S8-4

Progress in Divertor and Edge Transport Research for Stellarator Plasmas

Aaron Bader[1], F. Effenberg[1], C.C. Hegna[1]

[1]*University of Wisconsin-Madison Madison WI USA,*

Stellarator divertor design is an open area of research. Current approaches include the helical divertor of LHD and the island divertor of W7-X. These divertor designs will be presented along with non-resonant divertors useful for quasi-symmetric devices. Additionally, the advantages and difficulties of each of these divertors will be described. Looking forward, implications for divertors on physics designs of new stellarators will be discussed.

1. Introduction

All high performance fusion devices require a mediation between the hot plasma and the first wall. This mediation region can take many forms, but one of the most encouraging is the divertor. In divertor configurations, the plasma is bounded by a last closed flux surface (LCFS) outside of which are open field lines that terminate on the first wall. In general, this region can include stochastic regions, magnetic islands, or both.

The divertor is tasked with many roles. It must ensure that the plasma that impacts the wall is sufficiently cool so that the wall does not melt. Furthermore, it must prevent impurities, especially high-Z impurities, from entering the plasma core. Finally, it must be transparent to impurities inside the plasma, especially the helium ash that is born from fusion reactions.

We will discuss the Island, Helical and non-resonant divertors in turn. In the last section we will discuss some implications on stellarator design.

2. Island Divertors

The island divertor is currently in use on the Wendelstein 7-X (W7-X) experiment [1]. The island divertor is suitable for low-shear stellarators, where it is possible to tune in a rational surface near the edge. In W7-X, an $\iota=1$ resonance is tuned to the edge producing a 5/5 island chain. These islands intersect the divertor plates.

The island divertor is very sensitive to the rotational transform. The physics design of W7-X is such to reduce both bootstrap and Pfirsch-Schluter currents. These optimizations lead to minimal changes of the plasma profiles from the vacuum configuration to the full performance configuration.

However, even the small currents that do exist on W7-X create concerns for the survivability of the divertor plate during plasma ramp-up. One solution to this problem involve implementing “scraper elements” to intercept some of the plasma flux during the initial plasma phase.

Additionally, W7-X has begun exploring impurity seeding activities to not only mitigate heat flux to the divertor walls and achieve detachment control, but also to potentially allow for startup scenarios without scraper elements. Impurity seeding experiments were performed both in the limiter campaign and the first island divertor campaigns [2,3]. These experiments showed that radiative cooling of the edge plasma can be stably achieved in the island divertor.

The island divertor, when implemented in W7-AS allowed access to a high density H-mode with good plasma performance [4]. It is expected that on W7-X, operation with the island divertor should yield fully detached, stable plasmas, with high performance.

3. Helical Divertor

The helical divertor is present on the Large Helical Device (LHD) [5]. On LHD the magnetic field is generated in part by two large helical coils. These coils also produce a diverting field.

In LHD, there exists a stochastic layer between the confined plasma volume, and the field lines that terminate on the divertor plate. The size of the stochastic layer can be manipulated by altering the axis position. Furthermore, resonant magnetic perturbation coils can be employed to produce edge islands. In one set of experiments, these edge islands were seen to aid in expulsion of helium from the core plasma [6].

The helical divertor has the benefit that the divertor strike points can be moved far from the confined plasma, limiting penetration of cold neutrals into the core. Recently, LHD has used the available space to introduce both baffling to make a closed divertor, and cryo-pumps. These have allowed good density control of the plasma [7]

It is an open question whether a helical divertor can coexist with stellarators optimized for neoclassical transport, such as in quasi-symmetric or quasi-omnigenous configurations.

4. Non-resonant Divertors

Optimized stellarators that do not use helical coils and have significant bootstrap current may not be able to use either island divertors or helical divertors. Bootstrap and Pfisch-Schluter currents can modify rotational transform profiles which need to be carefully maintained in island divertors. Fortunately, many optimized stellarator configurations, including the quasi-symmetric configurations, possess sharp “ridges” on the plasma boundary. These ridges tend to channel flux similar to a divertor X-point.

Provided that the LCFS does not intersect the wall, and that there are no large magnetic islands, divertor behaves roughly similar between different configurations altered by bootstrap current [8]. This is because while bootstrap currents tend to modify the shape of the LCFS, they do not alter the location of the ridges. Such a divertor is referred to as non-resonant because it does not rely on a specific resonance in the rotational transform. Non-resonant divertors provide a possible alternative divertor configuration suitable for quasi-symmetric devices, although they have not been tested experimentally.

The non-resonant divertor would require a last closed flux surface surrounded by a stochastic region that mediates between the plasma and the divertor walls. Furthermore this stochastic layer needs to be maintained as the configuration changes from startup to the operating point.

5. Design Considerations

When designing new configurations, the divertor should be included. Currently there are no easily calculated metrics for divertor performance as exist for, say, neoclassical transport. Optimizations for divertor shapes exist for tokamaks, but so far these have not been applied to 3D systems. Furthermore, proper evaluation of divertor behavior can only be done with expensive modeling, such as EMC3-EIRENE, which is difficult to implement in an optimization loop. The divertor experiments on W7-X and LHD will guide us in improving divertor shape and performance.

Nevertheless, it is possible to consider divertors in at least some aspects of stellarator optimization, even without knowledge of ideal shapes. For non-resonant and island configurations, divertor placement is most effective near strongly shaped regions with large geometric curvature. An example of such a region is the tip of the crescent shape of W7-X, which is where the divertor is located. Fortunately, coil sensitivity is not overly strong in that region [9], so it is possible to pull the coils farther back from the plasma in these regions. Coil optimization and design should favor coil expansion in divertor reasons to allow for the placement of divertor modules, cryo-pumps, baffling, etc.

5. Conclusions

Stellarator divertors are significantly more complicated than the two-dimensional tokamak equivalents. Nevertheless, encouraging results from the helical divertor in LHD and the initial operational period at W7-X with the island divertor show that good particle control and stable detachment is achievable in stellarators. Non-resonant divertors provide a pathway forward for quasi-symmetric stellarators and other configurations not optimized for minimizing the plasma currents.

Acknowledgments

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References

[1] Y. Feng: Fus Eng. Des. **438** (2013) S497.
[2] F. Effenberg et al: Nuc. Fus. **56** (2017) 036021
[3] F. Effenberg et al: “Investigation of 3D effects on heat fluxes in performance-optimized island divertor configurations at Wendelstein 7-X" submitted 2018 to Journal of Nuclear Materials and Energy
[4] Y. Feng et al: Plasma Phys. Control. Fus. **44** (2002) 611.
[5] T. Morisaki et al: Nuc. Fus. **53** (2013) 063014.
[6] O. Schmitz et al: Nuc. Fus **56** (2016) 106011.
[7] G. Motojima et al: Nuc. Fus. **58** (2018) 014005.
[8] A. Bader et al: Phys. of Plas. **24** (2017) 032506
[9] E. Paul et al: Nuc. Fus. **58** (2018) 076015