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Advanced probe edge diagnostics for fusion devices

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Abstract. Summary paper on advanced probe edge diagnostics techniques for fusion devices is presented.

1. Introduction

Since the 1990s it became increasingly clear that boundary plasmas play a major role in magnetic fusion devices (MCD), and strongly relate to and even dominate central plasma processes. On the one hand, the conditions of the boundary plasma are crucial to obtain high fusion triple products; on the other hand, plasma-surface interactions, a sufficiently low impurity concentration in the fusion volume, heat removal and helium exhaust which directly relate to the boundary plasma, have emerged as equally important goals, and even more difficult to reach in the state of self-sustained thermonuclear burn. Successful resolution of these issues is critical to establish the viability of the MCD concept for a fusion power reactor.

All these requirements invoke a complex interplay of core plasma, boundary plasma, and atomic and surface physics. Hence, there is an ongoing effort regarding plasma diagnostics which is essential to improve our understanding of the MCD boundary. The employment of edge diagnostics has to take into account the specific properties of the plasma edge, taken here to be synonymous with the plasma boundary. In magnetic confinement devices the plasma is confined within closed magnetic surfaces, normally generated by a combination of fields due to external conductors and/or by currents flowing in the plasma. A thorough understanding of the processes occurring in the plasma boundary is necessary for the optimization and confident up-scaling of today's results to future plasma machines and finally to a fusion reactor.

The plasma boundary can be divided into two regions: the region inside the separatrix or the Last Closed Flux Surface (LCFS), and the scrape-off layer (SOL) which is outside the LCFS. All experiments prior to the 1970's were not large enough to produce core plasmas well separated from the influence of the walls; strictly speaking, up to that time only boundary plasmas have been investigated. Energy and particles are transported from the plasma core along steep gradients (scale lengths of order 10 mm) of plasma parameters characterizing the first region, the radiating layer, which is also characterized by the significant presence of neutral particles. Ions generating from the plasma core are lost to the surrounding wall structures and neutralized with reemission (recycling

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loop) of hydrogenic species and release of wall impurities by physical and chemical mechanisms. The species and properties (density, velocity, spatial distribution, radiation, etc) of the neutral particles in the radiating layer are determined by plasma-wall interaction and transport processes. The radial extent of this radiating layer inside the LCFS is determined by the ionization lengths of the neutral particles, and is of order 10 cm. The SOL refers to the region outside the LCFS where magnetic field lines are open, i.e. they intersect material surfaces like limiters or divertor plates; hence, the SOL is characterized by the competition between transport parallel and perpendicular to the magnetic field, and is directly related to the requirements for power and particle exhaust.

In contrast to the core plasma of a tokamak, axisymmetry does not exist for the boundary plasma which has a complex structure determined by the magnetic field topology, the very non-uniform walls, and the transport properties of the plasma along and across the magnetic field. In many cases the boundary structure is fully three-dimensional and various asymmetries can occur. Furthermore, the boundary plasma can be subject to rotations, auxiliary heating, pellet injection, magnetic field ergodization, etc. The experimental characterization of such a complex and turbulent edge plasma-where more quantities (such as neutral impurity and hydrogen influx ratio, flow speeds of hydrogen and impurity ions, heat- and particle outflux rates to surfaces, etc.) need to be known than in the central plasma imposes strong requirements to theoretical models as well as to diagnostics. Furthermore, due to the sometimes limited reproducibility of specific discharge conditions, it is necessary to measure simultaneously the (radial profile of) plasma parameters (e.g. using fast probe manipulators; see Section 2).

