New Concept Input and Output Systems for High Power Gyroklystron


*Institute for Plasma Research and Electrical Engineering Department, University of Maryland, College Park, MD 20742

Abstract. In order to obtain the high mode purity of a TE_{011} mode in an overmoded gyroklystron input cavity while maintaining high coupling efficiency, a coaxial dual-cavity input structure with an outer TE_{411} mode and an inner TE_{011} mode coaxial cavity has been designed to get a reasonable low Q and to avoid mode distortion due to a single coupling aperture between an input waveguide and input cavity. A quality factor of 73 and a resonant frequency of 8.570 GHz with high mode purity have been obtained for the inner TE_{011} mode coaxial cavity. Furthermore, in order to inject the output power of a second harmonic gyroklystron (17.136 GHz) into our future pulse composer and accelerator system, a coaxial TE_{021} output cavity with a TE_{02}-TE_{01} mode converter is proposed and designed as the output structure of the gyroklystron. The output power can be extracted radially, and at the same time the TE_{02} mode is converted to TE_{01} mode into a inner coaxial waveguide.

INTRODUCTION

In order to build a multi-TeV linear collider with a reasonable length, a high accelerating gradient and high RF frequency are required. A high power and high efficiency gyroklystron is considered to be one of the most promising RF sources to fulfill these requirements[1]. Pulsed gyrotron amplifiers have record performance at frequencies significantly above X-Band, e.g., output peak powers exceeding 30 MW were achieved with an efficiency near 30% at the frequency of 19.76 GHz at the University of Maryland[2,3]. Furthermore, the high power and high efficiency performance of a three-cavity coaxial gyrokystron has been demonstrated in a recent experiment with a peak power of 75 MW and an efficiency of 32% at the frequency of 8.6 GHz[4,5].

In the development of a gyroklystron for achieving higher power levels with higher efficiency to satisfy the requirement of the multi-TeV linear collider, one of the
most important things is to improve mode purity in the low Q input cavity of our gyrokystron. A weak or distorted operating mode in the input cavity will greatly reduce the interaction efficiency of an input RF signal and electron beam and will lower the gain of the gyrokystron amplifier since small changes or field perturbations at the input cavity can result in large amplified changes at the output cavity. However, high mode purity of a TE$_{011}$ mode is very difficult to realize in an overmoded input cavity with a single excitation aperture, especially in a low Q cavity. A possible way to excite a TE$_{011}$ mode with high mode purity is to split the input power with appropriate amplitude and phase by several azimuthally separated apertures in an intermediate coaxial cavity[6].

For injecting the output power of our second harmonic gyrokystron into our future pulse compressor and accelerator, a TE$_{021}$ output cavity with TE$_{02}$-TE$_{01}$ mode converter is proposed. The output power will be coupled radially to a inner waveguide which is inside the inner conductor of the coaxial cavity. At the same time, the TE$_{02}$ mode will be converted into TE$_{01}$ mode. This output structure will eliminate spurious oscillations in the output waveguide and should decrease the sensitivity of the tube to load mismatches. It will help to improve output cavity stability by allowing lossy ceramics to be placed after the cavity at the entrance of the beam dump. Furthermore, it will allow the implementation of a depressed collector.

In this paper, we report the numerical designs of the coaxial dual-cavity structure having an outer TE$_{411}$ mode and an inner TE$_{011}$ mode coaxial cavities and the TE$_{02}$-TE$_{01}$ output cavity structure with a 3-D electromagnetic code (HFSS)[7]. The cold test results of the input system are also presented.

**INPUT CAVITY SYSTEM**

A schematic diagram of the dual-cavity coaxial input structure is shown in Fig. 1. An X-Band microwave signal with a frequency of 8.568 GHz is injected into the outer coaxial cavity of the input system through a rectangular aperture from a WR-90 waveguide. The outer coaxial cavity should be excited to resonate in the TE$_{411}$ mode at 8.568 GHz. The TE$_{411}$ mode is magnetically coupled to the inner coaxial cavity of the input structure through four rectangular slots to excite a TE$_{011}$ mode resonating at the same frequency as that of the outer coaxial cavity. The two coupling slots which are at the two sides of the input aperture are azimuthally spaced 45 degrees with respect to the input WR-90 waveguide while the whole four coupling slots are spaced 90 degrees respectively so as to align with the maxima of the TE$_{411}$ mode magnetic field. Lossy ceramics are put in the drift regions near the inner coaxial cavity in order to adjust the cavity loading for obtaining a reasonably low Q in the input system. The first requirement for this dual-cavity input structure is that the Q of the TE$_{011}$ mode in the inner coaxial cavity should be around 70 or less in order to avoid self-oscillations[4]. Another important requirement is that a major portion of the input electromagnetic
energy should be stored in the inner $\text{TE}_{011}$ cavity since the energy stored in the outer cavity will not be able to be involved in the beam-wave interaction. As much of the total energy is required to be stored in the inner $\text{TE}_{011}$ cavity.

