ISTTOK real-time control assisted by electric probes

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Abstract. The ISTTOK tokamak (Ip = 7 kA, B_T = 0.5 T, R = 0.46 m, a = 0.085 m) was recently upgraded with a new multiple-input multiple-output control system, where the user can specify the combination of real-time diagnostics to produce the observed plasma quantities to control any actuator. The present observed quantities are: (i) plasma current, (ii) plasma position and (iii) plasma density, all of which are actively "feedbacked" by the system.
Four-quadrant Langmuir probes were installed in ISTTOK on inner, outer, top and bottom parts of a poloidal section at a 75 mm radius. The floating potential signals measured by the four probes are fed to the control system to estimate the plasma position using a linear model. The model is based on a well known characteristic of the ISTTOK plasma, in that the floating potential varies linearly with respect to the radial position for an extension of about 10 mm (from ~70 mm to ~80 mm). By using only this set of electric probes for plasma position feedback, it was possible to obtain an alternate current (AC) discharge with 40 semi-cycles, surpassing 1 second without loss of ionization during plasma current reversal.

1. Introduction

The ISTTOK [1] tokamak (whose parameters are described in table 1) was upgraded [2] with a new control system for the automatic control of the alternate current discharges [3][4]. With this system it was possible to test several strategies for plasma control taking advantage of the Multi-Input Multi-Output (MIMO) [3] features installed. One of the tested strategies was the use of electrostatic probes for the real-time control of the plasma position. This type of control was successfully demonstrated, providing an additional diagnostic to control the plasma position at the ISTTOK tokamak, either used as a standalone diagnostic or in conjunction with other diagnostics traditionally used for plasma position control.

In order to provide a real-time feedback control of the plasma parameters several diagnostics were integrated in the control system: (i) mirnov coils, (ii) tomography [5], (iii) interferometer, (iv) magnetic sine probe, (v) magnetic cosine probe, (vi) H_α radiation bolometer, (vii) loop voltage measurement and (viii) electric probes [6] which are this paper main subject.

To actuate on the plasma, several actuators were integrated in a multiple MIMO configuration; (i) two power supplies for the vertical and horizontal magnetic fields based on a switching mode H-bridge with MOSFETs in parallel [7], (ii) a primary field power supply with the same characteristics as the other two but based on an IGBT H-bridge and a (iii) gas injection piezoelectric valve.

The control system is based on the Advanced Telecommunications Computing Architecture (ATCA) standard [8][9], where two types of functional boards are used, the acquisition board and the control board. Each acquisition board includes 32 differential Analog-to-Digital Converter (ADC) channels which acquire data from the following real-time diagnostics/measurements: (i) tomography,

(ii) Mirnov coils, (iii) interferometer, (vi) electric probes, (v) sine and cosine probes, (vi) bolometer, (vii) current delivered by the power supplies, (viii) loop voltage and (ix) plasma current. On the control board, the algorithms are executed with a control cycle of 100 μs on an Intel$^{\mathrm{TM}}$ Q8200 chip with 4 cores running at 2.33 GHz. The real-time control system was programmed in C++ on top of the Multi-Platform Real-Time Framework (MARTe) [10] which is also used in several other fusion research laboratories [11].

Table 1. ISTTOK parameters.

Parameter	Value
Plasma current	7 kA
Toroidal field	0.5 T
Major radius	0.46 m
Minor radius	0.085 m

2. ISTTOK electric probes

The ISTTOK electric probes are used to characterize the plasma poloidal asymmetries [12] and are also used for indirectly estimating the plasma position by measuring the floating potential in four poloidal angles. There are four sets of electric probes installed in ISTTOK (depicted in fig. 1), poloidally separated by 90° and located at the top, bottom, inner and outer positions of a poloidal cross-section. The distance from the pins to the vacuum vessel centre is 75 mm, while the plasma limiter is located at 85 mm.

The control system acquires the data (floating potential) from one pin of each of the four sets of electric probes. The data collection is synchronized with the control cycle which runs at a fixed period of 100 μs.

