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MASTer: A high-performance stable temperature controller for high-pressure multi-anvil presses

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ABSTRACT

Maintaining stable high temperatures under pressure remains a challenge in high-pressure, high-temperature experiments using multi-anvil presses (MAPs). Temperature fluctuations exceeding 10 °C at high pressures are common and particularly problematic with LaCrO₃ heaters, which can experience significant power fluctuations and even failure due to substantial resistance changes—an issue conventional thyristor-controlled heating systems cannot effectively manage. To address this limitation, we have developed the Multi-Anvil Stable Temperature controller (MASTer), a high-performance heating system optimized for MAP experiments. MASTer enables precise, high-speed measurement of heating parameters and power output control, incorporating a gentle regulation strategy to enhance stability. It ensures consistent heating across various heater types, including LaCrO₃, with power fluctuations limited to ±0.1 W and temperature fluctuations to within ±2 °C in most cases. The design, operating principles, user interface, functionality, and performance of the heating system are discussed in detail.

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I. INTRODUCTION

The multi-anvil press (MAP) is a high-pressure and high-temperature (HP-HT) apparatus that is widely used to simulate planetary interiors, synthesize novel materials, and study physical properties under extreme conditions. Since its invention by Hall in 1958,¹ the MAP has undergone significant developments enabling it to reach pressures up to 120 GPa² and temperatures up to 4000 K.³ Advances in MAP technology have also enabled *in situ* X-ray⁴ and neutron⁵ observations, as well as measurements of key physical properties such as acoustic velocity⁶ and electrical conductivity.⁷ One of the key advantages of the MAP over the diamond anvil cell (DAC) is its ability to provide a stable and homogeneous temperature field in large-volume samples, which is essential for prolonged HP-HT experiments.

Conventional MAP heating systems, typically industrial thyristor systems, have a line regulation of ±1%–2% for ±10% of the

input variation and a load regulation of up to ±5% for the load change from zero to maximum. As the multi-anvil heater is very small, resulting in a very low thermal inertia, the sample temperature can easily fluctuate by ±20 K at 2000 K. In addition, the capacity of common commercial thyristors is more than 6 kW, while the power required for multi-anvil experiments is 200–400 W. This mismatch makes it difficult to accurately adjust the sample temperature to the target temperature. For these reasons, a heating system that can precisely control the sample temperature with a tiny heater is necessary.

Among various heater materials, LaCrO₃ is particularly useful for MAP experiments. It can reach temperatures above 3000 K at pressures above 3 GPa⁸ and provides a more uniform temperature field than other heaters. However, maintaining stable heating with LaCrO₃ using conventional systems is challenging. Its resistance decreases significantly with rising temperature: at 500 K, for example, it is only several percent of its ambient value. Such

a dramatic decrease makes it difficult to stabilize power using a thyristor-based controller, which struggles with measurement accuracy, control speed, and power stability. Furthermore, a thyristor system attempts to regulate both power supply fluctuations (line regulation) and heater resistance changes (load regulation) using a single function, which is insufficient for maintaining stable operation. Therefore, a special heating system that can stabilize the heating using a LaCrO_3 heater is desired.

To overcome these challenges, at the Center for High Pressure Science and Technology Advanced Research (HPSTAR), Beijing, we have developed the Multi-Anvil Stable Temperature controller (MASTer), a high-performance heating system for MAP experiments. MASTer features fast and precise measurement of heating parameters, accurate power control, and a gentle approach control strategy. It effectively stabilizes heating for various heater types, particularly LaCrO_3 , maintaining power fluctuations within ± 0.1 W and temperature fluctuations within ± 2 °C in most cases. This advance marks a significant milestone in achieving high-temperature precision in MAP experiments.

II. SYSTEM DESIGN AND EXPERIMENTAL METHOD

A. Composition

Figures 1(a) and 1(b) show a photograph and a schematic of the MASTer system, which consists of a programmable AC power supply (IT7803-350-30U, ITECH), five high-precision digital multimeters (DMMs; each a DMM6500, Keithley, with 6.5-digit accuracy), and a voltage transformer with five selectable secondary voltage levels (5, 10, 20, 50, and 100 V). As shown in Fig. 1(a), all components, except for the PC, are housed within a cabinet, allowing convenient access to the DMM panels and manual adjustment of transformer

voltage levels via the front panel. Figure 1(b) illustrates the operation of the system: the power supply generates a sinusoidal waveform with adjustable amplitude at 50 Hz. The voltage transformer regulates the voltage and current before applying them to the heater. The five DMMs independently measure the primary and secondary voltages U_1 and U_2 , the primary and secondary currents I_1 and I_2 , and the electromotive force (EMF) from a thermocouple placed inside the heater. Dedicated PC software with a graphical user interface (GUI) was developed to acquire real-time data from the DMMs, display U_1 , U_2 , I_1 , I_2 , and EMF on a monitor, and control the output voltage of the power supply. The devices communicate with the software via a 100 Mbps LAN connection. Given the 8–10 ms upstream–downstream latency between the DMMs and the control PC, and that one cycle of a 50 Hz AC signal lasts 20 ms, the system achieves a maximum sampling rate of 30 root mean square (RMS) measurements per second.

