Ion temperature measurement on tokamak Golem

Author: Dario Cipciar **Date:** 24.9.2020

Faculty of Science, Masaryk University, Department of electronics

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1. Abstract

We have performed a systematic measurement of ion and electron temperature on tokamak Golem using a ball-pen and Langmuir probe. The ion temperature can be estimated from the electron branch of swept BPPs I-V characteristics with high temporal resolution. A radial profile of ion and electron temperature was created by measuring with a stationary probe placed at five different radial positions. Average values of ion temperature were estimated from synthetic RFA-like I-V characteristics.

2. Experimental setup and data preparation

In this experimental campaign we have performed measurements of ion temperature (T_i) and electron temperature (T_e) using stationary electric probes at different radial positions during discharge in Ohmic (OH) regime. Discharge parameters were set to:

Voltage on condenser batteries powering toroidal magnetic field coils: $U_{Bt} = 1300$ V,

Current drive field source voltage: $U_{CD} = 550$ V,

Current drive trigger delay: $\tau_{CD} = 0$ ms,

Requested gas pressure: $p = 8$ mPa.

Since only one ball-pen probe (BPP) could be placed on the vertical manipulator, we have preformed two identical discharges for the same radial position of the manipulator. During one of the discharges the electron temperature was measured using a relation between floating potential of ball-pen probe (ϕ^{BPP}) and floating potential of Langmuir probe ($V_\mathrm{fl}^{\mathrm{LP}}$). The coefficient $\alpha_\mathrm{LP} - \alpha_\mathrm{BPP} = 2.5$ was measured on tokamak Golem [1]. Electron temperature can be obtained as:

$$T_\mathrm{e} = \frac{\phi^{\mathrm{BPP}} - V_\mathrm{fl}^{\mathrm{LP}}}{\alpha_\mathrm{LP} - \alpha_\mathrm{BPP}} \tag{1}$$

During the second discharge the Ball-pen probe was biased with voltage of 0 to +80 V, at a sweeping frequency of 50 kHz. The data was collected with a sampling rate of 1 MHz. The radial position of manipulator was set to 80, 75, 70, 65 and 60 mm. Lowpass filter was applied in order to remove structures with much higher frequency than the voltage sweeping frequency. During this experimental campaign we found the typical cut-off frequency as 370 kHz. The same cut-off frequency was previously found also at COMPASS. Example of signal clean-up is shown on Figures 1, where the capacitive current is reconstructed, and 2, where the lowpass filter is applied. After capacitive current and background noise is removed the signal can be separated into individual I-V characteristics, which can be fitted from the plasma potential V_p using a 4-parameter fit. Since magnitude the magnetic field was changing during the whole discharge we have used the unweighted method for fitting the I-V characteristics. The formula used for 4-parameter fitting is:

$$I(V) = \exp(\alpha_\mathrm{BPP}) I_\mathrm{sat}^{+} [1 + R(V - \Phi)] - I_\mathrm{sat}^{+} \exp((\Phi - V)/T_\mathrm{i}). \tag{2}$$

The fitting parameters obtained are the ion temperature (T_i), plasma potential (Φ), ion saturation current (I_sat^{+}) and linear increase of electron current is described by slope (R). Examples of I-V characteristics fit resulting

