Preliminary Research of Energy Recovery Scheme for High Efficiency klystron

Fei Li, Zusheng Zhou, Yu Liu, Ouzheng Xiao, Dayong He,

Jindong Liu, Nan Gan, Yiao Wang, Abid Aleem

lifei87@ihep.ac.cn

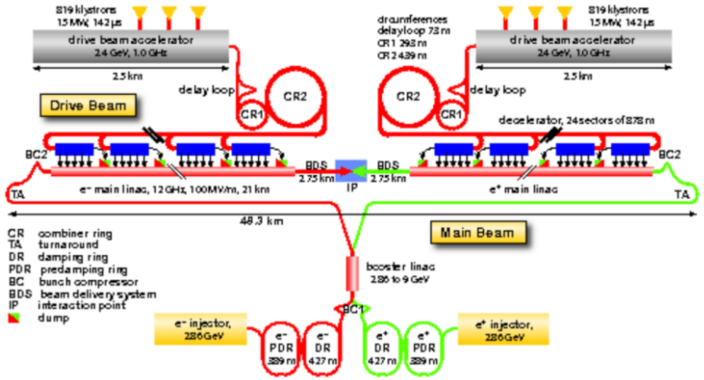
Oct. 24, 2023

Contents

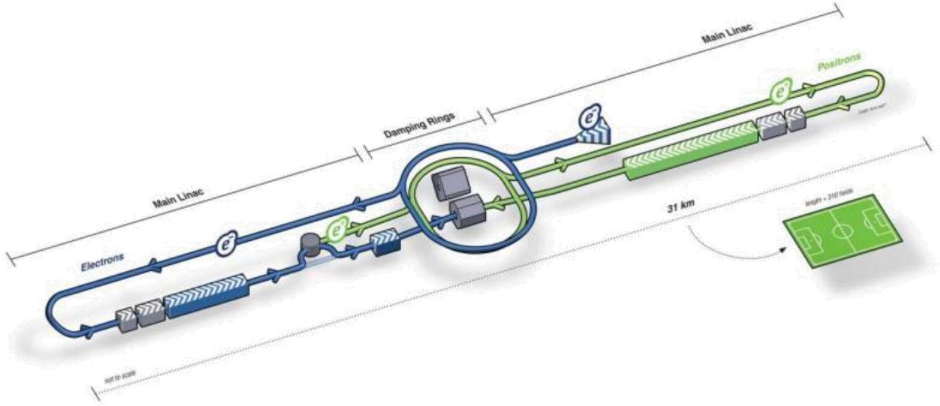
Background

Accelerator facilities require energy-saving solutions

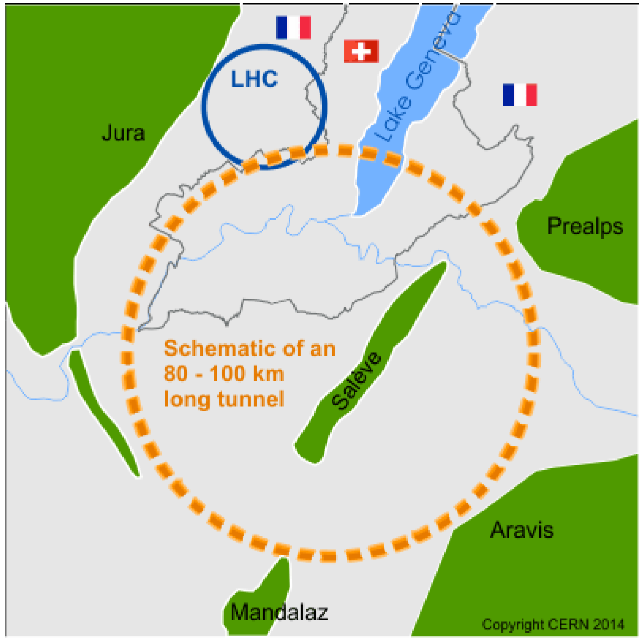
- The energy consumption of large-scale accelerator facilities is increasing (ILC、CLIC、FCC、CEPC…).
- RF power sources accounts for a significant proportion.
- The klystron waste power is ultimately converted into thermal energy.
- There is no precedent for applying an energy recovery scheme to high-power klystrons.



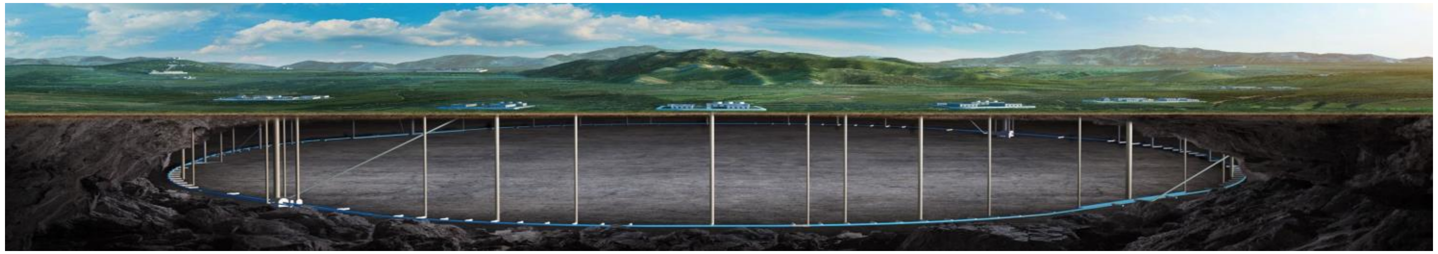
CLIC 3 TeV: 1 GHz, $P_{\mathrm{RF,total}}$ = **180 MW**



ILC 0.25 TeV: 1.3 GHz, $P_{\mathrm{RF,total}}$ = **20 MW**



FCC-ee: CW, (0.4 & 0.8) GHz, $P_{\mathrm{RF,total}}$ = **105 MW**



CEPC 0.24TeV: 0.65 GHz, $P_{\mathrm{RF,total}}$ = **60 MW**

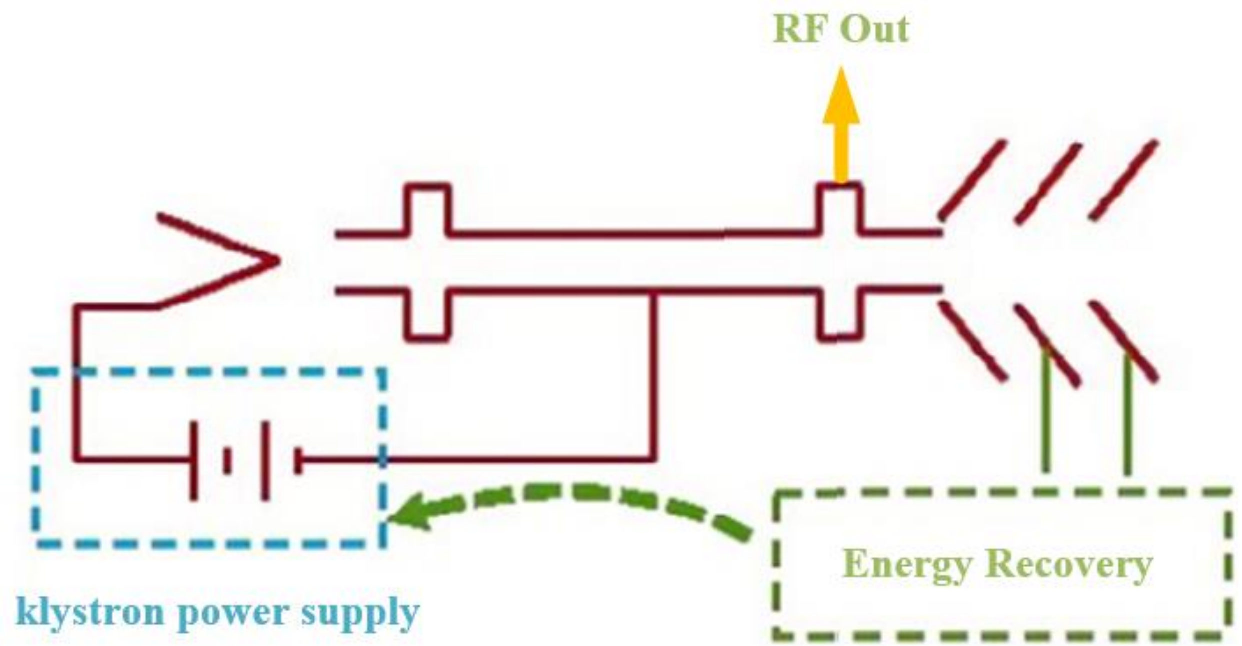
Research significance

- **The significance of energy recovery scheme**
  - Enhancing efficiency of RF power source.
  - Reducing the power consumption of cooling water.
  - Decreasing operational costs.
  - Environmental protection, energy conservation, and resource recycle.
- **Energy-saving measures for the in-development RF**

Development Strategy	Design Efficiency	Progress
Continuous-wave klystron	65%	Prototype has completed testing/62%
Single-beam high-efficiency klystron	78%	Initial testing of the prototype/70.5%
Multi-beam high-efficiency klystron	80.5%	currently being processed

The self-conversion efficiency improvement of klystrons has reached its limit, and the energy recovery scheme can open up a new frontier for overall system efficiency enhancement.

