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ABSTRACT

Otherwise stable DIII–D discharges can become nonlinearly unstable to locked modes and disrupt when subjected to resonant $m = 2$, $n = 1$ error field caused by irregular poloidal field coils, i.e. intrinsic field errors. Instability is observed in DIII–D when the magnitude of the radial component of the $m = 2$, $n = 1$ error field with respect to the toroidal field is B_{r21}/B_T of about 1.7×10^{-4}. The locked modes triggered by an external error field are aligned with the static error field and the plasma fluid rotation ceases as a result of the growth of the mode. The triggered locked modes are the precursors of the subsequent plasma disruption. The use of an "$n = 1$ coil" to partially cancel intrinsic errors, or to increase them, results in a significantly expanded, or reduced, stable operating parameter space. Precise error field measurements have allowed the design of an improved correction coil for DIII–D, the "C-coil", which could further cancel error fields and help to avoid disruptive locked modes.

INTRODUCTION

Locked modes are observed in many tokamaks [1–5]. The locked mode is typically a nearly purely growing non-axisymmetric magnetic field perturbation, *i.e.* non-rotating, with poloidal mode $m \approx 2$ and toroidal mode $n = 1$. Because of the mode's low frequency, detection requires combinations of magnetic loops whose signals are integrated and distinguished from the background equilibrium magnetic field. When mode rotation ceases, the locking tends to occur with the radial field aligned at the same location; this location depends on the externally applied error field [4].

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Characteristics of discharges with locked modes include reduced confinement, no soft x–ray sawteeth, loss or prevention of the H–mode, divertor target hot spots and cessation of the plasma fluid rotation at $q = 2$. In DIII–D, most disruptions are preceded by a locked mode; experimentally, reducing the $m = 2$, $n = 1$ error field allows routine operation in a wider stable parameter space without locked modes and disruptions.

ERROR FIELDS IN DIII–D

Careful measurements of DIII–D error fields indicate that the dominant sources of $m \approx 2$, $n = 1$ error fields arise from non-concentric outer poloidal field (F) coils which produce the vertical field [6]. Typically, the intrinsic relative error field from the F-coil currents for a single-null divertor (SND) discharge with q at the 95% flux surface of 3.6 in DIII–D is $B_{r21}/B_T|_a \approx 1.7 \times 10^{-4}$ where B_{r21} is the $m = 2$, $n = 1$ helical radial error field at minor radius $a = 0.68\,\mathrm{m}$ and B_T is the toroidal field.

THE $n = 1$ COIL

To partially cancel or increase the intrinsic $n = 1$ error fields, the "$n = 1$ coil" is used on DIII–D. The $n = 1$ coil is a circular, 56 turn coil placed non-concentrically on top of DIII–D as shown in Fig. 1; also

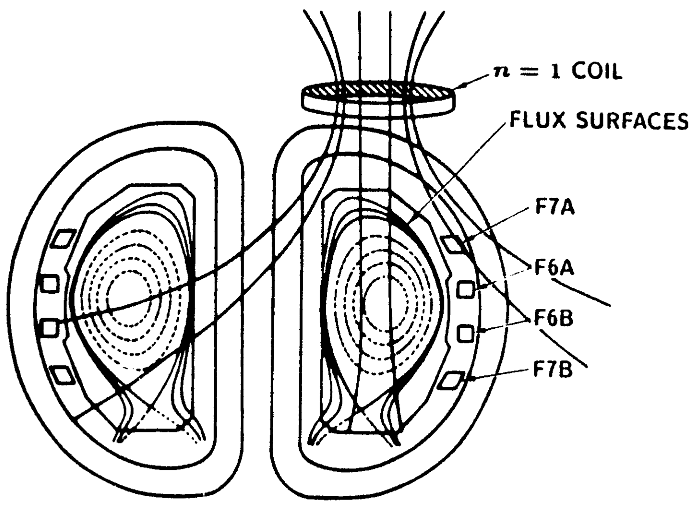

Fig. 1. Location of the $n = 1$ coil; also shown are the outer F-coils (F7A, etc.) that make the vertical field.

shown are the outer F-coils, F7A, etc., which make most of the error field. The $n = 1$ coil makes predominantly $n = 1$, $m = 1$ and 2 components. With the appropriate current, the net $m = 2$, $n = 1$ error field can be substantially reduced or increased. The $n = 1$ coil is now routinely used in DIII–D to reduce error fields; the coil current is controlled by a feedback algorithm which depends linearly on the currents in F-coils, F7A, F6A, and F6B based on the measured error fields from these coils. To minimize the $m = 2$, $n = 1$ error field, the current in the $n = 1$ coil is automatically adjusted to compensate for changes in plasma current, β, discharge shape, etc.

