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AN OVERVIEW OF THE FIRST EXPERIMENTAL RESULTS WITH DIVERTOR CONFIGURATION DISCHARGES IN THE KTM TOKAMAK

B. CHEKTYBAYEV[1], I. TAZHIBAYEVA[1], E. BATYRBEKOV[2], D. OLKHOVIK[1], E. KASHYKBAYEV[1], A. DUISEN[1], A. LEE[3], V. PAVLOV[3], V. DOKUKA[4], R. KHAYRUTDINOV[4]

[1] *Institute of Atomic Energy of the National Nuclear Centre of the Republic of Kazakhstan, Kurchatov, Kazakhstan*
[2] *National Nuclear Centre of the Republic of Kazakhstan, Kurchatov, Kazakhstan*
[3] *Tomsk Polytechnic University, Tomsk, Russian Federation*
[4] *NRC «Kurchatov Institute», Moscow, Russian Federation*

e-mail: Chektybaev@nnc.kz

Abstract

This paper presents the first experimental results obtained with divertor configuration discharges in the KTM tokamak, a unique facility designed for testing plasma-facing materials and advancing plasma physics studies. Stable ohmic discharges in a divertor configuration were successfully produced. The results demonstrated that the operational parameters of the KTM tokamak have approached the design values, confirming the capability of the device to sustain divertor configuration plasmas under baseline conditions. The absence of wall coatings provided valuable data on plasma-wall interactions with the graphite wall, which will be important for subsequent experiments involving boronization. These achievements validate the readiness of the KTM facility for further experimental programs aimed at additional plasma heating with ICRF system, investigation of plasma–wall interactions, and materials testing under high heat flux conditions relevant to future fusion reactors. The results establish a foundation for the continued development of KTM as a major experimental platform in the field of fusion materials science.

1. INTRODUCTION

The development of fusion energy requires reliable plasma-facing components that can withstand the extreme conditions inside fusion devices. In this context, dedicated experimental platforms play a crucial role in investigating plasma–material interactions, testing new materials, and advancing plasma physics research. The Kazakhstan Tokamak for Material Testing (KTM) was specifically designed as the world's first tokamak dedicated to a wide range of first-wall material studies relevant to future fusion reactors, including ITER. From a plasma physics perspective, KTM is also of significant interest due to its distinctive design features.

KTM is the first operating tokamak with an aspect ratio of 2, which, according to current classifications, makes it the largest spherical tokamak currently in operation. The device is equipped with a transport sluice system and a movable divertor, which enable the replacement of material samples without depressurizing the vacuum chamber. These features create unique opportunities for systematic investigations of divertor and first-wall performance under reactor-relevant conditions.

The movable divertor table of the KTM accommodates 20 cassettes, enabling the simultaneous installation of various materials. The design parameters of KTM include a plasma current of 750 kA, a toroidal magnetic field of 1 T, a divertor configuration with plasma elongation of k=1.7, and a density of $5\cdot10^{19}$ m^{-3}. With the application of additional ion cyclotron resonance heating, the discharge duration is expected to reach 5 s, while the calculated thermal loads on the divertor surface will range up to 20 MW/m^2 [1,2].

Fig. 1 provides a general view of the KTM tokamak.

This work is a continuation of the studies on the step-by-step commissioning of the KTM tokamak into operational mode [3, 4]. In 2023, stable plasma discharges were obtained in the limiter configuration with an elongation exceeding the natural values: at k=1.5, plasma current amplitude of 500 kA, and extended duration up to 2 s [5].

In 2024, experimental campaigns were conducted to achieve discharges with a divertor configuration as well as to improve and optimize plasma discharges with the divertor configuration.

Fig. 1. General view of the KTM tokamak

This paper presents the first experimental results on achieving stable ohmic plasma discharges in the divertor configuration at the KTM tokamak. The main parameters of these discharges are described, together with the conditions under which they were realized. These results mark a significant milestone in the operational development of KTM and establish a foundation for next studies involving additional plasma heating and comprehensive investigations of plasma–material interaction processes.

