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ABSTRACT

Non-axisymmetric (error) fields in tokamaks lead to a number of instabilities including so-called locked modes [1] and resistive wall modes (RWM) [2] and subsequent loss of confinement. They can also cause errors in magnetic measurements made by point probes near the plasma edge, error in measurements made by magnetic field sensitive diagnostics, and they violate the assumption of axisymmetry in the analysis of data. Most notably, the sources of these error fields include shifts and tilts in the coil positions from ideal, coil leads, and nearby ferromagnetic materials excited by the coils. New measurements have been made of the n=1 coil-related field errors in the DIII–D plasma chamber. These measurements indicate that the errors due to the plasma shaping coil system are smaller than previously reported and no additional sources of anomalous fields were identified. Thus they fail to support the suggestion of an additional significant error field suggested by locked mode and RWM experiments.

1. INTRODUCTION

Tokamaks and similar magnetic confinement devices depend on axisymmetric external magnetic fields for plasma confinement, and small non-axisymmetric contributions to these fields (error fields) can cause serious instabilities and loss of confinement. Since very small error fields ($\delta B/B_T \sim 10^{-4}$) can cause troublesome modes, small errors in the positioning of coils or owing to the coil leads or nearby magnetic objects can have serious consequences. As a result, careful attention must be paid to the positioning of coils in the design and construction of new devices, and additional specialized “correction coils” may be needed to correct inadvertent field errors. This is of particular concern for fusion reactor-size devices, such as the proposed ITER and FIRE, where it appears necessary to limit field errors to even smaller values [3].

In this paper, we report the preliminary results of measurements of the coil-related error fields in DIII–D. These measurements were motivated by inconsistencies between the results of recent experiments and reported error fields from the coil systems. Measurements were made of the m,n = 0,1 fields at R = 1.64 m (near the typical plasma major radius) using an apparatus that was an extension of the apparatus used for previously reported measurements [4]. These are interpreted in terms of small displacements of the coils in the horizontal plane $\boldsymbol{d}$ and tilts $\boldsymbol{\alpha}$ of the coil axis with respect to the apparatus axis.

2. APPARATUS

DIII–D is a non-circular cross-section tokamak with major radius R_0 = 1.66 m, minor half width a = 0.66 m, and maximum elongation of ~2 (Fig. 1) [5]. The toroidal coil system consists of 144 turns in 24 bundles with a maximum current of 126 kA producing a field at R_0 of 2.1 T. There are 18 poloidal field coils (F1A-F9A and F1B-F9B) that shape and position the plasma plus the ohmic heating coil.

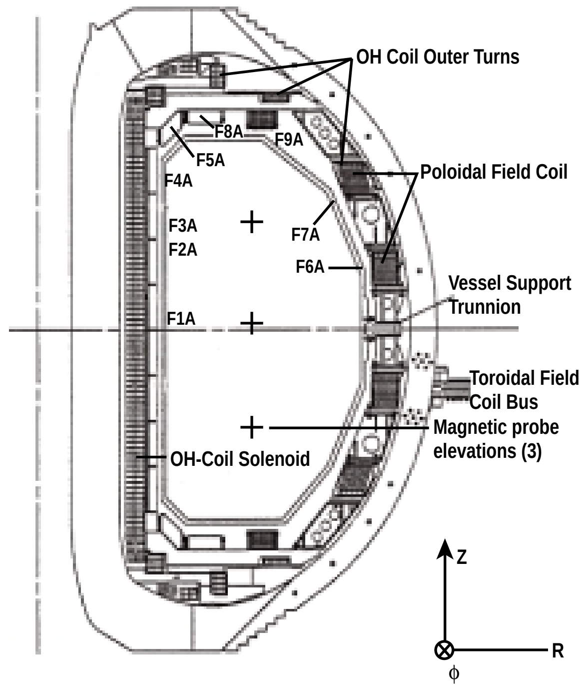

Fig. 1. Cross-sectional view of DIII–D showing coil locations and the radius and elevations at which probe measurements were made.

