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THE TRIROTRON*

J. V. Lebacqz, A. J. Dudas and W. R. Fowkes†

Summary

A radially directed rotating electron beam can be generated in a circular traveling wave resonator (TWR) sustaining a pure traveling wave. After being accelerated by a dc potential, the beam induces a traveling wave in a concentric output TWR, in which the beam energy is converted to RF with very high efficiency. Results of calculations of drive power and efficiency, as well as special matching and coupling requirements, are reviewed.

I. Principle of Operation

The trirotron is an RF vacuum tube amplifier being developed in an attempt to combine the inherent high efficiency of the gyrocon[1] with a simpler drive system. Here, the drive system consists of a circulating waveguide resonant at the device frequency. This waveguide is concentric to the output resonator, which in all respects is similar to the gyrocon output. The phase propagation constant of the two waveguides is adjusted so that the drive resonator guide can be located inside the output resonator, leaving space for a dc accelerating field between them. The central portion of the inner wall of the input resonator is replaced by a cathode, insulated from the remainder of the waveguide. The outer wall opposite the cathode is replaced by grids (see Fig. 1).

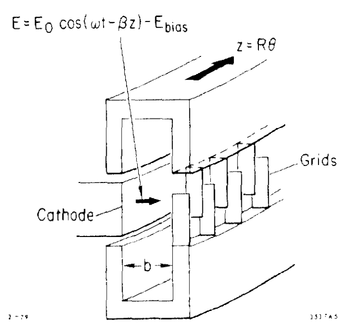

Fig. 1. The input resonator: beam formation region.

The electron beam formed in the input resonator by the circulating wave rotates as the wave and is accelerated by the dc field before entering the output resonator. For both resonators, the "b" dimensions are determined by designing to maximize the energy transfer in the output and to minimize drive power in the input. Both considerations result, in a first approximation, in fields and distances very close to "multipactor" conditions. The name trirotron stands for TRIode producing a ROtating beam for RF amplification.

Obviously, in order to produce a rotating beam one must insure that the input resonator supports a pure traveling RF wave. Also, from simple energy considerations, the efficiency of the device will depend on the angular spread of the beam as it enters the output resonator. The majority of the work reported here has been devoted to the analysis of the beam formation in the trirotron, and in the very stringent requirements imposed on the matching of the input resonator to insure that a pure traveling wave results.

II. Beam Formation

The angular spread of the beam can be adjusted from 0 to 180° by superimposing a dc bias on the RF electric field in the input waveguide resonator. Using standard waveguide wave equations, a computer program was written to study beam angular spread. For a frequency of 353 MHz and a 1 cm RF gap, RF fields of 100 to 400 kV/m and dc bias fields of 10 to 200 kV/m were considered.

In addition to beam spread, it is also necessary to evaluate the beam current and the current distribution along the angular spread of the beam. This was done by dividing the beam into a number of beamlets along the θ dimension and computing the effective gap voltage across the waveguide at the time of emission of each beamlet $(E_0 \cos\phi - E_{bias}) \times b$. That value is then applied in Child's Law to determine the current density emitted at each angle of the RF wave along the cathode. The results are plotted in Fig. 2 for

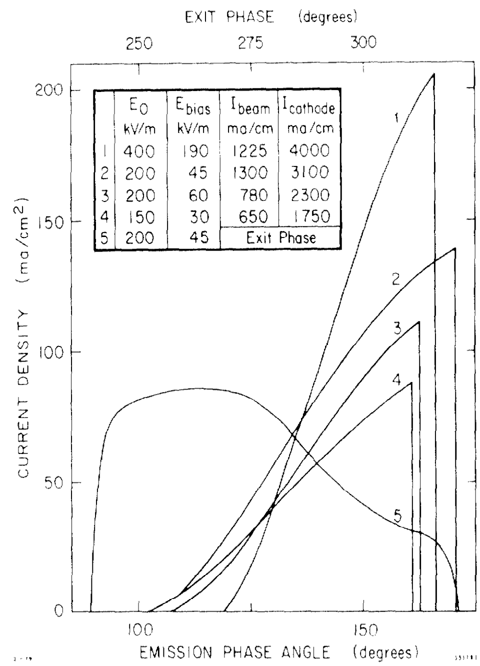

Fig. 2. Beam current density in input resonator.

several conditions of bias and RF field. The table in the figure gives an estimate of the beam current for a beam of 1 cm axial length, and of the total cathode emitted current per cm axial length. These differ because many emitted electrons are returned to the cathode.

Since the transit times are different for different emission angles, the angular current density distribution will be different at the exit. Curve 5 of Fig. 2 shows the calculated exit current density for the case $E_0 = 200$ kV/m, $E_{bias} = 45$ kV/m.

