Integrated Operation of Steady-State Long Pulse H-Mode in EAST

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Recent EAST experiment has successfully demonstrated long-pulse steady-state scenario with a good plasma performance through the integrated operation since the last IAEA in 2016. A discharge with a duration over 100 s has been obtained with multi-RF power heating and current drive. Plasma parameters are as follows, plasma current \( I_p = 0.4 \, \text{MA} \), poloidal \( \beta_p \sim 1.2 \), toroidal magnetic field \( B_t = 2.5 \, \text{T} \), elongation \( \kappa = 1.6 \), the safety factor at the 95% normalized poloidal flux surface \( q_{95} \sim 6.6 \). The zero-loop voltage and pulse length (\sim 250 times the current relaxation time) indicate the really steady state condition. Small ELMs were obtained in this long pulse H-mode discharge which facilitates the RF power coupling in the H-mode phase. In the operation, the optimization of X-point, plasma shape, the outer gap and local gas puffing near LHW antenna were investigated to maintain RF power coupling and particle exhaust and to avoid formation of hot spot on the 4.6 GHz LHW antenna. Global parameters of \( B_t \) and line averaged electron density were optimized for higher current drive efficiency of LHW and on-axis deposition of ECH. A peaked electron temperature profile was observed with a weak ITB at \( \rho \sim 0.4 \). No obvious MHD instabilities were found in the whole discharge. The maximum tungsten divertor temperature monitored by the IR camera shows the temperature raises quickly in several seconds and reaches a stable value \sim 500°C. As a key element, wall conditioning was addressed before long pulse plasma operation. Several difficulties are reported in the development of this 100 s long pulse discharge. To achieve the next goal (\sim 400 s long-pulse H-mode operations with \sim 50% bootstrap current fraction), 0D predictions have been carried out. The modelling suggests that steady-state high performance will require not only increased injected power, but also significantly improved energy confinement quality. The recent long pulse H-mode has demonstrated several key elements and will increase a confidence in achieving high performance, steady state discharges with more key elements in integrated control on EAST.

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Abstract

Recent EAST experiment has successfully demonstrated long-pulse steady-state scenario with a good plasma performance through the integrated operation since the last IAEA in 2016. A discharge with a duration over 100s using pure RF power heating and current drive has been obtained with the required characteristics for future long pulse tokamak reactors such as good plasma performance ($H_{98}(\rho_{2}) \approx 1.1$) with eITB inside $\rho<0.4$, small ELMs (frequency $\approx 100$-$200$ Hz), good control of impurity and heat exhaust with the tungsten divertor. The optimization of X-point, plasma shape, the outer gap and local gas puffing near LHW antenna were integrated with global parameters of $B_T$ and line averaged electron density $<n_e>$ for higher current drive efficiency of LHW and on-axis deposition of ECH in the long pulse operation. Recently, a high $\beta_p$ scenario ($\beta_p \approx 1.9$ & $\beta_N \approx 1.5$, $<n_e>/n_{GW} \approx 0.80$, $f_{BS} \approx 45\%$ at $q_{95} \approx 6.8$) demonstrated for CFETR steady-state scenario was successfully maintained over 24s with the improved capabilities. Towards the next goal ($\geq 400s$ long-pulse H-mode operations with $\sim 50\%$ bootstrap current fraction) on EAST, an integrated control of current density profile, pressure profile and the radiated divertor should be addressed in the near future.

1. INTRODUCTION

The achievement of steady state, long pulse operation with high performance is one of the major challenges for present-day tokamaks. To demonstrate this scenario, it is necessary to consider a simultaneous integration of engineering technology and physics issues, such as external current drive, heat flux, active plasma control and so on.