LOW DENSITY LOCKED MODES DRIVEN NON-LINEARLY UNSTABLE BY $m = 2$, $n = 1$ ERROR FIELD

Locked modes occur at both low and high density, at low q, at high beta or when bursts of impurities enter a discharge. Low density locked modes have a reproducible critical density that depends on the magnitude of the error field; reducing the density $\bar{n}$ at fixed $B_{r\,21}$ or increasing $B_{r\,21}$ at fixed $\bar{n}$ leads to a locked mode under similar conditions [4]. Low density, ohmic target plasmas (without locked modes) are important for the S–mode (TFTR), the hot-ion-mode (DIII–D), the VH–mode (DIII–D) and for rf current drive experiments.

In DIII–D, reducing the $m = 2$, $n = 1$ error field allows stable operation atlower densities without locked modes and disruptions; the converse is true, as with larger error fields, the stable parameter space is reduced. This is shown in Fig. 2 where the critical low density for locked modes and the magnitude of the $m = 2$, $n = 1$ error field are plotted versus $n = 1$ coil current; for zero current the error field is from intrinsic F-coil irregularities. The stability is non-linear in that for small perturbations discharges are stable and for larger error fields locked modes occur.

THE C-COIL

The $n = 1$ coil is a poor match to the m spectrum of intrinsic error fields; furthermore, with no phase control, the $m = 2$, $n = 1$ error field cannot be completely nulled. Nevertheless, the $n = 1$ coil is useful in avoiding locked modes.

A better matched and phase controllable error field correction coil, "the C-coil," has been designed for DIII–D. The C-coil consists of six sections which encircle the tokamak at the midplane (see Fig. 3). Both

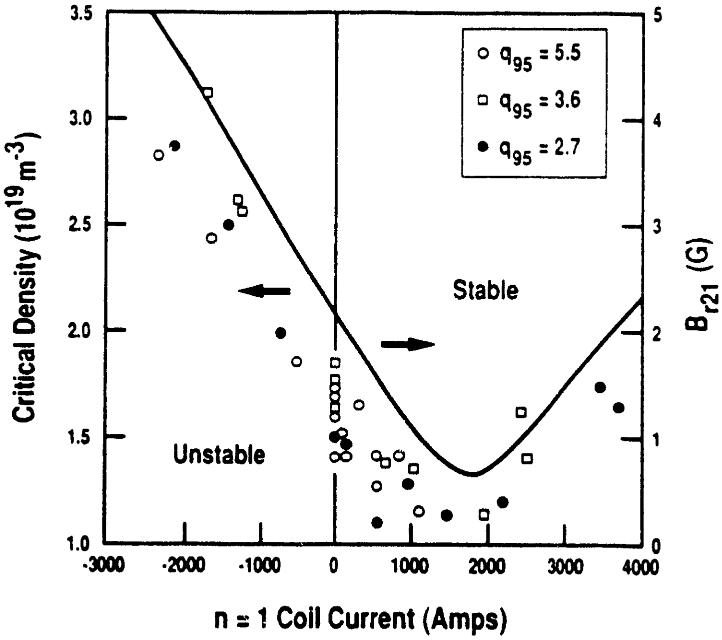

Fig. 2. Critical low density for locked modes and the $m = 2$, $n = 1$ error field versus $n = 1$ coil current; for zero current, the error field is from intrinsic F-coil irregularities. Discharges are of plasma current 0.95 MA, single-null divertor, ohmically-heated with $B_T = 1.0$ T for $q_{95} = 2.7$, $B_T = 1.3$ T for $q_{95} = 3.6$ and $B_T = 2.0$ T for $q_{95} = 5.5$.

