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# Sustained Detachment with the Self-Regulated Plasma Edge beneath the Last Closed Flux Surface in LHD

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Self-sustained detachment has been obtained in the Large Helical Devise (LHD). Strong hydrogen gas puffing of ~200 Pa·m$^3$/s after a density feedback phase successfully detaches the plasma from the divertor plate with high reproducibility. High electron density of over $1 \times 10^{20}$ m$^{-3}$ is sustained without gas puffing until the heating beam stops and the high-density flat top for 2 seconds has been demonstrated. Throughout the detachment phase, the minor radius of the hot plasma column shrinks to ~90 % of the last closed flux surface, which corresponds to the $\iota/2\pi = 1/q = 1$ rational surface.

**Keywords:**

high-density, detachment, recycling, fueling efficiency, particle confinement, Serpens mode

Reduction of the divertor heat load is one of the crucial issues for designing a fusion reactor. Edge plasma cooling by increasing the density or introducing impurities such as neon as a radiator is effective to reduce the divertor heat load by detaching the plasmas from the divertor plates. This kind of detachment has been intensively studied in many tokamaks [1] and also in a stellarator, W-7AS [2]. In LHD, however, sustained detachment has not been achieved until up to now [3].

In the moderate density regime in LHD, the radiation from main plasma, $P_{\rm rad}$, increases in proportion to the density. As the density increases further and approaches to the density limit, $P_{\rm rad}$ begins to increase nonlinearly with the density. When $P_{\rm rad}$ reaches 30 – 40 % of the total heating power, the thermal instability takes place and finally the discharge is terminated by radiative collapse [4]. Just before the radiative collapse, the plasma column shrinks and detaches from the divertor plates only transiently. Basically, our strategy to achieve a long lasting detachment phase was to sustain this transient detachment by controlling the gas puffing. To minimize the influence of recycling flux and maintain high reproducibility, density feedback of gas puffing is effective. After the feedback phase, very strong gas puffing of 240 Pa·m$^3$/s at the maximum is applied for 0.1 – 0.2 seconds to shrink the plasma column. Self-sustained detachment is achieved by this operation. This new state has been dubbed the "Serpens mode", for self regulated plasma edge 'neath the last closed flux surface.

In Fig. 1, shown are the waveforms from a neutral beam (NB) heated hydrogen discharge where detachment is sustained for 2 s. The NB port-through power, $P_{\rm NB}^{\rm PT}$, of ~8 MW is applied from 0.8 to 3.3 s (Fig. 1(a)). The line-averaged density, $\bar{n}_{\rm e}$, is rapidly increased to $> 1 \times 10^{20}$ m$^{-3}$ at ~1.1 s by short but strong gas puffing of $\Phi_{\rm puff}$ ~200 Pa·m$^3$/s after the density feedback phase (Fig. 1(b)). Then, $P_{\rm rad}$, which is estimated from the radiation from a wide-angle view of the plasma encompassing the entire poloidal cross-section and about one-third of the field period in the toroidal direction [5], increases and the ion saturation current measured on the divertor plate, $I_{\rm sat}$ (Fig. 1(b)) decreases significantly ($I_{\rm sat}$ normalized by $\bar{n}_{\rm e}$ is ~1/10 of that in the attached phase), indicating that detachment is occurring. This reduction of $I_{\rm sat}$ is also observed at different toroidal sections. Correspondingly, the neutral pressure, $p_0$ (Fig. 1(c)) and the H$_\alpha$ intensity (Fig. 1(d), where the line-of-sight passes through the vicinity of plasma center) also decrease. These suggest that the recycling flux is reduced. Since the high-density is sustained with the reduced recycling, an improved fueling efficiency for the recycling neutrals and/or an improved particle confinement is expected. It should be noted that spikes are recognized in $I_{\rm sat}$, H$_\alpha$ and C$_{\rm III}$ signals. Unlike the usual detachment in other devices, the detachment phase is sustained without gas puffing. No impurity gas puffing is applied in this case and the intrinsic carbon (sputtered from the divertor tiles) is thought to be the main radiator. The electron temperature at the edge region of $\rho = 0.9$ ($\rho$ is the normalized minor radius), $T_{\rm e09}$, decreases below 100 eV as shown in the bottom of Fig. 1. Here we define an effective radius of the hot plasma boundary, $\rho_{\rm 100eV}$, by an average of $\rho$ where $T_{\rm e}$ is in the range of 50 to 150 eV (Fig. 1(e)). In the attached phase before 1 s, $\rho_{\rm 100eV}$ is slightly larger than 1, indicating that the hot plasma is filled to the last closed flux surface (LCFS). As the