B. Principles

The MASTer system is based on three fundamental principles. First, a high-stability power supply ensures precise voltage control. Its load regulation remains within $0.05\% + 0.05\%$ FS, even when the commercial power supply fluctuates by up to 10%. However, in practice, commercial power fluctuations at MAP experiment sites rarely exceed 1%, meaning that actual stability is significantly better than the specified limit. This feature allows the system to generate a stable voltage with minimal variation, effectively mitigating external fluctuations. Second, accurate and fast measurement of heating parameters enables real-time regulation against power fluctuations and heater resistance changes. Voltages and currents—particularly on the secondary (heater) side—are precisely tracked using 6.5-digit DMMs and a current transformer with 0.10% FS accuracy,

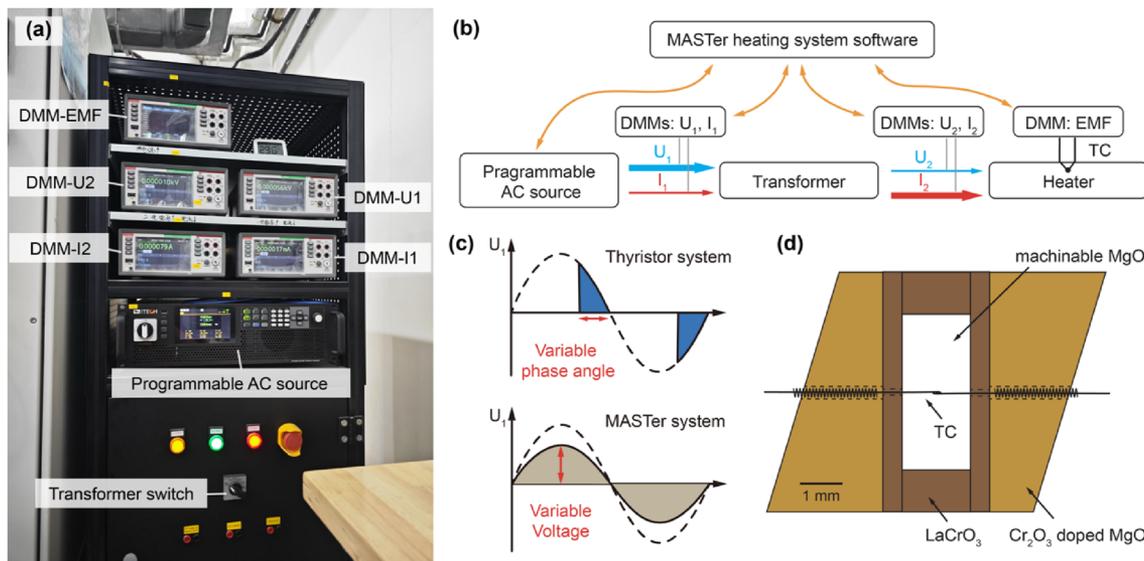


FIG. 1. (a) Assembled MASTer heating system cabinet. (b) Schematic of MASTer system composition. The yellow arrows indicate the data communication between the PC and the devices, and the blue and red lines indicate voltage and current outputs, respectively. Abbreviations: DMM, digital multimeter; EMF, thermo-electromotive force; TC, thermocouple. (c) Schematics of output voltages produced by a thyristor system and the MASTer system. (d) Schematic cross section of the test assembly.

achieving a sampling rate of 30 measurements per second. Furthermore, synchronization of DMM data within each cycle corrects accumulated timing discrepancies across devices, ensuring reliable detection and response to abrupt resistance shifts. Last, a gentle regulation strategy, characterized by establishing a gradual approach path to the target voltage, prevents excessive system response to sudden changes. When the heater resistance changes by a factor of q , the output voltage is adjusted proportionally by $q^{1/n}$, where n (typically 6) defines the gradual scaling factor. This strategy minimizes instability and prevents oscillation, resulting in more stable regulation.

Figure 1(c) compares the output voltages of the MASTer system and a thyristor-based system, which is typically used in industrial applications with power levels exceeding kilowatts and heating volumes larger than 1 L. Owing to the high thermal inertia of such large systems, power fluctuations have a minimal impact on temperature stability. However, when applied to the much smaller heater in a MAP cell, thyristor-based regulation proves ineffective for several reasons. First, thyristor systems have lower voltage regulation precision, typically $\pm 0.5\%$ FS or worse, compared with the more stable AC power source in the MASTer system. Second, voltage regulation is achieved by adjusting the conduction phase angle, but since the input voltage is not a perfect sinusoidal wave, fluctuations occur even when the phase angle is fixed, introducing additional uncertainty. Third, thyristors regulate voltage by segmenting the sinusoidal wave, creating discontinuities in the time

domain, which complicates precise RMS measurements, particularly for devices relying on analog-to-digital converter (ADC). These limitations make thyristor-based regulation unsuitable for the precise control required in MAP cell heating applications.

C. Interface and function

As shown in Fig. 2, the system has a user-friendly interface divided into three sections. The measurement section, located at the top left of the main window, displays key heating parameters, including temperature and primary and secondary voltage and current, as well as derived values such as heating power and resistance. The control section, at the bottom left, offers power and temperature control modes, allowing users to increase these parameters to preset values at a user-defined constant rate. The graph section, on the right, provides real-time visualizations of heating parameters over the past 5, 10, or 15 min. It also displays temperature–power and resistance–power relationships, aiding in the detection of abnormalities during heating. All data is recorded in a heating log file at selectable sampling rates of 1, 5, 10, or 30 times per second. Additionally, the high-speed, synchronized readings of the system enable precise measurement of quench rate after power cutoff, achieving a maximum resolution of 30 readings per second, comparable to previous work.^{9,10} Users can further customize control parameters, including the reference temperature, index root operation factor q , and temperature–EMF tables, ensuring flexibility for various experimental needs.

