

The NSTX-U Research Program: closing the gaps towards a Fusion Pilot Plant

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Abstract: There is significant interest both within and outside the U.S. in producing net electricity in a Fusion Pilot Plant based on the Spherical Tokamak concept. With 12 MW of neutral beam heating, 6 MW of High Harmonic Fast Wave heating, and the capability of 2 MA, 1 T, 5 sec discharges, the National Spherical Tokamak Experiment-Upgrade (NSTX-U) is uniquely positioned to target several science and technology gaps in physics regimes close to those expected in a compact, steady-state FPP. In particular, NSTX-U will target the most significant gaps: core confinement improvement, heat flux mitigation, and non-inductive operation in a core-edge optimized plasma with majority self-driven current. NSTX-U capabilities will allow for assessing confinement improvements seen in NSTX and other STs in physics regimes much closer, than ever before, to those anticipated in ST-based FPPs. Both conventional and transformative heat flux mitigation methods, such as liquid lithium plasma facing components, will be developed and tested in-situ in NSTX-U at incident heat fluxes of ~ 100 MW/m², which will inform plans to upgrade to fully heated, high-Z wall and full liquid lithium divertor capability. Non-inductive operating scenarios will be developed through a unique high- β_N , high- κ route.

Introduction

To develop an attractive engineering solution for a cost-effective, compact steady-state Fusion Pilot Plant (FPP), three critical gaps must be closed. The first is improving core energy confinement, the second is to mitigate the high heat fluxes expected in compact systems, and the third is to sustain the plasma non-inductively. Recent studies [1,2] have shown that core energy confinement can strongly influence the size and external heating power required for producing net electric power in a cost-effective FPP. In particular, Ref. [2] showed that energy confinement is the single most critical parameter for reducing FPP cost, with the estimated capital cost decreasing by 50% as $H_{98y,2}$ increases from 0.9 to 1.9.

Not only must a FPP operate with significantly improved confinement over the baseline $H_{98y,2}$ that is being assumed in a number of conventional designs, but solutions to mitigate the steady-state and transient high heat fluxes expected in fusion power producing devices must be developed in an integrated fashion.

NSTX-U [3] is uniquely positioned to assess the ability to close these scientific and technology gaps in an integrated fashion. NSTX-U, with its higher plasma current (2 MA), toroidal field (1T), longer pulse length (5 s), and external heating (up to 12 MW NBI, 4 MW High Harmonic Fast Wave) will be able to assess physics regimes extending well beyond those accessed by NSTX and in a range anticipated for the Spherical Tokamak (ST)-based STEP [4] and STAR [5] Pilot Plants, as is shown in the Fig. 1. Furthermore, NSTX-U can operate with very high heat

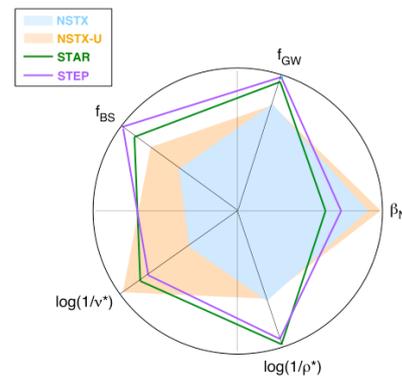


Fig. 1 Physics parameters for NSTX (achieved), NSTX-U (projected), and projections for the STAR and STEP FPP designs.

fluxes (~ 100 MW/m²), and it will be extending the lithium wall conditioning research started on NSTX to implement high-Z walls and a complement of liquid metal components in a phased approach to assess this transformative technology for heat flux reduction, which can be implemented on a variety of magnetic confinement devices at any aspect ratio. NSTX-U will also explore the high- β_N , high- κ route to non-inductive operation with an integrated core-edge solution.

Confinement

Low aspect ratio is potentially an attractive physics basis for a FPP, with the normalized confinement improving much more strongly with decreasing collisionality in STs [6], with $\Omega_c \tau_E \sim B \tau_E \sim \nu^{*-0.8}$, than in conventional aspect ratio tokamaks, where $\Omega_c \tau_{E,ITER98y2} \sim \nu^{*-0.2}$ to 0.0 . The strong increase of normalized confinement with decreasing collisionality in STs offers a potential route to FPP design should these trends continue as parameter regimes extend towards those expected in FPPs.

