Gyrokinetic understanding of the fundamental physics behind the divertor heat-flux width and the SOL plasma behavior

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The total-f gyrokinetic particle-in-cell code XGC has been used across the separatrix and SOL to study the fundamental multiscale physics behind the divertor heat-flux width and the SOL plasma behavior. Realistic tokamak geometries and plasma profiles from the experimental EFIT data (NSTX, DIII-D, C-Mod, and JET) are used for initialization of the simulation, with a neutral recycling coefficient at the material wall. Plasma profiles are allowed to evolve according to the intrinsic transport. Electrostatic gyrokineic ions, drift-kinetic electrons and Monte-Carlo neutral particles are used, which are undergoing the ionization and charge-exchange interactions. Neoclassical, turbulence, and neutral particles physics are included together consistently. A fully non-linear Fokker-Planck collision operator is utilized to account for the non-Mawellian plasma.

Simulations show that in today's tokamaks, the ion neoclassical orbit drift behavior – giving rise to the X-point orbit loss effect – tends to lead the setting of the divertor heat-flux width. Sheared ExB-flow across the magnetic separatrix surface is strong, and turbulence is "blobby" but found to play a support (ambipolarity) role in setting the divertor heat-flux width. Unlike in the core plasma, plasma transport in SOL and across the separatrix is multi-dimensional and not automatically ambipolar, making the intrinsic generation of ExB flow to be a critical self-organizing factor. Relation between the up-stream "scrape-off layer width" and the "down-stream divertor heat-flux width" is not strong, in contrast to the assumptions made in the reduced modelings. Most of the important ion orbit dynamics that leads the divertor heat-flux width physics occurs below the midplane, which implies that the length of the divertor leg and the magnetic structure in the divertor chamber could be more important factor than the upstream plasma profile.

In ITER with full magnetic field, however, simulations find that the mean ExB flow shear is weak due to the small ρ_* effect, that the turbulence pattern becomes of streamer type with long radial correlation length, and that the radial turbulence mixing effect leads over the neoclassical ion drift effect in setting the divertor heat-flux width. As a result, the heat-flux width becomes several times greater than the value predicted following the trend from the present tokamaks (the so-called Eich scaling). This does not mean that the ion orbit loss effect, which is distinct below the midplane, is subdued. The X-point orbit loss effect is enhanced by the radial streamers and becomes an important "ambipolarity" source with the enhanced electron streamer transport. Again, the relation between the up-stream "scrape-off layer width" and the down-stream divertor heat-flux width is not strong, and implies that the magnetic structure in the divertor chamber could be an important factor in setting the divertor heat-load width. Additionally, it is interesting to find that a recent modeling NSTX-U plasma in XGC with an X-point at extremely inboard side near the bottom of center stack (high triangularity) yields a >2X enhanced divertor heat-flux width over Eich scaling. Relation between this finding and the ITER result is under investigation and will also be presented.

In order to compare explicitly the gyrokinetic, non-Maxwellian SOL plasma behavior against the fluid equations, turbulence-free XGC simulations have also been performed. The fluid equations based on the CGL closure show a significant deviation from the gyro-kinetic solutions. For example, the density/pressure variation between the up-stream and the down-stream is much stronger in the gyrokinetic plasma due to the non-Maxwellina enhanced off-diagonal viscosity, again weakening the relation between the up-stream "scrape-off layer width" and the down-stream "divertor heat-flux width."