Enabling Advanced Plasma Shapes on MAST-U Spherical Tokamak EX-S

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A newly developed controller assessment framework enabled access, with minimum on-machine development time, to the advanced plasma shapes required for exhaust physics and high power plasma core experiments on the MAST-U spherical tokamak (Fig. 1). This framework, based on control-oriented, experimentally validated models, provides rapid development, assessment, and implementation of plasma shape controllers with a minimum experimental time and high success. This allows development of complex, novel plasma shapes satisfying physical requirements, operational constraints as well as time and budget limitations. This approach can be applied to any new tokamak to develop desired plasma shapes and enable rapid transition to its main mission.

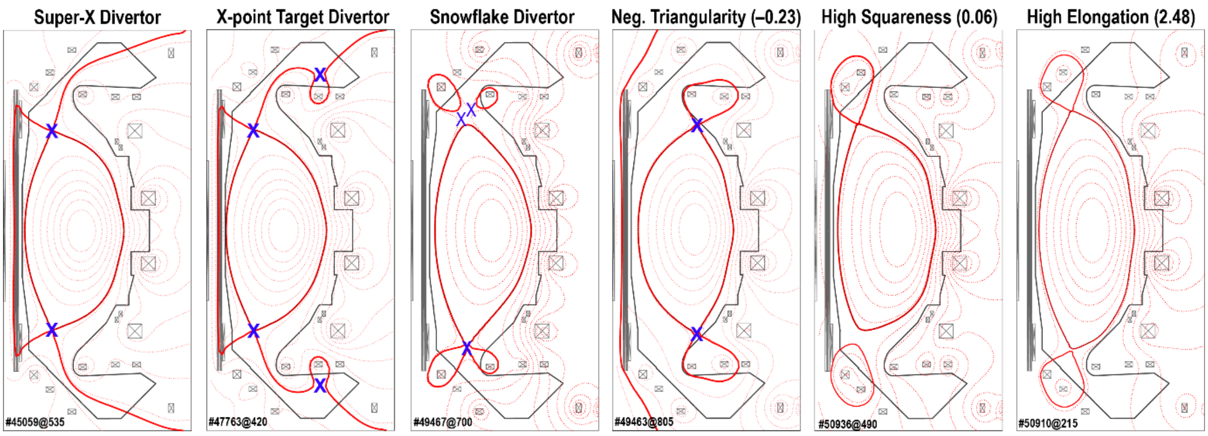

Figure 1: Some of advanced divertor plasma shapes achieved during the 2023 experimental campaign on MAST-U and negative triangularity, high squareness and high elongation shapes achieved in 2024.

The TokSys suite of codes [1] has been adapted to MAST-U as the foundation for the presented controller assessment framework. The device electromagnetic model, experimentally validated power supply and magnetic diagnostic models, as well as linear and quasi-linear (also known as GSevolve) plasma models have been adapted and experimentally benchmarked on MAST-U. These allowed open-loop plasma simulations and development of plasma shape controllers. Connection of the resultant plant model in a closed loop with the plasma control system (PCS) used to control the real machine enabled implementation and assessment of the developed plasma shape controllers in the same environment as the real experiment.

As MAST-U initially lacked plasma shape controller testing and relied on plasma operations with on-the-fly tuning and debugging of the control, first-of-the-kind assessment tools were developed for MAST-U following the principles laid down by ITER [2,3] and added on top of TokSys, making the discussed assessment framework. These tools allow controller design for the plasma shape parameters (Fig. 2-left) based on frequency separation and provide the poloidal field magnetic coil responses required to actuate the desired shape parameter (Fig. 2-right) decoupled from other shape parameters. The controller can be automatically tested statically, by applying a small perturbation to the target equilibrium, and dynamically, via linear and full-shot quasi-linear plasma simulations using the real PCS with the newly implemented controller. The assessment of the controller can be performed for different plasma parameters (resistance, internal inductance, plasma beta, etc.) to evaluate the controller performance metrics and compare them with the design values.