Energy recovery scheme



Typical klystron

Energy recovery klystron

- **Typical klystron:** The waste power directly strikes the collector of the klystron, converting into heat, which is then carried away by the water cooling system.
- **Energy recovery klystron:** The waste beam power is recovered through the depressed collector, reducing the power demand from the electrical grid while maintaining the same RF.

Research Content

Which issues will be addressed?

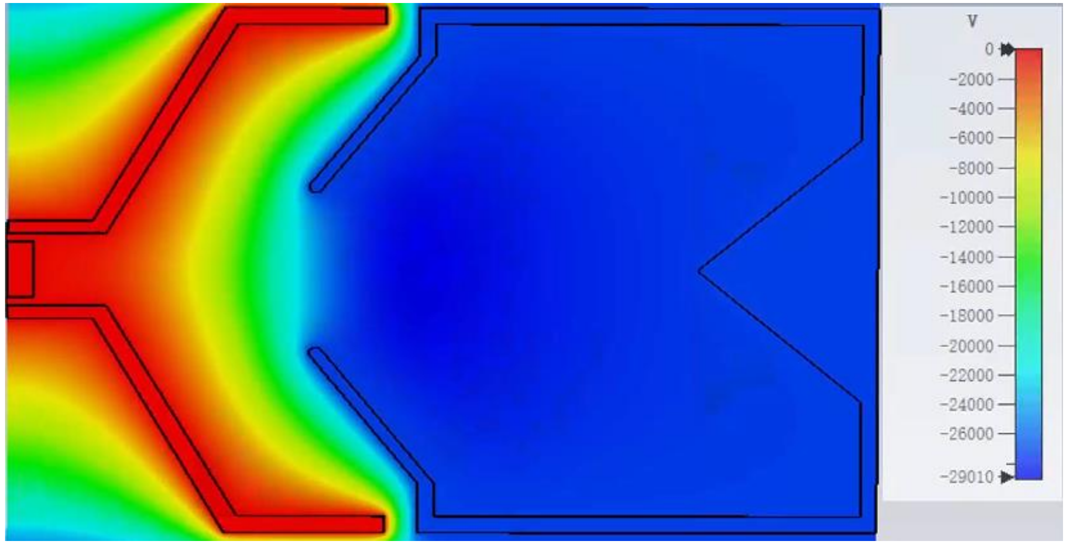
This project is based on the high-efficiency klystron of CEPC. We are setting up a small-scale validation platform without considering RF output and energy dispersion optimization. We are designing a low-power prototype to verify the feasibility of the energy recycling scheme.

- **The following contents will be addressed in this project**

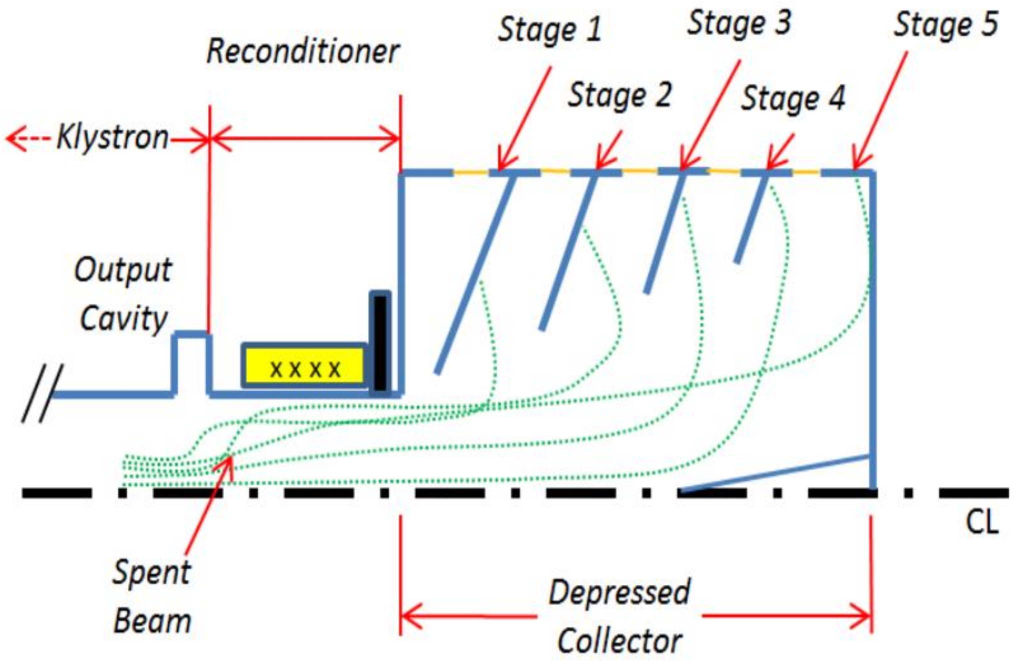
- Design of an efficient energy recycling scheme for high efficiency klystron.
- Design of the depressed collector(e.g. Cooling structure, Insulation , ceramic welding) .
- Design of the Energy recovery power source(e.g. cathode power supply, collector power supply) .
- Establishing an energy recovery experimental platform to validate the feasibility of the efficient energy recycling.

The depressed collector principle

- By providing one or more potentials lower than the interaction region to the depressed collector, abandoned electron beam , upon entering the collector, decelerate due to the electric field forces, reducing the heat generated upon impact, and enabling the recovery of current on the electrodes.



Electric field distribution within a three-stage depressed collector



Depressed collector electron trajectory

Theoretical analysis of wasted beam energy

- Based on the existing design of the efficient klystron for CEPC, with a linear operating efficiency of 68% and an output power of 700 kW, a depressed collector design is being implemented to recover wasted beam energy.

Calculation formula based on the theory of abandoned electron beam energy distribution：

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

– V_i is the electrode voltage;

– I_0 is the electron beam current.

–J_{waste} is the probability distribution of wasted beam energy.

