PERFORMANCE OF TRANSMISSION LINE SYSTEM AT 42±0.2GHZ FOR AN INDIGEOUS GYROTRON SYSTEM

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Abstract

In high microwave power applications like gyrotron, transmission line system, calorimetric dummy load, etc, requires design, modeling, simulation and evaluation of transmission line system before fabrication of the same is undertaken. Under the aegis of Department of Science and Technology (DST), a multi-institutional program for the development of a gyrotron operating at 42±0.2GHz/200kW/3secs in TE_{03} mode has been undertaken. It is currently in an advance stage of test and commissioning at Institute for Plasma Research (IPR). It is desired for plasma applications that the output mode of gyrotron in TE_{03} mode is to be converted to HE_{11} mode for efficient coupling to plasma. The HE_{11} mode (TEM_{00} mode), has an electric field distribution very close to that of an ideal Gaussian mode. This gaussian like mode is preferred for high-power transmission through overmoded corrugated waveguides, which gives insertion loss lower than that of any other modes. The proposed design of transmission line system converts unpolarized TE_{03} mode into polarized HE_{11} mode. The ripples walled mode converters are designed for converting TE_{03} to TE_{01} in two steps. TE_{01} mode is converted to TM_{11} by bending a smooth waveguide at an angle of 34.94°. Finally TM_{11} mode is converted to HE_{11} mode. Miter bend for TE_{01} mode andHE_{11} mode are also designed. The designed corrugated waveguide operates at 42±0.2GHz. The Final design of all the components are verified using simulation studies carried out in CST-MWS. Performance optimization has been carried out prior to fabrication process. At this point in time, fabrication of many of the mode converters has been completed and miter bends are under mechanical fabrication process. As a part of a design, transmission line system is mechanically compatible to high vacuum and 1bar pressurization. The system includes two design approaches whose performances are compared in terms of insertion loss, bandwidth and cost effective manufacturing. Both the proposed design approaches of transmission line system have total insertion loss of 1.3 to 1.5dB. The bandwidth of first design approach is wider as compared to second. Flexibility of manufacturing process of transmission line system is an advantage of second approach. The Salient point of design and simulation studies of transmission line system are discussed and highlighted in the manuscript.

1. INTRODUCTION

The recent progress using high power millimeter waves such as electron cyclotron resonance heating (ECRH), lower hybrid current drive (LHCD) for plasma production, current drive and other applications. These applications make use of high-power millimeter-wave generated from the gyrotron for efficient plasma coupling [1]. High power gyrotron with quasi optical internal mode converters are currently in wide use. The indigenously designed and developed gyrotron under aegis of DST is in advance stage of commissioning at Institute for Plasma Research. (IPR). The operating frequency of the gyrotron is 42±0.2GHz/200kW/3secs in TE_{03} mode. It is preferred to couple microwave power to plasma in HE_{11} mode. In order to achieve this, external mode converters are designed [2-3]. In this approach optimization of physical dimensions of mode converters is attempted.

The output diameter at the mouth of gyrotron is Ø85mm. with this diameter optimization of mode converters and transmission line systems is difficult. The length of the mode converters are long and fabrication difficulties are encountered. Two linear down tapers from Ø85 are used to reduce the diameter to Ø31.75mm. Based on these geometrical parameters the proposed system is evaluated. The calculation of the cut-off frequency and maximum power handling capacity has been carried out. The cut-off frequency for respective mode converters is calculated for optimized radius.

The cut-off wavelength for (TE_{mn}) and (TM_{mn}) is given by equation (1) and (2).

For TE_{mn}, $$\lambda_{c,mn} = \frac{2\pi a}{\chi'_{mn}} \quad (1)$$

For TM_{mn}, $$\lambda_{c,mn} = \frac{2\pi a}{\chi_{mn}} \quad (2)$$

where, $\lambda_{c,mn}$ is cut-off wavelength, a is waveguide radius, χ'_{mn} is derivative of roots of bessel's function and χ_{mn} are the roots of the bessel's function.

The cut-off frequency is calculated by equation (3) given below,

$$f_{c,mn} = \frac{c}{\lambda_{c,mn}} \quad (3)$$

where c is speed of light 3×10^8 meter per second. The calculated value of cut-off frequency is shown in table-1.

