Investigations of impurity seeding and radiation control for long-pulse and high-density H-mode plasmas in JT-60U

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ABSTRACT: Reduction of heat loading appropriate for the plasma facing components (PFCs) such as the divertor and the first wall is crucial for a fusion reactor. Impurity gas seeding is one of techniques to decrease peak heat flux to the divertor both in steady-state and transient phases. Power handling by large radiation power loss has been studied in the ELMy H-mode plasmas on JT-60U with argon (Ar) gas seeding [1, 2] since good confinement (HH≥0.85) was obtained up to high density ($\bar{n}_e/n^{GW}$~0.8-0.9, n^{GW} is the Greenwald density). On the other hand, it was not clearly understood to sustain the good confinement plasma with the large radiation power under the wall saturated condition where particle recycling flux changes during the long discharge. In this paper, control of the large radiation in the good energy confinement plasma was, for the first time, investigated. Total radiation fraction of P_{rad}/P_{abs} = 0.8-0.9 was maintained continuously during Ar gas puffing (up to 13 s so far), and control of radiation power in the main plasma has been investigated during outgas condition from the PFCs.

1. Introduction

Reduction of heat loading appropriate for the plasma facing component (PFC) such as the divertor is crucial for a fusion reactor. Impurity gas seeding is one of techniques to decrease the peak heat flux both in steady-state and transient phases. Power handling by large radiation power loss has been studied in the ELMy H-mode plasmas with argon (Ar) gas seeding on the JT-60U [1, 2], where good confinement (HH≥0.85) was obtained up to high density ($\bar{n}_e/n^{GW}$~0.8-0.9, n^{GW} is the Greenwald density) and large radiation fraction (P_{rad}/P_{abs} ~0.7-0.8). On the other hand, control of the large radiation in the good energy confinement plasma was not established under the wall saturating condition in the long discharges, i.e. outgas from the first wall was dominated in the global particle balance [3].

In this proceeding, experiments to maintain high density plasmas with the large radiation fraction were performed, and control of the radiation fractions in the main and divertor plasmas was investigated using different impurity seeding (Ar and Ne). Control of the large radiation fraction in the long ELMy H-mode plasmas is shown in Section 2. Characteristics of the ELMy H-mode and the edge plasma are described in Section 3. Control of the large radiation fraction under the large wall saturated condition is discussed in Section 4. Summary and conclusion are given in Section 5.

2. Impurity seeding in long pulse H-mode plasma

Impurity seeding of Ar, Ne and their combination was investigated in the long pulse H-mode discharges (30-35s), where I_p = 1.05-1.2 MA, B_t= 2.0-2.3 T, P_{NB} = 12-18 MW, R_p = 3.4 m, a_{mid}= 0.88-0.90 m and plasma triangularity of δ = 0.3-0.37. In order to improve the energy confinement, the H-mode plasma with internal transport barrier (ITB) was also investigated as well as the standard H-mode plasmas.

2.1 Ar and Ne gas seeding in H-mode plasma with an internal transport barrie

Figure 1 shows temporal evolutions of the plasma parameters for the typical H-mode plasma with the internal transport barrier (ITB) with combination of Ar and Ne gas seeding. After start of the Ar gas puff to the main chamber (up to 0.5 Pam^3s^{-1}, i.e. $2.5x10^{20}$ Ar s^{-1}) at t = 5 s as shown in Fig.1(c), Ar^{+14} and radiation power at the main plasma (P_r^{main}) are increased, then small Ne gas puff to the divertor (0.05 Pam^3s^{-1}, i.e. $2.5x10^{19}$ Ne s^{-1}) starts from t = 7 to 9 s. NBI injection power is controlled to maintaine the plasma stored energy (W_{st}) of 2.0 MJ during the plasma discharge (t = 7 – 30 s), while W_{st} is decreased slightly at the high density plasma ($\bar{n}_e$= 3-3.6x10^{19} m^{-3} and $n_e(\rho=0.16)$ = 4.4-6 x10^{19} m^{-3}) although all units of 20.5 MW are injected after t = 16s. Radiation power loss at the divertor (P_r^{div}) is increased gradually from 5 to 11 MW with the divertor recycling flux, while P_r^{main} is maintained at a constant level of 3.2-2.5 MW with the constant Ar puff rate of 0.85 Pam^3s^{-1}, i.e. 4.3x10^{20} Ar s^{-1}.

