Simulation Study of Final Stage Power Amplifier and Coupler for Coaxial Cavity Electron Accelerator

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Date: 2025-09-16T22:39:42+00:00

Abstract

The coaxial cavity electron accelerator is a reentrant electron accelerator for industrial irradiation processing, whose RF power transmission system utilizes a TH781 tetrode in its final-stage power amplifier, with the amplifier’ s anode output cavity directly connected to the accelerating cavity via a coaxial coupler. This paper systematically simulates and optimizes the final-stage power amplifier in the power source system of the coaxial cavity electron accelerator, and separately optimizes the couplers for 10 MeV and 40 MeV coaxial cavity electron accelerators of different energies using CST Microwave Studio, obtaining coupler parameters that enable efficient RF power feeding into the cavity. Additionally, secondary electron effects in the coaxial coupler section are simulated, analyzing locations prone to secondary electron multipactor phenomenon and the corresponding RF power ranges, which provides valuable reference for the design, installation, commissioning, and operation of this type of accelerator.

Full Text

Final Power Amplifier and Coupler for the Recirculating Coaxial Resonator Cavity Electron Accelerator

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Abstract

The Recirculating Coaxial Resonator Cavity Electron Accelerator is a recirculating electron accelerator primarily used for industrial irradiation processing. In its radio frequency (RF) power transmission system, the final-stage power amplifier employs a TH781 tetrode, with the amplifier’ s anode output cavity directly connected to the accelerating cavity via a coaxial coupler. This paper presents a systematic simulation and optimization of the final-stage power amplifier in the power source system of the Recirculating Coaxial Resonator Cavity Electron Accelerator, and separately optimizes the coupler for two different energy configurations: 10 MeV and 40 MeV. Using CST Microwave Studio, the optimal coupler parameters for achieving efficient RF power transfer into the cavity are obtained. Additionally, secondary electron effects in the coaxial coupler are simulated, analyzing the regions prone to secondary electron multiplication phenomena and the corresponding RF power ranges. These findings provide valuable reference for the design, installation, commissioning, and practical operation of this accelerator type.

Keywords: Recirculating Coaxial Resonator Cavity Electron Accelerator; tetrode power amplifier; coaxial coupler; secondary electron effect; secondary electron yield

1. Introduction

The Recirculating Coaxial Resonator Cavity Electron Accelerator is a high-power, recirculating industrial electron accelerator capable of operating in CW mode. This accelerator concept was first proposed by J. Pottier in 1989 [1], and the first Rhodotron TT-200 was developed by IBA in Belgium in 1993, achieving the target specifications of 10 MeV and 100 kW [2][3][4][5]. IBA has since developed a series of Rhodotron accelerator products to meet diverse industrial needs, including models TT-50, TT-100, TT-200/TT-300, TT-300HE, and TT-1000. These models offer differentiated energy-power combinations: the TT-50 (10 MeV, 2 mA) suits low-dose-rate irradiation applications such as food preservation with its compact design enabling mobile platform integration; the TT-100/TT-200 series serves as mainstream models for medium-to-high power scenarios like medical device sterilization and semiconductor material modification [6]; the TT-300HE achieves 125 kW average power and 1000 kW peak power through enhanced water cooling for high-yield isotope production [7]; and the flagship TT-1000 delivers 80 mA, 560 kW beam output for ultra-large-scale irradiation facilities such as tire pre-vulcanization. Current limitations on Rhodotron accelerator power enhancement primarily involve RF system power and efficiency constraints, beam dynamics and stability issues from excessive beam current, thermal management and material tolerance challenges, structural design and engineering complexity, and economic and practical application considerations. The 10 MeV and 40 MeV accelerators studied here have parameters similar to the TT-200 and TT-300HE [8], respectively. The key feature of the Recirculating Coaxial Resonator Cavity Electron Accelerator is its use of a coaxial RF resonant cavity for electron beam acceleration, combined with dipole bending magnets arranged around the accelerating cavity to enable repeated acceleration. This unique acceleration method offers advantages including compact structure, high average beam power, high electrical efficiency, and the ability to extract beams at different energies.

