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Divertor Design: Issues Raised by Steady State and Advanced Tokamak Operation

COSTER David P.*
Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany

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Abstract

Both steady state and advanced scenarios place constraints on the design of a divertor. Primarily these are related to imposing a minimum divertor density as well as the choice of target materials. There is also a competition between operational flexibility and divertor performance.

Keywords:

divertor, modelling, triangularity, transport barrier, edge density, divertor density

1. Introduction

Steady state and advanced scenarios both have implications for the design of an effective divertor. The requirements for steady state have two aspects: the first, reasonably well understood technically (though still challenging), is the issue of active cooling; the second, and somewhat more open-ended issue, is that of compatibility between the divertor and whatever main plasma requirements that are imposed by the current drive scheme required for steady state (most particularly any requirements for low density). The advanced scenarios also impose requirements: for an experimental machine the divertor might need to be compatible with a range of plasma shapes (in particular a range of triangularities); for both an experimental machine and for a reactor the divertor would need to be compatible with whatever density or other plasma conditions that were required by the advanced scenarios (possibly lower densities than might be optimal for best divertor operation). For a reactor additional constraints would be imposed by divertor lifetime considerations as well as tritium retention if carbon is used.

This paper examines some of these issues as illuminated by B2-Eirene simulations of the edge and divertor for ASDEX Upgrade and other machines.

Corresponding author's e-mail: dpc@ipp.mpg.de

2. B2-Eirene

B2-Eirene [1,2] is the combination of two codes, a fluid plasma code (B2) [3,4] capable of treating multiple species and a Monte-Carlo neutrals code (Eirene) [5] capable of treating the detailed production and subsequent evolution of background and impurity neutrals. It has been in use for a number of years now for modelling existing experiments and making predictions for future machines [6-13]. Its use on a number of existing machines and the detailed comparison of code results with experiment have increased the confidence of the community of it as a predictive tool for future machines, as have comparisons with other similar codes (EDGE2D-NIMBUS at JET and UEDGE from Livermore).

A series of code runs have been done in modelling ASDEX Upgrade with a range of divertor input powers, densities and impurity concentrations. Similar simulations have also been performed with B2-Eirene for ITER [14-16] and for other machines with B2-Eirene and other codes. All of these simulation results have shown the importance of divertor density in target heat loads, pumping and impurity contamination of the main plasma.

For a given input power, the peak heat load decreases with increasing density. The plasma temperature at the target also falls at the same time decreasing the production of impurities from physical sputtering. The changed pattern of temperature gradients in the divertor at higher density also means that the impurities are better retained in the divertor. Higher densities also mean a higher pump rate and the better exhausting from the plasma of the He ash that would be produced in a reactor. All of the above are predicted by the edge simulation codes and have also been seen in experiments. What the codes can then do is apply the same techniques to reactor designs and make predictions of their performance.

The key issue that emerges from these code studies is of a certain minimum divertor density which is necessary to ensure peak power fluxes below design limits, adequate pumping of helium and the prevention of impurity contamination of the main plasma. This minimum density, or better, range of densities because it can be somewhat altered by additional radiation from impurities and by the exact details of the target design, has severe implications for steady state and advanced tokamak operation in future reactor sized devices.

Another important issue is the stability of the divertor operation. The divertor regime envisaged is usually detached or semi-detached and has to be maintained, avoiding complete detachment, which usually leads to the formation of an X-point MARFE and a disruptive density limit, and avoiding too strong re-attachment which would raise the power flux to the target above design limits. This will probably need to be done under feedback control of the edge density or power flux to the target and will have to be done in such a way as not to destabilize any transport barriers (H-mode and/or internal). As predicted by modelling, supplying attached parts at the target away from the strike point (e.g. by shaping of the divertor as in ASDEX Upgrade) is the proper tool to maximize the stable divertor operation window with early onset of detachment close to the strike point.

3. Steady State

Many of the current tokamaks have divertor structures that are either not actively cooled at all, or are cooled on a time scale of many times the pulse length (cooling times of minutes compared to pulse lengths of seconds). This allows for relatively thick target plates. For steady state (or long pulse) operation the heat has to be removed at the same rate as the plasma deposits it to the target. This means that all heated surface require active cooling. This raises the complexity of the design and also imposes a target thickness constraint (otherwise there is too large a temperature differential between the surface and the coolant). Thus there tends to be a competition between maximum heat handling capacity (thinner target material) and lifetime given that there will be some erosion of the target during machine operation. These issues are technically challenging but have been solved or are close to being solved.

As a consequence of steady-state operation, active control of the divertor condition will be necessary to avoid instabilities due to complete detachment as triggered e.g. by wall outgassing on a long time-scale.

Steady state operation in a tokamak also imposes an additional, indirect, complication: that imposed by the choice of current drive mechanism(s). The choices for current drive include neutral beam, radio-frequency and bootstrap. For most of these schemes, efficiency is best at low densities (or at high temperatures, which, given a β limit, means a lower density). In order to achieve steady state burn most current reactor designs envisage a substantial fraction of bootstrap current, which brings us to the issue of advanced scenarios.