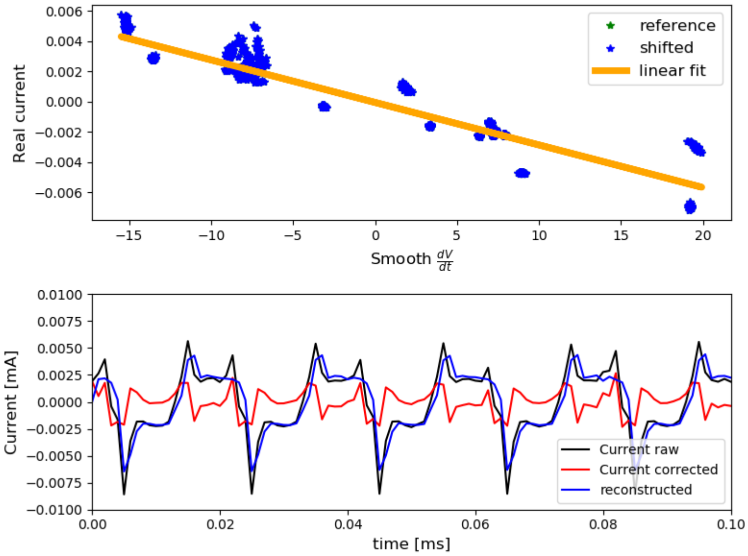

Figure 1: Capacitive current reconstruction and removal, shot: 33445

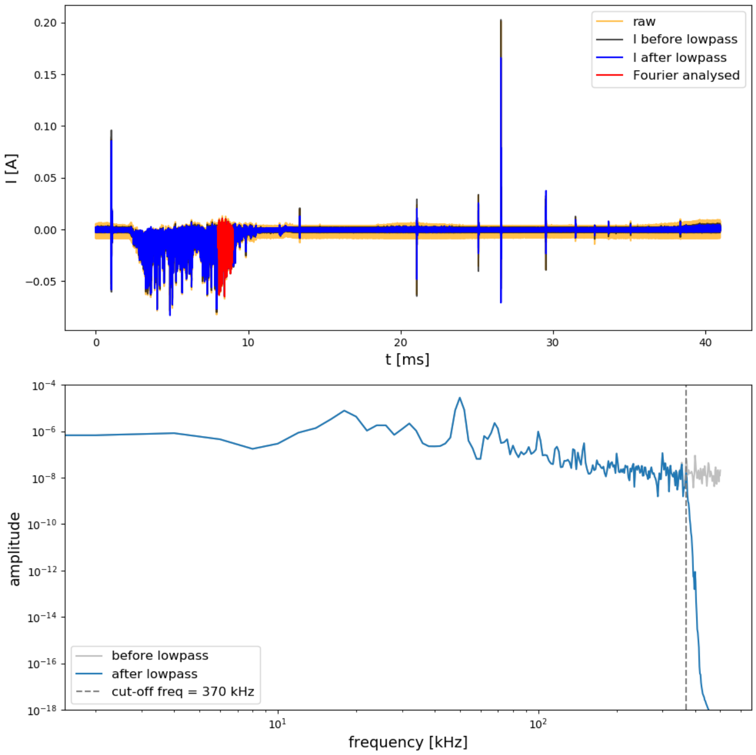

Figure 2: Filtering and a Fourier analysis of signal, shot: 33445

in low, medium and high T_{i} are shown on Figure,3 and 4. The coefficient α_{BPP} was calculated using empirical relation [1] measured at Golem :

$$\alpha_{\mathrm{BPP}} = \alpha_{\mathrm{LP}} - 1.89 B_{\mathrm{t}} + 1.85, \tag{3}$$

where $\alpha_{\mathrm{LP}} = 2.7$ was estimated for Golem in [1]. As for B_{t} we have used an average value of B_{t} in interval chosen for the ion temperature measurement.

Since the Ion temperatures resulting from 1 ms measurement at given position are not normally distributed, we can not assign mean and a standard deviation of the measurement to construct averaged temperature radial profile. We must use a more complex approach similar to analysis of data from a Retarding Field Analyser

