Enlarging the divertor wetted area through the lobe structure intertwined by the stable and unstable manifolds of the outermost X-cycle

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Poincare-Bendixson theorem prohibits chaos in autonomous 2D continuous dynamical systems, such as a perfectly axisymmetric magnetic field in tokamaks. However, chaos, being well-known for its long-term unpredictability, is allowed to exist (and extensively) in 3D or higher-dimensional autonomous flows. In a magnetic confinement fusion (MCF) machine where the axisymmetry is not guaranteed, flux surfaces are not necessarily well-nested and can break, particularly at the edge. This is supported by simulations [1] and experimental findings [2-4], *e.g.* the distinctive pattern of field line connection length (L_c) distribution (viewed at an iso-ϕ-section and on the divertor plates) and strike-line splitting.

This intriguing phenomenon has sparked interest in understanding the global magnetic field structure after flux surfaces are not expected [5,6]. Instead, *stable and unstable manifolds* are examined, which are two dual types of *invariant manifolds* (all field lines never leave the set). The stable and unstable manifolds of the outermost X-cycle in MCF machines are crucial in determining the plasma transport in the scrape-off layer when the edge magnetic field is chaotized. Based on the *invariant manifold growth* formula in cylindrical coordinates [7,8], a more comprehensive understanding of them is acquired, laying the foundation for designing and optimizing a more compact divertor with improved closure.

The EAST tokamak is taken as an example to display the relevant structures and an approach for divertor optimization, which needs to be combined with a proactive resonant magnetic perturbation (RMP) to induce the desired manifolds. Fig. 1 shows a 3D perspective, while Fig. 2 shows an iso-ϕ-section at $\phi=0$, where ϕ is simply the azimuthal angle of the standard cylindrical coordinates.

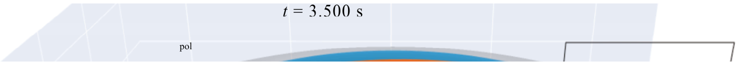

Figure 1. 3D view of stable and unstable manifolds at a time slice of EAST (EFIT + RMP vacuum)

The lobe structure formed by these intertwined manifolds holds promise for significantly increasing the divertor wet area, as shown in Fig. 2 and Fig. 3 by the comparison of the ϕ-increasing field line connection lengths $L_c^{\rightarrow}$ distribution on the outer target plate before and after being aligned with the manifolds on purpose. The specialized design featuring a wide 2D ribbon pattern footprint on the divertor plate, as opposed to the 1D strike line on a conventional divertor plate, inherently offers more redundancy in power-endurance capacity.

The figures presented illustrate an initial exploration of this potential, depicting the change of the footprint pattern when better aligned with the manifolds. Further efforts are needed to consider physical and engineering implications, such as the influence on neutral closure, to ensure the practicality of the divertor design and avoid operation risks. This design approach may not be riskier than the conventional ones thanks to the fact that the outermost

Figure 2. With plasma-facing components being more compact and more aligned to the manifolds, the distributions of $L_c^{\rightarrow}$ on the outer divertor plate are drawn later in Fig. 3.