DESIGN AND SIMULATION ANALYSIS OF OUTPUT SYSTEM FOR A TRIPLE-FREQUENCY GYROTRON

Debasish Mondal, **Beemagani Ravinder**, S. Yuvaraj, A. K. Jha, and M. V. Kartikeyan

Indian Institute of Technology Tirupati, India

The 9th ITG International Vacuum Electronics Workshop (IVEW) 2024

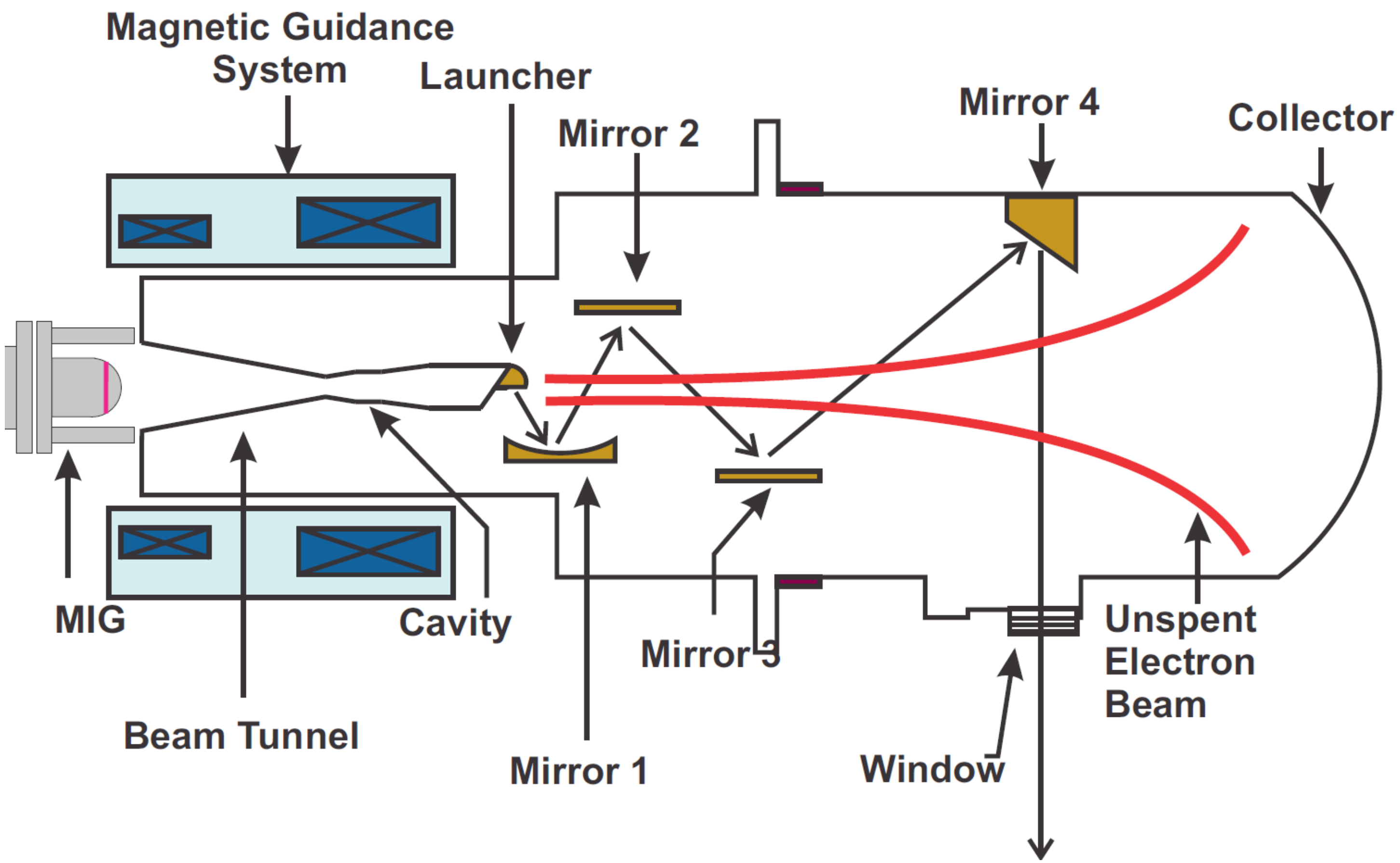
August 28 - 30, 2024

Physikzentrum, Bad Honnef, Germany

Contents

- Design studies of Nonlinear Taper
- Design studies of Quasi-Optical Launcher (QOL)
- RF Window
- Iterative Phase Retrieval Algorithm: Mirror Synthesis
- Conclusion

