RF Energy Recovery Power Conversion for Particle Accelerators

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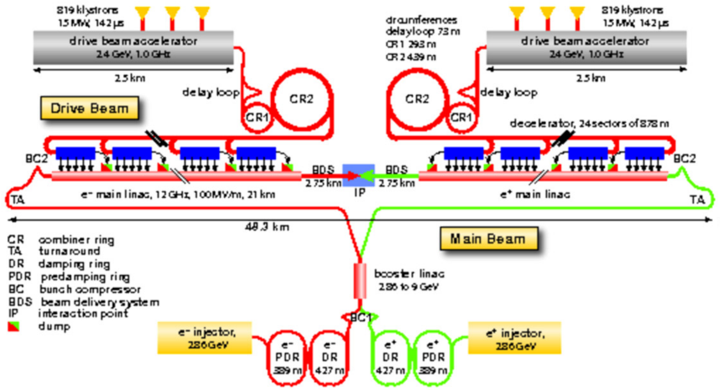
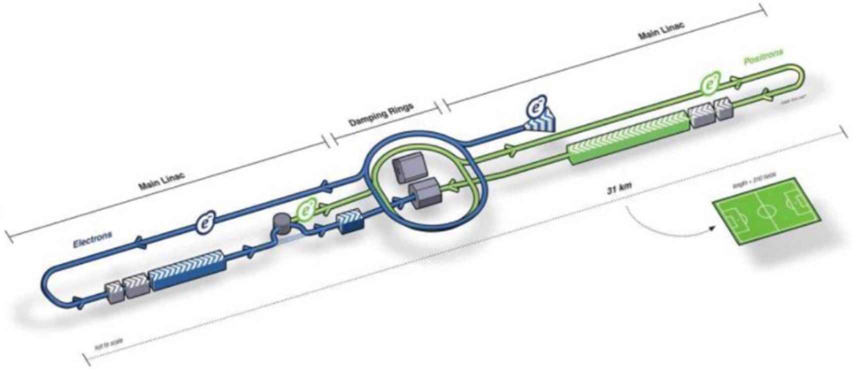
INTRODUCTION

- RF power sources are key equipment that provide the required high-frequency electromagnetic energy in particle accelerators.
- The power consumption of large-scale accelerator facilities (ILC, CLIC, FCC, CEPC, …) , operate at the hundred-megawatt level, leading to extremely high annual operating costs.
- All residual beam energy is converted into heat in various forms and removed by the water-cooling system.

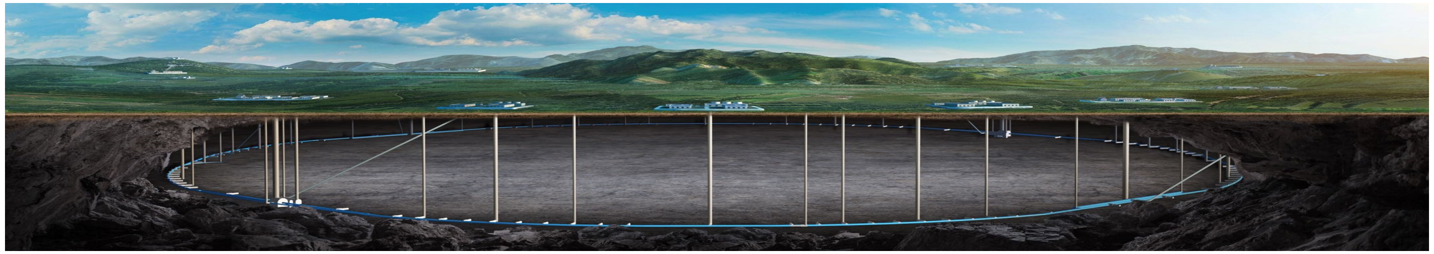
Green, environmentally-friendly and cost-effective accelerator facilities have become a hot research topic worldwide.



