

Sensitivity of the diamagnetic sensor measurements of ITER to error sources and their compensation



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HIGHLIGHTS

- In the paper we discuss the sensitivity analysis for the measurement system of diamagnetic flux in the ITER tokamak.
- Some compensation formulas have been tested to compensate the manufacturing errors, both for the sources and the sensors.
- An estimation of the poloidal beta has been carried out by estimating plasma's diamagnetism.

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ABSTRACT

The present paper is focused on the sensitivity analysis of the diamagnetic sensor measurements of ITER against several kinds of error sources, with the aim of compensating them for improving the accuracy in the evaluation of the energy confinement time and poloidal beta, via Shafranov formula.

The virtual values of measurements at the diamagnetic sensors were simulated by the COMFLUX code, a numerical code able to compute the field and flux values generated in a prescribed set of output points from massive conductors and generalized filamentary currents (with an arbitrary 3D shape and a negligible cross section) in the presence of magnetic materials. The major issue to face with has been to determine the possible deformations of sensors and electromagnetic sources. The analysis has been carried out considering the following cases:

- deformed sensors and ideal EM (electromagnetic) sources;
- ideal sensors and perturbed EM sources;
- both sensors and EM sources perturbed.

As regards the compensation, several formulas have been proposed, based on the measurements carried out by the compensation coils; they basically use the value of the flux density measured to compensate the effects of the poloidal eddy currents induced in the conducting structures surrounding the plasma.

The static deviation due to sensor manufacturing and positioning errors has been evaluated, and most of the pollution of the diamagnetic flux has been compensated, meeting the prescribed specifications and tolerances.

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1. Introduction

Diamagnetic diagnostics measure the variation of toroidal flux induced by the plasma in tokamak devices. This quantity is

commonly used as a constraint in equilibrium reconstruction codes. It is also useful to estimate other physical quantities, like the total diamagnetic energy content, the confinement time of the plasma and the poloidal beta β_p . Their precise estimation is relevant for improving the quality of tokamak plasma discharges in terms of flatness of the plasma current and safety factor profile [1–3].

The diamagnetic flux diagnostic system, placed on the inner part of the vacuum vessel wall basically consists of a diamagnetic loop

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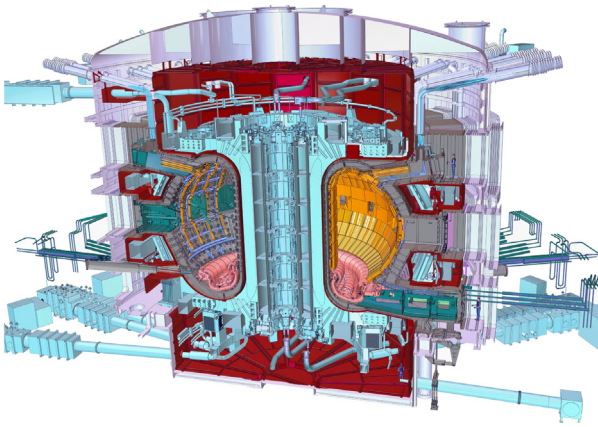


Fig. 1. View of the ITER tokamak (courtesy of ITER organization).

- TF (toroidal field), PF (poloidal field) and CS (central solenoid) coils (assembly/manufacturing tolerances and dynamic deformations);
- Plasma;
- Nonaxisymmetric coils (e.g., ELM coils);
- Bus bars and twist pitch of conductors in the winding packs of the main field coils;
- FM (ferromagnetic) inserts, NBI (neutral beam injector) iron and other iron components in the blanket modules;
- Eddy currents, mainly in VV (vacuum vessel), blanket modules, and divertor cassette.

Some of these effects just produce an offset that is automatically removed by the time integration of the diamagnetic loop voltage, e.g. large part of the signal coming from the TF coils and the iron components. Some others can be compensated by linear combination of the error sources (e.g., the current in a PF coil that is not perfectly circular). The remaining ones, mainly those due to the eddy currents, can partially be compensated using the whole set of diamagnetic measurements (combining them via suitable compensation formulas).

For the sensors attached to the vessel, the set of deviations considered will include thermal expansion and deformation of the vacuum vessel via parametric study. A parametric study was carried out for the local sensors positioning and tilting error. We refer to [9–13] for the orders of magnitude of the PF, CS and TF coils deformations.

For the study we considered the nominal scenario and two additional operative conditions, chosen in such a way to separately consider and compensate the eddy current effects. In detail, we took into account the following cases:

- Nominal scenario:
 - nominal geometry at operating temperature (OT);
 - static deviations (at flat top) for taking into account the assembly errors and the thermal effects;
 - dynamic deviation from static geometry (including thermal expansion of the diamagnetic loops);
- Fast transients (for the nominal geometry at OT):
 - Breakdown and Ramp-up
 - Edge Localized Mode (ELM)
 - Major Disruption (MD).

The fast transients are simulated using the 3D eddy current code CARIDDI using the assumptions commonly adopted for electromechanical analyses [14]. For each selected operative condition, in Table 1 it's possible to find some of the most meaningful parameters, including:

- the plasma current and the diamagnetic flux;
- the poloidal and toroidal total components of the eddy currents induced in the VV;
- the required accuracy for the diamagnetic flux measurements [5].

and a compensation system. The diamagnetic loop measures the total toroidal flux Φ , which is the sum of the plasma diamagnetic (or paramagnetic) flux, the toroidal field flux, the spurious poloidal flux due to PF coils and the magnetic flux generated by ELM coils and eddy currents. The compensation system has the rule to extract from this sum the only addend attributable to the diamagnetic flux, canceling the remaining contributions. Special attention should be paid to reduce the pick-up due to ferromagnetic inserts, misalignments of the flux sensors, or magnetic fields due to active and passive conductors.

When the compensation system is unable to meet the specifications, the accuracy needs to be increased with additional compensation coils and/or formulas [4,5]. In the present paper the implementation of the diamagnetic loop system [6], designed for the ITER international reactor tokamak (Fig. 1), will be reviewed and its performances will be assessed.