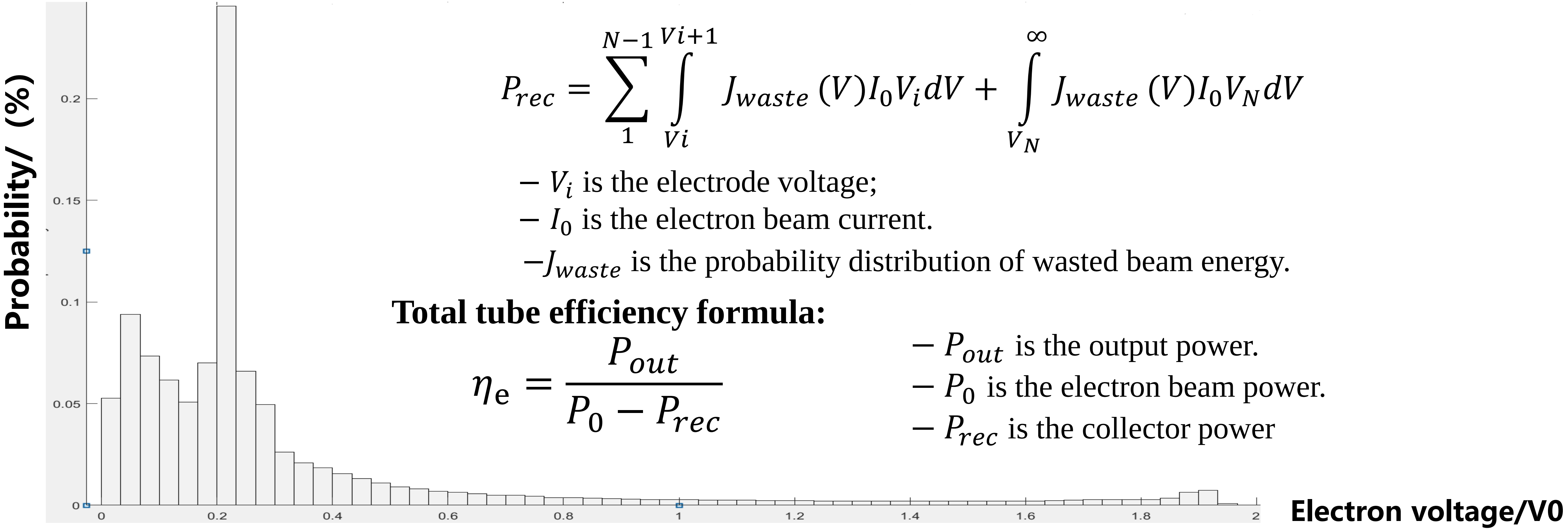
Total tube efficiency formula:

$$\eta_{\mathrm{e}} = \frac{P_{out}}{P_0 - P_{rec}}$$

– P_{out} is the output power.

– P_0 is the electron beam power.

– P_{rec} is the collector power

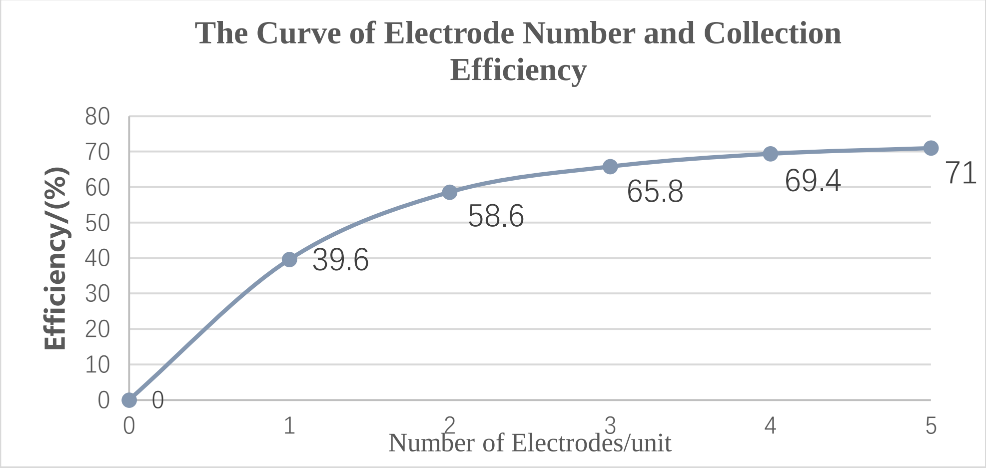


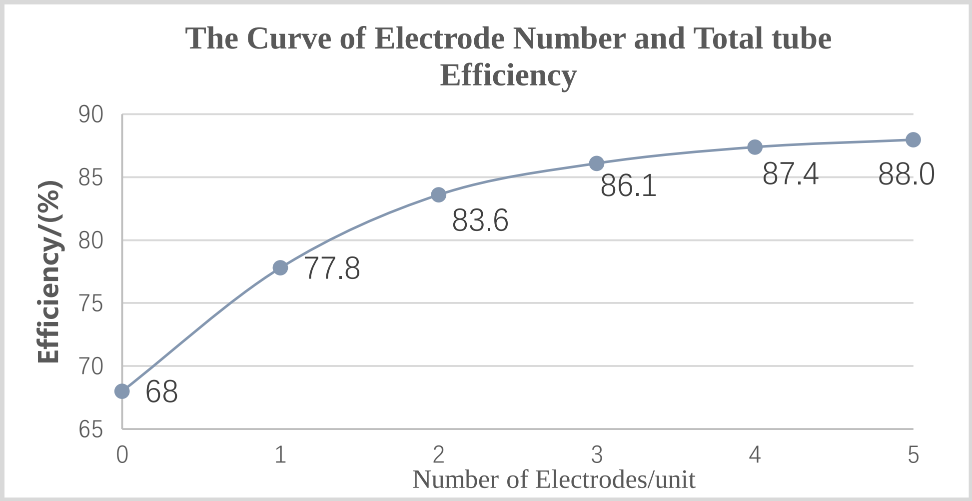
The probability distribution of wasted electron beam energy in CEPC efficient klystrons

Analysis of the Number of Electrodes and Efficiency

- Determining the electrode voltage based on the energy distribution of the abandoned electron beam.
- The recovery efficiency increases as the number of collector electrodes increases.
- The increase in the number of electrodes leads to greater complexity in manufacturing and operational challenges.

Number of electrodes	Electrode voltage(kV)	Recovery efficiency	Total tube efficiency
0		0%	68%
1	22.7	39.6%	77.8%
2	22.7/109.3	58.6%	83.5%
3	22.7/83/109.3	65.8%	86.1%
4	22.7/46/63/109.3	69.4%	87.4%
5	22.7/36/68/85/109.3	71.0%	88.0%