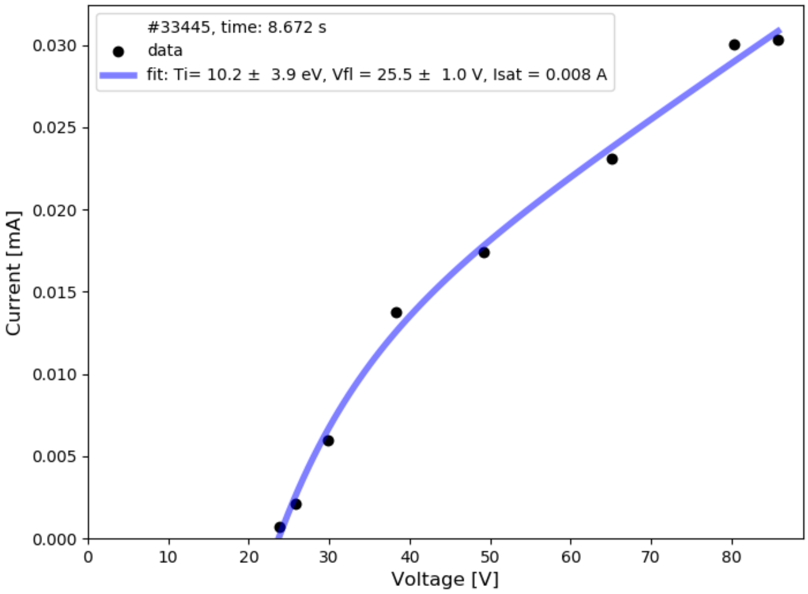

Figure 3: Example of 4-parameter fit of the electron branch, shot: 33445

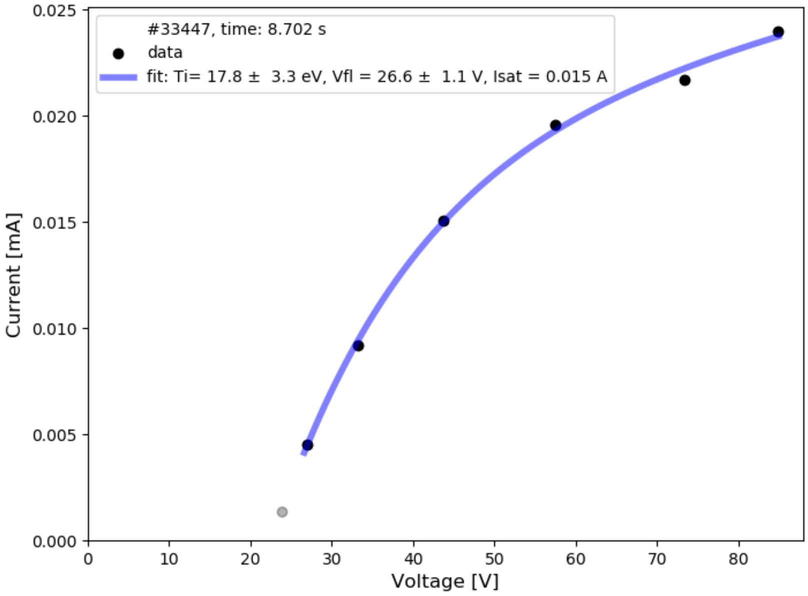

Figure 4: Example of 4-parameter fit of the electron branch, shot: 33447

(RFA). To simulate such RFA-like I-V characteristics we input the estimated values of parameters T_i, ϕ, and I^{+}_{sat} into equation describing the exponential decay of ion current with coefficient T_i given as:

$$I = I^{+}_{\mathrm{sat}} \exp\left(\frac{\phi - V}{T_\mathrm{i}}\right), \text{ where } (V > \phi) \tag{4}$$

The parameter V is generated as an array ranging between 0 to 200 V with 1 Volt sampling. Below plasma potential $I = I^{+}_{\mathrm{sat}}$. Example of this fitting approach is shown on Figure 5. In order to compare results of multiple discharges their macroscopic parameters must follow similar behaviour. Comparison of macroscopic parameters characterising discharges where the ion temperature was measured (#33445, #33447, #33449,

