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PLASMA CURRENT AND POSITION CONTROL IN KTM TOKAMAK

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Abstract

This paper presents the development and implementation of plasma current and position control systems on the KTM tokamak. The design of the plasma controllers was based on a linear response model of plasma current and position. The system was tested in several experimental campaigns with ohmic plasma discharges on KTM, without plasma density control. Stable limiter and diverted plasma configurations with plasma current up to 500 kA and elongation up to k = 1.7 were obtained. A method was developed for measuring plasma current and position in the presence of passive conductors inside the measurement loop. The induced eddy currents in the passive conductors increase the total current inside the vacuum vessel and affect the position of the current centroid within the measurement loop. These results represent the first successful demonstration of plasma control on KTM and provide a basis for further development of advanced magnetic control, including fast vertical stabilization and shape control.

1. INTRODUCTION

The Kazakhstan Tokamak for Material testing (KTM) is a compact device dedicated to plasma-material interaction research [1]. The main objective of its scientific program is the testing of candidate first-wall and divertor materials for future fusion reactors under high heat and particle fluxes. Key parameters of the KTM tokamak are reported in TABLE 1.

TABLE 1. KTM TOKAMAK BASIC PARAMETERS

Parameter	Value
Major radius R_0 [m]	0.9
Minor radius a [m]	0.45
Aspect ratio R_0/a	2
Elongation k_{95}	1.7
Toroidal field B_{t0} [T]	1
Plasma current I_p [kA]	750
Pulse length [s]	1 (OH)
	5 (ICRH)

In KTM experiments, a single-null, vertically elongated plasma is formed. Such a configuration is vertically unstable, and its maintenance requires reliable magnetic control of plasma current and position (both radial and vertical).

This work presents the plasma current and position control system developed for the KTM tokamak. Section 2 provides a description of the KTM tokamak, including a brief overview of its electromagnetic system, power supplies, and magnetic diagnostics. Section 3 discusses the plasma current and position control system, covering the method used for plasma current and position measurements and plasma controller design process. Experimental results are presented in Section 4.

2. KTM TOKAMAK

2.1. Electromagnetic system

The geometry of KTM is shown in FIG. 1. Its electromagnetic system consists of 20 toroidal field (TF) coils, a single central solenoid (CS) for ohmic heating, six poloidal field (PF) coils for plasma shaping, and two horizontal field coils (HFC) connected in anti-series for vertical stabilization. In addition, two passive stabilization (PS) coils are installed inside the vacuum vessel and connected in anti-series. All coils are made of copper, with active coils water-cooled. The vacuum vessel (VV) and the divertor facility (DIV) are made of stainless steel and are toroidally continuous. The thickness of the VV is approximately 3–5 mm.

The HFC coils are currently not employed in experiments due to technical reasons. PF coils are used instead for plasma vertical position control.

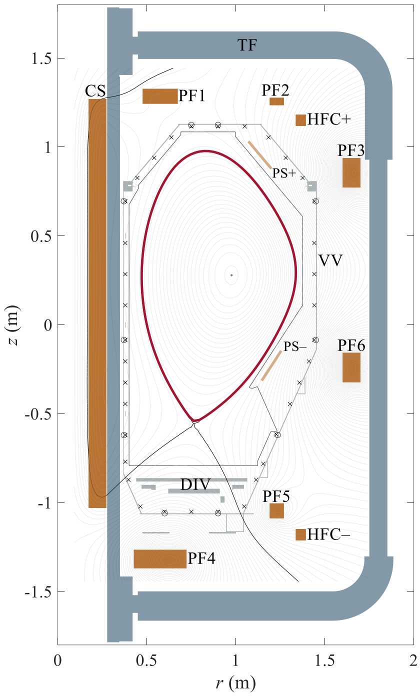

FIG. 1. Poloidal cross-section of the KTM showing the CS, PF, HFC and PS coils, together with the vacuum vessel (VV) and divertor facility (DIV) layout. Circles and crosses respectively indicate the positions of flux loops and magnetic probes installed inside the VV.

2.2. Power supply

All power supplies of the KTM electromagnetic system [2] are fed from a single 230 kV, 50 Hz grid. Twelve-pulse thyristor converters are used to drive currents in the TF, CS, and PF coils while the HFC coils are powered by an IGBT H-bridge inverter. The CS, PF and HFC power supplies provide four-quadrant operation.