2. EXPERIMENTAL CONDITIONS

Plasma discharge experiments were performed in ohmic heating mode without preionization or auxiliary heating systems. Hydrogen was employed as the working gas. All scenarios were simulated using the DINA evolutionary code. The toroidal magnetic field on the axis was B_T=0.9 T. Plasma discharges were initiated by utilizing the magnetic flux in the central solenoid during its magnetization reversal from +15 kA to –25 kA. The interior of the vacuum chamber, including the divertor table, was lined with graphite tiles; no additional protective coatings (such as boronization or carbonization, nor lithuiumization) were applied to the walls. Fig. 2 depicts the interior surface of the vacuum chamber, which is entirely covered with graphite.

Fig. 2. Internal view of the vacuum chamber

One of the key aspects of plasma discharge generation at this stage is the use of the PF1 and PF4 poloidal field coils, to control the vertical plasma position. These coils operate within the slow control loop. A model of the KTM electromagnetic system with the vacuum chamber is presented in Fig. 3.

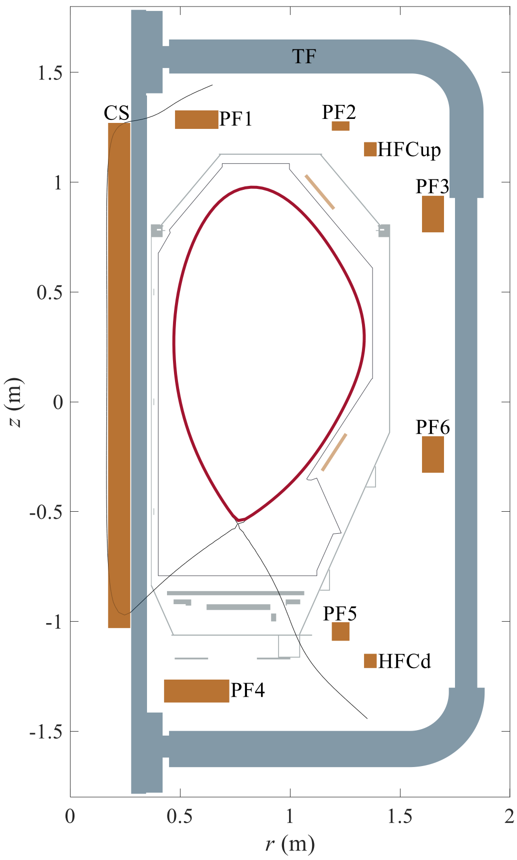
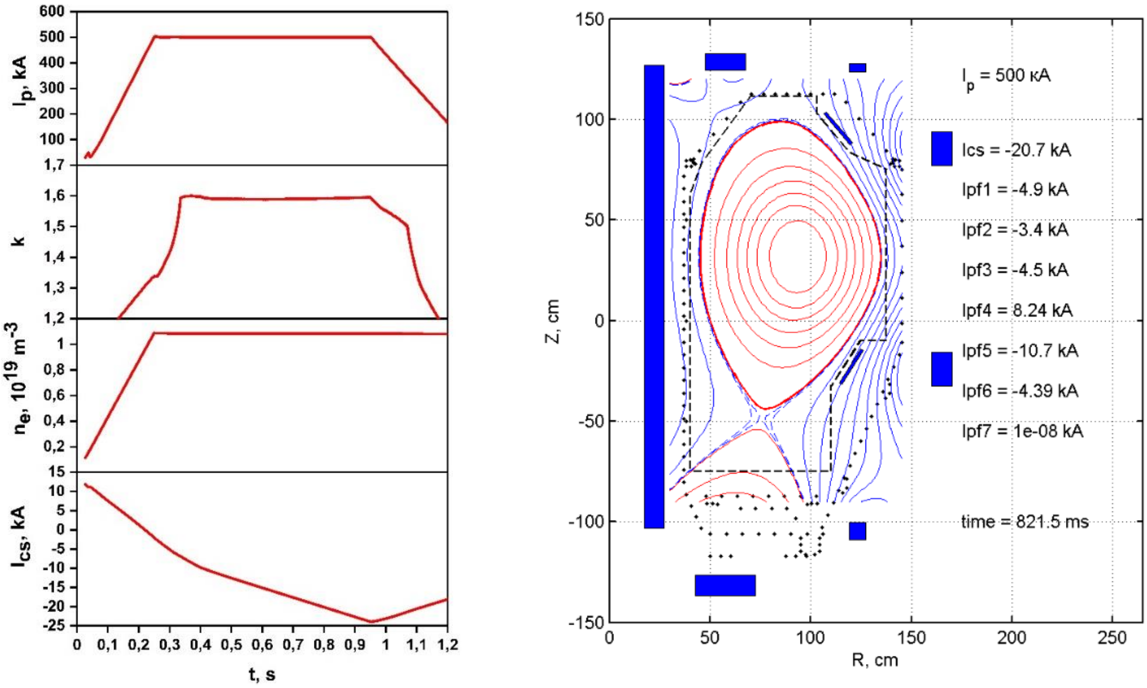


