ELM propagation in the low- and high-field-side Scrape-off Layer of the JT-60U tokamak

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Abstract. In JT-60U, the filament structure of Edge Localized Modes (ELMs) is measured at three poloidal locations, and their temporal evolution is investigated at the inner (high magnetic-field-side, HFS) SOL as well as outer (low magnetic-field-side, LFS) SOL. At the inner SOL, filament structure with 7-8 temporal multi-peaks in ion-saturation probe signals and other diagnostics is, for the first time, measured close to the separatrix. The delay of the first peak after the start of MHD activity is faster than the characteristic time of the parallel convection from the outer midplane, and the Mach numbers of the plasma parallel flow reach ion sonic levels. These results show that ELM filaments extend from the outer to the inner plasma edge, and that a part of the filaments are ejected into the inner SOL. The toroidal mode numbers ($n$) and poloidal width of the filaments ($\delta z$) are evaluated from the interval of the multi-peaks and duration of each peak, yielding $n \sim 18-44$ and $\delta z \sim 2-6$ cm on the HFS SOL, while $n$ and $\delta z$ are comparable on the LFS SOL. After the multi-peaks appear, flow reversal of the SOL plasma toward is observed over a wide region of the inner SOL.

1. Introduction

Experimental data on edge and SOL plasma dynamics during ELMs has recently progressed by use of time-resolving diagnostics such as fast visible and infrared TV cameras, Langmuir probes and Beam-Emission-Spectroscopy [1-8]. In particular, evolution of ELM filaments has been measured, which is of great interest understanding heat and particle transport from the plasma edge to Plasma Facing Components (PFC) such as the divertor and the first wall [3, 9]. In JT-60U, time evolution of the ELM plasma has been measured with reciprocating Mach probes at different poloidal locations (i.e., outer midplane, divertor null-point, and above the inner baffle) [10, 11], and recently the sampling system was improved in order to measure the fast response of the plasma up to 500 kHz and those were synchronized with the principal fast diagnostics such as $D_\alpha$ emission and magnetic pickup coils. In this paper, the filament structure and evolution are investigated to compare the characteristics on the outer (low magnetic-field-side, LFS) and inner (high magnetic-field-side, HFS) SOLs. Especially noteworthy are measurements of filament structures and their transport at the inner SOL. Plasma parameters and diagnostics are presented in section 2. Evolution of the inner and outer SOL plasmas is presented in section 3. Filament structures at the outer and inner SOLs are discussed in sections 4 and 5, respectively. A summary is presented in section 6.
2. Experiments and diagnostics

ELM plasma propagation is investigated in Type-I ELM my H-mode discharges for the plasma current ($I_p$) of 1 MA, toroidal magnetic field ($B_t$) of 1.86 T, plasma triangularity ($\delta$) of 0.32, elongation ($\kappa$) of 1.4, safety factor at 0.95 of the minor radius ($q_{95}$) of 3.3, neutral beam power ($P_{NB}$) of 5.5 MW, averaged electron density ($n_e^a$) of 1.9 - $2.1 \times 10^{19}$ m$^{-3}$, and the plasma volume ($V_p$) of 80 m$^3$. Here, $P_{NB}$ is 1.5 times larger than the threshold power scaling necessary for L-H transition [12]. The ELM frequency is the range of 25 - 45 Hz.

Three Mach probes are simultaneously inserted into the different poloidal locations of the SOL, but their position relative to the flux surfaces at the LFS midplane are different since the insertion speed and the flux expansion of the magnetic field lines are differ at each location. 10-15 ELM events are measured at different radial positions during the inward movement of the reciprocating Mach probe (over ~ 0.5 s), and the SOL plasma conditions are not disturbed by the probe.

![Figure 1. Main diagnostics for the edge and SOL measurements. Radial viewing chords of Thomson Scattering system, poloidal array of Charge eXchange Recombination Spectroscopy are plotted. Radial resolution of toroidal CXRS is about 6 cm. Three reciprocating Mach probes measure radial profiles of ion saturation currents, electron temperature and floating potential at the outer midplane, X-point and above the inner baffle. 18 target probes are installed on the inner and outer divertor plates. Three viewing chords of the $D_\alpha$ brightness measurement for the main and divertor are shown.](image)