The power handling capacity of the respective mode converters[4] at atmospheric pressure are calculated using the empirical relation. The relation between the maximum power that can be handled between the respective mode converters is highlighted in by equation (4).

$$P = 3.98\times10^{-3}(a)^2(\frac{\lambda}{\lambda_g})E^2_{rms} \quad (4)$$

where $\frac{\lambda}{\lambda_g} = \sqrt{1-\left(\frac{\lambda}{\lambda_c}\right)^2}$. The guidelines [5] for calculation of the power handling capacity for respective mode converters is given by following equation (5) and (6). Table-1 gives summarizes cut-off frequency and power handling capacity of the respective mode converters.

For TE_{mn}/TM_{mn}, $$P_{max} = 1790\times a^2\sqrt{1-\left(\frac{f_{c,mn}}{f}\right)^2} \quad (5)$$

For TE_{0n}, $$P_{max} = 1805\times a^2\sqrt{1-\left(\frac{f_{c,0n}}{f}\right)^2} \quad (6)$$

Table-1 Summary of cut-off frequency and power handling capacity

Sr. No.	Waveguide Mode	Waveguide radius (mm)	Cut-off frequency (GHz)	Power handling capacity (kW)
1	TE_{03}	42.5	11.4	3.26×10^3
2	TE_{02}	31.75	10.6	1.82×10^3
		15.875	21.1	0.393×10^3
3	TE_{01}	31.75	5.77	1.82×10^3
		15.875	11.5	0.455×10^3
		6.16	29.7	0.065×10^3
4	TM_{11}	31.75	5.77	1.80×10^3
		15.875	11.5	0.451×10^3
5	TE_{11}	31.75	2.77	1.80×10^3
		15.875	55.3	0.447×10^3

Two possible approaches for mode conversion are highlighted below,

(i) $TE_{03} - TE_{02} - TE_{01} - TM_{11} - HE_{11}$

(ii) $TE_{03} - TE_{02} - TE_{01} - TE_{11} - HE_{11}$

In the first approach ease of fabrication using axis-symmetric ripple walled waveguide[6,7] is advantage over second approach in which fabrication limitations in terms of realizing internal serpentine structure. In the first approach TM_{11} mode is converted to HE_{11} mode by varying corrugation depth linearly from smooth walled waveguide to $\frac{\lambda}{4}$ [3,8-13]. The TE_{03}-TE_{01}-TM_{11}-HE_{11}design approach is preferred keeping in mind the fabrication limitation.

2. ANALYTICAL APPROACH OF PROPOSED TRANSMISSION LINE SYSTEM

The proposed design of transmission line system includes two options for this adapted mode conversion approach (TE_{03}-TE_{01}-TM_{11}-HE_{11}) as shown in figure-1. The first option of the system gives wider bandwidth. However, flexibility in mechanical fabrication of entire system was achieved using second option. The design of all the transmission line components has been carried out based on telegraphyst's equations [19-20]. The general coupling equations for individual mode converter in circular waveguide are given by,

$$\frac{dA_m}{dz} = -i\beta_m A_m - iC_{[m][n]}A_n$$
$$\frac{dA_n}{dz} = -i\beta_n A_n - iC_{[m][n]}A_m \qquad (7)$$

where A_m and A_n are the respective amplitudes, β_m and β_n are the respective propagation constant and $C_{[m][n]}$ is the coupling between corresponding mode. The analytical approach to evaluate microwave performances of down tapers, three mode converters namely TE_{03}-TE_{02}, TE_{02}-TE_{01},TE_{01}-TM_{11},TM_{11}-HE_{11},TE_{01} miter bend, HE_{11} miter bend and HE_{11} corrugated waveguide has been carried out using CST-Microwave Studio Suite. Figure-1 shows the simulation studies of the proposed approaches at respective output planes.