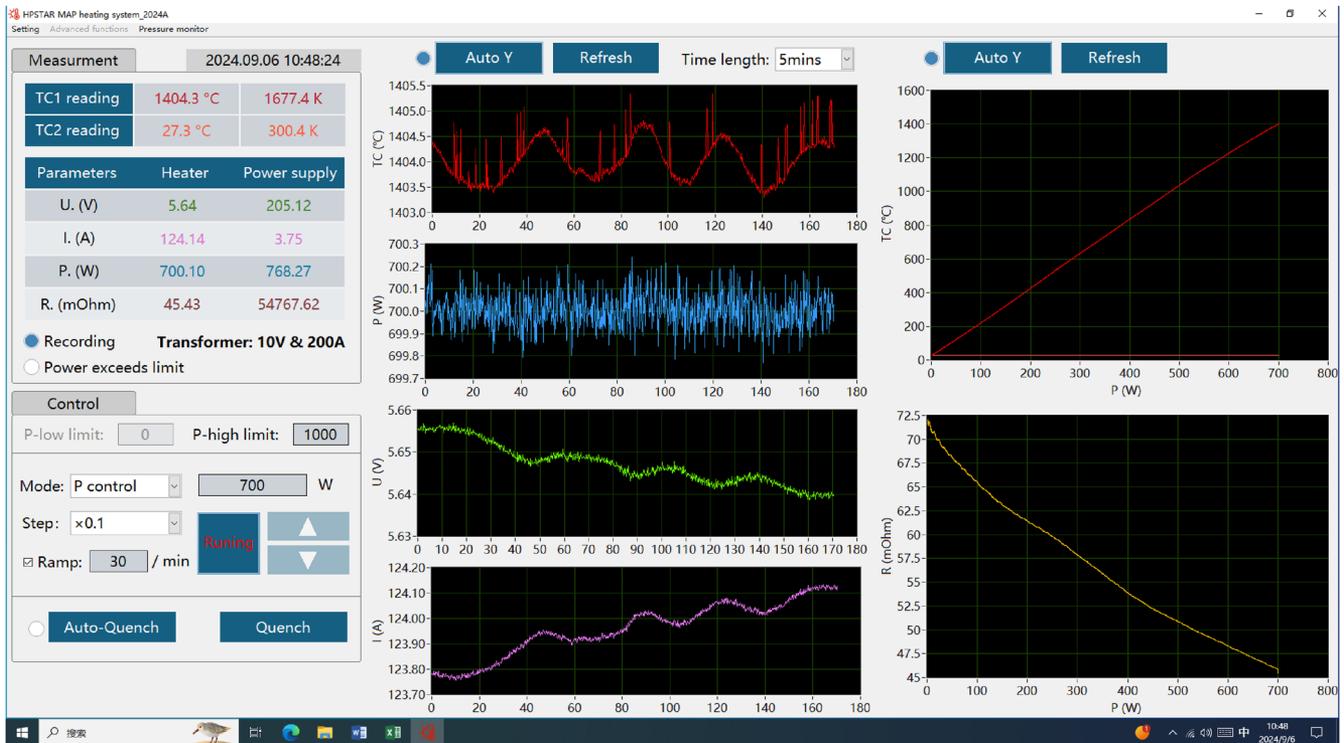


FIG. 2. Interface of MASTer heating system.

D. Performance test

For the comparative tests, a 7/3 cell assembly with a LaCrO_3 heater was used, as shown in Fig. 1(d). The pressure medium was an octahedron made of MgO doped with 5 wt. % Cr_2O_3 , while the heater was a cylinder made of doped LaCrO_3 (S6 type, Mino Ceramic Co., Ltd.). Temperature measurements were performed using a W97Re3-W75Re25 (D-type) thermocouple, with its junction positioned at the geometric center of the assembly. To prevent tensile breakage caused by pressure medium flow, thermocouple coils made of the same material were incorporated. The heater's interior was filled with machinable MgO to eliminate external influences. Further details of the assembly can be found in previous MAP studies.

The tests were conducted in a 1500-ton Kawai press at ~ 23 GPa, with heating first applied using the MASTER system and then by the thyristor system. Heating data were obtained directly from the data logs of both systems. The heating current waveform over multiple power line cycles was converted into a voltage signal via a current transformer and recorded using a DMM in voltage mode. Simultaneously, thermocouple signals were monitored with both a DMM and an oscilloscope (Tektronix MSO44) to ensure precise temperature tracking.

III. RESULTS AND DISCUSSION

A. Heating regulation performance

Regulating a heater under HP-HT conditions requires both rapid and precise adjustments against its resistance changes. This challenge is particularly pronounced in semiconductor heating elements such as LaCrO_3 , whose resistance decreases exponentially with increasing temperature owing to its Arrhenius-type conductivity.¹¹ At the start of heating, the LaCrO_3 heater's

resistance drops sharply to one-tenth of its initial value, causing power instability. Without proper control, the resulting temperature–resistance–power mismatch can cause severe fluctuations, potentially leading to heater failure or blowout, as shown in Fig. 3. Even at high temperatures, where resistance fluctuations are less significant, achieving stable power output in a small furnace remains difficult, owing to the precision limits of the heating system. To evaluate these challenges, we conducted a comparative heating performance test using a 7/3 assembly with a LaCrO_3 heater, which presents challenges on both sides. We heated the compressed assembly using our MASTER system, in both power control and temperature control modes.