4. Advanced Scenarios

In addition to bootstrap current drive, advanced scenarios are also favoured because of the possibility of enhanced confinement in the form of internal transport barriers. This possibility raises the hope for a cheaper route to fusion power generation.

The current reference design for ITER envisages a standard operating regime using ELMing H-mode. This regime has been seen on a large range of machines and has been demonstrated for long times during a discharge. In this regime there is a region of reduced heat transport in the edge region of the plasma. The possibility of an additional or alternative transport barrier somewhat further in has provoked a great deal of interest both in the experimental and theory communities since it opens up the possibility of more attractive reactor designs. For these designs to prove useful they need to be demonstrated in steady state and also in a manner compatible with the other constraints, including that of particle and heat exhaust.

The steady state issue means active profile control which impacts the divertor design directly in that any additional direct heating of the plasma or heating arising from current drive would also need to be exhausted, and indirectly in the form of constraints on plasma density for the scheme to function. It is this indirect effect that could prove extremely troubling for designing an integrated solution.

Two routes are open with the internal transport barrier: with or without an H-mode barrier at the edge.

With two transport barriers there is always the danger that the one barrier might destabilize the other: transiently the inner barrier might starve the outer of the power flux that is needed to maintain the H-mode barrier; the establishment of the outer (H-mode) barrier or the presence of ELMs might change the density profile destabilizing the inner barrier. More importantly for this work, the double barrier solution might only be possible with too low a divertor density. To see this, assume a certain density at the mid-plane separatrix, this density being that minimum necessary for power and particle handling discussed above. Then with each of the transport barriers there is an increase in the density associated with the reduced transport in that barrier. This then implies a particular density at the centre which, together with the temperature required for fusion to occur, might be incompatible with β limits.

The other scenario with only an internal transport barrier makes things somewhat easier in some ways: with an L-mode edge the transport in the edge is likely to be somewhat higher and this would raise the critical divertor density associated with the peak heat flux; having no minimum heat flux crossing the separatrix to maintain the H-mode allows for the possibility of more core radiation lessening the divertor load; the disappearance of ELMs would also have positive implications for the lifetime of divertor targets. On the down side it is not clear that the transport improvement would be enough, and there might still be an issue of the critical divertor density. It might also be difficult preventing the transition to the H-mode.

There is also an additional impact of advanced scenarios on divertor design — it is not yet clear which particular triangularity would be best to optimize the advanced scenario operation. There might also be the issue of double null or ion grad-B drift away from the divertor operation. This raises the issue of operational flexibility versus performance.

5. Operational Flexibility Versus Performance

There are two competing issues in divertor design: maximizing performance and maximizing operational flexibility. In maximizing performance the divertor is optimized for target lifetime, heat handling capacity and pumping efficiency. However this usually means a highly shaped target with, for example, vertical targets. Operational flexibility, on the other hand, is usually best achieved with the simplest possible target scheme allowing the maximal flexibility in strike point position, plasma triangularity, *etc.*

This route converges to the use of simple, horizontal target plates as in DIII-D or the early JET phases. Even here, semi-detached and stable operation is possible due to the plasma plugging effect which provides sufficient divertor baffling to achieve detachment. However, in contrast to optimized divertors, the onset of divertor detachment is usually at higher upstream densities. With non-optimized divertors the pumping efficiency is often lower and there might be difficulties in adequately pumping the plasma.

Some current machines have concentrated more on configurational flexibility; others, especially as they have approached reactor relevant normalized power levels, have been forced to optimize the divertor design for power handling and so have lost configurational flexibility. For a reactor the constraints of power handling and pumping are likely to severely limit operational flexibility and hence to fix the plasma shape. The plasma would thus be optimized for one particular triangularity and set of target strike point positions. Before fixing the design, therefore, the desired triangularity would need to be known.

6. Choice of Materials

The issue of target material also influences the critical divertor density, principally in terms of the divertor plasma temperature and the physical sputtering threshold, but also in the heat handling capabilities of the various materials and their response to transient increases in heat loading (ELMs, VDEs and disruptions). In some ways it is not so much designing for steady state that is the problem, it is designing for the deviations from steady state. ELMs, disruptions, VDEs — all need to be included in the design.

Of the possible choices, C has perhaps the best response to these transient events with no liquid phase, good material properties and some self regulation of the divertor radiation arising from chemical sputtering. The chemical sputtering is also carbon's principal drawback: tritium trapping in the redeposited carbon will pose severe problems. Beryllium has a low melting point and physical sputtering threshold but has the advantage of being a low Z material and was used for a while at JET. Tungsten has good material properties and a high sputter threshold but its high Z so that main plasma contamination might pose a problem. There might also be a problem with melt layer loss after a disruption (or possibly giant ELMs).

7. Summary

For good divertor operation (lowering the peak heat flux below design limits, adequately pumping the helium ash and retaining impurities in the divertor) a certain minimum divertor plasma density is required. The minimum density can be changed over a limited range by changes in the radial transport coefficients, impurity radiation and divertor design (both geometry and material), but will impose constraints on the design for both steady state and advanced tokamak scenarios. The importance of an integrated solution where issues related to core confinement as well as divertor operation are included cannot be over emphasized.

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