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SUPER ENGINEERING

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China’s “Artificial Sun”: Experimental Advanced Superconducting Tokamak (EAST)

Keywords tokamak, controlled nuclear fusion, superconducting, fusion energy

Project Owner: Hefei Institutes of Physical Science, Chinese Academy of Sciences
Overall Design Unit: Institute of Plasma Physics, Chinese Academy of Sciences
Construction Unit: Led by the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) in collaboration with multiple domestic research institutions, universities, and enterprises

1 Overview of the EAST device

The Experimental Advanced Superconducting Tokamak (EAST), a national key scientific project of the “Ninth Five-Year Plan,” is the world’s first fully superconducting non-circular cross-section tokamak fusion experiment device designed and developed independently by China. The principle of tokamak nuclear fusion is creating a toroidal magnetic cage through magnetic fields. This approach uses the tendency of charged particles to spiral along magnetic field lines, thereby confining high-temperature and high-density deuterium-tritium plasmas to increase the probability of nuclear reactions and achieve fusion energy output. The primary objective of constructing the EAST device is to aim at the forefront of fusion energy research, and conduct joint experimental research on the fundamental physics and engineering issues of steady-state, safe and efficient operation in advanced tokamak nuclear fusion domestically and internationally, provide scientific basis for the design and construction of nuclear fusion engineering test reactors, and promote the development of plasma physics and other related disciplines and technologies (Wan, 2007). Supported by the Chinese Academy of Sciences and relevant departments, ASIPP began superconducting tokamak research in the early 1990s. The EAST project was formally approved in 1998 and construction started in October 2000. It was completed in March 2006, with the first plasma achieved in September 2006. The main body of the EAST device stands 11 m high, with a diameter of 8 m and a weight of 400 tons. It is comprised of six major components: an ultra-high vacuum chamber, longitudinal field coils, poloidal field coils, internal and external thermal shields, an external vacuum cryostat, and a support system (Li, 2016). The vacuum chamber of the EAST device is a D-shaped (non-circular cross-section). Compared to other international tokamaks, its three unique characteristics—non-circular cross-section, full superconductivity, and actively cooled internal structure—make it more advantageous to achieve steady-state, long-pulse, high-parameter operation. The main technical features and specifications are as follows: 16 D-shaped large superconducting longitudinal magnetic coils generating a magnetic field strength of $B_T = 3.5$ T; 12 large superconducting poloidal magnetic coils providing a magnetic flux variation of $\Delta\Phi \geqslant 10$ Volt-seconds (Li, 2007); these poloidal field coils can generate plasma currents of $\geqslant 1$ million amperes through these coils. The duration of the operation is expected to reach 1,000 s, with temperatures exceeding 100 million degrees under high-power heating. The overall structure of the EAST device is shown in Fig. 1.

2 Structure and technical challenges of the EAST device

EAST was designed based on the latest advancements of

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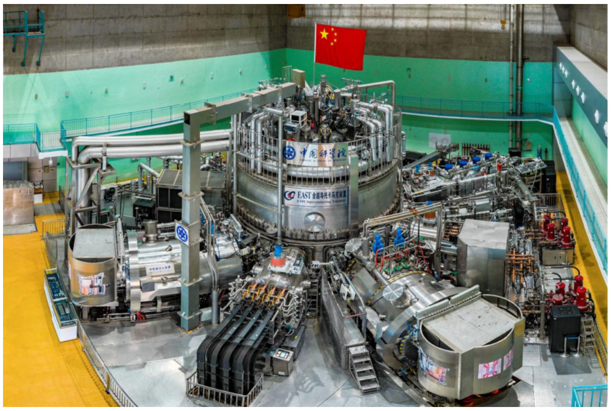

Fig. 1 The fully superconducting tokamak device (EAST).

tokamak research in the late 20th century. Its primary goal is to study the scientific and engineering challenges associated with the steady-state advanced operating modes of near-core plasmas. As the next-generation upgrade of HT-7, EAST is not only larger in scale, but also has 3 unique characteristics: a non-circular cross-section, full superconductivity, and an actively cooled internal structure, as shown in Fig. 2. These features are particularly beneficial for exploring steady-state advanced plasma operating modes. The engineering construction and physical research of EAST can provide direct experience for the construction of International Thermonuclear Experimental Reactor (ITER) project, and serve as an experimental device for ITER to provide long-pulse steady-state advanced high-parameter non-circular plasma platform. It will play a leading role in global research on developing steady-state high-performance plasma physics, contributing to the development of ITER and fusion energy.

