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SUPER-X ADVANCED DIVERTOR DESIGN FOR MAST UPGRADE

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Abstract

Conventional divertor technologies may be insufficient for a fusion reactor environment. The Super-X Divertor (SXD) is an advanced concept that employs extreme manipulation of the diverted magnetic field in an effort to moderate the plasma conditions at the target. The layout for the SXD incorporated into the proposed upgrade to MAST is presented, along with preliminary results from boundary plasma transport modelling with the SOLPS 2D fluid code.

1. Introduction

The fraction of exhausted power required to be radiated in reactor-scale devices will be significantly higher than in ITER (~70%)[1], with DEMO design studies[2] indicating values of 90% or greater. It is unclear if impurity seeding of the plasma edge, in conjunction with a conventional divertor geometry, can achieve such high radiative fractions without significantly degrading core energy confinement[3].

When examining this problem in the context of divertor design, it is useful to review the operational requirements for high performance: heat flux and thermal cycling tolerance (to avoid melting, brittle fracture, or “blooming” in the case of carbon), erosion resistance (low plasma temperatures at the targets to minimise physical sputtering), particle control (impurity retention, pumping of hydrogen and helium), preservation of material properties (thermal conductivity and integrity), and mitigation of uncontrolled fuel retention (tritium trapping). Note that it is necessary to meet all of these objectives in a reactor-scale device, unlike in most present-day tokamaks – this is mentioned here explicitly because discussions have a tendency to focus on power handling alone.

During the design process, there are several “actuators” or “control tools” available for manipulating the boundary plasma, in an effort to meet the above requirements: magnetic geometry, layout of structures, choice of plasma facing material, thermal engineering, particle injection (gas, small pellets, etc.), pumping, and to a lesser extent, electrical biasing of the targets. The Super-X Divertor (SXD) focuses primarily on optimising the first item in the list. The basic idea is reviewed in Section 2 and the MAST Upgrade specific implementation is discussed in Sections 3. Section 4 contains a few comments devoted to justifying the additional cost and effort associated with an SXD.

2. The Super-X Divertor (SXD)

The SXD concept is detailed in reference [4]. In brief, additional divertor polodal field coils are employed so that the boundary plasma is extracted into a separate sub-divertor chamber; see Figure 1. Moving the strike-point to larger R increases the geometric size of the plasma wetted area, reducing the target heat flux density. A less obvious but essential feature is the generation of a quasi-null in the sub-divertor poloidal magnetic field, which increases the parallel connection length – that is, a field line trajectory in this region is predominately toroidal so that the distance between the midplane and the target is substantially increased through circumnavigation of the torus. The importance of this is illustrated by a relation[5] for the normalised scrape-off layer (SOL) collisionality, $^{*}_{SOL}$:

$$^{*}_{SOL} \propto \frac{n_u L}{T_u^2} \qquad (1)$$

where n_u and T_u are the upstream values of plasma density and temperature, and L is the along-the-field-line connection length between the divertor targets. Simply put, the longer the field line, the more opportunity for SOL particles to experience collisions for a given set of upstream parameters. If $^{*}_{SOL}$ is large enough then a temperature gradient forms in the SOL, reducing the temperature at the target plate, T_t, as required for the moderation of erosion rates. In addition, larger L increases the characteristic residence time for impurities in the boundary, raising the radiated power and further suppressing T_t. The dependencies are nonlinear and proper accounting requires a transport code; SOLPS[6] modelling results demonstrating these effects are presented in [4].

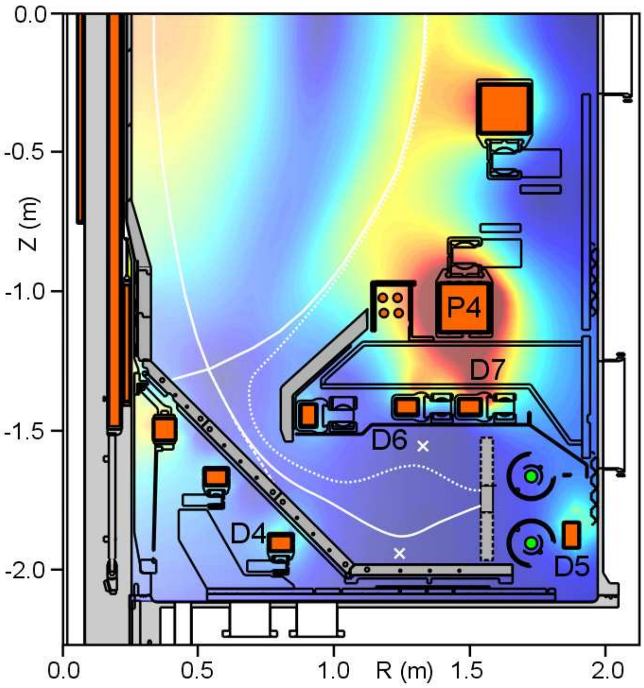

Figure 1: MAST Upgrade Super-X Divertor (SXD) conceptual design. The dotted line is the flux surface 1 cm outside the separatrix at the outer midplane, and the dashed line shows the trajectory of the divertor leg during standard operation. The poloidal field coils (orange) are shown. The coloured contours indicate the poloidal component of the magnetic field (blue = low field, red = max. field). Two cylindrical cryopumps (green) are mounted behind the vertical SXD target.

Note that extraction of the divertor leg into the sub-divertor does not imply decoupling from the core plasma, i.e. impurity ions are still free to stream along the magnetic field lines, contrary to the strong baffling of neutral particles.

