Feedback of Plasma-Materials Interaction on Scrape-Off Layer Plasmas

Xianzhu Tang*, Zehua Guo, & Scott Hsu, Los Alamos National Laboratory
Email: xtang@lanl.gov; Phone: 505-665-2141

Plasma Feedback by Plasma-Materials Interaction (PMI)

The plasma exhaust of particle and energy to a material surface is regulated by a non-neutral sheath that is on the order of plasma Debye length [1]. This is generally known as the sheath boundary condition for plasma exhaust, which provides both a physical constraint for plasma sustainment [2-6] and a boundary condition for fluid and reduced kinetic (such as drift-kinetic or gyrokinetic) modeling of tokamak plasmas [7,8]. The precise sheath boundary condition involves two quantities at the sheath entrance. The first is the well-known Bohm criterion which constrains the parallel exit flow speed to be sonic or supersonic at the sheath entrance. The second concerns the sheath energy transmission, which is the species energy flux normalized by the plasma particle flux times the local plasma temperature. Ideally this dimensionless parameter is an intrinsic property of the plasma sheath, so a general result can be used as the boundary condition for SOL modeling.

The feedback of the material wall to the SOL plasma, which is in response to the sheath particle and energy transmission to the wall, is through the so-called plasma recycling. Although impact electrons are typically absorbed by the wall surface, the ions are mostly returned to the plasma, but as neutral particles. In other words, the ion particle recycling coefficient, which is the ratio of returned neutral and impacting ion flux, is approximately unity. The ion energy recycling, which is defined as the ratio of the returned neutral energy flux and the incoming ion energy flux, sensitively depends on the choice of the wall material. Recent molecular dynamics simulations [9] have shown that for light ions such as helium on a tungsten wall, the dominant recycling process is reflection. As the result, the returned neutrals retain most of their original kinetic energy, and provide near-unity energy recycling coefficient.

A key piece of plasma physics in sheath energy transmission and ion energy recycling is the sheath potential drop. This comes about because kinetic energy is transferred from the electron channel to the ion channel by sheath electric field. As the result, the ion energy flux at the wall is higher than that at the sheath entrance, by the amount of the sheath potential drop per electron. Coupled with near-unity energy recycling at the tungsten wall by helium ions, this energy flux diversion from the electron channel to ion channel suggests a stronger returned neutral energy flux, reducing the overall plasma energy exhaust to the wall. Consequently light ions can find a high-Z reflective wall difficult to offload the plasma energy flux, creating a bottleneck in overall plasma energy exhaust. The sheath potential drop has a critical role in quantifying this effect.

Predictive Modeling of Sheath Energy Transmission & Potential Drop

The appropriate modeling tool is first-principle kinetic codes that resolve the Debye length and the gyro-orbits of both electrons and ions. We have performed such simulations with comparable electron and ion temperature, and examined the detailed physics that determine sheath potential drop and sheath energy transmission [10]. These simulations are performed in the most relevant regime for a detached SOL plasma, so that the bulk plasma is sufficiently collisional to reach an approximate local Maxwellian. Near the wall, since the mean-free-path is much longer than the plasma Debye length, our kinetic simulations resolve the Knudsen layer physics and provide accurate results on both sheath potential drop and sheath energy transmission, and their dependence on the sheath Knudsen number, which is defined as the ratio of plasma mean-free-path and the plasma Debye length. A key finding is that within the Knudsen layer, the plasma inevitably develops temperature anisotropy and electron/ion temperature separation, and sheath energy transmission needs to take into account this complication, for both ions and electrons. The results [10] are much-improved sheath energy transmission coefficients and the sheath potential drop, which have been adopted in SOL modeling using the SOLPS code [11]. An essential next step is to extend these kinetic simulations and reduced model construction to the cases of oblique magnetic incidence and wall electron emission, both of which are expected for ITER.

SOL Fluid Modeling with Anisotropic Plasma Temperature

For its computational efficiency, fluid models based on Braginskii closure have been widely used in SOL modeling for current tokamak experiments and ITER design. Recent kinetic studies [12,13] have shown that temperature anisotropy can be strong in the SOL, especially in the near-divertor region. A much desired improvement in SOL fluid modeling is the inclusion of temperature anisotropy, especially for plasma ions. To this end, the fluid closure by Chodura et al for anisotropic plasmas [14] is a promising direction. Since the regime of validity for the perturbative scheme in the Chodura closure is in a very restrictive collisionality regime, it is imperative to perform kinetic calculations to contrast and assess the accuracy of the closure [15], along with ways to improve the closure. This is also an area in which innovations in multiscale modeling, such as the hybrid fluid-kinetic formulation [16], can be a game changer.

