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Output System of a 42/84 GHz, 0.5 MW, Dual Regime Gyrotron

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ABSTRACT

In this paper, the design studies of the output system are carried out for a dual regime Gyrotron in the context of India's requirement of clean energy. This design study consists of a dimpled wall quasi-optical launcher (QOL) and RF window. After proper coupling of energy from beam to RF wave, the amplified wave need to be down-convert in a Gaussian-like beam (much simplified lower order). The launcher is designed with a commercial software LOT/Surf3d. This Gaussian-like mode coming out from the gyrotron vacuum system through the RF window is coupled to the corrugated waveguide using Matching Optic Unit (MOU) section. The complete design of the RF window is carried out using gyrotron design suite version 4.0 (GDSv4.0 2016).

Keywords: Dual regime gyrotron; GDSv4.0; Quasi-optical launcher; LOT/Surf3d; RF window; Mode selection

1. INTRODUCTION

There is an ever-increasing demand for Gyrotrons in the millimeter/sub-THz regime of the spectrum for a variety of critical applications like electron cyclotron resonance heating (ECRH) in thermonuclear fusion reactors[1-3]. At frequencies 28-170 GHz, these Gyrotrons produce hundreds of kilowatts of output power (CW to long pulse) and they have been used very successfully for plasma heating in tokamaks and stellarators[1-3]. To solve the various problems related to uneven heating, plasma generation, etc., step-tunable and multi-frequency gyrotrons are better option[4], without a major change in the system. These gyrotrons are capable of delivering hundreds of kilowatts of long-pulse to continuous-wave output power.

Output transmission lines (corrugated HE_{11}-mode waveguide) operate on lower-order linearly polarised modes like HE_{11}. One drawback of using such a high-frequency mode for Gyrotron operation is to design the output coupling system which can be used for higher-order asymmetric modes. Quasi-optical mode converters are used to convert these higher-order modes to linear polarised modes and coupling of these modes with the transmission line. RF window couple this lower order mode to a transmission line from the gyrotron vacuum system with low reflection from window material. The beam which we got from the output window is not a perfect Gaussian mode, but we want an almost perfect Gaussian beam. To increase Gaussian mode content of beam and to reduce astigmatism and ellipticity of beam, MOU is used[5]. For the design of such MOUs, one should know the amplitude and phase information of the beam at the mirror positions. The phase of the beam can be obtained iteratively by phase retrieval algorithm[5,6], or the Irradiance method[7]. The matching optic unit consists of two/three mirrors that direct the output beam from the window towards the corrugated waveguide transmission line.

The mode-pair and the RF behaviour of this gyrotron operating at 42/84 GHz dual regime were alsopresented[8]. As compared to the single frequency mode converter, dual- or multi-frequency mode converters are tricky and critical to design for optimal results i.e. Gaussian content factor more than 98%. The reason behind this is that we have less flexibility to optimise the physical design parameters in dual- or multi-frequency mode converters. Hence, the current manuscript deals with the design and study of the comprehensive output system of multi-frequency gyrotron operating at two distinctly spaced frequencies i.e. 42/84 GHz. The gyrotron supports $TE_{6,3}$ and $TE_{15,4}$ respectively. MOU of the presented paper contains a Chemical Vaporised Deposition-Boron Nitrate (BN-CVD) RF window and Quasi-optical mode converter placed in the gyrotron assembly as shown in Fig. 1.

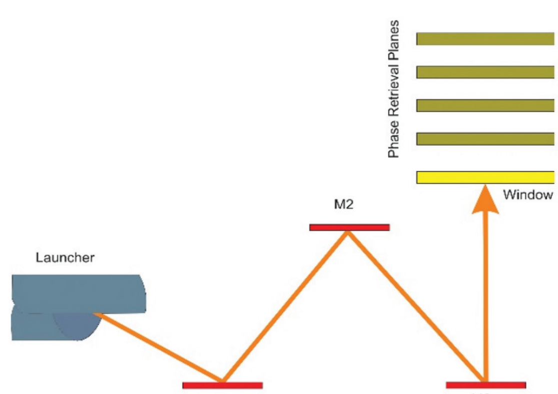

Figure 1. MOU of a gyrotron assembly.

