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NEW CHALLENGES FOR ERROR FIELD CORRECTION

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GENERAL ATOMICS

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Addressing New Challenges for Error Field Correction EX-S

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Experiments in DIII-D have shown a greater challenge for error field correction in ITER than previously thought. While correction of the dominant n=1 error field reduces incidence of locked modes, new measurements show that residual fields still limit performance, with modeling indicating that this is due to an increase in non-resonant components. The situation is exacerbated by an amplification of error fields in H-modes, which act to brake plasma rotation and destabilize intrinsic m=2 n=1 tearing instabilities. New scalings for this process have been obtained and compared with new calculations of the error field expected in ITER, indicating that correction needs to reduce the expected error fields by ~50% to avoid instability. This is found to be comparable to the best levels of error field correction achievable with a well-optimized dual-toroidal-array internal correction coil set on DIII-D (Fig. 1). The results suggest that ITER needs to consider a locally targeted, multi-harmonic error field correction strategy, possibly also deploying its edge localized mode (ELM) control coils for this purpose.

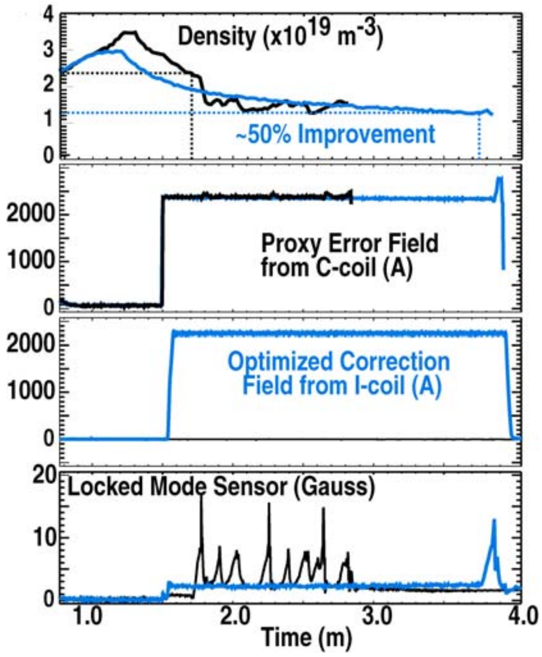

Fig. 1. The locked mode density limit with a proxy C-coil error field (black) improves by 50% when optimal correction (deduced from a phase scan measurements of mode onset) is applied with DIII-D I-coils (blue).

ITER-like low torque H-mode plasmas are found to be highly susceptible to error fields because of resistive responses to error fields and proximity to intrinsic tearing instability. The resistive response interpretation is confirmed by new modeling with the MARS-F single fluid MHD code, which shows little change in ideal response, but a substantial reduction in shielding and a rise in resonant tearing as rotation is reduced (Fig. 2). Experimentally, such a response leads to torques that slow the plasma rotation. As inherent tearing stability is found to depend on rotation shear [1], this braking leads directly to destabilization of the tearing mode.

This process has been measured for torque-free H-modes in DIII-D to obtain a new scaling for tolerable error field, which projects low thresholds in ITER. This is expressed in terms of the component of the plasma boundary field that couples through ideal MHD to generate resonant m=2 n=1 fields at the q=2 surface in the plasma:

$$\frac{\delta B_{boundary}}{B_{\mathrm{T}}} = \left[1.3-\left(\beta_{\mathrm{N}}-1.8\right)\right]\times\frac{\left(n_{\mathrm{e}}/10^{20}\ \mathrm{m}^{-3}\right)\left(R/6.2\ \mathrm{m}\right)^{0.725}\left(q_{95}/3.1\right)^{0.83}}{\left(B_{\mathrm{T}}/5.3\ \mathrm{T}\right)^{1.02}}\times10^{-4},$$

where the q_{95} dependence is inferred from previous Ohmic studies. This indicates error field levels at the plasma boundary need to be below 1.3×10^{-4} of toroidal field, B_{T}, for the ITER Q=10 baseline H mode. But, updating ITER's Monte Carlo model of error field sources for the above "coupling through ideal MHD" formalism indicates the actual intrinsic error field measured this way may be as high as 2.8×10^{-4}. This suggests a ~50% reduction of error field would be required in the ITER baseline – with even better correction needed at higher β.

