

Progress toward commissioning and plasma operation of NSTX-U *

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The National Spherical Torus Experiment - Upgrade (NSTX-U) project has entered the last phase of construction, and preparation for plasma operations is now underway. A recent areal view of the NSTX-U test cell is shown in Fig. 1, with the newly installed 2nd NBI beam box. The major mission of NSTX-U is to develop the physics basis for an ST-based Fusion Nuclear Science Facility (FNSF) [1]. The ST-based FNSF has the promise of achieving the high neutron fluence needed for reactor component testing with, relatively modest tritium consumption. At the same time, the unique operating regimes of NSTX-U can contribute to several important issues in the physics of burning plasmas to optimize the performance of ITER. The NSTX-U program further aims to determine the attractiveness of the compact ST for addressing key research needs on the path toward a fusion demonstration power plant (DEMO).

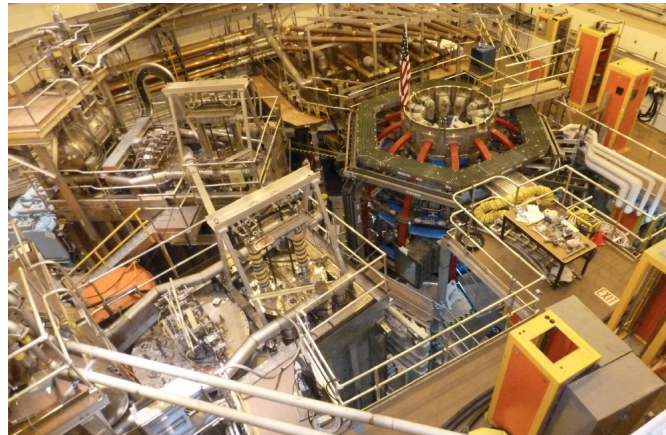


Fig. 1. Areal view of the NSTX-U Test Cell. The newly installed 2nd NBI beam box can be seen in the foreground.

NSTX-U will double the toroidal magnetic field B_T , plasma current I_p , and NBI heating power compared to NSTX, and increase the TF flat top pulse length from 1 s to 6.5 s. The NSTX-U and NSTX device parameters are given in Table 1. The new center stack, shown in Fig. 2, will provide $B_T = 1$ Tesla (T) at a major radius of $R_0 = 0.93$ m compared to 0.55 T at $R_0 = 0.85$ m in NSTX, and will enable a plasma current I_p of up to 2 mega-Amp (MA) for 5 sec compared to the 1 MA for 1 sec in NSTX. The anticipated plasma performance enhancement is a quadrupling of the plasma stored energy and near doubling of the plasma confinement time, which would result in an order of magnitude increase in the fusion performance parameter $n\tau T$. With $\beta_T \sim 25\%$ at $B_T = 1$ T, the absolute average plasma pressure in NSTX-U could become comparable to that of present-day tokamaks. A much more tangential 2nd NBI system, with x 2-3 higher current drive efficiency compared to the 1st NBI system, is installed (Fig. 1). NSTX-U is designed to attain the 100% non-inductive operation needed for a compact FNSF design [1, 2]. With higher fields and heating powers, the NSTX-U plasma collisionality will be reduced by a factor of 3-6 to help explore the trend in transport toward the low collisionality FNSF regime. If the favorable trend observed on NSTX holds at low collisionality, high fusion neutron fluences could be achievable in very compact ST devices.

	R_0 (m)	A_{min}	κ	I_p (MA)	B_T (T)	t_{TF} (s)	NBI (MW)	f_{NI}, f_{BS} (%) @1MA
NSTX	0.854	1.28	2.8	1	0.55	1	7	<70, <60
NSTX-U	0.934	1.5	2.8	2	1	6.5	14	≤100, ≤80

