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# Some experiments with the tunnel probe in a low temperature magnetized plasma

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**Abstract.** Experiments were performed using a Tunnel Probe (TP) inside the weakly-ionised plasma of the Linear Magnetized Plasma Device (LMPD). The TP is designed as a concave probe, which should annihilate the problem of sheath expansion in the ion branch of the I-V characteristic. As the ion saturation current is consequently well defined, the ion parallel current and plasma density can be more accurately calculated. Furthermore the ratio between the ion saturation currents on the two collectors (tunnel ring and the back-plate) can be used to derive the electron temperature. The TP has been repeatedly used with success on the former Castor and Tore-Supra tokamaks and will be used on the upgraded version of Tore-supra, namely the WEST tokamak, as well [1, 2]. It was however never used successfully in a low-temperature plasma.

We studied the feasibility of the TP use in a low-temperature plasma for direct measurements of plasma temperature and density. The various probe characteristic dimensions, such as the distance between the two collectors, the aperture size and the probe radius were varied to see influence of the individual probe feature. We also varied the level of magnetization of the charged particle species, the background gas pressure (which influences the electron energy distribution function), the plasma density (important for the ratio between the  $\lambda_D$  and the ion Larmor radius). The sensitivity of the probe alignment to the magnetic field lines was also studied. We found, that the ion saturation current does not necessarily saturate and that the probe works according to expectations only in a limited amount of regimes.

## 1. Introduction

Electric probes maintain a secure position among the diagnostic tools in plasma environments, be it in technological plasmas, fundamental research or nuclear fusion. They have been used with success from the starts of laboratory plasma physics, since they can provide good temporal and spatial resolution for measuring plasma parameters. Many different and advanced probes have been designed and put to use since the simplest of them, the Langmuir probe (LP), a small cylindrical piece of wire, was inserted into plasma for the first time. However, all probes inherently have some issues, as it is impossible to fulfil all requests regarding the probe size and shape at the same time.

One of the most persisting issues with the convex probe types (like the LP) is the non-saturation of the ion branch of the current-voltage characteristic (I-V). That is because the



sheath edge expands away from the probe surface with increased bias, effectively increasing the collection area for the ions. The increase of the sheath thickness is often in the same order of magnitude as the probe itself, which is due to the fact, that the probes are kept small to reduce its influence on the surrounding plasma. Even for larger, dome shaped probes active in tokamak divertors it was shown that the ion branch often does not saturate [1]. Since the ion saturation current is usually used in calculations of plasma density, Mach number and in measuring of the fluctuations in the tokamak scrape-off-layer, it is unwise to neglect the problem of the sheath expansion.

A new probe, a so-called tunnel probe, appeared in use on tokamaks a some years ago [2] and it manages to overcome the difficulties arising with the sheath expansion by strongly defining the collection area. The probe is of a rather simple concave design, reminding us of an inverted Langmuir probe.

Our goal was to construct a tunnel probe, that we would be able to use inside our Linear Magnetized Plasma Device (LMPD), located at Jožef Stefan Institute, Ljubljana.

## 2. Tunnel probe

Therefore, the tunnel probe was invented consisting of two collectors, a ring (tunnel collector) followed by the backplate. The collectors are electrically isolated from each other. The orifice of the probe should always be normal to the magnetic field in order to function properly. In that way, the surface of the tunnel shall always be parallel to the magnetic field and the backplate shall always be normal to the magnetic field.

The idea behind this design is that the probe's collectors enclosed in a cylindrical cavity can only be reached by charged plasma particles through that single orifice on the front of the probe. The expansion of the sheath (and pre-sheaths) with biasing of the collectors should therefore appear only inside the cavity.