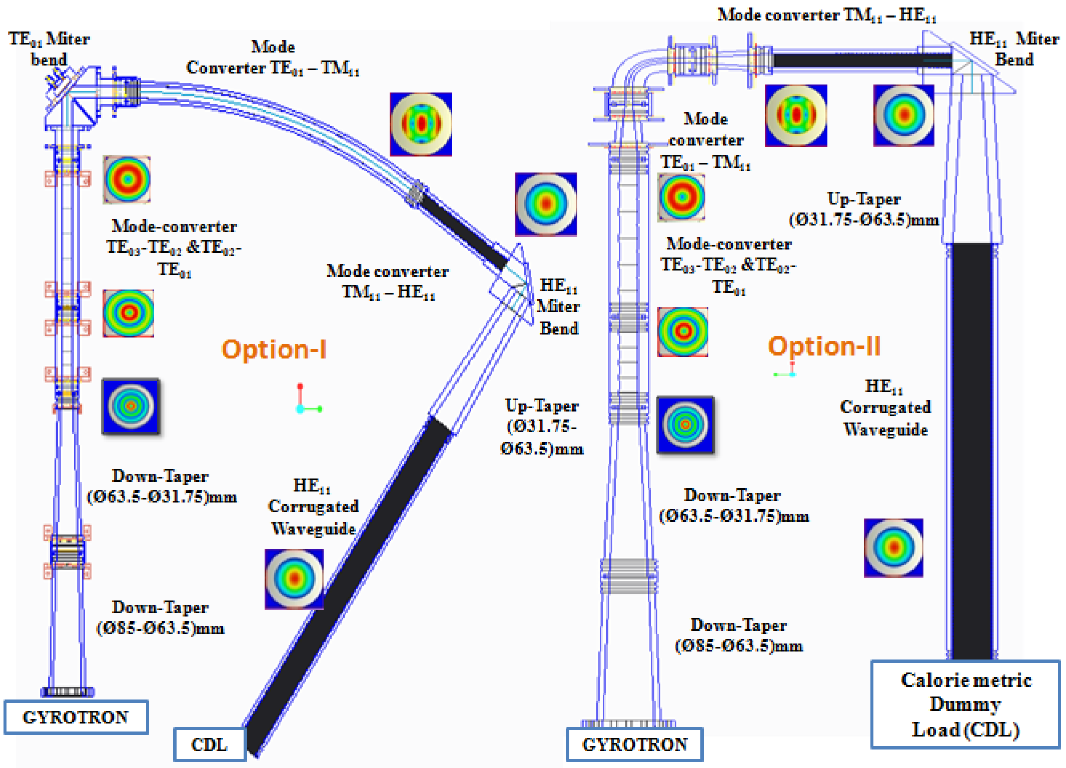


Fig.1. Schematic of design approaches of proposed transmission line system

The geometrical dimensions, conversion efficiency and insertion loss of the individual components of the transmission line are summarised in table-2. The output diameter of gyrotron is Ø85mm.The optimization of down taper using linear approach has been carried out[21,22].The mode converters for TE_{03}-TE_{02}, TE_{02}-TE_{01} are based on ripple walled configuration[6,7]. Owing to geometrical limitations a TE_{01} miter bend based on gap theory[23] has been designed. Evaluation for microwave performance based on simulation studies using CST-microwave studio suite has also been carried out. The design approach for the two options along with snapshots at the respective output planes is highlighted in figure-1. The first option in the proposed design approach has a TE_{01} miter bend and a mode converter TE_{01}-TM_{11} with a smooth bend of 34.94°. The other option has a TE_{01}-TM_{11} mode converter with a 90° parabolic bend at an optimum radius of 6.16mm. The design of TM_{11}-HE_{11} mode converter is based on[3,12-13]. The TM_{11} to HE_{11} mode converter uses linear variation of grove depth from smooth wall to $\frac{\lambda}{4}$ over a length of 292.74mm. The finite dimensions of this mode converter are based on optimized fabrication technique available within the local industry. The up taper of the HE_{11} miter bend from

31.75mm to 63.5mm has simulation insertion loss of 0.097dB. The simulated insertion loss of corrugated waveguide with groove depth of $\frac{\lambda}{4}$ [1.785mm] and periodicity of $\frac{\lambda}{3}$ [2.38mm] is 0.1dB However, the analytical calculation shows a deviation from the simulation studies. The total insertion loss of the complete transmission line system including mode representative for the two options from simulation studies is approximately 1.3dB.

