EPJ Web of Conferences 157, 02010 (2017) DOI: 10.1051/epjconf/201715702010
22 Topical Conference on Radio-Frequency Power in Plasmas

Recent progress of RF-dominated experiments on EAST

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Abstract. The research of EAST program is mostly focused on the development of high performance steady state scenario with ITER-like poloidal configuration and RF-dominated heating schemes. With the enhanced ITER-relevant auxiliary heating and current drive systems, the plasma profile control by coupling/integration of various combinations has been investigated, including lower hybrid current drive (LHCD), electron cyclotron resonance heating (ECRH) and ion cyclotron resonance heating (ICRH). The 12 MW ICRH system has been installed on EAST. Heating and confinement studies using the Hydrogen Minority Heating scheme have been investigated. One of the importance challenges for EAST is coupling higher power into the core plasma, experiments including changing plasma position, electron density, local gas puffing and antenna phasing scanning were performed to improve ICRF coupling efficiency on EAST. Results show that local gas injection and reducing the k|| can improve the coupling efficiency directly. By means of the 4.6 GHz and 2.45 GHz LHCD systems, H-mode can be obtained and sustained at relatively high density, even up to ne ~ 4.5×10^{19} m^{-3}, where a current drive effect is still observed. Meanwhile, effect of source frequency (2.45GHz and 4.6GHz) on LHCD characteristic has been studied on EAST, showing that higher frequency improves penetration of the coupled LH (lower hybrid) power into the plasma core and leads to a better effect on plasma characteristics. Studies demonstrate the role of parasitic effects of edge plasma in LHCD and the mitigation by increasing source frequency. Experiments of effect of LH spectrum and plasma density on plasma characteristics are performed, suggesting the possibility of plasma control for high performance. The development of a 4MW ECRH system is in progress for the purpose of plasma heating and MHD control. The built ECRH system with 1MW source power has been successfully put into use on EAST in 2015. H-mode discharges with L-H transition triggered by ECRH injection were obtained and its effects on the electron temperature, particle confinement and the core MHD stabilities were observed. By further exploring and optimizing the RF combination for the sole RF heating and current drive regime, fully non-inductive H-mode discharges with V_{loop}~0V has progressed steadily in the 2016 campaign. The overview of the significant progress of RF dominated experiments is presented in this paper.

1 Introduction

Experimental Advanced Superconducting Tokamak (EAST) [1-3] is dedicated to provide a unique platform to address plasma physics and technology issues relevant for ITER under long-pulse operation conditions. Recently, great efforts [4] have been made on both physics and technology fronts to accomplish this mission with all ITER-relevant auxiliary heating and current drive systems, enabling the investigation of plasma profile control by coupling/integration of various combinations. By means of the 4.6 GHz and 2.45 GHz lower hybrid current drive (LHCD) systems, H-mode can be obtained and maintained at relatively high density, even up to ne ~ 4.5×10^{19} m^{-3}, where a current drive effect is still observed; A new small/no ELM H-mode regime has been demonstrated to be a good solution to the problem of divertor transient heat load, which facilitate the exploration of long-pulse high-performance H-mode operation on EAST. In addition, significant progress has been achieved on EAST, including: i) Demonstration of a steady-state scenario (fully non-inductive with V_{loop} ~ 0.0V at high β_P ~ 1.8 and high performance ($H_{98,y2}$> 1.0) in upper single-null (ε ~ 1.6) configuration with the tungsten divertor; ii)Discovery of a stationary ELM-stable H-mode regime with 4.6 GHz LHCD.This overview will report the main advances in RF dominated steady-state H mode scenarios. The progress on RF physics will also be presented.

2 RF Heating and Current Drive systems

To fulfil the physical objectives of EAST and increase the relevance to ITER, over 30 MW CW heating and current-drive (H&CD) power have been installed on EAST. Figure 1 shows the distribution of auxiliary heating systems on EAST. Besides a new LHCD system (at 4.6 GHz) and NBI system, an ECH system, which would offer greater flexibility with regards to plasma

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DOI: 10.1051/epjconf/201715702010

shape and plasma stabilization, is under developing for pressure and current density profile control on EAST.

