Design and Testing of Frequency-Doubling Gyroklystrons at University of Maryland

By

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Chapter 1: Introduction

This Scholarly Paper describes in detail, my contribution to the recent progress of the Gyroklystron Program at the University of Maryland. In particular, I will describe the changes in and operation of the current four-cavity frequency-doubling gyroklystron at 17.136 GHz and design of a new six-cavity tube with output at 22.848 GHz for a proposed high-gain microwave tube.

In this chapter, I will give an overview of UMD gyroklystrons to date and in particular, past operation and results of the current four-cavity system. Chapter 2 will present the latest changes made in the current system. Chapter 3 deals with the design and simulation results of a new, scaled six-cavity microwave tube at 22.848 GHz and simulations for sensitivity of cavities to radial and axial offsets.

1.1 University of Maryland Gyroklystrons to date

Prior to 1994, cylindrical gyroklystrons were researched at University of Maryland. The very first series of tubes was made of two first-harmonic cavities operating at the fundamental cyclotron frequency of 9.87 GHz [1]. But these tubes encountered several instabilities due to spurious oscillating modes. As a result, very little power was produced (less than 50 kW). The most troublesome spurious oscillations took place in the drift regions and the gun downtaper before the microwave circuit. To eliminate these modes, more lossy ceramics were placed in both these regions. This allowed high beam power and velocity ratio (alpha) to be used, thus resulting in better amplification. An increase in the Q of the cavities and magnetic field tapering resulted in 24 MW peak power with efficiency of 34% at 9.87 GHz [2]. Four three-cavity fundamental tubes followed next.

The maximum peak power achieved for a three-cavity fundamental tube was 27 MW with an efficiency of 32% and a gain of 50 dB [3]. Next, higher harmonic cavities were designed and studied. A series of two-cavity TE_{021} tubes resulted in a maximum peak power of 32 MW with efficiency of 28.6% at 19.76 GHz [4]. A two cavity TE_{031} tube was also tested, which gave a low power of 1.8 MW with efficiency of 2% at 29.57 GHz [5].

In 1994, coaxial tubes were investigated and tested in the 30 MW test bed. But the performance was mostly limited due to melting of the tungsten support pins.

Investigation to achieve higher power levels in the 100 MW range started next. For practical purposes, the beam voltage was maintained at 500 kV but the beam current had to be increased. A decision was made to increase the average beam radius. Coaxial geometry was chosen so that drift tubes would not be overmoded and would be cut-off to the operating mode. After a period of two years to upgrade the modulator and electron gun, coaxial three-cavity first-harmonic tubes gave a maximum peak power of 75 MW at 8.6 GHz with an efficiency of 32% and a gain of 29.7 dB [6]. Subsequently, research began into second-harmonic coaxial tubes at 17.14 GHz. The maximum peak power obtained by a three-cavity second-harmonic circuit with TE_{021} in the output was 27.7 MW with an efficiency of 13% [7]. The latest tube to be tested was a four-cavity circuit with TE_{021} in the output. The maximum peak power achieved was 18.5 MW at 17.14 GHz [8]. An instability was detected in the input cavity, which limited the velocity ratio (α) to below 0.9 (the design value was 1.4). The magnetron injection gun emitter had considerable temperature variation around it. This instability and other aspects of this four-cavity tube are discussed in the next subsection of this chapter.

1.2 Past operation on the four-cavity tube and associated problems

The four cavity tube consisted of an input cavity operating in the TE_{011} mode and the rest of the cavities operating in the TE_{021} mode. From now on, we will call this a 1222 tube. Fig 1 shows an engineering diagram of the 1222 tube.

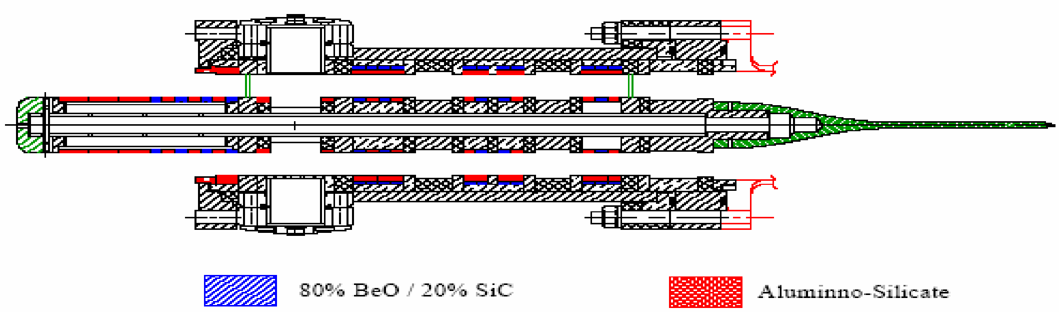


Figure 1. Layout of the four-cavity gyroklystron

Theoretical results:

Simulations done using numerical codes COAX [9] and MAGYKL [10] predicted a peak output power of 85 MW corresponding to an efficiency of 34.3%, gain of 56.8 dB for an alpha of 1.4 and input power of 180 W. COAX is used to adjust the cavity dimensions to get the proper resonant frequency for each cavity and Q-factor of the output cavity. MAGYKL is a large-signal computer code which computes system efficiency.

Experimental results:

The region of optimal performance of the 1222 gyroklystron was identified to be at 450 ± 10 kV beam voltage and 550 ± 20 A beam current. The values for magnet currents were: Gun Coil: 200 ± 1A, Kurly: 255 ±1A, Larry: 378 ±1A and Moe: 320 ±1A (Kurly, Larry and Moe are the names assigned to the three power sources which supply currents to the seven magnets around the microwave tube).The highest peak power measured was 18.5 MW with the anechoic chamber diode crystal and 18.1 MW with the peak power analyzer. The corresponding efficiency is 7%. A gain of 24 dB (input power: 73 kW) was obtained. Frequency scanning done with the Spectrum Analyzer indicated the peak output pulse to be at 17.15 GHz. These experimental results were much worse than predicted by theoretical simulations. The reasons for this were narrowed down to the following problems:

1) The actual value of alpha for the experiments on the tube was around 0.9, as against 1.4 (the value at which the gyroklystron was designed to operate).
2) The input cavity suffered from oscillations which became significant when alpha exceeded 0.9. At this point, the reflected power from the input cavity exceeded the drive power from the magnetron. A typical instability pulse in the input cavity is shown in Fig. 2. A spectrum analyzer frequency scan showed the peak of the instability at 7.5 GHz with a bandwidth of about 100 MHz.
3) The ultimate cause of the instability in the input cavity was believed to be the emitter of the Magnetron Injection Gun (MIG). The thermionic emitter of the gun showed significant temperature variation around it, with a variation of 70°C for a nominal temperature of 925°C. The pyrometric readings are shown in Fig. 3.

