Addressing the Error Field Correction Challenge for ITER

R.J. Buttery[1], A.H. Boozer[2], N.M. Ferraro[1], J.M. Hanson[2], R.J. La Haye[1], Y.Q. Liu[3],
J.-K. Park[4], H. Reimerdes[5], M.J. Schaffer[1], J.A. Snipes[6], E.J. Strait[1], and the DIII-D Team

[1]*General Atomics, PO Box 85608, San Diego, California 92186-5608, USA*
[2]*Columbia University, New York, New York 10027, USA*
[3]*EURATOM/CCFE Fusion Association, Culham Science Ctr, Abingdon OX143DB, UK*
[4]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA*
[5]*ÉPFL-CRPP, Euratom Association, 1015 Lausanne, Switzerland*
[6]*ITER Organization, 13115 St Paul Lez Durance, France*

Error Fields are 3D perturbations to the magnetic field that naturally arise in the design and construction of a tokamak, or result from techniques to control other events such as edge localized modes (ELMs). The fields brake plasma rotation which destabilizes deleterious tearing modes, either by decreasing the intrinsic stability of the modes through decreased rotation shear [1], or by coupling to a resonant surface to arrest rotation and drive tearing directly [2]. Thus error fields must be minimized through careful design of the tokamak, augmented by application of correction fields from additional perturbation coils located about the device.

Investigations of Error Field Correction

Error fields tend to couple to a plasma principally through an ideal MHD response [3]. This response modifies the internal plasma fields that lead to braking and rational q resonant fields. This field interaction tends to be dominated by the component of error field that drives the least stable ideal mode. Thus it is theorized that, adjusting phase and amplitude of a correction field to cancel this ideal component is expected to achieve good correction. However, experience on a range of devices [4] has shown only modest benefits with this approach (~0-50%, measured in terms of access to low density, which scales linearly with error field amplitude). This indicates a more complex error field interaction, and so experiments were performed on DIII-D with simulated error fields of prescribed structures or correction fields better aligned to the ideal mode structure, in order to elucidate the physics of error field correction.

Correction of a Known Proxy Error Field

The first experiment utilized a dedicated coil array (the external "C-coils", 6 toroidally displaced coils located on the midplane outside the vessel) to generate a large amplitude proxy error field with pure $n = 1$ structure, thus raising the density limit for locked modes,

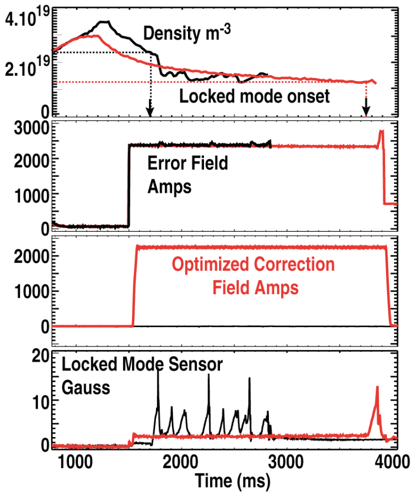

Fig. 1. The locked mode density limit (horizontal dotted lines) with a proxy C-coil n=1 error field (black) improves by 50% when optimal correction fields (deduced from a phase scan measuring mode onset thresholds) are applied with the DIII-D I-coils (red).

as expected. A second array (the “I-coils”, two rows of 6 toroidally displaced coils located inside the vacuum vessel above and below the outboard midplane) was used to correct this proxy error field and recover access to low density without mode locking. Applied fields were further optimized with offsets to compensate for intrinsic error fields in the device (i.e. from coil feeds for example). Experiments were executed at high density, requiring large fields to induce locked modes, and so greater dominance of the applied field over the intrinsic error. I-coils were ramped with differing phases to measure mode thresholds and deduce the optimum I-coil field for proxy field correction. However, it is found (Fig. 1) that with optimal correction of the proxy field, the improvement in the locked mode density limit in Ohmic plasmas is only 50%, indicating that residual fields must still be coupling to the plasma. As the proxy+correction fields are virtually pure n=1, it is hypothesized these fields couple to multiple resonant surfaces and/or non-resonantly across the plasma; if the interaction were through a single resonance, then it would always be possible to achieve perfect correction by suitably adjusting phase and amplitude of the correction.

