On Heat Loading, Divertors and Reactors

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Abstract. It is shown that the limited thermal power handling capacity of the standard divertors (used in current as well as projected tokamaks) forces extremely high ($\sim 70-90\%$) core radiation fractions $f_{rad-core}$ in tokamak fusion reactors [1, 2, 3] with heating powers considerably larger than ITER-FEAT [4]. Such high $f_{rad-core}$ can have severe consequences on core confinement and stability to the extent that small, economical high power fusion reactors operating with standard divertors (SD) are not likely to meet the daunting requirements for confinement, stability, and helium exhaust. High power density operation in advanced modes that have internal transport barriers (ITBs) [5, 6] is not expected to lead to a workable fusion power reactor due to the high $f_{rad-core}$ necessary with a standard divertor.

The core confinement and stability problems caused by high $f_{rad-core}$ are shown to be adequately addressed by X-Divertors (XD) which, by flaring field lines just before they hit the divertor plates, considerably enhance the divertor thermal capacity. The use of this new class of divertors will lower the bar on confinement sufficiently that extrapolation of confinement observed in present devices could be enough for a fusion reactor.

1. Introduction

In this paper we propose a solution to the enormous heat-handling problems that are expected to afflict an economical Deuterium-Tritium (DT) burning tokamak fusion power reactor. Since the fusion power output of power reactors (P_F = 2500-3600MW) [7, 1, 2, 3, 8] is considerably larger than that of ITER-FEAT (P_F = 400MW) [4, 9, 10, 11, 12], a typical power reactor will need to get rid of ∼ 500-1000MW - a value 4-8 times larger than ITER-FEAT. Without assistance from copious radiation, the standard divertor configuration (developed for relatively modest needs of ITER-FEAT) could hardly handle such prodigious amounts of heat. The fraction of the heating power that will need to be radiated (to avoid damage to the divertor) is so high that a fusion reactor is forced into a physical regime of high $f_{rad-core}$ that is very different from the one pertinent either to the current machines or to ITER-FEAT.

Our solution to the thermal exhaust problem is to modify the magnetic geometry of the divertor. By creating an X-point near the divertor plate, the magnetic field in the open field line region is flared to increase the area over which the heat is spread. We have also demonstrated that this new configuration (called the X-divertor or XD) along with acceptable magnetic equilibria can be created with coils that may be located behind neutron shields. The desired geometry is accessible with fairly moderate currents in the additional coils. The resulting increase in the plasma-wetted area considerably reduces the amount of required radiation before the thermal flux is incident on the divertor plate. The X-divertor brings the required radiation fraction (for a high power reactor) much closer to the range where ITER-FEAT is expected to operate.

The X-divertor can become a serious reactor candidate only if relatively simpler and traditional mechanisms fail to solve the exhaust problem. If one could radiate, for instance, substantial fraction of the thermal power without affecting the stability and confinement of the core plasma, a "radiation solution " will be ideal. This paper, therefore, has two major parts:

1) An extensive analysis of the possible "radiation solutions" leading to the conclusion that the radiation requirements for a power reactor fitted with a standard ITER-like divertor (SD) are so high that most reactor designs are arguably unworkable. Borrowing from ITER the estimate for maximum power that can flow into the SOL, the core radiation fractions ($(f_{rad-core})$) must be as high as $\sim 70-90\%$. With such high radiative losses of the core heating power, the core confinement requirements for reactors based on advanced tokamak (AT) operating modes with high β_N and high boot bootstrap current fractions reach daunting levels.

2) The difficulty with finding an acceptable and attractive "radiation solution" drives us to an investigation of the X-divertor concept. We find that with the addition of the XD-coils, numerically computed magnetohydrodynamic (MHD) free boundary equilibria show that the magnetic flux can be greatly expanded in the region of the divertor plate without affecting the capability to create highly shaped equilibria with high elongation and triangularity. It is shown that this is possible with XD-coils which could be located behind a neutron shield. It is further shown that, by using small non-axisymmetric coils, undesirable linkings (with PF coils inside the TF coils) can be avoided. The ripple produced by non-axisymmetric coils turns out to be acceptably small. With XD-coils, the magnetic flux expansion may be increased by up to an order of magnitiude compared to the standard geometry, while simultaneously increasing the field line length by a factor of two or more. It is impossible to obtain this combination with the standard divertor geometry.