Figure 1 shows the plasma configuration and location of edge diagnostics such as the Thomson scattering system, charge-exchange recombination spectroscopy, and three reciprocating Mach probes. The magnetic flux surface corresponding to corresponding to 3 cm outside the separatrix at the LFS midplane ($\Delta r_{mid} = 3$ cm) is also shown, and the magnetic field lines between the HFS and LFS SOLs are connected within $\Delta r_{mid} = 8$ cm. Figure 2 shows radial profiles of ion and electron temperatures, electron density and toroidal rotation velocity at the plasma edge, which are measured between ELMs. The electron temperature, density and toroidal component of the parallel plasma flow in the SOL are measured by the Mach probes with the voltage sweep of 1 ms, and these profiles are obtained in 0.5 s. Here, data during transient period (~ 5 ms) in each ELM event are excluded, and the radial coordinate is mapping to the radius at the LFS midplane. Electron and ion temperatures, electron density and toroidal rotation velocity at the pedestal top ($T_e^{ped}$, $T_i^{ped}$, $n_e^{ped}$ and $v_i^{ped}$) are 0.8 - 0.9 keV, 1.0 - 1.2 keV, 1.4 - 1.6$x10^{19}$ m$^{-3}$ and ~ 28 km/s, respectively. Thus, the loss fraction of the pedestal stored energy, ($\Delta W_{ELM}/W_{ped}$), due to Type-I ELMs is evaluated to be 0.09 - 0.12, where $W_{ped} = (3/2)n_e^{ped}(T_e^{ped} + T_i^{ped})/V_p^{ped}$, and the plasma volume inside the pedestal ($V_p^{ped}$) is 70 m$^3$.

In the SOL, an in-out asymmetry of electron temperature is observed, while electron densities near the separatrix at the HFS and LFS SOLs are comparable. These result in a lower plasma pressure at the HFS SOL than at the LFS SOL. During the steady-state period, the plasma flow in the SOL is generally observed from the LFS SOL to the HFS divertor through the SOL opposite the X-point region (here, the top) [13]. The toroidal component of the SOL flow is evaluated as $v_i^{SOL} = M_sC_s^{SOL}(B/B_\parallel)$, where the Mach number of the SOL flow ($M_s$) is calculated from the ratio of ion...
saturation currents at the ion- and electron-sides of the Mach probe using Hutchinson’s formula [14]:

$$M_{//} = 0.4 \ln [j_{s}^{i} / j_{s}^{e}]$$

$C_{n}^{\text{SOL}}$ is the plasma sound velocity in the SOL, assuming $T_{i} = 2T_{e}$. Here, $M_{//}$ near the separatrix is relatively low (0.2 - 0.3) in the main SOL, i.e., at the LFS midplane and above the HFS baffle, and $v_{i}^{\text{SOL}} \sim 10 \text{ km/s}$ is larger than that measured just inside the separatrix ($v_{i}^{\text{edge}} \sim 3 \text{ km/s}$), but lower than $v_{i}^{\text{ped}}$. On the other hand, in the LFS divertor, a subsonic level of $M_{//} \sim 0.45$ near the divertor X-point is measured, which corresponds to $v_{i}^{\text{ped}} = -20$ to -30 km/s and is produced by reduction of the plasma pressure in the magnetic-sheath of the divertor. The direction is towards the divertor, which may cause the friction force to the edge plasma, provided that $v_{i}^{\text{edge}}$ near the X-point is similar to the measurement at the LFS edge.

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3. Fast evolution of the SOL plasma during ELM

Figure 3 shows an example of one ELM event, i.e. rapid changes in magnetic fluctuations ($B_{p}$), $j_{s}$ at the upstream (electron drift) side of the midplane probe (34 cm below the midplane) and the divertor strike-point ($j_{s}^{\text{mid}}$ and $j_{s}^{\text{div}}$, respectively), and $D_{\alpha}$ brightness viewing the main plasma and the divertors. The corresponding midplane radial locations ($\Delta r^{\text{mid}}$) for the midplane Mach probe, and the target probe are 1.0 cm and 0.2 cm, respectively. The amplitude of $B_{p}$ rapidly increases after $t = 5509.946 \text{ ms}$ as seen as a vertical line ($t_{0}^{\text{MHD}}$) and this defined as the start for the time delay for various signals. The $D_{\alpha}$ signals, both in the main plasma and divertor, generally start to increase immediately after $t_{0}^{\text{MHD}}$ as shown in figure 3 (c). The large $B_{p}$ turbulence is accompanied by plasma ejected from the edge region [11,15]. During the early period of the large $B_{p}$ turbulence (about 0.1 ms after $t_{0}^{\text{MHD}}$), large multi-peaks of $j_{s}^{\text{mid}}$ appear both at the upstream and downstream sides of the Mach probe. Characteristics of the large multi-peaks of $j_{s}^{\text{mid}}$ are investigated in the following sections. Then, the base-level of $j_{s}^{\text{mid}}$ is increased on a longer time scale ($\sim 0.5 \text{ ms}$), and the maximum base-level and the delay are presented as $j_{s}^{\text{mid}}(\text{base})$ and $\tau^{\text{mid}}(\text{base})$, respectively.
Figure 3. (a) Magnetic fluctuations at the LFS midplane, (b) \(j\) at upstream side of the midplane Mach probe for the midplane distance (\(\Delta r_{\text{mid}}\)) of 1 cm, (c) \(j\) at the LFS divertor for midplane distance of 0.2 cm, (d) \(j\) at the HFS divertor for midplane distance of 0.4 cm, (e) \(D_\alpha\) brightness viewing the main plasma and the HFS and LFS divertors. Delays of the maximum base-level of the midplane \(j\), start of the divertor \(j\) base-line increase and the first divertor \(j\) peak are represented by \(\tau_{\text{mid}}(\text{base})\), \(\tau_{\text{div}}(\text{peak})\) and \(\tau_{\text{ License}}(\text{start})\), respectively.

