Multi-Chord Beam Diagnostics of Plasma at the GOL-NB Device

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Abstract—A multi-chord beam diagnostic system for an open multiple-mirror trap GOL-NB is described. The system is based on a 10 keV ribbon beam of fast neutral hydrogen atoms generated by a wide-aperture ion injector with an arc plasma source. The plasma linear density profile is calculated from the attenuation of the beam after passing through the plasma. This paper discusses the design of the diagnostics and its capabilities, and also presents the measured profiles of the linear plasma density in the experiment on filling the trap with the starting plasma. The modernized version of diagnostics and the expected increase in its resolution are described. The prospects of using the Charge eXchange Recombination Spectroscopy (CXRS) method on the existing element base are evaluated.

Key words: open multiple-mirror trap, corrugated open trap (GOL-NB), low-temperature plasma, hydrogen beam, plasma spectroscopy

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1. INTRODUCTION

The concept of multiple-mirror plasma confinement was first proposed in 1971 by G.I. Budker, V.V. Mirnov, and D.D. Ryutov [1]. The effectiveness of this idea was demonstrated at the GOL-3 facility, where a significant increase in the plasma confinement time was observed when a multiple-mirror magnetic field configuration was turned on [2]. The development of the physics of open traps and, in particular, multiple-mirror confinement, led to the emergence of the GDMT project—a gas-dynamic multiple-mirror trap with the reactor-class plasma [3, 4]. GDMT is a combination of physical and technological solutions tested at the GOL-3 [2] and GDT (gas-dynamic trap) [5] devices. The main task of the facility is to obtain thermonuclear plasma in a gas-dynamic trap (expected operating range: \( n \sim 10^{19} - 10^{21} \) m\(^{-3}\), \( T_e \sim 0.05 - 1.2 \) keV). At the same time, in order to increase the efficiency of longitudinal confinement, it is planned to install multiple-mirror sections in place of the “standard” magnetic mirrors. The main task of the GOL-NB device is to demonstrate the effect of suppressing longitudinal losses under conditions when the free path of ions is greater than the length of an elementary plug cell \( \lambda \geq l \), but the possibility of their scattering by plasma oscillations arising in the collective flow of plasma through the multi-mirror system appears. The expected parameters of the plasma in the device in the purely gas-dynamic mode are \( n = 3 \times 10^{19} \) m\(^{-3}\) and \( T_i \sim 30 \) eV. In this configuration of the experiment, \( \lambda \sim 2 \) m, with the length of the elementary mirror cell of the multi-mirror section GOL-NB, \( l = 0.22 \) m [6]. The GOL-NB device consists of a central mirror cell operating in the gas-dynamic mode, two solenoid sections creating a corrugated magnetic field, and two end expanders (see Fig. 1). The starting plasma is created by an arc plasma gun [7], its further heating is carried out using neutral beams with an energy of 25 keV and total power of up to 1.5 MW. Thus, GOL-NB is one of the transitional stages between GOL-3 and GDMT. The GOL-NB project is discussed in more detail in [8].

In parallel with the commissioning of the GOL-NB facility, a diagnostic complex was mounted on it, consisting of a set of electrostatic probes, multi-chord plasma beam probing, pulsed gas injection meters, calorimetry of transmitted heating neutral beams, photo and video recording of plasma images, survey spectroscopy and measurement systems for auxiliary electrophysical parameters. At this stage, a neutral particle analyzer and diagnostics of Charge eXchange Recombination Spectroscopy (CXRS) based on neutral hydrogen beams are in the final stages of commissioning. To date, the facility uses one diagnostic and two heating beams of fast neutral hydrogen atoms. The diagnostic beam is used for the diagnostic system for multi-pass plasma probing.
Such diagnostics have been known for a long time [9–11]. The idea of the method is the attenuation measurement of fast neutral atoms passing through the plasma. Beam attenuation can be written as:

\[ \frac{dn_b}{dt} = -\sum_i n_i n_b \langle \sigma_{a_i} v_{a_i} \rangle f, \]  

(1)

where \( n_b \) is the density of the beam atoms, the sum over \( i \) denotes various processes due to which the attenuation occurs, \( n_i \) is the density of the corresponding type of particles, \( \sigma_{a_i} \) is the cross section of the process, and \( v_{a_i} \) is the relative velocities of colliding particles. Averaging is performed over the particle distribution function.

