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Super X divertors for solving heat and neutron flux problems of fusion devices

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ABSTRACT

We present a new magnetic geometry, called the Super X divertor (SXD), that could potentially solve the enormous heat exhaust problem of next-generation high power-density experiments and fusion reactors. With only small changes in net coil currents, the axisymmetric SXD modification of the standard divertor (SD) coils greatly increases the divertor radius, the line length, and the plasma-wetted area. The lower B at large R decreases parallel heat flux and hence lowers the plasma temperature at SXD plates to below 10 eV, allowing higher divertor radiation fractions. The SXD could safely exhaust five times more heat than an SD, is unique in allowing adequate shielding of divertor target from neutron damage, and can enable much improved, reactor-relevant core plasma performance.

1. Introduction

A putative steady-state fusion reactor [1–4] will have much higher power, neutron flux, and pulse duration than current fusion devices [5]. Several intermediate experiments [6–9] have, therefore, been proposed to experimentally investigate some of the crucial scientific and engineering problems in building a dependable and economic power-producing thermonuclear fusion reactor. These next-generation fusion experiments (NGFEs) as well as eventual fusion reactors must solve the formidable problem of heat exhaust. The heating power P_h (= auxiliary heating power P_{aux} + 20 % of the fusion power P_f) increases by a factor of six as we go from the two largest current Tokamaks (JET in European Union (EU), with major radius R =3 m, and JT-60 in Japan, with R =3.4 m, each with P_h~20 MW > P_f) to ITER (R =6.2 m, to be constructed in EU over the next decade, designed for P_h=120 MW <P_f~ 400–500 MW). The jump in P_h is equally dramatic from ITER to even a moderate power fusion reactor (P_h~400–720 MW, P_f~2000–3600 MW). The safe exhaust of this huge heating power, without destroying the narrow divertor plate which must handle all the heat that is not radiated, and without damaging the quality of the main plasma (e.g., good confinement at high β = plasma pressure/magnetic pressure) is perhaps the most serious roadblock on the way to fusion reactors.

Invoking the oft-used empirical estimate P_h/R_0 (R_0 = plasma major radius) as a measure of the severity of the heat flux problem, Table 1 of Ref. [10] shows that the P_h/R_0 is ~5–6 times ITER for reactors, and 2–4 times ITER for NGFEs. Though the large size and relatively low power density of ITER makes P_h/R_0 just low enough to allow a standard divertor (SD) to handle ITER heat flux, SDs seem unlikely to work for reactors or future high power-density (HPD) devices. Any attempt to save the divertor by radiating power (primarily from the core) would destroy good core confinement at high β, which is essential for future HPD devices.

To overcome the heat flux problem peculiar to all HPD devices, we modify the magnetic geometry of the divertor to generate the Super X divertor (SXD). Various modifications of magnetic divertor geometries have been tried before[11]. The main difference between these divertors, the standard divertor (SD), the X divertor (XD) proposed earlier by the authors [10], and the SXD is that, by using an extra X-point, the SXD puts the divertor plates at the largest major radius R_{div} possible inside the toroidal field (TF) coils. The SXD uses only axisymmetric coils carrying almost the same total amp-meters as the standard divertor while making very little change to the core plasma configuration. In doing so, the SXD also increases the magnetic line length L to the outer divertor plate by large factors over the SD or XD. The normal area of each flux tube also increases at large R because the net magnetic field decreases

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with increasing R. This decreases the parallel heat flux and allows the plasma temperature to fall to below 10 eV near the outer divertor plates (with high temperature at the separatrix), allowing more divertor radiation and also reducing divertor plate damage. Under given engineering constraints (e.g., maximum of 10 MW/m^2), these factors combine in imparting SXD a heat handling capacity (i.e., the maximum total heat flux that the plasma is allowed to safely inject into the divertor) several times bigger than SD or XD. The SXD also allows much improved core plasma performance, and greatly increased shielding of divertor targets from neutrons.

In Section 2 we describe the basic SXD design, and show several SXD configurations (Figs. 1–3) generated using the MHD equilibrium code CORSICA [12]. These equilibria span a wide range – aspect ratios from 1.4 to 4, component test facilities (CTFs) with Cu coils to reactors with superconducting (SC) coils, etc. They all display the defining characteristics of the new geometry: highly increased R_{div}, L, and plasma-wetted area A_w. In Section 3 we show, through theoretical estimates and 2D SOLPS [13] simulations, the many beneficial effects of SXD, *viz.*: reduced peak and average heat fluxes on the divertor, lower plasma temperature at the divertor plates, and higher divertor radiation capacity. Calculations with the neutron transport code MCNPX [14] show about a 10-fold increase in the shielding of SXD divertor plates from neutrons (as compared to SD). In Section 4, we discuss some limitations as well as other plausible advantages of SXD, and possible simulations and experiments to test them.

