CONFERENCE PRE-PRINT

PREDICTION OF HEAT FLUX SPLITTING BY NON-AXISYMMETRIC MAGNETIC FIELD IN THE REALISTIC TOKAMAK WALL AND DIVERTOR BASED ON 3D CAD MODEL

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Abstract

Control of divertor heat loads is a critical challenge for the safe and efficient operation of reactor-scale fusion devices. Externally applied 3D magnetic fields for edge localized mode (ELM) control induce complex plasma responses and alter heat and particle transport to divertor targets. In this work, we present a full orbit (FO) particle simulation approach to model divertor heat flux splitting by 3D field, implemented in the POCA code, enabling more physically consistent predictions compared to field line tracing (FLT) approach. The FO approach provides additional detail on peak amplitudes and hot spot formation compared to the FLT. The FO simulations are extended to realistic 3D wall and divertor geometries based on 3D CAD model by integrating a novel collision detection algorithm. Simulations with 3D CAD geometries further reveal realistic striation structures under resonant and non-resonant RMP configurations. The developed method can be an alternative for quantitative prediction of divertor heat fluxes throughout further improvement and integration with digital twin.

1. INTRODUCTION

Control of divertor heat loads in magnetic confinement fusion devices is a critical issue for efficient and safe operation of reactor-level fusion systems. Considering the H-mode operation as the baseline operation regime in the fusion reactors, the edge localized modes (ELMs) are the dangerous instability for the safety of plasma facing components including divertor target. This has motivated and promoted the development of control strategies of the ELMs. One of the most successful ELM control scheme is the application of resonant magnetic perturbations (RMPs) generated by externally installed non-axisymmetric (3D) magnetic field coils. Suppression and mitigation of ELMs by the RMPs have been demonstrated in the worldwide fusion devices and are planned as one of main strategies for ELM control in the H-mode operation scenarios [1].

In addition to suppression of the ELMs, the applied RMPs and 3D magnetic field in general result in complicated plasma responses such as toroidal rotation braking, enhanced fast ion losses, and modification of magnetohydrodynamic activities. The RMPs modify heat and particle fluxes across the separatrix through formation of magnetic islands and stochastic field layers, leading to structural changes in heat load patterns onto the divertor target. Achieving both ELM suppression and divertor heat load reduction simultaneously is therefore a key requirement for successful operation of fusion reactors. For this purpose, heat load dissipation methods such as rotating RMPs, intentionally misaligned RMPs, and detached divertor operation are actively under investigation [2, 3].

Predicting the heat flux structure in the presence of RMPs is critical for understanding the transport mechanisms of RMP driven heat and particle fluxes to the divertor and for forecasting the divertor heat flux profiles under a variety of 3D magnetic field environments. The field line tracing (FLT) technique has been popularly utilized to predict and analyze heat flux striation patterns on the divertor target induced by the RMPs. The FLT has been successful to qualitatively analyze experimentally observed lobe structure of heat flux on the divertor [4]. While this approach heavily relies on the 3D field model, i.e. either vacuum or plasma response, it serves as a useful guide for understanding the role of plasma response in the transport mechanism of heat and particle flux driven by the RMPs. A more advanced approach utilize full three dimensional plasma transport modelling of the edge-divertor region based on the fluid formalism, as has been demonstrated by the 3D transport codes such as EMC3-EIRENE [2]. While this approach incorporates rich physics including atomic processes in the wall and divertor target boundary, it is computationally demanding depending on the level of physics. Although the full 3D divertor simulation has a great potential for direct quantitative prediction of divertor heat load structure, more physical and numerical investigations are necessary and presently ongoing.

In this report, we introduce an alternative approach based on the full orbit (FO) particle simulation technique to predict the heat flux splitting by the RMPs in tokamaks. The particle orbit code POCA [4, 5] is extended to include realistic 3D wall and divertor structures from the 3D CAD model.

