Analysis of the Possibility of Measuring the Electron Plasma Density of the T-15MD Tokamak by Probing with Electromagnetic Waves of the Submillimeter Range

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Abstract—The passage of probing beams of the submillimeter range in the T-15MD tokamak chamber along various chords is considered in this paper. Microwave generators with submillimeter radiation and HCN lasers with a radiation wavelength of $\lambda = 337 \, \mu m$ are widely used in interferometers in many plasma systems as sources of probing beams. The possibility of using a solid-state microwave generator and an HCN laser in the form of probing radiation sources with wavelengths $\lambda = 915$ and $337 \, \mu m$, respectively, for measuring the electron concentration in the T-15MD tokamak plasma is considered. The paper does not present full-fledged designs of T-15MD tokamak interferometers but examines the passage of the probing beams in the vacuum chamber in order to determine the influence of refraction. Schematic diagrams of interferometers with indicated wavelengths are also presented and discussed, and the results of calculations of the relative error of the phase shift due to deviation of the probe beam are presented. A design of emitting and receiving antennas is proposed. Introducing and receiving the probe beam is carried out through the T-15MD tokamak equatorial pipe and through the upper and lower pipes. In the probing channels passing through the equatorial pipe, the beams are reflected from the mirror fixed on the inner wall of the vacuum chamber. The possibility of measuring the main plasma parameter—the average electron density—when probing with electromagnetic radiation with a wavelength of $\lambda = 915 \, \mu m$, as well as the possibility of multichannel phase measurement when probing a plasma chord with electromagnetic radiation with a wavelength of $\lambda = 337 \, \mu m$, in the T-15MD tokamak is shown.

Keywords: tokamak T-15MD, electron plasma density, microwave interferometer, HCN laser interferometer, refraction

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INTRODUCTION

In studies of high-temperature plasma carried out on tokamaks, the average electron concentration across the cross section of the plasma cord is a key characteristic. Interferometric sensing of plasma by millimeter and submillimeter electromagnetic waves is a traditional method of its measurement [1, 2]. Another important plasma characteristic is the spatial distribution of electron density in the cord. Multichord interferometry is used to solve this problem [3–5].

The interferometry method is based on probing the plasma with ordinary electromagnetic waves along different chords of the cross section. As the probing beam passes through the plasma, an additional phase shift is acquired, whose magnitude depends on the density of the probed plasma [1, 2, 6]:

$$\phi = \frac{\lambda e^2}{4\pi m_e\varepsilon_0 c^2} \int_{A}^{B} n_e(x)dx,$$

where $e$ is the charge of the electron, $m_e$ is the mass of the electron, $\varepsilon_0$ is the vacuum dielectric constant, and $c$ is the speed of light in a vacuum.

It is necessary that the probing radiation frequency $\omega$ greatly exceed the plasma frequency $\omega_p(x)$ along its entire path:

$$\omega \gg \omega_p(x) = \sqrt{\frac{n_e(x)e^2}{\varepsilon_0 m_e}}.$$

By measuring the magnitude of the phase shift caused by the presence of the plasma, we can determine the chord-averaged density

$$n_e = \frac{1}{L} \int_{A}^{B} n_e(x)dx = \frac{4\pi m_e\varepsilon_0 c^2 \phi}{L \lambda e^2}.$$

It is worth noting that the phase shift is determined at an intermediate frequency for convenience and unambiguity of measurements [1, 4, 6].
Presently, the T-15MD tokamak is under construction at the National Research Center Kurchatov Institute [7] (Fig. 1). This is the first large Russian facility with an elongated cross section and divertor configuration similar to ITER, which will make it possible to carry out the research aimed at supporting the ITER and DEMO projects [8, 9]. The key parameters of the prospective T-15MD tokamak are as follows:

| Parameter                                      | Value          |
|------------------------------------------------|----------------|
| Plasma current \( I_p \), MA                  | Up to 2        |
| Aspect ratio \( A \)                            | 2.2            |
| Large torus radius \( R_0 \), m                | 1.48           |
| Small plasma radius \( a \), m                 | 0.67           |
| Cross-section elongation \( k_{95} \)          | 1.7–1.9        |
| Triangularity \( \delta_{95} \)               | 0.3–0.4        |
| Toroidal field at plasma axis \( B_{T0} \), T  | Up to 2.0      |
| Discharge plateau duration \( \Delta \text{plateau} \), s | Up to 10      |
| Plasma current plateau duration 2 MA, s         | Up to 1.5      |
| Plasma heating power \( P_{aux} \), MW         | Up to 20       |
| Plasma density \( n_e \), m\(^{-3} \)         | Up to \( 1 \times 10^{20} \) |

