DESIGN OF A 10 MW, 91.392 GHZ GYROKLYSTRON FOR ADVANCED ACCELERATORS

W. Lawson, University of Maryland, College Park, MD 20742, USA
R. L. Ives, J. Neilson, M. E. Read, Calabazas Creek Research, Inc., Saratoga, CA 95070, USA

Abstract

A gyroklystron system is under development at Calabazas Creek Research, Inc. to produce 10 MW of peak power at 91.392 GHz via the interaction of a 500 kV, 55 Amp beam with a 5 cavity second harmonic circuit. The expected interaction efficiency and gain are 37.4% and 56 dB, respectively. The electron gun is a double-anode, magnetron injection gun (MIG) designed to produce a rotating annular electron beam with an average perpendicular to parallel velocity ratio of 1.6 and a parallel velocity spread of 4%. The gun design is described in Sect. 1 below, and the microwave circuit design is discussed in Sect. 2.

1 MAGNETRON INJECTION GUN

The 91.392 GHz MIG design is nominally scaled from a 20 GHz MIG built by CPI (formally Varian) which ran successfully for many years at the University of Maryland [1]. The electron gun parameters are given in Table 1. The nominal beam power is 27.5 MW, and the magnetic compression is 38.4. The control anode is adjusted to produce the required average velocity ratio. The magnetic field profile is generated by a set of superconducting coils which is complemented by a room temperature bucking coil located near the control anode – main anode gap.

The *EGUN* code [2] is used to simulate the beam characteristics. The simulated trajectories are displayed in Fig. 1, and the key simulated results are given in Table 2. With the exception of the space-charge limit, the results presented here assume a uniform cathode loading. The effect of non-uniform emission is small. The average velocity ratio is selected from experience as a value that should enable interaction efficiencies approaching 40%. The beam radius is constrained so that drift regions are cut off to the operating mode. The predicted beam clearance is typical for W-Band gyroklystrons. The simulated axial velocity spread is due only to ballistic effects and is extremely low for a non-laminar gun with such a relatively large current (~50% of the space-charge limit). The peak cathode electric field appears on the tip of the nose, and the peak field on the control anode appears on the 90° bend on the back side of the electrode. These fields were calculated by *EGUN* and do not consider the effects of the insulators, dielectric oil, and the gun enclosure.

Table 1: Electron gun parameters

Beam voltage (kV)	500
Beam current (A)	55
Control anode voltage (kV)	53.8
Cathode radius (cm)	0.8519
Emitter slant length (cm)	1.3345
Average cathode loading (A/cm^2)	7.7
Emitter angle (deg)	20.5
Cathode magnetic field (kG)	724

Table 2: Simulated performance

Average velocity ratio	1.6
Axial velocity spread (%)	3.38
Average beam radius (mm)	1.649
Peak anode field (kV/cm)	61
Peak cathode field (kV/cm)	77
Peak mod anode field (kV/cm)	95
Space-charge limit (A)	109
Beam clearance (mils)	13.8

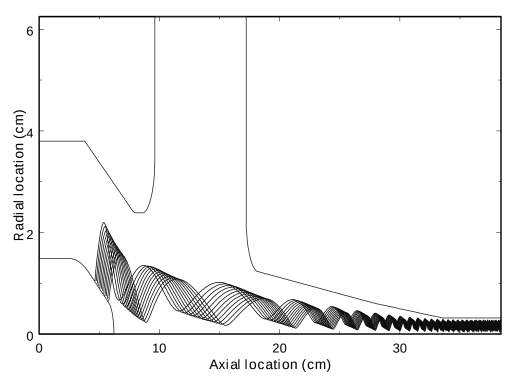

Figure 1: Electron gun trajectories simulation

The solid line in Fig. 2 indicates the dependence of axial velocity spread on current for a velocity ratio (α) of 1.6. As indicated, the velocity spread stays below 10% for currents from 40 A to 80 A. The corresponding change in the control voltage, required to keep α at 1.6, is indicated by the dashed line and goes from 51.5 kV to 56.5 kV. The dependence on control anode voltage is nearly linear. The optimal current is 55A with the spread given in Table 2.

