Validation of ISTTOK Plasma Position Controller

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Abstract. Active control of plasma position on the ISTTOK tokamak is of extreme importance due to the inherent instability caused by an unfavourable curvature of the external equilibrium magnetic field. The consequences of this instability can be suppressed by applying a dynamic equilibrium field. A digital real-time plasma position control system for ISTTOK has been developed to perform this task. This system uses magnetic measurements to determine the plasma position and feeds the control signal to power supplies that generate the equilibrium fields. After commissioning, the results obtained have shown some discrepancies between the magnetic plasma position reconstruction and several other diagnostics, such as tomography. This discrepancy at some extent is due to the effect of the external magnetic fields on the poloidal magnetic measurements. This work presents a study that addresses this issue. In a future work it will lead to the development of a corrected plasma position algorithm, aiming at obtaining improved performance of plasma discharges and controlled plasma column displacements.

Keywords: Tokamak, Plasma Position, Magnetic Probes
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INTRODUCTION

Real-time plasma control is an important aspect of the advanced operation of every tokamak. In large devices such as JET, or the future reactor ITER, the processes to control are slow when compared to smaller devices. The former usually have control response times of the order of several milliseconds while the latter must have controllers capable of performing on the time-scale of a few hundred microseconds.

The ISTTOK tokamak is a large aspect ratio fusion device with an iron core, circular section, and the parameters represented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{maj} / R_{min}$</td>
<td>46 cm / 8.5 cm</td>
</tr>
<tr>
<td>Max. $B_{TOR}$</td>
<td>0.5 T</td>
</tr>
<tr>
<td>Inductive Flux</td>
<td>0.25 V.s</td>
</tr>
<tr>
<td>$I_p$</td>
<td>~5 kA</td>
</tr>
<tr>
<td>Discharge Duration</td>
<td>~30 ms</td>
</tr>
<tr>
<td>Plasma Density ($r=0$)</td>
<td>~4x10^{18} m^{-3}</td>
</tr>
<tr>
<td>$T_e (r=0)$</td>
<td>~120 eV</td>
</tr>
<tr>
<td>$\tau_e$</td>
<td>~0.8 ms</td>
</tr>
</tbody>
</table>

A real-time system was developed to control the ISTTOK plasma position. This system has been extensively tested and it was found that its performance could be enhanced. Namely, the plasma position calculation algorithm is affected, at some extent,
by the external equilibrium magnetic fields which must be compensated in real-time. To evaluate this discrepancy, in this study the results of the position calculated with data from the magnetic probes is compared with the same calculation with data from ISTTOK tomography diagnostic.

This article is organized as follows. In Section II it presents the real-time plasma position control system and tomography diagnostic implemented on ISTTOK; in Section III the proposed enhancements to the controller are described; the results obtained to evaluate the enhancements are presented in Section IV; and the conclusions and future work steps of this study are in Section V.

**SYSTEM DESCRIPTION**

The ISTTOK plasma position control system, depicted in Fig. 1, consists on a poloidal array of 12 magnetic probes installed on a single toroidal location of ISTTOK, a set of integrator modules, a digital processing module, vertical field and horizontal field power supplies and actuator coils for the vertical and horizontal equilibrium fields [1].

The equilibrium magnetic field is generated by the current flow in two sets of coils: i) a quadrupole configuration connected to the vertical field power supply; ii) a dipole connected to the horizontal field power supply. These are two switching power supplies [2] whose output current is stabilized by an internal PI+ON/OFF controller (vertical field power supply) and PI (Proportional-Integral) controller (horizontal field power supply).
Figure 2. Plasma position calculation from tomographic data (blue represents zero emissivity and dark red maximum emissivity). (a) tomography raw data; (b) tomographic reconstruction by the pixel method; (c) threshold mask; (d) convex hull around the masked area and its geometric center.

The plasma position controller system is implemented in the digital processing module and it determines the necessary response from the actuators. The data acquisition and processing board used for this module is the transient recorder PCI-TR-512 [3] intelligent card based on PCI (Peripheral Component Interconnect) technology with 8 galvanically isolated analog channels, a DSP (Digital Signal Processor) for data processing and feedback control on the plasma R and Z directions, an FPGA (Field Programmable Gate Array) to control data acquisition and a multichannel buffered serial port for communication with both power supplies.

The tomography system at ISTTOK [4] has 3 views, each with 10 lines of sight: a top, a bottom and a front view. This system allows to reconstruct the plasma emissivity, in the ultraviolet region of the spectrum, excluding the $H_\alpha$ due the low efficiency of the sensors at that frequency. The reconstruction algorithm used in this work is the pixel algorithm [5].