The RF power transmission system of the Recirculating Coaxial Resonator Cavity Electron Accelerator comprises a signal source, pre-solid-state power amplifier, and final-stage power amplifier [2]. In the final-stage power amplifier, the tetrode anode connects to a $1/4\lambda$ disc-shaped output resonant cavity, which directly connects to the accelerating cavity via a coaxial coupler. While multiple solid-state power amplifiers can alternatively be used in the final stage, with each amplifying the pre-stage signal and feeding it directly into the accelerating cavity through several couplers [9], this approach, though facilitating monitoring of the final power amplifier status, lacks the structural compactness of the tetrode amplifier scheme and introduces greater complexity in phase synchronization among multiple solid-state power sources. This paper focuses on simulating the final-stage power amplifier and coupler for the Recirculating Coaxial Resonator Cavity Electron Accelerator using tetrode amplifiers, including secondary electron effect simulations for the coupler. The study employs the commercial electromagnetic simulation software CST Microwave Studio [10] for electromagnetic field and RF transmission characteristics of the accelerating cavity, final-stage power amplifier, and power coupler, while CST Particle Studio [11] simulates secondary electron effects within the coupler.

2. Working Principle of the Recirculating Coaxial Resonator Cavity Electron Accelerator

The accelerating cavity structure of the Recirculating Coaxial Resonator Cavity Electron Accelerator can be approximated as a section of short-circuited coaxial line [12] with copper-plated inner surfaces to enhance the cavity quality factor. The electromagnetic field established in the cavity operates in the $1/2\lambda$ TEM mode, as shown in [Figure 1: see original paper]. The electric field direction is perpendicular to the cavity’ s central axis, reaching maximum magnitude at the central plane perpendicular to the axis and decreasing cosinusoidally to zero along the axis, forming a $1/2\lambda$ distribution. The magnetic field direction is tangential to circles surrounding the central axis, zero at the central plane and opposite in direction above and below it, with magnitude varying sinusoidally from the cavity ends toward the central plane, also forming a $1/2\lambda$ distribution. This field distribution offers the advantage that electrons accelerated at the central plane move collinearly with the electric field direction without transverse electric field components, and since the magnetic field is zero at the central plane, no bending field exists.

The specific acceleration process for electron beams in the coaxial cavity accelerator proceeds as follows: electrons generated by the electron injector enter the accelerating cavity radially, accelerating as they travel toward the central cylindrical inner conductor. After passing through an aperture into the central cylinder, the electric field direction in the cavity reverses, and electrons are accelerated again when they emerge into the opposite side of the cavity. The beam then enters the bending magnet region, where magnets redirect it back into the accelerating cavity for further acceleration. This process repeats until the beam reaches the required energy for extraction.

The cavity quality factor Q and effective shunt impedance Ze are core metrics for evaluating cavity performance, with values related to the inner and outer conductor radii [13]. Parameter scanning optimization yields cavity dimensions that simultaneously optimize both Q and Ze, with final design parameters listed in .

3. Simulation of Final Power Amplifier and Coupler

The final power amplifier and coupler of the Recirculating Coaxial Resonator Cavity Electron Accelerator are positioned above the accelerating cavity, connected via an extremely short coaxial feedline that minimizes transmission losses and ensures a compact overall structure. The main components include a cathode input resonant cavity, anode output resonant cavity, high-power tetrode, and coaxial coupler. The core component is a TH781 tube from THOMSON, capable of operating near 107.5 MHz in both CW and pulse modes [14], with average power up to 200 kW in CW mode, meeting the RF power requirements of the Recirculating Coaxial Resonator Cavity Electron Accelerator.

3.1 Final Power Amplifier

The final power amplifier’ s output cavity resonates with the tube’ s output capacitance, with RF power magnetically coupled to the coaxial coupler. The coupler’ s characteristic impedance is approximately 35 Ω. The coupler inserts into the accelerating cavity, with its inner and outer conductors connected to coupling loops that magnetically feed power into the cavity to establish the electromagnetic field required for electron acceleration. CST Microwave Studio models the anode output cavity structure with a simplified tube model, as shown in [Figure 2: see original paper]. Interelectrode capacitances are incorporated as lumped-parameter capacitors in the high-frequency model, with the total grid-anode and screen-anode capacitance set to 60 pF.

The electromagnetic simulation model simplifies many small details compared to the engineering model. The output coupler is coaxial, with a waveguide port 2 at the intermediate cross-section and the tube anode as port 1. Port 2 has 35 Ω characteristic impedance, while port 1 has 490 Ω impedance. Both 10 MeV and 40 MeV Recirculating Coaxial Resonator Cavity Electron Accelerators operate at 107.5 MHz. Broadband scanning from 0–500 MHz in the RF transmission simulation reveals not only the operating frequency behavior but also higher-order mode frequencies to avoid their effects during operation.