At a beam energy of 5–15 keV and the considered plasma parameters (temperature \( T_e \sim T_i \leq 100 \text{ eV}, n \sim 2 \times 10^{19} - 2 \times 10^{20} \text{ m}^{-3} \)), the process of resonant charge exchange dominates. A less significant contribution (about 10–20%) is made by electron impact ionization. This is due to the smaller cross section of the process in the considered energy range [12, 13]. After averaging over the plasma particle distribution function, one can obtain the effective interaction cross section, which integrally leads to the attenuation of the beam. In the case of charge exchange, due to the difference in the velocities of the beam atoms and plasma ions, the process looks like scattering by stationary particles. To calculate the effective cross section of electron impact, the measured temperature of plasma electrons, \( T_e \sim 10 \text{ eV} \), was used [14].

Taking into account all of the above, the beam current density after it passes through the trap should be calculated as follows:

\[ J = J_0 e^{-\int n_i \sigma_{ex} v_{ex} dl} e^{-\int n_i \sigma_{ion} v_{ion} dl} e^{-\int n_i \sigma_{coll} v_{coll} dl}, \]  

(2)

where \( J \) is the current of the beam passed through the plasma, \( J_0 \) is the total current of the beam, and exponential factors correspond to the processes of charge exchange, ionization by electron impact, and collisions with neutral hydrogen atoms in the chamber of the device, respectively. Under the conditions of GOL-NB \( (n_i \sim 10^{19} \text{ m}^{-3}, T_i \sim 5 \text{ eV}, T_e \sim 10 \text{ eV}) \), the effective cross section of charge exchange \( \sigma_{ex} \sim 1 \times 10^{-15} \text{ cm}^2 \) [12], ionization by electron impact \( \sigma_{ion} \sim (5–9) \times 10^{-17} \text{ cm}^2 \) [13]. The losses of the beam due to its stripping on the gas presented in the chamber of the facility, taking into account the performed calibration experiments, can be neglected; in particular, this situation is consistent with the experience of using similar diagnostics, for example, [8, 10].

Thus, by measuring the ratio of the current density of the attenuated beam to the non-attenuated one, it is possible to determine the linear plasma density \( n_l \).

A practical formula can be obtained from equation (2)

\[ \int n dl = \frac{1}{\sigma_{tot}} \ln \frac{J_0}{J}, \]  

(3)

here, \( \sigma_{tot} \equiv 1.1 \times 10^{-15} \text{ cm}^2 \) is the total effective cross section for beam losses.

Due to the fact that the diagnostic beam has a sufficiently high equivalent current density, a system of secondary emission sensors (SES) can be used to cal-

![Fig. 1. General scheme of the GOL-NB device.](image-url)
calculate the beam attenuation, in particular, it can register only particles that have passed through the plasma; however, in this case, an additional calibration experiment without plasma is required.

The spatial resolution of this method is determined by the intrinsic angular spread of the beam, the parameters of the SES system, and by the scattering of neutral atoms of the beam by plasma ions. However, the influence of the latter factor is insignificant. The transport cross section for elastic scattering of hydrogen atoms on protons is \( \sigma_{tr} \approx 10^{-22} \text{ cm}^2 \) [15], which allows one to estimate the increase in the angular spread of the beam \( \Delta \theta^2 = \sigma_{tr} n l \approx 0.4 \text{ mrad} \). The measured value of the initial angular spread of the beam is 18 mrad (see Section 2), therefore, in this work, we neglect the influence of the scattering of beam atoms by plasma ions on the diagnostic accuracy.

As a result, such a diagnostic system makes it possible to calculate the linear density of plasma ions. A similar purpose can be performed by a multi-chord interferometric system that diagnoses the linear density of electrons. However, in our case, the presence of the available elemental base, first of all, a wide-aperture beam of fast hydrogen atoms, made it possible to quickly implement a diagnostic system of multi-chord plasma probing by measuring the attenuation of the flux of fast atoms that passed through the plasma.

The aim of the work described in the article was the development of a diagnostic complex designed to measure plasma parameters in the GOL-NB device based on beams of fast hydrogen atoms. To achieve this goal, the following tasks were solved: adaptation and modernization of the multi-chord plasma sensing system by measuring the attenuation of a wide-aperture diagnostic beam used in the GOL-3 experiments [16] under the conditions of a full-scale GOL-NB experiment, assessing the applicability of the CXRS method on available atomic hydrogen beams, and its practical implementation in the cross section of injection of a heating beam.

