Magnetic probe response function calibrations for plasma equilibrium reconstructions of CDX-U

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A novel response function calibration technique has been developed to account for time-dependent nonaxisymmetric eddy currents near magnetic sensors in toroidal magnetic confinement devices. The response function technique provides a means to cross calibrate against all available external field coil systems to calculate the absolute sensitivity of each magnetic field sensor, even when induced eddy currents are present in the vacuum vessel wall. The response function information derived in the calibration process can be used in equilibrium reconstructions to separate plasma signals from signals due to externally produced eddy currents at magnetic field sensor locations, without invoking localized wall current distribution details. The response function technique was used for the first ever equilibrium reconstructions of spherical torus plasmas, when applied to the Current Drive Experiment-Upgrade (CDX-U) device. In conjunction with the equilibrium and stability code (ESC), equilibria were obtained for recent CDX-U experiments with lithium plasma-facing components. A description of the CDX-U magnetic sensor configuration and the response function calibration technique will be presented along with examples of resulting plasma equilibrium for CDX-U lithium wall operations.
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INTRODUCTION

The reconstruction of plasma equilibrium in the presence of transient nonaxisymmetric currents can be a challenge, especially for short duration plasmas such as found in the Current Drive Experiment-Upgrade (CDX-U).

The CDX-U facility is capable of Ohmically driven spherical plasma operations in toroidal fields up to 2.3 kG. The achievable plasma duration is about 20 ms with a maximum plasma current of about 90 kA. In all of the experiments described in this article, deuterium was the working gas.

Most recently CDX-U has become involved in studies of plasma-edge interactions, particularly with the development of lithium coated plasma-facing components (PFCs). A series of experiments using a large area lithium-filled limiter tray has resulted in observations of increased plasma performance as measured by increases in peak plasma current which are correlated with measurements of a reduction in oxygen impurities and recycling at the lithium-filled tray surface.[1]

As part of the effort to further quantify the observed performance enhancements, work has been underway to build a set of well-calibrated magnetic diagnostics to be used in calculating CDX-U plasma equilibrium reconstructions. This article focuses on the new technique used to absolutely calibrate the CDX-U Mirnov coil, and flux loop arrays which provide measurements of vacuum magnetic field components used in constraining the location of the plasma boundary in equilibrium reconstructions.

CDX-U MAGNETIC DIAGNOSTICS

Mirnov coils are small multiturn coils used to measure local time changing magnetic fields.[2] CDX-U has a total of 27 Mirnov coils, grouped into four sensor sets. Each individual sensor has 25 turns wound in two layers on a 1/8 in. core. The four sensor sets are arranged to provide full coverage of the poloidal field outside the plasma boundary, but because of port constraints the sets could not be located at a single toroidal location.

A calibration estimate based on the assumed sensor geometry is not adequate for absolute calibration of the Mirnov coils due to the potential internal variations between sensors. An *in situ* calibration of Mirnov coils is typically done by pulsing of individual poloidal field (PF) coils and comparing measured signals to expected signal using Green's function calculations of the isolated PF coil and sensor system. Such a calibration of the CDX-U Mirnov coils is complicated by the close proximity to port openings in the conductive CDX-U vessel and limitations in the capacitor bank driven PF coil current wave forms. As a result, the Mirnov coils are sensitive to eddy currents generated in the conductive wall structures, including nonaxisymmetric eddy currents around nearby port openings.

CDX-U is also equipped with a set of poloidal flux loops embedded in the center stack as well as a pair of flux loops along the upper and lower outer corners of the vessel wall located inside the vacuum vessel. Each flux loop consists of a single turn wound toroidally. Flux loops are only sensitive to the lowest order axisymmetric component of eddy currents. Because these loops are single-turn structures, a simple analytic estimate of their sensitivity should agree quite well with any *in situ* calibration technique.

