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DEVELOPMENT OF RENEWED WAWEGUIDE SYSTEM FOR MICROWAVE DIAGNOSTICS IN URAGAN-2M STELLARATOR

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This paper presents initial proposal for the development of quasi-optical (QO) microwave technology for Electron Cyclotron Emission (ECE) and reflectometry diagnostics in the Uragan-2M (U-2M) stellarator. For the existed ECE radiometer systems and for the operational plasma parameters of U-2M new quasi-optical beam separation dichroic filter is designed. For such filter the mechanical parameters and performed attenuation characteristic are calculated. Frontend antenna/splitter system for the combined ECE/reflectometry radiation detection is presented. As an example, QO beam pattern for the ECE receiving antenna is numerically calculated.

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INTRODUCTION

Fusion research requires understanding of transport of energy and particles in toroidal devices. Microwave diagnostics are useful to study transport physics because they are sensitive diagnostics with high time and spatial resolutions. One of the unresolved issues in the plasma confinement is a clarification of various types of instabilities. Various methods utilizing electromagnetic wave with wavelength range around millimeter-wave have been developed to measure such instabilities. The electron cyclotron emission is a well-established technique to measure the electron temperature (T_e) in toroidal confinement devices. The intensity from outgoing ECE radiation from the plasma is proportional to T_e and the ECE frequency is proportional to the magnetic field, which is different in different radius. For many years both Uragan family stellarators [1-5] were equipped with conventional single antenna heterodyne radiometer [6-8]. In the microwave reflectometry, the reflected frequency depends on the electron density (n_e), since the higher density plasma reflects the microwave with higher frequency, and the phase delay or the time delay of the reflected signal corresponds to the radial position. Radial energy transport via fluctuations could be detected as well.

Taking into account that some of the microwave diagnostic complexes that were installed and used on the Uragan-2M stellarator were damaged during the ongoing war, it became necessary to start their restoration and renewal. This paper presents some general propositions on development of the microwave technology for ECE and for future reflectometry diagnostics.

1. EXPERIMENTAL SET-UP AND DIAGNOSTICS UNDER CONCIDERATION

U-2M is a middle size stellarator with sixteen additional toroidal magnetic field coils, they are uniformly arranged along the torus length. It utilizes the (m = 2 periods in the toroidal direction; l = 2 (helical coils)) torsatron configuration scheme with eight poloidal magnetic field coils. The major torus radius is $R_0 = 1.7$ m, the average last closed flux surface minor radius is $\bar{a} \approx 0.2$ m. A general view of the U-2M stellarator is shown in Fig. 1.

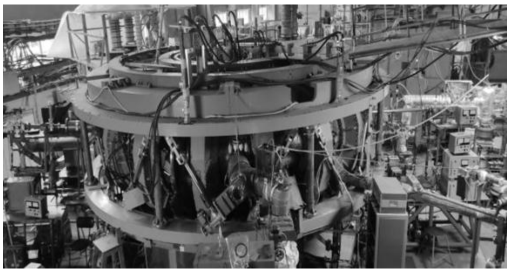

Fig. 1. General view of the Uragan-2M stellarator

The receiving equipment for the ECE diagnostics is located in one of the poloidal cross-section (Fig. 2), where plasma column is horizontally elongated, the corresponding relative (B/B_0) magnetic field is changing from 0.8 to 1.2.

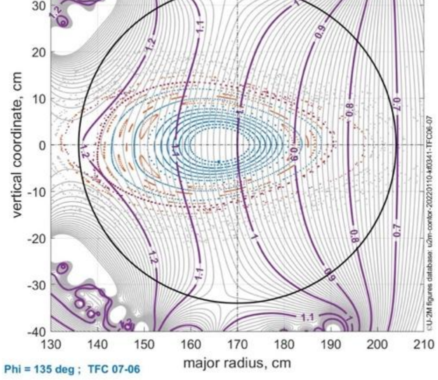

Fig. 2. Contour plot of B/B_0 (solid contours) and flux surfaces (dotted contours) in the plasma cross-section. The U-2M vacuum chamber is drawn as a circle with center coordinate R_0; Z_0 (170.0; 0.0)