Figures 4(a) and 4(b) illustrate the power–temperature relationship in power control mode, in which the power was increased at a constant rate of 30 W/min to 200 W and then 400 W, before being reduced back to 200 W and finally to 0 W at the same rate. Throughout this process, the temperature response was monitored. When the power was held at 400 W for 5 min, the power fluctuations remained within ± 0.1 W, and the temperature drifted only slightly from 1590 to 1567 °C, with fluctuations within ± 1 °C. Figures 4(c) and 4(d) show the power–temperature fluctuations in temperature control mode, in which the temperature was increased at a constant rate of 50 °C/min to 600 °C, then to 1000 °C, and then to 1600 °C, before being reduced at the same rate to 1000 °C and then to 600 °C. When the temperature was held at 1600 °C for 7 min, fluctuations remained within ± 1 °C, while the power drifted slightly from 417 to 423 W, with fluctuations within ± 0.1 W. For benchmarking, we attempted to heat the same assembly using a thyristor system. Although the power control mode was successfully implemented, the temperature control mode proved ineffective, even after the resistance change had stabilized following the MASTER system tests. This highlights the limitations of thyristor-based regulation for precise temperature control under HP-HT conditions.

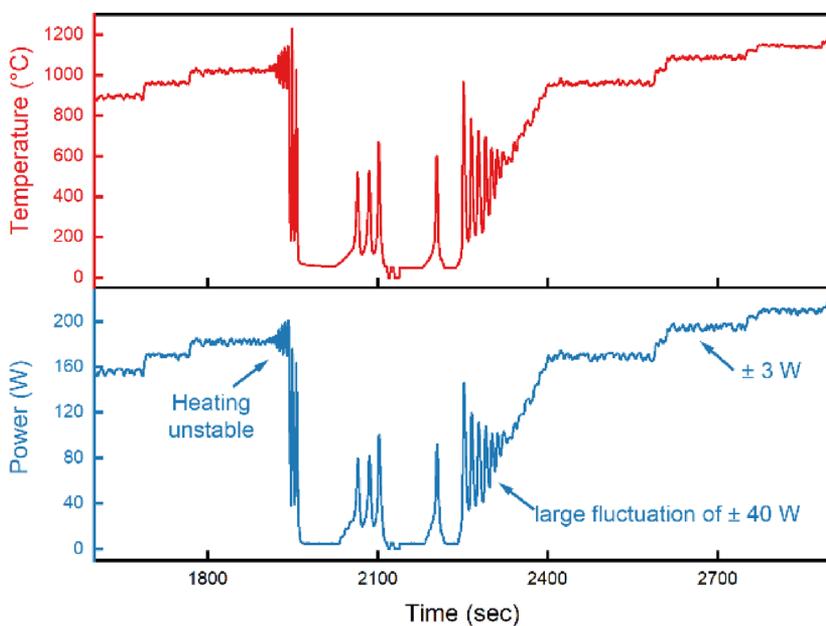


FIG. 3. Large fluctuations in temperature and power when a thyristor system operates with a LaCrO_3 heater.