2. The Super X divertor (SXD)

To provide a context for the SXD invention, we remind the reader that changing the *edge* magnetic geometry of the magnetic bottle from limiters to divertors had a major impact on *core* plasma – it heralded the arrival of the H-mode (even the Internal Transport Barrier (ITB) must have an H-mode edge). The basic cause of the improvement in core confinement is the increased isolation of the core plasma from the container. The price one pays is that the heat flux gets concentrated on a very small area in the standard divertor (SD) configuration.

Our first attempt to spread the heat flux led to the X divertor (XD) [10], which increases the plasma-wetted area by flaring the open magnetic field lines with an extra X-point downwind from the main X-point[10]. However, the XD heat capacity remains far below the demands of HPD devices; it is just modestly better than an SD using a highly tilted plate. The SXD (Figs. 1 and 2), building on the limiter-SD-XD progression, further increases the "distance" (physical as well as magnetic) from the plasma to the divertor plate by maximizing its radius R_{div}. This key realization was that such change in the edge magnetic geometry is easy to achieve and has many beneficial consequences for the core plasma.

2.1. Divertor radius is an important "knob"

Since parallel heat transport along open field lines to the divertor plates generally dominates cross-field transport, the plasma-wetted area A_w on the divertor plates is approximately set, via $\nabla \cdot \mathbf{B} = 0$, to be

$$A_w = \frac{B_{p,sol}}{B_{div}} \frac{A_{sol}}{\sin(\theta)} \approx \left[\frac{B_p}{B_t}\right]_{sol} \frac{R_{div}}{R_{sol}} \frac{A_{sol}}{\sin(\theta)} \quad (1)$$

where R_{sol}, W_{sol}, and A_{sol} are the radius, heat flux width, and heat flux area of the scrape-off layer (SOL) at the midplane for the corresponding divertor plates, θ is the angle between the divertor plate and the *total* magnetic field B_{div} at the plate, and the subscripts $p(t)$ denote the poloidal(toroidal) directions. W_{sol} is set by the plasma. For a given W_{sol} and B_p/B_t at the midplane, A_w can be increased only by reducing θ or by moving the divertor plate to a larger major radius

