§1. Impact of RMP on Divertor Footprints in LHD

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Helical divertor in heliotron/stellerator configuration naturally leads to non-axisymmetric divertor footprints and understanding of its relation to the plasma parameters and magnetic field structure is important for the divertor heat and particle flux control in the present and future machines. The goal of this experiment was to investigate the effect of plasma response to the applied RMP fields on the footprints variation and the link to the island healing and growth induced by the RMP.

A divertor IR camera was used to observe outer divertor footprints on the surface of a material probe, inserted into the vacuum vessel on the outer side. We varied plasma density, RMP phase, and the NBI power and took divertor strike line images from the IR camera to look into how these variations affected footprint pattern. Also looked into was the magnetic probe data to measure plasma response data in order to reconstruct the evolution of both the amplitude and the phase difference between the applied RMP and the plasma response fields. It is noted that the LHD RMP system is n=1 only and the phase difference is in the poloidal direction (θ).

As expected, a different radial location of magnetic axis (R_{ax}) produced a very different strike line heat flux intensity and here we report only results for R_{ax} =3.6 m for convenience. A reference discharge with no RMP showed that the spatial distribution of heat flux footprints is rather uniform along the helical direction, at least within the measurement area. This is a little surprising given that LHD plasma is intrinsically 3D and the footprint structure should be also non-axisymmetric. High density (5e19 m^{-3}) plasma is found to lead to higher heat flux, as expected. When the RMP was applied, heat flux distribution became more non-axisymmetric in the helical direction compared to the non-RMP case. This result is contrary to that in tokamaks, where a splitting of separatrix occurs and therefore striations in the radial direction are observed [1]. The fact that non-axisymmetric heat flux deposition is primarily along the helical direction, *i.e.*, along the strike line, has a potentially adverse implication, which means that the applied RMP raises peaking factor of heat flux deposition in the toroidal direction rather than the spreading of heat flux to a wider divertor area. This effect has to be further investigated by extending measurement area to cover wider divertor strike lines in toroidal and poloidal directions.

The plasma response behavior was analyzed and compared to the IR footprint asymmetry behavior. First of all, when the phase difference was 0, the applied RMP was amplified due to the in-phase interference and penetrated into the plasma. This led to the magnetic island growth and was confirmed by the electron temperature (T_e) profile from the Thomson scattering data, *i.e.* wider flat spots in the island locations. The IR footprint data demonstrated strong non-axisymmetry in the helical direction (see the black case in Fig. 1), consistent with the expectation and argument from the role of plasma response in the formation of islands and its relation to the asymmetric divertor footprints. On the other hand, when the phase difference was 180^o, it is believed that out-of-phase interference occurred between the RMP and plasma response fields, which should have canceled (screened) the RMP fields. Indeed this screening effect was confirmed by the healing of magnetic islands and again was accompanied by the shrink of island, measured by the flat spot size in the T_e profile. This screening effect is thought to have reduced the degree of non-axisymmetric footprint pattern and indeed the measured IR data does show that the asymmetry is weaker than the island growth case (red in Fig. 1).

As the next step, the relationship between the plasma response and collisionality was looked into. A previous study [2] revealed that high collisionality is favorable for island growth. In this experiment, the plasma density was varied to change collisionality and it was confirmed that the island growth by high collisionality led to more non-axisymmetric IR heat flux footprints. Given that the asymmetry is primarily along the strike line, as discussed above, this result indicates that high collisionality plasma could produce more non-axisymmetric divertor heat flux deposition in LHD and therefore divertor detachment [3] would be necessary to reduce the negative impact.

One thing that is planned in the near future is the plasma response modeling, *e.g.*, VMEC (ideal) and HINT2 (resistive), and its inclusion in the field line tracing for divertor footprints to be compared to the experimental observation. This modeling should be used in the B-field model for the 3D transport code, *e.g.*, EMC3-Eirene, ultimately to calculate heat flux footprints to be compared to the measured IR heat flux.

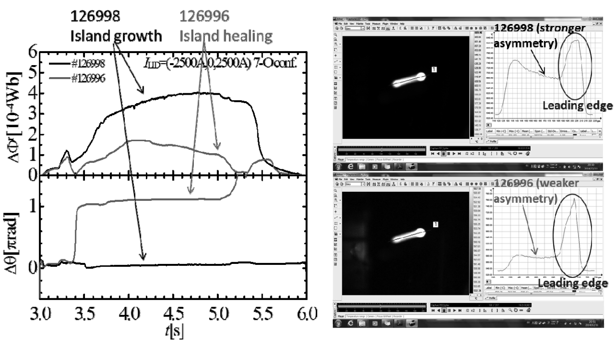

Fig. 1 Amplitude (upper left) and phase difference (lower left) of the applied RMP fields, measured by the magnetic probes, for two different cases of magnetic island behavior; island growth and island healing. The right two plots are the IR images of outer divertor footprints. It is seen that the asymmetry of footprint pattern in the helical direction becomes stronger in the island growth case (upper right) compared to the island healing case (lower right)

[1] J-W. Ahn, et al, Nucl. Fusion **50** (2010) 045010
[2] Y. Narushima, et al, Plasma and Fusion Research **8** (2013) 1402058
[3] M. Kobayashi, et al, Nucl. Fusion **53** (2013) 093032