PLASMA COLUMN POSITION MEASUREMENTS USING MAGNETIC DIAGNOSTICS IN ADITYA-U TOKAMAK

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Abstract

In a tokamak, plasma is generated and confined magnetically. To have a tokamak plasma for a longer duration as well as to achieve the required parameters of plasma, an equilibrium plasma is required. Due to several forces acting on the plasma column in a tokamak, the plasma column tends to move horizontally and/or vertically leading to many adverse events including termination of plasma. The movement of plasma column is stabilised using equilibrium magnetic fields (vertical magnetic fields). The required magnitude of the equilibrium field depends on the plasma parameters. The dynamical variation of the plasma parameters throughout the discharge demands appropriate alterations of magnitude of equilibrium magnetic field in real time during the discharge to obtain a stable plasma column position inside the tokamak. To determine the appropriate magnitude of this equilibrium magnetic field, accurate measurement of plasma column position throughout the discharge with good temporal resolution is a necessity. Upgraded ADITYA has several magnetic diagnostics installed and used for the real time estimation of positional shifts both in horizontal and vertical directions. This paper summarises several important and interesting outcomes regarding these estimations.

1. INTRODUCTION

Among several challenges in fusion and tokamak science, one of them is to keep plasma sustaining for a longer time scale and in this regard a real time position control in a tokamak is of great importance. In a tokamak, plasma is generated and confined magnetically. Due to the presence of toroidal plasma current in different magnetic field configurations, there exist radial forces, overcoming which is absolutely necessary to obtain controlled plasma [1-3]. To keep the plasma column position steady at the centre of the machine, a proper vertical magnetic field value (introduced by vertical field coils, fast feedback coils in ADITYA-U, for example) is required. Hence, for the optimization of plasma position in a tokamak, real time plasma column position needs to be measured accurately. Besides, disruptive instabilities in plasma are also related with the large plasma displacements [1]. These are few of the reasons a real time plasma column estimation and hence its control we are looking for. Magnetic diagnostics is one of the promising as well as useful methods for achieving a real time plasma column location and is taken into account in case of several tokamaks [1-3]. Different approaches from the data of magnetic pick-up coils are adapted for this estimation [1-4] e.g. discrete probe method [5, 6], multi-pole method [7-9] etc.

Upgraded ADITYA is a medium size tokamak of major radius 0.75 m and minor radius 0.25 m, with circular vacuum vessel. As ADITYA-U is designed for shaped plasma, a proper real time measurement of positional shift of plasma column in both horizontal and vertical directions is of great importance. In upgraded ADITYA tokamak also, several magnetic diagnostic systems are installed and utilized for measuring plasma column position. The paper is subjected to the estimation of temporal variation of plasma column position by analysing the data acquired during plasma operations in ADITYA-U using different magnetic diagnostics, like Mirnov probes, Sine-Cosine coils, external magnetic pick-up probes, flux loops etc. and then comparison of these results with that from other diagnostics for benchmarking and reliability. Finally, they are fed for the real time plasma position control in horizontal direction.

