Contributions of NHTX to high-performance steady-state plasma development

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The National High-power Advanced Torus (NHTX) is described[1] largely in terms of its contributions to Theme 3, "Taming the Plasma-Material Interface." However, beyond the requirement for accessing Demo-relevant high heat flux and high first-wall temperature, very long pulse-length (10^3s per pulse, 10^6s per year, both extensible) operation is required to enable equilibration of the plasma facing components. Achieving these pulse durations is only possible with full non-inductive current drive and is effectively steady-state. Further, while NHTX does not rely on very high performance to achieve its PMI mission, access to high β, high bootstrap fraction, and high confinement is possible. Thus, NHTX could contribute strongly to the development of high-performance steady-state plasmas. Below we outline NHTX contributions according to the issue list of ReNeW Theme II.

1. Measurement

The very long pulses planned for NHTX and the very high temperature of the first wall and divertor will provide the main non-nuclear aspects of diagnostic requirements for Demo. In particular, the high power, high duty factor and Demo-relevant PFC materials and temperature will provide highly relevant experience with coatings of mirrors and windows. The special challenge on NHTX to develop regimes without significant off-normal events, neither significant ELMs nor disruptions, will drive the development of diagnostics that can permit control and assurance of this stable mode of operation.

2. Control

An important issue for proposed AT and ST Demo operating scenarios is the challenge of operating with very high bootstrap fraction (90-99%), high beta (within 10% of the ideal-wall stability limit), and low toroidal rotation for very long pulses. With a powerful and flexible neutral beam injection (NBI) system, control of the current and rotation profiles in NHTX is expected to be developed for optimizing confinement and stability for very long pulses to fulfill the NHTX PMI mission. With operation at higher density near the Greenwald limit, and possibly with NBI counter injection, high bootstrap fraction (80-90%) and high normalized beta ($\beta_N \sim 6\text{-}7$) can in principle be accessed at low toroidal rotation. In this Demo-relevant environment, control methods for error fields, resistive wall modes, ELMs, and (possibly) NTMs can be developed and optimized for very long pulses. NHTX can also be utilized to assess the real-time diagnostic and control requirements for stable steady-state high-performance operation.

At intermediate Greenwald fractions (~0.5), initial calculations for NHTX indicate that 170GHz X-mode EC waves launched far off-midplane and at the outboard side of the plasma can be efficiently absorbed at the 3rd (and 4th) harmonic high-field-side resonances. Thus, scenarios with reduced momentum input and strong electron heating

[1] See http://www-pub.iaea.org/MTCD/Meetings/FEC2008/ft_p3-12.pdf

could be tested in NHTX with application to ST-CTF, ST-Demo, and higher aspect ratio Demo concepts. Further, with lower Greenwald fraction operation prototypical of ST-CTF (~0.25), driven current efficiencies of 20-30kA/MW are achievable inside $r/a < 0.4$. With 10-30MW of ECCD, local driven current densities comparable to the average equilibrium current density (~1MA/m^2 in NHTX) appear achievable, and direct NTM control may in fact be possible on NHTX enabling tests of very long-pulse NTM control with application to ST-CTF and ARIES-AT.

3. Integration

NHTX is designed to access high divertor heat flux (P/R = 40-50MW/m) for a wide range of H-mode confinement enhancement factors (H_{98}=0.8-1.5) and normalized densities (Greenwald fraction = 0.3-1). Thus, NHTX can inform the accessibility of H_{98} up to 1.5 as assumed for ST-CTF operation and approaching the value of H_{98} = 1.6 assumed for FDF operation. Similarly, NHTX is projected to be capable of operating in steady-state at normalized β values (baseline β_N = 4-5, range = 3 to 6-7) that can prototype scenarios with beta values below the no-wall limit to values approaching the ideal-wall limit. At low density, NHTX can assess scenarios with a mid-range (50-70%) of bootstrap fraction, while at higher density (Greenwald fraction ~ 0.8) the bootstrap fraction is projected to be 80-90%, which is approaching the nearly-fully bootstrapped scenarios proposed for ST and AT DEMO at similar normalized density. The pedestal and ELM regimes of NHTX would also be directly relevant to CTF, and the configuration flexibility of NHTX would enable optimization of RMP ELM control.

Uniquely in the world program, NHTX can test the compatibility of the Demo-relevant PFC-related characteristics of long pulse, high power, and a high-temperature first wall with high plasma performance. As is well known, plasma wall interactions have critically important, and not fully understood, effects on integrated plasma performance. Just as one example among many, very long pulse operation with Demo-prototypical plasma conditions may have strong effects on operation at high performance with heat-flux mitigation by gas puffing to provide partial divertor detachment. The balance between gas-puff, plasma pumping, wall pumping and divertor exhaust may be quite different under these circumstances than under conditions experienced to date.

