

## Plasma $\beta$ -Effects on Edge Magnetic Topology and Divertor Heat Flux at LHD

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Divertor heat flux patterns in a stellarator or a tokamak with resonant magnetic perturbations show distinct structures due to the stochastic edge magnetic topology [1]. The edge topology is characterized by closed flux surfaces gradually breaking up and forming a volume of islands and open stochastic field lines. These open field lines are the major radial transport channel in the edge due to the fast energy and particle transport parallel to the field line. MHD equilibrium codes like HINT2 [2] can predict the magnetic topology but need to be cross-checked to experimental measurements. Focusing on the magnetic edge, this work presents a systematic comparison of experimentally obtained heat flux pattern and the calculated equilibrium magnetic field structure at the Large Helical Device (LHD).

Since pressure gradients  $\nabla p$  in a plasma in a magnetic field  $\vec{B}$  need to be balanced with an electromagnetic force  $\vec{F} = \vec{j} \times \vec{B}$ , so called diamagnetic currents  $\vec{j}$  are driven. These currents induce changes in the magnetic topology depending on the plasma  $\beta$ , which is the ration of thermal pressure to magnetic pressure. Typical influences are a shift of the magnetic axis position (Shafranov shift), a change of the last closed flux surface (LCFS) and an increase in edge stochastization [4] [5]. Fig. 1 shows the Poincare plots of torus inboard region in a poloidal cross section using magnetic equilibria calculated with HINT2 for different plasma  $\beta$ . Magnetic field lines have been traced from start points along the major radius in the range from  $R > 2.6\text{m}$  (blue) to  $R < 3.1\text{m}$  (red). While at low  $\beta$  only the outermost field lines (blue and green) lead to the divertor, at high  $\beta$  even inner field lines (red) show strong radial diffusion.

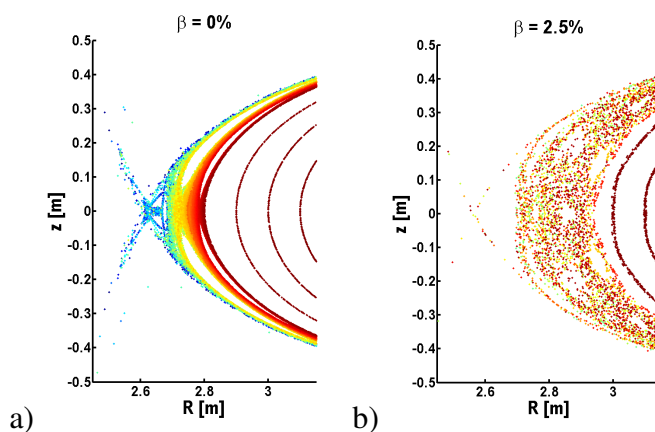


Figure 1: inboard side Poincare plot; color denotes radial start point of field line

Figure 1 shows the Poincare plots of torus inboard region in a poloidal cross section using magnetic equilibria calculated with HINT2 for different plasma  $\beta$ . Magnetic field lines have been traced from start points along the major radius in the range from  $R > 2.6\text{m}$  (blue) to  $R < 3.1\text{m}$  (red). While at low  $\beta$  only the outermost field lines (blue and green) lead to the divertor, at high  $\beta$  even inner field lines (red) show strong radial diffusion.

In order to characterize the magnetic field lines hitting the divertor two quantities have been calculated. The connection length ( $L_C$ ) represents the distance along a traced open field line between the intersection points with the divertor or plasma vessel. Typically, the field lines with short  $L_C$  do not penetrate deep into the plasma and thus do not carry much energy to the plasma facing components. The distance of each point along the field line to the LCFS will be denoted as  $d_{LCFS}$ .

The helical divertor at LHD consist of two rows of graphite tiles wound helically around the plasma torus. It follows the same tenfold toroidal symmetry as the main helical magnet field coils of this heliotron type magnetic confinement machine. The edge particle fluxes were measured with Langmuir probes at two different positions. The divertor tiles of the inboard side of torus section ten (10I) are observed with an infrared camera. Fig. 2 shows a top view of the location of measurements as well a their relativ position in one divertor segment.

