# Recent Progress of long pulse H-mode operation on EAST

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**Abstract**

Recent progress of long pulse H-mode operation on EAST is reported. A steady state long pulse H-mode discharge duration over 100s with ITER like tungsten divertor has been obtained using only RF heating and current drive. 0D modeling suggests high power injection and high confinement quality are prerequisites for the next goal of high bootstrap current ($f_{bs}$~50%). Techniques of broadening current density profile for improving confinement is demonstrated.

## 1. Introduction

Long-pulse steady-state operation is one of the most challenges to a fusion reactor, which requires the resolution of several issues, such as external non-inductive current drive (CD) and self-generated bootstrap current, robust plasma heat flux and particle exhaust control and so on. High $\beta_P$ scenario is attractive since it stays away from current limit to maximize self-driven bootstrap current towards the high pressure for high performance with smaller requirement of external CD.

Experimental Advanced Superconducting Tokamak (EAST), as a first fully superconducting tokamak, aims to develop steady state long pulse scenario and relevant physics research in support to steady state of ITER and CFETR [1]. In order to investigate long-pulse steady-state tokamak physics, EAST has also equipped with capabilities of dominant electron heating, low input torque and ITER-like tungsten divertor.

## 2. Progress of long pulse H-mode operation on EAST

EAST (major radius R=1.8 m, minor radius a=0.45 m, plasma current $I_p$<1.0 MA toroidal field $B_T$<3.5T) has a flexible Poloidal Field (PF) control system with a set of 12 independently power supplies and a pair of internal water-cooled coils, accommodating both single null and double null divertor configurations. EAST is equipped with an actively water-cooled ITER-like tungsten divertor with power handling capability of ~ 10 MW/m$^2$, upper and lower divertor cryo-pumps for particle exhaust, and high power continuous wave (CW) injection for plasma current drive and heating by Lower Hybrid Current Drive (LHCD), Electron Cyclotron Heating (ECH) and Ion Cyclotron Resonant Frequency (ICRF).

On EAST, the fully non-inductive high $\beta_P$ scenario has been developed towards more ITER-relevant conditions. Building on the previous long pulse H-mode experiments, a recent discharge of duration over

100 seconds [2-3] has been obtained through the multi-RF power combination, shown in Fig.1. The plasma configuration is the upper single null. Loop voltage was well controlled to be zero which indicates fully non-inductive current drive condition. Small ELMs were obtained in this long pulse H-mode discharge, which facilitate the RF power coupling in the H-mode phase. A confinement enhancement factor relative to standard H-mode, $H_{98y2}$ of 1.1-1.2 was achieved and maintained constant during the discharge. The electron temperature profile and transport analysis suggest that eITB exists inside the rho<0.4 regime. A good impurity and particle fluxes control was achieved by applying on-axis ECRH, possibly due to the control of core density and temperature profiles. The total radiation power was kept almost constant in the whole discharge.

