Contributions of NHTX to the ST Development Path

Rob Goldston, Jon Menard (PPPL), Steve Sabbagh (Columbia University)

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 the requirement for Demo-relevant high P/R (power / major radius) without excessive P/S (power / surface area) drives the design of NHTX to low A. The ST is particularly well suited to this mission, also, because it provides excellent access for diagnostics, for heating and current drive, and for PFC services. Extreme flexibility is provided by the feature that the entire vacuum vessel can be changed out with a single vertical lift.

A low aspect ratio device at the current NHTX "existence proof" design point would also be able to contribute very substantially to the ST development path. Here we outline those contributions according to the issue list articulated by the ST Panel.

Start-up and Ramp-up

While NHTX will be equipped with a solenoid for inductive start-up, it can be designed to test each of the other techniques being considered for ST start-up in support of ST-CTF and ST-Demo, including CHI, plasma guns, EBW, PF induction with external coils, and limited solenoidal flux as would be available from a MIC solenoid or an iron core. Ramp-up can be studied with NBI, HHFW, EBW/ECH, LHCD and appropriate combinations thereof. Pomphrey et al.[2] have found that Resonant Magnetic Perturbation coils can be used to form a low transform stellarator configuration in NHTX. The closed magnetic surfaces that are created would be well suited to confining the energetic electrons required for low density LHCD or ECCD start-up and ramp-up experiments. Results from NHTX will provide key confidence for extrapolation to the 10 MA current range required for ST-CTF.

Plasma-Material Interface

NHTX is designed to excel in the area of the plasma-material interface[3]. Its long pulses, high power and high-temperature walls, as well as excellent accessibility and flexibility make it uniquely well suited to addressing this critical issue for the ST. Both P/R and P/S in NHTX are very similar to their values in ST-CTF. Trace tritium capability will assure the ability to study tritium retention with ST-CTF relevant high temperature PFC's. NHTX will be designed to test a range of plasma facing materials, both solid and liquid, as well as a range of divertor geometries, including the Super-X configuration. It will be equipped with pumping to explore the low density operation required for ST-CTF to meet its current-drive efficiency requirements.

---

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

[2] See White Paper by Pomphrey et al., submitted to this workshop.

[3] See White Papers by Goldston, by Goldston & Doerner, and by Wilson, Goldston and Hosea submitted to Theme 3 workshop.

Electron Energy Transport

NSTX and MAST results indicate that electron energy confinement depends strongly on electron collisionality, and scales differently than in standard aspect ratio tokamaks. In particular, the observed electron energy confinement scaling with magnetic field is nearly linear, whereas the dependence is much weaker in tokamaks. This finding is a strong motivation for proposed upgrades of MAST and NSTX to higher field (and current) to expand the ST operating space to within a factor of 2 of the magnetic field expected in ST-CTF. There are several possible micro-instabilities that may contribute to electron transport in the ST, including: CTEM, ETG, micro-tearing, and GAE modes. Because of the complexity of anomalous electron transport mechanisms, developing a predictive capability for electron transport is extremely challenging for both STs and tokamaks, but the ST data base is much less complete. ST operation at the full ST-CTF magnetic field would provide critical data for assessing whether sufficiently high electron temperature can be achieved to support the proposed high fraction (~50%) of neutral beam current drive proposed in ST-CTF. The size and toroidal field strength of the NHTX and ST-CTF conceptual design points are comparable (both within 25%), and the expected plasma current of NHTX at low Greenwald fraction (~0.25) would be 4-5MA (with positive neutral beam injection) which is within a factor of 2 of the proposed operating plasma current for ST-CTF (8-10MA). As a result, NHTX is projected to access plasma collisionalities within a factor of 2-3 of ST-CTF. Thus, NHTX could provide definitive assessments of the transport mechanisms most likely to dominate ST-CTF plasmas and provide greatly enhanced confidence in ST-CTF design. Importantly, for the baseline Greenwald fraction of NHTX (~0.4-0.5), the electron collisionality of NHTX is comparable to that expected in an ST-DEMO and could help inform electron confinement expectations for ST-DEMO.

Integration at High Beta

As described above, the size, field, current, normalized density, and collisionality (and ρ^*) of the NHTX conceptual design point are sufficiently close to that of ST-CTF that integrated scenarios developed on NHTX are highly relevant to ST-CTF. 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. Similarly, NHTX is projected to be capable of operating at normalized β values (baseline β_N = 4-5, range = 3 to 6-7) that can prototype ST-CTF operating 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-DEMO at similar normalized density. Kink/ballooning, resistive wall mode (RWM), and ELM control will be afforded by a flexible non-axisymmetric coil system, which could also be designed to impart external magnetic rotational transform (as mentioned above). The pedestal and ELM regimes of NHTX would also be directly relevant to ST-CTF, and the configuration flexibility of NHTX would enable optimization of RMP ELM control.

Magnets

NHTX will address many of the concerns associated with ST 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, for example. Furthermore, the maintenance scheme planned for NHTX is very similar to that planned for ST-CTF and ST-Demo, including 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.