During previous experiments ECE diagnostic utilizes a conventional single antenna super-heterodyne radiometer [6, 7] one of which is operated at the single tunable frequency of the second harmonic for the X-mode (X2) in the upper part of the K_a-band (32...39 GHz). The frequency range was chosen according to the value of the toroidal magnetic field of $B_0 =$ 0.68...0.72 T. The other one is the multichannel V-band (57.60; 6.64; 2.67; 8.71; 4.75 GHz) radiometer which is prepared to operate at the higher magnetic field (up to 1.1 T) at the second harmonic of the X-mode. Both radiometers could be used as monitors for the presence of the suprathermal electrons.

Plasma parameters (magnetic field and electron density) upon which the ECE system could be operate is shown in the Fig. 3, where characteristic frequencies for the U-2M plasmas are presented.

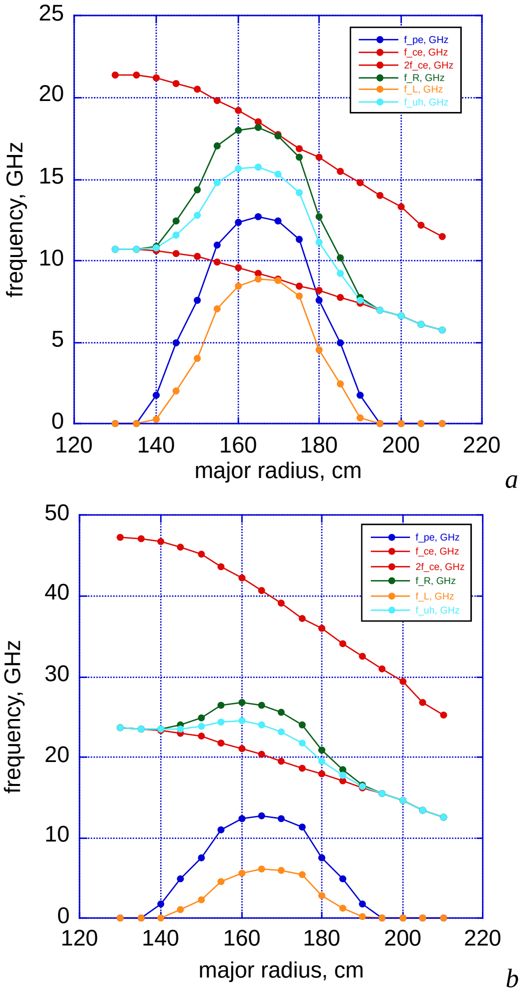

Fig. 3. Characteristic frequencies for U-2M plasmas on the viewing line of ECE diagnostics (horizontally elongated fluxes) in the case of R_{ax} *= 165 cm,* $n_e = 2\cdot10^{12}$ *cm*$^{-3}$ *and* B_0 *= 0.316 T (a) and* B_0 *= 0.8 T (b) in U-2M*

It is obvious that existing ECE equipment which operate in the frequency bands 27...41 and 57...75 GHz could be used for U-2M plasma experiments only for the case of higher magnetic field ($B_0 >$ 0.7 T). The values of electron density that will determine the frequency range for the reflectometry and could be increased significantly. This will change the radial position of corresponding cut-off density. The operational values are: $n_e = (2...6.5)\cdot10^{12}$ cm^{-3}.