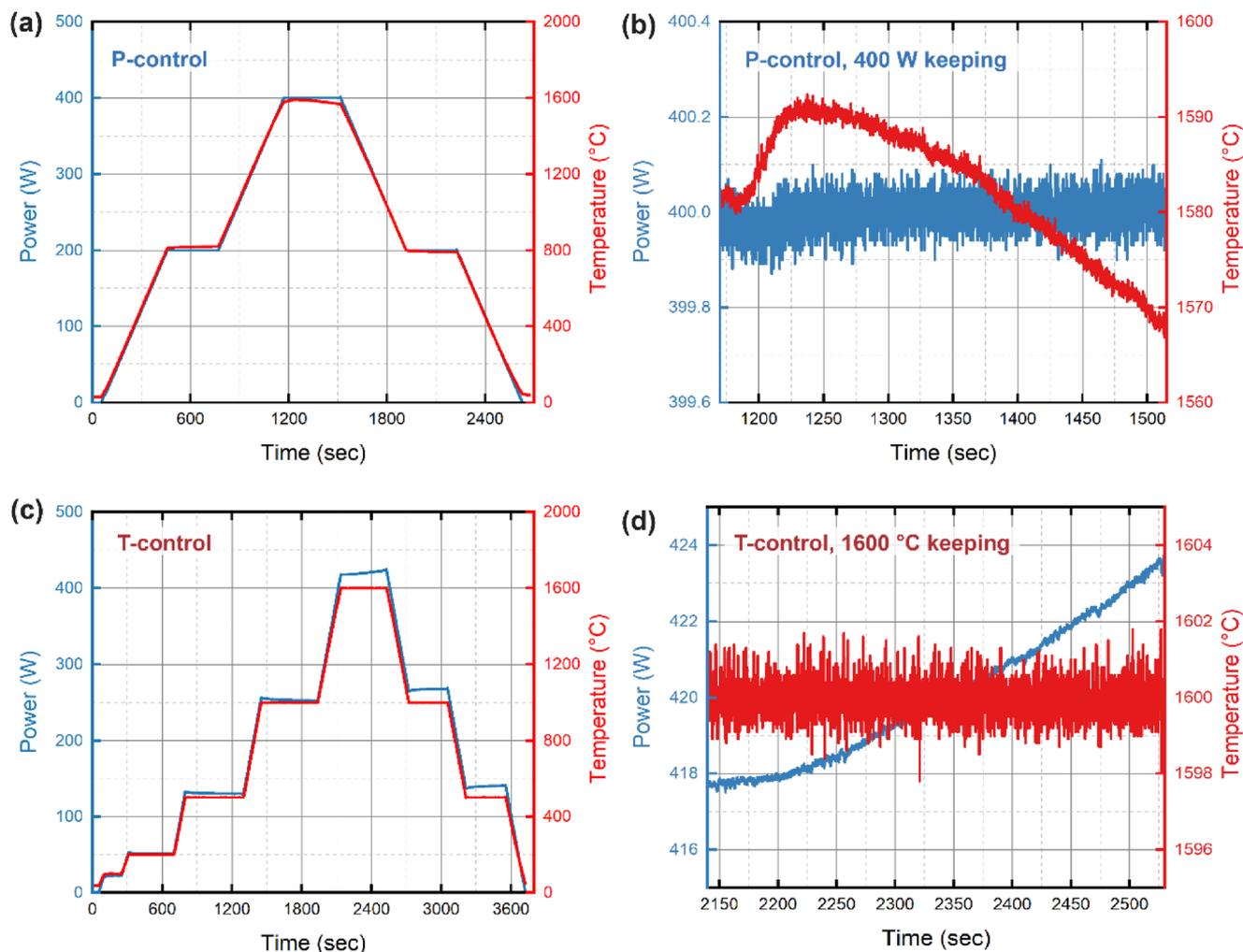


FIG. 4. Power (blue) and temperature (red) profiles vs time. (a) and (c) Overall heating profiles in power and temperature control modes, respectively. (b) and (d) Profiles during power hold with enlarged Y-scales in power and temperature control modes, respectively.

Figures 5(a) and 5(b) compare power and temperature fluctuations at a constant output power of 400 W for both systems. The MASTer system maintained power fluctuations within ± 0.1 W, whereas the thyristor system exhibited fluctuations ranging from +0.4 to -1.4 W. Similarly, temperature fluctuations in the MASTer system remained within ± 1 °C, whereas the thyristor system fluctuated by ± 5 °C or more. Figure 5(c) shows the secondary heating current waveform for both systems. The thyristor system produced a chopped sinusoidal curve, whereas the MASTer system generated a nearly perfect sinusoidal AC current. Figure 5(d) compares the EMF signals from both systems. Since the thermocouple was not electrically insulated from the heater, both signals contain noise. The raw data, shown as a dark violet curve, were collected using an oscilloscope at a sampling rate of 1 MHz and processed using a 40–60 Hz bandpass filter to isolate the thermocouple waveform from electromagnetic interference, resulting in the light violet curve. In

the MASTer system, the EMF waveform is fully sinusoidal, whereas in the thyristor system, it is chopped sinusoidal. Additionally, the thyristor system's waveform is symmetrical in voltage, but asymmetrical in time, causing higher peak EMF values than those observed in the MASTer system. The lower peak EMF in the MASTer system reduces measurement errors caused by asymmetric noise, improving accuracy, since the signal remains time-independent.

To assess the MASTer system under more demanding conditions, we conducted a heating test using a 6/1.5 assembly with a small LaCrO_3 heater (outer/inner diameter 1.2 mm/0.8 mm), known for its high-temperature generation efficiency.¹² The experiment was conducted at 35 GPa, and, as shown in Fig. 6(a), a temperature of 1727 °C was achieved with only 139 W of power. Thanks to the high performance of the MASTer system, power fluctuations remained within ± 0.1 W, and temperature fluctuations were limited to ± 3 °C over a 30-min observation period [Fig. 6(b)]. This fluctuation aligns