Figure 1(f) shows that good confinement factor of $H_{H98(y,2)}$ = 0.95 – 0.88 is maintained during 19 s (t = 7 to 26 s) with the large increase of the radiation fraction, i.e. f_{rad}^{tot} = $(P_r^{main}+P_r^{div})/P_{abs}$ = 0.75-0.95, where the Greenwald density fraction ($\bar{n}_e/n^{GW}$, n^{GW} is the Greenwald density) = 0.70-0.84. Such good confinement plasma is degraded shortly due to a large breakdown of NBI (ΔP_{NBI} = 4 MW) at t = 26 s.

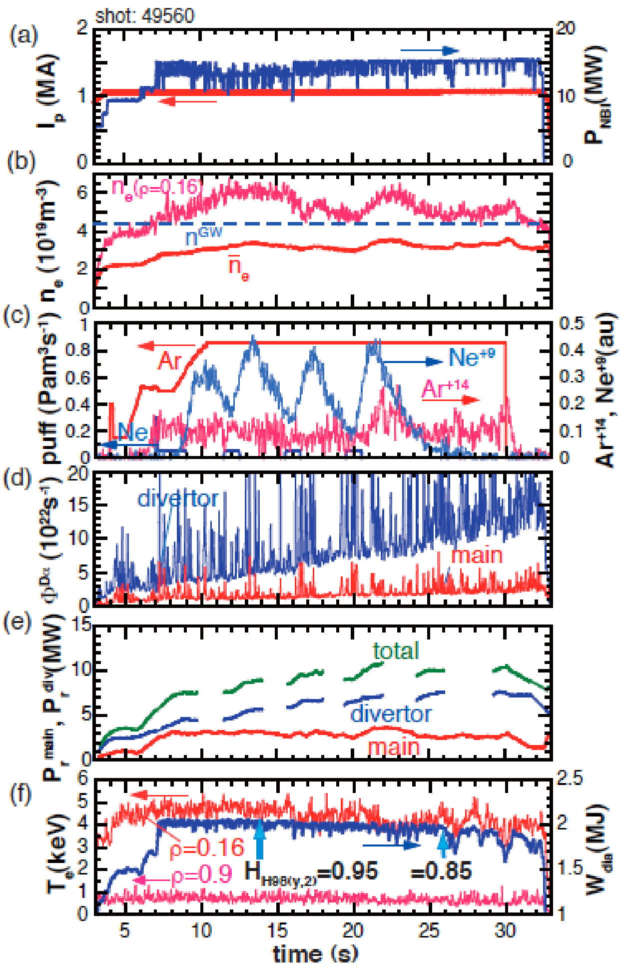

Fig.1 (a) plasma current, NBI power, (b) electron densities, $\bar{n}_e$ and $n_e(\rho=0.16)$, measured by FIR interferometer and YAG Thomson scattering, (c) Ar and Ne puff rates and brightness of Ar^{+14} and Ne^{+9}, (d) deuterium recycling fluxes in main and divertor, (e) radiation power in the main and divertor, (f) electron temperatures measured by YAG Thomson scattering and the stored energy.

2.2 Radiation fraction and confinement with impurity seeding

Extensive heat reduction is required to establish a tokamak reactor, and control of the radiation loss in the main and divertor plasmas with appropriate impurity seeding is crucial for sustaining the good confinement plasma. In the previous JT-60U experiments, Ar seeding was performed for various equilibrium configurations of the ELMy H-mode plasmas [4, 5]: Ar seeding was combined with deuterium gas puffing in order to enhance the radiation power both at the edge and divertor plasmas, while the good confinement plasma condition with an ITB ($H_{H98(y,2)}$ = 0.8-1.05) with the high radiation fraction (f_{rad}^{tot} = 0.6-0.9) was sustained only within 2 s. Figure 2 shows $H_{H98(y,2)}$ and f_{rad}^{tot} as a function of the Greenwald density fraction: previous Ar seeding experiments for the cases of (i) standard ELMy H-mode (δ =0.36), (ii) high triangularity (δ =0.5), (iii) the outer strike-point on the dome-top, are compared to (iv) standard ELMy H-mode only with strong deuterium puff, and they are represented by closed circles, closed squares, triangles, open circles, respectively.

