Locked-Tearing Mode Control by 3D Magnetic Field with Presence of Static Error Fields

[1]M. Okabayashi, [2]S. Inoue, [3]E.Strait, [4]Z. Taylor, [3]C. Paz-Soldan, [3]J. de Grassie,
[1]N. Ferraro, [5]J. Hanson, [1]S. Jardin, [3]R. La Haye, and [1]N. Logan
[1]Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543-0451, USA
[2]National Institutes for Quantum and Radiological Science and Technology, 801-1 Mukoyama, Naka, Ibaraki 311-0193, Japan
[3]General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
[4]ORAU Oak Ridge Associated Universities, PO Box 117, Oak Ridge, TN 37831, USA
[5]Columbia University, 2960 Broadway, New York, NY 10027-6900, USA

We reported in IAEA 2016 [1] that a rotating 3D field with magnitude comparable to pre-existing error field has a very unique advantage for optimizing tokamak concept for practical reactors. The rotating field can avoid tearing mode locking, achieve H-mode reocovery and sustain the H-mode edge while simultaneously preserving high core confinement configuration. A recent simulation study with a non-linear Reduced MHD code "AEOLUS-IT" [2,3] has proposed the possibility of "shielding-out" resonant error field by rotating 3D field.

A magnetic approach of locking avoidance is to rotate the mode by synchronizing the external rotating 3D field. As expected from the inductive motor analogy, both static error field and rotation 3D field are aimed to penetrate into the tearing mode structure for better performance (called "full penetration") and large slipping between the mode and applied 3D field causes the branch separation; " bifurcation" [4]. However, the non-linear simulation showed that around this bifurcation boundary, the rotating 3D field can shield the resonant error field component out from the tearing mode structure, suggesting a possibile "stable window" existence. In this condition, the static error field still tightly are coupled with

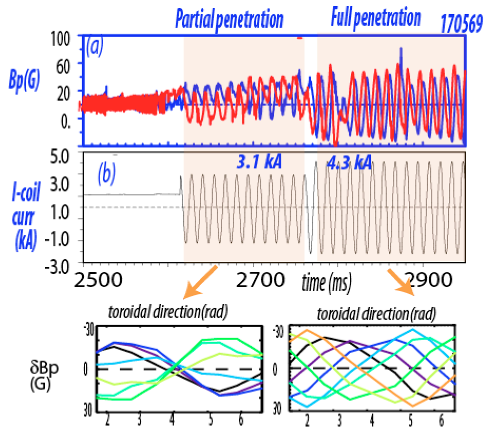

Fig.1. (a) two magnetic sensor signals separated toroidally by 100 degrees; (b) I-coil current; (c) and (d) are observed toroidal magnetic sensor Bp signals for partial penetration- and full- penetration phase respectively over one cycle period. These sensors are located at LFS midplane. (#170569)

tearing mode structure, but the rotating 3D field couples tearing structure as a shielding layer. The condition is called as “partial-shielding” or “partial-penetration” depeding upon the emphasis. A critical parameter is the magnitude of the rotating 3D field relative to the error field. The simulation is with a cylindrical non-linear reduced MHD code and a single-helicity assumption. Nonetheless, as shown later, DIII-D experiments in a toroidal geometry support the hypothesis by taking into account that multiple poloidal Fourier mode components exist due to the toroidicity and shaping. Here, we discuss the simulation results with the DIII-D experiments of partial penetration and another example with feedback operation.

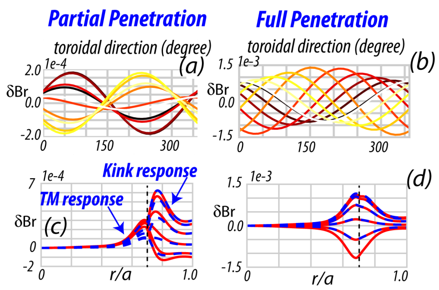

Fig.2. the code simulation results for partial and full- penetration.
(a) the perturbed magnetic δBr (normalized to the poloidal magnetic field) for partial penetration and (b) for full penetration. The code simulation of δBr radial structure behavior over one cycle are shown (c) for partial penetration and (d) for full penetration, where the solid lines show the first one half cycle and dotted lines are the following one half cycle.

