ELM and Pedestal Structure Studies in KSTAR H-mode Plasmas

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Abstract. The Edge Localized Modes (ELMs) and pedestal structure are studied in Korea Superconducting Tokamak Advanced Research (KSTAR) ELMy H-mode plasmas. KSTAR H-mode plasmas have three distinctive types of ELMs: large type-I ELMs with low ELM frequency \(f_{\text{ELM}}\sim 10 - 50\ \text{Hz}\) and good confinement \(H_{98(y,2)}\sim 0.9 - 1\), smaller, possibly type-III, ELMs with high ELM frequency \(f_{\text{ELM}}\sim 50 - 250\ \text{Hz}\) at a reduced confinement \(H_{98(y,2)}\sim 0.7 - 0.8\), and a mixed, large and small, ELM regime with good confinement \(H_{98(y,2)}\sim 1\). The NBI power scan shows that ELM frequency is increased with increasing input power for large ELMs, which is a typical behavior of type-I ELMs. In type-I ELMs, precursor-like signals can be measured by the magnetic sensors, while they are not observed in the other two ELM types. Low field side (LFS) profile of electron temperature \(T_e\) from the ECE measurement and pedestal profile of toroidal velocity \(V_t\) from the charge exchange spectroscopy (CES) measurement show continuous to build up on the LFS during the inter-ELM period. However, the recovery of \(T_e\) pedestal from the CES after the ELM crash does not occur until it finally rises back up at the last stage of the inter-ELM period, \(i.e. > 80\%\) of the ELM cycle. The estimated electron pedestal collisionality for the type-I ELMy regime is \(\nu_e\sim 0.5-0.6\). A second L-H transition during the L-mode phase after the end of 1st H-mode stage occurs for some discharges when the divertor configuration is restored by the plasma control system. Characteristics of this “late H-mode” are compared to those for the main H-mode. An ideal MHD stability analysis for ELMy H-mode plasmas is also carried out by the ELITE code in order to investigate unstable domains for the ELM occurrence, as well as its sensitivity to a range of estimated/measured profiles. In this work, the experimental investigations of the characteristics of the ELM and the pedestal structure during the ELM in the KSTAR H-mode plasmas is reported, and the preliminary results from the ideal MHD analysis for ELMy H-mode plasmas is presented.

1. Introduction

H-mode with \(H_{98(y,2)}\sim 1\) is a required operational scenario for ITER and the access condition and performance optimization have been extensively studied for decades in various tokamaks. While the understanding of physical mechanism responsible for the H-mode pedestal phenomena with various types of Edge Localized Modes (ELMs) has advanced rapidly in recent years, a significant part of fundamental physical processes are still to be examined and the suggested models be tested in the present day machines.

Korea Superconducting Tokamak Advanced Research (KSTAR) [1, 2] is a superconducting, long-pulse tokamak which began operation in 2008. Since the first H-mode obtainment in 2010 with Neutral Beam Injection (NBI) heating [3], H-mode study has been an
important element of the experimental program in the KSTAR as the H-mode characteristics in the long-pulse superconducting tokamak may have crucial implication for ITER. Even with rather fixed operation parameters and relatively low heating power ($I_p=0.6 \text{ MA, } B_t=2 \text{ T, } P_{\text{NBI}} \leq 1.5 \text{ MW}$), H-mode plasmas with multiple types of ELMs, including clear type-I ELMs and a mixed ELM (type-I + small ELMs) regime, and different confinement qualities have been produced. Note that type-I ELMs in other machines are generally observed only when the heating power is well above the L-H power threshold ($P_{\text{thr}}$) [4]. One factor that appeared to have influenced ELMs in KSTAR is the shape of poloidal plasma cross section. The shaping parameters are known to affect confinement and to change the ELM characteristics in other machines. A range of elongation ($\kappa$ up to 1.8 – 1.9) and triangularity ($\delta$ up to 0.8 – 0.9) have been achieved and higher $\delta$ appears to lead to the mixed ELM regime in KSTAR.

