ERROR FIELD MODE STUDIES ON JET, COMPASS-D AND DIII-D, AND IMPLICATIONS FOR ITER

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Abstract

New experiments on COMPASS-D, DIII-D and JET have identified the critical scalings of error field sensitivity and harmonic content effects, enabling predictions of the requirements for larger devices such as ITER. Thresholds are lowest at low density, a regime proposed for H mode access on ITER. Results suggest a moderate error field sensitivity ($\delta B/B \sim 10^{-4}$) for ITER, comparable with the size of its intrinsic error, although there are uncertainties in scaling behaviour. Other studies on COMPASS-D and DIII-D show that sideband harmonics to the (2,1) component play an important role. Thus a correction system for ITER will be important, with flexibility to correct sidebands desirable, possibly assisted by beam rotation. Such a system has been designed and is capable of reducing multiple harmonic error levels to $\sim 2\times10^{-5}$.

1. INTRODUCTION

1.1. Background

Non-axisymmetric error fields are a cause of concern for any next generation tokamak device like ITER. They can drive the formation and growth of locked modes in *otherwise MHD stable plasmas*. This can lead to a disruption and an associated vertical displacement event which for a large device are potentially damaging and reduce the operational lifetime. Early experiments on error field locked modes in Ohmic plasmas - most notably COMPASS-C [1], DIII-D [2] and JET[3] - showed error field sensitivity increases with size and magnetic field. Also the modes are more easily produced in low density plasmas, and so are of most concern in ITER during the early heating phase, proposed for access to H mode. This places design and operational constraints on ITER, and some form of error field correction, possibly with neutral beam rotation, is considered essential.

Such a correction system has been designed for ITER. To predict the requirements of this system, it is vital to have reliable estimates of the error field sensitivity and type of correction required (in terms of field harmonics and required flexibility). However, much of the early work was conducted in differing shape plasmas and with different harmonics of error field applied, and usually only considering the (2,1) component of error field - more recent results [4] have shown that other harmonics also play a crucial role. This shows the need for dedicated cross-machine scaling experiments. Thus, there are two basic issues to examine:

- the role of sideband harmonics and whether they will need independent correction
- the scaling behaviour, to predict level of correction required for ITER

In this paper, we summarise the results of extensive campaigns on COMPASS-D, DIII-D and JET to examine these issues. These use similar ITER-like plasmas on all three machines to assist comparisons. New models have been constructed to represent the combined effects of harmonics. This has enabled a consistent approach to comparison and extrapolation of results. Rotation and heating effects have also been examined in additional heating studies. The results and implications for the correction system for ITER are discussed, with latest approaches to design summarised.

1.2 Mechanism

Error fields inevitably arise in any tokamak from sources such as coil positioning errors, eddy currents, coil feeds and connections, etc. Experimentally the resonant (2,1) error field component (denoting in terms of Fourier harmonics ‘m,n’ for poloidal and toroidal mode numbers, respectively) has been observed to induce dominantly (2,1) locked modes in a range of tokamaks [1,2,3]. This is understood [1,5] to occur when the magnetic torque exerted by the error field in the vicinity of the q=2 surface overcomes plasma inertia and viscous torques, stopping the MHD fluid and allowing island growth. This torque arises from interaction with currents flowing on the resonant surface that effectively shield out the perturbation, preventing tearing. Once the rotation slows to about half its initial frequency, there is an abrupt transition to locked mode and significant tearing - a process known as ‘***mode penetration***'. From torque balance considerations [6,7], the criteria for critical error field *from a single harmonic*, B_{rmn}, for mode penetration can be obtained as:

$$\frac{B_{pen}}{B_T} \quad \omega_0 \tau_A \left(\frac{\tau_{rec}}{\tau_v}\right)^{1/2} \qquad (1)$$

where τ_A, τ_v and τ_{rec} are the Alfvén, viscous, and magnetic reconnection times, respectively, which can also be expressed in terms of plasma parameters through various confinement scalings.

1.3. The experiments

To examine error field behaviour, error fields can be simulated with asymmetrically placed bars or saddle coils. COMPASS-D, DIII-D and JET are equipped with various coils for this purpose. For example DIII-D, shown in Fig 1, has a six-segment correction coil and an n=1 coil, as well as substantial sources of intrinsic error from poloidal and toroidal field coils. This enables examination of a range of harmonic spectra. The majority of its data comes from double-null plasmas, with which it typically operates. COMPASS-D, which is equipped with 8 or 10 toroidal bars in each of four quadrants, has very low intrinsic error (below statistical variation of experimental measurements), and operates with single null plasmas. Thus it is ideally suited to generation of a wide range of harmonic spectra in a controllable manner. JET has two pairs of symmetrically designed *internal* lower saddle coils. Thus, the harmonic spectra is fixed, but as the largest device, with access to higher fields, it provides the most ITER-relevant data, important for scaling and predicting ITER requirements.