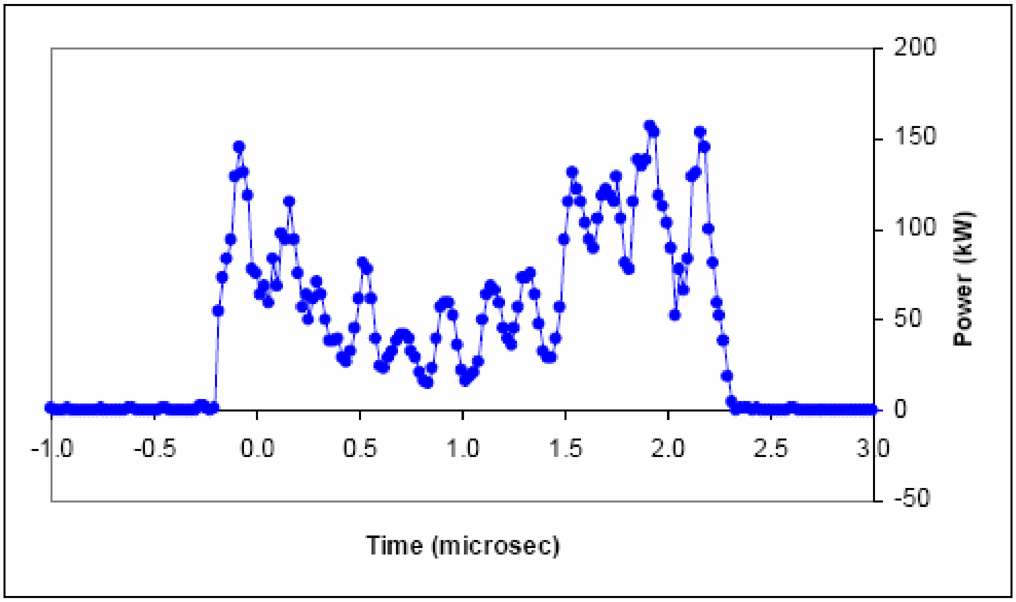


Figure 2. Instability pulse observed in input cavity

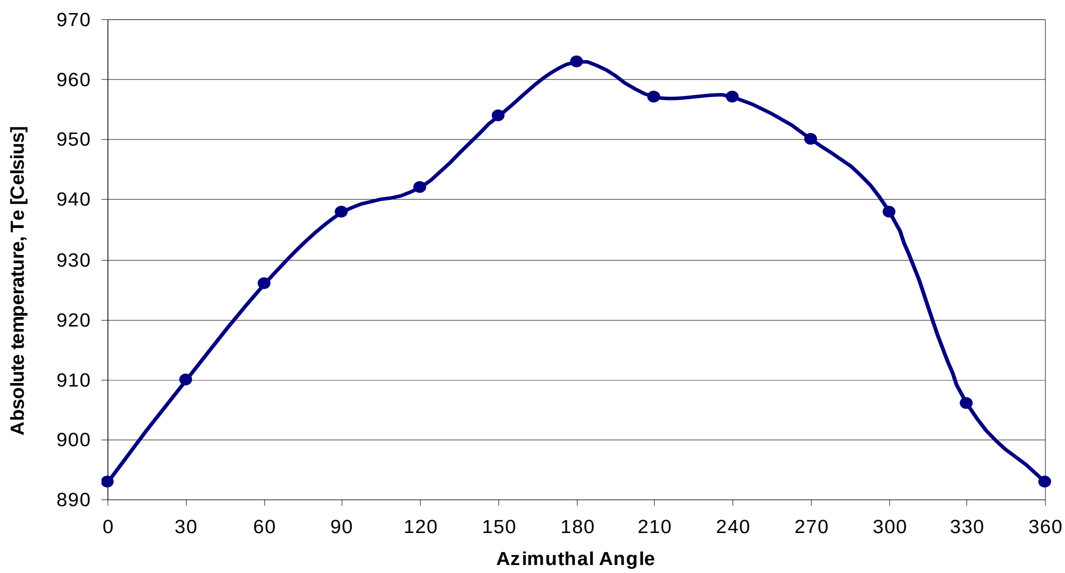


Figure 3. Temperature variation around the electron gun

This temperature variation was believed to be due to non-uniformities of the heater element. The MIG is operated in the temperature limited regime, and hence any variation in the temperature around the emitter will lead to a variation in electron emission from the gun, and hence a non-uniform current density. Radiation data showed that the beam current density possibly varied as much as 50% across the beam. This means that for the nominal beam current of 550A, the effective values of beam current were between 336A and 688A. The radiation data is shown in Fig. 4.

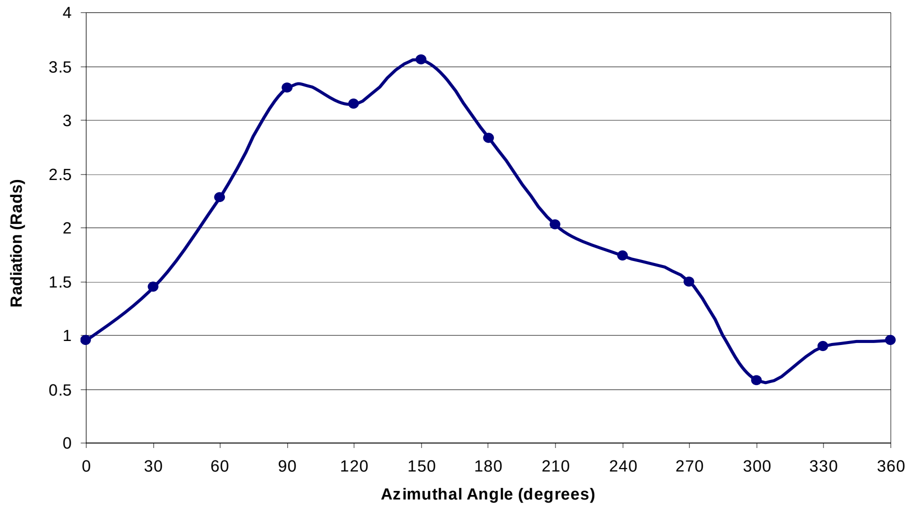


Figure 4. Radiation variation around the electron gun

Thus it became clear, that the variation in temperature around the emitter led to a considerable variation in current density and hence alpha at various points. This in turn decreased the output power and hence, efficiency. Moreover, spurious modes might be excited at those locations where the current exceeds the start of oscillation current value.

Chapter 2: Changes made in the system

After analyzing the causes of the observed discrepancy in the theoretical and experimental results outlined in Chapter 1, we made appropriate changes in the system. These included an improved electron gun and a redesigned input cavity.

2.1 New Magnetron Injection Gun

A new Magnetron Injection Gun (MIG) acquired from Calabazas Creek Research has been installed in the system. Pyrometric studies on the gun indicated a much less severe temperature variation in the emitter. Figs 5 and 6 compare the variation in the temperature and radiation, of the new and old MIG emitters, respectively.

