NEW QUASIOPTICAL RECEIVING SYSTEM FOR ELECTRON CYCLOTRON EMISSION DIAGNOSTICS IN URAGAN-3M STELLARATOR

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A new electron cyclotron emission antenna was designed to be installed outside of Uragan-3M vacuum tank. The system will be utilizing different diagnostic port to minimize the length of the output microwave beam. Its design is based on Gaussian beam optics and consists of two plane and two concave mirrors. The concave mirror surfaces are defined using the concept of elliptical surface, where the origin of emission and outside detection antenna coincide with foci of ellipsoid. The new electron cyclotron emission antenna will be installed for a 2015 experiment to measure the electron temperature profile and its fluctuations. This paper reports the general design of the new quasi-optical antenna system.

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INTRODUCTION

Electron cyclotron emission (ECE) measurement is a powerful diagnostics for electron temperature profile measurement of high temperature plasmas confined in magnetic field. For many years Uragan-3M (U-3M) stellarator was equipped with conventional single antenna heterodyne radiometer [1, 2]. The present antenna and waveguide system utilize mostly X-band (λ=0.03 m) conventional microwave components to deliver EC radiation from plasma to the detection system. This antenna is not optimized for the frequency range of the second harmonic of ECE (32…40 GHz) for the central magnetic field 0.7 T of U-3M stellarator. The direction of the conical horn (with diameter D=0.06 m) is fixed in the equatorial plane of the plasma and shifted in the direction of low field side to the distance which correspond the position of the inner surface of the helical coils at the radial position $R_{\mathrm{ant}} = 1.21\ \mathrm{m}$. Thus, its directivity is set to be at near field (NF) zone of the antenna (Fig. 1), which in the terms of antenna dimension D and radiation wavelength λ separates with far field (FF) zone and has to satisfy following condition: $R(\mathrm{FF}) \geq 2D^2/\lambda$.

1. QO ANTENNA SYSTEMS

1.1. FOCUSING OF THE QO BEAM

During past experiments a relatively little attention was paid to the ECE antennae and ‘optics’ of viewing the U-3M plasmas. The EC emission, with a frequency of more than 30 GHz, is transported according the quasi-optical (QO) phenomenon. One can see the clear benefits that will follow such a controlled and well defined view of receiving QO antenna system. They are: much better spatial resolution of localization of ECE radiation origin, possible removal of data ambiguities caused by reflection from helical coils and other inner structure of U-3M, and better possibility of definitive measurements on the polarization state of radiation (O-, X-wave separation). Following the framework of the QO antenna system design that was considered in [3-4] the general layout is presented in the Fig. 2.

For QO system focusing of the beam by an elliptical mirror (or equivalent lens) can be described as follows.

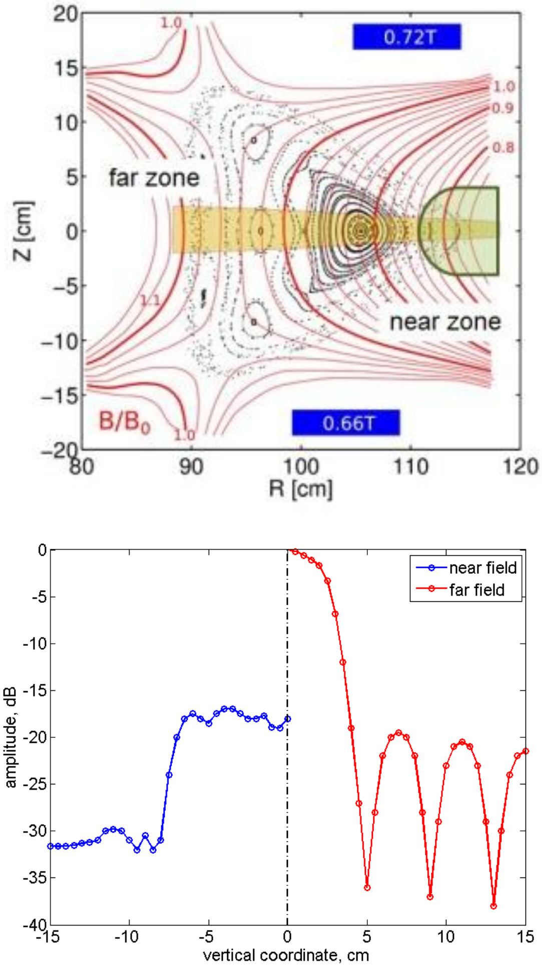

Fig. 1. Schematic view of conical horn beam for NF zone and FF zone with Poincaré plot of the U-3M magnetic fluxes and magnetic field (upper); calculated corresponding NF and FF antenna patterns