2. Plasma boundary diagnostics by probes

The understanding of the plasma edge and the control of edge conditions critically depend on measurements of the local plasma parameters. Reviews of techniques used for edge plasma diagnosis can be found in [1, 2]. Probe measurements (one of the earliest approaches in plasma diagnostics, dating back to I. Langmuir) complement spectroscopy by providing detailed profiles of local plasma parameters, as well as quantities like electric fields in the edge plasma which are difficult to determine spectroscopically, and the role of which in plasma confinement and exhaust is now widely recognized [3]. Furthermore, electrostatic turbulence-driven transport, which is generally believed to be the origin of anomalous edge particle transport in tokamaks, can only be fully evaluated with probes [4, 5]. In plasmas in which probes can survive, this diagnostic remains the easiest and most accurate way to measure local particle fluxes. This means that frequently only the edge is accessible, but its importance fully justifies the continued use of probes. It is wrong to assume that because of plasma-probe interaction probes are of less value than other diagnostic techniques: the presence of (much larger) surfaces in the plasma boundary as limiters, walls or divertor plates is inevitable.

Tokamak plasma diagnosis by electrical probes has been reviewed by Matthews [6]. Probe techniques for plasma edge diagnostics in magnetic confinement devices can be broadly divided into two categories: electrical (active) and surface collection (passive) methods. With electrical probes real time measurements are obtained as electrical currents drawn from the plasma; they encompass different types of Langmuir probes, and advanced electrical probes [6] such as gridded energy analyzers, mass spectrometers and probe arrays for the study of turbulence. With collector probes (not treated in this paper), on the other hand, the deposition of impurities on a collecting target or the implantation of particles within a surface are studied after exposure of the material to one or a number of discharges.

Langmuir probes are still one of the most commonly applied diagnostics in fusion devices as a relatively simple and inexpensive method to obtain time-averaged and fluctuating data from the edge plasma. The difficulty with direct plasma particle flux measurements is mainly in the understanding of the local perturbation of the plasma by the probe and of the relation of the local plasma parameters to the unperturbed plasma far from the probe. Different construction schemes are used to cope with the thermal load: (fast) moving probes [5], heat sink probes in good thermal contact with a big (cooled) heat sink; and flush mounted probes (in material surfaces which are exposed to the plasma at grazing incidence). The construction has to be compatible with the experimental demands; there is no optimal probe design suitable for every purpose. In Section III, the diagnosis of boundary plasmas will be illustrated, taking example by some types of advanced electrical probes developed on the tokamaks CASTOR and COMPASS at IPP in Prague (Czech Republic), and TEXTOR at Forschungszentrum Jülich (Germany) to measure plasma flows, T_e and T_i , and the plasma potential Φ_p.

3. Electrical probes

3.1. Plasma potential

Among the most important parameters is the electric space potential of the plasma which is usually called the plasma potential Φ_{pl}. Potentials can only be determined with respect to a certain reference potential, which is usually the wall. A Langmuir probe consists of a small electrode of various forms which is inserted into the plasma and externally biased with respect to the plasma potential. However, since the plasma potential is not directly accessible, the bias has to be applied with respect to the external reference electrode. A probe is called "cold" as long as it only passively registers the charge carrier fluxes towards it, but does not emit particles. The solid line in figure 1 shows a typical current-voltage characteristic, $I_p = I_p(V_p)$, of a cold probe in a conventional plasma, consisting of electrons and single-charged positive ions, where both particle species have Maxwellian velocity distributions [7]. At COMPASS it has been found [8] that in the vicinity of the inner and outer strike points of the divertor, the electron energy distribution can be approximated by a bi-Maxwellian with a dominating low-energy electron population (4-7 eV) and a minority of higher energy electrons (12-25 eV). The Langmuir probe characteristic is asymmetric, since the ion saturation current is much smaller than the electron saturation current, wherefore the floating potential V_{fl} of such a probe is more negative than Φ_{pl}. The reason for the strong discrepancy between the currents lies in the fact that the electrons have a much smaller mass than the ions and therefore a much higher mean velocity and average flux than those of the ions. The relation between the floating potential of a cold probe and the plasma potential in the case of a conventional Maxwellian plasma is well known from simple probe theory (T_e in eV):