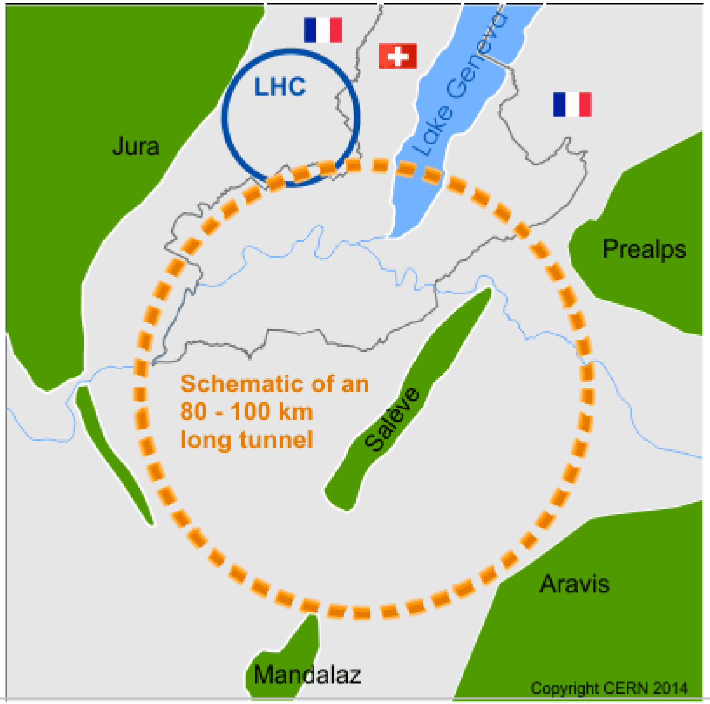
CLIC 3 TeV: 1 GHz, $P_{\mathrm{RF,total}}$ = **180 MW**



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



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



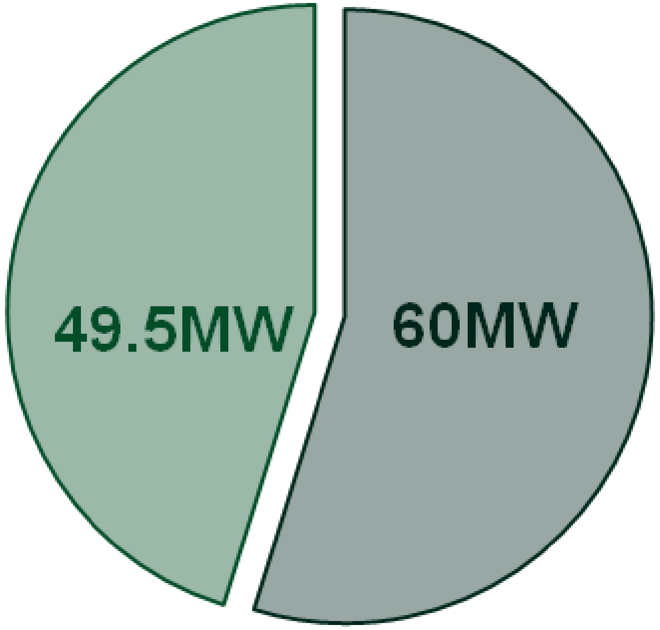
FCC-ee: CW, (0.4 & 0.8) GHz, $P_{\mathrm{RF,total}}$ = **105 MW**

INTRODUCTION

CEPC TDR Power Consumption Breakdowns@Higgs with 30GeV injection Linac and 30MW SR/beam

	Location and electrical demand(MW)						
	Ring	Booster	LINAC	BTL	IR	Surface building	TOTAL
RF Power Source	96.9	1.4	11.1				109.5
Cryogenic System	11.6	0.6	-		1.1		13.4
Vacuum System	1.0	3.8	1.8				6.5
Magnet Power Supplies	52.3	7.5	2.4	1.1	0.3		63.5
Instrumentation	1.3	0.7	0.2				2.2
Radiation Protection	0.3		0.1				0.4
Control System	1.0	0.6	0.2	0.0	0.0		1.8
Experimental devices					4.0		4.0
Utilities	31.8	3.5	2.0	0.6	1.2		39.1
General services	7.2		0.3	0.2	0.2	12.0	19.8
RF system			0.8				0.8
TOTAL	203.4	18.2	18.9	1.8	6.8	12.0	261.1

