plasma-wall interaction group" investigates dynamical process on the surface of plasma-facing materials such as chemical spattering of divertor plate and yielding hydrocarbon, by means of molecular dynamics (MD) simulation, and its extended model. By using binary collision approximation, density functional theory, MD and kinetic Monte-Carlo simulations, the formation mechanism of the tungsten nano-structure generated by the bombardment of helium ions has been investigated by separating into the following four processes, i.e., the penetration of helium, the diffusion and aggregation of helium, the growth of helium bubble, and the growth of fuzzy nano-structure.

"Multi-hierarchy physics group" studies complex multi-hierarchy phenomena relating to fusion plasmas by developing various multi-scale or multi-hierarchy models and numerical techniques. The multi-hierarchy simulation model (MARIS) has been extended to one with a 2D hierarchy-interlocking scheme in the both upstream and downstream direction and was applied to plasma inflow problem from MHD domain to PIC domain. The mechanism of symmetry breaking in blob propagation and its effect on plasma transport have been studied with a three-dimensional electrostatic plasma particle simulation.

"Simulation science basis group" aims to develop innovative analysis tools of complex simulation data such as scientific visualization on CompleXcope, and various numerical techniques for utilizing powerful supercomputing resources. We have developed an in situ visualization tool for PIC simulation, and the interface tool to read the experimental data of dust trajectories in LHD and visualize them in the virtual-reality space with the software Virtual LHD.

A large-scale computer system, the Plasma Simulator (PS) is a high-performance computer system to support the studies in confinement physics of fusion plasmas and their theoretical systematization, the exploration of science of complexity as the basic research, and other collaborative researches to advance and establish simulation science. The main system is HITACHI SR16000 model M1, which has the total peak performance 315TFlops and the total main memory 40TB. The Plasma Simulator was ranked as the 118th in the world on the TOP500 List of the high-performance computers. LHD Numerical Analysis Server is used primarily for the LHD Experiment Project and its related simulation projects, and the research collaboration with the universities and the institutes. The LHD Numerical Analysis Server (HITACHI SR16000 model XM1) consisted of four nodes. The peak performance and the main memory of each node are 844.8Gflops and 128GB, respectively. The computer working group has continuously worked to support various collaboration research activities with utilizing the large-scale computer systems under the NIFS collaboration programs.

The social events and other academic activities including the plasma simulator symposium, the Toki lectures on simulation science, symposium on hierarchy and holism in natural sciences, training course on the NIFS computer systems, and various domestic and international workshops were hosted to provide the opportunity for scientists to exchange opinions and academic information on fusion simulation science and for students to learn plasma physics and fusion simulation science.

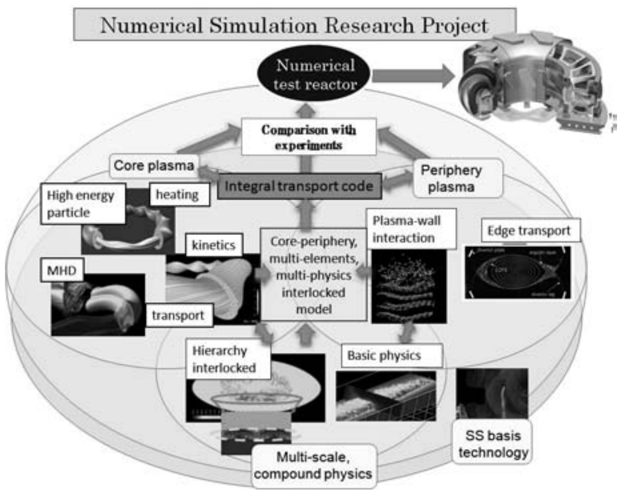

Figure 1: Concept of the Numerical Simulation Research Project.

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