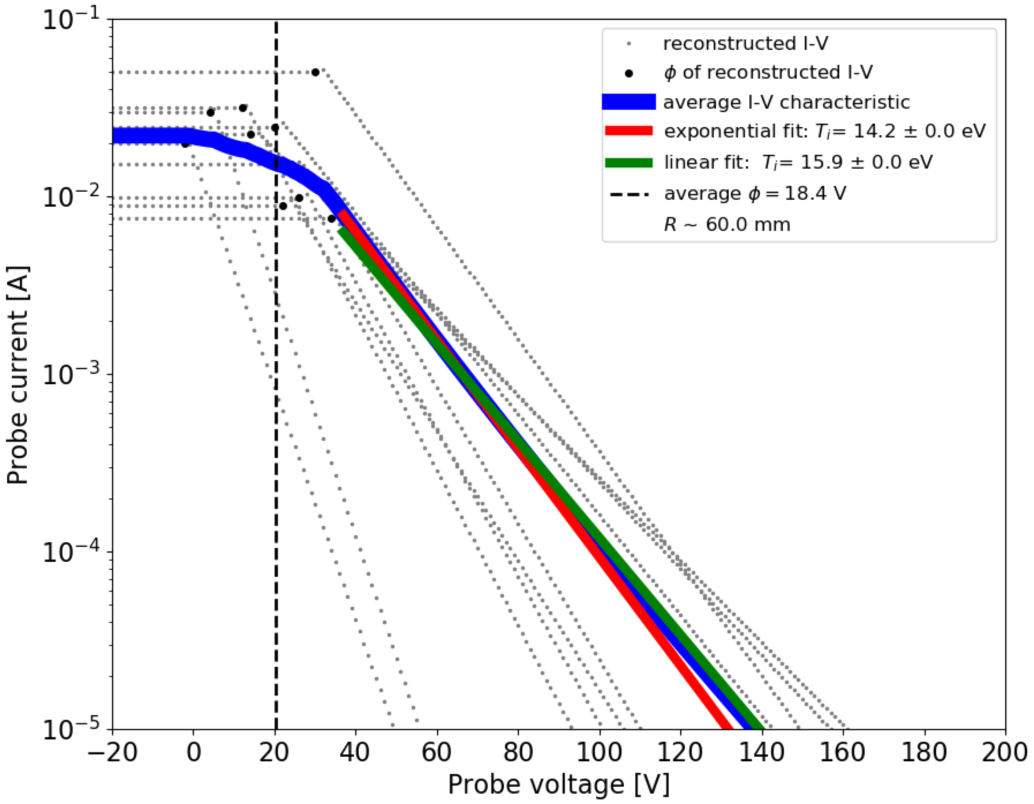

Figure 5: Example of linear and exponential fit of the RFA-like I-V characteristic, shot: 33447.

#33451 and #33453) is show on Fig. 6. The two vertical lines mark the beginning and end of the interval chosen for the analysis. In this interval the plasma current I_{p} is almost constant and magnitude of the magnetic field B ranges between 0.30 to 0.34 T for all discharges. From the first graph on Fig. 6 it is evident that the plasma had high impurity content. Since the discharges have almost same macroscopic parameters we can construct a radial profile of ion and electron temperature from all ten consecutive discharges (#33445 - #33452). Another important discharge characteristic is the radial position of the last closed flux surface (LCFS or Separatrix) relative to the position of the probe head. We can estimate its position based on a fact that LCFS is separating region of closed magnetic field lines (central plasma) and a region of opened field lines (scrape off layer). The region between central and SOL plasma, where the rotation of plasma is changing its direction is called Shear layer. Separatrix is than located at a radial position where the poloidal rotation of plasma is equal to zero:

$$\vec{E}_{\text{r}} = -\frac{\mathrm{d}\phi}{\mathrm{d}r}, \tag{5}$$

where $\vec{E}_{\text{r}}$ is radial electric field vector. Thus, radial position of Separatrix can be found using LP and BPP in a floating regime as a maximum of plasma potential ϕ. The radial profile of plasma potential shown on Fig. 7 would suggest that separatrix is located at radial position of 65 mm. The local maximum at position of 75 mm may not be taken into consideration, since we expect a growth in plasma potential toward core plasma. However, the spatial resolution is very low, thus we can not estimate the position of separatrix with certainty during this experimental campaign.