**ARRANGEMENT OF PROBING CHORDS**

Emitting and receiving conical antennas are usually used for plasma probing in the tokamak chamber. It is convenient to use identical receiving and radiating antennas. The plan is to beam the plasma along both the vertical and the horizontal and inclined chords. Radiation input and its absorption after the plasma irradiation along the vertical channel are carried out through the upper and lower sockets, respectively, and for the horizontal and inclined channels, this is done via the equatorial socket, in which case the probing rays are reflected from flat mirrors mounted on the inner wall of the vacuum chamber of the T-15MD tokamak (Fig. 2).

The design of the proposed mirrors makes it possible to make adjustments within a 7° apex cone by rotating the supporting discs shaped as solid cylinders.

The design proposed includes the possibility of adjustment of the horn antennas by the bellows block (Fig. 3). Alignment is possible within a 1.5° apex cone. The angle of the cone part of the antenna has an upper limit [10] to preserve the radiation phase front shape. For probing at a wavelength of \( \lambda = 915 \) μm, the apertures of the horn antennas were chosen with a diameter of 50 mm; for \( \lambda = 337 \) μm, this size was 40 mm. At the same time, the diameter of the mirror reflector is about 100 mm, which significantly exceeds the diameters of the antenna apertures in both cases. It is worth noting that the antennas are located in the vacuum chamber of the tokamak, and the soldered glass vacuum windows of resonant thickness installed on the bellows units of the antennas are used to separate the vacuum part from the atmospheric one.

Sockets with connection flanges with a nominal diameter of 63 mm are needed to mount such antennas on the equatorial, upper, and lower flanges of the chamber. The dimensions of the flanges and their mutual arrangement allow for probing the plasma along the chords as shown in Fig. 4. The vertical probing channel is labeled V0, the horizontal channels are H0, H1, H-1, H2, H-2, H3, H-3, and the inclined ones are U1, U2, U3, D1, D2, D3. For input and absorption of the probing radiation through the equa-
toroidal nozzle, the antennas placed on it are separated along the toroidal path.

It is possible to increase the number of sounding channels through the considered flanges by using nozzles of smaller nominal diameter and reducing the apertures of the antennas. However, because of refraction, this approach will increase the number of channels for which the center of the probing beam is misaligned with the receiving antenna because of its decreased aperture.

When propagating in plasma with a transverse density gradient, the probing beam acquires an axial deflection, owing to which only a part of the probing radiation reaches the receiving antenna.

The following procedure is used to calculate the refraction. First, the ray trajectory in a medium with a refractive index gradient was determined using the equation \[ \frac{1}{R} = N \frac{\text{grad} \mu}{\mu}, \]
where \( N \) is the normal vector to the radiation trajectory; \( R \) is the radius of curvature of the radiation trajectory; and \( \mu \) is the plasma refractive index for an ordinary wave, which is determined by the following formula:

\[ \mu = \left(1 - \frac{e^2}{h^2} \frac{1}{\omega^2} \right)^{1/2}. \]

In calculations, the plasma electron concentration distributions were given in the parabolic profile approximation with maximum concentrations of \( 2 \times 10^{19}, 5 \times 10^{19}, \) and \( 1 \times 10^{20} \) m\(^{-3} \) for the cases of circular and elongated plasma cross sections. Then, the refraction equation was solved numerically by the Euler method. As a result of the calculations, the values of the axial deflection of radiation for each chord were obtained for the wavelengths used.

In addition, as the beam deviates from the rectilinear trajectory, its optical path changes, which leads to a change in the phase of the radiation arriving at the receiving antenna. The magnitude of the relative change in the phase of the probing radiation caused by the change in the trajectory due to refraction was also calculated.

**T-15MD Tokamak Interferometer with the Probing Radiation Wavelength \( \lambda = 915 \mu m \)**

The source for the probing radiation with wavelength \( \lambda = 915 \mu m \) in the T-15MD tokamak interferometer is a synthesizer which generates signals with frequencies of 7.45898 GHz, 7.45713 GHz, and 77 MHz using one quartz resonator REF (Fig. 5a).

