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ADDRESSING NEW CHALLENGES FOR ERROR FIELD CORRECTION

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GENERAL ATOMICS

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Addressing New Challenges for Error Field Correction

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Abstract. Experiments and analysis have shown an increased challenge for error field correction in ITER due to a need to correct additional field components, not previously considered. Error fields are 3D non-axisymmetric fields that naturally arise in the design and construction of a tokamak. They can brake plasma rotation to destabilize deleterious tearing modes. This process, long known to pose a challenge in Ohmic plasmas, is exacerbated in H-modes by an amplification of error fields due to ideal and resistive MHD effects, and a tendency for tearing modes to spontaneously form even before the braking brings the plasma to a halt. New scalings for this process have been obtained and compared with updated calculations of the expected error field in ITER, now incorporating plasma response effects. This indicates that ITER's correction coils need to reduce the expected error fields by ~50% in magnitude to avoid instability – comparable to the best levels of error field correction achievable in devices around the world when using well optimized single correction arrays. DIII-D experiments and modeling have explored the limits and physics of error field correction. In particular 'proxy error field' experiments confirmed that limits to correction performance can arise even with relatively pure large amplitude n=1 fields. Modeling of these studies shows that while error correction did indeed reduce tearing-resonant components of error field, non-resonant components and braking torques from Neoclassical Toroidal Viscosity (NTV) effects were actually doubled. Further experiments using a correction field more purely aligned with the plasma ideal MHD modes yielded no improvement over standard correction, consistent with non-resonant components playing a role. The results suggest that ITER needs to consider a locally targeted, multi-harmonic error correction strategy that also minimizes NTV braking from error fields. This should include the option to use error correction coils individually, to achieve a more local correction of fields, possibly augmented by its edge localized mode (ELM) control coils in order to minimize generation of adverse field components.

1. The Challenge of Error Field Correction for ITER

Error Fields have long been known to pose a concern for Ohmic operation in ITER [1]. Harmonics of these 3D fields naturally resonate with rational q (plasma safety factor) flux surfaces in the plasma. However, because tokamak plasmas generally rotate, these fields are mostly shielded out by image currents at rational surfaces. But with finite resistivity, this interaction generates an electromagnetic torque [2] which changes the phase of the imaging response from perfect shielding to enable slight tearing. Viscous coupling of this tearing structure to the bulk plasma keeps it out of phase with the error field and mostly suppressed, but if the field is large enough, the electromagnetic torque can overwhelm the rotation leading to a bifurcation to large scale tearing, termed 'penetration', which can ultimately cause a plasma terminating disruption. These effects pose a particular concern at low plasma density, where decreased viscosity and inertia enable a resonant surface to be more readily and more locally stopped, and at low plasma rotation, where shielding will be weaker. Thus Ohmic regimes seemed most susceptible, and a 3-coil array error field correction system was designed for ITER (Fig. 1) to cancel resonant 1/1, 2/1 and 3/1 harmonics of error field in the plasma (denoted by *poloidal*/*toroidal* mode numbers as m/n), using a vacuum approximation to calculate field.

However, the realization that error fields drive ideal-MHD responses in the plasma [3-5] has since transformed understanding of the field. These *kink*-resonant responses perturb current paths in the plasma, thereby generating additional non-axisymmetric fields and *tearing*-resonant components. This effect actually dominates over the externally applied ('vacuum') field, which is mostly shielded out even in low β plasmas [5]. The most detrimental harmonics are higher m components of the error field that drive a kink-like response, which in turn generates tearing parity fields at the rational surfaces. Further, this response increases with β [6] as the plasma approaches the stability limit for the kink instability, where the modes become more readily driven. This increases concern for H-modes, making them potentially more sensitive to error fields than lower β Ohmic plasmas. But it also suggests that error fields may be more readily corrected, by addressing just the component of field that resonates with the least stable ideal mode of the plasma, thereby removing most of the ideal-MHD response and the associated tearing parity fields they generate.

