Fast Dynamics of Type I and Grassy ELMs in JT-60U
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Abstract. In order to understand the physics of the ELM trigger and determining the ELM size, fast ELM dynamics of type I ELMs and grassy ELMs have been studied in JT-60U using new fast diagnostics of a lithium beam probe and charge exchange recombination spectroscopy which can measure electron density and ion temperature with high spatial and temporal resolutions. The evolution of the pressure profile is evaluated for the first time by the detailed profile measurement of the density and temperature pedestals. After a type I ELM crash, the recovery of pedestal density is faster than that of electron and ion temperature. Just before type I ELM crash, the pedestal ion pressure in co-rotating plasmas is higher than that in counter (ctr)-rotating plasmas. We found that the radial extent of the pressure gradient at the pedestal region in co-rotating plasmas is wider than ctr-rotating plasmas. The result suggests that the ELM size is determined by the structure of the plasma pressure in the whole pedestal region. As for the dynamics of grassy ELMs, the collapse of density pedestal is smaller and narrower than that of type I ELMs, as observed in the collapse of temperature pedestal. Thus, it is confirmed that both conductive and convective losses due to grassy ELMs are small.

1. Introduction
For a steady state operation of the tokamak fusion reactor, H-mode with the edge localized mode (ELM) is an attractive scenario in terms of the density and impurity controllabilities. Although ELMy H-mode has a good compatibility of a high performance and steady state operation, a damage to a divertor plate due to a large ELM heat load is a critical problem for the plasma facing components. Therefore, mitigation of the ELM heat load has been investigated in various tokamaks.

In order to control the ELM size and frequency, ELM mitigation techniques and operations in small ELM regimes have been developed and successfully demonstrated. In addition, recent experimental results show that the toroidal plasma rotations also affect the ELM size and frequency [1-3]. To improve the ELM controls, the mechanism of ELM triggering and the determination of ELM affected area are key physics for the ELM control techniques, because the ELM triggering and ELM affected area decide the ELM frequency and size, respectively. In this paper, the ELM dynamics of type I and grassy ELMs is experimentally

![Figure 1. Plasma configuration and arrangements of the diagnostics (LiBP, CXRS, YAG Thomson scattering, FIR interferometers of edge and core regions)]
investigated to understand the ELM trigger and ELM affected area.

In JT-60U, fast dynamics of type I ELMs [4] and grassy ELMs [5] have been studied extensively. However, the time resolution of $T_i$ measurement and the spatial resolution of $n_e$ measurement were not high enough to discuss the profile of pedestal pressure. The experimental observation of the pressure profile has been awaited in order to investigate the behavior of the pressure profile as an ELM trigger and the radial extent of the ELM affected area. To understand the detailed ELM physics, new diagnostics of a lithium beam probe (LiBP) ($\Delta R \sim 1 \text{cm}$, $\Delta t = 0.5-2.5 \text{ms}$) and a charge exchange recombination spectroscopy ($\Delta R \sim 0.6 \text{cm}$, $\Delta t = 2.5 \text{ms}$) have been developed and installed in JT-60U. Then, the evolution of the pressure profile during an ELM cycle can be evaluated for the first time.

This paper is arranged as follows; Fast dynamics of the edge density profile during type I ELM is presented in Sec. 2. The behaviors of the density and temperature profiles in cases of co- and counter-rotating plasmas are shown in Sec. 3. Comparison between low and high Ip plasma with co-rotations is described in Sec. 4. The evolution of the pressure profile and the gradient is shown in Sec. 5. The ELM affected areas are compared between grassy and type I ELM in Sec. 6. Conclusion is in Sec. 7.