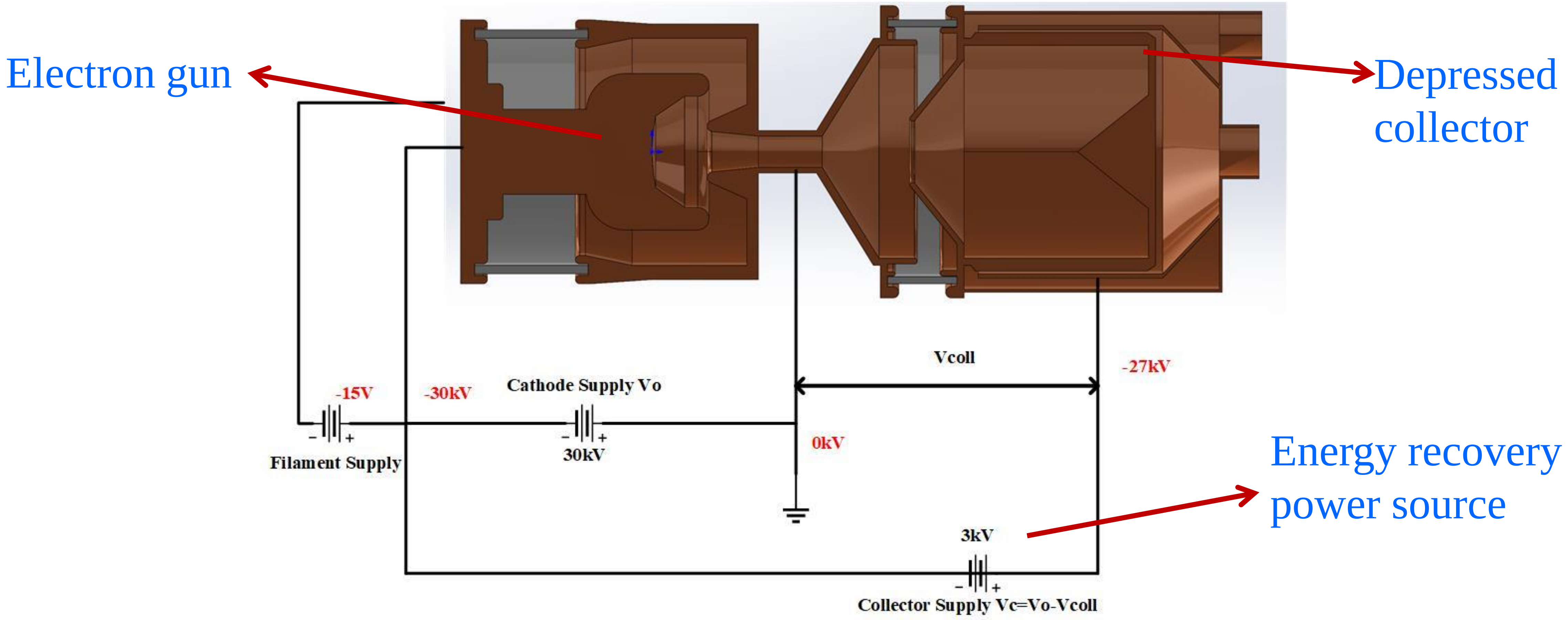




Design Scheme

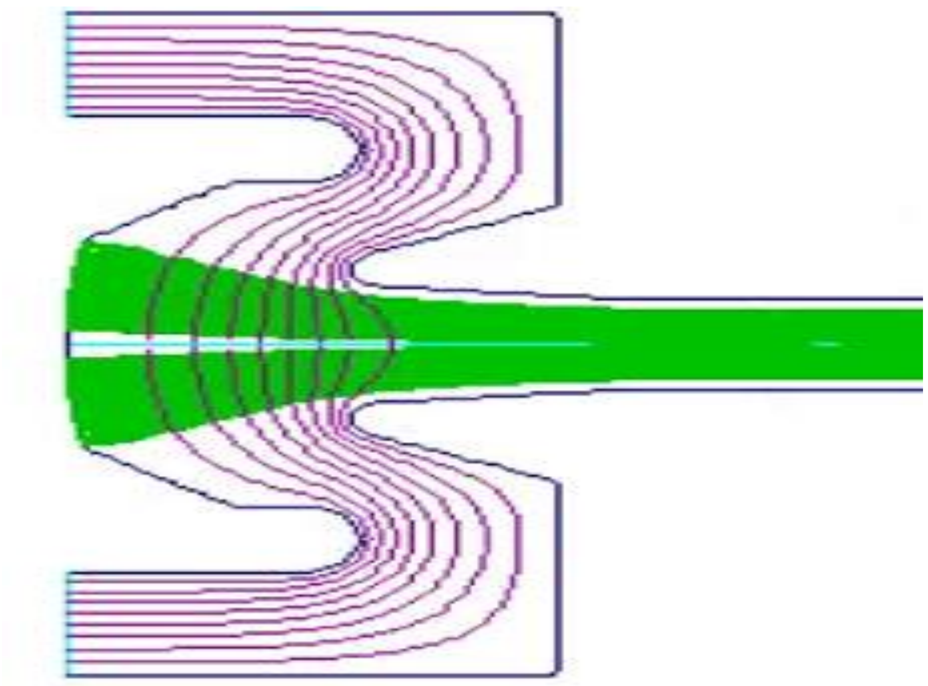
Structure of the validation platform

- The structure of the validation platform.

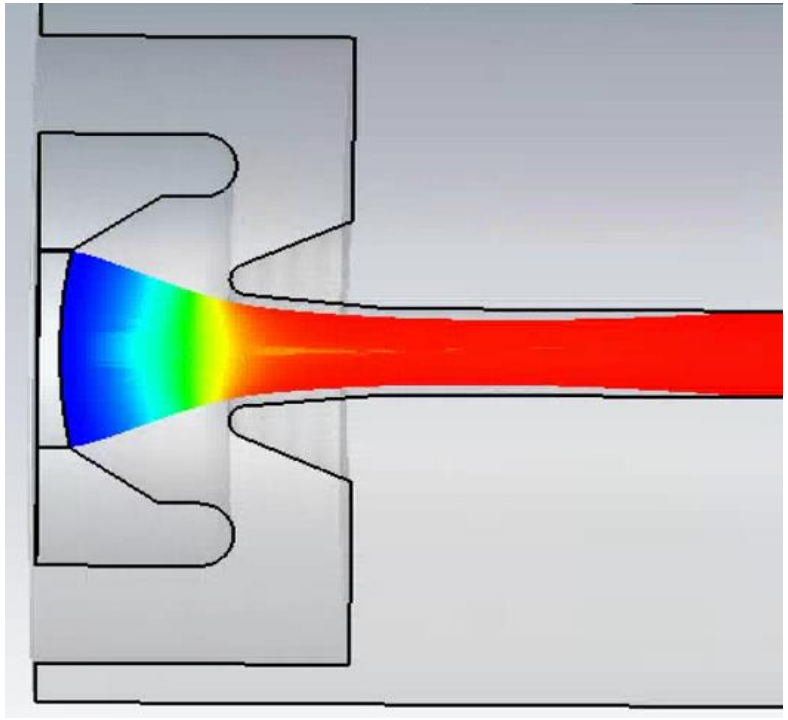


Electron gun design

- The electron gun is designed based on the same cathode as the efficient klystron.
  - Beam voltage: 30 kV.
  - Beam current: 4.5 A.
  - Perveance : 0.86 μP .
  - Anode maximum electric field: 3.0 kV/mm.
  - Maximum electric field at the focusing electrode: 2.9 kV/mm.



