DEVELOPMENT OF STEADY-SATE OPERATION SCENARIOS WITH FULL TUNGSTEN LIMITER/DIVERTOR IN ITER-RELEVANT CONFIGURATION ON EAST

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Abstract

The major goal of EAST is to demonstrate long-pulse high-performance regime with tungsten wall for scientific understanding in support of future fusion device. The revised ITER baseline has been proposed together with its associated new research plan. In support of the R&D required for the new ITER baseline, EAST has successfully demonstrated long pulse fully non-inductive H-modes up to 100s at $T_e(0)$ > 8.5keV with type II ELMs under both boronized and uncoated metal wall with zero torque injection by RF-only heating. Further, a high poloidal beta (β_p) scenario has been developed in boron wall at q_{95} ~ 5.0-7.0, a range attractive for ITER steady-state operation, with high energy confinement quality (H_{98y2} ~ 1.0-1.3, β_N ~ 1.6-2.1) by dominant electron heating. To account for the ITER heating and current mix, we have also explored a fully non-inductive high β_p regime with ITER-like heating scheme in LSN configuration and active water-cooled tungsten divetor. With the enhanced EAST capabilities, we are planning to extend the performance with boron wall expected in ITER-relevant configuration, which can offer unique contributions in support of the ITER new research plan.

1. INTRODUCTION

Aiming at efficient low-cost fusion reactors, tokamak steady-state operations are required with high-performance long-duration plasma fully sustained by non-inductive current including high self-generated bootstrap current and minimized external power source. ITER (International Tokamak Experimental Reactor) steady-state scenario research aims at fully non-inductive plasma with optimizing performance at the fusion gain Q≥5 and the burning time up to ~3000s [1]. Recently the revised ITER new baseline has been proposed [2]. The key element is switching first wall (FW) material from beryllium (Be) to tungsten (W) [3] incorporating a boronization system [4] to mitigate plasma operation risks to the ITER Project's goals, together with an improved understanding of the implications of the use of W plasma-facing components (PFC) for plasma operation and performance [5]. The new ITER baseline brings new challenges with the associated open R&D issues for operation phases and requires the physics evaluations supports from present experimental research [5].

EAST (Experimental Advanced Superconducting Tokamak) [6] is the first fully superconducting tokamak aiming at demonstrating long-pulse steady-state high performance plasma sustained in a long duration and delivering relevant for ITER and future fusion reactors. It has achieved a record H-mode plasma over 1066-second with the total injected energy up to 3.05GJ with lithium coating wall [7]. As ITER-relevant configurations, it is equipped as active water-cooled tungsten (W) limiter/divetor by boronization, flexible plasma control and heating/current drive systems. To support ITER new research plan, a dedicated set of joint ITER-EAST experiments have been performed on EAST [8]: optimization and characterization of boronization, ECW assisted plasma start-up on the tungsten limiter/divertor, and the impact of W on the H-mode operational space with and without boron coatings. For wall conditions with boron coating, to improve the uniformity and quality of the boron film, optimization and characterization of boronization through ion cyclotron wall conditioning (ICWC) and glow discharge cleaning (GDC) plasma has been investigated [9]. For plasma initiation, ECW assisted start-up has been carried out and robust breakdown and plasma initiation at ITER-like low toroidal electric fields has been demonstrated with optimized magnetic field configurations in a large range of prefill gas pressure [10]. It also demonstrated ECW assisted breakdown and the current ramp-up in the limiter phase [3]. For assessment of the impact of W as first wall material on plasma performance, the H-mode experiments have been implemented by ECH and NBI. The impacts of ELM type, separatrix-to-W limiter gap on plasma performance are studied and the details of the experimental results can be found in [5,11]. These are essential to explore boronization technology and its impact on plasma confinement at EAST within full metal and W divertors. Recently, EAST has successfully demonstrated long pulse fully non-inductive H-modes up to 100s using boronized metal wall with zero torque injection by RF-only heating.