Stability and Steady-State Control

With a powerful and flexible neutral beam injection system, control of the current and rotation profile in NHTX could be developed for optimizing confinement and stability for very long pulses for ST-CTF. The flexibility in profile and β_N operational regimes, and plasma rotation control afforded by variation of NBI and the application of a broad spectrum non-resonant magnetic fields to induce torques, will allow research to understand the physics of kink/ballooning and resistive wall mode optimization over a large range of equilibria and β_N approaching ST-DEMO levels. Especially important in this study is the reduced ion collisionality, rotation control, and hot particle profile variation, which influence RWM stabilization and non-resonant neoclassical toroidal viscosity (NTV) torques on the plasma. Similarly, control methods for error fields, resistive wall modes, ELMs, and (possibly) NTMs can be developed and optimized to minimize variations in plasma stored energy and neutron production for very long pulses in a stability parameter regime directly relevant to ST-CTF. NHTX can also be utilized to assess the real-time diagnostic and control requirements for stable steady-state high-performance operation, and to simulate the impact of reduced diagnostic capabilities and 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 and ST-DEMO.

Disruptions

NHTX will provide a bridge between current experiments and ST-CTF on the prior detection of disruptions, their impacts and their mitigation. Flexibility of equilibrium and rotation profile, coupled with advanced physics-based control systems for global instability detection (e.g. resonant field amplification detection, state-space RWM control) will provide the greatest capability to minimize plasma stored energy fluctuations. The long pulses and high duty factor operation of NHTX in ST-CTF prototypical operating modes will allow disruption prediction techniques to be qualified, and the operation modes themselves to be optimized. Conditions can be established in which repetitive relatively large ELMs are used to determine the largest repetitive ELM energy loss that is acceptable for adequate first-wall lifetime in ST-CTF. Regimes with these levels of ELMs can then be developed for scientific study and validation.

RF Heating and Current Drive

NHTX can be equipped with the full complement of RF systems that would be planned for ST-CTF and ST-Demo, since NHTX will have similar field strength and plasma density to these devices. The device is designed to test the impact of 50 MW of heating.

For optimal flexibility this will likely include ~30 MW of continuous NBI heating, and ~30MW of installed RF capability (see discussion of NTM control below).

Ion Scale Transport

With ~30MW of co-injected neutral beams and with operation at normalized densities comparable to those expected in ST-CTF, NHTX is expected to operate with high toroidal rotation and rotational shear such that ion turbulent transport is strongly suppressed and a "hot-ion" H-mode is routinely accessed. This ion-scale turbulence and transport regime is directly relevant to the operating scenarios proposed for ST-CTF and experience with these regimes on NHTX would significantly enhance the confidence in designing ST-CTF with respect to ion energy confinement expectations.

Fast Particle Instabilities

The magnitude and range of fast-ion instability drive is expected to be markedly 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 marginally susceptible to TAE avalanches observed on NSTX. TAE avalanches driven by fusion alphas may also be a concern for ST-CTF, and if present, could cause redistribution and/or loss of both the fusion alphas and the neutral beam current drive. Short-pulse (~few seconds) 50/50 D/T experiments on NHTX could shed light on alpha confinement and instability drive for the first time in an ST. However, additional calculations are needed for NHTX and ST-CTF to assess expected alpha confinement – in particular for proposed operating scenarios with low internal inductance and/or reduced plasma current.

Neoclassical Tearing Modes

Initial calculations for 110kV neutral beams in NHTX indicate that variations in injection tangency radius and/or vertical position can provide off-axis current drive with high efficiency enabling steady-state scenarios with elevated q profiles with $q_{min} > 2$. Such operating scenarios have been proposed for ST-CTF to avoid NTMs resonant with low-order rational surfaces (3/2, 2/1). Thus, NHTX could provide definitive tests of the ability to avoid low-order NTMs with equilibrium current profile control without direct active feedback control of the NTM and assess the stability of these reduced l_i equilibria to more global instabilities. Further, in over-dense plasma conditions accessible on NHTX, EBW current-drive could be developed and tested for NTM control for both ST-CTF and ST-DEMO. Interestingly, at the low Greenwald fractions (~0.25) proposed for ST-CTF, 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 with driven current efficiencies of 20-30kA/MW 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 and ST-CTF - provided the low-order rational surfaces are sufficiently far from the plasma edge.

Continuous NBI Systems

NHTX as currently conceived works very well with 110 kV neutral beams, upgraded to steady-state operation as had been designed for the TPX Project. This experiment will provide the U.S. fusion community with its first physics and technology experience with continuous beam operation, and will allow many of the issues identified by the Theme 5 ST Panel to be studied in a practical environment.

Conclusion

NHTX is extremely well suited to providing a bridge to ST-CTF and ST-Demo. Due to its long pulse, high power, high-temperature first wall, excellent access for diagnostics, heating and PFC services and high flexibility, it will provide a uniquely capable test-bed to develop the science and technology to proceed with the following steps in the ST development path.