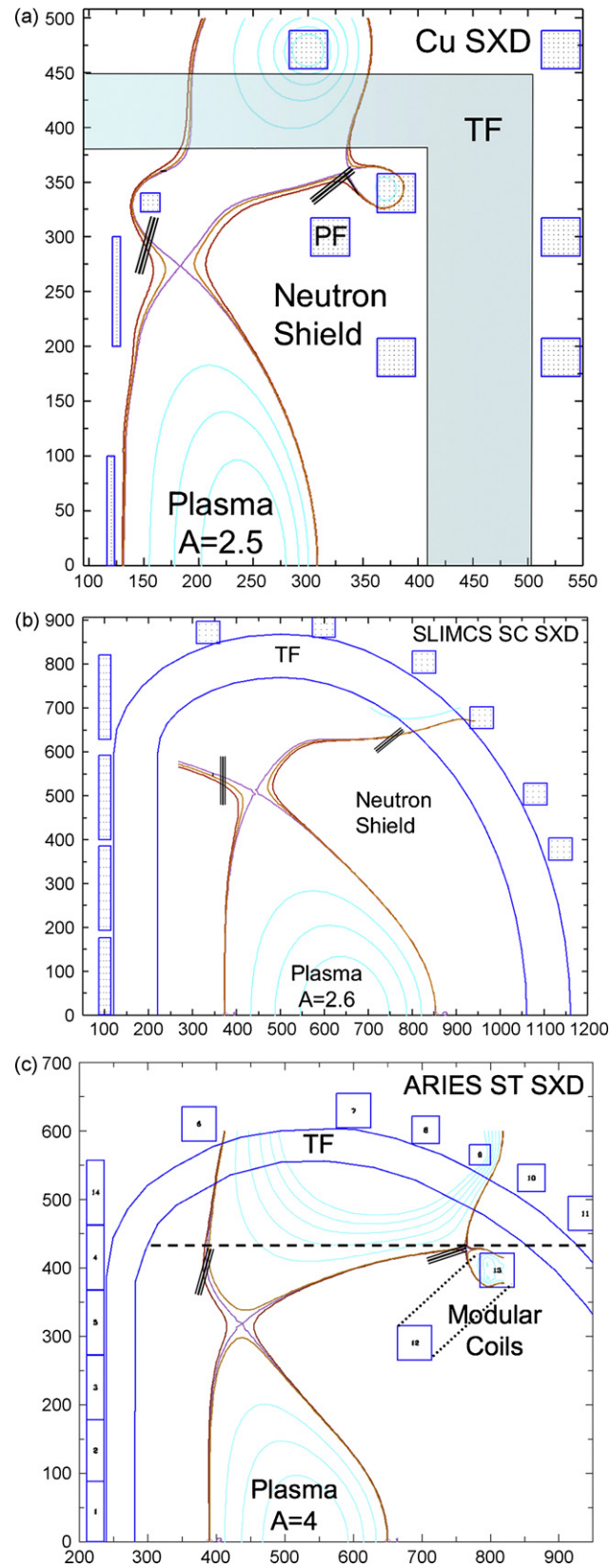

Fig. 1. Examples of SXD CORSICA double-null equilibria for (a) an HPD experiment (HPDX) with Cu coils, (b) SLIM-CS reactor with all superconducting (SC) coils outside TF, and (c) ARIES-ST, using modular coils [10] that can be extracted between TF coils.

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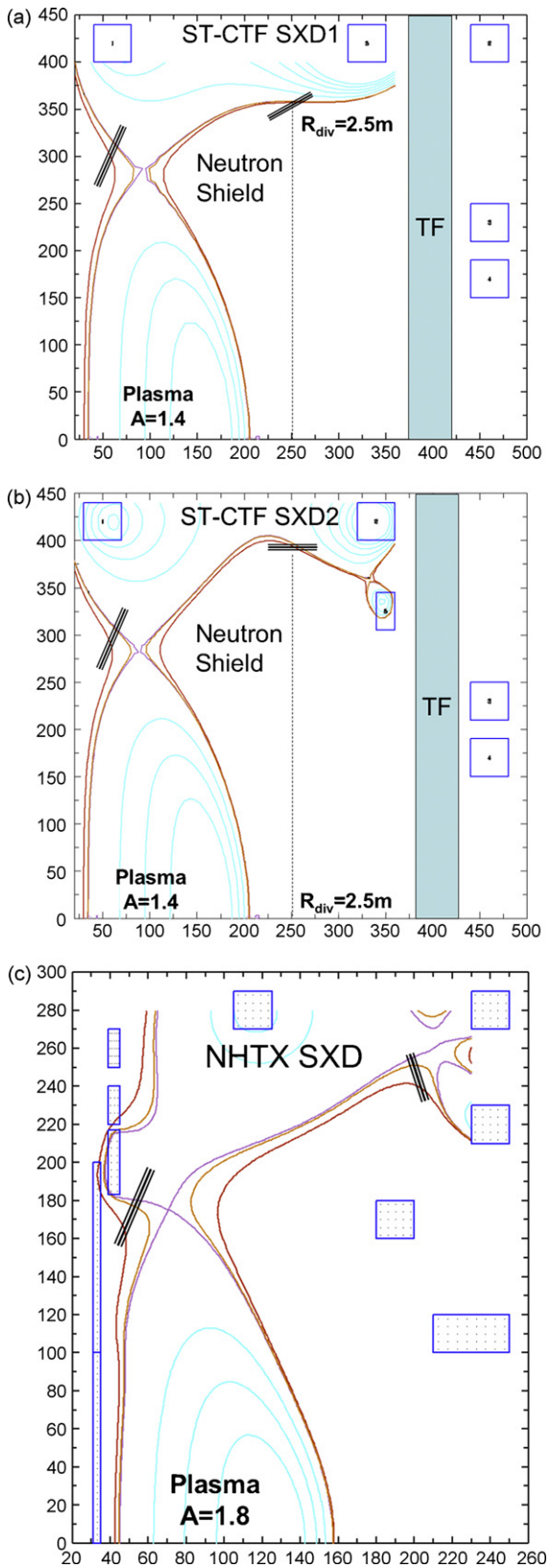

Fig. 2. SXD CORSICA equilibria for some low-A HPD devices: (a and b) ST-CTF SXDs made by just moving SD coils, (c) NHTX.

R_{div}. However, engineering constraints are generally expected to put a limit of 1° on the minimum θ [15](ITER θ is 2.3°). The Super-X divertor (SXD) is based on the realization that maximally increasing R_{div} is the only "geometrical knob" in Eq. (1) to increase A_w.

Along with a large increase in R_{div}, the magnetic line length L can be increased by decreasing the poloidal field in the long divertor leg. Large R also reduces the parallel heat flux $q_{||}$ in the divertor because the area of each flux tube increases as the total B decreases. Large R_{div}, long L, and lower $q_{||}$ are generically achieved with extra X-points (as in the XD); hence the name Super-XD (SXD).

