# PROBE DIAGNOSTICS FOR PLASMA EDGE CHARACTERIZATION

Guido Van Oost

*Department of Applied Physics*
*Ghent University*
*Rozier 44*
*B-9000 Gent, Belgium*
guido.vanoost@Ugent.be

## I. INTRODUCTION

The remarkable progress in magnetic fusion research in the past three decades has been obtained by building successively larger devices, more powerful heating systems, and mastering the art of plasma positioning, shaping and profile control and of wall surface treatment and impurity control.

The recent results obtained on JET (Joint European Torus), the largest tokamak in the world, have contributed significantly to this progress, and to date, values very close to breakeven have been obtained in reactor-grade D-T fusion plasmas on this device[1]. Furthermore these experiments have permitted, for the first time, to study in a realistic way effects of fast alpha particles on the plasma, thus providing crucial information for the design of a next step large tokamak, aimed at demonstrating the technical feasibility of fusion for large scale energy production. The success of the D-T experiments on JET and on the late American tokamak TFTR proves the scientific feasibility of controlled nuclear fusion.
In addition, important technical objectives such as tritium processing and remote handling have been reached.

Also other areas like longe pulse operation, power exhaust and control issues have seen impressive progress. Providing a steady state non-inductive current drive capability is one of the most significant issues facing tokamak research and this has been addressed by exploiting the current drive capabilities of auxiliary heating systems. New opportunities for further improvement in steady state operation and plasma performance are opening with the development of advanced tokamak scenarios [1,2]

## II. IMPORTANCE OF THE PLASMA EDGE IN MAGNETIC FUSION EXPERIMENTS

During the last decade it became increasingly clear that edge plasmas play a major role in magnetic fusion experiments, and strongly relate to and even dominate central plasma processes. There is e.g. a growing awareness that the plasma edge is determinant for the establishment of high confinement regimes such as H-mode and VH-mode[3,4]. The interaction of fusion plasmas with the surrounding walls influences the plasma performance in various ways and causes several technological constraints on the way to a steady state reactor. Therefore, there has been increasing emphasis on edge studies and a number of tokamaks like TEXTOR and the late Canadian tokamak TdeV officially committed to the study of plasma-surface interactions.

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 selfsustained thermonuclear burn. Successful resolution of these issues is critical to establish the viability of the tokamak confinement concept as a fusion power reactor.

The control of the power which will not be absorbed by the plasma, radiated to the first wall, nor deposited by the fusion neutrons in the reactor blanket structure or blanket material, remains one of the most challenging problems. Heat fluxes of about $5MW/m^2$ on plasma-facing components like divertor plates of the next step tokamak are typical, and values as high as $20MW/m^2$ can be expected under abnormal conditions. Furthermore, the final power exhaust concept has to be compatible with the requirements of good core confinement and of sufficient particle exhaust: the efficient removal of the ‘helium ash’ as the alpha particles are called once they become thermalized, is essential to prevent the helium

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concentration from building up to such a high value that the D-T fuel becomes too dilute and the fusion 'fire' is extinguished[17].

All these requirements invoke a complex interplay of core plasma, edge plasma, and atomic and surface physics. Hence, there is an ongoing effort regarding edge diagnostics which is essential to improve our understanding of the tokamak boundary.

## III. BOUNDARY OF A TOROIDAL DEVICE

The employment of edge diagnostics has to take into account the specific properties of the plasma edge, taken to be synonymous with the plasma boundary.
In magnetic confinement devices the plasma is confined within closed magnetic sufaces (see Fig.1), normally generated by a combination of fields due to external conductors and by currents flowing in the plasma.

The Last Closed Flux Surface (LCFS) or separatrix is determined by either mechanical solid limiters or magnetic limiters (divertors) which protect the wall from excessive heat loads. The main disadvantage of a limiter is that impurities leaving its surface as neutrals penetrate into the confined plasma and become ionized there. In a divertor, the LCFS is defined solely by the magnetic field and plasma-surface interactions are remote from the confined plasma. Whether impurity shielding due to a divertor is sufficiently effective to justify the extra complexity and expense of the divertor has still to be resolved.

Three different definitions can be given for the plasma boundary: (1) the region in which plasma transport parallel to the magnetic field is important; (2) the region characterized by a significant presence of neutral particles; and (3) the non-fusion part of the plasma volume. All experiments prior to the mid-seventies were not large enough to produce core plasmas well separated from the influence of the walls; strictly speaking, up to that time only edge plasmas have been investigated.

