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Diamagnetic measurements in the STOR-M tokamak by a flux loop system exterior to the vacuum vessel

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Diamagnetic measurements of poloidal beta have been performed in the STOR-M tokamak by a flux loop placed exterior to the vacuum chamber with compensation for the vacuum toroidal field using a nonenclosing coplanar coil, and vibrational compensation from auxiliary coils. It was found that in STOR-M conditions (20% toroidal magnetic field decay over discharge) there is significant influence on the diamagnetic flux measurements from strong residual signals, presumably from image currents being induced by the toroidal field coils, requiring further compensation. A blank (nonplasma) shot is used specifically to eliminate the residual component which is not proportional to the toroidal magnetic field. Data from normal Ohmic discharge operation is presented and calculations of poloidal beta from coil data ($\beta_\theta \sim 0.5$) is found to be in reasonable agreement with the values of poloidal beta obtained from measurements of electron density and Spitzer temperature with neoclassical corrections for trapped electrons. Contributions present in the blank shot (residual) signal and the limitations of this method are discussed. © *2009 American Institute of Physics.* [DOI: 10.1063/1.3126526]

I. INTRODUCTION

It is well known that equilibrium exists between magnetic and kinetic pressures in magnetically confined plasmas.[1,2] The diamagnetic flux arises due to the diamagnetic current. This current acts so as to reduce the externally applied magnetic field, and by definition is diamagnetic. Paramagnetism in a tokamak also occurs through "self-transformer" action. The net change in toroidal flux $\Delta\Phi$ is proportional to $1-\beta_\theta$ where β_θ is the poloidal beta factor. Although diamagnetic measurements have long been performed, the research in this field is still very active. Recent publications focus on continual improvement of this challenging diagnostics,[3–5] as well as its application to plasma feedback controls.[6,7]

Diamagnetic measurements allow the determination of global plasma quantities such as the total kinetic energy in the plasma without the need for separate measurements of plasma temperature and density profiles. A relatively simple method has been implemented for the STOR-M tokamak ($R=0.45$ m, $a=0.125$ m, and $I_p=20$ kA). Limitations on space and choice of mounting location, port availability, and the high magnitude of structural vibrations are special challenges faced by small tokamak researchers during the design and implementation of such diagnostics. As well, STOR-M has a nonconstant (drooping) magnetic field during discharges, presenting further challenges in diagnostic design. The magnetic field decreases by about 20% over the plasma discharge duration of approximately 50 ms. For example, these limitations exclude the possibility performing diamagnetic measurements using the differential technique[6] due to size restrictions inside the vacuum chamber, and methods requiring constant toroidal field (TF) current, such as filtering TF Rogowski signals.[8] Ultimately, an externally mounted compensated coil with use of blank (nonplasma) shot data was selected. It is important to note that this blank shot is not only for the removal of the TF field or for error estimation,[9] but also for the direct removal of strong residual signals in the compensated diamagnetic coil signal. Toroidal current breaks prevent the formation of image currents in the chamber walls in the toroidal direction. Because there are no poloidal current breaks in STOR-M, poloidal image currents can appear in the chamber walls. The poloidal image current is expected to be composed of a large component which is proportional to TF, and a small residual component which is not proportional to TF. This residual component in the image currents is especially large in STOR-M due to the strongly decaying magnetic field (approximately 20% over the discharge duration). However, this blank residual signal can be stored and subsequently subtracted from the plasma shot. The subtraction of the residual signal in a blank shot is especially important for a small tokamak with small diamagnetic signals.

In the general case, the flux due to diamagnetism of tokamak plasma can be estimated as about 1% of the external toroidal magnetic flux. Therefore, the accuracy of the flux measurement should be better than 1 part in 1000 to ensure a 10% accuracy in the poloidal beta measurement. For small tokamaks such as STOR-M, the accuracy of the flux measurement should be on the order of 0.01% due to the low beta. The 14 bit data acquisition system used to record the coil signals provides about 0.012% accuracy. Magnetic flux introduced by plasma current (e.g., the diamagnetic flux) can be separated from total flux measured (diamagnetic and external TF) using a conventional compensation coil mounted outside the chamber. The toroidal flux produced by