Fig. 2. Model of the KTM electromagnetic system with the vacuum chamber

For vertical plasma control and rapid stabilization in the KTM tokamak, a fast control system utilizing the HFC coils was originally designed. However, due to technical circumstances and the unavailability of this control circuit at the time of the divertor configuration plasma discharge experiments, the PF1 and PF4 coils were employed instead. Preliminary calculations of vertical plasma position control using the PF1 and PF4 coils [6, 7] demonstrated the feasibility of vertical stabilization in the divertor configuration within a plasma current range of 500–700 kA.

Such calculations were performed on the basis of previously obtained limiter configuration discharges with a plasma current of 500 kA [5]. Using these experimental data, discharge scenarios were modeled for a single-null divertor configuration with elongation up to 1.7. Several scenarios were calculated, differing by the plasma density at the plateau stage, ⟨ne⟩, ranging from $1 \cdot 10^{19}$ m^{-3} to $5 \cdot 10^{19}$ m^{-3}. Fig. 4 presents an example of a calculated discharge scenario with a plasma current amplitude of 500 kA, a divertor configuration with plateau elongation k = 1.6, and an average plasma density of ⟨ne⟩ = $1 \cdot 10^{19}$ m^{-3}.

In these calculations, it was assumed that the plasma density increases simultaneously with the plasma current and reaches its limiting value at the plasma current plateau. Plasma vertical elongation was also assumed to occur during the current ramp-up phase, with the divertor configuration forming immediately after the plasma current reached the plateau (Fig. 4a). The plasma current ramp-up rate was set at 2.5 MA/s.



a) Calculated evolution of the plasma current I_{pl}, plasma density ⟨ne⟩, central solenoid current Ics

b) Equilibrium plasma configuration at the plasma-current plateau at time t=821.5 ms

Fig. 4. Calculated parameters of a plasma discharge scenario with a divertor configuration, elongation k = 1.6, plasma density ⟨ne⟩ = $1\cdot10^{19}$ m^{-3} and current in central solenoid

Measurement and control of plasma parameters were carried out using the following set of diagnostics: electromagnetic probes, Rogowski coils, a high-speed camera, a wide-view VIS spectrometer, monitors of the hydrogen Hα line and the carbon CIII line, a hard X-ray monitor based on a NaI scintillator, a wide-view pyroelectric bolometer, infrared pyrometers, and a long-wave infrared (LWIR) thermal imaging camera for divertor surface temperature measurements [4]. The arrangement of diagnostics on the KTM vacuum chamber is shown in Figure 5.

Due to the failure of the microwave interferometer, plasma density was not measured during these experiments. The Hα and CIII monitors were installed in an equatorial port and provided a horizontal line of sight through the plasma toward the inner cylinder of the vacuum chamber. The infrared pyrometers were positioned to observe the plasma along the same line of sight.

In the experiments, additional hydrogen was injected into the vacuum chamber to increase plasma density. The gas was supplied through a vertical track port on the chamber's top lid and was controlled programmatically according to a predefined timing diagram.

