LONG-PULSE ELM-FREE H-MODE REGIME WITH FEEDBACK-CONTROLLED DETACHMENT UNDER BORONIZED METAL WALL IN EAST

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1. ABSTRACT

The presence of metallic plasma-facing components (PFCs) presents a fundamental challenge for achieving sustained high-confinement mode (H-mode) operation in tokamak fusion devices. Plasma-wall interactions induce significant material erosion while generating metallic impurities that both contaminate the core plasma and degrade energy confinement. This challenge is exacerbated by the edge localized mode (ELM) instabilities - transient events that produce intense heat fluxes capable of sputtering additional wall material. For viable reactor operation, three critical requirements must be simultaneously satisfied: 1) ELM suppression or mitigation to eliminate impulsive thermal loads, 2) maintenance of high energy confinement quality, and 3) establishment of stable divertor detachment to reduce steady-state heat fluxes. While individual demonstrations of these elements exist, their synergistic integration in long-pulse scenarios remains unrealized, particularly without compromising plasma performance through impurity accumulation or confinement degradation. Here, we present the first demonstration of a stationary, ELM-free H-mode regime sustained for 50-100 seconds with simultaneous divertor detachment on the EAST superconducting tokamak. This milestone was achieved through feedback-controlled nitrogen seeding in the divertor region under ITER-relevant conditions: boron-coated full metallic PFCs, dominant ECRH electron heating and intrinsically low toroidal rotation. The sustained operation exhibited robust performance with energy confinement factor H_{98y2}~1.1 and 60-70% of the Greenwald density at q_{95} down to 5.2. This represents the first integration of four critical reactor requirements in long pulse: ELM suppression, high confinement, metallic wall compatibility, and stable detachment.

An improvement in the energy confinement was observed by nitrogen seeding and divertor detachment with an increase in the pedestal electron temperature and pressure, and a significant reduction in low-frequency turbulence in the pedestal steep-gradient region. The propagation velocity measured by Doppler backscattering (DBS) in the electron diamagnetic drift direction is more than doubled at the pedestal, suggesting increased E×B shear flow, which may be responsible for the suppression of the low-frequency turbulence. Meanwhile, a high-frequency broad-band turbulence peaking at ~600 kHz appears in the pedestal steep-gradient region, propagating in the electron diamagnetic direction. Simulations using CGYRO code identify trapped-electron-mode (TEM) in this region with characteristics in good agreement with the high-frequency turbulence, which drives outward particle and electron heat transport, could facilitate impurity exhaust and the maintenance of ELM suppression. In future fusion reactors, this turbulence-dominated edge regime is more likely to appear, as turbulence suppression by the E×B flow shear is expected to be significantly weaker than that in present tokamaks [1]. The combined experimental/simulation results establish a viable path toward reactor-relevant ELM-free scenarios for future tokamak fusion reactors, resolving the long-standing "exhaust-confinement" compatibility problem under full metal-wall conditions through pedestal turbulence manipulating, which is essential for harvesting fusion energy.

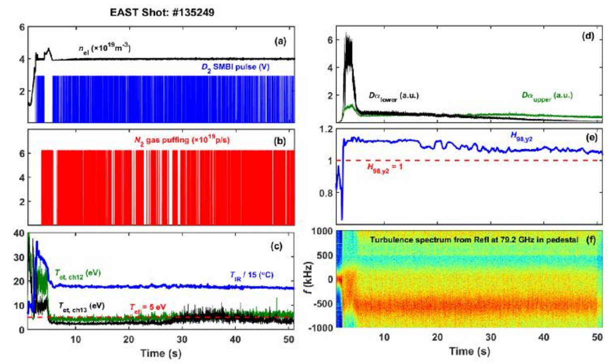

Fig. 1 A long-pulse ELM-free H-mode plasma of ~50s, with feedback-controlled divertor detachment by nitrogen seeding in EAST with boronized metal wall. (a) Central-line-averaged electron density (black) and deuterium SMBI pulses (blue); (b) Nitrogen injection rate; (c) Electron temperature (green and black) measured by divertor Langmuir probes and peak surface temperature of the lower outer divertor measured by inferred camera; (d) Upper (green) and lower(black) $D\alpha$ emission; (e) Energy confinement factor H_{98y2}; (f) Frequency spectrum measured by a channel of the multichannel poloidal correlation reflectometer at 79.2 GHz.