Figure 3(c) shows that \(j_{\text{div}}\) at the LFS strike-point starts to increase after \(t = 5510.052\) ms, i.e., after the early period of the large \(\tilde{B}_p\) turbulence, then large multi-peaks appear in \(j_{\text{div}}\). The first large \(j_{\text{div}}\) peak appears at \(t = 5510.105\) ms during the increase in the \(j_{\text{div}}\) base-level. The plasma convection time from the LFS midplane to the LFS divertor is calculated as \(\tau_{\text{div}} = L_{\text{div}} / C_{\text{ped}} = 105\) µs, where \(L_{\text{div}} = 30\) m is the connection length from the LFS midplane to the divertor and \(C_{\text{ped}}\) is the plasma sound velocity for the pedestal plasma, i.e. \(\sqrt{(T_{\text{ped}}/m)} = 2.8 \times 10^5\) m/s for \(T_{\text{ped}} = 1.2\) keV and \(T_{\text{ped}} = 1.0\) keV. Time delays of the start and the first peak in \(j_{\text{div}}\) enhancement (\(\Delta t = t - t_{\text{MHD}}\)) are comparable to and larger than \(\tau_{\text{ License}}\), respectively.

Here, \(D_\alpha\) signals at the HFS and LFS divertors increases simultaneously during the early period of the large \(\tilde{B}_p\) turbulence. At the same time, a large increase in heat flux density is measured both at the HFS and LFS strike-points (\(q_{\text{div}} \sim 150\) and 170 MW/m², respectively) with the infrared TV camera at a relatively slow frame rate of 250 µs. Figure 3(d) shows that time delays of the start and the first peak in the HFS \(j_{\text{div}}\) enhancement are comparable to \(\tau_{\text{div}}(\text{start})\) and \(\tau_{\text{div}}(\text{peak})\) at the LFS divertor. The HFS results cannot be explained by sonic convective transport of the ELM plasma from the LFS SOL to the HFS divertor; transport mechanism of the ELM filaments in the HFS SOL is discussed in section 5.

4. ELM filament propagation at LFS midplane

4.1. Time evolution of multi-peaks

Figure 4 shows the expanded time evolution of \(\tilde{B}_p\), \(D_\alpha\) brightness at the main plasma, \(j_{\text{mid}}\) at the upstream and downstream sides of the Mach probe as a function of the time delay from \(t_{\text{ MHD}}\), which is shown in figure 3. Multiple large positive peaks are observed from the two sides of the Mach probe,
which indicates that exhausted ELM filaments extend to the Mach probe location along magnetic field lines. Three peaks in the upstream $j_{s,\text{mid}}$ are observed at $\Delta t = 9, 30, 53$ $\mu$s. The second peak (5.2-5.7x10$^4$ Am$^{-2}$) is larger than the first peak (2.5x10$^5$ Am$^{-2}$), but the maximum value of the second peak is not clearly identified due to large fluctuations. Three peaks in the downstream $j_{s,\text{mid}}$ are observed at $\Delta t = 9, 28, 43$ $\mu$s simultaneously except for the third peak, which is delayed by 6 $\mu$s. Here, the first peak (6x10$^4$ Am$^{-2}$) is larger than the other peaks (3.2x10$^5$, 2.2x10$^5$ Am$^{-2}$). After appearance of the multi-peaks, the upstream and downstream $j_{s,\text{mid}}$ values reach 0.5-0.8x10$^5$ Am$^{-2}$.

Characteristics of the first $j_{s,\text{mid}}$ peak are presented in reference 16. The upstream $j_{s,\text{mid}}$ is typically larger than the downstream $j_{s,\text{mid}}$ near the separatrix. On the other hand, in the far SOL ($\Delta r_{\text{mid}} > 3$ cm), they are comparable at the outer flux surfaces. Radial propagation of the first ELM filament is investigated to quantify the fast propagation of the filaments. Here, the averaged value of the first $j_{s,\text{mid}}$ peaks at the upstream and downstream sides and the delay of the upstream $j_{s,\text{mid}}$ peak are defined as $j_{s,\text{mid}}(\text{peak})$ and $\tau_{s,\text{mid}}(\text{peak})$, respectively. In this paper, we focus on evaluation of the spatial size and toroidal mode numbers from the duration ($\Delta r_{\text{mid}}(\text{peak})$) and separation ($\tau_{s,\text{mid}}(\text{peak})$) of the multiple peaks.