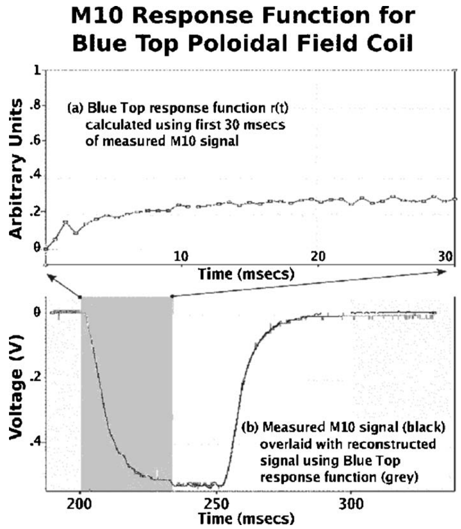

FIG. 1. (a) Response function for the M10 sensor and blue top PF coil pairing. (b) Depiction of the M10 measured signal (black) compared against the reconstructed signal using the blue top response function (gray). The shaded region indicates the 30 ms time window used to calculate the response function.

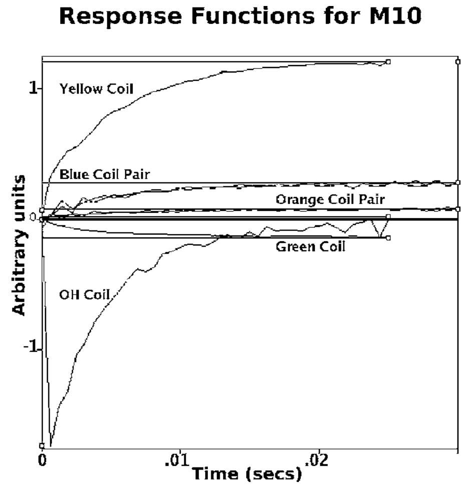

FIG. 2. Calculated response functions for M10 sensor and each CDX-U PF coil system. All response functions reach asymptotic values within 20 ms. The M10 sensor is most sensitive to the CDX-U yellow and blue PF coils as can be seen from the relatively large asymptotic response function values associated with these PF coil systems.

RESPONSE FUNCTION CALIBRATION

Axisymmetric eddy currents in conductive structures are traditionally simulated in tokamak environments by modeling these structures as a composition of small resistive elements. Simulations which could account for nonaxisymmetric eddy current contributions would require a detailed three-dimensional (3D) model of the conductive structures which can be difficult to accurately describe and computationally expensive to simulate. The new analytic response function approach avoids modeling the conductive structures altogether. Instead, the signal contributions of all induced eddy currents are captured in a matrix of time-dependent response function.[3]

For a given PF coil current $I(t)$, which produces a voltage signal, $V(t)$, in a specified Mirnov coil, a response function $r(t-\tau)$ can be defined such that

$$V(t) = \int_0^t r(t-\tau)\frac{dI(\tau)}{d\tau}d\tau, \tag{1}$$

and the magnetic field at the sensor, $B(t)$, can be found from $V(t)$ by using the physical calibration factor C:

$$B(t) = CV(t). \tag{2}$$

The response functions are determined from a series of calibration pulses of individual PF coil systems. Sensor signals are recorded and a numerical representation of the response function is calculated over a finite set of time points. The calibration PF coil current wave form need only to be sufficiently long compared to the decay time of eddy currents in the structures. Once the response function for a PF coil and sensor pair has been calculated, it can be reused to accurately simulate the measured sensor signal due to a range of PF current wave forms of varying shapes.

Figure 1 illustrates the calculation of the response function for a Mirnov coil, M10, near the midplane along the CDX-U center stack and a single PF coil system, designated as the blue top coil on CDX-U. The response function is calculated using the first 30 ms of available PF coil current data. The simulated sensor response agrees quite well with the measured signal, even for times not used in the response function calculation.

At the asymptotic limit, when the response function reaches a nearly constant value, the expected magnetic field $B|_\infty$ can be approximated with the time-independent Green's function value for an isolated current-sensor pair geometry G such that

$$B|_\infty = CV|_\infty = Cr|_\infty I_\infty = GI|_\infty, \tag{3}$$

and C can now be expressed as

$$C = \frac{G}{r|_\infty}. \tag{4}$$

In the case of the blue top coil and M10 sensor pairing, the calculated calibration factor for the M10 sensor is 1.01 T/V.