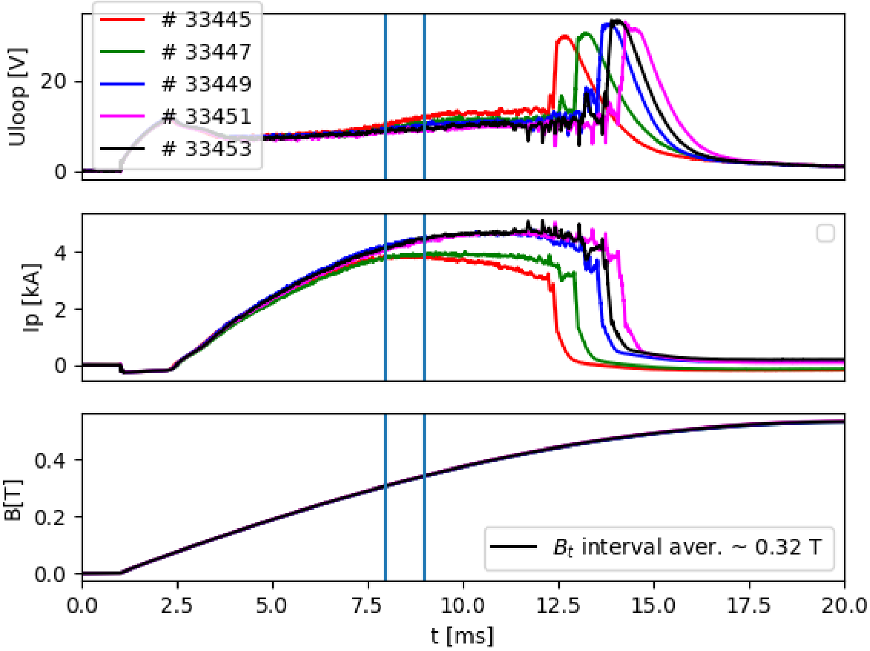

Figure 6: Macroscopic parameters comparison.

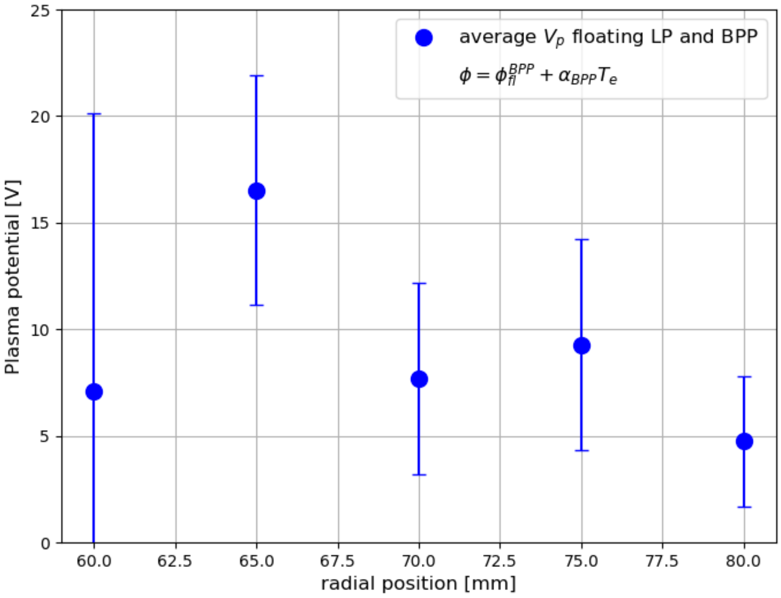

Figure 7: The radial profile of plasma potential (**??**) for estimation of separatrix position.

3. Results

The sweeping frequency of BPP allows the measurement of ion temperature with 10μs resolution. However, only 5% of all measured IV-characteristics in the given interval have passed the filtering criteria typically set as:

$$T_{\mathrm{i,err}}/T_{\mathrm{i}} > 0.6,$$

$$V_{\mathrm{p,err}}/V_{\mathrm{p}} > 0.6,$$

$$T_{\mathrm{i}} < (V_{\mathrm{peak}} - V_{\mathrm{p}})/1,$$

where $V_{\mathrm{peak}} = 80$ V is the peak value of voltage applied on the BPP.

The shortage in successfully obtained temperatures is mainly due to the low sampling frequency of the data acquisition system (DAS) (1 MHz). In order to correctly and precisely estimate 4 parameters describing the IV-characteristics it is crucial to have the exponential part of the curve well defined. Lack of measured data points leads to increased relative errors of estimated parameters. Taking that into consideration we have increased the maximum relative error condition to 80% for the purpose of constructing the radial profile. The comparison of temporal profiles of T_{i} at different radial positions filtered with 80% relative errors is shown on Fig 8 and 9.

