SIMUTANEOUS ELM SUPPRESSION AND DIVERTOR DETACHMENT COMBINED BORON POWDER AND NE GAS INJECTION IN EAST

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Integrated power exhaust and ELM control is crucial for core-edge integration in future fusion devices like ITER. This study investigates the synergistic effects of solid Boron (B) powder injection and Ne gas injection in the EAST tokamak with a tungsten divertor. The complementary roles of B and Ne in radiative cooling are explored to optimize power exhaust and ELM control strategies. B, a candidate wall conditioning material for ITER [1, 2], has been successfully applied in fusion devices for ELM suppression [3, 4], improved wall conditions [5], and enhanced radiation while reducing heat flux [6]. Neon (Ne) will be an optimized radiator for ITER [7], but unavoidable radiation inside the separatrix challenges sustaining H-mode [8]. The cooling factor of B at Te<~10eV is <1000 times larger than Ne but much smaller than Ne at ~ 10eV <Te < ~100eV. Investigating the synergistic effects of B and Ne injection can provide valuable insights into optimizing power exhaust and ELM control strategies

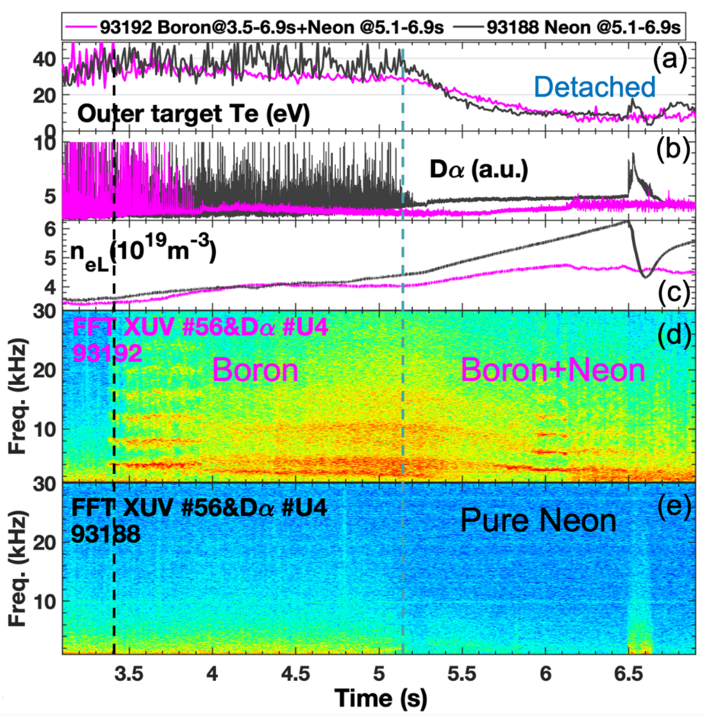

Figure 1 Time evolution of the experimental parameters for shot#93192 (black) with B powder injection~20mg/s from3.4s to 7s and Ne injection (1.2×10^{20} particle/s) from 5.2s to 7s and shot#93188(magenta) with pure Ne injection(1.4×10^{20} particle/s) from 5.2: Ip=500kA, n_{GW} <0.7, Bt=2.5T, H98 ~1.2, total heating power~4MW, Ti(0)~1.1keV, Te(0)~5keV. Vertical dash lines represent the start times of B and Ne injection. (a) outer target electron temperature by Langmuir probes, (b)upper divertor D_α emission, (c) core line averaged density, (d) cross-power spectrograms of XUV#56 and D_α#U4 for shot#93192, showing EHM (d) cross-power spectrograms of XUV#56 and D_α#U4 for shot#93188, no EHM observed.

Experiments were conducted on EAST using an impurity powder dropper for continuous, controllable B powder injection near the upper X-point [9] and piezoelectric valves for Ne injection at the upper outer target. In upper-single null plasmas with a favorable ion grad-B drift direction, B powder is injected into the private flux region just above the upper X-point at a flow rate of approximately $1\text{-}8\times10^{20}$ atoms/s. ELM suppression is observed, and the inner divertor plasma achieves detachment while the outer divertor remains attached. Interestingly, supplemental Ne gas injection during the ELM suppression phase leads to thermal load reduction (energy detachment, but no particle detachment) of the outer target plasma, as confirmed by a reduction in peak target electron temperature dropping from ~45 eV to ~7eV (Fig.1(a)) and a decrease in peak surface temperature from ~250°C to ~100°C. During the ELM suppression and detachment phase, the emergence of edge harmonic modes (EHM) is observed (Fig.1(d)), which drive outward particle transport and slow down the density ramp-up and core radiation due to Ne injection. Compared with only Ne injections with a lower rate, combining a large-rate B and Ne injection reduces core radiation by up to 15% while increasing edge radiation near the X-point. Reversing the time sequence of B and Ne injections, the initial pure Ne injection causes energy detachment and ELM-free H-mode with impurity accumulation, followed by mixing with B injection before EHM triggering, resulting in a gradual decrease in core radiation and middle/high-Z impurity emission. The EHM further enhances impurity outward transport. Notably, only Ne injection without B assistance induces core impurity accumulation and H-L transition. Without Ne injection, pure B injection flushed out core tungsten and increased plasma stored energy by up to 30% in the ELM-absence plasma, but no outer target detachment was observed. This reduction in core radiation is attributed to the beneficial effects of B injection on wall conditioning (Fig. 2) and impurity transport. B injection proves beneficial for mitigating the retention and recycling of Ne impurities from the wall. Similar to other machines [5, 6], the cumulative effect of B powder injection on C, O, and W was confirmed simultaneously by averaging the visible and EUV spectroscopy signals as the cumulative injected mass of B was increased (Fig. 2).