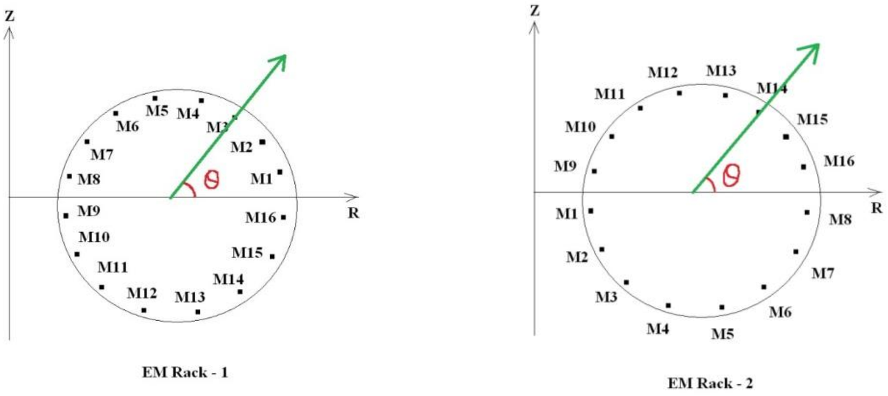
2. EXPERIMENTAL SET-UP

2.1. Magnetic probes for position estimation in ADITYA-U

After up-gradation ADITYA has several diagnostics for the estimation of positional shift of plasma column in both horizontal and vertical directions and only the magnetic diagnostics are subject of the paper. These magnetic diagnostics include two sets of Mirnov garlands [5, 10], each of which contains sixteen number of probes, four external pick-up coils, flux loops [10-13], Sine and Cosine coils [14]. Each of the Mirnov probes contains 176 number of turns (N) and an effective area (NA) of 0.0308 square meter on average with maximum 10% of uncertainty in NA (A is avg. area of each turn). The distance of each Mirnov probe from the center of vacuum vessel is about 28.5 cm and a schematic diagram is given in Fig. 1. The two Mirnov garlands are distinguished by EM Rack 1 and 2, as they are connected with electromagnetic rack 1 and 2 respectively. Four external tangential magnetic pick-up coils are mounted at the toroidal location of cut of vacuum vessel and are distributed on a poloidal plane with equal angular separation, as shown in Fig. 2. According to their angular distances (Θ) with respect to the axis coinciding with the major axis of the machine, they are named as ExT45, ExT135, ExT225, and ExT315 respectively. Each of them is 35 cm apart from the center of vacuum vessel and has 0.1111 meter square of effective area (NA). There are six flux loops installed in ADITYA-U, among which four are working. Flux loop 2 and 4, having radii 1.05 m and 0.45 m respectively, are taken care of for our estimations and are shown in Fig. 2 schematically. Other details of these diagnostics are enlisted in Table 1.

TABLE 1. EXPERIMENTALLY MEASURED VALUES OF DIFFERENT PARAMETERS FOR FEW MAGNETIC DIAGNOSTICS THAT ARE SUBJECTED FOR OUR PRESENT STUDIES

Diagnostics	Inductance (L) in μH (@100 Hz)	Resistance (R) in Ω	Response time (t = L/R) in μs	Response Frequency (f = 1/t) in kHz
Mirnov Probe	60.0	3.0	20.0	50.0
Flux Loop Out 2	30.0	3.5	8.6	116.3
Flux Loop Out 4	20.0	2.1	9.5	105.3
External Tangential Probe	575.0	3.5	164.3	6.1
Sine Coil	230	15	15.3	65.4
Cosine Coil	315	25	12.6	79.4



EM Rack - 1

EM Rack - 2

FIG. 1. Schematic diagram of the two Mirnov garlands, connected with EM Rack-1 and 2 respectively, in ADITYA-U. Though, the nomenclature according to the figure is available [16], we can also specify them with their angular position, θ, for the uniqueness.

2.2. Calibration of magnetic probes

Before going to the analysis of the data from the magnetic diagnostics, they need to be calibrated. Due to any kind of discrepancy as well as imperfection during fabrication and installation of magnetic diagnostics may result in enormous error in the outcome. Also, any kind of induced source of current in the vicinity of these diagnosing systems has a great impact on the final outcome of the data. Due to these important aspects, the positions determining magnetic probes were needed for the in-situ calibration, though they were separately calibrated in laboratory experiments. Thus, an in-situ calibration experiment for the magnetic diagnostic systems was conducted with the help of a rigid current carrying copper conductor as dummy plasma inside the vacuum vessel, with the facility of moving this conductor at the interval of 2 cm and 4 cm in horizontal and vertical directions respectively, from the centre of vacuum vessel and by driving current through the conductor at different rise and fall rates, comparable with the frequency of plasma current's magnitude and positional changes. The temporal change of the driven current through the central conductor induces voltage to all the magnetic probes and diagnostics and the corresponding data are recorded in the storage devices for the analysis. Fig. 3 gives the schematic of the experimental circuit with Mirnov probe as the magnetic diagnostics and the summary of currents with different rise and fall rates, which are controlled by putting different external inductors in series of the primary circuit, is provided in Fig. 4.