Schematic of Gyrotron



Schematic of Output System

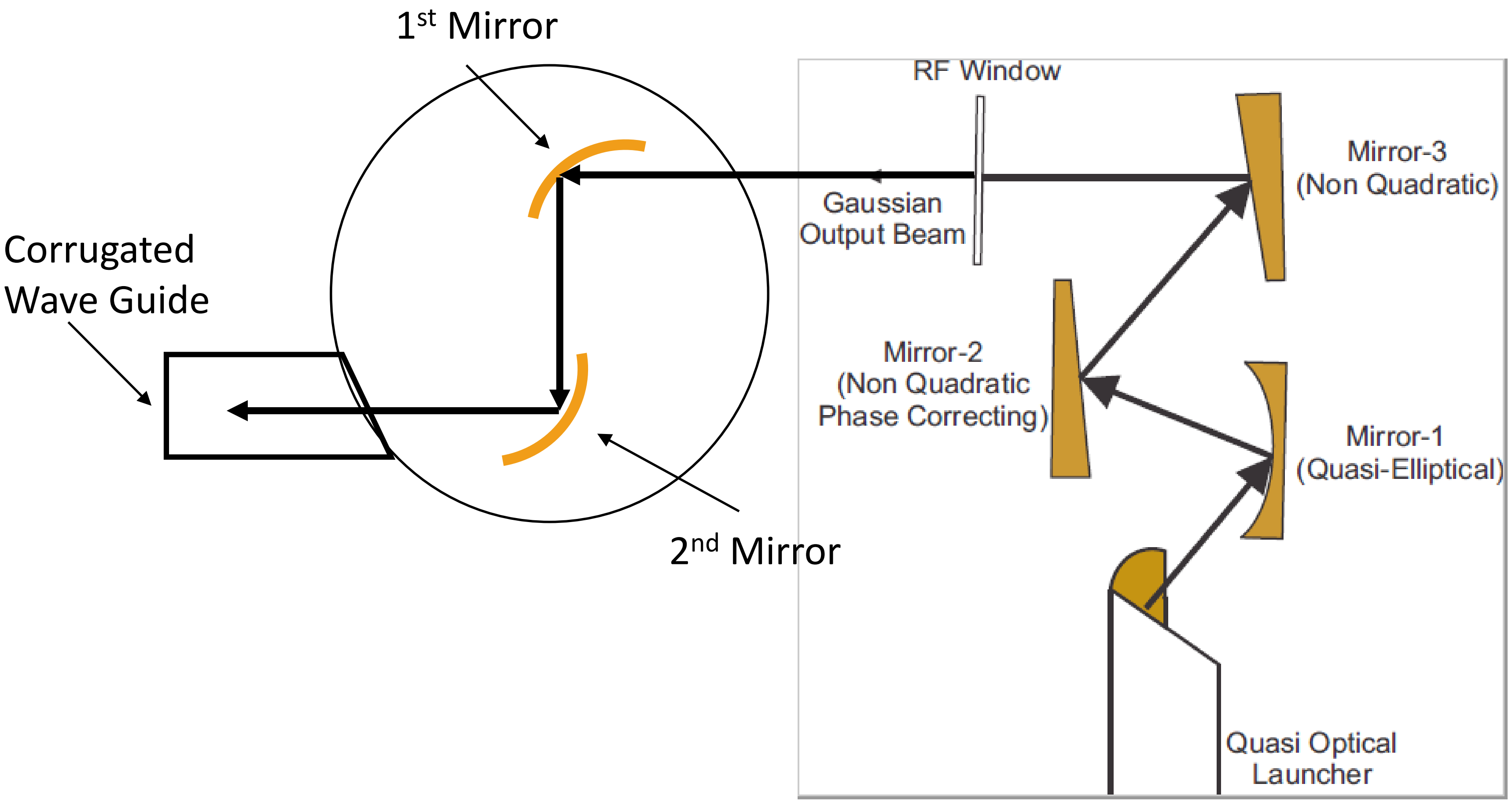


Figure: Schematic of the output system in gyrotron.

Design Goals

Component	Design goal
Interaction Cavity	Less mode conversion, high-quality factor, and better field profile, reduce reflected RF waves propagation towards the T-MIG
Nonlinear Taper (NLT)	Mode conversion should be avoided, length of NLT should be small
Quasi Optical Launcher (QOL)	The length of QOL should be small, fields at the cut edges should be minimum, and GCF should be high
RF Window	High mechanical and thermal strength, and ability to handle high power
Matching Optic Unit (MOU)	Maintain beam ellipticity and reduce incident beam astigmatism

Design Studies of a Nonlinear Taper

The Basic Impetus To Carry This Work

- A nonlinear taper (NLT) is an essential waveguide structure that connects the output of the interaction cavity to the quasi-optical launcher (QOL).
- The NLT is integrated (L’3) into the gyrotron system, featuring an axial profile comprising a uniform mid-section (L2) with length of 35 mm, a down tapered input section (L1) of 20 mm.
- This configuration allows for a larger collector size, enhancing the collection efficiency of the spent electron beam.

Design Studies of Non-linear Taper

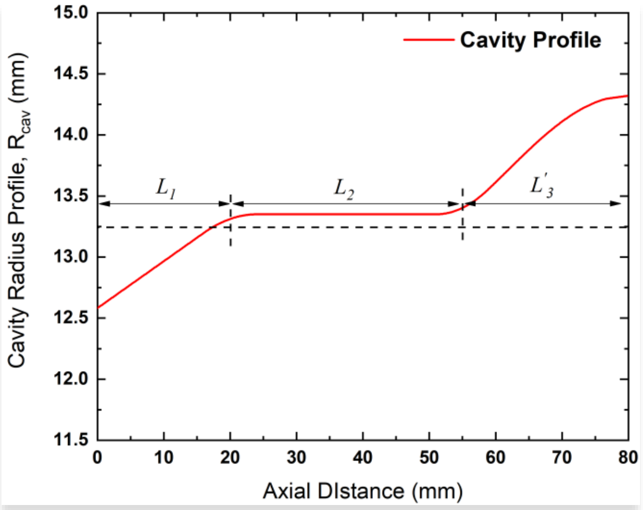


Figure: NLT attached to the interaction cavity of the triple-frequency gyrotron operating at 42 GHz, 84 GHz, and 95 GHz using GDS

Table: The Design Parameters of Nonlinear Taper for Triple-frequency Gyrotron Operating at 42 GHz, 84 GHz and 95 GHz