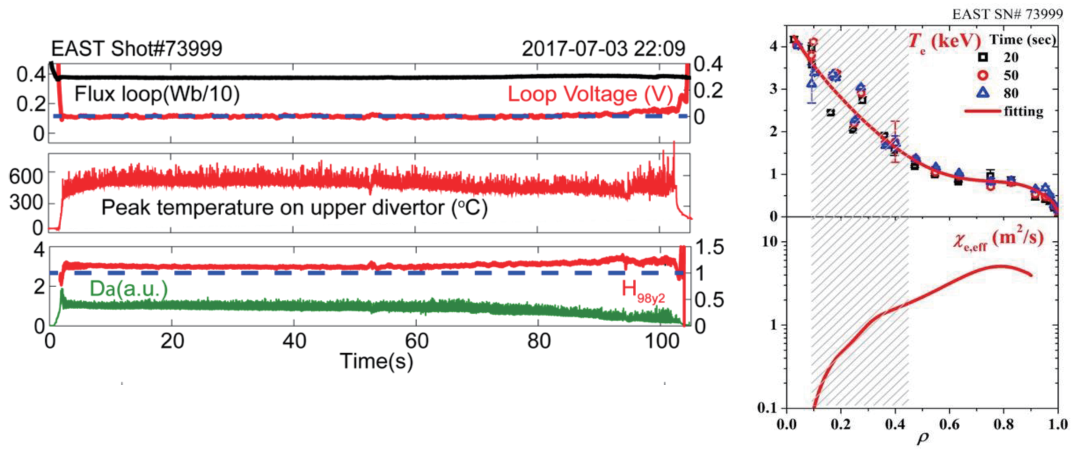


Fig.1 On the left are time histories of flux loop, loop voltage, peaked temperature on the upper divertor, confinement enhancement factor $H_{98y2}$, and the $D_\alpha$. On the right is measurements of the radial profile of the electron temperature at several times and experimental thermal diffusivity of electron.

More high $\beta_P$ experimental results on EAST were performed and are summarized in figure 2, where the grey boundary shows the operational space. It shows that the regime of nearly zero loop voltage is typically obtained at the moderate density, ($\langle n_e \rangle \sim 2.5 \sim 3.5 \times 10^{19}$ $m^{-3}$), while relatively high $\beta_P$ are accessed with the combined heating of NBI and RF. On EAST, increasing <ne> will require more external CD power or more self-driven bootstrap current to compensate the reduced LHCD efficiency. In addition, the confinement versus $\beta_P$ shows that the confinement increases with the increase of $\beta_P$, which suggest that higher $\beta_P$ allows higher confinement. This result is consistent with the high $\beta_P$ joint experiment on DIII-D, where Shafranov shift was believed as the dominant stabilizing effect for the suppression of the turbulence at low toroidal rotation [4].

As one of the key elements for long pulse operation, the efficiency of LHCD was systematically investigated and compared between two LHW systems, i.e., 2.45GHz and 4.6GHz [5]. In the experiments, we found that 4.6GHz has the higher current drive efficiency and better confinement than 2.45GHz because of weaker non-linear effect. And also, strong lithium coating which changes edge parameters, like reducing edge recycling and increasing electron temperature, suppresses non-linear effect, enabling a higher LHCD efficiency. For long pulse operations, the off-axis LHCD, one side, was used to save flux consumption, the other side was to optimize the current density profile to avoid MHD activities like sawtooth.

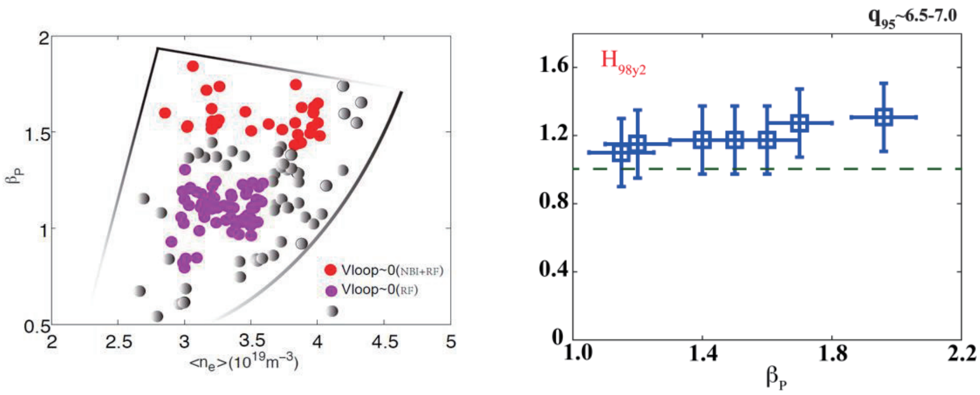


Fig.2 On the left is the EAST high $\beta_P$ operational space; the right is confinement versus the value of $\beta_P$

**3. Future plan for developing high $\beta_P$, high bootstrap current fraction scenario**

To meet the next goal of EAST long pulse operation (50% $f_{bs}$), a 0D model has been used to calculate steady state solutions at $I_P$= 450 kA with varying levels of total injected power (shown in figure 3). The calculation suggests that steady-state at high performance requires not only increased injected power, but also significantly improved energy confinement quality. The calculations show that at present level of confinement ($H_{98y2}$=1.1), quadrupling (from ~4 MW to ~16 MW) the injected power can only barely double the $\beta_P$ (from ~0.9 to 1.8). If higher confinement can be accessed, steady-state high performance with $\beta_P \geq 2.5$ is possible to obtain 50% bootstrap current fraction.