A number of relatively small ferromagnetic structures are located in the vicinity of the tokamak. These range from a number (15) of 14000 cm^3 shielded enclosures for pyrometers and infrared camera just outside the poloidal shaping coils between F9A and F9B and as near as 20 cm from the outer surface of a poloidal coil to a large shielded room 18 m^3 in volume at R = 6.4 m and z = –4.1 m. Typically, these iron structures have an order of magnitude more impact on these measurements than they do on plasma operation. A large iron structure, the support for the “n=1” coil, was identified and removed during the preparations for these measurements.

The majority of the data reported here was taken using an in-vessel array of inductive probes (NA = 0.8 to 1.6 m^2) measuring the radial, toroidal, and vertical components of the field, B_R, B_ϕ, and B_Z respectively, at eight equally spaced points on the circumference of a circle (Fig. 2). The apparatus is similar to that reported previously [4]. The apparatus was centered on the lower inner vacuum vessel wall. To aid in identifying systematic errors; a) all three components of the field data were used, b) the apparatus was positioned at three different elevations z = –0.742 m, z = +0.044 m, and z = +0.752 m (denoted L, M_0, and U respectively), and c) at z = +0.044 m, the apparatus was rotated by an angle of 65° toroidally (denoted M_{65}).

Data collection was optimized for detecting the relatively small values of each component of B for n ≥ 1 by using the first probe for each field component as the reference probe and wiring the probes to electrically subtract the output of the first probe from that of the other seven probes before integrating and recording the values (see inset Fig. 2). The value of a particular probe

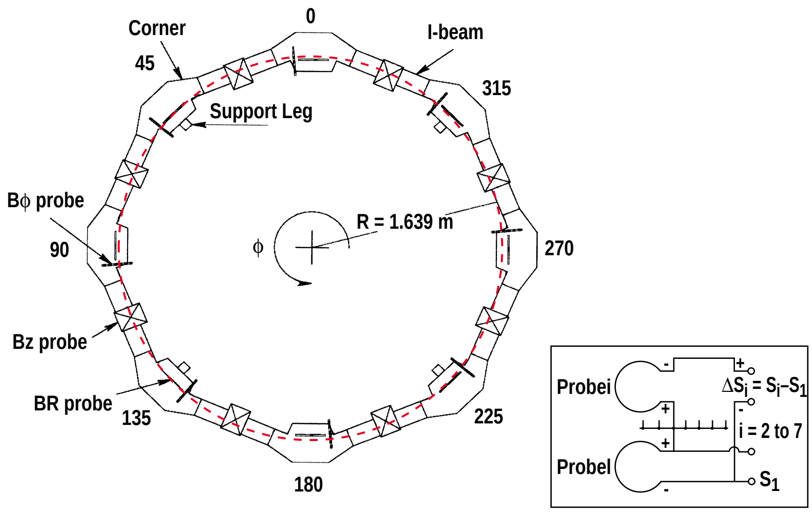

Fig. 2. A simplified top view of the probe apparatus showing the probe locations. The probe electrical wiring scheme is shown inset.

signal for a given coil was determined by averaging over an interval of ~1 s near the end of the coil pulse after the signal had reached steady state. The data set was assembled by pulsing each coil individually. The field shaping coils were operated at ~2000 A, and the toroidal field coil was operated at 20 kA, although on several occasions it was operated at 120 kA (2.1 T). For typical discharges in DIII–D, currents in the outer field shaping coils are as large as 10 kA (at a plasma current of 2.5 MA), while the inner poloidal coil currents are less than 5 kA.

3. ANALYSIS

A typical data set consists of eight toroidally distributed points for each of three field components (statistical variation ~ ±0.1% of B). These data were fit to models of a tilted and shifted coil using two different techniques. The first used a linear expansion for small shifts and tilts of a coil, and it was used to efficiently process the large sets of data. The second technique used one-turn approximations for the coils and transformed them to shifted and tilted positions in order to model the expected fields. It was carried out in a spread sheet, and the best shifted and tilted position to fit the data was calculated using non-linear least square minimization. This technique had the advantage that it was much easier to add features to the model such as the existence of a ferromagnetic dipole, and to do systematic studies. The two models obtained essentially identical answers.