Also, the synthesizer multiplies the frequency of 7.45898 GHz by 44, and thus the generated frequency of 328.195 GHz is radiated to probe the plasma in the tokamak along one of the chords. The signal coming from the vacuum chamber arrives at the mixer and is fed to the mixing unit, which also receives a 7.45713 GHz signal with a preliminary frequency multiplication by 22 inside the mixer. At the output of the mixing block, a signal with an intermediate frequency of 81.4 MHz is produced. In order to transfer the measurements to the baseband frequency, this signal is down-converted by another mixer by mixing with the 77 MHz signal coming from the synthesizer. As a result, a signal with frequency of 4.4 MHz is obtained, the phase of which carries information about the average electron density of plasma probed. It is worth noting that, when probing along the central chords through the equatorial nozzle in the case of the maximum plasma density of \( 1 \times 10^{14} \) cm\(^{-3} \) in the center, the phase shift reaches \( 70 \times 2\pi \) radians when taking into account the double passage through the plasma. This signal is fed into the

![Fig. 4. Arrangement of probing chords in vacuum chamber of tokamak T-15MD: (1) equatorial flange for installation of radiating and receiving antennas; (2) flange for installation of vertical channel radiating antenna; (3) flange for installation of vertical channel receiving antenna; (4) places for installation of probing channels mirrors through the equatorial flange.](image-url)
data acquisition and processing system (DAPS), where it is digitized and subsequently processed with FPGA boards. The method is based on comparing the current phase of the signal from the detector with the initial phase at \( t = 0 \).

The results of calculations of the magnitude of axial deviation \( \Delta \) and the magnitude of the relative change in phase of the probing radiation with a wavelength of \( \lambda = 915 \mu m \) due to the change in the trajectory caused by the refraction deviation of the beam \( \Delta \phi/\phi \) are given in Table 1 for the circular plasma configuration and in Table 2 for the elongated configuration.

It can be seen that, because of refraction in the case of a circular plasma configuration starting from the maximum density of \( n_0 = 5 \times 10^{19} \text{ m}^{-3} \), the center of probing radiation does not get to the receiving antenna

| Probing channel | \( n_0 = 2 \times 10^{19} \text{ m}^{-3} \) | \( n_0 = 5 \times 10^{19} \text{ m}^{-3} \) | \( n_0 = 1 \times 10^{20} \text{ m}^{-3} \) |
|-----------------|-----------------|-----------------|-----------------|
|                 | \( \Delta \phi/\phi, \% \) | \( \Delta, \text{mm} \) | \( \Delta \phi/\phi, \% \) | \( \Delta, \text{mm} \) | \( \Delta \phi/\phi, \% \) | \( \Delta, \text{mm} \) |
| U2              | 3.9             | 29              | 10.5            | 74              | 23.9            | 150             |
| U1              | 0.6             | 15              | 1.7             | 39              | 3.7             | 82              |
| H3              | 2.7             | 26              | 7.2             | 67              | 15.9            | 137             |
| H2              | 1.1             | 20              | 2.9             | 52              | 6.3             | 108             |
| H1              | 0.3             | 11              | 0.7             | 28              | 1.5             | 59              |
| H0              | 0               | 0               | 0               | 0               | 0               | 0               |
| H-1             | 0.3             | -11             | 0.7             | -28             | 1.5             | -58             |
| H-2             | 1.1             | -20             | 2.9             | -52             | 6.4             | -107            |
| H-3             | 2.7             | -26             | 7.2             | -67             | 16.0            | -136            |
| D1              | 0.3             | -14             | 0.8             | -36             | 1.9             | -77             |
| D2              | 3.2             | -39             | 9.0             | -103            | 21.9            | -222            |
| V0              | 0               | 0               | 0               | 0               | 0               | 0               |

Table 1. Calculation results for radiation with wavelength \( \lambda = 915 \mu m \) in the circular plasma cord configuration.
(hereinafter highlighted in bold) along multiple chords. At higher densities, it remains possible to probe the plasma only along the central horizontal and vertical chords. In the case of an elongated configuration of the plasma cord at the maximum electron density $n_0 = 5 \times 10^{19}$ m$^{-3}$, the center of probing radiation will reach the receiving antennas only in a few channels, and the beam of the vertical channel experiences a significant deflection.