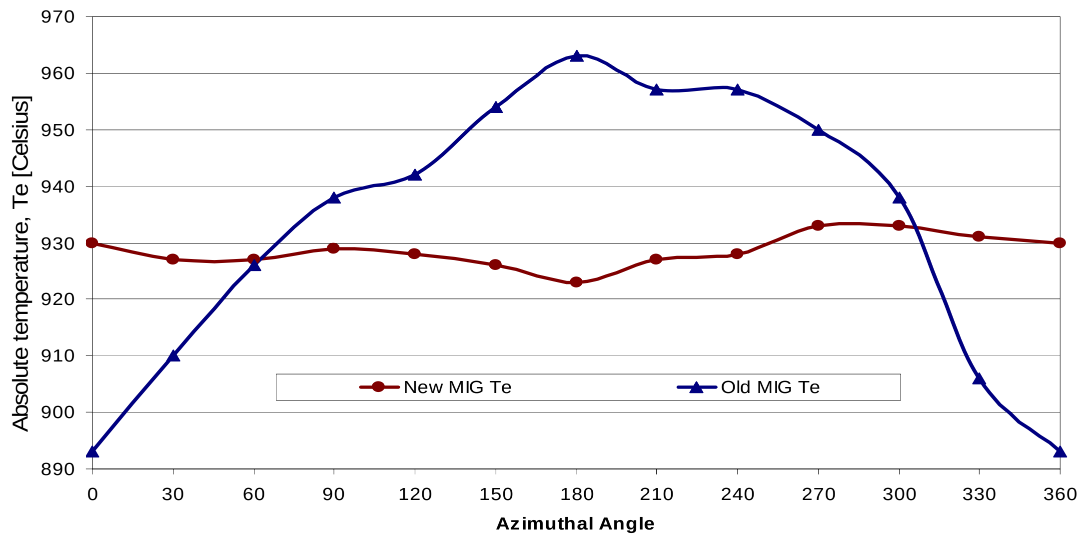


Figure 5. Comparison of azimuthal temperature variations for the new and old gun

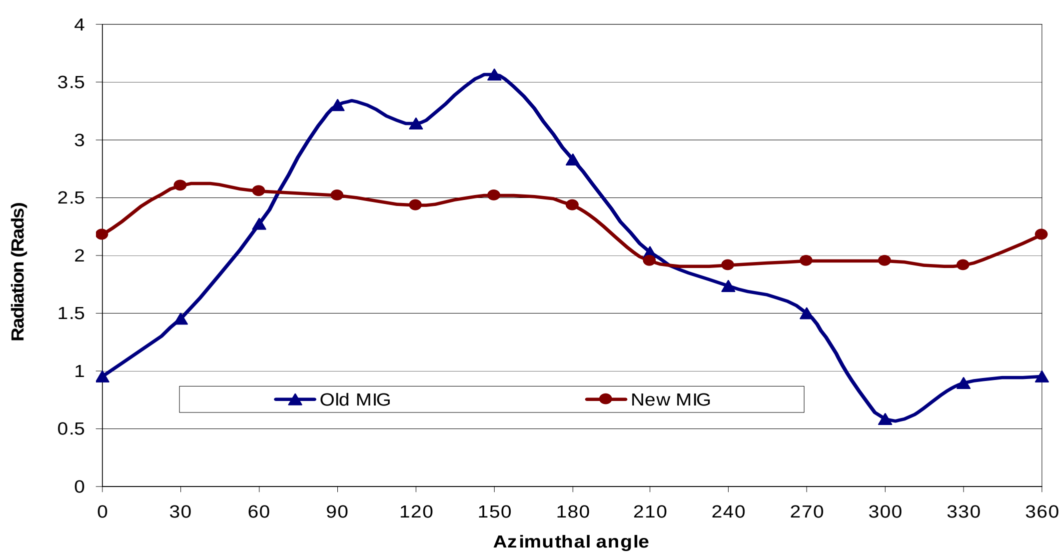


Fig.6. Comparison of azimuthal radiation variations for the new and old gun

2.2 Redesign of input cavity

The input cavity was redesigned to provide better coupling to the electron beam and decrease the probability of excitation of spurious modes [11]. Three changes were made:

1.The overall length of the cavity was reduced.

2. The Q-factor was reduced.

3. The geometrical structure was changed i.e. the cavity was now defined by a change in radius of the outer conductor as against the inner conductor.

Reducing the cavity length and Q-factor reduced the interaction of the beam with spurious modes in the cavity. A change in the cavity step from the inner conductor to the outer conductor allowed ceramics to be placed in the center of the cavity. The inner conductor radius was equal to the drift region radius and the cavity was defined solely by a variation in the outer cavity. While the cavity length changed from 2.90 to 1.96 cm, the aperture/opening of the cavity changed from 2.25 to 1.91 cm, thus covering 97% of the cavity. This again allows the input signal to couple more strongly with the beam in the input cavity.

Chapter 3: Design of a six-cavity frequency-doubling gyroklystron at 22.848 GHz

3.1 Design approach and Large-signal behavior

The accelerating gradient in an accelerating structure is given by,

$$E_a \, \alpha \, P^{1/2} f$$

So in order to provide higher accelerating gradients, RF sources should operate at higher frequencies [12]. Under a recent contract from the Department of Energy, we designed a new high-gain frequency-doubling gyroklystron with output in the TE_{021} mode at 22.848 GHz. This is in collaboration with the Stanford Linear Accelerator (SLAC) program, and has its output frequency eight times the original SLAC frequency (2.856 GHz).

The design here describes a scaled version of a second-harmonic six-cavity microwave circuit with output at 17.136 GHz, which is being used in an ongoing project at University of Maryland. The six-cavity tube comprises of three cavities operating in the TE_{011} mode, and the remaining three cavities operating in the TE_{021} mode. The drive frequency is 11.424 GHz and the maximum input power available is 1 kW. The output frequency is double the drive frequency. Most quantities in the original circuit (17.136 GHz) and electron beam parameters have been either scaled up or down, by the ratio 17.136:22.848 i.e. 0.75, to give optimum performance at the new frequency of 22.848 GHz. The radii and lengths of all cavity regions and drift regions have been scaled down from the initial dimensions initially and later optimized numerically, changing them slightly, to give optimum efficiency. Q factors are scaled up from 60 and 320 for the first-harmonic and second- harmonic cavities respectively, to 80 and 426 for the same. These circuit parameters are given in Table I. The electron beam current and the guiding center radius are scaled down to 367 A and 1.92 cm respectively. The beam voltage of 500 kV is same as in the original design. Thus the beam power is about 184 MW. The magnet currents are provided by four existing power supplies which put a constraint on the maximum magnetic field achievable. The input power of 1 kW comes from a traveling-wave-tube (TWT). A TWT is being used because we desire to have a phase-controllable source (as against a free-running coaxial magnetron). Numerical simulations predicted that all cavities were stable up-to an average velocity ratio of 1.4 and efficiencies as high as 37% and output power of 68 MW were possible. Even for average velocity ratio as low as 1.0, efficiency of the order of 20% and output power of 37 MW has been predicted.

The system parameters have been shown in Table II. Layout of the tube along with the magnetic field profile and the growth of alpha with axial distance along the tube, have been shown in Fig. 7. The inner and outer conductors of the coaxial tube have been shown by solid lines. The magnetic field profile, for optimum performance of the tube, has been shown by the dashed line. The alpha varies in the tube along with changes in the magnetic field strength. This is given by the dotted line.

TABLE I

CIRCUIT PARAMETERS

Cavity	Length (cm)	Inner radius (cm)	Outer radius (cm)	Freq. (GHz)	Q
Input / 1st harmonic bunchers	1.505	1.368	3.166	11.424	80
Antepenultimate	1.288	1.216	2.646	22.828	426
Penultimate	1.299	1.216	2.646	22.806	426
Output	1.653	1.241	2.619	22.836	426
Output lip	0.633	1.308	2.536	-	-

TABLE II

SYSTEM PARAMETERS

Parameter	Value
Beam voltage (kV)	500
Beam current (A)	367
Guiding center radius (cm)	1.92
Drive frequency (GHz)	11.424
Average velocity ratio	1.4
Axial beam spread (%)	4
Maximum drive power available (kW)	1.0

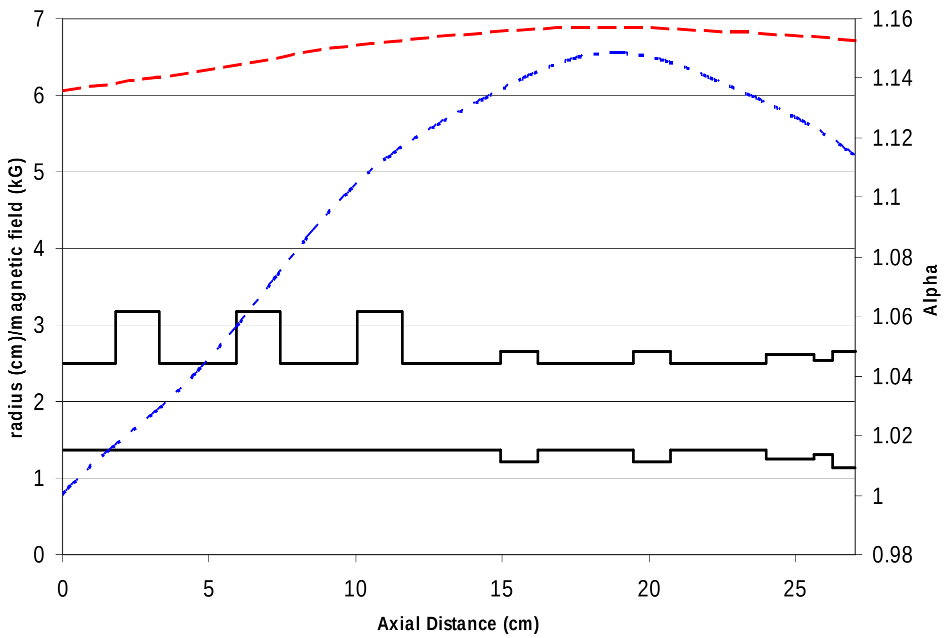
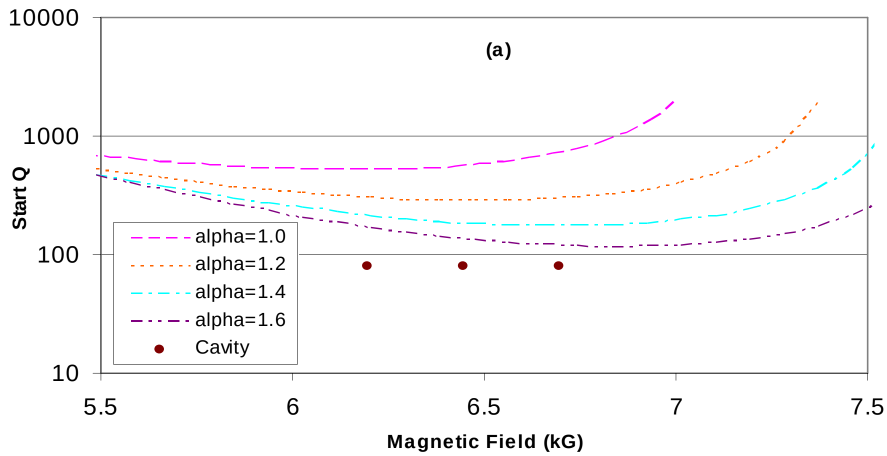
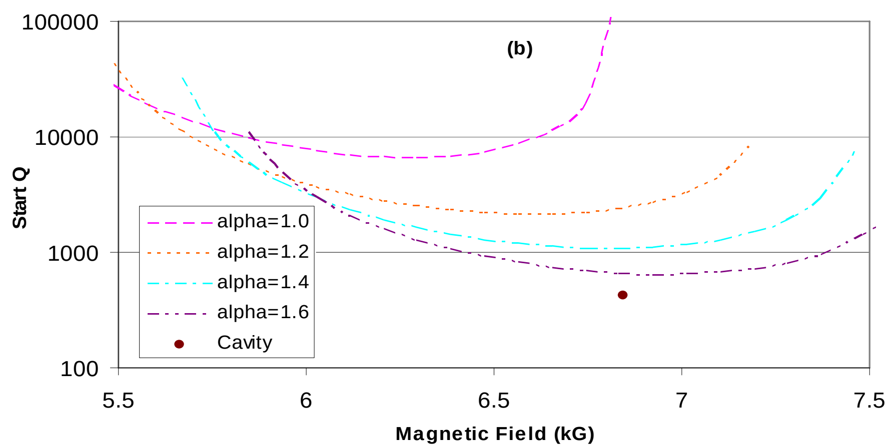


