Impurity Injection to Plasmas with Improved Plasma Confinement

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(Received 20 February 2001 / Accepted 26 August 2001)

Abstract
Impurity gas injection effects were investigated in ELMy H-mode and reversed shear plasmas from viewpoints of divertor heat flux and power balance. In ELMy H-mode discharges with Ar seeding, the pedestal stored energy and good energy confinement was maintained as the radiation fraction, $P_{rad}/P_{inj}$, was increasing up to 0.88. The ELM energy deposition to the divertor normalized by the pedestal stored energy decreased moderately as a function of $P_{rad}/P_{inj}$, while ELM frequency was reduced significantly. With Ne seeding and moderate D$_2$ gas puffing rate, the radiative divertor plasma was produced in a reversed shear plasma with good plasma confinement $H_{99} = 1.8$. Radiation loss profiles and divertor heat flux profiles clearly revealed the divertor plasma detachment due to X-point MARFE.

Keywords:
JT-60U, ELM, H-mode, ITER, divertor heat flux, MARFE, Argon, Neon

1. Introduction
It is recognized [1] that small amount of radiative impurity seeding is necessary to dissipate power in the upstream of the divertor region and to reduce heat flux to the target plates in fusion reactors. Dilution of plasmas and degradation of the energy confinement must be suppressed to the allowable level and the radiation amount must be maximized in the best choice of impurity species.

Neon (Ne) had been seeded to the plasmas with improved plasma confinement, such as ELMy H-mode plasmas and reversed shear plasmas, before and after the installation of W-shaped pumped divertor in JT-60U [2,3]. Small amount of seeded Ne and accompanied deuterium (D$_2$) gas promoted dense and cold divertor plasmas so that intrinsic carbon ions radiated in the Scrape-Off Layer (SOL) and divertor plasmas. Radiating loss fraction by Ne in the main plasma was small compared with the divertor radiation. In ELMy H-mode discharges with Ne injection, ELM activity became smaller as the radiation fraction increased up to 80% of the input power as the X-point MARFE grew up. The divertor plasma was detached and heat flux was vanished at both the inner and outer strike points of separatrix. However H-mode plasma confinement was degraded to as low as $H_{99} = 1.2$, as the X-point MARFE grew up [2].

In 1999, the pumping slot of the outer divertor was opened and radiation feedback control was introduced. These modification enhanced impurity control in the main plasma by puff and pump technique, which encouraged argon (Ar) injections.
2. Experimental Setups

In ELMy H-mode discharges with Ar injection, confinement improvement of $H_{\text{HH98}}(y,2) - 1$ was obtained with a high radiation loss power fraction (80%) at electron density of $n_e < 0.7\, n_{\text{GW}}$ (Greenwald density) [4]. By applying radiation feedback control, stationary ELMy H-mode plasmas were sustained in the region of electron density $n_e < 0.7\, n_{\text{GW}}$ and the total radiation loss power $P_{\text{rad}} < 0.8\, P_{\text{net}}$, where $P_{\text{net}}$ is the net heating power [5]. Ar gas was injected in the main plasma chamber. Deuterium gas was injected from the top of the plasma in the main plasma chamber.

The SOL and divertor plasmas in ELMy H-mode discharges with Ar seeding is significantly different from those in ELMy H-mode discharges with Ne seeding. Since with Ar seeding, the radiation power and the electron density is increased with a low deuterium gas puff rate, the recycling level of the SOL and divertor plasma is kept low and the H-mode confinement is kept high. The radiation loss power from the main plasma is as large as that from divertor plasma. Since the cooling rate of Ar has a large peak at several hundreds eV as a function of electron temperature, seeded Ar ions increase radiation loss in the outer region of the main plasma and a radiation mantle is produced. Small degradation of energy confinement is represented by the observation that the pedestal ion temperature was maintained [4]. The regular type-I ELMs are maintained, while the frequency of ELM is decreasing. Since ELM heat flux determine the life time of ITER divertor plates [6], behavior of ELM heat flux is an important issue to be investigated.

Heat flux to the divertor target plates is calculated from time evolution of the plate temperature. Temperature of target plates is measured by an infrared camera system. The infrared camera is viewing the W-shaped divertor tangentially through a set of mirrors and a sapphire vacuum window. A slow sampling digitizer captures radial profiles of temperature with the time resolution of 12.5 milliseconds during a discharge and time averaged heat flux profiles are calculated. A fast sampling digitizer captures radial profiles of temperature with the time resolution of 250 microseconds for one second and ELM heat flux is calculated.