$$\Phi_{pl} = V_{fl} + T_e \ln\left(\frac{I_{es}}{I_{is}}\right) \tag{1}$$

When the electron temperature T_e is known, it is in principle sufficient to measure the floating potential of a cold probe, and to calculate the plasma potential. However, on the one hand it is not so easy to measure T_e with sufficient accuracy, and on the other hand T_e can fluctuate during the measurement and there can be temperature gradients in the region of investigation (which is always the case in the edge region of a hot magnetized plasma). Moreover, also the ratio R between the ion and the electron saturation currents cannot always be determined precisely, especially in a strong magnetic field [7]. Furthermore, the entire characteristic of a cold probe shifts to the negative side and will therefore deliver erroneous results for the plasma potential whenever there is a stronger deviation of the electron velocity distribution function from a Maxwellian, e.g. in case of an electron drift or runaway electrons.

The two other characteristics in figure 1 show that the floating potential of a probe becomes identical to Φ_{pl} when the characteristic is symmetric. This can also be proven theoretically.

In principle there are two ways to achieve equal currents on both sides of the characteristic (i.e. R=1) and thereby a shift of the floating potential towards the plasma potential:

- Either compensate the plasma electron saturation current by an almost equally strong current on the negative (left-hand) side of the characteristic (dashed line in figure 1); see below: emissive probe.
- Or reduce the plasma electron saturation current on the positive (right-hand) side of the characteristic, until it becomes equal to the ion saturation current (dotted line in figure 1); see below: ball-pen probe.

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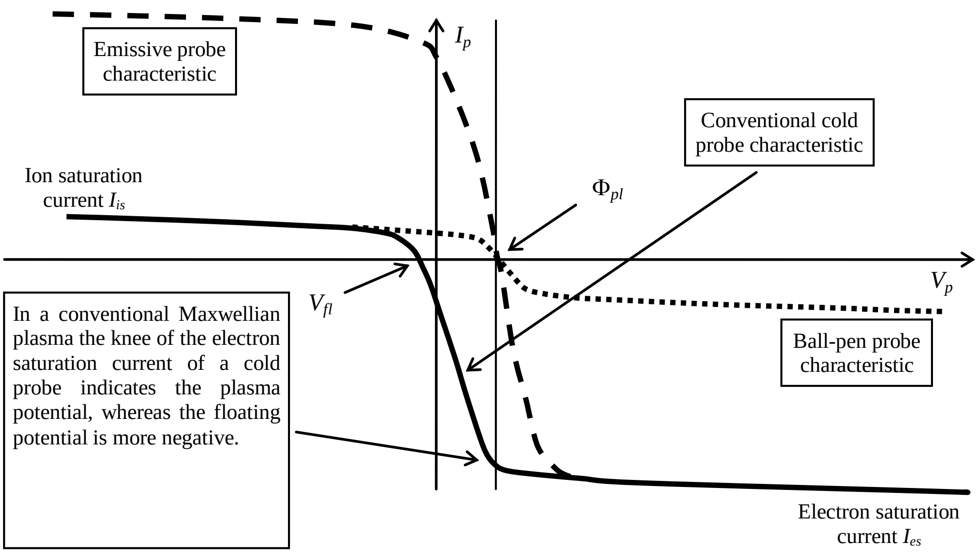

Figure 1. Typical current-voltage characteristics of a cold probe (solid line), of an emissive probe (dashed line), and of a ball-pen probe (dotted line) in a plasma with Maxwellian velocity distributions for the electrons and ions. Concerning the two latter probe types see below.