[Figure 3: see original paper] shows the S11 and S21 curves for the final power amplifier and coupler from 0–500 MHz. S11 reaches a minimum at 107.5 MHz, with additional minima near 381 MHz and 468 MHz corresponding to higher-order mode (HOM) responses of the anode output cavity. Eigenmode simulation of the simplified output cavity model alone yields eigenmode frequencies of 384.5 MHz and 448.7 MHz in the 300–500 MHz range, closely matching the S11 peak frequencies. The minor discrepancies arise from model simplifications that exclude power absorbers and fine coupler structures to reduce mesh count and eigenmode solver computation time.

3.2 Coupler

The Recirculating Coaxial Resonator Cavity Electron Accelerator employs a coaxial RF coupler with inductive coupling at one end to the tetrode amplifier' s anode output cavity and magnetic coupling at the other to excite the accelerating cavity field. The coupling loop, located near the upper surface where magnetic field strength is maximum, connects the coupler' s inner and outer conductors. Coupling coefficient adjustment is achieved by rotating the coupling loop, which has a loop area of 3040 mm^2. [Figure 4: see original paper] shows the overall coupler structure. The upper section' s outer conductor connects to the tetrode output cavity, while a ceramic window sealed with rubber O-rings between inner and outer conductors separates the coupler' s vacuum from the output cavity' s atmospheric environment. The lower end seals to the cavity with rubber rings and establishes electrical contact via metal spring fingers.

Different beam power levels require different tetrode power amplifier configurations: the 10 MeV Recirculating Coaxial Resonator Cavity Electron Accelerator produces 100 kW beam power using one tetrode amplifier and coupler, while the high-energy version achieves 40 MeV and 125 kW average power through 12 acceleration passes [15], requiring three tetrode amplifiers and power couplers to meet beam power and cavity field establishment requirements. Coupler parameters are listed in .

As shown in , a single coaxial coupler must withstand up to 200 kW average RF power at full load, making thermal management critical for system reliability. The coupler transmits TEM-mode electromagnetic waves with current flowing along inner and outer conductor surfaces. CST simulations indicate that at 200 kW RF power, the heat flux densities on inner and outer conductor surfaces are 870 W/m^2 and 260 W/m^2, respectively. The inner conductor experiences higher electromagnetic field intensity and has a smaller surface area, necessitating active water cooling. As shown in [Figure 5: see original paper], 16°C cooling water at 80 L/min flows from the top inlet through internal cooling channels to the bottom, then returns through the entire inner conductor to the top outlet.

[Figure 6: see original paper] presents thermal-structure sequential coupling simulation results from ANSYS Workbench. Steady-state thermal analysis shows peak inner conductor surface temperature of 16.88°C and peak outer conductor surface temperature of 48.88°C near the cavity connection. Structural mechanics simulation reveals maximum deformation of 0.04 mm and maximum equivalent stress of 34.83 MPa under thermo-mechanical coupling, both occurring near the outer conductor’ s cavity connection. The ceramic window experiences 30 MPa maximum equivalent stress, but with O-ring seals providing elastic compensation in both axial and circumferential directions, no structural failure risk exists under actual operating conditions.

3.2.1 Single Coupler Simulation The RF coupler section connecting to the tetrode anode output cavity includes an adjustable short-circuit plane for impedance matching, as shown in [Figure 2: see original paper]. [Figure 7: see original paper] shows how different short-circuit plane heights affect S11 and S21 near 107.5 MHz. Scanning reveals optimal S-parameters at approximately 60 mm height, with further optimization yielding 62 mm as the optimal short-circuit plane height.

Coupler installation position and coupling loop rotation angle both affect RF power coupling efficiency. For the 10 MeV accelerator’ s single coaxial coupler, the coupler cross-section serves as the input port for RF power feed simulation. Scanning the coupler’ s radial installation distance R from the cavity center and rotation angle α of the coupling loop about the coupler axis identifies values that minimize reflected power. As shown in [Figure 8: see original paper], the three couplers for the 40 MeV accelerator are also arranged above the resonant cavity, installed with 120° angular separation in a centrally symmetric configuration to ensure uniform electromagnetic field distribution.

[Figure 9: see original paper] shows S11 curves for different coupler positions R. For inductive (magnetic) coupling, the coupling loop should be located where the cavity magnetic field is maximum, which occurs near the upper and lower end surfaces close to the inner conductor. Since the coaxial resonator’ s inner and outer conductors feature rounded corners for improved heat dissipation, the scan avoids interference between the coupling loop and these corners by varying the coupler axis distance R from the cavity axis between 450–700 mm. Optimal S11 occurs near R = 600 mm, with the final value selected as R = 603.5 mm.