2. DICHROIC HIGH-PASS FILTERAS A MICROWAVE BEAMS SPLITTER

In the microwave frequency range, the dichroic filter (DF) is a metal plate with a large number of circular holes. The holes work as circular waveguides, and thus the DF can be used as a conventional high-pass filter (HPF). Fig. 4 shows a simple calculation of the cutoff response of a 10…100 GHz dichroic filter [8]. This value is chosen to split reflectometry and ECE 2X radiation from the plasma. Evaluation of the hole's diameter could be done according the formula of cut-off frequency in the circular waveguide. We must solve for the electric field E_z from the wave equation in cylindrical coordinates. It could be written as $E_z(\rho,\phi,z) = e_z(\rho,\phi)\exp(-j\beta z)$, where z is the direction of wave propagation, can be written as (1):

$$\frac{\partial^2 E_z}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial E_z}{\partial r} + \frac{1}{\rho^2}\frac{\partial^2 E_z}{\partial \phi^2} + k_c^2 E_z = 0. \qquad (1)$$

Here $k_c^2 = k^2 - \beta^2$ is wave number. The general solutions could be written as: $e_z(\rho,\phi) = (A\sin n\phi + B\cos n\phi)J_n(k_c\rho)$. Under the boundary conditions for the TM_{nm} wave and $E_z(\rho,\phi) = 0$ at $\rho = a$, the solution can be obtained as, $J_n(k_c a) = 0$. Then we can get $k_c = p_{nm}/a$, where p_{nm} is the m throat of Bessel function $J_m(x)$, $p_{01} = 2.405$, cut-off frequency is: $f_{\mathrm{c,nm}} = k_c/2\pi(\varepsilon\mu)^{0.5}$, $f_{\mathrm{c,01}} = p_{01}/2\pi a(\varepsilon\mu)^{0.5}$, finally for practical convenience one can use simplified relation for TM_{01} mode (2):

$$f_{\mathrm{cut}}[\mathrm{GHz}] = 229.48/D_{\mathrm{hole}}\,[mm]\,. \qquad (2)$$

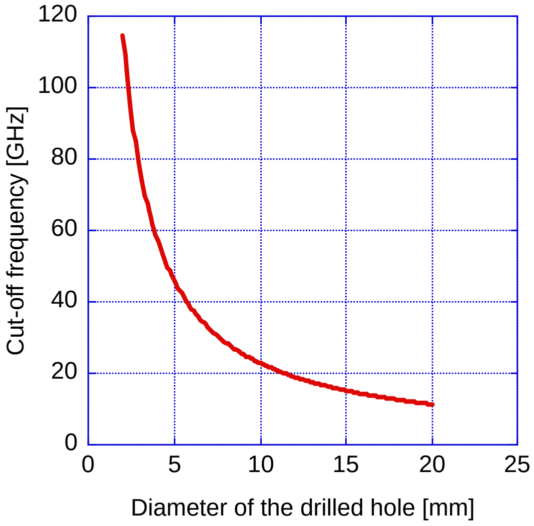

Fig. 4. Calculated cut-off frequency for the HPF dichroic plate (cylindrical waveguide approximation) vs its drilled hole diameter

According to this calculation for the designed dichroic platecut-off frequency of 19.123 GHz the diameter of the drilled holes must be 12 mm. Those holes are arranged (Fig. 5) in triangle-hexagon manner and their centres separation must be 11.64 mm in vertical 13.44 mm in horizontal directions. This filter rejects signals at frequency lower than 19.123 GHz by the level close to -15 dB. Although there are some sharp undulations in a pass-band range (higher than

20 GHz) for the real thing the performance of the filter. The overall filter characteristics (Fig. 6) are better than that of a wave guide section HPF. Finally, we decided that the dichroic filter and the small horn antenna would be employed as ECE detector frontend. Simultaneously filter plate could be act as a good reflector for the lower frequency range and will direct microwaves to the reflectometer antennae.

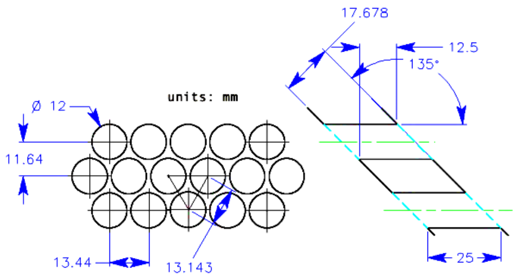

Fig. 5. The geometry of the drilled holes for the dichroic HPF with cut-off frequency equal 19.123 GHz