To determine the plasma position from the emissivity reconstruction, which is a matrix, it was considered that the maximum emissivity area was on the core of the plasma column, as the ISTTOK plasma has ultraviolet emissions at the core. A threshold mask is applied to the emissivity matrix to isolate the regions where it is greater than a specified value. If the plasma is completely formed usually there is only one such region, the core. The position is obtained as the geometric center of the convex hull [6] of that region. This procedure is illustrated in Fig. 2.
PLASMA POSITION CALCULATION ENHANCEMENTS

The plasma position calculation algorithm used in the controller consists in determining the R (horizontal) and Z (vertical) coordinates of the magnetic center of the plasma, measured from the center of the vacuum chamber, using the expressions:

\[
\left\{\begin{array}{c}
R_P = \frac{\sum R_{probe}^i H_p^i}{\sum H_p^i} \\
Z_P = \frac{\sum Z_{probe}^i H_p^i}{\sum H_p^i}
\end{array}\right.
\]

where \( R_{probe}^i \) and \( Z_{probe}^i \) are the coordinates of the \( i \)th probe and \( H_p^i \) is the poloidal magnetic field value measured by the \( i \)th probe. Tests were performed by comparing the position results obtained with these expressions with the more accurate current filaments method and, since ISTTOK is a large aspect ratio device, the differences were negligible.

The proposed enhancement consists in subtracting the external magnetic field calculated theoretically, considering that the dipole and quadrupole sets of coils are composed of toroidal current carrying filaments. The expressions used to calculate the theoretical magnetic field produced by a single toroidal filament at the positions of the probes are:

\[
\left\{\begin{array}{c}
H_R = \frac{I}{2\pi \sqrt{R^2 + Z^2}} \left( \frac{R_{fil}^2 + R^2 + (Z + Z_{fil})^2}{R^2 + (Z - Z_{fil})^2} \right) E(\kappa) - K(\kappa) \\
H_Z = \frac{I}{2\pi \sqrt{R^2 + Z^2}} \left( \frac{R_{fil}^2 - R^2 - (Z - Z_{fil})^2}{R^2 + (Z - Z_{fil})^2} \right) E(\kappa) + K(\kappa)
\end{array}\right.
\]

where \( I \) is the filament current, \( R_{fil} \) and \( Z_{fil} \) the coordinates of the filament position, \( R \) and \( Z \) the coordinates of the point where the magnetic field is being calculated (in our case the position of each probe), \( K(\kappa) \) and \( E(\kappa) \) are the elliptical integrals of the first and second kind, respectively, and \( \kappa \) is given by:

\[
\kappa = \frac{4RR_{fil}}{(R + R_{fil})^2 + (Z - Z_{fil})^2}
\]

Obviously, this is a complex expression to evaluate numerically in real-time, but careful inspection shows that all the parameters in these equations are constant and the only variable is the filament current \( I \). Thus, in real-time these calculations reduce to multiplications of the currents by previously calculated factors.

RESULTS

To validate the enhancements proposed to the plasma position calculation two consecutive discharges were made. The first, named Shot 1 and corresponding to ISTTOK discharge number 16279, consisted on preprogrammed equilibrium magnetic fields acting on the plasma. The second, named Shot 2 and corresponding to ISTTOK discharge
number 16280, consisted only on the same applied magnetic fields, no other fields or plasma were created.

The magnetic field at each probe was measured in both discharges and the plasma position was calculated in four cases: (i) with the raw magnetic field data measured during Shot 1 ($R$ and $Z$), since this is the actual implementation of the controller; (ii) with the magnetic data from Shot 1 corrected by subtracting the theoretical magnetic field ($RT$ and $ZT$); (iii) with the magnetic data from Shot 1 corrected by subtracting the magnetic data measured in Shot 2 ($RE$ and $ZE$); (iv) with the tomographic reconstruction information ($RTOM$ and $ZTOM$).

Fig. 3a shows the plasma current during the discharge with plasma and Fig. 3b shows the equilibrium field currents applied during both discharges. The vertical field power supply was turned on 6 ms after the beginning of the discharge at 130 A and turned off 7 ms after that. The horizontal power supply was turned on during the entire duration of the discharge, applying a current of -40 A during 30 ms. Fig. 4a shows the plasma position calculated for cases (i), (ii) and (iv). Fig. 4b shows the position calculated for cases (i), (iii) and (iv).

From these figures it can be immediately seen that $R$ and $Z$ are always displaced when compared $RT$, $ZT$, $RE$, $ZE$, $RTOM$ and $ZTOM$. No effect is noticeable in the calculated position with the original magnetic data when either power supply is switched on or off. However, when the vertical power supply is turned on the proposed theoretical correction leads to a better match with the results from tomography.

CONCLUSIONS AND FUTURE WORK

This work leads to the conclusion that the influence of the external magnetic fields on the poloidal array of magnetic probes can, in some extent, explain the difference in the plasma position calculated with data from these probes and from tomography. When the vertical magnetic field is turned on the theoretical correction causes the match between the horizontal position calculated with these two diagnostics. The real-time
Figure 4. Plasma position for discharge #16279 calculated from: (a) raw magnetic signals (R, Z), theoretically corrected magnetic signals ($R_T, Z_T$) and tomography ($R_{TOM}, Z_{TOM}$); (b) same as (a) except the corrected signal which is empirically corrected ($R_E, Z_E$).

Implementation of this correction may lead to a better controller for the ISTTOK plasma position.

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REFERENCES