For a paraxial rays approximation mirror acts as a phase transformer with corresponding phase change $\Delta\varphi$ proportional to the square of the distance r of the ray from the axis of propagation $\Delta\varphi = \pi r^2/\lambda f$ where f is the focal length. Following the formalism of Kogelnik and Li [5] the phase transforming properties, the thin lens formula $1/f = 1/R_1 + 1/R_2$, where R is radii of the phase front curvature, will be transform into:

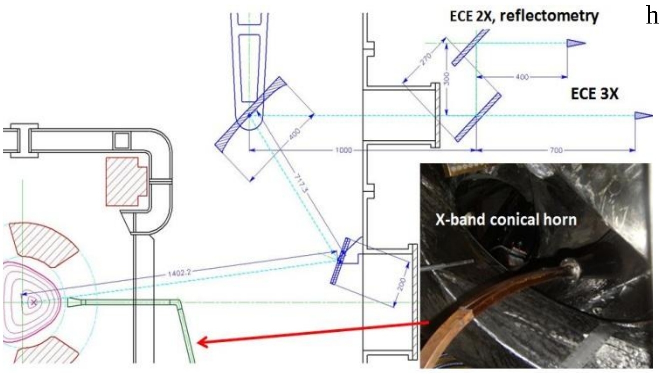

Fig. 2. Layout of the proposed QO antenna system for the U-3M ECE system. Old X-band conical horn

$$\frac{1}{f} = \frac{1}{d_1[1+(\pi w_{01}^2/\lambda d_1)]} + \frac{1}{d_1[1+(\pi w_{01}^2/\lambda d_1)]}. \qquad (1)$$

The output beam parameters (subscript index 2) could be presented in terms of input beam. Depending of which parameter beam waist at the focus (w_{0i}) or corresponding waist distance (d_i) have to be easily evaluated into the following equations:

$$\frac{d_2}{f} = 1 + \frac{(d_1/f)-1}{[(d_1/f)-1]^2+(\pi w_{02}^2/\lambda f)^2} \quad , \qquad (2.a)$$

$$\left(\frac{w_{02}}{w_{01}}\right)^2 = \frac{1}{[(d_1/f)-1]^2+(\pi w_{02}^2/\lambda f)^2} \quad . \qquad (2.b)$$

A particularly useful case of the QO beam focusing is that occurs when the waist of the input beam is located at a distance equal to the focal length of the mirror $(d_1 = f)$. Then one can see that $d_2 = f$ the location of the output waist is independent of the wavelength (frequency) of the radiation, and $w_{02}/w_{01} = \lambda f/\pi w_{01}^2$ the beam waist at the certain distance expanded wider for the smaller wavelength.

1.2. FOCUSING OF THE BEAM BY MEANS OF ELLIPTIC SURFACE

The radial spatial resolution of the radiometer is determined by the frequency resolution of the instrument. Toroidal and poloidal resolution depends on corresponding beam radii (perpendicular to radial direction). Since that the highest resolution has to be at the plasma centre it is practically the best way to create QO beam which has minimal waist at the plasma centre. This could be done by imaging some adjustable aperture with the help of a lens or of a mirror. However two effects could complicate the simple geometric optics picture. First the diffraction spreads the beam by an angle given approximately by the ratio of the radiation wavelength to the vacuum window diameter.

It is essential that the output vacuum window diameter has to be twice wider than the beam waist at this position. Secondly, refraction by the plasma itself could spread the beam significantly. It becomes particularly important when the viewing direction does not coincide with the direction of density gradient. To get smaller refraction effect one has to use higher frequencies, thus, having possibility to measure higher harmonics.