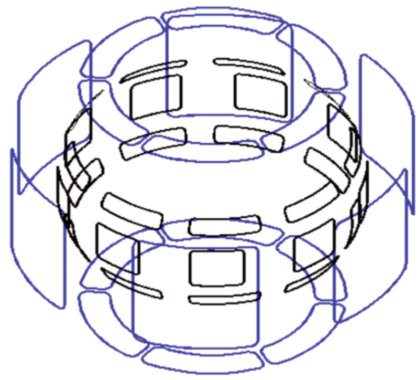

Fig 1: ITER's planned error field correction coils (blue) and ELM control coils (black). [18]

However, while the dominant ideal MHD mode response interpretation has been validated in many ways [4-6], it breaks down in the situation of error field correction for two reasons: firstly, the error field correction process inherently changes the harmonic mix of the non-axisymmetric fields, thereby potentially driving different processes and effects as the drives to the least stable ideal mode are reduced. Secondly, in ITER-like H-modes, the plasma is found to be relatively close to tearing instability, which leads to a potential for tearing mode destabilization without completely stopping plasma rotation, as well as the possibility of additional torques from a driven resistive response to the fields at resonant surfaces.

1.1. Increased Error Field Sensitivity in H-mode

These processes have been observed in particular in low torque H modes on DIII-D (Fig. 2) [7], where 3D field coils are ramped from optimized error correction to increase the amplitude of non-axisymmetric fields. This brakes the plasma enabling a rotating 2/1 mode to spontaneously appear, which then locks, destroying confinement. The enhanced sensitivity is in part associated with an increased resistive response at low rotation, inferred from observations of a developing magnetic response to probing fields as rotation is reduced at constant β. The effect is evident in modeling using the MARS-F single fluid code which predicted a

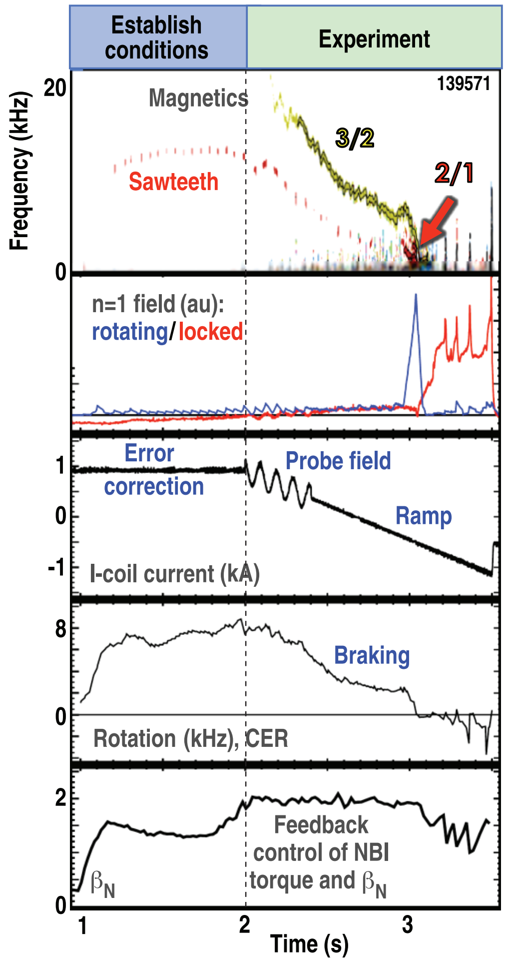

Fig 2: Increasing error field (panel 3) brakes plasma and triggers a 2/1 mode. [7]

corresponding fall in shielding (Fig. 3). This effect was found to be much stronger with more realistic two fluid simulations using more realistic viscosity and conductivity values with the M3D-C[1] code, which shows a much reduced screening compared to the MARS code, being only 5-10 times lower than the vacuum response for the high rotation experimental case shown. This confirms that the plasma is expected to become substantially more susceptible to tearing and error fields as rotation is lowered.

The scaling of mode onset thresholds in torque free plasmas from the experiments described above has been combined with previous Ohmic error field sensitivity scalings [1] to yield an overall prediction for ITER H mode error field thresholds as:

$$\frac{\delta B_{boundary}}{B_\mathrm{T}} = \left[1.3-\left(\beta_\mathrm{N}-1.8\right)\right]\times\frac{\left(n_\mathrm{e}/10^{20}\ \mathrm{m}^{-3}\right)\left(R/6.2\ \mathrm{m}\right)^{0.725}\left(q_{95}/3.1\right)^{0.83}}{\left(B_\mathrm{T}/5.3\ \mathrm{T}\right)^{1.02}}\times 10^{-4}, \qquad (1)$$

This is expressed in terms of the component of the error field at the plasma boundary that couples through ideal MHD to generate a resonant m=2/n=1 field at the q=2 surface in the plasma [10]. It 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 to avoid triggering 2/1 modes.