The Partial / Full 3D field penetration

The experimental study has been carried out in DIII-D with rotating 3D field magnitude slightly less than a critical value for full penetration [Fig.1]. A similar observation in ohmic plasma was reported in ref. [5]. The plasma condition studied was the ITER baseline-scenario development target with q95=3.2-3.8. With less than a critical amplitude of rotating 3D field from the I-coil and a frequency of 75Hz (slightly above the wall resistive frequency of ~50Hz). The I-coil current was increased by 30% in the middle of the discharge to observe mode structure shift from partial-penetration to full-penetration. The observed mode structure in partial peentration shows “standing-wave-like” response along the toroidal direction and in full penetration period the magnetic structure propagates [Fig. 1(c) and (d)]. The magnetic structures seen in the simulation [Fig.2 (a,b)] are in a good qualitative agreement with the experimental observation in both regimes.

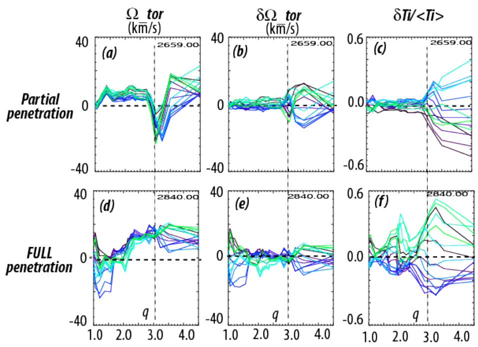

Fig. 3: Radial profiles of rotation and Ti perturbation in partial and full penetration, plotted vs. safety factor q. The traces cover two cycles of 3D field rotation. (a) toroidal rotation, (b) the perturbed toroidal rotation and (c) normalized perturbed component of carbon Ti profile for partial penetration period; and (d), (e) and (f) are for full penetration.(#170569)

The radial location of observed mode response is shown in Fig. 3 by three quantities; the toroidal rotation Ω_tor, perturbed rotation $\delta\Omega\_tor$, and normalized ion temperature perturbation δTi/<Ti>. In partial siekding (or penetration) regime, the mode structure is similar to the simulation result, but the location is shifted radially to q≥3, not at q~2 as predicted [Fig.2 (c)]. It is noteworthy that the mode analysis at early time with fast TM rotation (several kHz) showed a typical TM mode character with dominantly rotating m/n=2/1. A weak response was observed inside of q < 3, suggesting that lower-m components of error field were weakened by shielding at the rational surface or the mode response amplification factor was reduced [Fig. 3(b,c)]. In the full penetration period the perturbation remained peaked strongly around q~3 and moderate amplitude became noticeable around q~2[Fig.3(e,f)]. The electron density and temperature profile showed typical H-mode edge steady gradient near the plasma edge (not shown) in the partial penetration period.

Possible shielding during feedback-controlled 3D field application.

The example in Fig. 4 is during tearing mode locking avoidance feedback-control operation [6]. Here, the feedback adjusted the coil current amplitude and phase (indirectly frequency) to the least-stable resonant magnetic perturbation (RMP) response, regardless to poloidal m-number of the mode. As seen in the high-field side (HFS) off-mid plane magnetic sensor [Fig. 4(b)] and also discussed later with Fig. 5, an RMP amplitude was initially built up near the edge outside ρ > 0.9 (q > 4) while the response near