4. Modeling

NHTX will be equipped with a full set of plasma diagnostics to permit the study and optimization of high-performance plasma operation. Coupled with results from KSTAR, EAST and JT-60SA, results from NHTX operating at A = 1.8 – 2.0 should provide the necessary breadth of data to challenge models of confinement and stability, and so permit an informed choice of aspect ratio for Demo. NHTX will be equipped with world-leading diagnostic capabilities for the plasma edge, scrape-off layer, and divertor region. Very broad diagnostic coverage will be provided for plasma-wall interactions. Thus NHTX will provide a unique opportunity to challenge and qualify advanced models of the plasma physics in this region, as well as the plasma-wall interactions at Demo-relevant heat and particle flux, long pulse, and high PFC temperature.

5. Auxiliary systems

NSTX will be equipped with a full set of auxiliary systems, including neutral beams, ICRF launchers, ECH launchers, LH launchers to test current ramp up (a full transformer is supplied as well), and pellet injectors. All of these systems will be tested at Demo-relevant high power and long pulse, and in a hot-walls environment. This will provide a uniquely valuable opportunity to determine the effects of the high-power plasma on these components, and the effects of these components on the plasma and plasma-facing components. The experience on Tore Supra was most salutory in this regard. For example the very long pulses at high power provided the opportunity to find *all* of the regions of unexpected power depostion on ICRF and LH antennas. The first-time use in NHTX of high-pressure (100 atm) He-jet cooled tungsten divertor components and of liquid-metal plasma facing components, at high power, long pulse and high temperature, is a critical step before employing such new technologies that must be implemented in CTF and Demo.

6. Magnets

NHTX will address many of the concerns associated with steady-state, high-field, normally conducting magnets at field strengths similar to those planned for ST-CTF and ST-Demo. Issues of demountable joint design at high current will be addressed directly, and this experience will benefit not only an ST-based component test facility design, but also possibly FDF design. Furthermore, the maintenance scheme planned for NHTX is very similar to that planned for ST-CTF, ST-Demo, and FDF, as it incorporates a single vertical lift to remove an activated vacuum vessel, for replacement (in the case of NHTX) with a vessel carrying an alternative PFC configuration.

7. Off-normal events

With 10^6 seconds of operation per year (extensible) and fully-non-inductive high-performance plasmas, NHTX will greatly advance the plasma control and disruption avoidance techniques needed for a tokamak Demo. Disruption issues that can be studied include: characterization of disruption type and frequency of occurrence, detection of disruption precursors and disruption avoidance for very long pulses, disruption mitigation, and studies of the impact of disruption electromagnetic and heat loads on the high-heat-flux and high-temperature plasma-facing-components prototypical of CTF and Demo.

While the plasma current of NHTX is relatively low (3-4MA) such that the runaway electron avalanche multiplier is many orders of magnitude lower than expected in CTF or Demo, runaway generation should be possible, and leading techniques for suppressing runaways can be tested. The interaction of runaways with Demo-relevant plasma facing components (i.e. high-temperature metallic walls and solid or liquid divertor) can also be studied.

For edge localized modes, conditions can be established in which repetitive and relatively large ELMs are used to determine the largest repetitive ELM energy loss that is acceptable for adequate first-wall lifetime in ST-CTF, FDF, and Demo. Regimes with these lower levels of ELMs can then be developed for scientific study and validation. Utilizing an extensive array of 3D magnetic field coils sets, NHTX could also simulate the impact of reduced 3D field coil capabilities (due to increased plasma-coil distance due to increased neutron shielding requirements) expected in the high neutron flux/fluence environment of ST-CTF/FDF and DEMO.

The magnitude and range of fast-ion instability drive is expected to be reduced in NHTX relative to present NSTX and MAST experience, since the NBI energy anticipated for NHTX (~110keV) is only modestly higher than in present experiments (70-90keV) whereas the toroidal magnetic field is expected to be ~4 times higher. However, at the highest ratios of fast-ion (from NBI) to total plasma beta, NHTX plasma may be susceptible to TAE avalanches as observed on NSTX. Short-pulse (~few seconds) 50/50 D/T experiments on NHTX could also shed light on alpha confinement and instability drive for the first time in an ST. ICRF can be used to energize a small minority of He ions in the plasma, to investigate the effects of He on the plasma facing components. These energetic particle capabilities would enable an assessment of the impact of frequent energetic particle loss on a Demo-relevant first wall.

Finally, while NHTX is expected to have a comprehensive diagnostic set for real-time control to support sustained long-pulse operation, once such regimes have been established and controlled, NHTX could also be used to simulate the impact of reduced diagnostic capabilities expected in the high neutron flux/fluence environment of ST-CTF/FDF and Demo.

Conclusion

NHTX is very well suited to developing the understanding and demonstrating the techniques necessary for steady-state high-performance operation of tokamaks as a function of aspect ratio, particularly as data from NHTX can be compared and contrasted with higher-aspect ratio operation of KSTAR, EAST and JT-60SA. Due to its long pulse, high power, high-temperature first wall, high access and flexibility, and ability to support advanced control tools, NHTX can provide experience with the integrated PMI and plasma characteristics most relevant to the high-performance operating scenarios proposed for CTF (ST and AT) and for Demo.