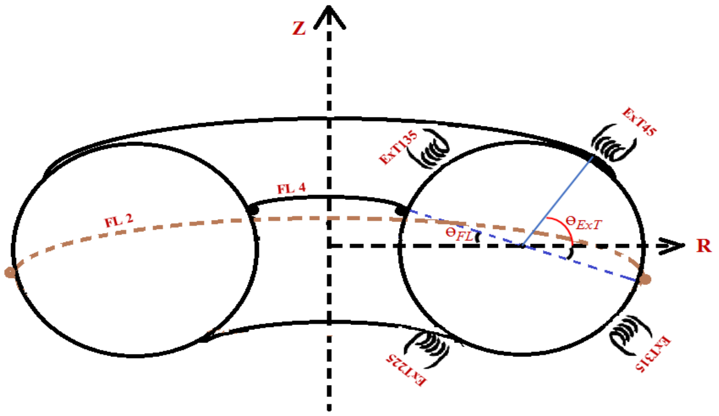


FIG. 2. Schematic diagram of two flux loops (FL 2 and FL 4) and four external tangential magnetic probes (ExT45, ExT135, ExT225, ExT315), as shown on a poloidal cross section of ADITYA-U. Here, Z and R carry the usual meaning i.e., vertical axis and axis along major radius of the machine respectively. The two flux loops make same angle Θ_{FL} with respect to R axis, whereas ExT45 is at an angle $\Theta_{ExT} = 45^o$ with respect to the same; other external probes are at 90^o apart from each other.

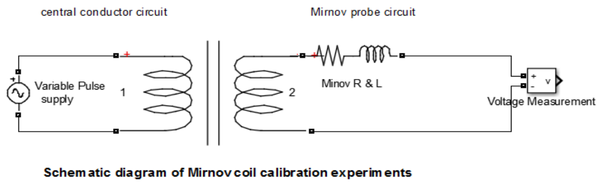


FIG. 3. Schematic diagram of experimental circuitry for in-situ calibration of Mirnov probes as the magnetic diagnostics.

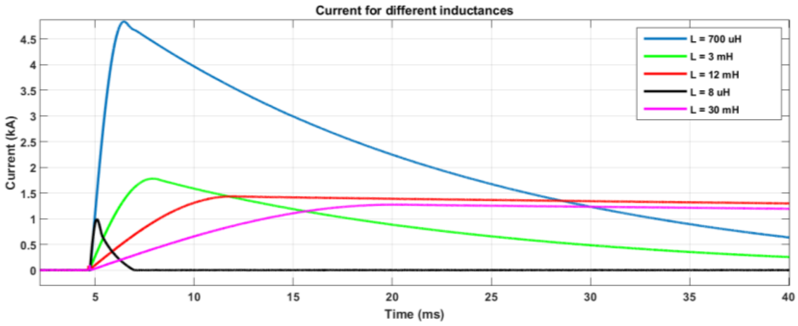


FIG. 4. Summary of different rates of current variation with time in central conductor that were driven separately.

2.3. Results

Now, we summarise the important and interesting results of calibration experiments, as follows.

2.3.1. Effect of toroidicity on poloidal magnetic field

In a Tokamak, plasma column is generated in toroidal geometry and the corresponding poloidal magnetic field generated by the plasma column gets denser towards inboard side starting from outboard, giving rise to a drop of poloidal magnetic field from inboard to outboard side. This fact is one of the most important observations of calibration experiment and reflected in all the diagnostics which are connected both at inboard and outboard sides. Due to the availability of sixteen Mirnov probes, picking up the tangential component of poloidal magnetic field, at different angular positions on a poloidal plane, we can easily observe this variation in magnetic field values experimentally and that is why data from Mirnov probes are chosen for this following analysis, as shown in Fig.