The article is organized as follows. Section 2 summarizes the main assumptions. Section 3 describes the diamagnetic measurement system to be installed in ITER. In Section 4 we recall and compare various compensation formulas usually adopted to minimize the effects of the eddy currents, showing how those usually adopted for the JET tokamak [7] do not satisfy the ITER accuracy requirements [5,7,8]. Section 5 proposes an alternative compensation formula. Section 6 illustrates the effects of main perturbation sources and geometrical imperfections on diamagnetic sensor measurements. Section 7 analyzes the benefits introduced by the compensation coils and the performance of the system in terms of diamagnetic flux and poloidal beta measurements. Finally, Section 8 reports the main conclusions.

2. Assumptions

In the present analysis we consider the following perturbation sources:

Table 1
Main data of the operating conditions.

Case	I_p [MA]	Φ_p [Vs]	Req. accuracy [mVs]	Total eddy currents [MA]
Breakdown + Ramp-up	<1.0	<0.01	10	<1.9 (tor)
ELM	15	0.42	117	<0.1 (pol)
				<0.1 (tor)
MD upwards: thermal quench	15	2.3	690	–1.0 (pol)
				0.75 (tor)
MD upwards: final phase of current quench	<1	~0	60	0.4 (pol)
				–13 (tor)
TF coil discharge	–	–	117	9 (pol)

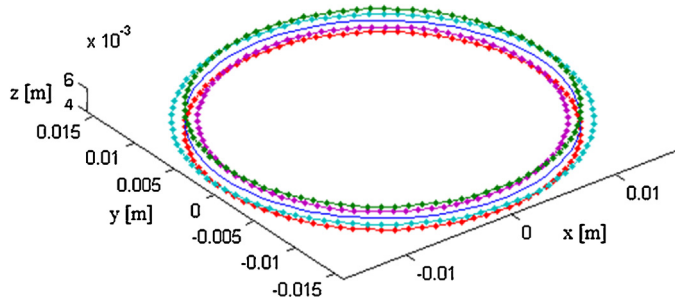


Fig. 2. The nominal flux loop (—) surrounded by four auxiliary curves (dotted) selected for the reconstruction of the vector potential map via interpolation, which is then used to obtain the magnetic flux via line integral.

For the analysis of the several perturbation sources on the diamagnetic flux, we utilized the following codes:

- the numerical package COMPFLUX [13], based on the Biot-Savart formula;
- the integral codes CARIDDI [14] and CARIDDI-MAG [15].

The COMPFLUX code allows to perform sensitivity analyses in case of small perturbations of field sensor positions or geometry of flux loops. These analyses usually require the knowledge of the fields and vector potentials at a large number of points and are very expensive in terms of CPU load, especially for the flux linked with a loop, calculated via circulation of the magnetic vector potential. The computational speed can dramatically be increased by pre-computing the vector potential at a set of points so as to get it at the remaining ones via interpolation. In particular, the full map of the vector potential, in the neighborhood of the nominal curve of each flux sensor, is reconstructed by using a third order interpolation of the values computed by analytical methods for the sampled points of the sensors itself and four auxiliary curves, parallel to the sensor and surrounding it in a regular way (see Fig. 2).

A similar treatment is used for pick-up coils. Magnetic materials are taken into account via a suitable set of magnetic dipoles. The vector potential calculation is carried out using Biot-Savart formula for filamentary currents and CARIDDI for 3D massive conductors.

The assumptions adopted for the simulations were in line with the indications given in the quality plan [13] and are hereafter summarized:

- the ITER operating scenario is specified in terms of prescribed time waveforms for the currents in the PF coils, in the TF coils and in the plasma; the transient phases of interest include breakdown, ramp-up and a typical major disruption (MD) upwards;
- the diamagnetic loop geometry is derived from [8,16] and considered as ideal, i.e. the linked magnetic flux is measured with no error or delay; actually, it is the time integral of the magnetic flux derivative, starting shortly before plasma breakdown when the TF coils are already energized (this aspect makes the compensation problem less critical);
- the plasma is simulated as a suitable number of axisymmetric filaments carrying a prescribed time-varying toroidal current superposed to an axisymmetric poloidal current located inside the vessel producing the prescribed diamagnetic flux;
- the symmetry module of the overall structure spans 40° toroidally ($0 \leq \varphi \leq 40^\circ$), with reflection symmetry at $\varphi = 20^\circ$;
- the computation tools were used for calculating the corruption of diamagnetic flux measurements due to all the sources including eddy currents, ferromagnetic materials and actuator coils.

The activity proceeded with a detailed analysis of the perturbations due to each *perturbation* source. The post-processing of the data and the sensitivity analysis for the evaluation of the effects of the non-ideality of the sensors on the diamagnetic flux measurement were carried out by the post-processor of COMPFLUX or directly by CARIDDI treating the diamagnetic loops as high resistance conductors.

3. ITER diamagnetic sensors

The diamagnetic loop system of ITER includes five sets of sensors.

3.1. Main diamagnetic loops

In ITER, there are three sets of in-vessel main diamagnetic loops fixed to the vacuum vessel, placed in the poloidal sections at $\varphi = 16, 136, 256^\circ$ (Fig. 3a). Each loop is the series of two turns covering

