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ORIGINAL RESEARCH

Taming the Heat Flux Problem: Advanced Divertors Towards Fusion Power

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Abstract The next generation fusion machines are likely to face enormous heat exhaust problems. In addition to summarizing major issues and physical processes connected with these problems, we discuss how advanced divertors, obtained by modifying the local geometry, may yield workable solutions. We also point out that: (1) the initial interpretation of recent experiments show that the advantages, predicted, for instance, for the X-divertor (in particular, being able to run a detached operation at high pedestal pressure) correlate very well with observations, and (2) the X-D geometry could be implemented on ITER (and DEMOS) respecting all the relevant constraints. A roadmap for future research efforts is proposed.

Keywords Divertor · Scrape-off layer · Plasma detachment

It is, perhaps, a commonly shared concern that the next great obstacle to the realization of fusion power may be the power exhaust problem [1–4] that becomes progressively more severe as we advance towards reactor conditions. The idea that innovative magnetic geometries, called advanced divertors (AD) [5–15], may present a most direct way to meet the daunting technological challenges of heat flux and erosion on material surfaces, is steadily gaining widespread acceptance in the community. In the recent past, both theorists and experimentalists have argued for the experimental investigation of such geometries-both on present experiments, and on proposed future experimental devices.

In order to extract the most benefit out of a dedicated international experimental program, it must be complemented by an equally strong commitment to theoretical investigations. It is only then that we may be fortified enough to judge, which, if any, of the "solutions" will extrapolate to future burning plasma devices. The theoretical and modeling program must address both general boundary physics issues common to all divertor configurations, as well as specific physics and technological issues that need to be studied to develop AD solutions.

Let us begin with a short summary of the proposed classes of advanced divertors:

1. The X-divertor (XD) [1–4, 6] introduces a second X-point near the divertor plate to enhance the poloidal flux expansion and line length (Fig. 1a). In addition to spreading the heat flux, the X-geometry could also facilitate highly desirable properties like higher levels of atomic power dissipation and detachment. The XD geometry is characterized by a divertor index [4], DI > 1; the DI is a measure of the flaring of field lines near the plate, and is unity for the standard geometry.
2. The Snowflake divertor (SFD) [12, 13] introduces a second X-point in the very close vicinity of the main plasma X-point (Fig. 1b) with the possibility to distribute plasma heat exhaust among multiple divertor legs, perhaps aided by a 'churning mode' [14] in the region of reduced poloidal field. It is thought that this topology may improve ELM characteristics and spread ELM energy deposition to multiple targets. For SFD, divertor index DI < 1.

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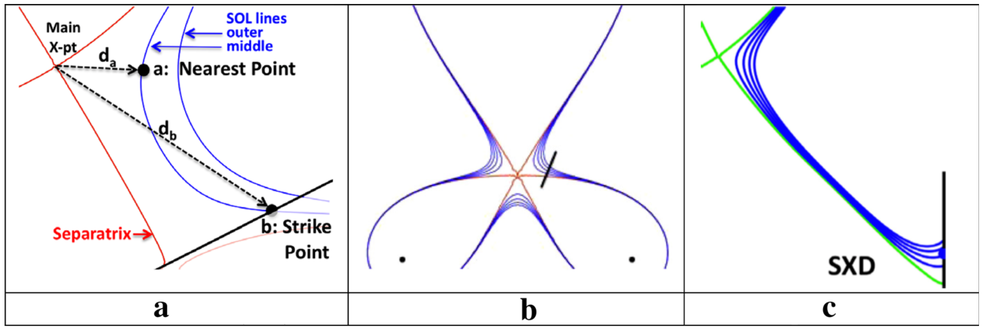

Fig. 1 Three types of advanced divertor (AD) magnetic geometries. **a** X-divertor (XD), **b** Snowflake (SFD), **c** Super-X (SXD)

3. The "Super-X" divertor (SXD) [7–11] further augments the advantages of X-geometry, by exploiting, in addition, the toroidal flux expansion created by moving the target plate to the maximum available major radius (Fig. 1c). The SXD therefore has the crucial, possibly critical advantage, that it may be appropriately shielded from direct neutron impact. The SXD is also expected to be particularly good at particle control making pumping easier and recycling low.
4. As a refinement of the SXD, X-point target divertor (XPT) [15] places an X-point in a divertor chamber at large major radius as a 'virtual target' with the idea of intercepting flux tubes that carry the highest parallel heat flux. Similar to the SXD, the toroidal flux expansion may help stabilize detachment fronts. The local X-point in the divertor can be a higher order null, taking advantage of a 'churning mode' to activate multiple sub-legs.

The XD and the Snowflake geometries are and will continue to be tested at DIIID [16] and NSTX [17]. Examining the X-point geometry will be one of the main thrusts of the MIT program. The much more demanding SXD will be first tested on the MAST upgrade [18, 19] in UK.