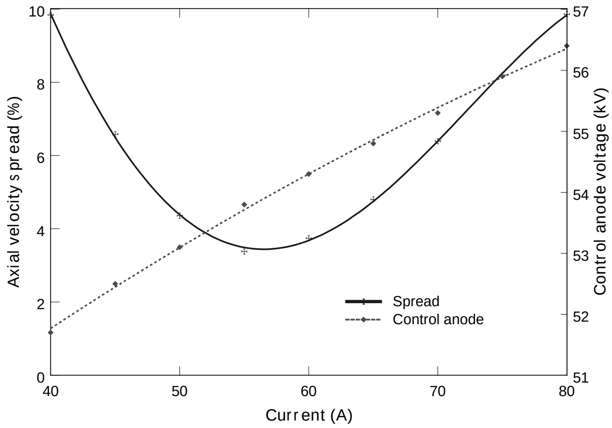

Figure 2: The dependence of spread on beam current

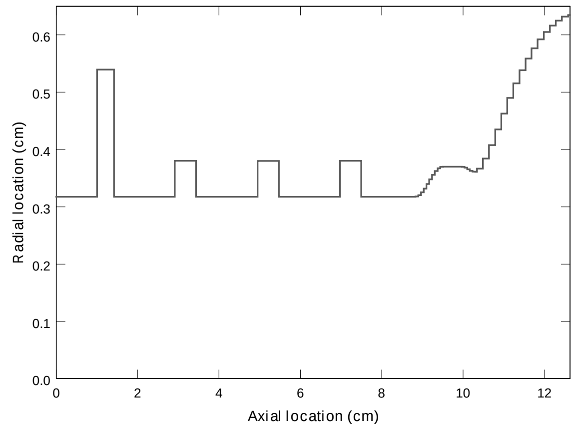

Figure 4: The five cavity circuit configuration

The dependence of average velocity ratio on control anode voltage (solid line) is shown in Figure 3. By changing the control anode voltage from 47 kV to 56 kV, α can be varied from 1 to 2. The corresponding axial velocity spread is given by the dashed line. The minimum spread occurs near an average velocity ratio of 1.5, but the spread remains below 5.5% throughout the variation in α due to a decline in the perpendicular velocity spread with increasing α.

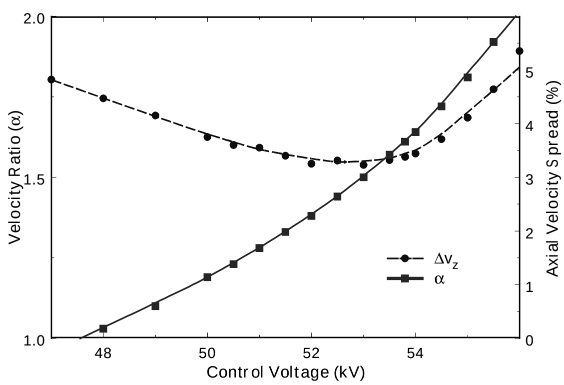

Figure 3: The dependence of velocity ratio on control anode voltage

2 MICROWAVE CIRCUIT DESIGN

A picture of the circuit layout is shown in Fig. 4, and the specifications for the tube are given in Table 3. Five cavities are used to achieve a large-signal gain in excess of 55 dB. The dimensions of all cavities are given in the table, along with the center frequencies and quality factors. The input cavity interacts at the first harmonic in the TE_{011} mode; all other cavities interact near the second harmonic in the TE_{021} mode. The nominal drive frequency is 45.693 GHz. The cavities are stagger-tuned to increase efficiency and bandwidth. The drift tube radius is 0.3175 cm between all cavities. The TE_{01} mode at the drive frequency and the TE_{02} mode operating frequency are cut off in the drift tube by 25% and 15%, respectively.

The walls of the first four cavities are formed by abrupt radial transitions. Mode conversion in the three intermediate cavities from the TE_{02} mode to the TE_{01} mode is minimized by adjusting the cavity lengths to provide destructive interference. This is required because the TE_{01} mode is not cutoff in the drift regions at 91 GHz. The diffractive quality factors for these cavities are greater than 20 million. The quality factors listed in the table for the intermediate cavities are derived from resistive losses that arise from lossy ceramics which are placed in the drift regions. About half of the input cavity loss comes from these ceramics, and the remaining loss comes from the coupling aperture. The input cavity has an outer coaxial cavity to facilitate the injection of power into the proper mode with low insertion loss.

Table 3. Microwave circuit cavity parameters

Parameter	Input	Bunchers	Output
Freq (GHz)	45.687	91.318 - 91.392	91.373
Mode	TE_{011}	TE_{021}	TE_{021}
Q factor	320	420	810
Radius (mm)	5.396	3.80	3.700
Length (mm)	4.162	5.24	4.610

The quality factors are chosen as a tradeoff between the desire to increase circuit gain and the need to insure that no spurious oscillations can exist in the cavities. The start oscillation conditions for various modes in the input cavity are given Fig. 5a. Each curve indicates the threshold Q as a function of magnetic field. Quality factors above a curve are unstable for the mode indicated. The required quality factor for the operating mode is also indicted in the figure. All modes with azimuthal indices from zero to four in the frequency range from 40 GHz to 110 GHz were investigated; only modes with start Qs below 1500 are shown in the figure. The code, which calculates start oscillation thresholds (*QPB*), assumes axisymetric geometry. This does not hold for the input cavity due to the input coupler; however, the threshold approximations for all modes are sufficiently large so that no problems are expected. The start oscillation thresholds

Table 4. Output cavity details.