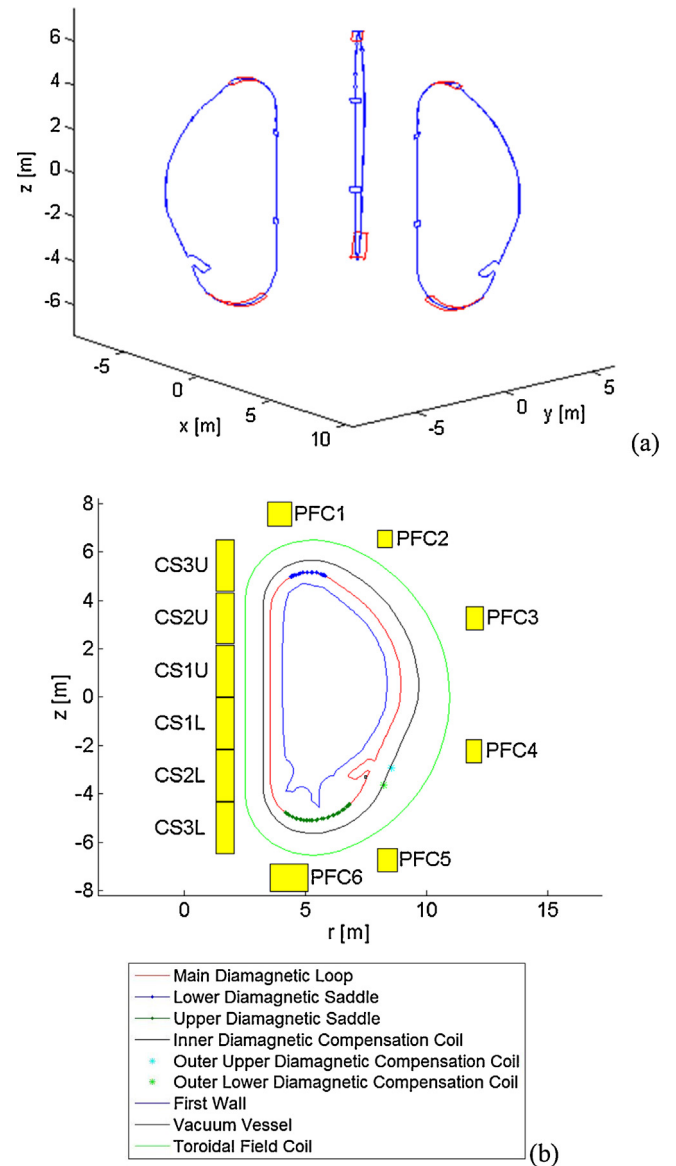


Fig. 3. Diamagnetic loop system: (a) toroidal location of main diamagnetic loops (blue) and diamagnetic saddles (red); (b) poloidal view. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

about 30 m² each, symmetric about a poloidal plane, which bypass obstacles, aimed at compensating the effects of the magnetic field perpendicular to the vessel (Fig. 3b). The nominal coordinates at operating temperature have been taken from [8,16]. They measure the total toroidal flux via time integration of the voltage

3.2. Inner diamagnetic compensation coils

The inner compensation coil system consists of three pairs of pick-up coils 120° apart, each measuring the toroidal field. Each sensor is square-shaped with each side 81 mm long, with 2 layers of 150 turns for an effective area of 1.97 m² each, located at $r = 7.48$ m, $z = -3.34$ m (Fig. 3b).

These sensors are used in combination with the outer compensation coils, to compensate the effects of the poloidal currents induced in the vacuum vessel.

3.3. Outer diamagnetic compensation coils

The outer compensation coil system includes three sets of pick-up coils 120 degrees located outside the vessel. Each set consists of two groups of pick-up coils, placed at two different heights and having an overall effective area of 20 m².

3.4. Diamagnetic saddles

Three sets of two saddles loops are placed at the top and the bottom of the main diamagnetic loop; their main aim is the compensation of vertical field pickup, which might be significant in case the two parts of a main diamagnetic loop are not symmetric with respect to the poloidal plane.

3.5. TF coils (back-up)

As the TF coils are magnetically coupled with the poloidal plasma current, the TF coil currents or voltages can be used as back-up measurements of the diamagnetic flux in case any of the sensors are not usable any more [17,18].

4. Compensation Formulas

Motivations for using compensation formulas have to be searched in the presence of sources of pollution of the measurement provided by the main diamagnetic loop. This measurement depends on the diamagnetic flux as well as many other contributions to the linked magnetic flux, generated by all other coils and structures surrounding the plasma. Therefore, using flux linked with the diamagnetic loop without compensation would yield a wrong estimation of the value of the diamagnetic flux and, consequently the poloidal beta.

The flux linked with the main diamagnetic loop Φ_{DL} is given by:

$$\Phi_{DL} = \Phi_p + \Phi_{TFC} + \Phi_{Tilt} + \Phi_{ExpTF} + \Phi_{EC} + \Phi_{PF} + \Phi_{ExpPF} + \Phi_{Ip} + \Phi_{Iron} + \Phi_{Other} \quad (1)$$

where Φ_{DL} : flux linked with the main diamagnetic loop; Φ_p : diamagnetic flux of the plasma; Φ_{TFC} : flux due to TF coil currents (nominal geometry); Φ_{Tilt} : flux due to tilting; Φ_{ExpTF} : flux due TF coil expansions; Φ_{EC} : flux due to the eddy currents (mainly in the VV); Φ_{PF} : pick-up due to PF coil currents; Φ_{ExpPF} : flux due PF coil expansions (thermal + electromechanical effects); Φ_{Ip} : plasma current pick-up; Φ_{Iron} : iron pick-up; Φ_{Other} : pick-up due to other sources (e.g., bus bars).

From (1), the diamagnetic flux can be expressed as:

$$\Phi_p = \Phi_{DL} - \Phi_{TFC} - \Phi_{Tilt} - \Phi_{ExpTF} - \Phi_{EC} + -\Phi_{PF} - \Phi_{ExpPF} - \Phi_{Ip} - \Phi_{Iron} - \Phi_{Other} \quad (2)$$

The various terms in (2) can be related to physical quantities (i.e. the currents in the poloidal and toroidal field coils, the plasma current and the eddy currents in the passive structures) and to the fluxes linked to the compensation sensors, as follows:

$$\Phi_{DL} = \int V_{DL} dt \quad (3a)$$

$$\Phi_{Tilt} := k_{Saddle}^T \Phi_{Saddle} \quad (3b)$$

$$\Phi_{TFC} = M_{pol,TF} I_{TF} \quad (3c)$$

$$\Phi_{EC} = k_O \Phi_{OutComp} - k_I \Phi_{InnComp} \quad (3d)$$

$$\left(\text{instead of } \Phi_{EC} = \tau_{VV} \frac{d\Phi_{DL}}{dt} \right) \quad (3d')$$

$$\Phi_{ExpTF} = \alpha_{TF} I_{TF}^3 \quad (3e)$$

$$\Phi_{Ip} = k_{pol}^T B_{pol} = k_{pol}^T \frac{\partial B_{pol}}{\partial I_p} I_p \quad (3f)$$

$$\Phi_{PF} + \Phi_{ExpPF} = k_{PF}^T I_{PF} \quad (3g)$$

where V_{DL} is the voltage on the diamagnetic loop, Φ_{Saddle} , $\Phi_{OutComp}$ and $\Phi_{InnComp}$ are the sets of measurements provided by the diamagnetic compensation system, I_{TF} and I_{PF} are the TF and PF circuit currents, respectively, $M_{pol,TF}$ represents the mutual inductances between PF coils and diamagnetic loops, τ_{VV} is the electromagnetic time constant of the vacuum vessel, I_p is the plasma current, B_{pol} is the set of poloidal field measurements in the vicinity of the main diamagnetic loop. The coefficients k_{Saddle}^T , k_O , k_I , k_{pol}^T , k_{PF}^T are determined via pseudoinversion using models or experimental data.

