SNOWFLAKE DIVERTOR STUDIES IN MAST-U TOKAMAK

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Following the first successful demonstration of the snowflake (SF) divertor [1] in ohmic L-mode plasmas in the MAST-U tokamak [2], recent studies have been focused on the SF plasma transport mechanism - the oscillatory twisting motion of plasma in the X-point region (the theoretically proposed "churning mode" [3]) and its impact on edge plasmas. The mode may facilitate heat and particle exhaust in MAST-U over eight strike points, which is a unique aspect of the experimental SF divertor implementation in MAST-U due to its up-down divertor configuration symmetry. Recently performed experiments have utilized a 3 MW neutral beam injection (NBI)-heated, 0.6 MA H-mode discharge scenario to further investigate the SF divertor and validate the modeling predictions. Results include: 1) The attainment of SF-exact, SF-minus, and SF-plus configurations that exhibited the expected SF geometric features over several confinement times, albeit with some degradation in core confinement; 2) Evidence of particle and heat redistribution within the convective SF zone, as indicated by measurements from target Langmuir probes and filtered divertor cameras; 3) Favorable qualitative comparisons with predictions from the multi-fluid transport code UEDGE [4], alongside an improved reduced-magnetohydrodynamic model of the churning mode [5]; 4) Divertor radiated power peaking at the poloidal field (PF) nulls, suggesting a potential pathway to the X-point radiator regime [6].

The SF divertor is characterized by a second PF null located near or at the main divertor X-point resulting in the formation of a broad low PF region and two additional divertor legs (strike points), in contrast to the standard divertor that features only two legs [1]. Studies of the SF divertor previously conducted in the TCV [7], NSTX [8], and DIII-D [9] tokamaks have now been extended to MAST-U, a medium-sized spherical tokamak equipped with an up-down symmetric set of 16 divertor magnetic coils, a comprehensive array of edge diagnostics, and a major research focus on advanced magnetic divertor configurations [10]. The free-boundary Grad-Shafranov equilibrium code FIESTA [11] was employed to design SF configurations with different inter-null distances d_{xx} and orientations, utilizing realistic divertor coil currents [2]. In these experiments, a feed-forward plasma control algorithm based on TokSys simulations was implemented to manage the location of the second PF null [12], enabling steady-state SF configurations for up to 200 ms. The geometric features of the experimental SF configurations included: 1) Inter-null distances d_{xx} =0.01-0.20 m (d_{xx}/a = 0.1-0.4, where a is the minor plasma radius), 2) Connection lengths of up to 30-35 m, an increase by a factor of 1.5-3 compared to the standard divertor (10-15 m) or the Super-X divertor (20-25 m), 3) Up-down symmetric or slightly asymmetric SF configurations, facilitating potential studies of up-down dissimilar divertors.

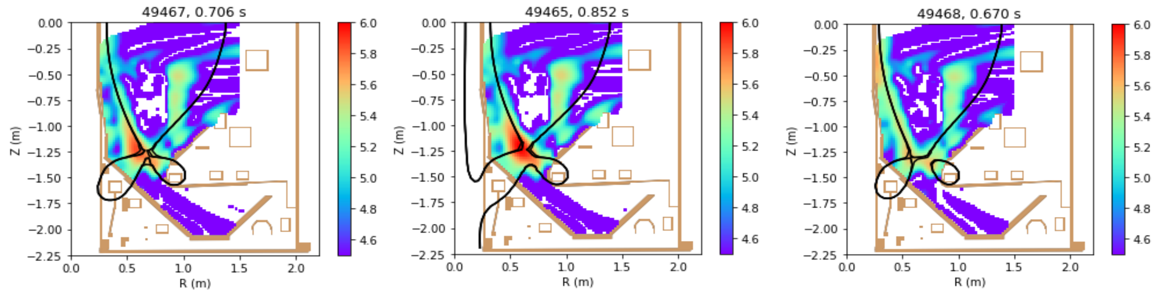

Figure 1. Divertor radiated power measured by the IRVB diagnostic in snowflake divertor configurations obtained in MAST-U: (a) SF-exact, (b) SF-plus, (c) SF-minus

