Engineering Assessment of a National High-power Advanced Torus Experiment (NHTX)

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Abstract— **A major challenge facing fusion development is the high heat flux power handling of plasma exhaust, for which a defining parameter is P/R, the ratio of exhaust power P to the radius R at which the divertor is located. Preliminary studies indicate that a compact, cost effective device can be constructed at PPPL exploiting existing infrastructure which could operate at P/R ~ 50, well in excess of levels available elsewhere and including future ITER operations. The mission for a National High-power advanced Torus Experiment (NHTX) would be to study the integration of a high P/R plasma-boundary interface with high-confinement, high-beta, non-inductive plasma operation.**

Keywords-fusion, high heat flux, plasma boundary

I. INTRODUCTION

A major challenge facing the development of fusion is the high heat flux power handling of plasma exhaust, for which a defining parameter is P/R, the ratio of exhaust power P to the radius R at which the divertor is located. Economic fusion power plant designs typically require P/R in the range of 100 MW/m. ITER will operate at P/R ~ 24 MW/m, while other planned long-pulse experiments range only up to P/R ~ 15 MW/m. Preliminary studies indicate that a compact, cost effective device can be constructed at PPPL exploiting existing infrastructure which could operate at P/R ~ 50, well in excess of levels available elsewhere and including future ITER operations. Moreover, such a device could be designed with high heat flux and plasma boundary testing as a primary objective and facilitate experiments on multiple first wall and divertor concepts in a preparatory D-D environment, followed by a brief D-T campaign. Thus the mission for a National High-power advanced Torus Experiment (NHTX) would be to study the integration of a high-power-flux plasma-boundary interface with high-confinement, high-beta, non-inductive plasma operation. The engineering assessment reported herein has identified and begun to develop solutions for the key engineering features of the machine.

II. DESIGN POINT

Parametric studies including basic physics and engineering algorithms [1] performed over a range of major radius R_0 and aspect ratio A have identified an attractive design point as summarized in Table I.

TABLE I. NHTX DESIGN POINT

Major Radius, R_0	1.0m
Aspect Ratio, A	1.8
Plasma Current, I_p	3.5MA
Toroidal Field, B_t	2.0T
Auxiliary Heating Power, P_{aux}	50MW
Pulse Length in D-D	1000s
Fusion Power in D-T	30MW

An isometric view of NHTX is given in Fig. 1 along with several plasma cross section views in Fig. 2, showing the flexibility in plasma shape control including variation in flux expansion at the divertor over a range of 3 to 30 times the midplane scrape-off-layer width. Fig. 3 shows a cross section of the machine.

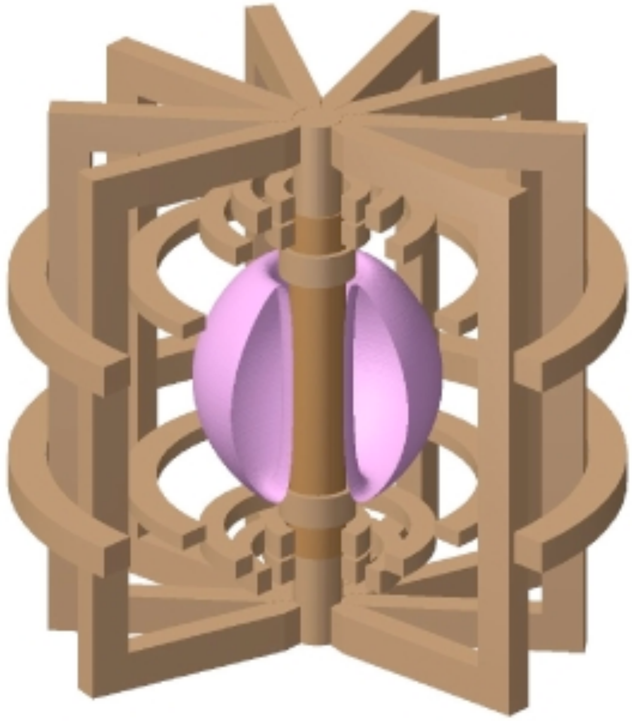

Figure 1. Isometric Viwe of NHTX

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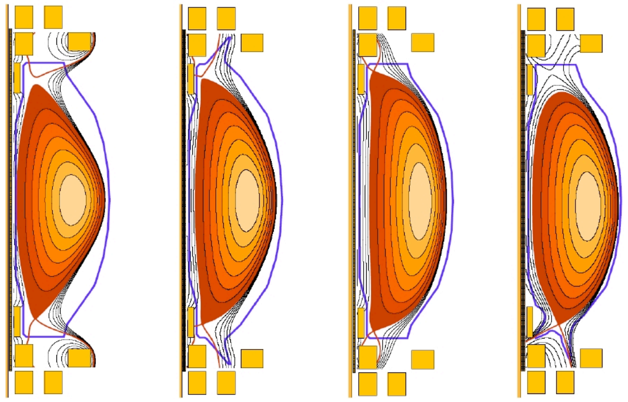