Profile measurement during ELMy H-modes was made for electron temperature ($T_e$) by Electron Cyclotron Emission (ECE) [5] and for toroidal velocity ($V_t$) and ion temperature ($T_i$) by Charge Exchange Spectroscopy (CES) [6] diagnostics. Although detailed profile measurements necessary for the ELM stability study are not routinely available at present, it is worthwhile to report phenomenological investigations of the ELM characteristics and global confinement properties at KSTAR and to compare the results to those from other machines. We also observed a 2nd L-H transition in a later stage (i.e. after the plasma returned to L-mode) of some H-mode discharges. This “Late H-mode” has different features from those for the preceding main H-mode. For example, the plasma is in a mixed ELM regime (type-I and small ELMs) and the plasma elongation is lower ($\kappa = 1.6 – 1.7$) than for the main H-mode stage ($\kappa = 1.8 – 1.9$). It is not yet clear how the transition to the late H-mode is triggered and work is currently underway. In addition, an ideal MHD stability analysis for ELMy H-mode plasmas is carried out by the ELITE code in order to investigate unstable domains for the ELM occurrence, as well as its sensitivity to a range of estimated/measured profiles.

A brief description of the experimental setup is given in section 2. Section 3 describes characteristics of ELMs. Profile measurement results during the inter-ELM period are given in section 4. Section 5 describes characteristics of late H-mode. The preliminary results of the ideal MHD stability analysis for ELMy H-mode were reported in section 6, followed by summary in section 7.

2. Experimental set-up

In the 2011 campaign, KSTAR H-mode plasmas were routinely obtained with the use of NBI ($0.7 \leq P_{\text{NBI}} \leq 1.5 \text{ MW}$). The electron cyclotron heating (ECH) with maximum power of ~0.3 MW for 110 GHz gyrotron and ~0.6 MW for 170 GHz was also used as another auxiliary heating method. The real-time EFIT (rtEFIT) was implemented as a part of the plasma control system but the iso-flux control capability was not available and the magnetic configuration was only optimized with a pre-programmed waveform of poloidal field coil currents, i.e. the feedback control was not possible. The post-discharge EFIT equilibrium reconstruction was also implemented with good agreements with the CCD camera image and divertor probe measurement for the plasma boundaries and the position of strike points, respectively. Details of equilibrium reconstruction process used in KSTAR can be found in Ref. 7. Various wall cleaning techniques, including the plasma facing component (PFC) baking up to ~250 °C, overnight helium glow discharge, and the PFC boronization using carborane, have been used to minimize impurity influx from the wall.
3. Characteristics of ELMy H-mode

KSTAR H-mode plasmas have three distinctive types of ELMs [8]: 1) large type-I ELMs with low ELM frequency (\(f_{\text{ELM}}=10-50\text{Hz}\)) and good confinement (\(H_{98(y,2)}=0.9-1\)), 2) smaller, possibly type-III, ELMs with high ELM frequency (\(f_{\text{ELM}}=50-250\text{Hz}\)) at a reduced confinement (\(H_{98(y,2)}=0.7-0.8\)), and 3) a mixed, large and small, ELM regime with good confinement (\(H_{98(y,2)} \sim 1\)). Figure 1 shows the parameter time traces for all three types of ELMs.

Although the maximum NBI heating power was only 1.5 MW, many of the KSTAR ELMs showed characteristics of type-I ELMs (see figure 1(a)) including low ELM frequency, large ELM size (up to \(-4\%\) of \(\Delta r/r_0\) and \(-7\%\) of \(\Delta W_{\text{tot}}/W_{\text{tot}}\)), and particularly the positive dependence of the ELM frequency on the heating power, \(i.e.\) increasing \(f_{\text{ELM}}\) with increasing power, according to the characterization in [9], confirmed experimentally in [4]. Figure 2 shows an example of two power levels (1.5 MW and 1.3 MW of \(P_{\text{NBI}}\)) and the ELM frequency is consistently higher for the 1.5 MW case. The ELM frequency for a specific ELM peak is calculated as the reciprocal of the time interval from the immediately preceding ELM peak. Figure 3 shows an example of power scan for the mixed ELM regime (see Fig. 1(c)) by means of beam modulation and ECH injection. Note that there is a time delay of \(\sim 150\) ms in the response of the ELM frequency to the change of the injected power at \(t=3\) sec, which is consistent with the beam slowing down time of \(100-150\) ms estimated for the given beam energy and plasma conditions.

