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# Fast measurements of the electron temperature in divertor region of the COMPASS tokamak using ball-pen probe

J. Adamek<sup>1</sup>, J. Seidl<sup>1</sup>, R. Panek<sup>1</sup>, M. Komm<sup>1</sup>, P. Vondracek<sup>1,2</sup>, J. Stöckel<sup>1</sup> and COMPASS team

<sup>1</sup> *Institute of Plasma Physics CAS, Prague, Czech Republic*

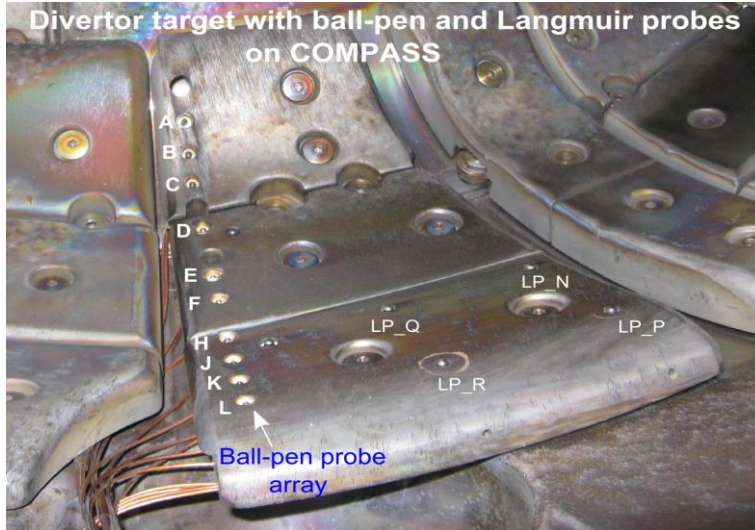
<sup>2</sup> *Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic*

## 1 Introduction

Investigation of the electron temperature and consequently the parallel heat flux on the divertor target during Edge Localized Modes (ELMs) is of importance for the ITER tokamak in order to determine the physical sputtering and melting of the plasma facing components and, consequently, the life time of the divertor targets. The electron temperature in divertor regions of present-day devices is typically measured by swept Langmuir probes or triple probe technique [1]. However, the measurement of its evolution during ELM filaments requires high temporal resolution, which has not yet been achieved by these techniques. Alternative option how to determine the electron temperature with high temporal resolution is to use direct measurements of the plasma ( $\Phi$ ) and floating ( $V_{fl}$ ) potential. The electron temperature  $T_e$  is consequently determined from the difference of both potentials normalized by the proper coefficient for specific gas and magnetic field [2, 3, 4]. The floating potential is routinely measured by Langmuir probe (LP) and the plasma potential can be directly measured by ball-pen probe (BPP) [4]. The BPP was used to measure plasma potential in the edge plasma on tokamak COMPASS [3, 5], ASDEX Upgrade [2, 3, 5], MAST [6] and ISTTOK [7] using probe manipulator. Recently, a new array of BPPs and dome-shaped Langmuir probes was installed also on divertor target of tokamak COMPASS. The first results of fast measurements of the electron temperature on divertor during ELMy H-mode with sub-microsecond time resolution are reported in this paper.

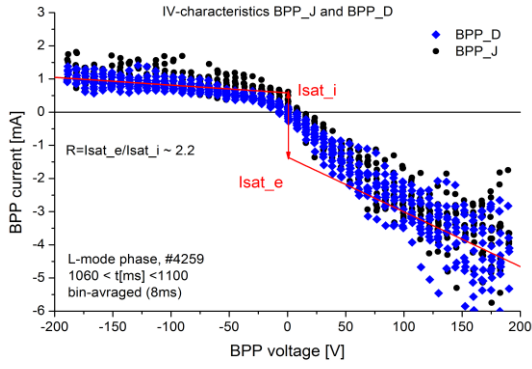
## 2. Divertor BPP and LP construction and experimental set-up

The new array of BPPs (labelled A to L) has been implemented directly to the graphite divertor target on tokamak COMPASS as shown in Fig.1. Each ball-pen probe is made of boron-nitride shielding tube with 6 mm diameter and stainless-steel collector with 3 mm diameter. The collector is retracted at  $h \sim 0.7$  mm below the graphite surface. Four additional dome-shaped LPs (Q, N, R, P) are also mounted on the same divertor target as seen in Fig.1. The LPs are made of graphite with 4 mm diameter and protruding 1.3 mm to the plasma. Toroidal distance between neighbouring LPs is roughly 6 cm and similar distance is applied also for BPP and LP. In current configuration, a set of probes BPP\_H, LP\_Q, LP\_N is located at the same poloidal

