The effects of field reversal on the W7-AS island divertor at low densities

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1. Introduction

In the last years, considerable effort has been made on W7-AS to explore the diversion properties of the boundary magnetic islands in high ι (≥0.5) configurations for control and exhaust of the edge plasma [1]. Besides investigating basic aspects of divertor operation, such as high recycling, detachment and impurity control, understanding the drift effects on the particle and energy balance between the contacting plates is essential to improve the divertor performance.

Poloidal asymmetry of the plasma distribution in the island SOL of low density discharges has been observed for W7-AS divertor configurations at ι≈5/9, with the inboard plates intersecting the islands through the O-point. Unlike in most single-null tokamak divertors where, generally, higher density is found on one divertor plate while higher power flux on the other, the W7-AS divertor experiments show that the density, the power flow and the particle flux distributions have the same phase shifts in the island SOL. After reversing the magnetic field, the observed asymmetry is reversed. This asymmetry can be explained by an $\mathbf{E}_r\mathrm{x}\mathbf{B}$ drift in the island SOL as follows. The radial temperature gradient within the open island surfaces, which are intersected and radially linked by the electrically conducting plates, leads to a radial gradient of the plasma electrostatic potential and hence to a radial electric field inside the islands. The $\mathbf{E}_r\mathrm{x}\mathbf{B}$ drift delivers additional particles and energy in the island SOL along the upper or lower island fans to the targets, depending on the direction of the toroidal field. This picture is in good agreement with the experimental observations. In order to understand the drift effects quantitatively, in a first step the 3D Monte Carlo transport code EMC3/EIRENE [2] has been extended to allow the treatment of the poloidal drift. Calculations show the same phase shift of the density contours as observed.

2. Experimental observations

At high ι (≥0.5), the edge magnetic structure of W7-AS is governed by inherent magnetic islands. Having a considerable size and an appropriate internal rotational transform, the ι=5/9 islands have been chosen for the divertor experiments. Ten symmetric divertor plates are installed on the inboard side of the wall with a toroidal location which is symmetric to the triangular cross sections (Fig. 1). Each plate intersects poloidally two islands and the radial intersection position can be easily changed by application of a vertical field shifting the magnetic flux surface configuration horizontally with respect to the plates. In this work, however, only a configuration with the plates cutting the islands through the O-point is considered, which allows easy estimation of the radial electric field throughout the islands. Each divertor plate is poloidally segmented into 8 tiles and calorimetry measurements on each tile give a poloidal distribution of the power load. In addition, a two-dimensional H_α diode array is fixed horizontally at the outside of the torus, looking at a plate poloidally.

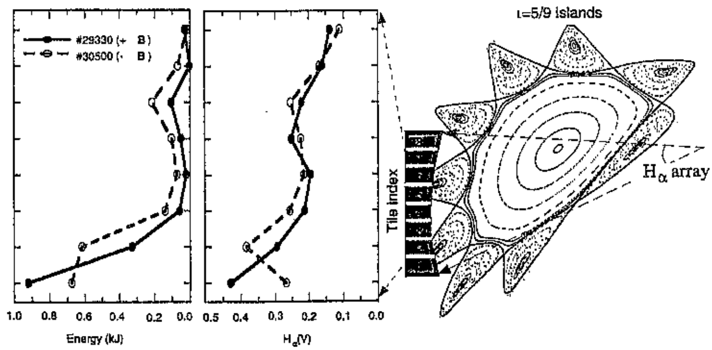

Fig.1 Right: poloidal cross section of the ι=5/9 configuration at the toroidal plane of an inboard plate. Left: calorimetry and H_α data for two discharges with B-field reversal.

The discharges investigated are at extremely low density ($<n_e>_{line}<10^{19}$ m^{-3}) with ECR heating power of about 200 kW. The results for two discharges with B-field reversal are compared in Fig. 1, in which the interaction of the two islands with the plate is well reflected by the diagnostics. It should be mentioned that the present inboard plates are not yet the optimized ones for W7-AS divertor operation. This explains why the power load and recycling are strongly inhomogeneous between the two islands. However, this does not affect the investigation of the drift problem addressed in this paper. We pay our attention only to the lower island, which, due to the longer connection length, carries higher particle and power flows to the plate. This island is cut by the two lowest tiles of the plate. Therefore, the two lowest diagnostic channels of the calorimeter and the H_α array are best suited to verify the differences in particle and energy flows between the upper and lower island fans. In the positive B-field case, higher energy and particle

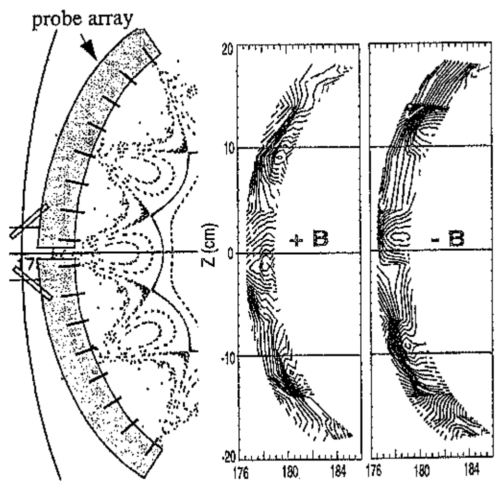

Fig.2. Left: Arrangement of the Langmuir probe array and the vacuum structure of the touching islands.
Right: Measured density contours for two low density discharges with B-field reversal.

outflows are found at the lower island fan, shifting to the upper one as the B-field is reversed.

