Radiative boundary plasmas with good core plasma confinement in JT-60U with W-shaped divertor

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Introduction

Reversed shear plasma with the internal transport barrier (ITB) is a promising operational regime for fusion reactors. In JT-60U, radiative divertor plasmas have been investigated in the reversed shear plasmas [1]. It has been demonstrated that the detached divertor operation is compatible with the improved confinement inside the ITB. After the modification of the divertor to the W-shaped pumped divertor in 1997, elaborate efforts have been payed to obtain the reversed shear plasmas as long as several seconds. This paper describes the radiative divertor experiment in JT-60U with the W-shaped pumped divertor, in which neon (Ne) and deuterium (D_2) gas injection was applied to the reversed shear plasmas which last several seconds.

1. Discharge characteristics

In the reversed shear plasmas of JT-60U, hollow current profile at the plasma start-up was frozen by neutral beam (NB) heating negative shear inside the plasma is enhanced with the growth of the ITB during the plasma current (Ip) ramp-up phase. In the Ip flat top phase (Ip = 1.2 MA, B_T = 3.5 T), NB beam power (P_{NB}) was carefully controlled to avoid disruptions. The stationary phase from t = 6 s to 9 s in such discharges was used for producing the radiative divertor plasmas. P_{NB} in the stationary phase was ranged from 18 MW to 20 MW. Neon gas puff pulse, 0.7 Pam^3/s x 0.4 s, was applied from the divertor gas puff position, which is located at the pumping slot at the bottom of the inner divertor. Continuous D_2 gas puff at the rate of up to 70 Pam^3/s was applied to the main chamber.

Figure 1 shows a typical discharge waveform from shot 29741. A reference discharge (shot 29740) without Ne and D_2 gas puffing is also shown in this figure. In shot 29741, radiation from the divertor (P_{rad}^{div}) increased by 4 MW and radiation from the main plasma, P_{rad}^{main} increased by less than 1 MW. Total radiation fraction, P_{rad}^{tot}/P_{net} was as large as 50% of the net input power. Neon exhaust was enhanced by D_2 gas puff and this enhancement is called as "puff and pump" effect. The puff and pump effect was vanished 200 ms after D_2 gas turned off.

The ion temperature (Ti) and electron temperature (Te) profiles and the electron density (n_e) profiles at t = 6.4 s in shot 29740 and those profiles at t= 8.5 s in shot 29741 are shown in Fig. 2 (a) and (b), respectively. Ti = Te outside the transport barrier and the large gradient in Ti inside r/a = 0.6 was observed in the target plasma, at t = 6.4 s in shot 29740. While the ITB radius shrunk to r/a = 0.5 and ion temperature was decreased due to increase in plasma density, the ITB was clearly observed both in Ti and ne profiles during D_2 gas puff, at t = 8.5 s in shot 29741. The plasma density at the separatrix changed from 1 x 10^{18} m^{-3} to 1.4 x 10^{19} m^{-3} due to the high recycling divertor.

Wall conditioning discharges, such as Taylor discharges and ELMy H-mode discharges with P_{NB} = 25 MW, were applied to maintain divertor recycling level low enough to obtain reproducible reversed shear plasmas. Without the wall conditioning, density build-up after t = 4 s due to the ITB formation was not observed.

2. Degradation of H-factor and divertor detachment

Once the ITB has degraded and destroyed, it was impossible to recover the ITB. In that sense, the degradation of the ITB is irreversible. Therefore the confinement in the reversed shear plasma is much more dependent on the history of the discharge than on the value of the plasma parameters, such as density and plasma parameters.

Figure 3 demonstrates that high gas puff rate determine the plasma confinement. In this figure, H-factor is plotted against D_2 gas puff rate (Q_{D2}). H-factor is the enhancement of the energy confinement over the ITER89 L-mode scaling and H89. Data points in this figure were sampled every 100 ms from the time just before the gas puffing for each discharges. From the trajectory of the data points, it is found that the upper limit of the H-factor decreases as a function of the D_2 gas puff rate. In other words, if the plasma has once experienced the high gas puff rate, H-factor must be lower than the upper value determined by the boundary shown in the figure.