It should be noted that unlike the original ITER three-harmonic vacuum error field threshold criteria, this formalism essentially considers a single dominant field component – that resonant with the ideal MHD response, which couples through to tearing-resonant fields. It does not include effects from non-resonant fields, which might further brake plasma rotation and so change thresholds. It was considered that in correcting error fields, one would drive less ideal modes and so generally reduce non-axisymmetric fields in the plasma – this turns out not to be the case, as shown later. Thus, while this represents the state of the art in the formalism, and is useful for quantifying the scale of the error field correction challenge, it must be born in mind that further effects and field components may play a further role.

1.2. Expected Error Field in ITER

To understand the degree of error field correction required in ITER, the Monte Carlo calculations of expected error field in ITER have been partially updated for the above formalism [11], using calculations from the IPEC code. For the ITER baseline burn scenario, this yields individual contributions from sources such as the solenoid, toroidal and poloidal field coils, test blanket modules, etc., in the range $\delta B_{boundary}/B_T$ ~1–5 x10^{-5} each, with an estimated maximum combined total overlap field of $\delta B_{boundary}/B_T$ = 2.8 x10^{-4}. This projection is a mixture of pessimism and optimism. On the one hand it simply adds up contributions from different sources (assuming they are phase aligned). But on the other hand, within each source of error, such as the PF coil set, it assumes an essentially random distribution of error fields, rather than any systematic trends (such as systematically similar misalignments), in compiling a vector summation to deduce error field. It therefore seems to be a rough but reasonable estimator of the scale of fields expected.

Thus to stay below the above predicted threshold ($\delta B_{boundary}/B_T$ = 1.3x10^{-4}) would require ~50% error field correction. In higher β regimes, this correction requirement would be

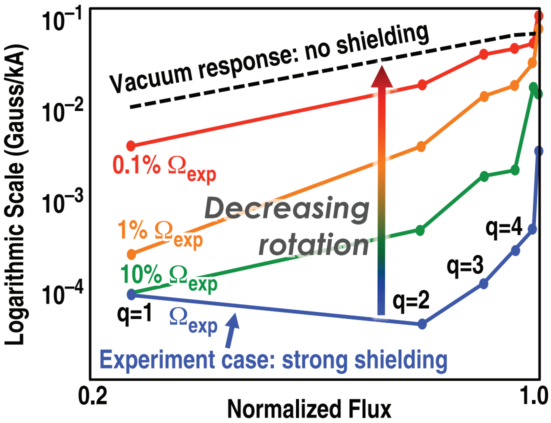

Fig. 3. The developing tearing response predicted by MARS-F as rotation is lowered from a high rotation stable experimental case. [7]

higher. The scaling in Eq. (1) also does not factor in any changes in underlying tearing stability with q_{95}, which are not well known, but it is noted that tearing stability appears to be a significant factor in setting tearing mode limits in H-mode [16]. Thus significant error field correction in ITER may well be needed, and understanding the relative capabilities of different correction coils is important to determine how to undertake this correction, whether further changes to plasma operation are needed, or if ELM coils are additionally required for error field correction.

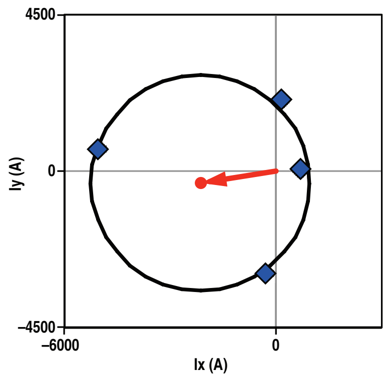

Fig 4: Applied I-coil phases and amplitudes at mode onset. Arrow indicates predicted optimal correction. [18]

2. Exploring The Effectiveness of Error Field Correction

Error fields have been found to pose significant limits to performance on a range of devices, including COMPASS-D and JET [12], DIII-D [13,14] and ALCATOR-CMOD [15], MAST [16] and NSTX [17]. So far, they have tended to pose greatest problems at low densities in Ohmic plasmas, and so to starting up a plasma. Thus these devices installed various types of error field correction coils – typically in toroidal arrays of picture frame like coils either inside and/or outside the vessel, which could therefore apply arbitrary phase and amplitude of a given harmonic structure in order to study error field limits and their correction. In all six devices, the low-density limit was found to scale linearly with error field, and so the density limit can be used as a way to characterize overall error field magnitude.

