LLNL-MI-669942

Develop a Validated Predictive Modeling Capability for ELMs under Detached Divertor Operations

Xueqiao Xu
Lawrence Livermore National Laboratory
xxu@llnl.gov
Friday, April 24, 2015

The objective of this White Paper is to propose guidelines on research needs for development of a validated predictive modeling capability for localized transient events under detached divertor operations. Potential benefits from the researches include filling national and international gap on theoretical research/simulation efforts to investigate the important topics on three-dimensional dynamical interaction between the ELMs and evolution of detachment. Based on the state-of-art high-fidelity simulation capabilities, the project has the potential to transform the future of plasma boundary simulations, including the pedestal, scrape off layer, and plasma-materials interactions, with new and better integrations and validation. It is expected to provide predictive modeling capability for ITER experiments and reactor designs.

Present-day tokamaks and future fusion reactors need a better divertor solution and high performance core/pedestal plasmas. The detached divertor operation offers great promise for a reduction of the heat flux onto the divertor target plates for acceptable erosion. However, the impact of divertor detachment operation by the gas puffing and impurity seeding is a great concern for high performance core/pedestal plasmas, which possibly increases core/pedestal density and impurities, leading to (1) density limits; (2) radiative instabilities and fluctuations; (3) dilution of the deuterium ions; and (4) reduced efficiency of non-inductive current drive for both RF and bootstrap current.

The completely detached plasmas have been experimentally achieved for both L-mode and H-mode discharges in tokamaks on ASDEX Upgrade [1, 2]. The similar evolution of detachment has been recently classified into four phases since ReNeW: (i) onset of detachment; (ii) fluctuating state; (iii) partial detachment of outer target; (iv) complete detachment. During fluctuating state of ELMing H-mode discharges, the inner target is detached and radiative fluctuations at the X-point with a frequency of 6–8 kHz appear during inter-ELM phases. During ELMs the inner target transiently reattaches and the radiative fluctuations vanish. The outer target stays attached. The complete detachment of both targets is correlated to the appearance of intense, strongly localized, stable radiation at the X-point. X-point radiation is accompanied by a loss of pedestal top plasma pressure of about 60%. However, the core pressure changes only by a small percentage. With impurity (such as nitrogen) seeding the edge-localized mode (ELM) frequency increases from the 100 Hz range to a broadband distribution at 1–2 kHz with a large reduction in ELM size. At the same time, the rather well-defined ELM frequency changes into a broadband frequency distribution.

There have been much attentions and research focus on development and validation of two-dimensional steady-state physics models for detached divertor operations [3, 4]. But even the most sophisticated codes are not able to reproduce all experimental observations related to divertor detachment of present-day experiments [5, 6], indicating that there might be some physical processes missing in the codes. For example, (1) in the classical picture, where the parallel transport is dominated by Spitzer heat conductivity, a steep temperature gradient develops at the detachment front as T_e is reduced, the classical Spitzer heat conductivity becomes problematic. The lack of the contributions from hot tail of non-Maxwellian distribution and nonlocal parallel thermal conduction are possible sources of discrepancies among other uncertainties regarding the sources of neutrals and impurities. (2) Observed significant radiation inside the confined plasma at the X-point during complete detachment indicates strong density and temperature gradients near the X-point region [1], which might lead to strong parallel gradient driven instabilities and enhanced transport. Nevertheless to say that there is no theoretical research/simulation efforts to investigate the important topics on three-dimensional dynamical interaction between the ELMs and evolution of detachment as described in ASDEX-U and other tokamak detached experiments.

There are critical research needs to develop a validated predictive modeling capability for localized transient events under detached divertor operations. The suggested elements for prospective researches would include: to (1) investigate density dependence of pedestal stability, turbulent transport and ELMs; (2) magnetic configuration (e.g., flux expansion) on edge pedestal performance; (3) the radiative fluctuations near X-point region; (4) churning motion/turbulent mixing in the vicinity of the second-order null for Snowflake divertor configurations and power sharing between multiple divertor legs; (5) develop integrated understanding of the interaction between the pedestal stability and transport and detached divertor operation. Taking into consideration recent progress on development of fluid [5-10] and Gyro-Landau-Fluid simulations [11-13] since ReNeW, leadership computing benefit, and readiness for progress within a ten-year time frame, the suggested prospective researches can start from the multi-species fluid and Gyro-Landau-Fluid models integrated with kinetic neutrals and drift kinetic ions for neoclassical drifts. Anticipated results would include obtaining fundamental understanding and validated predictive modeling capabilities on

1) Control of detachment
2) Loss of detachment during ELMs
3) Radiation shortfall
4) Effect on pedestal and core confinement
5) Reduction of heat flux and temperature at divertor
6) Radiation distribution, stability and limits
7) Guidance for ITER experiments and reactor designs.

[1] F. Reimold, *et al*, *Nucl. Fusion* **55** 033004 (2015)
[2] S. Potzel, *et al*, *Nucl. Fusion* **54** 013001(2014)
[3] J.M. Canik, *et al.*, Journal of Nuclear Materials (2014)
[4] C. Guillemaut *et al.*, Nucl. Fusion 54 (2014) 093012.
[5] Wischmeier M. *et al*, *J. Nucl. Mater.* **390–391** 250–4 (2009)
[6] J.M.Canik, *et al*, Overview of Boundary/PMI Model Validation, BPMIC Workshop, 2/10/15, San Diego, CA
[5] B.D. Dudson, M.V. Umansky, X.Q. Xu, P.B. Snyder, H.R. Wilson., Comput. Phys. Commun. **180**, (2009) 1467.
[6] X.Q. Xu, B.D. Dudson, P.B. Snyder, M.V. Umansky and H.R. Wilson, Phys. Rev. Lett. **105** (2010) 175005.
[8] X. Q. Xu, J. F. Ma, and G. Q. Li, Phys. Plasmas, **21** (2014) 120704.
[9] T.Y. Xia, X.Q. Xu and P.W. Xi, Nucl. Fusion **53** (2013) 073009.
[10] T.Y. Xia and X.Q. Xu, submitted to Nucl. Fusion **53** (2014).
[11] X.Q. Xu, *et al*, Phys. Plasmas, **20** (2013) 056113.
[12] A. M. Dimits, I. Joseph and M. V. Umansky, Phys. Plasmas 21, 055907 (2014).
[13] C. H. Ma, X. Q. Xu, et al, Phys. Plasmas **22**, issue 5 (2015).

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Written for FES Community Planning Workshops 2015: Integrated Simulations for Magnetic Fusion Energy Sciences.