CEPC power consumption @TDR

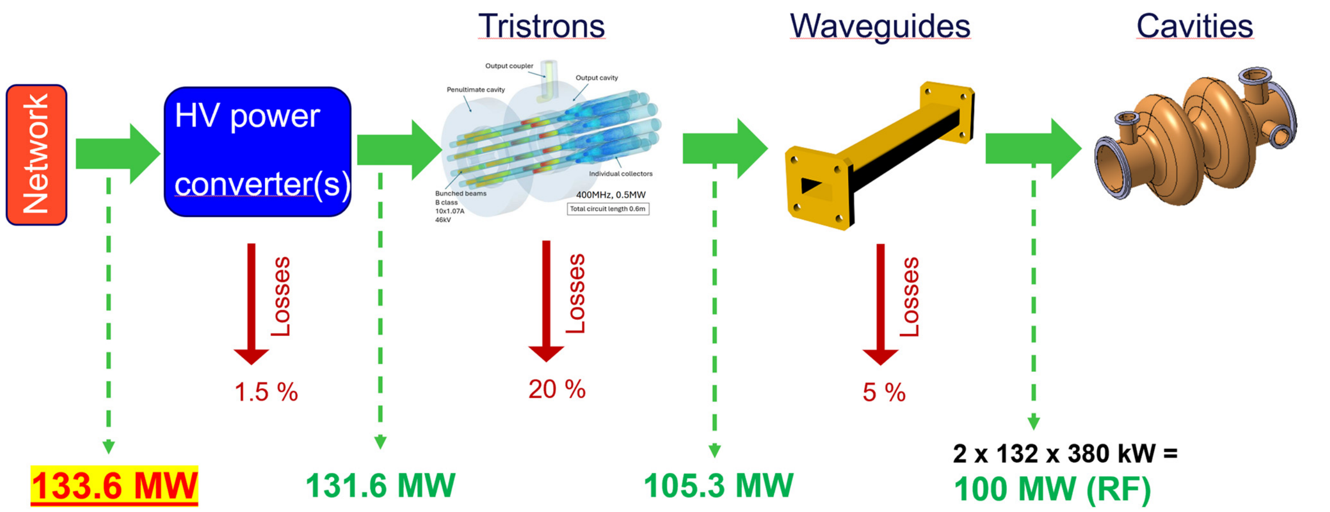


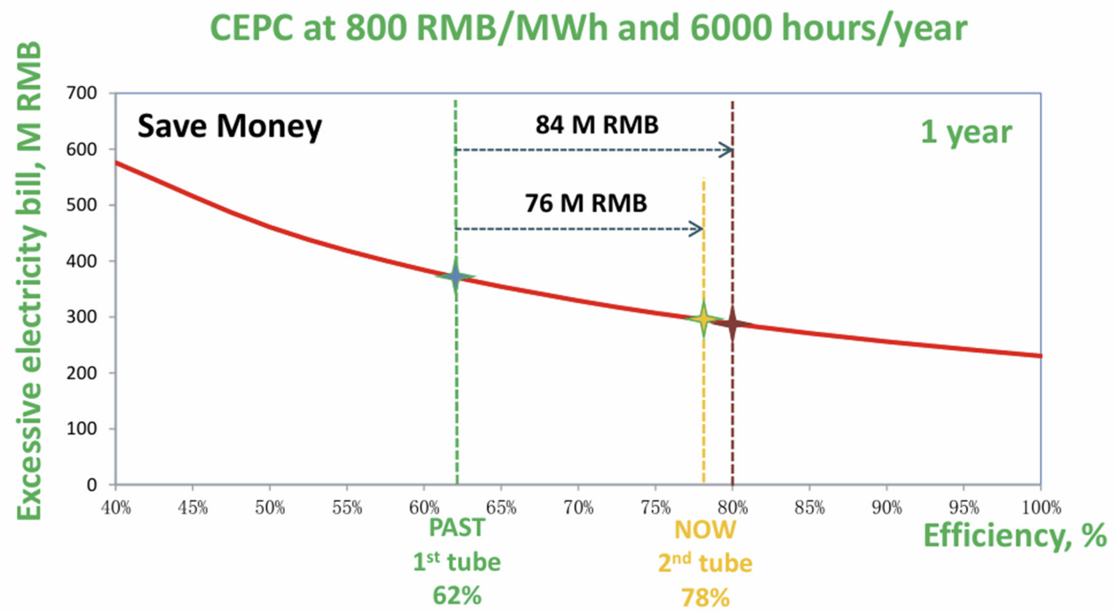
Among them, the grid power demand is 109.5 MW (the klystron efficiency is calculated at 75%). FCC 80%[1]

- Taking CEPC as a example, its total RF power consumption reaches 110 MW according to the TDR design. Improving the efficiency of RF power sources is essential to resolve the high-energy-consumption.

