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Development of High-Efficiency Energy-Recovery Klystrons*

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Based on the high efficiency klystron scheme of circular electron positron collider (CEPC), the depressed collector design is proposed to improve the overall efficiency of RF power source. The depressed collector technology has been applied in low power microwave electronic vacuum devices such as traveling-wave tube(TWT) and klystron for TV communications. The velocity of electrons entering the klystron collector is scattered, and it is difficult to use the depressed collector to sort the velocity of electrons. This paper presents a simulation study of the depressed collector for the high-efficiency klystron intended for the CEPC, establishes its basic design scheme, and demonstrates through simulation results that its efficiency can exceed 85%.

INTRODUCTION

The depressed collector is an important method to improve the efficiency of microwave tubes by recovering the energy of waste electrons. This technology has been widely used in TWT, and its collector recovery efficiency is more than 70%. Fig. 1 shows the basic principle of an energy recovery device. At present, the application of depressed collector on klystron is mainly used in low power klystron for TV and communication, but there is a little research on depressed collector technology of high power klystron. The fabrication and testing of the Phase I prototype have been successfully completed, marking the conclusion of the preliminary investigation into the energy recovery scheme. In Phase II, the energy recovery configuration specifically designed for the CEPC high-efficiency klystron will be experimentally validated. Simulation results have already demonstrated an efficiency exceeding 85%. Fabrication of the Phase II hardware is now underway, with high-power testing scheduled for August 2026.

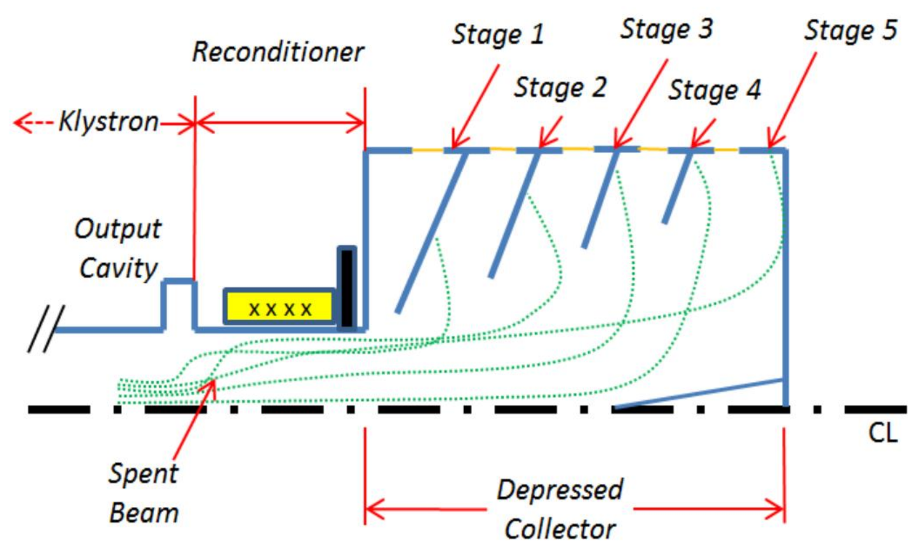

Fig.1.Depressed collector structure

DEPRESSED COLLECTOR PRINCIPLE

Based on the high efficiency klystron of CEPC, the depressed collector scheme is designed. The high efficiency tube has a saturated output power of 800kW and a design efficiency of more than 75%. The main design parameters of the high-efficiency klystron are shown in Table 1. High-power testing of the klystron was successfully completed in 2024(Fig 2).

Table 1: Klystron parameters of CEPC

Operating frequency	650 MHz
Output power	≥800 KW
Beam voltage	113 kV
Beam current	9.5 A
Beam perveance	0.25 μP
Efficiency	≥75%

Fig.2.CEPC P-band high-efficiency klystron

The energy distribution of electrons entering the collector is shown in Fig. 2. The following formula is used to obtain the recovery power of the multi-stage depressed collector:

$$P_{rec} = \sum_{1}^{N-1} \int_{V_i}^{V_i+1} J_{waste}(V) I_0 V_i dV + \int_{V_N}^{\infty} J_{waste}(V) I_0 V_N dV$$

where Jwaste is the probability density function of electron energy distribution.

