Topic: EX-S

Robust Correction of 3D Error Fields in Tokamaks and ITER*

J.-K. Park[1], J. E. Menard[1], S. P. Gerhardt[1], M. J. Schaffer[2], R. J. Buttery[2], H. Reimerdes[3], D. A. Gates[1], R. M. Nazikan[1], R. E. Bell[1], B. P. LeBlanc[1], R. La Haye[2], A. H. Boozer[3], S. A. Sabbagh[3], S. M. Wolfe[4], the NSTX Research Team, the DIII-D Research Team, and the TBM research team (email: jpark@pppl.gov)

[1]Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
[2]General Atomics, San Diego, California, USA
[3]Columbia University, New York, New York, USA
[4]MIT Plasma Science and Fusion Center, Cambridge, Massachusetts, USA

Important progress has been made for the correction of 3D fields in tokamaks using improved understanding for plasma response by the Ideal Perturbed Equilibrium Code (IPEC) [1] and its applications to various error field correction experiments [2,3]. The key to error field correction is to reduce the part of 3D fields that breaks magnetic surfaces significantly, often by an order of magnitude more than the rest, and thus dominantly degrades tokamak plasmas. The dominant 3D fields change little across different plasma profiles and configurations. The empirical corrections of intrinsic fields for NSTX, DIII-D, and CMOD L-mode plasmas can be explained consistently based on the robust structure of the dominant 3D fields. An extreme case can be found in the DIII-D mock-up experiments for the ITER Test Blanket Modules (TBMs). Although the TBM 3D fields are highly localized and thus can not be corrected by typical error field correction coils, the optimal level of operations could be achieved since the I-coils in DIII-D can effectively control the dominant part in TBM 3D fields. The robust structure of the dominant 3D fields is also persistent in H-mode, as shown in the recent locking experiments in NSTX and DIII-D H-mode plasmas. The implications are favorable for ITER, since the highly reliable 3D field compensation can be provided for a wide range of different plasmas if the correction coil is designed based on the robust patterns of the dominant 3D fields [4].

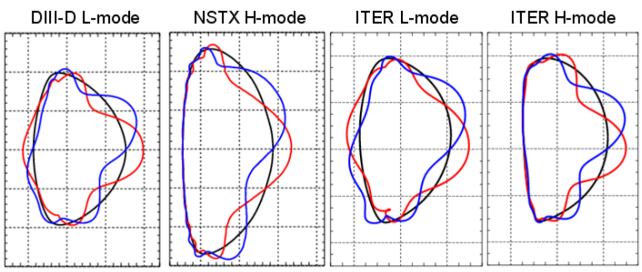

Figure 1. The structure of the dominant n=1 3D fields for different plasmas and tokamaks. The red is the Cosine part and the blue is the Sine part of the external field, measured at the plasma boundary (black).

The structure of the dominant 3D fields remains very robust across different tokamak plasmas. The dominant 3D fields are spatial distributions of magnetic fields that maximize the total resonant field, which drives magnetic islands and thus breaks magnetic surfaces at the resonant surfaces. It can be defined on the plasma boundary, by decomposition of 3D fields based on coupling between their distributions on the boundary and total resonant fields in the core. The resulting normal distribution can be represented by $\delta B_n^x = C(\theta)\cos\phi + S(\theta)\sin\phi$. The structures of Cosine $C(\theta)$ and Sine $S(\theta)$ factors change little across different tokamak plasmas (Figure 1) and have much greater weighting at the low field side. Other parts of 3D field, including higher n>1 components, are insignificant in driving magnetic islands in the core and plasma locking.

The empirical corrections of intrinsic error fields in major US tokamaks can be explained consistently by the structure of the dominant 3D fields. The large error fields from the

NSTX inboard side can be effectively mitigated by a correction field from the outboard side with the only ~5% of the amplitude of the intrinsic error fields. DIII-D I-coil corrections are optimal with ~240º toroidal phasing between upper and lower set of I-coils, since then I-coil fields can produce the pattern of the dominant 3D fields with up to ~60% overlap. If the helical pitch of unperturbed magnetic field becomes opposite, the optimal phasing becomes ~120º (-240º) as validated in Right-Handed (RH) plasma operations with the reversed B_T. CMOD A-coil corrections can be effective despite its far distances from plasmas since the coils can control the fields at the outboard side.