The standard mode of operation of the TP is having both collectors biased highly negatively in order to repel all the electrons and collect all the ions coming through the orifice. There are two well defined parameters that you can obtain from a single measurement. The first one is obviously the parallel ion current density, where we can generally say that

$$j_{\parallel,+} = \frac{I_{probe}}{A_c} = Ze_0 n_k v_k \quad (1)$$

where  $Z$  is the ion charge number,  $e_0$  is the elementary charge,  $n_k$  and  $v_k$  are ion density and velocity at a designated point in front of the collector, where we are able to employ the conservation of the ion flux. In the most common approach we use the Debye sheath edge as the point, where we assume that the ion velocity equals the ion acoustic speed and the density evaluation is based on the Boltzmann factor. It is obvious, that even such a simplistic approach has an issue with defining the collection area  $A_c$ , when we move from a 1-d case to a realistic cylindrical case with the Langmuir probe, where the expansion of the sheath is present. The Child-Langmuir law can be used to describe the enlargement of the sheath due to the voltage between the bulk plasma and the collector. In the simplest form it relates the maximum current between planar electrodes and the voltage between them.

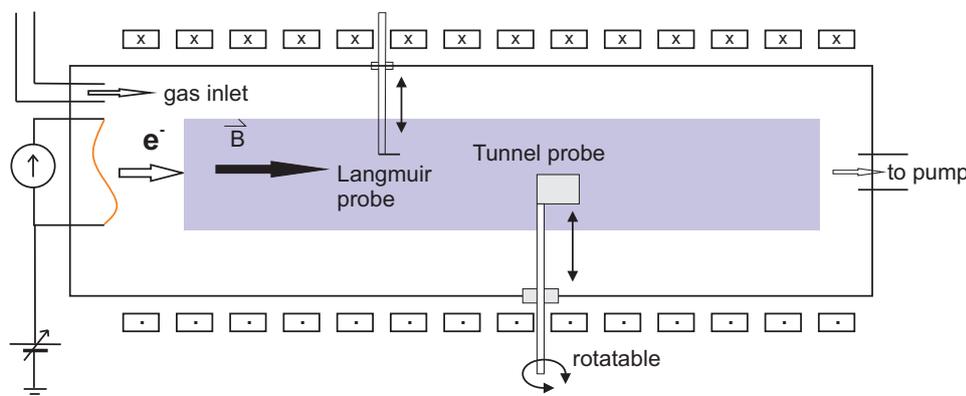
$$j_{CL} = \frac{4\epsilon_0}{9} \sqrt{2e_i/m_i} \frac{V_b^{3/2}}{d^2} \quad (2)$$

The second quantity, that we can extract from such measurement is the temperature of the electrons, which seems strange at first, since no electrons are collected at such negative bias. However, electrons do enter the probe cavity and the processes of plasma-wall transition are contained inside it. The ratio of the collection of the ions is defined by two competing

mechanisms, namely the magnetization of the ions and the electric force that drags the ions to the collectors. By increasing the magnetization we increase the chance that the ion entering the cavity will reach the back plate. On the other hand, if we increase the sheath thickness in front of the tunnel (with bias or by changing plasma properties), more ions will be deflected from their orbits into the ring collector.

### 3. Experimental setup

The experiments were conducted in the Linear Magnetized Plasma Device (LMPD), located at the Jožef Stefan Institute, Ljubljana, Slovenia. The plasma in LMPD is a hot filament discharge. The plasma chamber is a cylindrical tube with length  $l_{LMPD} = 1.5m$  and diameter  $d_{LMPD} = 17cm$ . The plasma is confined by an axial magnetic field of up to  $B = 0.4 T$  using solenoid with 14 coils.



**Figure 1.** Schematic of the Linear Magnetized Plasma Device - LMPD.

The LMPD is a flexible device, with 9 radial ports and 1 axial port. Different working gases ( $H_2$ ,  $He$ ,  $Ar$ ,  $O_2$ ,  $N_2$ ) can be used and the working gas pressure can vary from around  $p = 10^{-4}mbar$  to around  $p = 10^{-2}mbar$ . Discharge voltage  $U_d$  and discharge current  $I_d$  can also be varied. Using these parameters we can alter the electron energy distribution function (EEDF) and the density of plasma, which both, in turn, change the sheath properties inside the tunnel and affect the ratio of ion currents on the two collectors.