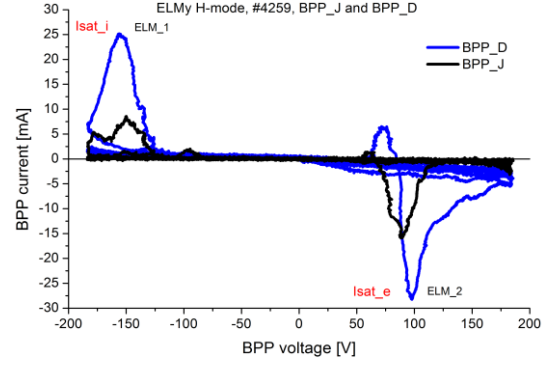


**Fig. 1:** Picture of the ball-pen probe (BPP) array and few dome-shaped Langmuir probes mounted on divertor target on COMPASS. The toroidal distance between BPP and LP is roughly 6 cm.

position. The Langmuir probes can operate in floating or ion saturation current mode ( $V_{\text{probe}} = -270$  V). The total exposed area of LP is approximately  $30 \text{ mm}^2$ . All signals are with a sampling frequency  $f = 5$  MHz. The BPPs are implemented to the divertor target as flush-mounted probes, which significantly reduce the direct impact of high heat flux on the probe material. On the other hand, the BPPs in the divertor are surrounded by large graphite (conducting) tiles, which is a new probe arrangement in contrast to the BPP mounted on probe manipulator. Therefore, in order to verify their  $I$ - $V$  characteristics, we have applied swept voltage ( $\pm 200$  V,  $f = 1$  kHz) on two BPPs (BPP\_J, BPP\_D) with significantly different poloidal locations. An example of resulting  $I$ - $V$  characteristics of both probes obtained during the L-mode phase ( $B_T = 1.15$  T, plasma current  $I_p = 300$  kA, density  $n_e = 6 \cdot 10^{19} \text{ m}^{-3}$ ) of H-mode discharge #4259 are plotted in Fig. 2. It can be seen that both probes provide nearly symmetric  $I$ - $V$  characteristics during the whole time interval. It is also seen that electron and ion branch of the  $I$ - $V$  does not saturate and therefore the evaluation of the ratio of the electron and ion saturation current  $R = I_{\text{sat}_e} / I_{\text{sat}_i}$  requires linear extrapolation of both branches. The linear fit in Fig.2 is calculated for BPP\_voltage  $> +100$  V on the electron branch and for BPP\_voltage  $< -100$  V on the ion branch. If we assume the the floating potential of BPP is close to the plasma potential  $\Phi$  then the logarithm of the ratio  $R$  is found close to  $\ln(R) \sim 0.8$ . The resulting value  $\ln(R)$  is close to the value obtained with BPP mounted on probe manipulator on tokamak AUG [2]. The determination of the ratio  $R$  during ELMs is difficult because of very short time scale of ELM filaments. However, the estimation of the electron and ion saturation current during ELM is shown in Fig.3. Two similar ELM events, ELM\_1 and ELM\_2, with the same D-alpha signal, were detected on swept BPP\_J and BPP\_D during ELMy H-mode phase of discharge #4259



**Fig. 2:** The bin-averaged  $I$ - $V$  characteristics of BPP\_D (diamond) and BPP\_J (circle) during whole L-mode phase of discharge #4259.



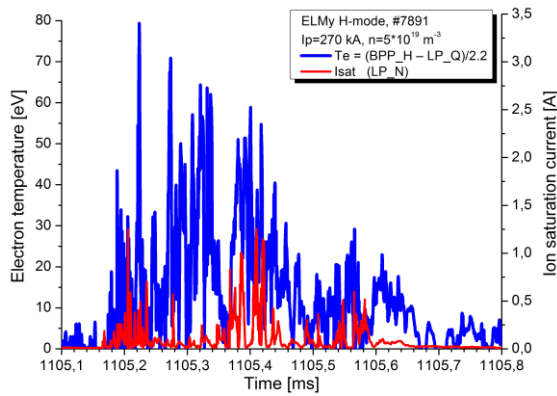
**Fig. 3:** The  $I$ - $V$  characteristics of BPP\_D (blue) and BPP\_J (black) during ELMy H-mode #4259 with two similar ELM events incoming to both probes.

( $n_e = 9 \cdot 10^{19} \text{ m}^{-3}$ ) at the moments with opposite value of applied voltage. This confirms that both values,  $I_{sat\_e}$  and  $I_{sat\_i}$ , are roughly balanced also within the ELM, with ratio  $1 < R < 2$  independent on probe position. Note, the investigation of ratio  $R$  of BPP during ELMy H-mode can be also found in systematic measurements on ASDEX Upgrade [2].