4.2. Radial propagation of filament
Radial distributions of $j_{s,\text{mid}}(\text{peak})$ and $j_{s,\text{mid}}(\text{base})$ are shown in figure 5(a). These distributions are deduced from four similar ELMy H-mode discharges, and the $j_{s,\text{mid}}(\text{peak})$ profile is an envelope of $j_{s,\text{mid}}$ peaks rather than a profile appearing at one moment. Here, field lines at $\Delta r_{\text{mid}} > 13$ cm are connected to the upper LFS first wall, while those between 3.5 cm < $\Delta r_{\text{mid}} < 13$ cm are connected to the LFS baffle. Values of the first $j_{s,\text{mid}}$ peaks are varied from 1x10$^5$ to 5.5x10$^5$ A/m$^2$ near the separatrix. The enhancement factor of $j_{s,\text{mid}}(\text{peak})$ compared to the $j_{s,\text{mid}}$ base-level between ELMs, $j_{s,\text{mid}}(ss)$, is 10 - 50 over a wide SOL region. Particularly, in the outer flux surfaces ($\Delta r_{\text{mid}} > 2$ cm), enhancement of radial propagation of $j_{s,\text{mid}}(\text{peak})$ is observed; its e-folding length ($\lambda_{\text{peak, mid}}$) of 7.5 cm is 2.5 times larger than those between ELMs ($\lambda_{\text{ss, mid}} = 3.1$ cm) and of $j_{s,\text{mid}}(\text{base})$ ($\lambda_{\text{base, mid}} = 3.5$ cm).

The radial propagation velocity of $j_{s,\text{mid}}(\text{peak})$ is evaluated as the average velocity from the separatrix to the Mach probe location, i.e., $v_{\lambda,\text{mid}}(\text{peak}) = \Delta r_{\text{mid}}(\text{peak}) / \tau_{\lambda,\text{mid}}(\text{peak})$. Figures 5(b) and (c) show distributions of $\tau_{\lambda,\text{mid}}(\text{peak})$ and $v_{\lambda,\text{mid}}(\text{peak})$ as functions of $\Delta r_{\text{mid}}$. Since $\tau_{\lambda,\text{mid}}(\text{peak})$ tends to increase with $\Delta r_{\text{mid}}$ for $\Delta r_{\text{mid}} < 5$ cm, $v_{\lambda,\text{mid}}(\text{peak})$ ranges between 0.4 and 1.5 km/s. The characteristic length of
the ELM radial propagation, $L_{⊥}^{ELM}$, is defined as the radial distance, where the first $j_{⊥}^{mid}$ peak moves during the parallel convection transport time to the divertor, i.e., $v_{⊥}^{mid}(peak) \cdot \tau_{⊥}^{SOL-LFS}$, resulting in $L_{⊥}^{ELM} = 4 \text{ - } 15 \text{ cm}$. It is found that the fast-radial-velocity ELM filaments reach the LFS baffle and the first wall. For $\Delta r^{mid} > 5 \text{ cm}$, $\tau_{⊥}^{mid}(peak)$ ranges between $40 \text{ - } 90 \mu s$, indicating a large $v_{⊥}^{mid}(peak)$ of $1.5 \text{ - } 2.9 \text{ km/s}$. As a result, $v_{⊥}^{mid}(peak)$ for the first $j_{⊥}^{mid}$ peak tends to increase with $\Delta r^{mid}$.

![Figure 5](image)

**Figure 5.** Radial distributions of the first $j_{⊥}^{mid}$ peaks (large circles), maximum base-level of $j_{⊥}^{mid}$ during ELM (squares), and $j_{⊥}^{mid}$ between ELMs (small circles). Representative e-folding lengths are shown for three distributions. Radial distributions of (b) time delay of the first $j_{⊥}^{mid}$ peak, $\tau_{⊥}^{mid}(peak)$, (c) averaged propagation velocity, $v_{⊥}^{mid}(peak)$.

![Figure 6](image)

**Figure 6.** Radial distributions of (a) peak to peak separation, $\tau_{p-p}^{mid}$, (b) peak duration, $\delta t_{pk}^{mid}$, for the first to forth $j_{⊥}^{mid}$ peaks for 20 ELM events. (c) Probability distributions of $\tau_{p-p}^{mid}$ and $\delta t_{pk}^{mid}$.
4.3. Evaluation of LFS filament structure

Filament size and mode numbers are investigated from the database of \( \nu_{\perp}^{\text{mid}}(\text{peak}) \), the \( j_{\perp}^{\text{mid}} \) peak duration \( (\delta t_{\text{pk}}^{\text{mid}}) \) and separation of the multi-peaks \( (\tau_{p-p}^{\text{mid}}) \). Values of \( \delta t_{\text{pk}}^{\text{mid}} \) and \( \tau_{p-p}^{\text{mid}} \) are defined as the full width of the peak and as the separation time between the beginning of adjacent peaks in the time evolution of \( j_{\perp}^{\text{mid}} \), respectively. For the three \( j_{\perp}^{\text{mid}} \) peaks in figure 4 (b), \( \delta t_{\text{pk}}^{\text{mid}} = 10, 23 \text{ and } 18 \mu s \) and \( \tau_{p-p}^{\text{mid}} = 12 \text{ and } 25 \mu s \). Radial profiles of \( \tau_{p-p}^{\text{mid}} \) and \( \delta t_{\text{pk}}^{\text{mid}} \) and their probability distributions are shown in figure 6, using the database from the first to the fourth \( j_{\perp}^{\text{mid}}(\text{peak}) \) in 20 ELM events from two similar ELMy H-mode discharges. It is found that average values of \( \tau_{p-p}^{\text{mid}} \) and \( \delta t_{\text{pk}}^{\text{mid}} \) are 31 \mu s \text{ and } 21 \mu s, \text{ and } 72\% \text{ of } \tau_{p-p}^{\text{mid}} \text{ and } 70\% \text{ of } \delta t_{\text{pk}}^{\text{mid}} \text{ are in a range of } 20 - 50 \mu s \text{ and } 10 - 25 \mu s \text{, respectively.}

