SPACE-CHARGE-LIMITED MAGNETRON INJECTION GUNS FOR GYROKLYSTRONS*

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Abstract

We present the results of several space-charge-limited (SCL) magnetron injection gun (MIG) designs which are intended for use with a 500 kV, 500 A gyroklystron with accelerator applications. The design performances are compared to that of a temperature-limited (TL) gun that was constructed for the same application. The SCL designs yield similar values for beam quality, namely an axial velocity spread under 3% for an average perpendicular-to-parallel velocity ratio of 1.5. The peak electric fields and the cathode loadings of the SCL designs are somewhat higher than for the TL design. Three designs are described in this paper. In the first design the space-charge limit is achieved by recessing the emitter into the cathode. The other two designs have control electrodes to which a voltage can be applied to change the beam current independently of the beam voltage. One of these designs can accept a bias sufficiently high to cut off the current completely, so that a DC power supply with pulsed electrode operation is possible. Details of all designs as well as a discussion of the advantages and disadvantages of the SCL designs as compared to the TL design are given.

INTRODUCTION

The standard electron gun configuration for gyro-devices is a temperature-limited (TL), Magnetron Injection Gun (MIG) [1]. These guns have a proven record of generating high-quality, rotating beams under ideal circumstances, but TL cathodes are known to be susceptible to azimuthal current density variations due to non-uniform emitter temperature distributions, non-uniform work-function distributions, cathode poisoning, etc [2,3]. These current variations lead to enhanced velocity spread in the beam, which in turn leads to the reduction of interaction efficiency and output power and possibly even to instabilities that significantly hamper the performance of the microwave sources.

One possible solution to this problem is to operate MIGs in the space-charge-limited (SCL) regime, as is done in klystrons and other linear-beam tubes. Although SCL emitters can experience the same types of variations in temperature and work function [4], the fact that the emission depends on the gun geometry and not the cathode temperature means that the azimuthal beam current density will not be adversely affected by these variations as long as there is sufficient heater power available to keep all of the emitter in the SCL regime.

When the cathode temperature of a TL MIG is increased until the SCL limit is reached, the beam quality, as measured by the axial velocity spread of the beam, is usually quite poor. However, if you modify the MIG design to compensate for the self-field of the electrons, simulations indicate that high quality beams can in fact be generated.

The design approach taken by our group is to start with an existing (constructed and utilized in our experiments) TL MIG design, and modify the cathode assembly dimensions to produce an SCL beam with the same basic characteristics of the TL beam. Neither the anode nor the magnetic field coils were modified in any way, although the coil currents were modified to produce the proper ratio of the beam's average perpendicular velocity to the average parallel velocity (α). With these restrictions, it is believed that our TL MIG could be converted into an SCL MIG fairly inexpensively.

SIMULATION RESULTS

The TRAK code [5] was used to simulate all the configurations described here. The electrode shapes and simulated beam trajectories are shown in Fig. 1. The nominal beam current and voltage are 500A and 500 kV, respectively. The average velocity ratio is α=1.5. The TL MIG is shown in Fig. 1a. A simple SCL MIG is shown in Fig. 1b. The space-charge effect drops the average electric field near the cathode, so a larger magnetic compression is required to compensate for the initial drop in perpendicular velocity. Thus a larger emitter radius is required to place the beam at the final radius needed for the microwave tube (about 26 mm). The cathode well is necessary to exclude electric field near the emitter and hence reduce the SCL limit. The remainder of the changes are made to minimize velocity spread.

Designs with control electrodes are shown in Figs. 1c and 1d. The first of these designs has only small control electrodes (SCE) to allow for current control via a small potential difference between the cathode and the electrodes. Although there are two electrodes, they were always assumed to be connected together for the simulation studies. The second design has control electrodes replacing the entire outer surface of the cathode, and the gray regions indicate the locations of ceramic insulators. This large control electrode design (LCE) allows for a sufficient control potential to cut off the beam entirely even if full voltage is applied between the cathode and the anode. In other words, the electrodes could be pulsed to allow the use of a DC power supply to generate the beam instead of a pulse-line modulator.

The dependence of beam current and beam quality on the control electrode voltages are given in Fig. 2. The SCL beam current as a function of the applied cathode – control anode voltage is given in Fig. 2a. A positive relative control voltage actually means that the control anode is more *negative* than the cathode, so the applied electric field at the emitter surface is further reduced and the SCL limit decreases. The curves are virtually identical for both designs and show that a 100% variation in current is achievable with a modest control voltage (about 33 kV is needed to completely cut off the current).

The dependence of the velocity spread on the control anode variations is given in Fig. 2.b. The magnetic field is adjusted to maintain α=1.5. Normally, axial velocity spreads less than 10% are considered adequate, and so although the lowest spread of less than 2% occurs near the nominal design point, sufficient beam quality is achieved for the full range of currents.

The results of the simulations at the nominal point are shown in Table I for all four designs. It can be seen that the control electrode SCL designs produce comparable beam quality as the NCE design and the TL design. The axial and perpendicular velocity spread values are slightly higher for the SCL designs in comparison to the TL design but are still extremely small. The peak anode fields are comparable and are low for all designs. The peak cathode electric fields for the NCE design and the SCE design are about the same, and are only 8% higher than that of the TL design. For the LCE design the peak cathode electric field is much less than the others, which is as expected due to the shielding from the control electrodes. However, the peak LCE control electrode field is essentially equal to the peak cathode fields in the other designs.