The paper is organized as follows. Section 2 describes the current status of the improved capabilities on EAST to support ITER new research plan and the recent progress towards development of long-pulse fully noninductive high-performance plasma with boron wall. Section 3 presents the development and characteristics of high β_p scenario in boron wall. Section 4 addresses several challenges towards ITER-relevant configurations. A summary and list of opportunities in steady-state scenario development on EAST are given in section 5.

2. CURRENT STATUS ON EAST TO SUPPORT ITER NEW RESEARCH PLAN

2.1. Current capabilities to support ITER-relevant research

With the major goal to demonstrate a long-pulse high-performance regime for scientific understanding in support of future fusion reactors, EAST can offer unique features such as dominant electron heating, zero/low torque. To facilitate long-pulse high-performance operation along the proposed modifications to the ITER new baseline, EAST has been equipped with fully active water-cooled high Z metal wall, using Mo as first wall, W divertors and a main W limiter as outer poloidal limiter, shown in Fig. 1(e). The water-cooled tungsten PFCs can withstand a heat flux of up to 10 MW m^{-2}[12]. To sustain long-pulse operation in ITER-relevant wall conditioning, low-recycling wall conditions are required for good particle control, instead of previous routine lithium coating, carborane $C_2B_{10}H_{12}$ [13] are currently used on EAST in the boronization process assisted by ion cyclotron wall conditioning (ICWC) and glow discharge (GD). In addition, an advanced pure boron powder dropper system has been installed allowing real-time particle control during the long-pulse duration. To enhance the plasma performance for fully noninductive steady-state operation, the total available source power of the auxiliary heating and current drive systems has been gradually increased up to 32 MW, including lower hybrid current drive (LHCD) system, ion cyclotron resonant frequency (ICRF) system, electron cyclotron heating (ECH) system and during neutral beam injection (NBI) system [12].

