

Design of a Low Cathode Loading, High Compression Ratio Electron-Optical System for D-Band TWTs

Kunqing Duan^{1,2}, Jun He¹, Qinglun Liu¹, Yongliang Liu¹, Dehui Zhai¹, Cha Gao¹, Muguang Li¹

¹ Discipline and Technology Center of Vacuum Electronic Devices and Systems, Aerospace Information Research Institute, Chinese Academy of Sciences

No.5 Yanqi East 2nd Road, Huairou, Beijing 101407, China

² University of Chinese Academy of Sciences

No.1 Yanqihu East Rd, Huairou District, Beijing, 101408, China

E-mail of corresponding author: skyboyhj@163.com

Abstract

This paper presents the design of a D-band electron optics system (EOS) for geostationary orbit (GEO) satellite applications using CST Studio Suite. A Pierce-type electron gun with an area compression ratio of 204 was developed, generating a 74-mA beam with a cathode emission current density below 2A/cm^2 . A periodic permanent magnet (PPM) focusing system with a peak axial magnetic field of 5020Gs was designed for beam confinement. Simulation results demonstrate stable, zero-interception transmission over a 40mm distance with a 100% transmission rate. This design provides a viable solution for high-power, long-life D-band traveling-wave tubes.

1 INTRODUCTION

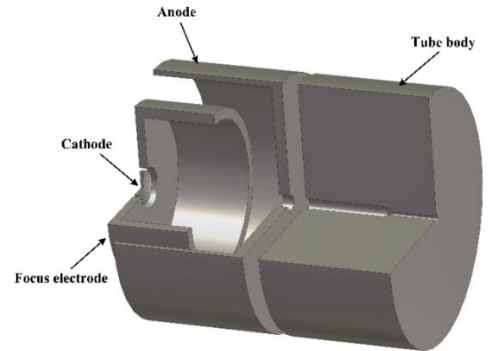
The growing global demand for high-speed satellite communications has driven operating frequencies into the sub terahertz regime. Owing to its ultra-wide bandwidth and exceptionally high data rates, the D-band has become a key focus for next generation high-throughput satellites (HTS) [1]. For geostationary Earth orbit (GEO) applications, power amplifiers face much more stringent requirements than in low Earth orbit (LEO) systems. They must provide sufficient power to overcome significant path loss while ensuring continuous operation, long lifespans, and excellent thermal stability. Against this backdrop, traveling-wave tubes (TWTs) remain indispensable for D-band high-power transmission due to their high gain, high efficiency, and outstanding adaptability to space environments [2][3].

Targeting D-band GEO satellite applications, this paper presents the design and optimization of a high-performance electron optics system (EOS). A Pierce-type electron gun with low cathode loading and a high compression ratio was developed to achieve high density beam emission while ensuring long cathode life. Additionally, a matching periodic permanent magnet (PPM) focusing system was designed to confine the beam. Simulations analyzing the beam trajectory under strong space charge effects confirm that the electron gun operates with a cathode emission current density below 2A/cm^2 and a compression ratio of 204. The complete EOS demonstrates highly stable and excellent beam transmission

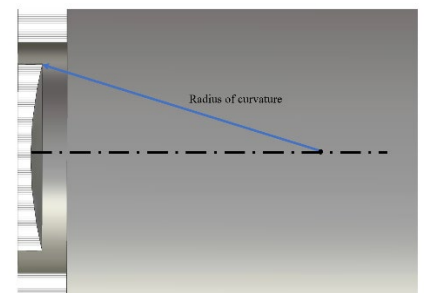
over a long distance, validating its suitability for high power D-band TWTs.

2 ELECTRON GUN DESIGN

This section details the design of the high compression ratio Pierce electron gun [4][5]. To overcome the strict dimensional constraints of the D-band slow-wave structure (SWS), the gun is optimized for strong convergence, yielding a highly laminar, high current density electron beam. The 3D geometry shown in Fig. 1 comprises a spherical cathode, a focusing electrode, and an anode. Iterative optimization of the electrode geometries and gaps resulted in a high area compression ratio, which effectively reduces cathode loading to extend device lifetime while meeting power requirements. Key parameters are summarized in Table I.



(a) 3D model of the electron gun



(b) cathode cross-sectional view

Figure 1 Electron gun structural model

Table 1 Design parameters of the electron gun

Anode Voltage	20.1 kV
Beam Current	74 mA
Cathode Emission Current Density	1.71 A/cm ²
Cathode Radius	1.2 mm
Beam Waist Radius	0.084mm
Beam Waist Position	20.051mm

The geometry of the cathode emission surface is critical for initial beam convergence and quality. As illustrated in Fig. 1(b), the cathode is designed with a spherical radius of curvature of 5mm to ensure strong initial convergence. Concurrently, the focusing electrode is optimized to provide adequate radial focusing forces to electrons near the cathode edge, effectively preserving beam laminarity during the initial acceleration phase.

The electron gun was simulated using the Particle Tracking solver in CST Studio Suite and MTSS. The field-free electron trajectories shown in Fig. 2 demonstrate that the emitted beam converges smoothly and passes through the anode aperture without interception. The corresponding beam envelope shown in Fig. 3 further indicates that the beam reaches a minimum waist radius of 0.084mm at an axial distance of 20.051mm from the cathode surface. As illustrated by the cathode emission current density curve in Fig. 4, the significant decrease in current density near the periphery of the emitting surface confirms that the focusing electrode and spherical cathode effectively suppress non-laminar emission of edge electrons, thereby ensuring the superior quality of the initial electron beam. These highly convergent characteristics perfectly satisfy the stringent high-current injection requirements of the D-band SWS.