Once the positions of the poloidal coils are determined for each of the four data sets, these data sets are combined into one overall assessment of the relative positions of the coils to a common axis. The poloidal field coils are taken as determining a common three dimensional reference frame. The center of the probe array for the M_0 data set is taken as the origin and the normal to the array plane at this point is taken as defining vertical. The shift and tilt of the axes of the other data sets are then transformed to this single axis using least squares minimization. This results in small corrections to the locations of the apparatus (of the order of 1 mm and 0.04°) for the remaining three data sets.

Estimates of typical errors in $\boldsymbol{d}$ and $\boldsymbol{\alpha}$ are ± 0.8 mm and ± 0.04°, respectively. Here errors in the vector quantities are quoted as one dimension which characterizes a circle around the point in the two dimensional plane. Combining the data sets reduces these errors to ± 0.5 mm and ± 0.03°, respectively.

Model calculations have shown that the additional dispersion in the outer coil data is likely due to the many ferromagnetic objects in the vicinity of the machine. A few such objects impact the effective position determined for a given coil by < 0.5 mm. A study of the data for evidence of a larger unknown iron object that would systematically shift a number of coil positions, identified none. Owing to the large number of small sources, the difficulty in characterizing them, and their relatively small contribution to the positions of the coils, these external dipoles are characterized in aggregate as contributing an additional systematic error of 0.5 mm to $\boldsymbol{d}$ and 0.02 to $\boldsymbol{\alpha}$. This term is added to the rms error to determine the final error in the coil positions (± 1.0 mm and +0.05°).

4. RESULTS

The data for both ***d*** and **α** are summarized in Fig. 3. For each of the four data sets, two separate measurements of the toroidal field center can be made using either $B_{1\phi}$ or B_{1R} data by calculating the point at which the n=1 amplitude would be zero (Fig. 4). Ideally, the result would be the same. The observed difference between the B_{1R}-determined axis and the $B_{1\phi}$-determined axis could be indicative of an error field component in the horizontal plane. However, when the apparatus was rotated 65°, the apparent axis shift also rotates 65°; this is indicative of a systematic error in the apparatus. Since the B_ϕ axis is essentially independent of array rotation, it represents the true axis of the toroidal field. The B_R data are sensitive to first order to small probe misalignments about their vertical axis, resulting in a contribution from the much larger B_T. The absence of a significant transverse error field was verified in a second independent data set. From these two data sets, we determine that the transverse error field is 0 ± 8 G. The magnitude of the toroidal field tilt cannot be separated from a possible n=1 vertical error field component. The value of B_{1z} is ≤20 G, corresponding to a possible tilt of 0.06°.