An electron emissive probe is usually realized by a small half-loop of tungsten or thoriated tungsten wire [7]. When such a probe is inserted into plasma and heated sufficiently, in the current-voltage characteristic the electron emission current Iem is observable on top of the ion saturation current I_{is} (cf. the dashed line in figure 1). This is due to the fact that a current of electrons emitted from the probe has the same sign as the current of positive ions flowing from the plasma to the probe. An emission current can flow as long as the bias of the probe is more negative than the plasma potential. By increasing the probe heating, the current on the left-hand side of the characteristic increases while the floating potential shifts to the right-hand side towards the plasma potential until a kind of saturation of this value is reached. Thus, when the emission current just compensates the electron saturation current (minus the ion saturation current, but this is usually negligible), the floating potential of such a probe equals the plasma potential: $V_{\mathrm{fl,em}} = \Phi_{\mathrm{pl}}$.

Up to now, emissive probes and heavy ion beam probes [9] were used for direct measurements of the plasma potential in tokamaks. However, the more widespread use of these techniques is hampered by various technical problems and peculiarities in the interpretation of the measured data. The heavy ion beam probe is a complex diagnostic, suitable for the measurement of the plasma potential in the interior plasma; moreover, its spatial resolution is limited. Directly heated emissive probes are rather fragile and of limited lifetime, and their exploitation on large fusion experiments is questionable. A laser heated emissive probe has been developed in view of fusion applications [10], allowing the use of materials like graphite for emissive wire probes, which are suitable for larger fusion devices.

An alternative approach to adjust R=1 which can be used only in magnetized plasmas, is the concept of the ball-pen probe (BPP) [11], approaching the principle of the Katsumata probe [12] (aiming at the measurement of the perpendicular ion energy distribution, and screening off electrons completely). The probe is designed so that the ratio R can be modified by changing the collecting areas for electrons and ions, taking advantage of the fact that the Larmor radii of electrons and ions are strongly different. The BPP has been developed on the small tokamak CASTOR (see schematic picture of figure 2). The probe consists of a conically shaped collector, which is shielded by an insulating tube made of boron nitride. The collector, which is movable inside the tube, is either completely shielded (h<0 in the left panel of figure 2) or partially exposed (h>0 in the right panel of figure 2) to the plasma. The probe collector can be biased by a swept voltage to estimate T_e and the ratio R from the I-V characteristics, or can be electrically isolated (floating) to measure the potential

V_{probe} and its fluctuations without the need of a power supply. In the ideal case, when the collector is hidden inside the tube, in principle only ions with sufficiently large Larmor radius can reach the collector surface, and the collecting area for electrons is zero. Consequently, the ratio $R = 0$. When the collector is moved outwards the electron current as well as R increase. At a certain collector position, the electron and ion currents are expected to be balanced (i.e., $R = 1$).

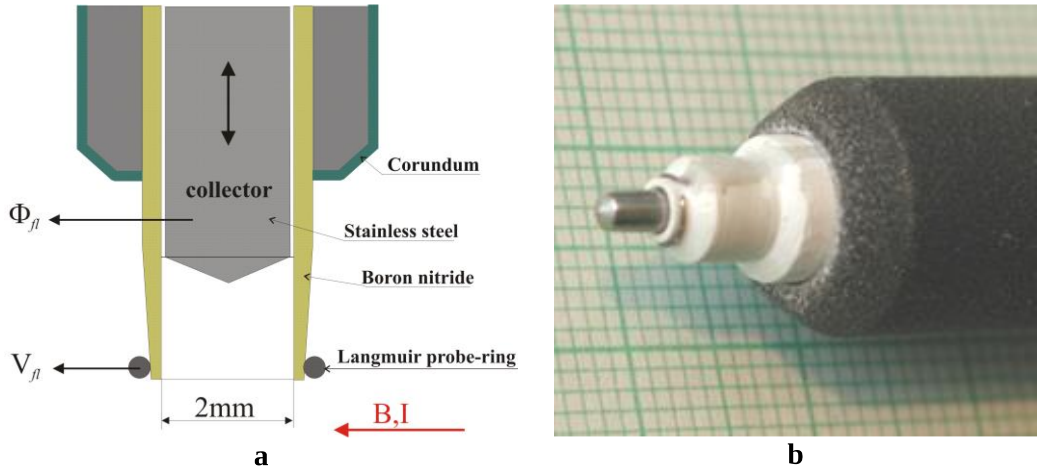

Figure 2. (a): Schematic of the ball-pen/standard Langmuir probe combination. The conical collector can be moved inside the boron nitride (BN) screening tube that acts as a shield for electrons, h is the position of the collector tip inside the tube relative to the top cross section plane of the shielding BN tube. The Langmuir probe is made of 0.2 mm diameter tungsten wire. (b): photograph (fully exposed collector).

