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Negative Triangularity plasmas on DIII-D: a novel approach to the core-edge integration problem

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Discharges with negative triangularity (NT) shape on the DIII-D tokamak are characterized by H-mode grade confinement and pressure levels despite maintaining edge pressure profiles typical of the L-mode regime. The L-mode phase is routinely observed to persist even when the power crossing the separatrix significantly exceeds the L→H power threshold expected from conventional scaling laws. For a given confinement factor, operation without an edge pedestal is beneficial in multiple aspects, such as eliminating the need for active mitigation or suppression of Edge Localized Modes (ELMs), low impurity retention and wider Scrape-Off Layer (SOL) heat flux width.

Following pioneering results obtained on the TCV tokamak[1], initial experiments were performed on DIII-D[2,3] in an inner-wall limited (IWL) up-down symmetric shape with elongation κ = 1.33 and triangularity δ = -0.4 at the last closed flux surface, while more recent experiments made use of a novel Lower Single Null (LSN) diverted shape specifically designed to probe the L→H power threshold and SOL physics (Figure 1). To maximize the top-bottom averaged negative triangularity and allow compatibility with high auxiliary power, the separatrix above the mid-plane features strong shaping with upper triangularity δ_u = -0.4, while the lower triangularity is close to zero so that the divertor strike points do not impinge on the outer wall.

Negative triangularity discharges in both IWL and LSN configurations were investigated for a plasma current I_P = 0.9 MA and confining magnetic field B_T = 2.0 T, resulting in q_{lim} ~ 4.3 and q_{95} ~ 4.5, respectively. While the IWL cases feature a line averaged density that increased with beam fueling and an effective charge (Z_{eff}) as large as three, LSN plasmas maintained an approximately constant line averaged density and Z_{eff} in the range 1.4-2.

The L→H power threshold is postulated to increase strongly with increasing negative triangularity. The H-mode transition was observed neither in IWL nor in LSN configurations at nominal values of plasma shape. In one diverted case, when the top triangularity was accidentally relaxed to δ_u = -0.2, the standard L→H transition was observed with 4 MW of auxiliary power; however, whenever the separatrix held its design value δ_u = -0.4, plasmas maintained L-mode edge pressure profiles even for auxiliary powers as high as 15 MW.

Negative triangularity discharges sustained H-mode grade confinement and normalized pressure levels despite the lack of an edge pedestal. More specifically, discharges routinely reached normalized pressure levels up to β_N ~ 3 and confinement factors of H_{98y2} ~ 1 with weaker power degradation of stored energy ($W \propto P_{aux}^{0.7}$) than predicted by the ITER-89P scaling law ($W \propto P_{aux}^{0.5}$). The confinement factors for the LSN configuration are up to 25% lower than those obtained in the IWL configuration, presumably due to the non-optimal shape with top-bottom averaged triangularity of -0.2 as opposed to -0.4. The ratio of impurity confinement time to energy confinement time, obtained by laser ablation of suitable targets, is measured in both configurations to be of order unity, or about 3 times lower than values typically obtained in H-mode plasmas. The SOL heat flux width is observed to be wider than for H-mode plasmas. In particular, while the inter-ELM power fall-off in the only H-mode case obtained is comparable to values obtained from the multi-machine scaling law, values in L-mode are typically 50% larger.

The lack of an edge pedestal, besides eliminating issues associated with ELMs, naturally removes the conflicting core-edge requirement intrinsic to the H-mode regime, for which the heat flux through the separatrix must be maintained at or above the L→H power threshold and possibly dissipated in large part in the SOL. Also in view of the technological advantages granted by positioning the divertor on the Low Field Side[4], these results suggest that a negative triangularity plasma operating without an edge pedestal might provide an attractive solution for operations in future reactors.

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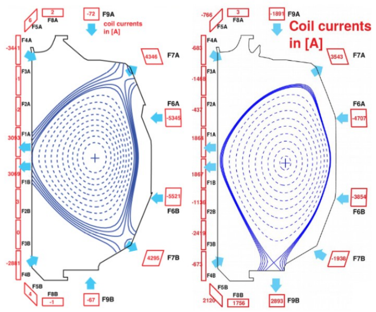

Figure 1: Poloidal cross section of NT plasmas on the DIII-D tokamak: IWL (left) LSN (right)

References

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