The energy of the electrons leaving the waveguide, whether to the accelerating region or returning to the cathode, is obtained from the computer program. Multiplying by the current previously obtained for each beamlet, and summing over the emission angle gives the total power absorbed by the electrons. Some of this power comes from the dc bias, but most of it is from the RF drive field. For the case of curve 5, the RF power required per cm of axial length of beam current is approximately 1 kW.

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†Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305.

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The calculations indicate that more than half of the total RF energy supplied to the input TWR will be dissipated on the cathode. This additional power supplied to the cathode will require some control of the heater power and may even require water cooling of the cathode under extreme power conditions.

III. The Input Circuit

The input TWR performance depends on minimizing the undesirable backward wave buildup which can cause amplitude modulation on the beam. Such a wave can result from relatively small residual reflections in the input coupler and TWR ring.[2] Two identical coupling loops are spaced 90^{o} apart and combined with a 3 dB hybrid to form a directional coupler with good directivity (Fig. 3). Two sets of tuners are required in the input TWR. One pair acts as a phase shifter to keep the input TWR tuned to the drive frequency while the other pair is used to eliminate any residual reflections in the TWR.

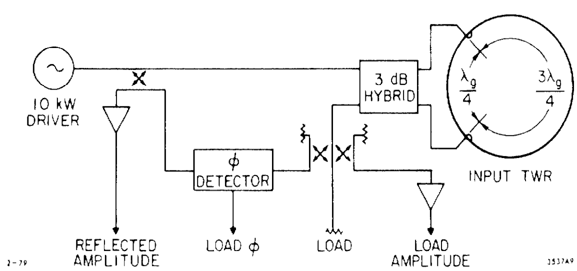

Fig. 3. Schematic diagram of RF drive and monitoring system.

The resonator shunt conductance is computed from the ridge waveguide power-voltage impedance, Z_0^*, and attenuation parameter τ and is given by $G_c = 1/R_{sh} = 2\tau/Z_0^*$. The effective beam loading conductance G_b, is determined from the peak RF voltage V_{RF}, and the calculated RF power P_e, transferred to all the electrons in the TWR, and is given by $G_b = 2P_e/V_{RF}^2$. The optimum coupling coefficient for the input resonator is given by $\beta_{opt} = 1 + R_{sh}G_b$ which corresponds to a directional voltage coupling ratio $C_{opt} = \sqrt{2\tau\beta_{opt}} = 0.317 \simeq 10$ dB for the specific device considered.

Tuning and matching of the input resonator must be satisfactorily monitored and controlled, since the backward wave should be kept to less than 10% of the forward wave. There is a critical value of effective reflection coefficient Γ_c beyond which the forward wave resonance becomes double peaked and the backward wave is intolerably large. The value of Γ_c for the device considered is 0.16, and the reflection coefficient should be kept to approximately $\Gamma_c/20$ to limit the backward wave.

A scheme for monitoring the TWR performance uses signals that are external to the resonator (Fig. 3). As the backward wave is tuned out, the reflected amplitude goes identically to zero. The load amplitude goes to zero at resonance only for optimum coupling. For coupling greater than optimum, the load phase can be compared to the input signal phase. Assuming $\Delta\phi = 0^o$ far off resonance, it will be 180^o at resonance and its rate of change will be a measure of loaded Q.

An iterative matching and tuning procedure will use the load amplitude and phase and the reflected amplitude signals as monitors.

IV. The Output Circuit

Paul Tallerico[3] helped us to modify his gyrocon program to adapt it specifically to our needs to study the efficiency as a function of a beam angular spread. The results are shown in Fig. 4 for a uniform current

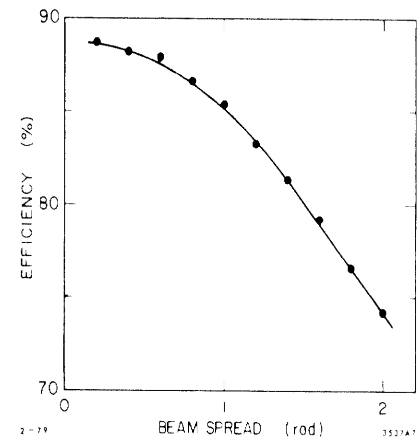

Fig. 4. Output efficiency vs. beam spread angle.

density beam. As can be seen even with a beam spread of over 80^o, efficiencies in excess of 80% are computed. In this case the efficiency is defined as the ratio of the power extracted from the beam in the output TWR, less wall losses, to the beam power; and does not include heater power or drive power. Optimum coupling from the TWR to the load is assumed.

Computer results indicate that part of the loss in electronic efficiency results from the tangential velocity component of the spent beam, created by the magnetic field component of the RF wave. A small axial dc magnetic field can cancel most of the remaining tangential velocity and enhance the computed efficiency for a given beam spread by several points.