2. Fast ELM Dynamics of Type I ELMs

Typical evolution of one cycle of type I ELM is investigated in ELMy H-mode plasma with co-toroidal rotation. Figure 1 shows the plasma configuration and arrangement of the diagnostics. The edge density profile measured by LiBP covers around 8cm from the separatrix along with a vertical line same as the FIR interferometer of core region and YAG Thomson scattering. In terms of the density collapse measured by LiBP, it is noted that the initiation of ELM collapse has the poloidaly asymmetry, and takes place in the localized region near the midplane at low field side. Figure 2 shows a waveform of one ELM cycle of type I ELM. The ELM energy loss is 89kJ corresponding to $\Delta W_{\text{ELM}}/W_{\text{ped}}$ of 8%. Frequency of ELMs $f_{\text{ELM}}$ is 37Hz. A drop of the pedestal density $n_{e,\text{ped}}$ at ELM reaches $\sim 30\%$ which is larger than the temperature drops (typically 10-20%). Just after ELM crash ($t=6.807-6.814s$), the increase in the separatrix density $n_{e,\text{sep}}$ corresponds to the increase of the density in scrape-off layer (SOL). These phenomena indicate the collapse of the density gradient due to ELM crash.
The recovery of the pedestal density is faster than the temperature. The time scale (~10ms) of the recovery of the pedestal density after ELM is similar to the reduction in line density $n_{el core}$. Figure 3 shows the comparison of the evolution of line density. The increase and decrease of line density occur outside and inside of density pivot as shown in Fig. 3(b). $n_{el IN}$ and $n_{el OUT}$ are line integrated values in the pedestal region. The boundary condition of integration is pivot point. The poloidal symmetry is assumed in evaluating the line integration along with the vertical line. The ELM collapse induces the reduction of the $n_{el IN}$. On the other hand, the waveform of $n_{el OUT}$ is similar to the line density $n_{el edge}$. Therefore, increase of $n_{el OUT}$ do not suggest the density exhaust; the time scale of the density collapse due to ELM is about 200µs. Increase of $n_{el edge}$ and $n_{el OUT}$ result from the increase of the SOL density caused by the enhanced recycling effect due to ELM crash [4]. In Fig. 3(a), $\Delta n_{el}$ indicates a variation from the pre-ELM value. $\Delta n_{el IN}$ and $\Delta n_{el OUT}$ are almost balanced ($n_{el IN} + n_{el OUT} \sim 0$) during this ELM cycle. However, $\Delta n_{el core}$ along with same vertical line decreases 2ms after the ELM collapse. Therefore, the slow reduction of $n_{el core}$ suggests the redistribution of plasma density to compensate most of the lost pedestal density because $n_{el core} (n_{el IN} + n_{el OUT})$ means the change of the density in the core region; $\Delta n_{el core}$ of $0.1 \times 10^{19} \text{m}^{-2}$

Figure 3. (a) Waveforms of $\Delta n_{el}$, (b) Radial profile of edge density. Dash lines are fitting curves using YAG Thomson scattering. SOL region is assumed to be exponential decay. $n_{el IN}$ and $n_{el OUT}$ are separated by pivot point.

Figure 4. Waveform of type I ELM in ctr-rotating plasma. Dashed lines indicate ELM onset. ($I_p=1.6\text{MA}$, $q_{95}=4.3$, $\delta=0.34$, $f_{ELM}=45\text{Hz}$, $P_{NB}=12.9\text{MW}$)
corresponds to 2% reduction of the density in the core region.

As for the temperature, the electron and ion temperature monotonically recover toward the next ELM. Since the pedestal profile and the time scale of the recovery are different between the temperature and the density, the evaluation of pressure profile during ELM is essential to the understanding of ELM physics.