The mission of Experimental Advanced Superconducting Tokamak (EAST) as the first fully superconducting tokamak (major radius $R \leq 1.9m$, minor radius $a \leq 0.45m$, plasma current $I_p \leq 1MA$) is to demonstrate high Beta, high bootstrap current fraction, long pulse, non-inductive scenario with metal walls, where the pulse duration should be long compared to the current relaxation time and the wall equilibration time. To reach high beta, long pulse steady state operation in EAST, several key issues such as LHW current drive at high density, improvement of core confinement, avoidance of high Z impurities concentration, heat flux handling, synergy effect between LHCD and ECRH have been investigated and integrated towards our objective. A steady state long pulse H-mode operation of $\geq 100$ seconds time scale using the radio frequency (RF) H&CD has been demonstrated. More recently, with the increased auxiliary heating and current drive capability, the operational regime has been extended.
This paper presents the recent experimental results and present understanding of the key elements required for the steady state long pulse operation. Firstly, the status of EAST capabilities in support of steady state long pulse operation is shown in section 2. In section 3, the integrated operation of 100s long pulse discharge is discussed. Section 4 presents the recent efforts on the extension of high $\beta_T$ towards high bootstrap current fraction. A summary and future plan is given in section 5.

2. STATUS OF EAST CAPABILITIES IN SUPPORT OF STEADY STATE LONG PULSE OPERATION

As a prerequisite for long pulse operation, EAST has equipped three continuous wave (CW) systems for plasma heating and current drive (H&CD): i) lower hybrid current drive (LHCD) systems, 2.45GHz(4MW)/4.6GHz(6MW) klystron power; ii) electron cyclotron heating (ECH) system, 140GHz/2MW gyrotron power and iii) ion cyclotron resonant frequency (ICRF) systems, 27MHz-80MHz(12MW) generator power. In addition, the 2 co-current neutral beam injection (NBI) sources, 2 counter-current NBI sources (80 keV, 4 MW) provide a unique opportunity to explore the plasma characteristics with high heating power and low momentum input through a balanced injection. More details of recent achieved maximum power were shown in table 1 in Ref.[1]. Note that another ~0.5MW ECH is available in the campaign 2018.

To facilitate long-pulse operations, EAST has installed a water-cooled tungsten divertor with power handling capability of ~10 MW/m² based upon cassette and mono-block technology[1][2][3]. Note that the lower divertor on EAST is covered by water-cooled graphite tiles, with power handling capability of ~ 2 MW/m², while the main wall is covered by molybdenum tiles. In addition, Divertor pumping with a large internal toroidal cryopump, which is located under the outer divertor target at the top and bottom of the machine, with the pumping speed of 76 m³ s⁻¹ for D₂ to facilitate density control and particle exhaust. Furthermore, supersonic molecule beam injection (SMBI) system has been routinely implemented for the density maintenance[4]. With this system, a higher fueling efficiency (15%~30%), shorter delay time (~5ms) and lower wall retention (reduced by ~40%) have been obtained to be compared with the conventional gas puff, where the delay time of conventional gas puff was ~50-80ms. Thus, the SMBI is routinely used for the electron density feedback control, especially in long pulse operation.

Also, EAST diagnostics have provided high-quality experimental data for plasma control and physics research, especially for long pulse operations. An eleven-chord, double-pass, radially-viewing and far-infrared laser-based POlarimeter-INTerferometer (POINT) system has been routinely operated for diagnosing the plasma current and electron density profiles throughout the entire plasma discharge[5]. The POINT system can be operated with a high time resolution of a few μs, which is able to detect fast MHD events, such as sawtooth crashes. Using the Faraday rotation profile measured by the POINT as a constraint condition, the profile of safety factor q can be inferred more accurately from the EFIT equilibrium calculation[6]. It is worthy to point out that EAST shape feedback control is realized by using the iso-flux control scheme adapted from the DIII-D plasma control system (PCS)[7]. Since the RT reconstructed plasma shape is based on a least-square fit to the external magnetic data, the precise long-time integrators for these magnetic measurements were required, especially in the long pulse discharges. The linear drift benchmarking and correction [8] were introduced into PCS to compensate the linear drifts from integrators before daily experiments. Radial profiles and other diagnostics can be seen in reference[9].

Previously, the auxiliary heating power of 4.6GHz LHW was met with the challenge of hot spots from the antenna that limited the delivered power to the plasma. When trying to inject high LHW power at 4.6 GHz (>2.0MW), strong hot spots were often observed on the guard limiter of the LHCD antenna, resulting in a sudden increase of impurity influx[1]. In campaign 2018, a new guard limiter of using water-cooled tungsten (shown in figure 1) with the power handling capability of ~10MW/m² has been installed, enables a higher power injection (>3.0MW) without the hot spot issue.