2.3. Magnetic diagnostics

The magnetic diagnostics of KTM include 12 flux loops, providing 10 independent poloidal flux measurements; 36 magnetic probes, each measuring two components of the poloidal magnetic field; and two sets of 18 saddle loops. The positions of the flux loops and magnetic probes are shown in FIG. 1. Coil currents are measured using Rogowski coils (RC). In addition, two RCs are installed to measure the current in the PS coils and to determine the total toroidal current inside the VV, including both the plasma current and the current in the divertor DIV.

3. PLASMA CURRENT AND POSITION CONTROL SYSTEM

The KTM plasma current and position control system is based on a two-loop architecture. The inner feedback loop is a coil current control loop, while the outer loop is responsible for plasma control. A simplified block diagram of the KTM plasma current and position control system is shown in FIG. 2. The feedforward current trajectories in the CS and PF coils are calculated using DINA code [3] and prescribed before the experiment. The global sampling time for the KTM plasma control system is 1.667 ms, and the overall system time delay is approximately 5 ms.

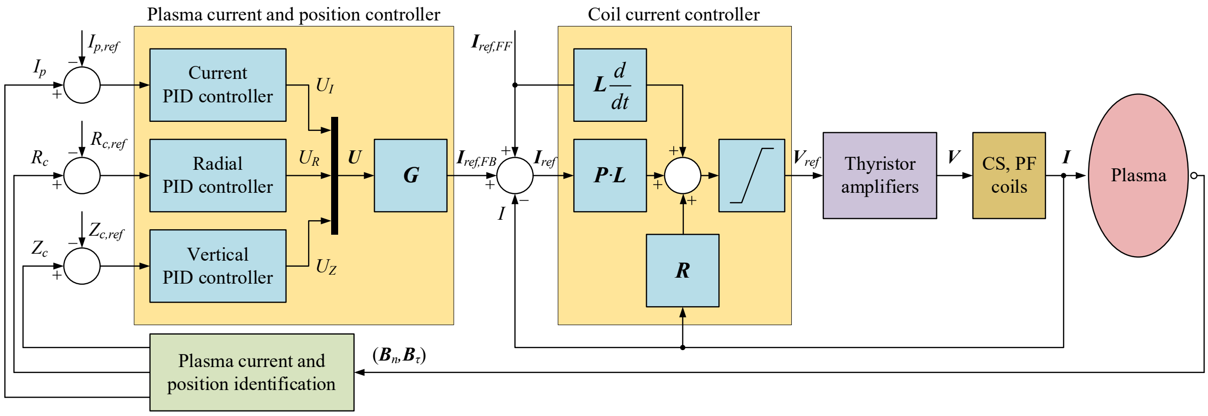

FIG. 2. Block diagram of the KTM plasma current and position control. Here, $\boldsymbol{L}$ *is a CS and PF coils inductance matrix,* $\boldsymbol{R}$ *is a diagonal resistance matrix,* $\boldsymbol{P}$ *is a diagonal gain matrix for coil current controller (typical values >40 dB),* $\boldsymbol{G}$ *is a circuit matrix;* I_p*,* R_c *and* Z_c *denote plasma current and current centroid position,* $I_{p,ref}$*,* $R_{c,ref}$ *and* $Z_{c,ref}$ *denote corresponding references,* $(\boldsymbol{B}_n,\boldsymbol{B}_\tau)$ *is a vector of measured values of normal and tangential components of the poloidal magnetic field,* $\boldsymbol{I}$ *and* $\boldsymbol{V}$ *are vectors of the currents in the coils and the voltages of the power supply,* $\boldsymbol{I}_{ref,FF}$ *and* $\boldsymbol{I}_{ref,FB}$ *refer to feedforward and feedback current reference*

3.1. Plasma current and position measurements

The measurement of plasma current and position in KTM is based on the theory of moments of the toroidal current density [4, 5]. For a known plasma current density J_p, the moments associated with the plasma current I_p and the position of the plasma current centroid (R_c, Z_c) are defined as:

$$\boldsymbol{p}_{IRZ} = \begin{pmatrix} I_p \\ R_c^2 I_p \\ Z_z I_p \end{pmatrix} = \begin{pmatrix} \int_\Omega J_p \, dS \\ \int_\Omega r^2 J_p \, dS \\ \int_\Omega z J_p \, dS \end{pmatrix}. \tag{1}$$