Thus, the interferometer with a wavelength of probing radiation $\lambda = 915$ µm on the T-15MD tokamak can measure the average electron plasma concen-

![Fig. 6. Block diagram of the interferometer with a wavelength of probing radiation $\lambda = 337$ µm (vertical chord not shown). Emitting, splitting, and mixing of radiation are carried out using quasi-optical elements rigidly attached to each other and to the flange of the unit.](image)

| Probing channel | $n_0 = 2 \times 10^{19}$ m$^{-3}$ | $n_0 = 5 \times 10^{19}$ m$^{-3}$ | $n_0 = 1 \times 10^{20}$ m$^{-3}$ |
|-----------------|-------------------------------|-------------------------------|-------------------------------|
| $\Delta \phi/\phi, \%$ | $\Delta, \text{mm}$ | $\Delta \phi/\phi, \%$ | $\Delta, \text{mm}$ | $\Delta \phi/\phi, \%$ | $\Delta, \text{mm}$ |
| U3              | 4.8                           | 29                            | 13.0                          | 75                            | 29.3                         | 149                         |
| U2              | 0.4                           | 12                            | 1.2                           | 32                            | 2.5                          | 66                          |
| U1              | 0                             | 3                             | 0.1                           | 8                             | 0.2                          | 17                          |
| H3              | 0.2                           | 9                             | 0.5                           | 23                            | 1.0                          | 46                          |
| H2              | 0                             | 4                             | 0.1                           | 11                            | 0.2                          | 24                          |
| H1              | 0                             | 0                             | 0                             | 0                             | 0                            | -1                          |
| H0              | 0                             | -4                            | 0.1                           | -9                            | 0.2                          | -20                         |
| H-1             | 0.1                           | -7                            | 0.4                           | -19                           | 0.7                          | -39                         |
| H-2             | 0.2                           | -9                            | 0.6                           | -23                           | 1.2                          | -47                         |
| H-3             | 0.3                           | -11                           | 0.9                           | -27                           | 1.8                          | -55                         |
| D1              | 0.3                           | -13                           | 0.8                           | -34                           | 1.7                          | -71                         |
| D2              | 0.9                           | -23                           | 2.5                           | -59                           | 5.3                          | -125                        |
| D3              | 4.6                           | -43                           | 12.6                          | -107                          | 28.9                         | -216                        |
| V0              | 0.3                           | -7                            | 0.9                           | -19                           | 1.8                          | -39                         |
tration through the equatorial nozzle of the installation, while in the case of a circular configuration of the plasma cord or with an elongated configuration, one needs the vertical channel, which works only in regimes with low electron density of the plasma. In other cases, it is necessary to use shorter wavelength radiation to reduce the negative effect of refraction.

**Table 3.** Calculation results for radiation with wavelength $\lambda = 337 \, \mu m$ in the circular plasma cord configuration

| Probing channel | $n_0 = 2 \times 10^{19} \, m^{-3}$ | $n_0 = 5 \times 10^{19} \, m^{-3}$ | $n_0 = 1 \times 10^{20} \, m^{-3}$ |
|-----------------|----------------------------------|----------------------------------|----------------------------------|
|                 | $d\varphi/\varphi$, % | $\Delta$, mm | $d\varphi/\varphi$, % | $\Delta$, mm | $d\varphi/\varphi$, % | $\Delta$, mm |
| U2              | 0.5 | 4 | 1.3 | 10 | 2.6 | 20 |
| U1              | 0.1 | 2 | 0.2 | 5 | 0.4 | 10 |
| H3              | 0.3 | 3 | 0.9 | 9 | 1.9 | 18 |
| H2              | 0.1 | 3 | 0.4 | 7 | 0.8 | 14 |
| H1              | 0   | 1 | 0.1 | 4 | 0.2 | 7  |
| H0              | 0   | 0 | 0   | 0 | 0   | 0  |
| H-1             | 0   | -1| 0.1 | -4| 0.2 | -7 |
| H-2             | 0.1 | -3| 0.4 | -7| 0.8 | -14|
| H-3             | 0.3 | -3| 0.9 | -9| 1.9 | -18|
| D1              | 0   | -2| 0.1 | -5| 0.2 | -10|
| D2              | 0.4 | -5| 1.1 | -13| 2.2 | -27|
| V0              | 0   | 0 | 0   | 0 | 0   | 0  |

**Table 4.** Calculation results for radiation with wavelength $\lambda = 337 \, \mu m$ in the stretched plasma cord configuration