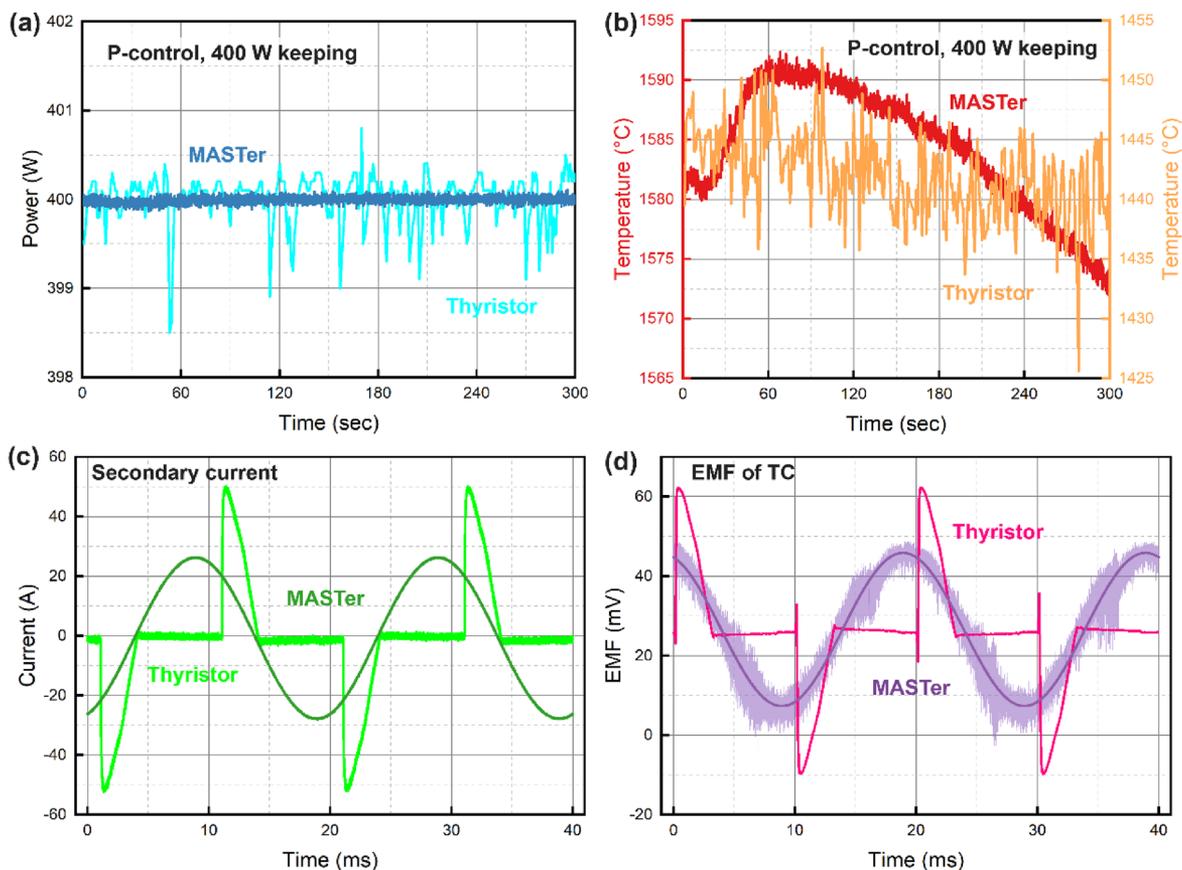


FIG. 5. (a) and (b) Comparisons of fluctuation and drift in power and temperature, respectively, over time in heating tests using the thyristor and MASTer systems at 400 W holding: blue, power with the MASTer system; cyan, power with the thyristor system; red, temperature with the MASTer system; orange, temperature with the thyristor system. (c) and (d) Comparisons of secondary current and EMF waveforms, respectively, for 40 ms during heating tests using the thyristor and MASTer systems at 400 W holding: dark green, current with the MASTer system; light green, current with the thyristor system; dark violet, EMF with the MASTer system; magenta, EMF with the thyristor system.

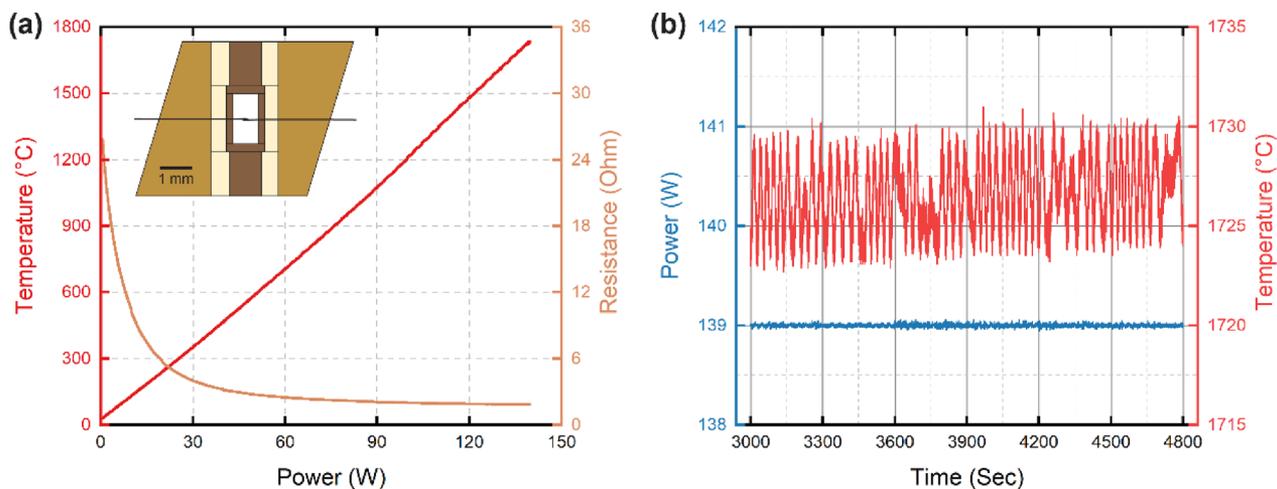


FIG. 6. Heating profiles of a 6/1.5 assembly with a LaCrO_3 heater. (a) Temperature and resistance curves vs power. The inset shows a schematic of the assembly used, in which an additional cylindrical layer of ZrO_2 provided better thermal insulation. (b) Power and temperature fluctuations over time at 139 W.