The moments of the current density can be determined from the values of the poloidal magnetic field on the boundary $\partial\Omega$. In the general form, the following integral relation holds for the moments:

$$p = \int_\Omega \chi J \, dS = \mu_0^{-1} \oint_{\partial\Omega} r^{-1} \left(\xi B_n + \chi B_\tau \right) d\tau, \tag{2}$$

here the conjugate pairs χ and ξ must satisfy the following equations:

$$\Delta^* \chi = 0, \quad \partial_r \left(r^{-1} \chi \right) = -r^{-1} \partial_z \xi, \quad \partial_z \chi = \partial_r \xi. \tag{3}$$

Since, in addition to the plasma, a current flows in the DIV conductors inside $\partial\Omega$, and the total toroidal current is $I_{tot} = I_p + I_{div}$, relation (2) cannot be applied directly to calculate the moments $\boldsymbol{p}_{IRZ}$ related to plasma current and position (1). To address this issue, the filamentary current method was adapted. The plasma and DIV are approximated by a finite set of filaments with fixed positions: n_p currents $\boldsymbol{i}_p$ located in the plasma region and n_{div}

currents $\boldsymbol{i}_{\text{div}}$ located in the DIV region. Obviously, the currents must satisfy the conditions $I_p = \sum \boldsymbol{i}_p$ and $I_{div} = \sum \boldsymbol{i}_{div}$. The moments associated with the plasma current, and position (1) can then be determined as:

$$\boldsymbol{p}_{IRZ} = \boldsymbol{M}_{IRZ}\boldsymbol{i}_p, \tag{4}$$

here

$$\boldsymbol{M}_{IRZ} = \begin{pmatrix} 1 & 1 & \cdots & 1 \\ r_1^2 & r_2^2 & \cdots & r_{n_p}^2 \\ z_1 & z_2 & \cdots & z_{n_p} \end{pmatrix}. \tag{5}$$

To determine the plasma currents $\boldsymbol{i}_{\text{p}}$, higher-order moments can be used. By analogy with (4), the m moments of all the currents $\boldsymbol{i} = [\boldsymbol{i}_p, \boldsymbol{i}_{div}]^{\text{T}}$ in Ω can be calculated as:

$$\boldsymbol{p} = \boldsymbol{M} \cdot \boldsymbol{i}. \tag{6}$$

On the other hand, the vector of moments p can be determined using a numerical approximation of the boundary integrals in (2):

$$\boldsymbol{p} = \boldsymbol{Q} \cdot \boldsymbol{b}, \tag{7}$$

where $\boldsymbol{b} = [\boldsymbol{B}_n, \boldsymbol{B}_\tau]^{\text{T}}$ is a vector of l of poloidal field measurements on the boundary $\partial\Omega$. The matrix $\boldsymbol{G}^{m\times l}$ can be constructed using multivariate statistical analysis, as described in detail by Braams J. in [5], where various families of χ and ξ for the calculation of the moments are also presented.

Using the Moore–Penrose pseudoinverse of the matrix $\boldsymbol{M}$ in (6), the matrix $\boldsymbol{P}_{IRZ}$ can be constructed to map from the measurement space $\boldsymbol{b}$ to the moment space $\boldsymbol{p}_{IRZ}$

$$\boldsymbol{P}_{IRZ} = \boldsymbol{M}_{IRZ}\begin{pmatrix}\mathbf{1}^{n_p\times n_p} & \mathbf{0}^{n_p\times n_{div}}\end{pmatrix}\boldsymbol{M}^{+}\boldsymbol{Q}, \tag{8}$$

where **1** and **0** denote the identity and zero matrices, respectively. By combining (6)–(8) with (4), a final numerical approximation is obtained for calculating the moments values associated with the plasma current and position

$$\boldsymbol{p}_{IRZ} = \boldsymbol{P}_{IRZ}\boldsymbol{b}. \tag{9}$$

3.2. Coil current controller

The current controller for the CS and PF coils is based on the well-known decoupling method [6], selecting the voltages for the power supplies in the form (see also FIG. 2)

$$\boldsymbol{V} = \boldsymbol{P} \cdot \boldsymbol{L}\left(\boldsymbol{I}_{ref} - \boldsymbol{I}\right) + \boldsymbol{R} \cdot \boldsymbol{I}. \tag{10}$$

This coil current controller provides good dynamic performance and low steady state error. In addition, this type of controller does not suffer from the wind-up problem, and it is easy to tune. The coil current controller has demonstrated reliable performance on KTM in experiments both in plasma and plasmaless discharges.