With the coupler position fixed, the coupling loop rotation angle is scanned. The effective area perpendicular to the cavity magnetic field affects coupling strength. The induced voltage amplitude in the loop under resonant mode can be calculated from Faraday’ s law [16] as shown in Equation (1), where ω is the RF angular frequency, Φ is magnetic flux through the loop, B and S are the maximum magnetic field perpendicular to the loop and loop area in TEM mode, μ is permeability, and $|H|$ is the magnetic field intensity amplitude at the loop location. The equivalent circuit in [Figure 13: see original paper] shows how induced voltage amplitude affects input power to the cavity, with larger induced voltage delivering more power. According to A.M. Poursaleh et al. [9], the effective loop area can be calculated using Equation (2), where μ_0 and ε_0 are the permeability and permittivity of cavity medium, μ_c is the surface permeability, and Z_0 and Z_s are the coupler characteristic impedance and cavity shunt impedance, respectively. For the no-beam-load case (critical coupling), scanning the coupling loop rotation angle from 0°-180° in 10° increments yields an optimum near $\alpha = 120°$, as shown in [Figure 10: see original paper]. Optimization gives $\alpha = 115.6°$ as the optimal rotation angle for unloaded conditions. At full load with 100 kW average beam power, the coupler should operate in over-coupled state with coupling coefficient $\beta \approx 2$, giving an optimal rotation angle of 128.1° based on Equation (2) and CST optimization.

The S11 minimum in simulations occurs at a frequency slightly above 107.5 MHz because actual cavity temperature rise during operation causes frequency drift downward. Therefore, the design resonant frequency is selected slightly above 107.5 MHz to compensate for this power-induced frequency shift. The resonant cavity uses carbon steel with copper plating to balance performance and cost. Cooling water enters through the inner conductor' s central pipe, distributes via guide plates to various cooling zones, flows through water jackets and cooling pipes, and returns through the outer conductor' s annular collector pipe. For the 10 MeV accelerator, inner surface power loss is approximately 60 kW at full power. With 16°C cooling water, [Figure 11: see original paper] and [Figure 12: see original paper] show maximum cavity deformation, inner surface temperature, and frequency shift versus cooling water flow rate. Increasing flow rate reduces peak inner surface temperature and frequency offset. Based on actual chiller operation, the cavity water flow rate is selected as 70-80 L/min.

3.2.2 Multi-Coupler Simulation The field established by three coupler input ports can be considered as the vector superposition of fields from each coupler operating individually. With three couplers, each coupler' s reflected signal equals the sum of its own reflection and transmission signals from the other two couplers. Thus, each coupler is influenced by the other two. Assuming no beam load, the accelerating cavity can be modeled as a series RLC circuit with transformer coupling to the couplers [17], as shown in [Figure 13: see original paper].

To maximize power transfer from amplifiers to the cavity while minimizing reflected power, optimal coupling coefficient β must be designed. For single-coupler, no-beam-load conditions, the ideal coupling coefficient equals 1 [18], meaning all power from the tetrode final amplifier feeds into the accelerating cavity. The coupling coefficient can be expressed as Equation (3), where Q_0 and Q_{ext} are the unloaded and external quality factors, and P_0 and P_{ext} are cavity wall loss power and power lost in external circuits at resonance, respectively. From the equivalent circuit in [Figure 13: see original paper] and the proportional relationship between power and resistance in series circuits, each coupler' s coupling degree is given by Equation (4).

To ensure uniform field distribution with three couplers feeding power, each coupler' s parameters and coupling degree must be identical, so $n_1 = n_2 = n_3$ and $R_1 = R_2 = R_3$ in Equation (4). Studies by Poursaleh A M, Jabbari I

[9] and Xie Xinhua [20] show that for N couplers feeding power simultaneously, if each excites fields in the same direction, the ith coupler’ s coupling degree follows Equation (5).

For three couplers feeding RF power into the resonant cavity without beam load (critical coupling), each coupler has identical coupling degree and the sum equals 1, requiring consistent parameters among couplers. Each final power amplifier connected to a coupler is driven by a corresponding pre-amplifier, with all pre-amplifiers controlled by one low-level system to ensure RF phase and amplitude consistency.

