Probe measurement of radial and parallel propagation of ELM filaments in the SOL of the COMPASS tokamak

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Introduction

During tokamak H-mode operations, the plasma is mainly carried in the scrape-off layer (SOL) by transient edge localized mode (ELM) filaments coming from the pedestal region with high energy and density. The magnitude of such carried heat fluxes can reduce the lifetime of plasma facing components of future fusion devices if not controlled. The understanding of ELM propagation across and along magnetic field lines is, however, still incomplete and measurements of some important quantities at relevant microsecond time scale are still not common.

The COMPASS tokamak is a compact device ($R = 0.56$ m, $a = 0.2$ m) with ITER-like divertor plasma configuration, capable of routinely achieving ohmic as well as NBI assisted H-mode. In this paper, we present fast measurements of plasma parameters by electrostatic probes in the SOL of the COMPASS tokamak during the ELMy H-mode with $B_T \approx 1.2$ T and $I_p \approx 280$ kA. The measurements are performed at the outer midplane using horizontal reciprocating manipulator and with fixed probes in the divertor region, which allows us to evaluate typical time scales of ELM propagation through the SOL and estimate characteristic velocities of the transport.

Experimental setup

In the experiment, we used Langmuir probes (LPs) to measure floating potential (V_{fl}) and ion saturation current (I_{sat}) and ball-pen probes (BPPs) [1, 2] provided fast measurement of the potential V_{BPP} that is close to the plasma potential [3, 4]. Probe head of the reciprocating manipulator was equipped with combination of both probe types as illustrated in Fig. 1 and on the divertor we used one pair of BPP and LP.

Magnetic reconstruction shows that for plasma current $I_p \approx 280$ kA the reciprocating probe crosses magnetic field lines that are connected to the divertor region with the divertor probes. As Fig. 1 shows, for such conditions the signals of I_{sat} and V_{BPP} during ELMs exhibit similar filamentary structure for both midplane and divertor probes. This allows us to directly correlate signals measured at the two poloidal locations.

All data were measured with 5 MHz data acquisition system. Combination of the probes thus allows submicrosecond measurement of electron temperature $T_e = (V_{BPP} - V_{fl})/2.2$ [3, 5], plasma density $n = 2I_{sat}/(eZ_iSc_s)$, radial plasma velocity $v_r = \Delta V_{BPP}(z)/\Delta z/B$, radial particle $\Gamma_r = nv_r$ and heat $q_r = \frac{3}{2}nT_ev_r$ fluxes, and parallel heat flux $q_{||} = \gamma T_e I_{sat}/S$, where $\gamma \approx 7$, $S = 4.9$ mm^2 is surface of the LP, Z_i and m_i are ion charge and mass, respectively, z is vertical coordinate and $c_s = \sqrt{\frac{e(ZT_e+T_i)}{m_i}}$ is local ion sound speed evaluated with assumption $T_i/T_e = 3$. We note that cross-comparison of T_e evaluated by this method with Thomson scattering shows good agreement for COMPASS L-mode [6] and that using V_{BPP} in the formula for radial component of the E×B drift reduces error due to neglected temperature fluctuations compared to the common case of v_r evaluated from the V_{fl} [7].

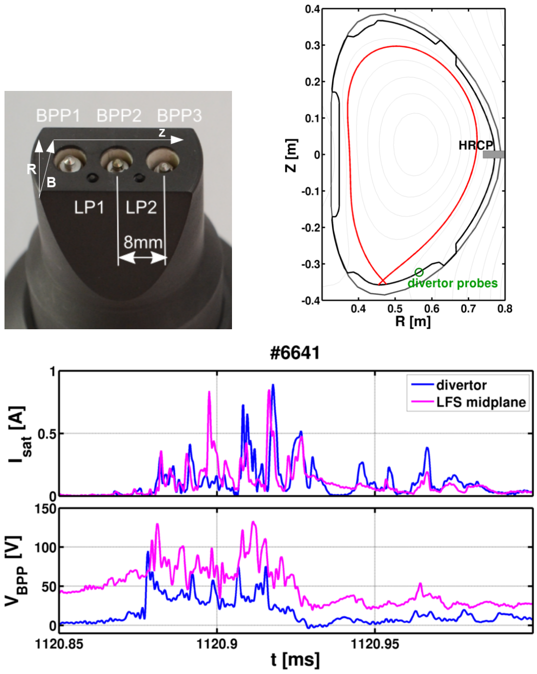

Figure 1: *Probe head of the horizontal reciprocating probe (HRCP) with V_{fl} measured by LP1 and I_{sat} by LP2 (top left) and illustration of the geometry (top right). Bottom: I_{sat} and V_{BPP} during ELM measured simultaneously by the HRCP and divertor probes.*

