Study on divertor particle and heat fluxes from electric probe measurements during ELMy H-modes in KSTAR

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HIGHLIGHTS

• The characteristics of the particle and heat fluxes were investigated during ELMs in H-modes under the LSN configuration in the KSTAR tokamak.
• There was relation between the ELM amplitude and the ELM frequency as \( \Delta W_{\text{RTM}} / W_{\text{RTT}} \propto 1 / f_{\text{ELM}} \) in the range of \( f_{\text{ELM}} \leq 200 \text{ Hz} \).
• The trends of the peak amplitude of the divertor flux near the OSP during ELMs due to the ELM mitigation and the plasma shaping were investigated.
• The ELMs were mitigated by MP field, SMBI and ECH. The ELM mitigations due to the MP field and the SMBI were stronger than one due to the ECH.
• Finally, the particle flux, evaluated at the far scrape-off layer (SOL) region, was estimated to less than 1% of the divertor particle flux.

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ABSTRACT

The characteristics of the divertor particle and heat fluxes were investigated during ELM bursts in ELMy H-mode plasmas with the lower single null (LSN) configuration in Korea Superconducting Tokamak Advanced Research (KSTAR). The particle and heat fluxes are evaluated from the electric probe measurements at the divertor region. It is found that the peak amplitude of the divertor flux during an ELM burst obtained near the outer strike point (OSP) decreases up to about 20% as the ELM frequency increases by a factor of \( \sim 6.5 \) due to the ELM mitigation and the plasma shaping, which is similar to the trend of the amplitude versus the frequency of the ELM observed in other tokamaks. The ELMs are mitigated by using several methods as magnetic perturbation (MP field), supersonic molecular beam injection (SMBI) and electron cyclotron heating (ECH) at the edge region. In addition, the particle flux, evaluated at the far scrape-off layer (SOL) region, is less than 1% of the divertor particle flux. In this work, results from the experimental investigations of particle and heat fluxes during ELM bursts from the electric probe measurements at the divertor and far SOL regions are presented.

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1. Introduction

The edge localized modes (ELMs) in H-mode discharges increase the scrape-off layer (SOL) plasma and produce burst-like particle fluxes on the divertor targets which are about ten times larger than the stationary particle flux between ELMs [1]. The large transient divertor heat pulses due to the ELMs (especially, type-1 giant ELMs) would be potentially an impact on the divertor design of the next-step high power tokamak such as ITER because the maximum power load on the divertor target, as a critical design parameter in the ITER, should be less than 10 MW m\(^{-2}\) [2] due to the thermal engineering limitation in the material. The activities on the ELM control have been carried out for reducing the divertor heat flux due to the ELM in several tokamaks such as experiments for investigating effect of plasma shaping on the ELM behavior [1,3] and for ELM mitigations by using methods as magnetic perturbation (MP) field [1,4], supersonic molecular beam injection (SMBI) [5] and electron cyclotron heating (ECH) [1,6] at the edge region.

Fig. 1 shows electric probe diagnostics (EPDs) [7] for the evaluation of heat and particle fluxes at the divertor and far SOL region in the Korea Superconducting Tokamak Advanced Research (KSTAR). The EPDs consists of a fixed edge Langmuir probe array (ELPA) with 40 single probes and 2 triple probes at the lower divertor region (called as DPs). There is another ELPA with 8 probes at the poloidal limiter (called as PLPs). The divertor particle fluxes were evaluated from the DP measurements for the estimate of heat flux on the divertor by using an electron temperature measured with a fast reciprocating Langmuir probe assembly (FRLPA) [7] at the outboard mid-plane, as the SOL region, in the KSTAR tokamak. From the experimental campaign of 2014, the electron temperatures near an
outer strike point and far SOL region, obtained from the triple probe measurements at lower outboard divertor, were able to be used for evaluating the divertor heat flux.

The PLPs were used to measure particle and heat fluxes at the far SOL region for study on the heat load on the outboard wall in the KSTAR. After the H-mode plasmas were routinely produced in the KSTAR tokamak, the investigations of divertor heat flux are needed to evaluate the power load on the divertor target in ELMy H-mode discharges because the heating power has been gradually increased for high plasma performance in the KSTAR tokamak. Thus, the initial investigation of the particle and heat fluxes at the divertor and far SOL regions was carried out from the DP and PLP measurements during ELMy H-mode plasmas. In this paper, preliminary results from the experimental investigations of divertor particle and heat fluxes in ELMy H-mode discharges are presented in Sec. 2, and the comparison between divertor and main wall fluxes is given in Sec. 3. Finally, the summary is described in Sec. 4.

