Probe measurements in plasma of a rectangular hollow cathode

S N Andreev¹, A V Bernatskiy¹ and V N Ochkin¹

¹ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Russia, 119991 Moscow, Leninskiy Prospekt, 53

bernatskiyav@lebedev.ru

Abstract. With the help of the created system of probe measurements, the parameters of electrons in an inhomogeneous plasma of a rectangular hollow cathode with a discharge in helium were investigated. The local values of the plasma potential \( U_p \), the average electron energy \( <E> \) and the electron concentration \( N_e \), and their energy distribution function (EEDF) are determined. Measurements have demonstrated significant spatial inhomogeneity. The EEDF curves have a double-peak structure, with the ratio between the maxima changing both in space and with pressure change.

1. Introduction

Recently, there has been a significant amount of interest in the task of controlling impurities in complex electrovacuum installations (in particular, tokamaks, for example, the largest ITER [1]). In recent years, we have developed new methods for quantitative spectroscopy [2-6], which allow solving the problem of controlling the plasma composition. To increase the sensitivity of spectral measurements, it is often necessary to carry out calibration probe measurements in order to establish the electron energy distribution function (EEDF) [7].

The purpose of this work was to create a new probe measuring system, a program for processing the received signals, and, as a consequence, the study of plasma parameters in various areas of a rectangular hollow cathode.

2. Experimental setup

Studies were conducted on an experimental installation "Leak" [2-5]. The installation is a vacuum chamber with a volume of 22 liters. The residual pressure is \( 5 \times 10^{-7} \) mbar. The system has many independent gas inlet channels, a heating system for the chamber walls, and pressure control.

The configuration of the discharge device on these installation models the geometry of the joints of blankets of the first wall of the ITER reactor [1]. The rectangular tungsten cathode (100×50×10 mm) has ceramic insulators outside. The anode is a stainless steel mesh (100×10 mm). The distance between the open part of the cathode and the anode was 10 mm. The general layout of the discharge unit is shown in figure 1. The UIP-1 power supply unit and the 2.6 k\( \Omega \) ballast are included in the discharge circuit.
Tungsten wire probes (diameter 0.1 mm, length 2 mm) with a ceramic insulator were used. During the research, 4 probes were placed in the gap between the anode and cathode (5 mm from the anode) along the open side of the cathode. The x coordinates of the probes parallel to the long side of the cathode are -20 mm, 0 mm, 20 mm, and 40 mm, respectively (coordinate 0 corresponds to the middle of the cathode).

The original device was created for measuring the current-voltage characteristics, the circuit is shown in figure 2. A high-voltage (±450V) APEX PA94 operational amplifier with a slew rate of 500 V/μs and an output current up to 100 mA was used as a controlled voltage source. To measure the probe current, an Analog Devices AD215 galvanically-decoupled amplifier with an AD620 buffer instrumentation amplifier was used. The device was connected to the National Instruments PXIe-6366 I/O board (16 bit, 2MS/s/channel) with the PXIe-1073 chassis. The DAC channel was used to control the APEX PA94, and the two ADC channels - for digitizing the values of the voltage, applied to the probe, and the values of the probe current (AD215 output). The program code for managing the measurement process is written in the NI LabView environment and allows one to set an arbitrary voltage on the probe and to store the values of the IVs for a series of measurements to a hard disk drive. Various methods of changing the voltage on the probe over time were used in a given measurement range: proportional (sawtooth waveform), noise (white noise with an amplitude equal to the required range with limited by the value of the derivative and without), as well as a mixed version, when part of the voltage range was scanned proportional (time) signal, and the other part contained a noise signal.
To obtain the second derivative of the I–V characteristic, the Savitsky-Golay (SG) algorithm was used [8]. The digitized values of the voltage and current of the probe of a series of measurements (usually the series consisted of 128-256 measurements of IVC of 6000 points, ~10 mS per scan) were used as input parameters of the processing program, which was built in the NI LabView environment. The recorded IVC data (pairs of current-voltage probe values) were averaged beforehand and brought to a regular voltage grid (requirement of the SG method). Then double differentiation was performed using the SG method with a polynomial of 3÷5 degrees and a variation of the filter window width, then averaging the obtained values of the second derivative over a series of measurements was made.