3. Divertor Heat Flux in ELMy H-mode Plasmas

Heat flux profiles during ELMy H-mode discharges with Ar injection was measured. Plasma parameters of those discharges were $I_p = 1.2\, \text{MA}$, $B_T = 2.5\, \text{T}$, $P_{\text{KB}} = 16–20\, \text{MW}$ and the plasma triangularity $\delta = 0.35$. There was no indication of increase in the radiation in near the X-point even in the discharges with the highest radiation fraction, $P_{\text{rad}}/P_{\text{net}} = 0.88$.

Radial profiles of the time averaged heat flux (averaged over 100 ms) are shown for discharges with the radiation fraction is 0.46, 0.7 and 0.88 in Fig. 1(a), (b) and (c). ELM frequency decreased as the radiation fraction increased. ELM frequencies were 140 Hz, 80 Hz and 0 Hz, respectively. As shown in Fig. 1(a), (b) and (c), the averaged heat flux reduced gradually as the radiation fraction increased. Heat flux to the divertor had peaks both at the inner and outer divertor when the radiation fraction is 0.46 and 0.7. While the ELM heat flux and the heat flux between ELM cannot be separated in this measurement, reduction of ELM frequency obviously contributed to reduced peak heat fluxes in the time average. While small heat flux remained in the outer divertor, the both inner and outer divertor plasmas were almost detached in the discharges with the highest radiation fraction, as shown in Fig. 1(c).

ELM amplitude might be represented by total energy deposited to the divertor by an ELM. In order to calculate heat deposition by an ELM, ELM heat flux density profiles were integrated over the total area of the divertor area by assuming toroidal symmetry and then integrated in time for duration of an ELM. As the radiation fraction increased in ELMy H-mode plasmas, ELM frequency was reduced. Change in ELM amplitude was small compared with the change in the ELM frequency. In Fig. 2, time traces of ELM heat load is compared between the discharge with $P_{\text{rad}}/P_{\text{net}} = 0.46$ and $P_{\text{rad}}/P_{\text{net}} = 0.72$. Averaged energy deposition is 79 kJ and 72 kJ, respectively, while ELM frequency is reduced by a factor of three. Further increase in the radiation loss fraction resulted in significantly larger reduction in energy deposition by ELMs. Details are discussed in the later section.

It was confirmed that ELM heat flux profiles were different every ELMs, as was already observed before the W-shaped divertor modification. Typical ELM heat flux profiles are shown in Fig. 3(a), (b) and (c) from the discharge with $P_{\text{rad}}/P_{\text{net}} = 0.46$. Another peak beside the outer strike point of separatrix, as shown in Fig. 3(a), and another peak beside inner strike point of separatrix, as shown in Fig. 3(b), were often observed. The heat flux to the inner divertor was larger than those to the outer divertor by a factor of two in average, however heat flux to the outer divertor dominated to that to the inner divertor in some ELMs, as shown in Fig. 3(c).
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Fig. 1 Averaged heat flux density profile in ELMy H-mode with (a) $P_{\text{rad}}/P_{\text{inj}} = 0.46$, (b) $P_{\text{rad}}/P_{\text{inj}} = 0.70$, (c) $P_{\text{rad}}/P_{\text{inj}} = 0.88$, Plasma equilibrium and divertor structure are shown below the heat flux profiles.

Fig. 2 Time traces of ELM heat load is compared between the discharge with $P_{\text{rad}}/P_{\text{inj}} = 0.46$ and the discharge with $P_{\text{rad}}/P_{\text{inj}} = 0.7$. 
4. Neon Injection to Reversed Shear Discharge

It was suspected in H-mode plasmas that the edge transport barrier was cooled by MARFE and the pedestal temperature was decreased. Therefore H-mode plasmas with high radiation fraction by Ne seeding led to degradation of H-mode plasma confinement, since the MARFE formation was inevitable.

However in the reversed shear plasmas, this situation may change. Since the transport barrier resides in the core region in the reversed shear discharges, edge plasma cooling by MARFE does not necessarily cool the transport barrier. In other words, the radiative SOL and divertor plasmas can be separated from the transport barriers (ITBs). This benefit and coexistence of the internal transport barrier with the radiative divertor plasma was successfully demonstrated [7]. (In a discharge shown in [7], the radiation power in the main plasma is underestimating due to a missing central channel bolometer.) Heavy D₂ gas puff, required to produce the radiative divertor plasmas in the reversed shear plasmas in high power heating and low recycling conditions, let to degradation of the ITB [2]. The next issue was to sustain good confinement of the ITB.