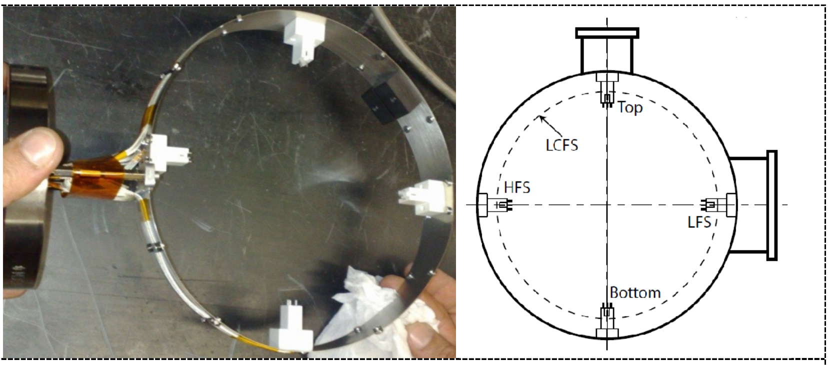

Figure 1. ISTTOK electric probes array and position inside the vacuum vessel

3. Position indirect determination using electric probes

The typical ISTTOK floating potential radial profile [13] is depicted in fig. 2. It can be observed that its value is monotonic on a region of about 10 to 15 mm inside the LCFS. Since the floating potential radial profiles are very similar for all poloidal positions, the plasma position on a given axis can be hinted from the difference between the floating potential of two opposed electric probes that define that axis. As such, the vertical position can be hinted from the floating potential measurements of the top and bottom electric probes, and similarly, the radial position estimation can be derived from the inner and outer probes.

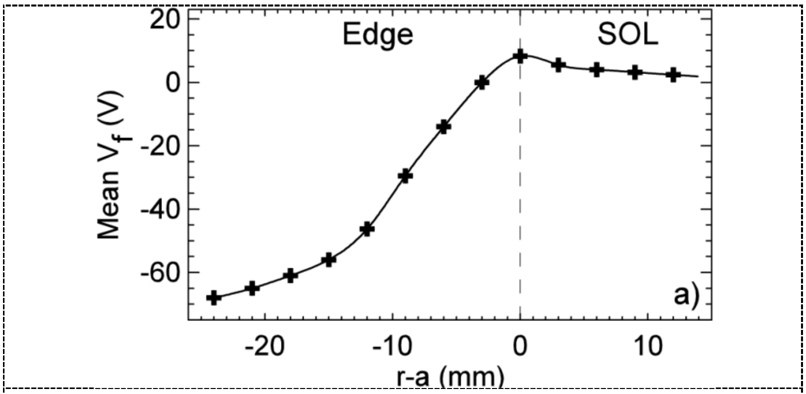

Figure 2. ISTTOK average floating potential versus distance to the LCFS

Taking into consideration the relation of the floating potential with the distance from the LCFS (fig. 2) and assuming circular plasma current only delimited by the ISTTOK inner carbon limiters, the approximate plasma position can be estimated by the electric probes using a linear model:

$$R_p = C_1 \text{ x } (Vf_{outer} - Vf_{inner}) + C_2$$
$$V_p = C_3 \text{ x } (Vf_{top} - Vf_{bottom}) + C_4$$

Where C_1-C_4 are constants estimated from the previous characteristic (fig. 2), R_p is the plasma radial position, V_p is the vertical position, Vf_{outer}, Vf_{inner}, Vf_{top}, and Vf_{bottom} are the floating potentials measured on the outer, inner, top and bottom probe positions respectively.

Figure 3 depicts a comparison between the radial position estimated with the electric probes and measured by the magnetic probes. As it can be observed, apart from an offset during the negative plasma current cycles, the position obtained from the two diagnostics follows a similar pattern.

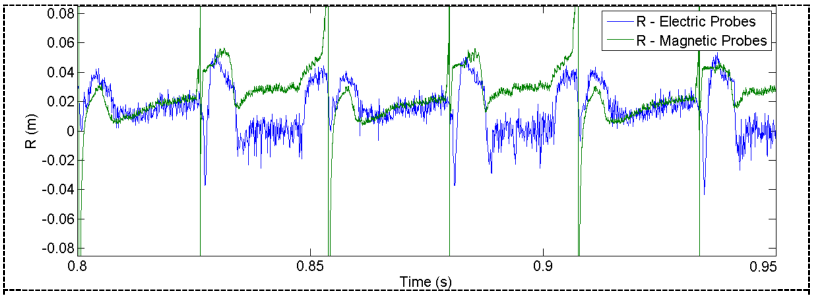

Figure 3. Comparison of the plasma radial position (pulse #34531) obtained from the magnetic probes diagnostic and from the electric probes diagnostic (without filtering).