As we mentioned before, our main goal was to explore the possibility of use of the tunnel probe inside a low temperature plasma device for measuring the *true* ion saturation current density and the electron temperature. In order to do that, two tasks were in front of us: *i. proper saturation of the ion branch of the I-V* had to be reached, which is not a given in case of convex Langmuir probes and *ii. distinction in the ratio of currents collected by the two collectors* had to be reached for different electron temperatures, which would mean, that we can separate different plasmas.

Since the TP method is applied using a simple model with a firm set of limitations, it is the geometry of the probe that has to be morphed accordingly to fit the probe into the model. The original author of the probe made several hundreds of PIC simulations for various plasma parameters for the scrape-off layer (SOL) plasma of the Tore-Supra and CASTOR tokamaks and chose the most suitable dimensions of the probe. However, the typical SOL densities are about two orders of magnitude above the ones in LMPD, as are the ion temperatures and the magnetic field density.

Nevertheless, we were able to find a suitable operational regime in LMPD. Namely, one of the more important parameters, the degree of magnetization of the ions (ion Larmor radius  $r_{L,i}$  and the ion cyclotron pitch  $l_{c,i}$ ), can be reached due to the low temperature of the ions in the

LMPD (we estimate it to be around  $T_i = 0.05$  eV). Because of that we can reach the degree of magnetization similar to Tore-supra even with 10 times lower magnetic field. For that reason, we also chose *He* instead of *Ar* ions, since lower mass decreases the  $r_{L,i}$ . If magnetization of the ions is too low, none will reach the backplate.

Another important parameter is the Debye length of the plasma ( $\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e e^2}}$ ). Here again the low density of the LMPD plasma comparing to Tore-supra SOL plasma is significantly compensated by the lower temperature of its electrons. It is important, that the Debye length is significantly smaller than the diameter of the probe tunnel  $\lambda_D \ll 2r_{TP}$ , otherwise the sheath will expand throughout the cavity and the ions will not reach the backplate. Furthermore, with larger Debye lengths, the sheath can nonetheless start expanding outside of the probe's cavity.

In the Table 1, we have the comparison of relevant parameters.

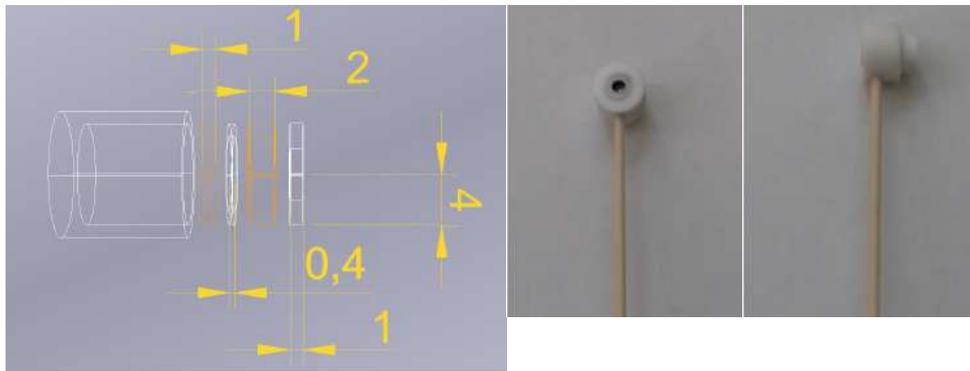
**Table 1.** Comparison of relevant parameters of Tore-supra SOL plasma and LMPD He plasma.

	Tore-supra	LMPD ( <i>He</i> )
B	3.5 T	0.4 T
$T_e$	20 eV	2 eV
$r_{L,i}$	$2.5 \cdot 10^{-4}$	$2 \cdot 10^{-4} m$
$l_{c,i}$	$1.6 \cdot 10^{-3} m$	$1 \cdot 10^{-3} m$
$n$	$5 \cdot 10^{18} m^{-3}$	$5 \cdot 10^{16} m^{-3}$
$\lambda_D$	$1.5 \cdot 10^{-5} m$	$5 \cdot 10^{-5} m$

Consequently we found the optimal dimensions for our configuration and they are written in Table 2. This dimensions are also presented in fig. 2.

