# 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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Control of divertor heat loads in the magnetic confinement fusion devices is a critical issue for efficient and safe operation of reactor-level fusion devices. 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, which has motivated and promoted development of control strategies of the ELMs. One of the most successful ELM control scheme is the application of resonant magnetic perturbations (RMPs) utilizing 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 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 a variety of plasma responses such as toroidal rotation braking, 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, which leads to structural changes of heat loads onto the divertor target. Simultaneous achievement of ELM suppression and divertor heat load reduction is therefore an important subject 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].

Prediction capability of the heat flux structure in the presence of RMPs is an important element to promote understanding of propagating mechanism of RMP driven heat and particle fluxes to the divertor and predict the heat flux profile in a variety of 3D magnetic field environments. Field line tracing (FLT) technique has been popularly utilized to predict and analyse heat flux striation pattern on the divertor target induced by the RMPs. It has been successful to qualitatively analyse experimentally observed lobe structure of heat flux on the divertor. While this approach largely depends on the 3D field model, i.e. either vacuum or plasma response, it provides a guide to understand the role of plasma response in the transport mechanism of heat and particle flux by the RMPs. More advanced method is a full consideration of three dimensional plasma transport in the edge-divertor region based on the fluid formalism, as has been demonstrated by the 3D transport codes such as EMC3-EIRENE [2]. This approach contains rich physics including atomic processes in the wall and divertor target boundary and thereby is computationally expensive. Though 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.

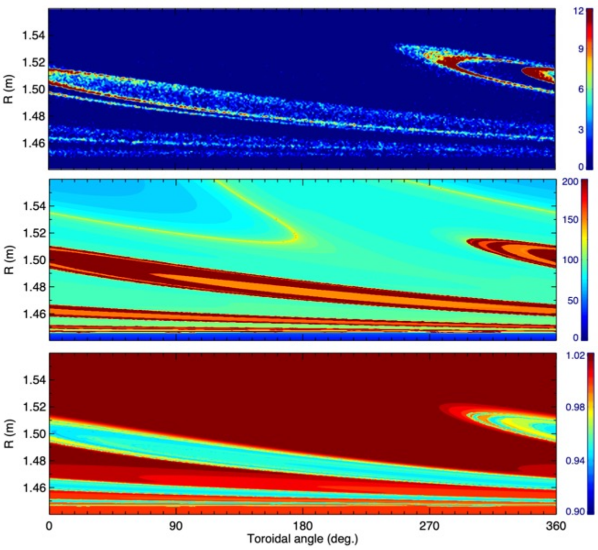


**FIG. 1. Divertor footprint reconstructed with lost particle distribution from full orbit simulation (top), field line connection length (middle) and minimum $\psi_N$ (bottom) from field line tracing simulation.**

For prediction of the heat flux splitting by the RMPs in tokamaks, we introduce an alternative method based on full orbit (FO) particle simulation utilizing the particle orbit code POCA [4, 5]. The POCA code launches test ion particles at the edge plasma region that spans the pedestal and separatrix. The test particles are uniformly distributed in the prescribed region set by an input parameter, e.g. $0.9<\psi_N<1.0$ is set as launching zone with the normalized poloidal flux $\psi_N$. The test particle energies are initialized by ion temperature profile given as input. The initial pitch of test particles is assumed as $v_{\|}/v=1$, where $v_{\|}$ is the ion velocity parallel to the magnetic field line. The launched test ions are then traced until they touch the first wall and 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 trajectory and final distributions of lost particles on the divertor target. Fig. 1 is the example of computed divertor lobe structure on the simplified 2D wall and divertor geometry, utilizing the FO and FLT simulations. These two approaches overall show consistent agreements in the striation patterns, while some discrepancies are found in the detailed structure probably due to considerations of finite orbit width and Larmor radius in the FO simulation.

A novel collision detection algorithm has been integrated into POCA code to enhance the feasibility of heat flux splitting simulations. We utilize a realistic 3D tokamak wall and divertor geometry derived from the 3D CAD model [6], which is extracted from full 3D geometric information of KSTAR CAD data and defeatured based on the required geometric complexity of the simulation. The collision detection algorithm employs the two-step broad-narrow phase approach to improve numerical efficiency. The integration of the 3D collision detection algorithm with the FO and FLT enables accurate tracing of full particle orbits and magnetic field line in the realistic 3D geometry, incorporating detailed segmental structures of the wall and divertor. Fig. 2 presents a typical divertor heat flux striation pattern computed using the FO simulation, which highlights detailed hot spots where intense collisions and heat deposition occur.

We will discuss the progress of predictive capabilities of heat flux splitting due to 3D magnetic fields in realistic tokamak geometry. The newly developed simulation technique, which incorporates a realistic 3D wall and divertor structure, will enable realistic heat flux pattern calculation induced by the RMP through integration into the digital twin framework [7]. This capability can serve as a tool for the maintenance and protection of machine component in present fusion devices. Further improvement of the capability is expected to provide a guide for design and optimization of future fusion devices, where divertor heat flux control remains a critical challenge.

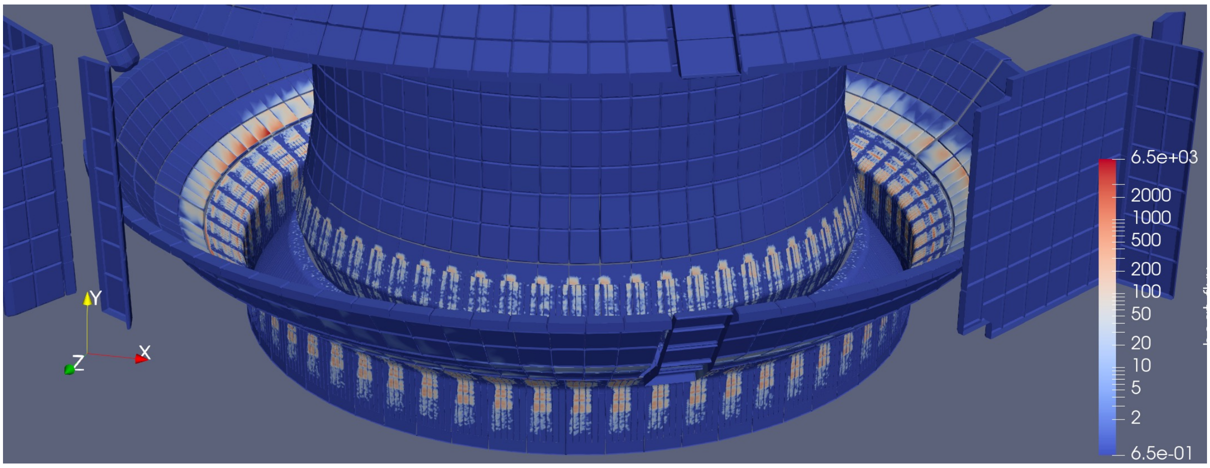


**FIG. 2. Divertor striation patterns by 3D magnetic field, computed with full orbit simulation in the realistic 3D CAD based KSTAR geometry.**

## ACKNOWLEDGEMENTS

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