2.2. Generic design method for SXD

Using CORSICA to design the SXD configurations for many devices starting from their SD versions, we usually place an extra PF coil (or move an existing one) at a large R and at about the same height z as the PF coil near the main X-point. As seen in Figs. 1–3, these two coils (to be called the main X-point coil and the SXD coil) create an extra X-point between them, due to which the near-vertical separatrix makes a sharp turn and heads out radially. Careful placement of the SXD coil (or splitting it into 2 or more coils – see Fig. 3) allows precise control of the strike point. The poloidal field along the long leg can then be further decreased either with small changes in positions and currents of coils near the leg or by adding one or two extra (low-current) coils if needed. Generally, the total Amp-meters in the PF coils change by only about ±5% from the starting SD case. After getting a basic SXD equilibrium, we further optimize L, A_w, θ by small changes in PF coils, while keeping changes in core plasma small and keeping the TF coils unchanged.

2.3. SXD examples

Our experimentation with CORSICA equilibria shows that, for a wide variety of plasma shapes (aspect ratios, elongations, triangularities, etc.), one can go from SD to SXD (by changing coil locations) with a minimal change in number of coils and net amp-meters – while keeping the core geometry essentially unaffected. The SXD design space is smooth (hence easy to find an SXD with CORSICA search scripts), versatile (SXDs have been designed for many cases), and quite robust (to small plasma and coil changes). Using a few scripts added to CORSICA, we can routinely generate SXD MHD equilibria for various existing and proposed devices, out of which some examples are shown in Figs. 1-3. Note that these examples are not fully optimized; they are meant to illustrate the flexibility, capabilities, and tradeoffs of the SXD design space to accomodate given constraints. Final optimization will involve further individual machine constraints.

Fig. 1 shows that SXD can be designed for a variety of TF coil shapes using either Cu or superconducting (SC) coils. The Cu SXD design in Fig. 1a is for the high power-density experiment (HPDX) discussed later in Section 3. The large radial extent of the TF coils in SLIMCS (Fig. 1b) and ARIES-ST (Fig. 1c) were dictated by the desire to use radially removable "cassettes". This allows more radial expansion room for SXD, but could also make PF coil design harder. Fortunately, this is not the case – the SLIM-CS SXD in Fig. 1b was obtained with only 5% increase in PF coil currents and very small changes in their locations. Although we have designed a similar SXD for ARIES-ST, in Fig. 1c, we show the intriguing option of using "modular" PF coil loops (not linked with TF) that can be installed and extracted between the TF coils (see Ref. [10] for earlier examples of such modular coils). SXD gives a choice between such options during systems design.

The SXD is critical for low aspect ratio (A) HPD devices (Fig. 2). The SXDs for the low-A component test facility (CTF) were obtained with the *same* number of coils as the SD design shown in Ref. [6], with 5%*less* total amp-meters in the SXD coils. It is possible that