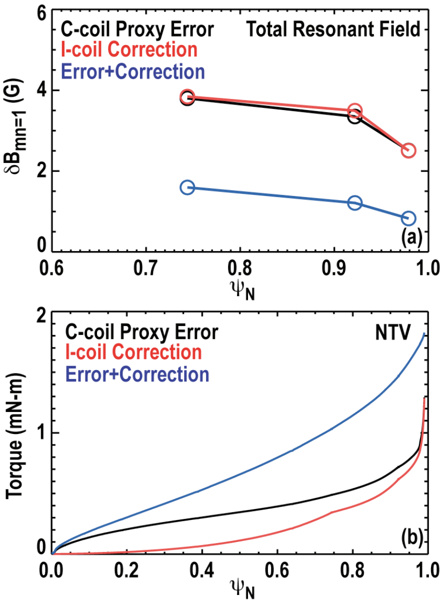

Fig. 2. IPEC modeling of resonant field strength (upper) and non-resonant field braking force (lower) vs poloidal flux (radial ordinate, circles indicate q= 2,3,4) for discharges in Fig. 1, with colors and symbols as described in text.

The above hypothesis was explored by modeling with the IPEC code, which calculates internal fields allowing for the ideal MHD response. IPEC analysis shows (Fig. 2) that while the I-coil fields (red) do indeed largely cancel the resonant components of the proxy field (black) to yield smaller resonant fields at various surfaces (blue, upper panel), non-resonant fields are actually increased (blue lower panel) leading to increased neoclassical toroidal viscosity (NTV) damping. This is a startling result. The reduction in resonant fields is associated with a weaker ideal MHD response. It might be thought that this would generally lead to reduced internal fields throughout the plasma and so less NTV also. But with hindsight, perhaps the IPEC result is not so surprising: when the additional I-coil field is added to the C-coil field, the total magnetic field energy goes up – so while ideal MHD resonant fields are reduced, other harmonics increase, leading to the rise in NTV damping. It is suggested that the resulting NTV rotation braking allows any residual resonant field to better penetrate the plasma and induce islands more easily, as discussed further in [5]. This will also lead to a different optimization of correction field to that expected with resonant field alone that must balance both resonant and non-resonant components.

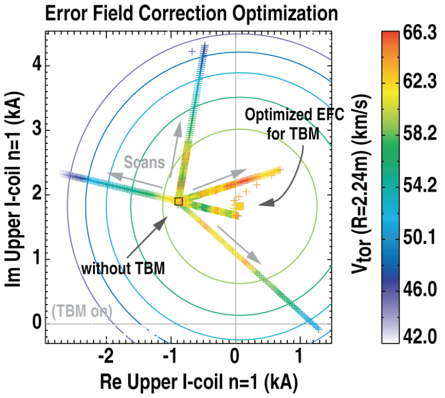

Fig. 3. Rotation optimization of TBM field by varying the I-coil correction field.

Test Blanket Module Error Field Correction

The above concepts were explored further in a second series of experiments testing correction of a more localized (and more non-resonant) error field source, as a simulator for a pair of ITER's test blanket modules (TBMs). The TBM applies a broad spectrum of toroidal mode numbers, although IPEC modeling [6] suggests a resonant interaction through ideal MHD dominated by $n=1$ components. Correction of the error field from the TBM mock-up was explored in H-mode plasmas using two techniques. First, the phase and amplitude of an I-coil $n=1$ correction field was adjusted by applying slow field ramps to maximize the plasma rotation (Fig. 3). This led to an extra 565 Amperes of I-coil correction field required with the TBM mock-up switched on, relative to optimum correction with it off. However, applying this correction in step-wise fashion [Fig. 4(a)] led to only a modest ~25% recovery of the rotation slow down caused by the TBM mock-up field, once again suggesting a substantial effect from the residual corrected TBM field. Further, this optimization differed from a second method [Fig. 4(b)], to minimize the magnetic response of the plasma to the applied TBM+correction fields (effectively a direct measurement of the plasma ideal response), which leads to a different phase and amplitude of I-coil correction (Fig. 5). This again indicates that the braking process arises from different components of the field to those that generate the ideal response – either non-resonant $n=1$ or higher n components of the field, consistent with the behavior in the proxy field studies.

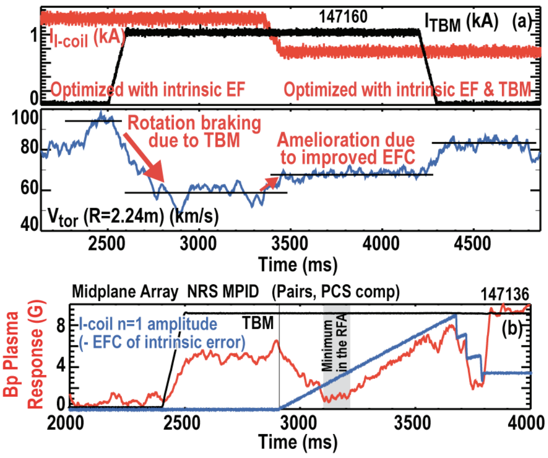

Fig. 4. Rotation optimization (a, upper 2 panels) or magnetic optimization (b, bottom panel) of TBM error with I-coils.