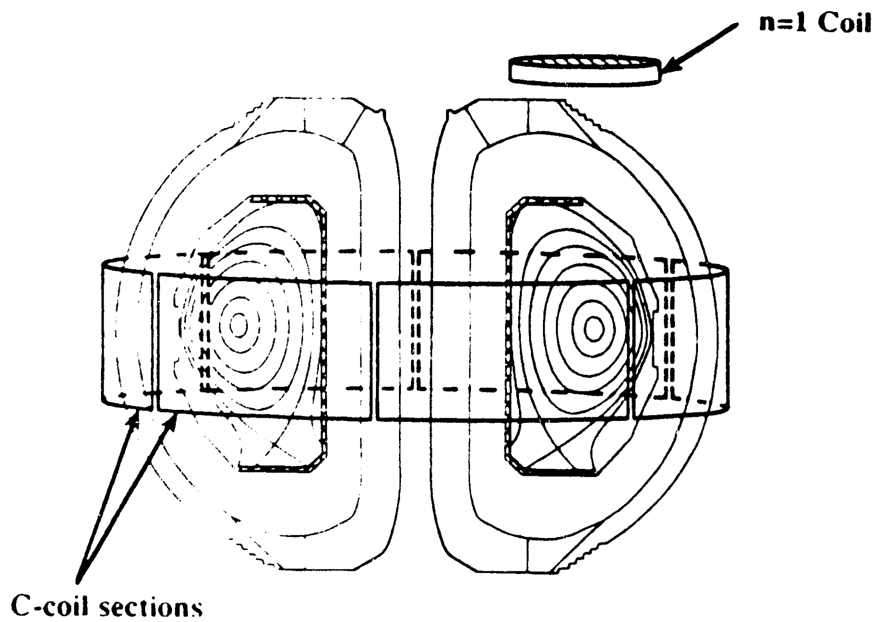

Fig. 3. Location of the six C-coil sections which are to encircle the tokamak at the midplane; the C-coil is tilted to better show the winding.

the $n = 1$ phase and amplitude can be adjusted by energizing opposite pairs with equal and opposite current (for odd n) and adjusting the current balance between the three pairs. Fourier analysis of the $n = 1$, m spectrum for SND discharge #65489 ($B_T = 1.3$ T, $q_{95} = 3.6$) is shown in Fig. 4: intrinsic F-coil errors only, corrected by the $n = 1$ coil ($m = 2$, $n = 1$ mode minimized) and corrected by the C-coil ($m = 2$, $n = 1$ mode nulled). The $n = 1$ coil partially cancels the $m = 2$, $n = 1$ component at the expense of an increased $m = 1$, $n = 1$ mode and little effect on the resonant $m = 3$, $n = 1$ error field. The C-coil will null the $m = 2$, $n = 1$ error field and substantially reduce the other resonant modes.

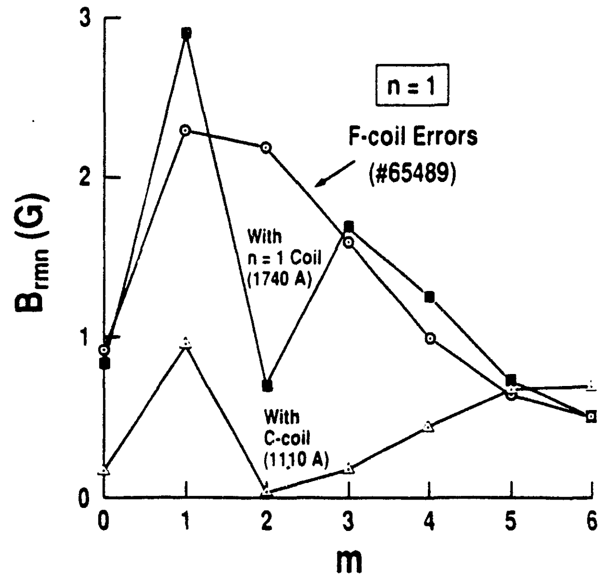

Fig. 4. Fourier analysis of the $n = 1$ low m field errors for a typical 1.3 T, single-null divertor discharge in DIII–D: intrinsic F-coil errors only, corrected by the $n = 1$ coil at 1740 A and corrected by the C-coil at 1110 A.

CONCLUSIONS AND FUTURE WORK

In DIII–D, locked modes precede disruptions and must be avoided for good operations. Otherwise stable discharges are driven non-linearly unstable by resonant, low m, $n = 1$ error fields. The dominant source of intrinsic $n = 1$ error fields in DIII–D is non-concentric outer poloidal field coils. Using an $n = 1$ coil to partially correct the $m = 2$, $n = 1$ error field increases the locked-mode-free operating parameter space and helps avoid disruptions.

A new, better correction coil, the C-coil has been designed. The C-coil is more flexible and is a better match to the intrinsic error field spectrum; it could help to further increase the stable operating parameter space and test the need for minimizing error fields in ITER. Combined with digital plasma control this could provide a new tool for ITER-relevant disruption avoidance investigations on DIII–D.

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