3. Type I ELM Dynamics in Co- and Ctr-Rotating Plasma

JT-60U reported that the normalized ELM energy loss ($\Delta W_{ELM}/W_{ped}$) in ctr-rotating plasmas is smaller than that of co-rotating plasmas [1]. It suggests that the toroidal rotation can change the ELM affected area. The ELM affected areas are compared between co- and ctr-rotating plasmas. Typical waveform of ctr-rotating plasma is shown in Fig. 4. $\Delta W_{ELM}$ in the ctr-rotating plasmas is smaller than the co-rotating plasma and the drop of the density and temperature are also small. Figure 5 shows the edge density across an ELM onset. The ELM frequency $f_{ELM}$ is 37Hz, and 15 ELMs are averaged in Fig. 4. Density pedestal structure is recovered 10ms after the ELM collapse. After pedestal formation, the edge density is almost steady state or slightly increased. Figure 6(a)
show the edge density profiles at \( t=-1\sim0 \) (before ELM), 1.5~2ms (after ELM) in comparison with co- and ctr-rotating plasmas. The shoulder of density pedestal is located at 4~5cm from the separatrix. In the co-rotating plasma, \( n_{e,\text{ped}} \) is higher than the ctr-rotating plasmas. Figure 6(b) shows the density loss fraction due to the ELM crash measured by LiBP and YAG Thomson scattering. Around the pedestal shoulder, 30% of density is lost in the co-rotating plasmas. The density loss fraction of the ctr-rotating plasmas is smaller than the co-rotating plasmas. Moreover, ELM affected area of the co-rotating plasmas is wider than that of the ctr-rotating plasmas.

Figure 7 shows the ion temperature behavior. Time evolution of the ion temperature as shown in Fig. 7(a) is obtained by same process in Fig. 5(a). The edge temperature is monotonically increased after the ELM crash. Fig. 7(b) shows the temperature profile in comparison between co- and ctr-rotating plasmas. The pedestal shoulders of density and temperature are located almost same position in these cases. The ion temperature profiles in co-and ctr-rotating plasmas before the ELM crash are almost same; however, the loss fraction of the co-rotating plasma is larger than the ctr-rotating plasmas as shown in Fig 7(c).

Figure 8. Waveform of type I ELM. Dashed lines indicate ELM onset in co-rotating plasma. (\( I_p=1.0\text{MA}, q95=4.1, \delta=0.39, f_{\text{ELM}}=75\text{Hz}, P_{\text{NIH}}=10.9\text{MW} \))

Figure 9. Comparison of high and low Ip plasma (a) Density profile of 1MA and 1.6MA before and after ELM. (b) Density loss fraction (c) Temperature profile (d) Temperature loss fraction.
Therefore, the previously obtained small ELM energy loss of ctr-rotating plasma results from small loss fraction and narrow ELM affected area for both density and temperature.

4. Type I ELM Dynamics of High and Low Plasma Current

ELM dynamics at high and low plasma current is investigated for the co-rotating plasmas. Figure 8 shows the typical waveform of low Ip plasma. Because of low f_{ELM}, behavior of the pedestal density is different from the high Ip case. The pedestal density is not saturated in some ELMs. Figure 9 shows the comparison between the low Ip(1MA) and high Ip(1.6MA) cases. The pedestal structure is wider in the low Ip plasma as shown in Fig. 9(a). It suggest the Ip dependence of pedestal width, however, the pedestal width of the density is also affected by the penetration length of the neutral particle. Since high density pedestal has shorter penetration length of neutrals, the pedestal width may be narrower. The density loss fraction profiles are observed as shown in Fig. 9(b), suggesting the convective loss (~TΔn) does not vary with plasma current or density. T_{i,ped} is almost same in both cases as shown in Fig. 9(c). However, temperature loss fraction profile of the low Ip case is narrower than the high Ip case. Therefore, the normalized convective and conductive loss fraction has different dependence on plasma current.

5. Type I ELM Dynamics of Ion Pressure

In the peeling-balloonning model, the pressure gradient and resultant edge current are key parameter of triggering ELM. As observed in Figs. 2 and 4, the total and pedestal stored energy were higher in the co-rotating plasma (W_{ped} = 1.08MJ) than that in the ctr-rotating plasma (W_{ped} = 0.83MJ), while the heating power was similar in both cases (P_{net}~10MW). Figure 10 shows the recovery of the ion pressure profile after the ELM crash evaluated by electron density and ion pressure assuming spatially uniform Z_{eff} and including dominant impurity of carbon. The large ΔW_{ELM} observed in the co-rotating plasma is characterized by the large reduction in the pedestal pressure as observed in Fig. 10(a) and (c). Evolution of the