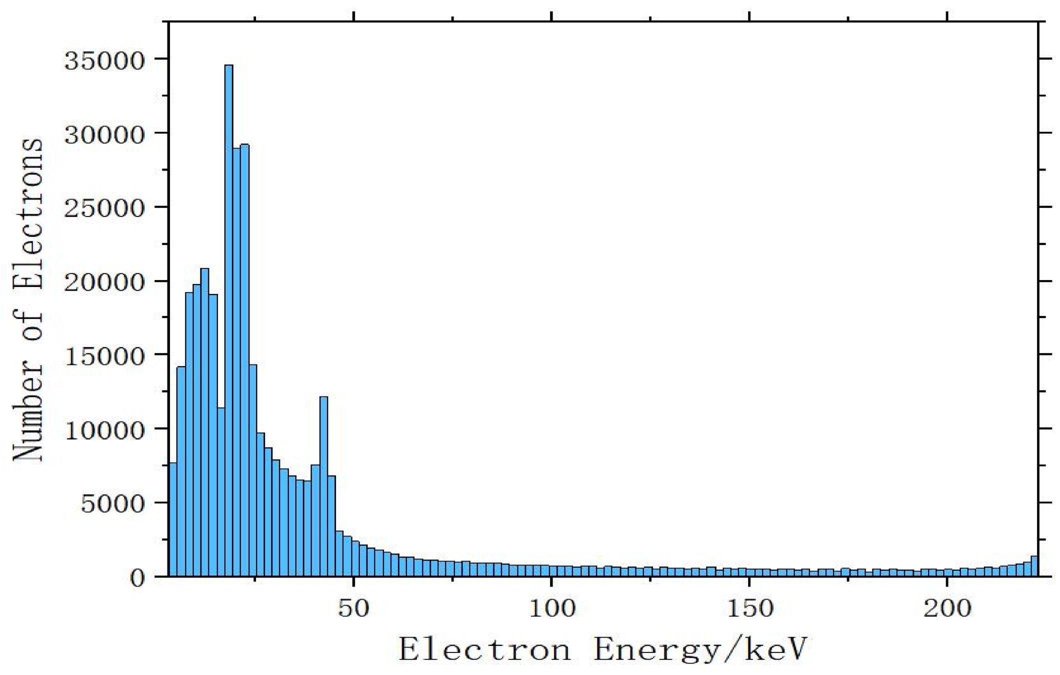

Fig.3.Energy distribution of waste electrons

VERIFICATION DEVICE

Before processing the depressed collector klystron, we use the energy recovery verification device to verify the key technology. The basic structure and machining of the verification device are shown in Fig. 4 and 5.