2. Power Handling - High Core radiation fraction

A commonly used metric for divertor heat loading is P_{heat}/R. Recent results from B2-Eirene simulations, however, suggest that P/R^3 is a more appropriate metric for devices on the scale of burning plasmas or reactors [13]. From Table 1, where both these metrics for ITER and for a variety of proposed reactors are calculated, we may conclude that both these metrics are far higher for reactors than for ITER-FEAT, showing the severity of reactor exhaust problems.

In table 1, we also show what $f_{rad-core}$ will be needed for reactors (including ITER) if we assume that the entire class has the same P_{SOL}/R (or P_{SOL}/R^3) as ITER, which with P_{SOL} = 100 MW and R = 6.2 m, provides the baseline reference. One can again notice the stark contrast between ITER and all other reactors; for the latter the core radiation fractions are in the range ~70-90%, reaching 78-90% for the more attractive advanced tokamak (AT) mode reactors. Such core fractions are far higher than on almost all present experiments operating AT modes. For either H or AT modes, ITER-FEAT is not expected to be able to operate as a burning plasma

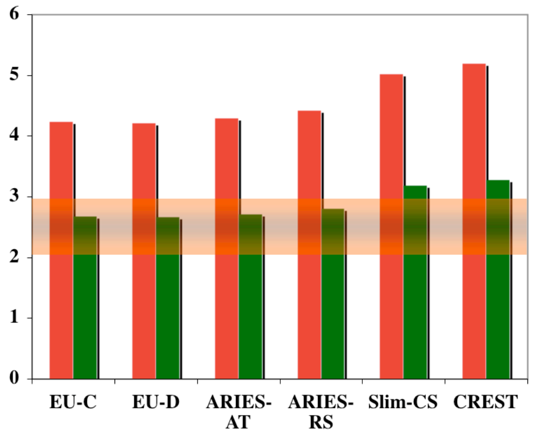

Figure 1: Required confinement enhancement above the ITER-89P L-mode scaling for SD (red) and XD (green). The range of present experimental results is also shown.

Device Name	**Heating P[MW]/ R[m]**	P_{heat}/R **[MW/m]**	P_{heat}/R^3 **[MW/m^3]**	$f_{rad-core}$ **P/R metric**	$f_{rad-core}$ **P/R^3 metric**	$f_{rad-core}$ **with XD**
DIII-D	10 / 1.6	6				
JET	17 / 3.0	6				
JT-60U	17 / 3.4	5				
ITER-FEAT	120 / 6.2	19	0.5	16%	16%	
ITER-EDA	300 / 8.2	37	0.5	56%	22%	
EU-A	1246 / 9.6	130	1.4	88%	70%	25 – 69%
EU-B	990 / 8.6	115	1.6	86%	73%	32 – 65%
EU-C	792 / 7.5	106	1.9	85%	78%	44 – 61%
EU-D	571 / 6.1	94	2.5	83%	83%	56 – 58%
ARIES-AT	387 / 5.2	74	2.8	78%	85%	46 – 62%
ARIES-RS	515 / 5.5	94	3.1	83%	86%	56 – 66%
Slim-CS	645 / 5.5	117	3.9	86%	89%	66 – 73%
CREST	691 / 5.4	128	4.4	87%	90%	68 – 79%

Table 1: Values of P_{heat}/R and P_{heat}/R^3 metrics for experiments, proposed burning plasma experiments and reactors. The range of $f_{rad-core}$ for XD corresponds to the two metrics.

for $f_{rad-core}$ ~70-90%. This places reactors in a regime which cannot be tested on ITER-FEAT. As we shall see, important phenomena like thermal instability and helium exhaust depend strongly on $f_{rad-core}$.

High $f_{rad-core}$, naturally, erodes the core heating power. We take $P_{net} = P_{heat}(1-f_{rad-core})$ as a measure of the net heating power. If the allowable power into the SOL scales as R^3, the H-mode reactors will require only a modest improvement over conventional H-modes. However, AT reactors require larger confinement enhancements than present experiments in similar operating modes. To appreciate the deleterious effects of high $f_{rad-core}$, we display in Fig.1 the confinement requirements for the AT reactors along with the confinement range of present experiments.(We use results reported from DIII-D and JT-60U which are closest to reactor conditions - values of β_N which are the largest achieved with low inductive current. (For DIII-D the parameters are $\beta_N = 4$ with H89P= 2.5[14], and for JT-60U, the parameters are $\beta_N = 2.5-3$ with H89P = 2.9-2.1[15, 16])