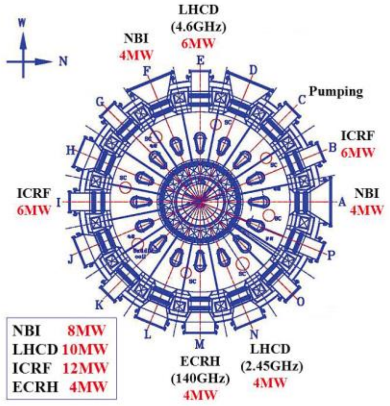


Fig.1. The distribution of auxiliary heating systems on EAST

2.1 ICRH system

The EAST ICRH system [5] has been developed to support long-pulse advanced tokamak fusion physics experiments. The source power of the ICRH system is 12.0 MW in total. The range of ICRH frequency is from 25 MHz to 70 MHz. The 8 ICRH sources at 25-70 MHz have been successfully commissioned at full power on water dummy load. An averaged maximum RF output power of 1.5 MW for each source has been achieved in a frequency range of 25-65 MHz with an efficiency varying from 60% to 70%.

The ICRH system consists of two antennas, each delivering 6.0 MW source power. One is a two toroidal, two poloidal strap (B-port) antenna and the other is a four-strap, folded strap (I-port) antenna. For B-port antenna [5], each strap is powered by one transmitter. Each poloidal pair at one toroidal location are phased at 180 and each toroidal pair is typically operated at [0, π] phasing. For the I-port antenna, each toroidal strap is powered by a single transmitter and can be phased relative to the other straps. During the 2016 experimental campaign, the ICRH system has been operated at total forward power up to 800 kW for 60s on long pulse H mode plasma on EAST.

2.2 LHW system

The long pulse operation of EAST relies exclusively on LHCD. Two CW LHCD systems are installed and operated in EAST campaign [6]. There are a 4.0 MW / 2.45 GHz system and a new 6.0 MW/ 4.6 GHz system utilizing 2 individual multi-junction phase antennas. Sustained plasmas over 400 s has been demonstrated by non-inductive current driven by LHCD systems. High current drive efficiency and nearly full non-inductive plasmas maintained by the new 4.6 GHz LHCD system. Technical solutions for long pulse high power system commissioning have been successfully demonstrated during the R&D activities.

2.3 ECRH system

As one of the most promising external heating methods, a long pulse electron cyclotron resonance heating (ECRH) system [7, 8] with 4MW power is under development at the frequency of 140 GHz (2nd harmonic X mode injection at a field of 2.5 Tesla), it will be used to provide central heating, optimize the plasma profiles for high pressure and good confinement as well as suppression of magneto-hydrodynamic (MHD) instabilities by a flexible two-mirror steerable antenna. At present, 1MW system was put into operation since 2015.

3 RF experiments on EAST

3.1 LHCD experiments at high density on EAST

LHCD experiments at high density in EAST aim at fully assessing conditions useful for enabling the LHCD effect into dense plasma core. To explore long pulse and high performance with LHCD, as shown in Fig.2, the capability of controlling current profile by optimizing lower hybrid (LH) spectrum with 4.6GHz LHCD system was demonstrated[9] on EAST. Results indicate the highest current drive (CD) efficiency and the most peaked current density profile occurs with $N_{//}^{peak}$=2.04, suggesting the possibility of profile control by changing the wave spectrum. The effect of LH frequency, with $N_{//}^{peak}$=2.1 for 2.45GHz and $N_{//}^{peak}$=2.04 for 4.6GHz and comparable directivities of the spectrum (0.74 vs. 0.76), on LHCD characteristics (ne =$2.0\times10^{19}m^{-3}$) with a same coupled power (1.05MW) in a lower single null (LSN) configuration was investigated in EAST (see Fig. 3) [10]. It shows the residual voltages (V_{loop}) are 0.27V and 0.15V, respectively, during 2.45GHz and 4.6GHz application, implying a better CD efficiency for 4.6GHz LH waves. Better plasma heating effect for 4.6GHz can be inferred from the time evolution of plasma stored energy (WMHD ~ 68.3kJ and 74.8kJ, respectively for 2.45GHz and 4.6GHz). The internal inductance (li) is higher with the 4.6GHz LH wave injection, meaning a more peaked current profile.