Figure 2. Cross section views of NHTX plasma showing (l to r) Double Null Divertor (DND) w/negative squareness, DND w/zero squareness, DND w/positive squareness, and ITER-like Single Null Divertor (SND)

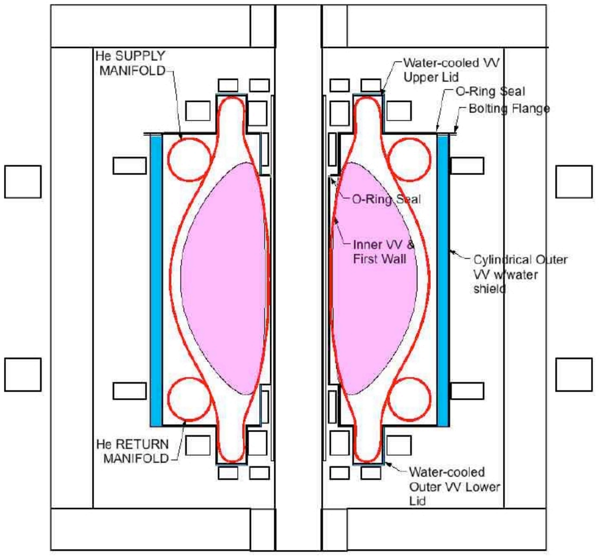

Figure 3. Cross section of NHTX device

III. MISSION ELEMENTS AND SOLUTIONS

The following section highlights the main elements of the mission and the solutions which have been incorporated. Key design features are described in subsequent sections.

A. High P/R

To maximize P/R the major radius of the machine is to be minimized. This also implies that the radius of the inner core of the device, containing the inner leg of the TF and the central solenoid (CS) should be minimized. For the CS, a limited inductive capability is assumed with a single swing of current to initiate and ramp the plasma current to flat top, with the CS current remaining at zero current for the remainder of the pulse. With this assumption for the CS, and the engineering algorithms in place for water cooled copper TF and PF coils, the systems code parameter scan indicates the minimum major radius which can handle 50MW of auxiliary heating power occurs at R_0=1.0m and that power handling vs. aspect ratio has a peak at A=1.8.

B. Non-Inductive Plasma Current Sustainment

With the CS providing initiation and ramp-up only, NHTX relies on non-inductive current drive (bootstrap, neutral beam injection (NBI), and radio frequency (RF)) for sustainment of the plasma current. To optimize the current drive capability of the NBI, two of the four existing TFTR NBI systems are positioned at the midplane elevation and two are located 25cm below the midplane. In addition, provision is included for adjusting the tangency radius of the beams +/-20cm with respect to the magnetic axis R_0.

C. Long Pulse

A 1000 second pulse length is chosen based on the equilibration time of plasma-wall interactions. Water-cooled copper coils are used for the TF and PF. For water-cooling of the coils and other components the thermal inertial of a large (~500 kgal) quantity of water is required, which is adequate for the 1000 second pulse length. The water would be stored in a large tank, and cooling towers would be used to reject the heat in the period between pulses, based on a 1 hour repetition period. The required electrical input power is 300MW which, for the 1000 second pulse length, must be supplied directly from the grid. Since the TFTR NBI system was rated for short pulses it will require modification to run for 1000 seconds. A plan for this pulse length extension was developed and quantified during the TPX design activity.

D. Flexible X-point Divertor Configuations

Multiple inner PF coils are included to provide a wide range of plasma shapes and divertor flux tube configurations.

E. Provision for Multiple Divertor and First Wall Tests

The TF inner leg bundle, TF upper radial limbs and PF coils, and top lid of the cylindrical outer VV are removable via vertical crane access. Thus the divertor and first wall/ inner VV is readily removable and exchangeable via access by an overhead crane.

F. Hot Reactor-Relevant First Wall

The inner VV/first wall is operated at reactor-relevant temperatures of 400~600C using helium. The inner VV is thermally isolated from the water-cooled 150C outer VV by the intermediate vacuum space plus thermal isolating mounts.

G. Capability for D-T Operation

The activation/contamination region is limited to the inner VV plus appendages such as the NBI ducts, etc. The ability to remove the inner VV and divertor assemblies by vertical crane is an advantage from a remote handling perspective. A water jacket outside the outer VV, in conjunction with the shielding of the TFTR Test Cell, provides the required neutron attenuation.