Parameters	Values
$L_1/L_2/L'_3$ (mm)	20/35/25
$\theta_1/\theta_2/\theta_3$ (°)	2.2/0/3
R_0 (mm)	13.35
R_{nlt} (mm)	14.32
Transmission Efficiency (%)	99.50 (42 GHz), 99.30 (84 GHz) and 99.37 (95 GHz)

Design Studies of a Quasi-Optical Launcher

The Basic Impetus To Carry This Work

- The QOL is used to convert the higher order cavity mode to a Gaussian-like beam which is radiated from a spiral cut at the end of the dimple wall waveguide.
- A QOL is designed with higher order perturbations included in the wall surface deformation so as to obtain the outgoing wave beam with high Gaussian content.
- The Gaussian beam radiated from the waveguide through spiral cut generates a beam with high Gaussian content and low diffraction losses (< 3%). Matching of output wave beam to the Gaussian beam with efficiency > 98%.

Parametric Studies of Quasi-Optical Launcher

Launcher Length	Axial Cut Length	Taper Angle	GCF	Remarks
170	35	0.003	97.49	Proper Wall Field Intensity
180	35.27	0.004	98.31	**Compromised Wall Field Intensity**
180	35	0.005	99.31	Proper Wall Field Intensity
170	35	0.002	98.92	**No Wall Field Intensity**
180	**35**	**0.005**	**99.68**	**Proper Wall Field Intensity**

Design Studies of a Quasi-Optical Launcher

Table: The Design Parameters Of Quasi-optical Launcher of Triple-frequency Gyrotron Operating at 42 GHz, (TE6,2), 84 GHz (TE10,4), And 95 GHz (TE12,4).

Parameters	Values
Launcher Length (mm)	180
Helical Cut Length (mm)	35
Launcher Radius (mm)	14.32
Taper Angle (Rad.)	0.005
Gaussian Content Factor (%) (LOT)	99.68 (42 GHz), 99.85 (84 GHz) and 99.91 (95 GHz)
Gaussian Content Factor (%) (Surf3D)	95.14 (42 GHz), 98.43 (84 GHz) and 97.36 (95 GHz)
Energy Conversion Efficiency (%)	92 (42 GHz), 99.42 (84 GHz) and 96.38 (95 GHz)

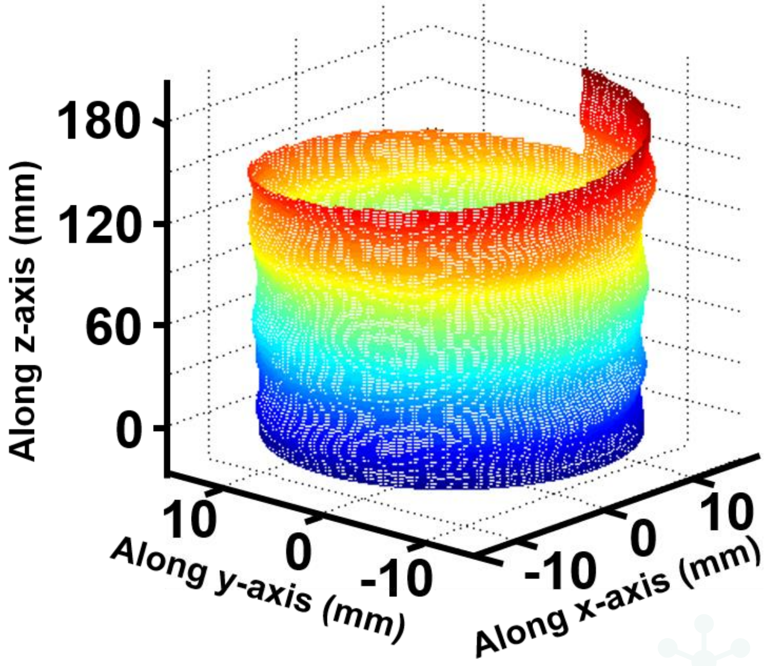
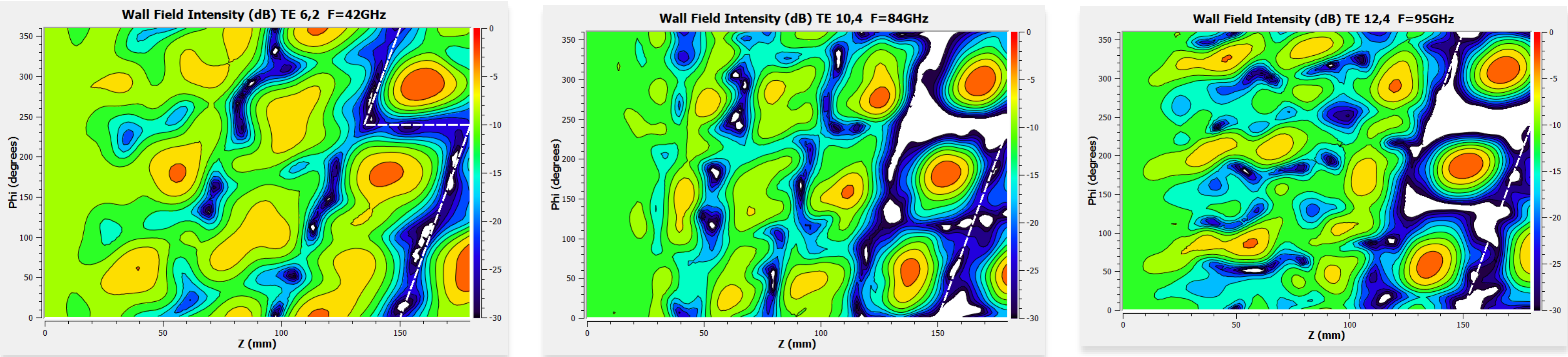