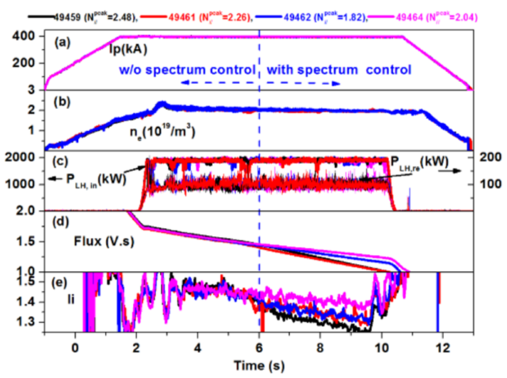


Fig. 2. Demonstration of LH spectrum on controlling current profile (4.6GHz)

Above results show that LH wave at 4.6 GHz exhibit stronger CD capability than at 2.45 GHz. As indicated by the parametric instability (PI) measurement by a radio frequency (RF) loop antenna (Fig. 4), it is speculated to be mainly ascribed to the less PI behavior with 4.6GHz LH wave. The effect of LH frequency (2.45 GHz and 4.60 GHz) on PI has been analysed by LHPI and MIT code in Ref. 6, both showing that PI is stronger with 2.45GHz wave. Based on the PI modelling, the LHstar suite of numerical codes [11] has been further utilised for calculating the driven current profile [6]. Due to the PI effect, the power deposited in the edge region, which cannot contribute to useful LHCD mechanism, is different, leading to a different LH current profile. Such result is qualitatively consistent with the much weaker LHCD effects that are routinely observed on EAST when operating with the 2.45 GHz frequency, in comparison with the 4.60 GHz case.

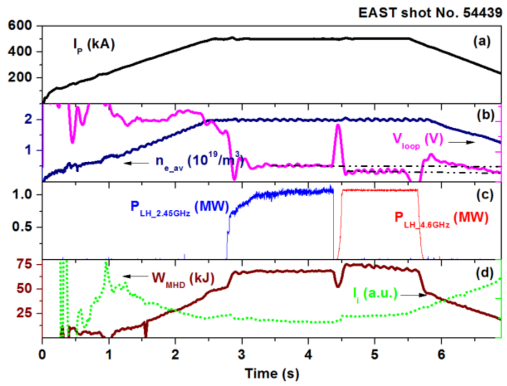


Fig. 3. Typical waveform of LH frequency effect on plasma characteristics

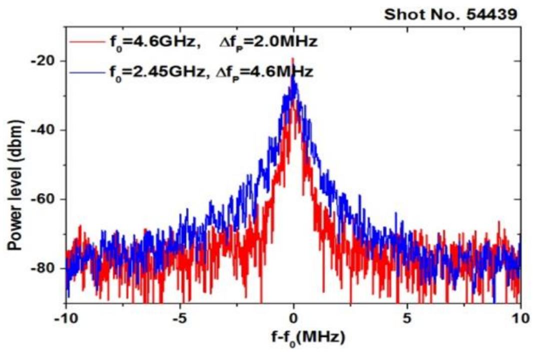


Fig. 4. PI signal by RF probe

With the 2.45GHz and 4.6GHz LHCD systems, high density H-mode is obtained and the typical waveforms are shown in Fig. 5, demonstrating the CD capability at high density. The electron cyclotron emission (ECE) signal drops quickly at the L-H transition, implying the decrease of LH driven current, possibly due to the concomitant density increase. Seen from the loop voltage and ECE signal, it is inferred that part of current is driven by LHW even if at the density of 4.5×1019m-3. Such density is higher than that of 1.5-2.5×1019m-3 obtained by 2.45GHz wave alone[12].

When injecting high LHW power at 4.6GHz, strong hot spots were often observed on the guard limiter of LHCD antenna by visible CCD (Fig. 6), leading to a sudden increase of impurity influx such as carbon and cooper, and often ending with disruptions. To identify the operation regime with hot spot occurring, a careful scan of global parameters such as plasma density, outer gap and LHW antenna phase difference was performed and the threshold power for the hot spots was around 2.5~3.0MW. The graphite tiles are damaged with the severest region located above the mid-plane. When using the RMP with rotating mode, hot spots could be slightly lightened by tuning the particle flux hitting on the guard limiter. More testing is still ongoing with a new guard limiter design to avoid strong particle flux directly hitting on the limiter.