3. MAST Upgrade Implementation

An upgrade programme for the Mega-Ampere Spherical Tokamak (MAST)[7] is currently underway, an important aspect of which is an SXD for the outer divertor; see Figure 1. A principle motivaton for the upgrade is to evaluate the bootstrap current fraction and off-axis neutral beam current drive, which require low confined plasma collisionality[8] and are the basis for steady-state operation in the proposed ST Component Test Facility (ST-CTF)[9,10]. The hope is that the SXD will expand the available operating space, i.e. maintain acceptable conditions at the target plates for a lower core collisionality than would be possible with a conventional divertor.

Notable design constraints on the new divertor are the reuse of the MAST vacuum vessel and preservation of the "short" central solenoid. These restrictions, together with the requirements for power handling (12.5 MW injected NBI power, 4 s pulse length) and core plasma shaping (0.47 < < 0.60 and 1.8 < < 2.5), largely determine the layout of the "declined" target plate and divertor coils for R < ~1 m.

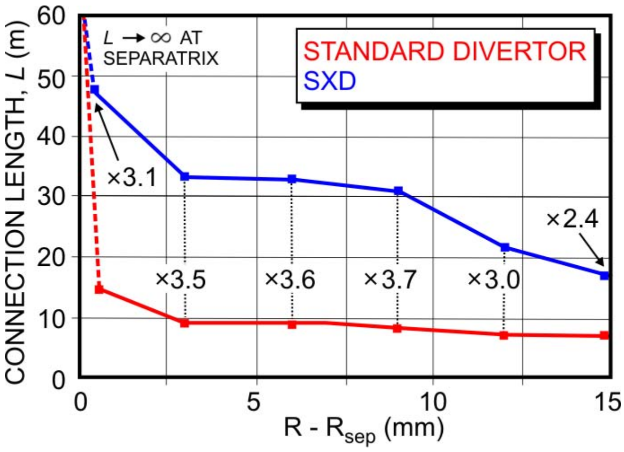

Figure 2: Connection length, *L*, between the outer midplane and the outer divertor target versus the radial distance from the separatrix, mapped to the outer midplane. *L* increases by a factor 2.5–3.5 when going from standard to SXD divertor operation. (Scenario A.1)

The FIESTA[11] free boundary equilibrium code was used to optimise the SXD coils (D4–D7) for redirecting of the strike-point to large R and generation of the broad quasi-poloidal null in the sub-divertor; the dotted line in Figure 1 is the flux surface 1 cm outside the separatrix, mapped to the outer midplane. A pair of x-points straddle the null, which are formed by interactions between D4–D5 and P4–D6&D7. The latter coupling results in large but acceptable forces on the respective coils (~30 Tonnes) and causes a minor convex distortion of the LCFS. Note that while the coil layout is the minimum set possible for an SXD in MAST Upgrade, systems with fewer coils and lower forces are straightforward to implement in more integrated designs[3].

Figure 2 shows the factor 2.5–3.5 increase in connection length across the SOL, as compared to the standard MAST-U divertor configuration with the outer strike-point at 0.75 m, as indicated by a dashed line in Figure 1. The results from initial SOLPS 2D fluid code simulations conducted at ORNL are plotted in Figure 3. The model parameters are deuterium + carbon, $D_\perp = 0.3\ m^2\ s^{-1}$, $_{e,i} = 1.0\ m^2\ s^{-1}$, $P_{NBI} = 1.8$ MW, $\Gamma_{core} = 3.3\times10^{20}\ D^+\ s^{-1}$, $R_{recycling} = 0.997$, which were set from comparisons between the model and experimental data for a MAST ELM-free H-mode discharge (17469 at 250 ms)[12]. The results are illustrative at present, but as anticipated, the SXD reduces the target heat flux and temperature significantly. Runs to increase the input power to 12.5 MW are underway.

Neutral particle conductance to the cryo-pump is increased by adding slats at the top and bottom of the vertical SXD target plate (Figure 1), with the strike-point region remaining toridally continuous. Kinetic modelling of the divertor gas with the MCNP5 code[13] is being used to optimise cryo-pump performance.

4. Rationale

There is a high probability that innovations in divertor design are necessary for managing several challenges associated with high duty cycle burning plasma devices. For example, in addition to moderation of the heat flux and plasma temperature in the divertor, a key advantage of the SXD is the opportunity to shield the remote target plates from neutrons, which is required for preserving the thermal conductivity of actively cooled targets[14]. It is acknowledged that the additional magnetic volume is expensive, but this has to be evaluated in the larger economic context – and the point is moot if the SXD turns out to be the only viable divertor solution. Due to the open vacuum vessel design, MAST is well positioned to perform a full-scale, near-term test of this potentially DEMO-relevant technology.

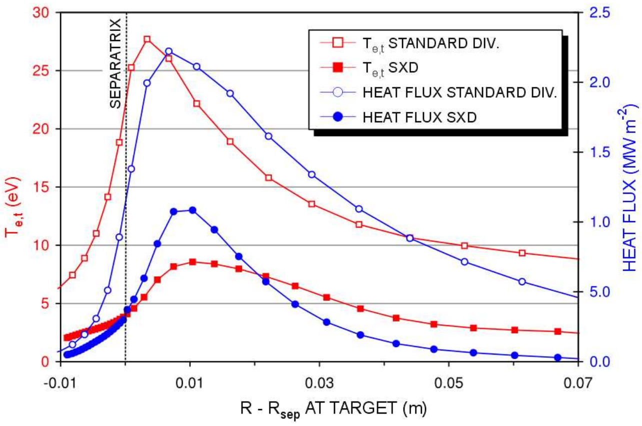

Figure 3: Preliminary SOLPS modelling results that illustrate the reduction in target temperature and heat flux with the SXD.

Acknowledgements

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