2. Divertor particle and heat fluxes during ELM bursts

2.1. Characteristics of ELM

In ELMy H-modes, it was found that there was the correlation between the ELM amplitude and frequency as reported in other tokamaks [1]. The ELM amplitude, which is defined as the energy drop during an ELM burst normalized to the stored energy $\Delta W_{\text{ELM}}/W_{\text{TOT}}$, decreases up to about 20% as the ELM frequency $f_{\text{ELM}}$ increases by a factor of $\sim 6.5$ within ranges of plasma parameters as shown in Fig. 2. Mostly, the trends of $\Delta W_{\text{ELM}}/W_{\text{TOT}} \propto 1/f_{\text{ELM}}$ can be observed for the range of $f_{\text{ELM}} \leq 200$ Hz as type I ELM.

The particle fluxes were evaluated by using the relation of $I_{\text{div}} = I_{\text{sat}}/(eS)$ from ion saturation current $I_{\text{sat}}$ measured with the DPs at the outer divertor region in ELMy H-mode discharges under the lower single null (LSN) configuration. Where $S$ is an effective area of each divertor probe, and $\alpha$ is the angle between the magnetic field and the divertor target surface. The value of $\alpha$ was assumed as $5^\circ$. Heat flux can be obtained from $q_{\text{div}} = \gamma kT_e \Gamma_{\text{div}}$ where $kT_e$ and $\gamma$ are electron temperature and sheath heat transmission coefficient at divertor region, respectively. The averaged value of $\gamma$ was theoretically predicted as $\sim 7$ from various models for case of $kT_e \sim kT_i$ [8]. The experimental values of $\gamma$ were reported as 2–20 in ASDEX-U [9,10], DIII-D [9,11], Tore-Supra [12], TCV [13], JET [14], JT-60U [9,15], and TEXT [17]. Here,
we assumed as \( \gamma = 7 \) in the evaluation of the heat flux with some uncertainty.

The peak amplitudes of the divertor fluxes \( q_\text{div,peak} \) and \( f_\text{div,peak} \) near an outer strike point (OSP) during the ELM bursts increase up to about 20\% as the magnitude of \( f_{\text{ELM}} \) increases by a factor of \( \sim 6.5 \) as shown in Fig. 3. The inverse proportion between the divertor fluxes and ELM frequency was clearly observed in case that \( f_{\text{ELM}} \) was less than 200 Hz, which was quite similar with the trend of \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \) versus \( f_{\text{ELM}} \). The experimental investigations of the inverse proportion between the divertor fluxes and ELM frequency due to plasma shaping and the ELM mitigation were presented in the following subsections. Here, the neutral beam (NB) was a major heating for achieving H-modes, and its power \( P_{\text{NB}} \) was 2.4–4.3 MW. Plasma density \( n_p \) was 0.7–8.0 \( \times 10^{19} \) m\(^{-3} \). The ELM frequency was obtained from the search method of local maximums in the smoothed \( \Delta \xi \) signal (smoothing with 10 points).

### 2.2. Effect of plasma shape and current on magnitude of peaked divertor flux

The plasma elongation \( \kappa \), as one of plasma shaping parameters, increases from 1.81 to 1.92 in the time range of 2.0–3.0 s (\( I_p = 0.63 \) MA, \( B_T = 2.0 \) T), and the safety factor \( q_{95} \) also becomes higher as from 4.96 to 5.76 as shown in Fig. 4.

It is found that \( f_{\text{ELM}} \) increases from 32 ± 8 Hz to 62 ± 20 Hz and the peaked value of divertor particle flux near the OSP during ELMs \( f_{\text{div,peak}} \) decreases from 0.20 ± 0.02 \( \times 10^{23} \) m\(^{-2} \) s\(^{-1} \) to 0.12 ± 0.03 \( \times 10^{23} \) m\(^{-2} \) s\(^{-1} \) due to the increase of \( \kappa \). The energy drop due to the ELM normalized to the stored energy \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \) decreases from 5.3 ± 0.6\% to 3.1 ± 0.7\% while the stored energy \( W_{\text{TOT}} \) is nearly constant as \( \sim 0.26 \) MJ. The behavior is similar to the experimental result reported in the DIII-D [3].