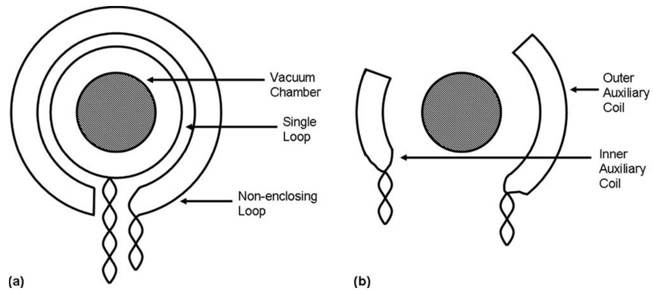

FIG. 1. (a) The primary (single loop) coil and the compensating (nonenclosing) coil located outside the vacuum chamber. (b) The set of auxiliary compensation coils. Although these coils are shown separately for clarity, they are installed coplanar in the same form.

TF coils is measured simultaneously with the plasma produced flux using a loop which does not enclose the plasma or the chamber wall.[10] Figure 1 shows the arrangement of these coils in STOR-M. Thus, the strong magnetic flux introduced by TF coils can be compensated for. However, for external mounting of the diamagnetic coil system, magnetic flux introduced by poloidal currents induced in the tokamak chamber walls cannot be properly compensated for using this set of coils because this flux is located inside the chamber only (neglecting the effects of flux leakage). In the case of constant toroidal magnetic field during the plasma discharge, this induced current is absent, and does not introduce magnetic flux. In the STOR-M tokamak, the toroidal magnetic field decreases by about 20% over the discharge and introduces a significant image current. In order to take this effect into account, a simple experimental technique with nonplasma shot data for additional compensation is adopted. Typically, more complicated systems relying on software[11,12] are used for fully compensating externally mounted coils. It is expected that for a machine with as large a drift of TF as STOR-M has, the so-called error flux or residual flux will be much larger than these machines previously reporting external diamagnetic measurement methods.

In STOR-M, the problem of residual flux due to image currents in the measurements is handled by use of a blank (nonplasma) shot. The fluxes sampled by the enclosing loop $\varphi^b{}_1$ and the non-enclosing loop $\varphi^b{}_2$ during a blank (nonplasma producing shot) are

$$\varphi_1^b = \varphi_{\mathrm{BT1}}^b + \varphi_{\mathrm{err}}^b,$$

$$\varphi_2^b = \varphi_{\mathrm{BT2}}^b,$$

where φ_{BT} is the flux due to the background TF picked up by each coil, φ_{err} is residual flux picked up by the enclosing coil, but not by the nonenclosing coil. This residual flux is likely due to image currents in the chamber walls, due to the presence of the TF coil current. A gain constant α is introduced to set $\varphi_{\mathrm{BT1}}^b = \varphi_{\mathrm{BT2}}^b$, and subtraction of these fluxes yields

$$(\varphi_1^b - \alpha\varphi_2^b) = \varphi_{\mathrm{err}}^b, \tag{1}$$

where the subscript b indicates the shots taken without plasma. The gain constant α is chosen such that the subtraction of the two coils produces an overall small signal φ_{err}^b during the discharge. The gain constant allows the BT flux sampled by the second coil (nonenclosing loop) to eliminate both TF and the proportional image current term from the first coil (single loop). Performing a blank shot allows collection of the residual flux due to residual image current term alone which can then be eliminated from the plasma bearing shots. The fluxes sampled by the enclosing loop $\varphi^p{}_1$, and the nonenclosing loop $\varphi^p{}_2$, during a plasma producing shot are

$$\varphi_1^p = \varphi_{\mathrm{BT1}}^p + \varphi_{\mathrm{err}}^p + \Delta\Phi + \delta\varphi_{\mathrm{ic},\Delta\Phi},$$

$$\varphi_2^p = \varphi_{\mathrm{BT2}}^p,$$

where again, φ_{BT} is the flux due to the TF coils, $\varphi^p{}_{\mathrm{err}}$ is the residual flux appearing due to residual image currents not proportional to the TF coil current, $\Delta\Phi$ is the flux from plasma diamagnetism and paramagnetism, and $\delta\varphi_{\mathrm{ic},\Delta\Phi}$ is the additional flux (separate from $\varphi^p{}_{\mathrm{err}}$) due to the additional image currents on the chamber induced by the combined paramagnetic and diamagnetic plasma current. Subtraction of these fluxes yields

$$(\varphi_1^p - \alpha\varphi_2^p) = \varphi_{\mathrm{err}}^p + \Delta\Phi + \delta\varphi_{\mathrm{ic},\Delta\Phi}. \tag{2}$$