Figure: The launcher’s Inner radius profile with deformed surface

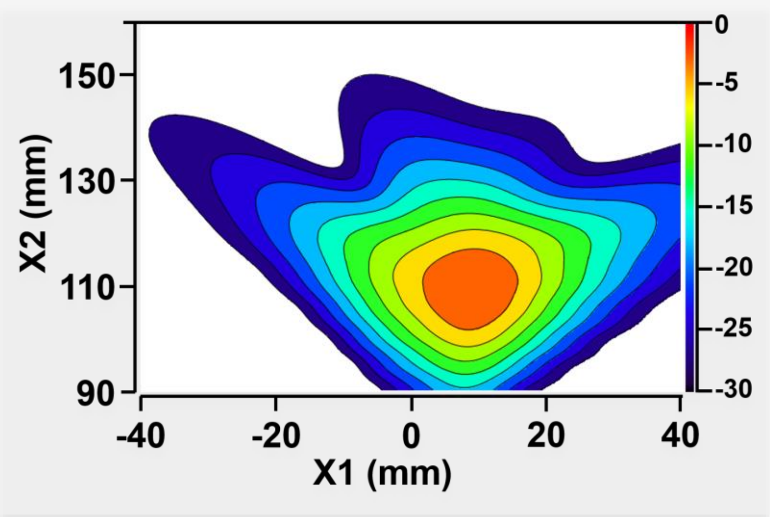
Quasi-Optical Launcher: Wall Field Intensity



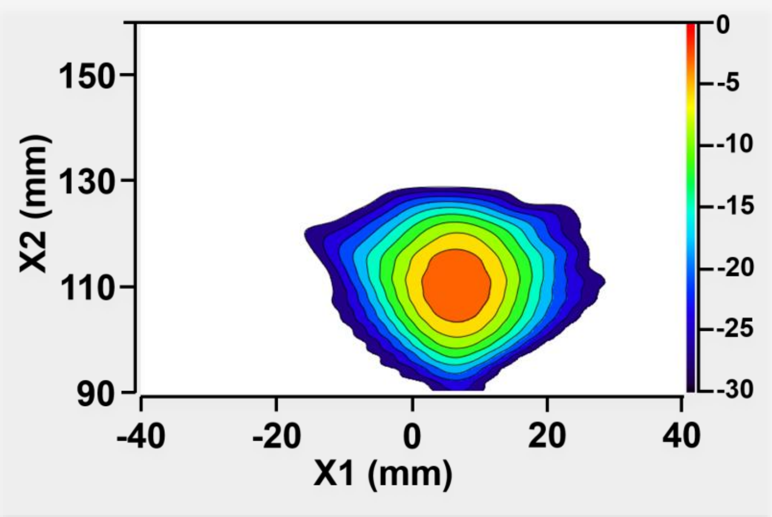
(a) (b) (c)

Figure: The wall field intensity on the launcher's open-cut length section of (a) 42 GHz, (b) 84 GHz, and (c) 95 GHz gyrotron obtained using LOT.

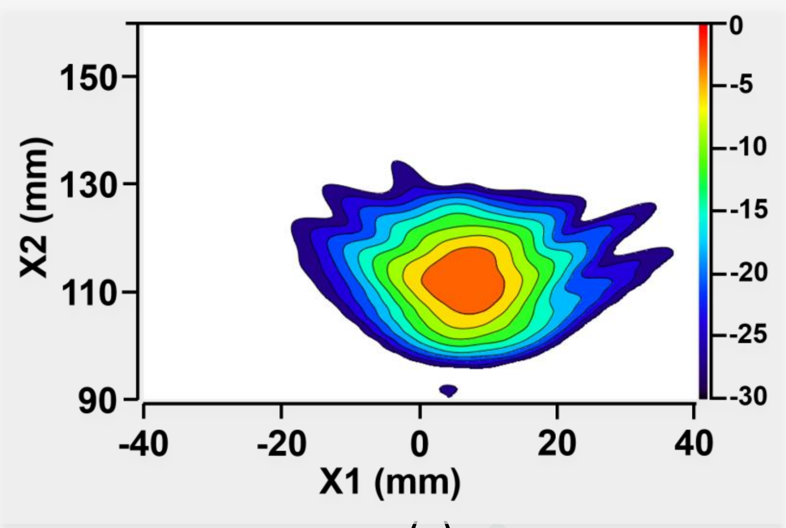
Quasi-Optical Launcher: Aperture Field Intensity at 14.32 mm



(a)



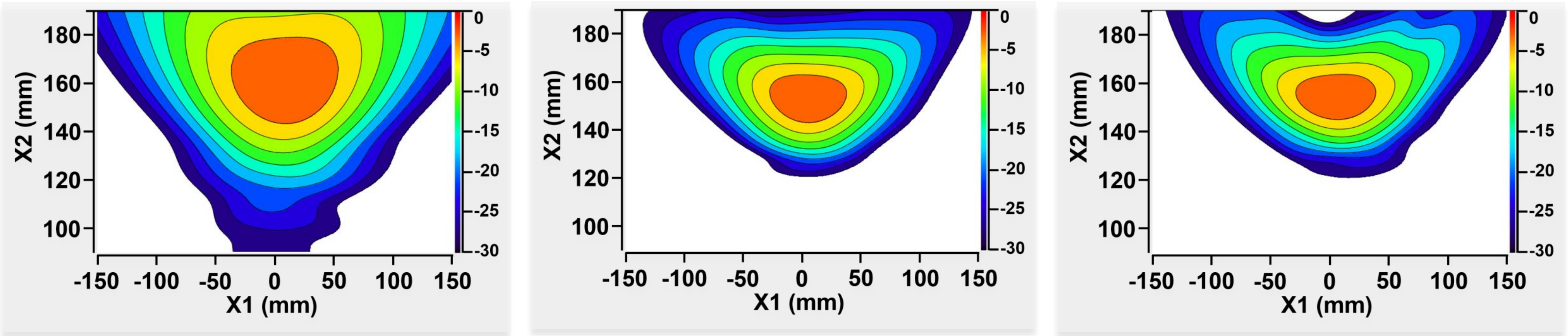
(b)