### 2.3. Effect of magnetic perturbation at the edge on magnitude of peaked divertor flux

The ELM is mitigated when the MP field with a step waveform (with \( n = 1 \) and 90° phasing) is applied to the plasma edge region in the time range of 3.0–5.0 s (\( I_p = 0.5 \) MA, \( B_T = 2.0 \) T) as shown in Fig. 6. The MP field was produced by all of resonant magnetic perturbation (RMP) coils (top, middle and bottom) [18]. It is found that \( f_{\text{ELM}} \) rises from 57 ± 34 Hz to 90 ± 18 Hz and the peaked value of divertor heat flux near the OSP during ELMs \( q_{\text{div,peak}} \) decreases from 7.9 ± 4.1 MWm\(^{-2} \) to 3.3 ± 1.5 MWm\(^{-2} \) due to the MP field. The value of \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \) is reduced from 5.4 ± 1.6\% to 4.8 ± 1.0\%. In addition, \( W_{\text{TOT}} \) decreases from 0.32 ± 0.01 MJ to 0.22 ± 0.01 MJ and there is the density pump-out (from \( \sim 2 \times 10^{19} \) m\(^{-3} \) to \( \sim 0.6 \times 10^{19} \) m\(^{-3} \) in the phase of the ELM mitigation due to the MP field. When the MP field is turned off, the values of three parameters are recovered again such as \( \Delta W_{\text{ELM}}/W_{\text{TOT}} = 6.3 \pm 1.8\% \), \( f_{\text{ELM}} = 50 \pm 36 \) Hz and \( q_{\text{div,peak}} = 5.8 \pm 2.7 \) MWm\(^{-2} \). Here, the values of \( \kappa \) and \( q_{95} \) were
Fig. 5. Time evolution of plasma parameters as increasing plasma current: plasma current, plasma density, stored energy, Dxa,  and divertor particle flux near the OSP (from top to bottom).

1.70–1.95 and 6.35–7.30, respectively. For \( n = 1 \) MP field, the similar trend was also observed when only middle RMP coil was activated.

The magnitude of the ELM is enlarged and \( f_{\text{ELM}} \) decreases when the MP field (with \( n = 2 \) and 0° phasing) is applied to the plasma edge region in the time range of 4.0–6.0 s (\( I_p = 0.5 \) MA, \( B_T = 1.9 \) T) as shown in Fig. 7.

The MP field was produced by all of RMP coils. It is found that \( f_{\text{ELM}} \) slightly decreases from 53 ± 22 Hz to 52 ± 17 Hz and \( q_{\text{div,peak}} \) increases from 3.0 ± 1.1 MWm\(^{-2}\) to 4.3 ± 2.1 MWm\(^{-2}\) due to the MP field. The value of \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \) is slightly reduced from 5.7 ± 1.9% to 5.2 ± 1.1%. In addition, \( W_{\text{TOT}} \) slightly increases from \( -0.23 \) MJ to \( -0.26 \) MJ, but there is the density pump-out (from \( \sim 2.6 \times 10^{19} \text{ m}^{-3} \) to \( \sim 1.8 \times 10^{19} \text{ m}^{-3} \)) in the phase of the MP field. When the MP field is turned off, the values of three parameters were slightly recovered again such as \( \Delta W_{\text{ELM}}/W_{\text{TOT}} = 5.3 \pm 0.8% \), \( f_{\text{ELM}} = 60 \pm 11 \) Hz and \( q_{\text{div,peak}} = 4.0 \pm 2.1 \) MWm\(^{-2}\). Here, both values of \( \kappa \) and \( q_{\text{BS}} \) decrease from \( -1.9 \) to \( -1.8 \) and from \( -6.2 \) to \( -5.5 \), respectively. This trend was almost opposite to the case of the MP field (with \( n = 1 \) and 90 phasing). Here, the dips in the \( W_{\text{TOT}} \) signal (its period of \( \sim 0.5 \) s) were due to the modulation of \( P_{\text{NB}} \) required for the special purpose in the beam diagnostics.