A typical experiment on COMPASS-D is shown in Fig 2: current in the error field coils is ramped up until a locked mode forms. The mode penetration can be directly measured, and is seen most clearly in magnetic measurements, due to the self consistent response of the plasma to the mode, which can amplify the applied n=1 field 2 or 3 times in Ohmic plasmas. Plasma rotation falls ahead of the mode, as the MHD fluid stops, leading to a change in ion and electron rotation.

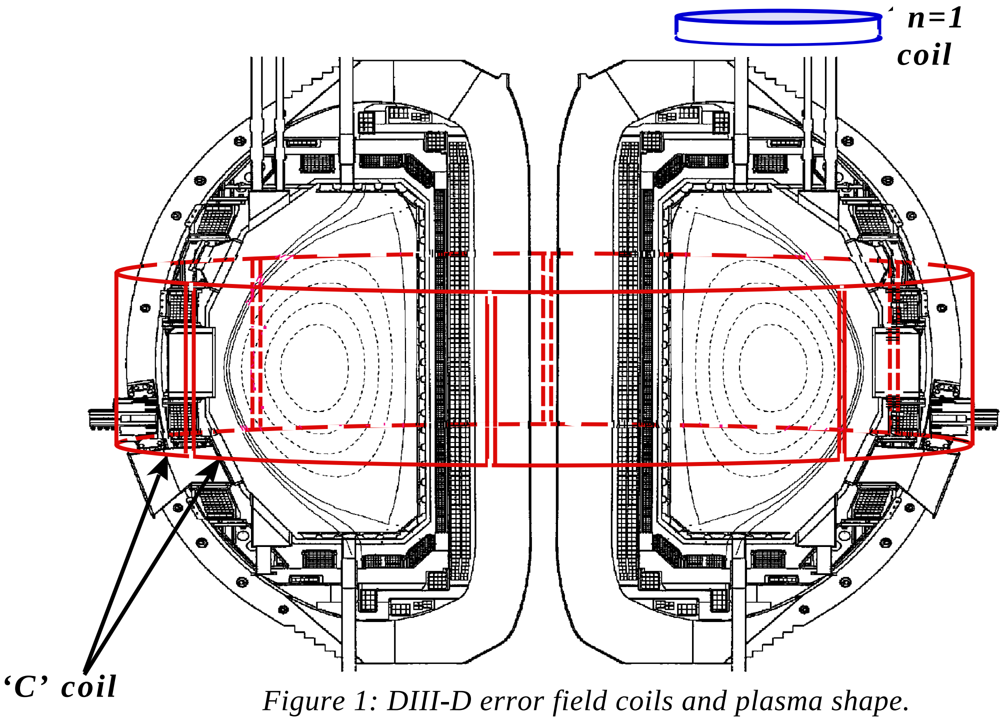

Figure 1: DIII-D error field coils and plasma shape.