2. FULL ORBIT FOLLOWING APPROACH

In this approach, test ion particles are launched at the edge plasma region that spans the pedestal. The test particles are uniformly distributed in the prescribed region set by an input parameter. In general, $0.9 < \psi_N < 1.0$ with ψ_N, the normalized poloidal flux is set as launching zone. The test particle energies are initialized by ion temperature profile given as input. In general, the initial pitch of test particles is assumed as $\lambda = v_{||}/v = 1$, where $v_{||}$ is the ion velocity parallel to the magnetic field line.

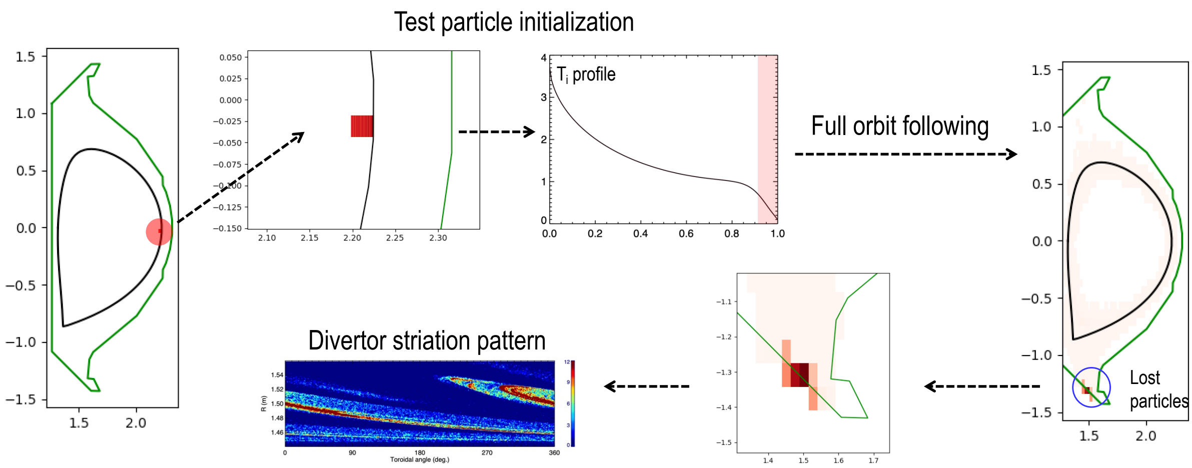

FIG. 1. Illustration of procedure of FO following simulation for prediction of divertor heat flux striation in the presence of 3D magnetic field.

The launched test ions are followed until they collide with plasma facing components including divertor target. The test particle motions are computed based on the FO following formalism, which enables full considerations of the finite Larmor radius effects on the particle trajectories and final distributions of lost particles on the divertor target. The gyro-motion of thermal ions can impact on the structure of heat profile on the divertor as the typical thermal ion Larmor radius at the H-mode pedestal is a few mm. Particle impact information of the lost particles hitting the divertor plates are collected for post-processing to construct 2D histogram of the number of lost particles on the target plate. This histogram represents the lost particle distribution on the target to be directly compared to the heat flux striation pattern measured in the experiment. Such procedures are briefly illustrated in Fig. 1.

A key input to this full orbit following simulation is the perturbed magnetic field structure produced by the RMPs, and in general, the 3D magnetic field. The 3D field information is computed with the perturbed equilibrium with either vacuum field approximation or plasma response model using the GPEC code [6] and provided to the POCA code as input. Any plasma response model can be easily taken into account in this simulation, as described in the previous studies. In this paper, plasma response computed by the GPEC is utilized as the input perturbed equilibrium.