The filter attenuation calculation was performed via cylindrical waveguide model. The amplitude of the microwave signal could be representing in the following form (3):

$$E = E_0 \exp(-\alpha_{c,01} L)\ , \qquad (3)$$

where $\alpha_{c,01}$ – attenuation constant (in dB/m), L – is the waveguide length. The approximated expression is (4):

$$\alpha_{c,01} = \frac{20.9}{a}\sqrt{1 - G^2_{c,01}}\left[1 - \frac{\delta}{2a}\frac{G^2_{c,01}}{1 - G^2_{c,01}}\right], \qquad (4)$$

where $G^2_{c.01} = f/f_{c.01}$ and $f_{c,01} = 2.405/(2\pi a)$, f – currently frequency, $\delta = 1/(\pi f \mu \sigma_c)$ is the skin depth, $\sigma_c = 1.38 \cdot 10^6$ S/mis electrical conductivity.

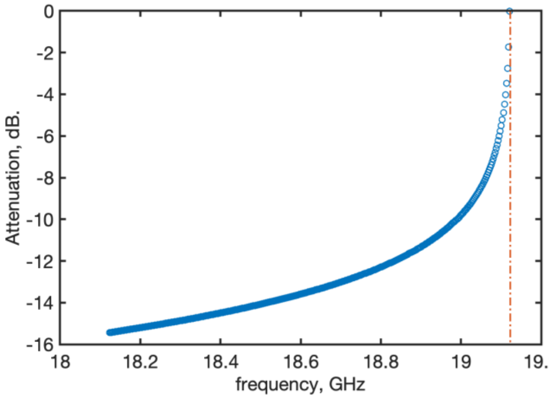

Fig. 6. Characteristic of the HPF (dichroic plate) microwave filter for the drilled holes diameter D h=12 mm and thickness of the plate h=12.5 mm. Cut-off frequency is 19.123 GHz

Fig. 6 shows the attenuation of the dichroic HPF characteristic in the vicinity of the cut-off region of 19.123 GHz. One can see the sharp decay of the calculated microwave signal amplitude. This permits the clear separation of the ECE and reflectometer operational bandwidths (please refer to the Fig. 3).

3. ECE / REFLECTOMETRY ANTENNAE FRONTEND

The reflectometer antenna launches the illumination wave to the plasma, and detects the reflected wave from the plasma. Incident and reflected microwave beams are calculated by using the QO beam approximation method [9, 10]. The illumination wave (emitted by the reflectometer antenna reflect$_{RX}$) has a beam diameter of 12 cm at the plasma edge. The reflection from the plasma is detected by the receiving antenna (reflect$_{RX}$). So, the beam diameter of the detected wave is as small as 3.5 cm.

A conceptual design of the microwave frontend for a combined ECE/REF diagnostic is shown in Fig. 7,a.

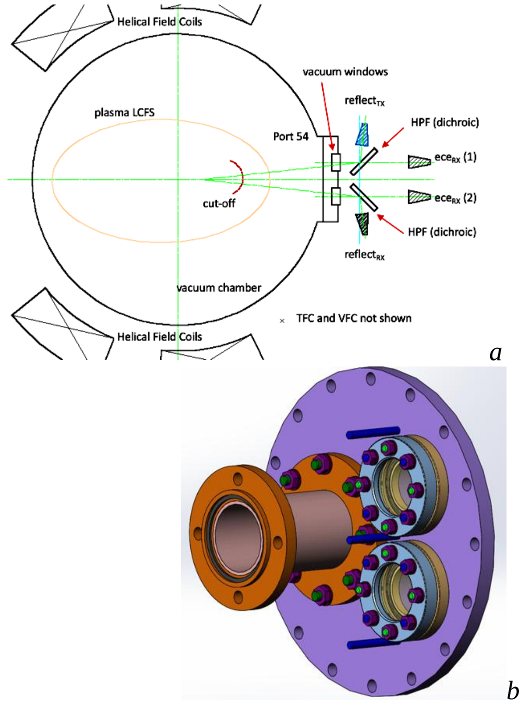

Fig. 7. The poloidal crossection of the diagnostic port 54 (a); the CAD model of the port 54 flange (b)

Two quartz vacuum break windows (Fig. 7,b) are already installed in the end of the 2021. The numerical calculation procedure according [11, 12] was done to estimate the QO beam pattern emitted from the position of ECE antenna (ece$_{RX}$ (1)).