The plasma potential $U_p$ was defined as the voltage at zero of the second derivative of the current-voltage characteristic. The average electron energy $<E>$ was determined by integrating the EEDF. The electron concentration of $N_e$ was determined by the well-known relationship:

$$N_e = \frac{4 \cdot I_d}{e \cdot v \cdot S},$$  

(1)

here $I_d$ is the value of the current on the IVC corresponding to $U_p$; $e$ is the electron charge; $v$ is the average electron velocity, $S$ is the probe area.

The method implemented within this work has a wider dynamic range compared to the previously proposed probe measurement methods [2, 3].

3. Experimental results and discussion

The measurements were carried out in a discharge in helium. The corresponding form of the measured EEDF is shown in figure 3. Figure 4 shows the results of measurements of the plasma potential $U_p$, the average electron energy $<E>$ and the electron concentration $N_e$ at pressures of 1 mbar and 4.4 mbar. The discharge current was 218 mA. Component measurements were performed at each of the four probes one at a time in sequence. The measurement time on one probe was ~15 s, thus, to conduct measurements sequentially on 4 probes, it took ~60 s. In all measurements, the voltage on the probe was applied in the form of noise.

![Figure 3](image-url)

**Figure 3.** Measurement results of EEDF at pressures of 1 mbar (a) and 4.4 mbar (b) (discharge in He) in different regions of the discharge gap. The discharge current was 218 mA.
Figure 4. Measurement results of $U_p$, $<E>$, $N_e$ in different areas of the discharge gap. The results for the discharge in He are given at pressures of 1 mbar and 4.4 mbar. The discharge current was 218 mA.

The measurement results demonstrate significant inhomogeneity of the measured parameters along the anode.

The EEDF curves have a double-peak structure, and the ratio between the amplitudes of the peaks varies both in space and with pressure change. At the periphery of the discharge gap, the number of high-energy electrons increases in comparison with the central part. As the pressure increases, this tendency persists, with the number of high-energy electrons generally increasing in the discharge.

The plasma potential $U_p$ has a minimum value in the middle of the discharge gap and increases toward the periphery. It strongly depends on the pressure in the system. At 1 mbar $U_p$ in the center of the cathode is $-16.8\pm0.5$ V, at 4.4 mbar $-35\pm1$ V.

The average energy $<E>$ also has a minimum value in the middle of the discharge gap and increases towards the periphery. At 1 mbar $<E>$ in the center of the cathode is $5.4\pm0.5$ eV, at the edge, it increases to a value of $9.9\pm0.5$ eV. At 4.4 mbar, the values of $<E>$ are $8.2\pm0.5$ eV at the center and $16.8\pm0.5$ eV at the edge respectively.

The concentration of electrons $N_e$ in the middle of the discharge gap has a maximum value and decreases to the periphery. At 1 mbar $N_e$ in the center of the cathode is $(16\pm1)\times10^{10}$ cm$^{-3}$, on the edge, it decreases to the value $(2.3\pm0.3)\times10^{10}$ cm$^{-3}$. At 4.4 mbar, the $N_e$ values are $(11\pm0.5)\times10^{10}$ cm$^{-3}$ in the center and $(3.3\pm0.3)\times10^{10}$ cm$^{-3}$ at the edge respectively. Thus, the change in $N_e$ along the discharge gap occurs almost by an order of magnitude.
4. Conclusion
With the help of the created system of probe measurements, investigations were carried out in a rectangular hollow cathode plasma. The main parameters of the plasma in the discharge in helium were determined: the plasma potential $U_p$, the average electron energy $<E>$, the electron concentration $N_e$, and the electron energy distribution function (EEDF). Measurements were carried out in various areas of the discharge device and demonstrated substantial inhomogeneity. The EEDF curve has a double-peak structure.

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