In order to complete the design of this dual-cavity input structure, there are 13 geometric parameters that have to be determined. As shown in Fig. 1, they are outer diameter $2r_{oo}$, inner diameter $2r_{oi}$ and axial length $L_o$ of the outer coaxial cavity; outer diameter $2r_{io}$, inner diameter $2r_{ii}$ and axial length $L_i$ of the inner coaxial cavity; the length $L_a$ and width $W_a$ of the coupling aperture; coupling slot length $L_s$ and width $W_s$; the inner diameter of the drift regions $2r_d$; distances between the edges of the inner coaxial cavity and ceramics in the drift regions, $d_i$ and $d_o$. The bore of our magnet system limits the outer diameter of the outer coaxial cavity $2r_{oo}$. The inner diameter of the drift regions $2r_d$ was chosen to cutoff the $\text{TE}_{011}$ mode at 8.568 GHz and allow enough clearance to the electron beam. The outer diameter of the inner coaxial cavity is equal to 3.325 cm and is determined by the size of the electron beam. The initial values of the dimensions of the outer and inner cavities were calculated separately by a scattering matrix code CASCADE[8,9]. An linear oscillation code called QPB that was developed at the University of Maryland was used to investigate the stability of the inner cavity according to the results of the CASCADE. The essential feature of this dual-cavity input structure is to transfer as much of the input power to the inner cavity resonating in the $\text{TE}_{011}$ mode as possible. The design was performed to minimize the mode impurity due to the sizing and shaping of the coupling aperture and slots, and at the same time to optimize the power transfer from the input waveguide to the dual-cavity structure and to ensure the most of the energy is stored in the inner cavities.

**FIGURE 1.** Schematics of the dual-cavity input structure.

**NUMERICAL DESIGN OF INPUT STRUCTURE**

The HFSS code is a finite-element code which evaluates in the frequency domain and is capable of calculating scattering parameters of multi port devices. The input
characteristic of this dual-cavity structure was calculated from scattering matrices at the input port. Considering the symmetry of the dual-cavity structure was respect to the x-y plane, the model of the dual-cavity structure was reduced in half for HFSS simulations in order to save simulation run-time. Azimuthal symmetry of the cavity had not been taken into account to further reduce the simulation volume, because it could prevent getting better insight of possible azimuthal asymmetry modes which may be excited in this overmoded structure.

The magnitude of the reflection coefficient at the input port, $|S_{11}|$, is plotted as a function of frequency in Fig. 2. There are two minima in the frequency range from 8.0 to 8.8 GHz. The first is at 8.568 GHz with a magnitude of –17 dB and the other is at 8.206 GHz with a magnitude of –5.5 dB. The shaded plots of the magnitude of electric field at the frequency of 8.568 GHz through an axial cutplane (x=0) and a transverse cutplanes (z=0) of the dual-cavity structure are shown in Fig. 3 (a), Fig. 3 (b). It is obvious that both the $\text{TE}_{411}$ and $\text{TE}_{011}$ modes are established with good mode purity in the outer and inner cavities, respectively. However, the $|S_{11}|$ minimum at 8.206 GHz in Fig.2 was found mostly corresponds to the $\text{TE}_{411}$ mode in the outer cavity mode. The stored electromagnetic field energy which is proportional to $|E|^2$ was integrated over the inner cavity for the frequency of 8.568 and 8.206 GHz, respectively. The results show that the $\text{TE}_{011}$ mode purity of 98% has been realized in the inner cavity of the dual-cavity structure within the frequency range we are interested in.