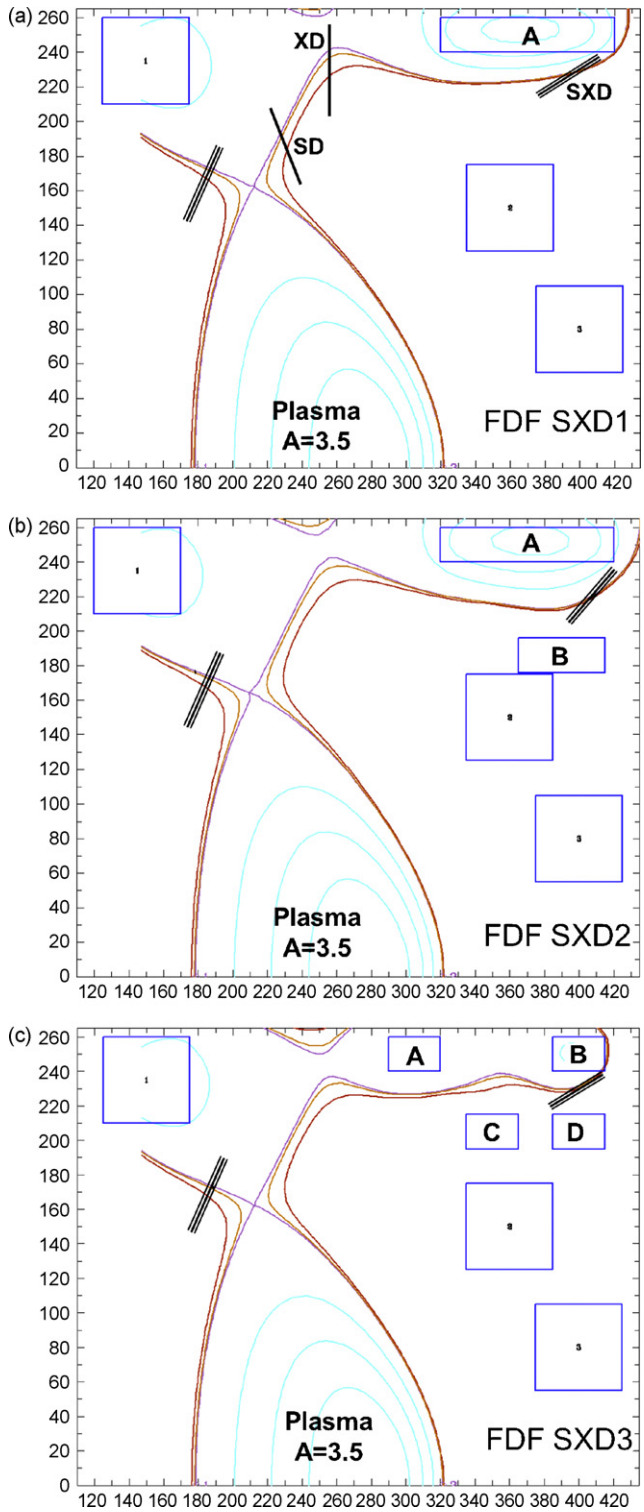

Fig. 3. Three SXD CORSICA equilibria for FDF with increasing L: (a) one SXD coil (A), also shown are SD, XD, and SXD plate locations for SOLPS comparisons, (b) split A into 2 coils A and B, and (c) split A into 4 coils, carrying the same total current as A. All Cu PF coils fit inside the nominal FDF TF coils [8] and can be neutron-shielded. Gains (over SD) in L are (a) 4.0, (b) 4.24, and (c) 4.69.

SXD could significantly improve the prospects for low-A CTFs and reactors.

Fig. 3 shows how the divertor (for FDF [8] in this case) can be further optimized by refinements of the SXD coil(s). In this case, splitting the SXD coil (labeled A) into 2 or 4 coils, such that the *total* current in the SXD coils stays the same, leads to increasing line length L. Again, the choice between such options offered by SXD depends on system goals and constraints.

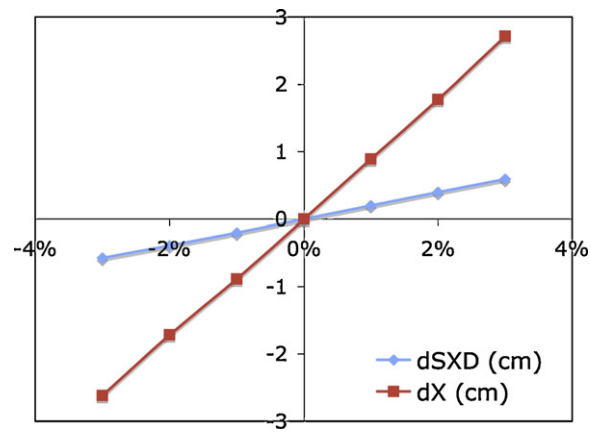

Fig. 4. Shift in SXD strike point (dSXD) along the target plate is much less than the total shift in main X point (dX) (or the 11 cm width of the plasma-wetted area on the FDF divertor) when plasma current is changed by ± 3 %.

3. Advantages of SXD

A striking, counter-intuitive advantage of SXD is that the strike point location is found to be *less* sensitive to plasma fluctuations for SXD than for SD; the strike point is controlled more by nearby SXD coils than by the far away plasma current. This surprising robustness of the SXD is confirmed, for example, for FDF (Fig. 3): changing the plasma pressure (or current) by ±3% (while holding coil currents and flux through the wall fixed to simulate sudden changes) moves the outer strike point only by ±0.5 cm (Fig. 4), a small fraction of the width of the plasma-wetted area (11 cm), and much less that the movement of the main X-point (±2.8 cm); this insensitivity seems to be a generic SXD feature.

Since the main plasma and the region near the main X point is nearly unchanged in going from SD to SXD, the sensitivity and control issues for up-down balance in SXD are about the same as for an SD. This has been checked by inserting small top-down asymmetry in SXD CORSICA equilibria.

3.1. CORSICA and SOLPS results for SXD

SXD equilibria generated with CORSICA show significant increases (Table 1) in L and R_{div}/R_x, where R_x is the major radius of the X-point. We report the line length L from a point (1/2) cm outside the outer plasma midplane separatrix to the divertor plate, and the maximum plasma-wetted area A_w allowed under the 1° minimum for the angle between the divertor plate and the total B field. The maximum heat flux that can be put into the divertor (without SOL radiation) is A_w times the 10 MW/m^2 limit. The SXD

Table 1
CORSICA results for SXDs in Figs. 1–3.