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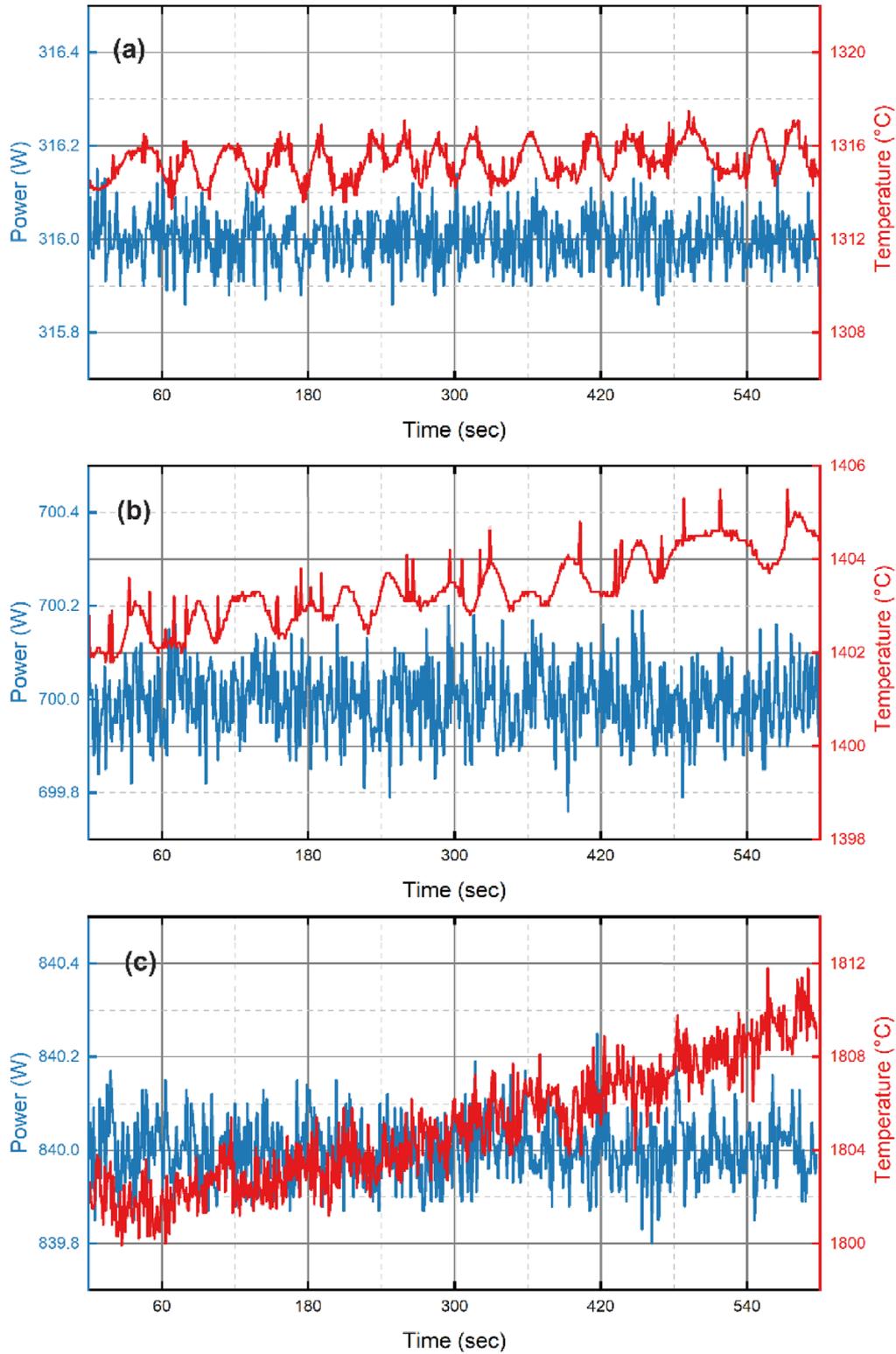


FIG. 7. Power and temperature fluctuations when the MASTer system was applied to (a) Re heater, 7/3 assembly (b) graphite heater, 14/8 assembly and (c) TiB₂ composite heater, 10/5 assembly.

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with our expectations, since power and temperature fluctuations should be proportional. The power was then maintained for 24 h, with a temperature drift of only 5 °C, demonstrating the long-term stability of the MASTer system. By contrast, if the thyristor system had been used to control this small heater, its ± 1 W power fluctuation would have resulted in ± 20 °C temperature fluctuations, leading to significant instability in HP-HT experiments.

B. Adaptability on various heaters

To evaluate the adaptability of the MASTer system, we tested its performance with various heaters, including Re, graphite, and TiB₂ composites, using different assembly designs. As shown in Fig. 7, the system effectively controlled heating power within ± 0.1 W, maintaining temperature fluctuations within ± 2 °C in power control mode without requiring parameter adjustments. This demonstrates the robustness of the MASTer system's control strategy, which ensures a gradual approach to the target temperature and adaptive response to changes. By contrast, the thyristor system relies on

proportional–integral–derivative (PID) regulation, which requires careful tuning of P, I, and D values for different heaters. Incorrect PID settings can lead to instability or excessive reactions to temperature fluctuations.

C. Application to high-temperature generation over 2800 °C

We further tested the performance of our system in generating stable high temperatures above 2800 °C using a 14/8 assembly with a LaCrO₃ heater at ~ 14 GPa. A low-thermal-gradient design, similar to that in Ref. 13, was implemented. As shown in Fig. 8(a), the thermocouple was electrically isolated from the heater using two Al₂O₃ sleeves, and its EMF–temperature relationship above 2310 °C was adapted from Ref. 14 and integrated into the MASTer system's configuration. Since the calibration was performed at ambient pressure, the actual temperature is estimated to be higher than its readings, for example, by about 150 °C higher at 2800 °C using the correction raised in Ref. 15. Notably, between