INTRODUCTION

- A complete RF power system consists of grid-side input, high-voltage power supply, klystron and microwave transmission units.
- Both high-voltage power supplies (>96%) and microwave transmission systems achieve (> 95%).
- However, conventional klystrons only 65%, which serves as the major efficiency bottleneck of the whole system.
- At hundred-megawatt operating levels, these losses lead to pretty big costs.
- So, It is estimated that increasing the klystron efficiency from 62% to 78% can save nearly 76 million RMB in annual operating costs.

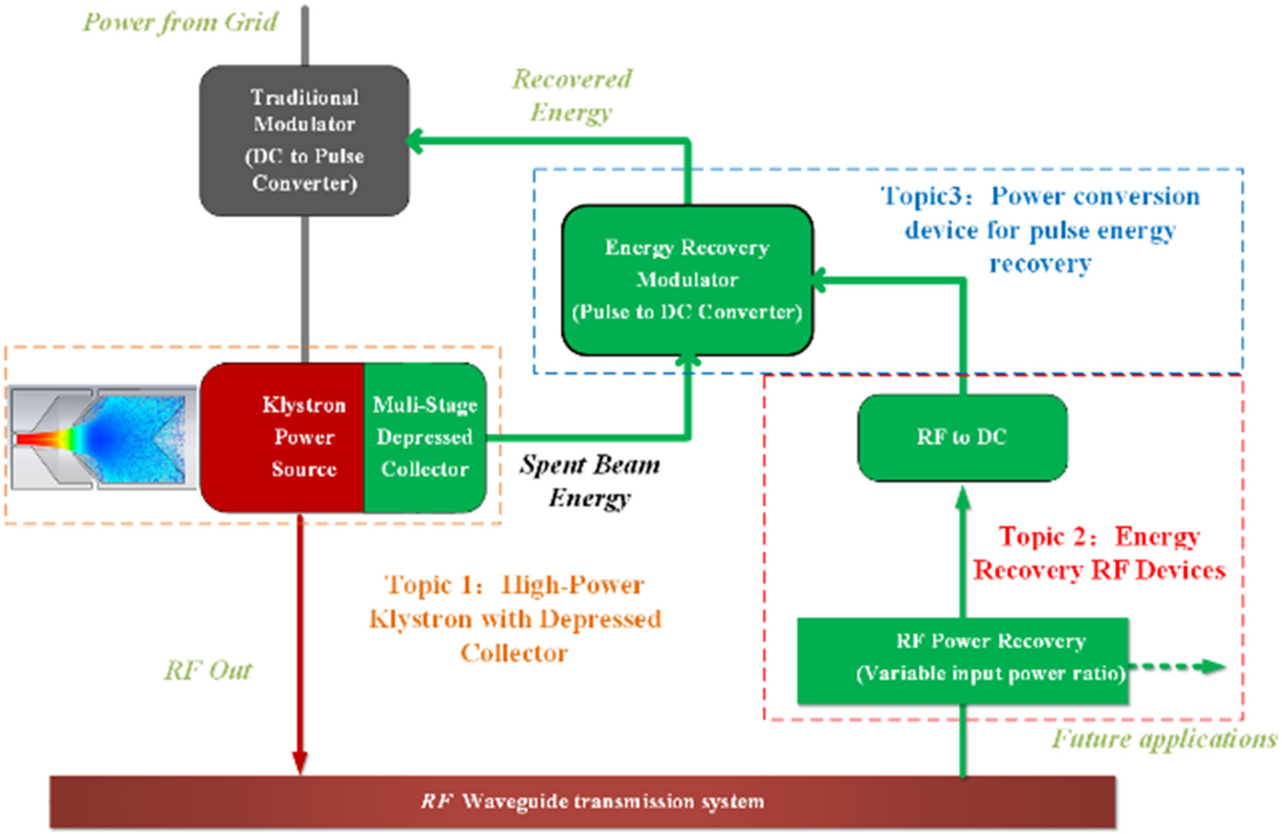




[1] J. Harikumaran. Powering RF systems of FCC. Accelerator Systems (SY Dept.), 2026

