Integrated operation in achieving steady-state H-mode plasma on EAST

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Abstract: A 100 sec long-pulse steady-state H-mode plasma with good energy confinement (H98(y,2) ~ 1.1) has been successfully achieved on EAST using RF heating and current drive. Recent EAST experiments with improved hardware capabilities have demonstrated steady-state fully non-inductive scenarios with extension of fusion performance (β_P~2.5 & β_N~2.0, $H_{98(y,2)}$~1.2, <ne>/n_{GW}~0.8, f_{BS}~50% at q_{95}~6.8) through integrated control of the wall conditioning and recycling, plasma configuration, divertor heat flux, particle and impurity control, and the effective coupling of multiple RF heating and current drive (H&CD) sources. This steady-state scenario was characterized with fully non-inductive current drive at high density with low rotation and high-frequency, small-amplitude edge localized modes (ELMs), and stable control of heat and particle exhaust using various technologies (e.g. RMP) on the ITER-like tungsten divertor. The optimization of the X-point, plasma shape, the outer gap and local gas puffing near the lower hybrid wave (LHW) antenna were integrated with global parameters of B_T, line averaged electron density <ne> for high LHW current drive efficiency, and on-axis deposition of ECH in the long pulse operation. The benefits of using ECRH to avoid tungsten accumulation in the core plasma, and enhancement of H&CD by the synergistic effect of ECH and LHW were demonstrated. A higher energy confinement is observed at higher performance with favorable B_T direction.

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 an integration of engineering technology and physics issues, such as external current drive, heat flux to the first wall and divertor, active plasma control.

As a superconducting tokamak, EAST is expected to demonstrate high performance, long pulse operation for steady state operation of ITER and CFETR. For this goal, EAST equipped flexible control system with 12 independent poloidal coil power supplies and a pair of internal coils both for 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 three continuous waves of LHW, ECH and ICRF for plasma heating and current drive.

To demonstrate the feasibility of operating fusion plasma in long pulse and steady state, EAST team has achieved long pulse operation [1][2][3] in L-mode and H-mode with zero loop voltage (shown in figure 1). Recently, fully non-inductive plasma operation using RF heating and current drive only is demonstrated for more than 100 sec in EAST experiments. The total injected RF power is about 3.2 MW, including 2.2 MW for LHW, 0.4 MW ECH and 0.5 MW ICRF. Figure 2 shows the truly steady state waveform of zero loop voltage and the unchanged magnetic flux of EAST SN# 73999. The peak temperature on upper divertor is well controlled by the water-cooling system in the ITER-like tunsten divertor. Thermal confinement in this long pulse plasma is slightly

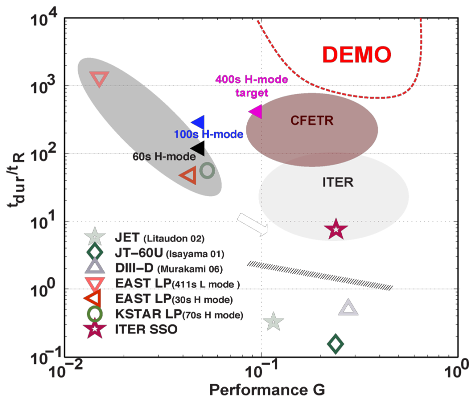

Figure 1 Overview of obtained and prospect of long pulse H-mode on EAST. Normalized plasma length as a function of plasma performance, G. Here, t_R is the resistive time and $G=\beta_N H_{89P}/q_{95}^2$

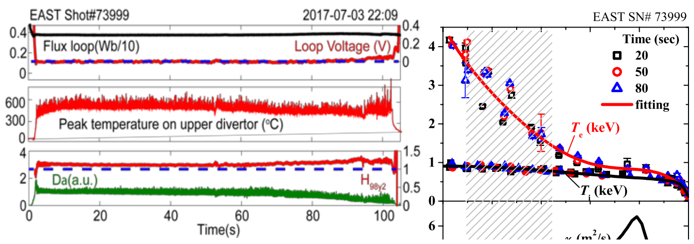

Figure 2 Time histories of flux loop, loop voltage, divertor temperature by IR camera, confinement factor H_{98y2}, and Da. Electron and ion temperature profiles and transport coefficient profiles（right）. Note that upper single null configuration and ITER like W divertor is also shown.

above standard H-mode, giving H_{98y2}~1.1. This plasma is also characterized by high frequency small amplitude edge localized modes (ELMs). The safety factor at the 95% of normalized poloidal flux surface (q_{95}) of this discharge is 6.6. Normalized poloidal beta (β_P) is about 1.2.