TABLE-2. COMPARITION OF PREDITED PERFORMANCE OF REPRESTATIVE COMPONENTS IN TERMS OF INSERTION LOSS, CONVERSION EFFICIENCY AND GEOMETRICAL DIMENSIONS

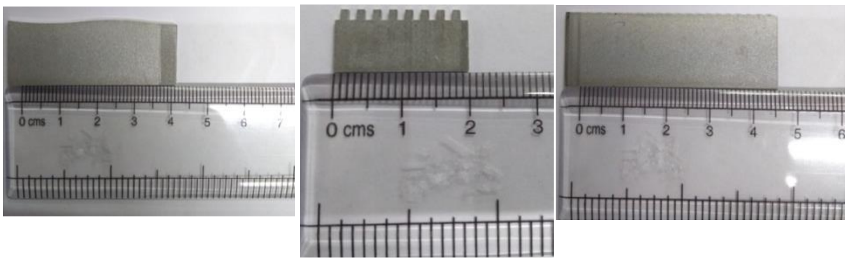
<table>
<tr><th rowspan="2">Sr. No</th><th colspan="4">Option - I</th><th colspan="4">Option - II</th></tr>
<tr><th>Components</th><th>Insertion Loss(dB)</th><th>Efficiency (%)</th><th>Length (mm)</th><th>Components</th><th>Insertion Loss(dB)</th><th>Efficiency (%)</th><th>Length (mm)</th></tr>
<tr><td>1.</td><td>Down Taper (ø85- ø63.5)</td><td>0.16</td><td>97.32</td><td>363</td><td>Downtaper01 (ø85- ø63.5)</td><td>0.16</td><td>97.32</td><td>363</td></tr>
<tr><td>2.</td><td>Down Taper (ø63.5- ø31.75)</td><td>0.0978</td><td>98.2</td><td>401</td><td>Downtaper02 (ø63.5-ø31.75)</td><td>0.0978</td><td>98.2</td><td>401</td></tr>
<tr><td>3.</td><td>TE_{03} to TE_{02}</td><td>0.079</td><td>98.19</td><td>214.8</td><td>TE_{03} to TE_{02}</td><td>0.079</td><td>98.19</td><td>214.8</td></tr>
<tr><td>4.</td><td>TE_{02} to TE_{01}</td><td>0.034</td><td>99.20</td><td>375</td><td>TE_{02} to TE_{01}</td><td>0.034</td><td>99.20</td><td>375</td></tr>
<tr><td>5.</td><td>TE_{01}Miter bend</td><td>0.14</td><td>96.82</td><td>171.38+ 171.38</td><td>TE_{01} to TM_{11} Parabolic bend</td><td>0.3</td><td>93.6</td><td>130+90 +130</td></tr>
<tr><td>6.</td><td>TE_{01} to TM_{11} (Smooth bend)</td><td>0.09</td><td>98.85</td><td>1379</td><td>TM_{11} to HE_{11}</td><td rowspan="3">TE_{11}: 0.77 TM_{11}: 9.19 (0.61)</td><td rowspan="3">TE_{11}:83.64 TM_{11}:12.0 HE_{11}=TE_{11} +TM_{11}= 95.64</td><td>292.74</td></tr>
<tr><td>7.</td><td>TM_{11} to HE_{11}</td><td rowspan="3">TE_{11}: 0.77 TM_{11}:9.1 9 (0.61)</td><td rowspan="3">TE_{11}:83.64 TM_{11}:12.0 HE_{11}=TE_{11} +TM_{11}= 95.64</td><td>292.74</td><td>HE_{11}Miter bend</td><td>200+200</td></tr>
<tr><td>8.</td><td>HE_{11}Miter bend</td><td>200+200</td><td>Up taper (ø31.75-ø63.5)</td><td>401</td></tr>
<tr><td>9.</td><td>Up taper (ø31.75- ø63.5)</td><td>401</td><td>Corrugated waveguide</td><td>0.1</td><td>97.86</td><td>1000</td></tr>
<tr><td>10.</td><td>Corrugated waveguide</td><td>0.1</td><td>97.86</td><td>1000</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Total</td><td>1.31<1.5</td><td></td><td>5169.3</td><td></td><td>1.38<1.5</td><td></td><td>3797.54</td></tr>
</table>

