DESIGN OF SINGLE-ANODE, MIG-TYPE GYROTRON GUN FOR A 35 GHz GYRO-TWT

J. M. Baird and A. C. Attard
B-K Dynamics, Inc.
Rockville, MD

ABSTRACT

The design of a diode-like, low velocity spread electron gun for a gyrotron amplifier is described. The total longitudinal velocity spread is calculated to be on the order of $\pm 2.5\%$ in a 70 kV, 9 A beam with a $v_\perp/v_z$ velocity ratio of 1.5. Less than $\pm$ 0.5% spread is attributed to electron ray optics effects. Gyrotron gun design approaches are discussed.

Introduction

Gyrotron oscillators and amplifiers require an entirely different type of electron gun. The ideal beam must not only have the proper geometry to maximize the rf interaction with the selected waveguide circuit mode, but for maximum efficiency there are two additional requirements: 1) the transverse velocity of the electrons must exceed the longitudinal velocity by a typical factor of 1.5 to 2 (intermixed helical electron trajectories are allowed); and 2) the spread in the longitudinal velocities must be small (on the order of 10-20% for oscillators, 2-5% for amplifiers).

Several methods for producing gyrotron beams are being investigated and different approaches may eventually be used for differing power level and velocity spread requirements. Historically, several beam formation schemes were proposed and tried by researchers investigating cyclotron wave interactions in the 1960's. In the USA, Chow and Pantell[1] (1960) first used a magnetically shielded, off-axis Pierce gun to produce a beam with helical electron trajectories. They later used a ring cathode version of the same approach. Wingerson[2] (1961) proposed the use of a bifilar helix to act as a transverse parametric pump on an axial pencil beam. Subsequent magnetic compression then yields high transverse velocities. Hirshfield, et al.[3] (1965) used this technique in some of the first truly definitive gyrotron experiments. Both of these beam generation schemes, as well as a related tilted-Pierce-gun scheme described by Korolov and Kurin[4] (USSR 1970), are based on magnetically-shielded, space-charge limited guns with the subsequent addition of the transverse velocity component in the beam. There has been a renewed interest recently in this general approach due to the desire to find ways to utilize standard gun technology and to achieve lower longitudinal velocity spreads.*

The high power gyrotron successes to date, however, have been achieved with modified magnetron injection guns (MIGs). These guns were first tried experimentally in the USA by Dickerson and Johnson[5] (1964) and were used by Schriever and Johnson[6] (1966) to produce a relatively high power cyclotron wave BWO. Gapanov,[7] et al. (1965) first reported the use of this type gun in the Soviet Union and subsequent work by Soviet researchers during the last decade has been extensive.[8-15]

Typical design practice is to generate hollow electron beams using temperature limited MIGs in which the transverse velocities are deliberately enhanced and controlled. (This differs sharply from the early space-charge limited MIGs[17,18] in which one of the design goals was the elimination of transverse velocities.) Control of the longitudinal velocity spread in the beam is one of the difficult problems in the design of gyrotron guns.

The three primary sources of velocity spread in a MIG-type, temperature-limited gyrotron gun are: 1) electron ray optics, 2) cathode thermal velocities, and 3) cathode roughness. In the ray optics case, longitudinal velocity spread arises from the spatial differences in the electron ray trajectories which originate at different points along the cathode. This includes trajectory related space-charge effects in the beam. In the other two cases, velocity spread is the result of a spread in the initial velocities at the cathode.

In this paper, we present the results of a study to design a low velocity spread gyrotron MIG for application in the 35 GHz gyro-TWT research program at the Naval Research Laboratory (NRL). In the gun design obtained, the velocity spread resulting from electron ray optics (including space-charge effects) has been virtually eliminated. Computer simulations of the gun show less than $\pm 0.5\%$ spread in the longitudinal velocity v_z. The total v_z spread at a velocity ratio of 1.5 is expected to be on the order of $\pm 2.5\%$, with the major contributions arising from cathode temperature and surface roughness.