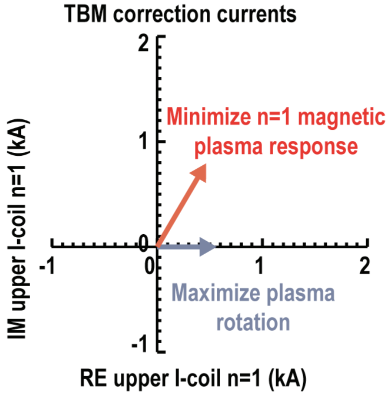

Fig. 5. Comparison of TBM correction based on rotation or magnetic response optimization.

Optimization with an "Ideal" Correction Field

An alternative approach to improve error field correction is to make the correction field better aligned with the least stable ideal mode, thereby applying less of the higher order components that might drive braking at additional surfaces. Analysis indicates the ideal mode structure is close to that expected at the sensors for a tearing mode, which is measured using toroidal and

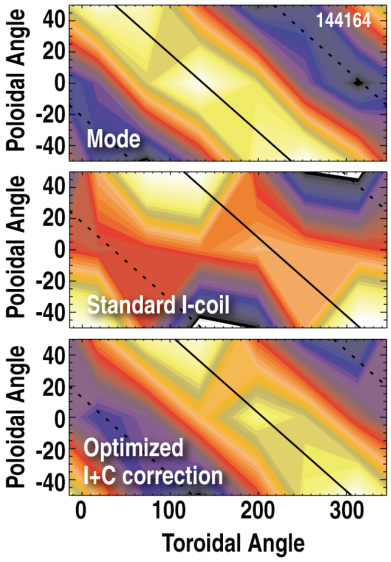

Fig 6. Measured fields at the saddle loops sensors (see text).

poloidal arrays of saddle loops (Fig. 6, upper). The standard I-coil correction (Fig. 6 mid panel) differs significantly from this, which will therefore generate additional field components in the plasma. However by adding a suitably phased C-coil field (Fig. 6, lower panel) a close match to the natural mode structure is possible – a "purer" correction field. Nevertheless, when this is applied in Ohmic density ramp-down experiments, it actually results in a marginally worse correction (a higher density limit) than I- or C-coil correction alone. This again indicates a role of additional field components beyond those expected from the ideal-MHD response and a purely resonant interaction.

Discussion – Addressing the ITER Error Field Correction Challenge

These results highlight the limitations of a single component approach to error field correction. Such an approach has led to a ~50% reduction in error field effects at best, with significantly less benefit in some devices [4], depending on the structure of the error and correction fields. For example, with the TBM mock-up above, only a ~25% rotation recovery was possible using single I-coil array correction field. In contrast, recent analysis of mode thresholds in ITER-like torque-free H-modes [1], combined with estimates of ITER's anticipated error field, indicates that error field magnitudes may need to be reduced by 50% or more to avoid disruptive $q = 2$ modes in ITER. This target will be challenging to achieve using conventional methods of error correction.

The studies reported in this paper indicate that it is important to compensate for higher order components, including non-resonant fields when performing error field correction. Thus, some further benefit may be gained be deploying multiple correction coil arrays to progressively reduce higher order components of error fields. However, the increase of non-resonant field braking when resonant fields are corrected, suggests a better strategy is to null out the error field with correction coils as close to the source as possible, rather than progressively adding more fields with additional arrays. This suggests ITER should maintain flexibility in its error field correction capabilities, both in terms of connections to its dedicated error field correction coils, but also in retaining the option of using its ELM coils for error correction, which may prove more effective in providing local correction fields better able to cancel error fields near their source. Further experiments should be pursued on present devices, to explore the benefits and best approaches for local or multi-harmonic error field correction, in order to guide ITER's approach to error field correction further.

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698, DE-FG02-89ER54297, and DE-AC02-09CH11466. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

[1] R.J. Buttery *et al.,* Nucl. Fusion **51**, 073016 (2011).
[2] R. Fitzpatrick and T.C. Hender, Phys. Fluids **B 3**, 644 (1991).
[3] J.K. Park *et al.,* Phys. Rev. Lett. **99**, 195003 (2007).
[4] R.J. Buttery *et al.,* Phys. Plasmas **19**, 056111 (2012).
[5] H. Reimerdes *et al.,* Nucl. Fusion **49**, 115001 (2009).
[6] M.J. Schaffer *et al.,* Nucl. Fusion **51**, 103028 (2011).