(c)

Figure: Aperture field intensity at a distance of 14.32 mm radially at the launcher open cut section for (a) 42 GHz, (b) 84 GHz, and (c) 95 GHz obtained using LOT.

Quasi-Optical Launcher: Field Intensity at 80 mm



(a) (b) (c)

Figure: Aperture field intensity at a distance of 80 mm radially for (a) 42 GHz, (b) 84 GHz, and (c) 95 GHz obtained using LOT.

Quasi-Optical Launcher: Far Field Intensity

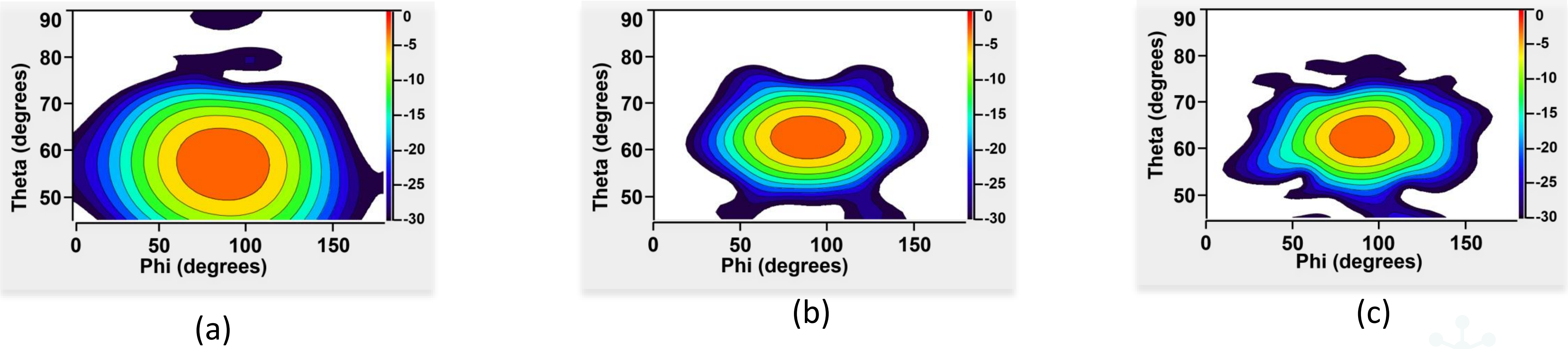


Figure: Far field patterns of the launcher (a) 42 GHz, (b) 84 GHz, and (c) 95 GHz obtained using LOT.

Design Studies of Brewster RF Window

The Basic Impetus To Carry This Work

- The RF window in the gyrotron's output system plays a critical role as a barrier separating the vacuum environment from the applicator.
- The window supports metallization, facilitating a vacuum seal between the ceramic window and metal flange.
- The disc thickness of the Brewster window should be calculated such that it support the triple-frequency operation of gyrotron.

Design Studies of Sapphire Brewster RF Window

$$\theta_B = \tan^{-1}\sqrt{\varepsilon_r}$$

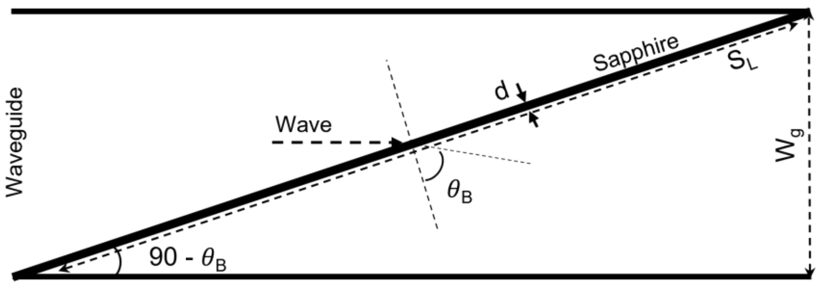


Figure: Schematic of the Brewster window showing waveguide dimensions and relevant angles