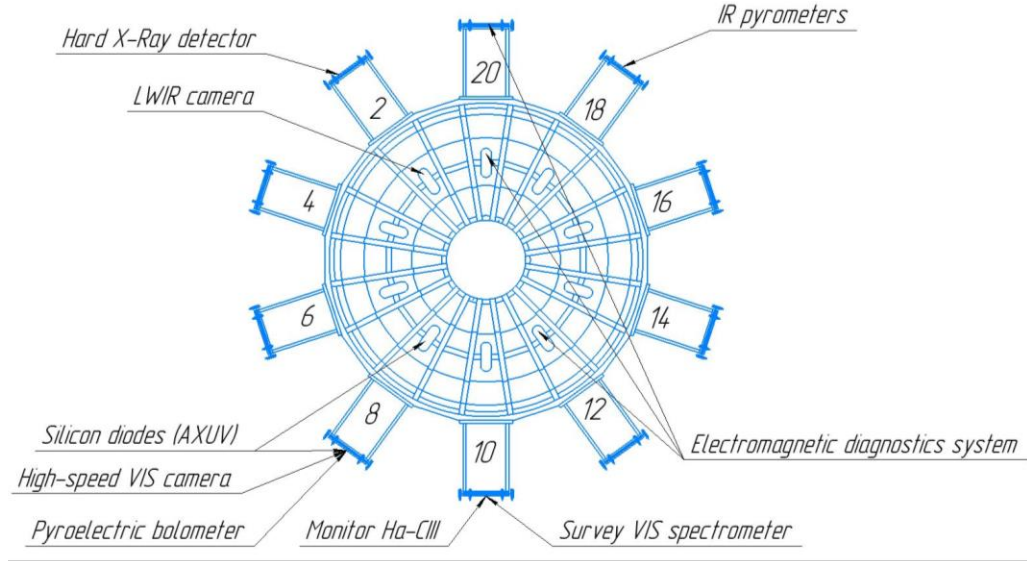


Fig. 5. Layout of the KTM diagnostics on the vacuum chamber

3. EXPERIMENTAL RESULTS

As a result of the experiments on KTM, stable plasma discharges with a single-null divertor configuration were obtained. Fig. 6 shows the parameters of a representative discharge with a plasma current of 500 kA and an elongation of k = 1.6.