**Table 2.** Dimensions of the tunnel probe used in the LMPD.

$l_{tunnel}$	$r_{tunnel}$	$r_{backplate}$	$r_{shutter}$	$l_{spacer}$
2 mm	3 mm	3 mm	2 mm	0.4 mm



**Figure 2.** Probe dimensions (left), pictures of the used probe (right).

Collectors in the probe were made of copper, the casing and the shutter were made of PTFE and the probe holder was made of  $Al_2O_3$ .

As mentioned before, the TP used in CASTOR and Tore-supra tokamaks was calibrated using data derived from PIC simulation. Since such data was not available for our configuration of probe and plasma, we had to "calibrate" the measurements to a different independent source for temperature measurements. We chose a Langmuir probe, which was installed in a different radial port inside LMPD at the same time, so we were able to do TP and LP measurements in practically the same plasma.

We altered the temperature of the electrons, or better - the EEDF, by changing the gas pressure. At higher pressures the EEDF is Maxwellian, since all the primary electrons suffer many collisions and get thermalized. By decreasing the gas pressure the temperature of electrons starts rising and then splits into two groups - essentially constructing a bi-Maxwellian distribution function. We have the thermalized group at around  $T_{e,l} = 2\text{eV}$  and the fast group of electrons at around  $T_{e,h} = 15 - 20\text{eV}$ .

So, which temperature are we then measuring with the TP? The deflection point for the ions, which defines the collecting area, is definitely somewhere close to the sheath entrance, which means, that according to theory [5], we should consider the effective screening temperature  $T_e^*$ . The  $T_e^*$  is the temperature which fulfils the Bohm criterion. It is defined by the following equation:

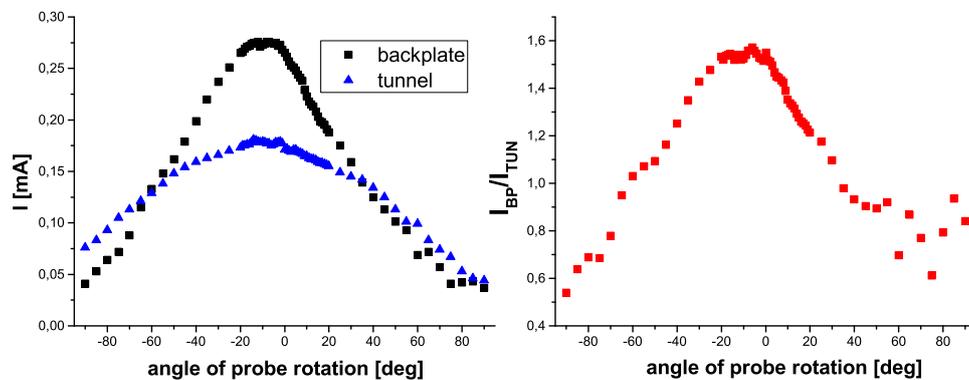
$$\frac{1}{n_j} \frac{dn_j}{d\Phi} = -\frac{e_0}{kT_e^*} \quad (3)$$

Here, the  $n_j$  is the sum of densities of all negative charge species. We made some estimates of the densities of the two electron groups using the first derivative probe method from LP [7]. Unfortunately the LP was oriented perpendicular to the magnetic field, therefore we had the magnetization parameter only around  $\Psi_0 \sim 40$ . From the measurements we saw, that the density of the fast electrons never exceeded 15% of the thermal population. According to [6] we could now neglect the fast group in the effective temperature calculations, meaning that our  $T_e^* = T_{e,l}$ .