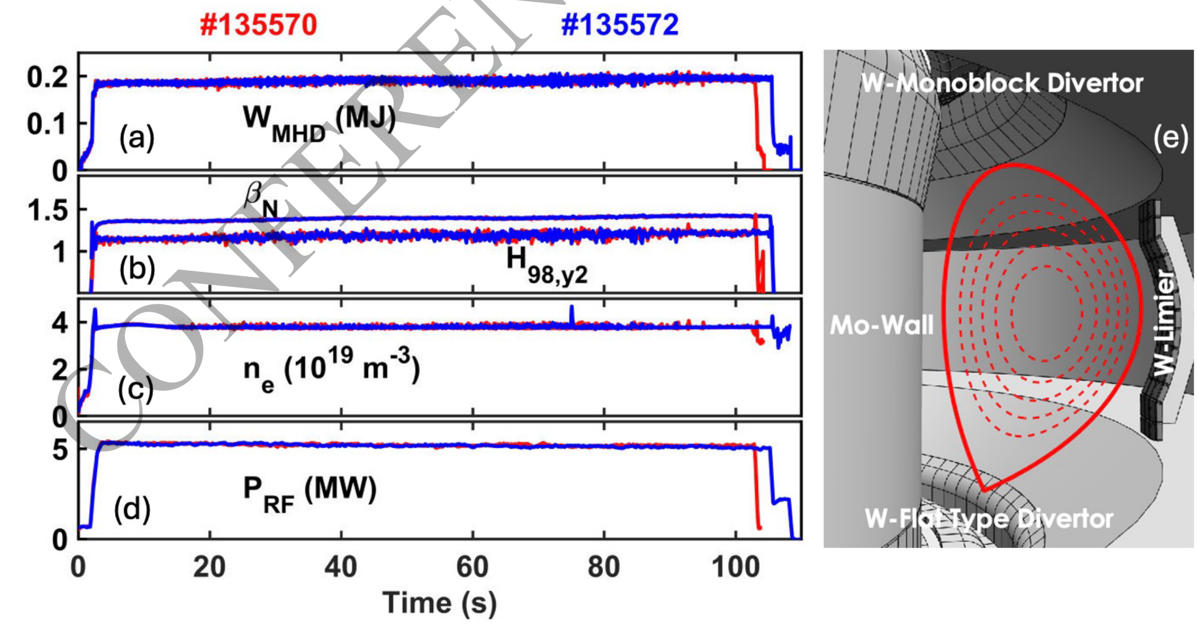

FIG. 1. (a)-(d) Time history of stationary ~100s H-mode plasma on full metal wall with P_{EC} ~ 3.0MW, P_{LH} ~ 2.2MW with optimization of heating and current driven coupling and well controlled high Z impurity. (e) Poloidal cross-section of EAST for the full metal PFCs equipped with Mo-wall, both fully active cooled outer poloidal W-limiter, and W-Monoblock upper divertor/W-Flat type lower divertor.

2.2. Demonstration of 100s fully non-inductive H-mode plasma with boron wall

With boronization instead of lithium-coating, Fig. 1(a)-(d) show that EAST has successfully demonstrated stationary ~100s fully non-inductive H-mode plasmas in Type II edge localized mode (ELM) regime at $T_e(0)$ > 8.5keV by RF-only heating with P_{EC} ~3.0MW, P_{LH} ~2.2MW. Confinement enhancement factor over H-mode confinement scaling in these conditions remains high at H_{98y2} > 1.1. To optimize heating and current driven coupling, the separatrix-W limiter gap is adjusted as 6cm. High Z impurities are well controlled. It is independent of the tungsten source from the main limiter and heating mix [5], thanks to the efficient W exhaust by type II ELMs and low core inwards neoclassical transport with no central fuelling by NBI and low rotation, as expected in ITER. In addition, operation with higher plasma density (f_{GW} > 0.6) can significantly reduce the edge electron temperature and the influx of medium and high-Z impurities. Furthermore, on-axis ECH is applied to avoid tungsten accumulation.

3. DEVELOPMENT OF HIGH-$\boldsymbol{\beta_p}$ SCENARIOS WITH BORON WALL

3.1. Fully non-inductive high β_p plasma by RF-only

To explore the steady-state operation with W-divertor in ITER-relevant configuration towards high fusion performance, Fig. 2 shows fully non-inductive high β_p plasma developed in boron wall at q_{95}~6.2, n_e/n_G~0.65, B_T~2.5T with high energy confinement quality (H_{98y2}~1.25/β_N~1.8) by dominant electron heating with P_{LH}~2.7MW, P_{EC}~2.0MW, P_{IC}~4.0MW. Fig. 2(e) shows the comparison of plasma kinetic profiles before and after ICRF injection. Here, the radial coordinate ρ used in this paper is the square root of the normalized toroidal magnetic flux. It is characterized by the existence of the weak internal transport barrier (ITB) in the electron temperature profile. Fig. 3 shows the calculated current density profiles for each component. The bootstrap current (“Bootstrap”) is calculated with the Sauter model. The current driven by EC waves (“ECCD”) is simulated with the coupled TORAY and CQL3D modeling, and the current driven by LH waves (“LHCD”) is simulated with the coupled GENRAY and CQL3D model. After ICRF injection, both T_e and T_i were increased, and the current profile was broadened. Bootstrap fraction was increased and more off-aixs, while LHCD fraction was reduced. This is due to the increased z_{eff} during ICRF which cause the lower LHCD efficiency.