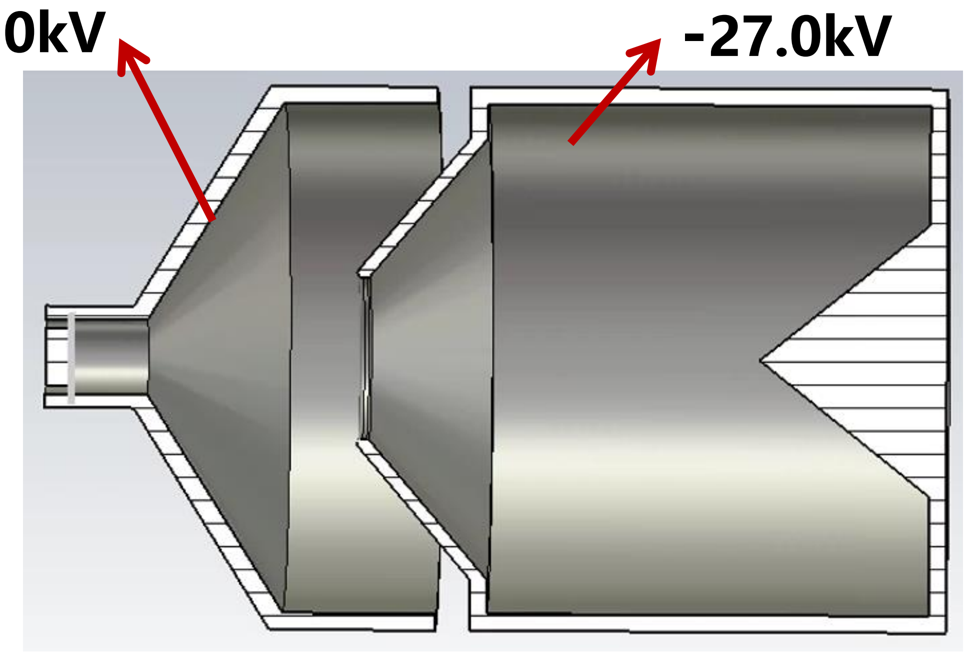
DGUN One-dimensional simulation result

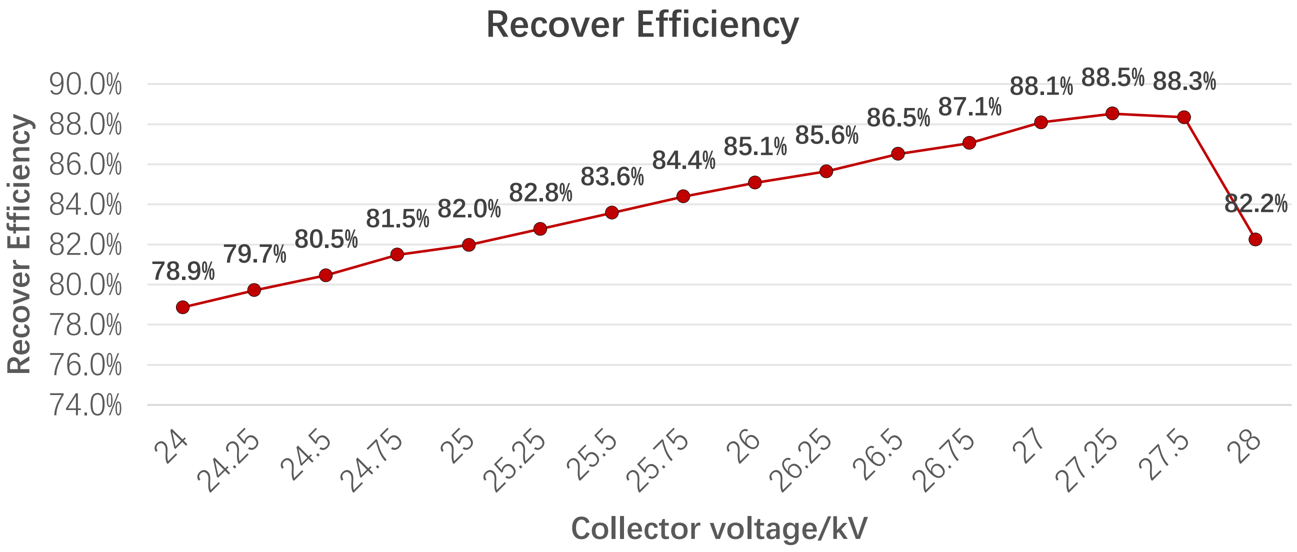


CST Three-dimensional simulation result

Depressed collector design

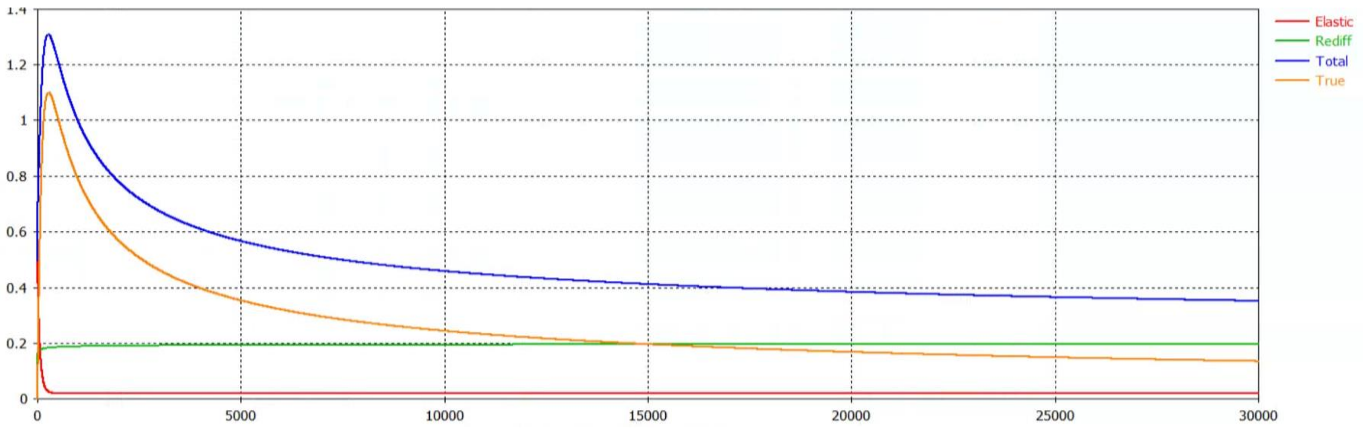
- The validation platform is designed with a single-pole depressed collector.
- Simulations are conducted to derive the electrode voltage drop and efficiency curve.
- When the voltage drop is too high, secondary electron backflow increases, lower efficiency.
- Taking all factors into consideration, the design voltage drop is set at 27 kV.



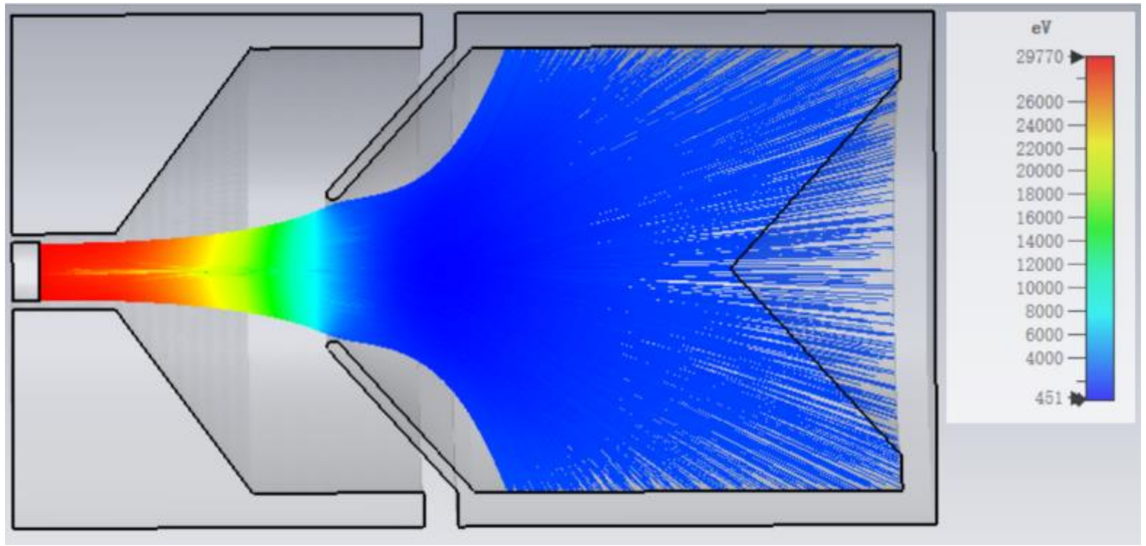


Beam optics design

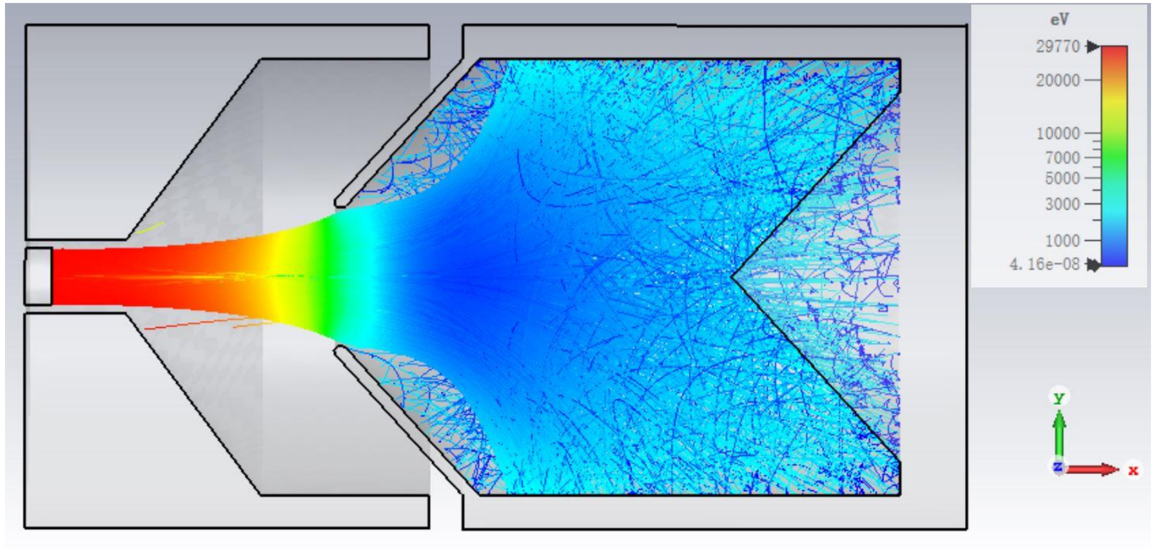
- Without considering secondary electrons, the voltage drop is 27 kV, and the collected current is 4.5 A.
- Considering secondary electrons, the collected current is 4.4 A, and the recovery efficiency is 88%.