The design of the diagnostics and the experimental technique are described in Section 2. Section 3 presents the results of experiments on measuring the chord profile of the linear plasma density in experiments on filling the GOL-NB trap with starting target plasma. In the final part, the prospects for the development of diagnostics for charge exchange spectroscopy (CXRS) using the element base available at the facility and the first results on the observation of emission spectra in the cross section of injection of heating beams are described.

2. CONSTRUCTION OF THE MULTI-CHORD PLASMA PROBING SYSTEM

The diagnostic injector is located at a distance of 7.3 m from the anode of the plasma gun (Fig. 1, item 5). This corresponds to a multi-mirror section between the center trap and the outlet expander. Such an arrangement of diagnostics makes it possible to observe changes in the plasma flow from the central trap, since a target plasma source which creates a counter flow is installed in the inlet expander. This arrangement is also optimal due to the uniqueness of the diagnostic system and its low mobility.

The basis for diagnostics is an injector of neutral hydrogen atoms based on an arc ion source. The design of the ion source and the power supply system are similar to those described in [17]. Gas entering through a compact hollow cathode is ionized using a magnetically insulated electric arc with a thin diaphragm channel (Ø7 mm, length 30 mm). For the primary stabilization of the arc current, and as a consequence of the formed ion beam, a plasma expander with a magnetic wall is used. Extraction and acceleration of ions is carried out using an ion-optical system (IOS) based on wire electrodes. However, this injector has a number of modifications: IOS consists of 3 electrodes, there is no magnetic lens, and the gas injection system has been modernized. The source creates a beam of hydrogen ions with adjustable energy \( E_p = 10-15 \text{ keV} \) with a duration of up to 500 \( \mu \text{s} \) (determined by the capability of the power supply system). Taking into account the low linear density of the plasma, the beam energy was chosen equal to 10 keV. The equivalent current density of the beam of neutral atoms at the location of the SES is \( J \sim 30 \text{ mA/cm}^2 \). The advantage of this injector is the large diameter of the formed beam (~100 mm), which exceeds the size of the diagnostic window in the solenoid chamber \( W \times H = 40 \times 80 \text{ mm} \). This makes it possible to measure the plasma profile in one experiment without the need to move the elements of the diagnostic system in space, but at the cost of losing part of the beam. However, the loss of a part of the total beam current in this case is permissible, since the current density is sufficient for recording the beam atoms using the SES. To reduce the leakage of gas from the recharge target into the operating volume of the trap, a molybdenum diaphragm with a 10 mm wide slit, which creates a ribbon beam, is placed in front of the entrance to the vacuum chamber of the setup.

The transmitted beam was recorded by a SES system with the following parameters, see Fig. 2a. We used 11 aluminum (secondary electron emission coefficient for 10 keV hydrogen atoms \( 0.7 \) at normal incidence [18]) 4 mm wide sensors with a step of 8 mm along the observation chord and located 260 mm from the camera center. To collect electrons and suppress cross-talk (situations where secondary emission electrons are captured by an adjacent sensor of the SES system), a grounded stainless foil shield is installed between the sensors. During the experiment, to facilitate secondary electron emission, a negative bias voltage was applied to the beam receiver according to the electrical circuit shown in Fig. 2c. Its optimal value.
was determined experimentally from the current-voltage characteristics of the detectors and amounted to 100 V. An analog-to-digital converter (ADC) with an input resistance of 50 \( \Omega \) was used to measure the current.

Before putting the diagnostic equipment into operation, a series of experiments was carried out, the task of which was to determine the angular spread of the atomic beam and the maximum spatial resolution of diagnostics, determined by this spread and the geometry of the SES. For this, a diaphragm with a horizontal slit 1 mm wide and 15 mm long (larger than the beam width) was placed in the beam path in the center of the trap. The diaphragm was moved along the trap radius with a step of 2 mm. As a result, the average statistical apparatus function of the sensitivity of a single SES was obtained, see Fig. 3. This graph was obtained by shifting the sensitivity profiles of SES in accordance with their chord position. In the figure, the experimental dependence is approximated by a Gaussian with a width \( \Delta R_{1/2} = 7.7 \pm 0.7 \text{ mm} \). Because signals are

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**Fig. 2.** Diagram of the construction of secondary emission sensors. (a) First option (11 linearly established SES), (b) an improved version (15 linearly installed SES), (c) a measuring circuit. (1) SES sensors, (2) shield elements, (3) insulator, vector \( \mathbf{B} \) shows the direction of the magnetic field induction, \( U = 100 \text{ V} \)—bias voltage, \( R_1 = 50 \Omega \) (to match the wave impedance of the cable and ADC), \( R_2 = 0.13 \text{ M}\Omega, C_2 = 100 \mu \text{F} \). The numbering in (a–c) is continuous; the numbers 1 and 2 in circles in (c) indicate where the sensors and screen elements are connected to the electrical measuring circuit.

