3. Numerical Simulation Reactor 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 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, eight research groups responsible for each task in the NSRP have been set up, 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 and scientific visualization. The project was renamed as the Numerical Simulation Reactor Research Project (NSRP) to accelerate the research activity towards the construction of the NTR in 2014.

We have promoted the NSRP activities to develop and improve various simulation codes as a basis 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 research activities and the typical examples of simulation results are as follows.

"Plasma fluid equilibrium stability group" studies macroscopic physics of core plasmas using nonlinear MHD and extended MHD models. The HINT2 and MIPS codes have been applied to the linear stability and nonlinear dynamics of the LHD plasma with resonant magnetic perturbation. The deformation of the pressure profile drives a mode localized around the X-point and destroys magnetic surfaces from the X-point in the nonlinear phase. In order to clarify effects of the dynamic ergodic divertor to ELM, the fully 3D MHD equilibrium of non-axisymmetric tokamak has been solved with use of the HINT code and the impact of the plasma rotation to the 3D MHD equilibrium has been discussed.

"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. The multi-phase simulation applied to DIII-D plasmas has showed a remarkable agreement with the experimental results in the amplitude profile of electron temperature fluctuations and the phase profile of n=3 mode.

"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. In order to apply the reduced model of the turbulent heat diffusivity for the ITG mode derived from the gyrokinetic simulation to the transport code at a low computational cost, an additional modeling has been done for the mixing length estimate. Electromagnetic gyrokinetic simulations including kinetic electrons, magnetic perturbations, and full geometrical effects have revealed that the electron energy transport reproduces the LHD experimental result for a high T_i discharge. A collision operator for multiple ion species plasma has been implemented to the gyrokinetic flux-tube code. Neoclassical toroidal viscosity in JT-60U and neoclassical poloidal viscosity in LHD have been evaluated using FORTEC-3D code, which solved the drift-kinetic equation in 3-dimensional magnetic 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 model of gas pumping by cryopumps has been introduced into EMC3-EIRENE code together with the models of gas-puffing and core fueling to analyze the effect of the close divertor configuration on neutral gas pressure. The core fueling condition causes significantly lower density and higher temperature by a factor of two in the outer region, R>4.6m because of increase of the plasma source in the core and decrease of recycling flux.

“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. To analyze the formation process of the tungsten nano-structure generated by the bombardment of helium ions, a hybrid simulation model has been developed, in which the diffusion of the helium atoms are simulated as simple random walk, while the deformation of the tungsten materials due to stress from helium bubbles are simulated by the MD. The hybrid simulation has successfully reproduced the formation process of the tungsten 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 influence of macroscopic dynamics on microscopic physics of magnetic reconnection has been examined using the MHD-PIC interlocking model. An extended MHD simulation with two-fluid and finite Larmor radius effects has clarified that the secondary KH instability appears due to strong flow shear in the nonlinear phase of RT instability.

“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. The task group has developed a visualizing tool for the simulation results such as magnetic field obtained from HINT2 code, 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.

“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. Recently, further extension has been conducted such as including ECH ray-tracing codes and the module for creating ascii files to be registered onto the International Stellarator-Heliotron Confinement Database. Inclusion of ECH ray-tracing code can significantly enhance systematic energy transport analysis of ECH- (and NBI-) heated LHD plasmas.

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 186th in the world on the TOP500 List of the high-performance computers. LHD Numerical Analysis Server (LNAS) is used primarily for the LHD Experiment Project and its related simulation projects, and the research collaboration with the universities and the institutes. The LNAS (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.

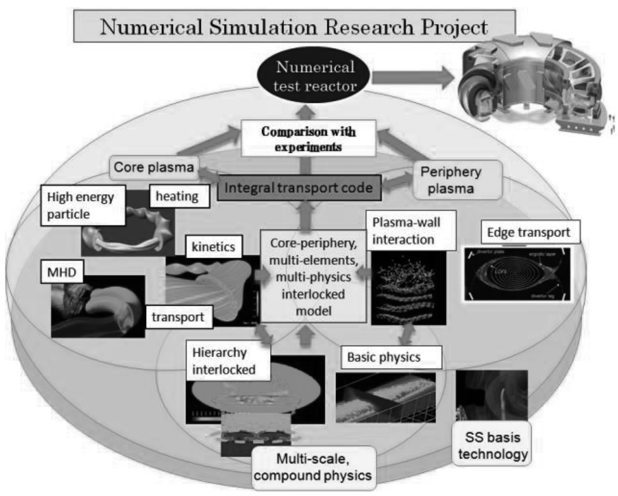

Figure 1: Concept of the Numerical Simulation Reactor Research Project.

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