The blank shot data [Eq. (1)] is subtracted from the plasma shot data [Eq. (2)], yielding

$$(\varphi_1^p - \alpha\varphi_2^p) - (\varphi_1^b - \alpha\varphi_1^b) = \Delta\Phi + (\varphi_{\mathrm{err}}^p - \varphi_{\mathrm{err}}^b) + \delta\varphi_{\mathrm{ic},\Delta\Phi}. \tag{3}$$

The presented method requires that the residual image currents present in the blank and plasma shots are identical, and the stray flux due to toroidal currents (such as plasma current, Ohmic heating (OH) coil current, and vertical field coil current), does not significantly contribute to these residual image currents. (This assumption is expected to be reasonable in stable plasma discharges if the current in the TF coils dominates the residual signal; this condition is examined in the results section.) It is then necessary to examine the condition

$$\varphi_{\mathrm{err}}^p = \varphi_{\mathrm{err}}^b,$$

which allows for the elimination of the residual flux by the method of baseline subtraction used in this paper. If the image current in the chamber walls is considered

$$R_c I_c = - L_c \dot{I}_c - M_{c,\mathrm{BT}} I_{\mathrm{BT}} - \Delta\dot{\Phi},$$

where R_c is the poloidal resistance of the chamber walls, L_c is the wall inductance, and $M_{c,\mathrm{BT}}$ is the mutual inductance between the chamber walls and the toroidal field coils. The use of a Laplace transform allows the image current term to be found as

$$I_c = -\frac{M_{c,\mathrm{BT}}}{R_c + sL_c} sI_{\mathrm{BT}} - \frac{1}{R_c + sL_c} s\Delta\Phi.$$

The enclosing loop measures the flux induced by this eddy current as $M_{1,c} I_c$. The two terms in the above equation can then be used to find the terms in Eq. (3).

$$(\varphi_{\mathrm{err}}^p - \varphi_{\mathrm{err}}^b) = -\frac{sM_{1,c}/R_c}{1 + s\tau_c} M_{c,\mathrm{BT}} (I_{\mathrm{BT}}^p - I_{\mathrm{BT}}^b), \tag{4}$$

$$\delta\varphi_{\text{ic},\Delta\Phi} = -\frac{sM_{1,c}/R_c}{1 + s\tau_c}\Delta\Phi, \tag{5}$$

where $\tau_c = L_c/R_c c$ is the time constant of the chamber walls ($\tau_c = 0.56$ ms for STOR-M).[13] Since the variation in the diamagnetic flux is slower than τ_c, $\delta\varphi_{\text{ic},\Delta\Phi}$ can be neglected. Equation (4) predicts that the plasma and blank residuals are identical in the case where τ_c is sufficiently less than the characteristic time variation in the TF currents τ_{BT}. In STOR-M, this time is approximately $\tau_{\text{BT}} = 250$ ms based on the approximately 20% decay in TF observed over 50 ms. The limiting value of τ_c is approximately 125 ms, and therefore the term in Eq. (4) can be neglected. This limitation is examined by requiring the contribution of Eq. (4) to be no greater than 10% of $\Delta\Phi$, and is found by

$$(\varphi_{\text{err}}^p - \varphi_{\text{err}}^b) = \frac{\tau_c}{\tau_{\text{BT}}} \times 0.002 \times 100 \times \Delta\Phi < 0.1 \times \Delta\Phi, \tag{6}$$

where the difference $(I_{\text{BT}}^p - I_{\text{BT}}^b)$ has been estimated to be about $0.002 I_{\text{BT}}$ based on measurements made at the toroidal feed line by a Rogowski coil, and the mutual inductance between the chamber and the TF current which has been assumed equal to that of the diamagnetic coil and the TF current $M_{c,\text{BT}} I_{\text{BT}} \cong M_{1,\text{BT}} I_{\text{BT}}$, which in general is about 100 times larger than the diamagnetic current. Examination of Eq. (6) shows that the $(\varphi_{\text{err}}^p - \varphi_{\text{err}}^b)$ term is expected to contribute approximately 0.04% error to the measurement of $\Delta\Phi$, and can therefore be neglected. Equation (3) then becomes

$$(\varphi_1^p - \alpha\varphi_2^p) - (\varphi_1^b - \alpha\varphi_2^b) = \Delta\Phi. \tag{7}$$