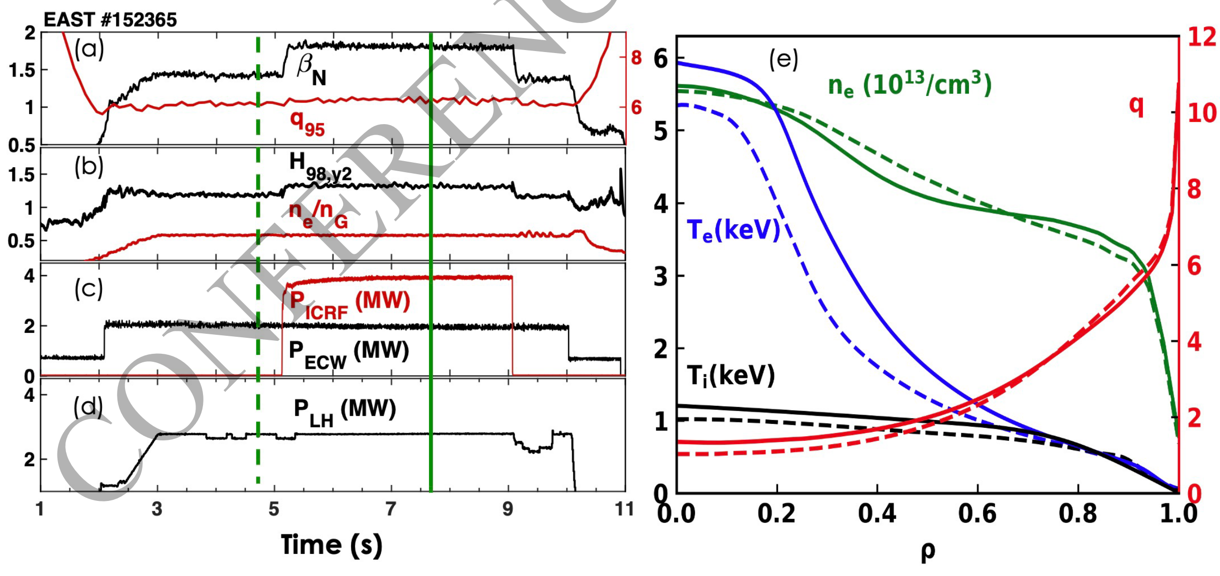

FIG. 2. Time traces for RF-only shot 152365 in high β_P scenario: (a) normalized beta (β_N), the safety factor at the 95% magnetic flux surface (q_{95}); (b) confinement enhancement factor over H-mode confinement scaling (H_{98y2}), Greenwald fraction (n_e/n_G); (c)injected power of RF for ICRF(P_{ICRF}) and ECW (P_{ECW}), and (d) LHW (P_{LH}); (e) Experimental kinetic profiles for 152365 at 4.7s (dashed) and 7.7s (solid): T_i (black), T_e (blue), n_e (green), and safety factor q(red).