The optimum directional coupling for the traveling wave resonator is related to the power-voltage impedance Z_0^*, the dc beam conductance G_0, and the one way voltage attenuation parameter τ by

$$C_{opt} = \left(\left(8G_0Z_0^*/\pi^2\right) - 2\tau\right)^{\frac{1}{2}} \quad .$$

In terms of a resonant cavity, the coupling coefficient is given by

$$\beta = Q_0/Q_{ext} = C^2/2\tau \quad \text{with} \quad Q_0 = \pi(\lambda_g/\lambda_0)^2/\tau \quad .$$

A TWR shunt impedance can be defined as

$$R_{sh} \equiv V_{RF}^2/2P_{diss} = Z_0^*/2\tau \quad .$$

The shunt conductance of the rotating beam in the output TWR is given by

$$G_b = \left(8G_0/\pi^2\right) - (2/R_{sh}) \quad .$$

Following this formalism the optimum coupling coefficient expression is identical to the output resonator of a klystron and is given by

$$\beta_{opt} = 1 + G_bR_{sh} \quad .$$

V. Conclusions

From the previous discussion it appears possible to produce a rotating beam in a traveling wave resonator resulting in amplifier efficiencies approaching those of the gyrocon, i.e., greater than 80%. A tube has been designed to operate at 353.2 MHz, at beam voltages of 56 to 64 kV and currents of 8 to 12 amps. A conceptual drawing of the device is shown in Fig. 5.

The fringing fields, which have been neglected so that the input circuit, output circuit and accelerating region could be considered separately, may cause problems because of feedback from the output resonator to the input. Depending upon the phase of the stray fields, the gain could be either increased until self oscillations occur or decreased to the point where the device is almost useless. Analysis of the feedback problem has not been attempted.

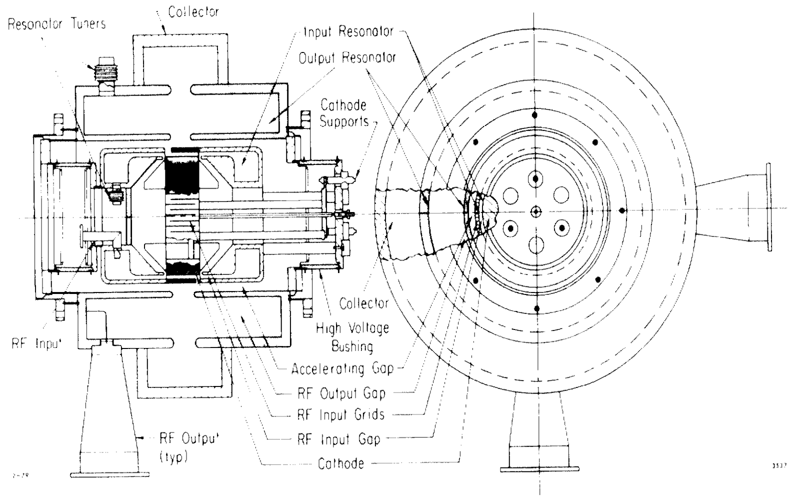

Fig. 5. Conceptual design of a 600 kW, 353 MHz trirotron.

The following dimensions have been used:

Cathode diameter	27.65 cm
Axial cathode length	9.00 cm
Input resonator OD	29.65 cm
Input grid fins	1 × 9 × .07 cm
Output resonator ID	37.65 cm
Output resonator OD	57.65 cm
Axial output resonator length	51.50 cm
Collector OD	80.00 cm
Axial collector length	20.00 cm

Efficiencies listed in the following table were computed assuming a uniform density beam, spread over 80° (produced by a drive power of ≃10 kW), with an axial length of 10 cm and no magnetic field efficiency enhancement.

Amps \ kV	56	60	64
8	81.1	80.4	81.0
10	81.4	81.4	81.3
12	80.7	81.6	81.4

Several simplifying assumptions were made in the calculations resulting in the above design. The relativistic correction factor has been neglected in the input resonator calculations. Secondary emission effects, which have been neglected throughout may result in multipactor in the input resonator between cathode and grid; with 95% grid transparency serious problems are unlikely.

The trirotron shows promise of being a highly efficient device at frequencies of 200 to 500 MHz, and power outputs of one-half to several MW CW. The efficiency is not a critical function of beam voltage, drive power, or bias voltage. Hence it appears possible to control the power output over a wide range by adjusting the dc bias or the drive power without loss of efficiency and with minimal phase variation between input and output. Some possible disadvantages include the drive system dc isolation, the need for accurate tuning of the input resonator and its coupler, the cathode heating by electron back-bombardment, and the low gain computed at approximately 15-18 dB.

Acknowledgments

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References

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