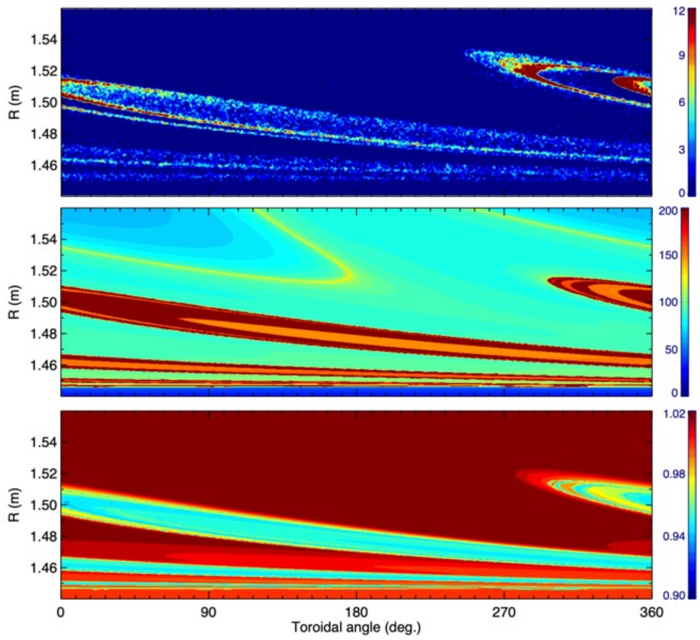

FIG. 2. Divertor footprint reconstructed with lost particle distribution from full orbit simulation (top), field line connection length (middle) and minimum ψ_N (bottom) from field line tracing simulation.

A reference divertor footprint pattern obtained from full orbit particle simulation is shown in Fig. 2. A KSTAR plasma is selected for this reference run, where the n = 1 3D magnetic field is applied. The 3D perturbed equilibrium is computed based on the magnetic equilibrium of the KSTAR plasma. The reference result is compared with the field line tracing simulation for the same plasma, which illustrates the divertor footprint with 2D contours of the field line connection length (Lc) and the innermost poloidal flux surface connected to the divertor target, i.e. min(ψ_N). The results from two different simulation schemes show largely similar divertor striation patterns as they are based on the same 3D magnetic field line structure.

It is interesting to note that FO simulations capture distinctive features in the detailed striation structure. Fig. 3 compare radial particle distribution from full orbit simulation with the FLT results at two toroidal locations, $\phi_1 = 45^o$ and $\phi_2 = 270^o$. Note the radial profile of min(ψ_N) contour is presented by 1-min(ψ_N). The most distinctive discrepancy is that more peaks at the outer radii are identified in the lost particle distribution by FO simulation than Lc and min(ψ_N), in particular, at ϕ_2. This is because the magnetic island and stochastic field layers formed by the 3D field are captured more clearly in the FO simulation as shown by stronger striations in Fig. 2. The FO simulation result also provides better illustrations for relative amplitudes of peaks, which appear as profile-like lost particle distribution. The FLT simulation result only presents the peak positions rather than distribution for this case, probably due to ignorance of finite Larmor radius and orbit width effects.

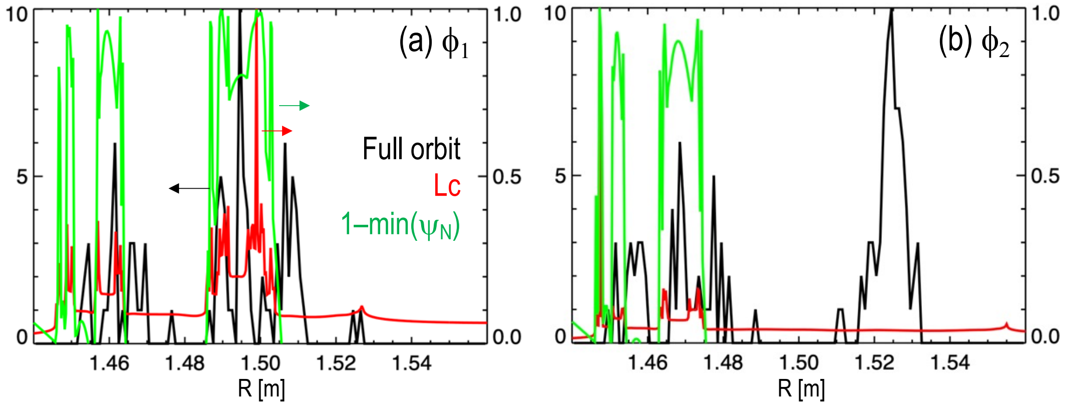

FIG. 3. Comparison of normalized radial profiles of Fig. 2 at the prescribed toroidal positions, (a) $\phi_1 = 45^o$ and (b) $\phi_2 = 270^o$.