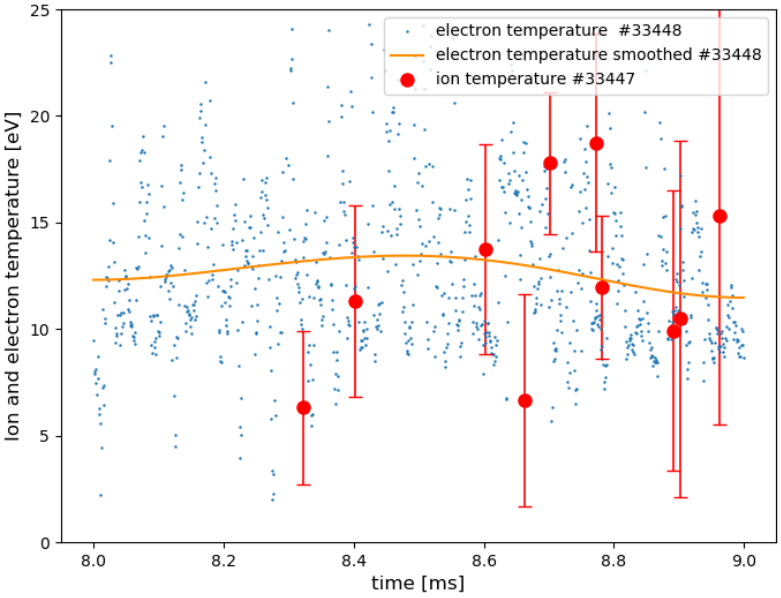

Figure 8: Ion and electron temperature measurement at radial position 60 mm. The maximum relative error was set to 80 %.

The radial profile shown on Fig. 10 was constructed from T_{i} measured with estimated relative error lower than 80 %. Red stars depict the fast (10 μs resolution) measurement, which at position of 65 mm clearly shows two populations of ions with low (background) and high (blob) temperatures. At this radial position we have constructed a probability distribution function of ion temperature energies. On Fig. 11 we can notice clearly non-Gaussian distribution of T_{i} with one peak at 7 eV and a hot tail peaking at 22 eV. The PDF measured during discharge 33445 exhibits similar properties as distribution functions previously measured at COMPASS tokamak. Since only few measurements of T_{i} in the region (70 - 80 mm) are available we can not accurately construct distribution functions or calculate the averaged RFA-like temperatures.

The FRA-like averaged temperatures calculated at three radial positions are shown on Fig. 10. We can notice that the ratio between averaged ion temperature and an average electron temperature is close to 1 at the radial position of 60 mm. What would indicate that core plasma is thermalised. Also the histogram shown on Fig. 12 constructed from fast T_{i} measurement at radial position of 60 mm indicates normal distribution almost identical to PDF of electron temperatures. The high average T_{i} at position of 65 mm is reflecting the large increase of plasma potential measured even by LP and BPP in a floating regime. We can also see that Ion temperature near the tokamak wall is higher than the electron temperature as is expected due to more effective parallel transport of electrons on to the tokamak limiter in comparison to ions. Measurement of high energy blobs expected in the SOL region would require to increase the range of swept voltage to at least 150 V for the criterion: $T_{\mathrm{i}} < (V_{\mathrm{peak}} - V_{\mathrm{p}})/1$ to be always satisfied.

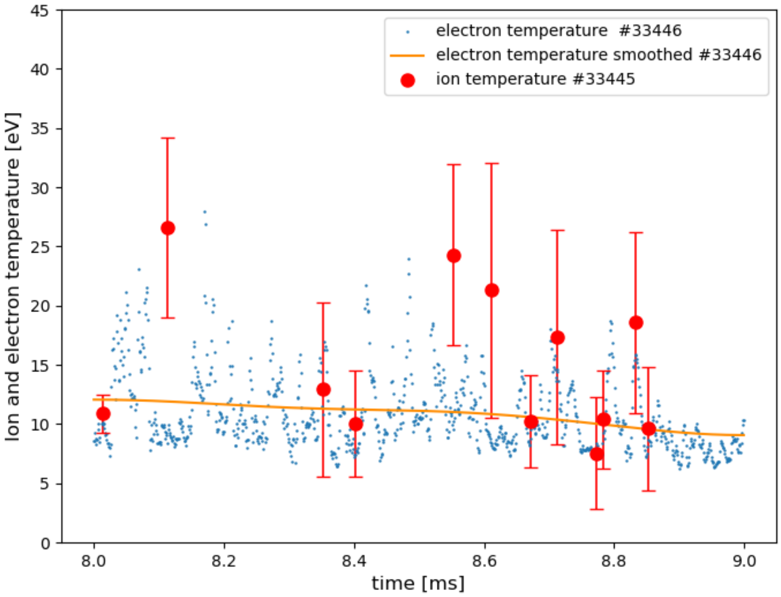

Figure 9: Ion and electron temperature measurement at radial position 65 mm. The maximum relative error was set to 80 %.