We have examined in detail the possible processes that could lead to enhanced SOL radiation. Following ITER design, we exclude full detachment as a suitable reactor option due to likely unacceptable confinement and disruptivity. Our basic tools consist of a 1-D fluid model and the two dimensional code UEDGE [17]. The 1-D fluid model includes convection, separate ion and electron equations, corrections to coronal radiation, and impurity entrainment. Most of the physics is delineated through the 1-D model while UEDGE is used as a benchmark for the 1-D code. The 1-D model indicates several dimensionless parameters that relate to the capability of a divertor SOL to radiate power. These are: 1) F = the radiation fraction of the SOL $f_{rad-SOL}$, if parallel transport were only due to Spitzer conductivity, 2) C = ratio of the maximum possible convective energy flux to the total energy flux. It measures the extent to which convective energy transport can increase $f_{rad-SOL}$, 3) R = the ratio of the maximum radiation distance from the plate to the width of the plasma-wetted area. It measures the degree to which radiation disperses power, and 4) E = the ratio of the convective force to thermal force. Higher E leads to better impurity entrainment. Higher values of F, C, R, and E are favorable for higher SOL radiation. However, all these parameters have a quite unfavorable scaling with increasing parallel heat flux. The upshot of this is that even a large increase in the impurity level in the SOL results in a rather small increase in the allowable power into the SOL. For high powers into the SOL, it is not possible to radiate a large fraction of the SOL power. This implies that the power must be radiated in the core.

Device Name **Divertor: SD/XD**	**F**	**C**	**R**	**E**
DIII-D	0.26	0.61	21	5.2
JET	0.38	0.5	22	6.4
ITER-FEAT	0.10	0.31	6.4	3.3
ITER-EDA	0.047	0.22	3.4	2.2
EU-A	0.008	0.09	1.0	0.9
EU-B	0.009	0.1	1.1	1.0
EU-C	0.009	0.1	1.2	1.0
EU-D	0.010	0.1	1.3	1.1
ARIES-AT	0.013	0.1	1.7	1.2
ARIES-RS	0.010	0.1	1.3	1.0
Slim-CS	0.007	0.08	1.1	0.9
CREST	0.006	0.08	1.0	0.8

Table 2: Values of dimensionless parameters F,C,R and E for Argon seed impurity for current experiments, proposed burning plasmas, and reactors

It is important to note that at relatively lower powers (the range of current experiments) it is, indeed, possible to substantially enhance the impurity radiation in the SOL. However, this does not extend to the high parallel heat flux regime of reactors. The adverse scaling of dimensionless parameters characterizing various physical processes is displayed in Table.2.

An example of a result from UEDGE which demonsrates this is shown in Fig.2. These runs were performed for ITER-FEAT geometry. When P_{SOL}=100 MW, UEDGE agrees with B2-EIRENE - the peak heat flux on the plate is slightly less than 10 MW/m^2. However, if $P_{SOL} = 150 MW$, then the peak heat flux exceeds 10 MW/m^2 for impurity levels in the SOL which correspond to $Z_{eff} > 4$ in the core. Such high Z_{eff} levels would result in radiating all of the heating power from the core.

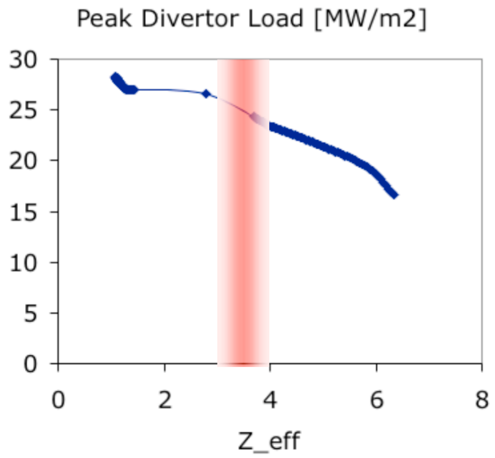

Figure 2: Peak heat flux (from UEDGE) vs Z_{eff} for Ne-seeded SOL.

A radiating mantle also meets a similar fate - attempts to limit the radiation primarily to the far edge of the plasma (so that confinement degradation might be avoided) fail because of an unfavorable scaling with temperature and with $n\tau_P$, the product of the density and the particle confinement time. It is found that for reactor parameters with an H-mode edge, the core radiation is not primarily isolated very near the edge, but rather pervades the entire core. For plasma profiles for AT operation with high beta, high bootstrap fraction and an ITB, a large majority of the radiation comes from inside the ITB. Thus a "radiating mantle" is not an effective reactor option.