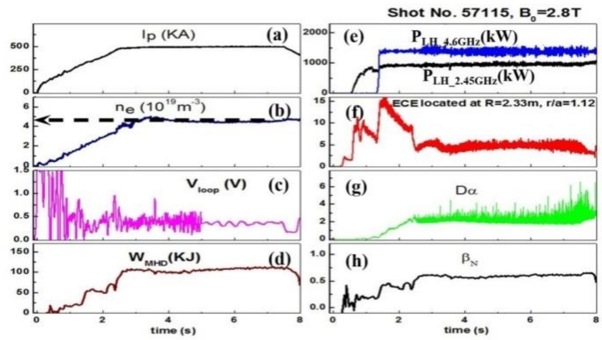


Fig. 5. H-mode with LHCD at high density

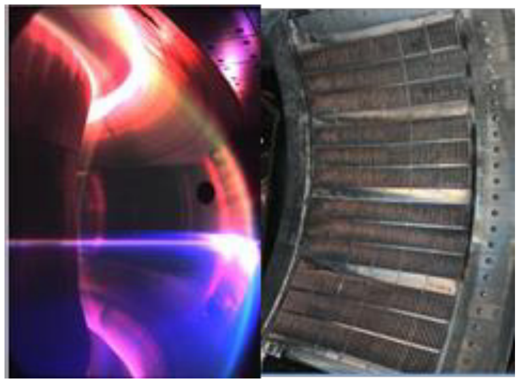


Fig.6. Hot spot observed by CCD and damage found in the 4.6GHz LHW antenna

3.2 ICRF Coupling and Heating on EAST

One of the importance challenges for EAST ICRH experiments is coupling higher power into the core plasma. The coupling of ICRF waves relies on the tunnelling of the fast wave between the antenna structure and the cut-off layer within the plasma. The experimental antenna loading is calculated from the input ICRF power measured by directional couplers and the maximum of the voltage in the transmission line measured by voltage probes. The antenna loading are calculated separately for each strap of each antenna. Here the mutual coupling between the straps is neglecting. Local gas puffing and antenna phasing scanning have been tested to improve ICRF coupling efficiency on EAST. The experimental results show that local gas injection and reducing the k parallel improves the coupling efficiency directly.

In order to study the ICRF coupling, some important experiments [13] including changing plasma position and electron density scanning have been performed. We change the gap between the limiter and the plasma last closed flux surface. The antenna is fixed in dipole phasing. As shown in Fig.7, the coupling resistance decreases with the gap. The results show that widening the gap will increase the evanescent layer width and reduce the coupling efficiency. This is also confirmed by the electron density measured by microwave reflectometry. ICRF antenna loading increase with the line averaged density of the core plasma. This is because increasing the central electron density is equivalent to pushing the position of the cutoff density to close to the antenna and reducing evanescent layer.

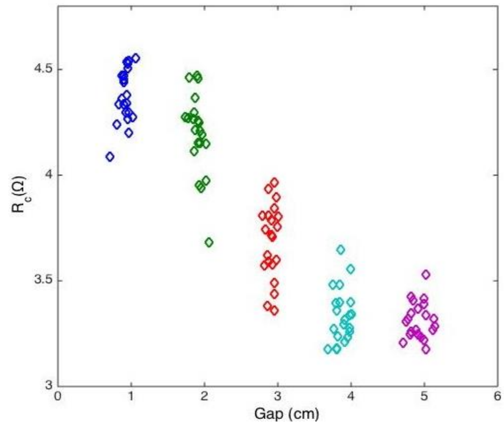


Fig.7. ICRF antenna loading versus gap between the limiter and the plasmas last closed flux surface.