| Probing channel | $n_0 = 2 \times 10^{19} \, m^{-3}$ | $n_0 = 5 \times 10^{19} \, m^{-3}$ | $n_0 = 1 \times 10^{20} \, m^{-3}$ |
|-----------------|----------------------------------|----------------------------------|----------------------------------|
|                 | $d\varphi/\varphi$, % | $\Delta$, mm | $d\varphi/\varphi$, % | $\Delta$, mm | $d\varphi/\varphi$, % | $\Delta$, mm |
| U3              | 0.6 | 4 | 1.6 | 10 | 3.3 | 21 |
| U2              | 0.1 | 2 | 0.2 | 4 | 0.3 | 8  |
| U1              | 0   | 0 | 0   | 1 | 0   | 2  |
| H3              | 0   | 1 | 0.1 | 3 | 0.1 | 6  |
| H2              | 0   | 1 | 0   | 1 | 0   | 3  |
| H1              | 0   | 0 | 0   | 0 | 0   | 0  |
| H0              | 0   | 0 | 0   | -1| 0   | -3 |
| H-1             | 0   | -1| 0   | -2| 0.1 | -5 |
| H-2             | 0   | -1| 0.1 | -3| 0.2 | -6 |
| H-3             | 0   | -1| 0.1 | -4| 0.2 | -7 |
| D1              | 0   | -2| 0.1 | -5| 0.2 | -9 |
| D2              | 0.1 | -3| 0.3 | -8| 0.6 | -16|
| D3              | 0.6 | -5| 1.5 | -14| 3.2 | -30|
| V0              | 0   | -1| 0.1 | -3| 0.2 | -5 |

The HCN-laser generates radiation with a wavelength of 337 $\mu m$ with a power of several tens of milliwatts. It is then separated into a measuring channel and a reference channel. In the measuring channel, the plasma is illuminated along the chords, while in the reference channel the laser beam passes through a frequency shifter, causing its frequency to change by 106 kHz. Then the probing beam of each chord is mixed with the reference beam and gets to the detector, from where the received signal of intermediate frequency of 106 kHz follows to the data acquisition system of the DAPS. The intermediate frequency signal unrelated to the plasma formed in the reference interferometer also gets to the DAPS, where the signals from detectors are digitized and further processed using FPGA boards.

By comparing the signals of the measuring interferometer and the reference interferometer at each time point, the phase shift caused by the presence of the...
plasma-induced phase shift in the measuring interferometer is determined at each point in time. In the case of the maximum plasma density of $1 \times 10^{14}$ cm$^{-3}$ at the center, the expected value of the phase shift reaches $30 \times 2\pi$ radians when probing along the central chords through the equatorial nozzle with allowance for double passage through the plasma. It is worth noting that there is a significant influence of vibrations when probing plasma with waves of this range; that is why most modern HCN laser interferometers are two-color. Since the 1980s, tokamaks at the Kurchatov Institute have used hollow dielectric supersized beam guides and other quasi-optical elements, which are also rigidly attached to the flange of the installation, such as those described in [14], to transmit the probing radiation in the interferometers. Such a solution significantly reduces the influence of vibrations on the phase measurements [12] and will make it possible to conduct them without resorting to probing with two wavelengths. The use of hollow dielectric supersized beamlines is also assumed for the transmission of probing radiation in the interferometers of the T-15MD tokamak.

The results of calculations of the magnitude of the axial deviation $\Delta$ and the magnitude of the relative phase change of the probing radiation with a wavelength $\lambda = 337 \mu$m due to the change in the trajectory caused by the refractive deflection of the beam $d\phi/\phi$ are given in Table 3 for the circular plasma configuration and in Table 4 for the elongated configuration.

As can be seen from the results of the calculation, in the case of both circular and elongated configurations of the plasma cord at densities at the center up to $n_0 = 1 \times 10^{20}$ m$^{-3}$, the signal arrives from most of the chords without significant deflection. Thus, it is possible to measure the electron plasma concentration in the T-15MD tokamak practically along all proposed chords and at substantially higher densities than when probing by radiation with a wavelength of $\lambda = 915 \mu$m.

**CONCLUSIONS**

The axial deflections of the probing beams and the relative differences in phase overflows were estimated for the T-15MD tokamak plasma for the cases of circular and elongated configurations with allowance for refraction. Calculations were performed for probing beams with wavelengths $\lambda = 915 \mu$m and $\lambda = 337 \mu$m for a parabolic plasma electron concentration distribution with maximum values of $2 \times 10^{19}$, $5 \times 10^{19}$, and $1 \times 10^{20}$ m$^{-3}$.

The design of emitting and receiving horn-type antennas has been proposed for radiating and receiving the signal reflected from the internal wall of the T-15MD tokamak via its equatorial nozzle and through vertical probing via the top and bottom nozzles of the T-15MD tokamak.

The possibility of measuring the main plasma parameter—the average electron concentration along the central chords when probing by radiation with a wavelength of $\lambda = 915 \mu$m—is shown.

Phase measurements when the plasma is probed by radiation with a wavelength of $\lambda = 337 \mu$m in the T-15MD tokamak can be carried out to determine the chord values of electron plasma concentration over practically all of the considered chords.

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