EUROFUSION WPMST1-PR(16) 15572

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Preprint of Paper to be submitted for publication in
43rd European Physical Society Conference on Plasma Physics (EPS)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Infrared measurements of the heat flux spreading under variable divertor geometries in TCV

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Introduction

In a divertor tokamak as ITER, a significant fraction of the heating power continuously leaves the plasma core across the separatrix and enters the scrape-off layer (SOL). In the SOL heat is primarily transported along magnetic field lines towards the divertor targets; the resulting heat fluxes on the material surface are particularly high at the strike points (SPs), where the separatrix intercepts the divertor target. The maximum heat flux onto the actively cooled structures in ITER is typically 20 MW/m^2 in steady state and up to 40 MW/m^2 during transients [1]; peak heat flux mitigation is currently a crucial research topic. One mitigation strategy is based on the optimization of the divertor geometry, which, for example, can be performed by changing the target flux expansion (f_x) or the divertor leg length; the former is defined as the ratio of the distance between two flux surfaces evaluated at the target ρ_t and upstream at the outboard midplane ρ_u, namely $f_x = d\rho_t/d\rho_u$. This paper presents a study of the influence of the outer divertor leg length on the heat flux profiles at the targets for low-confinement (L-mode), Single-Null (SN) plasmas. Analyzed data belong to a recent MST1 campaign performed at TCV. The investigated divertor configurations, together with the corresponding inner and outer leg connection length C_l profiles (the C_l is defined as the length of the magnetic field lines from the outer midplane, where the majority of heat enters the SOL, to the divertor target) are shown in figure 1: the outer divertor leg C_l was varied by acting on the vertical position of the magnetic axis z_{mag} while keeping the plasma shape and divertor configuration (e.g. f_x) similar. When the plasma is moved upwards, away from the floor, the outer leg C_l increases. The scan has been performed with ohmic heating only, at multiple values of plasma current ($I_P = 130$ to $340\ kA$) and ohmic power ($P_\Omega = 130$ to $400\ MW$), constant density ($n_e \approx 3 \cdot 10^{19} m^{-3}$), both in forward field (ion gradB drift downwards) and reversed field (ion gradB drift upwards).

Experimental setup and diagnostics

The heat flux on the material surfaces in TCV is measured using Langmuir Probes (LPs) and InfraRed (IR) thermography. A preliminary LP analysis for this experiment has been presented

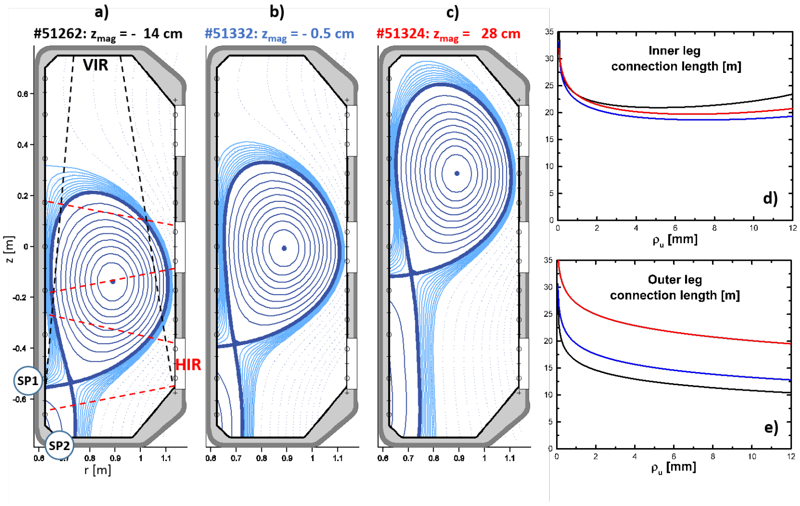

Figure 1: Scan of z_{mag} in forward field: poloidal views of the magnetic reconstruction (a-c) and C_l profiles for both the inner (d) and outer (e) divertor leg as a function of the outboard midplane distance to the separatrix, ρ_u. The field-of-views of the VIR and the HIR (lower and middle plane ports) are also indicated.