3. SENSITIVITY ANALYSIS

The geometric tolerances of the proposed transmission line with representative components based on the microwave performance has been studied. It is used as a guiding principle for stipulating the fabrication tolerances on various high power microwave components. For carrying out simulation studies, Microwave Studio (CST) software has been used. All the mode converters and transmission line components have been designed and bench marked using simulation studies. The predicted microwave performance with estimated geometrical tolerances is elucidated. Further, the microwave performance of these high power components with respect to the fabrication tolerances on the internal diameter is also explored. It has been found that by and large the cumulative mechanical tolerances on the total length, structural profile inside the mode converter, radius of the mode converter and other mechanical dimensions are stringent. Based on the simulation studies, cumulative mechanical tolerances beyond 100µm during fabrication are not preferred. The aim to obtain the finished product based on the guidelines from simulation studies has been the main theme of the exercise.

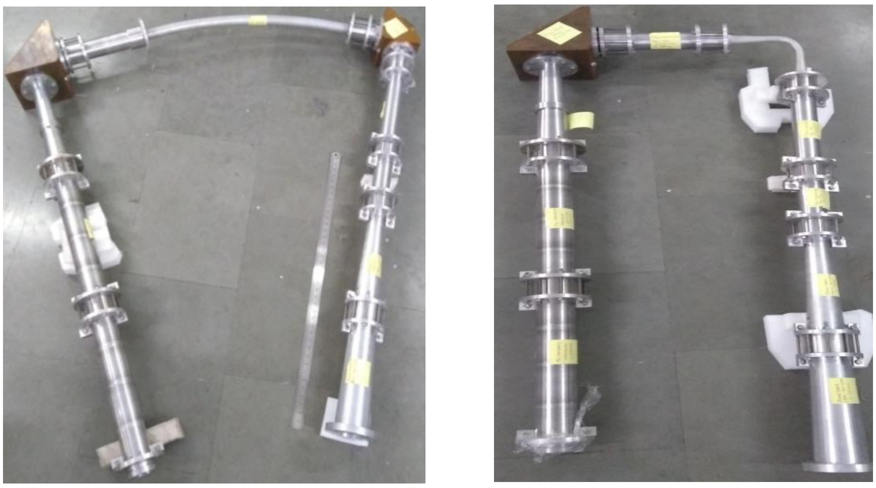
4. CURRENT STATUS OF FABRICATED COMPONENTS

The fabrication of the individual components along with mechanical seals has been carried out within the Indian industry. The mechanical seal has been tested for evacuation to $2*10^{-6}$ torr with helium leak rate of $5*10^{-7}$ torr. liter/sec as measured with helium leak detector in sniffer mode [MSLD-ADIXEN-ASM-142]. The fabrication process is identified based on evaluation of pre-fabricated samples and is highlighted in figure-2. The fabrication of the component has been carried out using CNC machine. Evaluation for microwave performance is envisaged using mode exciters and vector network analyzer [ZVA-50]. Figure-3 highlights the assembly of the fabricated components.



TE03-TE02/TE02-TE01 *CorrugatedWaveguide* *TM_{11}-HE_{11}*

Fig.2. Pre-farbication samples of mode converters and corrugated waveguide



Option-I *Option-II*

Fig.3. Integrated transmission line system, Option-1 and Option-2

5. CONCLUSION

The final optimized design, simulation studies on predicted microwave performance has been carried out. The fabrication of individual components has also been successfully carried out. The typical insertion loss for representative components of transmission line is approximately 1.3dB. The mechanical seal connecting various components of transmission line has also been tested for pressurization of 1bar absolute pressure and vacuum compatibility. It is anticipated that the microwave performance of the individual components will be measured using vector network analyzer. Subsequently representative components would be redesigned appropriately if deviation from predicted microwave performance is seen.

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ACKNOWLEDGEMENTS

Authors would like to thank Board of Research in Nuclear Sciences (Department of Atomic Energy-Govt. of India) for giving financial support under the grant no. 39/14/11/2016-BRNS/34163 and Institute of Plasma Research, Gandhinagar-India for providing technical Support and simulation facilities. Authors would also glad to CHARUSAT University for giving consisted support for carrying out this research work.