Detached divertor state is indicated as closed symbols and attached divertor state is indicated as open symbols in Fig. 3. Plasma detachment is judged by the value of $_{out}$/ $_{in}$. Here $_{out}$ and $_{in}$ are particle flux to the outer divertor and that to the inner divertor, respectively. It has been observed that F_{out} / F_{in} increases suddenly from less than one to 3 ~ 4 when the divertor detachment starts in JT-60U. As shown in the figure, discharges which has experienced the gas puff rate more than 40 Pam^3/s had the divertor detachment. Sustainment of the detachment may be possible with Q_{D2} = 14 Pam^3/s if the plasma density is high enough. However in the discharge with the marginal density, such as in shot 29794, the divertor plasma went back to the attached state with Q_{D2} = 20 Pam^3/s. Therefore it is inferred that Q_{D2} > 20 Pam^3/s is the necessary condition to initiate the divertor detachment.

Figure 4 plots H-factor against divertor radiation fraction, P_{rad}^{div}/P_{net}, in three discharges. While H-factor was ~1.6 before the gas puff in both shot 29741 and 29783, degradation of H-factor in shot 29783 is much worse than degradation of H-factor in shot 29741 as a function of P_{rad}^{div}/P_{net}. In shot 29796 with H-factor = 1.4 at the start, H-factor as a function of P_{rad}^{div}/P_{net} is the worst. Edge plasma density was more appropriate to describe the plasma density at the divertor detachment than the central plasma density. The plasma detachment started when edge density reached ~ n_{eU1} = 3 x 10^{19} m^{-3}. Here n_{eU1} is the edge line averaged density.

The ITB degraded significantly during high Q_{D2} puffing. Figure 5 shows time evolution of Ti profiles measured by the charge exchange spectroscopy from t = 7.0 to 7.8 s in shot 29783. The gas puff rate was ramped up from 0 at t = 6.8 s to 60 Pam^3/s at t= 7.2 s and sustained until t = 9.0 s. Large radius of the ITB and steep gradient in Ti profile at t = 7.0 s, is typical for the reversed shear plasmas in JT-60U. At t = 7.2 s the gradient in Ti was already decreased inside r/a = 0.5. Since Ti profile in shot 29741 has steeper gradient at the time of the same n_{eU2}, this change is due to the degradation of the energy confinement rather than change in NB deposition profile. Here n_{eU2} is the central line averaged density. Gradient in Ti profile continued to decrease in time toward t = 7.8 s, as shown in this figure.

3. Neon exhaust

Exponential decay time of neon content was estimated for the period which the transport barrier is observed in Ti profiles and Q_{D2} is constant. Neon content in the main plasma is represented by Ne X intensity measured by VUV spectroscopy. The neon decay time is plotted as a function of Q_{D2} in Fig. 6. The experimental result in ELMy H-mode plasmas [2] with Ip = 1.2 MA, B_T = 3.5 T and P_{NB} = 25 MW is also shown in this figure. The neon exhaust was enhanced as a function of Q_{D2}. The enhancement, characterized by the slope in the figure, in the reversed shear plasmas is smaller by a factor of three than that in ELMy H-mode plasmas. While the improved neon resident time inside the ITB is speculated from the result, ion transport analysis using neon profiles is necessary to prove it.

Discussions

The core plasma confinement degrades in a few hundreds milliseconds, much shorter than the period required to get the divertor detachment with high Q_{D2}. Therefore it was impossible to get divertor detachment before the H-factor degradation with high Q_{D2}. In the discharge with the medium Q_{D2}, as large as 25 Pam^3/s, that edge plasma parameters, such as the edge plasma density and the divertor radiation fraction, reached very close to those required for the divertor detachment at the end with a small degradation of the energy confinement. Therefore Q_{D2} for the divertor detachment must be reduced as low as possible to avoid confinement degradation. Since it will require a several seconds with such a low Q_{D2}, it is important to increase steadiness and H-factor of the target plasma before neon and D_2 gas puff in the present frame of the experiment.

