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Impact of Island Geometry on Island Divertor Performance

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1. Introduction

Stable partial detachment with more than 80% of the SOL power being radiated at the edge has been achieved in the W7-AS island divertor without significant loss of the global energy confinement. The new HDH-regime [1] found in W7-AS provides a high separatrix density, which is necessary for plasma detachment in the island divertor [2]. Furthermore, the strong decrease of the impurity confinement time in the core of HDH-plasmas [3] prevents the radiation layer from shifting inwards and thereby avoids a radiative collapse. However, divertor experiments have shown that a stable detachment cannot be established for rather small islands or when the connection length becomes too large [4], in spite of the presence of the HDH-regime. The connection length and the target-core distance are two key geometric parameters, which not only change the relative weight of the parallel and cross-field transports in the island divertor but also directly affect the efficiency of impurity and neutral screening through the islands. In this paper we present a detailed numerical analysis, based on 3D modeling with the EMC3-EIRENE code, aiming at understanding how and to what extent the island geometry affects the plasma, neutral gas and impurity transport in the island divertor.

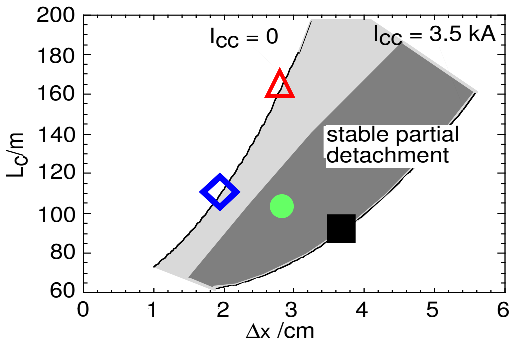

Figure 1: Stable partial detachment is restricted to large Δx and small L_c ranges (shadowed region). Four configurations are selected for numeric studies.

2. Experimental observations

Experimental studies on the geometry-dependence of detachment stability for the island divertor were carried out by proper combination and fine adjustment of ι and control coil current I_{cc} [4]. The connection length L_c and the target-core distance Δx (the distance between the targets and the closest X-point to the targets) were varied over a large range. As shown in Fig. 1, stable partial detachment is restricted within a region of large Δx and small L_c.

3. Simulation results

In the numeric studies the two geometric parameters L_c and Δx are varied separately through appropriate choice of four configurations as shown in Fig. 1. Cross-field transport coefficients are kept fixed through all the computations. Carbon released from the divertor plates through sputtering processes is considered to be the only impurity species, with the yield being linearly coupled with the recycling flux. With a fixed SOL power P_{sol} detachment is achieved in the simulations by increasing the separatrix density n_{es}. Then, n_{es} is further increased in small steps until the radiation zone shifts into the core. Figure 2 shows the dependence of carbon radiation on n_{es} for the four selected configurations. With decreasing Δx or enlarging L_c, the detachment transition shifts to higher densities and the detachment range becomes smaller. Note that both a smaller Δx and a larger L_c will increase the weight of cross-field transport.

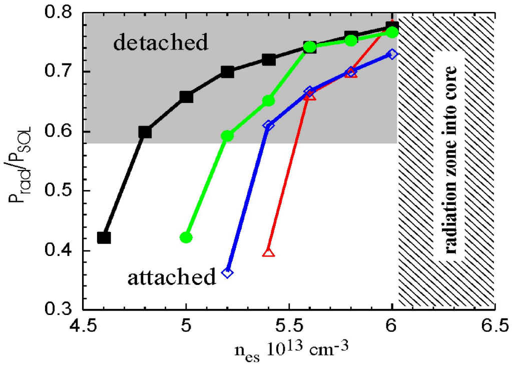

Figure 2: Carbon radiation normalized to P_{sol} as a function of n_{es} and configuration.

When detachment occurs the radiation layer detaches from the divertor plates and shifts towards the X-points located just in front of the targets, independent of the configuration selected. Around this X-point the magnetic field lines have the largest radial expansion, which minimizes the cross-field heat transport and thereby favors a radiation condensation. With increasing plasma density, however, the radiation distribution in the island SOL for different configurations develops in two different ways. Two typical radiation patterns are identified as shown in Fig. 3. For the two stable configurations (larger islands and smaller L_c, see Fig.1), the radiation zone gradually shifts poloidally away from the divertor region to the X-points located on the inboard side of the torus. When n_{es} increases further, the radiation zone extends poloidally to form a radiation belt on the high-field side. At the same time, the radiation belt shifts inwards and finally moves into the confinement region. In contrast, the small Δx or the large L_c for the two unstable configurations leads to an intensive and strongly localized radiation in the divertor region. Increasing the plasma density causes a much faster inward shift of the radiation zone to

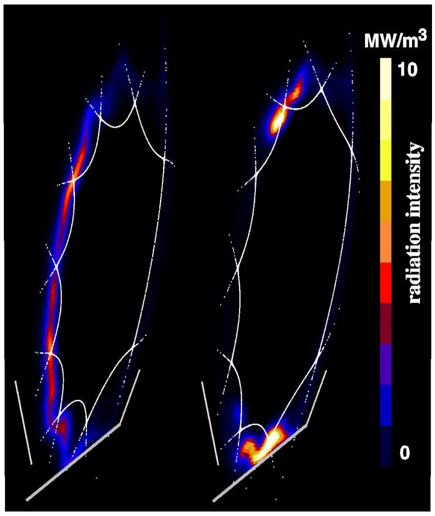

Figure 3: Two typical radiation patterns are identified by the code.
Left: Inboard side radiation for large Δx and small L_c
Right: Divertor radiation for small Δx or large L_c

touch the closed region than for the inboard side radiation case. Once the radiation zone moves into the core, however, the radiation zone shifts to the inboard side to form a radiation pattern which is almost identical to the first case.