Another serious effect of high $f_{rad-core}$ is the excitation of a virulent thermal instability peculiar to a self-heated fusion plasma. The instability is particularly serious for ITB plasmas. We use a model of the thermal instability where the stored energy is $\sim P_{net}^{\epsilon}$. The exponent ϵ is taken from experiments on JET to be 0.5 - 1 for ITB plasmas [18, 19]. Analysis shows that the most stable assumption is to use a constant density profile so the stored energy varies as the temperature. For simplicity the temperature profile is taken to be constant and similar to experiments. With these simplifications, and starting from a steady state, the growth rate of temperature perturbations can readily be derived and is shown in Fig.3. For the high $f_{rad,core}$ forced by a standard divertor (SD), the growth rates of the thermal instability are many times larger than the energy confinement time. It is questionable whether a sufficiently robust feedback scheme for such instabilities can be devised.

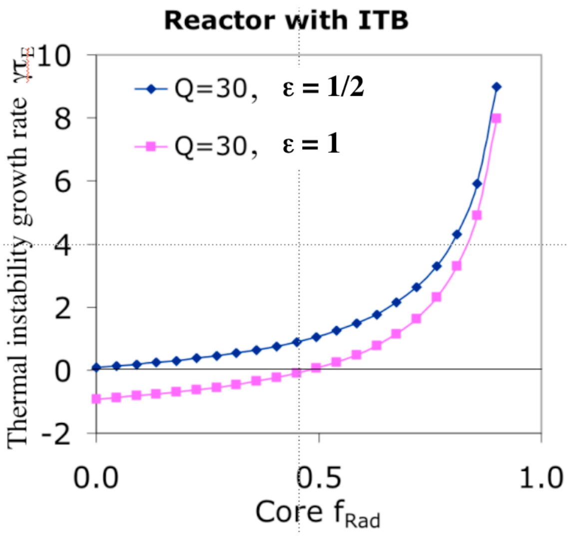

Figure 3: Thermal instability growth rates for Argon.

Even if it were somehow possible to obtain ITBs with high enough confinement, the plasma transport will be too low for adequate helium exhaust. To analyze this situation, we build a model similar to that of Wade et al. [20]. Assuming temperature and electron and impurity density profiles pertinent to an ITB reactor, the fusion heating and radiation power can be computed from known cross sections. The heat diffusivity χ, consistent with the profiles and the net heat fluxes, can then be derived. The source of helium from fusion can also be computed. To compute helium density, one needs appropriate helium transport coefficients. We assume purely diffusive helium transport, motivated by the JT-60U [21] result that the helium diffusivity inside the ITB is found to be between 0.2 - 1.0 times the ion heat diffusivity (and the helium pinch in the ITB is assumed zero). The ion heat flux is about $\sim$ 70% of the total heat flux. These results allow the helium density to be determined via a 1D transport analysis. For a sufficiently low helium diffusivity, the helium in the core builds up until the radiation rate inside the ITB exceeds the decreasing fusion heating rate. The maximum tolerable impurity peaking before this occurs, naturally, depends on helium diffusivity. In Fig.4, the maximum tolerable impurity peaking is plotted versus helium diffusivity. For core radiation fractions $f_{rad,core} \sim$ 85%, most of the existing experiments lie in the range of radiation collapse for a reactor. For $f_{rad,core} \sim$ 70%, most of the data is outside the range

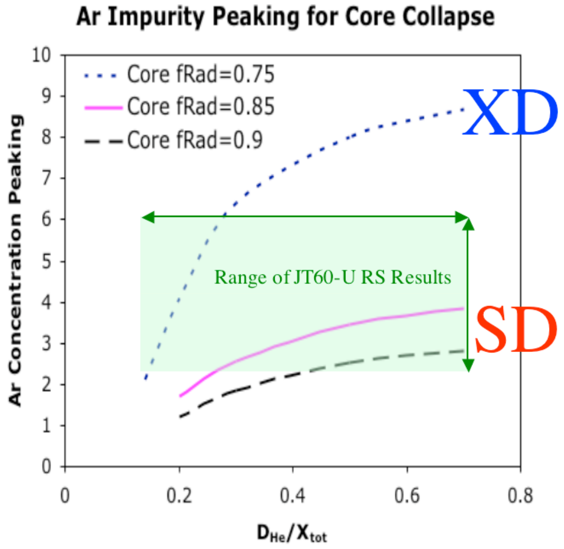

Figure 4: Region of helium-induced thermal collapse.

for radiation collapse. Thus, there exists a substantial possibility of core collapse due to helium buildup in ITB discharges with an SD.