![Figure 1. The new tungsten guide limiter of 4.6GHz LHW antenna](image)
3. INTEGRATED OPERATION IN ACHIEVING 100S LONG PULSE H-MODE OPERATION

So far, EAST has successfully demonstrated the steady state long pulse H-mode operation using pure RF H&CD. A discharge of duration over 100s (101.2s) has been obtained through the multi-RF power combination, i.e. ~0.5 MW LHW at 2.45 GHz, ~1.7 MW LHW at 4.6 GHz, ~0.4 MW ECH and ~0.5 MW ICRF (as seen in Figure 2). The plasma configuration is the upper single null with the strike points on the tungsten divertor. Plasma parameters are as follows: plasma current $I_p$=0.4MA, normalized poloidal beta ($\beta_p$)=1.2 toroidal magnetic field $B_r$=2.5 T, plasma elongation $k$=1.6, the safety factor at the 95% normalized poloidal flux surface $q_{95}$~6.6. The pulse length is ~ 250 times the current relaxation time ($\tau_R$~0.4 s). Loop voltage was well controlled to be zero which indicates the fully non-inductive current drive condition. After 90s, a gradual increase of loop voltage causes when ECRH cuts off. Small ELMs (frequency ~100-200 Hz) were obtained in this long pulse H-mode discharge which facilitates the RF power coupling in the H-mode phase. No obvious MHD instabilities were found in the whole discharge. The sawtooth free plasma with a central safety factor q(0) above the unit, $T_e(0)$ ~ 4.0keV, $<n_e>$ ~2.8x10^{19} m^{-3} were obtained with a confinement enhancement factor relative to standard H-mode, $H_{98y^2}$ of 1.1-1.2. The maximum tungsten divertor temperature monitored by the IR camera shows the temperature raises quickly in several seconds and reaches a stable value, ~500°C. The peaked electron temperature profiles were observed as shown in figure 3. The TRANS power balance analysis shows that the effective electron thermal diffusivity is reduced in the plasma core regime, which is consistent with the improved confinement.

The full reconstruction using external magnetic probe measurements together with the constraints of pressure profile information from Thomson scattering, X-ray Crystal Spectrometer and Charge Exchange Recombination Spectroscopy and the POINT data via EPIT code was carried out. Then calculated profiles of the ECCD using TORAY, the LHCD using GENRAY and CQL3D code, and the bootstrap current using the Sauter model are shown in figure 4, where the LHCD is found to supply ~75% and the bootstrap current ($I_{bs}$) is found to supply nearly 23% of the total plasma current in this long pulse discharge.

The optimization of X-point, plasma shape, the outer gap and local gas puffing near LHW antenna were investigated to maintain RF power coupling and particle exhaust. In separate experiments, the LH power and outer gap was systematically scanned to avoid the formation of hot spot on the 4.6 GHz LHW antenna. A final large outer gap of ~8cm and moderate LH power were chosen for the long pulse operation. Meanwhile, global parameters of $B_r$ and line averaged electron density $<n_e>$, which were sensitive to LH accessibility and current drive efficiency, were optimized for higher current drive efficiency of LHW together with on-axis heating of ECRH. The on-axis heating of ECRH was superimposed on the LHW during the whole H-mode to avoid the high-Z impurity accumulation and control high-Z impurity content in the plasma core[10].
The predictive modelling using GENRAY and CQL3D code shows that the on-axis heating of ECRH provides a way to control LHW deposited more power near the centre, consistent with the experimental formation of peaked current density profile and eITB. Note that the effect of the interaction between ECH and LHCD was demonstrated with the early turned off of ECH in separate experiments[11].

As a key element, wall conditioning was addressed before long pulse plasma operation. The vacuum chamber was continuously heated and kept to ≤200°C with hot nitrogen for few weeks. Glow discharge cleaning and ion cyclotron resonance discharge cleaning were routinely used together with lithium coating. Low-Z material of silicon and lithium coating on the first wall are the two methods used in EAST, and lithium is proven to be more effective than silicon to control fuel recycling. The H/(H+D) ratio reduced from the initial 30~50% to ≤10% after 3-4 times lithium coating for ICRF H minority heating.