Although the direct measurement of velocity spread in gyrotron guns has not yet been implemented at NRL (or elsewhere in the USA), indications are that the gun design described here will improve the velocity spread by a factor of 2 to 4 from the guns now in use. This new gun is being fabricated and will be used in experiments underway to enhance the efficiency of the NRL 35 GHz Gyro-TWT.

35 GHz Gyrotron MIG Design

Gyro-TWT experiments to date at NRL have utilized a temperature limited MIG which was initially designed for use in Circular TE_{0n} mode gyrotron oscillators. The design parameters of this gun are as follows.[20]

Beam Voltage	V_0	= 70 kV
Current	I_0	= 9A
Velocity Ratio	$v_\perp/v_z$	= 1.5
Guiding Center Radius	b_0	= 0.252 cm
Larmor Radius	a_0	= 0.052 cm
Interaction Mag. Field	B_0	= 12.96 kG
Cathode Mag. Field	B_c	= 1860 G
Cathode Current Density	J_c	= 4 A/cm^2
Cathode Angle	ϕ_c	= 10°
First Anode Voltage	V_a	= 35 kV
Long. Velocity Spread	$\Delta v_z/v_z$	= $\pm$ 8%

* Non-MIG approaches to gyrotron guns are actively being pursued at NRL, Yale University, Varian and RCA.

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Although this gun served well in oscillators, the velocity spread is excessive for amplifier work and has precluded the attainment of high efficiency in these devices. The goal of the new gun design reported here is to reduce the longitudinal velocity spread below ±2.5%. A constraint on the design is that it must be able to replace the original NRL gun on existing gyrotron amplifiers. This constraint requires that the first seven design parameters listed above be retained. The final four, however, have been changed to 10A/cm^2, 40°, no intermediate anode, and ±2.5% respectively.

The first step in the design approach was to tilt the cathode at a sufficiently high angle to attain a laminar flow beam throughout the gun acceleration region. This helps to eliminate one source of velocity spread in the beam caused by periodic space charge fields.[13] Then, by repeated computer simulations of the electron trajectories (using the Herrmannsfeldt Code[21]) while successively making small changes in the cathode electrode shape, a design configuration was found. This design yielded virtually no velocity spread attributable to electron ray optics (including the space charge for a 9A beam).

The final gun design with a set of 8 electron ray trajectories is shown in Figure 1, and a plot of the final velocity ratio for each ray is given in Figure 2. The standard deviation of the longitudinal velocity spread for 8 to 15 rays is less than 0.5%. Note that the beam is accelerated directly to full potential without the use of an intermediate electrode, although in principle there is nothing to preclude the use of a modulating anode placed along one of the equipotential lines shown in Figure 1. Note also that the cathode is designed to operate in the flat magnetic field region produced by the superconducting solenoid (a plot of axial field is superimposed on the gun geometry). A trim coil in the solenoid permits the magnetic field at the cathode to be adjusted. A mesh unit in the simulation is 0.5 mm.

The sensitivity of the velocity ratio and the velocity spread to the experimental parameters of a) cathode longitudinal position with respect to the solenoid, b) gun voltage, and c) cathode magnetic field B_z are shown in Figures 3, 4, and 5 respectively. In each of these Figures α is the velocity ratio $v_\perp/v_z$ and $\Delta\alpha$ is shown by the vertical bars on each data point. The ratio of standard deviation to mean longitudinal velocity ($\Delta v_z/v_z$) is shown as a percentage.

Note from Figure 3 that a longitudinal position tolerance of about 0.5 cm appears to be available throughout which reasonably low velocity spreads and the proper velocity ratio are achieved. Figures 4 and 5 illustrate that some trimming is also available through beam voltage and cathode field adjustments. Note that the sensitivity of α to changes in these variables matched theoretical expectations from adiabatic gun theory.

Because velocity spread from the trajectory ray tracings is so small, the dominant velocity spread in the final beam will arise from initial velocities at the cathode. These come from the thermal velocities of emitted electrons and from cathode surface roughness. An estimate can be obtained for the contributions of these two velocity spread components based on calculations of the initial transverse velocity spread and adiabatic compression theory.