The results of systematic BPP measurements of the floating potential V_{fl} and the ratio R on the collector position are plotted in figure 3-right. It is evident from the figure that ln(R) is always positive for any collector position. It indicates that electrons are present in the shadow of the shielding tube, and that the electron current is always higher than the ion current. This is in contrast with the simple model based on the electron and ion gyromotion along the magnetic field lines, which is described above. Nevertheless, ln(R) attains a minimum (i.e. ln(R)=0.1), when the tip of the collector is slightly inside the shielding tube ($h = -0.5\text{mm}$). In this situation the probe potential is close to the plasma potential. According to (1) the difference between plasma and probe potential is in order of volts in this case ($T_e \approx 10$eV). Although the electrons can in principle enter the BPP tunnel, it is assumed that a part of them with favorable of the velocity components parallel and perpendicular to the magnetic field, can bypass the tunnel. As such the tunnel works as a filter in velocity phase space, deforming the Maxwellian distribution of particle velocities, which is one of the assumptions of Langmuir probe theory. However, 2D cartesian Particle-In-Cell simulations [13] of a simplified model of the BPP have verified the validity of (1). When R is close to unity, the floating potential of the collector corresponds to the plasma potential obtained by the analysis of the first derivative of the IV characteristics.

It is seen from figure 3 that the value of the probe potential significantly decreases when the collector is more and more exposed to the plasma. When the collector is fully outside the shielding tube ($h \approx 1.5$mm), the probe operates as a conventional single Langmuir probe and measures the floating potential V_{fl}^{O}. It is interesting to note, that the probe potential is approximately constant and equal to the plasma potential Φ, when the collector is hidden inside the tube. The reason for this behaviour is not clear. However, it has practical importance for the direct plasma potential measurements by this probe, because the collector can be hidden at any position inside the shielding tube deeper than in the previous case ($h = -0.5\text{mm}$) and protected against high energy flux. Therefore, such a robust Katsumata-type probe [14] with flat collectors has been used on the larger devices RFX (reversed field pinch) in Padova and on ASDEX Upgrade in Garching. On ASDEX

Upgrade a quadrupole BPP (probe head with 4 BPPs with different retraction depth $h = -0.5\,\mathrm{mm}$, -1mm,-2mm, and-3mm) mounted on a fast reciprocating manipulator has been used for direct measurements of the edge plasma potential in ELMy H-mode discharges [15]. It was found that all the BPPs measure the radial profile of the plasma potential independently of the position of their collector, which is in good agreement with measurements on CASTOR.

The credibility of the BPP has been proved not only with emissive probe and self-emitting Langmuir probes during deep reciprocation on COMPASS and ASDEX Upgrade, but also the Doppler reflectometry measuring radial electric field on ASDEX Upgrade [16]. Its capability of resolving both plasma potential and electron temperature on the turbulence (microsecond) time scale was demonstrated [17] with results consistent with a model based on SOL interchange-driven turbulence transporting both energy and particles by blobs. In addition, in the limiter shadow, BPP seems to yield more credible T_e (sharply decreasing down to 1eV), where swept Langmuir probes show improbable and constant T_e~10eV.