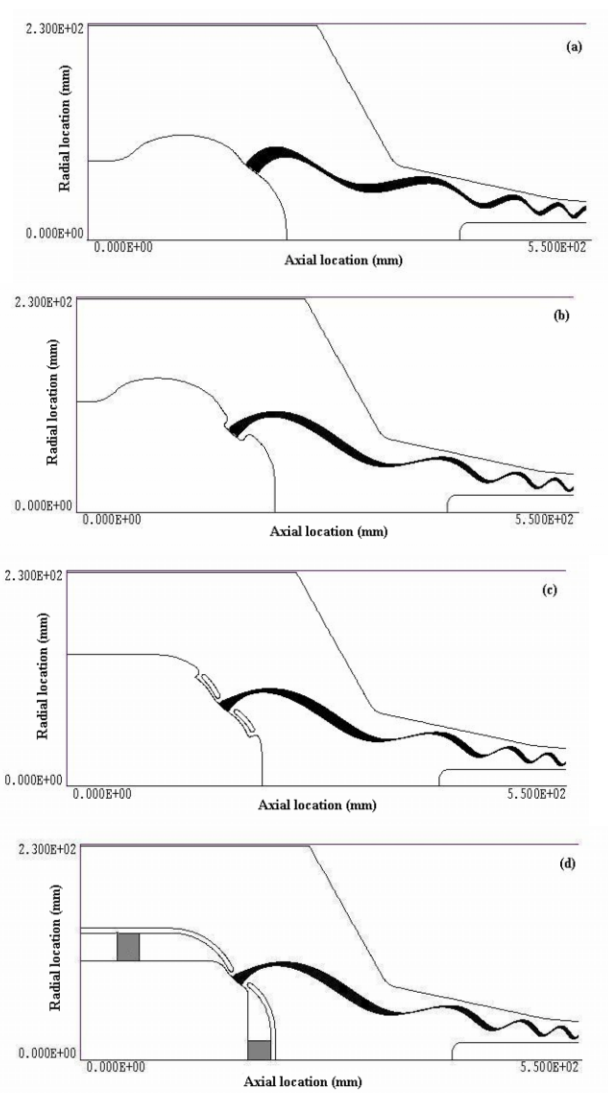
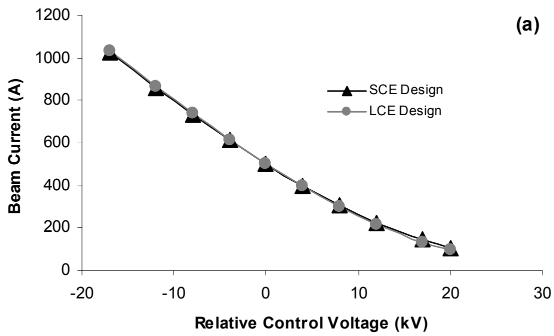


Figure 1. Layout drawing of 500kV, 500A MIG designs: (a) TL design, (b) NCE design, (c) SCE design, (d) LCE design.

The magnetic compression, which is the ratio of the axial magnetic field in the microwave circuit (around 5 kG) to the magnetic field at the cathode center, is about 30% higher for the SCL designs, but is still quite low for MIG standards, where compressions up to 40 are typically used. The average emitter radii are larger for the SCL designs, but the widths of the emitters are smaller in order to improve the beam quality, and the net effect is that the average cathode loading is about 1 A/cm^2 higher for the SCL designs than for the TL design.



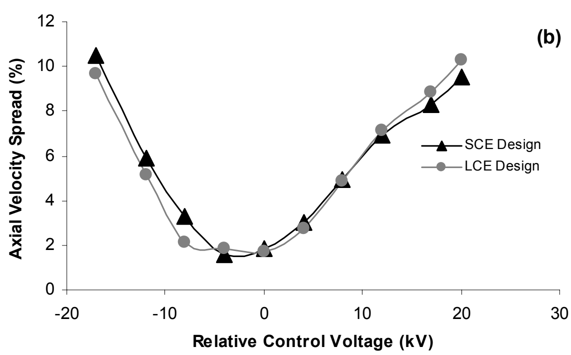


Figure 2. The dependence of beam parameters on the relative control voltage: (a) the beam current, (b) the axial velocity spread.

SUMMARY

It was found that TL and SCL MIGs give comparable results for beam quality and that control electrodes can be used to achieve independent current control. While SCL MIGs have larger peak fields, emitter temperatures, cathode loadings, and magnetic compressions, these differences are not large and so SCL MIGs should be able to solve the azimuthal current density inhomogeneity problems which often plague TL MIGs.

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Design Parameter	**TL Design**	**NCE Design**	**SCE Design**	**LCE Design**
Emitter radius (mm)	75.12	84.12	84.12	84.12
Emitter length (mm)	16.9	13.0	13.0	13.0
Magnetic compression	9.22	12.00	11.87	11.92
Simulation Results				
Axial velocity spread (%)	1.14	2.50	1.86	1.74
Perpendicular velocity spread (%)	0.51	1.10	0.80	0.75
Peak anode field (kV/cm)	27.3	31.1	29.9	30.6
Peak cathode field (kV/cm)	86.1	93.1	93.5	10.2
SCL current (A)	1759	504	503	501
Cathode loading (A/cm^2)	6.17	7.33	7.32	7.29

Table I. Design parameter and simulation results for the 500kV, 500A, MIG designs with $\alpha = 1.5$.