ELM waveforms

Fig. 2 shows time evolution of the measured quantities on the midplane manipulator during a single ELM. The 5 MHz data sampling allows us to clearly distinguish individual filaments that form the ELM. Duration of each filament is typically $\sim 3-10$ μs, duration of the whole ELM $\sim 50-100$ μs. Fig 2a demonstrates that MHz sampling rate is necessary for their correct resolution and slower techniques of temperature measurement would significantly underestimate peak amplitudes of $q_{||}$ inside the filaments. Fig. 2b shows that electron temperature and I_{sat} fluctuations are correlated inside the ELMs. In the near SOL there are visible 150-300 kHz oscillations of the floating potential (Fig. 2f) and consequently also of the electron temperature before the ELMs. These oscillations are observed also on magnetic diagnostics and they may be associated with MHD modes destabilized due to rise of the pedestal before the ELM crash. Oscillations of the local radial velocity during ELMs can reach ∼10% of the local ion sound speed (Fig. 2e). This value of v_r is associated with local turbulent motion inside the filament and is larger than the characteristic radial velocity of the whole ELM, as will be shown later. Radial heat flux q_r changes sign due to its dependence on the local v_r and reaches peak values of $\sim 0.1\ q_{||}$.

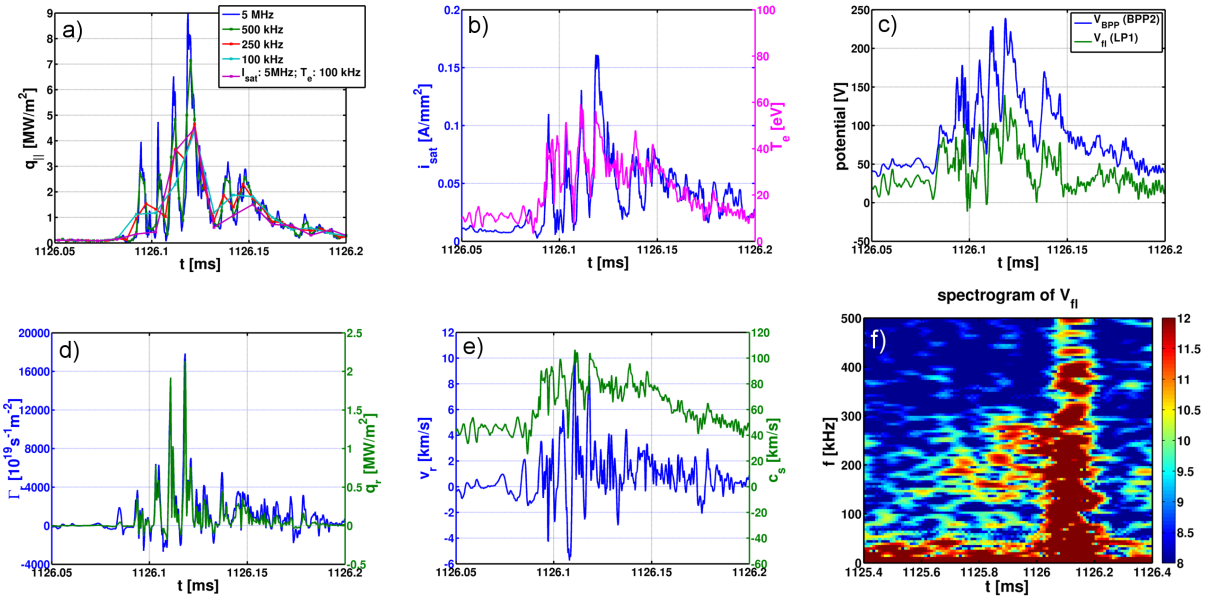

Figure 2: *a) Temporal evolution of parallel heat flux during ELM measured at R*= 0.744 *m with 5 MHz sampling and emulated dependence of its waveform on the sampling rate of the diagnostics. Temporal evolution of b)* I_{sat} *and* T_e*; c)* V_{BPP} *and* V_{fl}*; d) radial particle* Γ_r *and heat* q_r *fluxes; e)* v_r *and local* c_s*. f) Spectrogram of* V_{fl} *oscillations before and during the ELM.*