However, experiments with error field correction indicate that obtaining this level of correction can be challenging. This was evident in the correction of intrinsic error on a number of devices [2-4], where correction coils had variable and sometimes quite limited benefit, ranging from near zero to ~50%, as measured in terms of reducing locked mode density limits. The behavior is dependent on the structure of the correction field relative to underlying error, with coils close to the plasma or in dual arrays tending to give the best correction. This limited benefit contrasts with the paradigm of a field interaction through ideal MHD [5], where a dominant least stable n=1 ideal mode would provide the main means of transmission of the error field to the core plasma. With such a paradigm, one would expect that a single coil array could effectively cancel the drive for the ideal mode, achieving very good correction. However, exploring this discrepancy is difficult with intrinsic error experiments, because of uncertainties in the error field structure, and other possible control or stability limits.

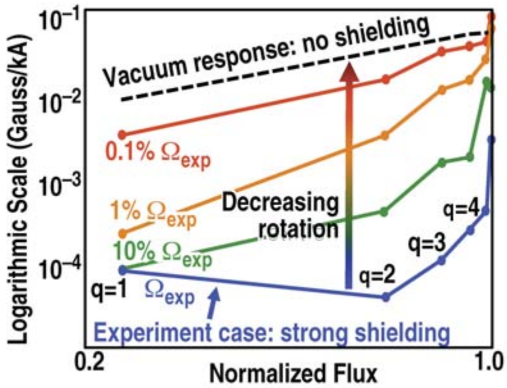

Fig. 2. The developing tearing response predicted by MARS-F as rotation is lowered from a high rotation stable experimental case.

New studies on DIII-D have addressed this issue, with results consistent with a paradigm that error fields also couple through higher order ideal modes and non-resonantly, to interact with the core plasma through more than a single resonant surface. This has been explored by utilizing two different coil arrays – one to provide a known pure n=1 proxy error field at much higher field amplitudes than the underlying intrinsic error, and the other to explore its correction. The benefits of correction can be measured in terms of a low-density limit for mode onset in Ohmic plasmas (found to scale linearly with field amplitude [6]). Results show (Fig. 1) that even with careful optimization of the correction field, a substantial residual error field remains, allowing only a 50% improvement in density access. If the field coupled through a single ideal mode, then internal fields could simply be cancelled by adjusting phase and amplitude of the correction. Further, if the interaction of any residual internal fields was through a single tearing resonance (such as m=2 n=1), this too could be cancelled by a single coil array. Thus the lack of perfect correction suggests a multi-component interaction of the n=1 fields. These hypotheses are confirmed by modeling with the IPEC and M3D-C1 codes, with IPEC indicating that as resonant harmonics are reduced by correction, non-resonant field components are increased, leading to a rise in NTV damping across the plasma.

The interpretation is consistent with further intrinsic error field correction experiments, where the correction field was structured (using independent upper, lower and midplane coil arrays) to match that of the least stable ideal mode. In this way it was hoped that the lowest order ideal response would be cancelled more efficiently, while minimizing drive for higher order ideal modes. However, this yielded no significant improvement over standard correction, suggesting that the residual fields from correction may be coupling through non-resonant effects. The interpretation is also consistent with studies of correction of a localized error source simulating ITER's test blanket module; here magnetic feedback error field optimization led to a different correction field from a careful rotation optimization.

These results indicate that ITER will need good error correction (≥ 50%), and that this should have sufficient harmonic flexibility to adapt to the underlying error field, cancelling it at more than one surface in the plasma, and preferably near its source. Multi-harmonic capability remains important in ITER's coil sets, even within a single toroidal mode number.

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[1] R.J. La Haye *et al.*, Phys. Plas. **17**, 056110 (2010).
[2] R.J. Buttery *et al.*, Nucl. Fusion **40** 807 (2000).
[3] J.T. Scoville *et al.*, Nucl. Fusion **43**, 250 (2003).
[4] S.M. Wolfe, *et al.*, Phys. Plas. **12**, 056110 (2005).
[5] A.H. Boozer, Phys. Rev. Lett. **86**, 5059 (2001).
[6] R.J.Buttery *et al.*, Nucl. Fusion **39** 1827 (1999).