Several difficulties have been encountered in the development of this long pulse H-mode discharges. The hot spot issue on the 4.6GHz LHW antenna is the first limitation when requires high LH power for external current drive. To avoid this hot spot issue, large outer gap, moderate LH power(<2MW) were chosen and a continuous local gas puffing was set up to increase the electron density in the SOL for better LH coupling. Another challenge to the long pulse operation is the strong hot spot on the lower divertor. This hot spot was due to overheating of the misaligned graphite tile was often observed, leading to an increase of plasma electron density over the target and a later disruption. A temporal trick of higher DRSP (2.5cm) was set in PCS to reduce particles to the low divertor, which slightly sacrifices the plasma volume. Note that a new lower ITER-like tungsten divertor with active water-cooling will be installed soon. To increase the fuel efficiency and reduce wall retention, the SMBI has been implemented for the electron density feedback control[4].

4. DEVELOPMENT OF HIGH BETAP SCENARIOS TOWARDS HIGH BOOTSTRAP CURRENT FRACTION OPERATIONAL REGIME

4.1. 0-D modelling

In the next few years, EAST aims to demonstrate ≥400s long-pulse H-mode operations with ~50% fbs. To achieve this goal, 0-D predictions have been carried out to calculate the total injected power at I_p= 450 kA with different assumptions for the energy confinement. This figure shows the possible operational space expressed by poloidal beta (proportional to the bootstrap current fraction), H98(y2) and line-average density for the plasma. The modelling results suggest that steady-state high performance will require not only increased injected power, but also significantly improved energy confinement quality (H98y2≥1.3). Excellent confinement with large radius ITB (like the scenarios developed in the EAST/DIII-D joint experiments[12][13]) may relatively lower the requirement of input power. High density was suggested, but not favourable for long pulse steady state operation since LH current drive efficiency decreases with the increase of electron density[14][15], whilst EAST largely relies on LH heating and current drive to achieve fully non-inductive operation. The further predictions using 1.5-D TRANSP including the effect of ECH and LHW interaction is ongoing.
4.2. Extension of operational regime with high bootstrap current fraction

With the installation of the new LHW guide limiter to avoid hot spot issue and the use of the second ECH system, EAST has the capability to explore higher $\beta_P$ operational regime in support of steady state operation of ITER and CFETR. Recently, the extension of high $\beta_P$ regime for higher bootstrap current fraction is obtained with $q_{95}$ in the range of 6.0-7.0. An example of EAST high $\beta_P$ discharge using pure RF H&CD is shown in figure 4. A high $\beta_P$ H-mode plasma at $I_p = 0.4\text{MA}$, anti-clockwise toroidal field $B_T = -2.5\text{T}$ (top-view with $B \times \nabla B$ to the X-point), $q_{95} = 6.8$ with $\beta_P \sim 1.9$ & $\beta_N \sim 1.5$, $\langle ne \rangle / \langle n_{GW} \rangle = 0.80$ was successfully maintained for 24s (figure 4). Note that the statistic results suggest that favourable $B_T$ reduces the divertor neutral particle density and recycling. A total of $\sim 4\text{MW}$ RF, including 3MW LHCD and $\sim 1\text{MW}$ ECH on-axis heating, was used for H&CD, where the loop voltage was kept in a low level, i.e., less than 0.005V.

In this discharge, a total energy $\sim 80\text{MJ}$ from RF was injected to the plasma for 20s. Since the divertor target plates is ITER like W divertor, the maximum tungsten divertor temperature measured by the IR camera shows the temperature raises and saturates $\sim 700^\circ\text{C}$. Further attempt to operation long pulse H-mode (>30s) was limited in duration by the leakage from upper divertor. The confinement property of this discharge is high and $H_{95y2} = 1.1-1.2$ was sustained for 20s until ECH turned off. No sawteeth was observed from soft X-ray (SXR) in the whole discharge. Note that the kinetic EFIT reconstruction was performed and the preliminary transport analysis shows that the LH current drive, the bootstrap cutter and EC current drive are $\sim 49\%$, $\sim 43\%$ and $\sim 7\%$ separately in this discharge. More data analysis is still ongoing.

