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 project 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 replaced in 2015, 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 magneto-hydrodynamics (MHD) and extended MHD models. By implementing plasma rotation to a 3D MHD equilibrium code HINT2, the fully 3D MHD equilibrium of non-axisymmetric tokamak is solved numerically and the impact of the plasma rotation to the 3D MHD equilibrium is discussed. The rotation effects on the MHD stability against the interchange modes in the LHD plasmas are studied with the numerical simulation, and the poloidal shear flow is found to stabilize interchange modes in LHD when the kinetic energy is sufficiently larger than the saturation level of the mode in the no flow case.

“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. Energetic particle driven geodesic acoustic mode (EGAM) in 3D LHD equilibrium is investigated with a hybrid simulation code MEGA for energetic particles and MHD. The simulation has showed that the pressure perturbation rotates poloidally in the nonlinear phase, and the rotation direction changes periodically. This rotation is found to be caused by the convection of the EGAM poloidal flow.

“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. Electrostatic microinstabilities in helical plasmas with LHD configurations are investigated by using the gyrokinetic Vlasov simulation code GKV with hydrogen isotope species and real-mass kinetic electrons. Comprehensive scans for the equilibrium parameters have clarified the physical properties of ion-temperature-gradient modes and trapped-electron modes, including the magnetic-configuration dependence such as the standard and inward-shifted plasma configurations. The impact of the differences in local and global neoclassical transport models on the transport analysis of real experiments have been benchmarked in LHD and TJ-II discharges.

“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. In order to control heat load on divertor plates, methods of power reduction such as advanced divertor concepts, impurity seeding, detachment are proposed and actively studied. The group has developed transport model of plasma, impurity and neutral particles in the peripheral plasma by using EMC3-EIRENE and applied to LHD discharge with neon gas puff. It is found that much neon accumulate in the ergodic region than carbon because neon has higher ionization energy and deeper penetration into the plasma.

“Plasma-wall interaction group” investigates dynamical process on the surface of plasma-facing materials such as chemical spattering of divertor plate and nanostructure formation process, by means of molecular dynamics (MD), Monte-Carlo (MC) simulations, and its extended model. Three-dimensional MD-MC hybrid simulation model has been developed and applied to the formation process of the tungsten fuzzy nanostructure generated by the bombardment of helium ions. The hybrid simulation has successfully reproduced the formation process of the fuzzy tungsten nanostructure in full 3D system. The simulation for argon irradiation to tungsten target has also been performed by using binary-collision-approximation model.

"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. 3D electrostatic particle simulation code has been improved to investigate the dynamics of the filamentary coherent structure, "hole", in which the plasma density is lower than background plasma. Numerical simulation has confirmed that the dipole potential structure is formed in the hole and that the hole propagates in the grad-B direction.

"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 point-sprite method has been applied to visualize the experimental data of dust trajectories in the virtual-reality space, together with the simulation results such as magnetic field obtained from HINT2 code and the device data of LHD using the software Virtual LHD

"Integrated transport simulation group" works on the development of core transport code in 3D configuration 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 extended through implementing additional modules for neoclassical transport and ECH deposition (LHDGauss) for 3D configurations. The module has also been added for creating the systematic data for the International Stellarator-Heliotron Confinement and Profile Database. Data uncertainty quantification tool and improvement of NBI modules for multiple-ion species plasmas are also highlights of recent development. Thus, this suite has provided researches for systematic validation studies based on experimental database.

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 was replaced by FUJITSU FX100 on June 1, 2015, which has the total peak performance 2.62PFlops and the total main memory 81TB. The Plasma Simulator was ranked as the 27th 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 (FUJITSU FX100) consisted of 144 computational nodes. The peak performance and the main memory of each node are 1.01Tflops and 32GB, 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.

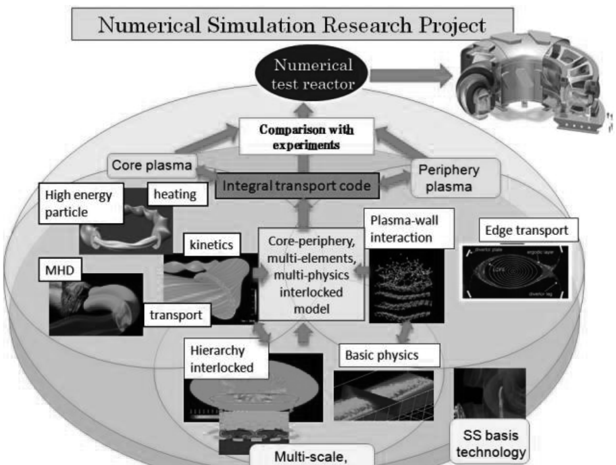

Figure 1: Concept of the Numerical Simulation Reactor Research Project.

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