Studies of edge plasma with the help of a movable Langmuir probe at the Globus-M spherical tokamak

V A Tokarev¹², V K Gusev¹, N A Khromov¹, M I Patrov¹, Yu V Petrov¹, and V I Varfalomeev¹

¹ Ioffe Institute, Saint-Petersburg, Russia
² E-mail: valentin.tokarev@ioffe.mail.ru

Abstract. The results are presented from the edge plasma studies performed with the help of a new nine-pin Langmuir probe. The design features of the probe head are discussed. The probe was used to measure the electron density, electron temperature and the Mach number profiles. The SOL width was determined and the power decay length was compared with the corresponding value calculated with the help of the known scalings.

1. Introduction
In the toroidal magnetic devices, the plasma core is surrounded by a region with open field lines connected to the divertor plates; this region is named the scrape-off layer (SOL). The processes occurring in SOL and at the plasma boundary are very important in terms of achieving the steady state burning fusion plasma [1]. They also affect the global properties of plasma confinement. Thus, the studies of the edge plasma parameters are very relevant.

The Langmuir probes (LPs) are successfully used in tokamaks and stellarators to investigate the edge plasma. LPs can measure such plasma parameters as the ion saturation current \( I_{is} \), electron temperature \( T_e \), and floating potential \( V_f \). If the \( I_{is} \) and \( T_e \) parameters are known it is possible to calculate the electron density \( n_e \). To estimate the radial (\( E_r \)) and poloidal (\( E_\theta \)) electric fields, the floating potential signals are used. These signals were recorded by the pins, which are installed at certain distances from each other in radial and poloidal direction [2, 3]. LPs are also successfully applied for studying fluctuations of the measured parameters [4].

In this work we present results from the edge plasma studies performed with the help of a movable Langmuir probe with a nine-pin head.

2. Experimental setup
Experiments were carried out at the spherical Globus-M divertor tokamak: a minor radius is \( a = 0.24 \) m, a major radius is \( R = 0.36 \) m, and the toroidal magnetic field near the plasma axis is \( B_T \approx 0.4–0.5 \) T. In the last experimental campaign, a new Langmuir probe was installed in the outer midplane of the machine from the low field side. The probe has a nine-pin head, which allows measuring the following parameters: the floating potential, ion saturation current, electron temperature, electron density and the Mach number. The graphite pins are mounted inside a boron nitride insulator. The probe head is protected by a graphite shield. The probe is driven by a linear magnetic manipulator which provides the shot-to-shot radial displacement of the probe and its rotation around the central axis.
The head design is shown in Figure 1; its specific feature is the possibility to replace the worn out components without disturbing the others. The necessary alignment of the head components is ensured by the tongue-and-groove construction. The pins are attached to the insulator matrix (see Figure 1 (5)) by means of a thread connection. At the same time, such attachment provides a tight connection between the pins, electric contacts and (see Figure 1 (4)) wires, which are installed on the probe rod.

**Figure 1.** General view and schematic of the nine-pin probe head. (1) graphite shield, (2) insulator, (3) graphite pins, (4) molybdenum electric contacts, (5) additional insulator, (6) insulator for wires, (7) connector with the rod, and (8) rod of the probe driver.

Diameter and height of the graphite pins are 1.6 mm and 1.5 mm, respectively; five of them (Single, Isat, V+, Vf1, Vf2) are installed on a lug with a height of 1.5 mm.

In the basic configuration of pins, the Vf1, Vf2, Vf3, Vf4 pins measure the floating potential. The Vf3 and Vf2 electrodes with different radial coordinates measure the radial electric field $E_r$, and the Vf1 and Vf4 pins with different poloidal coordinates measure the poloidal electric field $E_\Theta$. Three pins (Isat, Vf2, V+) form a triple probe which measures the electron temperature and density; and the Mach1 and Mach2 pins form the Mach probe [5].

### 3. SOL width measurements

The power decay length $\lambda_q$ in the SOL is one of the main factors that determine power flux density falling onto the divertor plate. Moreover, $\lambda_q$ is one of the crucial parameters for operation of the future fusion devices. However, no theoretical models are developed to predict the power decay length [6]; therefore, various scalings are used to estimate it.

Taking into account that, at the Globus-M tokamak, the parameters $R$, $B_T$ and plasma current $I_p$ are relatively small, the measurements of the power decay length are very demanded, because they supplement the available database.

The electron temperature and density decay lengths were determined in two series of deuterium shots (see Figure 2).

Measurements of the plasma profiles were performed in two series of shots with lower single null configuration. The first one includes shots #37068–37074 with $B_T = 0.4$ T, line averaged density $<n_e> \sim 2 \times 10^{19} \text{ m}^{-3}$, $I_p \sim 180$ kA, and the second series includes shots #37062–37066 with $B_T = 0.5$ T, $<n_e> \sim 2 \times 10^{19} \text{ m}^{-3}$, $I_p \sim 225$ kA.
Figure 2. Electron temperature and density profiles for a series of shots #37068-37074, #37062-37066.

The power decay length was calculated according to a simple SOL approach using the following expression [7]:

$$\lambda_q = \left( \frac{1}{\lambda_{n_e}} + \frac{3}{2 \lambda_{T_e}} \right)^{-1},$$

where $\lambda_{n_e}$ and $\lambda_{T_e}$ are decay lengths of the electron density and temperature, respectively, obtained from experimental data. The results obtained were compared with the Goldston estimate [8] and Eich scalings [6, 9].