5, along with a comparison with the magnetic field for a circular current carrying conductor using well known theoretical formulations [14, 15].

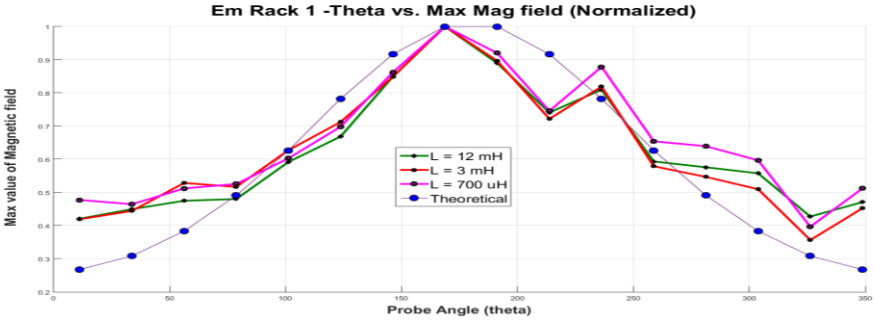


FIG. 5. Normalised magnetic induction at Mirnov garland-1 probe positions, both from theoretical and experimental data in case of three inductance values, as indicated in legend box, with the current carrying conductor, kept at R = 75cm, Z = 0 cm. The abscissa stands for the angular position of the probe, according to Fig. 1, and ordinate gives the normalised (with respect to maximum value) magnetic field.

2.3.2. Temporal variation of signals: a clue towards additional sources

According to Fig. 4, the induced voltage signal at any magnetic diagnostics is supposed to reach zero when the source current is at peak and this is not the case that most of the magnetic diagnostics show. The time when the raw signals go to zero for the probes at the low magnetic field side (outboard) differ from that for the probes at high field side (inboard) as well as from time of peak of source current. This mismatch is elaborated for two Mirnov probes in case of a typical shot #t1331, as shown in Fig. 6 and is suspected to come from the induced voltage at the conducting materials in the vicinity of the diagnostic systems.

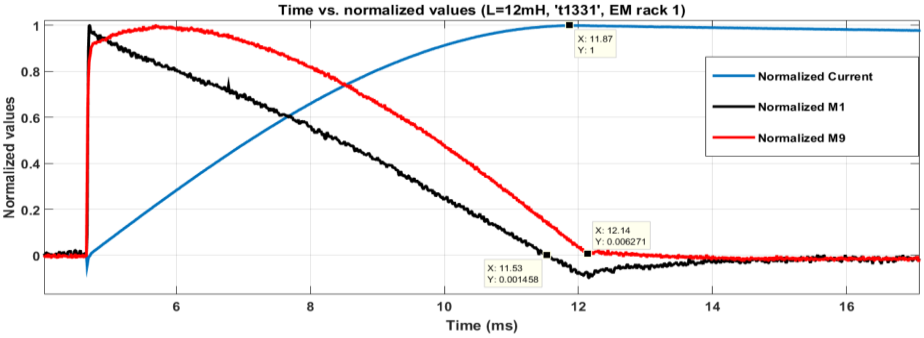


FIG. 6. Temporal variation of Mirnov probe's raw signals – one at inboard (M9), other at outboard (M1), along with the source current in central conductor, in normalised form for an arbitrary shot t1331 with L = 12 mH. The signal zero and the current peak are not time-synchronised.

2.3.3. Position of central conductor

The temporal mismatch, as explained in sec. 2.3.2, has a great impact on the estimation of position of the central conductor in both horizontal and vertical directions in terms of a slight variation of dX (horizontal shift) and dY (vertical shift) with time, though the reality is not so for the fixed conductor. Though this discrepancy is reflected in the estimations from different magnetic diagnostics, Fig. 7 is provided in case of Mirnov probes.