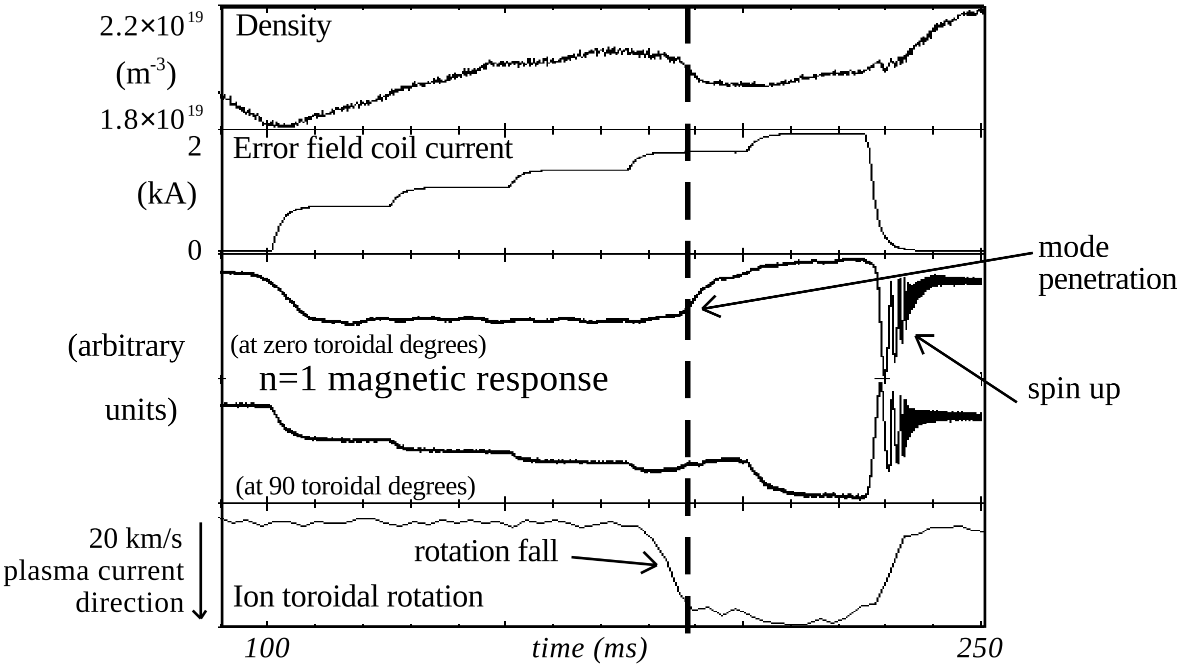

Figure 2: Error field mode penetration using toroidal bars on COMPASS -D.

2. EFFECT OF SIDEBAND HARMONICS

Initial work on DIII-D [4] identified the role of sideband harmonics (3,1 and 1,1 components) in formation of modes resulting from viscous coupling of drag on surfaces other than the q=2 surface. In addition to this, it is also possible that these harmonics may couple directly to q=2, via the resonant response of q=1 and q=3 surfaces generating additional (2,1) field at q=2 (ie toroidal coupling). To consider the sideband harmonic effects properly, we express the torque applied directly by the error field at a given resonant surface (r_j) as [7]:

$$T(r_j) = \left| \sum_m B_m C_m^j \right|^2 \qquad (2)$$

where B_m are complex numbers representing size and orientation of Fourier harmonics of the error field, with complex coefficients $C_m^{\ j}$ representing the toroidal coupling of the components at r_j. (In ref 8, this is expressed in terms of toroidal ring functions with real coefficients representing coupling to the currents at the edge of the plasma). In addition to this, torques applied at neighbouring resonant surfaces may, by viscous coupling, apply a torque at r_j, so the total torque at r_j has the form:

$$T_{tot}(r_j) = T(r_j) + \sum_{k \neq j} A_k^j T(r_k)\,. \qquad (3)$$

where $A_k^{\ j}$ are real viscous coupling coefficients. $A_k^{\ j}$ and $C_m^{\ j}$ can be determined experimentally by fitting, assuming torque required for penetration is constant in all cases (for identical plasma conditions).

Experiments have been performed on COMPASS-D and DIII-D to investigate the form of this torque. On COMPASS-D the mixture of Fourier harmonics may be varied by using different combinations of toroidal bars. In particular, independently-powered coil combinations with 2 different dominant (m,n) combinations are used. Figure 3 shows how the penetration threshold varies as the current in a dominantly (2,1) field coil combination ($I_{2,1}$) is varied against a dominantly (3,1) combination. The studies are conducted with single-null plasmas with an ITER-like elongation (~1.6) and shape. There is strong interaction between the (2,1) and (3,1) combinations, but the locked mode formed always remains a dominantly (2,1) mode. Similar results are obtained from the interaction of dominantly (1,1) and (2,1) combinations. The Fourier components of the error field current have been evaluated and a general form for the torque fitted to the data [see Eqs 2 and 3], the result is:

$$T_{tot}(q=2) \quad B_{pen}^2 = 0.13|B_{1,1}|^2 + |(0.21+0.02i)B_{1,1} + B_{2,1} + (0.85\text{-}0.17i)B_{3,1}|^2 + 1.69|B_{3,1}|^2 \qquad (4)$$

where the Fourier analysis is performed in straight field line co-ordinates at q=2 with the complex coefficients representing a polar form. The principal mode-locking effects are the torque that the (2,1) and (3,1) modes apply at the q=2 surface, and the viscous drag from the torque applied at q=3 ($|B_{3,1}|^2$ term). 'B_{pen}' can be thought of as *the equivalent threshold for a pure (2,1) field.*