2. EXPERIMENTAL RESULTS

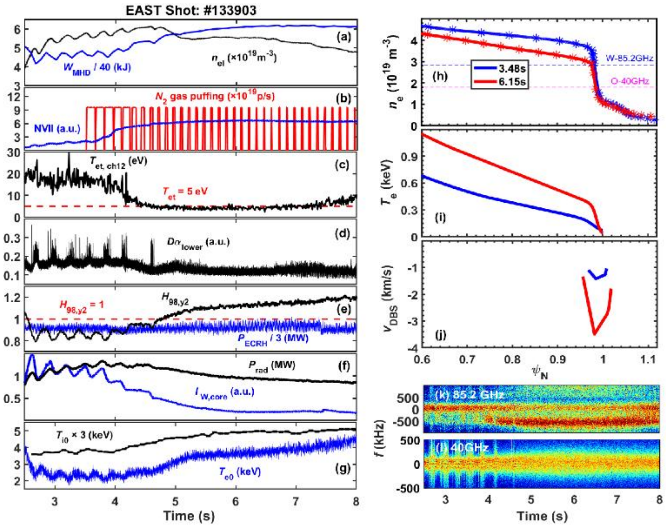

Fig. 2 An ELM-free H-mode plasma at q_{95}=5.2 with divertor detachment being achieved by divertor nitrogen seeding and X-point AXUV radiation feedback control in EAST with boronized metal wall. (a) Plasma stored energy (blue), central-line-averaged electron density (black) measured by a polarization interferometer; (b) Nitrogen injection rate from the lower divertor with pulse width modulation (red) and nitrogen NVII line emission from the plasma core measured by an EUV spectrometer (blue); (c) Electron temperature measured by divertor Langmuir probe channel 12; (d) $D\alpha$ line emission from lower divertor; (e) Energy confinement enhancement factor H_{98y2} (black) and ECRH injected power (blue); (f) Total radiation power from the plasma confinement region measured by bolometer arrays (black) and tungsten line emission from the plasma core measured by an EUV spectrometer (blue); (g) Electron temperature on axis (blue) measured by an ECE diagnostic and ion temperature on axis (black) measured by a X-ray crystal spectrometer; (h) Electron density profiles at 3.48s (blue) and 6.15s (red) measured by a sweep-frequency reflectometer with the horizontal dashed lines indicating the electron density values corresponding to the channel frequencies; (i) Electron temperature profiles measured by a Thomson scattering system; (j) Perpendicular propagation velocity measured by a DBS diagnostic; Frequency spectra measured by a multichannel poloidal correlation reflectometer at (k) 85.2 and (l) 40 GHz.

Figure 2 shows a typical ELM-free H-mode discharge at q_{95}=5.2 with divertor detachment being achieved by divertor nitrogen seeding and X-point AXUV radiation feedback control. The plasma became completely ELM-free (Fig. 2d) when the outer target plate of the lower divertor enters detachment (Fig. 2c). The plasma energy confinement was significantly improved with H_{98y2} reaching 1.2 (Fig. 2e). The tungsten impurity radiation in the plasma core region and the total radiation power were significantly reduced (Fig. 2f), suggesting that this plasma regime exhibits an excellent impurity control capability. n_e at the pedestal top decreases during divertor detaching (Fig. 2h), and T_e at the pedestal top is nearly doubled with a significant increase in the pedestal T_e gradient (Fig. 2i). The propagation velocity measured by DBS is more than doubled (Fig. 1j). Figures 2(k)&(l) show turbulence frequency spectra measured by a multichannel poloidal correlation reflectometer in the pedestal region with the microwave frequencies, corresponding electron densities and radial positions for each channel shown in Fig. 1h. During N_2 seeding, a high-frequency turbulence mode with a peak frequency at ~600 kHz, propagating in the electron diamagnetic direction, appears in the pedestal steep-gradient region, meanwhile, the amplitude of a low-frequency turbulence mode decreases, as seen at the 85.2 GHz channel (Fig. 1k). The amplitude of ECM (Edge Coherent Mode, a mode at 40-50 kHz with multiple harmonics) is also reduced, as seen at the 40 GHz channel (Fig. 1l) which is located at the lower part of the pedestal steep-gradient region.

A significant decrease in n_e and increase in T_e at the pedestal with impurity seeding was also seen in JET with ITER-like wall [2] and AUG with full-tungsten wall [3]. The reason could be at the onset of divertor detachment the power flow to the divertor is significantly reduced, resulting in less ionization of recycling neutral particles due to the so-called ‘power starvation’ effect [4]. And since most of the fueling in the pedestal region comes from the recycling neutral particles, the pedestal particle source is reduced, and thus density decreases at the pedestal.

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