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A new probe for ion temperature measurements in the tokamak scrape-off layer

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1. Introduction

Ion temperature in the tokamak scrape-off layer (SOL) is notoriously difficult to measure and thus rarely available. A new kind of the robust Langmuir probe, the so-called segmented tunnel probe (STP), was designed for this purpose. It consists of a hollow conducting tunnel a few millimetres in diameter and typically 5 mm deep, closed at one end by an electrically isolated conducting back plate (Fig. 1.). The tunnel axis is parallel to the magnetic field. To remove the electron component of the incident plasma flux, both conductors are negatively biased with respect to the tokamak vessel. The ions that flow into the orifice are diverted onto the tunnel surface by the intense radial electric field in the magnetic sheath.

In this paper, we show, that the ion distribution along the tunnel decays with a characteristic scale length, which is a function of the ion temperature. Therefore, by dividing the tunnel into two segments, the ion temperature T_i can be found from the ratio of ion current to the first and the second segment, $R_c = I_{seg1}/I_{seg2}$. The advantage is that the probe is operated in DC mode and thus provides fast measurements of ion temperature as well as of the parallel ion current density $J_{//,i}$. Moreover, due to clearly defined tunnel orifice, this probe is not subject to the uncertainties of collecting area from which classical convex probes suffer.

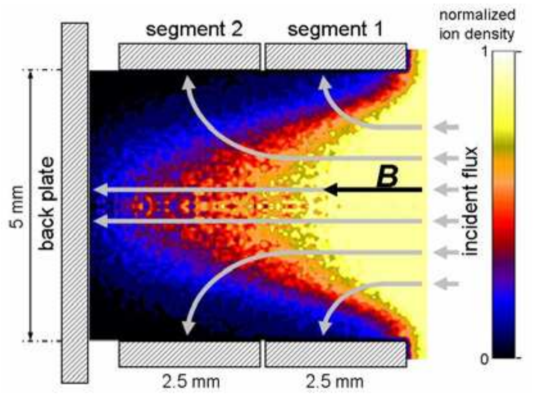

Fig. 1. Schematic of STP. The ion guiding centre trajectories are shown by gray arrows.

We will present preliminary results of the numerical simulations and the experimental testing of the STP prototype at CASTOR tokamak.

2. Kinetic simulations

Kinetic simulations of the probe are necessary for its calibration and, consequently, for the interpretation of the experimental data. We used the two-dimensional Particle-in-Cell (PIC) code XOOPIC [1]. Due to the axial symmetry of the probe the XOOPIC code enables to simulate whole region inside the tunnel. The simulation model is shown in Fig. 1. Maxwellian electrons and ions (protons) are injected from right hand side with given temperatures ($T_{i,e}$) and current densities ($J_{//,i,e}$). As the ions move along magnetic field lines into the tunnel, they are redistributed between the back plate and the tunnel walls. The code calculates the spatial particle distribution along the tunnel (Fig. 2), which enables to evaluate the ratio R_c. More than 100 simulations for typical values of the edge-plasma parameters of CASTOR tokamak as well as of other tokamaks have been performed (i.e. $J_{//,i}$ = 0.5 ÷ 5 kAm^{-2}, T_e = 5 ÷ 40 eV and T_i = 5 ÷ 40 eV).

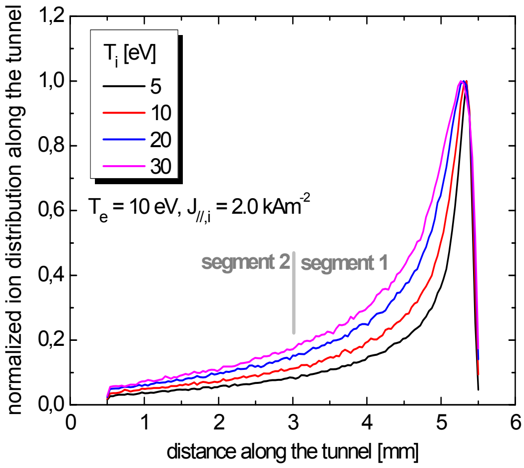

Fig. 2. Ion distribution along the tunnel calculated by the PIC simulations.

The ratio R_c does not depend only on T_i, but to some extent also on electron temperature T_e and parallel ion current density $J_{//,i}$. However, T_e is measured simultaneously by the same probe in DC mode (see [2]). The value of $J_{//,i}$ is directly obtained as a total current to the tunnel segments and the back plate divided by the area of the tunnel orifice. Therefore, the ion temperature $T_i = T_i(R_c, T_e, J_{//,i})$ is unambiguously determined from the calibration curves of STP. From the simulation database we have derived the preliminary analytical fitting formula for T_i

$$T_i = -50.2 \times \ln\left[\frac{(R_c - 3.31)J_{//,i}^{1.91}}{3.48 J_{//,i} - 7.67 \cdot 10^{-2} T_e + 2.40 \cdot 10^{-3} T_e^2}\right] \quad \text{for } 0.5 < J_{//,i} < 2.0 \text{ kAm}^{-2}. \quad (1)$$

For the time being, in the region of 2.0 < $J_{//,i}$ < 5.0 kAm^{-2} the ion temperature has been estimated using the fitting by a neural network. An analytical fit for this region is under preparation.

plasma centre, however, it is lower than electron temperature. Between the radii of 65 mm (LCFS position) and 85 mm (limiter radius) the T_i profile flattens. In this region, the effect of the plasma pre-sheath starts to play role - the electron and ion temperatures become comparable, and, in the second half of this region, T_i is already higher than T_e ($T_i / T_e \approx 1.5$). In the third region, for $r > 85$ mm, the connection length is already short and comparable with plasma pre-sheath region. While the electron temperature further decreases, the ion temperature increases considerably and the ratio of T_i / T_e approaches the value of 3-4. This is probably caused by a complex processes taking place in this region such as volumetric power losses, hydrogenic recycle process, impurity radiation etc. However, it is necessary to take into account that due to low densities close to the tokamak wall, the plasma in the STP is no more sufficiently shielded and the reliability of measurement decreases.

4. Conclusion

We have presented a new kind of a robust Langmuir probe for fast ion temperature measurement – Segmented Tunnel Probe. Using PIC simulations, the physics of the probe was studied and its calibration has been performed. Moreover, we present preliminary experimental results obtained by the first prototype of STP, which was successfully tested in the CASTOR tokamak. The radial ion temperature profile was measured and compared with electron temperature profile. Due to complexity of multidimensional fitting we do not have till now an analytical formula for the whole region of ion current density typical in SOL and, therefore, we also used fitting by the neural network. However, constructing of analytical formulae is under work now. In addition, the probe performance will be enhanced by the optimization of the position of the tunnel segmentation, taking into account secondary electron emission and tests on larger devices. The optimized SPT could become a standard diagnostic tool for ion temperature measurement in the edge tokamak plasma.

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