Configuration Studies for an ST-based Fusion Nuclear Science Facility

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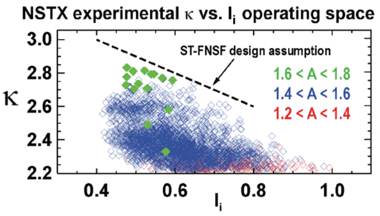

***Figure 1** - NSTX elongation vs. internal inductance and ST-FNSF design assumption*

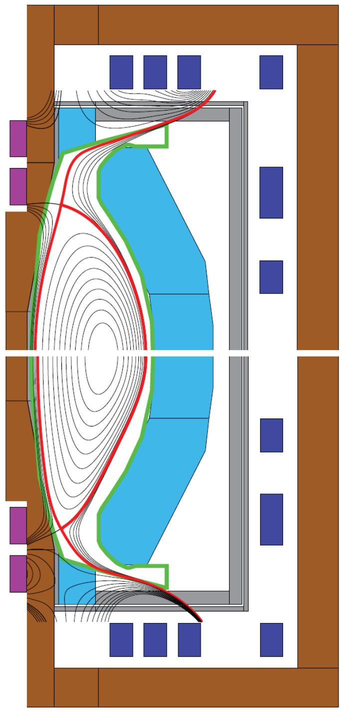

***Figure 2** – R_0 = 1.6m ST-FNSF: TF coils (brown), divertor / outboard PF coils (purple / dark blue), vessel and shielding (gray), breeding blankets (light blue), limiter outline (green), and plasma poloidal flux contours (black and red). Upper / lower plots are l_i = 0.82 / 0.40 and κ = 2.55 / 3.0.*

A Fusion Nuclear Science Facility (FNSF) could play an important role in the development of fusion energy by providing the nuclear environment needed to develop fusion materials and components [1-7]. The spherical tokamak (ST) is a leading candidate for an FNSF due to its potentially compact size and modular configuration. A key consideration for the choice of FNSF configuration is the range of achievable missions as a function of device size. Possible missions include: providing high neutron flux (1-2MW/m^2) and fluence (3-6MWy/m^2), demonstrating tritium self-sufficiency (tritium breeding ratio TBR ≥ 1), and demonstrating electrical self-sufficiency [7]. All of these missions must also be compatible with a viable divertor and first-wall solution. U.S. studies during the past two years have for the first time developed ST-FNSF configurations simultaneously incorporating: (1) a poloidal field (PF) coil set supporting high κ and δ for a range of l_i and β_N values consistent with NSTX/NSTX-U previous/planned operation, (2) a long-legged/Super-X divertor [8] analogous to the planned MAST-U divertor [9] which substantially reduces projected peak divertor heat-flux and has all outboard PF coils outside the vacuum chamber and as superconducting to reduce power consumption, (3) a blanket configuration capable of TBR ~ 1, and (4) a vertical maintenance scheme in which blanket structures and the centerstack (CS) can be removed independently. Progress in these ST-FNSF mission vs. configuration studies including dependence on plasma major radius R_0 for a range R_0 = 1 – 1.6m will be described.

Figure 1 shows the elongation κ vs. internal inductance l_i achieved on NSTX for a range of aspect ratios, and achievement of 5-10% higher κ will be assessed on NSTX-U utilizing improved vertical control. The ST-FNSF design assumption consistent with NSTX/NSTX-U is shown by the dashed line in Figure 1 and follows $\kappa_{x\text{-point}} = \kappa_{max\text{-}ST}(l_i) \equiv 3.4 - l_i$. Figure 2 shows the coil, vessel, divertor, and blanket configuration consistent with achieving equilibria with aspect ratio A=1.7-1.77, $\kappa_x = \kappa_{max\text{-}ST}(l_i)$, triangularity δ_x = 0.54-0.6, and a fixed divertor strike-point radius R_{sp} at large major radius $R_{sp} \approx 1.5\text{-}1.6 \times R_0$ with total field-line angle of incidence θ_B of ≥ 1°. Importantly, the projected peak divertor heat flux $q_{\perp\text{-}max}$ can reduced by up to a factor of 3 relative to a conventional divertor to 3-5 MW/m^2 [10] for the nominal surface-average neutron wall loading $\langle W_n \rangle$ = 1MW/m^2, and $q_{\perp\text{-}max}$ below 10MW/m^2 is achievable for $\langle W_n \rangle$ = 2MW/m^2. This coil set can also maintain fixed R_{sp} and θ_B for the expected operating β_N = 0 – 6. For this range of l_i and β_N, the outboard squareness varies from ζ_{out} = -0.15 to 0.1 and the centerstack and blanket shapes are consistent with this range.

