DEPRESSED COLLECTORS FOR GYROTRONS

M.E. Read, W. Lawson[1], A.J. Dudas and A. Singh[1]
Physical Sciences, Inc., Alexandria, VA 22314

INTRODUCTION

The gyroklystron is a potential source for driving advanced accelerators, such as the proposed 300-500 GeV electron-positron collider. Sources with frequencies higher than those commonly used in accelerators (e.g. 2.9 GHz) are desired because higher accelerating gradients can be created, thus reducing the length and cost of the device. Because of the inherent advantages of gyrotrons, such a source is expected to be able to produce significantly higher power at high frequencies than that possible with a linear beam tube. A 10 GHz, 30 MW gyroklystron is being developed at the University of Maryland to demonstrate this potential.[1]

However, it is recognized that the gyroklystron's efficiency is inferior to its linear beam counterpart because gyrotrons extract energy primarily from only beam rotational motion. Thus, for high average power systems, as a large accelerator clearly is, a method for enhancing the efficiency is important.

For example, a scaling study relevant to the electron-positron collider predicts a required average RF system power of 100-200 MW. If the capital costs of the input power supply and regulator and cooling system are $0.40 per Watt,[2] then an increase in the efficiency from 30% to 63% would result in a $140 million saving in a 200 MW system. Coupled with expected savings in operating costs, this clearly points out the importance of efficiency enhancement.

Depressed collectors are commonly used in linear beam tubes. The total efficiency, η_t, of a tube with a depressed collector is given by $\eta_t = \eta_e/(1-\eta_r(1-\eta_e))$, where η_e and η_r are the electronic and collection efficiencies, respectively. This relationship is plotted in Figure 1, which shows that substantial increases in the total efficiency can be obtained with collection efficiencies over 60%.

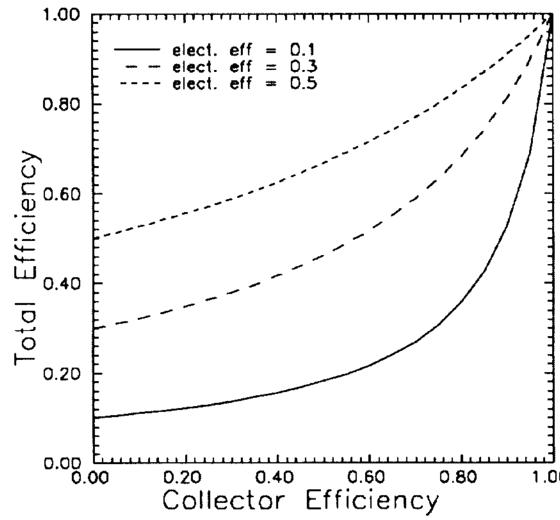

Figure 1. Total efficiency of a microwave tube with a depressed collector, as a function of the collector and electronic efficiencies.

DESIGN ISSUES

Conversion of Rotational to Axial Motion

A depressed collector can recover only that energy which is associated with axial motion. The beam in a gyrotron has most of its energy in rotational motion, which then must be converted for efficient collection. In addition, in order to focus the electrons electrostatically in the collector, the magnetic field, which is inherently large in a gyrotron, must be reduced to less than ≈ 100 G. These two requirements can be partially accomplished through an adiabatic reduction of the magnetic field. However, at a given field, the scale length of the larmor orbit in the axial direction becomes very large, and further adiabatic decompression would require a prohibitively long and large diameter system. To further reduce the field in a reasonable length, a cusp can be effective. The magnetic field at which the cusp can be used is limited to a maximum value, since too large a step in the field will heat the beam excessively. For a magnetic decompression f_m ($\equiv B_i/B_o$) the average perpendicular velocity, v_p which will be imparted to the beam will be approximately

$$v_p = 0.5\ v_{po}\ (1 + (r_g/r_l)^2)^{1/2} /\surd f_m \qquad (3)$$

v_{po} is the average perpendicular velocity prior to decompression. Initial simulations of a collector for the 30 MW gyroklystron (using EGUN, by W. Herrmannsfeldt) indicate that the velocity ratio, α, can be reduced from ~1.5 to ~0.2 using adiabatic decompression over a length of ≈ 1/2 meter. The magnetic field at this point is approximately 500 G. A pole piece can be used to reduce the field to an arbitrarily low value, with v_p/v_{po} ≈ 0.3. As determined through simulation of the beam trajectories in the collector, this heating does not appear to degrade the collection mechanism.