A potentially significant source of error is the signals induced by vibration of the diamagnetic coils inside the nonuniform TF. The relative size of the error signals due to vibrations may be particularly large compared to the diamagnetic signal in small tokamaks. In STOR-M, it has been estimated that vacuum chamber vibrations could create spurious signals comparable to the diamagnetic signal. Mechanical isolation of the diamagnetic coil form the chamber, and the auxiliary compensation coils serve to provide a means of compensation for these signals created from vibrations. In theory, the auxiliary coils provide a null signal in the absence of vibration. When vibrations are present, the signal resulting from the coils is used to remove the vibration component from the flux loop signal.[11]

The poloidal beta can be calculated from the measured change in flux $\Delta\Phi$, toroidal field B_φ, and plasma current I_p as

$$\beta_\theta = 1 - \frac{8\pi B_\varphi(r=a)}{(\mu_0 I_p)^2}\Delta\Phi. \tag{8}$$

The plasma is paramagnetic for $\beta_\theta < 1$ and diamagnetic if $\beta_\theta > 1$. The plasma energy confinement time in Ohmic discharge is calculated in terms of the poloidal beta from

$$\tau_E = \frac{3}{8} R_0 \mu_0 I_p \frac{\beta_\theta}{V_l - \dfrac{d}{dt}(L_p I_p)}, \tag{9}$$

where the denominator contains the plasma loop voltage V_l corrected for the inductive voltage drop. The plasma loop inductance L_p is assumed to be constant in the calculation. R_0 is the plasma major radius.

For the purpose of verification of the performance of the diamagnetic coils, the poloidal beta term is also calculated from measurements of the line averaged density made using a 4 mm microwave interferometer, and estimate of the electron temperature made using the neoclassical resistivity[14]

$$\eta_n = \frac{\eta_S}{1 - 1.95\sqrt{\varepsilon} + 0.95\varepsilon}, \tag{10}$$

where ε is the inverse aspect ratio of the tokamak ($\varepsilon = a/R$), and η_S is the well known Spitzer resistivity.[15] The inductive correction due to varying plasma current is also applied to plasma resistance before calculating resistivity. Spitzer-neoclassical resistivity has been previously confirmed in Zarnstroff *et al.*[16] It was shown in TFTR from direct measurements of electron temperature by Thompson scattering diagnostics and by theoretical calculations that correction for toroidally trapped particles is necessary.

II. EXPERIMENTAL APPARATUS

A polyoxymethylene plastic (trade name Delrin from DuPont) form is used to mount the coils. This material was chosen for strength and for low conductivity. The compensation and auxiliary coils are made from eight turns of 28 AWG magnet wire, while the primary coil is a single loop of the same type of wire. Twisted pair cable is used to reduce noise pickup by the coil leads. All twisted pairs exiting the coil form are enclosed in a specially constructed shielded cable, which leads to a DA-15 female connector. The cable was purposely routed so as to not cross through the vertical plane of the machine, helping to minimize electromagnetic noise pick up. A male DA-15 connector mounted on a shielded distribution box near the tokamak allows for signal acquisition through male BNC connectors. Signal measurements were made by connecting the coils through the distribution box directly to a National Instruments PCI-6133 data collection card which provides sufficient resolution (14 bit over a 1 V range yielding 0.012% accuracy), and were processed on a computer after the discharges.

Mechanical isolation of the diamagnetic coil assembly from the vacuum chamber was achieved by mounting the assembly directly to the massive phenolic yoke structures support for the TF coils, where the level of vibration is estimated to be ~0.1 mm. This reduces the vibration induced error signal to approximately 6.5% of the diamagnetic signal,[10] without the auxiliary coil compensation. These signals are then compensated for using a set of auxiliary coils arranged in opposition such that their signals cancel in the absence of vibrations,[17] greatly reducing the contribution of vibration errors. This is a benefit of mounting the coils external to the chamber compared with internally mounted

FIG. 2. Diamagnetic coil assembly mounted in STOR-M (center, white form mounted on bellows). Also in the picture at the bottom is one of the structural mounts physically isolating the coil from the vacuum chamber.

coils, which present significantly larger vibration errors due to the large vibration of chamber walls. The mounted assembly is pictured in Fig. 2.