Heating and confinement studies using H minority heating regime show a typical L-mode behavior. The ICRF heating efficiency is averaged at 35%. The heating efficiency can be improved when combined with the lower hybrid wave. The confinement of purely ICRF heated plasmas has been studied on EAST. The result of calculation shows that there is a good agreement with the result of the ITER89-P empirical scaling. And we found that the energy confinement of ICRH essentially follow an L-mode scaling.

3.3 Preliminary results from ECRH

It is generally known that ECRH is a highly controllable heating tool and the power deposition profiles can be changed by adjustment of the launcher in poloidal and toroidal directions. Fig. 8 shows the range of EC power deposition. The experimental locations were obtained by power modulation method and the simulated results were from TORAY code. It is seen that the locations can be varied in the region of $\rho < 0.8$ and good agreement between the experiments and simulations are achieved, which validates the steerable performance of the launcher.

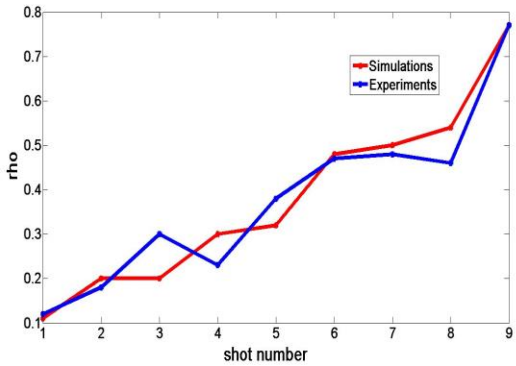
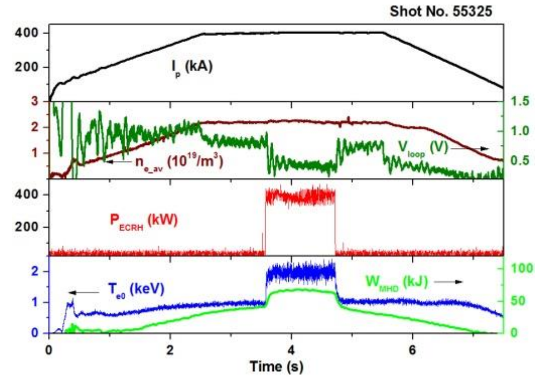
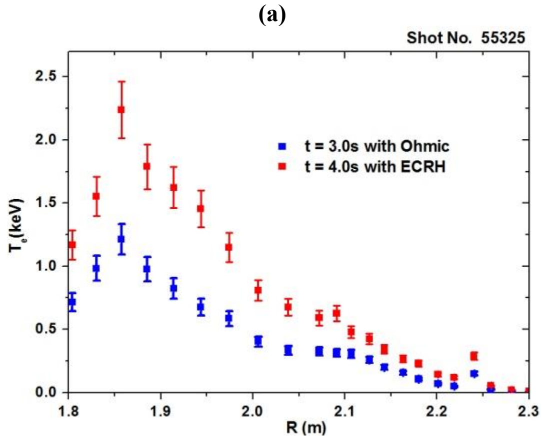


Fig.8. Comparison of EC power locations between experiments and simulations.

Good plasma heating effects were obtained during ohmic target plasma [8] and H-mode phase by 400 kW EC waves injection. As shown in Fig.9, the electron temperature measured by electron-cyclotron emission (ECE) radiometer increases globally during ECRH phase.



(a)



(b)

Fig. 9. (a) Typical waveform of ECRH power injected into Ohmic plasma, and (b) comparison on Te profiles measured by the electron-cyclotron emission (ECE) radiometer between Ohmic heating and ECRH phases.

An H-mode discharge with L-H transition was triggered by ECRH as illustrated in Fig.10 characterized by a sharp drop in Dα emission, an increase in line-averaged density (ne_av) and plasma stored energy (ΔW_{MHD} ~ 78 kJ).

