Features of design of the Doppler reflectometry diagnostics at the L-2M stellarator intended for operation under conditions of high ECRH power

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Abstract. Features of design of the Doppler reflectometry diagnostics at the L-2M stellarator are discussed. This contact-free diagnostics is intended for experiments carried out under conditions of high-power microwave plasma heating at a frequency of electron cyclotron resonance. Resources of the proposed Doppler reflectometry scheme were studied with allowance for the installation of a new system of rejection microwave filters involving the Fabry–Perot resonance filter and pin-shaped waveguide filters. The simulation results of the resonator-filter operation as well as the results of test measurements using the MVNA-8-350 millimeter vector network analyzer are presented.

1. Introduction
Contact-free diagnostic methods are very important for the fusion facilities with the magnetic confinement of high-temperature plasma. The Doppler reflectometry (DR) diagnostics [1] is such a contact-free technique that provides information on poloidal rotation of plasma basing on the frequency shift of the backscattered radiation spectrum; it is used at many tokamaks and stellarators.

One of the overall used methods of plasma heating is microwave plasma heating at a frequency of electron cyclotron resonance (ECR). A gyrotron complex with a power of up to 24 MW at a frequency of 170 GHz will be used at the International Tokamak-Reactor (ITER) for additional microwave plasma heating. The MIG-3 gyrotron complex with a power of up to 1 MW for ECR plasma heating at a frequency of 75.3 GHz (the second harmonic of gyrotron frequency) was put into operation at the L-2M stellarator [2]. The launch of the MIG-3 complex made it possible to achieve a record to date specific power of 4 MW/m³ which can be inputted into plasma, which strongly exceeded those achieved at the other toroidal fusion facilities: up to 0.4 and 0.04 MW/m³ at the T-10 tokamak and the LHD stellarator, respectively. In the experiments at the L-2M stellarator, it was found that, at such high ECRH specific power, the spurious signal at a working frequency of the gyrotron complex exceeds the useful signal in the receiving path of the DR diagnostics [3].
The goal of the research was to provide the stable operation of the DR diagnostics in experiments on high-power ECR plasma heating. To reduce the effect of an external signal at a frequency of 75.3 GHz and noise signal in a frequency range of range 60–80 GHz, it was necessary to create a new system of filters. In the new system of filters, we have used band-stop filters. These filters can provide strong signal attenuation (suppression) in a certain frequency range \( \Delta f \) near the central frequency \( f_0 \) \[4\].

Because of the design features of the diagnostics (in particular, the small overall dimensions of the waveguide paths), the installation of additional pin-shaped filters, similar to those in \[1\], was not possible. It was required to design and manufacture a compact band-stop filter with a central suppression frequency of 75 GHz. We have designed a filter consisting of the Fabry–Perot resonators arranged successively. In the millimeter and submillimeter frequency range, the Fabry–Perot resonance filters are actively used in various diagnostics and radioastronomical instruments \[5–8\]. In \[5, 6\], two-dimensional flat metal grids deposited on transparent insulating bases are used as reflectors. The characteristics of such filters strongly depend on the accuracy and quality of the grid deposition. We used the Fabry–Perot resonators with flat round mica plates (dielectric constant of mica is \( \varepsilon = 6 \)) with a diameter of \( D = 80 \) mm and a thickness of \( S = 0.1 \) mm.

Along with the modification of the DR diagnostics, the optimization of data analysis algorithms was performed and the new software was developed. The first test measurements showed an improvement of the signal-to-noise ratio, which made it possible to use the DR diagnostics in the experiments with ECRH powers of up to 1 MW at the L-2M stellarator.

1.1. Pin-shaped waveguide filters

Three band-stop filters (F2, F3, F4 in Figure 1) based on half-wave resonators were made using 8-mm-wide waveguides. Metal pins with a diameter of 0.9 mm were inserted into the waveguides perpendicularly to their long side. The number of pins required was determined experimentally to achieve the necessary suppression ratio. As a result, the F2 filter consists of 40 pins, and each of the F3 and F4 filters consist of 30 pins. The distance between the pins (waveguide inhomogeneities) was calculated as half-wavelength of the gyrotron wave in the waveguide, which is a noise disturbance for the diagnostics:

\[
\lambda_H = \frac{\lambda}{\sqrt{\varepsilon \mu + \left(\frac{\lambda}{\lambda_{cr}}\right)^2}}
\]

Figure 1. Schematics of the Doppler reflectometer filtering system. (A) antenna; (LS) lens system; (F1) the Fabry–Perot resonance filter; (F2), (F3), and (F4) pin-shaped waveguide filters; (DC) directional coupler; (D1), (D2) detector heads, and (G) microwave generator.

Here, \( \lambda_H \) is wavelength of the gyrotron extraneous wave in the waveguide; \( \varepsilon \mu \) is the dielectric constant, we take it equal to 1, since the waveguide is filled with air; \( \lambda \) is the wavelength of the extraneous wave with the interfering frequency in vacuum; \( \lambda_{cr} \) is the critical wavelength of the wave
that can propagate in a 8-mm-wide waveguide. Taking into account that, in our experiments, the H\textsubscript{10} wave is generated, we obtain the critical wavelength of $\lambda_{cr} = 14.4$ mm. Diameter of pins is $a = 0.9$ mm, and so the distance between the pins is 2.07 mm.