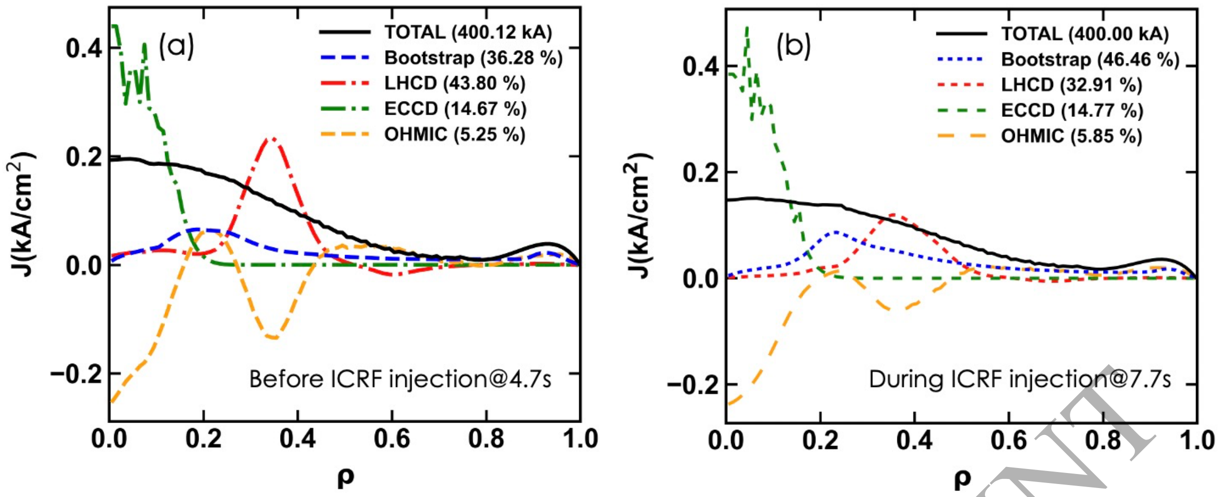

FIG. 3. Comparison of the total current density profiles(black) for shot 152365 (a)before and (b)during ICRF injection with bootstrap (blud), LH (red), EC(green) with negligible ohmic (dot line) current components.

Fig. 4 shows that before the injection of ICRF power, an m/n=3/2 tearing mode was present in the plasma core. This indicated a lack of effective heating in the mid-radius region (ρ~0.3), where the safety factor q=1.5 [14]. Following the application of ICRF, the m/n=3/2 tearing mode was suppressed, demonstrating that ICRF achieved effective core heating. However, upon termination of the ICRF power at t=9s, the m/n=3/2 mode reappeared. Furthermore, the spectral analysis of magnetic fluctuation signals at the edge revealed the excitation of an n=2 Beta-induced Alfvén Eigenmode (BAE) during the ICRF phase. This core-localized BAE mode had a frequency of approximately 72 kHz. It is known that BAEs typically compete with sawtooth oscillations. The emergence of this BAE mode suggests an improvement in fast ion confinement in the core after ICRF injection [15].

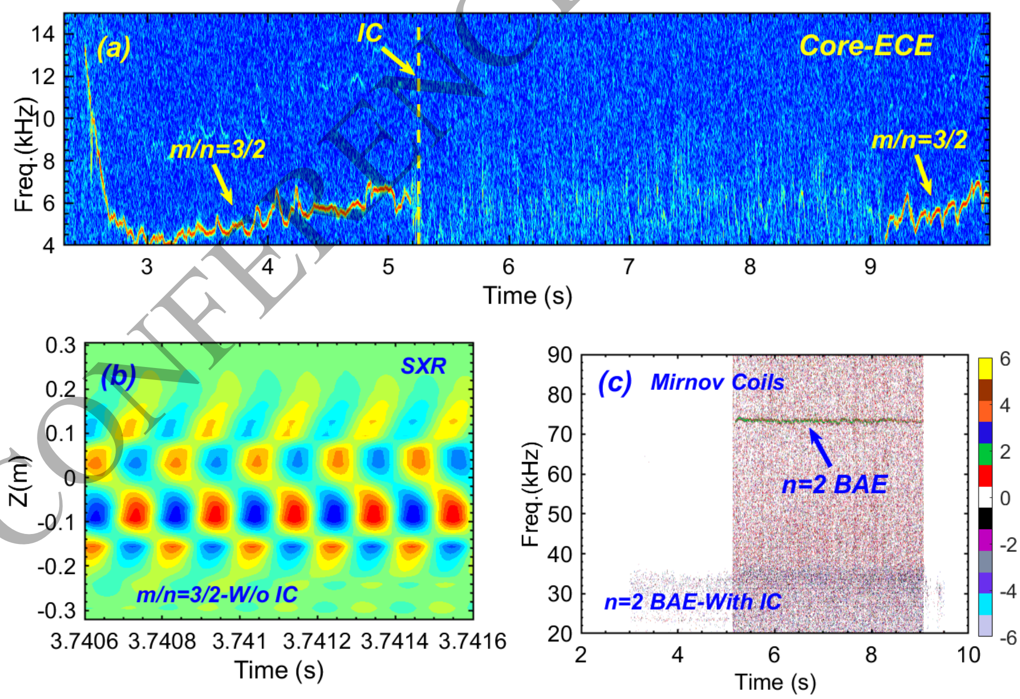

FIG. 4. (a) Time evolution of frequency spectrum for core ECE for shot 152365; (b) time-space contour plot extracting the SXR fluctuation signal corresponding to the 3/2 mode using the FFT method before ICRF injection with the Z-coordinate of the intersection of each SXR observation chord with the line R = 1.85; (c) the excitation of an n=2 Beta-induced Alfvén Eigenmode (BAE) during the ICRF phase measured by magnetic fluctuation signals.