3. EXTENSION TO REALISTIC WALL AND DIVERTOR BASED ON 3D CAD MODEL

It is noted that in the previous approach in Sec. 2, we consider the 2D wall and divertor structure extracted from 2D equilibrium reconstruction as the simulation boundary for collision detection of the test particles. We extend this 2D computational boundary to the realistic 3D tokamak wall and divertor geometry derived from the 3D CAD model [7]. This model is extracted from full 3D geometric information of KSTAR CAD data and defeatured based on the required geometric complexity of the simulation. This extension enables inclusion of details of the machine components, in particular, of the wall and divertor in tokamaks.

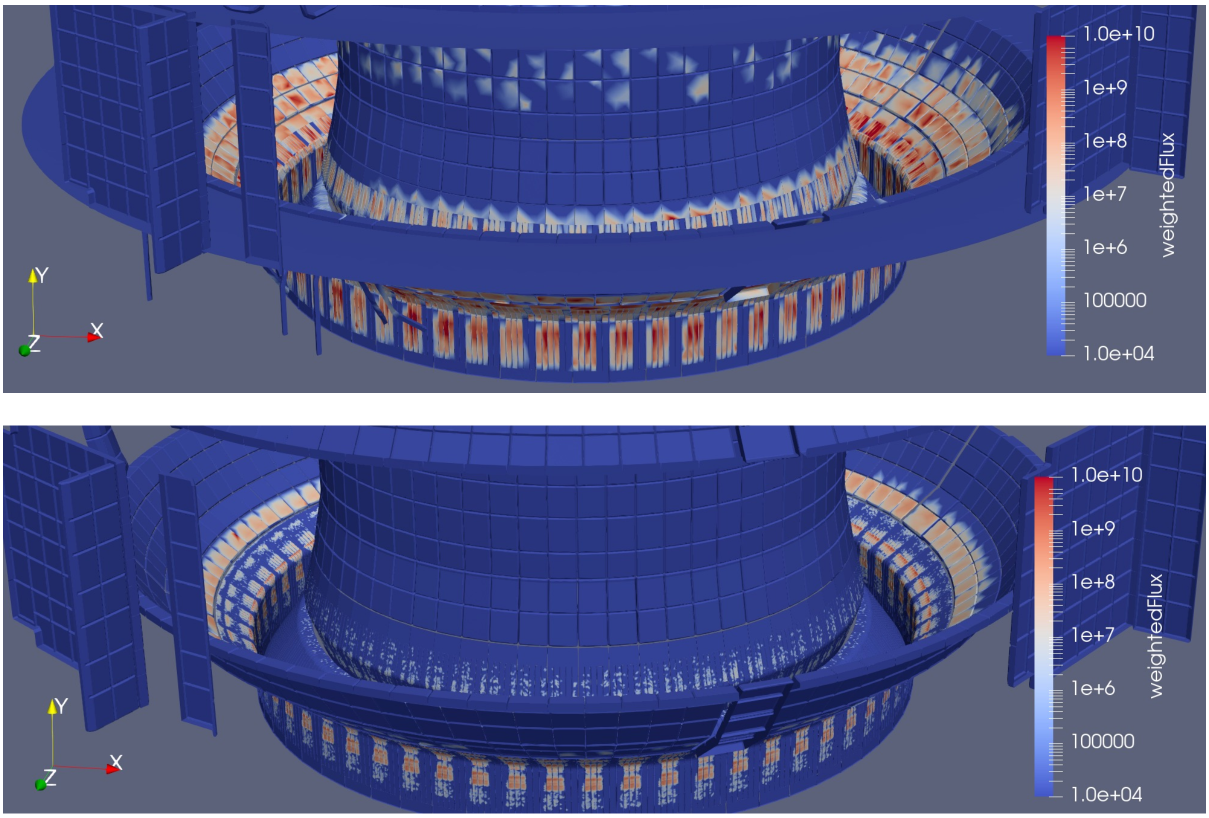

FIG. 4. Divertor striation patterns by 3D magnetic field, computed with full orbit simulation in the realistic 3D CAD based KSTAR geometry, with n=1 3D magnetic field of (top) +90-degree and (bottom) 0-degree phasing.