Case	Fig.	L (m)	L/L_x	R_{div}/R_x	$A_w(m^2)$
HPDX	1a	53.0	2.98	1.89	7.93
SLIMCS	1b	78.0	2.70	1.63	7.03
ARIES	1c	66.1	1.93	1.72	8.20
CTF 1	2a	26.6	2.08	2.74	10.35
CTF 2	2b	37.3	2.72	2.84	9.76
NHTX	2c	38.1	3.40	2.89	5.31
FDF 1	3a	61.9	3.99	1.86	5.57
FDF 2	3b	66.6	4.24	1.88	5.73
FDF 3	3c	73.6	4.69	1.85	5.57

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line lengths are ∼2–5 times greater than the line lengths L_x to the main X-point (Table 1).

For given CORSICA equilibria, SOLPS calculates inter alia the peak heat flux on the divertor plate, and plasma temperature T_{plt} at the location of the peak heat flux. The total power into the SOL and the edge density are set by the specific device – the goal is find the maximum P_h while keeping the peak divertor heat flux below the 10 MW/m^2 limit.

Of many SOLPS calculations for CORSICA equilibria, the ones pertaining to NHTX are reported in [16], where only the SXD (but not any of the SDs – with or without flux expansion) was found to be able to keep the peak divertor heat flux below the 10 MW/m^{2}limit. SOLPS is first run without adding any impurities. The plasma temperature T_{plt} at the location of the peak heat flux on the plate indicates whether radiation will be effective. In general, SOLPS confirms that adding impurities gives very little radiation if T_{plt} is high (well above 100 eV) – as found for most SD cases.

SOLPS runs find that the SD is rather inadequate for any high power-density machine. The peak heat flux stays well above 10 MW/m^2 and T_{plt} stays at around 150 eV; high T_{plt} allows almost no impurity radiation. Basically, the parallel heat flux $q_{||}$ into the divertor scrape-off-layer (SOL) is so large for the HPD devices that the plasma just "burns through" all the way to an SD divertor plate [17]. SOLPS calculations show that the SDs are always deep in the sheath limited regimes for these devices. The SXD, on the other hand, provides long enough line lengths L and enough decrease in $q_{||}$ at large R_{div} for the plasma temperature to drop sufficiently for the plasma to avoid this undesirable regime.

3.2. Further SXD advantages

The SXD-caused increase in A_w and decrease in $q_{||}$ at the plate are purely geometrical. A_w alone increases the maximum heat flux that can be put on the divertor plate by ∼2–3 (Table 1), but the longer line length L and diminished $q_{||}$ also boost the maximum allowed power (P_{sol}) into the SOL in two significant ways:

(1) The maximum divertor radiation fraction and cross-field diffusion are both enhanced by L. The much longer L in the SXD restores the capacity for substantial radiation even at high $q_{||}$, boosting P_{sol} relative to the SD by another factor of 2. The longer line lengths lower the plasma temperature at the plate (a highly desirable result) at relevant high upstream $q_{||}$. The large R_{div} also reduces $q_{||}$ near the plate because the area of each flux tube increases as the total B decreases ($\nabla \cdot \mathbf{B} = 0$). These results are obtained from an elaborate and detailed 1D code [10], and from the 2D code SOLPS [13].
(2) As plasma flows to the divertor along the extended field lines, cross-field diffusion effectively widens the SOL, resulting in a larger plasma footprint on the divertor plate. From standard models of SOL diffusive processes (see [18], p. 269, Eq. (5.79)), one expects the SOL width to scale with the connection length as $L^{2/9}$, leading to an increase in the SOL width by ∼1.43.

With all these enhancements, the acceptable P_{sol} in SXD geometry could go up by a factor of 5 or more as compared to the SD or XD or any other purely flux-expanding configuration (including the snowflake [19]). Such enhancement can be critical for the next-generation HPD devices.

3.3. Heat flux problem is serious for all HPDXs

Given the hard material limit of q_{max}=10 MW/m^2, the maximum steady-state power allowed on the divertor plate P_{plt}= $q_{max}A_w$ is proportional to W_{sol}. The SOL power width is very narrow because the heat transport in the SOL is much faster along the open field lines than across them. The largest uncertainty in predicting W_{sol} for HPD devices comes from the lack of a "definitive" theory or model based on data. The most recent (2007) ITER physics basis [9] estimates that ITER W_{sol}∼3–5 mm, in stark contrast to W_{sol} estimates from the 1999 ITER physics basis [20] that were larger by about a factor of 4. Following similar procedures (based, presumably, on a more advanced physics understanding and empirical data as compared to the 1999 ITER report), the estimates for W_{sol} in HPD devices come out to be rather small – generally smaller than that of ITER. Smaller W_{sol} implies a reduced A_w (the plasma-wetted area) that implies an acuter exhaust problem that could be tackled only by an advanced configuration like SXD.