Experiments performed on DIII-D have used DND configuration, ramping down the density or ramping up C-coil or n=1 coil currents until an error field locked mode forms. Here the harmonic mix was altered by varying the mix of natural error field and specifically applied fields from the n=1 and C-coils [9]. The analysis of this data is more complex as applied error fields vary with PF and TF coil currents, and thresholds must be measured by ramping down density. The sources of error from the TF coils are also unknown. Thus results must be simultaneously fitted for plasma parameter scaling, harmonic variation and intrinsic error. Adopting a form which includes both viscous and direct coupling, as in COMPASS-D, yields:

$$\bar{n}_e(10^{19}m^{-3}) = 0.6\frac{(B_T/2.1T)^{0.04\pm029}}{(q_{95}/3.3)^{080\pm058}}B_{pen}(G) \qquad (5a)$$

where the torque $T_{tot}(q=2) \sim B_{pen}^{\;2}$, and B_{pen} takes the form for q_{95}=3.3,

$$B_{pen}^2 = 0.28B_{1,1}^2 + (0.25B_{1,1} + B_{2,1} - 0.05B_{3,1})^2 + 0.51B_{3,1}^2 \qquad (5b)$$

with a similar form at q_{95}=4.6. The quality of the fit is shown in Fig 4, which demonstrates the linear density scaling. The coefficients are all real because of the up-down symmetry of the DND configuration. Data is taken at four combinations of q_{95} and toroidal field, which ensures no degeneracy with other fitting parameters. This form (Eq 5b) gave a much better fit, and more realistic estimates of TF coil intrinsic error, than a purely viscous coupling form. The very limited range of a factor of 1.4 in both q_{95} and B_T (at fixed q_{95}) makes the DIII-D best-fit exponents relatively uncertain, but within this uncertainty, the relative threshold (B_{pen}/B_T) does not decrease much faster than $1/B_T$.

These COMPASS-D and DIII-D results are important for two reasons. First, they show that to understand the locked mode physics in a given machine where the harmonic mix varies, it is important that harmonic coupling effects be taken into account. Second, they show that it is probably desirable to correct the (1,1), (2,1) and (3,1) error field components independently. The (1,1) correction may be necessary, despite the relatively weak coupling, because (1,1) field errors will typically be larger than (2,1) or (3,1) field errors on ITER - the amplitude of the error-field spectra that arise from coil construction and positioning tolerances typically scales as ~1/m, and (1,1) is constant with radius.

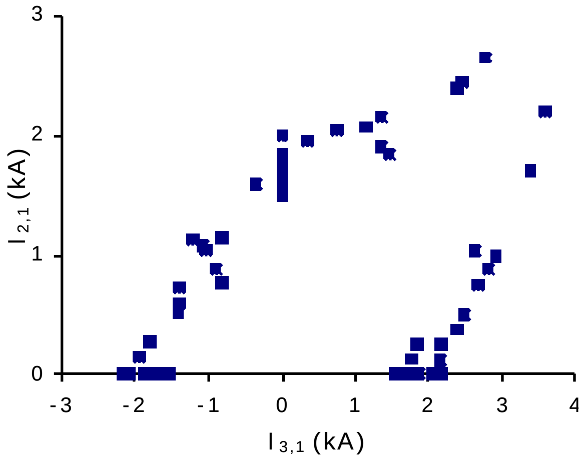

Figure 3: COMPASS-D error-field coil currents for mode penetration in low-density Ohmic plasmas ($2{\times}10^{19}m^{-3}$). Note (3,1) coil alone can induce locking at high current values.

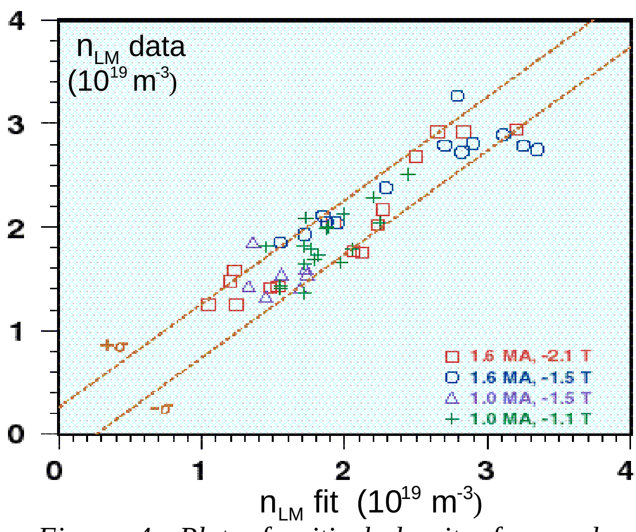

Figure 4: Plot of critical density for mode locking on DIII-D vs predicted level from fit due to variation in plasma parameters and harmonic content.