Typically, the required correction field is determined by performing a phase scan of fields from the perturbative coils (Fig. 4). Field amplitude is ramped with a given toroidal phase until a mode forms. This is then repeated with other coil phases. Assuming the same total field (intrinsic + applied) at penetration in each discharge enables deduction of the machine intrinsic error in terms of equivalent coil currents. Optimal correction is then obtained by applying currents to reach the center of the circle fit to points marking error field threshold.

Comparing experience between these devices a number of trends emerge. This is explored in detail in [18], but the main outcomes are discussed here. Firstly, it is found that single correction coil arrays had variable and sometimes very limited benefit (in terms of low density access), ranging from near zero (e.g. JET's EFCC coils) to ~50% (DIII-D dual array internal 'I-coils' or C-MOD's dual array 'A-coils'). This suggests that it is not enough to simply adjust phase and amplitude to minimize drive to a single dominant ideal-MHD mode (which in turn drives the tearing parity field). Additional field components must couple in other ways to help trigger instability. Even within a given device, different coil arrays can have different levels of effectiveness (e.g. 'saddle' cf 'EFCC' coils on JET or 'C' cf 'I' coils on DIII-D), confirming that there are some less desirable harmonics to apply (indeed JET's EFCCs appear to be near orthogonal to its error field). Also it is found that combining coil sets can improve correction (e.g. DIII-D n=1 + C-coils [14]), indicating more directly that more than one field component matters in optimizing error correction. Dual coil arrays (such as DIII-D I-coils or C-MOD A-coils) appear somewhat more effective than single coils arrays perhaps through cancelling out some core resonances. Further, while DIII-D has shown that fields that align with the ideal MHD least stable mode are most effective at correction, no device has found the ~90% improvement predicted by the ideal response model [5], indicating that additional field components must play a substantial role, comparable to the dominant mode that couples through to the 2/1 tearing surface.

2.1. Proxy Error Field Experiments

Clearly, the lesson for ITER is to maintain flexibility so that it is able to deploy a structure of correction field that works well for whatever source of error field it encounters. But is there a preferred structure, that is generally more efficient, and how many degrees of independence are needed? To study these issues a 'proxy error field' experiment was set up in DIII-D, to generate a known (and modelable) source error field with one coil array (the 'C-coils') and correct it with a second coil array (the 'I-coils'), as in Fig. 5. Both fields had a relatively pure n=1 structure, but as in a realistic error field correction situation, quite different poloidal spectra.

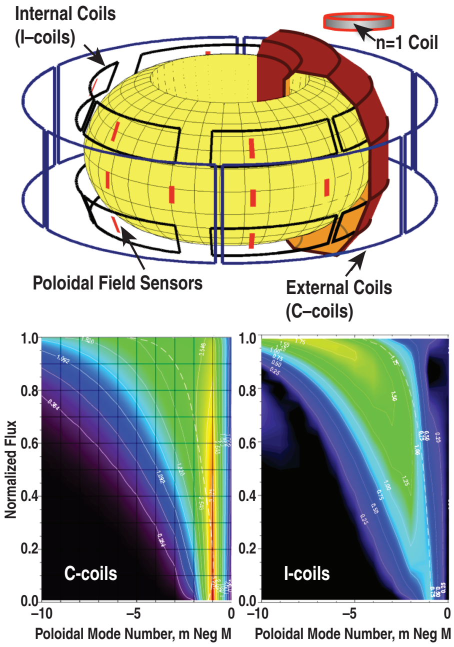

Fig 5: Geometry (upper panel) and harmonic structure (lower panel, color indicates strength of different poloidal harmonics at different radii) of DIII-D C- and I-coils. [18]

Discharges were obtained by first ramping the density to a high value to then enable application of a significant amplitude C-coil proxy field without immediately inducing tearing modes. I-coils were then ramped with various phases relative to the C-coil field to determine the optimal correction field, or apply that correction. The phase scan was performed by rotating the C-coil proxy field phase past the fixed I-coil phase so that the phase scan measured just the proxy field correction requirements, not the machine intrinsic error as well. To reduce uncertainties from machine intrinsic error field, a phase scan of C-coil current ramps was performed prior to the I-coil experiments, to re-optimize the C-coil currents for correction of the machine intrinsic error field. These were applied as offsets to the C-coil proxy fields. Finally, the I-coil phase was chosen to be orthogonal to the measured machine error and its correction by the C-coils, in order to minimize the effects of inaccuracy in the intrinsic error correction (the residual field would be mostly orthogonal to the proxy field).