It is worth noticing that:

- in (3a) the integration drift & pick-up of connection cables are not considered;
- for other coils, pitch in the winding packs, bus bars, feeders, connections and cables we can use the same treatment as TF coils in (3c);
- the sampling time request for B_{pol} ranges from 100 μ s to 1 ms; therefore expression (3d) should be preferred to (3d') adopted in the JET tokamak due to the noncompliance of the conditions required from Nyquist-Shannon theorem (in ITER the VV behaves as a low-pass filter having a time constant of about 300 ms with a cut-off frequency of 5 Hz);
- in (3e) the mechanical expansion itself is proportional to I_{TF}^2 whereas the field scales linearly with I_{TF} ; additional terms related to the interactions between PF and TF coils could also be considered;
- the coefficients of k_{pol}^T in (3f) are computed observing the correlation between the poloidal pick-up coil signals and the spurious diamagnetic loop measurement in a suitable set of pulses; an alternative way might be based on pulses in which the helicity of the plasma current is reversed;
- the pick up from the iron can be approximated as an offset, which is automatically removed using time integration of the voltage, plus a linear term that can be treated similar to (3f);
- in (3g) the coefficients of k_{PF}^T are computed from correlations in dry runs.

The time evolution of the TF coil currents is given by:

$$U_{TF} = R_{TF} I_{TF} + L_{TF} \frac{dI_{TF}}{dt} + M_{TF,VV} \frac{dI_{VV}}{dt} + N_{TF} \frac{d\Phi_P}{dt} \quad (4)$$

where U_{TF} is the applied voltage, R_{TF} the resistance, L_{TF} the inductance, I_{VV} the vessel current, $M_{TF,VV}$ the mutual inductance with the VV, N_{TF} the number of turns. The flux Φ_P might then be estimated by using the superconducting TF coils as back-up sensors, if the other diagnostics are unusable:

$$\Phi_P = \frac{1}{N_{TF}} \int \left(U_{TF} - L_{TF} \frac{dI_{TF}}{dt} - M_{TF,VV} \frac{dI_{VV}}{dt} \right) dt \quad (5)$$

The integration drift is considered elsewhere.

5. Selection of the compensation formulas

The compensation formulas have been tested in the fast TF coil discharge shown hereafter.

The choice of the compensation formula for the eddy currents is directly related to the presence of the compensation coils inside and outside the vacuum vessel, and the possibility to approximate the flux contribution due to the eddy currents in one of the following ways:

$$\Phi_{EC} = \frac{2\pi}{\mu_0} M_{DL,VV} (R_{in} B_{in} - R_{out} B_{out}) \quad (6a)$$

$$\Phi_{EC} = c^T [B_{in} B_{out_L} B_{out_U}] \quad (6b)$$

where μ_0 is the vacuum magnetic permeability, $M_{DL,VV}$ is the mutual inductance between diamagnetic loop and VV, R_{in} and R_{out} are the radial coordinates of the compensation coils, B_{in} and B_{out} (lower and upper) are the toroidal field components measured by the pick-up coils, c is a set of coefficients. Formula (6a) is based on the assumption of 2D axisymmetry, whereas we apply its generalization to the 3D case (6b).

Three different sets of coefficients c have been tested:

1. c_1 using the outer upper compensation coils;
2. c_2 using the outer lower compensation coils;
3. c_3 taking into account 3D local effects (mainly ports) on B_{in} and rescaling B_{outU} as in the first set;

where c_1 and c_2 of (6b) are given by (6a), whereas c_3 is determined via pseudoinversion using models or experimental data.

Fig. 4 shows that the performance of the formulas using the upper outer compensation coils are better.

The compensation formulas based on the inner and upper outer compensation coils provide good estimations (with an error of 220 mVs).

The effect of the ELM coils is significant and depends on the frequency. At steady state (below 2 Hz) where a 15 kAt current in a middle ELM coil it yields 20 mVs spurious pick up on the closest Diamagnetic Loop, whereas the effect is smaller at high frequency due to the reaction field of the eddy currents induced in the vessel. Using the compensation formulas, it is possible to get a good reconstruction of the plasma flux, using VV current compensation for the ELM event, as shown in Fig. 5.

The eddy current contribution is about 13.5 Vs in the presence of a TF coil fast discharge due to TF current quench (18 Vs produced by the external TF source in 200 ms). The compensation formulas based on the inner and upper outer compensation coils provide good estimations (within an error of 220 mVs) of the diamagnetic flux of the plasma.