in [2]; this paper focuses on IR measurements. The TCV IR thermography system consists of two IR cameras; a recent upgrade of the system (October 2015) has improved its capabilities for measuring divertor heat loads in multiple magnetic geometries for both strike points simultaneously. The first IR camera (Vertical InfraRed, VIR) is mounted on the top of the machine and images the vessel floor, where the outer strike (SP2) of a SN plasma sits (see figure 1); typical acquisition rate and spatial resolution are 400 Hz and 2.5 mm in full-frame respectively. The second camera (Horizontal InfraRed, HIR) is mounted on a lateral port and monitors a portion of the central column, where the inner SP (SP1) is located; typical rate of acquisition and resolutions are 200 Hz and 0.8 mm in full frame and using a 25 mm focal-length lens. The HIR field-of-view can be doubled by using a fish-eye lens (12.5 mm focal-length), while reducing the spatial resolution by a factor 2; also, the camera can be alternatively mounted on the lower or mid plane port (shown in figure 1). The upgrade of the TCV IR system has involved also the software. A number of challenging issues have been addressed, including the shaking of the video during the discharge and the contamination from non-thermal light for the VIR.

Results

A direct comparison of the heat flux profiles from different shots requires first to decouple the spreading effect of the target heat flux profile due to any variations in the f_x from variations of the profile due to the increased C_l; the technique adopted here is to map the target heat flux profile on the outboard midplane in two steps. Firstly, target and upstream locations with the same poloidal magnetic flux ψ are coupled; the upstream coordinated ρ_u is defined as the outboard midplane distance to the separatrix. Secondly, the parallel (along field lines) heat flux on the target is computed by considering the field line grazing angle γ ($q_{\parallel,t} = q_{\perp,t}/sin(\gamma)$); then, assuming no volumetric losses along the flux tubes, the relation $q_{\parallel,u}/q_{\parallel,t} = B_{tot,u}/B_{tot,t}$ can be derived and the parallel heat flux is mapped upstream as $q_{\parallel,u} = q_{\parallel,t} \cdot B_{tot,u}/B_{tot,t}$.

The quantity chosen as ordering parameter is the *average connection length*: this is obtained by averaging the outer leg C_l profile in the first 2 mm of SOL (figure 1). IR measurements clearly indicate that an increase of the outer C_l induces a drop of the total power reaching the floor (figure 2a), a decrease of the peak heat flux (figure 2b) and an increase in the $\lambda_{int,u}$, discussed later, for both forward and reversed field (figure 2c).

Further results can be obtained if the parallel heat flux profile is parametrized by the convolution of a decaying exponential and a Gaussian [3]. The dependencies of $\lambda_{q,u}$ (SOL-power fall-off length) and S_u (spreading factor) on the outer leg C_l in both forward and reversed field conditions are reported in figure 3; in figure 4 the experimental $q_{\parallel,u}$ profile with the fitting curve for three plasma positions (forward field) are also presented. The trend for $\lambda_{q,u}$ is consistent with that for $\lambda_{int,u}$; also, no clear dependence of the spreading factor S_u on C_l is found. Both results confirm the LP analysis ([2]) and are similarly unexpected. According to purely diffusive models, a longer C_l is usually associated with a greater cross-field diffusion in the private-flux region, which should lead to a greater S_u; conversely, the influence on the SOL power decay length is not expected to be so strong. The inner divertor heat flux profile displays a double-peak shape in forward field, as reported for JET [4] and TCV [5], and may be caused by enhanced $\vec{E} \times \vec{B}$ drifts in the SOL [5]. An extension of the standard heat flux profile parametrization is here proposed by considering the effect of drifts as a cross-field radial redistribution of heat from the separatrix region to the far-SOL. This mechanism is parametrized by introducing a sink-source function, shown in figure 4: the power missing from the separatrix region (negative part of the profile, 'sink') is found on the far-SOL region (positive part, 'source'). Analytically, the function is the superimposition of two half-wavelets functions via the Heaviside step function; the areas of the two are constrained to be equal for the conservation of the total power. One of the main potentialities of the extended parametrization is the possibility to extract from a doubly-peaked profile the equivalent Eich profile (shown in figure 4, black dashed-line) and thus its parameters, for example $\lambda_{q,u}$ and S_u. Data analysis is proceeding also in other di-