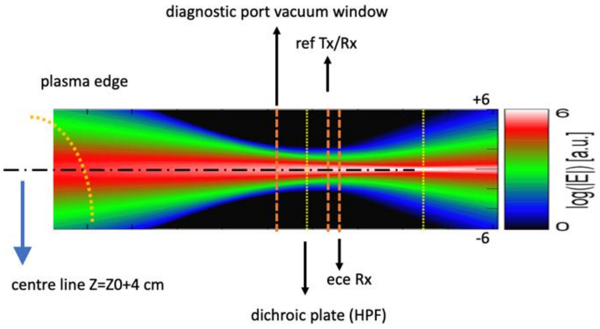

Fig. 8. The QO beam pattern numerical calculation. The beam emitted from the position of ECE antenna

The simulation result is presented in the Fig. 8. The geometry of the feed horns will be under the consideration in the future research. Nevertheless, we have to mentioned that output horn diameter must be chosen in a way to fulfill the necessary conditions not to truncate the gaussian beam at the vacuum window.

This must be done to avoid the backward (from the window) reflected radiation.

CONCLUSIONS

One of the main topics in plasma fusion research is to understand the transport of energy and particles in toroidal devices. For many fusion devices microwave diagnostics (electron cyclotron emission and reflectometry) are routinely operate and are very useful to study transport physics. Those investigations are very important because microwaves are sensitive diagnostics with high time and spatial resolutions. This article presents the first proposals for the installation of a new microwave combined antenna system. Part of this will be a restoration of the old system, which was damaged due to wartime actions.

Combined ECE and reflectometry antenna frontend is designed to operate under main plasma parameters in Uragan-2M stellarator experiment. The band width of the ECE system (upper part of the K_a-band (32...39 GHz)) is suitable to operate for the high magnetic field ($B_0 > 0.7$ T) scenarios. V-band (57.60; 6.64; 2.67; 8.71; 4.75 GHz) radiometer system will be used as monitor of the possible suprathermal electron presence. To extend the ability of the ECE system to operate with any other microwave diagnostics (reflectometry or interferometry) in the same or lower frequency range, a quasi-optical splitter (dichroic plate) is used. For frequencies below the cutoff frequency, the dichroic filter acts as a plane mirror with a very low leakage rate. The suitable dichroic filter is designed. It has following characteristics: drilled hole diameter – 12 mm; corresponding cut-off frequency – 19.123 GHz; triangle-shaped hole center separation – 13.143 mm; plate thickness – 16.678 mm; attenuation – -15 dB (2 GHz bellow the cut-off frequency).

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РОЗРОБКА МОДЕРНІЗОВАНОЇ ХВИЛЬОВОДНОЇ СИСТЕМИ ДЛЯ МІКРОХВИЛЬОВОЇ ДІАГНОСТИКИ СТЕЛАРАТОРА УРАГАН-2М

Р.О. Павліченко, М.В. Заманов

Представлено початкові пропозиції щодо розробки квазіоптичної (КО) мікрохвильової технології для електронно-циклотронної емісійної (ЕЦЕ) діагностики та рефлектометрії для стеларатора Ураган-2М (У-2М). Для існуючих радіометричних систем ЕСЕ та параметрів робочої плазми У-2М розроблено новий квазіоптичний діахронічний фільтр розділення квазіоптичного пучка. Для такого фільтра розраховано механічні параметри та отримано характеристику ослаблення. Представлено фронтальну антено-розгалужувальну систему для комбінованого детектування випромінювання ЕЦЕ-рефлектометрії. Як приклад, проведено чисельний розрахунок діаграми спрямованості приймальної антени ЕЦЕ.