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**Fig. 3.** The total instrumental function of a separate SES sensor, obtained by measuring the current with SES in a test experiment without plasma by cutting off part of the beam of hydrogen atoms with a narrow movable slotted 1-mm-wide diaphragm located in the axial section of the installation. Markers correspond to signals of SES with a different location of the diaphragm along the height \( h \) relative to the installation axis, the solid line—interpolation by a Gaussian, the dashed line—the expected form of the instrumental function for the improved SES system.
a convolution of the angular spread of the beam (we assume that it is sufficiently well approximated by a Gaussian) and the instrumental function of SES (which in this case can be represented as a meander with a period of 8 mm), the angular spread of the beam is $\Delta \theta_{1/2} = 18 \pm 1.8$ mrad.

The use of one set of SESs, recording only the beam atoms that have passed through the trap, in each series of experiments with plasma requires an additional test experiment calibrating the current state of diagnostics. This requires firing a diagnostic beam into a device with a full magnetic field, but without plasma. In further processing, the data from this shot is used to calculate the attenuation. This method places high demands on the stability of the beam current and pulse repeatability, as well as on the amount of collected statistics of experiments. Another problem with the method is poor temporal resolution. This is due to the instability and short duration of the diagnostic beam pulse, as a result of which the value of the currents from the SES per pulse must be averaged. However, despite these shortcomings, this diagnostic system has sufficient accuracy the error of the measured values is 10%. These measurement results are in good agreement with other diagnostics [15, 19].

After a series of experiments, it was found that the beam current density and the signal-to-noise ratio make it possible to reduce the transverse size of the sensors and, accordingly, to increase their number, which should lead to an increase in the spatial resolution of diagnostics. The modernized of SES system consists of 15 cylindrical sensors made of oxygen-free copper with a diameter of 2 mm, see Fig. 2b. A grounded support plate acts as a shield, in the slots of which the sensors are located. Thus, effective suppression of cross-talk with SES is achieved. The new location at a distance of 130 mm from the center of the camera of the SES system, in combination with a large number of sensors, should lead to an increase in the spatial resolution of diagnostics. The calculated hardware function of SES is shown in Fig. 3 (dotted line) and has a width $\Delta R_{1/2} = 5.3 \pm 0.5$ mm. To reduce the influence of the angular spread of the beam, the distance from the SES system to the plasma was reduced. The approximation limit of the SES system was determined by the probability of ignition of a magnetron discharge, i.e., in a given local place, the magnetic field of the facility is almost zero, and as a result, does not affect the operation of SES.

It was also decided to improve the measurement technique. For this, a second set of SES was created, installed in front of the plasma at the same distance from the center of the chamber as the SES system, which records the atoms passed through the plasma. This input beam profile makes it possible to increase the measurement accuracy and to get rid of the need to make a frequent calibration shot, eliminating the uncertainty associated with the instability of the diagnostic injector. At present, the entire set of SES has been installed and experiments are underway to calibrate it.

3. RESULTS OF EXPERIMENTS ON MULTI-CHORD PROBING OF PLASMA

Multi-chord probing diagnostics was successfully used on the starting configuration of the GOL–NB device [15, 19]. With the help of it, a complex of electrostatic probes was calibrated to measure local plasma parameters. As a result, the process of formation and transportation of the starting plasma from an arc source through a long multi-mirror solenoid was studied.

First of all, to register an attenuated beam, it was necessary to experimentally verify the absence of interference in the SES system from the presence of plasma in the device. These interferences include secondary emission current from UV radiation and fast neutral plasma particles, as well as electromagnetic interference from the power supply systems of the plasma gun, magnetic solenoid coils and other powerful electrical systems of the facility. In Fig. 4a the current of the plasma gun, the signal from the sensors, and the signal increased by a factor of 50 are presented. It can be seen that the secondary electron emission current is recorded only when the diagnostic beam is switched on. The current of the beam of neutral atoms itself is unstable (see Fig. 4b); therefore, it becomes necessary to average the signal over time. The result of averaging is a set of 11 points (based on the number of sensors). A typical example of such a profile without plasma in a device is shown in Fig. 4c. The reproducibility of the profile and amplitude of the signals determines the final measurement error of the linear density (10%), indicated in Section 2. The drop of the current at the edges of the profile occurs due to the shading of the sensors caused by the geometry of the window nozzle. Since the ratio of the currents of the attenuated and non-attenuated beams is necessary to determine the linear density, differences in the individual sensitivity of SES do not affect the result.