The ELM plasma filaments extend large distances along the magnetic field lines in SOL, \text{ and they are observed to move in the radial and toroidal directions. First, values of } \delta t_{\text{pk}}^{\text{mid}} \text{ are closely related to the structure and dynamics of the plasma filament. Radial and poloidal scales of the plasma filament can be evaluated from the measurements of the radial and toroidal velocities, respectively. The radial scale of the plasma filament is evaluated as } \delta r_{\text{pk}}^{\text{mid}} = \delta r_{\text{pk}}^{\text{mid}} \nu_{\perp}^{\text{mid}} \text{, provided that the plasma filaments cross the Mach probe in the radial direction perpendicular to the field lines with the radial distribution of } \nu_{\perp}^{\text{mid}}(\text{peak}) \text{ as shown in figure 4. Figure 5 (c) suggests that radial scale of } \delta r_{\text{pk}}^{\text{mid}} \text{ increases since } \nu_{\perp}^{\text{mid}}(\text{peak}) \text{ increases with radius, and } \delta r_{\text{pk}}^{\text{mid}} \text{ increases from } 0.5 - 4 \text{ cm near separatrix } (\Delta r^{\text{mid}} < 5 \text{ cm}) \text{ to } 1 - 8 \text{ cm in the far SOL.}

On the other hand, the poloidal scale of the plasma filament is evaluated as \( \delta \alpha_{\text{pk}}^{\text{mid}} = \delta \alpha_{\text{pk}}^{\text{mid}} \nu_{\perp}^{\text{mid}}, \text{ tan}(\alpha) \), provided that the plasma filaments extending along the magnetic field line pitch angle of } \alpha \text{ move in the toroidal direction with the rotation velocity at the pedestal } (\nu_{\perp}^{\text{ped}}) \text{ and they cross the Mach probe [17]. Here, the poloidal rotation velocity of the pedestal top is also measured (4 - 8 km/s in the electron diamagnetic direction) and the corresponding rotation frequency (~ 0.8 kHz) is small (about a half of the toroidal one), thus the effect of the poloidal velocity is not considered. From the experimental parameters of } \nu_{\perp}^{\text{ped}} \sim 28 \text{ km/s as shown in figure 2 and } \alpha = 8^\circ \text{, one finds } \delta \alpha_{\text{pk}}^{\text{mid}} = 2 - 5 \text{ cm for } \delta \alpha_{\text{pk}}^{\text{mid}} = 10 - 25 \mu s \text{. The toroidal mode numbers } (n) \text{ are deduced from } \tau_{p-p}^{\text{mid}} = 20 - 50 \mu s \text{ as shown in figure 6 (a) and (c) as } n = 2\pi R^{\text{FS}} / (\nu_{\perp}^{\text{ped}} \cdot \tau_{p-p}^{\text{mid}}) \text{, where the major radii at the LFS Mach probe } (R^{\text{FS}}) \text{ is } 4.3 \text{ m, resulting in } n = 18 - 44 \text{. These values of } n \text{ are too large compared to those found in other experiments } (n = 10 - 20) [18] \text{, which are consistent with peeling-balloonning model.}

5. ELM filament propagation at HFS SOL

5.1. Time evolution of multi-peaks

Effects of plasma drifts and fast SOL flow on the divertor plasma and impurity transport have been recently studied in many tokamaks [13,19-22]. Plasma transport in the HFS SOL plays an important role on particle control and impurity transport in the L-mode plasma. Influence of the transient plasma transport produced by the ELM is also of great interest. Thus, filament structure and the dynamics in the HFS SOL are presented here using the fast measurement from the Mach probe.

