MAGNETIC FIELD STUDIES NEAR SEPARATRIX

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Abstract

Vacuum magnetic fields are studied in the vicinity of the separatrix of modular Advanced Stellarator coil configurations with reactor dimensions. A modular divertor appears to be not feasible because of the complicated field structure. Rational ι-values inside of and near the plasma edge should be avoided. A system with comparatively small islands at $\iota = 5/11$ outside of the separatrix is seen to be relatively insensitive against a m = 1 perturbation and should allow the use of pumped limiters for edge control.

Introduction

In stellarators, the closed magnetic surfaces are separated from the region of outer open field lines by a usually well defined separatrix. It was often proposed to use this characteristic of the stellarator topology for a "natural" divertor, in order to achieve an edge control of the plasma. For toroidal systems with $\ell = 3$ modular non-planar coils, flux bundles of the separatrix region were found to encircle the coils at particular positions / 1 /, and the UWTOR-M fusion reactor / 2 / is designed with a modular divertor.

For modular Advanced Stellarators like the Garching experiment Wendelstein VII-AS, magnetic vacuum fields and also finite-β topologies / 3 / inside the separatrix were published so far. Details near and outside of the separatrix are of interest, in order to study the question of a modular divertor in such fields with reduced secondary currents. Vacuum fields of modular coil systems in fusion reactor dimensions are considered, having major radii of $R = 25$ or $20\,m$, and 6 coils in each of the 5 field periods. Figure 1 shows a schematic of such systems. In the first part of the paper, the spatial structure of the magnetic field outside of the separatrix is investigated numerically by following field lines. The second part concentrates on the presence of "natural" magnetic islands in the vicinity of the separatrix at rational values of the rotational transform, gives evidence of their removal by the fields of resonant currents, and shows effects of superimposed perturbation fields.

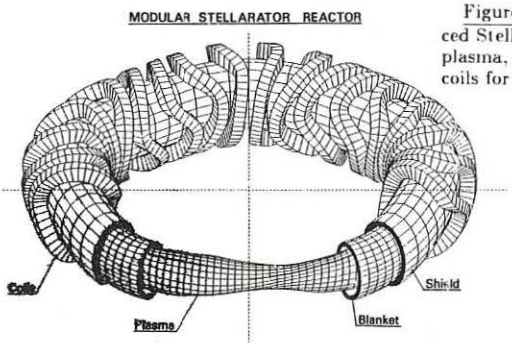

Figure 1: Schematic of a modular Advanced Stellarator, showing the contours of the plasma, of blanket and shield, as well as the coils for three of the five field periods.

Flux Bundles Outside of Separatrix

For a modular coil system similar to that of Figure 1 with $R = 25.5\,m$ and average radii of the coil centers, $r_c = 5.8\,m$, a number of 100 field lines is launched outside of the separatrix, at distances of 10 to 20 % of the average separatrix radius, $r_s \approx 1.6\,m$. (Starting points in 10 equally spaced toroidal planes within a field period, at 10 poloidal positions of approximately equal angular and locally different radial distance; integration step width small compared to the grid size of stored local field values). The intersection points of the field lines are marked on elliptically shaped outer surfaces. At a surface with average radius $r \approx 2 \cdot r_s$, the symmetry pattern of the starting points is still visible. The field lines merge at $r = 3.5\,m$, see top left of Figure 2, (abscissa = 1 field period, ordinate = 1 minor circumference). They show a reasonable concentration at $r = 3.8\,m$ (lower left part of the Figure), where 70 intersection points are obtained after 2 minutes CPU time of the Garching CRAY-1 computer. At $r = 5\,m$, one of the field line clusters is absent and 15 minutes CPU time are required for about the same number of intersections. Reversing the direction of integration, the pattern is mirror reflected as expected, but only 10 % more intersection points appear after a doubling of the CPU time. The lengths of the field lines for this case range between 3.5 and 100 times the circumference $2\,\pi\,R = 160\,m$.

