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Letter

Realization of minute-long steady-state H-mode discharges on EAST

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Abstract

In the 2016 EAST experimental campaign, a steady-state long-pulse H-mode discharge with an ITER-like tungsten divertor lasting longer than one minute has been obtained using only RF heating and current drive, through an integrated control of the wall conditioning, plasma configuration, divertor heat flux, particle exhaust, impurity management, and effective coupling of multiple RF heating and current drive sources at high injected power. The plasma current ($I_p \sim 0.45$ MA) was fully-noninductively driven ($V_{loop} < 0.0$ V) by a combination of ~2.5 MW LHW, ~0.4 MW ECH and ~0.8 MW ICRF. This result demonstrates the progress of physics and technology studies on EAST, and will benefit the physics basis for steady state operation of ITER and CFETR.

Keywords: long pulse steady state, RF heating, H-mode

(Some figures may appear in colour only in the online journal)

The Experimental Advanced Superconducting Tokamak (EAST) [1–4] is the first fully superconducting tokamak device with major radius $R \sim 1.8$ m, minor radius $a \sim 0.45$ m, plasma current $I_p < 1.0$ MA [5] toroidal field $B_T < 3.5$ T, and is expected to demonstrate high power and long pulse operation up to 1000 s. EAST equipped 12 independently poloidal field power supplies [6] and a pair of internal coils, accommodating both single null and double null divertor configurations. EAST is also equipped with an actively water-cooled ITER-like tungsten divertor with power handling capability of ~ 10 MW m^{-2}, upper and lower divertor cryopumps for particle exhaust, and continuous wave of lower hybrid current drive (LHCD) for plasma current drive and electron heating at 2.45 GHz [7, 8] and 4.6 GHz [9, 10], an electron cyclotron heating (ECH) [11] at 140 GHz and an ion cyclotron resonant frequency (ICRF) system [12] at 33 MHz for electron and ion heating respectively.