Figure 7. Schematic of a six-cavity coaxial tube showing the inner and outer conductors (solid lines), magnetic profile (dashed line) and evolution of alpha along the tube (dotted line)

Theoretical Stability studies for the cavities show that the first harmonic cavities and second harmonic buncher cavities are stable upto a velocity ratio of 1.6. However, the output cavity is unstable for a velocity ratio exceeding 1.4. A small-signal stability code, QPB, is used for this purpose [10]. The code calculates the product of beam power and the start oscillation Q for several values of magnetic fields. This result is divided by the beam power, gives the value of start of oscillation Q. These values are then compared with the design Q of the particular cavity. A cavity is unstable (or self-oscillates) if the design Q lies above the start Q at a given value of magnetic field. Start oscillation curves for various cavities is shown in Fig. 8. Fig. 8 (a) depicts the stability condition for the operating TE_{011} mode in the first-harmonic cavities. Similar curves for the second-harmonic bunchers and output cavity are shown in Fig. 8 (b) and c) respectively.





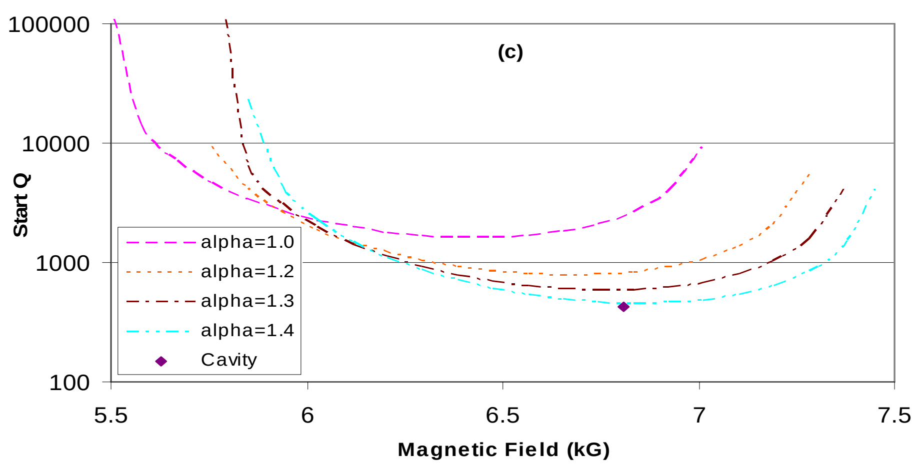


Figure 8. Start oscillation curves for (a) first-harmonic cavities, (b) second-harmonic bunchers, and (c) the output cavity. Diamonds in the plots represent the value of magnetic field and Q for the particular cavity.

The parameters varied, in order to achieve the most optimum performance in terms of efficiency and stability, were drive power, magnetic field profile and cold cavity resonant frequencies. The drive frequency, dimensions and quality factors listed in Table I were kept unchanged. We found that for maximum operating efficiency of the tube, the magnetic profile as shown in Fig. 7, with minimum and maximum values of 6 and 6.8 kG respectively. The dependence of efficiency and gain on alpha is shown in Fig. 9. It can be seen that the increase in gain is almost linear with alpha, as expected, with a slope of ~8-9 dB per unit alpha.

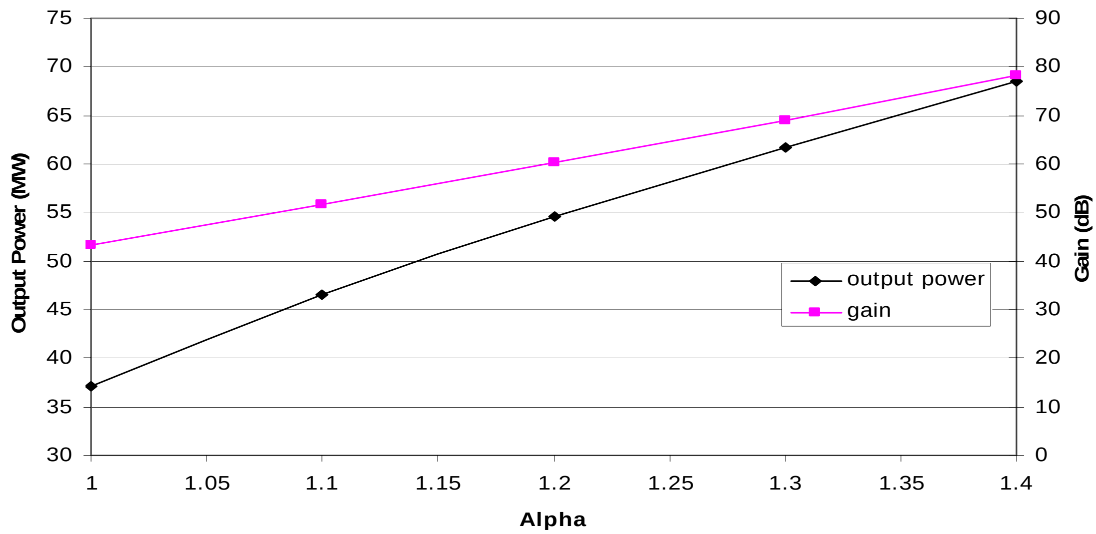


Figure 9. Dependence of efficiency and gain on average velocity ratio.

Fig. 10 shows the normalized drive curves for various values of alpha. The alpha=1.0 and alpha=1.1 curves show the typical nonlinear behavior expected for a frequency-doubling device. The alpha=1.2, 1.3 and 1.4 curves do not exhibit the nonlinear behavior for drive power less than 20%, because the cavities are getting near to the start oscillation values.