 DOI: 10.1051/epjconf/201715702010

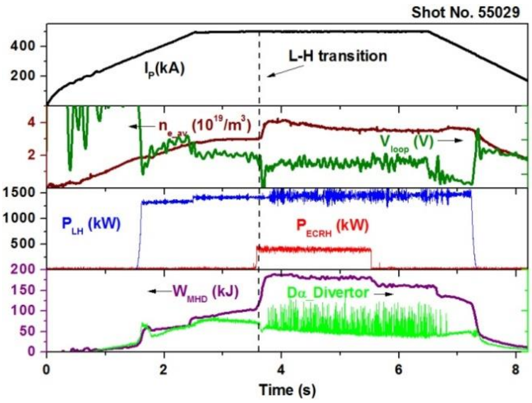


Fig. 10. Time histories from an ELMy H-mode discharge with L-H transition triggered by ECRH

The continued EC beam injection has been applied to stabilize the m/n=2/1 tearing mode on EAST tokomak. The stabilization effect is investigated as shown in the Fig.11 (a). It is found that the island width can be reduced up to 60% of the initial size before the EC beam on, with the gyrotron power of 320 kW and deposited at 0.5. As the beam deposition position moves away from the original position, the stabilization effect gradually reduces and the mode is even enhanced by the heating in the plasma core. The m/n=2/1 mode is also stabilized when co-ECCD is applied, even though its stabilization effect is less significant than ECRH. However, the counter-ECCD seems to have few effects on the mode stabilization.

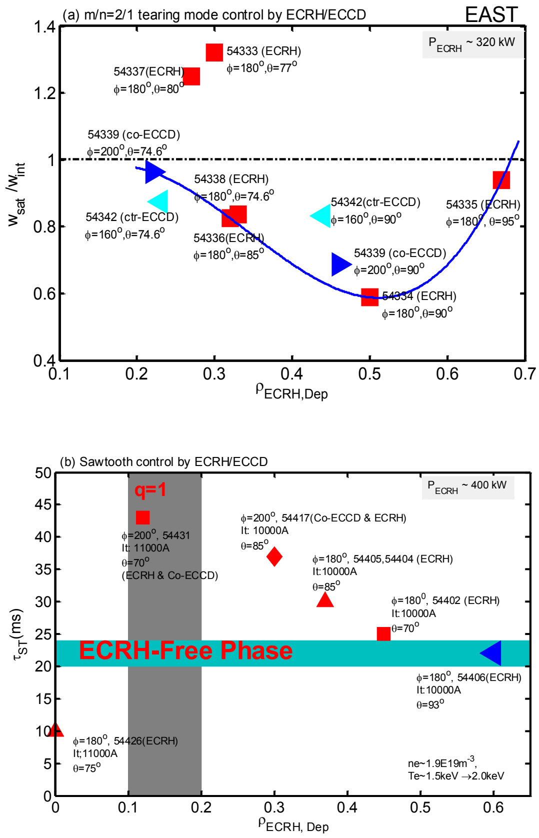


Figure.11. (a) The m/n=2/1 tearing mode control by ECRH/ECCD. The dashed line indicates free stabilization effect, above which the mode is enhanced and below which the mode is stabilized. (b) Sawtooth control by ECRH/ECCD. Sawtooth period reaches its maximum at about q = 1 surface.

The sawtooth period is found to be minimized in EAST experiments [14] when the ECRH resonance location is deposited to be just inside the q =1 surface, as shown in the Fig. 11(b). When ECRH deposition is outside the q = 1 surface, the sawtooth oscillation is stabilized (characterized by prolonged sawtooth period), and the sawtooth periods gradually decrease as ECRH deposition position sweeps away from q = 1 surface.

4 Long pulse discharge by H&CD systems

4.1 High electron temperature discharge

Stationary long pulse plasma of high electron temperature was produced on EAST for the first time through an integrated control of plasma shape, divertor heat flux, particle exhaust, wall conditioning, impurity management, and the coupling of multiple heating and current drive power. As shown in Fig.12, a discharge[15] with a lower single null divertor configuration was maintained for 103 s at a plasma current of 0.4 MA, q95 ≈7.0, a peak electron temperature of >4.5 keV, and a central density ne(0)~2.5×10^{19} m^{-3}. This scenario allows the further work on the synergy of electron heating by LHW and ECH and electron thermal transport in the near future. It further introduced an example of integrated “hybrid” operating scenario of interest to ITER and CFETR.