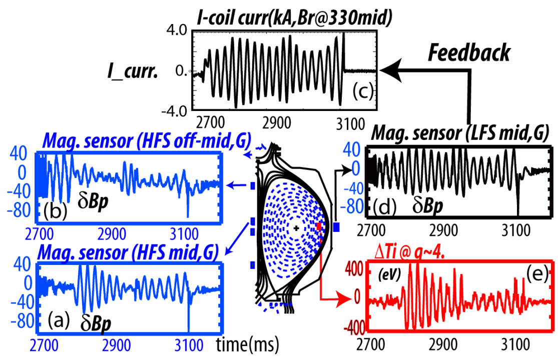

Fig.4. The feedback schematics for multi tearingmode layer control: (a) magnetic sensor signal at HFS midplane, (b) magnetic sensor signal at HFS off-midplane, (c) feedback I-coil current, (d) magnetic sensor signal at LFS midplane (used for feedback), (e) the perturbed ion temperature time evolution around q~4 (#161243)

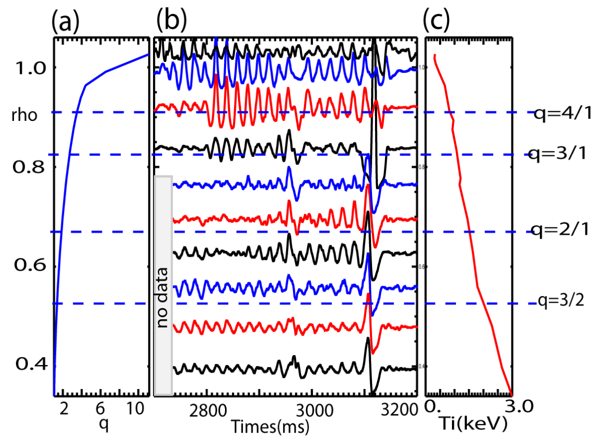

Fig. 5. The perturbed ion temperature time evolution at various radii: (a) q-profile, (b) normalized perturbed ion temperature at various radii, and (c) Ion temperature profile averaged over two oscillatory cycles at t=2900ms(#161243)

q~2- 4 (internal δTi/<Ti>) was very minimal [Fig.4 (e)]. Approximately 100 ms later, the RMP amplitude near the edge collapsed and an inner mode grew around ρ ~0.9 (q~ 3-4). The radial shift sequence of mode appearance and disappearance is observable by the δTi/<Ti> radial dependence as shown in Fig. 5. The edge activity seen by the magnetic sensor off-mid plane is also visible around ρ = 0.95 -1, although the δTi/<Ti> decay at t=2800 ms does not seem so sharp as seen by the probe signal, partly due to low spatial resolution [Fig. 4.(a)].
When the initial edge activity abruptly decayed away, a second mode around q~4 quickly grew with inner domain around q=3-4. Then, at about t=2950 ms, a third mode (likely 2/1) was excited sharply with the fast growth rate of 20-30 ms around q~2. The growth in the outer domain q~ edge to 4 is marginal, but, the amplitude in the core becomes larger, leading to a mini-collapse at about t=3000 ms. After recovery from the mini-collapse, the resurgence of mode activity around q~2 (2/1 mode) was coherently coupled to the mode around q>4 leading to the major collapse. The appearance/disappearance of the outer activity in time coincides with disappearance/ appearance of inner RMP. This flip-flop type mode change can be interpreted as the decrease of “shielding out” of resonant error field in the outer domain resulting in the amplification of inner RMPs. The shielding layer, excited near the edge (ρ > 0.9 with q>4), can impact the tearing mode response over a broad radial area covering q=2-4.

In summary, The hypothesis of shielding out resonant error field by rotating external 3D field is qualitatively consistent with DIII-D observations and useful for better understanding of the process of the simultaneous achievement of H-mode recovery and the sustainment of High core confinement.

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(1) M. Okabayashi et al., 2016 IAEA Fusion Energy Conf. (Kyoto, Japan,) (Vienna: IAEA) EX/P3-16, (2) S. Inoue et al., NF 57 (2017) 116020, (3) S. Inoue et al., PPCF 60 (2018) 025003, (4) R. Fitzpatrick, NF33, 1049 (1993)., (5) H. Jin et al., PPCF 57 (2015) 104007, (6) M. Okabayashi et al., NF 57 (2017) 016035