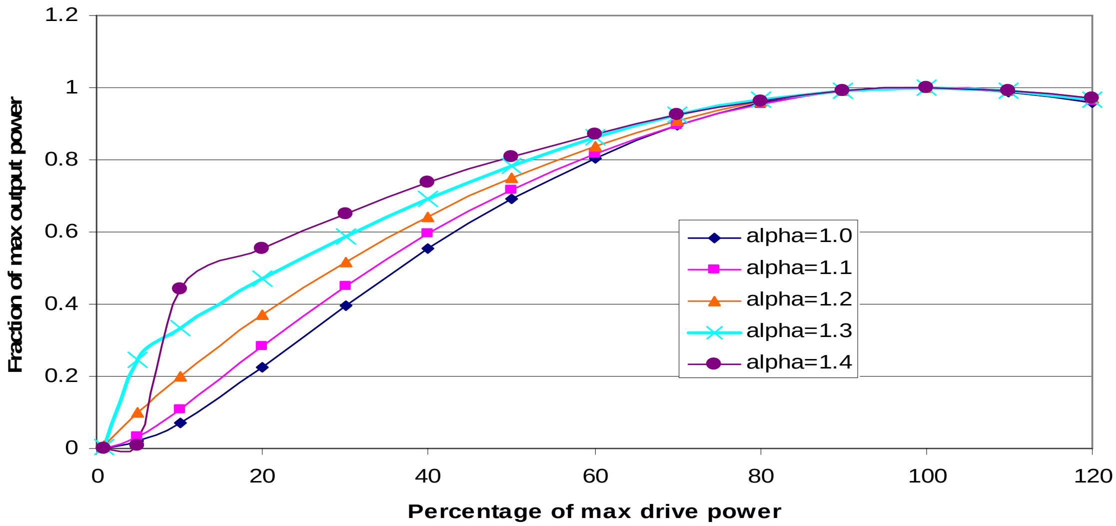


Figure 10. Normalized drive curves for various values of velocity ratios

In Fig. 11, we plot the dependence of efficiency with increasing beam velocity spread. The resulting drive power optimized to achieve the highest efficiency for a given beam spread is also shown in the figure. Fig. 12 shows the bandwidth achievable for an alpha of 1.0 and beam spread of 4%. The predicted bandwidth of the frequency-doubling circuit is 49 MHz, which is consistent with the Q-factors of cavities.

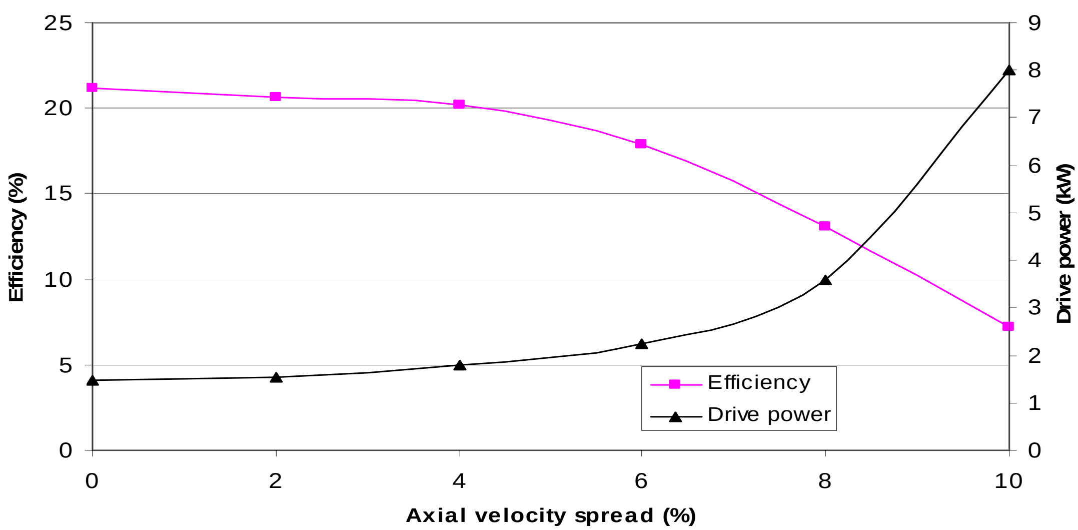


Figure 11. Dependence of efficiency on axial beam velocity spread

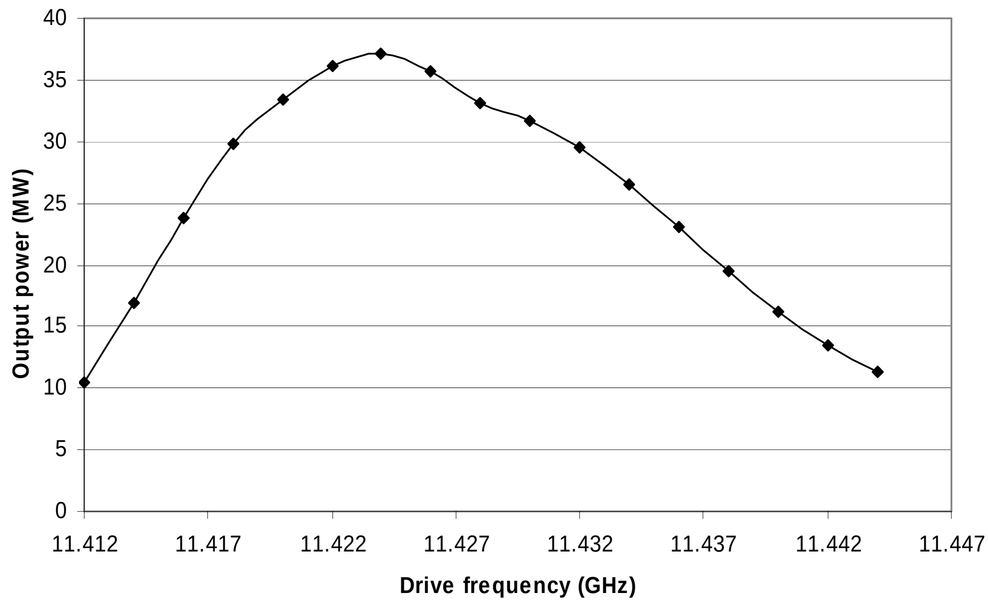


Fig.12. Bandwidth curve

3.2 Simulations for Tolerances

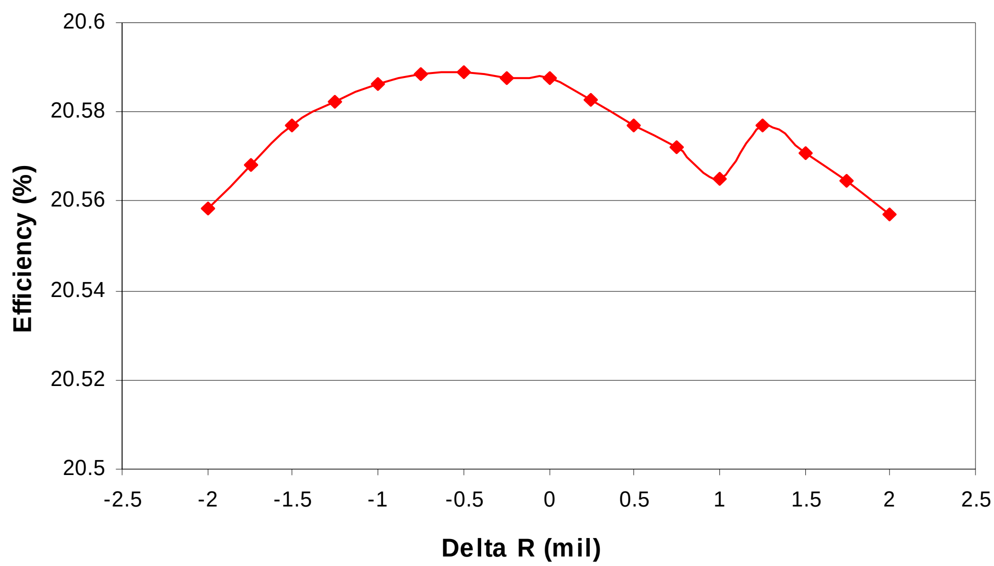
I did simulations with the help of COAX and MAGYKL codes to study the sensitivity/tolerances for radial and axial variation in cavities for the six-cavity tube at 17.136 GHz. However, the same results apply to the 22.848 GHz tube, because it is just a scaled version and hence, the response of the tube to relative changes in the dimension, should be the same.