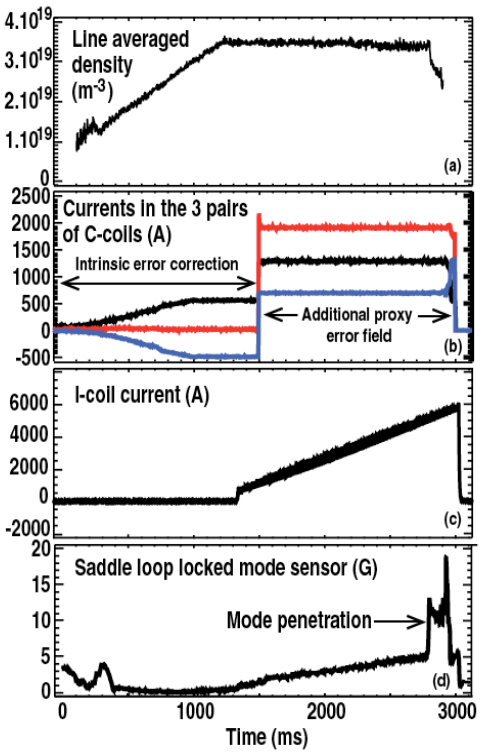

Fig. 6: Proxy error field experiment: (a) density is ramped up; (b) currents in 3 toroidally opposite pairs of C-coils are deployed to correct intrinsic error field, then apply proxy error field; (c) I-coil currents are then ramped (in 3 pairs, one shown) to trigger a mode; (d) mode formation ('penetration') observed. [18]

A typical experiment is shown in Fig. 6. As the density was ramped up, C-coils were applied to correct just the intrinsic machine error. Once high density was reached, C-coils were switched to apply the additional proxy error field with 2 kA peak amplitude and n=1 sinusoidal distribution in toroidal angle. I-coils were then slowly ramped to determine the level that induces a static tearing mode. The resulting n=1 I-coil currents at mode penetration are in fact those of Fig. 4, where the vector orientation of points represents the phase of the I-coil field relative to that of the applied C-coil proxy field for four discharges. Fitting with an offset circle, optimal correction of the proxy error is obtained with 2.2 kA amplitude currents in the I-coils, and at a phase of –171 deg – close to perfect opposition to the C-coil proxy field (a small difference might be expected as fields are structured differently). This I-coil correction field was then applied to density ramp-downs with proxy field still deployed, to determine the benefits of correction in terms of locked mode density limits, as in Fig. 7.

It can readily be seen from Fig. 7 that even though only n=1 fields are applied, correction only gives a 50% improvement in the density limit - 1.28x10^{19}m^{-3} cf 2.46x10^{19}m^{-3} uncorrected. It should be noted that these levels are well above the limits without proxy field, where the underlying C-coil correction of machine error accesses 0.44x10^{19}m^{-3}. As this will have a different spectra than the proxy field, it is subtracted in quadrature [1,18] yielding only small corrections to the proxy experiment limits, to 2.42 and 1.28x10^{19}m^{-3} respectively. A larger error bar arises from the circle fit (Fig. 4, σ~17%) contributing to a 0.2x10^{19}m^{-3} uncertainty in corrected proxy density limit.