3.2. Explore high β_p plasma using ITER-like heating scheme

To account for the ITER heating and current mix, we have also explored high β_p regime without lower hybrid wave systems shown in Fig. 5. All the ITER H&CD systems were used and found suitable for high β_p plasmas in a LSN configuration. High performance has been achieved with β_p ~ 2.1, β_N ~ 1.85, H_{98y2} ~ 1.2 at q_{95} ~ 6.2, n_e/n_G~0.65, P_{EC} ~ 2.0MW, P_{IC} ~ 3.0MW, P_{NB} ~ 3.0MW. The preliminary results for contributors to current drive analyzed by TRANSPT show that: f_{NI} ~ 65%, f_{BS} ~ 38%. The target q-profile was pre-shaped by ECCD at an early phase of the discharge. This included the application of a suitable voltage for NBI heating and optimized density and gap to improve ICRF coupling [16].

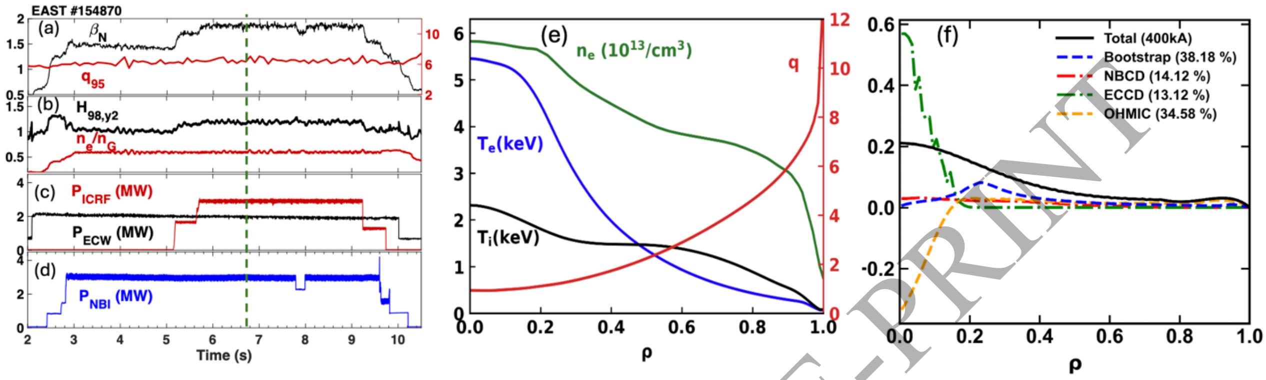

FIG.5. Time traces for shot 154870 in high β_P scenario using NBI instead of LHCD as ITER-like heating scheme: (a) normalized beta (β_N), the safety factor at the 95% magnetic flux surface (q_{95}); (b) confinement enhancement factor over H-mode confinement scaling (H_{98y2}), Greenwald fraction (n_e/n_G); (c)injected power of RF for ICRF(P_{ICRF}) and ECW (P_{ECW}), and (d) NBI (P_{NB}); (e) Experimental kinetic profiles at 6.7s: T_i (black), T_e (blue), n_e (green), and safety factor q(red);(f) the total current density profiles(black) with bootstrap (blue), NBCD (red), EC(green) and ohmic(orange) current components .