Experimental Validation

Traditionally PMI and SOL studies are performed as integrated experiments on large tokamaks, even though the feedback of PMI on SOL hinges on a set of well-defined separate physical processes. There is a great opportunity to finding a practical solution of tokamak plasma exhaust by making fundamental discovery of the underlying physics. These include direct and/or indirect measurements of recycling coefficients, sheath energy transmission coefficients, sheath potential drop, and parallel heat flux. Innovation of dedicated diagnostics, along with targeted experimental design based on precise predictions of theory/simulation/modeling, is the key to allow rapid progress in the next 5-10 years.

References:

[1] P. C. Stangeby, The Plasma Boundary of Magnetic Fusion Devices (Taylor & Francis, 2000).
[2] G. D. Hobbs and J. A. Wesson, Plasma Physics 9, 85 (1967).
[3] H. Kimura, H. Maeda, N. Ueda, M. Seki, H. Kawamura, S. Yamamoto, M. Nagami, K. Odajima, S. Sengoku, and Y. Shimomura, Nuclear Fusion 18, 9 (1978).
[4] R. C. Bissell, P. C. Johnson, and P. C. Stangeby, Phys. Fluids B 1, 1133 (1989).
[5] S. Jachmich, T. Eich, W. Fundamenski, A. Kallenbach, R. A. Pitts, and J.-E. Contributros, Journal of Nuclear Materials 363-365, 1050 (2007).
[6] S. Marsen, T. Eich, M. Groth, S. Jachmich, and B. Sieglin, Journal of NuclearMaterials 438, S393 (2013).
[7] R. Schneider, X. Bonnin, K. Borrass, D. P. Coster, H. Kastelewicz, D. Reiter, V. A. Rozhansky, and B. J. Braams, Contrib. Plasma Phys. 46, 3 (2006).
[8] C. S. Chang, S. Klasky, J. Cummings, R. Samtaney, A. Shoshani, L. Sugiyama, D. Keyes, S. Ku, G. Park, S. Parker, N. Podhorszki, H. Strauss, H. Abbasi, M. Adams, R. Barreto, G. Bateman, K. Bennett, Y. Chen, E. D. Azevedo, C. Docan, S. Ethier, E. Feibush, L. Greengard, T. Hahm, F. Hinton, C. Jin, A. Khan, A. Kritz, P. Krsti, T. Lao, W. Lee, Z. Lin, J. Lofstead, P. Mouallem, M. Nagappan, A. Pankin, M. Parashar, M. Pindzola, C. Reinhold, D. Schultz, K. Schwan, D. Silver, A. Sim, D. Stotler, M. Vouk, M. Wolf, H. Weitzner, P. Worley, Y. Xiao, E. Yoon, and D. Zorin, in SCIDAC 2008: SCIENTIFIC DISCOVERY THROUGH ADVANCED COMPUTING, Journal of Physics Conference Series, Vol. 125, edited by Stevens, RL (US DOE Off Sci; Cray; IBM; Intel; HP; SiCortex, 2008) p. 12042, 4th Annual Scientific Discovery through Advanced Computing Conference (SciDAC 2008), Seattle, WA, JUL 13-17, 2008.
[9] V. Borovikov, A.F. Voter, and X.-Z. Tang, Journal of Nuclear Materials 447, 254-270 (2014).
[10] X.-Z. Tang & Z. Guo, "Sheath energy transmission," submitted for publication (2015).
[11] J. Canik and X.-Z. Tang, Sherwood Fusion Theory Conference (2015).
[12] Z. Guo, X.-Z. Tang, and C. McDevitt, Physics of Plasmas 21, 102512 (2014).
[13] Z. Guo and X.-Z. Tang, Physical Review Letters 109, 135005 (2012).
[14] R. Chodura and F. Pohl, *Plasma Phys.* 13, 645 (1971).
[15] Z. Guo, X.-Z. Tang, and C. McDevitt, Transport Task Force Workshop (2015).
[16] X.-Z. Tang, C. J. McDevitt, Z. Guo, and H. L. Berk, Physics of Plasmas 21, 032706 (2014)