The Goldston estimate for $n_e$ decay length is [8]:

$$\lambda_{n_e}^{\text{Goldston}} = \frac{2 \rho_p}{R},$$

where $\rho_p$ is the ion Larmour radius in the poloidal magnetic field.

Eich scaling based on the conventional tokamaks database is expressed as [6]:

$$\lambda_q^{\text{Eich-2011}} = 0.73 B_T^{-0.78} (T) q_{\text{cyl}}^{1.2} p_{\text{SOL}}^{0.1} (MW) R^0$$

where $q_{\text{cyl}}$ is the cylindrical safety factor given by the following expression:

$$q_{\text{cyl}} = \frac{2 \pi \alpha B_T}{\mu_0 I_p} \left( 1 + \frac{\kappa^2}{2} \right),$$

where $\varepsilon = a/R$ is aspect ratio and $\kappa$ is elongation.

$P_{\text{SOL}}$ is power that crosses the separatrix; it could be estimated as $P_{\text{SOL}} \approx P_{\text{OH}} - P_{\text{rad}} \cdot P_{\text{rad}}$ and it is about 20% in deuterium plasma of the Globus-M tokamak [10].

The advanced Eich-2013 scaling is expressed as follows [9]:

$$\lambda_q^{\text{Eich-2013}} = 2.7 \cdot 10^{0.45} \left( \frac{1 + \frac{\kappa^2}{2} }{2} \right) I_p^{-0.9} P_{\text{SOL}}^{-0.02} a^{0.3} R^{0.36}.$$
Table 1. Power decay lengths in SOL.

| $B_T$, T | $I_p$, kA | $\lambda_{Te}$, mm | $\lambda_{ne}$, mm | $\lambda_{Goldston}$, mm | $\lambda_{q_r}$, mm | $\lambda_{q_r}$, mm | $\lambda_{q_r}$, mm |
|----------|-----------|---------------------|-------------------|-----------------|----------------|----------------|----------------|
| 0.4      | 180       | 13.2 ± 0.6          | 11.3 ± 2.7        | 16              | 4.9 ± 0.5      | 7.0            | 4.0            |
| 0.5      | 225       | 9.3 ± 1.4           | 12.5 ± 2.5        | 15              | 4.1 ± 0.5      | 5.4            | 3.4            |

4. GAM observations

Zonal flows (in particular, their high frequency branch known as geodesic acoustic modes (GAM)) play an important role in the turbulent transport. GAM is characterized by specific fluctuations of the density perturbations, radial electric field, as well as poloidal and parallel velocities [12]. GAM research is developing rapidly, because it is responsible for suppression of the plasma drift turbulence during the transition to the H-mode. The results of GAM investigations at the Globus-M tokamak performed using the Doppler reflectometry were summarized in [13].

Langmuir probes are used to measure the spatial structure associated with GAMs [14]. Moreover, the multi-pin probe head allows measuring simultaneously several plasma parameters which are significant for the GAM detailed characterization.

In the preliminary experiments, to identify GAM, we have used the floating potential signal from a Langmuir probe, and the auxiliary signal of $D_\alpha$ emission. The observations were performed in OH shots #36985–36969 with the upper single null configuration, $B_T = 0.4$ T, and $I_p \sim 140$ kA. The probe was located approximately 6 mm inside the separatrix and it successfully survived under conditions of considerable thermal loads.

The GAM oscillations revealed themselves on the spectrograms shown in Figure 3. Clearly distinguished peaks are seen in the frequency range of 25–28 kHz.

![Figure 3. Low-frequency part of the spectrum of the floating potential and $D_\alpha$ emission intensity.](image)

To estimate the GAM frequency, the following expression was used [14]:

$$f_{GAM} \sim \left( \frac{c_s}{2\pi R} \right),$$

where $c_s \approx (2T_e/m_i)^{1/2}$ is the ion-sound speed. The electron temperature determined using the triple probe technique was 40 eV, therefore, according to expression (6), $f_{GAM} \sim 28$ kHz. Thus, as a result of these measurements, it was shown that, at the Globus-M tokamak, the frequency of GAM oscillations is in good agreement with expression (6).
5. SOL flow
Plasma flow along the magnetic field lines (SOL flow) considerably contribute to the heat and particle transport at the plasma boundary [15].

![Mach number profile in shots #37068-37074.](image)

Figure 4. Mach number profile in shots #37068-37074.

Preliminary measurements of the Mach number of the SOL flow ($M_\infty$) were performed in shots #37068–37074 with the lower single null configuration, $B_T = 0.4$ T, $<n_e> \sim 2 \times 10^{19}$ m$^{-3}$ and $I_p \sim 180$ kA. The results obtained (see Figure 4) are consistent with the data observed in many tokamaks with the same divertor configuration [16].

6. Conclusions
Successful operation of the nine-pin movable Langmuir probe was demonstrated. The decay lengths of the SOL plasma parameters in the Globus-M tokamak were determined and found to be in satisfactory agreement with the scalings. Further we plan to conduct the experiments with a reciprocating probe [17], which will allow obtaining the profiles of plasma parameters in a single shot. In these measurements, the nine-pin probe head tested in this work will be used.

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