H. *Low Cost*

Cost is minimized by exploitation of the existing PPPL infrastructure (Test Cell, buildings, electric power, CS/PF AC/DC converters, and NBI). Simple design solutions are sought for the water-cooled copper coils and their support structures, as well as the outer VV.

IV. KEY DESIGN FEATURES

A. *Double Vacuum Vessel*

As part of the NHTX mission to investigate plasma-wall interactions under conditions relevant to the design of future reactors, the NHTX first wall must operate at an elevated temperature up to 600C, substantially higher than prior devices which have operated with first walls as hot as 300 C (e.g. JET). The NHTX design will utilize a cold outer VV with an integral water-cooled jacket and a hot first wall structure, itself a closed toroidal vessel, located within the outer VV, thermally isolated by a small vacuum gap and by structural mounting standoffs constructed of thermally insulating ceramic material and Inconel bolts. An additional important feature of this configuration is that the region within the inner vessel will be sealed from the colder region in the space between the inner and outer vessels, thus eliminating impurity influx from the colder region to the plasma. The NHTX design permits the use of the overhead crane to lower the inner VV into the outer VV after first removing the upper TF/PF coil assembly and outer VV upper lid, such that the first wall can be readily exchanged as part of the experimental program. The structural mounting of the inner vessel is an important issue since NHTX operations involving D-D or D-T will produce neutrons which will activate the structure causing it to emit gamma rays, and radioactive tritium may contaminate exposed surfaces. Thus, there would be significant radiation exposure to personnel entering the vessel. The solution chosen for NHTX, depicted in Fig. 4, avoids the need for inner VV entry.

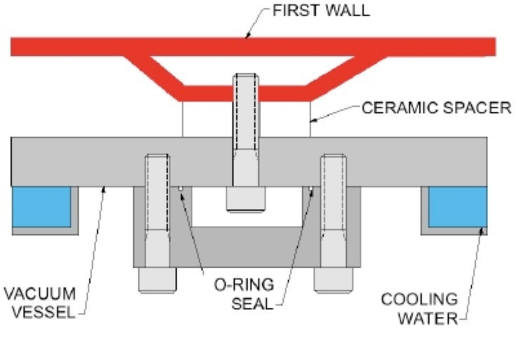

Figure 4. Inner VV (First Wall) Mounting Scheme

An additional issue is to provide access to the plasma space for NBI, diagnostics, etc., while maintaining separation of vacuum spaces between the two vacuum regions, and allowing maintenance/assembly without personnel access to the inner VV. The NHTX solution is to provide special matching ports on the inner and outer VV as shown in Fig. 5. On the inward end of the bellows, an annular flange is mounted with the annulus extending into the port's cross-sectional area where it is accessible manually from outside. When preparing to change out the first wall these are disconnected, withdrawn from the inner VV and flattened against the inner wall of the outer VV in preparation for inner VV removal.

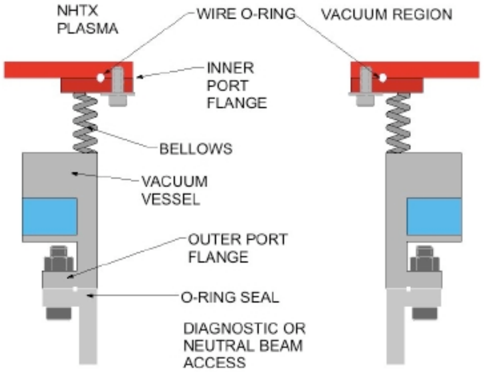

Figure 5. Scheme for Mating Ports between Inner and Outer VV

The heating/cooling system for the plasma's first wall will use high pressure helium flowing in many small, parallel tubes welded to the outside of the inner VV.

B. *TF Structural Support*

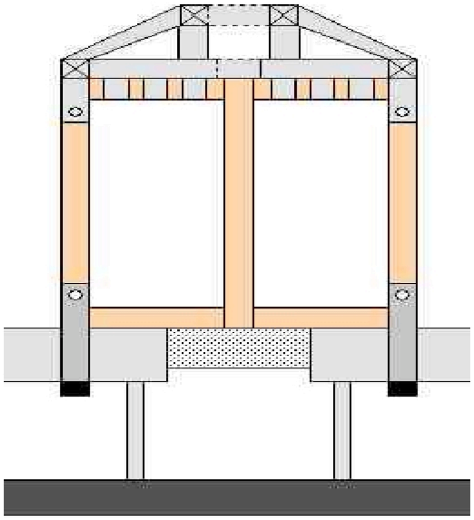

Figure 6. TF Structural Support

The in-plane magnetic pressure of the TF coil results in vertical forces on the upper and lower radial limbs totaling 23MN. The solution adopted by NHTX is to react those loads via the massive TF outer legs. The vertical forces are transferred to an umbrella structure on the top of the device and to a massive floor beam structure (within the pedestal on which TFTR was mounted). Using clamps and clevis pin joints the loads are transferred from these structures to the vertical limbs where the resultant stress is acceptable due to the massive cross section of the outer limbs. Out-of-plane forces are reacted via external "X" cross braces between adjacent TF outer legs.