Figure 7 shows the time evolution of } D_\alpha \text{ brightness at the HFS and LFS divertors, } \tilde{B}_p, \text{ and } j_{\perp} \text{ at the upstream and downstream sides of the HFS Mach probe } (j_{\perp}^{\text{HFS-up}} \text{ and } j_{\perp}^{\text{HFS-down}}) \text{ and } j_{\perp} \text{ at the HFS strike point } (j_{\perp}^{\text{HFS}}) \text{ during an ELM event, which is different time as shown in figure 3. The local distance from the separatrix to the Mach probe is } 1.1 \text{ cm, which corresponds to just outside of the separatrix when mapped along the flux surface to the LFS midplane } (\Delta r^{\text{mid}} = 0.3 \text{ cm}). \text{ It is found that multi-peaks appear only in } j_{\perp}^{\text{HFS-up}} \text{ with the delay of } 53 \mu s \text{ after } t_{\alpha}^{\text{MHD}}. \text{ The large peak observed on the LFS is not seen in } j_{\perp}^{\text{HFS-down}} \text{, although } j_{\perp}^{\text{HFS-down}} \text{ does increase after } \Delta t = 53 \mu s \text{. During the } j_{\perp}^{\text{HFS}} \text{ increase, } j_{\perp} \text{ at the HFS strike-point } (j_{\perp}^{\text{HFS-HFS}}) \text{ also increases but again a large peak is not observed.}
Figure 7. Time evolutions of (a) $D_{\alpha}$ brightness in the LFS and HFS divertors, (b) magnetic fluctuations, $\tilde{B}_p$, (c) ion saturation currents, $j_s$, at the up-stream and down-stream sides of the HFS Mach probe ($\Delta r_{\text{mid}} = 0.3$ cm), (e) $j_s$ at the HFS divertor strike-point ($\Delta r_{\text{mid}} = 0.3$ cm), as a function of delay from the start of large $\tilde{B}_p$ turbulence.

Figure 8. Enlarged time evolutions of (a) $D_{\alpha}$ brightness in the main plasma and the HFS divertor, (b) $j_s^{\text{HFS}}$ at upstream and downstream sides of the HFS Mach probe as shown in figure 7. Delay of the first $j_s^{\text{HFS}}$ peak, separation and duration of three peaks are shown by $\tau_{\text{HFS}}^{(\text{peak})}$, $\tau_{p-p}^{\text{HFS}}$ and $\delta t_{pk}^{\text{HFS}}$.

Figure 8 shows an expanded time evolution of the $D_{\alpha}$ brightness at the main plasma and HFS divertor, $j_s^{\text{HFS-up}}$ and $j_s^{\text{HFS-down}}$, which were shown in figure 7. During the early period of the $j_s^{\text{HFS}}$ increase $(\Delta t = 50 - 250 \mu s)$, about seven large peaks appear in $j_s^{\text{HFS-up}}$ at $\Delta t = 66, 110, 130, 148, 180, 202$ and $242 \mu s$. The peak duration ($\delta t_{pk}^{\text{HFS}}$) is between 10 and 22 $\mu s$, which is comparable to those measured at the LFS midplane. The separation of the maxima ($\tau_{p-p}^{\text{HFS}}$) is between 25 and 55 $\mu s$, which is larger than that at the LFS midplane. The peak values of $j_s^{\text{HFS-up}} (j_s^{\text{HFS-up}(\text{peak})})$ are between $5.6 \times 10^5$ and $9.8 \times 10^5$ Am$^{-2}$, and they are significantly larger than $j_s^{\text{HFS-down}} (\sim 1.2 \times 10^5$ Am$^{-2}$). Large enhancement in $j_s^{\text{HFS-up}}$ shows that the fast parallel plasma flow towards the HFS divertor is associated with the filaments, and the corresponding Mach number reaches close to the sonic level (0.7 to 1). Delays of the first to forth $j_s^{\text{HFS-up}}$ peaks $(\Delta t = 68 - 145 \mu s)$ measured are smaller than the characteristic time of the convective transport from the LFS midplane to the HFS Mach probe, i.e., $\tau_{LFS-HFS} = L_{LFS-HFS}/C_{\text{s ped}} = 186 \mu s$, where the distance from the LFS midplane to the HFS Mach probe along the field line, $L_{LFS-HFS}$ is 55 m. On
the other hand, the delay of the first peak is only slightly larger than the characteristic convection time from the HFS midplane to the HFS Mach probe: $\tau_{HFS-HFS} = L_{HFS-HFS}/C_{ped} = 46 \mu s$ ($L_{HFS-HFS} = 12$ m). Thus, provided that ELM filaments extend to the HFS edge region along the field lines, and they are ejected into the SOL, those short delays can be explained as convection from the HFS midplane to the probe.

5.2. Radial distribution of HFS filaments

Figure 9 (a) shows the radial distributions of the large $j_{HFS}^{\text{up}}$ peaks ($j_{HFS}^{\text{peak}}$), the maximum base-level after appearance of the large peaks ($j_{HFS}^{\text{base}}$) and $j_{HFS}^{\text{up}}$ between ELMs ($j_{HFS}^{\text{ss}}$) as functions of the LFS midplane radius. Enhancement factors of $j_{HFS}^{\text{peak}}$ are 20 - 50, which are comparable to those at the LFS midplane (10 - 50). Very large enhancement (30 - 50) of $j_{HFS}^{\text{peak}}$ is often observed near the separatrix ($\Delta r_{mid} < 0.6$ cm). On the other hand, in the outer flux surfaces, such large $j_{HFS}^{\text{peak}}$ values are not observed and e-folding length of $j_{HFS}^{\text{peak}}$ mapping to the LFS midplane is $\lambda_{peak}^{HFS} = 3.2$ cm, which is about a half that at the LFS midplane ($\lambda_{peak}^{mid} = 7.5$ cm).