## 4. Results and discussion

### 4.1. Susceptibility to the probe orientation

First thing of interest was the susceptibility of the measurements to the probe orientation with respect to the magnetic field. The probe should be oriented exactly along the magnetic field axis in order to work properly. We made a sweep from  $+90^\circ$  to  $-90^\circ$  with  $0^\circ$  being along the magnetic field. We can see the ion saturation currents to the backplate and the tunnel on the left graph in fig. 3. Here we can see a slight offset of the  $0^\circ$  position, which we corrected afterwards



**Figure 3.** Helium discharge,  $p = 4 \cdot 10^{-4}$ ,  $I_d = 2.2\text{A}$ ,  $U_d = 60\text{V}$ ,  $B = 400\text{mT}$ ,  $I_{sat}^-$ .

for subsequent measurements. Since the interesting quantity is in fact the ratio of both currents, we had a look at how it varies with the tilting angle (right graph in fig. 3)

Here we can see, that the ratio is not significantly affected around the middle position, giving us an angle of confidence of at least  $\pm 5^\circ$ , which is quite good.

#### 4.2. Measuring the ion parallel saturation current density $J_{\parallel}$ with tunnel probe

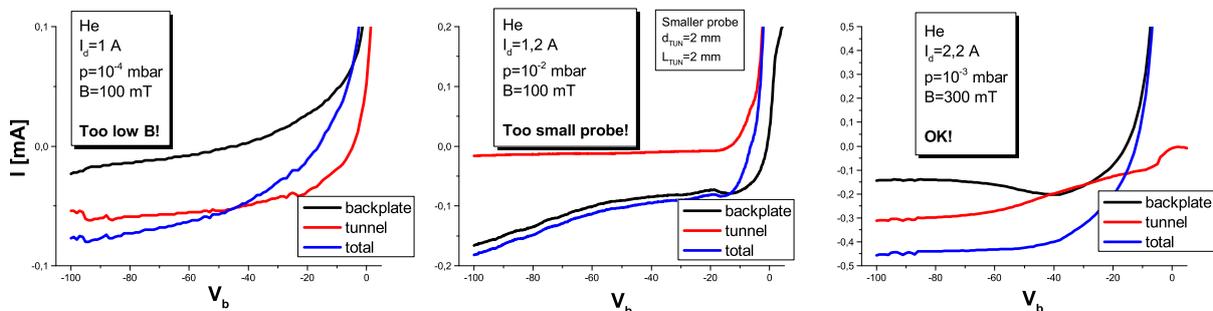
Next we shall present different cases of configurations of the TP and the plasma parameters in Fig. 4 to present the issues associated with the dimensioning of the probe. In the leftmost picture we can see, that the ion branch of the I-V does not saturate. Furthermore, we can notice that the current to the tunnel is significantly higher than the current to the backplate. This means that the probe diameter (same probe dimensions as presented in Table 2) is too small. However, significantly increasing the probe size would be contradictory to the rule of avoiding plasma perturbations by the probe. Such probe can therefore only work with higher magnetization of the ions. In the middle picture of fig. 4 we again do not have saturation of the ion branch. In this case the probe had a radius of only  $r_{\text{tunnel}} = 1$  mm. In this case we can see, that almost all ions are collected by the tunnel. We also tried the same probe with a longer tunnel, however it was very difficult to set the correct length where the current to the tunnel collector would be of a comparable size to the tunnel to the backplate.

We got best results when we used the probe with dimensions stated in Table 2. At high enough magnetic field densities we would then obtain I-V's similar to those presented in [4] as can be seen in the rightmost picture of fig. 4. We would now be able to correctly measure the parallel ion saturation current density.