NSTX-U is well positioned to answer the question of whether the favorable confinement trend continues at lower collisionality and to understand and control the dominant turbulence underlying transport in these more reactor relevant regimes. These lower collisionality regimes will be accessible in NSTX-U even with modest confinement assumptions of $H_{98y2} \sim 1$ to 1.2 . Projections based on a recent version of the Multi-Mode Model (MMM) [7], which has had reasonable success reproducing NSTX performance over a range of beta and collisionality, indicate potential reductions in collisionality by over a factor of five, to values expected for STEP and STAR (see Fig. 2). These projections also indicate normalized confinement times more than five times greater than those achieved in NSTX, and lead to plasmas with stored energies greater than 1 MJ (see Fig. 2). The large reduction in collisionality gives high leverage for establishing the confinement trends and developing predictive models in the phase space closer to FPP conditions.

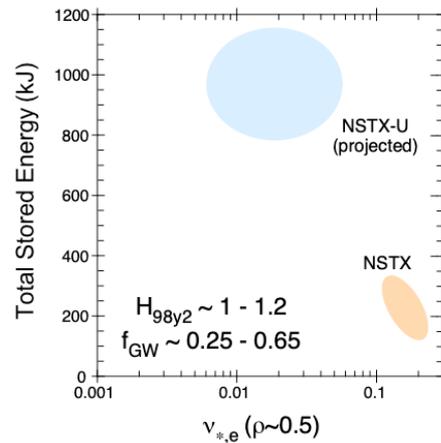


Fig. 2 NSTX-U projections of total stored energy based on the Multi-Mode transport Model as a function of electron collisionality at the half radius.

Of significant importance is to diagnose and understand the microturbulence that controls confinement in these regimes, and to develop schemes to control it. Gyrokinetic calculations indicate that in these projected low collisionality regimes, the high- β Kinetic Ballooning Mode (KBM) dominates in the central plasma region, while Trapped Electron (TEM) and Electron Temperature Gradient (ETG) modes dominate in mid-region and towards the edge. Gyrokinetic analysis of burning-plasma phase STEP plasmas [8] also indicate dominance of a hybrid β -driven KBM/ITG/TEM mode in the inner half of the plasma, and that rotation shear levels comparable to the diamagnet shear leads to mode suppression. NSTX-U is well-positioned to assess the role of rotation, with comprehensive diagnostics, and with rotation control actuators: 12 independent neutral beam sources with torque variations of a factor of seven, High Harmonic Fast Waves (HHFW) for low torque studies, and neoclassical toroidal viscosity from applied 3D edge magnetic perturbations.

In the plasma edge, achieving high pedestal pressure is key to improving confinement throughout the plasma, and it is central to realizing a core-edge optimized plasma. Recent work has resulted in the development of a “gyrokinetic critical pedestal” model, which indicates the importance of KBMs in determining the pedestal structure [9]. This work was able to explain the pedestal height-width scaling observed in NSTX, and it showed that a bifurcation between wide and narrow pedestals exists. The wide pedestal branch exhibits higher pedestal pressure in ELM-free discharges, important for reducing transient heat loads on the plasma facing components (PFCs).

Super-Alfvénic fast ions from the neutral beam will occupy regions of phase space overlapping with those in α -heated plasmas, allowing NSTX-U to explore fast-ion instabilities and their non-linear behavior that might be expected in FPPs.

