Tearing mode stabilization by slowly rotating 3D field in the partially penetrated regime in the presence of an error field

[1]M. Okabayashi, [2]S. Inoue, [1]N. Logan, [3]E.J. Strait, [3]Z. Taylor, [3]J. de Grassie, [1]N. Ferraro, [4]J. Hanson, [1]S. Jardin, [3]R.J. La Haye, [5]L. Sugiyama

[1]Princeton Plasma Physics Laboratory, USA

[2]National Institutes for Quantum and Radiological Science and Technology, Japan

[3]General Atomics, PO Box 85608, San Diego, USA

[4]Columbia University, 2960 Broadway, New York, USA5

[5] Laboratory for Nuclear Science, Massachusetts Institute of Technology, MA, USA

1. Introduction

Tearing mode (TM) responses to a rotating 3D resonant magnetic perturbation (RMP) in DIII-D experiments are consistent with simulations of the non-linear resistive reduced MHD code AEOLUS-IT [1,2]. In the partially penetrated regime [Figure 1], the TM can not only be unlocked but also stabilized in the presence of a static error field (EF). The reduction of EF amplitudes broadens the stabilized window, and the external field 3D field including EF can be shielded out [1,2]. In this regime, a single helicity structure is formed when the external 3D field rotates with a frequency slightly higher than a critical value, avoiding the full-penetration regime but reaching to a rational surface after the uncorrected EF has already formed a locked magnetic island. The combination of mode structure with external-kink-like response at lower minor radius and the TM-like structure at lower minor radius with respect to rational surface produces a single-helicity response in single rational surface simulations [Figure 2].

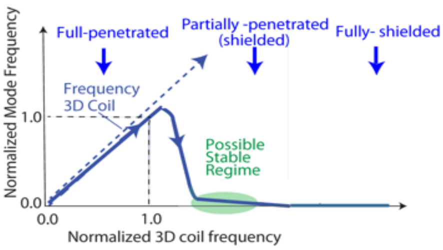

Figure 1: Schematic of the penetrated and shielded regimes in reduced resistive MHD model. by . Inoue[1,2]

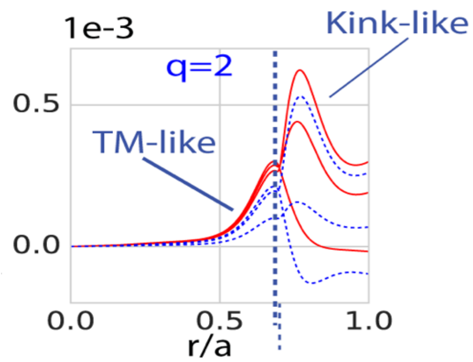

Figure 2: the response mode structure in partially-penetrated regime. by S. Inoue [1,2]

2. Experiments of rotating 3D field penetration

In this paper, we report two examples of tearing resonant penetration by slowly-rotating 3D field; the one in this section is to apply the 3D field at locking onset and the other in the next section to reduce the NBI torque input to induce locking onset. To widen the stable regime by minimizing the static error field influence in DIII-D experiments, we applied the rotating 3D field via a modified Dynamic Error Field Compensation (DEFC) feedback scheme originally designed for control of the plasma response to a static error field. Here, a rotating 3D field is controlled by adjusting the phase between the magnetic sensor signal and 3D field coil current in order to sustain the TM rotation. This scheme, DEFC plus Torque Injection approach is a useful tool for TM locking avoidance. Figure 3 is an example of the plasma response to ~50Hz 3D penetration. The plasma response can be divided into three phases. The early period Phase-(I) was dominated by the response around very near plasma edge (rho ≥ 0.95), which appeared just after the application and the plasma response was decreased after 100 ms. Then, the second period Phase-(II) began at a little inward around rho ~ 0.9. It is to be noted that the domain around q~3-2 had the smallest response. When the plasma response was slowly decreased, the third period Phase-(III) began with response around q~2 increase. The Thomson electron temperature and density profiles corresponding to each periods are shown in Figure 4. Thomson Te and ne profiles are shown with the maximum and minimum edge displacement over two oscillatory period. Phase-(I) in Figure 3 shows that a clear drop in both electron temperature T_e and electron density n_e occurred simultaneously in time around ρ=0.9, suggesting a well-defined magnetic island containing closed flux surfaces. In Phase-(II), the active domain of $\Delta T_i/\langle T_i \rangle$ moved toward the core after the mode in Phase-(I) decayed. The structure developed double helicities spreading to ρ=0.85 (q=3) from the edge. The T_e pedestal location was shifted to ρ=0.85, but the density profile inside remained nearly constant