The intermediate ELMs (see figure 1(b)) have different characteristics from those for the
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Figure 3. Dependence of ELM frequency on heating power for large ELMs in the mixed ELM regime. Time trace of (a) line average density, (b) divertor $D_{a}$, (c) ELM frequency, (d) NBI power (modulated from $t=2.5$ sec), (e) ECH power, and (f) total heating power ($P_{\text{NBI}}+P_{\text{ECH}}$). The NBI modulation from $t=2.5$ sec reduces the NBI heating power to 1.1MW and the addition of ~0.4 MW ECH from $t=3$ sec raises the total auxiliary heating power ($P_{\text{aux}}=P_{\text{NBI}}+P_{\text{ECH}}$) back up to 1.5MW. The frequency of large ELMs decreased with lower $P_{\text{NBI}}$ with time delay of ~150ms and went up again when the total power was raised (see panel (c)). Tiny ELMs between large ELM peaks also disappeared during the lower power.

Figure 4. Comparison of type-I (red) and intermediate (blue) ELMs; (a) ELM size vs. ELM frequency, (b) ELM size vs. Greenwald fraction, and (c) H98(y,2) vs. Greenwald fraction. Figures (a) and (b) are for the same time slices.

ELMs usually have increased fluctuation level in the low frequency band (25-50 kHz) during the inter-ELM period for a few tens of ms before the ELM burst (see Fig. 5(a)). This is different from the ELM precursors observed in AUG [12], but is similar to the type-I ELM precursor at JET [13]. The precursors are not observed in the intermediate and mixed ELMs as shown in Figs. 5(b) and 5(c), which is not the same as that for type-III ELMs in AUG [12]. Also, intermediate ELMs show higher level of broadband fluctuation during the inter-ELM period than the other two types of ELMs. Another thing to note is that the intermediate ELMs might be type-III and it is consistent with its higher ELM frequency and smaller ELM size. However, a power scan data and the relation with the ELM frequency are necessary to confirm this.

We have also carried out wavelet analysis of Mirnov signal and found that type-I other two types of ELMs. Results from other machines indicate that the ELM size defined as a pedestal energy loss ($\Delta W_{\text{ELM}}/W_{\text{ped}}$) has a negative dependence on the Greenwald fraction ($\bar{n}_{e}/\bar{n}_{e}$) for type-I ELMs [10, 11] but currently there is no routine measurement of pedestal $T_{e}$ and $n_{e}$ profiles in KSTAR, therefore we use $\Delta \bar{n}_{e}/\bar{n}_{e}$ to look for the ELM size dependence on $\bar{n}_{e}/\bar{n}_{e}$. Figure 4(a) and 4(b) show that the size of type-I ELMs decrease with increasing ELM frequency and Greenwald fraction, while that of the intermediate ELMs does not show a clear correlation with either $f_{\text{ELM}}$ or $\bar{n}_{e}/\bar{n}_{e}$ (both the type-I and intermediate ELM data were obtained from multiple discharges). The size of intermediate ELMs is $\Delta \bar{n}_{e}/\bar{n}_{e} < 2\%$ in Fig.4 and even smaller than 1% in some other discharges. Figure 4(c) shows the variation of H98(y,2) for type-I and intermediate ELMs as a function of Greenwald fraction. It is seen that confinement degrades with increasing density for both types of ELMs and the overall H-factor for the intermediate ELMs is noticeably lower than for type-I ELMs. This indicates that...
Figure 5. Wavelet analysis of toroidal Mirnov signal for (a) type-I ELMs, (b) intermediate ELMs, and (c) mixed ELMs. Increased level of fluctuation (ELM precursor?) during the inter-ELM period before the ELM burst is observed for type-I ELMs in the 25-50 kHz band and lasts for 40-50 ms.