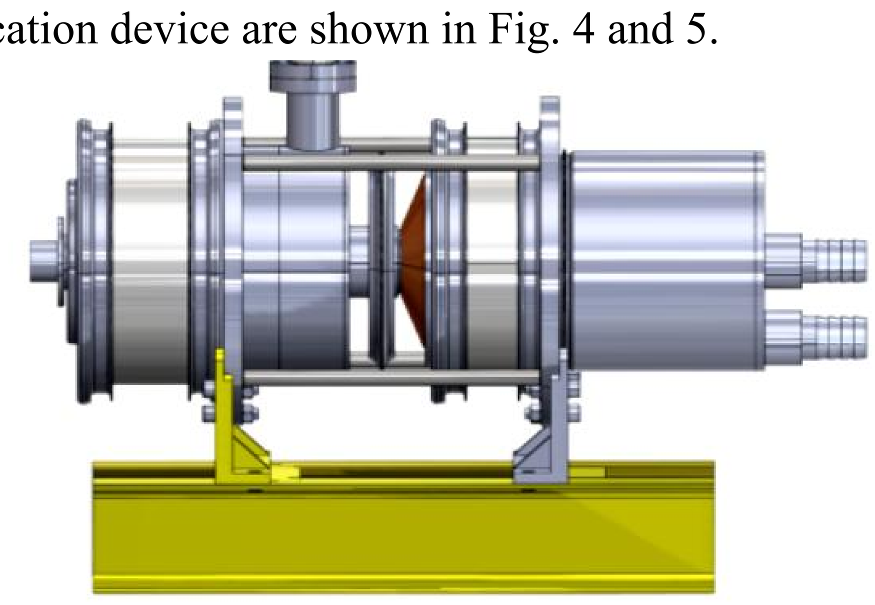

Fig. 4. Structure of energy recovery verification device

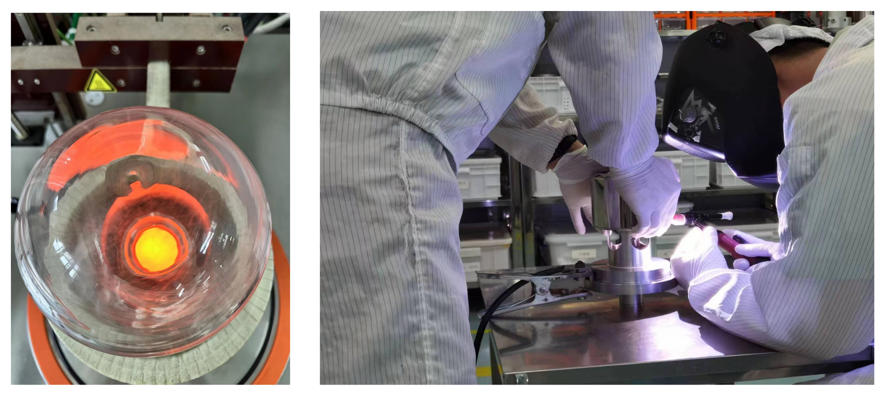

Fig. 5. Mechanical machining

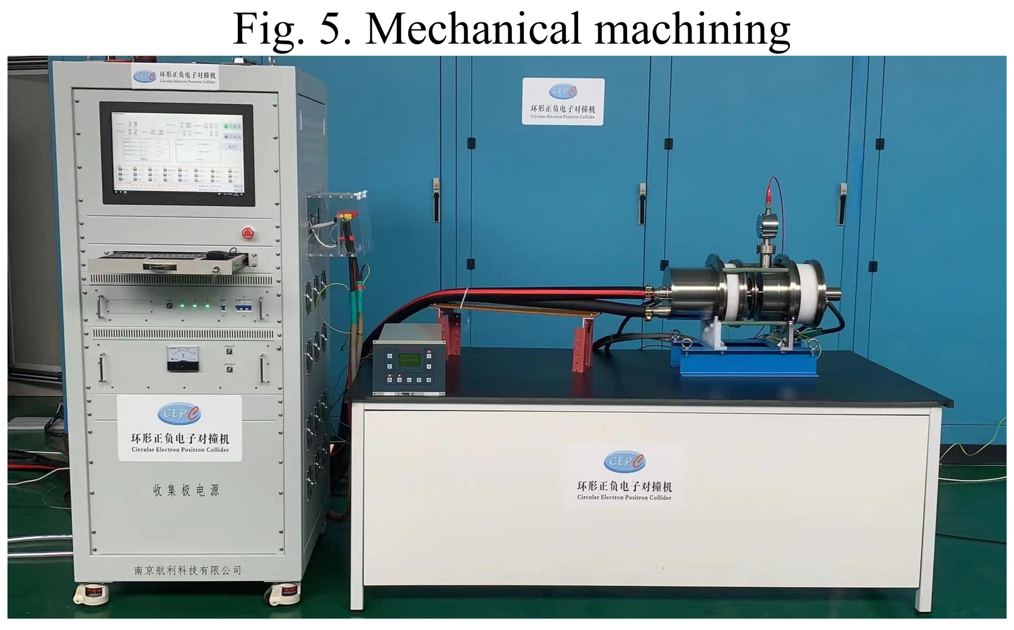

Fig. 6. Test platform

After the mechanical machining was completed, we proceeded with the setup of the test platform, as shown in Fig. 6. Testing was completed in November 2024, successfully validating the energy recovery technology(see fig7).

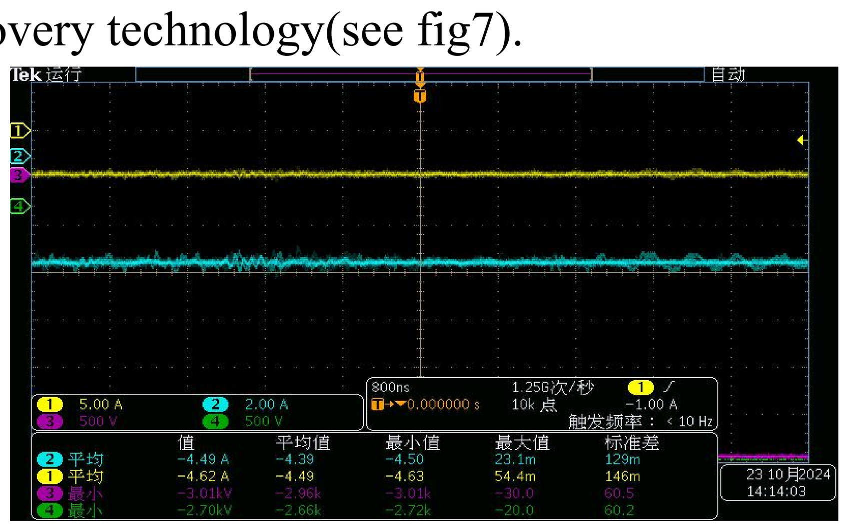

Fig. 7. Current and voltage waveforms

ENERGY-RECOVERY KLYSTRONS

In the second phase, we designed a single-stage depressed collector based on the prototype structure. The configuration is shown in Fig 8.

The electrode voltage is scanned in CST, and the results are shown in Fig. 9. Simulation results have already demonstrated an efficiency exceeding 85%. Fabrication of the Phase II hardware is now underway, with high-power testing scheduled for August 2026.