Table 1. NSTX and NSTX U Parameters

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stubs at both the lower and upper ends that bolt to flex joints to the outer TF legs. Each conductor is provided with a cooling passage soldered into a groove on one side of the wedge with resin-based flux. All of the NSTX upgrade coils will be vacuum pressure impregnated using the CTD resin system CTD425, which is a cyanate ester spoxy blend with low viscosity to aid the impregnation process. The shear bond strength of the cured epoxy-glass composite is 40 MPa even at 373 degrees K. The turn-to-turn insulation is rated for 3.8 kV. The OH coil is being wound in place on a 2.5 mm thick cylinder of moldable Aquapour mandrel material cast over the cured TF bundle. The Aquapour mandrel material is designed to easily wash away after coil curing, to leave a thin but uniform air gap between the TF bundle and OH coil for thermal expansion and motion between the two coils. Once the Aquapour has been removed, the TF bundle will be supported externally at the top and bottom of the Center Stack to center it within the OH coil. The TF bundle is connected to the outer TF legs using a high strength Full-Hard C15100 Cu-Zr copper alloy flex joint. The flex joint has to accommodate the vertical cyclic movement due to the growth of the TF bundle (~ 1 cm), while resisting the $j \times B$ force of ~ 130 kA of current through the joint. The flex connection was fabricated from a solid U-shaped copper alloy piece by making 15 precision parallel cuts via electric discharge machining. The flex joint has successfully passed a ~ 300k cycle load test. The doubling of magnetic fields and plasma currents increases electromagnetic forces by ~ a factor of four. Accordingly, the vacuum vessel and the support structures were enhanced. To protect NSTX-U from unintended failures due to the power supplies delivering current combinations and consequential forces or stresses beyond the design-basis, a digital coil protection system (DCPS) is being implemented. The DCPS is designed to prevent accidental (either human or equipment failure) overload beyond the design conditions of the structure which the power supply system could generate, even while each individual power supply is operating within its allowable current range. Approximately 100 force-based and 14 thermal algorithms are anticipated with a 200 μ s update rate. Redundant current measurements for each coil and plasma current will be provided as inputs.

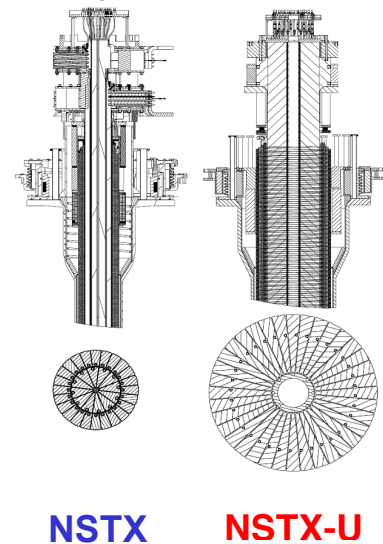
In addition, NSTX-U will have a 6 MW High-Harmonic Fast Waves (HHFW) system for heating and current drive. The HHFW antennas are being modified with compliant feeds for ~ four times larger disruption loads and improved voltage stand-off. The total auxiliary heating power of 20 MW provided by the NBI and HHFW systems will allow NSTX-U to uniquely produce FNSF/DEMO-relevant high divertor heat fluxes of ~ 40 MW/m². Innovative divertor heat and particle solutions, such as the up-down symmetric, high flux expansion snowflake divertor configuration, will be used to control these heat fluxes. NSTX-U is also equipped with a set of six non-axisymmetric (3-D) control coils, which can be independently controlled to enhance plasma stability at high beta, control error fields, and apply resonant magnetic perturbations for ELM control. NSTX-U will continue to explore the use of lithium PFC coating techniques for enhanced plasma performance, and divertor power and particle handling. A lithium granular injector will be implemented for ELM pacing at high injection rate to control impurities and reduce the peak ELM heat flux. Coaxial helicity injection (CHI) will be used to create plasmas with up to ~500 kA non-inductively, and develop the solenoid-free tokamak/ST design basis needed for FNSF. If successful, it can also simplify the design of conventional reactors. NSTX-U first plasma is planned for November 2014, at which time the transition to plasma operation will occur.

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[1] J.E. Menard, S. Gerhardt, M. Bell et al., *Nucl. Fusion* **52**, 083015 (2012).

[2] S. P. Gerhardt, R. Andre, and J.E. Menard, *Nucl. Fusion* **52**, 083020 (2012).

[3] L. Dudek, J. Chrzanowski, P. Heitzenroeder, et al., *Fusion Engineering and Design* **87**, 1515 (2012).



NSTX **NSTX-U**
 Fig. 2. NSTX and NSTX-U center stack schematics and the TF coil cross sections.