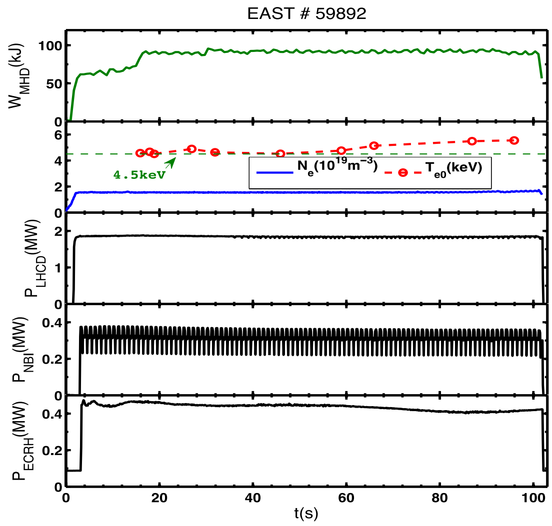


Fig.12. 102-sec long pulse discharge with Te> 4.5keV

4.2 long pulse H mode

To further explore the coupling or integration of several key physics process issues, long-pulse operation [16] has been explored on EAST. Fig. 13 shows a discharge of duration over one minute with the multi-RF power combination, i.e. 0.4 MW LHW at 2.45 GHz, 2.1 MW LHW at 4.6 GHz, 0.4 MW ECH and 0.8 MW ICRF. The

DOI: 10.1051/epjconf/201715702010

plasma parameters are as follows: Ip ~ 0.45 MA, toroidal magnetic field BT = 2.5 T, elongation k~1.6, and safety factor q95~6. The loop voltage was well controlled to be slightly negative, which indicates a fully non-inductive 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, H98y2 of 1.1~1.2, was achieved and maintained constant during the discharge, with a line averaged electron density ~3.0 × 10^{19} m^{-3}.

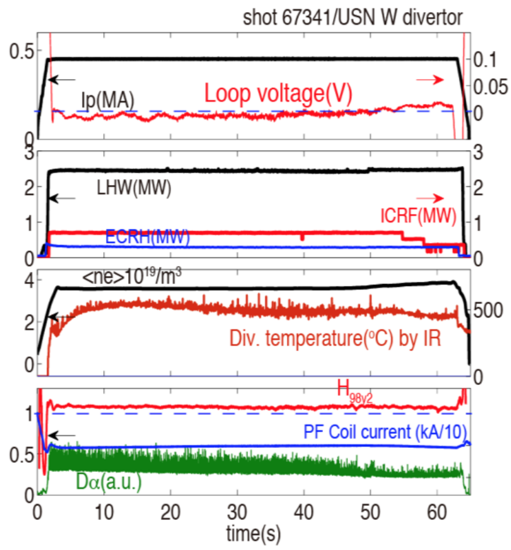


Fig. 13. Overview of >60s long-pulse RF-heated Steady-state H-mode discharge. From top to bottom panel: 1). Plasma current (Ip) and Loop voltage (V); 2). Line averaged density and divertor temperature; 3). LHW, ECRH and ICRF power; 4). H98y2 factor, PF current and Dα signal

5 Summary

On EAST, a series of long-pulse H-modes have been successfully achieved towards more ITER-relevant condition, such as low torque injection, RF-dominated heating and current drive with an ITER-like tungsten divertor. These newly achieved H-mode scenarios may offer a promising regime for long-pulse high-performance operation. To accomplish this, great efforts have been made to control both steady state and transient ELM induced divertor heat fluxes. EAST could be in operation with more than 30 MW CW heating and current drive power (LHCD, ICRH, NBI and ECRH), enhanced diagnostic capabilities and full actively-cooled metal wall from 2015. The upgraded EAST capabilities provide very high potential to investigate the critical issue for long pulse H mode operation with dominant electron heating and low torque input, which is essential for ITER and future reactors.

Acknowledgements

This work was supported partly by National key research and development program (grant nos 2016YFA0400600, 2016YFA0400601 and 2016YFA0400602). This work was supported partly by National Magnetic confinement Fusion Science Programme (grant nos 2015GB101001, 2015GB103002, 2015GB102003, 2013GB106001B, 2013GB112003). This work was also supported partly by the National Natural Science Foundation of China under grant nos11675213, 11375235, 11175206, 11305211, 11275233 and 11375236.

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