For average estimates of W_{sol}, P_{plt} (with A_w corresponding to SD) is considerably smaller than P_h for all HPDXs. A large part of P_h would have to be dissipated lest it destroy the plate. The oft-invoked mechanism for this is radiation from the core (P_{cr}) and from the SOL (P_{sr}). A "Radiative Solution" would work if the total $P_{rad} = P_{cr} + P_{sr} \geq P_h - P_{plt}$. Here we summarize only the main results of a thorough investigation of "Radiative Solutions" [10] for SD or XD-based configurations:

(1) The maximum possible SOL radiation P_{sr} (such as the value adopted in [9], without full detachment and likely unacceptable confinement loss or disruption probability) is quite inadequate for reactors and for HPD devices. It remains much much smaller than P_h.
(2) Consequently for reactors with SD, the required core radiation fraction f_{cr}=P_{cr}/P_h will reach ∼0.7–0.85. Such an enormous f_{cr} is likely to have serious and debilitating consequences on core confinement, thermal stability, and dependability for a fusion power reactor, especially in high power-density reactors with ITBs.
(3) High core radiation mode is not attractive for any HPD devices. The severe loss of heating power makes their operation in desirable modes with high bootstrap current and high β very unlikely.
(4) Notwithstanding possible uncertainty in the W_{sol}, there is no "Radiative Solution" with SD for HPDXs. Even with 50 % core radiation, the heat fluxes in a reactor (or in a relatively compact HPDX) are still way beyond the capacity of the SD; the problem becomes considerably worse for advanced tokamak (AT) reactors.

Since 50 % core radiation(f_{cr} =0.5) is about the most that a well-confined, high β, reactor-relevant plasma core can tolerate, the exhaust problem can be solved only through engineering a big gain in the maximum $P_{sol} = P_{plt} + P_{sr}$. This is what the SXD does; the gain being ∼ 5 times over SD. To the best of our knowledge, no other solution comes close given the 1° plate tilt restriction.

The SXD also seems fully compatible, and often appears to be synergistic, with other methods such as using liquid metals or trying to increase the cross-field transport in the divertor (but not the main plasma) by ergodization. The MHD drag to liquid metal flows is much smaller in the lower B field of the SXD. The long legs of the SXD may allow ergodization without affecting the main plasma. Of course, these expected refinements and synergies of SXD need to be further tested.

3.4. Simultaneous heat and neutron problems

SXD is also ideally suited to solve another problem crucial to neutron-producing plasmas. Unlike SD, the heat-bearing SXD divertor plate can be readily shielded from the neutrons as it can be placed behind extra neutron shielding, out of the line-of-sight, and far from the plasma (Fig. 2). Computation with the Monte Carlo Neutron Transport code MCNPX [14] for the HPDX configuration of

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Fig. 1 a show that it is easy to create a neutron shield that drops the neutron flux on the SXD divertor plate by factors of 10 or more. Of course, the detailed design of such shielding will depend on specific devices, but the large R_{div} of SXD allows more than enough flexibility. In contrast, a typical SD is too near the main plasma to be shielded well from neutrons.

Divertor technologies developed for ITER depend on high temperature, high thermal conductivity materials which degrade strongly for the neutron fluence expected in a reactor. For copper alloys, the temperature window between brittleness and creep strength narrows unacceptably; for carbon based materials there is considerable swelling and degradation of thermal conductivity. It is much more difficult to simultaneously solve the heat and neutron problems – as required for divertor plates – than solving each separately. Thus, CTFs and reactors will need the large neutron shielding capability of the SXD – in fact, this may be as compelling an argument as heat flux for the necessity of SXD.

4. SXD limitations and issues to be explored

The long divertor leg, of course, raises the issue of the costly TF field volume. We note that the SXD plates fit nicely inside the toroidal field (TF) coils in corners that often go unused – no extra TF volume is needed specifically due to SXD. Any static toroidal field ripple at the SXD plates can be handled by slight shaping. Thus the SXD is not expected to significantly increase the cost of a tokamak design – the TF coil shape is generally dictated by other considerations such as servicing strategy.

Certainly, SXD cannot gain much increase in R_{div} if the TF coils in a given device are very close to the plasma, or some pre-existing structures come in the way, leaving no room for SXD. Though this may preclude SXD deployment on some existing devices (without significant changes), we note that we have not found this to be a problem in the many future CTFs and reactors (some shown here in Figs. 1–3). Further, if one finds that SD simply cannot handle the heat flux in future HPD devices, then one will have to weigh the cost of increasing the TF coil volume to accommodate the SXD against giving up high power-density ambitions. This becomes an issue of system goals vs. costs.