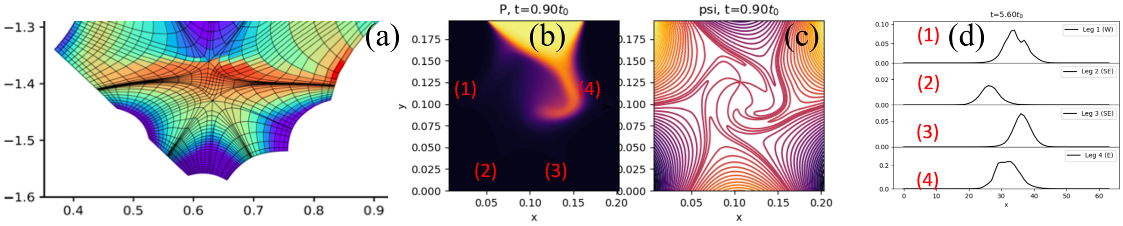

Figure 2. (a) The radiated power peaking in the SF-plus divertor from UEDGE simulations [4], (b)-(d)The churning mode MHD code predictions for the SF divertor pressure, normalized poloidal magnetic flux evolution as well as the parallel heat flux redistribution over the four strike points

The H-mode confinement was successfully maintained in the 3 MW NBI-heated SF discharges, albeit with a reduction of 10-30% during the SF phase. Increases were observed in both pedestal magnetic shear and q_{95}. The pedestal electron pressure height was reduced by up to 25% because of the pedestal temperature reduction while the width remained unchanged. Notably, the pedestal MHD stability operating point was modified, as evidenced by the change in the ELM regime from small or no ELMs to medium-sized ELMs during the SF phase.

Several divertor diagnostic measurements highlighted key features of the SF configurations. Measurements from target Langmuir probes indicated increased ion flux in the secondary SF strike points. Additionally, the multi-wavelength imaging diagnostic revealed increased Fulcher molecular band emission at the additional strike points. These signs of secondary strike point activation were consistent with particle and heat redistribution taking place in the SF convective zone and were in qualitative agreement with the UEDGE model that used ad hoc analytically estimated enhanced poloidal transport coefficients 0-490 m^2/s around the PF nulls [4]. The infrared video bolometer (IRVB) diagnostic showed that the radiated power density peaked around the PF nulls (where the connection lengths were the highest), also consistent with the UEDGE results (Fig. 2a) [4]. The agreement varied for the SF transport levels in UEDGE, i.e., radiation peaking in the model was observed with the weakest plasma mixing and was distributed at the highest mixing levels.

To put the SF transport model on a firmer basis, the previously developed reduced MHD model of the churning mode [5] was extended to both the SF-plus and SF-minus configurations. The formation and evolution of the churning mode are driven by the toroidal field curvature and the vertical plasma pressure gradient (highest during ELMs). Modeling results indicate enhanced convective transport at low d_{xx}. However, as d_{xx} is increased, the magnetic equilibrium can be significantly modified by the churning mode, and the overall SF heat flux redistribution arises from a combination of distorted SF equilibrium and enhanced transport. Simulation results are utilized to derive time-averaged two-dimensional plasma heat and particle diffusivities, the convective zone size, as well as heat flux profiles and redistribution fractions over the additional strike points (as shown in Fig. 2). These findings are used to improve UEDGE simulations and facilitate comparisons with experimental data, in particular, with SOL blob/filament dynamics measured by the MAST-U upper X-point region fast filtered camera.

In summary, recent MAST-U H-mode experiments demonstrated successful SF configurations, and evidence of particle and heat redistribution. Multifluid and MHD code transport modeling is used to study the churning mode offset conditions and impact on divertor exhaust. The unique SF geometry and transport characteristics could improve exhaust control in future tokamak designs. Supported by US DOE SC FES under Contracts DE-AC52-07NA27344, DE-AC05-00OR22725 and DE-SC0018992.

References

[1] D.D. Ryutov, Phys. Plasmas 14 (2007) 064502; D.D. Ryutov et al., Phys. Plasmas 15 (2008) 092501.
[2] V.A. Soukhanovskii et.al. NME 33 (2022) 101278.
[3] D.D. Ryutov et al., PPCF 54 (2012) 124050; D.D. Ryutov et al., Phys. Scr. 89 (2014) 088002.
[4] A. I. Khrabryi et al., NME 26 (2021); A. I. Khrabryi et al., Nucl. Fusion 62 (2022) 016007
[5] M. V. Umansky and D. D. Ryutov, Phys. Plasmas 23 (2016) 030701
[6] M. Bernert, et. al., Nucl. Fusion 61 (2) (2021); V. A. Soukhanovskii et. al., NME 41 (2024) 101790
[7] F. Piras et al Phys. Rev. Lett. 105 (2010) 155003; H. Reimerdes et al PPCF 55 (2013) 124027
[8] V.A. Soukhanovskii et al Nucl. Fusion 51 (2011) 012001; Phys. Plasmas 19 (2012) 082504
[9] V.A. Soukhanovskii et al Nucl. Fusion 58 (2018) 036018
[10] J.R. Harrison et al Nucl. Fusion 64 (2024) 112017
[11] G. Cunningham, Fusion Eng. Des. 88 (2013) 3238
[12] H. Anand et al Nucl. Fusion 64 (2024) 086051