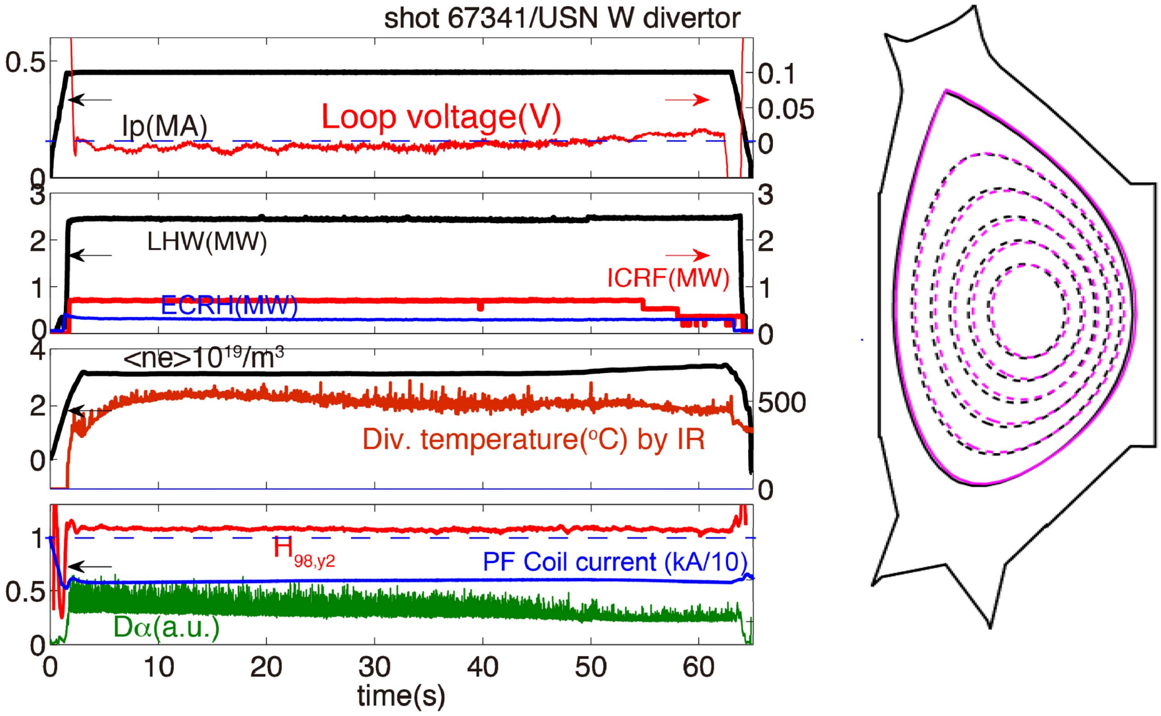

Figure 1. On the left are time histories of the plasma current I_p, loop voltage, auxiliary heating power of LHW, ICRF and ECRH, line averaged density, divertor temperature measured by IR camera, confinement enhancement factor H_{98y2}, PF coil current, and the balmer-alpha emission of deuterium D. On the right is the upper single null configuration.

Building on the previous 32 second long-pulse H-mode [13] experiment, EAST has recently demonstrated long-pulse steady-state H-mode operation using radio frequency (RF) power for heating and current drive. A discharge of duration over one minute has been obtained through the multi-RF power combination, i.e. $\sim$0.4 MW LHW at 2.45 GHz, $\sim$2.1 MW LHW at 4.6 GHz, $\sim$0.4 MW ECH and $\sim$0.8 MW ICRF, as shown in figure 1. The plasma configuration is the upper single null. The plasma parameters are as follows: $I_p \sim 0.45$ MA, toroidal magnetic field $B_T = 2.5$ T, elongation $k \sim 1.6$, and safety factor $q_{95} \sim 6$. The loop voltage was well controlled to be slightly negative, which indicates a fully noninductive current drive condition. It is also worth pointing out that the loop voltage increases and crosses over zero after 50 s. Small edge localized modes (ELMs) are obtained in this long-pulse H-mode discharge, with low energy ejection per ELM event. These small ELMs facilitate the RF power coupling in the H-mode phase and the avoidance of shape oscillation caused by large ELMs. A confinement enhancement factor relative to the standard H-mode, H_{98y2} of 1.1–1.2, was achieved and maintained constant during the discharge, with a line averaged electron density $\sim 3.0 \times 10^{19}\ \mathrm{m}^{-3}$. The analysis of the related physics mechanism of the improved confinement for this long-pulse H-mode is still ongoing.

The maximum tungsten divertor temperature measured by the tangential infrared radiation (IR) camera [14] shows that the temperature increases quickly in the first 5 s and reaches 500 °C (maximum) in 10–15 s. In comparison, it took 70 s for the lower divertor temperature to saturate in the previous long-pulse (102 s) L-mode, high T_e lower single null discharge [15]. From this, one may conclude that the EAST ITER-like tungsten upper divertor has a better power handling capability than the graphite lower divertor.

The upper single null configuration for this discharge is realized using the iso-flux [16] control scheme in collaboration with DIII-D. During operation, careful optimization of the plasma shape like X-point and the outer gap was performed for the maintenance of the high RF power coupling and the avoidance of the formation of hot spots on the 4.6 GHz LHW antenna. Note that a linear correction was used to remove linear drifts of the integrators for this long-pulse operation.

Since the EAST poloidal flux is limited ($\sim$9 Vs), a very long discharge duration requires a fully noninductive operation. In this 60 s H-mode, the early $\sim$0.4 MW LHW (2.45 GHz) was utilized to lower the loop voltage for a better shape control in the I_p ramp-up phase. When the plasma current reaches the flattop, another 2.1 MW LHW (4.6 GHz) was coupled to the plasma to reach and maintain zero loop voltage. Meanwhile, the plasma density and plasma wall separation were carefully optimized for better RF coupling and higher LHCD efficiency.