2.1 Superconducting tokamak: A necessity for steady-state operation

Early international mainstream tokamak devices, such as the UK’s European Joint Tokamak (JET), the United States’ Tokamak Fusion Test Reactor (TFTR), and Japan’s JT-60, were conventional Tokamaks capable only of pulsed operation, with each discharge lasting only a few seconds. However, future tokamak fusion reactors must operate in steady-state conditions, which necessitates the development of superconducting tokamaks. Advanced fully superconducting tokamaks are not only capable of steady-state operation, but also efficient and safe, which are essential for fusion reactors. Before EAST, four superconducting tokamaks have been constructed worldwide: T-7, T-15, Traim-I, and Tore Supra. However, these devices have superconducting magnets only in the longitudinal coils and are not fully superconducting tokamaks. T-7, the world’s first superconducting tokamak, was built by the former Soviet Union as an engineering experimental device. It was later upgraded by ASIPP and became the important HT-7 superconducting tokamak experimental device. Therefore, no fully superconducting tokamak existed globally at that time. Future international thermonuclear experimental reactor (ITER), subsequent engineering demonstration reactor (DEMO) and fusion power plants, all require steady-state operation. The upcoming ITER (Figs. 3 and 4) is a large-scale, fully superconducting tokamak. To minimize the risks of its construction and operation, a smaller-scale fully superconducting tokamak experimental device should precede ITER, to provide essential engineering and physical foundations for such a large-scale fully superconducting fusion reactor.

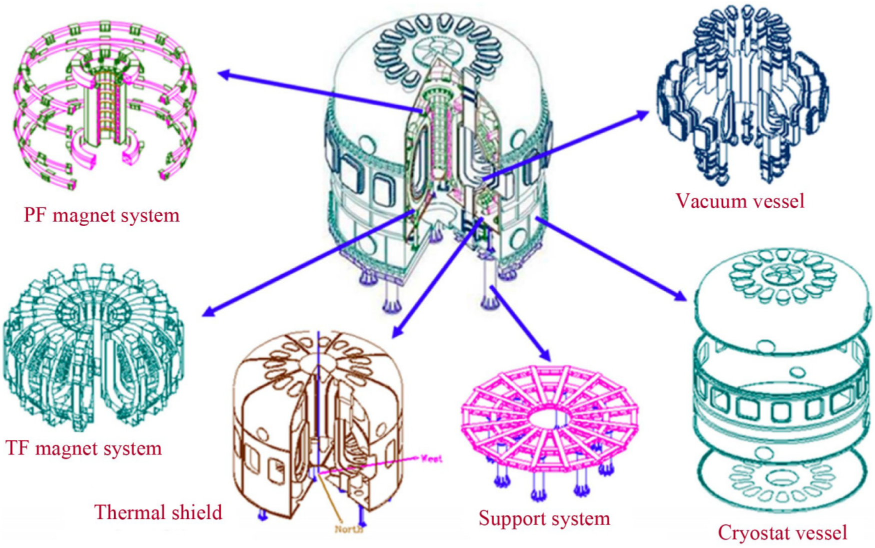

Fig. 2 Main structural components of the EAST tokamak device (Wan and Xu, 2015).

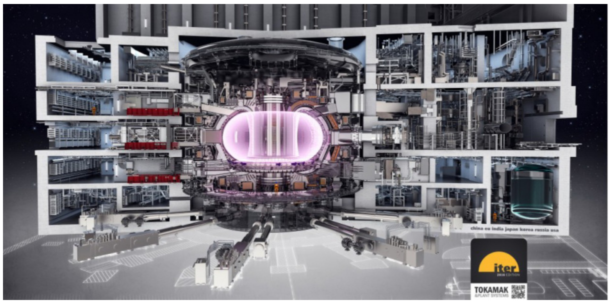

Fig. 3 Schematic of the International Thermonuclear Experimental Reactor (source: ITER official website).