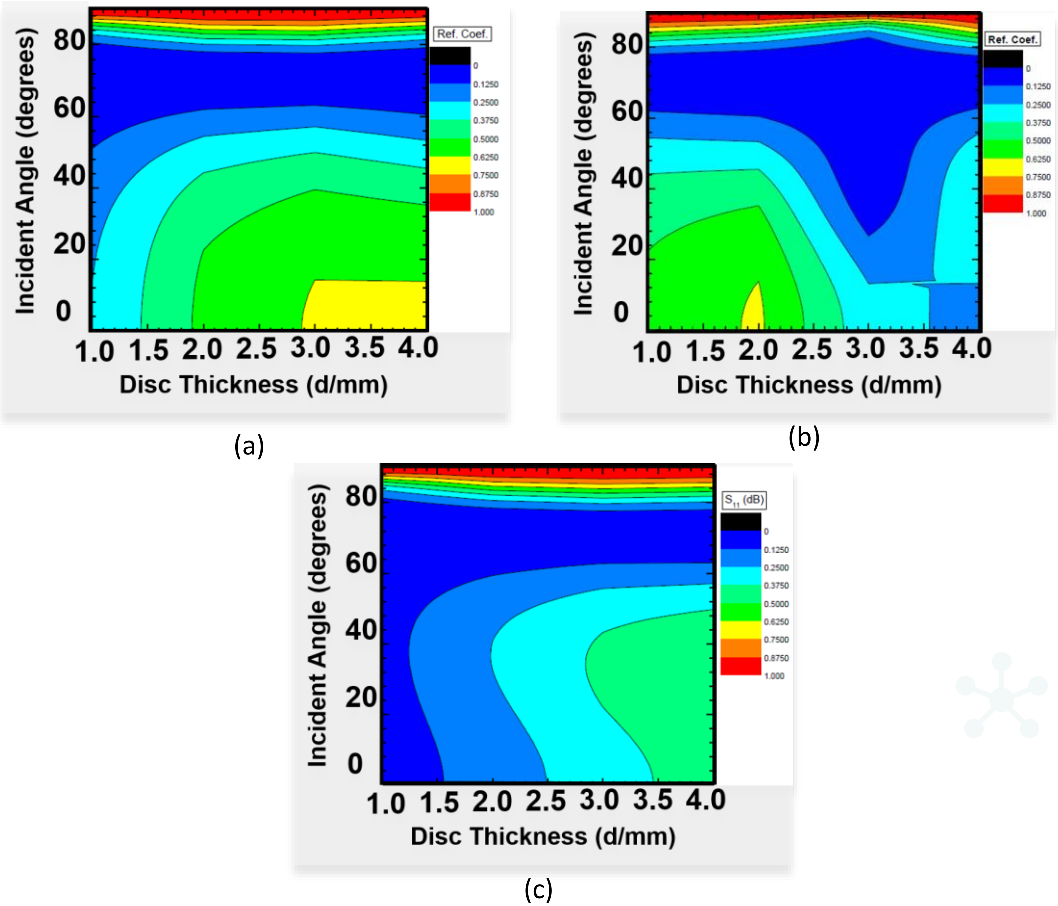


Figure: Contours of reflection coefficient as a function of disc thickness and incident angle for a Sapphire Brewster window at (a) 42 GHz, (b) 84 GHz, and (c) 95 GHz.

Design Studies of Sapphire Brewster RF Window

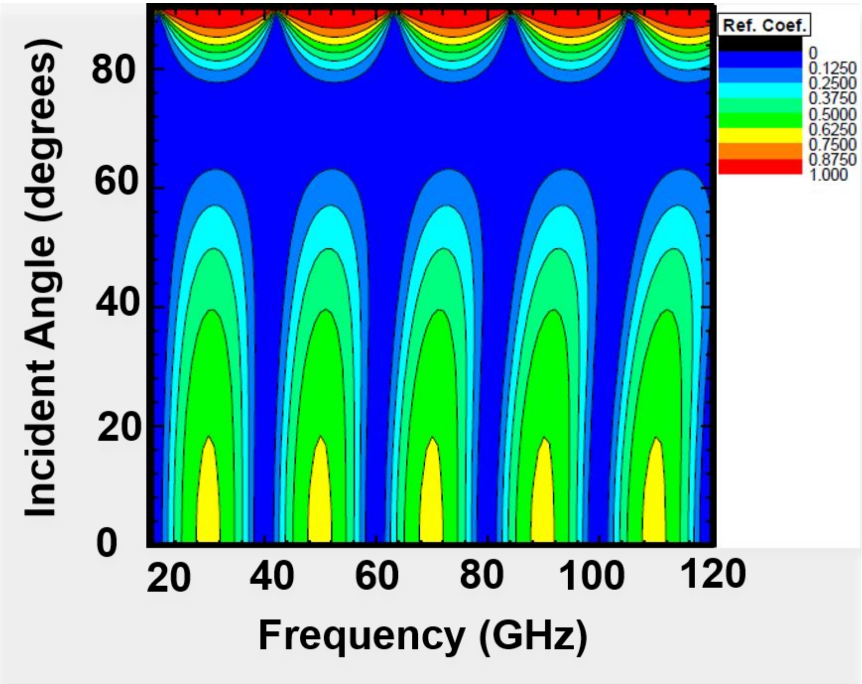


Figure: Contours of reflection coefficient as a function of frequency and incident angle for a Sapphire Brewster window using GDS

Table: The Window Dimensions as Part of The Designed Circuit for A Single Output Component for Triple-frequency Gyrotron Operation

Parameters	Values
Window Material	Sapphire (Al_2O_3)
Window Aperture Diameter (W_g) (mm)	50
Disk Thickness (mm)	2.45
Disk Dielectric Constant	9.41
Dielectric strength (kV/mm)	48
Slant length (S_L) (mm)	162
Brewster angle (θ_B)	72 °

Design Studies of Matching Optics Unit (MOU)

The Basic Impetus To Carry This Work

- The design of the Matching Optics Unit (MOU) for triple-frequency 42-84-95 GHz gyrotron to reflect the wave to the tokamak.
- The diameter for the corrugated waveguide should be 63.5 mm, and the Gaussian-shaped RF beam at the waveguide input should have a waist size of approximately one-third of the waveguide diameter.
- A synthetic Gaussian beam (SGB) is to be introduced for realistic beam intensity assumptions exhibiting intensity divergence and off-axis incidence with distance.
- The design ensures efficient coupling of the output beam to the corrugated waveguide while preserving beam ellipticity and astigmatism.