The sawtooth period and amplitude are influenced by factors such as the thermal plasma pressure, energetic particles, plasma equilibrium, and plasma rotation [17]. In this experiment, the plasma rotation and equilibrium remained essentially unchanged before and after the injection of ICRF power. From Fig. 6(a), prior to ICRF heating, the sawtooth period was 20 ms with a crash amplitude of approximately 3%. Following the application of high-power ICRF, the sawtooth period increased and the crash amplitude became more pronounced. The period stabilized at 25 ms, showing no significant change from its pre-ICRF value. In contrast, the sawtooth crash amplitude underwent a substantial change, increasing to 8%. This indicates that ICRF provides effective on-axis heating.

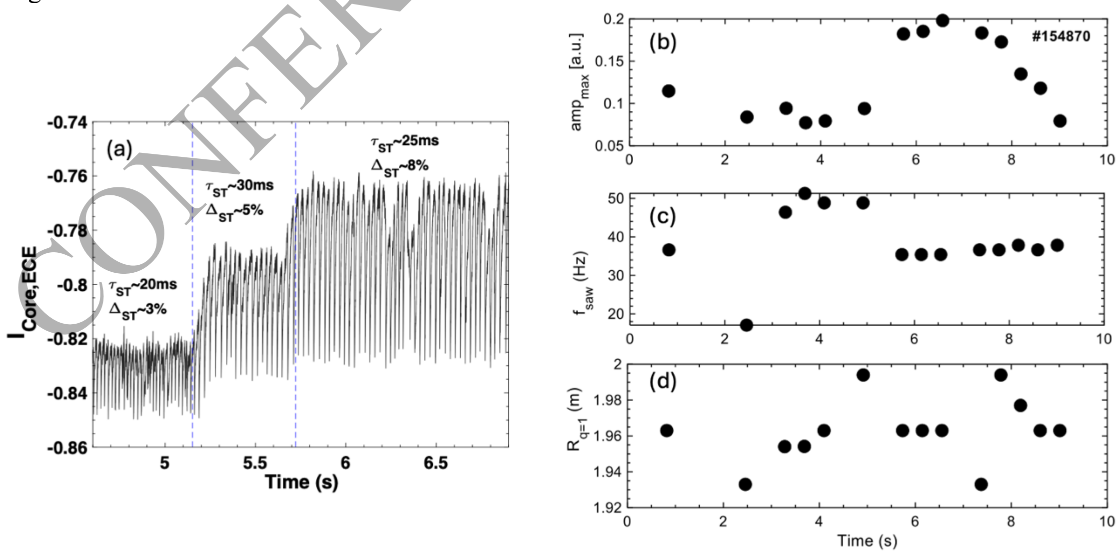

FIG. 6. Time evolution of (a) core ECE radiation intensity in arbitrary units, where the relative variation indicates the amplitude of the sawtooth crash; the sawtooth (b) amplitude, (c) period and (d) position for shot 154870 in high β_P scenario.