3. SCALING STUDIES

Turning now to the dependence of the penetration threshold on plasma parameters. It will be assumed that this has power law form $B_{pen}/B_T \quad n^{\alpha_n} B_T^{\alpha_B} q_{95}^{\alpha_q} R^{\alpha_R}$, in line with confinement scaling approaches. Experiments have been performed on COMPASS-D and JET with a single parameter (n_e, B_T or I_P) varied at a time to determine the exponents. On DIII-D these coefficients are extracted from the fitting process described in section 2 and given in Eq (5). The thresholds now reported on JET are much higher than those reported for earlier limiter experiments [2], where error field levels were based on calculated design intrinsic errors, suggesting additional sources of error field. Changes from limiter to SND shape have little effect on the threshold. The measured exponents are given in Table I.

TABLE I. Parameter dependence of the penetration threshold scaling. Values in parentheses are inferred by addition, otherwise they are direct result of an experimental scan.

Parameter	α_n (density varied)	α_B (I_P and B_T varied with q_{95} fixed)	α_q (plasma current varied)	$\alpha_B+\alpha_q$ (toroidal field varied)
JET	0.94	-1.2	(0.05)	-1.15
DIII-D	0.99	-0.96	0.83	(-0.13)
COMPASS-D	1.0	-2.9	1.6	-1.1

It can be seen that there is good agreement on the scaling of the density threshold (α_n). The scaling with toroidal field (α_B) is shown in Fig 5: results are consistent within error bars between JET and DIII-D (although there is a limited range in DIII-D data) but differ significantly with COMPASS-D. This is thought to be related to the variation of measured plasma velocity with toroidal field which is stronger in COMPASS-D than in the larger machines. This introduces a note of caution for extrapolation, indicating that changes in regime or rotation can have significant effects - a weakness of global scaling when the physics depends on local rotation (Eq 1). Differences in α_q are likely to be due to the different error field harmonic compositions and their variation as the q_{95} changes.

4. CRITICAL ERROR FIELD LEVELS FOR ITER

Error field thresholds have been determined for plasmas with the ITER shape, q_{95} and density, and so for extrapolation to ITER one must take account of the size and B_T scaling. The scaling to the ITER toroidal field (5.7T) from the various machines is shown in Fig 5. Determining the machine size scaling is more problematical - since the COMPASS-D data is in a different regime (different toroidal field scaling, also rotation scaling differs) it cannot be used in an empirical cross-machine extrapolation to ITER. Given differences in the error field spectra and plasma shape, an extrapolation based on DIII-D and JET is rather uncertain. Thus the size scaling is inferred from a dimensional constraint

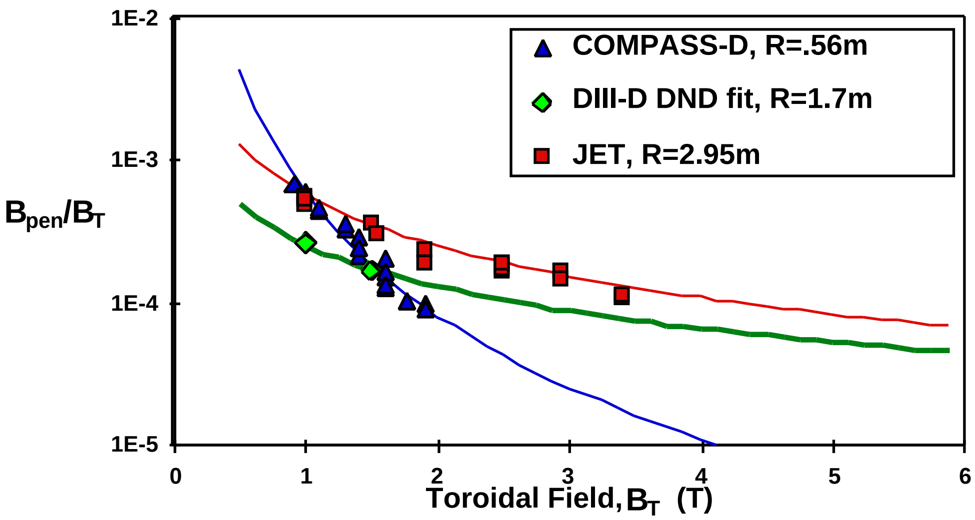

Fig 5: Scaling with B_T of the penetration threshold in COMPASS-D, DIII-D and JET at a density of n_e=1.6x10^{19}m^{-3} and q_{95}=3.3. The sideband harmonics are taken account of using the expression (4) for COMPASS-D and JET (SND) and (5b) for DIII-D (DND), which as noted above gives the equivalent threshold for a pure (2,1) field.