A Langmuir probe array consisting of 16 probes is used to measure the density distribution of the edge plasma. The probe array is poloidally shaped to follow the main edge structure of the configuration and toroidally placed on a triangular cross section (Fig. 2). It can be shifted horizontally inward and outward by a few cm, thus providing 2D plasma density distribution in the region of interest. The resulting density contours from the probe array for the two field cases are illustrated in Fig. 2, in which the poloidal structure of the island chain is clearly identified. However, up/down asymmetries in the density contours emerge, showing a strong dependence on the field direction. Comparing density contours for the positive B-field with the vacuum island structure, we find that the plasma density is higher on the lower island fan than on the upper one. As the B-field is reversed, the higher plasma density shifts to the upper island fan, showing a simple correlation with the B-field direction.

3. Theoretical considerations and 3D simulations

As the observed asymmetries change with B-field reversal, the classical drifts are reasonably considered to play an important role because of their close dependence on the B-field direction. We examine the classical drifts, in order to isolate the candidates which can explain our experimental observations. The classical drift terms contributing to the fluid equations of Braginskii [3] are the electric drift $\mathbf{E}\times\mathbf{B}$ and the diamagnetic drift $\mathbf{B}\times\nabla P$. As has been shown by Chankin [4], the diamagnetic drift and the corresponding diamagnetic energy flux are dominated by divergence-free parts which do not deliver particles and energy to the target, nor give rise to any particle or energy accumulation or sink. The non-divergence-free components are due to spatial variations of the magnetic field, i.e. $\mathbf{B}\times\nabla B$ and $\nabla\times\mathbf{B}$. In a net-current-free stellarator such as W7-AS, the latter term is directly related to the plasma diamagnetic current and, in practice, can be neglected for the low density discharges involved in this paper. The $\mathbf{B}\times\nabla B$ term is a vertical drift and, therefore, its effect on the asymmetries in the islands is strongly reduced by the helical path of the islands around the torus.

According to these considerations, we can restrict our attention to the electric field drifts $\mathbf{E_r}\times\mathbf{B}$ and $\mathbf{E_\theta}\times\mathbf{B}$. The former is related to the radial gradient of the sheath potential due to the temperature drop towards the O-point. The latter is due to the potential drop along the B-field line from up- to downstream, associated with the parallel E-field arising from the thermal force. Following the particle flux estimation made by Chankin for tokamak divertors [5], we have the total radial and poloidal particle drift fluxes:

$$\Gamma_r \approx N2\pi R(kT_{e,up}-kT_{e,down})n_e/eB \text{ and } \Gamma_\theta \approx N2\pi R3kT_{e,down}n_e/eB,$$

where N is the poloidal periodicity of the configuration. Since N=1 for single-null divertor tokamaks, the drift effects in N>1 island divertors like W7-AS (N=9) are more pronounced than in tokamaks. Comparing the radial and poloidal drift fluxes, we find that the condition for Γ_θ dominating over Γ_r is $T_{e,down} \gg (T_{e,up}-T_{e,down})/3$. This is the case for the low density discharges discussed here. Heat transport simulations with the EMC3/EIRENE code showed that the temperature is about 90 eV at upstream position, dropping to 60 eV at the target, which agrees with the downstream temperature deduced from the Langmuir probe array data. A radial drop in temperature of about 20 eV was estimated from the Monte Carlo code. The resulting positive and negative poloidal drift velocities were inserted into the code, leading to the same phase shift of the density contours as observed (Fig. 3), which can be briefly explained as follows. In the picture assumed here, the particles created by low recycling in the main plasma and diffusing outside across the LCFS experience a poloidal drift in addition to the parallel montion along the island fans. A particle accumulation results in the upper or lower island fan, depending on the B-field direction.

The convective power flux driven by the poloidal drift is estimated to be ~90 kW, which is about half of the total heating power. This implies stronger asymmetry of the power fluxes between the upper and lower island fans than the one observed. One reason for the discrepancy is that the power fluxes along the upper and lower island fans cannot be sharply resolved by the two lowest channels of the calorimeter. Secondly, due to the large ratio of connection length to island size, a significant fraction of the drift power flux can circulate around the island between the discontinuous plates without reaching them. A quantitative assessment of these effects for island divertors needs a selfconsistent 3D treatment of the drifts, which is beyond the present capability of the EMC3/EIRENE code.

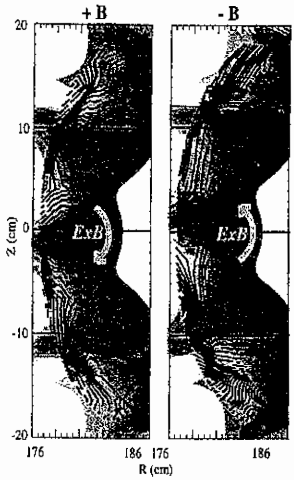

Fig. 3. Density contours from the probe array (curves) compared with the EMC3/EIRENE results for positive and negative B-field.

4. Conclusions

For low density, low recycling discharges, poloidal asymmetries in the island SOL have been observed for the W7-AS divertor configurations at ι=5/9, with the islands deeply cut by the present inboard plates through the O-point. Higher density, power flow and particle flux are measured for the lower or upper island fans, depending on the direction of the toroidal magnetic field. The asymmetries are considered to be driven by an $\mathbf{E}_T\mathbf{x}\mathbf{B}$ drift resulting from the radial temperature gradient in the island. The E_TxB drift delivers additional particle and energy fluxes along the island fans to the divertor plates, leading to the same phase shift of the density, energy and particle flux distributions in the island. 3D Monte Carlo calculations including the poloidal drift can well reproduce the density asymmetries measured by the 2D Langmuir probe array.

5. References

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