Under adiabatic beam flow conditions, the transverse velocity spread $\Delta v_\perp/v_\perp$ is conserved and the transverse velocity anywhere in the beam is related to that at the cathode by the factor $(B/B_c)^{1/2}$. Using these relationships along with conservation of energy, it can be shown that

$$\frac{\Delta v_{zo}}{v_{zo}} = \alpha^2 \frac{\Delta v_{\perp o}}{v_{\perp o}} = \left[\frac{\alpha^2}{v_{\perp o}}\left(\frac{B_o}{B_c}\right)^{1/2}\right]\Delta v_{\perp c}$$

Using the design values for the MIG gun and the values of initial transverse velocities at the cathode ($\Delta v_{\perp c}$) derived by Tsimring[10], we obtain the following two velocity spread components due to thermal effects and cathode roughness:

$$(\Delta v_{zo}/v_{zo})_{THERM.} = \pm 1.8\%$$

$$(\Delta v_{zo}/v_{zo})_{ROUGH.} = \pm 1.7\%$$

Combining these with the ± 0.5% spread due to electron ray optics gives an RMS combined spread of ± 2.5%.

The velocity spread due to surface roughness assumes a highly polished cathode with a surface finish on the order of 0.1 μm. It appears at this time that special cathode techniques will be required to meet this specification.

The gun described here is now being fabricated at NRL and will be used in conjunction with ongoing amplifier efficiency studies in Summer, 1981.

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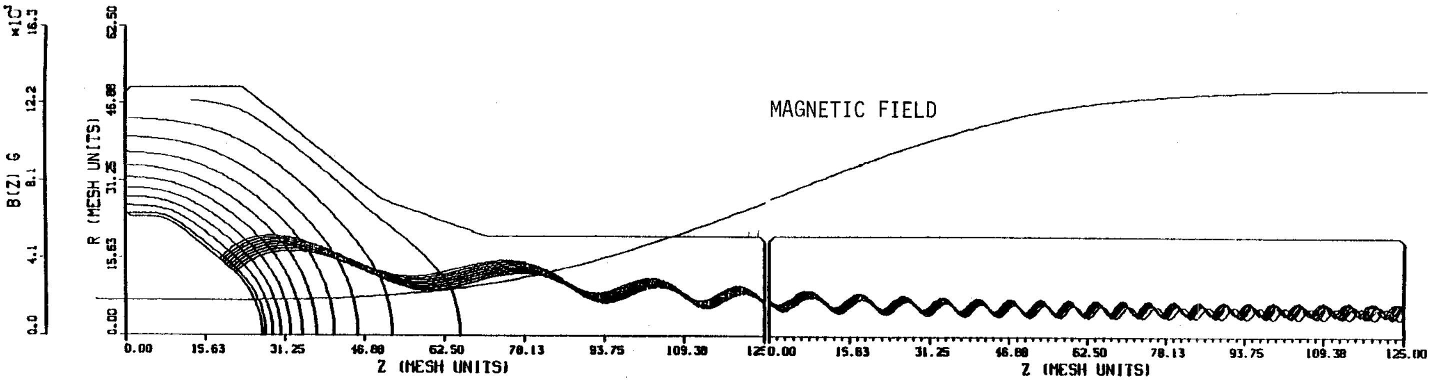

FIGURE 1: GYROTRON GUN PROFILE WITH ELECTRON RAY TRAJECTORIES, EQUIPOTENTIALS, AND AXIAL MAGNETIC FIELD PLOT.