Figure 6. (a) Temporal evolution of $D_\alpha$ during a type-I ELMy H-mode, and radial profiles of (b) toroidal velocity ($V_t$) and (c) ion temperature ($T_i$) during an inter-ELM period [8]. Four time slices during the inter-ELM period are color coded. The vertical dash line represents the radial location of separatrix from the EFIT reconstruction.

4. Profile measurement in inter-ELM period

The temporal evolution of low field side (LFS) $T_i$ and $V_t$ profiles measured by CES diagnostic [6], which has spatial and temporal resolution of up to 5 mm and 10 ms, during an inter-ELM period is shown in Fig. 6. The $V_t$ profile crashes immediately after the ELM burst but its pedestal quickly begins to increase and the whole profile continues to build up during the period until it crashes again after the next ELM burst. However, the recovery of $T_i$ pedestal after the crash does not occur until it finally rises back up at the last stage of the inter-ELM period, i.e. > 70 - 80 % of the ELM cycle. This result is contrary to the observation from other machines such as DIII-D [14] that the pedestal height of $T_i$ slowly increased throughout the ELM cycle after an initial jump early in the cycle, i.e within 10-20% of the inter-ELM period. It might also suggest that the ion component of the pressure plays a more important role in the ELM destabilization in KSTAR, but obviously more work is needed to identify specific processes responsible for the ELM stability physics.

Measurement of $T_e$ profile was made by the ECE diagnostic [5], with the absolute calibration of a radiometer system completed for the 2nd and 3rd harmonics of electron cyclotron frequencies for the $B_t$ range of 1.5-3 T. The present radiometer frequency range of 110-162 GHz is optimized for the operation of $B_t$ range of 2.5-3 T. Figure 7 is an example of such a measurement for inter-ELM period of a $B_t$ =2.4 T H-mode, with and without ECH heating. A significant portion of both the LFS and HFS $T_e$ profiles was measured for pure 2nd harmonic frequencies although it did not quite reach the pedestal region yet. The central $T_e$ is 3 - 4 keV and the whole profile is rather peaked. Although the pedestal $T_e$ could not be
observation of in-out asymmetric \( T_e \) profile remains unclear and needs more study to be clarified. Confirmation with the Thomson scattering data LFS is stronger at higher density. The underlying mechanism of this asymmetry remains unclear and needs more study to be clarified. Confirmation with the Thomson scattering data.