Power Exhaust

NSTX-U is poised to develop the technology and science to mitigate high heat fluxes due to the narrow scrape-off layer heat flux widths on the order of ~ 1 mm projected for FPPs [10]. Reduced required external heating power associated with high confinement in itself leads to reduced power exhaust, which in turn can lead to longer lifetimes of the divertor, first-wall, and breeding blankets, leading to lower capital costs. However, further reduction is necessary. NSTX-U will study both conventional methods of heat flux mitigation (strike point sweeping, snowflake divertors, and radiation), and through innovative liquid metals, which are an attractive solution for heat flux mitigation and removal [11]. Because of previous favorable confinement results using lithium evaporation ($H_{98y,2}$ values of 1.8 on NSTX-U [12], and up to 2 on LTX-beta [13]), NSTX-U is ideally suited to the use of liquid lithium components. Its flexible PF field coil set can provide equilibria that can focus perpendicular heat fluxes of ~ 100 MW/m² on the outer divertor with 10 MW of auxiliary heating at full plasma current and toroidal field (Fig. 3). Development of this technology is not specific to low aspect ratio tokamaks; it is applicable to any magnetic confinement device at any aspect ratio. The liquid lithium research will be phased; initially, small inserts will be tested in low and high heat flux environments. These results will inform an upgrade to fully heated, high-Z wall and a full liquid lithium divertor.

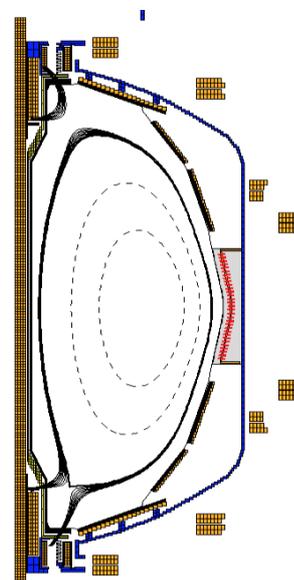


Fig. 3 NSTX-U equilibrium purposefully developed to yield 100 MW/m² on outer divertor.

Non-inductive operation with integrated core-edge

Development of steady-state, high-performance non-inductive scenarios is critical for ST-based Pilot Plants due to limited space at low aspect ratio to support a shielded, OH center column. Fully non-inductive scenarios have been developed for both the STEP and STAR design points. These scenarios rely on very high levels of self-driven (bootstrap) current, which can further reduce the capital cost of a FPP by eliminating the need for high-levels of external current drive.

NSTX-U will take a unique approach to developing non-inductive scenarios through a

combination of high- β_N (and high- β_N/l_i) and high- κ , both of which are essential for maximizing the bootstrap fraction ($f_{BS} \propto \kappa\beta_N/l_i$) and fusion power production ($P_{fus} \propto (R/a)^{-1}[\kappa\beta_N B_T]^4$). NSTX-U is unique among operating STs with its capability of producing high-beta, high-elongation plasmas (see Fig. 4). The ability to operate stably at high- β_N/l_i and high- κ was shown in NSTX with a combination of passive stabilization by close-fitting conducting plates and by active stabilization of the Resistive Wall Mode by induced 3D magnetic perturbations. These stabilization techniques resulted in obtaining stable plasmas with β_N/l_i values of up to 14, well above the no-wall stability limit [14]. Conventional aspect ratio tokamaks have less stabilizing field curvature, and achieve β_N/l_i values of only up to 5, restricting the non-inductive scenarios to those with larger fractions of external current drive. The greater stability at low aspect ratio is attributed not only to the passive and active control methods, but also to the stabilization of global MHD modes by kinetic effects [15], which are predicted to improve in the lower collisionality regime projected for NSTX-U. Scenario modeling has resulted in fully non-inductive operation sustainable for up to 20 to 30 current relaxation times at $\beta_N=3.8$ to 4.5 in NSTX-U at the 1 MA level. Both physics-based and AI-based control schemes will be developed to maintain plasma stability and avoid/mitigate disruptions in these scenarios.

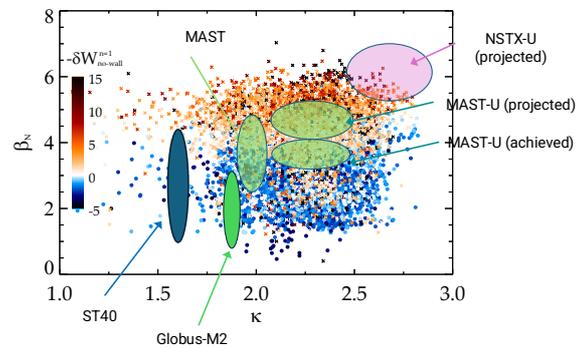


Fig. 4 Normalized beta vs elongation operating space for various STs, on a backdrop of points from NSTX.

Acknowledgements

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