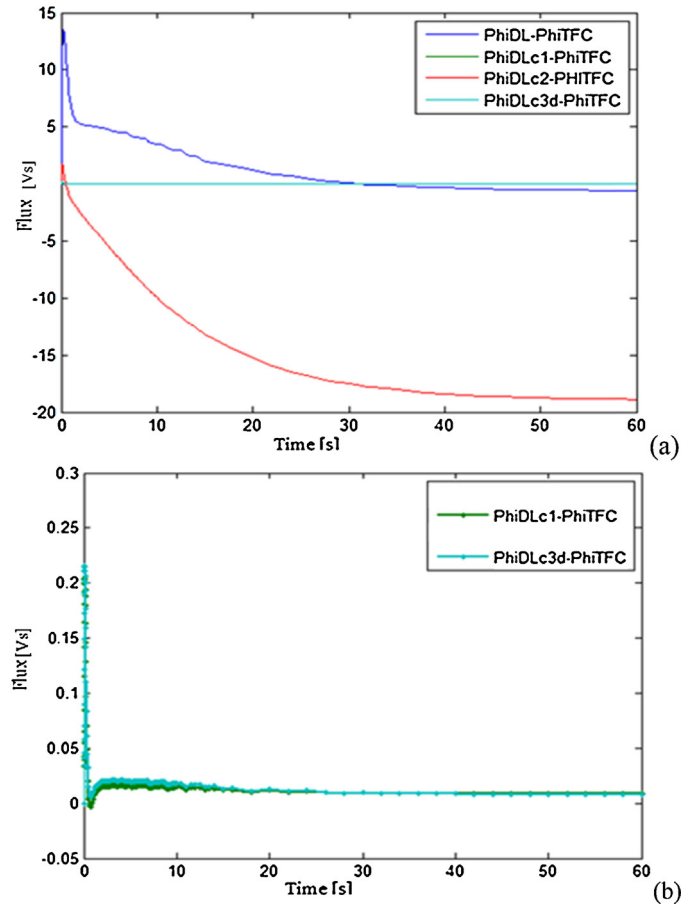


Fig. 4. Fast TF coil discharge. PhiDL is the diamagnetic loop signals, PhiTFC is the flux due to the TF coil, therefore PhiDL-PhiTFC is the eddy current contribution (up to about 13.5 Vs in the fast transient). The other curves represent the difference from the compensated signals (TFDLc1, TFDLc2, TFDLc3d) and the flux directly linked to the TF coil currents. The compensation formulas based on the inner and upper outer compensation coils provide good estimations (with an error of 220 mVs): (a) behavior of the various formulas; (b) behavior of the two formulas that do not use the lower outer compensation coils.

6. Assessment of performances of the diamagnetic flux measurement system

6.1. Thermal expansion, noise and integration drift

Table 2 reports the required accuracy and the analysis of the measurements provided by the Main Diamagnetic Loop are summarized in case of pollution due to noise, integration drift and thermal expansion. Note that thermal expansion at Operating Temperature of 103 °C (0.136% from Room Temperature) can mostly be compensated by monitoring the temperature during a pulse.

6.2. Geometrical deformations and eddy currents

The COMPFLUX code allows to carry out a sensitivity analysis in case of perturbations of the position of field sensors or the geometry of the flux loop.

For each flux sensor, the code computes four auxiliary curves located close to the nominal curve, instead for the field sensors the field is computed in six points around the nominal sensor. The vector potentials computed for a set of sampled points of the auxiliary curves can be used for the reconstruction by using a third order interpolation of the vector potential map in the neighborhood of the nominal curve.

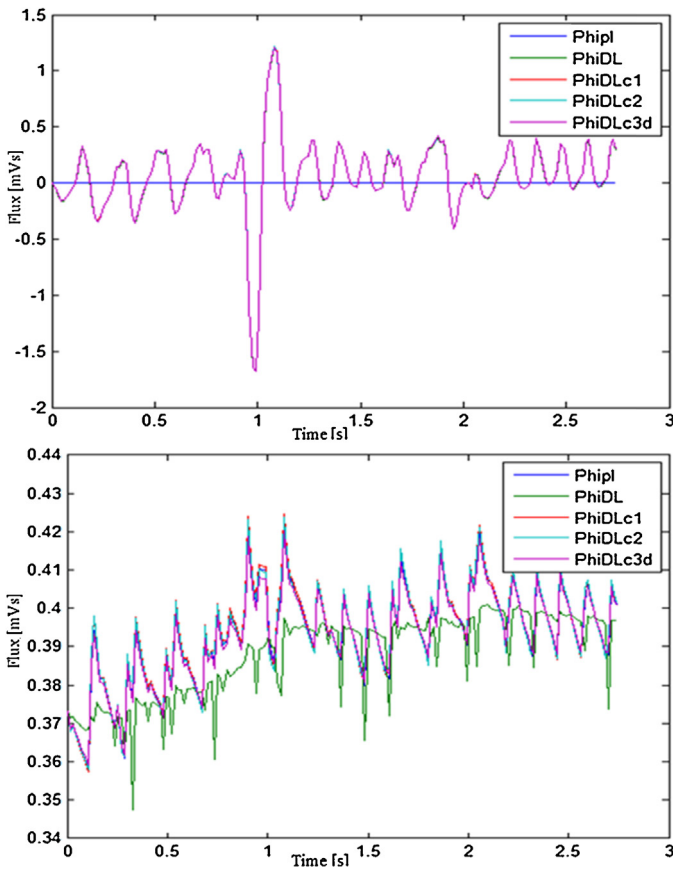


Fig. 5. Use of compensation formulas during ELMs: effects of the poloidal field variation (up) and the toroidal field variation (down).

In this way, at a low computational cost, it is possible to carry out a sensitivity analysis for a large set of perturbations of the flux sensors. In particular, with a single electromagnetic analysis (carried out by any processor: COMPFLUX or CARIDDI), it is possible to make a wide sensitivity analysis of the impact of diamagnetic loop deformation.

Hereafter, the results obtained for various effects of the main Diamagnetic Loop (tilt, displacement, deformation) and eddy current are summarized, besides the required accuracy for the

evaluation of the diamagnetic flux (see Table 3). The non-rigid deformation is obtained by a random displacement of 4 points of the main loop with 1 cm standard deviation and spline interpolation along the path of the loop.

Table 3 also reports the effects on the measurements using ideal sensors with and without compensation formulas.

We notice that:

- horizontal tilt is more sensitive to the poloidal field (toroidal currents) (e.g., during breakdown, ramp-up and current quench);
- vertical tilt and radial shift are more sensitive to toroidal field (poloidal currents) (e.g., during ELMs and thermal quench);
- in the scenarios where the significant component of eddy currents is toroidal, e.g., breakdown & ramp-up, the accuracy requirements are met without compensation, while during fast disruptions, the accuracy requirements are met with compensation formulas, provided that the compensation coil misalignment is (or can be estimated) within 1.0° .

Table 4 reports the combined effects of different disturbance sources:

- Ideal sensors
- Noise + Integration drift
- Main diamagnetic loop Tilt + Eddy currents
- Inner Coil Tilt + Eddy currents
- Inner Coil Tilt + Noise

As eddy currents are relevant only during transient phases, the results in Table 4 show that the combined effects of eddy currents with the tilting of a PF coil is the hardest to be compensated, while the compensation is effective when the measurement deviations are due only to the effects of PF/CS/TF coil manufacturing.