Careful wall conditioning is a key element of a successful long-pulse plasma operation. The vacuum chamber was continuously heated and kept at $\leqslant$200 °C with hot nitrogen for $\sim$2 weeks before the campaign. During the experimental period, effective methods of glow discharge and ICRF cleaning were routinely carried out together with lithium coating [17]. The H/(H+D) ratio gradually reduced from the initial 30%–50% to 5%–10% after several days (normally 3–4 days) of lithium coating for ICRF minority heating. Up to $\sim$50 s, the plasma density was controlled with the continuous injection of gas puff (feed forward) and supersonic molecular

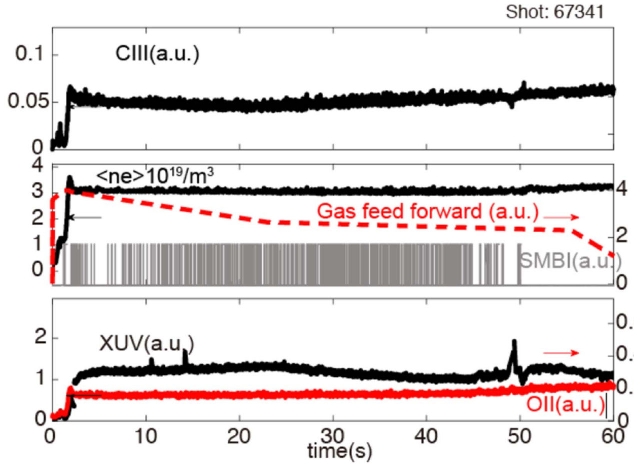

Figure 2. Time history of impurities of CIII, XUV, OII and line averaged density feedback controlled by SMBI, together with the gas feed forward.

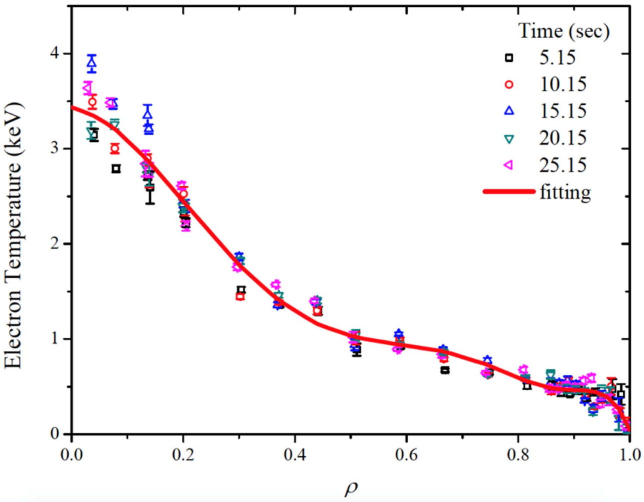

Figure 3. Several time-slice electron temperature profiles measured by Thomson scattering for the long-pulse steady-state operation.

beam injection (SMBI) [18] feedback in the first ~50 s operation (shown in figure 2). After 50 s, a strong hot spot is observed on the lower divertor by visible CCD, leading to an increase of plasma electron density over the target. It is also shown that the light impurity density indicated from carbon and oxygen ions, e.g. CIII at 464.7 nm, OII at 441.5 nm, and total radiation power indicated by the XUV signal is being kept at a very low level. After 20 s, the carbon increased slowly, probably coming from insufficient water-cooling of the LHW guard limiter.

In summary, a steady-state long-pulse H-mode discharge with an ITER-like tungsten divertor lasting longer than one minute has been obtained with a plasma current fully driven by LHW, assisted by ECRH and ICRF. To achieve this, the integrated control of the wall conditioning, plasma configuration, divertor heat flux, particle exhaust, impurity concentration, and the effective coupling of multiple heating and current drive has been developed. In a preliminary analysis, it is found that the core electron temperature profile (figure 3) shows an ITB feature [19] when using 0.4 MW of on-axis ECRH. This newly achieved long-pulse steady-state H-mode scenario demonstrates the progress of physics and technology studies on EAST, and will benefit the physics basis for steady state operation of ITER and CFETR [20].

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