The plasma boundary can be divided into two regions: the region inside the LCFS, and the scrape-off layer (SOL) which is outside the LCFS. 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 loop) of hydrogenic species and release of wall impurities by physical and chemical mechanisms (Fig.2).

The term recycling summarizes all processes that are involved in the exchange of particles and energy between the plasma and material surfaces. Recycling is also an important contribution in fueling the core plasma with particles, and in most experimental cases this dominates over the fueling by external means such as gas puffing. The wall can thus be regarded as a sink as well as a source for charged particles and energy. A thorough understanding of the processes involved is necessary for optimization and confident up-scaling of today's results to future plasma machines and finally to a fusion reactor.

The species (hydrogenic particles and impurities) and properties (density, velocity, spatial distribution, radiation…) of the neutral particles in the radiating layer are determined by plasma-wall interaction and transport processes; therefore, the measurement of neutral particle properties is essential to understand these 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 edge plasma which has a complex structure determined by the magnetic field topology, the very nonuniform walls, and the transport properties of the plasma along and across the magnetic field. In many cases the edge structure is fully three-dimensional and various asymmetries can occur. Furthermore, the edge 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.

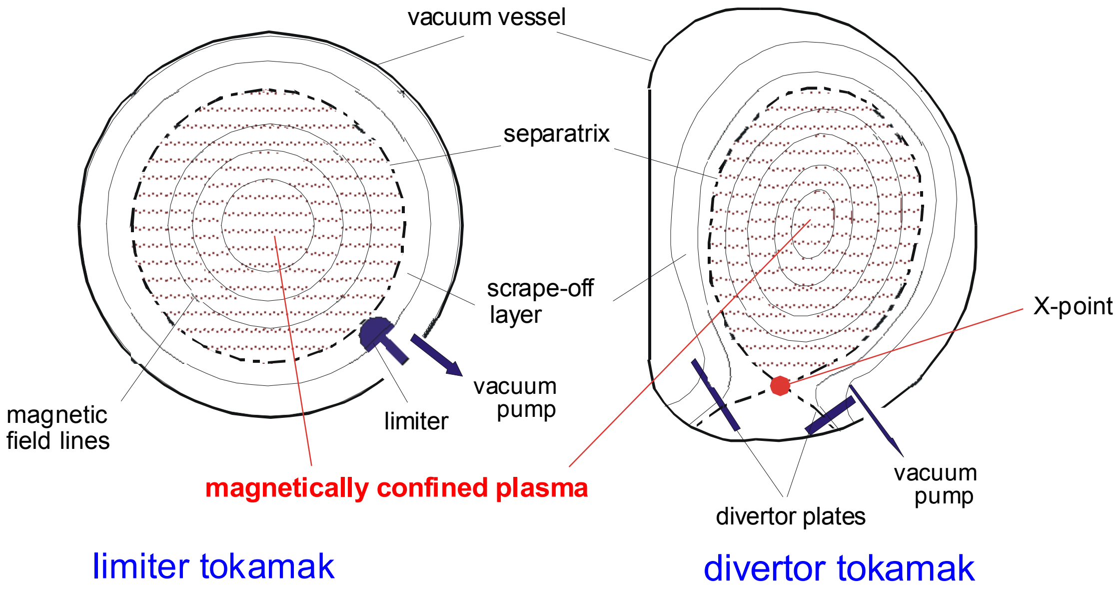

*Fig. 1: Schematic diagram of poloidal flux surfaces in a tokamak (a) with a limiter and (b) with a divertor. The toroidal field is normal to the paper*