3.2. Electron and ion temperature

Among the various diagnostic tools to measure the electron temperature T_e in a plasma, probes are the least expensive, simplest and most versatile. Probes can be used in most types of plasma, even in the edge plasma of medium-size tokamaks, and they allow localised measurements with good spatial resolution. The usual and best known method to determine T_e with a cold probe is to register the current-voltage characteristic (see figure 1) and to evaluate the exponential increase of the electron current in the retarding field region. A disadvantage of this method is its low temporal resolution which naturally is limited by the frequency with which the characteristic can be scanned. In principle also the difference between the floating potential V_{fl} and the plasma potential Φ_{pl} (1) contains the value of the electron temperature.

The Langmuir probe-ring attached around the BN tube of the ball-pen probe (figure 2) is fully exposed to the normal flux of electrons and ions from the plasma. Therefore, its floating potential corresponds to the conventional value. Thus the difference between the floating potentials of the correctly adjusted ball-pen probe (for $h \cong -1$ mm where $R(h) = 1$) and that of the Langmuir probe-ring can be used for calculating T_e [18] according to (1).

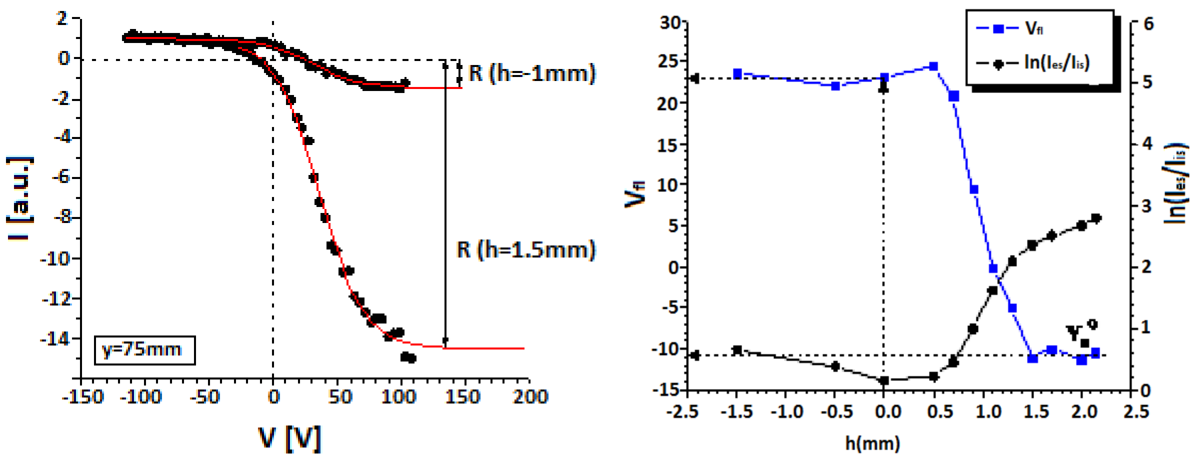

Figure 3. (a) -Example of I-V characteristics of the BPP in CASTOR for two different collector positions. The h value is negative when the collector is hidden inside the shielding tube. (b) - The variation of the floating potential V_{fl} and $\ln(R)$ with respect to the collector position. The probe head is at plasma radius 75 mm.