![Figure 9. Radial distributions of (a) $j_{HFS}^{\text{peak}}$ peaks (red circles), maximum base-level (squares) during ELMs, and $j_{HFS}^{\text{up}}$ between ELMs (blue circles) measured at upstream-side of the HFS Mach probe, (b) Mach numbers corresponding to $j_{HFS}^{\text{peak}}$, $j_{HFS}^{\text{base}}$, $j_{HFS}^{\text{ss}}$, (c) delay of the $j_{HFS}^{\text{peak}}$ peaks. All profiles are mapped to the LFS midplane radius. Parallel transport times from LFS midplane to the HFS probe, and from HFS midplane to the HFS probe are shown.]

The Mach numbers for $j_{HFS}^{\text{peak}}$, $j_{HFS}^{\text{base}}$ and $j_{HFS}^{\text{ss}}$ are shown in figure 9 (b): $M_{HFS}^{\text{peak}}$, $M_{HFS}^{\text{base}}$ and $M_{HFS}^{\text{ss}}$, respectively. $M_{HFS}^{\text{peak}}$ increases from 0.2 - 0.3 away from the separatrix to near unity as close to the separatrix, i.e., a sonic level of the fast SOL flow is observed near the separatrix ($\Delta r_{mid} < 0.8$ cm). The delay of $j_{HFS}^{\text{peak}}$, i.e., $\tau_{HFS}^{\text{peak}}$, is plotted in figure 9 (c). Characteristic times of the convective transport from the LFS midplane, i.e., $\tau_{\text{conv}}^{\text{LFS}}$, and from the HFS midplane, i.e., $\tau_{\text{conv}}^{\text{HFS}}$, are also shown assuming a constant $C_{ped}$ of $2.9 \times 10^5$ m/s, using $M_{HFS}^{\text{peak}}$ data shown in figure 9 (b) and connection length varying with the radial position of the HFS probe. $\tau_{HFS}^{\text{peak}}$ is comparable or larger than $\tau_{\text{conv}}^{\text{HFS}}$, except in the far SOL ($\Delta r_{mid} > 2$ cm). These facts suggest that the ELM filaments are ejected into the HFS SOL during the early period of ELM, and that the radial extent of the filament is mostly limited to flux surfaces in the narrow region with $\Delta r_{mid} < 1$ cm.
It is also found that the flow reversal of the SOL plasma occurs over a wide SOL region ($\Delta r_{\text{mid}} < 4$ cm) after the appearance of the multi-peaks. As a result, the plasma and impurity transport at the HFS SOL and divertor is influenced by two transient convective fluxes during the ELM event: one is the large, short convective flow from the upstream SOL, and another is the flow reversal over a wide SOL region, both of which can play an important role in deposition profiles of impurities.

5.3. Evaluation of LFS filament structure
Filament size and mode number are investigated from the database of the $j_s^{\text{HFS-up}}$ peak duration ($\Delta t_{\text{pk}}^{\text{HFS}}$) and separation of the multi-peaks ($\tau_{\text{p-p}}^{\text{HFS}}$). Figure 10 (a) shows the radial distributions of $\tau_{\text{p-p}}^{\text{HFS}}$ and $\Delta t_{\text{pk}}^{\text{HFS}}$ for the $j_s^{\text{HFS-up}}$ peaks as a function of corresponding LFS midplane radius, $\Delta r_{\text{mid}}$. Values of $\Delta t_{\text{pk}}^{\text{HFS}}$ are independent of $\Delta r_{\text{mid}}$. Multi-filaments at the HFS appear near the separatrix, where the radial distance is less than 3 cm corresponding the LFS midplane flux surfaces of $\Delta r_{\text{mid}} < 1$ cm. In section 4.3, the radial scale of the filament near the LFS separatrix ($\Delta t_{\text{pk}}^{\text{HFS}}$) is 0.5-4 cm, so relative small radial size of filaments may appear at the HFS SOL.