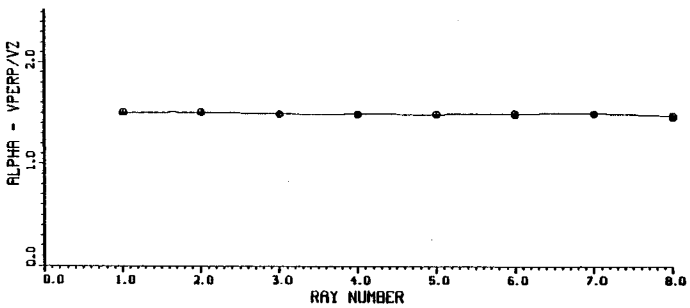

FIGURE 2: VELOCITY RATIO VERSUS ELECTRON TRAJECTORY NUMBER FOR AN EIGHT RAY GUN SIMULATION.

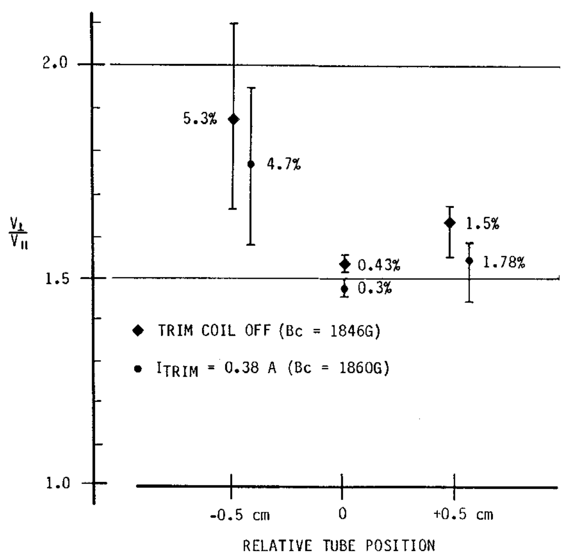

FIGURE 3: VELOCITY RATIO VERSUS THE CATHODE POSITION RELATIVE TO THE SOLENOID. DOTS SHOW AVERAGE VALUES AND BARS SHOW TOTAL SPREAD IN VALUES. STANDARD DEVIATION OF V_z IS GIVEN IN PERCENT.

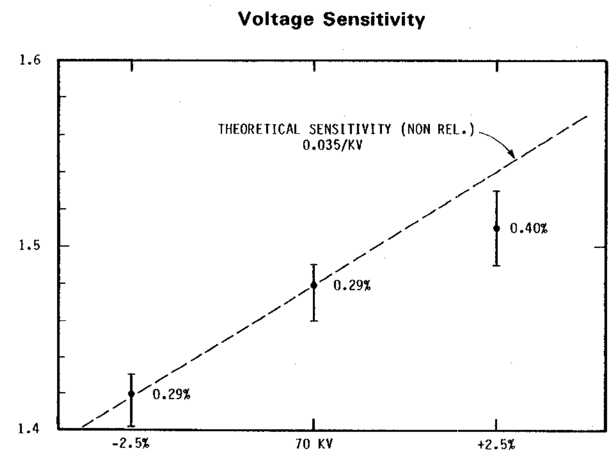

FIGURE 4: SENSITIVITY OF VELOCITY RATIO TO BEAM VOLTAGE.

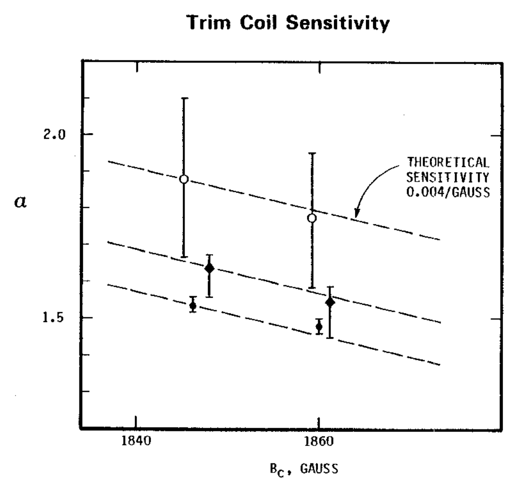

FIGURE 5: DATA OF FIGURE 3 RE-PLOTTED VERSUS CATHODE MAGNETIC FIELD.