($\alpha_R=2\alpha_n+1.25\alpha_B$), required by invariance scaling in the collisional high β plasma model [10]. For JET, DIII-D and COMPASS-D this gives $\alpha_R=0.4\pm0.2$, 0.79 ± 0.3 and -1.65, respectively. This approach, while not wholly satisfactory for a local effect, is routinely used as a consistency requirement on confinement time scalings - we discuss the discrepancies below.

In ITER it is likely that the time of greatest danger for inducing a locked mode occurs during the low density phase proposed for H-mode access. The most relevant data to take, requiring least extrapolation, is from JET (largest toroidal field and machine size): this predicts a threshold in terms of pure (2,1) field ($B_{2,1}/B_T$) of 1.25×10^{-4} for ITER reference parameters ($n_e\sim2\times10^{19}m^{-3}$, $q_{95}=3.3$, R=8.1m, $B_T=5.7T$). This is confirmed by the limited data range from DIII-D DND plasmas (which predicts 2.0×10^{-4}). The effect of harmonic content is taken into account as explained in the Fig 5 caption. The COMPASS-D scaling results, which predict order of magnitude lower thresholds, highlight the uncertainty in the ITER predictions - if the physics regime (eg local q=2 rotation behaviour) changes over the range of extrapolation, then the scaling may also change significantly, as is seen to be the case between JET and COMPASS-D

5. ADDITIONAL HEATING EFFECTS AND ITER

Experiments on COMPASS-D showed that ECRH resonant near q=2 can remove error field locked modes [11]. Another possibility to avoid locked modes is to raise the error field threshold using neutral beam injection to spin the plasma. Simple calculations [12] indicate that 5 to 10 MW of tangential counter-injected (most efficient direction since this adds to the intrinsic Ohmic rotation) 1 MeV beams in ITER would increase the error field threshold by about a factor of 5 (slightly higher power co-injected beams - the present ITER design basis - would have the same effect).

The increase in threshold with NBI has been demonstrated experimentally on DIII-D in L-mode [13], although in higher β regimes on DIII-D, the threshold decreased as the β-limit was approached. Increases were also seen on JET, originally in field ripple experiments [14] and in more recent dedicated scans, as shown in Fig 6, where 2MW of co-injected neutral beam doubled thresholds (higher beam powers preventing penetration with the saddle coil fields). This contrasted with ICRF heating on JET (which has a much weaker effect on rotation), where even at higher β's ($\beta_p\sim1$ for 10MW heating), thresholds are similar to Ohmic values, though the details of this are not fully understood. Transition to H-mode also seems to have little effect, indicating that error fields are still a potential problem for ITER in the early heating phase, until density is raised.

6. CORRECTION OF INTRINSIC ERROR FIELD

6.1. Measurement of intrinsic error field

Given that error fields can impose operational limits, detection and correction methods need to be examined. Both COMPASS-C and DIII-D used in-situ coil arrays to determine error fields. In the case of DIII-D, a coil array temporarily installed within the vacuum vessel was used to map-out PF coil errors [9]; the contribution to the error field spectrum from the TF coils is determined by multivariate

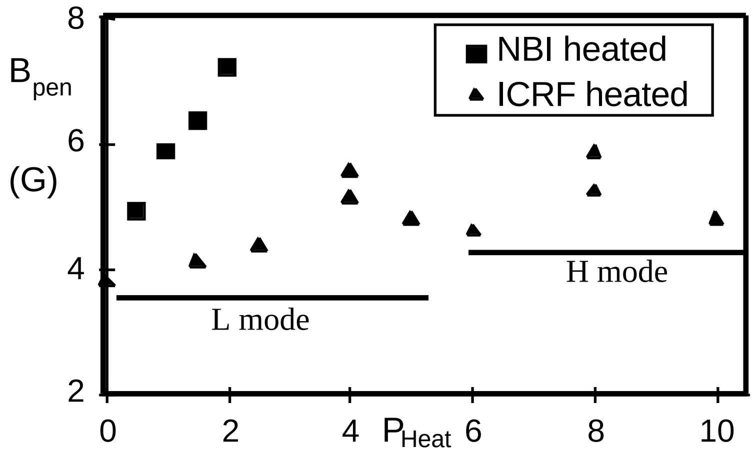

Fig 6: Effect of neutral beams, ICRF and H-mode transition on error field thresholds on JET.

fits. In COMPASS-D's case, an array permanently installed outside the vacuum vessel was used to minimise errors during construction [15]. JET experiments have determined the error field (though not its detailed sideband structure), with a plasma-based detection method, by making measurements with a range of applied error field phases [16].