Secondary electron emission coefficient



Single-stage depressed beam optics (without considering secondary electrons)

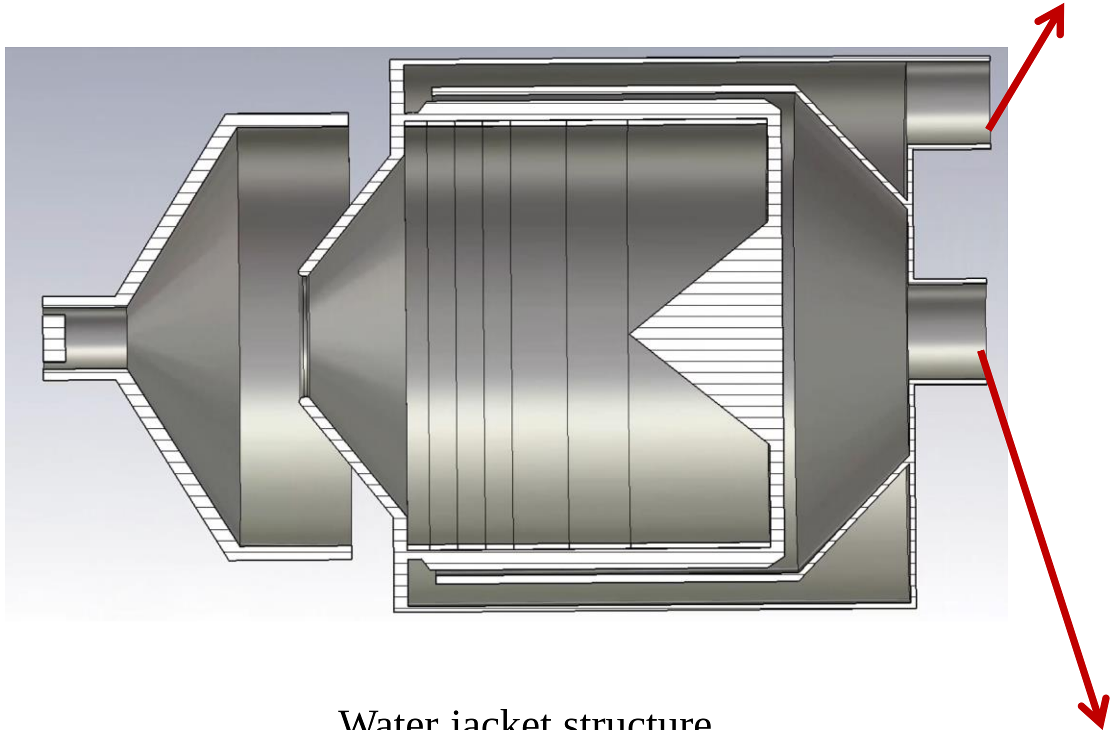


Single-stage depressed beam optics (considering secondary electrons)

Cooling structure and thermal analysis

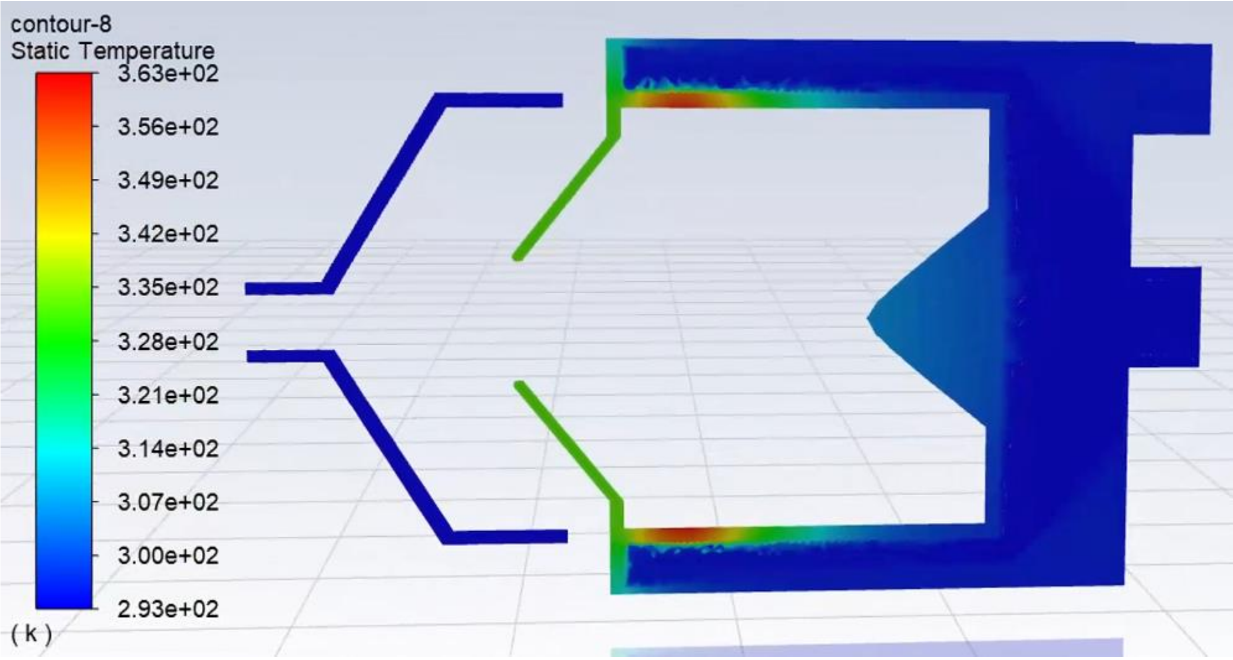
- Using deionized water for cooling.
- The thermal analysis results are shown in the figure.
- The initial temperature is 25°C, The flow velocity is 1.5 m/s, The maximum temperature reaches 90°C.

Outlet



Water jacket structure

Inlet



Distribution of the collector water cooling temperature

The parameters of the power supply

- The energy recovery power supply consists of the cathode power supply and the collector power supply.
- The cathode power supply provides a voltage of 30 kV, a beam current of 4.5 A, and an output power of 3 kW.
- The collector power supply has a voltage of 3 kV, an output power of 13.5 kW, and provides a collector voltage drop of 27 kV.

	Cathode supply	**Collector supply**	**Filament supply**
Output voltage	-15kV ~ -30kV	1500V ~ 3000V	-10~-15V
Average output current	≤100mA	≤4.5A	≤40A
Stability	$\leq 10^{-3}$	$\leq 10^{-2}$	$\leq 10^{-2}$
Output ripple	$\leq 10^{-3}$	$\leq 10^{-3}$	$\leq 10^{-2}$

The energy recovery power supply parameters

The principle of energy recovery power supply

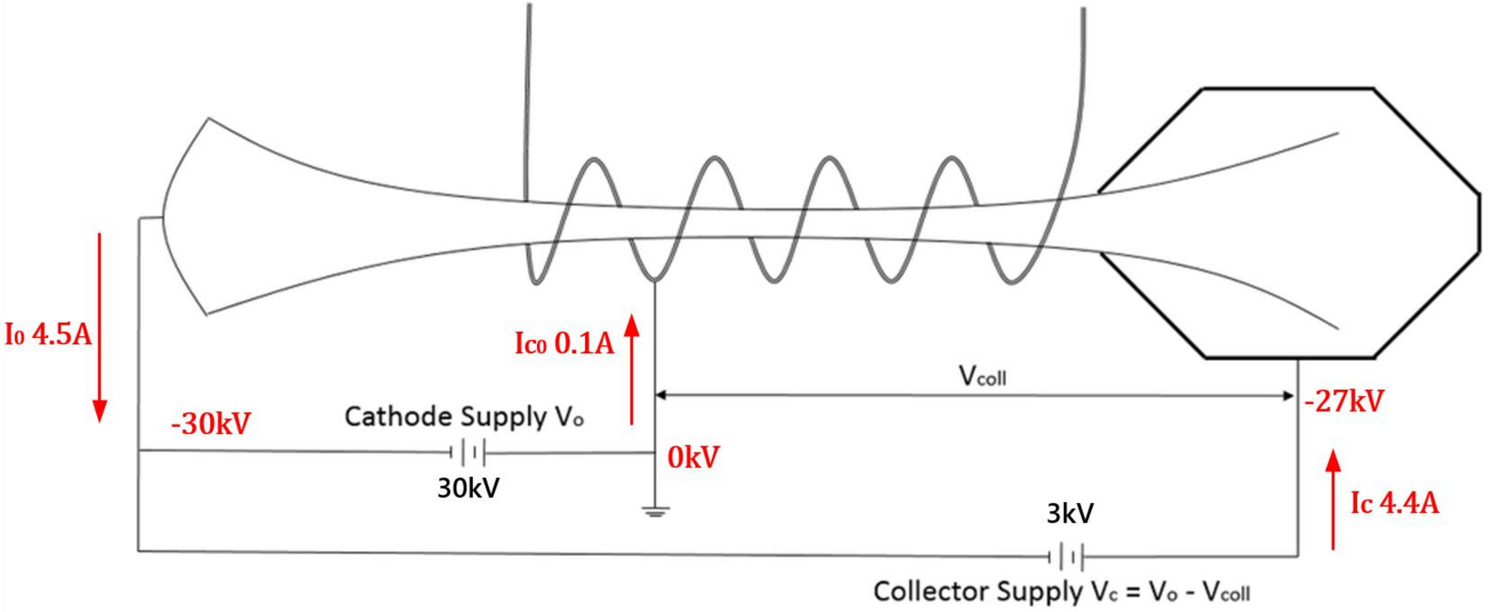
$$P_0 = V_0 \cdot I_0 = 30kV \cdot 4.5A = 135kW$$