The dimensions of individual cavities were entered in COAX which gave the resonant frequency (f) and Quality factor (Q) for each of them. The output of this code was in turn used as an input to MAGYKL, along with other beam parameters, to get the corresponding tube efficiency for a change in radius/length of a single cavity. I also studied random cases of offsets of radii and lengths of the various cavities to determine the worst possible case.

The procedure followed was as follows: First, I varied the diameters (outer diameter in case of first harmonic and symmetric inner and outer diameters for second-harmonic cavities) by about ± 2 thousandths of an inch in steps of 0.25 thousandths. By looking at the corresponding curves for radial offset versus efficiency (from COAX and MAGYKL), we decided on radial tolerances such that the efficiency does not fall below 0.5-1% of the original value (which is 20.587%). The change in resonant frequency was also studied.

Input cavity:

The plot for radial offset versus efficiency for the fundamental input cavity shows that it is not very sensitive to changes in the radius of the cavity. The efficiency falls by about 0.03% for a change of 2 mil change of diameter. The frequency changes by about 2.5-3 MHz for a 2 mil diameter change. Similarly, a change of about 6 MHz is observed per mil change in axial length of the cavity.



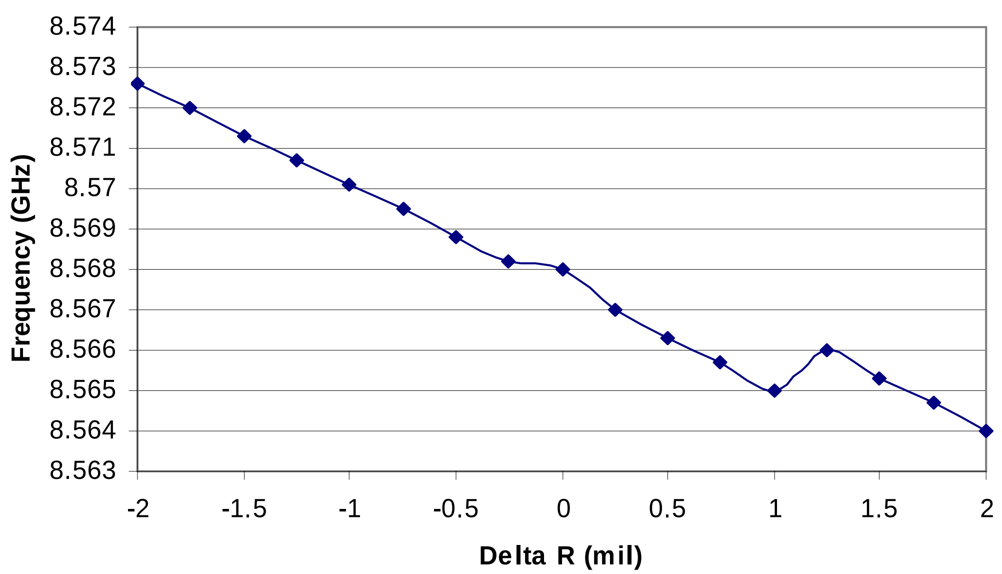
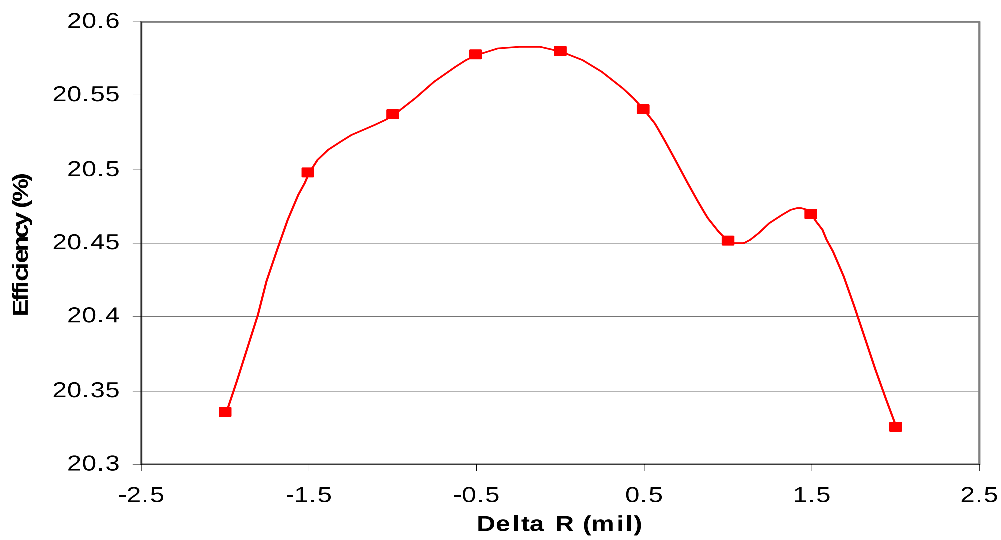


Figure 13. Sensitivity study for input cavity

First Harmonic Buncher cavities:

The second and third cavities are first- harmonic bunchers, and have similar sensitivities as they have same dimensions. The efficiency changes by about 0.13% for a 2 mil change in diameter. The frequency sensitivity is about 2.5 MHz for 2 mil change in diameter. Again it seems that the first harmonic bunchers are not very sensitive to changes in radius. But, the frequency changes by ~6 MHz per mil change in the length of cavity.