The evolution of the divertor surface temperature  $T_S(t)$  measured by the infrared camera was analyzed with a thermal model (THEODOR [3]). Calculating the heat propagation in two dimensions (along a surface profile line and into the bulk) provides the incoming heat flux  $Q$  as a boundary condition. Surface layers deposited on the divertor usually lead to an overestimation of heat fluxes during plasma and a negative flux afterwards. A reduced heat transfer coefficient between layer and bulk allowed to compensate this effects.

An experimental  $\beta$ -scan at LHD was conducted by repeating equivalent discharges at different magnetic field strength ( $0.5T < B < 2.75T$ ). Experiments used the same vacuum magnetic configuration and NBI heating scenario. The data was selected with regard to comparable plasma density and currents. Comparing the heat flux distribution along a divertor profile line with the connection length of field lines starting from the profile shows a strong correlation (see fig. 3). The calculated  $L_C$  values have been limited to 500m. The accuracy in  $s$  of the local correlation is better than 6mm as the position of the divertor tiles has been calibrated after the experiments.

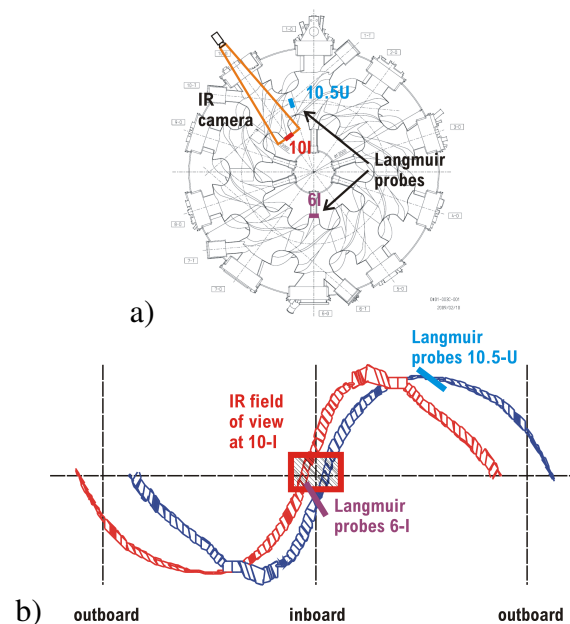


Figure 2: measurements areas at LHD

With increasing plasma  $\beta$  secondary peak structures at  $s \approx 25\text{mm}$  move to the left in fig. 3 and the major strike line at  $s \approx 75\text{mm}$  broadens and shifts to the right hand side. While the peak shift is a clear indicator of a changed magnetic topology, the broadening could also be based on increased perpendicular transport due to the reduced magnetic field strength.

Fig. 4 shows the LCFS penetration in a color plot, where the horizontal axis represents the distance  $s$  along the profile and the vertical axes the length  $l$  along each field line. The color represents  $d_{LCFS}$  and indicates an oscillating approximation and detachment of field lines from the LCFS. Although all field lines starting from  $s < 80\text{mm}$  penetrate equally close to the LCFS, only those which stay close to the core plasma carry the peak heat load. Even at  $s \approx 12\text{mm}$ , where field lines have two close contacts to the LCFS, they deliver more heat flux to the divertor than those field lines at  $s \approx 45\text{mm}$ .

The  $\beta$  induced changes of the magnetic topology are not local. Fig. 5 shows the calculated  $L_C$  pattern on the inboard half of one segment of the helical divertor. The vertical axes represents the poloidal angle  $\theta$  from the torus top ( $\theta = 90$ ) to the bottom ( $\theta = 270$ ) while the horizontal axes is the toroidal angle  $\varphi$ . Low  $\beta$  calculations (fig. 5 a)) show slope like structures at the inboard divertor which move with increasing  $\beta$  to the top and bottom. Two narrow strike lines remain at the torus inboard side for  $\beta = 2\%$ , which for higher  $\beta$  both shift towards each other shrinking the private flux region between them.