3.3. Plasma linearized model

The design of plasma control systems in tokamaks is usually carried out based on linear time-invariant models of the plant. Such models are constructed by linearizing the system of circuit equations [7, 8] that describe the current dynamics in the tokamak electromagnetic system with plasma included:

$$\boldsymbol{L}\cdot\frac{d\boldsymbol{I}}{dt}+\boldsymbol{R}\cdot\boldsymbol{I}+\frac{d\boldsymbol{\Psi}_p}{dt}=\boldsymbol{V}, \tag{11}$$

here $\boldsymbol{L}$ and $\boldsymbol{R}$ are the inductance and resistance matrices of the conductors – the CS, PF, and PS coils, as well as the VV and DIV elements; $\boldsymbol{I}$ is the vector of conductor currents; $\boldsymbol{V}$ is the voltage vector (with nonzero elements only for the active CS and PF coils); and $\boldsymbol{\Psi}_\mathrm{p} = f(\boldsymbol{I}, I_p, \beta_p, l_i,\ldots)$ is the plasma flux linkage with the conductors. The values of $\boldsymbol{\Psi}_\mathrm{p}$ are determined by solving the Grad–Shafranov equation at a given base equilibrium point. Typically, to define the base equilibrium points we use reference plasma evolution scenarios in the tokamak calculated with the DINA code. These scenarios specify the evolution of coil currents together with the integral equilibrium parameters (I_p, β_p, l_i, q_{95},…), as well as the plasma position and shape parameters. To obtain the equation linking the plasma current with the conductor currents, we apply frozen flux condition [9, 10]. Finally, we arrive at the linear state-space model:

$$\begin{aligned}\dot{\boldsymbol{x}}&=\boldsymbol{A}\cdot\boldsymbol{x}+\boldsymbol{B}\cdot\boldsymbol{u},\\ \boldsymbol{y}&=\boldsymbol{C}\cdot\boldsymbol{x}+\boldsymbol{D}\cdot\boldsymbol{u},\end{aligned} \tag{12}$$

where the output vector $\boldsymbol{y}$ includes coil currents, plasma current, and plasma position.

3.4. Plasma controller

Since this is our first experience with plasma control in a tokamak, the choice of plasma controllers was made in favor of classical PID controllers [11]. Three independent PID controllers are used to control the plasma current, as well as the radial and vertical plasma positions (see FIG. 2). All three controllers have the transfer function of the form:

$$W_{\mathrm{PID}}=K\left(K_P+\frac{K_I}{s}+\frac{K_D s}{T_f s+1}\right), \tag{13}$$

where K, K_P, K_I, K_D are the controller gains, and T_f is the derivative filter time constant. The circuit matrix $\boldsymbol{G}$ is used to produce feedback current reference $\boldsymbol{I}_{ref,FB}$ in the coils, which allows the control action from the plasma controllers to be distributed among the selected coils. The $\boldsymbol{G}$ matrix is designed in such a way as to virtually connect the coils in series, so that the feedback currents produce the required vertical and horizontal fields. One CS coil is used for plasma current control. For plasma radial control, the equilibrium coils PF3 and PF6 are used in series, while the PF1 and PF4 coils are responsible for vertical position control; these coils are connected in anti-series so that the feedback currents flow in opposite directions

The plasma current and position controllers have output limits and can provide control actions in the range of few kA. To avoid integrator saturation, an anti-windup scheme is employed.

Loop shaping technique was used to tune plasma controllers, with particular attention to the vertical position controller to obtain a stable feedback loop. DINA code simulations were used to test the plasma control system.

4. EXPERIMENTAL RESULTS

The plasma current and position control system was used in several experimental campaigns on the KTM tokamak. All discharges were carried out with ohmic plasma heating and without plasma density control. Stable limiter and diverted plasma configurations with elongation up to $k = 1.7$ were successfully obtained. A typical vertical instability growth rate in discharges with diverted plasma was $\gamma = 10\ \mathrm{s}^{-1}$.

FIG. 3 (a) shows the plasma current and the position of the plasma current centroid in discharge #6301 with diverted plasma; for comparison, the total toroidal current and the position of the total current center inside the VV are also presented. The presence of the conducting DIV inside the measurement loop ∂Ω affects both the current and the vertical position of the total current centroid. At the plasma current flattop phase, the current in the DIV is approximately 5 kA, which is about 1% of the plasma current; however, the vertical position of the total current center is 1.5 cm lower than the plasma position, which is a significant value. The current in the DIV has practically no effect on the radial position of the total current centroid.