Uptaper length (cm)	.6770
Downtaper length (cm)	0.3300
Lip radius (cm)	0.3610
Lip length (cm)	0.0415
Output taper length (cm)	2.241
Output waveguide radius (cm)	0.635
Upstream power (%)	0.022
TE_{02} mode purity (%)	99.800

for the first buncher cavity are shown in Fig. 5b. Although the intermediate cavities are stagger-tuned, the degree of detuning is sufficiently small that the start oscillation curves for the other intermediate cavities are nearly identical. A log scale is used for the dependent axis because of the wide variations in the curves. The cavity operates at 80% of the threshold for the TE_{021} mode. The only potentially troublesome mode is the TE_{211} mode which, nonetheless, is expected to be stable.

Table 5. Simulated results.

Output frequency (GHz)	91.386
Drive power (W)	24.42
Nominal Magnetic field (kG)	27.7
Electronic efficiency (%)	37.38
Output power (MW)	10.28
Gain (dB)	56.24

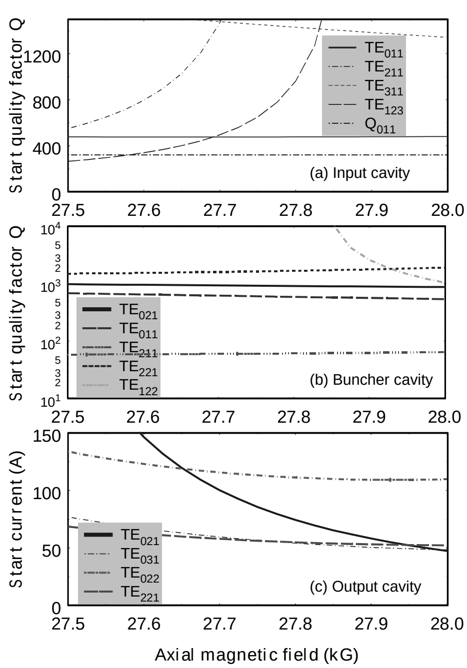

Figure 5: Start oscillation curves

Adiabatic radial wall transitions are used to define the output cavity for two reasons. First, the transitions reduce the maximum wall loading in the output cavity. Second, the adiabatic transitions allow for greater flexibility in selecting the cavity length, which is essential in order to maximize conversion efficiency. The output cavity has a diffractive lip to achieve the required Q. The final output taper utilizes a dolph-chebychev profile to minimize mode conversion. The other tapers follow simple sinusoidal variations. Details of the output cavity dimensions are given in Table 4. The simulated mode purity of the output signal is over 99.8%. The fraction of power which travels into the drift region towards the penultimate cavity is less than 0.022% of the power that enters the output waveguide. The start oscillation curves for the output cavity are given in Fig. 5c. Because the quality factors of all modes are dominated by diffraction and are calculated by the scattering matrix code, the results are given in terms of the start current. It can be seen from the figure that the cavity is just stable at the nominal magnetic field of 27.7 kG to the TE_{221} and the TE_{031} modes.

The code *MAGYKL* was run to obtain the system efficiency. *MAGYKL* has been compared to experimental results for other gyroklystrons and has always given good agreement.[3] The simulated results from *MAGYKL* are given in Table 5. The system was optimized with respect to magnetic field profile using the actual dimensions of the superconducting coils. The system was also optimized with respect to cold cavity resonant frequencies and Qs, drift tube lengths, and drive frequency and power. The optimal results for the simulated beam parameters include a gain and efficiency of 56 dB and 37.4%, respectively, which translates to an output power of over 10.3 MW. The peak wall loading in the output cavity has been simulated and is within acceptable levels.

3 SUMMARY

A W-Band, second harmonic, gyroklystron circuit was designed that advances the state-of-the art in peak power density for microsecond-length pulsed amplifiers by about an order of magnitude. The *EGUN* simulations indicate that the required high-quality, low spread beam can be generated by a double-anode MIG with conservative values for peak electric fields and cathode loading. The gyroklystron is currently under construction.

REFERENCES

[1] V. L. Granatstein and W. Lawson, *IEEE Trans. Plasma Sci.*, vol. 24, pp. 648-665 (1996).

[2] W. B. Herrmannsfeldt, SLAC Report SLAC-PUB-0331, Stanford, CA, Oct. 1988.

[3] M. Blank et al., *IEEE Trans. on Plasma Sci.*, vol. 26, pp. 409-415, 1998.