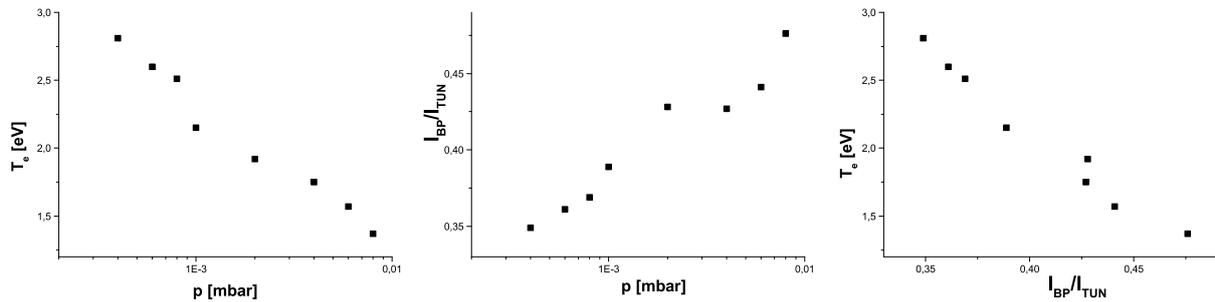
#### 4.3. Measuring the electron temperature $T_e$ with tunnel probe

Next up were the electron temperature measurements. Here we would proceed with simultaneous measurements of I-V's with the Langmuir probe and collector current ratio with the tunnel probe. We would vary the temperature by changing the gas pressure. The temperature would be obtained from the slope of the I-V characteristic. As discussed before, with lower gas pressure the temperature of the thermalized electrons would rise (as well as the effective screening electron temperature).

As we see in the first graph in fig. 5, there is a logarithmic relation between the electron temperature and the working gas pressure. Similarly, there is a logarithmic relation also between the gas pressure and the ratio of the currents to the tunnel collector  $I_{TUN}$  and to the backplate collector  $I_{BP}$ , respectively (middle graph in fig. 5). If we join these two graphs, we obtain the relationship between the electron temperature  $T_e$  and the current ratio  $I_{BP}/I_{TUN}$ . The resulting dependence could be described as linear, which means, that in principal it is possible to use the



**Figure 4.** Tunnel probe - 2 cases of wrong probe dimensioning (left and middle) and a case of finding the correct dimensions (right).



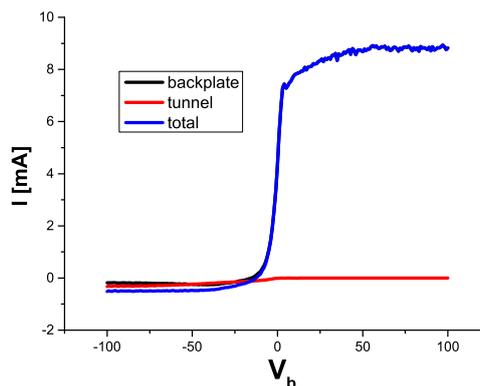
**Figure 5.** Measuring the temperature  $T_e$  using the tunnel probe. The  $T_e$  was varied by changing the gas pressure in the vessel. Helium discharge,  $p = 4 \cdot 10^{-4} - 8 \cdot 10^{-3}$ ,  $I_d = 2.2A$ ,  $U_d = 60V$ ,  $B = 400mT$ .

TP for direct measurement of electron temperature, as long as it has been calibrated to another method for electron temperature evaluation.

The results are as expected. For higher electron temperatures the Debye shielding is less effective. Because of that the sheaths around the tunnel collector expand more towards the axis of the tunnel and  $I_{TUN}$  rises in comparison to  $I_{BP}$ . The TP appears to work like that also in the tokamak. We realize that this is only one of the mechanisms, since collisions, return current heating etc. should be taken into account, but it matches the results nonetheless.

#### 4.4. Saturation of the electron branch of the I-V characteristic

Lastly we have had a look into the electron branch of the I-V characteristic to see if electron saturation is possible for this type of probe. This is something, which was not successfully done in the tokamak TP. In fig. 6 we see that electron branch does indeed saturate for high enough bias and as expected, the backplate collects almost all of the current, since the electron cyclotron radius is very small comparing to the probe radius. This opens new possibilities as electron saturation current could be used for calculations as well.



**Figure 6.** The full current-voltage characteristic with tunnel probe. Saturation of currents is seen in the electron and the ion branch. Helium discharge,  $p = 1 \cdot 10^{-3}$ ,  $I_d = 2A$ ,  $U_d = 60V$ ,  $B = 300mT$ .

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