2nd Asia-Pacific Conference on Plasma Physics, 12-17,11.2018, Kanazawa, Japan

MHD Stability of Negative Triangularity Tokamaks

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The divertor heat load is a major concern for fusion reactors. This led Ref. [1] to propose a negative triangularity tokamak as the product of a design philosophy that shifts the focus of optimization efforts away from the plasma core, prioritizing instead the reactor boundary. The negative triangularity tokamaks can have a larger separatrix wetted area, more flexible divertor configuration design, wider trapped particle-free scrape-off layer, lower background magnetic field for internal poloidal field coils, and larger pumping conductance from the divertor plenum. However, the stability beta limit is a concern. Recent TCV and DIII-D experiments have increased the interest in negative triangularity by showing that such discharges exhibit H-mode-level confinement features with L-mode-like edge behavior without ELMs [2,3]. This motivates us to extensively examine the MHD stability of negative triangularity tokamaks. We constructed the equilibria using the VMEC equilibrium code, with the bootstrap current included from the Sauter formula. We then investigated the stability using the AEGIS code supplemented by the DCON code.

First, using the numerically reconstructed experimental equilibrium, our computation confirmed the stability of the beta normal of 2.6 achieved in DIII-D experiments against low-n MHD kink modes. This is slightly lower than the positive triangularity cases with the same types of density and temperature profiles.

Next, we analyzed the equilibrium parameters in greater depth. We found that the negative triangularity configuration leads to a lower safety factor value especially near the edge. This feature tends to favor the advanced tokamak scenario with high bootstrap current fraction and peak pressure profile. Indeed, we were surprised to find that the negative triangularity configuration can actually achieve even higher beta normal than the positive triangularity case in certain cases. As shown in Fig. 1, our calculations show that in some higher bootstrap fraction, high poloidal beta, negative triangularity cases the beta normal limit can reach 8 li(I/aB) for low n (1-5) modes, twice the limit usually encountered for positive triangularity. The beta value seems to be limited by the high n ballooning modes, which may be improved by the profile optimization and non-local effects.

In conclusion, our results indicate that the negative triangularity tokamaks are not only good for divertor design, but also can potentially achieve:

1. High beta, steady state confinement with very high bootstrap current fraction.
2. ELM free performance.
3. Reduced disruptivity, since it is stable against low-n kink modes, and its beta limit is determined by high n modes.
4. High resistive wall mode beta limit.
5. High reactor fusion productivity with peak pressure profile, etc.

Noting that the high n modes contribute only to the “soft” beta limit and both TCV and DIII-D experiments show reduced turbulence levels in the negative triangularity discharges, we conclude that for steady-state confinement in the advanced tokamak scenario, high beta constitutes an additional, previously unappreciated advantage to the negative triangularity tokamak.

References
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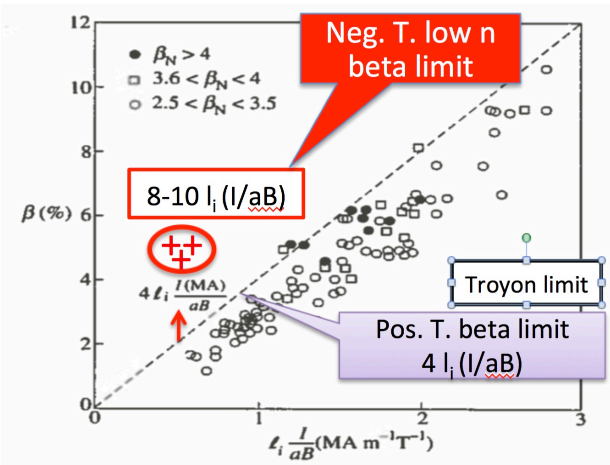
Figure 1:



* This research is supported by Department of Energy Grants DE-FG02-04ER54742 & DE-FG02-97ER54415.