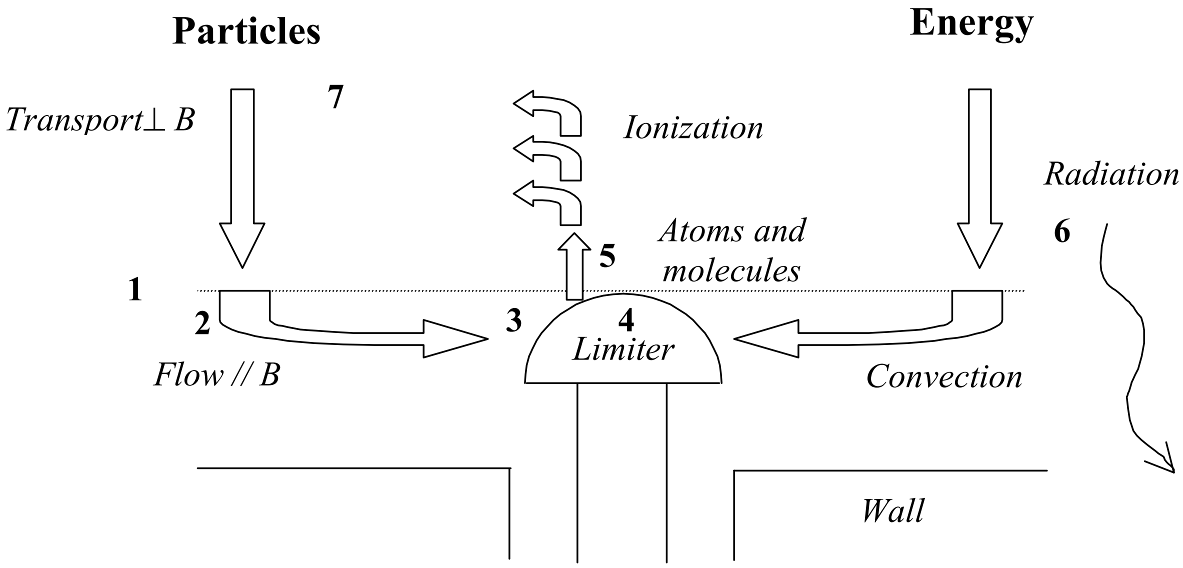

*Fig.2 : Schematic overview of processes in the plasma boundary (taking example by the case of a limiter machine): 1) Magnetic structure, 2) Transport in the SOL, 3) Particle- and heat flux to the wall, 4) Interaction mechanisms and impurity release, 5) Transport of neutral particles and ions, 6) Line radiation, 7) Coupling edge-core. (courtesy U. Samm)*

- Debye Length: $\lambda = 8.510^{21}\frac{T_e^2}{n_e}$ $[m, keV]$
- Velocity: $v_i = 3.09\,10^5\sqrt{\frac{T_i}{A}}$ $[m/s]$
- Mean free path: $\lambda = 2.3510^5\sqrt{\frac{T_e}{n_e}}$ $[m, keV]$
- Gyroradius: $\rho_i = 4.5710^{-3}\sqrt{\frac{m_i}{m_p}}\frac{\sqrt{T_i}}{B}$ $[m, keV, tesla]$

| *T [eV]* | n [$m^{-3}$] | *Vp [m/s]* | $\lambda_D$ [mm] | $\lambda$[m] | $\rho_p$ [mm] |
|---|---|---|---|---|---|
| 1000 | $10^{20}$ | $3.09\ 10^5$ | 0.024 | 85 | 2.28 |
| 100 | $10^{19}$ | $9.77\ 10^4$ | 0.024 | 8.5 | 0.72 |
| 50 | $10^{20}$ | $2.19\ 10^4$ | 0.002 | 0.21 | 0.16 |

***Table 1: Characteristic parameters***

$$\Gamma = n_e c_s \qquad \textit{with} \quad c_s = 1.3810^4\sqrt{\frac{T}{A}} \qquad [m/s]$$

Example (Hydrogen): equivalent current J = Γ.e

| $n_e$ [$m^{-3}$] | $T_e$ [eV] | Γ [1/$cm^2$s] | J [A/$cm^2$] |
|---|---|---|---|
| $5.10^{18}$ | 20 | $3.\ 10^{19}$ | 4.9 |
| $10^{19}$ | 50 | $9.8\ 10^{19}$ | 15 |
| $10^{19}$ | 100 | $1.4\ 10^{20}$ | 22 |
| $10^{20}$ | 3 | $2.4\ 10^{20}$ | 38 |

***Table 2: Particle flux***

| **Quantities of interest** | **Some related questions** | **Method of measurement** |
|---|---|---|
| $n_e$ and $T_e$ profiles | gradients, asymmetries | atomic beams, electrical probes |
| identification of impurities | impurity sources | emission spectroscopy, mass spectrometry |
| neutral particle fluxes | sources, recycling, confinement | emission spectroscopy |
| particle velocities | release mechanisms, ion temperature | Doppler spectroscopy, LIF |
| spatial distribution of neutrals and ions | particle transport, screening of SOL impurity level | emission spectroscopy,<br>charge exchange spectroscopy |
| particle density | particle transport | LIF |
| plasma flow | flow characteristics<br>plasma rotation, drifts | electrical probes |
| fluctuations of $n_e$ and $T_e$ | turbulent transport | electrical probes, atomic beams |

***Table 3***

## IV. PLASMA EDGE DIAGNOSIS BY PROBES

The understanding of the plasma edge and the control of edge conditions critically depend on measurements of the local plasma parameters. Typical parameters are given in Tables 1&2.

