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

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An important progress has been made for the correction of 3D fields in tokamaks, with the 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 corrections is to reduce a part of 3D fields that breaks magnetic surfaces significantly, often by an order of magnitude more than another, and thus that is most dangerous to tokamak plasmas. The most dangerous 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 most dangerous 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 most dangerous part in TBM 3D fields. The structure of the most dangerous 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 since the highly reliable corrections of 3D fields can be utilized over wide range of different operations in ITER when the design of coils are articulated based on the patterns of the most dangerous 3D fields [4].

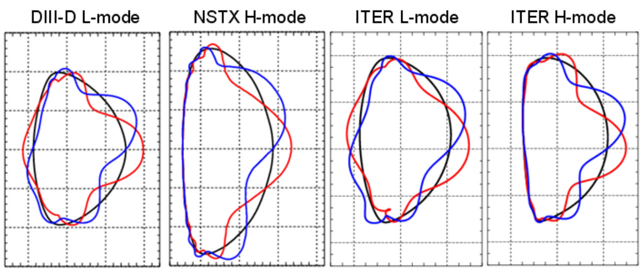

Figure 1. The structure of the most dangerous n=1 3D fields for different plasmas and tokamaks. The red line is the Cosine part of the external field, and the blue is the Sine part, measured at the plasma boundary (black lines).

The structure of the most dangerous 3D fields remains very robust across different tokamak plasmas. The most dangerous 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 for the core. The resulting normal distribution can be represented by $\delta B_n^x = C(\theta)\cos n\phi + S(\theta)\sin n\phi$. 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.

The empirical corrections of intrinsic error fields in major US tokamaks can be explained consistently by the structure of the most dangerous 3D fields. The large error fields from the NSTX inboard side can be effectively mitigated by a correction field from the outboard side by the only ~5% amplitude of the intrinsic error fields. DIII-D I-coil corrections are optimal with ~240° toroidal phasing between upper and lower set of I-coils, since then I-coil fields can produce the pattern of the most dangerous 3D fields as similar as ~60%. If the helical pitch of unperturbed magnetic field becomes opposite, the optimal phasing becomes ~60° 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.

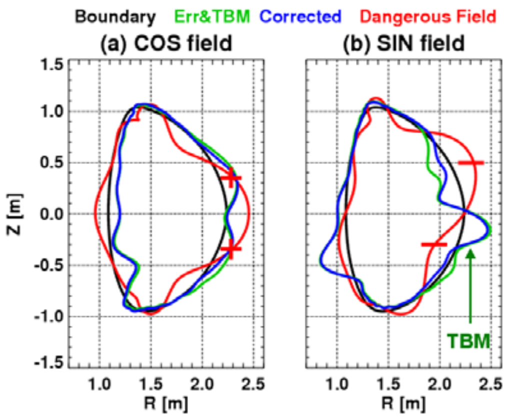

Figure 2. The spatial structure of TBM fields in addition to intrinsic error fields in DIII-D (Green), corrected fields by I-coils (Blue). Cosine part is coupled positively (marked as +) and Sine part is coupled negatively (-) to the most dangerous 3D fields (Red).

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 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 most dangerous 3D fields by decreasing the minus Sine part to be comparable to the plus Cosine part and thus by minimizing the overlap with the most dangerous 3D fields (Figure 2). Other parts of 3D field, including higher n>1 components, are insignificant in driving magnetic islands and plasma locking.

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 most dangerous 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 most dangerous 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 and IPEC is being applied to ITER and the existing EFCC design is being assessed [4].

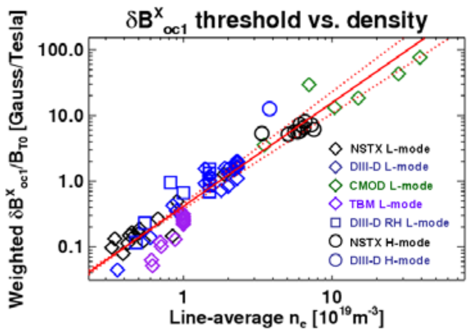

Figure 3. The correlation between the critical amplitudes of the overlap external field and locking density for various cases.

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