This discharge based on previous long pulse H-mode discharge developed in EAST are characterized by the existence of the eITB. In order to understand the reason for the extension of high $\beta_P$ regime, a comparison of $T_e$, $n_e$ and $q$ profiles are shown in figure 7, where 81163 was replaced by 80307 because of some profiles data are not available in 81163. A higher electron density profile from core to edge for discharge 80307 are shown figure 7, since the line averaged density ($\langle ne \rangle = 4.5 \times 10^{19} \text{m}^{-3}$) in discharge 80307 is

\begin{figure} [h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Time history of several parameters for high $\beta_P$ discharges. From top to bottom, normalized poloidal beta & normalized beta, loop voltage & line averaged density over Greenwald density limit, LHW&ECH power.}
\end{figure}

\begin{figure} [h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Comparison of plasma profiles between EAST long pulse discharge at $t=50\text{s}$ (black curves) and the recent discharge 80307 at $t=4.1 \text{s}$ (red curves), from top to bottom are electron density profile, electron temperature profile and safety factor profile}
\end{figure}
much higher than 73999 (ne~2.8x10^{19} m^{-3}). Meanwhile, a reasonable high T_e in plasma core (increase by 0.6 keV) is observed with the second ECH on-axis heating. A difference in the safety factor profile can also be seen in figure 7, where 73999 is a monotonic q profile while the other case shows a slightly reverse shear inside rho<0.4. This feature may cause by two reasons. One side, the LHCD profile becomes more off-axis with higher density for discharge 80307, because the radial penetration of the wave is reduced at higher density and the wave deposited closer to the plasma edge. The other side is 80307 has the higher value of \beta_p which can generate more off-axis bootstrap current. Thus, a final reverse shear is formed. Comparison the EAST/DIII-D Joint experiment in DIII-D[16], a further optimization of q profile with the increase of q(0) for high bootstrap current, high confinement with large radius ITB should be addressed.

The recent experimental explorations of a low/zero loop voltage, high \beta_p scenario for the demonstration of higher bootstrap current fraction operation on EAST are summarized in figure 8, where the solid bluish yellow circles show the operation space before the campaign 2018 and the red open diamonds are the recent RF discharges. It shows that the regime of previous discharges is typically obtained at the moderate line averaged density (<n_e> < 3.5 \times 10^{19} m^{-3}). The recent low loop voltage operation at higher density with a range of 3.5-5.0 \times 10^{19} m^{-3} largely depends on the higher bootstrap current, which can compensate the reduced LHCD efficiency at higher density. Note that the \beta_p used here were calculated from EFIT equilibrium reconstruction[17].

![Figure 8. Extension of EAST operational regime with the plot of \beta_p versus line averaged density](image)

5. SUMMARY AND FUTURE PLAN

In all, recent EAST experiment has successfully demonstrated long pulse steady-state scenario with a good plasma performance through the integrated operation since the last IAEA in 2016. A discharge with a duration of 101.2 s has been obtained with multi-RF power heating and current drive. The zero-loop voltage and pulse length (~ 250 times the current relaxation time) indicate the truly steady state condition. Small ELMs were obtained in this long pulse H-mode discharge which facilitates the RF power coupling in the H-mode phase. The optimization of X-point, plasma shape, the outer gap, local gas puff near LHW antenna and avoidance of high Z impurity with on axis ECH were integrated in this long pulse operation. Meanwhile, global parameters of B_T and line averaged electron density of <n_e> were optimized for higher current drive efficiency of LHW together with on-axis deposition of ECH. A peaked electron temperature profile was observed with a weak ITB at rho~0.4. No obvious MHD instabilities were found in the whole discharge. The maximum divertor temperature was well controlled with plasma configuration using the ITER like tungsten divertor. With the installation of new tungsten LHW guide limiter for 4.6GHz antenna and the use of the second ECH system, a high \beta_p scenario (\beta_p~1.9 & \beta_N~1.5, <n_e>/n_c>~0.80 at q_95~6.8) over 24s has also been demonstrated with fbs~45%.

The recent long pulse H-mode has demonstrated several key elements in integration and will increase a confidence in achieving higher performance, steady state discharges on EAST. A goal of \geq 400s long-pulse H-mode operation with \sim 50% bootstrap current fraction is launched. 0-D predictions suggest that achieving this high \beta_p scenario will require not only increased injected power, but also significantly improved energy confinement quality. A further integrated control of current density profile, pressure profile and the radiated divertor[18] should be addressed in the near future on EAST.
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