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Extreme Low-Edge Safety Factor Tokamak Scenarios via Active Control of Three-Dimensional Magnetic Field on RFX and DIII-D

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High current, stable tokamak plasmas with edge safety factor below or around 2 are attractive for magnetic fusion due to favourable high fusion gain and higher confinement. But they have long been considered inaccessible in modern devices owing to the unforgiving MHD instabilities. Even in tokamaks with a resistive wall, the onset of an n=1 resistive wall mode leads to a disruptive limit at edge safety factor q_edge =2 (for limiter plasmas) and q_95≈ 2 (diverted plasmas).

This paper reports how for the first time two very different tokamaks, a large MA-class shaped device like DIII-D and a high aspect ratio circular experiment like RFX-mod, have robustly overcome the edge safety factor = 2 limit by active control of plasma stability and demonstrate that operation below 2 is possible for hundreds of resistive wall times.

In addition these experiments reveal a new tool to control sawtooth frequency and amplitude, a result that has the potential of extending the tokamak operating space even further by avoiding deleterious giant sawteeth. The application of 3D fields with a strong n=1 component that couples to the m=1,n=1 internal kink is found to significantly reduce the sawtooth amplitude and increase their frequency, demonstrating the benefits of this helical state.

Experimental results have been compared with theory and numerical models. The experimental stability limit has been identified in DIII-D limiter plasmas as q_edge=2.08 ± 0.011, slightly higher than the external kink mode limit q_edge=2.0 predicted by ideal MHD analysis (DCON). In both devices the approach to the stability limit is characterized by the onset of an n=1, m=2 mode and growth rate of the order of τwall, consistent with ideal MHD predictions. RFX-mod shows that at q_edge<2.0 the growth rate of the uncontrolled modes decreases as q_edge is lowered towards 1.5, i.e. indicating stability improvement as q_edge=1.5 is approached from above. This is consistent with external kink mode stability expected from ideal MHD theory at q_edge<2.0: a peak in the external kink growth rate is expected near, but below q_edge=2.0, followed by a decrease in the growth rate. Sawtooth destabilization via applied magnetic perturbation is explained with the nonlinear MHD PIXIE3D code as a purely nonlinear effect, and not simply a modification of the (1,1) kink linear stability.

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