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Understanding of the ohmic breakdown physics in a tokamak by considering the multi-dimensional plasma responses

Min-Gu Yoo[1,2], Yong-Su Na[2], Jeongwon Lee[3], Young-Gi Kim[4], Jayhyun Kim[3]

[1] Princeton Plasma Physics Laboratory, Princeton, United States
[2] Department of Nuclear Engineering, Seoul National University, Seoul, Korea
[3] National Fusion Research Institute, Daejeon, Korea
[4] Culham Centre for Fusion Energy, Abingdon, United Kingdom

e-mail (speaker): myoo@pppl.gov

The ohmic breakdown is one of the major methods to initiate the plasma in a tokamak by applying external toroidal electric fields to make the electron avalanche. Although the ohmic breakdown has been generally used in many tokamaks over several decades, the underlying physical mechanism has been still obscured because of the time-varying complicated structure of the external electromagnetic fields. Due to a lack of theoretical understanding, previous studies just assumed that the electrons perfectly follow the magnetic field line and the electrical interactions between the charged particles are totally negligible. Based on these assumptions, the classical Townsend avalanche theory, which was developed 100 years ago, has been widely adopted to analyze the complicated electromagnetic topology of the ohmic breakdown.

However, we found clear evidence from the KSTAR experiments that the Townsend theory is not valid for the ohmic breakdown; The estimated growth rate of the electron avalanche is much slower than that of the Townsend theory, and the homogeneous plasma density along the magnetic field line during the avalanche cannot be explained. We realized that the electric fields generated by the plasma charged particles, which were ignored in the Townsend theory, is strong enough to change the overall avalanche process completely. This plasma response against the externally given electromagnetic fields is a key to understand the ohmic breakdown physics properly. For this purpose, we established a theoretical model and developed a 3-dimensional particle simulation code BREAK [1] to study the ohmic breakdown physics in a realistic complex electromagnetic topology self-consistently.

As a result, we proposed a novel theory, namely a turbulent ExB mixing avalanche [2], which systematically considers multi-dimensional plasma responses in the complex electromagnetic fields. This theory clearly revealed the crucial roles of the self-electric fields generated by the plasma charged particles. Above a critical plasma density, the self-electric fields are produced in the poloidal plane and the parallel component of the self-electric fields cancel out that of external toroidal electric fields. This cancellation causes a drop of the ohmic heating power and so the electron temperature and the avalanche growth rate is decreased. The perpendicular component of the self-electric fields induces a strong turbulent ExB transport. The enhanced perpendicular transports by the ExB drifts are dominant over the parallel transports along the magnetic field lines in the poloidal plane. Due to the mixing effects of turbulent ExB vortices, the plasma density rapidly homogenizes along the poloidal magnetic field line and then slowly move across the magnetic field line. This new avalanche model is verified by successfully reproduction of the KSTAR experimental results as shown in Figure 1. In addition to the comprehensive understanding of the fundamental mechanisms, we also provide a simple and clear methodology, or a topology analysis method, to expect the plasma evolution in the complex electromagnetic topology before expensive numerical simulations or experiments. This new method would be very helpful to design the robust and optimized ohmic breakdown scenarios in current tokamaks and future devices such as ITER.

References
[1] M.-G. Yoo, *et al.*, Computer Physics Communications **221** (2017) 143
[2] M.-G. Yoo, *et al.*, Nature Communications **9** (2018) 3523

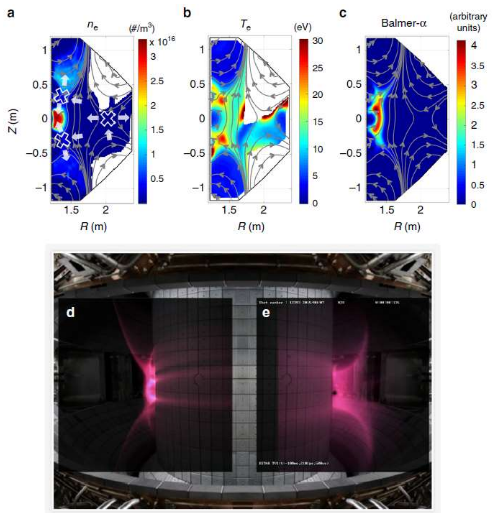

Figure 1. Comparison between simulation results (a-d) and KSTAR experiments (e): **a.** electron density, **b.** electron temperature, **c.** Balmer-alpha line emission, **d.** A synthetic diagnostic of visible camera, **e.** visible camera image from KSTAR [Reprinted from Fig. 10 of [2] licensed under CC BY 4.0.]