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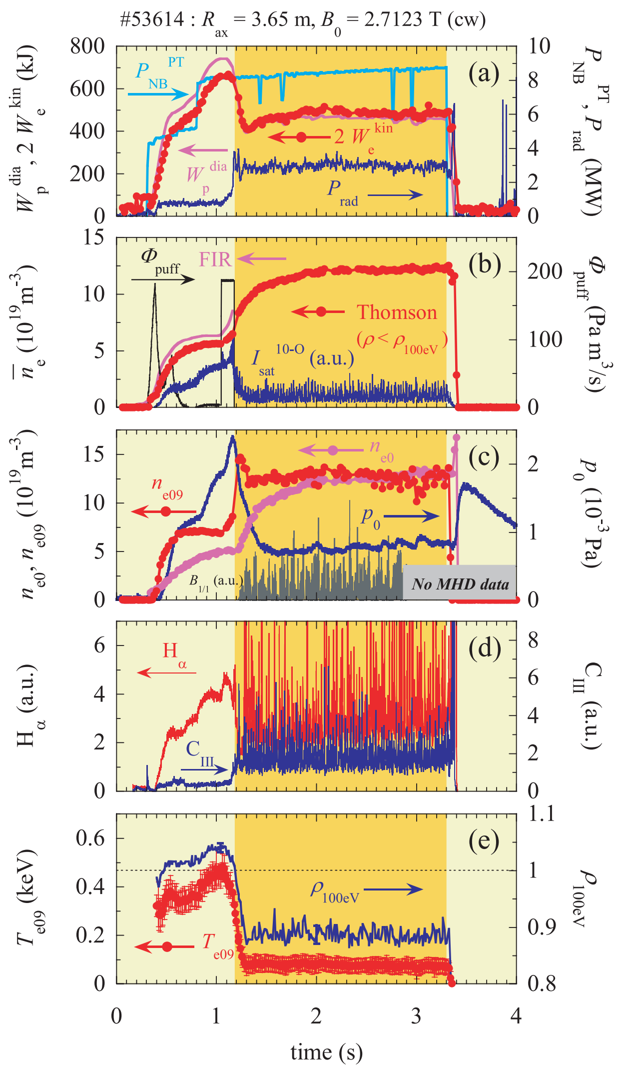


Fig. 1 Typical waveforms in the detachment discharge sustained for 2 seconds (Serpens mode).

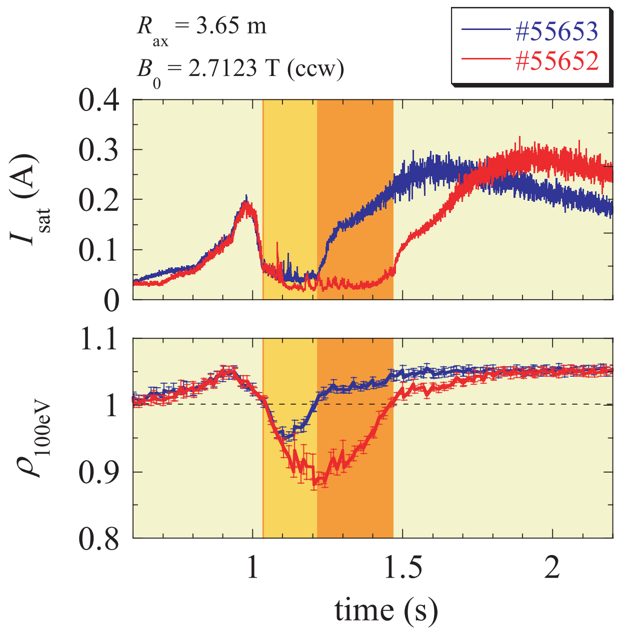


Fig. 2 Reattachment after a short detachment phase.

detachment proceeds, the hot plasma column shrinks and $\rho_{100\mathrm{eV}}$ decreases to 0.88±0.02, which corresponds to the radius of $\iota/2\pi$ = 1 rational surface, and destabilization of $m/n$ = 1/1 MHD fluctuation is observed (Fig. 1(c)), where $m$ ($n$) denotes the poloidal (toroidal) mode number. Also in the other discharges obtained in the same magnetic configuration, $\rho_{100\mathrm{eV}}$ ranges from 0.85 to 0.9 as long as the detachment phase is sustained.

Slight shortage of the strong gas puffing results in the reattachment as shown in Fig. 2. It is apparent from this figure that $I_{\mathrm{sat}}$ decreases and stays at low level as long as $\rho_{100\mathrm{eV}}$ is less than 1. In other words, detachment occurs when the hot plasma boundary lies beneath the LCFS. In these cases, however, the detachment phases are not sustained. At least, it is necessary to decrease $\rho_{100\mathrm{eV}}$ below 0.88, to achieve the Serpens mode as in Fig. 1. Excess reduction of $\rho_{100\mathrm{eV}}$ to less than 0.85 merely leads to the radiative collapse. There is no discharge where the detachment phase is self-sustained with $0.9 < \rho_{100\mathrm{eV}} < 1$ to date. This suggests that the transition to Serpens mode occurs when $\rho_{100\mathrm{eV}}$ becomes close to (or, slightly less than) the radius of the $\iota/2\pi = 1$ rational surface.

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