Whitepaper for DOE Workshop on Integrated Simulations for Magnetic Fusion Energy Sciences
Topic B: Plasma boundary, including the pedestal, scrape off layer, and plasma-materials interactions

Integrated Modeling and Simulation of Edge and SOL Phenomena to Predict Performance of Plasma-Facing and Nearby Components

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Motivation. Edge plasma evolution plays major role in tokamak plasma confinement and determines/control the High-confinement mode (H-mode) operation. Experiments show the complex character of the edge plasma interaction with tokamak components and as a result the complex self-consistent behavior of plasma in the entire SOL. The edge plasma drift and contact with plasma facing components (PFCs) results in mixing of D-T plasma and material impurities, affects toroidal plasma motion, and redistributes energy load. Our modeling of the NSTX and ITER devices during abnormal and disruptive operations showed strong coupling between evolution of divertor plasma and parameters of the escaped core fuel plasma. Spatial and temporal distributions of the escaped particles determined the heat load of divertor component, parameters of divertor plasma shielding, drift of contaminations. The divertor plasma motion affects in turn the SOL magnetic field structure and core plasma has the noticeable feedback from the boundaries. As a result, erosion of the divertor and wall surfaces depends on the spatial and temporal variation of the SOL disturbance and should be modeled self-consistently with 3D modeling of entire device. The HEIGHTS (High Energy Interaction with General Heterogeneous Target Systems) computer package was upgraded to fit the NSTX geometry for full 3-D simulation of reactor environment. This modeling includes calculation of plasma energy deposition in target material, heat conduction in bulk, debris vapor evolution, lithium vapor-plasma heating, photon generation and transport, with taking into account the local magnetic fields directions and magnitudes. The HEIGHTS initial simulations showed that the integrated approach for modeling of NSTX edge plasma allows to resolve in details the plasma evolution and to predict the main parameters of device components heat loads and erosion (Fig.1). The calculation results are of obvious importance as initial conditions for modeling edge plasma phenomena and for plasma facing components damage, Li splashing and possible mitigation techniques.

Approach. The included models are being improved continuously and integrated code is being upgraded and benchmarked. The Monte Carlo-based kinetic model of the escaping core particles is developed for integration with the magnetohydrodynamic (MHD) models of the initiated edge plasma where the escaping particles are used as an input volume source [1]. This full 3D model allowed to make the end-to-end simulation of the contaminated dense plasma near the tokamak walls in the entire NSTX device SOL. We should stress that the presence of strong spatial effects cannot be described with simple and lower-dimensional models. The complex feature of the magnetic field induced plasma drift in SOL and divertor nearby areas is the starting point to determine the hydrodynamics evolution and radiation phenomena at the surface of plasma-facing components. The quadtree adaptive mesh refinement (AMR) algorithms with 5 level sub-layers were developed and implemented in HEIGHTS to significantly enhance the accuracy of the calculation and to reduce the computational time. We implemented, verified and benchmarked (Fig.2) our new Monte Carlo kinetic model integrated into HEIGHTS simulation package to study the spatial profile of ion and electron energy deposition of the escaped core particles of both inner and outer divertor plates for NSTX and ITER-like device parameters, magnetic field complex structure and the components' geometry [2]. Correct peak location, profile match, and total energy demonstrate good agreement between our calculations and the experimental data (Fig.2). The flux distribution has a slightly narrower footprint in comparison with the experimental results since these calculations considered unperturbed escaped core particles. Taking into account

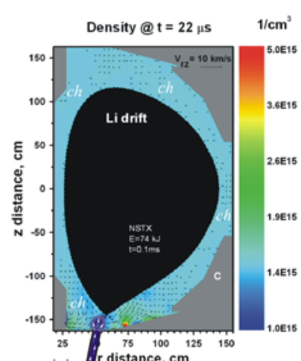

Fig.1. Calculated Li drift in the NSTX SOL[1]. inj – neutral gas injection

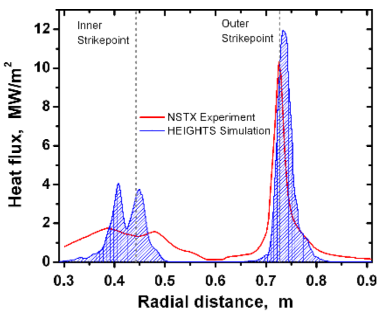

Fig.2. Heat flux footprint at the NSTX divertor surface. Power shot PNBI = 4.9MW [3]

the edge plasma injection and shielding will result in broader particle/heat flux distributions and the reduction of peaks. We also studied the influence of initial temperature of the core-escaping particle on the divertor heat load footprints. For accurate prediction of the actual divertor damage and to gain more physical insights of various processes we calculated, for the first time, details of the electron-ion composition and contribution to the surface heat fluxes at both the inner and outer divertor plates. The new upgraded packages showed capabilities to simulate the combined multiscale picture of the under-, near surface, and the SOL physical processes in whole tokamak device of an arbitrary geometry. In the integration with the comprehensive Monte Carlo radiation transport block, the preliminary calculations confirmed the close interconnection of the divertor plasma radiation balance and divertor design including the divertor plasma composition. We will use our Monte Carlo methods for the detailed calculations of photon deposition and propagation through SOL, the wall/vapor plasma, and to nearby components to have possibility of the injected neutral gas influence accounting. The multiscale approach and realistic 3D description of SOL processes showed the self-consistent character of the divertor plasma evolution that agrees well with recent experimental observations [4]. Simulations showed the interconnection of energy load to two divertors through the toroidally drifting escaped core particles: the ions and electrons can change gyration pitch and drifting status (trapped particle – passing particle) due to interaction with divertor plasma (Fig. 3). A part of the escaped particles roams between inner and outer divertors around the abandoned core. The preliminary results [1, 2] confirmed the extreme importance of the self-consistent character of the edge plasma phenomena where plasma composition is the key factor in the physical chain: plasma composition – radiation transport – energy redistribution – plasma dynamics – stability – plasma-facing component lifetimes. This chain should be simulated within the scope of the SINGLE integrated computer package because of the high self-consistency and indirect interdependencies (such as radiation transport) in SOL.

Impact. Our proposed work has two main objectives. The first objective is integrated 3D simulations of reactor environment in close connection with experimental studies at NSTX-U device to predict the edge plasma phenomena during interaction with the device components, energy and mass redistribution in SOL including the radiation lost, study of the escaped core particles drift, prediction and optimization of the heat load properties of new NSTX-U divertor designs. It includes also simulation of the edge plasma conditions for the Li splashing initiation, study of the neutral gas injection influence on liquid metal splashing (Fig.1.), development of the mitigation techniques. The second objective of the proposed work is in further enhancement of physical models and methods, predict realistic response to abnormal events, accommodate future upgrades and design changes, enhance the package to accelerate simulations of full 3D reactor environment coupling all interaction phases from core to SOL to divertor and feedback.

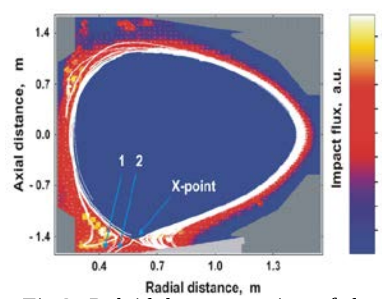

Fig.3. Poloidal cross-section of the impact particle flux in NSTX: white lines show particle trajectories; arrows 1 and 2 show location of heat load peaks at the inner divertor

References:

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