In order to reduce Q_{D2} for the divertor detachment further, the main plasma radiation loss must be increased. Argon injection may be preferable, since Argon radiates more effectively in the edge plasmas than Neon.

Conclusions

The radiative divertor experiment was carried out in the reversed shear plasma of JT-60U with the aid of Ne and D_2 gas puffing. Detached divertor plasma was obtained by puffing D_2 gas more than 40 Pam^3/s, while H-factor was reduced to 1.2. It was found that high rate of D_2 gas puffing degrade the ITB in less than a few hundreds milliseconds, leading to decrease in H-factor significantly.

The neon exhaust was enhanced by D_2 gas puffing, however the enhancement is smaller by a factor of three than that in ELMy H-mode plasmas.

References

[1] K. Itami et al. 1996 Fusion Energy Conf., Montreal, 1996 vol. 1 (International Atomic Energy Agency, Vienna, 1997) p. 385.
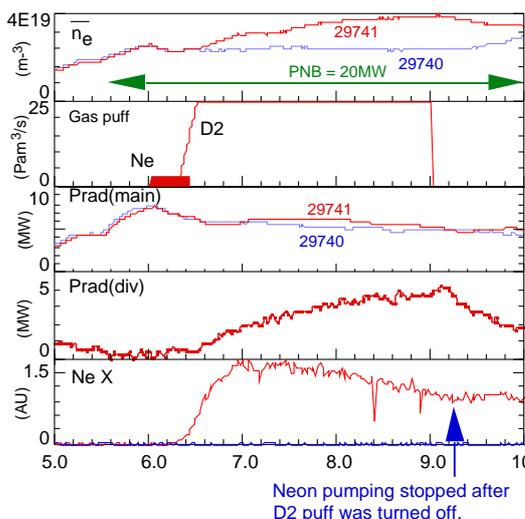
[2] K. Itami et al., J. Nucl. Mater. 266-269 (1999) 1097.
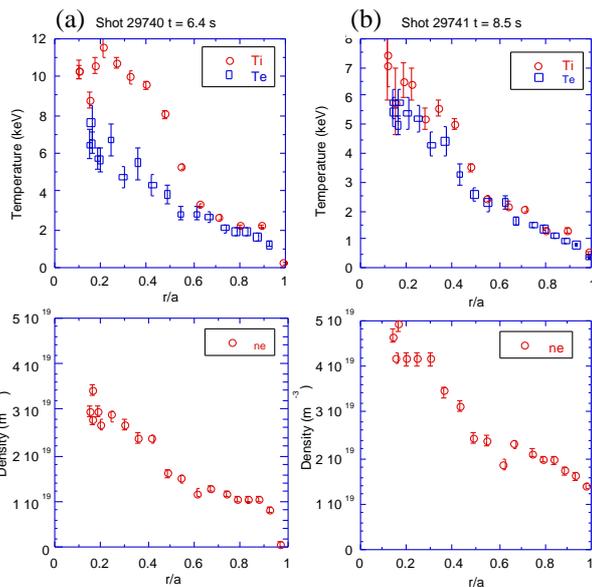
Fig. 1 Typical waveform of this experiment.