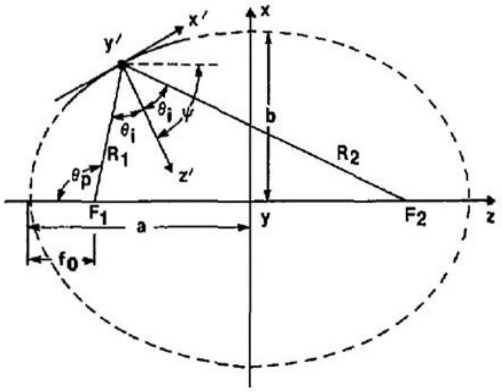

Fig. 3. Geometry of the elliptic surface with general notations

Once radiation passes through the window it must be transported to the detector. This can be distance of many meters. But before transporting the beam it is essential to insert a polarizer to obtain the desired mode of polarization before transporting the beam. The transportation could be done either by QO waveguides or by trains of QO lenses. The antenna consists of four stainless steel mirrors. Three of them are plane mirrors and one is the concave elliptical mirror. This is done to optimize the mirrors layout, which is determined by the spot size of the QO beam at the plasma center and the beam passed through the vacuum window, matching it to the size of the horn detection antenna. In order to select pure X-mode polarized beam, a wire grid polarizer has to be installed outside vacuum window. To improve the measured microwave intensity, it is desirable to enlarge elliptical mirror, which faces the plasma. To enhance the spatial resolution of the QO system in comparison to the present conical horn antenna the plasma spot size must be at least one order smaller than plasma radius

1.3. DESIGN OF THE ELLIPTIC CONCAVE MIRROR SURFACE

An offset ellipsoidal reflector acts as 'virtual' ideal thin lens and could be evaluated via the incident and reflected phase front radii of curvature R_1, R_2. They could be matched by an equivalent lens focal length f; and by the angle of incidence θ_i. Then the standard equation of the ellipsoid for the Cartesian coordinates x, y, z (Fig. 3) has form:

$$\frac{z^2}{a^2} + \frac{x^2+y^2}{b^2} = 1. \qquad (3)$$

Translating to x', y', z' coordinates and after simple transformations Eq.3 will have the form:

$$z' = \frac{-B-\sqrt{B^2-4AC}}{2A}, \qquad (4)$$

where A, B, C are the functions of x', y'

$$A = a^2 \sin^2\psi + b^2 \cos^2\psi,$$

$$B = 2\begin{bmatrix} b^2x'\sin\psi\cos\psi - a^2x'\sin\psi\cos\psi \\ -b^2\cos\psi\left(\sqrt{a^2-b^2}+R_1\cos\theta_p\right) \\ -a^2R_1\sin\psi\sin\theta_p \end{bmatrix},$$

$$C = b^2\left[x'\sin\psi - \begin{pmatrix}\sqrt{a^2-b^2} \\ +R_1\cos\theta_p\end{pmatrix}\right]^2 + a^2\left(x'\cos\psi + R_1\sin\theta_p\right)^2 - a^2b^2 + a^2y'^2$$

For the chosen two radii of ellipse $R_1 = 2.12\mathrm{m}$ and $R_2 = 1.0\mathrm{m}$ the focus is $f = 0.6794872\mathrm{m}$.

It is shown in the Fig. 6 that antenna design is optimized to path through the limited space between helical coils, and small vacuum window port. The focusing spot diameter is about 0.04 m at HWPM (-3dB level). The output part of the QO beam has diameter of 0.09 m and went through the vacuum window without truncation. The diameter of the window is 0.2 m and it larger than the 1.41σ parameter. Here, σ is the width at which the beam intensity is $1/e^2$ of that at the beam center.