The results of current and plasma position control in the KTM tokamak in shot #6302 with diverted plasma are shown in FIG. 3 (b). The diverted configuration was formed by 2.55 s of the discharge, after vertical displacements of the plasma did not exceed 0.5 cm

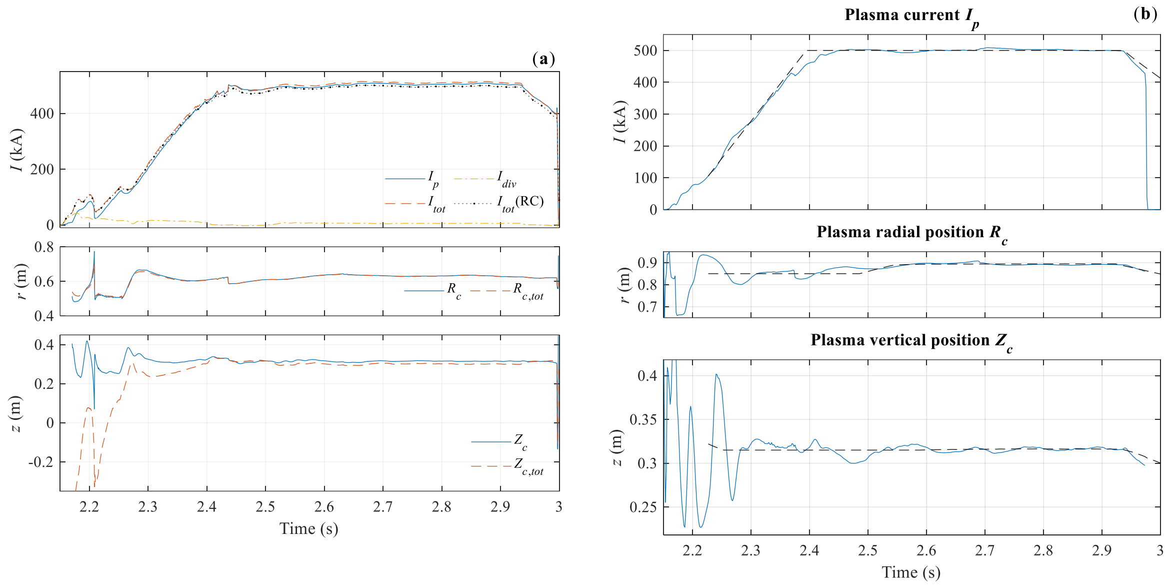

*FIG. 3. (**a**) – Plasma current I_p and plasma centroid position (R_c,Z_c) waveforms together with total toroidal current I_{tot} and its centroid position ($R_{c,tot}$, $Z_{c,tot}$) obtained in shot #6301. Additionally, the DIV current I_{div} and total current I_{tot}(RC) measured with a Rogowski coil are also shown. (**b**) – Plasma current and position waveforms obtained in shot #6302 with a diverted plasma; solid line refers to the measured values and dashed line refers to the references.*

Several plasma shapes obtained in the KTM discharges are presented in FIG. 4.

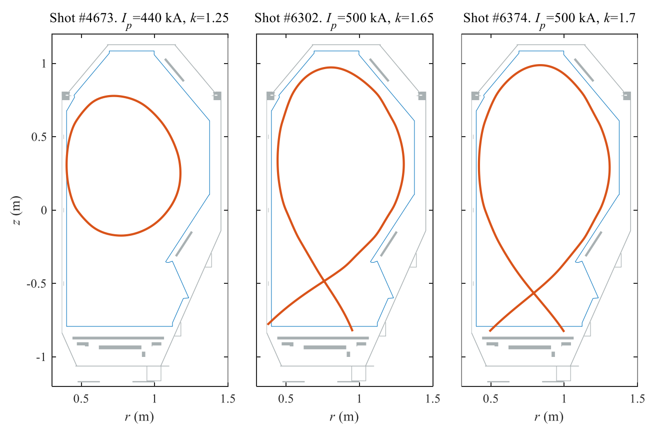

FIG. 4. Plasma cross section for one limited and two diverted stable equilibrium configurations obtained in KTM experiments

5. CONCLUSION

The plasma current and position control system has been successfully implemented and tested on the KTM tokamak. Stable limiter and diverted plasma configurations with plasma current up to 500 kA and elongation up to $k = 1.7$ were obtained using classical PID controllers. A method has been developed for measuring the plasma current and position in the presence of passive conductors inside the measurement loop. These results represent the first experience of plasma control on KTM and provide a basis for further development of magnetic control, including fast vertical position control and shape control.

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