Iterative Phase Retrieval Algorithm: Mirror Synthesis

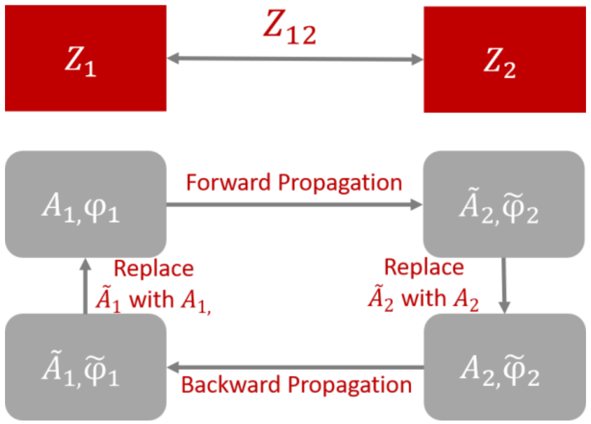


Fig: Two-plane illustrates the iterative phase retrieval algorithm technique where plane 1 and plane 2 are denoted as z_1 and z_2.

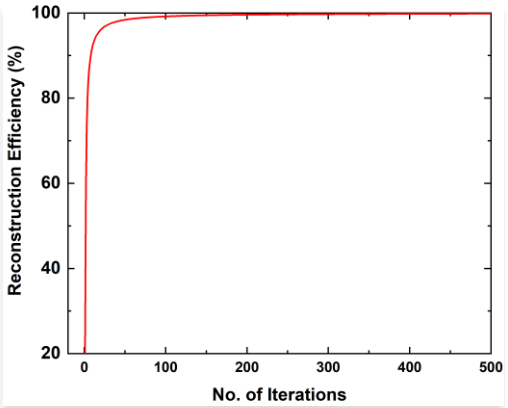
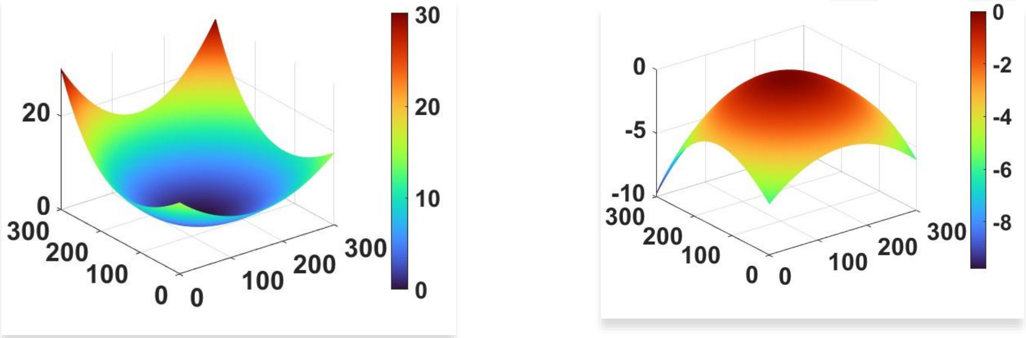


Fig: The effectiveness of the reconstruction in terms of the number of iterations



(a) (b)

Fig: The optimized mirror profile of (a) mirror 1 and (b) mirror 2.

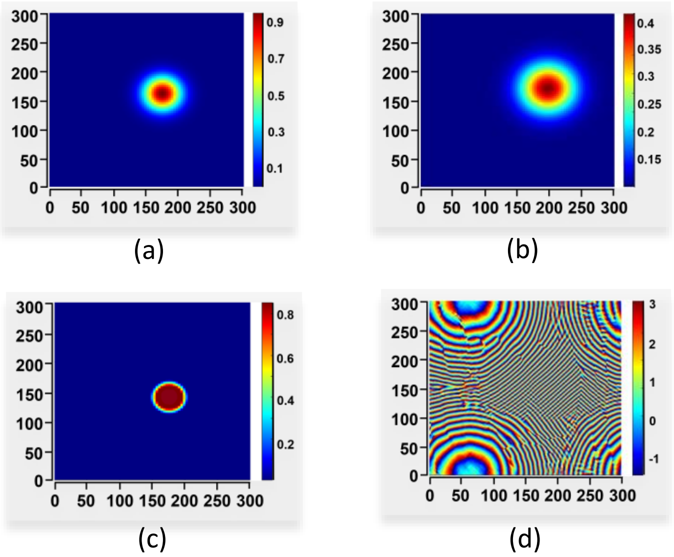


Fig: (a) The Synthetic Gaussian Beam (SGB) contour at z_1, (b) The SGB contour at z_2, (c) the reconstructed SGB contour at z_2, and (d) the retrieved phase.