3. ANALYSIS OF DATA AND POSITIONAL ESTIMATIONS

The principle of positional estimations of magnetic diagnostics works on the basis of Faraday's law of induction and a difference in the induced voltages at two diagonally opposite points (diagnosing systems) gives the positional shifts of the plasma column. Using this principle, horizontal position profiles are estimated using Mirnov probes [15, 16], external tangential probes [15, 16], flux loops [11-13], Cosine coil [14], and vertical position profiles are found using Mirnov probes, external tangential probes, Sine coil [14].

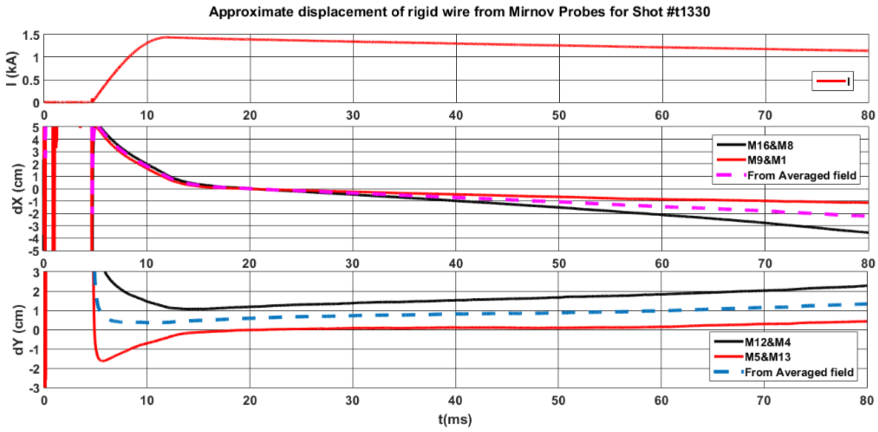


FIG. 7. Temporal variation of positional shift of central conductor, kept at R = 75 cm, Z = 0 cm (dx = 0, dy = 0), in horizontal direction (dX) from Mirnov probe 1, 9 and 8, 16 and in vertical direction (dY) from probe 4, 12 and 5, 13, along with that using their averaged values for an arbitrary shot (# t1330, L = 12 mH).

Taking the data from the diagnostics for the plasma shots, it is taken through several processing and corrections that are schematically shown in sequence, in Fig. 8. Correcting for the hardware gain, the data from the time window of interest are filtered with a low-pass filter below 2 kHz and then are corrected for the signals from coils that are operated during plasma shots, and hence the magnetic fields or fluxes due solely plasma column are obtained. These are finally used for the estimations of dX or Δ'_x and dY or Δ'_y. Consequently, these results are corrected for the unwanted induced signals, as discussed in sec. 2.3, using the following formulations:

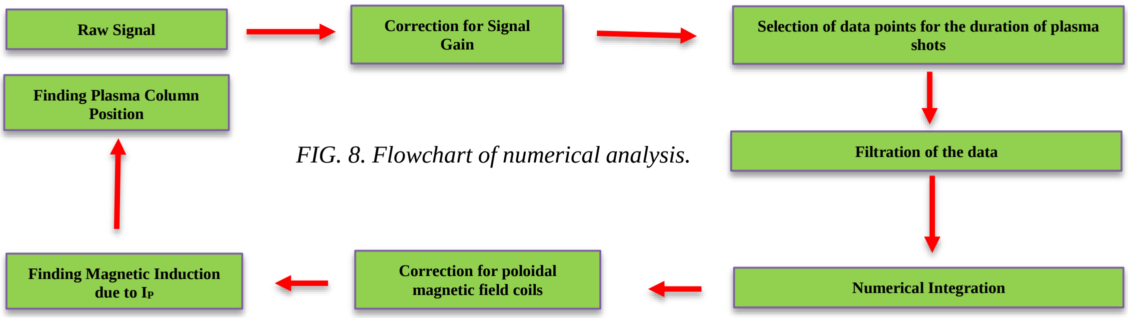


FIG. 8. Flowchart of numerical analysis.

$$\Delta_x = \frac{\Delta'_x}{m} - \delta \text{ and } \Delta_y = \frac{\Delta'_y}{n},$$

where m, n and δ are diagnostic-specific unknown constants, which are discussed in the following section in details.