In conclusion of this part: The initially poor field line concentration, their different lengths, and the change of the position of the intersection points when varying the aspect ratio of the boundary surfaces, makes such magnetic structures undesirable as to connect the plasma edge to divertor plates.

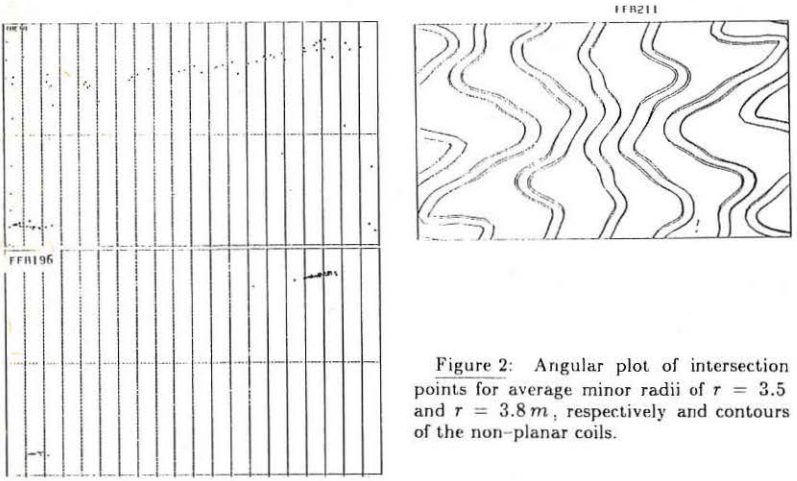

Figure 2: Angular plot of intersection points for average minor radii of $r = 3.5$ and $r = 3.8\,m$, respectively and contours of the non-planar coils.

"Natural" Magnetic Islands near Separatrix and Perturbation Fields

The Advanced Stellarator properties of the magnetic vacuum fields depend on the specific shapes of the coil bores and of the contours of the toroidal excursions. The coils provide a rotational transform ι which can be easily changed in the computations by a small variation of the coil aspect ratio. Systems with a low number of e.g. 6 coils per field period tend to show some negative shear. Already without the influence of external perturbations, "natural" magnetic islands can be seen near the plasma edge, at a rational value of the rotational transform $\iota = 5/N$, with integer $N = 9 \ldots 13$. Such islands were demonstrated / 4 / in the vacuum field studies for WVII-AS.

An example of 10 comparatively large islands is shown in the left part of Figure 3, for the toroidal positions of 0 and 1/2 field periods. In this particular case, outside of each X-point (O-point), further O-points (X-points) exist in an otherwise open field topology. In order to reduce the size of the natural islands, small currents outside of the islands and "resonant" with $\iota = 5/10$ were considered by A. Schlüter and W. Lotz[1]. These currents reduced the island size in the case of WVII-AS, at resonant $\iota = 5/10 \ldots 5/13$.

Following that approach, resonant currents are applied for the above example. Two current polygons are obtained by an outward projection of the inner O- and X-points, towards points at a radial distance of about 80 % of the separatrix radius, see insert of Figure 3. The whole chain of inner islands is removed by currents which introduce about 0.2 % of the average magnetic field at the position of the neighbouring island. The outer O-points are still present, see top of the right half of Figure 3. Increasing the currents in the same current polygons from 30 to 50 kA, removes the islands of a similar case at $\iota = 5/9$. In these two examples, the aspect ratio of the resulting configuration is approximately the same as that of a configuration with a neighbouring irrational value of the rotational transform.