Although the characteristic of the dual-cavity structure should be mostly determined by the inner cavity, the resonant frequency indicated by the $|S_{11}|$ minimum at 8.568 GHz in Fig.2 may not be the actual resonant frequency of the inner cavity. The resonant frequency and Q of the inner cavity were obtained by plotting $W_{\text{inner}}$ as a function of frequency as shown in Fig.4, where $W_{\text{inner}}$ is the time-averaged electromagnetic energy stored in the inner cavity and $W_T$ is the total energy stored in

![FIGURE 2. $|S_{11}|$ versus frequency obtained from a HFSS simulation.](image)
the outer and inner cavities. The peak of the $W_{\text{inner}}$ versus frequency curve (circle) gives the resonant frequency of the inner cavity, which is found to be 8.574 GHz. The Q of 73 is determined from the “half-energy” bandwidth. In Fig. 4, the fraction of the energy stored in the inner cavity with respect to the total stored energy in the two cavities, $W_{\text{inner}}/W_T$, is also plotted versus the frequency (square). The curve shows that 81.3% of the total stored electromagnetic energy is in the inner cavity at the frequency of 8.568 GHz.

FIGURE 3. Shaded plots of the magnitude of electric field $|E|$ at 8.568 GHZ.

FIGURE 4. Normalized time-averaged electromagnetic energy stored in the inner coaxial cavity and its fraction to the total stored electromagnetic energy as a function of frequency.
COLD TEST SET-UP AND RESULTS

A prototype of the coaxial dual-cavity input structure was built according to the above-mentioned simulation results. A schematic of the cold test setup for this coaxial dual-cavity structure is shown in Fig. 5. A microwave signal was injected into the cavity through a 10 dB dual directional coupler from an HP83050B sweep oscillator. A coaxial probe with a 0.025 cm diameter inner conductor tip was axially inserted into the inner coaxial cavity from the drift region. The thin tip was oriented to be capable of coupling to the azimuthal electrical component of the microwave signal in the inner cavity. The probe was fixed on a stand, its axial and radial position were controlled precisely by a micrometer. Input, reflection and probe signals were picked up by three HP85025B detectors respectively and measured by an HP8757C scalar network analyzer. A PC was connected to the network analyzer and sweep oscillator to record data.

FIGURE 5. Cold test set-up.

In the cold test, the lossy ceramic rings of carbon-impregnated alumino-silicate (CIAS) and 80% BeO - 20% SiC were symmetrically put at the both sides of the inner coaxial cavity in the drift regions[10]. The CIAS and BeO-SiC rings were placed alternately along the inner conductor. Two layers of the CIAS and BeO-SiC rings were placed along the outer conductor with the CIAS at inner layer and BeO-SiC at outer layer. As shown in Fig. 1, there were eight ceramic rings along the inner and outer conductors at the both sides of the inner coaxial cavity, respectively. The traces of the $|S_{11}|$ and probe signals are shown in Fig. 6. It can be seen that the characteristics of $|S_{11}|$ as a function of frequency is similar to that of obtained from the HFSS simulation (refer to Fig. 2). Two minima, corresponding to the inner and outer cavity modes respectively, are observed in this frequency range. A –21 dB reflection minimum occurs at 8.582 GHz showing that more than 99% of the input microwave signal at this frequency was injected into the dual-cavity structure. The minimum due to the outer cavity mode is found at 8.322 GHz with –14.8 dB. The probe signal provides the real frequency response of the inner coaxial cavity. As shown in Fig. 6, a peak is found at 8.599 GHz, and a 3 dB bandwidth of 126 MHz gives a Q of 68. After the probe...
loading of the coaxial probe was taken into account, the resonant frequency of 8.609 GHz and Q of 62 were found for the TE_{011} mode in this input cavity.

![FIGURE 6. Traces of \( |S_{11}| \) and probe signal of the dual-cavity input structure.](image)

A perturbation method was employed to identify the field strength in the inner cavity of the asymmetry ceramic loading dual-cavity input structure[11]. A small metal nut with a diameter of 0.25 cm was put at the center plane (x-y plane) of the inner cavity and moved radially step by step by a micrometer. A frequency sweep was performed and a resonant frequency was measured every time the nut was moved by 5 mils. The frequency signal was picked up in the inner cavity at a fixed position by the coaxial probe with its center conductor tip in the center plane oriented to azimuthal direction. The resonant frequency shift \( \Delta f \) is shown in Fig. 7 as a

![FIGURE 7. Frequency shift versus radial position of perturbation.](image)
function of the radial position of the metal nut, where \( \Delta f = f - f_0 \), \( f \) and \( f_0 \) are the cavity resonant frequency with and without metal nut in the inner cavity, respectively. In our case, the profile of \( \Delta f \) in Fig.7 reflects the radial distribution of the electric field of the microwave signal in the inner cavity according to the perturbation theory. It is obvious that only one peak exists between the inner conductor and wall of the inner coaxial cavity. The probe was moved around center axis azimuthally, and no frequency shift was observed. The results are consistent with the characteristic of the TE\(_{011}\) mode. The peak position shown in Fig.7, \( r = 2.139 \) cm, is close to what was obtained from the HFSS simulation, \( r = 2.164 \) cm. Several orientations of the tip of the coaxial probe were used and the above-mentioned measurement was repeated, no other obvious peaks were observed.