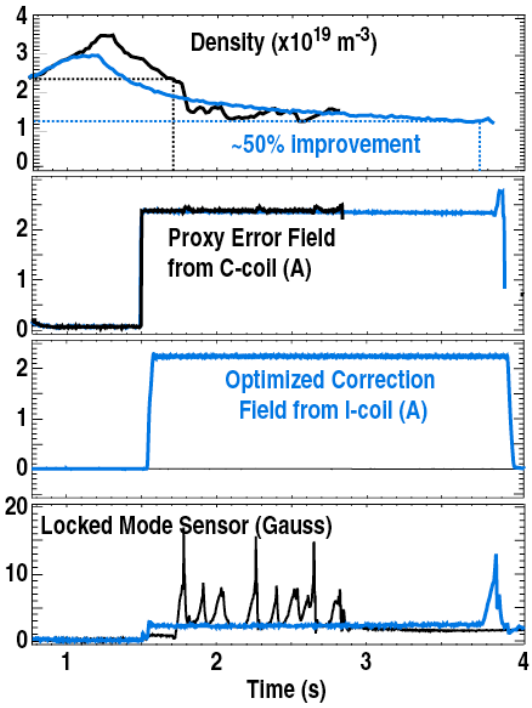

Fig. 7. The locked mode density limit with a proxy C-coil error field (black) improves by 50% when optimal correction (deduced from phase scan measurements of mode onset) is applied with DIII-D I-coils (blue). [18]

Thus correction fields have not fully corrected the operational effect of the proxy field. To explore the reasons for this, modeling was performed with the IPEC code, based directly on the experimental data and kinetic EFITs, to extra diagnostic shots taken with beam blips. Firstly, the modeling of the actual currents applied shows (Fig. 8) that the correction field has indeed reduced tearing resonances (blue curves) – but not to zero, as might be expected with optimum correction. Further, as shown by the green curves based on model-adjusted currents: because the different field components combine linearly, it is possible to completely cancel one tearing resonance (also making other resonant components close to zero). This suggests that the relevant metric underlying the experimental optimization of correction field is not purely related to tearing resonances. The modeling also confirms that these results are affected little by the much smaller intrinsic error fields present.

But how then is the corrected proxy error field acting to cause modes? Modeling of the non-resonant fields has generated an explanation (Fig. 8 lower). This shows that while tearing-resonant components are reduced, non-resonant components are increased leading to increased braking torques from Neoclassical Toroidal Viscosity (NTV) effects. Virtually identical rises in NTV are seen either with the experimental optimal correction (blue) or with a theoretically optimized correction to zero the resonant 2/1 field. This is a startling result, running counter to an intuition that expected reducing tearing-resonant fields would be achieved by reducing coupling

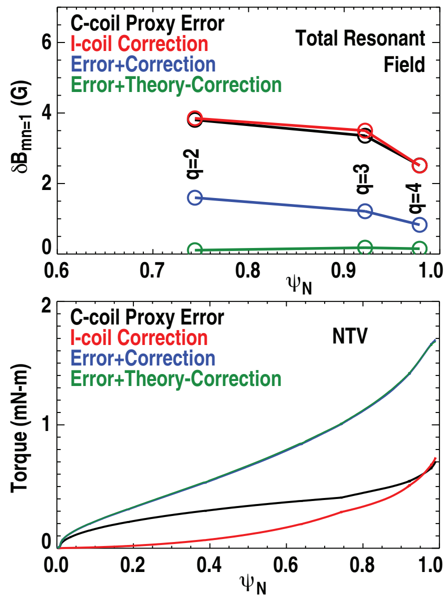

Fig. 8. Modeling the proxy error field correction experiments with IPEC. Upper panel: total resonant field at q=2, 3 and 4. Lower panel: NTV braking.

to the ideal mode, which would generally reduce non-axisymmetric fields in the plasma. It highlights that some field components are effectively orthogonal to the ideal mode. In another sense, this result is less surprising – to apply correction one adds fields from a second coil array; thus it might be reasonable to suppose that adding extra non-axisymmetric field might apply more drag to the plasma. Thus it is hypothesized that empirical experimental error field correction is optimizing a metric combining resonant and non-resonant fields. When optimum correction is applied, this reduces (but does not zero) tearing resonant components, and increases non-resonant braking, enabling the residual resonant components to penetrate more easily. This hypothesis is also compatible with experience correcting error fields from a mock-up ITER test blanket module [19], where only a 25% recovery in rotation degradation is obtained, consistent with resonant field reduction being accompanied by increases in non-resonant field braking. The hypothesis might be further tested by looking for a correction that zeros the resonant part and observing whether there is still a full mode penetration (rather than just braking to a low rotation level).