4. DISSCUSSION AND CHALLENGES TOWARDS ITER-RELEVANT CONFIGURATIONS

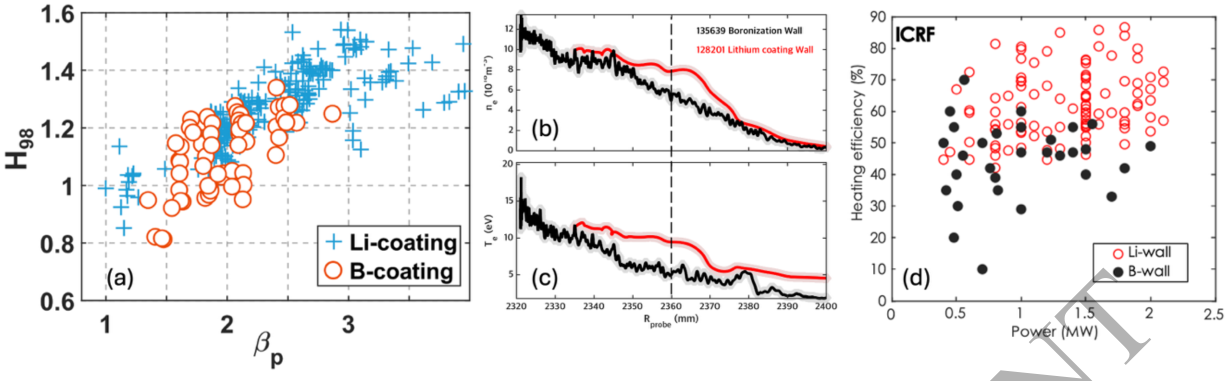

FIG. 7. (a) Normalized confinement quality H_{98} against β_p for RF-only scenario comparing between lithium-coating and boron-coating; edge plasma density (b) and electron temperature (c) profiles measured by fast reciprocating probe systems where LHW antenna and ICRF antenna located at R~2.36mm; (d) the impact of wall conditions on ICRF heating efficiency.

Fig. 7(a) shows that improved confinement quality is achieved with the extension of fully non-inductive H-mode plasmas to higher β_p both for lithium-coating and boron-coating wall. For the improved core energy confinement quality with zero torque injection, the previous understanding points to the strong effect of Shafranov shift (α-stabilization) on the turbulent transport in the higher β_p regime. However, compared with lithium-coating wall, energy confinement with boron-coating wall is basically reduced by ~10-15% with the lower edge plasma temperature and density profiles in SOL shown in Fig. 7(b)(c) measured from fast reciprocating probe systems. Edge profiles are changed with different wall conditions. With boronization, it is the challenge to broaden the current and pressure profiles to explore higher β_p operation with q_{min}>1.5. Important synergistic effects are leveraged toward this result, which relies on the impact of wall conditions on RF powers for heating and current drive. Reproducible H-mode plasmas with electron cyclotron resonant heating (ECRH) alone have been obtained on EAST in a wide range of plasma parameters for both lithium and boron coating [18]. No significant difference is found in the plasma confinement between the two conditioning methods. For lower hybrid current drive (LHCD) efficiency, simulations indicate that the plasma density and temperature parameters in SOL play an important role in [19]. Lower electron temperature in SOL with boronization can reduce the parametric decay instability (PDI) behavior and collisional absorption power, hence to reduce the LHCD efficiency with respect to that with lithiation, similar as the previous study [20]. Fig. 7(d) shows the reduced ICRF heating efficiency. The reduced edge density may decrease the antenna coupling. The impact of wall conditions on heating and current driven efficiency will be investigated further and understood for enhancing H&CD efficiency in the metal wall.

5. SUMMARY

In support of the R&D required for the new ITER baseline, EAST has successfully demonstrated long pulse fully non-inductive H-modes up to 100s at Te(0) > 8.5keV with type II ELMs under both boronized and uncoated metal wall with zero torque injection by RF-only heating. Furthermore, a high poloidal beta (β_p) scenario has been developed in boron wall at q_{95} ~ 6.2, a range attractive for ITER steady-state operation, with high energy confinement quality (H_{98y2} ~ 1.25/β_N ~ 1.8) by dominant electron heating. To account for the ITER heating and current mix, we have also explored high β_p regime without lower hybrid wave systems. With the enhanced EAST capabilities, e.g. ECH power upgraded to 8 MW, ICRF power increased to 6 MW, LHW power with 4.6GHz PAM upgraded to 4.0MW, etc., we are aiming at extending the performance to the lower collisionality with boron wall. Use external actuators (LHW, ICW, ECW) to modify local profiles (e.g. T_e and T_i) and broaden current profile to mitigate turbulent transport and core MHDs to improve performance. Current experiments on EAST also reveal a challenge: the core T_i may 'clamp' far below T_e, a direct threat to fusion performance. Near term plan is to increase electron-ion thermal energy transfer to enhance electron-ion energy coupling via n_e, T_e control; to raise core T_i through enhancing Shafranov shift, fast ion dilution and/or fast-ion mode-driven flow shear. With the enhanced EAST capabilities, we are planning to extend the performance with boron wall expected in ITER-relevant configuration, which can offer unique contributions in support of the ITER new research plan.

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