- **Figure 7(a)** and a pedestal density of \( \rho_{\text{ped}} \leq 0.8 \) for the late H-mode plasma. The late H-mode also has different ELM characteristics from the main H-mode and we suspect this may be due to the shaping parameter change, \( i.e. \) a typical H-mode discharge in KSTAR has the L-H transition at \( t=2-3 \) sec and the H-mode state lasts for a few seconds, then an H-L back transition takes the plasma back to the L-mode state and it continues until the plasma consumes all the available flux. However, we have observed a \( 2^{nd} \) L-H transition at a later stage of some H-mode discharges (see Fig. 8) \[8,17\]. Plasma elongation at the L-H transition time is noticeably lower (\( \kappa=1.6-1.7 \) for the late H-mode than for the main H-mode (\( \kappa=1.8-1.9 \)). For the discharges in this study, the late H-mode plasmas have densities in a substantially wider range of Greenwald fraction (\( 0.36 \leq \rho_s/\rho_g \leq 0.57 \)), while densities in the preceding main H-mode were in a narrower range (\( 0.36 \leq \rho_s/\rho_g \leq 0.42 \)). Among the plasma parameter changes, the \( T_i \) and \( V_i \) increase induced by the transition to the late H-mode is significantly lower than that for the main H-mode. The late H-mode also has different ELM characteristics from the main H-mode and we suspect this may be due to the shaping parameter change, \( i.e. \) accurately identified due to the absence of data from \( r \approx 2.15 \) m, the continuous restoration of the LFS \( T_e \) profile during the inter-ELM period after the ELM crash is clearly exhibited while the HFS profile only shows little change. This result is compared to the data from AUG [15], where distinct phases have been observed in the build up of the pedestal \( T_e \) profile at \( \rho_{\text{ped}}=0.8 \). However, \( T_e \) profile at \( \rho_{\text{ped}}=0.8 \) remained almost the same during the entire ELM cycle in this work. Although the ELM \( T_e \) crash is stronger on LFS than HFS both with and without ECH heating (see Fig. 7), the discrepancy between the LFS and HFS \( T_e \) profiles is significantly larger in case of ECH heating, for which we do not have a good explanation at present. Note that a similar observation of in-out asymmetric \( T_e \) profile was reported at JET [16], where cases of different LFS/HFS \( T_e \) at the same flux surface are presented and the trend of larger ELM \( T_e \) crash on LFS is stronger at higher density. The underlying mechanism of this asymmetry remains unclear and needs more study to be clarified. Confirmation with the Thomson scattering data in the next campaign and more detailed transport analysis will enable us to unfold the physics responsible for these observed profile changes. If we assume a pedestal \( T_e \) of \( \approx 1 \) keV from figure 7(a) and a pedestal density of \( n_e \approx 2.35 \times 10^{19} \text{ m}^{-3} \) from the measured line average density of \( T_e \approx 2.35 \times 10^{19} \text{ m}^{-3} \) at \( t=2.4 \) sec, the neoclassical electron pedestal collisionality, \( \nu_e^* = q_{\phi}^2 R e^{1.3} \lambda_{\text{ce}}^{-1} \), is estimated to be \( \nu_e^* \approx 0.5 - 0.6 \). Note that type-I ELMs observed in other tokamaks occurred in a wide range of collisionality, \( 0.05 \leq \nu_e^* \leq 5 \).

5. Characteristics of 2\(^{nd} \) H-mode

A typical H-mode discharge in KSTAR has the L-H transition at \( t=2-3 \) sec and the H-mode state lasts for a few seconds, then an H-L back transition takes the plasma back to the L-mode state and it continues until the plasma consumes all the available flux. However, we have observed a 2\(^{nd} \) L-H transition at a later stage of some H-mode discharges (see Fig. 8) \[8,17\]. Plasma elongation at the L-H transition time is noticeably lower (\( \kappa=1.6-1.7 \) for the late H-mode than for the main H-mode (\( \kappa=1.8-1.9 \)). For the discharges in this study, the late H-mode plasmas have densities in a substantially wider range of Greenwald fraction (\( 0.36 \leq \rho_s/\rho_g \leq 0.57 \)), while densities in the preceding main H-mode were in a narrower range (\( 0.36 \leq \rho_s/\rho_g \leq 0.42 \)). Among the plasma parameter changes, the \( T_i \) and \( V_i \) increase induced by the transition to the late H-mode is significantly lower than that for the main H-mode. The late H-mode also has different ELM characteristics from the main H-mode and we suspect this may be due to the shaping parameter change, \( i.e. \)
Figure 9. (a) ELM size vs ELM frequency plot for large ELMs in main (red) and late (blue) H-mode, and for small ELMs in late H-mode (green). Plot (b) is an enlarged version of the same plot for large ELMs in (a). Figure (c) is the $H_{98}(y,2)$ vs Greenwald fraction plot for main (red) and late (blue) H-mode phases. This is for the same discharges for (a) and (b) but the averaging time window is different.

Figure 9(c) compares $H_{98}(y,2)$ for the main H-phase to that for the late H-phase. The H-factor for the late H-mode is rather flat, $H_{98}(y,2)=0.9 – 1.1$, even with the wider range of Greenwald fraction ($0.45 \leq \phi_e/n_e \leq 0.6$) than for the main H-mode ($0.35 \leq \phi_e/n_e \leq 0.4$).