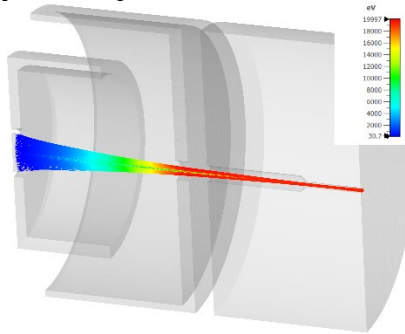


Figure 2 Electron trajectories without an external magnetic field

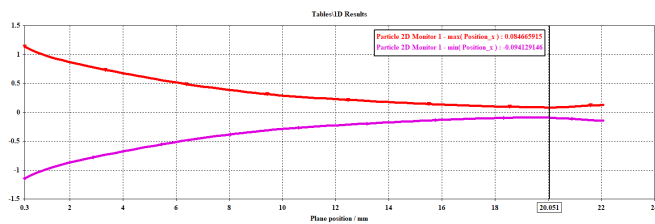


Figure 3 Electron beam envelope without an external magnetic field

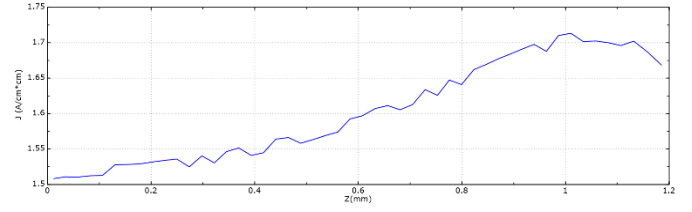


Figure 4 Emission current density distribution across the cathode surface.

3 INTEGRATED SIMULATION AND BEAM TRANSPORT ANALYSIS

To achieve stable beam confinement, a periodic permanent magnet (PPM) focusing system was designed and simulated using the MTSS [6]. As illustrated in Fig. 5, the optimized magnetic circuit generates a sinusoidal axial magnetic field with a peak flux density of 0.5T and a period of 10mm. By precisely matching the magnetic period to the electron beam plasma wavelength, the radial space-charge forces are effectively neutralized.

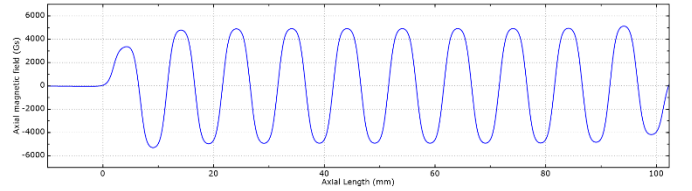


Figure 5 Axial magnetic field distribution curve

Building on this magnetic field profile, integrated beam transport simulations were performed to evaluate the overall performance of the electron optics system (EOS). Figure 6 presents the simulated beam envelope along the 40-mm interaction length. Under the precise confinement of the MTSS-computed field, the 74mA electron beam maintains a stable dynamic equilibrium with absolutely zero interception.

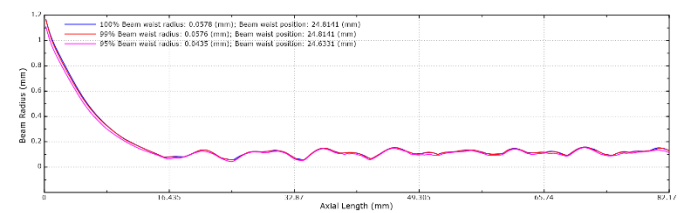


Figure 6 Electron beam envelope

4 CONCLUSION

In conclusion, a high-performance electron optics system is developed for D-band GEO satellite TWTs. The design centers on an optimized Pierce-type electron gun that operates at 20.1kV and 74mA, achieving a high area compression ratio of 204. By strictly limiting the cathode emission current density to below 2A/cm², the design

effectively ensures the extended operational lifetime required for space environments. Furthermore, integrated simulations incorporating a PPM field computed by MTSS demonstrate stable, zero-interception beam transmission over a distance of 40mm. These findings validate the proposed EOS as a highly reliable and robust beam source for the engineering development of high-power D-band traveling-wave tubes.

REFERENCES

- [1] T. S. Rappaport, T. E. Humphreys, and S. Nie, "Spectrum opportunities for the wireless future: from direct-to-device satellite applications to 6G cellular," *npj Wireless Technology*, vol. 1, no.8, Dec. 2025.
- [2] Lohmeyer Whitney Q., Raichelle J. Aniceto, and Kerri L. Cahoy, "Communication satellite power amplifiers: Current and future SSPA and TWTA technologies," *International journal of satellite communications and networking*, vol. 34, no. 2, pp. 95-113, Apr. 2016.
- [3] Basu Rupa, Jeevan M. Rao, Trung Le, Rosa Letizia, and Claudio Paoloni, "Development of a D-band traveling wave tube for high data-rate wireless links," *IEEE Transactions on Electron Devices*, vol. 68, no. 9, pp. 4675-4680, Jun. 2021.
- [4] J. R. Pierce, "Rectilinear Electron Flow in Beams," *Journal of Applied Physics*, vol. 11, no. 8, pp. 548-554, Aug. 1940.
- [5] J. R. Pierce and L. M. Field, "Traveling-Wave Tubes," *Proceedings of the IRE*, vol. 35, no. 2, pp. 108-111, Feb. 1947.
- [6] Q. Hu, "Study of Numerical Simulation and CAD Technique for Electron Optics System of Microwave Wave Tubes," Ph.D. thesis, Dept. Phys. Electron., Univ. Electron. Sci. & Technol., Chengdu, China, 2011.