### 1.2. Fabry–Perot Resonance Filter

The proposed filter is the Fabry–Perot resonator-interferometer with two parallel mica plate reflectors. To obtain a band-stop filter, we need to have an interference minimum at a frequency of 75 GHz ($\lambda_0 = 4$ mm). We can use the well-known relation:

$$2d_0 = m\lambda_0,$$

(2)

where $d_0$ is the resonator length in vacuum, $m$ is integer number, $\lambda_0$ is length of an electromagnetic wave in vacuum. So, the resonator length is:

$$d_0 = m\lambda_0/2,$$

(3)

For $m=1$ and $\lambda_0 = 4$ mm, the resonator length is $d_0 = 2$ mm. However, in our case, we use mica plates with a permittivity of $\varepsilon = 6$ and a thickness of $S = 0.1$ mm. These parameters should be taken into account when calculating the resonator length. The wavelength of an electromagnetic wave in mica is equal to:

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon}}.$$

(4)

With allowance for relation (4), the resonator length $d$ can be calculated as:

$$d = d_0 - \Delta d,$$

(5)

where $\Delta d$ is the difference between the resonator length in vacuum and the length of the resonator with allowance for mica plates. It can be calculated as follows:

$$\Delta d = m\frac{nS(\lambda_0 - \lambda)}{2},$$

(6)

where $m$ is an integer ($m = 1$, in our case), $n$ is the number of mica plates in one resonator ($n = 1$), and $S$ is thickness of mica plates ($S = 0.1$ mm). Thus, we get $\Delta d \approx 0.3$ mm, $d = 1.7$ mm and the distance between plates in the resonator is $l = 1.5$ mm. The filter with four Fabry–Perot resonators was chosen to be used in the filtration system.

### 1.3. Numerical modelling of the Fabry–Perot resonance filter.

The 3D-model (XYZ coordinate system) of the Fabry–Perot resonance filter was created using the computer-aided design system Electro-Magnetic Professional (CAD EMPro) from Keysight Technologies (formerly Agilent Technologies). The band-stop filter with the Fabri-Perot resonators was simulated by several pairs of coupled mica plates, arranged one after another at a distance of $l$ from each other. The plates were installed inside a coaxial waveguide perpendicularly to its axis to ensure the propagation of TEM wave. The calculations were carried out using the Finite Element Method (FEM) by the Agilent FEM Simulator block [9], the boundary conditions at the edges of the countable domain were set in the form of a Perfect Matching Layer (PML). Waveguide ports were installed on both sides of the filter.

### 2. Simulation and measurements results

The filter characteristics were measured with a frequency step of 10 kHz using the MVNA-8-350 vector network analyzer from AB Millimetre Company.

The losses (or transmission coefficient S21) of the pin-shaped waveguide filters were measured in the ranges of 29–41 GHz (operating frequency range of the DR diagnostics) and 62.5–100 GHz. The transmission coefficient of the pin-shaped filter does not exceed 0.5 dB in the operating frequency
range of the Doppler reflectometer and it is more than 30 dB at the ECR frequency (75.3 GHz). Taking into account the fact that three waveguide filters are used in the filter system (F2, F3 and F4 in Figure 1), the suppression of the ECRH frequency (75.3 GHz) in the waveguide section of the filter system should be about 60 dB in each detector channel.

Using the model, the transmission coefficient of the Fabry–Perot filter was calculated in the frequency range of 40–80 GHz. Figure 2 shows the results for the optimized model (curve 2). As can be seen, at a frequency of 75.3 GHz, the attenuation coefficient $S_{21} = -21.9$ dB was obtained. We note that the attenuation at frequencies of 35 and 40 GHz calculated using the optimized filter model does not exceed –0.9 dB. Figure 2 also shows the measured transmission coefficients of the Fabry–Perot resonance filter. Due to the specifics of the used analyzer, its readings can be taken only at discrete spectral ranges. It should be taken into account that all measurements were carried out under conditions of the continuous generation of low-power radiation in MVNA-8-350 vector network analyzer (about some hundreds of milliwatts).

3. Conclusions
The first experiments at the L-2M stellarator using the upgraded Doppler reflectometer showed that, due to optimization of the filter system, the gyrotron radiation is suppressed in the detector channels at least by 80 dB. The presented diagnostics scheme provides conducting experiments on ECR plasma heating using gyrotrons with a power of up to 1 MW.

In the course of optimization of the Doppler reflectometry diagnostics at the L-2M stellarator, the band-stop Fabry–Perot resonance filter for the frequency band of 70–80 GHz made of doubled mica plates was simulated for the first time. The measured suppression coefficient of the filter in a given frequency band is in good agreement with calculated one. We received evidence that when the wavelength of the resonator changes even by a few tenths of millimeter, the filter transmission band can also change, so we note that it is very important to observe the accuracy of resonator dimensions when manufacturing the resonator. Measurements of the filter characteristics showed that the actual suppression coefficient $S_{21}$ of the manufactured filter is $-19.5$ dB at a frequency of 75 GHz which is close to the calculated one ($-21.9$ dB).
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