6.3. Ferromagnetic materials and non-axisymmetric coils

In various plasma scenarios we have analyzed the effects of:

- ferromagnetic inserts (Fig. 6), test blanket modules and neutral beam injector;
- feeders, bus bars and ELM coils (Fig. 6).

Table 2

Effects of thermal expansion, noise and integration drift on Main Diamagnetic Loop.

Case	Breakdown + Rampup	MD UP	
		Final phase of thermal quench	Final phase of current quench
Required accuracy (mVs)	10	690	60
I_p (MA)	<1	15	<1
Φ_p (Vs)	<0.01	2.3	~0
Thermal expansion RT → OT* (mVs)	360	360	360
Noise 2σ (mVs)	<0.4	4.1	
Integration drift 2σ (mVs)	~0	0.2	

Table 3

Eddy Currents compensation in presence of ideal and non-ideal sensors (in the last case, the effects of tilt/displacement/deformation (2σ) of the main DL have been considered).

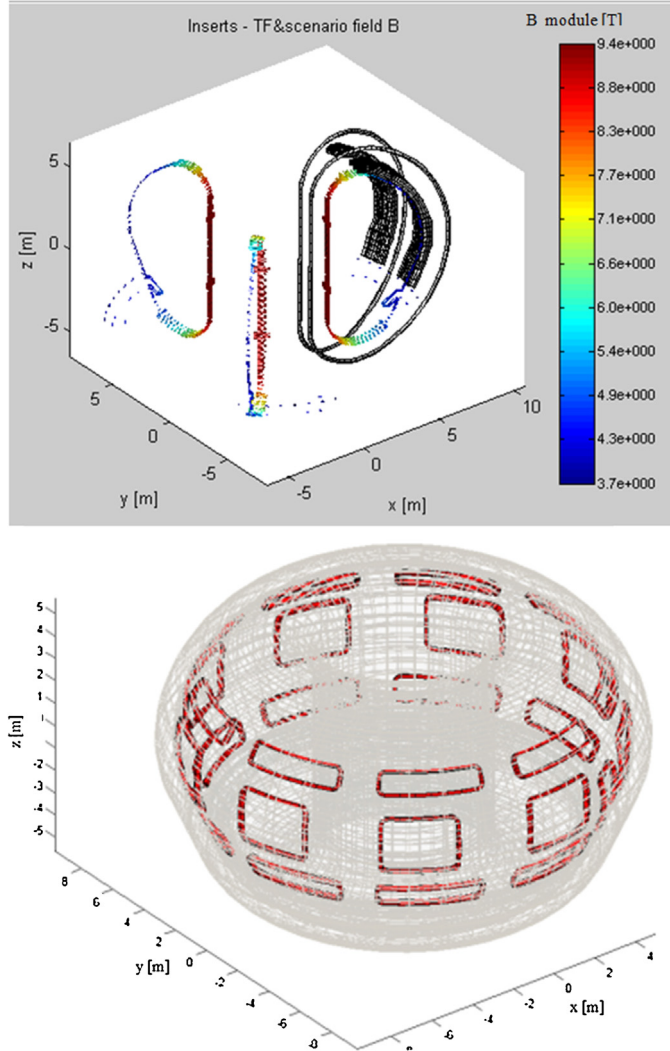
Case	Req. acc. [mVs]	No deform. without/with compens. [mVs] ^a	$2\sigma = 0.1^\circ$ horizontal tilt [mVs]	$2\sigma = 0.1^\circ$ vertical tilt [mVs]	$2\sigma = 1$ cm radial shift [mVs]	$2\sigma = 1$ cm random deform. [mVs]
Breakdown + Ramp-up	10	<1/<1	<1.10	<0.03	<0.03	<0.48
TF Coil Discharge	117	13,500/220	N.A.	N.A.	N.A.	N.A.
ELM	117	30/3	2	2	2	2
MD UP Thermal quench	690	1500/10	0.17	0.26	1.30	5.1
MD UP Current quench	60	700/70	2.20	0.04	0.56	4.5

^a Mostly due to toroidal field variation, i.e., poloidal currents.

Table 4

Compensation in presence of various perturbations.

Case	Required accuracy [mVs]	Ideal sensors [mVs]	Noise & integration drift [mVs]	Main DL tilt + eddy	Inner coil tilt + eddy	Inner coil + noise
BD + Rampup	10	0	<0.4	<1.3	<22	29
ELM	117	3	4	2	2	29
MD-UP Thermal quench	690	10	4.1	5	2	29
MD-UP Current quench	60	70			213	

**Fig. 6.** Location of ferromagnetic inserts (up) and ELM coils (down).

The largest effect (about 250 mVs) is due to the ferromagnetic inserts (Fig. 6). However, since the time integration of the Diamagnetic Loop voltage starts at the beginning of the pulse, the effect is limited to about 50 mVs, can be experimentally estimated and then partially compensated. The effect of the feeders on the DL flux is about 5 mVs and can be compensated.

Table 5Equilibria and maximum values of expected diamagnetic flux errors (2σ interval).

Eq. #	I_p (MA)	Actual β_p	Actual $\Delta\Phi$ (Vs)	Req. err. (mVs)	ExpErrU (mVs)	expErrC (mVs)
30	3.00	0.0843	0.0878	5	0	33
50	15.00	0.5937	1.1568	116	5	33
182	15.00	0.6000	1.0346	119	5	33
131	2.53	0.1881	0.0574	4	0	33
230	9.36	2.4752	-1.0743	48	2	33
184	15.00	0.5991	1.0890	119	5	33

7. Estimation of the poloidal beta by using the diamagnetic loop measurements

A way of estimating the poloidal beta is based on the following equation [19]:

$$\beta_{DIA} = 0.5S_1 + 0.5S_2 \left(1 - \frac{R_t}{R_0}\right) + \mu_i \quad (7)$$

where S_1 and S_2 are Shafranov integrals, R_t is the radial position of the current centroid, R_0 is the major radius, and the diamagnetic parameter μ_i is estimated directly from the diamagnetic loop diagnostic as follows:

$$\mu_i \cong -\frac{4\pi B_{t0} R_0}{B_{pa}^2 V_p} \Delta\Phi \quad (8)$$

where $\Delta\Phi$ is the diamagnetic flux, B_{t0} is the vacuum toroidal field at the major radius, V_p is the plasma volume, $B_{pa} = \mu_0 I_p / P_p$, P_p is the plasma perimeter. In this way a first estimation of the poloidal beta is obtained through the following expression:

$$\beta_{DIA}^{(1)} = 0.5S_1 + 0.5S_2 \left(1 - \frac{R_t}{R_0}\right) - \frac{4\pi B_{t0} R_0}{B_{pa}^2 V_p} \Delta\Phi \quad (9)$$

in which the accuracy of S_1 and S_2 measurements is expected to be much better than the diamagnetic flux.