Progress in the study of the reversed shear plasmas towards steady state realized reproducible target plasmas and good plasma confinement with lower heating power. Optimization of beam heating scenario may help more robust ITB against high recycling and radiative divertor. With moderate gas puffing rate ($Q_{D2} = 7.5$ Pa m³/s) and Ne seeding, the radiative divertor plasma was produced in a reversed shear plasma with $I_p = 0.9$ MA, $B_T = 3.5$ T. Figure 4 shows waveforms of the discharge. As shown in this figure, plasma edge is ELMy H-mode edge. Divertor plasma recycling was increasing with D₂ gas puffing after Neon injection. Neon gas was injected with $Q_{Ne} = 1.4$ Pa m³/s for $0.3$ s from $5.4$ s. While the divertor radiation was still increasing after $t = 6.0$ s, the plasma confinement was increasing. Since ELM activities was fading out during this period, improvement in $H_{98}$ factor was due to the growth of the
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Fig. 4 Waveforms of the reversed shear discharge, in which the radiative divertor plasma was produced.

Fig. 5 Divertor heat flux profiles at (a) $t = 5.3$, (b) $t = 5.8$ and (c) $t = 6.6$ s.

Internal transport barrier. Increasing confinement was also helpful to reduce conducting power to the divertor slightly and to promote dense and cold plasmas. In the past, degrading confinement during the D$_2$ gas puffing caused to increase conducting power and to disturb the radiative divertor plasmas.

Fig. 5(a), (b) and (c) shows and divertor heat flux profiles at three different time during this discharge. Before the gas puffing at $t = 5.3$ s, divertor heat flux is peaking near both the inner and outer strike point of separatrix. After neon injection at $t = 5.8$ s, the inner divertor plasma is detached and the heat flux near the separatrix was decreased dramatically. At $t = 6.6$ s, X-point MARFE is grown up and divertor radiation loss concentrated around X-point. Both the inner and outer divertor plasmas were detached and the heat flux to the outer divertor was also decreased dramatically. The radiation loss profiles at $t = 6.6$ s and those at $t = 5.3$ s...
are compared in Fig. 6. The divertor tiles and the plasma equilibrium are also shown. The radial profiles are obtained from 13 bolometers, of which chord are shown in solid lines in Fig. 6. The radial positions of bolometers are defined as the intersection position of those chords and \( Z = -1.2 \) m. The vertical profiles are obtained from 6 bolometers, of which chord are shown in dashed lines in Fig. 6. The vertical positions of bolometers are defined as the intersection position of those chords and \( R = 3.1 \) m. While bolometer signal was line integral of radiation emissivity, radiation concentration near the X point due to MARFE was found in both the radial and vertical profiles. The X-point MARFE was growing up from \( t = 6.0 \) s to \( t = 6.6 \) s and the reversed shear plasma confinement was increasing. Therefore the reversed shear plasma confinement was not disturbed by edge plasma cooling by X-point MARFE. Thomson scattering measurement and CXRS measurement has shown that the ITB at \( r/a = 0.6 \) is clearly observed and reversed shear \( q \)-profile was observed in MSE measurement at the time that both the inner and outer divertor plasmas were detached [8]. Impurity accumulation was not significant, since neon and carbon density profiles are similar to the electron density profiles. Impurity transport coefficient is discussed in the ref. [8].

5. Prospect to ITER

Heat flux to the divertor must be reduced as low as 5–10 MW/m² in ITER because of the thermal stress in the divertor structure. In order to satisfy 5 MW/m² of the divertor heat flux in ITER, more than 75% of the input power must be dissipated by radiation loss in upstream of the divertor targets. However it has been recognized that the energy losses associated with ELMs in ELMy H-mode plasmas are the most serious concern for the practical life time of the divertor targets. Temperature rise of the target materials above threshold for sublimation or threshold for melting can cause significant increase in erosion by each ELMs.

In efforts to estimate heat flux due to ELMs by ITER R&D divertor physics experts activity, multi-
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machine database of the divertor plasma parameters has been compiled. While no direct estimate about the ELM heat flux density including radiation loss effect is not obtained, empirical fitting curve of $\Delta W_{\text{ELM}}/W_{\text{ped}}$ was obtained as a function of $\tau_i$ [6]. Here $\Delta W_{\text{ELM}}$ is loss in the stored energy of the plasma by an ELM and $W_{\text{ped}}$ is the pedestal stored energy. Here $\tau_i$ is the ion parallel loss time from the edge plasma to the divertor along the SOL and $\tau_i$ is a function of the pedestal plasma parameters. Based on this scaling, $\Delta W_{\text{ELM}}/W_{\text{ped}}$ is estimated to be 0.12 at $\tau_i = 200$ µs of ITER. This gives ELM heat flux density marginal for 10^6 ELMs in life time of the divertor materials [6], if all the energy is assumed to be deposited onto the divertor targets. Since a fraction of energy is dissipated by radiation loss in the SOL and divertor plasma, this scaling gives the upper limit of heat flux to the divertor.