Fig. 4 Full view of the ITER facility (source: ITER official website).

2.2 Radiofrequency heating and non-inductive current drive: Foundations for high-confinement steady-state operation

The high-confinement operation mode is considered the fundamental steady-state operating mode for future fusion experimental and engineering reactors due to its high efficiency and economic viability. A major challenge for high-confinement mode (H-mode) is the sudden collapse of the plasma edge temperature and density pedestal, induced by edge-localized modes (ELMs). The strong pulse heat flux released during this process can overload the divertor heat load, cause the sputtering damage of target material, and lead to the influx of impurities into the core plasma, resulting in significant disruptions. Achieving long-pulse, steady-state H-mode in experimental devices presents substantial challenges.

However, high-confinement steady-state operation requires more than the simple use of fully superconducting magnets; it also presents more complex physical challenges. Whether ITER can achieve high-confinement steady-state operation remains an open issue within the field of magnetic confinement fusion. Traditional tokamaks operate based on the transformer principle, relying on magnetic flux variations of the central solenoid to drive toroidal plasma current and heat the plasma. In today's large and medium-scale devices, relying solely on current heating can only raise the plasma's central electron temperature to a maximum of approximately 3 keV, which is insufficient to reach the deuterium-tritium fusion ignition conditions (10–20 keV) (Wan and Xu, 2015). More importantly, the magnetic flux provided by the central solenoid (volt-seconds) is finite, and the duration of the induced current is also limited, preventing steady-state operation in principle. Steady-state operation requires the non-inductive current fraction to reach 100%, and this non-inductive current is primarily generated by external drivers and bootstrap current driven by the plasma's own pressure gradient.

The ultimate goal of nuclear fusion research is to establish a stable, continuously operating fusion reactor. However, the ohmic heating and inductive current drive in traditional tokamaks are insufficient for this requirement, thereby necessitating the consideration of auxiliary heating and non-inductive current drive. The main auxiliary heating methods include radiofrequency (RF) waves and neutral beam injection (NBI) generally. In magnetic confinement fusion, waves span a frequency range from tens of MHz to hundreds of GHz, collectively referred to as RF waves. When RF waves are injected into the plasma, the appropriate wave frequency and polarization direction can produce wave-particle interactions. When the interaction process is symmetric in the particle velocity distribution, it results in plasma heating; when asymmetric, it can also induce a current drive effect. RF heating primarily includes three types: ion cyclotron resonance heating (ICRH), electron cyclotron resonance heating (ECRH), and lower hybrid current drive heating (LHCD). These three heating methods correspond to a wide range of wave source frequencies (Yan et al., 2024).

EAST experiments have discovered a series of mechanisms by which RF waves control key plasma parameters, including: utilizing RF waves to control the electron pressure distribution; generating localized fast electron current channels through multi-wave synergistic effects, applied to control the current density distribution (Wan and Li, 2003); and discovering that lower hybrid waves drive plasma rotation at the boundary and provide a momentum source for core plasma rotation, thereby offering a method for plasma rotation control based on RF waves (Shi et al., 2011). These mechanisms provide important pathways for using RF waves to control plasma parameters such as pressure, current density, and rotation speed profiles.

3 Research achievements of the EAST device

Since its construction and commissioning in 2006, the EAST device has completed over 150,000 plasma discharges. Through an open and shared institutional management model, EAST has consistently led international advancements in both the engineering and physics of steady-state plasma operation. The long-pulse H-mode has been selected as the foundational operation mode for ITER, with the core parameters of ITER's design based on the characteristics of this mode. Early devices were mostly conventional tokamaks. Although high-confinement discharges were achieved, the stability of such discharges over extended durations was not verified. Additionally, prolonged discharges posed significant challenges related to the stability of heating systems, thermal accumulation on the first wall, particle retention, impurity control, and the management of various plasma instabilities.