Reviews of techniques used for edge plasma diagnosis can be found in [5,6]. Table 3 gives a survey on quantities of interest to be measured, some questions related to them and the appropriate method of measurement [7].

Optical methods (which will not be treated here) provide a large variety of measurements at the plasma boundary. In particular emission spectroscopy[8] with intrinsic plasma particles is very well suited for robust and routinely operated diagnostics. The proper choice of observation geometry taking into account the 3D character of particle transport and radiation is crucial for the interpretation procedure. The method of Laser Induced Fluorescence (LIF)[9] can overcome many of these problems, but is technically more difficult. Atomic beam supported emission spectroscopy provides a large variety of measurements and in particular high space- and time resolution [10]. Beam divergence and the energy of the beam particles (required penetration depth) are the key parameters with respect to the spatial resolution.
Tokamak plasma diagnosis by electrical probes has been reviewed by Matthews [11].

Probe measurements- one of the earliest approaches in plasma diagnostics- 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[12]. 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.
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 makes the prospects bright for 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 surfaces in the plasma boundary as limiters, walls or divertor plates is inevitable.

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 Langmuir probes, and advanced electrical probes[11] such as gridded energy analyzers and mass spectrometers. In collector probes, 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 tokamak discharges.
Langmuir probes are still one of the most commonly applied diagnostics in tokamaks 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, 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 the following, the diagnosis of tokamak boundary plasmas will be illustrated. Because of the affiliation of the author, the examples will be mainly from the tokamak TEXTOR.
In collaboration with the University of California at San Diego, a fast scanning probe has been developed on TEXTOR, which is suitable for today's high performance machines, where the high plasma temperature and density would erode the metal tips and contiminate the plasma with high-Z materials[13]. This fast scanning probe drive design (see Fig. 3) has three main new features:
(1) detachable and modular probe head for easy maintenance, (2) a combination of high heat flux capability, high bandwidth, and low-Z materials construction, and (3) low weight, compact, inexpensive construction. The probe is mounted in a fast pneumatic drive in order to reach plasma regions of interest and remain inserted long enough to obtain good statistics while minimizing the heat flux to the tips and head. The drive is pneumatic and has been designed to be compact and reliable to comply with space and maintenance requirements of tokamaks. The probe described (see Fig. 4) here has five tips which obtain a full spectrum of plasma parameters: electron temperature profile Te(r), electron density profile $n_e(r)$, floating potential profile $V_f(r)$, poloidal electric field profile $E_\theta(r)$, saturation current profile $I_{sat}(r)$, and their fluctuations up to 3 MHz.

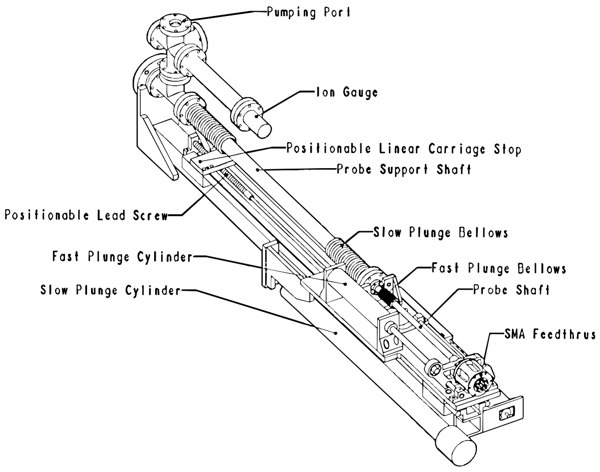

*Fig.3 Fast scanning probe view showing the cylinders for the fast and slow plunges* [13]