In Fig. 5 the ion linear density profiles measured over three shots (nos. 4016, 4018, and 4020) are presented. The obtained results are approximated by a Gaussian with a width at half-height $\Delta h_{1/2} \approx 5.5 \pm 0.5$ cm.

Chord measurements of the linear density of ions should allow reconstructing their density profile. However, when trying to do this, the so-called “incorrect inverse problem” arises, which leads to a sharp increase in measurement errors and, as a consequence, low accuracy of the calculated radial profiles. Therefore, the main task of this diagnostics is the most accurate measurement of the ion linear density profile.
4. PROSPECTS OF CXRS DIAGNOSTICS AT GOL-NB

In world practice, injectors of fast neutral atoms are actively used as a basis for CXRS (ChargeeXchangeRecombinationSpectroscopy) diagnostics [20]. The idea behind the CXRS is based on the analysis of the spectra of fast recombinant atoms. Doppler line broadening allows one to measure the velocity of atoms, and their intensity—to estimate the radial distribution of the ion density. Such diagnostics are often and successfully used on many tokamaks [21, 22].

In addition, there is a technique for measuring the distribution function of ions on the basis of analyzers of neutral atoms, which also arise during the recombination of plasma ions on the atoms of the beam, see, for example [23]. This technique has a number of similarities with CXRS, in particular, the need to inject fast neutral atoms into the plasma, the ability to determine the ion temperature and composition of the plasma. At GOL-NB, it is planned to operate in parallel the CXRS system and the neutral particle analyzer, which is currently being commissioned, which will increase the degree of reliability of the information obtained on the plasma parameters. However, a discussion of a diagnostic system based on an atomic recombination analyzer is beyond the scope of this article.

For the correct operation of the CXRS diagnostic system, a sufficiently high radiation intensity of recombinated atoms is required. Focusing on the use of a photomultiplier (or its semiconductor analogue based on avalanche photodiodes with additional signal amplification) with an amplification factor of up to $K \approx 10^8$, as well as reasonable parameters of the system for collecting the luminous flux, the required specific power of radiation from the plasma in the range of the $H_{\alpha}$ line should be at least $\sim 3 \mu W/cm^3$. Assuming that this type of radiation occurs directly during charge exchange, its power can be estimated as follows, see, e.g., [24]:

$$I_{CX}(\lambda) = \frac{h\nu}{2\pi} \int n_i(l)n_0 \times Q_{\text{eff}}(l)dl,$$

where $n_i$ is the density of plasma ions, $n_0$ is the density of particles of the neutral beam, $Q_{\text{eff}}$ is the effective emission coefficient of the $H_{\alpha}$ line, and LOS denotes integration along the observation line. In this case, the effective emission coefficient is $Q_{\text{eff}} > 4 \times 10^{-10}$ cm$^3$/s [25]. For the available diagnostic beam with an equivalent current density of $\sim 30$ mA/cm$^2$, the total power along the observation chord with a transverse size of $\sim 1$ cm should be about $10 \mu W/cm^3$, which theoretically makes it possible to measure the ion temperature profile of the thermal component of the plasma flowing out through the multi-mirror solenoid, along three observation chords.
In addition to the diagnostic injector, the GOL-NB device uses two powerful heating injectors with an energy of 30 keV and a current density of ~0.9 A/cm². If they are used as the basis for CXRS diagnostics, the power of the recharging radiation should be ~300 μW/cm³, which will make it possible to use photographic systems based on C-MOS or CCD cameras with bandpass filters for registration.

To study the process of accumulation of fast ions during the injection of heating beams, a series of experiments was carried out to record the emission spectrum from the plasma region in the injection cross section. The geometry of the beam injection at the GOL-NB facility is such that this cross section corresponds to the stopping point of captured fast ions. A photograph of the plasma glow in the red spectral wavelength range of the beam injection region is shown in Fig. 6. As can be seen, against the background of plasma radiation, transport as well as recombination radiation from the plasma in the region of direct motion of fast atoms, are not visible. This shows the low radiation power of the \( H_\alpha \) lines of the corresponding atoms shifted along the spectrum due to the Doppler effect.