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2. DUAL-REGIME RF WINDOW DESIGN

Gyrotron is a vacuum electron device and needs a boundary to separate the vacuum inside the system and the outer free space. This boundary is known as RF window should exhibit proper mechanical as well as thermal strength to withstand such high-pressure difference and heat. At the same time should persist a good transmission characteristic. In the present design study, Chemical Vaporised Deposition-Boron Nitrate (BN-CVD) has been chosen as the window material. BN-CVD can withstand comparatively higher beam power due to low loss tangent, high thermal stress level.

For the dual regime operation, window width is kept fixed such that, maximum transmission occurs at a series of frequencies (42 and 82.305 GHz). At 42 GHz, disk thickness is equal to half wavelength, and at 82.305 GHz, it is twice the half-wavelength i.e. 1.605 mm.

Table 1 shows the optimal design parameters to support good transmission i.e. transmission efficiency more than 99 %, S_{11} below -50 dB, and negligible reflection at the operating frequencies as shown in Fig. 2

3. QUASI-OPTICAL LAUNCHER (MODE CONVERTER) DESIGN

The dimpled wall quasi-optical mode converter is used to down-convert the operating mode-pair to Gaussian-like (HE_{11}) mode. The launcher is connected to the interaction structure via the nonlinear uptaper (NLT) section. The main hurdle in designing NLT and launcher is that transmission from taper should be maximum and mode conversion should be less for mode-pair selected as well Gaussian mode factor for both operating frequency at the output of the launcher should be more than 95%.

Table 1. Design parameters for single disk window

Window material	BN-CVD
The radius of the window (mm)	45
Disk thickness (d) (mm)	$1\times\lambda/2$, for 42 GHz $2\times\lambda/2$, for 84.305 GHz
Dielectric constant (ε_r)	4.7
Transmission efficiency	99.68%, for 42 GHz 99.17 %, 84.305 GHz

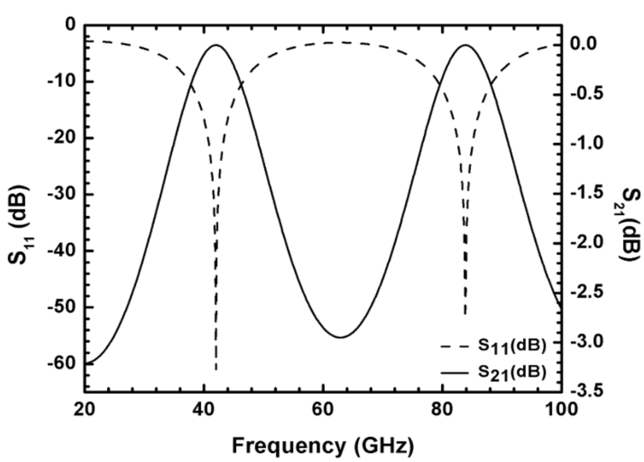


Figure 2. S_{11}, S_{21} plots for the BN-CVD RF window.

To achieve ≈ 99.89% transmission efficiency for both the operating frequencies, taper length is optimised as 59.52 mm. The output of the NLT is then connected to the mode converter with a radius equals to 1.07 * R_{cav} (cavity radius) for the present case. The Gaussian mode content of the down-converted beam should be more than 98 %. Perturbations made on the inner radius of the launcher increase the Gaussian mode content. To obtain a proper mode-conversion with a minimum loss we have tried two different designs. The design parameters with their respective Gaussian content has been tabulated in Tables 2 and 3.

Table 2. Launcher design parameters (Design 1)

Launcher length (mm)	148.7
Helical cut length (mm)	48.3
Launcher radius (mm)	18.74
Taper angle (rad.)	0.007
Gaussian content factor	98.91% (for 42 GHz) 99.21% (for 84.305 GHz)

For the first launcher design, the wall field intensities which give the beam concentration on the launcher wall section based on geomatic optics (g.o.) are shown in Fig. 3. Aperture field intensities are shown in Fig. 4 which gives the information of beam at the launcher helical cut. Far-field profiles are shown in Fig. 5 which shows the beam intensities (beam profile) at the far-field of the launcher (located at a distance $> 2D^2/\lambda$; where D is the helical cut length of the launcher).