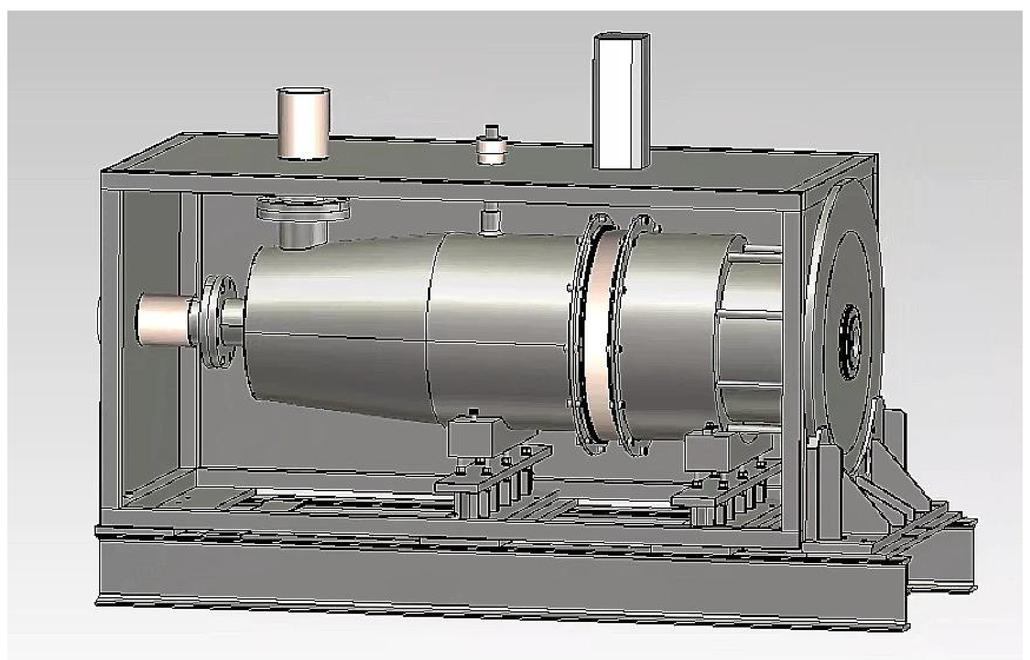

Fig. 8. Structure of the depressed collector.

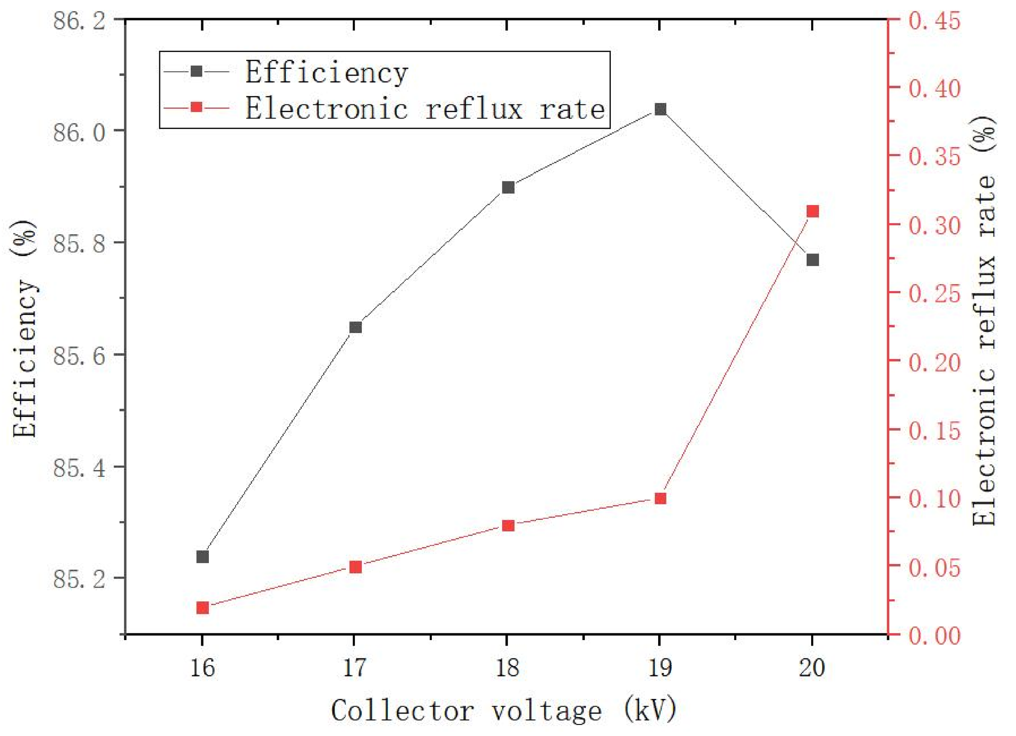

Fig. 9. Simulation results

SUMMARY AND OUTLOOK

This paper focuses on the high-efficiency CEPC klystron and conducts a theoretical analysis of the collector suppression, determining the electrode parameters. To validate the key technologies of the energy recovery klystron, an energy recovery verification device consisting of an electron gun and a collector was designed and fabricated. After completing the high-power testing, we will proceed with the design of a high-efficiency klystron with a depressed collector, aiming to increase the efficiency from 75% to over 85%.

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