4. Conclusion

Using Ball-pen and Langmuir probe we were able to measure the ion and electron temperature during ten consecutive discharges (#33445 - #33452) at five different radial positions. The parameters of all discharges during which Ball-pen probe was in swept regime are shown on Figure 6. We have chosen an interval where the intensity of magnetic field ranged from 0.3 to 0.34 T. The resulting ratio of average T_i (obtained from RFA-like I-V characteristics) to average T_e near core plasma region is close to 1 which indicates that the core plasma is thermalised (see also histogram on Fig. 12), while in the regions closer to the tokamak walls the $T_\mathrm{i} > T_\mathrm{e}$.

Due to low sampling frequency of data acquisition system (1 MHz) we have increased the maximum relative error of measured T_i to 80 %. However, even with increased relative error criterion the successfully obtained T_i values represent only 5 -10 % of all measured I-V characteristics. Thus in the future campaign we need to prioritize higher DAS sampling frequency. Also measurement of high energy blobs (>30 eV) in Main-SOL requires to increase the range of swept voltage up to at least 150 V. This can be obtained by adding DC power supply in series with swept signal generator. More spatially detailed measurement of radial profile of ion temperature would help to support credibility of the used method. Low impurity content is also essential for credible investigation of T_i behaviour, since we do not know how exactly impurities affect the measurement.

References

[1] P. Mácha, Edge plasma parameter measurements of the GOLEM tokamak using ball-pen and Langmuir probe. Bachelor thesis, ČVUT, 2018.

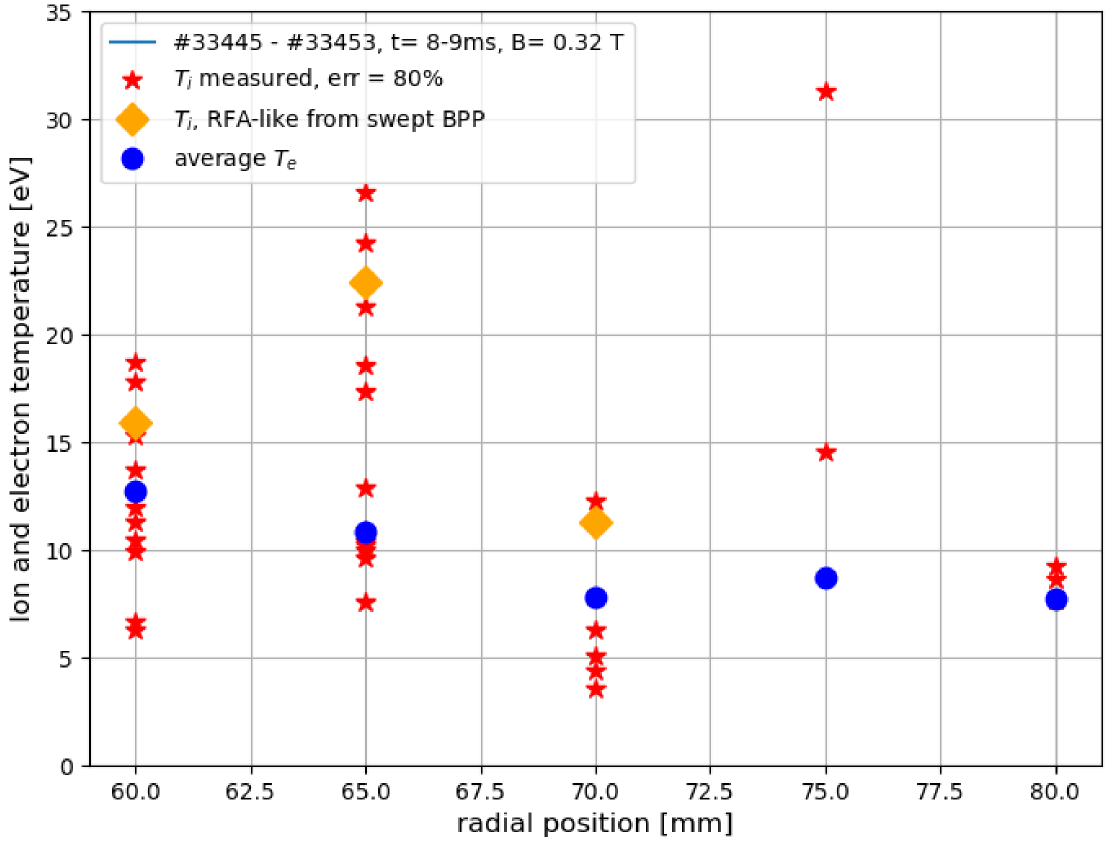

Figure 10: The radial profile of ion and electron temperature constructed from ten consecutive discharges (#33445 - #33454). The maximum relative error condition was set to 80%.