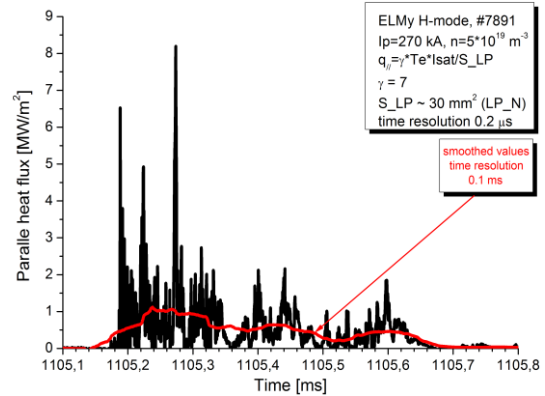
### 3 The electron temperature within ELM filaments

The investigation of the electron temperature  $T_e$  with a sub-microsecond temporal resolution is based on fast measurements of BPP and LP potentials,  $\Phi^{BPP}$  and  $V_{fl}$ , and formula  $T_e = (\Phi^{BPP} - V_{fl})/2.2$ . The coefficient 2.2 is obtained from the  $\ln(R)=2.8$  of LP in deuterium plasmas (assuming  $T_i = T_e$  and no secondary electron emission) minus the  $\ln(R)$  of BPP. The values of  $\ln(R)$  of BPP on COMPASS, shown in Fig.2, and on AUG [2] are in agreement within the error bars. Therefore, we are using value of  $\ln(R)=0.6$  of BPP for both devices. Note, the same formula was already used for comparative measurements of the electron temperature by BPP/LP mounted on reciprocating manipulator and Thomson scattering on COMPASS [3], AUG [3] and MAST [6] during L-mode plasma with a very good agreement of both techniques. The first results of fast electron temperature measurements within the ELMs using BPP/LP mounted on horizontal manipulator were performed on COMPASS [8]. However, this is the first time measurement of the electron temperature within ELMs using BPP/LP on divertor with sub-microsecond time resolution. At first, both Langmuir probes, LP\_Q and LP\_R, were connected as a floating probe in order to calculate the cross-correlation coefficient. It has been found that cross-correlation coefficient is within the range 0.8-0.9 for L-mode, ELM free H-mode and ELMy H-mode phase of discharge #7876. It confirms that both LPs and BPP\_H are well magnetically connected. In the following H-mode discharge #7891 the LP\_R was switched to the  $I_{sat}$  regime ( $V_{bias} = -270 \text{ V}$ ). It allowed us to provide simultaneous measurements

of the electron temperature  $T_e$  by combining BPP\_H and LP\_Q and ion saturation current  $I_{sat}$ . The time evolution of the electron temperature and ion saturation current during ELM event is plotted in Fig.4. It is seen that the value of the electron temperature is strongly varying within the filament structure. However, it must be noted that a small part of resulting  $T_e$ , roughly 9% of total signal during H-mode phase, has values below 0 eV, because in some cases it is observed during ELM filaments that both signals,  $\Phi^{BPP}$  and  $V_{fl}$ , are slightly shifted in time. This can be caused by a small misalignment of BPP and LP with respect to the magnetic field lines or dif-



**Fig. 4:** The time evolution of the electron temperature and ion saturation current during one ELM event in H-mode #7891 on divertor on COMPASS.



**Fig. 5:** The time evolution of parallel heat flux obtained from  $T_e$  and  $I_{sat}$  measurements and heat transmission coefficient  $\gamma=7$  during one ELM event in H-mode #7891.

ferent dimensions of each probe. However, the major part of  $T_e$  values can be used in order to estimate the value of parallel heat flux  $q_{||} = \gamma * T_e * I_{sat} / S_{LP}$ , where  $\gamma$  is the value of heat transmission coefficient and  $S_{LP}$  is the total exposed surface of LP\_N. The time evolution of  $q_{||}$  during one ELM is plotted in Fig.5. It is seen that value of parallel heat flux during ELMs reaches a couple of  $\text{MW}/\text{m}^2$ . These values are obtained roughly 6 cm from strike point on low field side. The red line represents smoothed values of parallel heat flux to 0.1 ms (10 kHz), which is comparable to resolution of common IR camera. In such case, the resulting values of  $q_{||}$  are below  $1 \text{ MW}/\text{m}^2$ , strongly underestimating the peak heat flux.

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