Here we discuss the actual energy deposition to the divertor by an ELM in JT-60U when the radiation loss is increasing, so that the prediction of ELM power to the divertor is improved in accuracy. In order to obtain the energy deposition to the divertor by an ELM, $\Delta W_{\text{IR}}$, time evolution of ELM heat flux profiles were integrated in time and space and then averaged over ELMs in 100 ms. The ELM frequency, $f_{\text{ELM}}$, was defined by the number of ELMs in 100 ms. In Fig. 7(a), $f_{\text{ELM}}$ and $\Delta W_{\text{IR}}/W_{\text{ped}}$ and are plotted as a function of the radiation loss fraction, $P_{\text{rad}}/P_{\text{net}}$ in the ELMy H-mode discharges. Here $W_{\text{ped}}$ is calculated by $3/2 n_{\text{e}} (T_i + T_e) V$. Here $n_{\text{e}}$, $T_i$ and $T_e$ are the electron density, ion temperature and electron temperature in the edge pedestal, respectively. $V$ is the plasma volume. While the change in ELM frequency is more than a factor of four, $\Delta W_{\text{IR}}/W_{\text{ped}}$ was decreased only by 36%. The reduction in $\Delta W_{\text{IR}}/W_{\text{ped}}$ is firstly attributed to the reduction of $\Delta W_{\text{IR}}$ by 23%. As shown in Fig. 7(b), where $W_{\text{ped}}$ and $\tau_i$ is plotted as a function of $P_{\text{rad}}/P_{\text{net}}$, in the same range, change in those two parameters are smaller than that in $\Delta W_{\text{IR}}$. $\Delta W_{\text{IR}}/W_{\text{ped}}$ is 0.1 for $\tau_i = 300$ µs on the scaling and effect of small change in $\tau_i$ is negligible.

In the discharge with $P_{\text{rad}}/P_{\text{net}} = 0.88$, ELM disappeared for 0.8 s when $P_{\text{rad}}/P_{\text{net}}$ exceeded 0.8. The stored energy of edge pedestal was still maintained when $P_{\text{rad}}/P_{\text{net}} = 0.88$, as shown in Fig. 7(b). Therefore it is suggested that increase in radiation loss by Ar puff in ELMy H-mode is useful for ITER both in extending life time of the divertor material by reducing number of ELMs significantly and in suppressing erosion rate by reducing ELM power deposition.

On the other hands, the good edge pedestal may not be required in increasing radiation in the reversed shear plasmas, if the sufficient energy confinement improvement is obtained by the internal transport barrier. This is the case in the discharge, shown in Fig. 4, in which ELM activity is disappeared and the energy confinement is increasing during radiative divertor phase. This is the potential benefit of the reversed shear plasma from the point of the erosion of the divertor target.

Fig. 7 (a) The ELM frequency, $f_{\text{ELM}}$, and the normalized ELM energy deposition to the divertor, $\Delta W_{\text{IR}}/W_{\text{ped}}$, are plotted as a function of the radiation loss fraction, $P_{\text{rad}}/P_{\text{net}}$. (b) The pedestal stored energy, $W_{\text{ped}}$ and the ion parallel loss time, $\tau_i$ is plotted as a function of $P_{\text{rad}}/P_{\text{net}}$. 

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6. Summary

Effects of Ar seeding on ELM heat flux in ELMy H-mode plasmas and effects of Ne seeding on the power balance in reversed shear plasmas were investigated.

In ELMy H-mode plasmas, an infrared (IR) camera measurement has shown that ELM heat flux is characterized by multiple peak profiles and short heat deposition time as fast as 750 μs. As $P_{\text{rad}}/P_{\text{tot}}$ increased up to 0.88, ELM frequency was reduced toward zero and $\Delta W_{\text{rad}}/W_{\text{gas}}$ was moderately decreasing. This result suggests that increase in radiation loss by Ar puff in ELMy H-mode is useful for extending life time of the divertor targets in ITER.

With Ne seeding and moderate D₂ gas puffing rate ($Q_{\text{D₂}} = 7.5$ Pa m³/s), the radiative divertor plasma was produced in a reversed shear plasma with good plasma confinement $H_{\text{99}} \sim 1.8$. Radiation loss concentrated around the X-point and peaks of divertor heat flux at strike points disappeared at the time that both the inner and outer divertor plasmas were detached.

References