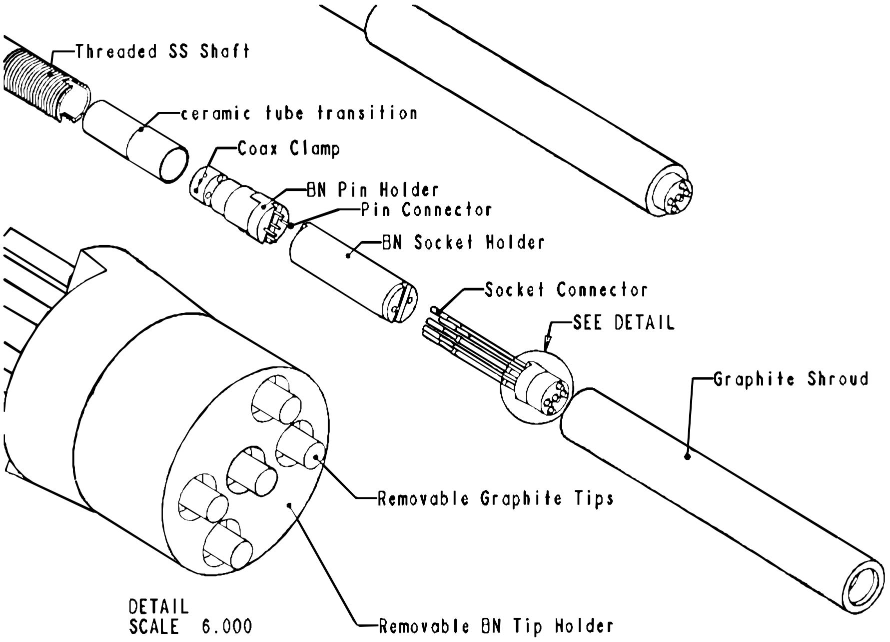

*Fig. 4. Probe head assembly and detail of boron nitride tip holder showing the modular construction which allows fast tip replacement* [13].

A Mach probe has been developed on TEXTOR. The geometry is shown in Fig. 5. The Mach probe is located in the equatorial outboard plane of TEXTOR. The probe can be moved radially between discharges. The angle of the probe surfaces with respect to the magnetic field, is changed on a shot-day basis. The probe consists of two graphite collectors separated by a boron-nitride insulator. The Mach probe is used in a double probe configuration, the sweeping frequency of the potential applied between the two collectors is 200Hz.A new method for the determination of poloidal plasma flow was developed[14], using this probe and plasma edge biasing[15], and was demonstrated through an experimental verification of the generalized Ohm's law[12] (see Fig. 6 and lecture of G. Van Oost, these proceedings).More advanced so-called Gundestrup probes[18,19] (used on the tokamaks TdeV, Tore Supra, CASTOR, TEXTOR, ISTTOK) can measure a polar diagramme of plasma flows and their impact on turbulence[20] .

Recently, advanced probes like the "tunnel probe" have been developed and tested on the CASTOR tokamak for the determination of electron and ion temperatures and their fluctuations[21,22].

In collaboration with the Royal Institute of Technology in Stockholm a surface collector probe for the study of ion fluxes in the SOL of TEXTOR has been developed[16].The method is based on the exposure of a solid surface to the SOL plasma and investigation of the deposit collected by surface sensitive spectroscopy and high resolution microscopy: ion beam analysis to measure areal densities and depth distribution of deposited atoms and atomic force microscopy to study the deposit structure. This experimental procedure enables to study the transport of impurity ions in the near wall region and processes of plasma – wall interaction, such as erosion and deposition. It may also be useful for testing candidate materials for the reactor first wall. A schematic view of the collector probe system and its control units is shown in Fig.7.

REFERENCES

[1] M. Keilhacker, Plasma Phys. and Contr. Fus. **41**, (1999) B1

[2] C. Gormezano, ibidem, B367; R.Wolf, these Proceedings

[3] K.H. Burrell, Phys. Plasmas **4** (1997) 1499

[4] M. Tendler, Plasma Phys. and Contr. Fus. **39** (1997) B371

[5] P.C. Stangeby and G.M. McCracken, Nucl. Fus. **30** (1990) 1225

[6] I. H. Hutchinson "Principles of plasma diagnostics", Cambridge University Press (1987 & 2002)

[7] U. Samm, Transact. of Fus. Technol. **33** (1998) 338

[8] A. Pospieszczyk, these Proceedings

[9] A.J.H.Donné, these Proceedings

[10] B. Schweer, Plasma Phys. and Contr. Fus. **37** (1995) A87, and these Proceedings

[11] G. F. Matthews, Plasma Phys. and Contr. Fus. **36** (1994) 1595

[12] G. Van Oost, these Proceedings

[13] J. Boedo et al., Rev. Scient. Instr. **69** (1998) 2663

[14] H. Van Goubergen et al., Plasma Phys. and Contr. Fus. **41** (1999) L17

[15] R.R. Weynants, G. Van Oost et al., Nucl. Fus. 32 (1992) 837

[16] M. Rubel, P. Wienhold, in Contributions to High-Temperature Plasma Physics (eds. K.H. Spatschek and J. Uhlenbusch) Akademie Verlag, Berlin, p. 445 (1994)