**OUTPUT SYSTEM**

The schematic of the TE\(_{021}\) mode output cavity with the TE\(_{02}\)-TE\(_{01}\) mode converter is shown in Fig. 8. An output microwave signal (17.136 GHz, TE\(_{021}\) mode) in the coaxial output cavity is coupled into another inner coaxial waveguide and then converted into a circular waveguide. Eight rectangular slots which are spaced 20\(^\circ\) azimuthally on the inner wall of the output cavity (the outer wall of the inner coaxial waveguide) are used to couple the output power into output waveguide and convert the TE\(_{02}\) mode into TE\(_{01}\) mode. The first requirement for this output structure is to have a pure TE\(_{021}\) mode at 17.136 GHz in the output cavity with a Q of 320. The second requirement is to be able to convert the TE\(_{02}\) mode into TE\(_{01}\) mode with high mode purity.

**FIGURE 8.** Schematics of the output structure.
NUMERICAL DESIGN OF OUTPUT STRUCTURE

HFSS and almost the same design procedure which was used to the input cavity design were applied for the modeling of the output structure. A small aperture was opened on the outer wall of the output cavity. A microwave signal was injected into the output cavity through the aperture from a WR51 waveguide. The magnitude of the transmission coefficient reflecting the transmission between the input waveguide and the output circular waveguide, \(|S_{21}|\), is plotted as a function of frequency in Fig. 9. Within the frequency range from 17 to 17.3 GHz, the highest peak is found at 17.136 GHz, and another peak is at 17.03 GHz. The shaded plots of the magnitude of the electric field at the frequency of 17.136 GHz at an axial cutplane \((x=0)\) and a transverse cutplane \((z=2)\) of the output structure are shown in Fig. 10 (a) and Fig. 10 (b), respectively.

FIGURE 9. \(|S_{21}|\) versus frequency obtained from a HFSS simulation.

FIGURE 10. Shaded plots of the magnitude of electric field \(|E|\) at 17.136 GHz.
It is clear that a TE$_{021}$ mode at 17.136 GHz was excited in the output cavity with high mode purity, and the TE$_{02}$ mode was successfully converted into a very pure TE$_{01}$ mode in the output waveguide at the same time. The time-averaged electromagnetic energy stored in the TE$_{021}$ mode output cavity is plotted as a function of frequency in Fig. 11. The Q of 320 is obtained from the “half-energy” bandwidth of the electromagnetic energy stored in the output cavity.

![Normalized time-averaged electromagnetic energy stored in the output cavity.](image)

**FIGURE 11.** Normalized time-averaged electromagnetic energy stored in the output cavity.

**SUMMARY**

The X-Band dual-cavity coaxial input structure was successfully designed via the HFSS simulations combined with the CASCADE codes, and the cold test input cavity was built and tested. The TE$_{011}$ mode with good mode purity and a reasonable low Q of 62 at 8.609 in the inner coaxial cavity were realized and verified experimentally through the S parameters and mode pattern measurements. The cold test and HFSS simulation results are in very close agreement. The numerical design of the TE$_{021}$ output cavity with TE$_{02}$-TE$_{01}$ mode converter has been carried out. The output cavity with high TE$_{021}$ mode purity and a Q of 320 has been obtained, and the TE$_{02}$-TE$_{01}$ mode conversion has been successfully demonstrated in the HFSS simulations. This output structure is under construction and will be tested and put in our next Ku Band gyrokystron with the dual-cavity input structure.
ACKNOWLEDGMENTS

This work is supported by Department of Energy, contract DE-FG02-94ER40855. One of authors (X. Xu) would like to thank Dr. W. R. Fowkes at SLAC, Stanford University for his helpful discussions and advice.

REFERENCES


5. W. Lawson, et al., to be published.