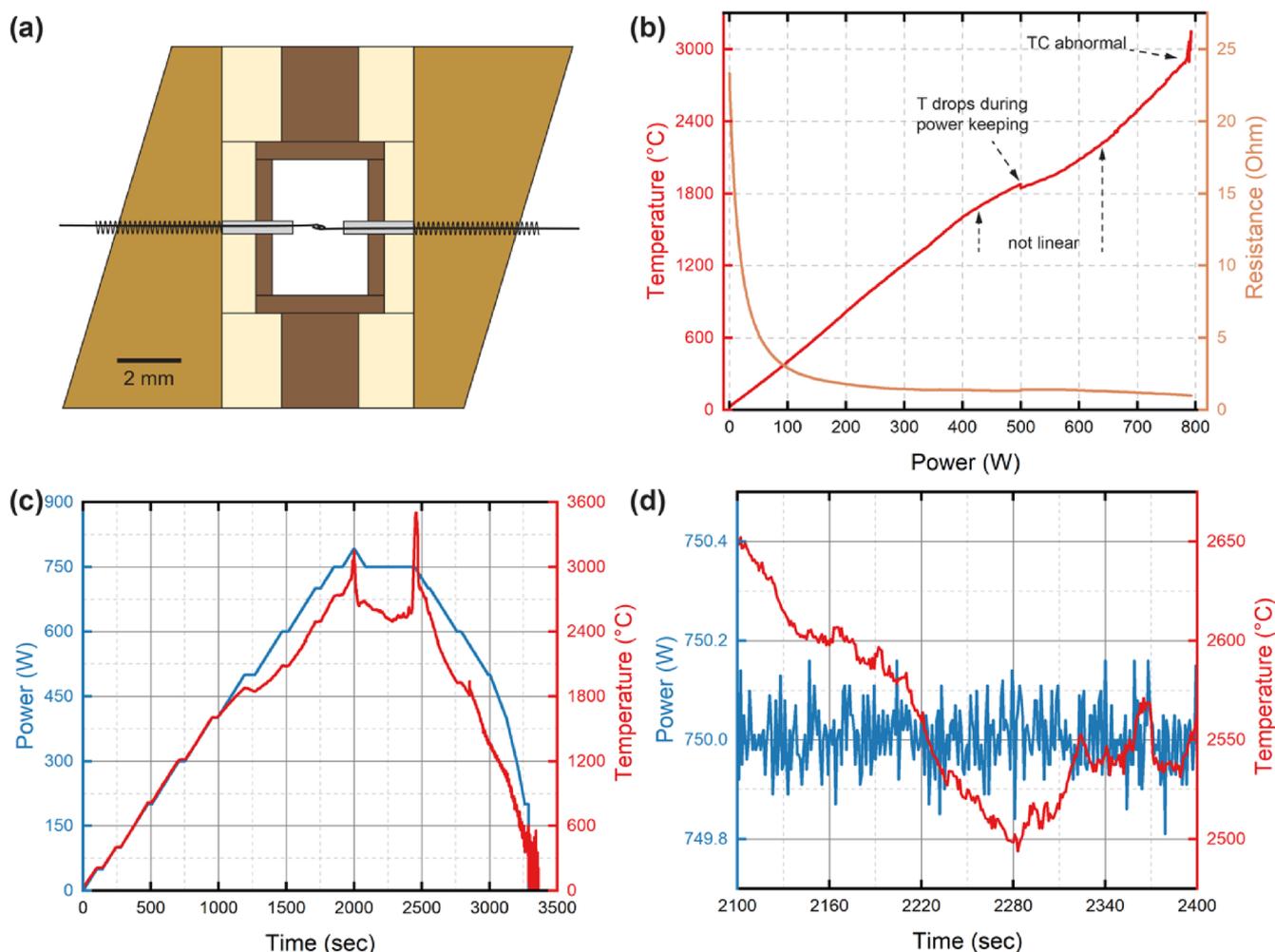


FIG. 8. Profiles of high-temperature generation over 2800 °C. (a) Schematic of the 14/8 assembly used. (b) Temperature–power and resistance–power relationships. (c) Heating power and temperature vs time. (d) Power and temperature fluctuations in 5 min at 750 W keeping.

1620 and 2110 °C, the EMF–temperature relationship deviates from linearity [Fig. 8(b)], likely owing to phase transitions in ZrO₂ or reactions with surrounding materials. At 2800 °C, the thermocouple readings began drifting higher than expected based on power input, while the EMF signal amplitude observed on the DMM screen increased by five to ten times. This anomaly, induced by an AC component, suggests that there was contact between thermocouple and heating circuits, which was confirmed by back-scattering electron image and energy-dispersive X-ray spectroscopic (EDS) mapping results on cross section of recovered assembly. The W/Re thermocouple melted and extended toward and probably came into contact with the heater, while the shape of the Al₂O₃ was maintained. Despite the thermocouple irregularities, the heater itself continued to function without abrupt resistance changes. The system maintained a stable power output of 750 W for ~5 min [Figs. 8(c) and 8(d)], with the estimated temperature ranging between 2550 and 2700 °C.

IV. CONCLUSION

MASTer, a high-performance heating system for MAPs, has been developed at HPSTAR. With its high-speed precise measurement of heating parameters and accurate output power control, combined with a gentle regulation strategy, the MASTer system ensures stable heating over various heater types, particularly LaCrO₃, and various assembly designs. It maintains power fluctuations within ±0.1 W and temperature fluctuations within ±2 °C in most cases. Notably, the system has been shown to effectively regulate a small LaCrO₃ heater in a 6/1.5 assembly, demonstrating its potential for expanding the accessible HP-HT space in MAP experiments. The stability, accuracy, and flexibility of the MASTer system will significantly enhance a wide range of MAP applications, including the investigation of planetary interior structures and chemistry, the synthesis of novel functional materials, and the conduction of *in situ* property measurements under HP-HT conditions.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have filed a patent application.

Author Contributions

Guoliang Niu: Investigation (equal); Software (equal); Writing – original draft (equal). **Shengbo Cao:** Investigation (supporting).

Bingmin Yan: Validation (equal). **Huiyang Gou:** Conceptualization (equal); Funding acquisition (equal); Writing – review & editing (equal). **Tomoo Katsura:** Conceptualization (equal); Software (equal); Writing – review & editing (equal). **Ho-kwang Mao:** Conceptualization (equal); Funding acquisition (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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