Research Advancing the Physics of Spherical Tokamaks in Preparation for Operation of NSTX-U

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Both scientific and technical innovation is needed for the realization of an attractive engineering solution for a timely and cost-effective Fusion Pilot Plant (FPP). The spherical tokamak provides a potential transformative route to a more compact and possibly lower cost FPP because of its fundamental properties of enhanced confinement and stability at low aspect ratio, which have been measured in the first generation of high-powered STs [1] (including NSTX). The National Spherical Torus Experiment Upgrade (NSTX-U) is a second-generation ST, which has expanded capabilities that allow it to explore regimes closer to, and in some cases overlapping with, those of burning plasma devices at both conventional and low aspect ratio. The research to be performed in NSTX-U is geared towards answering specific physics questions to determine whether the low aspect ratio path to a FPP is a viable one. The research program will also explore the potentially transformative technology of liquid metal plasma facing components for mitigating the high power exhaust expected in FPPs. This research forms the basis for experimental operation of NSTX-U, which will commence in 2026.

In preparation for operation of NSTX-U, research continues to advance the physics of spherical tokamaks [2]. To extend confinement physics of low-*A*, high beta plasmas to lower collisionality levels, understanding of the transport mechanisms that set confinement performance and pedestal profiles is being advanced through gyrokinetic simulations [3,4], reduced model development [5], and comparison to NSTX experiment. A width-height scaling based on a linear kinetic-ballooning-mode threshold model that explained the experimental scaling observed in NSTX was developed [6]. To develop stable non-inductive scenarios needed for steady-state operation, various performance-limiting modes of instability were studied, including MHD, tearing modes, and energetic particle instabilities [7]. The understanding of reversed magnetic shear operation for improved stability has been advanced [8,9]. Predictive tools were developed, covering disruptions, equilibrium reconstruction [10], and control tools [11,12]. Improved simulation of RF heating [13], including machine learning approaches [14], were also a focus. To develop power and particle handling techniques to optimize plasma exhaust in high performance scenarios, innovative lithium-based solutions are being developed [15] to handle the very high heat flux levels that the increased heating power and compact geometry of NSTX-U will produce, and will be seen in future STs.

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