C. *TF Joint*

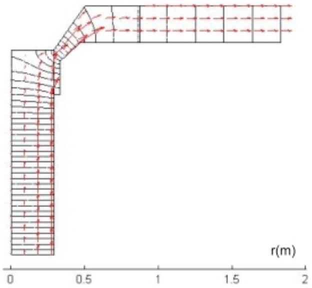

Figure 7. Current Flow and Voltage Contours Around TF Joint

The demountable TF joint is a challenging aspect of the design, considering the high current, large forces, and thermal displacements. The solution chosen for NHTX is a lap joint which is designed to minimize variations in current density across the joint, to exploit the in-plane magnetic force to close the joint, and to align the pattern of current flow with the flux spilling out of the CS to minimize out-of-plane forces. In addition, by matching the thermal growth of the TF central bundle with the outer legs, issues due to differential expansion are minimized.

D. *Coil Cooling*

The TF and PF coils require aggressive water-cooling and will reach equilibrium temperature distribution in a time period much less than the 1000 second pulse length. The TF inner bundle will utilize multiple parallel cooling passages per turn. Each wedge shaped turn will be constructed from two pieces with milled grooves. Copper tubes will be placed in the grooves and the pieces joined by soldering.

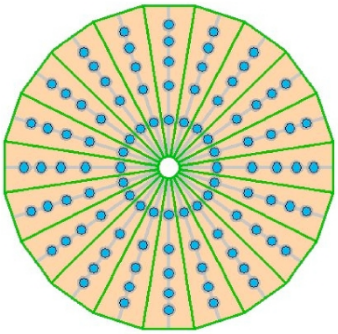

Figure 8. Midplane Cross Section of Inner TF Bundle

The inner PF coils can be cooled using conductors extruded with cooling passages and cooling flow paths over multiple turns. Because of their larger diameter, the outer PF coils require an alternate approach. The solution chosen for NHTX is to construct the outer PF coils using a strip-wound configuration with cooling tubes soldered into groves on the two edges of each strip, and with water path lengths of one half turn (inlet and outlet manifolds located 180° apart).

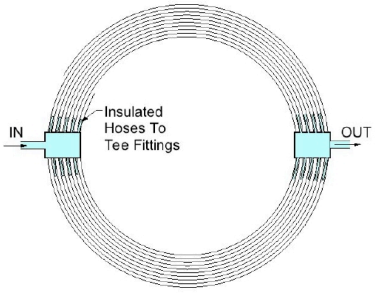

Figure 9. Cooling Scheme for Outer PF Coils

E. *Power Supplies*

Based on discussions with the local utility grid operator it was determined that 300MW of power could be obtained from the grid. The concept for the power supply system puts the relatively quiescent loads (TF and auxiliary heating) on the grid, and the dynamic pulsed loads (CS and PF) on one of the two existing MG sets as summarized in Table II.

TABLE II. NHTX POWER REQUIREMENTS

	Ramp (MW)	Sustainment (MW)
TF	96	88
CS	308	0
PF	100	37
Auxiliary Heating (NBI & RF)	0	166
Balance of Plant	10	10
Total MG	408	37
Total Grid	106	300

To simplify the TF coil construction it was decided to minimize the number of turns (20) and use a very high current TF power supply (240V, 500kA) located close to the machine. For the CS and PF power supplies, existing AC/DC converters at PPPL can be reconfigured in series and parallel as required to supply the loads for 1000 second pulses, repeated once per hour. To take 300MW from the local 138kV grid connection, a combination of switched capacitors and Static Var Compensation (SVC) will be used for reactive compensation.

CONCLUSION

A high P/R long pulse experimental device can be constructed at PPPL exploiting existing infrastructure to achieve cost economy. By incorporating suitable features the device can facilitate experimentation on multiple divertor and first wall concepts.

REFERENCES

[1] C. Neumeyer, Y-K Peng, C. Kessel, P. Rutherford, “Spherical Torus Design Point Studies”, PPPL Report No. 4165, June 2006