Table 3. Launcher design parameters (Design 2)

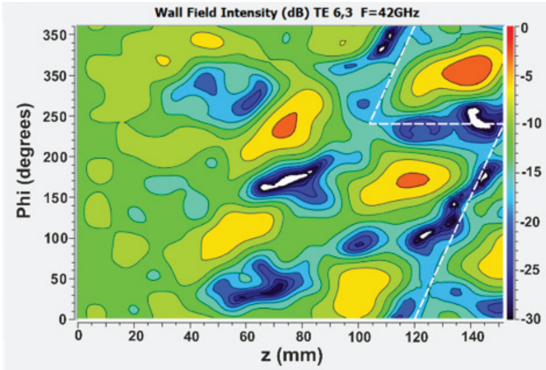
Launcher length (mm)	208.4
Helical cut length (mm)	51.9
Launcher radius (mm)	18.74
Taper angle (rad.)	0.007
Gaussian content factor	99.06% (for 42 GHz) 99.47% (for 82.305 GHz)

Similarly, for the second launcher design, the wall field intensities which give the beam concentration on the launcher wall section based on geomatic optics (g.o.) are shown in Fig. 6. Aperture field intensity is shown in Fig. 7. The far-field profile is shown in Fig. 8.

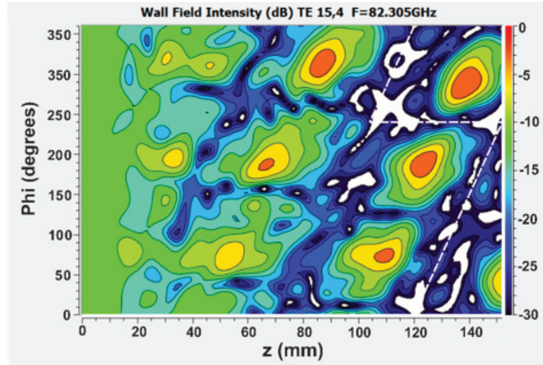
From the comprehension of Figs. 3 and 6, it is evident that there are losses due to the diffraction of the beam from launcher cut at 42 GHz operation, which in turn generates the heat around the cut section and deteriorate the mode purity.

Aperture field intensities for both the designs are quite similar (Figs. 4 and 7). If we compare the far-field intensities of the two designs, we can infer that the second design is very much suitable for the presented dual regime operation because of the good convergence of the beam in the far-field region.

Based on the comparative analysis presented in the previous section, the second design has opted for the further design of the mirror section and matching optic unit (MOU). Generally, two or three mirrors are sufficient for proper propagation of beam from launcher cut to a corrugated

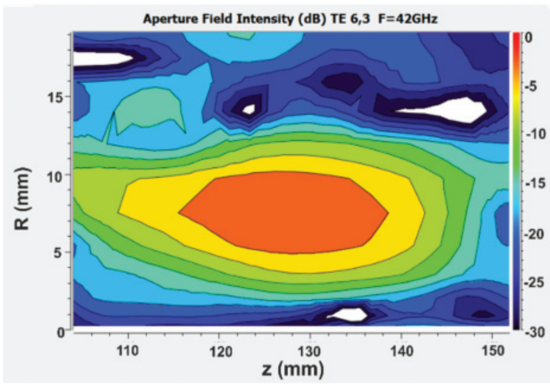


(a)

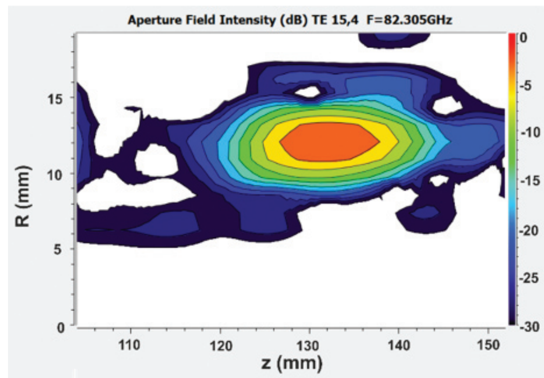


(b)

Figure 3. Electric field intensity (dB) for: (a) the 42 GHz operation and (b) the 84 GHz operation.