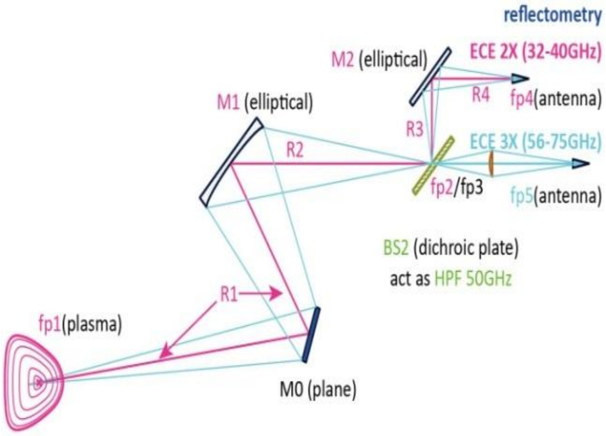

Fig. 4. Schematic view of QO mirrors layout. The system consists of three mirrors, and one beam splitter. The layout is determined by the spot size at the plasma and the beam is passed through the vacuum window, matching it to the conical type waveguide antennas from the air side

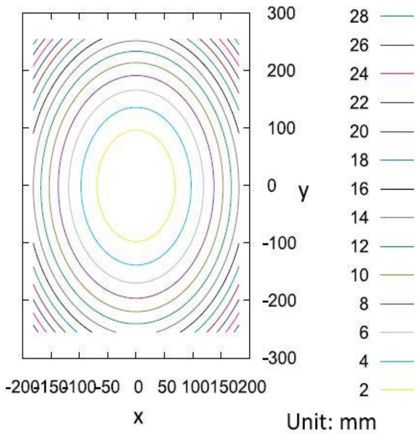

Fig. 5. Poincaré plot of the elliptic mirror surface of the main focusing mirror M1

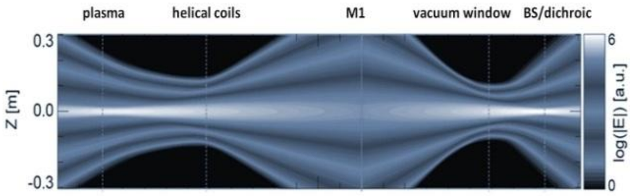

Fig. 6. Calculation of the QO 37 GHz beam pattern (to simplify beam geometry strait line approach is chosen)

1.4. DICHROIC PLATE

In the microwave frequency range, the dichroic filter (DF) is a metal plate with many holes. The holes work as circular waveguides, and thus the DF can be used as a conventional high-pass filter. Figure 9 shows a calculation of the cutoff response of a 50 GHz dichroic filter. This value is chosen to split ECE 2X and ECE 3X radiation from the plasma. Evaluation of the holes diameter could be done according the formula of cut-off frequency in the circular waveguide. Maxwell equation for the electric field in cylindrical coordinates could be written as $E = E_0(r,\theta)\exp\,(i\omega t - \gamma z)$, where z is the direction of wave propagation, can be written as:

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_\theta}{\partial \theta^2} + k^2E_z = 0.$$

Here $k^2 = \omega^2\varepsilon\mu + \gamma^2$ is wave number. Under the boundary conditions for the TM_{mn} wave $r = R_{\mathrm{hole}}$ $E_z = 0$, the solution can be obtained as $E_z = J_m(k_{mn}r)$, $k_{mn} = j_{mn}/R_{\mathrm{hole}}$, where j_{mn} is the zero point of $J_m(r)$, $j_{01} = 2.40482$, cut-off frequency is: $\omega_{\mathrm{cut}} = k_{mn}/(\varepsilon\mu)^{0.5}$, $\omega_{\mathrm{cut}} = cj_{01}/R_{hole}$, finally for practical convenience one can use practical relation:

$$f_{\mathrm{cut}}\,[\mathrm{GHz}] = 0.22948/D_{\mathrm{hole}}$$

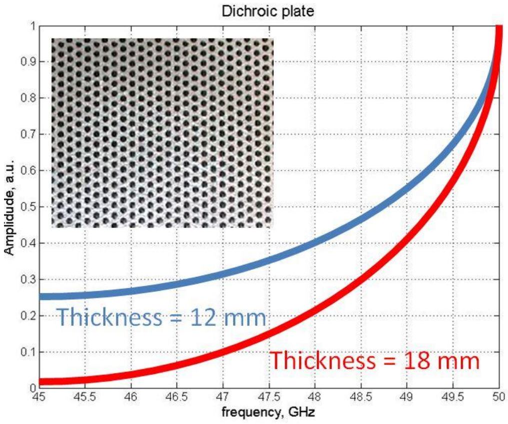

Fig. 7. Calculated HPF (cut-off frequency set to 50 GHz) for different thickness of the dichroic plate $t_1 = 0.012\ m$ and $t_2 = 0.018\ m$