Due to the exterior mounting of the coils, the signal will be attenuated and potentially filtered (cut off) due to the effects of eddy currents in the stainless steel chamber.[15] The skin time at the bellows (0.5 mm stainless steel) is $\tau_s \sim 1.5\ \mu$s. The skin time at the thicker stainless steel chamber wall (5 mm) is $\tau_s \sim 15\ \mu$s. The overall skin time is expected to be between these two values, and is much shorter than the expected characteristic time of plasma equilibrium evolution, which is on the order of a millisecond. The filtering effect of the vacuum chamber does not prevent this measurement from being performed externally to the vacuum chamber. The attenuation of the signal due to the chamber (bellows section) in the 1 kHz range has been estimated by skin effect calculation (modeling the flexible bellows as a cylinder) to be approximately 0.8 (significantly better than the chamber walls where the attenuation factor is approximately 0.3), meaning the exterior mounting is acceptable in terms of signal strength.

The four coils produce the following voltages: the voltage arising in the single loop coil V_{Dm}, the voltage arising in the compensation coil V_c, the voltage arising in the inner auxiliary coil, $V_{\text{aux-inner}}$, and the voltage arising in the outer auxiliary coil, $V_{\text{aux-outer}}$.

The compensated signal is calculated from

$$V_{\text{meas}} = V_{Dm} - k_1 V_c - k_2(V_{\text{aux-inner}} - k_3 V_{\text{aux-outer}}),$$

where k_1, k_2, and k_3 are gain constants satisfying the condition that V_{meas} is a minimum in the absence of plasma. The gain constants are determined one after another in steps:

(1) k_1 is chosen such that result of $V_{Dm} - k_1 V_c$ is at a minimum for blank shot data.
(2) k_3 is chosen such that the result of $V_{\text{aux-inner}} - k_3 V_{\text{aux-outer}}$ is at a minimum for blank shot data.
(3) k_2 is then chosen such that V_{meas} is at a minimum for blank shot data.

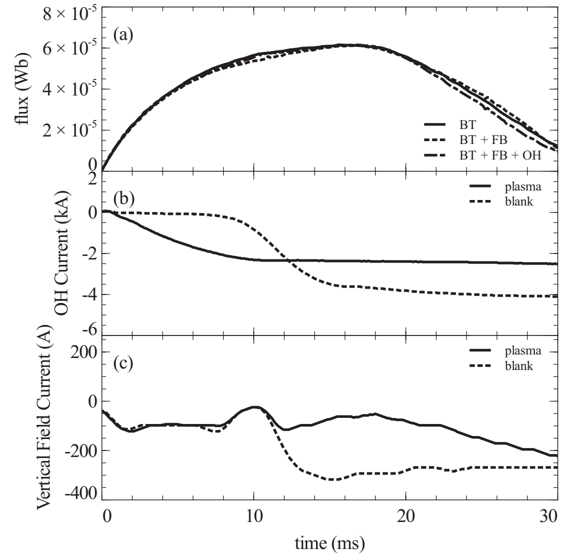

FIG. 3. (a) Contribution of the TF coils (BT), position FB system, and OH coils to the blank shot baseline. (b) OH current from plasma and blank shots. (c) Vertical field current from plasma and blank shots.

The measured voltage during a plasma producing shot is then compensated by the residual voltage (minimum measurement of V_{meas} in a blank shot) measured during a blank shot. When integrated numerically and the residual voltage subtracted, the final result provides $\Delta\Phi$, the change in plasma flux due to paramagnetism and diamagnetism.

III. EXPERIMENTAL RESULTS

A series of blank shots and normal Ohmic discharges were conducted and data were collected from the coils. In order to produce a blank shot, steady-fill and gas puffing were disabled and the tokamak coils (TF, OH, feedback, etc.) were energized while the chamber was held at vacuum. The measured signal from the blank shot was then subtracted from the signal measured during normal operation. It is expected that the primary contribution to the measured residual signal (blank shot data) is due to image currents arising from the current in the TF coils.

