China's HL-3 tokamak achieves H-mode operation with 1 MA plasma current

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In a remarkable achievement, China's new-generation magnetic confinement fusion device, the HL-3 tokamak (formerly known as HL-2M), achieved high-confinement mode (H-mode) operation with a plasma current of 1 mega amperes (MA) for the first time on August 25th, 2023. This breakthrough signifies a noteworthy milestone in China's controlled nuclear fusion research, bringing us one step closer to the burning plasma phase.

The HL-3 tokamak is a large-scale research facility for controlled nuclear fusion in China. It was designed and constructed by the Southwestern Institute of Physics (SWIP) and features an aspect ratio of 2.8, a plasma current (I_p) of 2.5–3 MA, a toroidal field (B_t) of 2.2–3 T, a major radius (R) of 1.78 m, and a minor radius (a) of 0.65 m. This advanced fusion device was designed to support the operation of the International Thermonuclear Experimental Reactor (ITER) and contribute to the development of forthcoming fusion devices. It integrates both technological and physical aspects to enhance our comprehension of fusion plasma physics, thereby facilitating progress in burning plasma control and fusion power generation. The facility is capable of addressing the following crucial issues in both physics and technology.

(1) Conducting tests and qualification assessments for various advanced divertor concepts, including snowflake (SF) and tripod, addressing both physical and technological aspects.
(2) Conducting tests and validation of plasma-facing components with high heat flux.
(3) Investigating high-performance plasma physics and designing relevant advanced scenarios compatible with low divertor heat flux.

The HL-3 tokamak has been a decade-long project, with the completion of its first plasma on December 4th, 2020, named HL-2M at that time.[1] In a short time frame, on October 19th, 2022, the HL-3 achieved operation with a plasma current of 1.15 MA. In less than a year, repeatable 1 MA high-confinement mode operation has been consistently achieved. The discharge waveform is depicted in Figure 1D1–1D6, with an overall auxiliary heating power of approximately 2.3 MW. At the L-H transition point, signified by the decrease in the D_α signal in Figure 1D3 and the edge density fluctuation in Figure 1D6, the line-averaged electron density is estimated to be approximately 4×10^{19} m^{-3} in Figure 1D4. The increase in plasma stored energy, as depicted in Figure 1D5, also suggests an improvement of the plasma confinement. Additional parameters comprise a plasma minor radius of approximately 0.62 m, an elongation ratio of about 1.38, and a q_{95} value of roughly 2.8.

The H-mode is an advanced operating regime in magnetic confinement fusion devices. This regime can improve the performance of the confined plasma by augmenting key parameters, thereby improving the economic efficiency of a fusion reactor. Since its initial discovery on the ASDEX tokamak in Germany,[2] it has been widely recognized as a hallmark of fusion devices operating at a high comprehensive level. In China, the first H-mode operation has been achieved in the HL-2A tokamak.[3] The H-mode regime is also one of the standard operating scenarios for the under-construction ITER. These reactor-scale devices typically operate with a plasma current exceeding 1 MA in order to achieve higher fusion triple product and energy gain.

"Just three years later after its first experimental campaign, the overall performance of HL-3 device has been greatly enhanced, e.g. vacuum conditions,