4. RESULTS

Following all the steps, as described in sec. 3, appropriate numerical codes are developed positions of plasma column in both horizontal and vertical directions are found, as shown in Fig. 9 for a randomly chosen typical plasma shot. Among three panels, as shown in Fig. 9, first one summarises the time profile of plasma current (I_P), current through vertical field coils (I_V) and through the fast feedback coils (FFB coil - I_{FFB}), as indicated in the legend box. Fast feedback coils are there to drive current for providing vertical magnetic field for plasma stabilisation in a faster way than that by I_V. The ordinate is in the scale of I_P and other currents are scaled for comparison purpose. I_V is so scaled that the difference of it with I_P gives, in both magnitude and sign, a clue towards the trend of horizontal movement of plasma column; when I_V is greater than I_P, the plasma column has a trend to move towards inboard direction and vice versa. Second panel is prepared to provide temporal variation of plasma column shift in horizontal direction, obtained from the Mirnov garlands, flux loops, Cosine coil and that from external tangential magnetic pick-up coils (indicated by ExtT ratio). The third panel is similarly prepared for vertical displacement of plasma column, except that from flux loops and Cosine coil, instead, results from Sine coil are plotted. The positions from the magnetic diagnostics are found in similar way for a number of plasma shots and are compared with that obtained from other reliable diagnostics, like fast camera imaging [17], Langmuir probes that are mounted at inboard and outboard sides, photo-diode based spectroscopic signals [18] etc. and finally found the constants m, n and δ that are introduced in sec. 3, as follows:

Mirnov garland-1: $\Delta_x = \frac{\Delta'_x}{2.0} - 0.5\ (cm), \quad \Delta_y = \frac{\Delta'_y}{2.5}.$

Mirnov garland-2: $\Delta_x = \frac{\Delta'_x}{4.0} + 3.0\ (cm), \quad \Delta_y = \frac{\Delta'_y}{2.5}.$

External Tangential Probes: $\Delta_x = \frac{\Delta'_x}{5.0} + 1.8\ (cm), \quad \Delta_y = \frac{\Delta'_y}{2.5}.$