The optimization of X-point, plasma shape, outer gap and local gas puffing near the LHW antenna were carried out to maintain RF power coupling and particle exhaust. 4.6GHz LH power and outer gap was systematically scanned to avoid the formation of hot spots. Global parameters of B_T and line averaged electron density <ne>, 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 ECH. The on-axis heating of ECH 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. Meanwhile, results in separate experiments show that the injection of the EC wave brings more electrons to resonate with the LH waves, which increases the enhanced driven current when combining the ECCD and LHCD[4]. Meanwhile, to increase the fuel efficiency and reduce wall retention, SMBI has been implemented for the electron density feedback control.

More recently, a high β_P H-mode plasma with favorable B_T[1], q_{95}~6.8 with β_P up to 1.9 & β_N up to 1.5, <ne>/nGW~0.80 was obtained and maintained for 24s (figure 3). These steady state levels of normalized plasma performance exceed the levels proposed for Phase 2 of CFETR operation. In this long pulse operation, a total of ~ 4MW RF, including 3MW LHCD and ~1MW ECH on-axis heating, was used for H&CD, where the loop voltage was kept in a low level, i.e., less than 5mV. Further attempt to operate long pulse H-mode (>30s) was

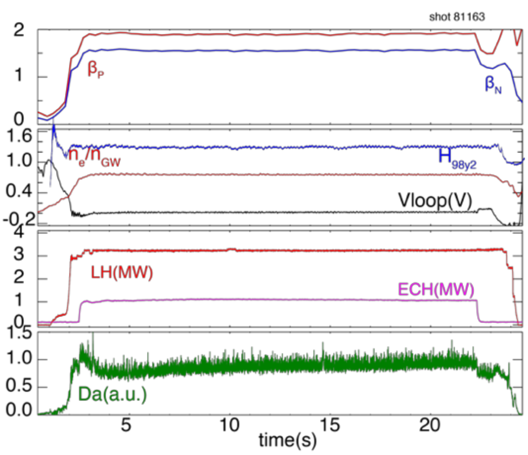

Figure 3 Time history of several parameters for high β_P discharge 81163. From top to bottom, normalized poloidal beta & normalized beta, loop voltage & line averaged density over Greenwald density limit, LHW&ECH power and Da.

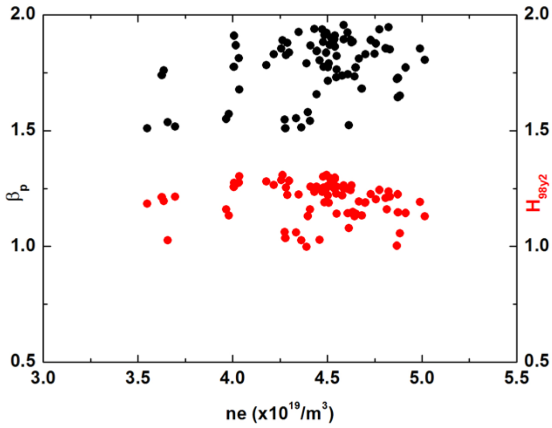

Figure 4, a plot of β_P, H_{98y2} versus electron density for EAST high β_P discharges

limited in duration due to a leak of water-cooling from up-divertor. The energy confinement quality of this discharge is high, with H_{98y2}~1.1-1.2 sustained for 20 sec until ECH turned off. Transport analysis shows that the LH current drive, the bootstrap current and EC current drive fractions are ~49%, ~43% and ~7% separately. Figure 4 shows β_P(black), H_{98y2} (red) versus electron density with favorable toroidal field. An extension of β_P and no degression on energy confinement at high line averaged electron density was obtained.

In all, several key elements, such as metal wall (tungsten divertor), pure RF (zero torque input), electron dominated heating, moderate bootstrap current fraction and good energy confinement, have been demonstrated in EAST high β_P scenario for the steady-state operation of CFETR. EAST is looking forward to achieving 400s long pulse H-mode operations (fig. 1) with ~50% bootstrap current fraction. Simulation shows that this goal requires not only increased injected power, but also significantly improved energy confinement quality. And also, a further integration of current density profile, pressure profile and the radiated divertor control should be addressed in the near future for steady state long pulse operation.

References

[1]X. Gong *et al* 2019 *Nucl. Fusion* 59 086030

[2]B.N. Wan *et al* 2019 *Nucl. Fusion* 59 112003

[3] A. Garofalo *et al* 2018 *Plasma Phys. Control. Fusion* **60** 014043

[4] H. Du *et al* 2018 *Nucl. Fusion* **58** 066011

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