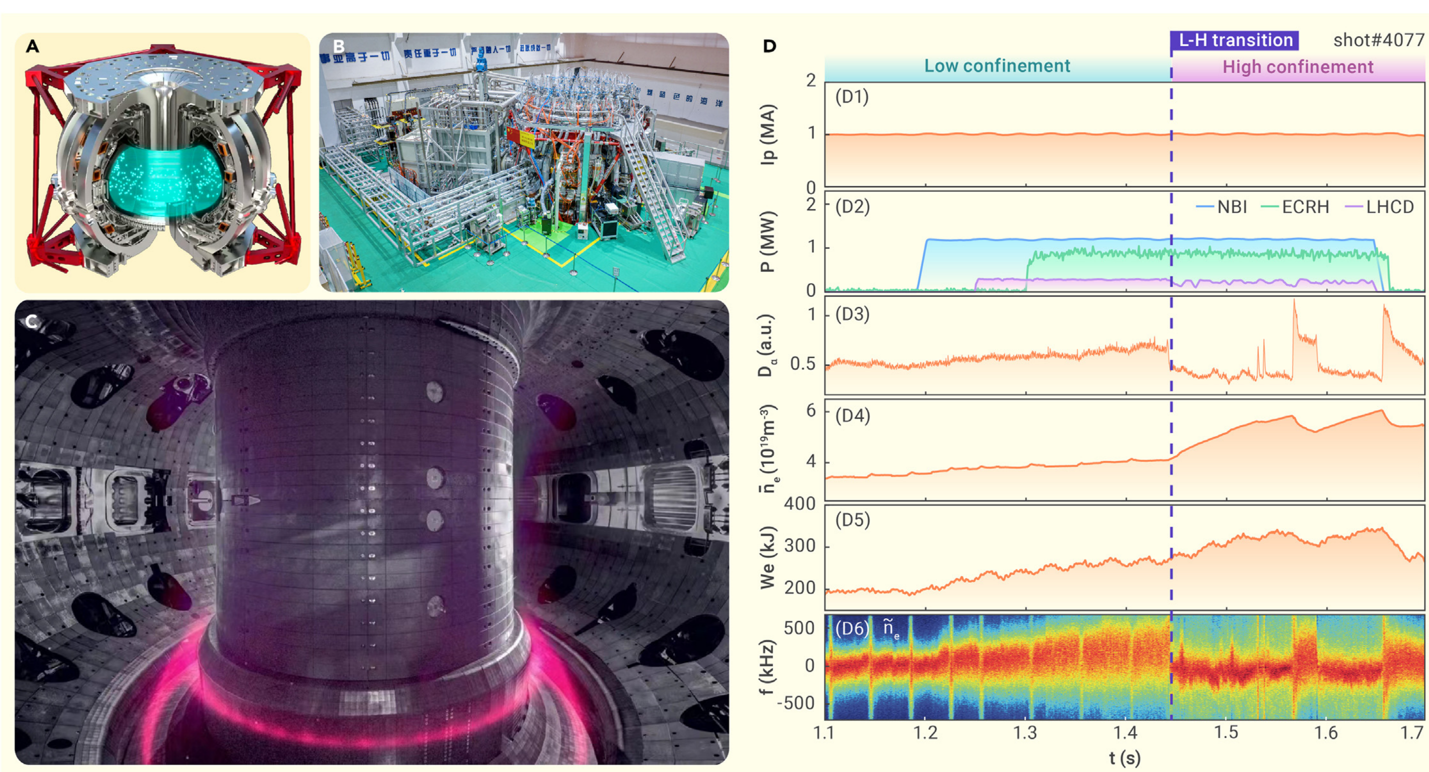

Figure 1. China's new-generation magnetic confinement fusion device, the HL-3 tokamak, achieved high-confinement mode operation with a plasma current of 1 MA for the first time (A) 3D animation of HL-3 main machine. (B) Photograph of HL-3. (C) Diagram of the plasma in the main chamber. (D) Parameters of the 1 MA H-mode discharge: (D1) plasma current Ip = 1 MA, (D2) auxiliary heating power (2.3 MW in total), (D3) D_α signal, (D4) center-line-averaged electron density, (D5) plasma stored energy, and (D6) density fluctuation at the plasma edge.

plasma control and auxiliary heating," Sun Hong Juan noted. She is one of the operators of the Joint European Torus (JET), the world's largest and most powerful tokamak performing D-T fusion plasmas. It is operated by UKAEA and collectively used by all European fusion laboratories within the EUROfusion consortium. "When I first heard about this news, my initial reaction was 'amazing,' as it exceeded my expectations," she said. In recent years, more and more breakthroughs have been achieved in fusion research. Scientists and enterprises in China also show great enthusiasm for fusion energy.

The H-mode operation with the 1 MA plasma current achieved by HL-3 is a critical step in achieving a high plasma performance of burning plasma. This achievement denotes a holistic enhancement across multiple systems following the second-phase upgrade of HL-3, encompassing plasma heating, operation and control, diagnostics, power supply, and other auxiliary systems. The subsequent phase will witness further development and enhancement of advanced plasma control, plasma heating, and current drive systems. This progress sets the stage for the subsequent phase of HL-3's objectives, focusing on augmenting the fusion triple product and refining the operational capabilities of high-performance plasma. "The HL-3 team will continue to develop key technologies and delve into frontier fusion plasma physics. The robust support strongly positions China to conduct burning plasma experiments and construct fusion reactors in the near future," affirmed Liu Ye, the director of SWIP.

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DECLARATION OF INTERESTS

The authors declare no competing interests.