According to this for the cut-off frequency of 50 GHz the diameter of the drilled holes D_{hole}, which are arranged (Fig. 7) in hexagon manner must be 4.6 mm. This filter rejects signals at frequency lower than 50 GHz by the level of more than -20 dB. Although there are may be some sharp undulations in a pass-band range (higher than 50 GHz) for the real thing the performance of DF is better than that of a waveguide-section-high-pass-filter. Finally we decided that the dichroic filter and the small horn antenna would be employed as ECE detector frontend. Simultaneously DP could be act as a good reflector for the lower frequency range.

CONCLUSIONS

Fusion research requires understanding of transport of energy and particles in toroidal devices. Microwave diagnostics (electron cyclotron emission and reflectometry) are useful to study transport physics because they are sensitive diagnostics with high time and spatial resolutions. Electron cyclotron emission (ECE) is employed to measure radial distribution of electron temperature (T_e) in toroidal confinement devices. The ECE intensity is proportional to T_e and the ECE frequency is proportional to magnetic field, which is different in different radius. In reflectometry, the reflected frequency depends on electron density (n_e), since higher density plasma reflects microwave with higher frequency, and phase delay or time delay of the reflected signal corresponds to the radial position.

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 other advantage of large aperture optics for ECE (or other microwave diagnostics) is to form an image of the reflecting/emitting layer onto an array of detectors (instead of single antenna) located at the image plane, enabling localized sampling of small plasma areas and to become a microwave imaging diagnostics. Microwave imaging diagnostics using the above techniques has a potential to visualize 3D view of turbulence.

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НОВАЯ КВАЗИОПТИЧЕСКАЯ СИСТЕМА ДЛЯ ПРИЕМА ЭЛЕКТРОННОГО ЦИКЛОТРОННОГО ИЗЛУЧЕНИЯ НА СТЕЛЛАРАТОРЕ УРАГАН-3М

Р.О. Павличенко

Разрабатывается новая квазиоптическая антенная система для анализа электронно-циклотронного излучения, компоненты которой будут установлены снаружи вакуумной камеры Ураган-3М. Система будет использовать другой диагностический порт, чтобы минимизировать длину выходного СВЧ-луча. Этот дизайн основан на принципах оптики гауссовых пучков и состоит из двух плоских и двух вогнутых зеркал. Вогнутые зеркальные поверхности описываются с помощью геометрии эллиптических поверхностей, при использовании которых положение источника излучения и приемной антенны совпадают с фокусами эллипсоида. Новая антенная система электронно-циклотронного излучения будет установлена для экспериментов по измерению профиля электронной температуры и ее колебаний в 2015 году. В общих чертах представлен дизайн новой квазиоптической антенной системы.

НОВА КВАЗІОПТИЧНА СИСТЕМА ДЛЯ ПРИЕМУ ЕЛЕКТРОННОГО ЦИКЛОТРОННОГО ВИПРОМІНЮВАННЯ НА СТЕЛАРАТОРІ УРАГАН-3М

Р.О. Павліченко

Розробляється нова квазіоптична антенна система для аналізу електронно-циклотронного випромінювання, компоненти якої будуть встановлені зовні вакуумної камери Ураган-3М. Система буде використовувати інший діагностичний порт, щоб мінімізувати довжину вихідного НВЧ-променя. Цей дизайн заснований на принципах оптики гаусових пучків і складається з двох плоских і двох увігнутих дзеркал. Увігнуті дзеркальні поверхні описуються за допомогою геометрії еліптичних поверхонь, при використанні яких положення джерела випромінювання і приймальної антени збігаються з фокусами еліпсоїда. Нова антенна система електронно-циклотронного випромінювання буде встановлена для експериментів по вимірюванню профілю електронної температури і її коливань в 2015 році. В загальних рисах представлений дизайн нової квазіоптичної антенної системи.