In the area of long-pulse H-mode operation, the EAST device has been continuously pushing its limits and achieving several breakthroughs in higher-parameter, long-pulse H-mode plasma operations:

1) In 2012, it achieved 30 s of H-mode;
2) In 2016, it achieved 60 s of H-mode;
3) In 2017, it achieved 101 s of H-mode;
4) In 2023, it achieved 403 s of H-mode.

On January 20, 2025, EAST successfully achieved steady-state, long-pulse H-mode plasma operation at temperatures exceeding 100 million degrees for 1,066 s, again setting a new world record for H-mode operation in tokamak devices. The successful realization of steady-state H-mode operation at the million-degree, thousand-second level fully validates the feasibility of steady-state H-mode operation for fusion reactors. This achievement represents a major turning point in fusion research, transitioning from basic scientific exploration to engineering practice, and marks a significant advance in the development of fusion energy. It holds profound implications for the construction and operation of future fusion reactors (Song et al., 2023).

4 Conclusions

The successful development of EAST carries profound scientific significance. Not only is it a fully superconducting tokamak, but it also features a highly elongated, non-circular plasma shape that improves plasma confinement. Its construction has positioned China as one of the few countries in the world with this type of superconducting tokamak, placing China at the forefront of global magnetic confinement nuclear fusion research. In the 10 to 15 years following its construction, EAST has enabled exploratory experimental research on cutting-edge physical issues related to the construction of steady-state advanced tokamak fusion reactors, allowing China to make significant contributions to the global effort to develop clean and virtually limitless nuclear fusion energy.

Competing Interests The authors declare that they have no competing interests.

References

Li J G (2007). Current status and development of China's superconducting tokamak. Bulletin of the Chinese Academy of Sciences, (05): 404–410 (in Chinese)

Li J G (2016). Current status and development of tokamak research. Physics (College Park, Md.), 45(02): 88–97 (in Chinese)

Shi Y J, Xu G S, Wang F D, Wang M, Fu J, Li Y Y, Zhang W, Zhang W, Chang J F, Lv B, Qian J P, Shan J, Liu F, Ding S, Wan B, Lee S G, Bitter M, Hill K (2011). Observation of cocurrent toroidal rotation in the EAST Tokamak with lower-hybrid current drive. Physical Review Letters, 106(23): 235001

Song Y T, Zou X L, Gong X Z, Becoulet A, Buttery R, Bonoli P, Hoang T, Maingi R, Qian J P, Zhong X M, Liu A D, Li E, Ding R, Huang J, Zang Q, Liu H, Wang L, Zhang L, Li G, Sun Y, Garofalo A, Osborne T, Leonard T, Baek S G, Wallace G, Xu L, Zhang B, Wang S, Chu Y, Zhang T, Duan Y, Lian H, Zhang X, Jin Y, Zeng L, Lyu B, Xiao B, Huang Y, Wang Y, Shen B, Xiang N, Wu Y, Wu J, Wang X, Ding B, Li M, Zhang X, Qin C, Xi W, Zhang J, Huang L, Yao D, Hu Y, Zuo G, Yuan Q, Zhou Z, Wang M, Xu H, Xie Y, Wang Z, Chen J, Xu G, Hu J, Lu K, Liu F, Wu X, Wan B, Li J (2023). Realization of thousand-second improved confinement plasma with Super I-mode in Tokamak EAST. Science Advances, 9(1): eabq5273

Wan B N, Li J (2003). Integration of LHCD and IBW heating for high-performance discharges under steady-state operation in the HT-7 tokamak. Nuclear Fusion, 43(10): 1279–1287

Wan B N, Xu G S (2015). EAST superconducting tokamak. Chinese Science Bulletin, 60(23): 2157–2168 (in Chinese)

Wan Y X (2007). Nuclear fusion energy and superconducting tokamak—National acceptance of the "Ninth Five-Year Plan" major scientific project EAST. Bulletin of the Chinese Academy of Sciences, (03): 243–246 (in Chinese)

Yan N, Xu G S, Wan B N (2024). The pathfinder of high-confinement steady-state physics in tokamaks—EAST. Physics (College Park, Md.), 53(11): 731–740 (in Chinese)