Current density profile control or optimization, as a key issue for improving the confinement quality, was performed on EAST. A promising technique of using a large fraction of LHCD to replace the Ohmic current was demonstrated when plasma reaches the flat top (see in figure 4). In a set of recent EAST experiments, the line averaged electron density was systematically varied in order to modify the deposition profile of the external LHCD, while keeping the plasma in fully non-inductive conditions to avoid Ohmic current penetration. The LHCD profile is expected to become more off-axis with higher density, because radial penetration of the wave is reduced at higher density. More detail can be found in Ref. [6]

Simultaneous magnetic and kinetic plasma control based on extremely simple data-driven models and a two-time-scale approximation has been developed [7] and will be used to active control the current density profile in EAST through the collaboration with CEA, which will further contribute to the high bootstrap current, high $\beta_P$ scenario development.

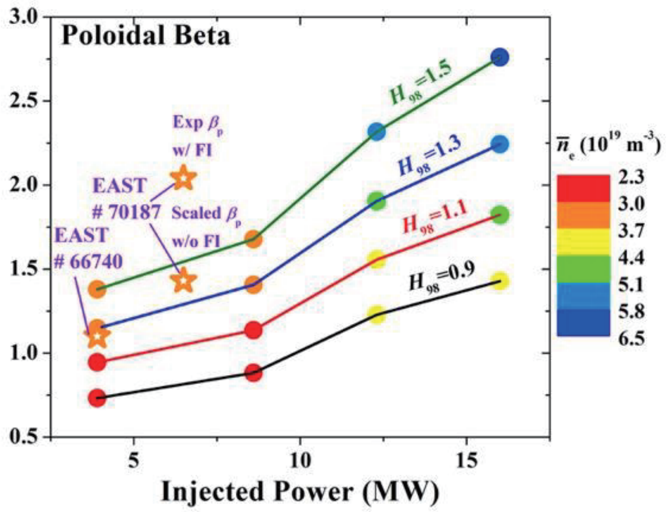


Fig.3 0D modeling predictions of poloidal beta versus injected power assuming plasma current $I_P$=450 kA and different levels of energy confinement quality.

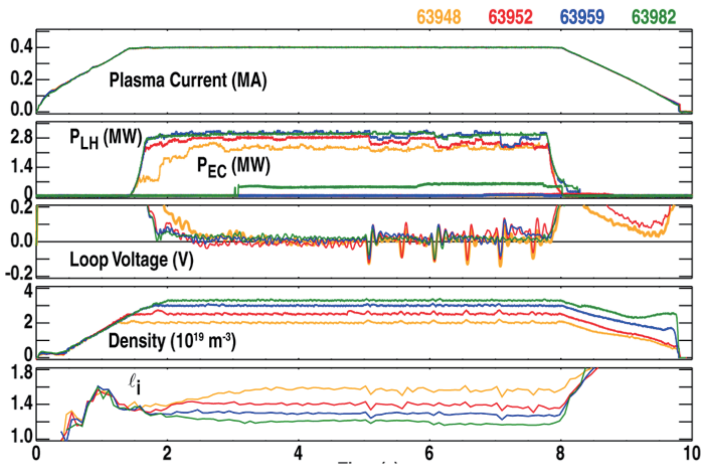


Fig.4 Density scan in fully non-inductive discharges operating on tungsten divertor shows broader current profiles with higher density.

## 4. Summary

In all, 100s long-pulse fully non-inductive steady-state scenario with a good plasma performance ($H_{98y2}$~ 1.1) and a good control of impurity and heat exhaust with the tungsten divertor has been demonstrated on EAST. The broader current profile control by varying the deposition profile of the external LHCD, which will further strengthen the high $\beta_P$ scenario development for achieving high-performance, steady-state on EAST in the near future. Next, EAST will aim to provide a suitable platform to address physics and technology issues relevant for steady-state advanced high-performance H-mode plasmas with high power injection. For this goal, a new lower divertor suitable for water-cooled tungsten PFCs will be installed in 2019.

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