Figure 3 examines the relative contribution of the OH and feedback systems to the residual signal. Figure 3(a) shows little differences between blank shots with only BT contribution, BT and OH contributions, and BT, OH, and feedback (FB) system contributions, indicating that the primary contribution to the blank shot is the TF coils. Contributions from the automatic FB and the OH coils are less than 3% of the contribution from BT. This is especially important as the influence of the TF system on the baseline shot data exhibits strong repeatability of better than 3% based on statistical analysis of repeated vacuum baseline shots. Figure 3(b) shows the difference between measurements of the OH current blank and plasma producing shots. Figure 3(c) shows the difference between measurements of the vertical field current blank and plasma producing shots. The figures indicate that while there are measureable differences between the

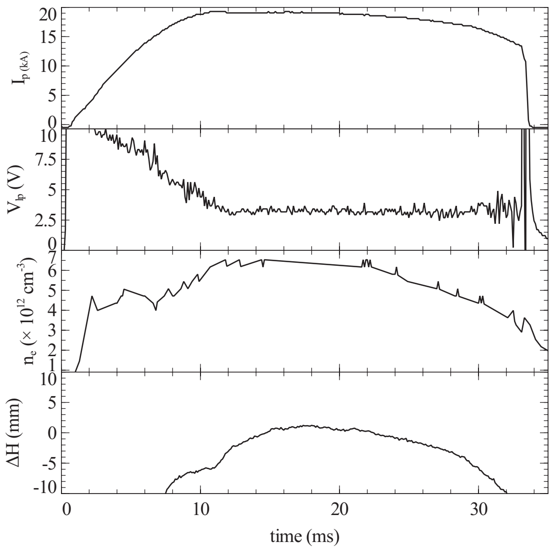

FIG. 4. Plasma current, loop voltage, average electron density, and plasma position for a typical normal Ohmic discharge (shot 204760).

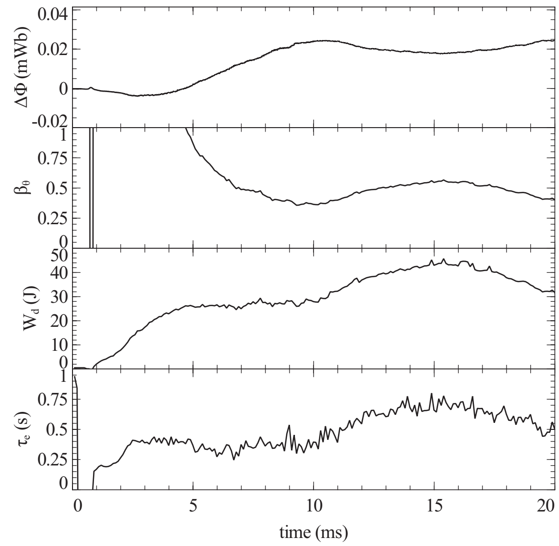

FIG. 6. Measured toroidal flux change, poloidal beta, bulk thermal energy, and energy confinement time (shot 204760).

blank and plasma shots, the contribution to the residual signal is negligible. Therefore, blank shot compensation of the signals is acceptable.

Figure 4 shows the plasma conditions for the plasma bearing shot examined in this paper. Plasma current peaks near 10 ms, and it is expected that the ΔΦ signal will peak at this time as well. Density is seen to be constant during the plasma current flat top stage. It is expected that poloidal beta will be relatively constant during the plasma flat top stage in this discharge.

Figure 5(a) shows the magnitudes of the raw measurements of ΔΦ taken from blank and from plasma shots, as well as the final compensated data. Figure 5(a) shows that the residual signal is significantly larger than the diamagnetic signal. Variations in the TF find their way in the measurement through the induced image currents. The FB and OH system signals can strongly depend on plasma conditions, which could potentially be a large source of error in the blank shot compensation. The FB and OH fluxes do not play major roles in the acquired signal. Figure 5(b) shows the relative contributions of fluxes produced by the FB and OH systems compared to the compensated flux signal in a blank shot. The FB signal is a maximum contribution, as the FB system saturates in the absence of plasma. The OH contribution may be at a minimum, since there is no plasma for the OH coils to link to. The results of Figs. 3 and 5 show that FB and OH fluxes are not significant compared to either the contribution of TF to the residual, or to the diamagnetic measurement.