Assuming elliptic geometry for the field line, Eq. (9) can be simplified giving the following alternative expression for the estimation of the poloidal beta [3]

$$\beta_{DIA}^{(2)} = 1 - \frac{E^2 + 1}{2E} \frac{8\pi B_{t0}}{\mu_0^2 I_p^2} \Delta\Phi \quad (10)$$

where E is the plasma elongation.

The effectiveness of expressions (9) and (10) was tested on a selection of six static equilibria extracted from the database of the EFIT++ code [20]. The same code was used for the reconstruction of all the plasma parameters by assuming that no noise was affecting the other measurements.

In Table 5 the actual values of the poloidal beta, the diamagnetic flux, the required accuracy of the diamagnetic flux measurement (reqErr), the expected error without eddy current compensation (expErrU), and the expected error with the eddy current compensation (expErrC) are reported. The errors are specified in terms of the 2σ confidence interval, σ being the standard deviation.

In Tables 6 and 7, the confidence intervals on diamagnetic flux shown in Table 5 have been mapped to the 2σ confidence intervals on the poloidal beta estimation errors by applying Eqs. (9) and

Table 6
Estimation results using Eq. (9).

Eq. #	β_p (accuracy bounds)		$\beta_{DIA}^{(1)}$ with actual $\Delta\Phi$	$\beta_{DIA}^{(1)}$ 2σ confidence interval (reqErr)	$\beta_{DIA}^{(1)}$ 2σ confidence interval (expErrU)		$\beta_{DIA}^{(1)}$ 2σ confidence interval (expErrC)		
30	0.084		0.086	0.034	0.138	0.086	0.086	-0.257	0.430
	0.030	0.138							
50	0.594		0.617	0.562	0.671	0.614	0.619	0.601	0.632
	0.514	0.674							
182	0.600		0.615	0.560	0.669	0.612	0.617	0.600	0.630
	0.520	0.680							
131	0.188		0.196	0.138	0.255	0.196	0.196	-0.287	0.679
	0.129	0.247							
230	2.475		2.559	2.501	2.617	2.556	2.561	2.519	2.599
	2.301	2.649							
184	0.599		0.618	0.564	0.673	0.616	0.620	0.603	0.633
	0.519	0.679							

Table 7
Estimation results using Eq. (10).

Eq. #	β_p (accuracy bounds)		$\beta_{DIA}^{(1)}$ with actual $\Delta\Phi$	$\beta_{DIA}^{(1)}$ 2 σ -confidence interval (reqErr)		$\beta_{DIA}^{(1)}$ 2 σ -confidence interval (expErrU)		$\beta_{DIA}^{(1)}$ 2 σ -confidence interval (expErrC)	
30	0.084		-0.426	-0.507	-0.345	-0.426	-0.426	-0.962	0.110
	0.030	0.138							
50	0.594		0.553	0.508	0.598	0.551	0.555	0.540	0.566
	0.514	0.674							
182	0.600		0.588	0.540	0.635	0.586	0.590	0.574	0.601
	0.520	0.680							
131	0.188		-0.475	-0.578	-0.372	-0.475	-0.475	-1.323	0.373
	0.129	0.247							
230	2.475		2.052	2.005	2.099	2.050	2.054	2.020	2.085
	2.301	2.649							
184	0.599		0.566	0.519	0.614	0.564	0.568	0.553	0.580
	0.519	0.679							

(10), respectively. In some cases, highlighted in red, the required accuracy bounds are exceeded.

Table 6 shows that formula (9) can be used without compensation; at low beta values, the compensation provides out-of-bound estimations for low beta values. Table 7 shows that formula (10) should not be used at low beta values in any case.

8. Conclusions

Most of the consequences due to thermal effects, sensor deformations or sources of magnetic field can be compensated. In particular:

- the thermal expansion yields a 360 mVs perturbation on the main diamagnetic loop measurement that can mostly be compensated;
- the effects of PF/CS/TF coils' manufacturing and set up deformation and misalignments can mostly be compensated;
- the effect of the toroidal plasma current pick upon a 0.1° tilted main diamagnetic loop is about 30 mVs; it can experimentally be measured (and then partially compensated in the other pulses) with two similar plasmas one with normal helicity, the other with reverse helicity.

As for the ferromagnetic structures, the largest effect is due to the ferromagnetic inserts (about 250 mVs); however, since the time integration of the Diamagnetic Loop voltage starts at the beginning

of the pulse, the effect is limited to about 50 mVs, can be experimentally estimated and then partially compensated.

The effect of the spurious sources on the diamagnetic flux measurement is small ($2\sigma = 5$ mVs at full plasma current) in static (no eddy) conditions, e.g. at flat top. However, the error is larger if the compensation formula is used ($2\sigma = 33$ mVs) because of the involvement of the compensation coils.

As for the non-axisymmetric coils, the effect of the feeders on the Diamagnetic Loop flux is about 5 mVs and can be compensated. The effect of the ELM coils is larger and depends on the frequency; at steady state (below 2 Hz) a 15 kAt current in a middle ELM coil yields 20 mVs spurious pick up on the closest DL. This signal is reduced at higher frequency (about 2 mVs at 500 Hz) due to the eddy currents flowing in the vicinity of the sources and of the sensors. Since the eddy current pattern depends on the frequency, the compensation of the effects due to the ELM coils based on current measurements can be properly made only in the two limits of steady state and high frequency.

The formulas using inner and outer compensation coils have been tested in the fast TF coil discharge; the eddy current contribution is about 13.5 Vs in the fast transient (18 Vs due to the external TF source in 200 ms). Those based on the inner and upper outer compensation coils provide good estimations (within an error of 220 mVs) making them usable when the toroidal currents in the VV are significant ($L-H$ and $H-L$ transitions, ELMs, plasma heating, disruptions).