To observe the spectrum of recombined atoms in the injection section of injecting hydrogen beams, we assembled a spectral system based on an MDR-12 spectrometer with radiation recording using an SDU-285 CCD camera. The geometry of the collection of radiation from the setup is shown in Fig. 7. In the figure, the beam injection is shown from left to right. The spectrometer line of sight is rotated approximately 45° against the beam injection line. Thus, this scheme allows one to resolve the emission lines of the atoms of the injected beam and recharged atoms of the plasma.

The emission spectrum near the \( H_\alpha \) line-averaged over two successive shots of the device is shown in Fig. 8. This radiation was recorded in the discussed section of the device when observed along a chord close to the edge of the plasma and corresponding to the line of sight in the direction of rotation in the magnetic field of captured fast ions, and then recombined and emitted photons with redshift (Fig. 8 (region 6)). The highest spectral power is recorded in the region of unbiased \( H_\alpha \). Also, the spectrum clearly shows the radiation corresponding to injected atoms with total, half, and 1/18 energies and located in the blue region from the unbiased \( H_\alpha \). Fractional energies arise due to
the acceleration of ions H\(^+\) and H\(_2\)O\(^+\) in the IOS of the injector.

The brightest central unbiased component of the H\(_\alpha\) line in the spectrum corresponds to the emission of recombined atoms obtained from the ions of the thermal component of the plasma. The power of this radiation makes it possible to quite confidently trace the behavior of the temperature of these ions, as was assumed in the analysis of the prospects for using this CXRS technique at the beginning of the section. In the high-resolution operating mode of the spectrometer, the measured width of the central line profile gives the calculated temperature of thermal plasma ions during injection of heating beams at a level of 1 \(\pm\) 0.5 eV. A discussion of the behavior of the temperature of the thermal component is beyond the scope of this article, since this is directly related to the physics of plasma heating and confinement in the device, as well as to the lack of a complete set of experimental data on the plasma behavior in GOL-NB, which, like the discussed diagnostic system, has recently begun to operate in its design configuration.

When the plasma captures the heating beams of hydrogen atoms, a population of fast supra-thermal protons appears. Recombination radiation from fast protons, corresponding to the red-shifted H\(_\alpha\) line emission, is recorded by this system at the noise level. As a consequence, it is still impossible to study the process of accumulation and confinement of fast ions in the device. However, this spectrum was obtained using a high-resolution spectrometer with a CCD radiation detector. In this regard, the authors have further plans to increase the sensitivity of this system by using a multichannel optical fiber combined with a photomultiplier, for example, as was done in [26]. A doublet of singly ionized carbon CII (657.8 and 658.288 nm) is also observed in the spectrum near the H\(_\alpha\) line. Presumably, carbon appears in the system from a residual vacuum, because the unit’s vacuum seals are made of viton, which can be a source of carbon-containing molecules.

These first experiments show the prospects of using the diagnostics of charge exchange spectroscopy on the GOL-NB device. In particular, to measure the parameters of the plasma flowing along the multi-mirror section, as well as with the subsequent modernization of diagnostics, the process of accumulation of fast ions in the central cell of the installation.

5. CONCLUSIONS

For the GOL-NB facility, a diagnostic complex was developed based on beams of fast neutral hydrogen atoms, which includes a multi-chord plasma probing system with a wide-aperture diagnostic beam and a spectroscopic system of recharged atoms in the cross section of heating injectors of hydrogen atoms. The multi-chord probing system allows one to measure the plasma linear density profile with an accuracy of 10\%.

In the course of its adaptation to the GOL-NB experiments, the spatial resolution was increased by \(\approx 25\%\) in comparison with the previous version of the diagnostic system used in the experiments of the first stage of the GOL-NB device. The spectroscopic system of recombined atoms makes it possible to measure the component composition of the injected heating beam, as well as to determine the temperature of the target plasma component generated by the plasma gun. Further plans for the development of this system are associated with an increase in the detection sensitivity of the radiation spread over the spectrum using a multichannel optical fiber combined with a photomultiplier, followed by registration with a high-speed high-resolution ADC. Such a detector will make it possible to measure the dynamics of the accumulation of fast ions in plasma.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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