Next, $\tau_{\text{p-p}}^{\text{HFS}}$ can be determined near the separatrix and scattered between 18 and 64 $\mu$s. Probability distributions of $\Delta t_{\text{pk}}^{\text{HFS}}$ and $\tau_{\text{p-p}}^{\text{HFS}}$ are shown in figure 10 (b), and 76% of $\Delta t_{\text{pk}}^{\text{HFS}}$ and 81% of $\tau_{\text{p-p}}^{\text{HFS}}$ are in a range of 10 - 30 $\mu$s and 20 - 50 $\mu$s, respectively. Average values are $\Delta t_{\text{pk}}^{\text{HFS}} = 24$ $\mu$s and $\tau_{\text{p-p}}^{\text{HFS}} = 38$ $\mu$s, which are slightly larger than those for the LFS midplane ($\Delta t_{\text{pk}}^{\text{mid}} = 21$ $\mu$s and $\tau_{\text{p-p}}^{\text{mid}} = 31$ $\mu$s). The poloidal scale of the plasma filament at the HFS SOL is evaluated from $\Delta t_{\text{pk}}^{\text{HFS}}$ by $\Delta t_{\text{pk}}^{\text{HFS}} = \Delta t_{\text{pk}}^{\text{HFS}} \cdot \tan(\beta)$, provided that the plasma filament is formed along the local field line pitch angle of $\beta = 6^\circ$ at the Mach probe, and that the toroidal rotation at the HFS SOL corresponds to $v_{\text{ped}}^{\text{HFS}} = v_{\text{ped}}^{\text{LFS}} \cdot (R_{\text{HFS}}/R_{\text{LFS}})$, where $v_{\text{ped}}$ ~ 28 km/s, the major radii at the HFS and LFS Mach probes are $R_{\text{HFS}} = 2.7$ m and $R_{\text{LFS}} = 4.3$ m. Again, effect of the poloidal velocity is not considered as is described in section 4.3 due to small poloidal rotation frequency (~ 0.8 kHz, about a half of the toroidal one at the LFS midplane). Then, $\Delta t_{\text{pk}}^{\text{HFS}}$ is 2 - 6 cm for $\Delta t_{\text{pk}}^{\text{HFS}} = 10 - 30$ $\mu$s. The toroidal mode number is estimated to be $n = 18 - 44$ from separation time of $\tau_{\text{p-p}}^{\text{HFS}} = 20 - 50$ $\mu$s. As a result, averaged filament size and mode numbers are comparable to those at the LFS SOL, suggesting the filament extends to the HFS SOL at least when it is ejected into the SOL.

![Figure 10](image_url)  
**Figure 10.** Radial distributions of (a) peak to peak separation, $\tau_{\text{p-p}}^{\text{HFS}}$ (open circles), and peak duration, $\Delta t_{\text{pk}}^{\text{HFS}}$ (closed circles), (b) Probability distributions of $\tau_{\text{p-p}}^{\text{HFS}}$ and $\Delta t_{\text{pk}}^{\text{HFS}}$.

6. Summary
Time and spatial structures of Type-I ELM filaments were investigated both at the High-Field-Side and Low-Field-Side SOLs, using reciprocating Mach probes with fast sampling rate of 500 kHz and synchronizing with the other principal fast diagnostics. Large multi-peaks of the ion saturation current
Filaments thus may extend to the HFS plasma edge and they are ejected into the HFS SOL and divertor. This convection flux causes large neutral desorption at the HFS divertor and "flow reversal" over a wide radial range of the HFS SOL.

For HFS and LFS SOLs, a large part of the peak-duration (Δt_{peak} = 10 - 30 µs) and the peak-separation (τ_{ϕ} = 20 - 50 µs) are independent of the radial and poloidal location. Radial and poloidal sizes were evaluated to be δr ~ 0.5-4 cm and δz ~ 2-6 cm, and toroidal mode number of n = 18 - 44 was estimated assuming a toroidal rotation velocity at the pedestal of ~ 28 km/s. However, n > 20 is too high to understand by conventional MHD (peeling-ballooning) model, and thus further study is necessary.

References
[1] Kirk A et al. 2004 Phys. Rev. Lett. 92 245002
[2] Herrmann A et al. 2004 Plasma Phys. Control. Fusion 46 971
[3] Eich T et al. 2005 Plasma Phys. Control. Fusion 47 815
[4] Kirk A et al. 2005 Plasma Phys. Control. Fusion 47 315
[5] Boedo J A et al. 2005 J. Nucl. Matter 337-339 771
[6] Endler M et al. 2005 Plasma Phys. Control. Fusion 47 219
[7] Boedo J A et al. 2005 Phys. Plasmas 12 072516
[8] Pitts R A, Fundamenski W, Erents S K et al. 2006 Nucl. Fusion 46 82
[9] Eich T et al. 2003 Phys. Rev. Lett. 91 195003
[10] Asakura N, Sakurai S, Naito O et al. 2002 Plasma Phys. Control. Fusion 44 A313
[11] Asakura N, Takechi M, Oyama N et al. 2005 J. Nucl. Matter. 337-339 712
[12] Ryter F and H-mode Threshold Database Group 2002 Plasma Phys. Control. Fusion 44 A415
[13] Asakura N and ITPA SOL and divertor Topical Group 2007 J. Nucl. Mater. 363-365 41
[14] Hutchinson I H 1988 Phys. Rev. A 37 4358
[15] Oyama N et al. 2004 Nucl. Fusion 44 582.
[16] Asakura N, Kawashima H, Ohno N et al. submitted to Nucl. Fusion 2007.
[17] Kirk A et al. 2005 Plasma Phys. Control. Fusion 47 995
[18] Kirk A et al. 2007 “Comparison of the spatial and temporal structure of type-I ELMs” this conference
[19] Asakura N et al. 2004 Nucl. Fusion 44 503
[20] LaBombard B, Rice J E, Hubbard A E et al. 2004 Nucl. Fusion 44 1047
[21] Fundamenski W, Andrew P, Erents K et al. 2005 J. Nucl. Mater. 337-339 305
[22] Pitts R et al. 2005 J. Nucl. Mater. 337-339 146