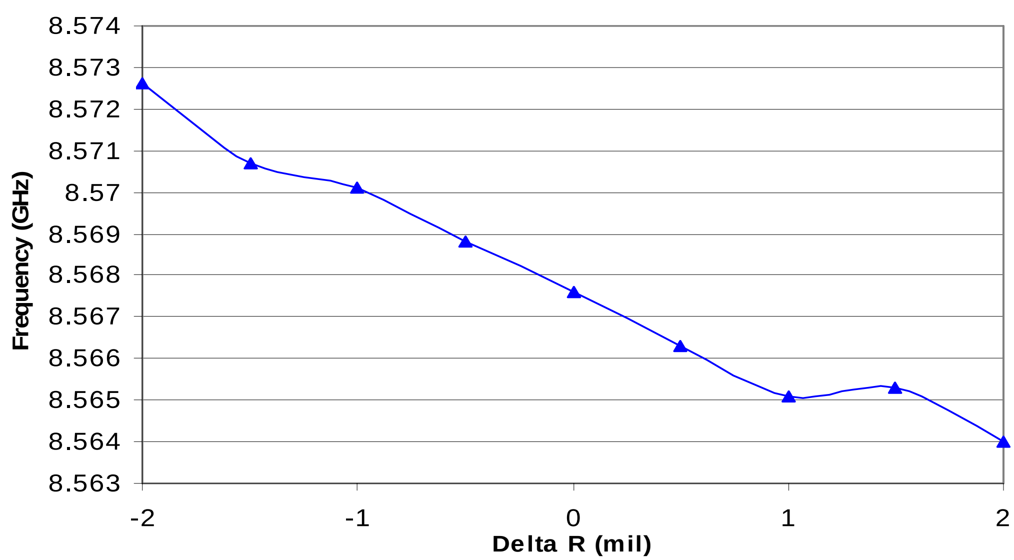


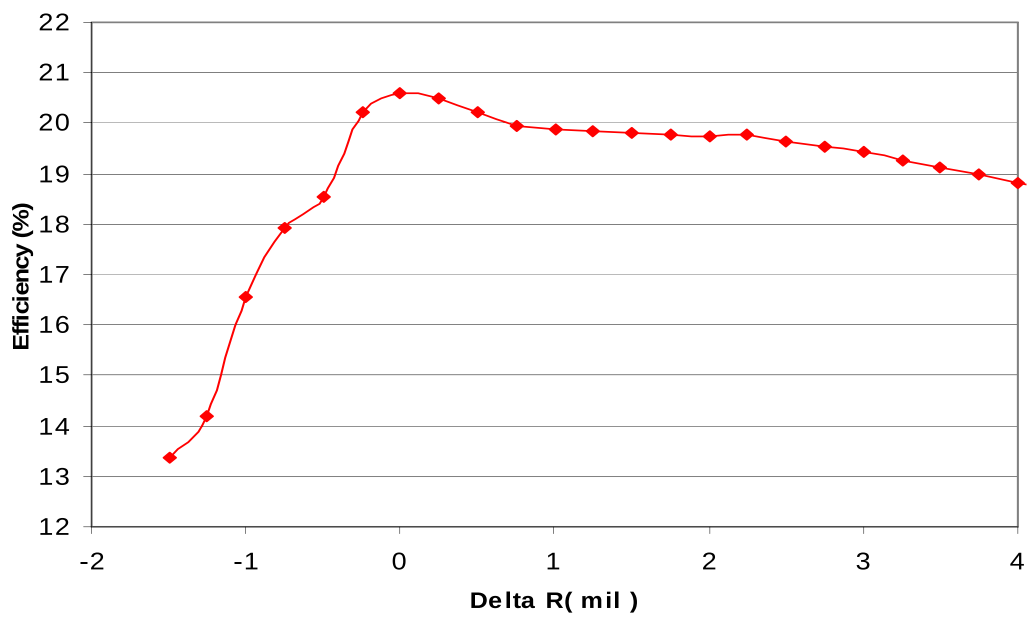
Figure 14. Sensitivity study for first-harmonic buncher cavities

Second Harmonic Buncher cavities:

The third and fourth cavities are the second- harmonic buncher cavities, i.e, the operating mode is TE_{021}. However, they are designed to have different dimensions and hence, different resonant frequencies, for overall optimum efficiency of the tube. Thus, they behave differently as far as the sensitivity to radial offset is concerned.

Antepenultimate cavity:

The antepenultimate cavity is the most sensitive to negative radial offsets, among all first and second harmonic cavities. It was observed that even a small negative radial offset would have a drastic effect on the efficiency of the tube. However a +2 mil of diameter offset would still keep the tube in the efficient region. The frequency changes by about 18 MHz for a +2 mil diameter change. For a change of 1 mil in axial length, the resonant frequency changes by ~2-3 MHz.



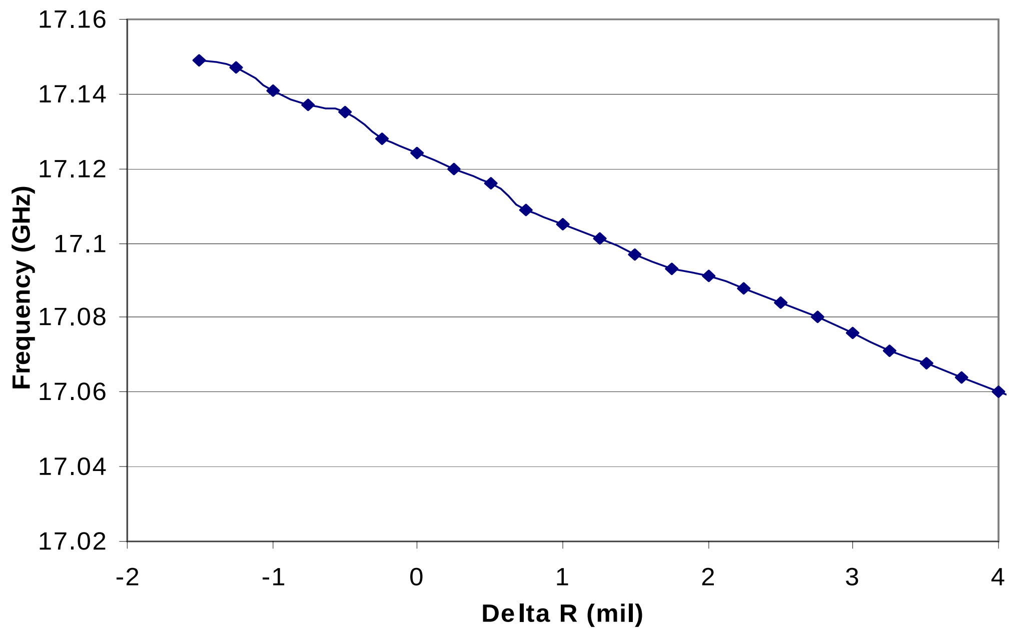
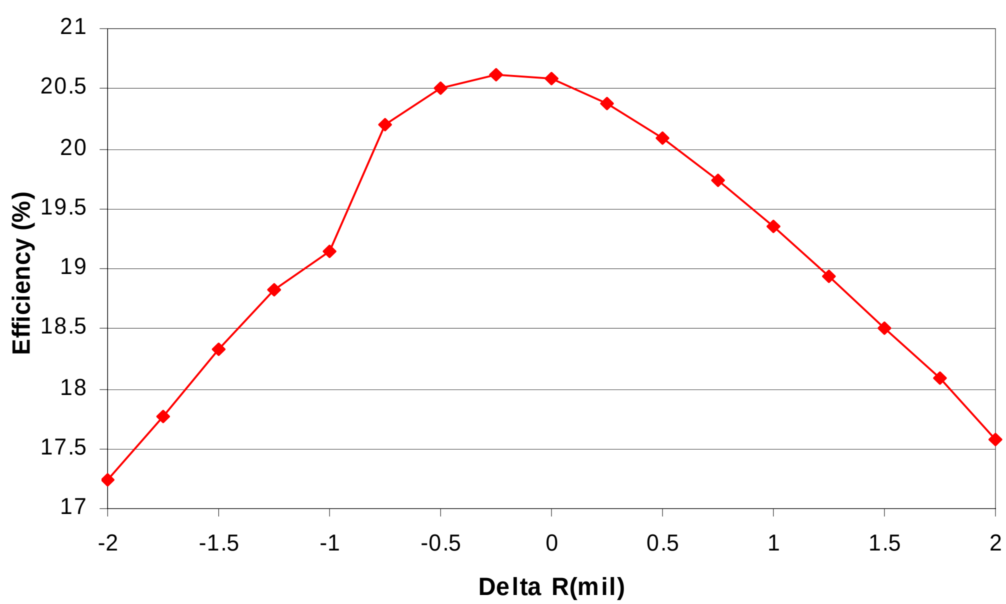


Figure 15. Sensitivity study for antepenultimate second-harmonic buncher cavity

Penultimate Cavity:

The penultimate cavity is not quite as sensitive as the antepenultimate cavity, but is much more sensitive than first-harmonic cavities. The efficiency changes by about 1.3% for a 1 mil change in diameter. The corresponding change in resonant frequency is about 14 MHz. Again, a 2-3 MHz change in frequency is observed with 1 mil change in length of cavity.