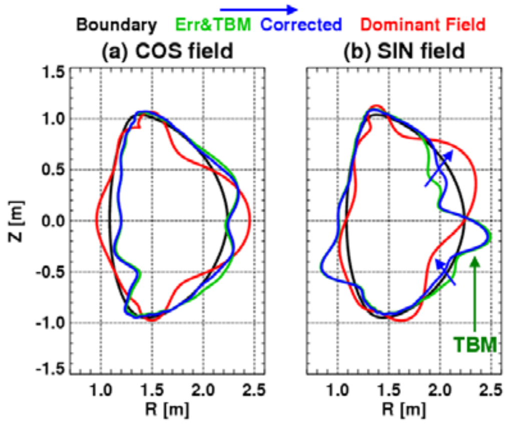

Figure 2. The spatial structure of TBM fields in addition to intrinsic error fields in DIII-D (Green), corrected fields including I-coils (Blue). Cosine part is coupled positively and Sine part is coupled negatively to the dominant 3D fields (Red). Sine part is decreased (Blue arrows) after the correction and compensates Cosine part.

The mock-up experiment for Test Blanket Modules (TBMs) in DIII-D has shown an extreme case. The mitigation of the highly localized TBM error fields, in addition to intrinsic error fields in DIII-D, was successfully demonstrated with I-coils by decreasing critical locking density down to the optimal level previously observed without TBMs. DIII-D I-coil correction fields can not remove the highly non-resonant TBM 3D fields, but can provide the effective control of the dominant 3D fields by decreasing the minus Sine part to be comparable to the plus Cosine part and thus by minimizing the overlap with the dominant 3D fields (Figure 2).

The recent error field threshold study in NSTX and DIII-D has extended the validity of the method to H-mode plasmas. When the overlap external field (δB^{x}_{oc1}) is defined as the inner product between the external field and the dominant 3D fields, the parametric scaling for critical amplitude can be greatly improved across devices and between L and H-mode plasmas (Figure 3). If the Error Field Correction Coil (EFCC) in ITER is carefully designed based on the effectiveness of the control for the dominant 3D fields, the robust and reliable corrections can be achieved against any kind of 3D fields over wide range of ITER operation scenarios. The new method is being applied to ITER using IPEC and the existing EFCC design is being assessed [4].

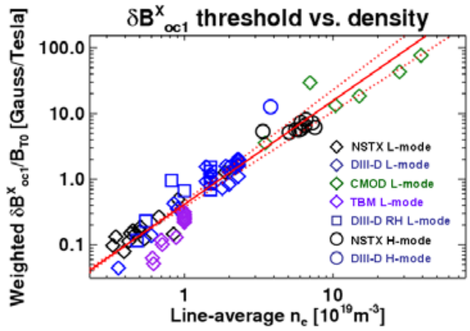

Figure 3. The correlation between the critical amplitudes of the overlap external field and locking density for various cases.

[1] J.-K. Park, A. H. Boozer, and A. H. Glasser, Phys. Plasmas **14**, 052110 (2007)

[2] J.-K. Park, M. J. Schaffer, J. E. Menard, and A. H. Boozer, Phys. Rev. Lett. **99**, 195003 (2007)

[3] J.-K. Park, A. H. Boozer, J. E. Menard, and M. J. Schaffer, Nucl. Fusion **48**, 045006 (2008)

[4] J. E. Menard, J.-K. Park, et al., the interim report for ITER IPEC TA (2010)

*This research was supported by U.S. DOE contracts DE-AC02-09CH11466, DE-FC02-04ER54698, and DE-FG02-89ER54297.