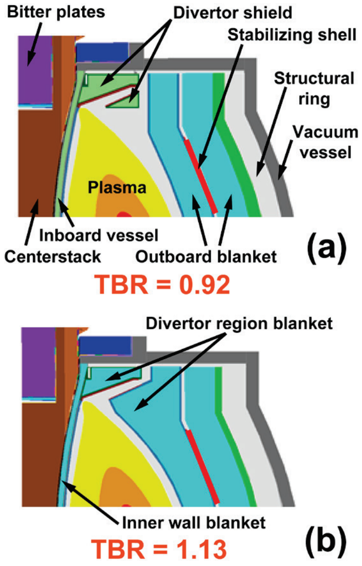

***Figure 3** – TBR versus blanket configuration*

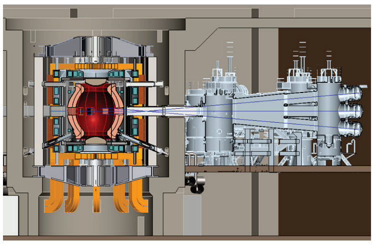
***Figure 4** – Side-view of ST-FNSF and NNBI*

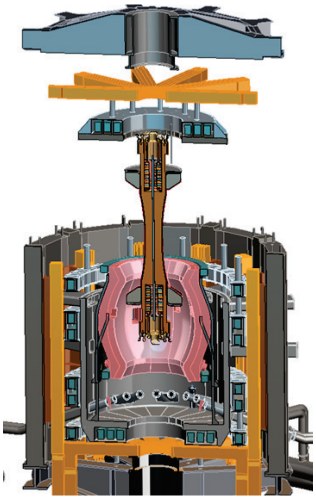
***Figure 5** – Vertical maintenance scheme*

Given the limited availability and high cost of tritium, it is likely necessary to achieve TBR near/equal to 1 in larger ST-FNSFs. Detailed 3D TBR calculations carried out for dual-coolant lead-lithium (DCLL) blankets find that the size threshold for achieving TBR ≈ 1 is R_0 ≈ 1.6m for configurations considered thus-far. A device cross-section used for initial TBR calculations for a snowflake divertor [10, 11] is shown in Figure 3 showing the components included in the calculations, and the light blue areas indicate the breeding blanket locations. Figure 3a shows that for an outboard-only breeding blanket including coolant channels, SiC Flow Channel Inserts, a 2cm W-TiC stabilizing shell for vertical stability, and no penetrations or Test Blanket Modules (TBMs), the calculated TBR is 0.92. TBR calculations indicate that neutron escape to the regions at the top and bottom of the CS is an important contributor to TBR reduction. Breeding at the ends of the CS by providing a more conformal outboard blanket and breeding in the divertor region increases the TBR to 1.06. This result is a major motivation for providing a breeding region at the CS ends as shown in Figure 2 and is a potential advantage of long-legged divertor configurations, i.e. moving divertor strike-points behind breeding regions. Replacing the 90% ferritic steel shield on the inboard vacuum vessel with a LiPb breeding region (see Figure 3b) increases the TBR to 1.13. Preliminary calculations indicate Neutral Beam Injection (NBI) ports reduce the TBR by at least 0.05, and near-term studies will compute TBR for the configuration of Figure 2, quantify the impact of NBI penetrations and TBMs on TBR, and also compute TBR for a smaller R_0=1.0m ST-FNSF.

Full non-inductive current drive is necessary for steady-state operation of an ST-FNSF, and 40-60MW of 0.5MeV Negative NBI (NNBI) is calculated to provide sufficient auxiliary heating and current drive (in addition to bootstrap current) for the R_0 = 1.6m configuration. The 0.5MeV NNBI sources to be used on JT60-SA are being used to inform ST-FNSF beam layout and port sizing. Figure 4 shows a side-view with 3 vertically stacked beam lines (vs. 2 for JT60-SA NNBI) to: minimize apertures at the blanket to maximize TBR, minimize NNBI space, and maximize the number of ports for TBMs and diagnostics. Lastly, Figure 5 illustrates the envisioned vertical maintenance scheme with capability to independently remove the centerstack or blanket modules.

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