As all components of the controller assessment framework are experimentally validated, assessment of the developed plasma shape controller in closed-loop simulations provides a qualified controller directly applicable in the real experiment and with minimal on-machine development time, primarily for the final adjustment of gains. Using this framework, new shapes with a negative triangularity, high squareness, and high elongation (Fig. 1) have been successfully developed, assessed in the simulation and applied on MAST-U during the 2024 experimental campaign, additionally to the advanced divertor shapes developed in 2023 [4], to enable studies on plasma exhaust, high-power plasma core, and ELM suppression physics.

Presently, the developed framework is essential for implementing new plasma shapes on MAST-U. However, it is not limited to MAST-U and can be utilized on any present and future tokamak to meet the time and shot budget constraints.

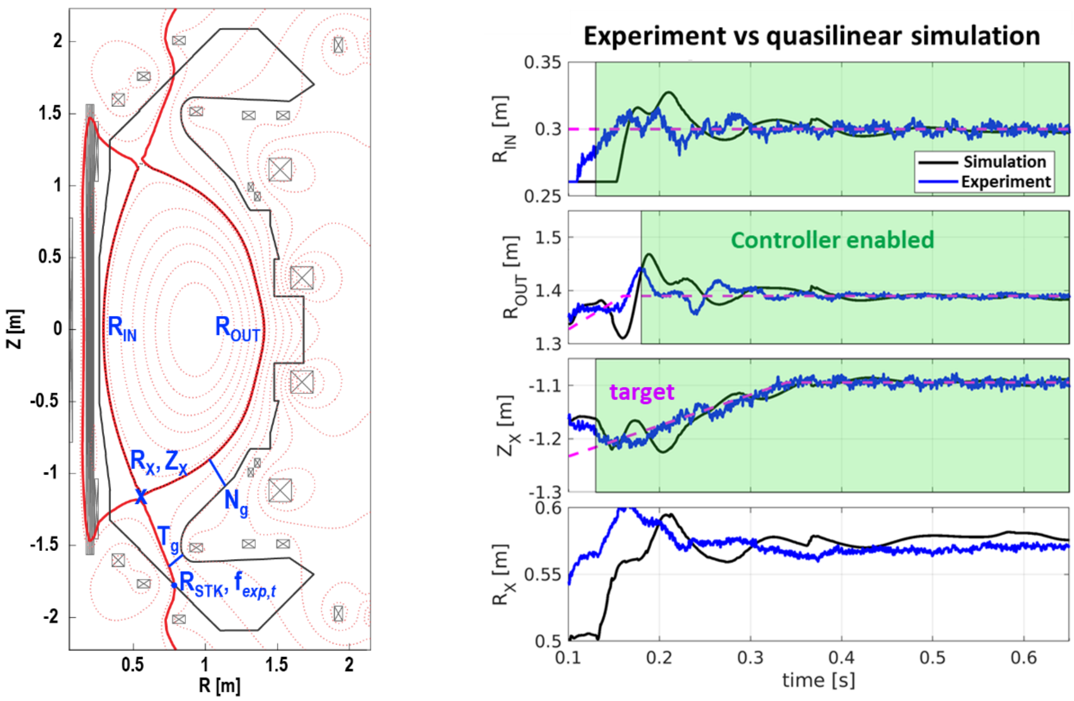

Figure 2: (left) Main plasma shape parameters controlled on MAST-U, where R_{IN} and R_{OUT} are inner and outer boundary radii at the mid-plane respectively, R_X and Z_X are coordinates of the X-point, R_{STR} is the radial coordinate of the strike point, $f_{exp,t}$ is the flux expansion at the target, N_g and T_g are so-called nose and throat gaps. (right) Comparison between control of R_{IN}, R_{OUT}, Z_X in the experiment and simulation, where R_X is not controlled but decoupled.

This material is based upon work supported by the U.S. DOE, under Award DE-SC0018991.

References

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