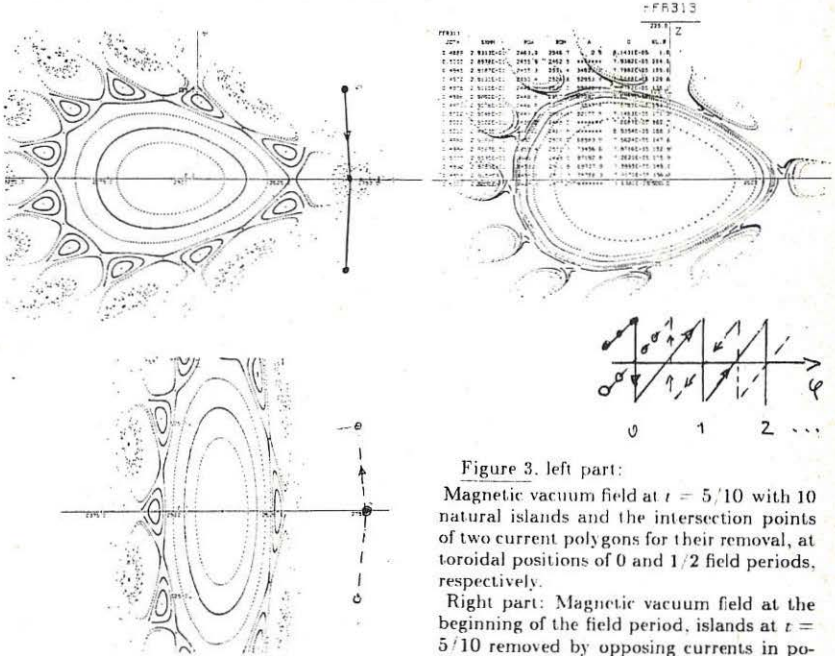

Figure 3, left part:
Magnetic vacuum field at $\iota = 5/10$ with 10 natural islands and the intersection points of two current polygons for their removal, at toroidal positions of 0 and 1/2 field periods, respectively.
Right part: Magnetic vacuum field at the beginning of the field period, islands at $\iota = 5/10$ removed by opposing currents in polygons as shown schematically in the insert

[1] W.Lotz and A.Schlüter :
private communication of their unpublished results for the fields of Wendelstein VII-AS

The effect of a homogeneous horizontal perturbation field is studied for the above configuration at $\iota = 5/10$, and for a different system, ASRA6C with $R = 20\,m$ and $r_c = 4.57\,m$. Whereas in the first case a homogeneous horizontal perturbation field $B_y/B = 4 \cdot 10^{-4}$ introduces a drastic reduction of the separatrix radius, ASRA6C with a prime number of 11 islands outside of the separatrix allows perturbation fields up to a value of 0.2 % of the average field $B = 5.3\,T$, at a small reduction of the separatrix radius, as shown in Figure 4.

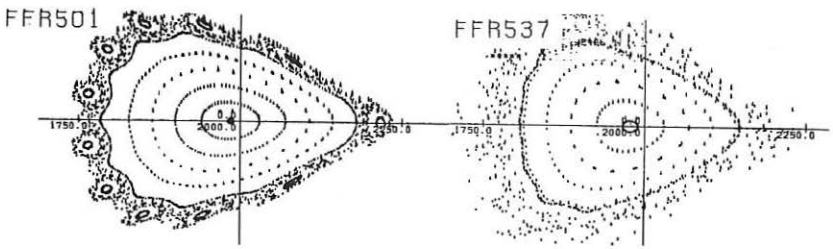

Figure 4: Magnetic vacuum field of ASRA6C showing 11 natural islands outside of separatrix at a value of $\iota = 5/11$, and effect of a homogeneous horizontal perturbation field $B_y/B = 0.2\%$ introducing a small reduction of the separatrix radius.

Summary and Conclusions

From the observed complicated structure of vacuum field lines outside the separatrix it appears that a modular divertor is not feasible in Advanced Stellarators as studied so far, unless the field topology could be changed by the action of further and yet unknown external currents. Magnetic islands at rational ι can be efficiently removed by small outer resonant currents, but the aspect ratio of the resulting configuration is not improved. Therefore, configurations at a neighbouring irrational rotational transform are preferred, avoiding inside and near the plasma edge rational $\iota = M/N$, with low integer values of M and N. Several such data sets are known. An example with comparatively small islands at $\iota = 5/11$ outside of the separatrix is seen to be relatively insensitive against a m = 1 perturbation and should allow the use of pumped limiters for edge control.

References

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