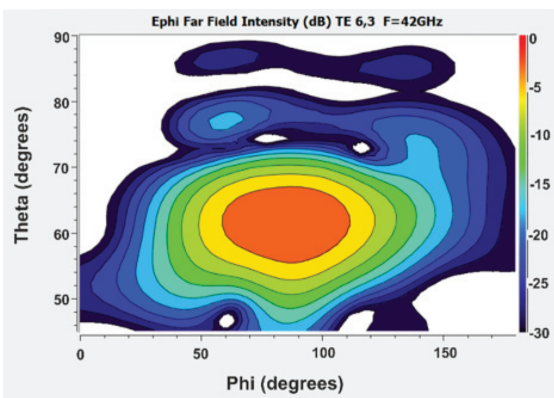


(a)

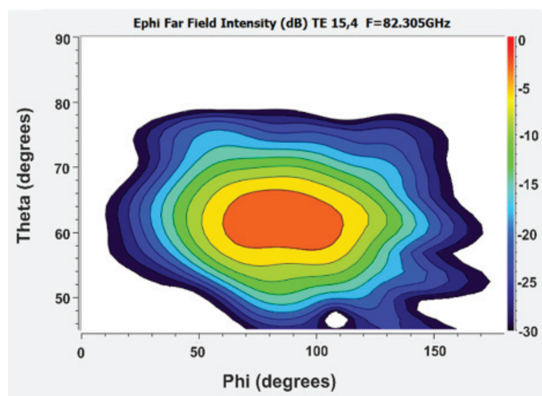


(b)

Figure 4. Aperture field intensity (dB) for: (a) the 42 GHz operation and (b) the 84 GHz operation.

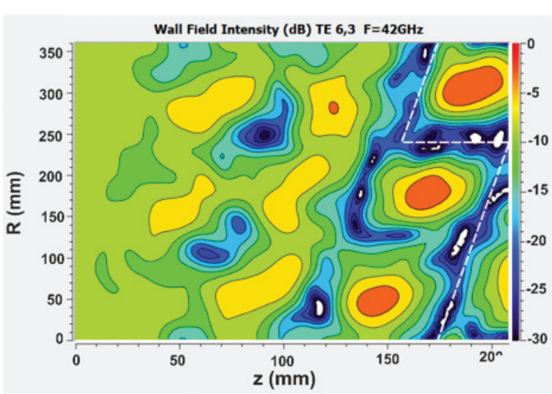


(a)

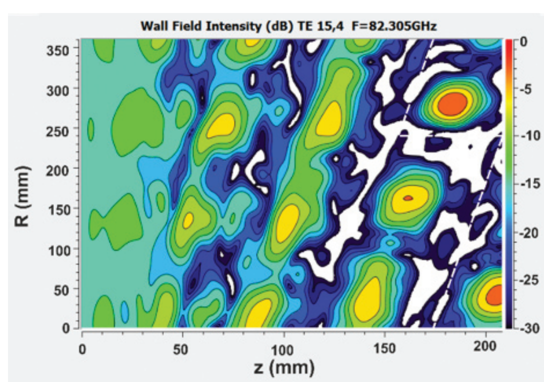


(b)

Figure 5. Far-field profile (dB) for: (a) the 42 GHz operation and (b) the 84 GHz operation.

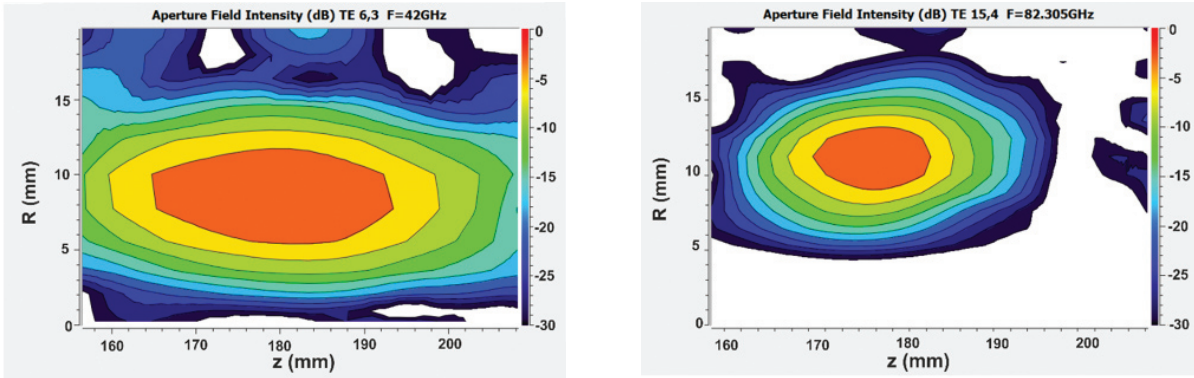


(a)