Sustainment of the high radiation plasma was carried out in the long pulse ELMy H-mode plasma with relatively good ITB ($H_{H98(y,2)}$ = 0.9-1) as a target for the impurity seeding. Recycling flux of deuterium was increased under the wall saturating condition as shown in

Fig. 2(d), thus the radiation power was controlled only by the impurity seeding of Ar, Ne and their combination, represented by closed diamonds, open squares, open diamonds, respectively.

Radiation fraction from the main plasma was large (0.35) for the Ar seeding compared to 0.23 for Ar and Ne, and 0.26 for Ne seeding. On the other hand, that from the divertor plasma was large (0.58) for Ar and Ne seeding compared to 0.36 for Ar, 0.55 for Ne seeding. As a result, best performance of the energy confinement, i.e. $H_{H98(y,2)}$ = 0.95 – 0.88 with the large radiation fraction of f_{rad}^{tot} = 0.75-0.95 was obtained for the combination of the Ar and Ne seeding case.

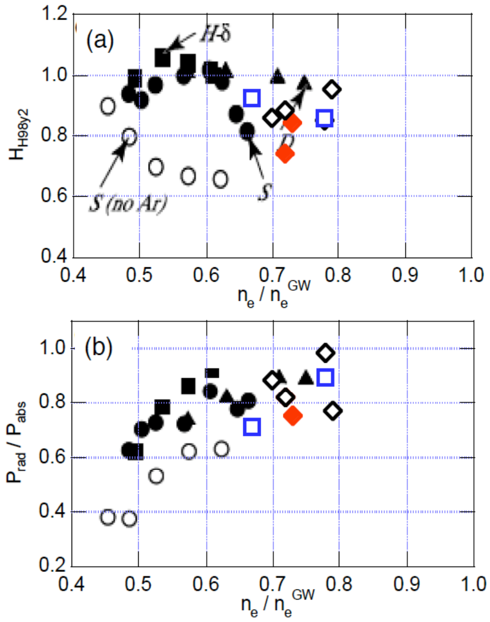

Fig.2 (a) Enhancement factor of the H-mode confinement, (b) radiation loss fraction, for impurity seeding of Ne (open squares), Ar (closed diamonds), Ar and Ne (open diamonds). Previous Ar seeding experiments for standard divertor ELMy H-mode (closed circles), with high triangularity (closed squares), with the outer strike-point on the dome-top (triangles) are also shown with the deuterium gas puff case (open circles) [5].

3. Mitigation of ELM energy loss

ELM characteristics changed from Type-I to Type-III with increasing P_{rad}^{main}, and Figure 3 shows ELM frequency (f_{ELM}), ELM energy loss fraction (W_{ELM}/W^{ped}), H-factor and f_{rad}^{tot} as a function of radiation power in the main plasma, i.e. f_{rad}^{main} = P_{rad}^{main}/P_{abs}, where P_{rad}^{main} includes radiation loss in core and SOL. In the similar discharges with large radiation fraction of $f_{rad}^{main} \geq 0.6$, ELM activity disappears and H_{89L} decreased from 1.4 to 1.25.

In the Type-I ELMy H-mode with Ar injection, relatively constant H_{89L} and W_{ELM}/W^{ped} are observed for $0.1 < f_{rad}^{main} < 0.4$. On the other hand, for $0.4 < f_{rad}^{main} < 0.6$, Type-III ELM appears and W_{ELM}/W^{ped} is reduced below the evaluation level (1.5%) with a gradually reduction in H_{89L}. For $f_{rad}^{main} > 0.45$, detachment of the diveror plasma both near the inner and outer strike-points is achieved, where T_e^{div} decreases below 10 eV. As a result, it is important to maintain slightly above f_{rad}^{main} = 0.4 for mitigation of both steady-state and ELM peak heat loadings with minimum degradation of the energy confinement.