Linear Langmuir probes had been placed as shown in fig. 2. The integrated ion saturation current  $\int I_S ds$  over all probes is a measure for the local particle flux and is compared to the heat deposition at 10I. Fig. 6 shows the integral values for different plasma  $\beta$ . The behavior of  $\int I_S ds$  at the inboard side of the 6I section resembles the total heat flux at 10I, which peaks to a maximum at  $\beta = 1.1\%$  and  $\beta = 1.5\%$  respectively. At the torus top at 10.5U instead,  $\int I_S ds$  has a maximum at  $\beta = 2.3\%$ . Not only does the region with slopes in the

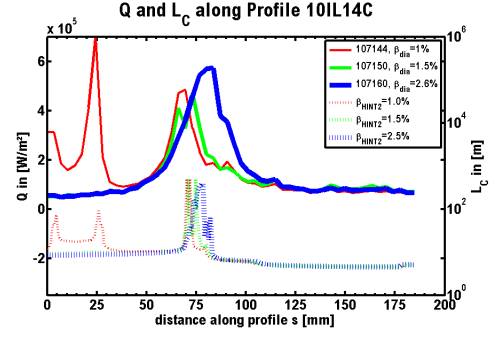


Figure 3:  $\beta$ -scan of heat flux and connection length profiles

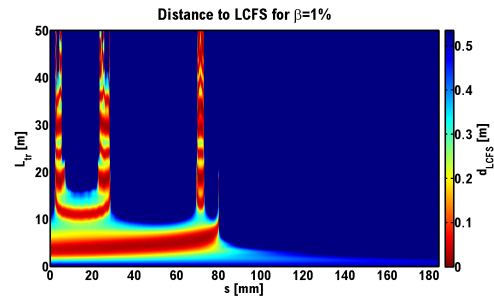


Figure 4: penetration of magnetic field lines calculated for for the same initial conditions as in fig. 3 (red dashed line)

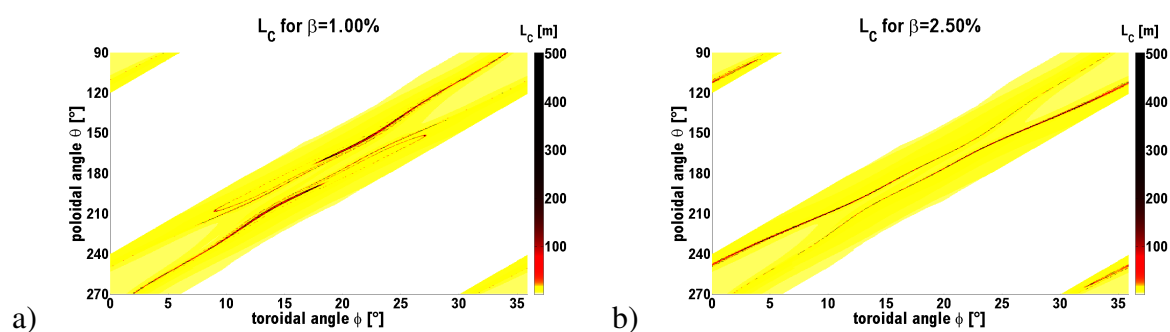


Figure 5: connection length along helical divertor at low and high  $\beta$

$L_C$  pattern move helically as shown in Fig. 5, but also the main heat and particle flux shifts from the inboard side to the top (and probably also to the bottom) part of the helical divertor.

## Summary

A comparative study of experimentally measured heat and particle fluxes to the helical divertor and the results of equilibrium code calculations was conducted at LHD. Heat flux peaks and their shift with increasing plasma  $\beta$  is strongly correlated to pattern of field lines starting from the divertor with long connection length  $L_C$  and multiple contacts to the LCFS. The structural changes indicate a helical shift of regions with long  $L_C$ . The particles and energy from the plasma appears to be heterogeneously deposited onto the helical divertor and to shift their peak deposition area with increasing  $\beta$ .

## References

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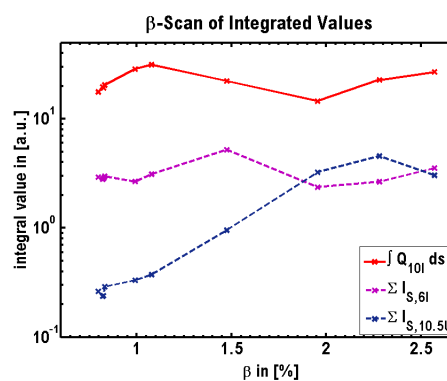


Figure 6:  $\beta$ -scan of  $\int Q ds$  and  $\int I_s ds$