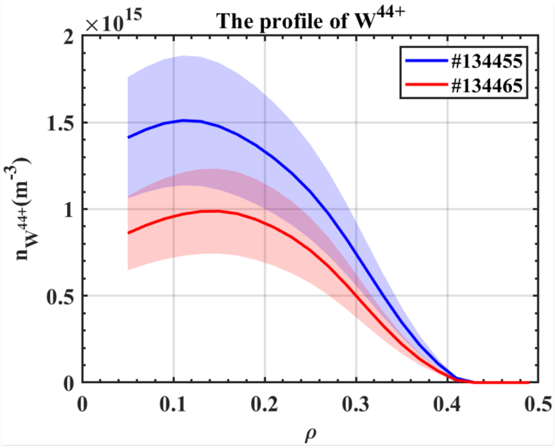

Figure 2 Comparison of W44+ density profile by VUV spectrometer during B powder injection for two shots with the same plasma parameters. The cumulative conditioning effect of B powder injection on W was suggested as B powder was successively injected between the two shots.

To further understand the synergistic effects of B and Ne injection, interpretive boundary plasma modeling was performed using the SOLPS-ITER code. B and Ne injection rate ratios were set up based on the experimental conditions, with fixed upstream density, temperature, and transport coefficient profiles, semi-quantitatively matching with divertor Te profiles measured by Langmuir probes. The results show that pure B injection reduces the peak target electron temperature from ~ 50eV to ~ 40eV, while low-rate pure Ne injection leads to a peak temperature of ~10eV, with the peak location far from the separatrix. Large-rate pure Ne injection further reduces the peak temperature to ~ 5eV. Notably, the combination of B and Ne injection decreases the peak temperature from 10 eV to 5 eV, demonstrating the complementary effect of the two impurities on detachment. The total radiation for cases with large-rate Ne injection (4.9×10^{20} atoms/s) and B+Ne injection (3.8×10^{20} atoms/s) is nearly the same, indicating that the synergistic use of B and Ne can achieve similar radiative cooling with a lower total impurity injection rate. Furthermore, SOLPS-ITER simulations reveal that by keeping the peak target electron temperature below 6 eV, a higher B to Ne injection ratio leads to lower core radiation and Z_{eff}. This finding suggests that an optimal balance between B and Ne injections can be achieved to maintain effective divertor cooling while minimizing the impact on core plasma performance.

The presented observations, along with the interpretive modeling by SOLPS-ITER, provide valuable insights into the synergistic effects of impurity mixtures. The successful integration of ELM suppression and divertor detachment through the combined injection of B powder and Ne gas in EAST tungsten divertor plasmas demonstrates the potential for optimizing power exhaust and ELM control strategies in future fusion devices. Further research will explore the sustainability of the synergistic effect over extended plasma conditions relevant to steady-state operation in future fusion reactors. *This research is sponsored in part by the U.S. Department of Energy under contracts DE-AC02-09CH11466.*

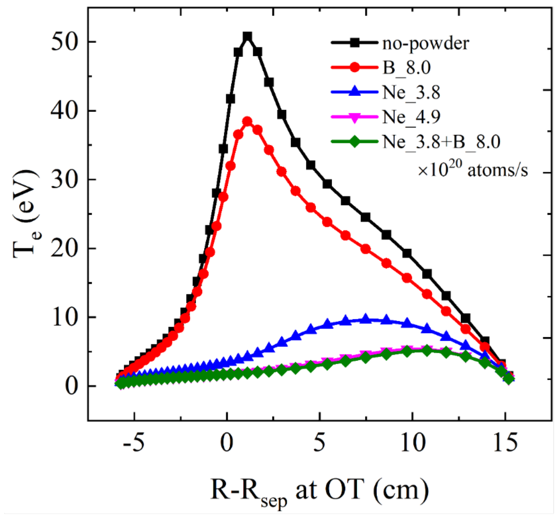

Figure 3 SOLPS-ITER simulated outer target electron temperature profiles for interesting cases labelled as the figure legend

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