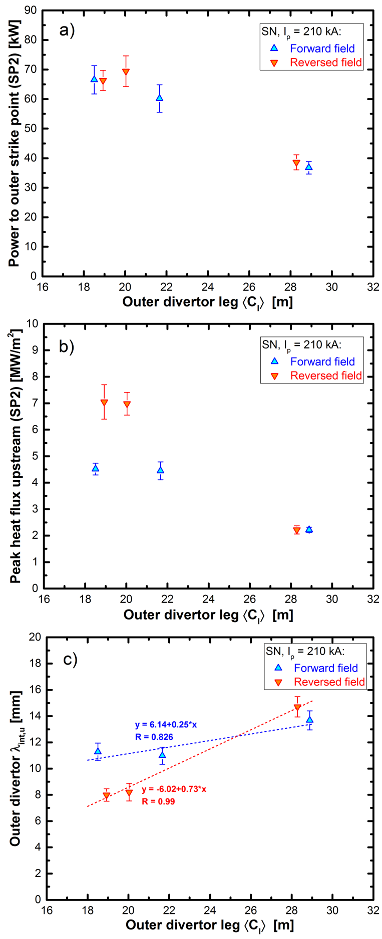

Figure 2: Power to outer strike point (a), peak value of $q_{\parallel,u}$ (b) and $\lambda_{int,u}$ (c) as a function of the outer leg C_l, both in forward and reversed field.

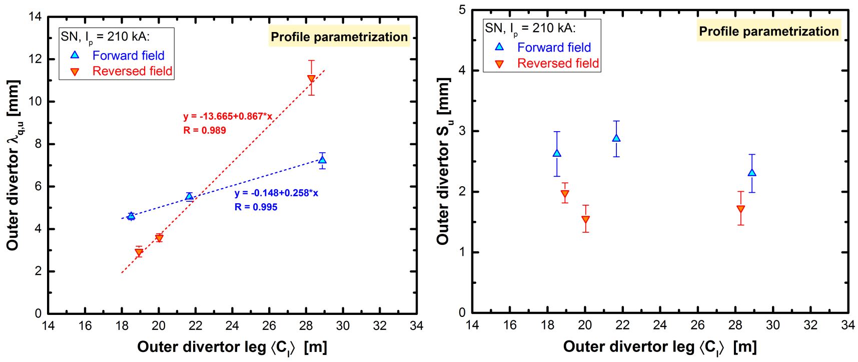

Figure 3: Outer leg $\lambda_{q,u}$ (left) and S_u (right) as a function of the outer leg connection length.

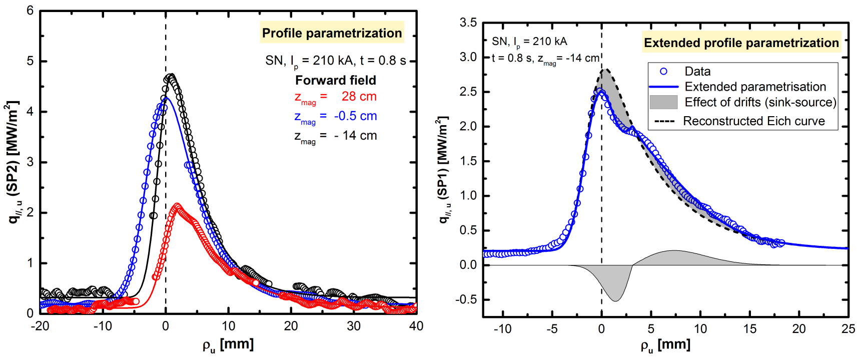

Figure 4: Example of parallel heat flux profiles mapped upstream for the outer (left) and inner (right) strike point. In the latter, the extended profile parametrization is also presented.

rections, among them scan of I_p, comparison between Deuterium and Helium, study of in-out asymmetry and comparison with recent scalings ([6]); for instance, $\lambda_{q,u}$ is found to decrease with increasing I_P ($\lambda_{q,u} \sim I_P^{-0.5}$), a dependence weaker than previous scalings ([3]: $\lambda_q \sim I_P^{-9/8}$).

Conclusion

The dependence of target heat flux spreading on the outer divertor leg connection length, for SN L-mode deuterium plasmas, has been investigated in TCV: the preliminary results, quite unexpected, indicate that the connection length influences positively the SOL-power fall-off length while no effect on the spreading factor is seen. Further investigations are currently underway to interpret these outcomes.

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