Generation of Synthetic Gaussian Beam (SGB)

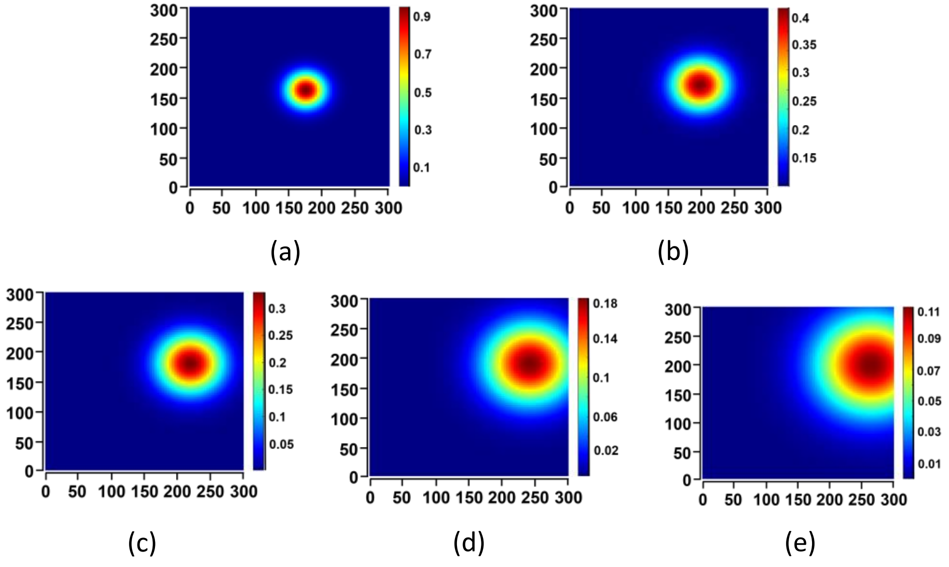


Fig: The field intensity divergence and off-axis incidence from the centroid position of the synthetic Gaussian beam (SGB) are plotted at various distances from the RF window section, with profiles at (a) 80 mm, (b) 380 mm, (c) 500 mm, (d) 750 mm, and (e) 1000 mm.

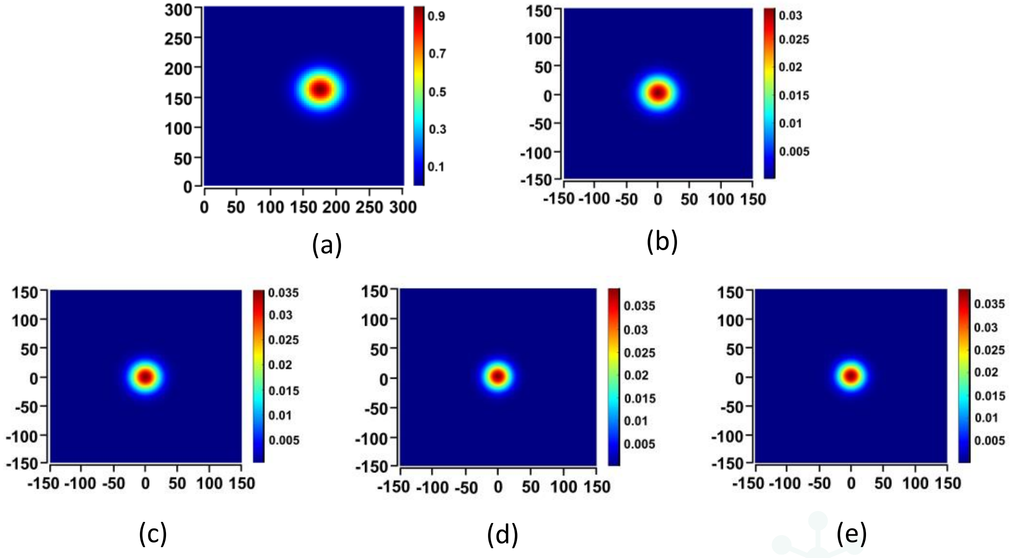


Fig: The field intensity convergence and minimized off-axis incidence of the SGB are plotted at various distances inside the MOU, with profiles at (a) 80 mm, (b) 380 mm, (c) 500 mm, (d) 750 mm, and (e) 1000 mm.

Conclusion

- This work reported a comprehensive design, optimization and analysis of the complete output system consisting of NLT, QOL, RF Window and the MOU.
- The output system supports the operation of the multi-frequency Gyrotron at 42/84/95 GHz with specified output powers/efficiency.
- The waveguide surface is converted to the high order cavity mode to a Gaussian-like beam in Quasi-optical launcher.
- The launcher has been designed by including higher-order perturbations in the wall surface deformations. The design studies are performed using the commercial software LOT.
- The beam coming out of the designed launcher has a Gaussian content of 98.68%, 99.85%, and 99.91% at the respective operating frequencies.
- The Brewster window supported all the triple-frequency operation of gyrotron.
- The application of the IPRA facilitated accurate wave phase and amplitude contour reconstruction.

References

1. G. S. BAGHEL and M. V. KARTIKEYAN, IEEE Trans. Electron Devices, 65(4) (2018), p. 1558–1563, doi: 10.1109/ted.2018.2808380.
2. S. YUVARAJ, G. S. BAGHEL, S. SINGH, and M. V. KARTIKEYAN, Private Commun., Indian Inst. Technol. Roorkee, Roorkee, (India, Internal Rep., 2018).
3. M. V. KARTIKEYAN, E. BORIE, and M. THUMM, (Springer-Verlag, Berlin, Germany, 2004).
4. J. NEILSON, in Infr. Millim. Waves, Conf. Dig. Joint 29th Int. Conf., 12th Int. Conf. Terahertz Electron., 2004, p. 667-668, doi: 10.1109/ICIMW.2004.1422267.
5. D. MONDAL, S. YUVARAJ, M. RAWAT, M. K. A. THUMM, and M. V. KARTIKEYAN, IEEE Trans. on Plasma Sci., (2024), p.1-8, doi: 10.1109/TPS.2024.3357837.
6. J. JIN, G. GANTENBEIN, J. JELONNEK, M. THUMM, and T. RZESNICKI, IEEE Trans. Plasma Sci., 42(5) (2014), p. 1380–1384, doi: 10.1109/tps.2014.2310903.

Thank You!