6. MHD analysis for ELMy H-mode plasmas

An ideal MHD stability analysis is being carried out by ELITE [18] code. A preliminary result of such analysis for a type-I ELMy H-mode is given in Fig.10. Here, we assume the pedestal $T_e$ profile is the same as the pedestal $T_i$ profile from the CES measurement and the core $T_e$ profiles is obtained from ECE. The $n_e$ profile is constructed by the hyperbolic tangent (tanh) fitting of the measured line average density by interferometer, based on two major assumptions as follows; 1) the profile peakness ($n_e(0)/\bar{n}_e$) of 1.3, and 2) the same pedestal position of as that of $T_e$. This enables us to estimate pressure gradient profile. On the other hand, the Ohmic current density profile is calculated by HELENA [19] and the bootstrap current in the current density profile is estimated based on the $T_i$ and density profiles with the Sauter’s model [20]. This process allows for the pressure gradient ($\alpha_{max}$) and current density ($\langle j \rangle /i_{max}$) diagram and the growth rates of toroidal mode number of 5 to 30 are calculated for the generated window by ELITE.

7. Summary

KSTAR ELMs appear to be categorized as three distinctive types: large type-I ELMs with low frequency and big ELM size with good confinement; intermediate ELMs with higher frequency and poorer confinement; mixed ELMs with large and small peaks with good confinement. Preliminary power scan data showed that the frequency of large ELM peaks for the type-I and mixed ELM regimes has a positive dependence on the heating power, a typical feature of type-I ELMs. The ELM size of intermediate ELMs is not correlated with either the lower $\kappa$ and higher $\delta$. Figure 9(a) and 9(b) show the plots of ELM size versus frequency for all three categories of ELM described above. The first thing to note is that the size of large ELMs for the main H-mode decreases with increasing ELM frequency but those for the late H-mode show larger scatter. On the other hand, small ELMs for the late H-mode reveal no correlation between the size and frequency. The confinement quality of late H-mode is as good as or above that of the main H-mode. Figure 9(c) compares $H_{98}(y,2)$ for the main H-phase to that for the late H-phase. The H-factor for the late H-mode is rather flat, $H_{98}(y,2)=0.9 – 1.1$, even with the wider range of Greenwald fraction ($0.45 \leq \phi_e/n_e \leq 0.6$).
ELM frequency or the Greenwald fraction, while it inversely depends on both quantities for type-I ELMs. We suspect the intermediate ELMs might be type-III because of their size and frequency characteristics distinctive from type-I ELMs and the poorer confinement quality. Mirnov signal shows an increased fluctuation level in the low frequency band (25-50 kHz) along with 300 – 400 Hz of oscillation during the inter-ELM period for type-I ELMy H-mode, while there is no precursor signal for the intermediate and mixed ELMs. Profile measurement during an ELM cycle indicates that the $T_i$ pedestal only jumps at the last stage (after 70-80 % of the ELM cycle) whereas the $T_e$ and $V_t$ pedestal steadily rises over the entire ELM cycle. This suggests that the ion component of the pressure might be more responsible for the ELM destabilization in KSTAR. The cause of late L-H transition is thought to be the restoration of plasma shaping, *i.e.* divertor configuration, and the detachment of inner separatrix from the wall. Only the mixed ELM regime appears during the late H-mode stage and the change in shaping parameters, *i.e.* lower $\kappa$ and higher $\delta$ than for the main H-mode, appears to be related to the change of ELM characteristics. Small ELMs between large ELM peaks in the mixed ELM regime have very different characteristics, *i.e.* tiny ELM size and no size dependence on the ELM frequency. In addition, a preliminary work of ideal MHD stability analysis for a type-I ELMy H-mode was done and the work was under way to investigate unstable domains for the ELM occurrence, as well as its sensitivity to a range of estimated/measured profiles. This work was supported by Korea Ministry of Education, Science, and Technology and the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

References