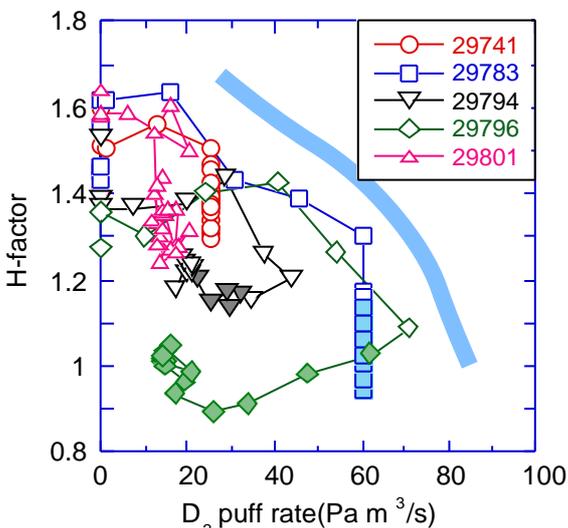*Fig. 2 Ti and Te profile and ne profie (a)before and (b) during gas puffing.*
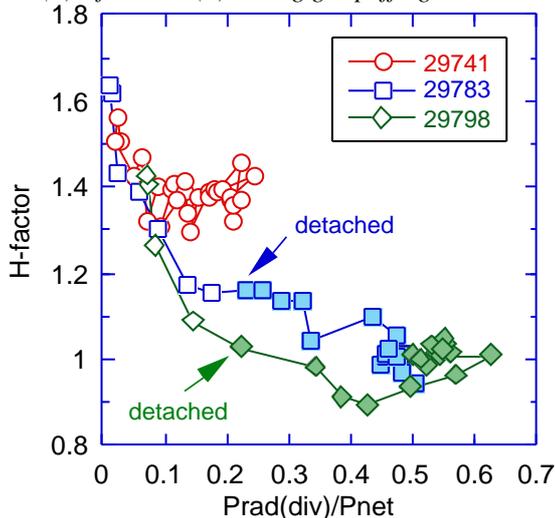

Fig. 3 Shot history in H-factor vs QD2

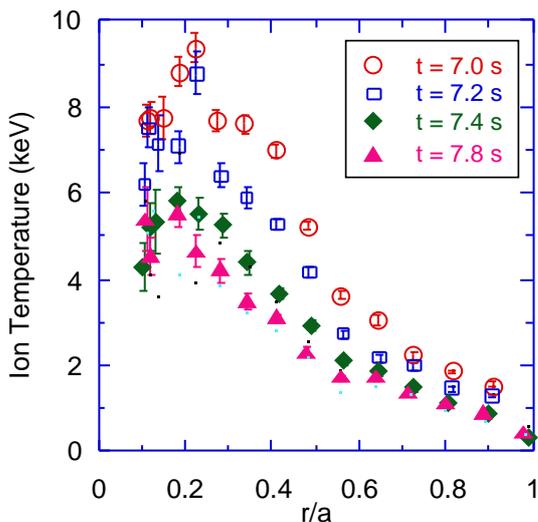*Fig. 4 Shot history in H-factor vs Praddiv/Pnet*
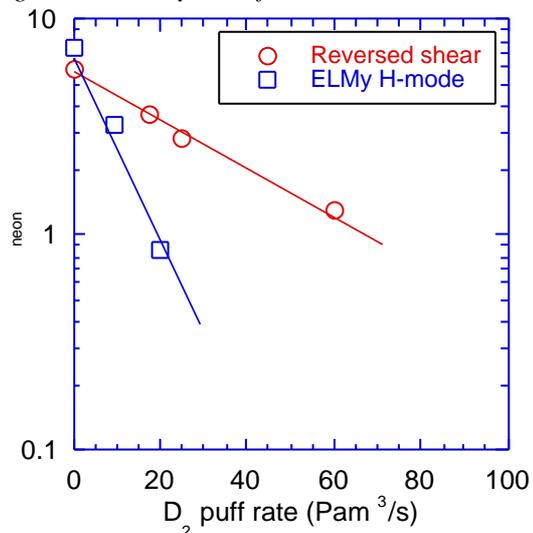

Fig. 5 Ti profiles during gas puffing in shot 29783

Fig. 6 Enhancement of neon exhaust