Measurement of the 'as-built' ITER error fields to the required precision with an in-situ coil array appears technically feasible, but will require both a relatively elaborate in-torus apparatus and scheduling of the measurement when the toroidal and poloidal field coil systems can be energised to nearly full levels (although substantial information can be gained from much lower levels of energisation). Development of an efficient plasma-based error field correction assessment means or procedure would obviate what otherwise appears to be a significant cost and schedule time requirement in the ITER device commissioning sequence. A possible mechanism may be to optimise plasma rotation by varying correction - this has yet to be demonstrated experimentally, although rotating modes on TEXT-U were seen to speed up with intrinsic error correction [17].

6.2. Magnetic correction experiments

Early COMPASS-D experiments showed [11] that correction without detailed matching between the spectrum of the error field and correction coil could prevent or remove modes. However, density ramp-down experiments on DIII-D and JET have shown that for optimal correction it is necessary to go beyond a system that can correct just one harmonic, as expected from the non-zero viscous coupling coefficients in Eqs (4) and (5). On DIII-D, where correction is routinely used, optimal correction with just the C-coil allows critical density for locked modes to be halved and with use of the n=1 coil as well, further reduction is possible. In density ramp-down experiments on JET, choosing a saddle coil field with near-optimal phase and amplitude to cancel the intrinsic error accesses 35% lower densities than with no correction, indicating the need for more degrees of freedom in the correction if further reductions are required. Also on JET, the application of saddle field to correct out intrinsic error *after* formation of a locked mode caused the mode to spin up and decay away in 8 out of 10 cases. Without this correction the mode stayed locked in 84% of 25 cases and led to a disruption as plasma current was ramped down.

6.3. ITER magnetic correction system

An intrinsic error correction system is presently being designed for ITER. This is designed to reduce the combined quantity (based on an earlier viscous coupling fit to DIII-D data [4]),

$$B_{pen} / B_T = \sqrt{(B_{2,1}^2 + 0.8\, B_{3,1}^2 + 0.2\, B_{1,1}^2)} \,/\, B_T \;\leq\; 2 \times 10^{-5} \equiv 2 \text{ units} \qquad (7)$$

Sophisticated probability analyses [18] of the expected errors from PF and TF coils (for example see Fig 7) suggest likely errors ~10^{-4} in terms of this quantity. New Monte Carlo studies have shown [19] that if more stringent coil misalignment tolerances are demanded [20], based on the estimated minimum possible misalignments, then PF and TF errors can be reduced somewhat, but this involves extra costs, and there will still be additional sources of error from the test blanket and the NB injector

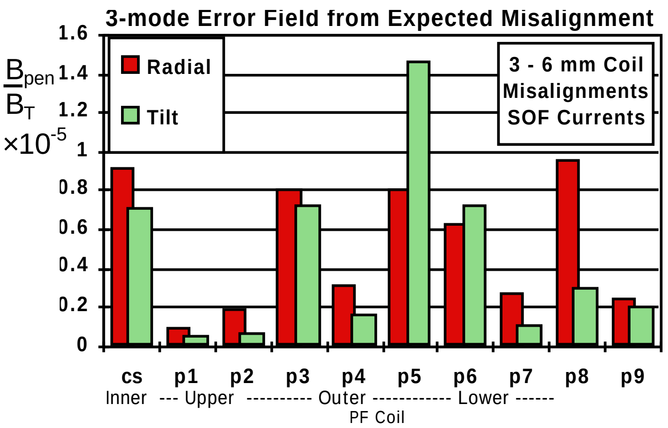

Fig 7: Predicted Errors of ITER PF misalignments

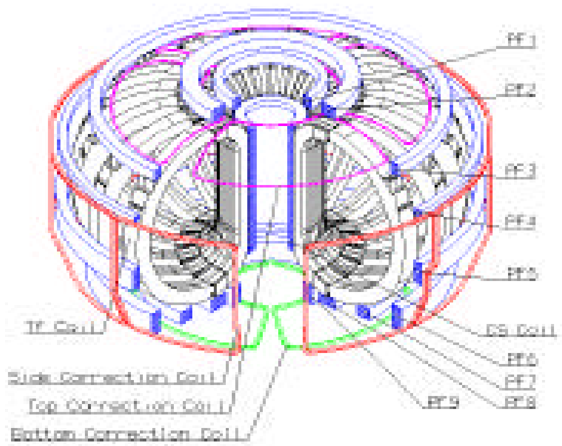

Fig 8: ITER FDR correction system

shielding. The studies show that the dominant contributions to B_{pen} are likely to be (1,1) components from the TF coils, with PF and TF contributing to (2,1) field equally [19].