3. X-divertors

Increased divertor heat capacity can be achieved by flaring field lines downstream from the main plasma X-point. We call such divertors X-divertors (XD, Fig.5, [22]) This can increase, by large factors of 5 or more, the plasma-wetted area on a divertor plate placed near the second X-point. The surprise is that the extra downstream X-point can be created with relatively small, reactor-relevant coils behind adequate (over 1 m) neutron shielding. Modest currents ($\sim 1/3$ plasma current) are needed in an extra pair of poloidal coils to cancel the small poloidal field at the new X-point. Each divertor leg (inside and outside) needs such a pair of coils. For a reactor, this would entail linked coils. To avoid this situation, the axisymmetric X-divertor coils can be replaced with smaller modular "picture-frame" coils that produce the same axisymmetric field components. Since the line flaring needs to be done only near the extra coils, the effects on the distant main plasma are small. Their non-axisymmetric ripple in the plasma are generally smaller than the ripple from the main toroidal field coils ($< 0.3\%$). In this respect, these X-divertors (XD) are completely different from the old bundle divertors which created a large ripple in the main plasma. The effects of the small ripple at the plate can be compensated by slightly undulating the divertor surface by a few millimeters to follow the field. The ripple is also small enough to consider cancellation by ferritic inserts.

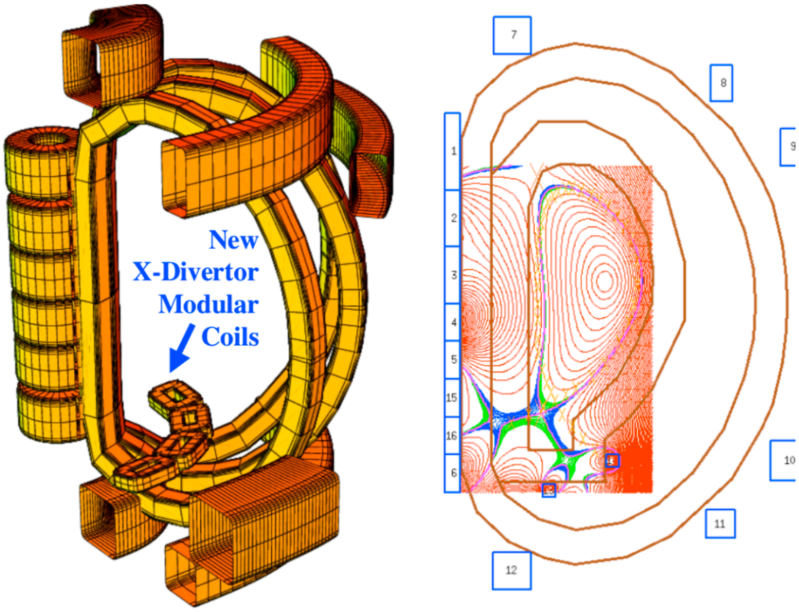

Figure 5: XDCoils and CREST equilibrium.

The reduction in poloidal field also increases the line length to the divertor plate by $\sim 2-3$ times as compared to an unusually highly tilted divertor plate with the same plasma-wetted area. Using 1-dimensional modeling (benchmarked with 2-D UEDGE results), we find that the extra field line length prevents excessive plasma temperatures at the plate. Conversely, at a given plate temperature allows $\sim$1.6-2 higher P_{SOL}. Furthermore, highly tilted plates are sensitive to plasma motion. For a given degree of sensitivity, the X-divertor configuration allows twice the plasma wetted area.

An additional advantage of X-divertors is that they make it easier to attain main plasma configurations of high triangularity. Such configurations have very beneficial MHD implications. Finally, the X-divertors are consistent with, and may in fact enable other ideas for improving divertor heat-flux limits. For example, the lowering of poloidal fields near the second X-point decreases the MHD drag, thus opening a viable design window for liquid metal divertors. It also simplifies attempts to enhance cross-field transport only in the divertor legs without affecting the main SOL.

We mention in passing that the liquid metal divertors [23, 24, 25] with a higher heat flux capacity may also be used; the liquid metal divertors are compatible with the new X-divertor (XD) ; they are, in fact, enabled by the new geometries.

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