The eddy currents in the phases of breakdown and ramp up have a negligible effect (about 2 mVs) on the Diamagnetic Loop flux; however, the effect is larger on the signal if the compensation formula is used (33 mVs).

During disruption the spurious signal is large (1.6 Vs, i.e., about 70% of the diamagnetic flux) if no compensation is used. The adoption of the compensation formulas allows to reduce the spurious signal to 380 mVs.

The spurious signals during ELMs are about 30 mVs and could be reduced to 3 mVs in the absence of noise.

In conclusion:

- in static (no eddy, say at frequencies lower than 0.1 Hz) conditions, e.g., flat top, the accuracy requirements are met without compensation;
- in phases when the significant component of eddy currents is toroidal, e.g., breakdown & ramp-up, the accuracy requirements are met without compensation;
- during fast disruptions (during both thermal and current quench), the accuracy requirements are met with compensation formulas, provided that the compensation coil misalignment is (or can be estimated) within 1.0°.

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References

- [1] A. Salar Elahi, M. Ghoranneviss, J. Fusion Energy 28 (2009) 394–397, <http://dx.doi.org/10.1007/s10894-009-9210-5>
- [2] B. Shen, Y.W. Sun, B.N. Wan, J.P. Qian, Rev. Sci. Instrum. (2007), <http://dx.doi.org/10.1063/1.2779213.093501>
- [3] E.J. Strait, E.D. Fredrickson, J.-M. Moret, M. Takechi, Fusion Sci. Technol. (February (2)) (2008) 304–334.

- [4] J.M. Moret, F. Buhlmann, G. Tonetti, Fast single loop diamagnetic measurements on the TCV, *Rev. Sci. Instrum.* 74 (November (11)) (2003) 4634–4643.
- [5] J.M. Moret, Final Report on ITER Magnetic Diagnostic Design Study on contract EFDA/04-1208, Part 1: Diamagnetic Loop System, October 2006 (private communication).
- [6] D. Testa, M. Toussaint, R. Chavan, J. Guterl, J.B. Lister, J.M. Moret, et al., The magnetic diagnostic set for ITER, *IEEE Trans. Plasma Sci.* 38 (3 (Pt. 1)) (2010) 284–294.
- [7] A. Costley, S. Allen, P. Andrew, L. Bertalot, R. Brnsley, X.R. Duan, et al., Measurement requirements and the diagnostic system on ITER: modifications following the design review, in: *Proceedings of 22nd IAEA FEC*, Geneva, IAEA-CN-165, IT, 2008, pp. P6–P21.
- [8] G. Vayakis, S. Arshad, D. Delhom, A. Encheva, T. Giacomini, L. Jones, et al., Development of the ITER magnetic diagnostic set and specification, *Rev. Sci. Instrum.* 83 (2012) 10D712.
- [9] J. Reich, J.-J. Cordier, B. Macklin, B. Giraud, D. Wilson, B. Levesy, G. Gokhan, Three dimensional tolerance investigations on assembly of ITER vacuum vessel, in: *SOFE 23rd IEEE/NPSS Symposium on Fusion Engineering*, vol. 1, no. 4, June 2009, pp. 1–5.
- [10] B. Lim, F. Simon, Y. Ilyin, C.Y. Gung, J. Smith, Y.H. Hsu, C. Luongo, C. Jong, N. Mitchell, Design of the ITER PF coils, in: *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3, 2011, p. 1918, <http://dx.doi.org/10.1109/TASC.2010.2092732>, 1921.
- [11] J. Knaster, V. Amoskov, A. Formisano, Y. Gribov, E. Lamzin, L. Martone, N. Maximenkova, N. Mitchell, A. Portone, S. Sytchevsky, P. Testoni, ITER non-axisymmetric error fields induced by its magnet system, *Fusion Eng. Des.* 86 (6–8) (2011) 1053–1056.
- [12] A. Foussat, P. Libeyre, N. Mitchell, Y. Gribov, C.T.J. Jong, D. Bessette, R. Gallix, P. Bauer, A. Sahu, *IEEE Trans. Appl. Superconduct.* 20 (June (3)) (2010) 402–406.
- [13] R. Albanese, R. Fresa, S. Minucci, R2.7-5: Final Report on Diamagnetic flux, Technical Report on F4E Grant No. F4E-2009-GRT-047 (PMS-DG) CRE-ATE.047_R2.7-5_v.d03, January 2013.
- [14] R. Albanese, G. Rubinacci, Integral formulation for 3D eddy current computation using edge-elements, *IEE Proc.* 135A (5) (1988) 457–462.
- [15] R. Albanese, G. Artaserse, T. Bellizio, G. Rubinacci, R. Fresa, B. Viola, M.F. Palumbo, F. Villone, Y. Liu, Coupling plasmas and 3D passive structures in the JET tokamak, *Int. J. Appl. Electromagnet. Mech.* 33 (2010) 533–540.
- [16] S. Peruzzo, F4E-GRT-047 1.3 Review of the baseline magnetic diagnostic system, ITER magnetic sensors database (Annex of the Report on the preliminary list of magnetic sensors and their positions) v.3.0, 12/01/2012, 2012.
- [17] K.A. Razumova, E.P. Gorbunov, *Atomnaya Energiya* 15 (1963) 363.
- [18] M.G. Bell, R.J. Marsala, J. Menard, Measurements of plasma diamagnetism in NSTX, *Bull. Am. Phys. Soc.* 46 (2001) 264.
- [19] A. Manini, J.-M. Moret, S. Alberti, T.P. Goodman, M.A. Henderson, *Plasma Phys. Control Fusion* 44 (2002) 139–157.
- [20] L.C. Appel, G.T.A. Huysmans, L.L. Lao, P.J. McCarthy, D.G. Muir, E.R. Solano, J. Storrs, D. Taylor, W. Zwingmann, Contributors to the EFDA integrated tokamak modelling task force, and JET EFDA contributors. A unified approach to equilibrium reconstruction, in: *33rd EPS Conference on Plasma Physics*, vol. 30I, Rome, 2006, p. 2.184.