These predictions for uncorrected intrinsic error levels are comparable with the predicted level of error field sensitivity for ITER ($B_{pen}/B_T \sim 1.25\times10^{-4}$ based on JET SND plasmas). Following earlier work indicating strong scaling and sideband harmonic effects, a conservative approach was adopted for design of the correction system. The resulting system, shown in Fig 8, uses 3 independent sets of coils each containing 2 independent currents, to allow correction of (1,1), (2,1) and (3,1) components simultaneously. This is capable of reducing normalised errors of 12×10^{-5} down to 2×10^{-5}. The approach represents a prudent option given the uncertainties in scaling (highlighted in particular by the COMPASS-D scaling discrepancies), as well as the statistical errors in scaling measurements and predicted intrinsic error. Given the limited benefit of single harmonic correction (as discussed for JET and DIII-D in section 6.2), multiple harmonic correction appears highly desirable.

7. CONCLUSIONS

Error field modes have been demonstrated to be a significant concern for next generation devices such as ITER. Experiments on JET, COMPASS-D and DIII-D have examined the scalings of error field sensitivity with a wide range of parameters. The best present extrapolations to ITER indicate a threshold to induce locked modes in low-density Ohmic plasmas of $B_{r2,1}/B_T\sim10^{-4}$ in terms of equivalent pure (2,1) field. This is comparable with the levels of intrinsic error expected to arise in the design and construction of ITER. Several error field correction methods (correction coils, ECRH and NBI rotation) have been shown to be experimentally viable in present tokamaks. Given the remaining degree of uncertainty in the size scaling, and other uncertainties, some level of error field correction is important, with a system capable of removing more than one harmonic desirable. Thus a three harmonic correction system has been designed, capable of reducing errors to $B_{r2,1}/B_T\sim2\times10^{-5}$.

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REFERENCES:

[1] HENDER T C et al, Nucl Fusion **28** (1992) 2091.
[2] LAHAYE R J et al, Phys Fluids **B4** (1992) 2098.
[3] FISHPOOL G and HAYNES P S, Nucl Fusion **34** (1994) 109.
[4] SCOVILLE J T et al, proc’s 37th APS (1996) Louisville, and LAHAYE R J et al, General Atomics report GA-A22468.
[5] FITZPATRICK R and HENDER T C, Phys Fluids **B3** (1991) 644.
[6] JENSEN T H, Phys Fluids **B3** (1991) 1650.
[7] FITZPATRICK R, Nucl Fusion **33** (1993) 1049.
[8] FITZPATRICK R and HENDER T C, Phys Plas **2** (1994) 3337.
[9] LAHAYE R J and SCOVILLE J T, Rev Sci Instrum **62** (1991) 2146
[10] CONNOR J W and TAYLOR J B, Nucl Fus **17** (1977) 1047.
[11] CAROLAN P G et al, Contr Fus and Plas Phys **18B** (1994) 214.
[12] LAHAYE R J, Gen Atomics Report GA-A22468 (1997).
[13] LAHAYE R J et al, Nucl Fus **32** (1992) 2119.
[14] SANTAGIUSTINA A et al, in Contr Fus and Plas Phys, proc’s 22nd EPS (1995) 461.
[15] CROSSLAND R T et al, Fusion Technology (proc’s 16th Sym London), Oxford (1991) 632.
[16] BUTTERY R J et al, proc’s 24th EPS (1997) P1 265.
[17] CRAVEN WA and WOOTTON A J, Nucl Fus **38** (1998) 585.
[18] GRIBOV Y, proc’s 24th EPS (1997) 977.
[19] LEUER J A et al, ‘A systematic approach to error field analysis in ITER’, Proceedings of 20th SOFT conference (1998) 513.
[20] SBORCHIA C et al, ‘Analysis of tolerances & error fields for the ITER magnet system’, Proceedings of 20th SOFT conference (1998).