[17] E. Rebhan and G. Van Oost, these Proceedings

[18] J.P. Gunn et al., Phys. Plasmas **8** (2001) 1995

[19] J.P. Gunn et al., Czech. J. Phys. **51** (2001) 983

[20] G.Van Oost et al., Plasma Phys. and Contr. Fus. **45** (2003) 621

[21] J.P. Gunn et al. , 19th IAEA Fusion Energy Conference, Lyon (2002), paper IAEA-CN-94/EX/P1-06

[22] R. Schrittwieser et al., submitted to Contr. Plasma Physics

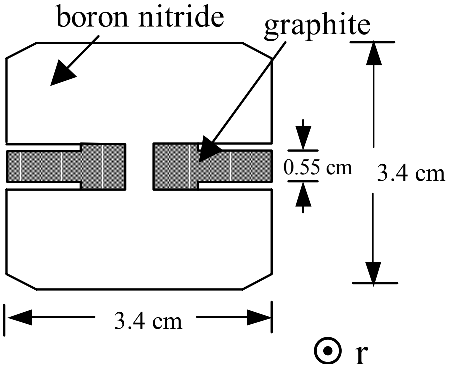

*Fig.5: Mach probe: two graphite collectors are flush-mounted in an isolating boron-nitride body.*

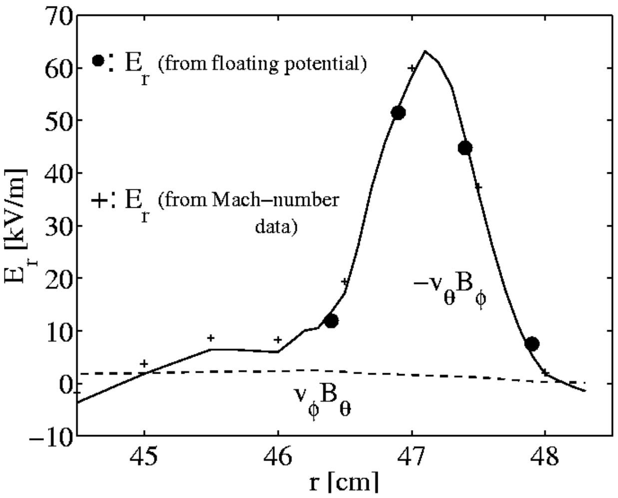

*Fig. 6: $E_r$ vs r: measured $E_r$ (●), calcuted $E_r$ (+), $-v_\theta B_\phi$ (plain curve), $v_\phi B_\theta$ (dashed curve)*

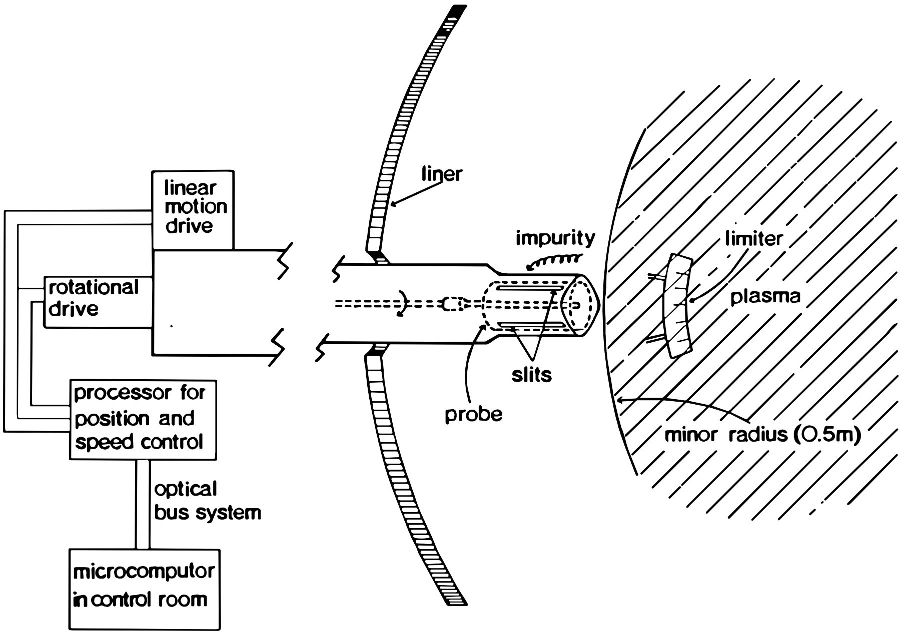

*Fig. 7 Collector probe and its control units*