Another oft-raised issue is "What about the inner divertor?" We note that SXD does not increase the load on the inner divertor plate as it decreases the load on the outer divertor plate. Secondly, the preferred geometry for HPD devices is the double-null (DN, as evidenced by its use in almost all future CTF and reactor designs). In DN geometries, the inner divertor is generally considered a non-issue because the typical ratio of heat flux to the outer and inner divertors is over 5 to 1. Thus, until the SXD is used to raise the power density by over 5 times (which seems adequate for most applications on the horizon), the inner divertor still remains a non-issue. This is borne out in our many SOLPS simulations.

Another set of relevant issues fall in the category of assessing the relative importance of parallel vs. cross-field transport in the long SXD legs. We note that, in general, any increase in cross-field transport (by any mechanism) will be good – it will increase the wetted area and thus reduce the peak heat flux. The long SXD leg does not pass so near the extra X-point (Figs. 1-3) that ergodic layers creating hot spots on the target is expected to be a debilitating issue, though this too needs to be checked.

4.1. SXD-suggested issues to be explored

As expected for any new idea, SXD suggests a variety of optimizations that need to be further explored and tested by simulations and/or experiments:

(1) A fully detached mode of divertor operation is recognized as leading to low heat flux on the divertor plates. Experiments with SDs find that the detachment front collapses to the main plasma X-point. This condition is very strongly correlated with a large loss of confinement, to the point where this mode is usually not considered viable. With the extreme line length increase in SXD, the plasma temperature at the plates drops significantly, so a detachment front may get created and arrested before backing up into the main plasma, thus allowing very desirable, stable detached operation.
(2) One could also enhance SOL turbulence in the long leg of the SXD, which, by spreading the heat, can cause a substantial reduction in heat load on the divertor plate.
(3) The long line length of the SXD is also expected to delay and spread out (in time) any transient heat flux pulses from the plasma. This improvement is expected to be proportional to the square root of the length increase, and may be significant for handling the critical problem of transient heat pulses.
(4) Handling high heat flux may seem like just an edge engineering problem but in reality it is deeply linked to the core physics because any exterior solution that seriously damages core physics is unacceptable. Only solutions compatible with "good" core physics are permitted, and they often improve the core physics. The SXD, for example, brings an expected but welcome bonus; it makes it possible to explore and access highly desirable, and perhaps essential, operating regimes for HPDXs, the high β regime furnishing a prime example. Because of enormously decreased radiation demands, one can operate at rather low edge densities enhancing the core density gradients that result in much higher bootstrap current, which in turn, allows much higher β for the same beta normal β_n (set by MHD stability). In addition, one could operate with a very high pedestal temperature only because the SXD can handle the enhanced heat load. We are testing this possibility by using coupled core-edge simulations.
(5) A physics issue against techniques using only flux expansion is following: neutral pressure is needed for He exhaust. Without a very long line length, the temperature at the divertor plate is very high in the SD, XD, and Snowflake geometries, leading to low recycling and hence low neutral pressures. This may make He pumping almost impossible for two reasons: directly due to the low pressure and also the resulting long mean path would imply very low transconductance through any reasonable pumping duct. The SXD may prevail by lowering the temperature at the plate and hence increasing neutral pressure, and by reducing the length of the pumping duct connection to the outside of the device, and increasing pumping duct area (greater major radius) if needed. We plan to test this using SOLPS.

5. Conclusion and future directions

By creating a "distance" (both physical and magnetic) between the core plasma and the divertor SOL, the SXD breaks some debilitating basic constraints, allowing both to be better optimized. With its increased plasma-wetted area and much larger line length, the SXD can simultaneously solve the steady-state heat flux problem, shield the divertor from neutron damage, provide a strong defense against transient heat loads, and probably synergistically enable reactor-relevant beta values with acceptable heat exhaust. For minimal extra cost, a tokamak with SXD can utilize the multi-pronged optimization of core beta (as in reactor studies like ARIES) – while staying consistent with present experiments and extrapolation uncertainties. No other divertor configuration that we are aware of does all this.

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The SXD invention, naturally, opens many new research issues and questions. These are being investigated further using theory, code simulations, and experiments. The NSTX[21], MAST[22], PEGASUS[23], and SST[24] groups are planning to implement and test SXD in their devices. SXD by now seems to have become an integral part of ST-CTF design evaluation [6].

The Super X divertor has the potential to seriously impact the fusion program in the short (HPDX, CTF) as well as the long term (Reactors). It is difficult to design an economic power reactor without a divertor of the SXD type, and it seems unlikely that any next-generation high power-density (HPD) machines could do without it.

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