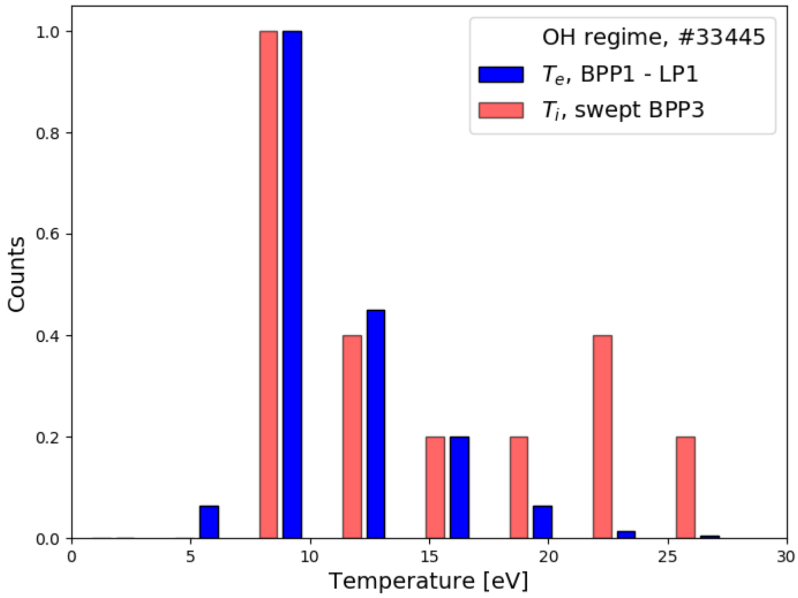

Figure 11: Distribution of ion and electron energies measured with 10 μs resolution at a radial position of 65 mm during 1 ms interval, #33445. The maximum relative error condition was set to 80%.

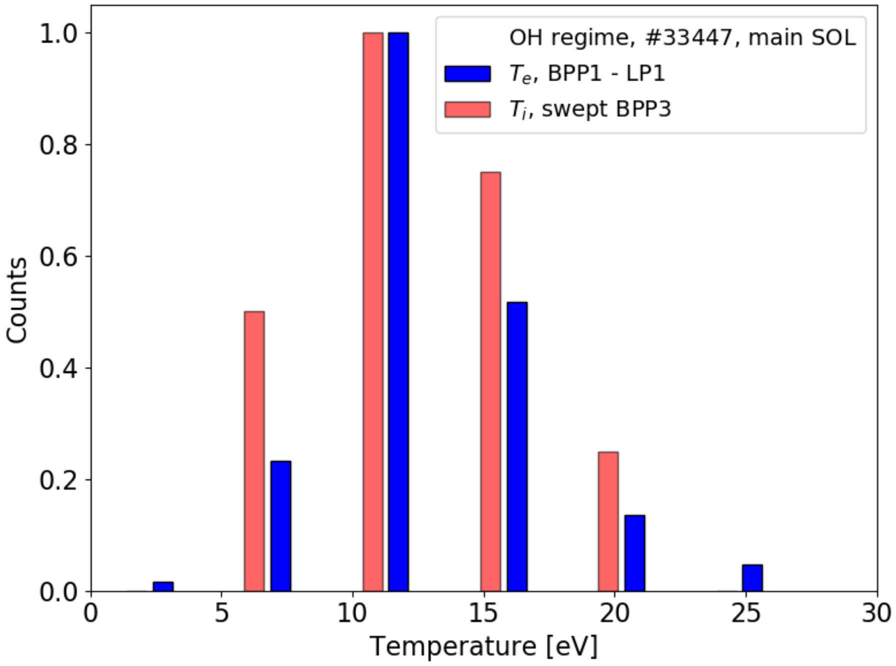

Figure 12: Distribution of ion and electron energies measured with 10 μs resolution at a radial position of 60 mm during 1 ms interval, $\#33447$. The maximum relative error condition was set to 80%.