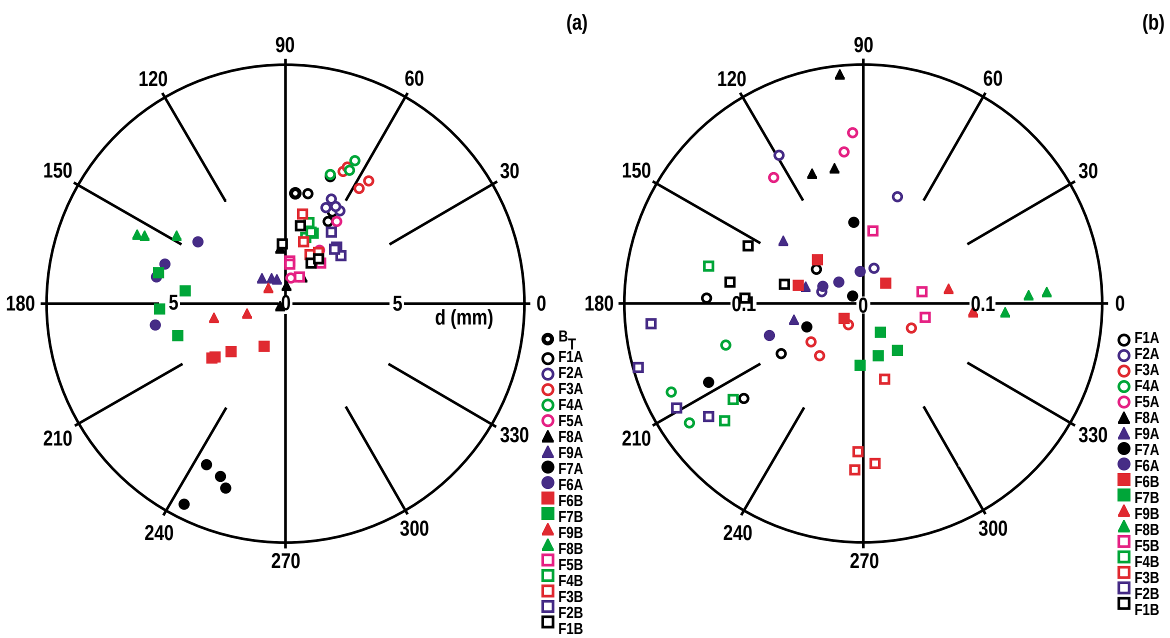

*Fig. 3. Summary of the data for the coil positions showing the data points for each of the four apparatus positions. In several cases, one point for a given coil is deleted because the statistical error is sufficiently poor that it would not contribute to the final location. (a) position **d** in the horizontal plane relative to a common measurement axis. (b) tilt **α** with respect to a common vertical axis.*

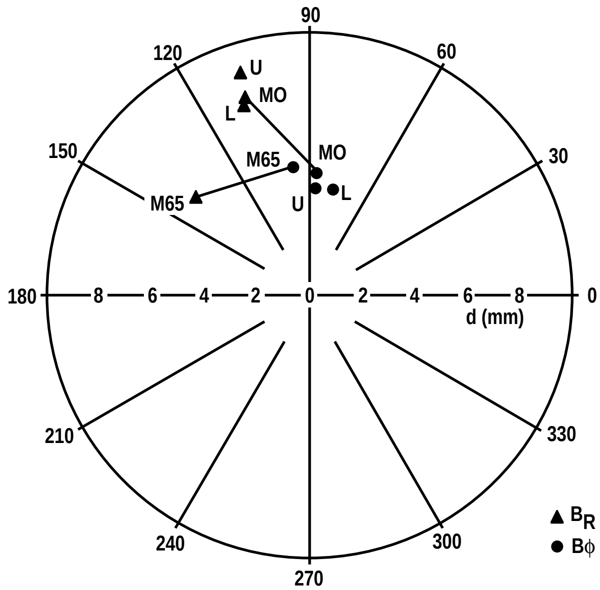

Fig. 4. The location of the axis of the toroidal field coil with respect to the axis defined by the poloidal field coil system as seen in Fig. 3.

The ohmic heating coil is also a potential source of error fields. The n=1 fields produced by the ohmic coil are as much as 6 G for a full ohmic coil current of 137 kA (at the very end of the discharge). The complex ohmic coil was modeled in detail with the result that by putting the major components in their known positions with respect to the plasma shaping coils and toroidal coil, the error fields could readily be accounted for.

The possibility that the interaction of the poloidal and toroidal coil systems was producing a significant source of error was also investigated. The additional n=1 error fields measured during simultaneous high current operation of the toroidal coil and F6A, F7A, F6B, and F7B were found to be less than 2 ± 2 G.

5. DISCUSSION AND SUMMARY

New results have been obtained for the magnetic field errors and relative positions of the DIII–D coil systems, plasma chamber, and nearby ferromagnetic objects. Care was taken to eliminate systematic error and to provide redundant data. The coil axes are generally co-linear to within ±5 mm but one coil (F7A) is displaced by 12 mm from the toroidal field coil axis. The axes of the coils are parallel to within ± 0.2°. These data indicate that the coils are closer to a common center than those previously reported [4]. No significant contribution from the toroidal field coil was observed, and there were no additional contributions from the interaction of the poloidal and toroidal coils.

A carefully designed apparatus that can be realigned *in situ* is important for making measurements with adequate precision as are enough systematic studies to evaluate and understand the nature of the errors. Iron objects in the vicinity of the tokamak were found to affect the measurements more so than they affect plasma operations.

These measurements do not support the presence of an additional large error field in the DIII–D plasma chamber associated with either the coils, especially the toroidal field coil, or a ferromagnetic object as suggested in Ref. [1] and [2]. The strong toroidal field dependent term suggested in Ref. [3] was not found; this finding has the potential of impacting the scaling relationship found therein for the locked mode density n_{LM}.

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