Number of Electrodes

Because the electronic efficiency of the gyrotron is predicted to be moderately high, the beam exiting from the cavity will have a significant energy spread. The electron spectra calculated for the 30 MW gyroklystron are shown in Figure 2. As can be seen, while there is a peak at roughly half the initial energy of 500 kV, a significant fraction of the beam electrons will have energies elsewhere

[1] Laboratory for Plasma Research, University of Maryland, College Park, MD 20742

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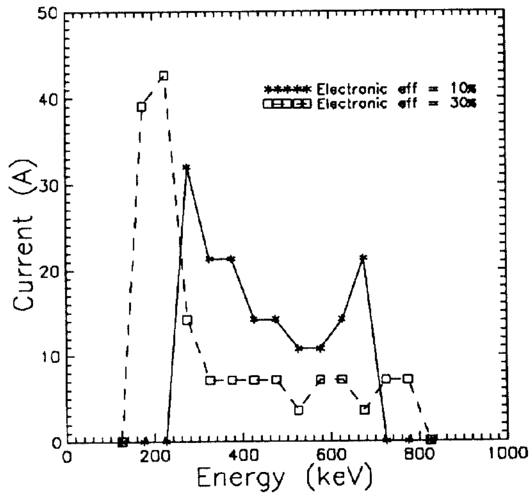

Figure 2. Energy spectrum of spent beam from 30 MW gyroklystron. The initial energy is 500 keV, the current, 150 A. Spectra for electronic efficiencies of 10% and 30% are given.

in the spectrum. To efficiently collect a beam with such a spectrum, multiple collection electrodes are required. The efficiency for 2, 3 and 4 element collectors, assuming roughly optimized electrode voltages and perfect collection on each electrode (no reflections or secondaries), has been calculated as given in Table 1. A 3 element collector appears most reasonable.

Table 1

Electronic Efficiency	Number of Electrodes	Collector Efficiency	Total Efficiency
10	2	79	35
10	3	84	41
10	4	86	45
30	2	71	59
30	3	77	65
30	4	80	69

Backscattered Electrons

At the voltages of interest, both true secondaries and reflected primaries will be encountered. Data in the literature indicate that the total backscatter coefficient over the range 100 kV - 300 kV is on the order of 0.3 for copper, and approximately 0.05 for graphite. (The graphite can be used as the actual electrode material or deposited on the surface of copper.) Even with this relatively modest coefficient, it will be important to avoid producing or reflecting electrons where they can be accelerated to another electrode or back to the cavity, thereby decreasing efficiency. This requires that the electrons impact on the electrodes on the side away from the cathode, i.e., the axial motion must be reversed.

DESIGN FOR A COLLECTOR FOR A 30 MW GYROKLYSTRON

A design for a depressed collector for the University of Maryland gyroklystron is shown in Figure 3. The trajectories of the primary electrons, shown in Figure 4, are from EGUN, with an initial beam energy spectrum for a gyroklystron efficiency of 30%. In order to focus, then deflect the high energy portion of the beam, a compound cusp was required, as shown. The collection efficiency of this design, ignoring effects of secondaries, etc., is 78%.

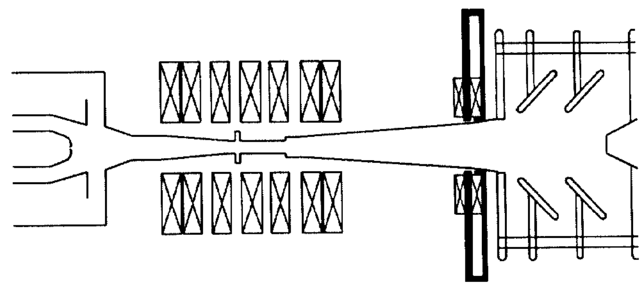

Figure 3. Schematic of a depressed collector for a 10 GHz, 30 MW gyroklystron, with a beam energy of 500 keV and a current of 150 A.

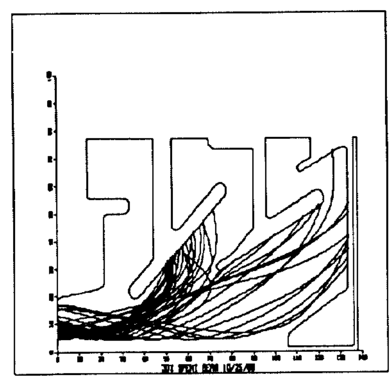

Figure 4. Trajectories of the primary electrons for the collector of Figure 3.

This is very close to the value given in Table 1, with the somewhat higher value achieved here produced by optimizing the collector potentials.

The effect of backscattered electrons has be studied by forming "secondary" cathodes at the electrode surfaces. This was done via modifications of EGUN.[2] The trajectories of first generation backscattered electrons from the electrodes of Figure 4 are shown in Figure 5. With careful design, no "electrons" were reflected back to the

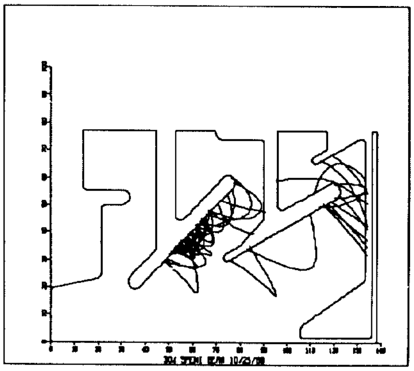

Figure 5. Trajectories of secondaries produced by the beam shown in Figure 4.

interaction region or scattered to positions where insulators would have to be placed. The energy lost to secondaries being accelerated from an initial electrode to one of lower potential is less than 2%. Thus the efficiency of the collector is calculated to be 76%. The overall efficiency of the gyrotron, with an electronic efficiency of 30%, would be 64%.

CONCLUSIONS

Detailed calculations indicate that a depressed collector for the U.Md. gyroklystron could have a high (≈ 76%) collection efficiency, yielding a doubling in the overall efficiency of the gyroklystron to 64%.

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