The ISTTOK control can be programmed as a mixture of feedback control and pre-programmed currents (on primary, vertical and horizontal coils) during any chosen time-window. The fig. 4 shows the typical behavior of the vertical field coils power supply during position feedback (color shaded areas) and pre-programmed current fed to the coils (unshaded areas) using the electric probes diagnostic in real-time.

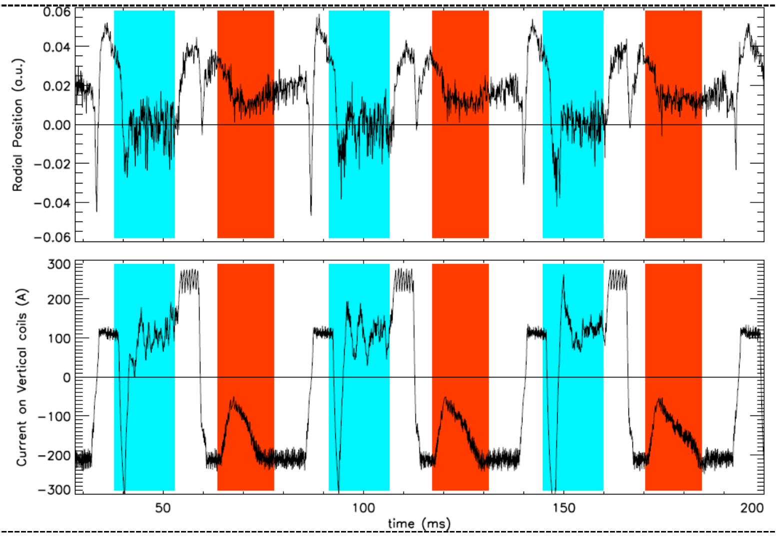

Figure 4. ISTTOK radial position feedback based on the plasma position estimation from the electric probes. The blue color represents a feedback time window on the positive plasma current cycles and the red color represents a feedback time window on the negative plasma semi-cycles. During unshaded areas the values of the current fed to the vertical coils are pre-programmed.

4. Results

The ISTTOK control system can be programmed to use weights for each diagnostic contribution for each plasma parameter. For the discharge depicted in fig. 4, the feedback control was exclusively done using the approximated plasma position given by the electric probes measurements.

As it can be observed in fig. 5 the feedback control of the plasma position using the electric probes enabled ISTTOK to obtain an AC discharge with more than one second of duration, corresponding to 40 times standard ISTTOK performance discharges, while maintaining a finite density during plasma current reversals, as one may observe in the line integrated density measurements obtained with the ISTTOK interferometer.

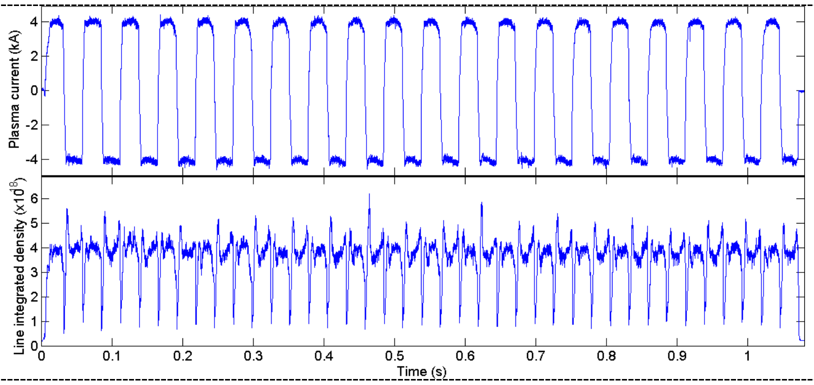

Figure 5. Plasma current (kA) and line integrated density (m^{-3}) on pulse 34717. 20 AC cycles (1.07s) operation with electric probes position feedback were achieved without loss of ionization during plasma current reversals.

5. Conclusions

The electric probes, along with other suitable real-time diagnostics, were successfully integrated in the ISTTOK CODAC system, rendering an effective mean to control the ISTTOK plasma in real-time, either by using it as a standalone feedback signal or integrated in a combination of several diagnostics to provide an adequate estimation of the plasma position.

The floating potential linear region, characteristic of the ISTTOK plasma just inside the LCFS, allowed for the use of a simple linear model to estimate the plasma position, which have proven to be as accurate as the standard magnetic probes plasma position diagnostic. As a result, long AC discharges were successfully achieved, which enables the ISTTOK machine to be used as a plasma-material interaction testing facility.

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