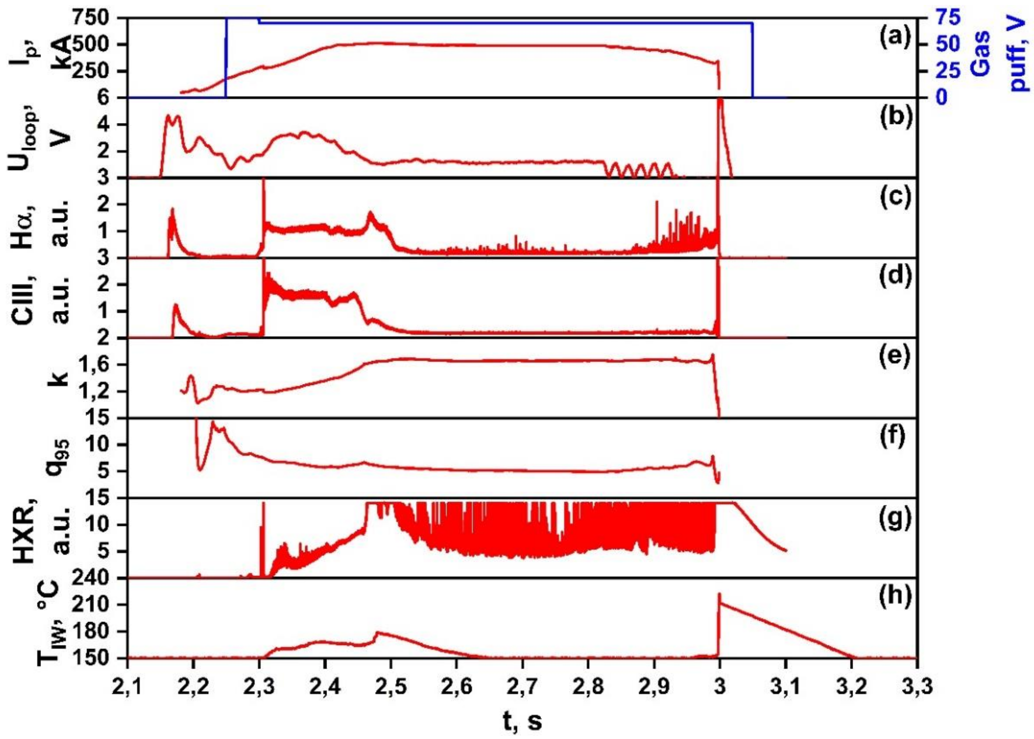
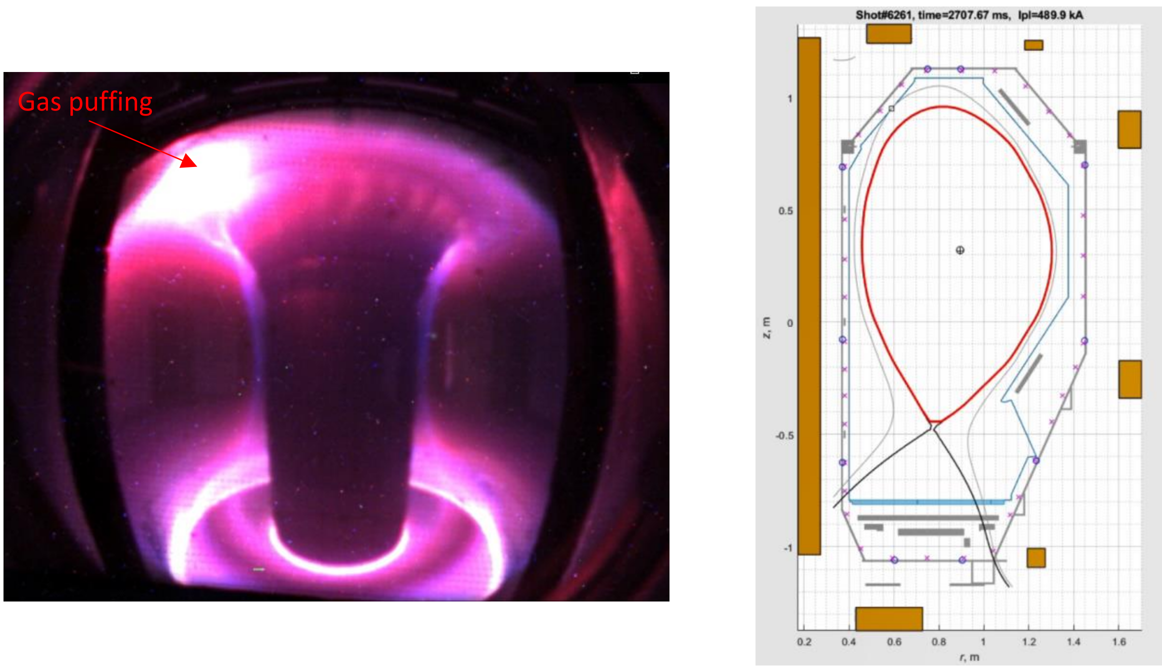