2.4. Effect of SMBI and gas puffing on magnitude of peaked divertor flux

The ELM is mitigated when three SMBIs (time duration: \( \sim 8 \) ms, \( \sim 2 \) ms, \( \sim 3 \) ms) are applied to the plasma edge region in the time range of 6.05–6.4 s (\( I_p = 0.4 \) MA, \( B_T = 1.9 \) T) as shown in Fig. 8. It is found that \( f_{\text{ELM}} \) rises from 80 ± 20 Hz to 188 ± 49 Hz and \( q_{\text{div,peak}} \) decreases from 2.7 ± 1.3 MWm\(^{-2}\) to 1.0 ± 0.6 MWm\(^{-2}\) after three SMBIs. The value of \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \) decreases from 5.9 ± 1.0% to 4.3 ± 0.8%, and \( W_{\text{TOT}} \) slightly decreases from \( -0.16 \) MJ to \( -0.15 \) MJ due to the SMBI. Here, both values of \( \kappa \) and \( q_{\text{BS}} \) decrease from \( -1.9 \) to \( -1.8 \) and from \( -7.8 \) to \( -6.8 \), respectively. The similar characteristic during the ELM mitigation due to the SMBI was experimentally observed in the recent work [19].

In addition, the ELM is mitigated and \( f_{\text{ELM}} \) becomes faster when \( D_2 \) gas was puffed to the divertor region in the time range of 7.5–9.5 s (\( I_p = 0.6 \) MA, \( B_T = 1.5 \) T) as shown in Fig. 9. It is found that \( f_{\text{ELM}} \) rises from 33 ± 14 Hz to 283 ± 83 Hz and \( q_{\text{div,peak}} \) decreases from 6.9 ± 3.2 MWm\(^{-2}\) to 0.3 ± 0.2 MWm\(^{-2}\) due to the gas-puff. The value of \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \) decreases from 5.4 ± 1.6% to 1.8 ± 0.4% and \( W_{\text{TOT}} \) also decreases from 0.34 ± 0.01 MJ to ~0.28 MJ. Here, the values of \( \kappa \) decreased from \( -1.9 \) to \( -1.8 \) and \( q_{\text{BS}} \) was 4.0–4.3.

2.5. Effect of ECH on magnitude of peaked divertor flux

The ELM is mitigated and \( f_{\text{ELM}} \) increases by the application of the ECH (\( @ 170 \) GHz, \( P_{\text{ECH}} = -0.8 \) MW) as shown in Fig. 10. The ECH is applied from 6.5 s during a plasma discharge (\( I_p = 0.5 \) MA, \( B_T = 2.4 \) T). It is found that \( f_{\text{ELM}} \) becomes from 80 ± 24 Hz to 110 ± 19 Hz and \( q_{\text{div,peak}} \) slightly decreases from 4.3 ± 1.5 MWm\(^{-2}\) to 3.7 ± 1.5 MWm\(^{-2}\) due to the ECH. The value of \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \) slightly decreases from 6.3 ± 0.9% to 5.7 ± 0.9% and \( W_{\text{TOT}} \) increases from –0.21 MJ to –0.22 MJ. Here, the values of \( \kappa \) and \( q_{\text{BS}} \) were –1.8 and –7.0, respectively. It was thought that the ELM mitigation was weak because most of \( P_{\text{ECH}} \) might be deposited inside the plasma...
edge. It was reported that the ELM mitigation was clearly observed as the ECH beam was moved towards the plasma separatrix in the TCV [6].

3. Comparison between divertor and main wall fluxes

The ELM was mitigated when the MP field (with \( n = 2 \) and 90° phasing) produced by all RMP coils is applied to the plasma edge region (\( I_p = 0.68 \text{ MA}, B_T = 1.8 \text{ T} \)). The peaked value of particle flux at the far SOL during an ELM burst \( I_{\text{OMP,peak}}^{\text{ELM}} \) was compared with \( I_{\text{div,peak}}^{\text{ELM}} \) during an ELMy H-mode plasma with the ELM mitigation due to the MP field. The value of \( f_{\text{ELM}} \) increases from 18 ± 9 Hz to 147 ± 36 Hz due to the ELM mitigation as shown in Fig. 11. \( I_{\text{OMP,peak}}^{\text{ELM}} \) and \( I_{\text{div,peak}}^{\text{ELM}} \) decrease from 0.98 ± 0.99 × 10^{21} \text{ m}^{-2} \text{ s}^{-1} to 0.10 ± 0.03 × 10^{21} \text{ m}^{-2} \text{ s}^{-1} and from 0.96 ± 0.14 × 10^{22} \text{ m}^{-2} \text{ s}^{-1} to 0.54 ± 0.08 × 10^{21} \text{ m}^{-2} \text{ s}^{-1}, respectively. In addition, the peaked value of heat flux at the far SOL during an ELM burst \( q_{\text{OMP,peak}}^{\text{ELM}} \) decreases from 18.4 ± 24.6 kW m\(^{-2}\) to 1.0 ± 0.3 kW m\(^{-2}\). From comparison between particle fluxes at divertor and far SOL regions, it is found that \( I_{\text{OMP,peak}}^{\text{ELM}} \) is less than 1% of \( I_{\text{div,peak}}^{\text{ELM}} \).