There exists a unique response function for each of the M PF coil and N sensor (Mirnov coil or flux loop) pairings, resulting in M by N equations to calculate N calibration factors providing a means of cross calibration. The cross-calibration information can be used as an error estimate of individual sensor calibrations and can also be used to optimize the modeled PF coil and sensor placement. Figure 2 depicts the response functions for the M10 sensor and each of the seven independently controlled CDX-U PF coil systems. The average calibration factor is 1.029 T/V with a 5%

TABLE I. Summary of plasma parameters derived from the ESC equilibrium reconstructions for CDX-U plasma discharge 0818051234 at the time of peak plasma current.

I_{plasma}	69 kA	$Area_{plasma}$	0.178 m^2
Major radius (R_0)	0.349 m	Minor radius (a)	0.211 m
$W_{kinetic}$	129 J	$W_{magnetic}$	313 J

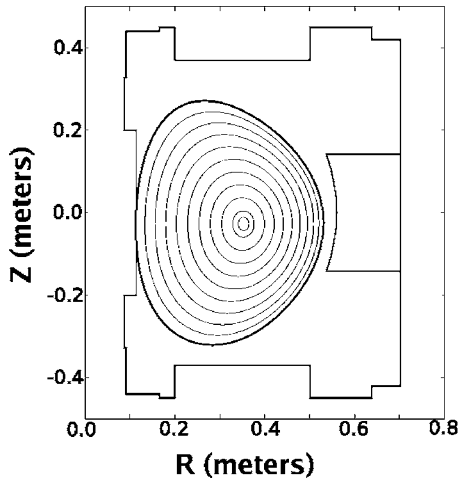

FIG. 3. Depiction of CDX-U plasma equilibrium surfaces for plasma discharge 0818051234, with emphasis on the last closed flux surface.

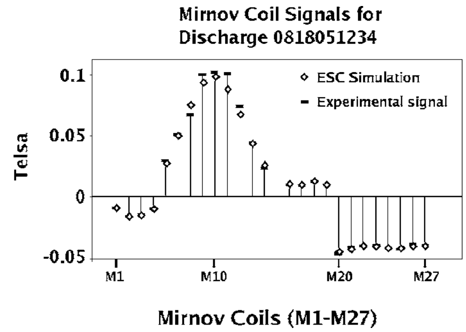

FIG. 4. Comparison of experimentally measured magnetic field to the ESC plasma equilibrium simulated magnetic field at the CDX-U Mirnov coil set.

error. A similar process was repeated for all Mirnov coils and flux loop diagnostics to determine the average calibration and associated error for each sensor.

CDX-U EQUILIBRIUM RECONSTRUCTIONS

The absolute calibration of the Mirnov and flux loops using the response function technique made it possible to reconstruct the first ever free boundary constrained CDX-U plasma equilibrium using the equilibrium and stability code (ESC).[4]

Table I summarizes equilibrium plasma parameters for the CDX-U plasma discharge 0818051234 at the time of peak plasma current. This discharge was part of an experimental campaign investigating the effects of large area lithium wall coatings on CDX-U plasma performance.

Figure 3 shows the ESC calculated plasma boundary and flux surface contours for CDX-U plasma discharge 0818051234 at the time of peak plasma current. The simulated Mirnov coil signals agree very well with the measured values (Fig. 4).

DISCUSSION AND FUTURE WORK

For the first time in the equilibrium reconstruction of spherical tokamak plasmas, an *in situ* calibration of magnetic diagnostics was implemented, based on the response function approach. This technique accounts for the nonaxisymmetric eddy currents present in the CDX-U vacuum vessel. The response functions encode the time history of eddy current contribution to the sensor signal, without requiring a detailed model of the conductive structures. The calibration process utilizes the pulsing of individual PF coils so that the analytic response function for each PF coil and sensor pairing can be recorded for cross-calibration purposes. The asymptotic value of the response function is used to derive the physical calibration factor for each sensor. The absolute calibration of the Mirnov and flux loop sensors made it possible to calculate the first ever plasma equilibrium reconstructions of the CDX-U plasmas.

Work is underway to incorporate the response function analysis from the sensor calibration into the ESC algorithm as an added constraint for placement of eddy currents in the conductive wall structures.

ACKNOWLEDGMENT

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