Even after a successful experimental demonstration, multiple considerations (physical and technological) might stand in the way of practical implementation of the given geometry in the fusion power producing devices of the future. Such crucial and weighty issues can be addressed only through vigorous theoretical investigation and design studies. Theoretical and modeling investigation should embrace the following Physics and technological issues:

1. The mechanisms that could allow *detachment* [20–26] must be achieved without degrading the edge transport barrier, and hence, H-mode confinement. Detachment is a combination of several very complex processes acting simultaneously: atomic physics, parallel and perpendicular plasma transport, and the effect of the magnetic geometry on the interplay of these processes. The ways that detachment can affect the H-mode transport barrier require a better understanding. Reliable extrapolation of experimental results to larger, more powerful machine requires improved models in all these areas.
2. A better understanding as to how the divertor geometry affects the Scrape Off Layer (SOL) [3, 4], *cross-field transport* and the SOL width [27–29]. It has been proposed that ADs can affect these processes, and so may offer a further avenue to controlling the plasma fluxes to surfaces
3. *Plasma erosion* in the divertor region, including surface modifications by the plasma, and the dependence of the Plasma Material Interaction (PMI) on plasma temperature, density and impurity species.
4. *Simulations* of experiments with advanced divertors for interpretation and understanding, e.g., using the CORSICA [30] and SOLPS [31–33] codes.
5. Advanced geometries inevitably modify the shape of the last closed flux surface to some degree; the resulting *effect on the core plasma*, and pedestal properties (especially ELM stability and dynamics) requires investigation.
6. *Helium exhaust* efficiency in the new geometries [33]. This is difficult to test on existing devices; simulations, therefore, are a must.
7. Realistic divertor plates have *corrugations* that can *limit the useful flux expansion* for attached divertor regimes [34]. These limitations arise because of the predominance of parallel transport in directing power to the plate, and hence, could be significantly ameliorated by higher levels of atomic dissipation and perpendicular transport near the plate.
8. The physics benefits of *low edge recycling*, obtained with liquid lithium Plasma Facing Components (PFCs), upon core performance.
9. The *feasibility* of creating desirable divertor geometries respecting engineering constraints on the poloidal field coils [6]. Some configurations, for instance, may require quite large PF coil currents [35]. Optimization studies are required to determine what geometries can be produced with feasible coils under burning plasma conditions.

10. The *stability and controllability* of different configurations can vary considerably. For example, we expect that some configurations are far more sensitive to perturbations than others, and also, some configurations lead to more severe axisymmetric vertical instabilities than others.
11. The interaction of new geometries with *fusion neutrons*:

    a. The divertor plate can be significantly shielded in some advanced geometries. The magnitude of this advantage, and the degree to which it might reduce the material development challenge for divertor materials, should be assessed.
    b. Tritium breeding can be improved significantly in some geometries- due to reduced parasitic losses in the divertor region. Again, the magnitude of this advantage should be assessed. The SXD may be most suited from the neutronic perspective.

12. The potential *liquid metals* as Plasma Facing Components (PFCs)-both low recycling materials (Li) and high recycling materials (Tin and alloys, Gallium, etc.)
13. Effects of the geometries on *thermo-hydraulic design* of the device-both in the divertor region and in entire main chamber.
14. Effects of the new geometries on the attainable *burn fraction*-which seriously impacts the tritium recovery system, tritium inventory (a serious safety issue), and requirements for the tritium breeding ratio.

Very different tools will be required for each of these very different areas and results in one area affect the investigations in other areas. Hence, an intense, encompassing and coordinated effort, spanning National Labs and Universities, is called for.

In collaboration with other researchers and institutions, the authors of the present paper have initiated a theoretical/modeling effort aimed at addressing the above issues. Some of the recent highlights of this effort are:

1. Recent DIIID experiments, exploring the XD, have very encouraging initial results showing that for similar levels of detachment, the flared XD geometry (DI $\sim$ 5–10) allows a greater pedestal pressure as compared to the SD configurations.
2. We have managed to design a range of XDs for normal ITER scenario [6] respecting all constraints [36, 37]. These XDs do not require any modifications to ITER hardware, viz., PF coils, divertor plates, or main chamber. They are a smooth variation starting from the ITER standard divertor, and could be run in the first phase of ITER.
3. We have Designed XD/SXD for Demo reactors under a variety of assumptions (e.g., vertical maintenance for K-Demo [38, 39], or the more ITER-like CREST design [40]).

In summary, solving the power exhaust problem in fusion reactors requires a resolute and determined program of theoretical and experimental research focused on the development of advanced divertors and the elucidation of their properties and effect on confinement. Recent developments since the Renew report give hope that prioritizing such a program would lead to critical advances in the prospects for fusion energy development.

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