Scanning the three coupling loops from 0°–180° yields an optimal rotation angle near 110°, as shown in [Figure 14: see original paper]. CST optimization gives $\alpha = 104.5°$ as the optimal unloaded rotation angle. The 40 MeV accelerator operates in pulsed mode at 12.5% duty cycle, with average power of approximately 100 kW for cavity wall loss and field establishment plus 125 kW beam power. Under actual operating conditions with 125 kW beam load, each coupler has coupling degree of 0.75 and total coupling coefficient $\beta_{\text{total}} > 1$ (over-coupled state). Using Equation (2) and CST results, the optimal rotation angle is 112.2°.

3.2.3 Coupler Secondary Electron Effect Simulation Secondary electron effects are oscillatory discharge phenomena generated by RF fields. Electrons emitted from structure surfaces accelerate in the high-frequency field and collide with surfaces again, producing secondary electrons. The number of secondary electrons depends on material properties and incident electron energy and angle. Repeated acceleration and collision cycles generate successive electron generations. When emitted electrons exceed incident electrons and electron trajectories satisfy specific oscillation conditions, electron current spontaneously increases, causing secondary electron multiplication [21].

Secondary electron yield (SEY), defined as the ratio of emitted to incident electrons, characterizes this phenomenon. Common SEY models include the Vaughan model [22] and Furman model [23]. The Furman model is particularly notable for its detailed physical mechanism analysis, separate consideration of different secondary electron types, and inclusion of probability models. This study adopts the Furman model. The coupler’ s inner and outer conductors are copper, while the ceramic window uses alumina. High-power RF operation requires special ceramic window treatment [24][25], typically TiN coating [26], which significantly reduces secondary electron effects. [Figure 15: see original paper] shows SEY curves for copper, alumina [26], and TiN [27] at 0° electron incidence.

Secondary electron multiplication poses significant risks for high-power RF transmission components and resonant cavities, potentially causing detuning and increased reflected power. Since the coaxial coupler transmits up to 200 kW average power, secondary electron effect simulation is essential. The coaxial section comprises three parts: alumina ceramic window, inner conductor, and outer conductor. The ceramic window, located in the final power amplifier output cavity, separates vacuum from the RF transmission environment, while the other end connects inner and outer conductors through the coupling loop.

[Figure 16: see original paper] shows the coupler component positions. The spacing between inner and outer conductors strongly correlates with secondary electron effects [28], so the coupler is divided into six sections (L1–L6) based on this distance. The ceramic window and sections L1, L2, L3 reside within the final power amplifier output cavity and must consider its electromagnetic field, as shown in [Figure 17: see original paper]. Excessive SEY can fracture the ceramic window, necessitating separate analysis. In simulations, all metal surfaces on inner conductor outer walls and outer conductor inner walls serve as initial electron emission surfaces. Electrons are uniformly distributed on metal surfaces with initial energies uniformly distributed in 0–10 eV and emission angles uniformly distributed within $±$45°. CST Particle Studio' s PIC solver simulates 50 ns duration.

[Figure 18: see original paper] shows SEY versus RF power at different coupler positions. SEY varies by location at the same power level. Except for the ceramic window, all positions have SEY < 1 across 0–600 kW, decreasing with increasing power. The ceramic window has SEY < 1 in 0–9.2 kW range, peaking at 1.135 at 20 kW. At full 200 kW CW operation, the ceramic window SEY is approximately 0.997, showing a continued decreasing trend with power. Thus, no significant damage occurs during high-power operation [28].

Conclusion

This study systematically analyzed the final power amplifier and coupler for tetrode-based Recirculating Coaxial Resonator Cavity Electron Accelerators, including simulation of the tetrode anode output cavity, analysis of S11 characteristics and higher-order mode frequencies across 0–500 MHz, and optimization of the adjustable short-circuit plane height. Simulations optimized single-coupler layout for the 10 MeV accelerator and three-coupler layout for the 40 MeV accelerator, determining optimal positions and coupling loop rotation angles for both critical and over-coupled states. Secondary electron multiplication simulations revealed ceramic window SEY < 1 in 0–9.2 kW range and SEY $= 0.997$ at full 200 kW load, indicating low risk of operational impact.

Funding: This research was supported by the Gansu Provincial Key Research and Development Program -Industrial Projects (Grant No. 25YFGA009); Gansu Provincial Key Talent Program (Grant No. 2025RCXM072, "Development of RF Grid-Controlled Thermionic Cathode High-Current Electron Gun Experimental Platform and Talent Team Construction"); Chinese Academy of Sciences STS Program Regional Key Project (Grant No. E12E701YS0); and Chinese Academy of Sciences "Western Light" Program (Grant No. E323701YXB).

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Note: Figure translations are in progress. See original paper for figures.