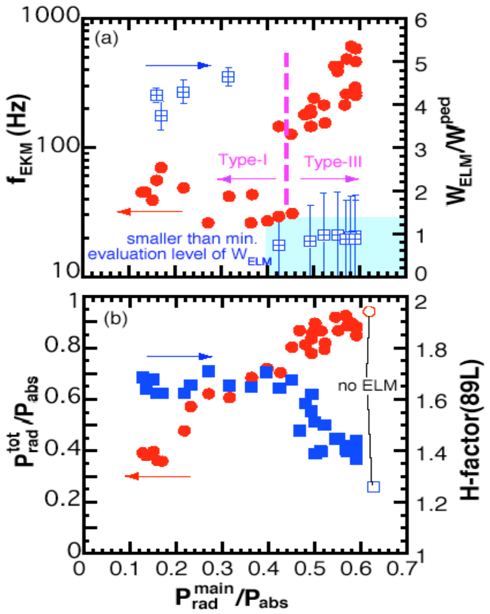

Fig.3 (a) frequency and energy loss fraction of ELM, (b) enhancement factor of the energy confinement and total radiation fraction, as a function of power ratio, P_{rad}^{main}/P_{abs}.

4. Wall saturation in long pulse discharges:

Tritium inventory in PFCs such as the divertor and the first wall is a critical issue for determining operation period of the reactor. Characteristics of the wall pumping and saturation in the long H-mode discharges with Ar gas puffing are compared with deuterium gas puff case [3]. Large f_{rad}^{tot} = 0.8-0.9 due to the enhancement of P_{rad}^{main}

was maintained during 16s (t = 8-24 s) for Ar gas puff case as shown in Fig. 3(a). On the other hand, for the large deuterium puff case (Fig. 4(b)), radiation power is mostly enhanced in the divertor region and the energy confinement is lower ($H_{89L} \leq 1.2$) than that for the Ar puff case.

Global deuterium pumping flux of the PFCs ($\Gamma_{wall} = \Gamma_{gas} + \Gamma_{NB} - \Gamma_{div}$, where Γ_{gas} and Γ_{NB} are deuterium gas puff and NB fuelling fluxes, and Γ_{div} is the diveror pumping flux) becomes negative, i.e. outgas from PFCs, after t ~ 10 s for the two cases. Both total injection flux ($\Gamma_{gas}+\Gamma_{NB}$) and $|\Gamma_{wall}|$ are small for the Ar puff case but gradually increase, while $|\Gamma_{wall}|$ for the D_2 puff case is saturated at ~$3x10^{21}$ D/s. The outgas is due to increment of the surface temperature of the first wall, while the dominant are of the outgas is different between two cases: one candidate is difference in temperature distribution in the main chamber due to difference in radiation distribution.

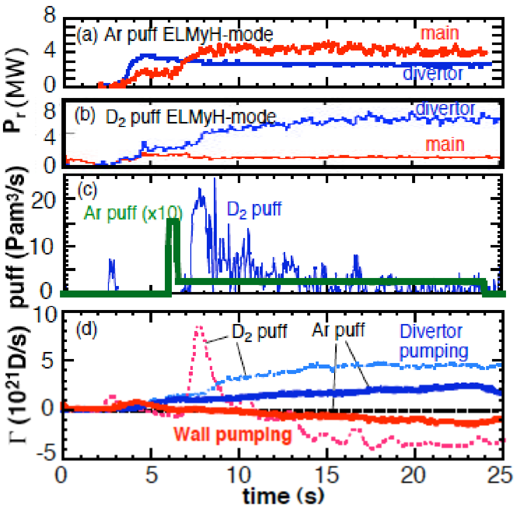

Fig.4 Radiation powers from the main and divertor plasmas, for (a) Ar gas puff and (b) D_2 gas puff. Comparison of (c) D_2 and Ar gas puff fluxes, (d) deuterium particle fluxes of the divertor pumping and wall pumping.

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