Thus, it can be estimated that the particle flux toward to the main wall is less than 1% of divertor particle flux during ELMs under some experimental conditions. Here, \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \) decreased from 7.0 ± 3.6% to 2.0 ± 0.3%, and \( W_{\text{TOT}} \) also decreased from ~0.37 MJ to ~0.26 MJ. The values of \( \kappa \) and \( q_{\text{SS}} \) decreased from 1.86 to 1.76 and from 4.3 to 3.7, respectively.

4. Summary

There was relation between the ELM amplitude and the ELM frequency as \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \propto 1/f_{\text{ELM}} \), and \( \Delta W_{\text{ELM}}/W_{\text{TOT}} \) decreased up to ~20% as the ELM frequency \( f_{\text{ELM}} \) increases by a factor of ~6.5 in the range of \( f_{\text{ELM}} \leq 200 \text{ Hz} \). From the experimental investigation of the divertor particle and heat fluxes during ELM bursts due to the plasma shaping and the ELM mitigations in the KSTAR tokamak, it was found that the peak amplitude of particle flux near the OSP \( I_{\text{div,peak}}^{\text{ELM}} \) decreased up to 60% when the plasma elongation \( \kappa \), a factor of the plasma shaping, increased from 1.81 to 1.92. Similar trends of the peak amplitude of divertor fluxes during an ELM phase were also observed in the ELM mitigations due to the MP field, the SMBI, and the ECH as following: the peak amplitude decreased up to about 37–86% as \( f_{\text{ELM}} \) increased by a factor of 1.4–2.4. The trend was more clearly shown in the ELM mitigation due to the MP field and the SMBI, comparing with the cases of the ECH. For the ELM mitigation due to the D\(_2\) gas puff, the peak amplitude of heat flux near the OSP \( q_{\text{div,peak}}^{\text{ELM}} \) was decreased up to about 4.3% as \( f_{\text{ELM}} \) increased by a factor of 8.6. In addition, it was observed that \( q_{\text{div,peak}}^{\text{ELM}} \) increased up to ~130% when plasma current \( I_p \) increased from 0.8 MA to 1.0 MA. The value of \( q_{\text{div,peak}}^{\text{ELM}} \) increased up to ~143% under experimental conditions when the \( n = 2 \) MP field was applied to the plasma edge region, which was contrary to the case of the ELM mitigation due to the MP field. Finally, it could be estimated that particle flux towards the main wall was two orders of magnitude smaller than the divertor particle flux.

Further investigation of the heat flux, together with evaluating the value of \( \gamma \) from the comparison between electric probe and infra-red camera measurements, will be required to estimate how
Fig. 9. Time evolution of plasma parameters during gas puff in the divertor region: elongation, plasma density, stored energy, $D_a$ with gas puff, $f_{ELM}$ and divertor heat flux near the OSP (from top to bottom). Here, the amount of $D_2$ gas-puff is $2.68 \times 10^{21}$ D/s.

Fig. 10. Time evolution of plasma parameters during ECH inside the edge region: elongation, plasma density, stored energy, $D_a$ with ECH waveform, $f_{ELM}$ and divertor heat flux near the OSP (from top to bottom).

Fig. 11. (a) Peaked value of particle fluxes near the OSP in the lower outboard divertor, peaked value of particle and heat fluxes in far SOL versus ELM frequency before and after the ELM mitigation due to the MP field (with $n = 2$ and $90^\circ$ phasing), and (b) plasma shape reconstructed from the RTEFIT, together with PLPs for measuring far SOL plasma for shot # 9286.
much transient power will be loaded on the divertor target during
ELM burst and to understand how the power load will be able to be
reduced by using methods for the ELM mitigation. In addition, the
study of the ELM effect on the profiles of the fluxes in the divertor
and SOL regions will be also carried out to understand the edge
divertor target during particle transport during ELMs in tokamaks.

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