Radial and parallel transport

ELMs originate in the pedestal region and propagate radially outwards across magnetic field lines. Figs. 3a,b show that in the SOL the radial decay length λ_{ELM} of the maximum of I_{sat} and $q_{||}$ carried by ELMs is several times larger than the decay length of the inter-ELM plasma λ_{inter}, in agreement with measurements on other devices, e.g. JET [8]. This is probably due to the large cross-field velocity of the ELMs that for the typical width of the SOL gives transition time of a similar order as the time of ELM expansion along the field lines. For the decay lengths we find typical ratios $\lambda_{Isat,ELM}/\lambda_{Isat,inter} \approx 4-6$, $\lambda_{Isat,ELM}/\lambda_{q||,ELM} \approx 1.5$ and $\lambda_{Isat,inter} \approx \lambda_{q,inter}$.

From position of the maximum of the cross-correlation function we have estimated time lag δt between ELM V_{BPP} signals recorded on the midplane and divertor probes. Results evaluated from six shots with the same I_p are shown in Fig. 3c. The cross-correlation of the signals grows during inward movement of the reciprocating probe from ~ 0.7 at the limiter position, reaching its maximum ~ 0.85 around $R = 0.741$ m. Dependence of δt on probe position shows linear trend that allows us to estimate typical radial velocity of the ELMs, $v_r \approx 1.2$ km/s, assuming that the time lag is given as $\delta t = \frac{R-R_0}{v_r} - \frac{L_{||}}{v_{||}} \sim \frac{R}{v_r}$ where R_0 is radial position of the field line connecting the correlated probes and $L_{||} \approx 1.75$ m is its length. In such case the divertor probe serves as a fixed reference and v_r is given by the slope of the linear dependence of δt on the position of the reciprocating probe.

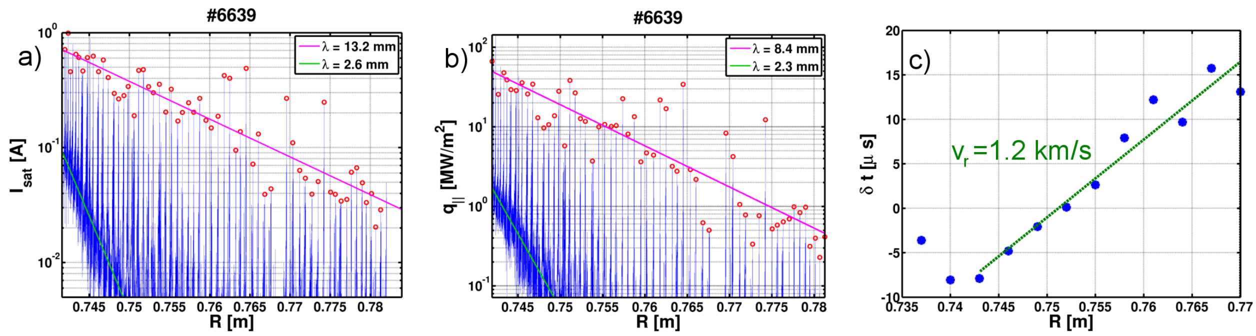

Figure 3: *Radial profiles of a)* I_{sat} *and b)* $q_{||}$ *during inward probe reciprocation in ohmic ELMy H-mode with Type-III ELMs. Peak amplitudes of the ELMs are marked by red circles. c) Time shift between* V_{BPP} *on the HRCP and divertor probes. Data were computed from 6 discharges with* $I_p = 280$ *kA, each dot represents average over* 3 *mm radial distance at midplane.*

Simple model of plasma expansion along the field line $\frac{dn}{dt} \approx -\nabla_{||}(v_{||}n) \approx \frac{v_{||}n}{L_{||}}$, together with observed exponential decay of ELM peak amplitudes $n(r) \approx e^{-\frac{r}{\lambda_{n,ELM}}}$, where we substitute $r = v_r t$, gives also estimate of the characteristic parallel velocity, $v_{||} \approx 140$ km/s. Here, we have combined v_r computed from cross-correlation of the potential with the decay length of density. Similar experiment with cross-correlation of I_{sat} signals is currently being prepared. The computed value of $v_{||}$ is about two orders of magnitude larger then the radial velocity of ELMs, comparable to the ion sound speed evaluated from the typical pedestal temperature. Since ratio of characteristic distances in parallel and radial direction is of the similar order, transit times of ELMs radially through the SOL are comparable (by a factor of ~ 3 larger) with characteristic time of their parallel expansion.

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