Particle-in-cell Simulations of Flush-Mounted Probes

A. Podolnik[1,2], M. Komm[1], R. Dejarnac[1], R. Panek[1], J. P. Gunn[3]

[1] *Institute of Plasma Physics ASCR, Prague, Czech Republic*

[2] *Faculty of Mathematics and Physics, Charles University in Prague, Czech Republic*

[3] *CEA, IRFM, F-13108 Saint Paul Lez Durance, France*

Flush-mounted probes are Langmuir probes which are embedded in a plasma facing component and which do not protrude inside the plasma from which they measure the parameters. However, in the presence of magnetic field, the measured quantities can strongly depend on the field lines inclination angle [1]. In this article, a kinetic approach is used to investigate the angular dependence of the magnetic field on flush probe *I*-*V* characteristics. Processing the simulated *I*-*V* curves using standard formulas shows an overestimation of electron temperature and other parameters due to non-saturation of the ion branch and analytical formulas are given to compensate this effect.

Numerical Setup

Simulations were made using the SPICE2 code ([2, 3]) developed in collaboration between IPP ASCR and CEA Cadarache. SPICE2 is a 2D-3V code based on particle-in cell technique that solves self-consistently the Poisson equation. Two types of Langmuir probes (LP) are modeled in this paper, flush-mounted and rounded probes, the latter being used as a reference. A scheme of the geometry used in the code, based on the COMPASS tokamak high field side limiter (Fig. 1), is shown in Fig. 2. Plasma parameters are set to typical values met in COMPASS scrape-off layer plasmas: $n_0 = 1\times10^{18}$ m^{-3}, $T_e = 15$, 20, and 25 eV, $T_i/T_e = 2$, $B_t = 1.0$, 1.2, and 1.4 T. A scan over the magnetic field inclination angle α with respect to the flat surface was performed from 2 ° to 90 °. For the reference case of rounded probes, only one run is used with intermediate values: $T_e = 20$ eV and $B_t = 1.2$ T. The SPICE2 model is used to provide probes *I*-*V* characteristics for the aforementioned plasma conditions. The data were evaluated by the following standard three- and four-parameter fit formulas:

Figure 1: *COMPASS high field side limiter with rounded and flush-mounted LPs.*

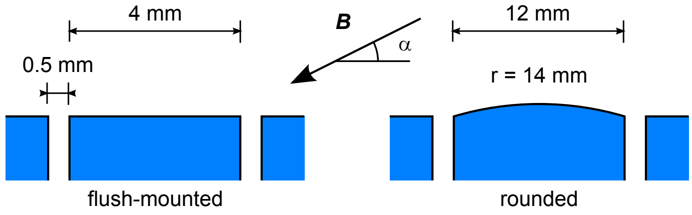

Figure 2: *Scheme and dimensions of simulated flush-mounted (left) and rounded (right) probes. Gap width is identical in both cases.*

$$I(V) = I_{sat}\left(1 - \exp\left(e\frac{V - V_f}{k_B T_e}\right)\right), \quad (1)$$

$$I(V) = I'_{sat}\left(1 + S\left(V_f - V\right)\right)\left(1 - \exp\left(e\frac{V - V_f}{k_B T_e}\right)\right), \quad (2)$$

with I_{sat} the ion saturation current, V_f the floating potential and T_e the electron temperature. Eq. (2) is derived to compensate the sheath expansion [4] by introducing the fourth parameter: the slope of ion current branch S. This formula fits simulated curves with higher precision and will be used for further processing of the data.

Simulation results and discussion

The current-voltage characteristics for different inclination angles for the 2 probes and for $T_e = 20$ eV and $B_t = 1.2$ T are shown in Fig. 3. As expected from experimental data [1], absolute values of the ion saturation current are increasing with the angle.

Fig. 4 shows T_e as a function of α for all simulated cases. For angle $< 40\,°$, T_e starts to deviate from its real value independently of B_t and for grazing angles ($\alpha < 5\,°$), the error made on T_e can reach 40 %. In order to compensate this effect and allow us to determine the correct value of T_e for shallow angles, the following scaling has been derived:

$$T_e(\alpha) = T_o\left((\alpha - \pi/2)^4\right) + T_{90}\,. \quad (3)$$

T_o represents the maximum overestimation of T_e for $\alpha = 0$ and T_{90} is the electron temperature with no sheath expansion and therefore should be equal to T_e when $\alpha = 90\,°$.

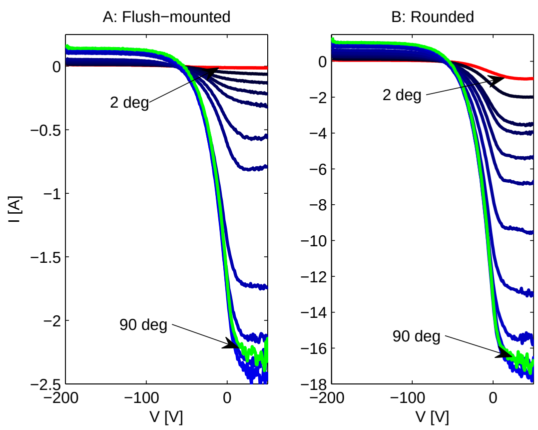

Figure 3: *Numerical I-V characteristics for* $2 \leq \alpha \leq 90\,°$ *for flush-mounted (A) and rounded (B) probes for* $T_e = 20$ *eV,* $B_t = 1.2$ *T*