Fig. 6. Plasma parameters for discharge #6261 with a divertor configuration

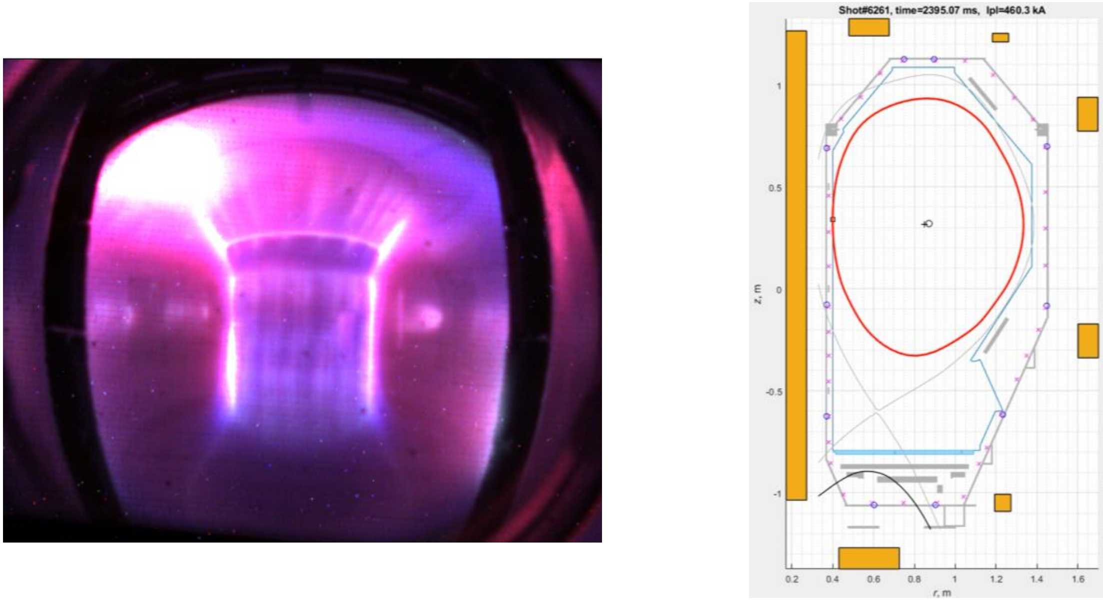
Figs. 7 and 8 show a video frame and the corresponding reconstructed plasma shape at the current plateau, as well as a thermal image from the thermograph at t = 2.707 s for the considered discharge #6261. The video frame shows light emission in the upper left corner, caused by the injection of working gas from the port on the vacuum chamber lid. For comparison, Fig. 9 shows a video frame and the reconstructed plasma shape at t = 2.395 s during the plasma current rise in a limiter configuration.



a) *b)*

Fig. 7. Plasma image in a divertor configuration, discharge #6261, t = 2.707 s.

Fig. 8. Thermal image of the divertor table surface from the thermographic camera for discharge #6261 at t=2.707 s



a) *b)*

Fig. 9. Plasma image in a limiter configuration, discharge #6261, t = 2.395 s.

As can be seen from the experimental data, the discharge evolution follows the calculated scenario (Fig. 4). The plasma elongation increases during the current ramp-up phase and stabilizes immediately after reaching the plasma current plateau, approximately 50 ms later. At the current plateau, the vertical elongation k of the plasma reaches 1.6.

Fig. 7 shows that the plasma exhibits a lower single-null divertor configuration. The transition of the plasma from a limiter to a divertor configuration is also confirmed by the decrease in the intensity of hydrogen Hα and carbon C III line emissions (Figs. 6 c,d), which occurs due to the detachment of the plasma from the inner wall.

During the plasma current rise, the intensity of Hα, C III, and hard X-ray emissions increases (Fig. 6). This is associated with plasma interaction with the first wall in the limiter phase of the discharge. The main interaction region is located on the inner wall at the equatorial plane, with a smaller contribution on the upper cone (Fig. 9). Thus, as the plasma current increases, interaction with the wall intensifies, leading to higher emission intensity of hydrogen Hα, carbon C III, and X-rays, consistent with the scenario in which the plasma remains in a limiter configuration before reaching the current plateau.

Plasma–wall interaction during the limiter phase heats the graphite tiles on the inner wall up to 180 °C (Fig. 6 h, first peak). After the plasma transitions to the divertor configuration and detaches from the wall, the intense interaction ceases, and the tiles cool down, further indicating the formation of a divertor configuration.

Thermal imaging (Fig. 8) shows heating of the divertor plate surfaces in the Outer Strike Point (OSP) region, while the Inner Strike Point (ISP) is located on the lower tiles of the central column. This heating pattern also confirms the formation of the divertor configuration. Surface temperatures of the divertor plates during these discharges reach up to 250 °C. At the current plateau, the outer separatrix is located at a large radius R=0.8–0.9m. Estimated thermal loads on the divertor surface for these discharges were up to 5 MW/m^2.

During plasma discharges with a divertor configuration, instabilities such as unipolar arcs and minor disruptions were observed during the current rise (Fig. 6, t = 2.3 s), followed by graphite particle injection into the plasma, as reported in [5].

The sinusoidal oscillations observed near the end of the discharge (Figs. 6 a,b) occur when the CS current reaches its maximum allowable value. They result from an improperly chosen method for calculating the CS current setpoint in the plasma current control system when the inductor reaches its maximum current limit. This issue was corrected in subsequent revisions of the PCS software.

