

# **Limiting the Divertor Heat Flux to Enable Fusion Nuclear Science Research at Low-A**

J.M. Canik<sup>1</sup>, A. Sontag<sup>1</sup>, M. Cole<sup>1</sup>, M. Kotchenreuther<sup>2</sup>, P. Valanju<sup>2</sup>  
*ORNL<sup>1</sup>, UT-Austin<sup>2</sup>*

## **1. Mission and Scope Summary**

The Report of the FESAC Toroidal Alternates Panel has recommended the development of the knowledge base required to construct a low aspect-ratio facility to perform fusion nuclear science as the ITER-era goal for the Spherical Torus program<sup>1</sup>. As part of this goal, a Tier 1 critical issue to be resolved is that of handling the high normal and off-normal heat flux. A possible means of drastically reducing the heat flux expected in the ST is through the implementation of a recent invention known as the SuperX-Divertor (SXD)<sup>2</sup>, which has been predicted to reduce the peak heat flux in ST configurations by as much as a factor of five. In this paper, we propose a thrust to perform the theoretical, experimental, and engineering research necessary to validate the SXD as a heat flux mitigation solution for a low-A Fusion Nuclear Science Facility (FNSF).

## **2. Closing a Research Gap to the ST ITER Era Goal**

The Toroidal Alternates Panel identifies the plasma-material interface as a Tier 1 critical issue that must be addressed in order to achieve the ITER-era goal for the ST. Although PMI was also identified as a gap by the Greenwald report, the handling of high normal and off-normal heat flux is even more difficult in an ST. This is partially due to the inherently compact nature of the ST; the small major radius of the divertor compresses the power exhaust into a small area. The large pitch of the magnetic field lines on the low field side also leads to short connection lengths in the scrape-off layer, which compounds the problem by both increasing the temperature at the target and making it difficult to spread the power flux through cross-field transport. In addition to these geometric challenges, the planned operational scenario for the ST of the ITER-era goal uses low normalized density to increase current drive efficiency. This may further reduce the spreading of power flux by cross-field transport if it lowers turbulence. A more pressing problem is that operation at low density, combined with the short connection lengths of the ST, makes the highly radiating, detached divertor envisioned for conventional tokamaks difficult to achieve. Similarly, a low operating density may make pumping and particle control more challenging.

Several possibilities exist for resolving this critical issue, including the use of novel divertors (e.g. the Snowflake<sup>3</sup>), or liquid metal targets<sup>4</sup>. Here we focus on the SuperX Divertor since, as discussed in the next section, this directly addresses the geometric power handling disadvantages of the ST. The basic concept of the SXD is to configure

the poloidal field coil set so that the separatrix below the X-point is extended to a much larger major radius, such that the strike point on the target is at 2-3 higher radius than the X-point. Additionally, the poloidal field is manipulated along the extended divertor leg in order to maximize the field line connection length as well as increase the flux expansion.

While these characteristics of the SXD would be an advantage for any toroidal confinement device, they directly confront the issues that make power handling in an ST so challenging. The increased radius of the divertor has the obvious advantage of spreading the power over of a larger area, but the improved connection length of the SXD also allows ST operation with reduced target temperature and greater divertor radiation more similar to the conventional tokamak. The benefits of the SXD have been confirmed in 2D divertor simulations of the NHTX ST-based divertor testing concept; with 50 MW input power in this R=1.0 m device, the simulated heat flux is reduced from more than 30 to 10 MW/m<sup>2</sup> from the geometric advantages alone (the added benefit of increased impurity radiation is excluded from these calculations).

We propose a thrust to perform the research necessary to be able to successfully implement the SXD on a FNSF device, as part of the ITER-era ST goal. While the SXD has the potential to resolve the Tier 1 critical issue of the high heat flux in an ST, work is needed to validate this, and also to confirm this divertor as a technology that can be incorporated into the machine design of a candidate FNSF. While this research must include both modeling and experiment to explore the expected benefits of the SXD, here we emphasize the need for an engineering analysis, which is required to ensure that the design can be made consistent with the requirements of a full FNSF facility.

### **3. Research Thrust to Validate the Super-X Divertor for an ST-based FNSF**

The first, fundamental area of research is to test to what level the SXD can resolve the PMI challenge in the ST. This can be explored via theory and modeling, such as the simulations mentioned in Section 2. These studies should be continued, and should be expanded to look at more physics, such as erosion and redeposition, resilience of the SXD to off-normal events, and the compatibility of an extended divertor with particle control and helium pumping.

On the experimental front, much of the needed validation of the SXD predictions will be provided by the MAST ST located in Culham, UK, which is currently planning an upgrade that includes installing an extended SXD-like divertor. While experiments investigating the SXD will also likely be run on US tokamaks such as DIII-D and the Pegasus ST, the MAST upgrade is emphasized here since it will provide immediate, thorough documentation of SXD performance at the low aspect ratio relevant to an ST-based FNSF. In addition to providing the necessary experimental tests of the superior power handling ability of the SXD, MAST will be able to provide data on particle control and helium pumping. The MAST experiments will test the compatibility of the SXD with plasma control systems, and also the impact of this very different edge configuration on core performance. Given the strong impact that edge

conditions have had on tokamak performance to date, these experiments will be crucial in showing that the SXD is consistent with the requirements of the core plasma in an FNSF.

The ultimate goal of this research is to develop the knowledge base to implement an SXD for a low aspect-ratio FNSF, and as such the engineering constraints on the design should be considered from the outset. As part of this, the physics design of such a machine needs to be reconsidered to include the SXD. For example, since the power handling requirements of the divertor will be reduced, it is possible that a more aggressive design may become feasible in terms of compactness or operating density. However, this needs to be explored more fully using system design codes.

The cost that implementing the SXD may add to the machine design must be thoroughly considered. For example, the number of poloidal field coils required to create the magnetic configuration may be greater than with a standard divertor. The placement of these coils may interfere with other components such as blankets and neutron shielding, and may themselves require additional shielding. However, adding coils and allowing them to be located as needed will presumably allow SXD designs that further reduce the peak flux, and so may offset the cost of the coil complexity.

The overall size of the SXD must also be considered in the design. While a larger divertor is naturally able to exhaust more power safely, this also makes it more difficult to incorporate into a machine configuration. In addition to simply finding room for the divertor, the impact on remote handling must be taken into consideration. This is especially important for a low aspect-ratio FNSF where a vertical-drop remote handling scheme is envisioned; the SXD should be sized to fit inside the blankets and be removed separately, or the overall duty cycle of the machine will suffer. On the other hand, having a very large divertor may allow the divertor to be shielded from neutron damage, reducing the requirements on material resilience. These issues must all be considered simultaneously, so that a divertor can be designed that is consistent with the power exhaust requirements, but also minimizing adverse impact on the machine.

#### **4. Summary of Research Areas**

- Continued modeling of SXD capabilities
- Support of experimental tests, likely performed at MAST
- Engineering analysis of and FNSF SXD
  - Incorporation of SXD into physics design
  - Establish benefits and costs of progressive implementations of SXD
  - Assess compatibility of SXD with other facility goals such as high availability

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<sup>1</sup> Report of the FESAC Toroidal Alternates Panel, November 2008

<sup>2</sup> P. Valanju et al., submitted to *Physics of Plasmas*

<sup>3</sup> D. Ryutov et al., *Phys. Plasmas* **15** (2008) 092501

<sup>4</sup> A. Evtikhin et al., *Plasma Phys. Control. Fusion* **44** (2002) 955