$$P_1 = V_0 \cdot I_{c0} + V_c \cdot I_c$$

$$= 30kV \cdot 0.1A + 3kV \cdot 4.4A = 16.2kW$$

$$\eta = \frac{P_0 - P_1}{P_0} = \frac{V_{coll} \cdot I_c}{V_o I_o} = \frac{27kV \cdot 4.4A}{30kV \cdot 4.5A} = 88\%$$

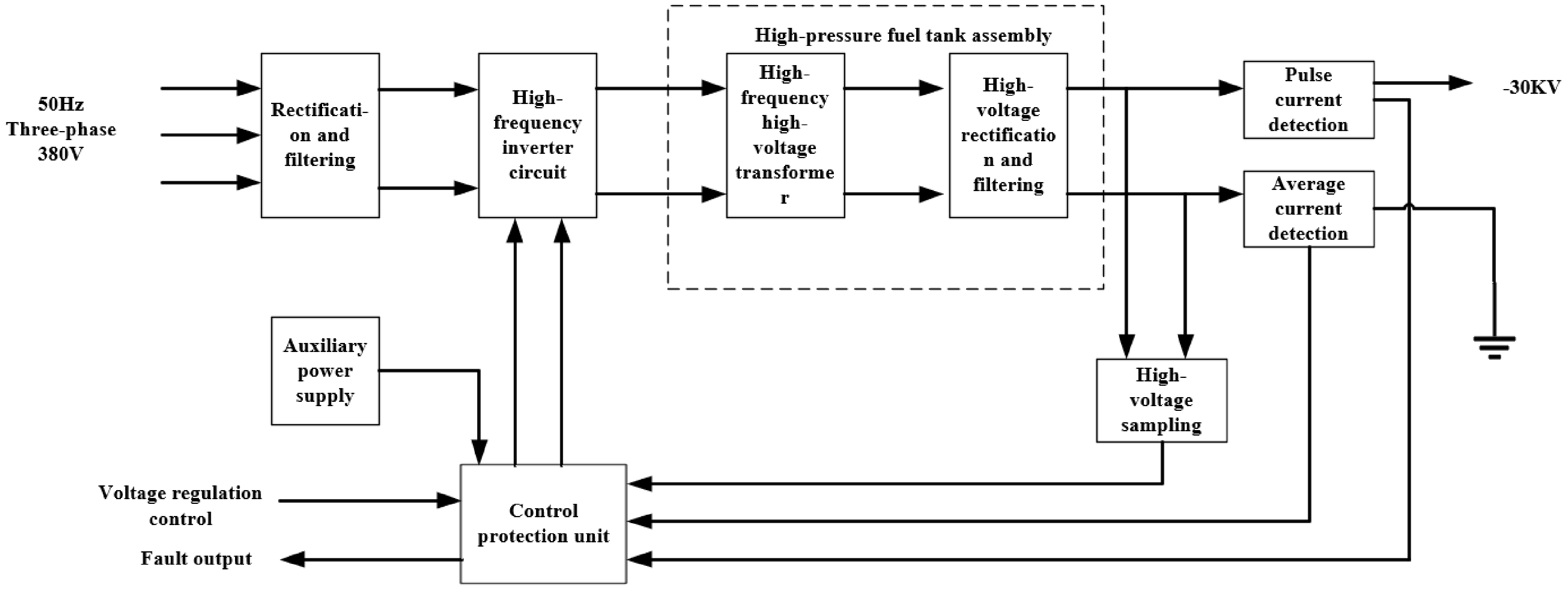
- V_{coll} is the collector voltage drop
- I_0 is the beam current.
- I_c is the collector current.
- P_0 represents beam power.
- P_1 is the actual power.
- η is the recovery efficiency.



Energy recovery power supply scheme

Design of the cathode power supply

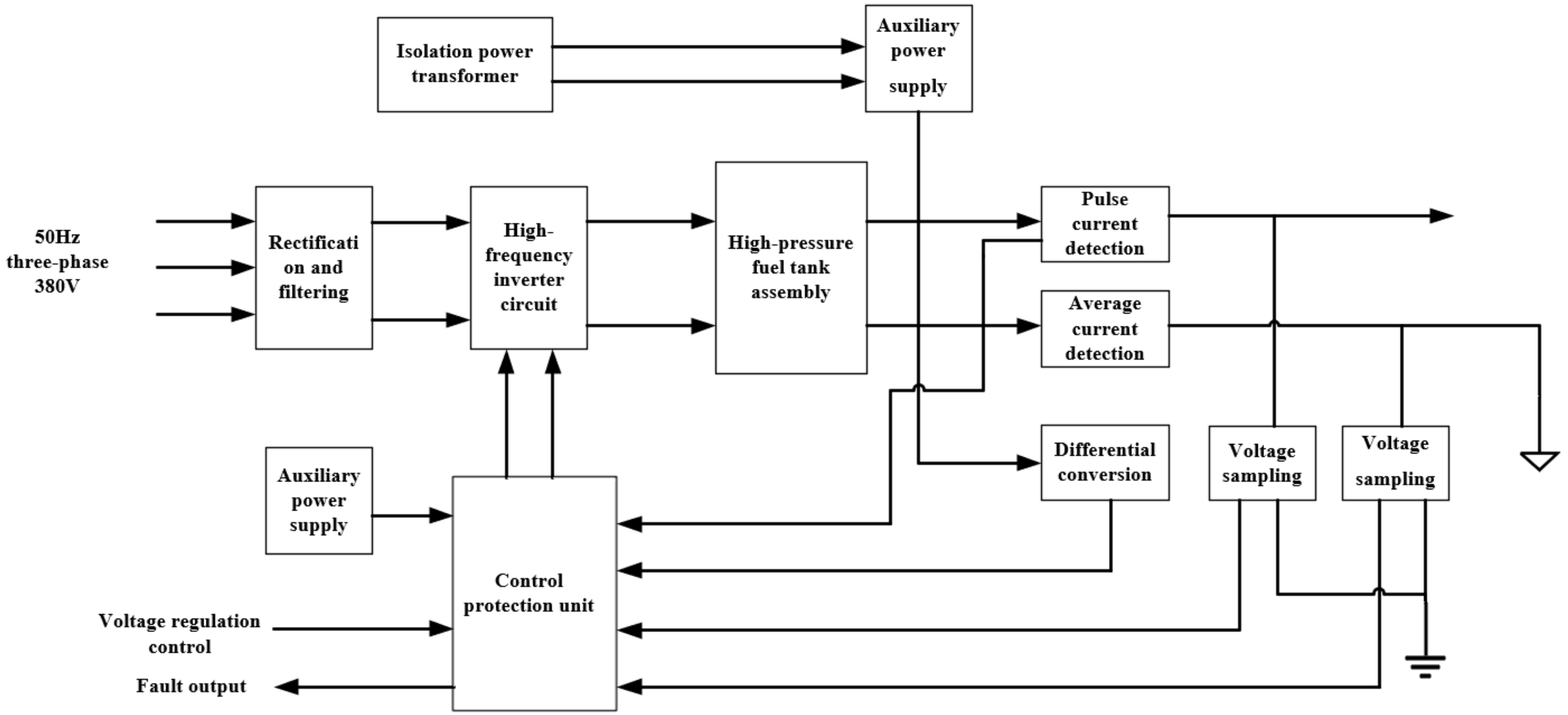
- The cathode power supply uses a three-phase bridge rectifier circuit. After rectification, it goes through LC filtering and then generates high-frequency square wave voltage via a high-frequency inverter. After boosting through a high-frequency high-voltage transformer, it is further rectified and filtered to obtain the required DC voltage.