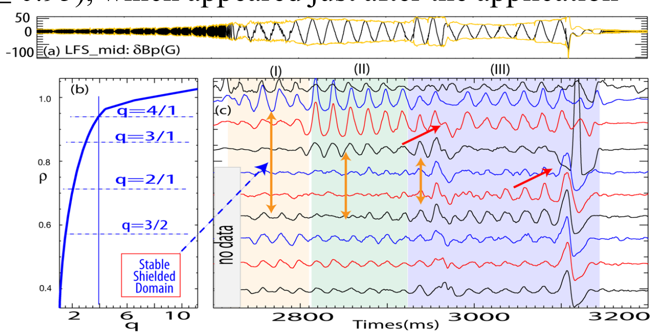

Figure 3: The perturbed $\Delta T_i / \langle T_i \rangle$ time evolution at various radii: (a) n=1 δBp at LFS midplane. (b) q-profile, (c) perturbed $\Delta T_i / \langle T_i \rangle$

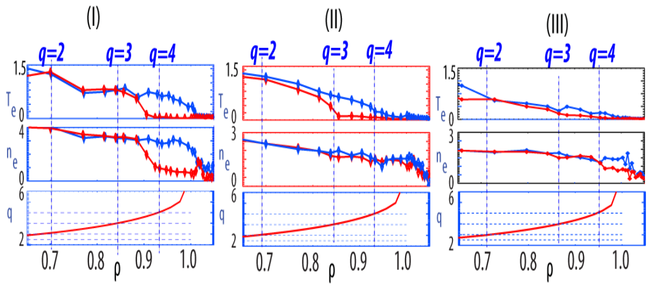

Figure 4: The phase-I,II,III period, Thomson electron temperature profile, density profile, and q-profile.

and a sharp H-mode pedestal was maintained. These $\Delta T_i/\langle T_i \rangle$ time evolution are consistent with shielding-out 3D field if the location of a single helicity TM radially drifted inward.

3. Shielding-out process in the H-mode edge recovery

Another example of is shown in reduction of toque and H-mode edge recovery [Figure 5]. Thomson profiles are shown in Figure 6 (the corresponding time slices are marked by dotted lines in Figure 5). The discharge (#166564) was sustained by the 3D rotating field through the DEFC-Torque injection which was applied t= 2500 ms just after the TM amplitude reached near possible locking onset (not shown). When the NBI torque input was reduced purposely from 6.0 to 2.4 Nm [Figure 5], the H-mode edge was lost within a few tens of milliseconds. The 3D external field control system struggled to sustain the mode rotation, as seen by the sharp drop around t ~ 3150-3280ms [Figure 5(a,b)] of mode rotation frequency from 50Hz to 30-20 Hz even when feedback requested the available maximum coil current of 4kA for maximum torque input. The $\Delta T_i/\langle T_i \rangle$ contour time evolution [Figure 5(g)] is shown versus the safety factor q. Before the torque reduction, the main response was located near q~4 while the amplitude around q=3-2 was minimal, interpreted as the 3D field penetrating up to q~4. After the torque ramp down, the response around q=2-3 increased, entering the full penetration regime. At t=3200ms, a mini collapse around q~2 indicates a magnetic forced reconnection took place and another larger collapse at q~2 propagated inward as well as outward. It is interesting to note that this q~2 collapse coincided with the initiation of H-mode edge recovery and the increase of edge density [Figure 6(e)]. After recovering the H-mode edge, the plasma