Along with extension to the realistic 3D wall and divertor structures, a novel collision detection algorithm has been integrated into the POCA code to enhance the feasibility of heat flux splitting simulations. The integrated collision detection algorithm employs the two-step broad-narrow phase approach to improve numerical efficiency in the FO simulation [7]. In the broad phase, the ion trajectory segments far from collisions with the wall mesh are excluded from collision detection process, while the triangle mesh elements that sufficiently close to the ion trajectory segments are separately identified. The narrow phase then employs a ray-casting method to confirm the collision events between the ion trajectory and the wall mesh and calculate the segment positions where the collisions are detected. Integration of the 3D collision detection algorithm with the FO and FLT in POCA code enables more accurate tracing of full particle orbits and magnetic field lines in the realistic 3D geometry, incorporating detailed segmental structures of the wall and divertor of KSTAR.

Fig. 4 presents typical divertor heat flux striation patterns computed using the FO simulation for typical KSTAR plasmas, where the n=1 +90-degree and 0-degree phasing 3D magnetic fields are applied. One finds that the +90-degree phasing, which is a typical 3D field configuration for ELM suppression in KSTAR, induces strong splitting patterns both in amplitudes and width due to strong resonant plasma response. The 0-degree phasing, which is largely non-resonant, creates relatively mild striations, consistent with general observations. The FO simulations with 3D CAD geometry qualitatively show clear n=1 structures and highlight detailed hot spots where intense collisions and heat deposition occur. At present, we can compute the lost particle distributions on the wall and divertor target. A physics based weight function including vector components of the wall and divertor meshes is necessary for quantitative calculation of heat flux distribution to be compared with measurements of divertor heat loads, which is in progress.

4. DISCUSSION

The newly developed simulation integrates the full orbit following technique, the advanced collision detection algorithm, and the realistic 3D CAD based wall and divertor structure. This enables calculations of the heat flux pattern induced by the RMP in the realistic tokamak geometry. Work is underway to integrate this simulation capability into the digital twin framework [8], which can serve as a tool for the maintenance and protection of machine component in present fusion devices. Further improvements are expected to provide a guide for design and optimization of future fusion devices, where divertor heat flux control remains a critical challenge.

A potential advantage of the FO simulation is that the FO includes the edge structure of ion density and temperature profile. In particular, presence of the H-mode pedestal against L-mode edge is the critical element to determine the divertor heat load and striation by the applied 3D magnetic field. Since the FLT approach basically relies on the perturbed equilibrium structure based on the axisymmetric equilibrium, it cannot distinguish the L-mode edge from the H-mode pedestal unless the equilibrium reconstruction is computed with kinetic considerations. On the other hand, the FO approach naturally incorporate the edge kinetic profile, which enables the kinetic components of test particles to play their role in the edge transport. This feature provides an important potential to the FO approach, which can be more physically consistent approach of divertor striations than the FLT throughout further development.

For more comprehensive and physically consistent simulations, physics such as phase-space distribution of test particles, collisional effects, and interactions with electrons and impurities need to be taken into account. In addition, further improvement of the 3D perturbed equilibrium, which set the baseline magnetic field line structure, will be essentially required. With these advances, the full orbit simulations in the realistic 3D tokamak geometry could become a powerful tool for predicting and analyzing divertor heat loads in the tokamak experiment with 3D magnetic field.

ACKNOWLEDGEMENTS

This research was supported by R&D Program of KFE-EN2541 and KFE-CN2502 through the Korea Institute of Fusion Energy (KFE) funded by the Government funds, Republic of Korea.

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