Cathode High Voltage Power Supply Schematic Diagram

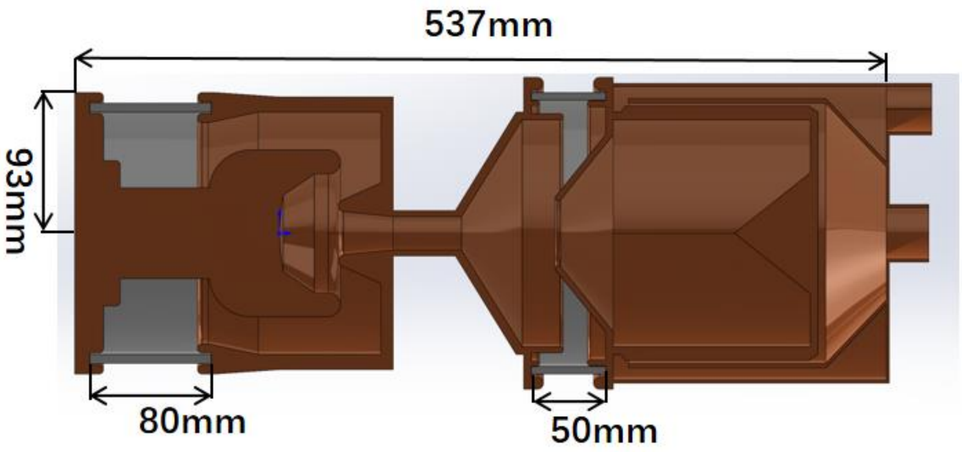
Design of the collector power supply

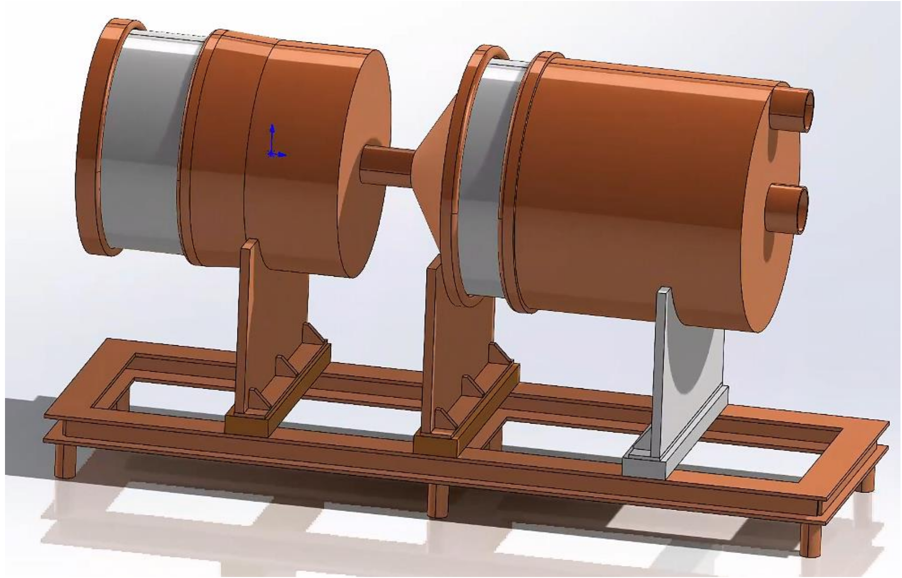
- The principle of the collector power supply is fundamentally similar to the cathode power supply, with the primary difference lying in the output voltage and power levels. The output voltage is typically floating at a high negative voltage relative to the cathode.



Collector High Voltage Power Supply Schematic Diagram

Structural Dimension Design





Collector and Bracket Diagram

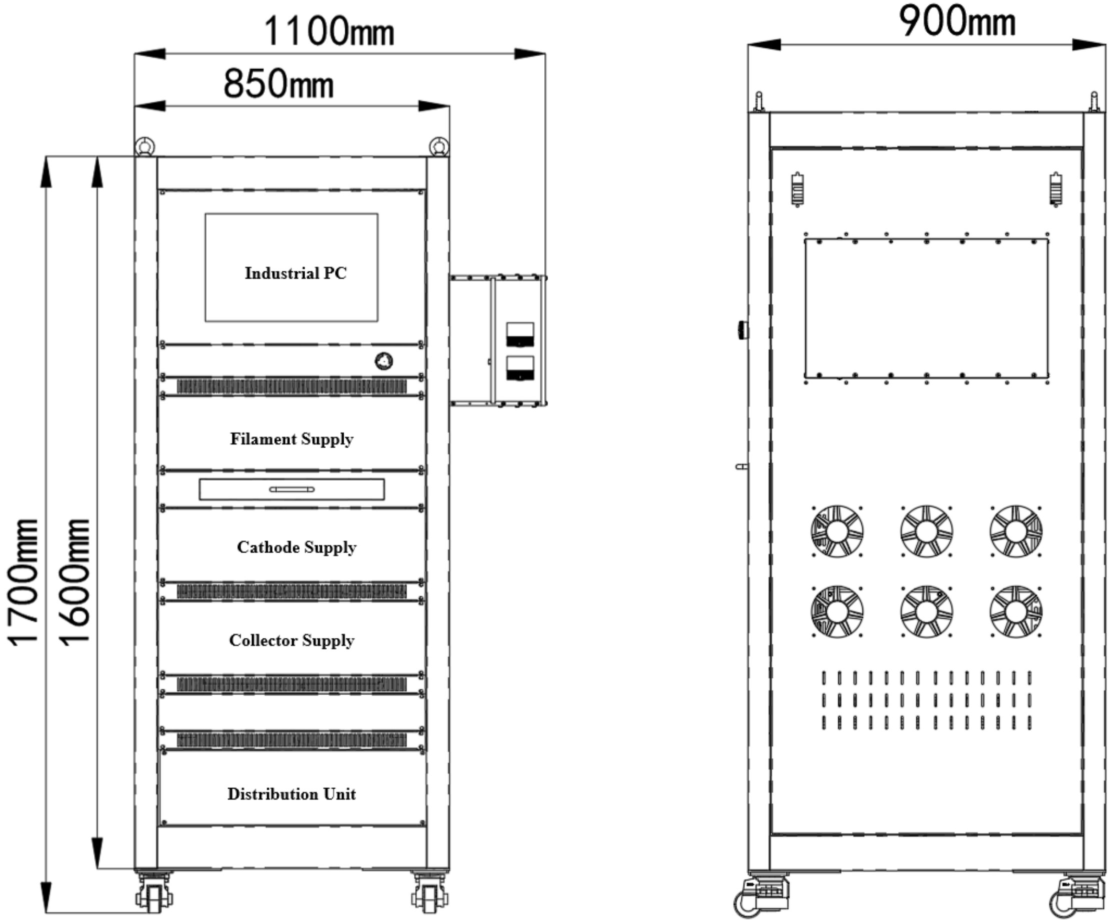


Diagram of Energy Recovery Power Supply Structure

Summary

Summary

• Conclusion

- This design is based on the high-efficiency klystron of CEPC and is aimed at verifying the feasibility of the energy recovery scheme.
- This design only focuses on the depressed collector and the energy recovery power source.
- The project goal is achieving a recovery efficiency exceeding 80%.

• Future plans

- After completing the verification of the energy recovery scheme, we will proceed with the development of klystron energy recovery.
- It is expected that the current 68% linear efficiency of klystron can be increased to over 88%, and even 90%, significantly reducing operational costs.

Thanks！