A new kind of robust Langmuir probe, the (segmented) tunnel probe (TP) has been developed for measurements of the electron and ion temperature [19, 20, 21].The probe is shown in figure 4 and consists of a hollow conducting tunnel (TUN) of 5 mm diameter that is closed at one end by an electrically isolated 5 mm diameter conducting back plate (BP). Both conductors are biased negatively to collect ions and repel electrons. The tunnel axis is parallel to the magnetic field B. Plasma flows into the orifice, and the ion flux is distributed between the tunnel and the BP [20]. The ratio $R_c = I_{TUN} / I_{BP}$ between the current to the tunnel (two segments shorted together) and that to the back plate, respectively, is determined by the thickness λ_{MS} of the magnetic sheath (MS) at the concave surface of the tunnel, and is therefore a strong function of T_e. The physics governing the TP is fundamentally different from that of a classical Langmuir probe (LP). The applied voltage on the LP is swept in order to measure a restricted part of the electron distribution function. The TP, on the other hand, is biased to a fixed potential that is sufficiently negative to repel all electrons. The temperature of the electrons is measured even though none are collected. The ion current for highly negative voltages is almost perfectly saturated, demonstrating the immunity of concave probes to sheath expansion effects, a problem that has always plagued convex LP applications [2,6]. Because it is concave, the electric field is contained inside the TP independent of the applied voltage. Furthermore, being oriented in the parallel direction, the TP does not collect the E×B component of the flow. The TP can operate in DC mode and therefore provides fast measurements of T_e (fluctuations), which is very important to understand transient heat transfer. Moreover, due to the clearly defined tunnel orifice, this probe is not subject to the uncertainties of collecting area from which classical convex probes suffer [2,6]. The tunnel radius should be roughly twice the thickness of the magnetic sheath. Precise self-consistent, two-dimensional kinetic "particle-in-cell" code XOOPIC [20] modelling is possible because of the simple TP geometry (classical Langmuir probes require extensive 3D simulations), and is used to determine the theoretical relation between the current ratio $R_c = I_{TUN} / I_{BP}$ and T_e. Qualitative agreement with classical LP measurements is found, but the electron temperature given by the TP is several times lower [22]. It has been found that this discrepancy can be caused by secondary electron emission. It suffices to correct the BP current assuming some reasonable value for the secondary electron emission coefficient. Suprathermal electrons can also contribute to the discrepancy since a swept LP is sensitive to it [23].

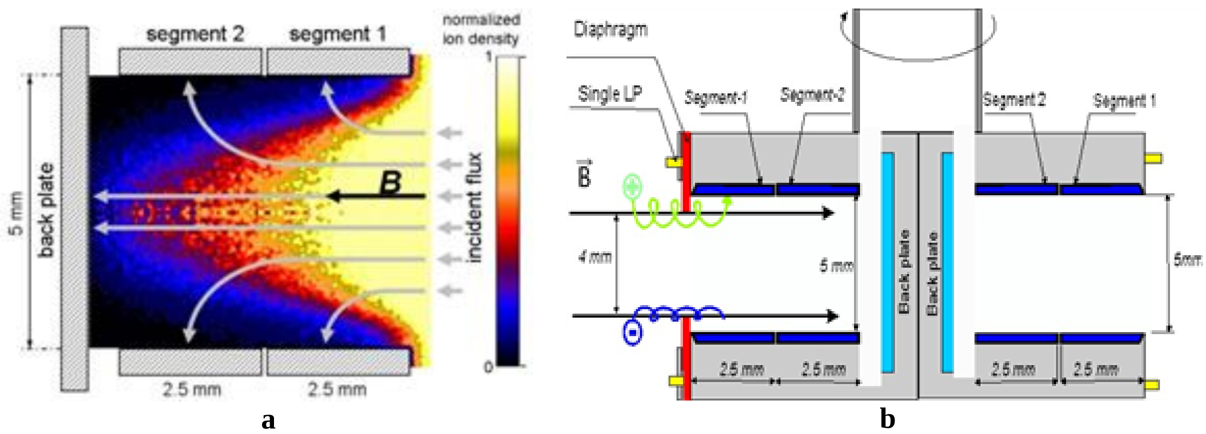

Figure 4. (a): schematic of the segmented tunnel probe (TP). The current collected by each of the three electrically insulated conductors is monitored separately. The ion guiding centre trajectories are shown by arrows. (b): modified TP; left hand side: ion-sensitive segmented Katsumata TP; right hand side standard segmented TP.

The ion temperature in the tokamak scrape-off layer is notoriously difficult to measure and thus rarely available. One of the most commonly applied probes for T_i measurements in the SOL is the retarding field analyzer (RFA) [6]. Unfortunately, since the RFA is working in a swept mode it does not allow the measurement of T_i with a sampling rate faster than a few milliseconds and thus cannot contribute to the measurement of fluctuations and transient phenomena like ELMs. Therefore, the development of a new probe diagnostics for T_i measurements in the SOL is an important issue.