![Figure 10](image_url)
pressure gradient indicates the faster recovery of co-rotating plasma as observed in Fig. 10(b) and (d). The achievable pressure gradient of the co-rotating plasma is larger than the ctr-rotating plasma. It suggests the stability limit can vary with the toroidal rotation. The region of strong pressure gradient over 100kPa/m is 1cm wider in the co-rotating plasma. Since the edge current depends on the pressure gradient, the wider gradient profile result in the wider edge current profile. Therefore, the ELM affected area of the co-rotating plasma may become wider according to the stronger and wider pressure gradient profile than the ctr-rotating plasma. A different radial profile of the most unstable mode (peeling-ballooning mode) due to the different pressure profile in the whole pedestal region is a possible explanation of different ELM size between co- and ctr-rotating plasmas.

Time evolution of the ion pressure gradient is mainly determined by the density profile, which recovers quickly (~10 ms) as shown in Fig. 5(a). Time evolution of the maximum pressure gradient toward the next ELM is shown in Fig. 11. In the low Ip co-rotating and high Ip ctr-rotating plasmas, the pressure gradient is not saturated until the next ELM onset; it suggests that the pressure gradient trigger ELM. On the other hand, in the high Ip co-rotating plasmas, the saturation of the pressure gradient is unclear; both the pressure gradient and the edge current may play a role for triggering the ELM crash.

6. Fast ELM dynamics of Grassy ELM
The small $\Delta W_{ELM}$ in grassy ELMs is characterized by the narrow radial affected area of the collapse of temperature pedestal [5]. However, the loss fraction of density pedestal has not

![Figure 11. Comparison of time evolution of the maximum pressure gradient at each case.](image)

![Figure 12. (a) Time evolution of edge density at each position in grassy ELM phase of mixture ELM. (Ip=1.0MA, q95=4.3, $\delta=0.54$, $f_{ELM}=200Hz$, $P_{NB}=9.4MW$) (b) D$_{\alpha}$ emission intensity from divertor. (c) Comparison of density profile with grassy and Type I ELMs. (d) Comparison of density loss fraction profile with grassy ($f_{ELM}=200Hz$ and 500Hz) and Type I ($f_{ELM}=75Hz$) ELMs.](image)
been measured. The fast dynamics of the density pedestal in grassy ELMs is measured by LiBP for the first time as shown in Fig. 12(a). The density pedestal structure is same between Type I and Grassy ELMs in same plasma current. Even for the low frequency of 200Hz (large amplitude) Grassy ELMs, the 20% of the pedestal density is lost and its radial extent was smaller (5cm) than that in type I ELMs (~20cm), as shown in Fig. 12(d). The collapse due to Grassy ELM of 500Hz is comparable to the noise level as shown in Fig.12(d). It suggests the density loss fraction depends on the frequency in case of Grassy ELM. Since the temperature loss fraction of grassy ELM is smaller than type I ELM, it is confirmed that both conductive and convective ELM losses due to Grassy ELM are small. The collapse of density pedestal is localized near the separatrix, suggesting localized eigen function at the edge region.

7. Conclusion

Fast dynamics of Type I and grassy ELMs are investigated using newly developed diagnostics. The behavior of pedestal density and ion temperature, thus pressure profile are observed for the first time. It is confirmed that the lost pedestal density is compensated by core density after ELM crash.

In comparison with co- and ctr-rotations, ELM affected of co-rotating plasmas is larger and wider than ctr-rotating plasmas. The pressure and the gradient are higher in co-rotating plasmas. Moreover, the pressure gradient is large and the radial extent of the gradient is wider than ctr-rotating plasmas. It may cause the wider radial eigen function of most unstable mode, and then, the ELM affected area may become large. In comparison with high and low Ip plasmas, the density loss fraction is similar; however, the temperature loss fraction of low Ip plasma is smaller than high Ip plasma. Therefore, the component of convection and conduction in normalized ELM energy loss has different dependence on plasma current.

The dynamics of edge density during grassy ELM is observed for the first time. It is found the density loss fraction is less than 20% and the radial extent is narrower than Type I ELM. Therefore, the convective and conductive loss of grassy ELM is much smaller than Type I ELM, and the frequency dependence of the density loss fraction is suggested.

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