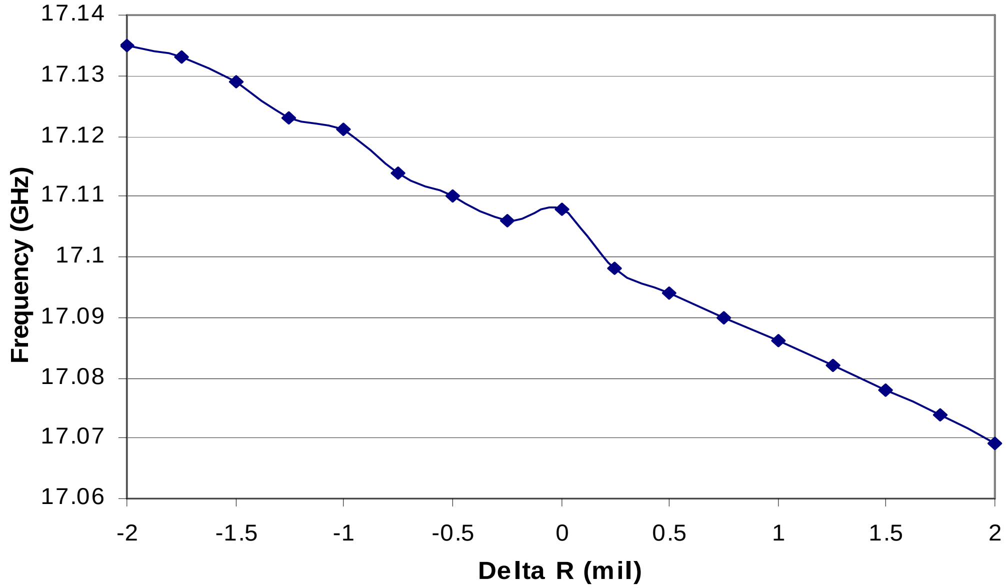
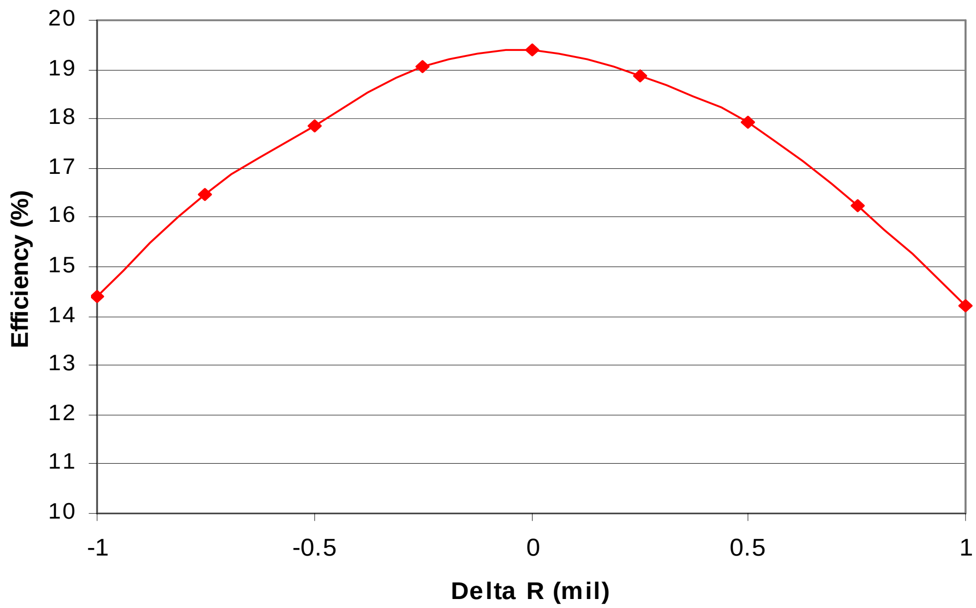


Figure 16. Sensitivity study for penultimate second-harmonic buncher cavity

Output cavity:

The output cavity is unique because this is where the beam ultimately gives up its energy, to amplify the microwave signal. The output cavity is the most sensitive to changes in radius, and the efficiency changes by more than 5% for a 2 mil change in diameter of the cavity region. The corresponding change in frequency is 20 MHz. Thus, the radial tolerance for the output cavity is limited to ±0.5 mil in diameter. The output cavity, like other second harmonic cavities, is not very sensitive to changes in axial length, and changes by ~2-3 MHZ per mil change in length.



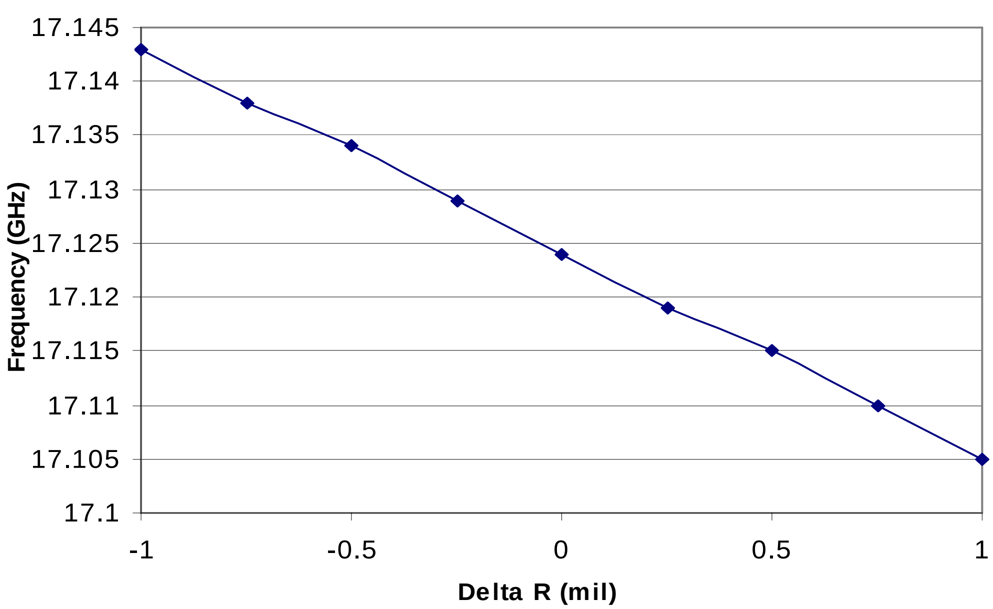


Figure 17. Sensitivity study for second-harmonic output cavity

From the above figures, it is simple to predict the change required in cavity radii or length, to fine-tune a particular cavity for resonant frequency. For first harmonic cavities, a change in radius will bring about a small change in the resonant frequency, while for the second harmonics, any change in radius of the cavity will have a drastic effect on the resonant frequency. The opposite is true for changes in axial length of cavities.

I also did a random variations’ study by changing the radii of each cavity by an amount equal to the tolerance limit. In the worst case, when all the cavities were radially offset by their tolerance value and the antepenultimate cavity was offset by -1 mil, the efficiency for alpha=1.0 was 16.28%.

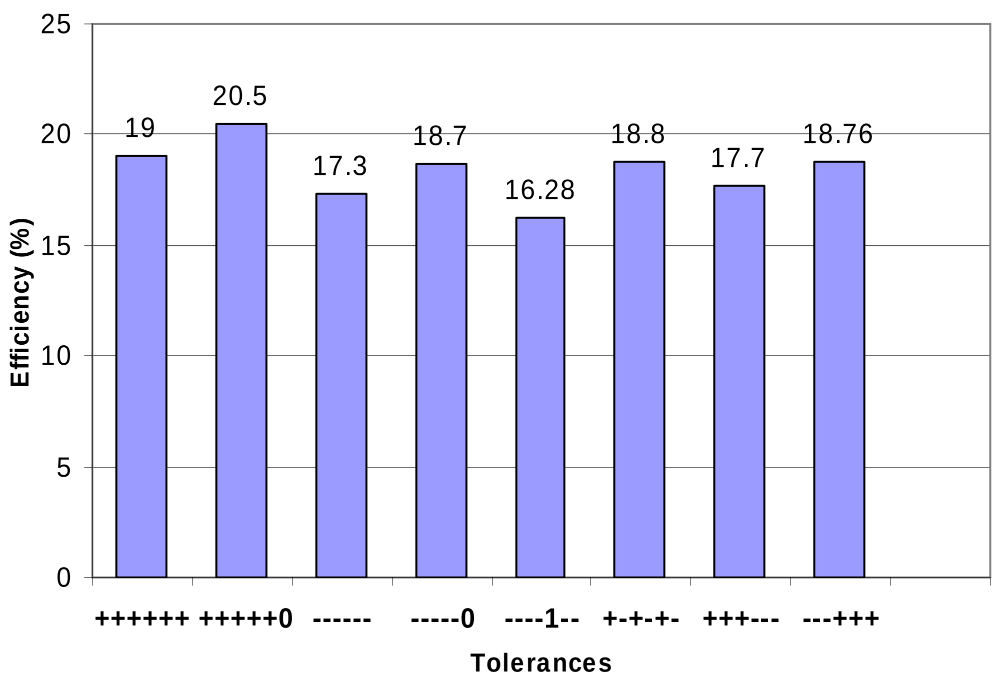


Figure 18. Random study for overall sensitivity of tube to radial variations

Chapter 4: Conclusion and future work

Through this paper, I have tried to document some of the important contributions that I made to the GKL program at the University of Maryland. Presently, we are in the process of hot-testing the 1222 tube with the new electron gun and re-designed cavity in place. The 111222 tube at 17.14 GHz is being cold-tested and will be installed in the system shortly. The use of this high-gain tube and a phase-controllable source (TWT) should soon allow us to successfully drive a linear RF accelerator.

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