The ions that flow into the orifice of the segmented TP (figure 4) are diverted onto the tunnel surface by the intense radial electric field in the magnetic sheath. XOOPIC simulations have shown that the axial distribution of ion flux onto the tunnel decays with a characteristic scale length that is determined by the relative strength of the radial acceleration of ions with respect to the incident parallel ion velocity. The latter is a function of the ion sound speed Therefore, by splitting the tunnel into two electrically insulated segments, the (parallel) ion temperature T_i can be found [24] from the ratio of ion flux to the first and the second segment, $R_c = I_{seg1} / I_{seg2}$.The advantage is that the TP is operated in DC mode and thus provides fast measurements of (parallel) T_i as well as of the parallel ion current density $J_{\|i}$.

The modified TP shown in the right panel of figure 4 allows to measure the perpendicular ion temperature [19]. In front of the entrance orifice of the tunnel an additional diaphragm can be mounted (at left-hand side only in figure 4), which transforms it into an ion-sensitive (Katsumata) probe, the modified Katsumata tunnel probe. Due to the diaphragm, which protrudes from the tunnel by 0.5mm around the entire circumference, the electrons should in principle not be able to reach the tunnel segments at any potential of all electrodes since their gyroradii are in the range of 20μm. The back plate is left floating, and the voltage on the diaphragm and both tunnel segments is swept simultaneously [24]. The segmented TP has reached the level of technical performance at which it starts to provide a wide range of useful scientific results and can be experimentally tested in larger fusion devices [19].

4. Magnetic probes

In the plasma interior magnetic fields are measured mostly using spectroscopic methods. However, particularly on small and medium sized fusion devices, magnetic probes are applied to study magnetic turbulence at the plasma edge. For this purpose standard pick-up coils as well as Hall sensors are used. Additionally, miniature Rogowski coils were successfully applied to measure edge current density profile and its fluctuations on CASTOR [25] and RFX [26]. From magnetic field measurements performed outside the plasma important properties like plasma current, energy content and MHD fluctuations together with their mode structure can be inferred. Such measurements utilize different types of coils. As the discharges became longer, the evaluation of B from its measured time derivative has become increasingly difficult, because the integration needs a precise determination of possible offsets in the preamplifiers [27].

Advancements in semiconductor technology hand in hand with a broad spectrum of industrial applications have driven development of new types of Hall sensors for magnetic measurements in recent years [28]. These sensors with their simple principle of operation and linear output voltage dependence on magnetic field are well established for many applications in experimental physics as well as in industry. A particular advancement is the availability of ‘integrated’ Hall transducers, where the sensing element together with the complex electronic circuitry is integrated on a single small chip with characteristic dimension of a few millimeters. The on-chip integrated circuits provide stabilization of the supply voltage, output voltage amplification, signal conditioning in order to suppress the high frequency noise, and elimination of temperature dependence of the sensor’s output. In particular, the output amplifier placed directly next to the sensing element significantly improves the frequency response and the signal to noise ratio. Because of the widespread industrial use of such sensors, their cost is rather low. Recently, Hall probes have been used to measure the absolute value of B directly together with its fluctuations in the boundary plasma of tokamaks [28, 29]. The strongest objection against the use of Hall sensors in the reactor type tokamak is their assumed vulnerability to radiation damage (in particular to the high neutron fluxes) [27]. The first results of irradiation tests of recently developed ‘radiation-hard’ Hall sensors [30, 31] were encouraging. The sensitivity of metal Hall sensors based on copper showed good agreement [32] with theoretically expected values and remained constant in the ITER expected temperature range between 100 and 250°C. Post irradiation characterization of samples irradiated up to a total neutron fluence of $2\cdot10^{18}$ cm^{-2} showed no effect on the sensitivity [32].

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