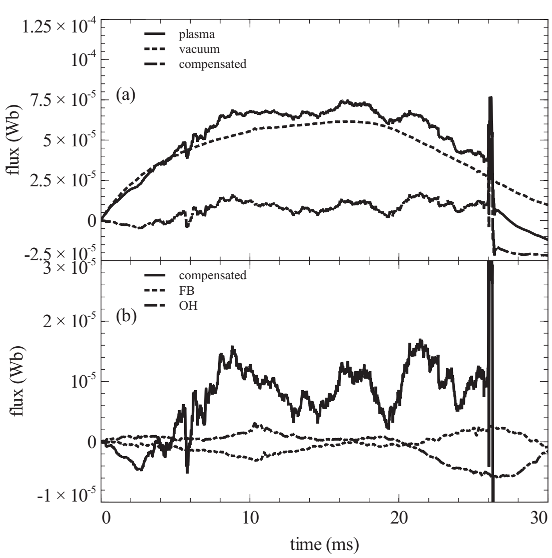

FIG. 5. (a) Plasma, vacuum, and compensated flux signals. (b) Relative sizes of the feedback and OH contributions to the final compensated shot (shot 204760).

Flux measurements and poloidal beta calculations are presented in Fig. 6. Figure 6 shows the expected peak in ΔΦ near 10 ms corresponding to the peak in plasma current (seen in Fig. 3). Poloidal beta calculated from the measured flux is near 0.5 (paramagnetic) throughout the flat top portion of the discharge. Bulk thermal energy and the global confinement time were calculated from the poloidal beta quantity.

The measured values of poloidal beta in the plasma current flat top are compared to values obtained from Spitzer resistivity calculations in Fig. 7. Reasonable agreement of about 10% between the two independent methods is shown. The Spitzer resistivity calculations suffer from the assumption that the effective ion charge of the plasma Z_{eff} is constant at a value of 1.5 in STOR-M. A nominal value of $Z_{\text{eff}}=1.5$ is typically assumed in STOR-M.[18] It is also as-

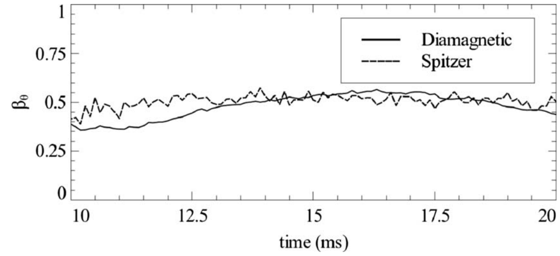

FIG. 7. Comparison of diamagnetically measured and Spitzer based calculations of poloidal beta (shot 204760).

sumed that T_i is 1/3 of the electron temperature T_e. It is likely that Z_{eff} shows some variation during the breakdown and current ramp up phase of the discharge,[19] and the value of 1.5 needs verification. If the Z_{eff} value varies within the range 1.2–1.7 in the STOR-M tokamak, and Spitzer calculations are affected by less than 10%.

It has been observed that the diagnostic becomes inaccurate in the case of discharges with minor plasma disruptions characterized by loop voltage spikes, and especially for large, rapid plasma horizontal position variations as also observed on other devices.[20] In the case of unstable (large position shift) plasmas, the diagnostic produces large drifting values. Error in the measurement of $\Delta\Phi$ has been found to be 3%, due to the reproducibility of the blank shots by direct comparison of multiple blank shots. Errors due to potential misalignment of the coil in the poloidal plane were found to be negligible by experiment. Overall error in the calculated value of poloidal beta during stable plasma operation is estimated at 5.6%, based on quadrature addition of the statistical errors and hardware limitations of the LeCroy data acquisition system used for the plasma current and TF measurements.

IV. CONCLUSIONS

Diamagnetic measurements using compensated coils mounted externally to the vacuum chamber with additional compensation from blank shots were performed on the STOR-M tokamak. The expected contributions from image currents which arise in the chamber walls due to the strongly decaying toroidal magnetic field were observed. It may be possible to further improve the diagnostic through precise circuit modeling of the image current contribution. The presented method provides reliable poloidal beta measurements during stable discharges with an error of 5.6%, with the major contribution being 3% from image currents which vary due to slight TF irreproducibility. Advantages presented by this method of measurement are the simplicity of construction and implementation, as well as the reduction in vibration error gained by external mounting. Since data from all the coils are digitized and stored, gain constant adjustments for compensation can be processed numerically as opposed to iteratively adjusting over a sequence of shots. This method is limited in applicability to stable plasma discharges, and to configurations where the L/R time constant in the chamber walls is small enough compared to the characteristic response time of the diamagnetic and TF currents. This method is likely not applicable to tokamaks lacking a sufficiently stable automatic feedback control system. The diamagnetically measured poloidal beta was compared to poloidal beta from Spitzer resistivity and density measurements and was seen to agree well.

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