Experiment data for stable detachments are consistent with the inboard side radiation picture. After transition to a stable detachment, both He-beam spectrometer viewing a upper divertor region [5] and the bolometer viewing a lower one [6] show a reduction of CIII emission and carbon radiation in the divertor region, although the global carbon radiation jumps to a higher level. Furthermore, at detachment, the divertor plate thermography shows a local hot spot remaining on the divertor plate segments which are magnetically connected to the outside of the torus, being an evidence for the inboard side radiation [4].

The evolution of the radiation zone in the island divertor is similar to that of Marfes observed in tokamaks, especially for the divertor radiation case. Nevertheless, whereas an X-point Marfe in a tokamak may be stable and can be maintained over a certain density range, a stable detachment related to the divertor radiation picture in the W7-AS island divertor has not yet been established. The reason for this will be discussed in the following section.

4. Detachment instability driven by neutrals

Divertor radiation lowers the temperature in the recycling zone. As a consequence, the islands become too cold to stop the recycling neutrals. The strong influence of the radiation location on neutral screening efficiency can be clearly seen in Fig. 4. For the divertor radiation case the neutral penetration flux into the core, Γ_{rc} which is normalized to Γ_{NBI} of a power of 2 MW, becomes much more sensitive to n_{es} and P_{sol} than for the inboard side radiation case. This means that a small change of n_{es} or P_{sol} can lead to a drastic change of Γ_{rc} and thereby introduces strong perturbation to the particle balance in the core. In fact, such a perturbation comes from the edge as the plasma changes its state from attach- to detachment. Once the transition occurs, Γ_{rc} suddenly increases. Because of the density screening effect of the HDH plasma (high density and flat profile), the penetrating neutrals are deposited in the edge region just inside the separatrix, leading to a local rise of density before the particles spread out in the core after a relatively longer time scale characterizing the core transport. This process can be described by the perturbation equation:

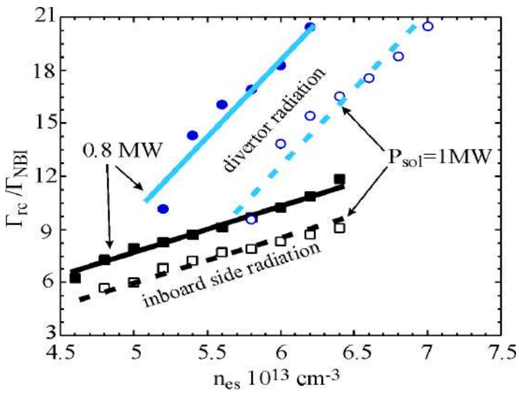

Figure 4: Neutral gas penetration flux into the core as a function of n_{es}, P_{sol} and configuration calculated by the 3D code.

$$\frac{\partial \Delta n_e}{\partial t} = \frac{1}{\lambda_0 A_s}\Delta\Gamma_{rc} - D\frac{\Delta n_e}{\lambda_0^2} \qquad (1)$$

where $\Delta\Gamma_{rc}$ is the change of the neutral penetration flux from attach- to detachment, Δn_e the corresponding change of the local core density within the neutral penetration depth λ_0, A_s the last closed flux surface and D the diffusion coefficient for the core. Ignoring the slower core transport and noting that Γ_{rc} is a function of n_{es} and P_{sol}, we have

$$\frac{\partial \Delta n_e}{\partial t} = \frac{1}{\lambda_0 A_s}\left(\frac{\partial \Gamma_{rc}}{\partial \mathbf{n}_{es}}\Delta \mathbf{n}_{es} + \frac{\partial \Gamma_{rc}}{\partial \mathbf{P}_{sol}}\Delta \mathbf{P}_{sol}\right) \qquad (2)$$

where $\partial\Gamma_{rc}/\partial n_{es}$ and $\partial\Gamma_{rc}/\partial P_{sol}$ can be derived from Fig. 4. Note that $\partial\Gamma_{rc}/\partial P_{sol} < 0$. As P_{sol} decreases with increasing Δn_e, due not only to the energy loss directly associated with neutrals but also to the increased core radiation resulting from the rise in density, the second term becomes positive and hence destabilizing. The growth rate of this instability is proportional to $|\partial\Gamma_{rc}/\partial P_{sol}|$ which is much larger for the divertor radiation than for the inboard side radiation. Note also the smaller detachment range for those configurations (see Fig.2). Decreasing n_{es} has a stabilizing effect on the growth of Γ_{rc} (see Fig. 4) and thereby the instability. The fact that stable detachment can only be established for sufficiently large islands and large field line pitch and the observation of the simultaneous and corresponding drop of P_{sol} and n_{es} through the stable detachment [2] confirm this theory.

4. Conclusions

Island divertor experiments show that a stable detachment requires sufficiently large islands and field line pitch. Numeric studies show that, under detachment condition, the radiation distribution in the island SOL is sensitive to the island geometry. Two typical radiation patterns are identified from the simulations, namely the inboard side radiation for large islands of large field line pitch and the divertor radiation for small islands or small field line pitch. Divertor radiation lowers the temperature in the recycling zone such that the islands become too cold to stop the recycling neutrals. A linear stability analysis based on 3D simulation results shows that a sudden increase of neutral penetration flux into core at detachment transition drives an instability, with a growth rate being directly related to the neutral screening efficiency. Decreasing the edge density has a stabilizing effect. These results are consistent with the experimental observations.

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