Flux Loop: $\Delta_x = \Delta'_x \cos(25^{\circ}) - 1.0\ (cm).$

Cosine Coil: $\Delta_x = \Delta'_x + 6.0\ (cm).$

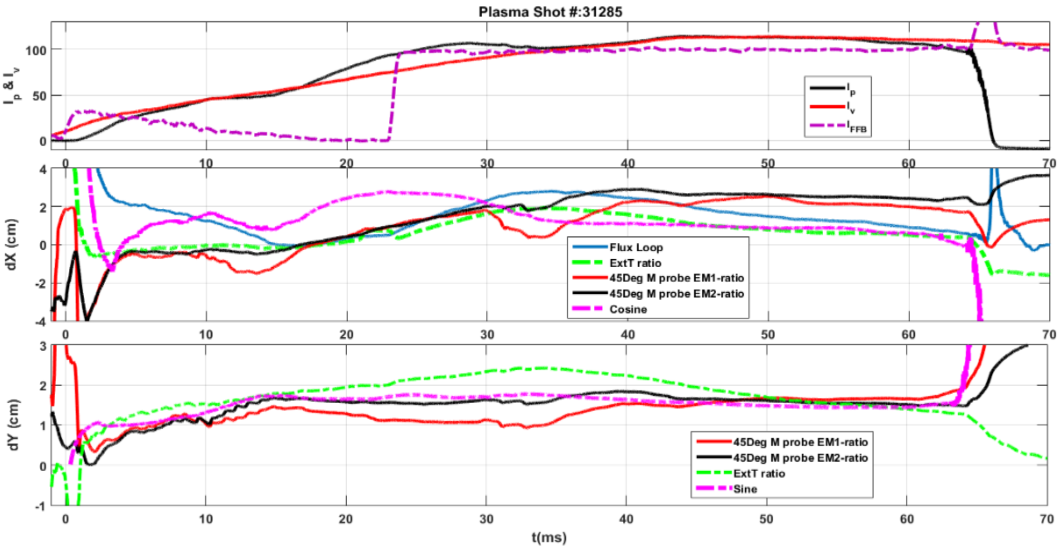


FIG. 9. Temporal variation of horizontal (middle panel) and vertical (bottom panel) shifts of plasma column for shot 31285, as obtained from various diagnostics. The top panel summarises the time variation of plasma current (I_P, in kA), current through vertical field coils (I_V, scaled) and fast feedback coils (I_{FFB}, scaled).

Fig. 9 confirms the play between the plasma current and vertical field currents that is captured in horizontal shift scenario and hence the reliability of the estimation process. The angle 25^{o} is introduced in formulation of flux loops as $\Theta_{FL} \sim 25^{o}$ according to Fig. 2.

5. DISCUSSION AND SUMMARY

The positional shifts of plasma column in both horizontal and vertical directions, which are found from the magnetic diagnostics, are in good agreement with each other in both temporal variation and magnitude and this is verified for a number of plasma shots. Then, these are compared with some reliable diagnostics data, other than the magnetic ones, to ensure the reliability and come out to be satisfactory enough. Finally, with the help of the estimated value of required equilibrium vertical magnetic field for a given Ip [16] and the applied vertical magnetic field during plasma shot at the same Ip, horizontal displacement is found for several plasma shots at the plasma flat-top region and for plasma shot 31285, this is provided for comparison in Table 2. For this estimation, maximum errors of 7% in the measurement of I_P and I_V are taken into account. The comparisons give a good agreement of our estimated values at plasma current flat-top, which is not the case at 35 ms or 60 ms for shot 31285 as seen from Fig. 9 and so the error in these cases are comparatively larger as presented in Table 2. Consequently we find the uncertainty in the estimation is of the order 10% in the plasma flat-top region. Thus, scaling of the estimated results with respect to other reliable ones is turned out to be good enough for the finer corrections over all kinds of unwanted as well as unknown errors, including the contributions from eddy sources. Finally, these final outcomes are ready to be fed for the real time position control in ADITYA-U.

TABLE 2. COMPARISON FOR SOME OF THE HORIZONTAL AND VERTICAL SHIFT VALUES AS OBTAINED FROM DIFFERENT MAGNETIC DIAGNOSTICS IN CASE OF PLASMA SHOT 31285. MG CORRESPONDS TO MIRNOV GARLAND AND EXT STANDS FOR EXTERNAL TANGENTIAL PROBES

Time (ms)	Horizontal Shifts (Δ_x) in cm						Vertical Shifts (Δ_y) in cm			
	Flux Loops	MG-1	MG-2	ExT	COSINE	Δ_x from Estimated Vertical Field	MG-1	MG-2	ExT	SINE
35.00	2.78	0.76	2.21	1.90	1.22	4.84	1.11	1.65	2.40	1.74
48.00	1.61	2.44	2.65	0.92	0.92	2.63	1.62	1.63	1.78	1.51
53.00	1.32	2.18	2.52	0.64	0.88	2.51	1.64	1.56	1.58	1.46
60.00	0.89	1.99	2.42	0.52	0.61	1.60	1.66	1.52	1.40	1.45

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