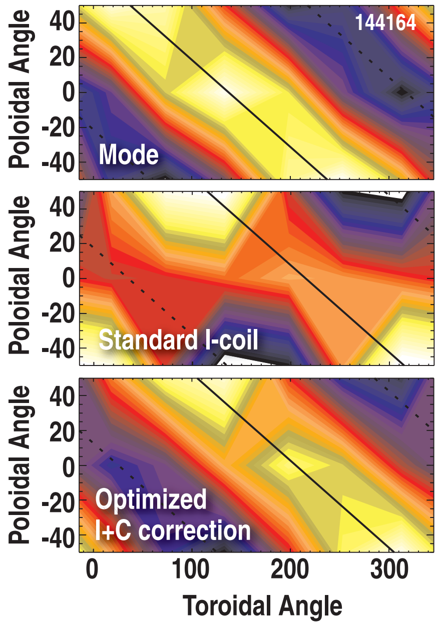

Fig 9: Measured radial fields at the saddle loops sensors (see text).

2.2. Ideal-MHD Aligned Correction

To further test the ideal MHD interpretation, a second experiment was conducted combining I-and C- coil to make a correction field that more closely aligned with the least stable ideal MHD mode. This is hypothesized to drive less of the higher order kink-resonant components which might drive braking at additional surfaces, and thus improve correction of the intrinsic error. Analysis indicates the ideal-MHD structure is close to the structure expected at the sensors from a 2/1 tearing mode, which is indicated in Fig. 9 (*upper panel*) from measurements using toroidal and poloidal arrays of saddle loops. The standard I-coil correction differs significantly from this (*middle panel*), effectively generating additional field components. However by adding a suitably phased C-coil field (*lower panel*) a close match to the natural mode structure is possible – a 'purer' correction field. The required phase and amplitude of this combined correction field for optimal correction is then deduced using the usual phase scan technique (as shown in Fig. 4). However, when this is applied in Ohmic density ramp-down experiments (Fig. 10), it actually results in a marginally worse correction (a higher density limit) than I- or C-coil correction alone. This limitation suggests that the coils are interacting with a single dominant resonant ideal mode, but with additional non-resonant effects and/or higher n fields still limiting the effectiveness of the correction.

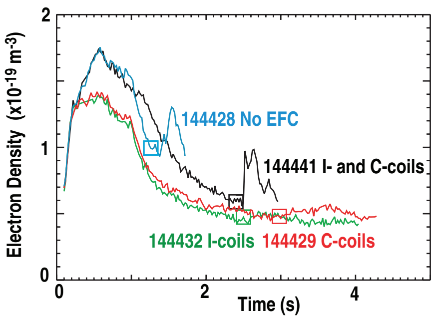

Fig 10: Locked mode density ramp down limits (squares) for various correction fields as labelled.

3. Discussion – Addressing the ITER Challenge

Experiments and modeling have identified a potential explanation for limitations to error field correction that are widely observed on many devices. Modeling indicates that while correction reduces tearing-resonant fields at multiple surfaces simultaneously, non-resonant fields and NTV braking are actually increased by the correction. This highlights that some field components do not couple to the ideal MHD response (which is reduced with correction), but penetrate directly into the plasma. While this result was initially surprising, as it was thought that reducing the ideal response would reduce all non-axisymmetric fields, the intuitive interpretation is simply that adding more fields to the plasma increases the total non-axisymmetric field in the plasma, and thus the NTV drag. This suggests that the optimal strategy for error field correction is to prevent the fields reaching the plasma, rather than simply energize more arrays of correction coils, which may cancel some components but drive others. This highlights that ITER must retain flexibility in its error correction coils, and should seek to energize correction coils locally, close to sources of intrinsic error, or more variably to correct distributed sources of error field, to reduce total field in the plasma. It is also important to use coils (or coil combinations) that do not generate strong field components elsewhere in the plasma. The ELM coils provide valuable extra flexibility in this regard (like the DIII-D I-coils), and should be retained as options for use in error field correction, alongside ensuring the standard correction coils are not hard-wired into combinations that require whole arrays to be energized at high levels around the machine.

More work is needed to further pin down the field components that matter most (e.g. the role of higher *n* fields) and demonstrate real time approaches to the optimization. Test blanket module experiments [19] add valuable insight in this regard. It is also important to demonstrate that these considerations can indeed achieve better correction through more flexible application of correction coil arrays. Further, the other data reported here – updated scalings for the processes leading to mode onset, and recalculation of the expected ITER error field using a correct physics model – highlight that ITER will need good error correction ($\geq 50\%$ of the anticipated irregularities), and that these matters remain important to address, not only for the Ohmic phase, but also for baseline Q=10 ITER operation.

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