Fig. 10 illustrates the evolution of currents in the CS, PF1, and PF4 coils, as well as the position of the plasma center in R and Z, both according to the calculated scenario (Reference) and as measured during the discharge (Measure).

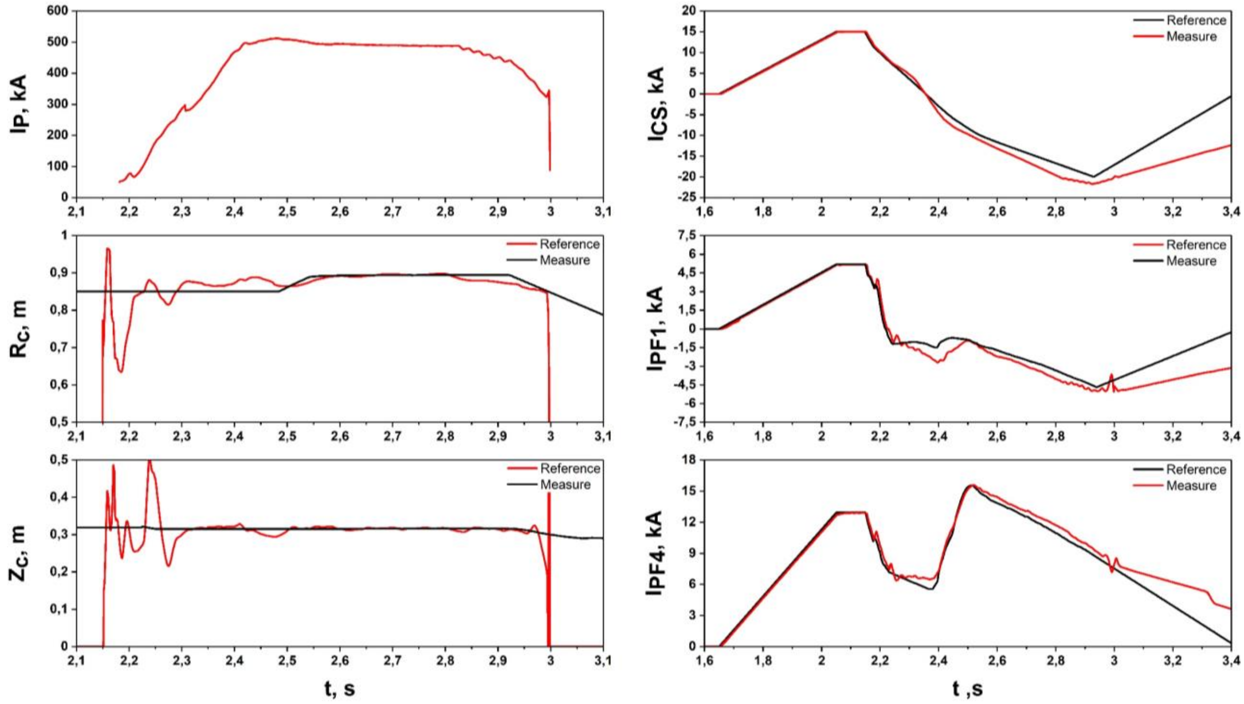


Fig. 10. Evolution of currents in the CS, PF1, and PF4 coils and the position of the plasma center in R and Z for discharge #6261.

Overall, the deviation of the plasma center position in Zc and Rc from the setpoint at the current plateau does not exceed ΔZc = 10 mm and ΔRc = 5 mm. The plasma control system effectively compensates for vertical plasma displacement. As can be seen in Fig. 10, the deviations of currents in the CS, PF1, and PF4 coils from their reference values are associated with the operation of the plasma current and position regulators.

4. CONCLUSION

Stable plasma discharges with a divertor configuration and a vertical elongation of k=1.6 were obtained on KTM, with a plasma current amplitude of 500 kA. These results represent a significant milestone in the operational development of KTM and provide a foundation for further studies involving additional plasma heating and comprehensive investigations of plasma–material interaction processes. The achieved results were subsequently used to carry out experiments aiming at plasma discharges with a nominal current of 750 kA.

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