It has been found that the overestimation of electron temperature is proportional to the real value of T_e. This relation can be described by the constant dimensionless ratio $R = T_{90}/T_o$. In-

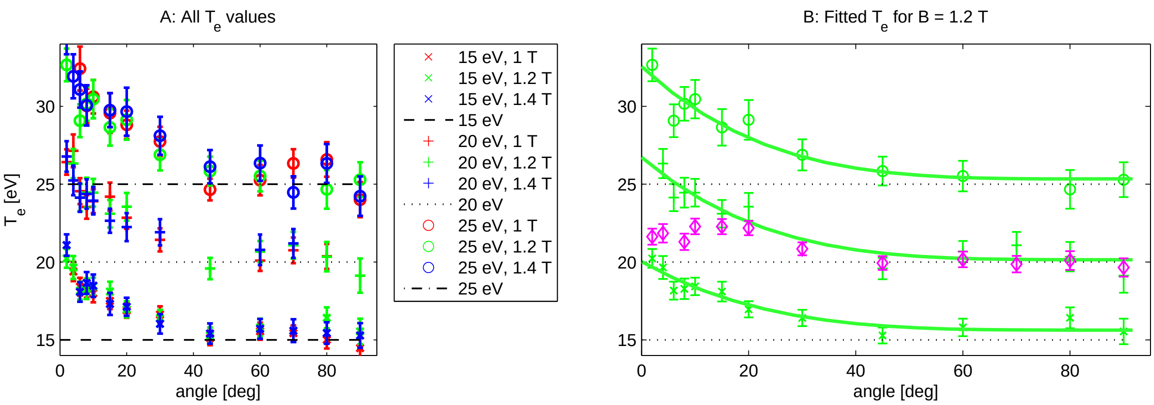

Figure 4: *A: Simulated T_e values for all scanbed combinations (red: $B_t = 1$ T, green: $B_t = 1.2$ T, blue: $B_t = 1.4$ T); B: Example of the fit with function (3) for $B_t = 1.2$ T. Magenta points show results for rounded probe.*

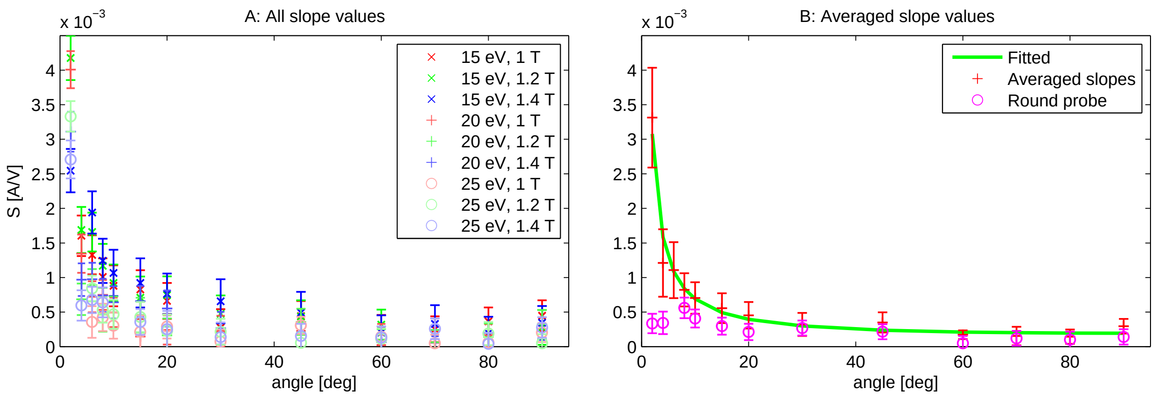

Figure 5: *A: Simulated S values for all scanned combinations; B: Fit of averaged slope values with function (4) compared with values given for the rounded probe case*

deed, all the simulated cases yield an average value $R = 20.0 \pm 1.4$. An example of fitted T_e using formula (3) is presented in Fig. 4 (B) along with the comparison to rounded probe result. Rounded probes simulations do not indicate such substantial differences from real plasma parameters when the inclination angle is small. The slope S of the ion branch of the I-V characteristic as defined in (2) does not depend on both B_t and T_e as it can be seen in Fig. 5 (A) but strongly depends on α. The following scaling is derived from all simulations:

$$S(\alpha) = D_1/\sin(\alpha) + D_2\,. \tag{4}$$

This equation matches the data with $D_1 = (1.042 \pm 0.089) \times 10^{-4}$ A/V and $D_2 = (9.0 \pm 2.6) \times 10^{-5}$ A/V.

Conclusions

Simulations of *I-V* characteristics were performed for flush-mounted and rounded probes using PIC technique for plasma conditions relevant to COMPASS tokamak and a wider range of magnetic field inclination angles. The flush probe shows significant dependency of measured quantities on the magnetic field inclination, while the rounding and larger size of the domed probe can partially compensate this effect.

This paper provides a scaling for the electron temperature which has a constant temperature independent parameter ratio R and scales as α^4 allowing to correct the value of measured T_e for any inclination angle.

In addition, it is shown that the angular dependency of the slope of the ion branch of the *I-V* characteristic does not depend on other parameters than α and scales as $1/\sin\alpha$.

Further studies will include density and size dependency scans for both rounded and rectangular flush-mounted probe geometry and comparison with experimental data. Comparison with the 3D version of SPICE2 code will be performed as soon as it is optimized to run extreme cases with small inclination angles.

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