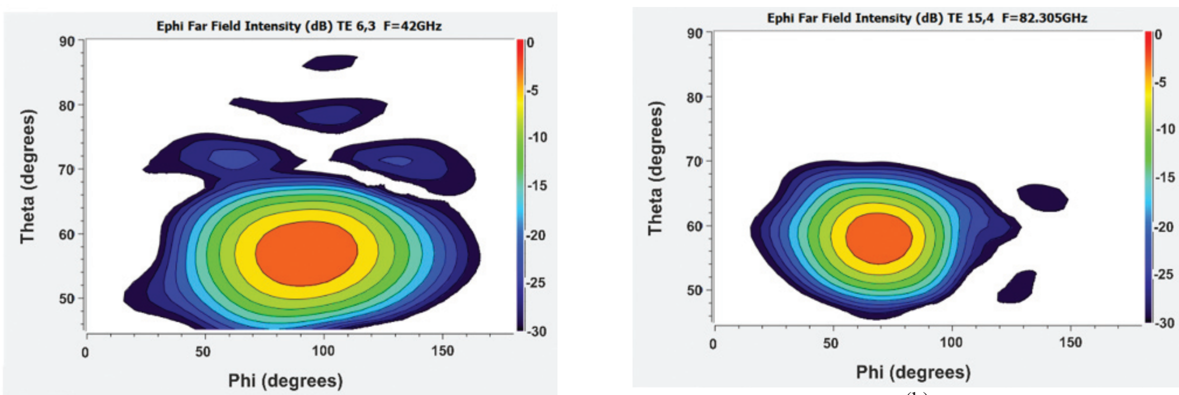
(b)

Figure 6. Electric field intensity (dB) for: (a) the 42 GHz operation and (b) the 84 GHz operation.



(a) (b)

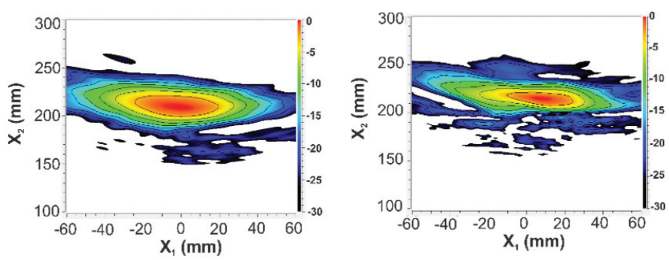
Figure 7. Aperture field intensity (dB) for: (a) the 42 GHz operation and (b) the 84 GHz operation.



(a) (b)

Figure 8. Far-field profile (dB) for: (a) the 42 GHz operation and (b) the 84 GHz operation.

waveguide, but in the current dual regime device, the fourth mirror will also be included for proper positioning of the beam at both the operational frequencies. The first step towards mirror system design is to obtain a beam profile at the position of the first mirror. Figure 9 shows the field intensities (using Surf3d) at the first mirror position i.e. ~40 mm from the axis in the radial direction and ~220 mm from the end of the launcher in the axial direction.



(a) (b)

Figure 9. Beam profile (dB) at 40 mm for (a) 42 GHz; (b) 84 GHz operation.

4. CONCLUSION

This paper gives the basic design aspects of a dual regime Gyrotron output system. NLT, quasi-optical mode converter, and RF window all together make a complete output system. NLT is designed such that it will couple the chosen mode-pair from interaction circuit to mode converter with very less or no mode conversion. Dimple type perturbations are used for enhanced efficiency of QOL in terms of Gaussian mode content in the output beam. BN CVD materials are used as a dielectric material for the RF window. CVD diamond is the best material for fabricating windows for megawatt-class Gyrotron though, for our design where output power is 0.5 MW, the BN CVD window can also fulfill the need. Comparative analysis between two QOL designs shows that launcher length and cut length should be optimised such that the output beam from the launcher for both the operational frequencies should have approximately the same position with minimum diffraction at the launcher cut. Beam profile at the possible mirror position has also been presented which supports the claim to use a single mirror system for presented dual regime operation.

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In the present paper, he has carried out theoretical and simulation work.

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In the present paper, he has performed the analytical and interpretational parts.