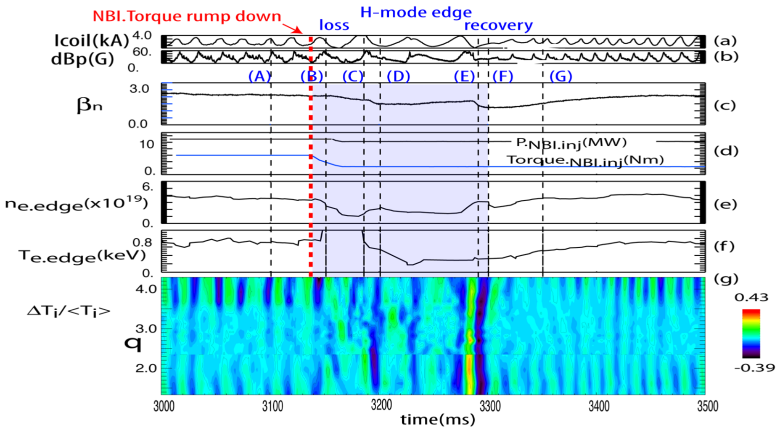

Figure 5: The $\Delta Ti/\langle Ti \rangle$ behavior with the NBI torque reduction

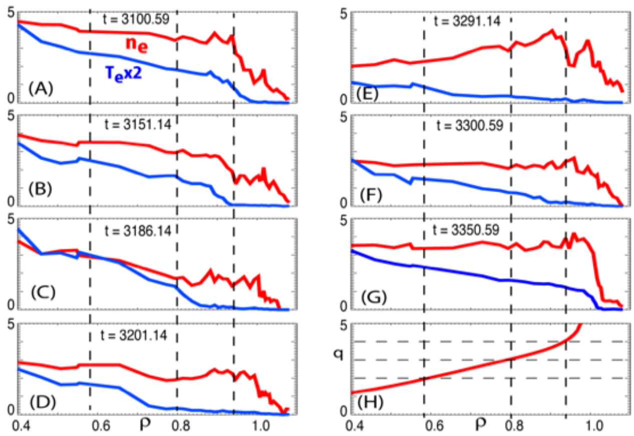

Figure 6: Thomson density and electron temperature profiles, (A-G) time mark is shown in Fig. 5 by dotted lines

response around q~2 remained minimal. This reduced response is interpreted as a reduction of the rotating 3D field penetration. According to the electron temperature profile [Figure 6(a-d)], the H-mode edge erosion process evolved with single- and double helicity-response and later remained as the multi-helicity state as in previous section until rapid recovery began [Figure 6(f-g)]. The maximum response in ΔTi/<Ti> [Figure 5(g)] is qualitatively consistent with in this full penetrated stage. The sustainment of a sharp H-mode edge gradient indicates additional stabilization mechanisms may take place with the 3D field influencing the edge density transport.

4. Summary

Recent reduced resistive MHD simulations [1-2] have proposed the advantage of partially-penetrated regime for avoiding TM locking in the presence of static error field. An external 3D field rotating as low as 50-100 Hz with a few times the amplitude of the static EF can stabilize the growth of the island width in present-day tokamak parameters. The response structure is a combination of the kink-like response and the TM-like response, forming a single helicity state. We reported here two examples of the application of slowly-rotating 3D fields; one is applying the 3D field to a marginally locked mode and the other is reducing the torque input towards the locking threshold. In both cases, the observed time evolution of plasma response to 3D field and the formation of single (double) helicity states are qualitatively consistent with the model penetration by taking into account of toroidicity and non-circular configuration. The upgrade of the AEOLUS-IT to multi-helicity version is in the progress. It is expected that the physics of shielding-out external 3D field will be discussed in a quantitative manner with multi-mode coupling formulation. The successful H-mode recovery was demonstrated after a sizable internal collapse was initiated around q~2 domain. The existence of sharp edge density gradient suggests that the application of slowly-rotating 3D field presence has another advantage affecting the edge transport.

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[2] Inoue,S., et all, 2018 IAEA Fusion Energy Conf. TH/P5-24, [3] Okabayashi, M., et al., 2018 IAEA Fusion Energy Conf., EX/P6-25.