R&D Progress overview

To further break through efficiency limits, our team looks into three main research areas:



- Sub-task 1: high-efficiency klystron with Multi-Stage Depressed Collector
- Sub-task 2: Energy-Recovery RF Device
- **Sub-task 3: Power Conversion Device for energy Recovery**

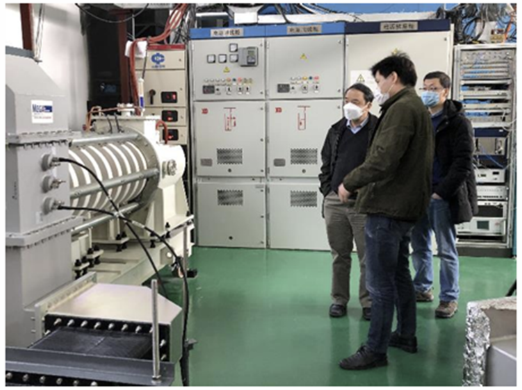
R&D Progress overview

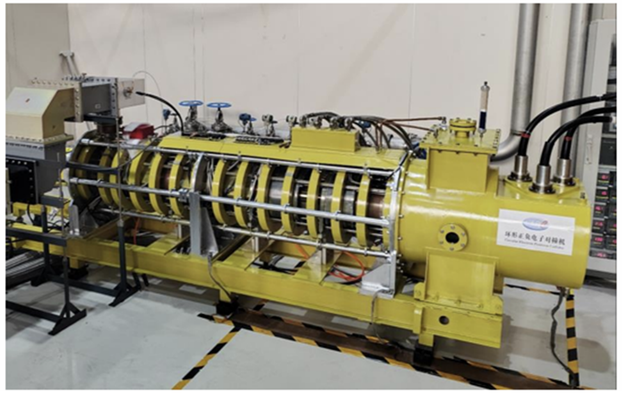
In terms of high-efficiency klystron development, our team has achieved Continuous improvement in efficiency klystron at IHEP

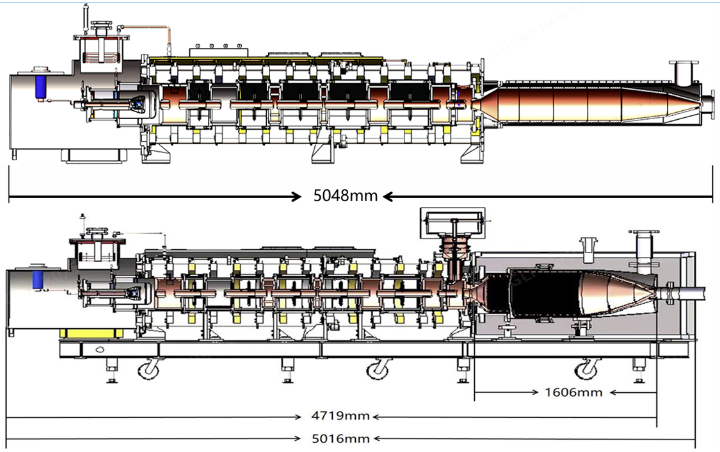
Progress	Scheme1(1st prototype)	Scheme2(2nd)	Scheme3(3rd)
	with Traditional Way	High voltage gun & Low perveance	MBK
Manufacture	Oct. 2017 Prototype manufacture	Jan. 2021Prototype manufacture	**Now:** Klystron prototype manufacture is in progress
Test	Mar. 2020 High power test at IHEP	Aug. 2024: CW 803kW with Eff. 78.5%	
	With efficiency: 62%		design efficiency: >80%

Energy recovery klystron(ERK)

Parameter	Value
Frequency	650 MHz
Beam Voltage	113 kV
Output power	800 kW
Beam perveance	0.25 μP
Beam current	9.5A
Efficiency(1 stage DC)	**≥85%**







High efficiency klystron prototype

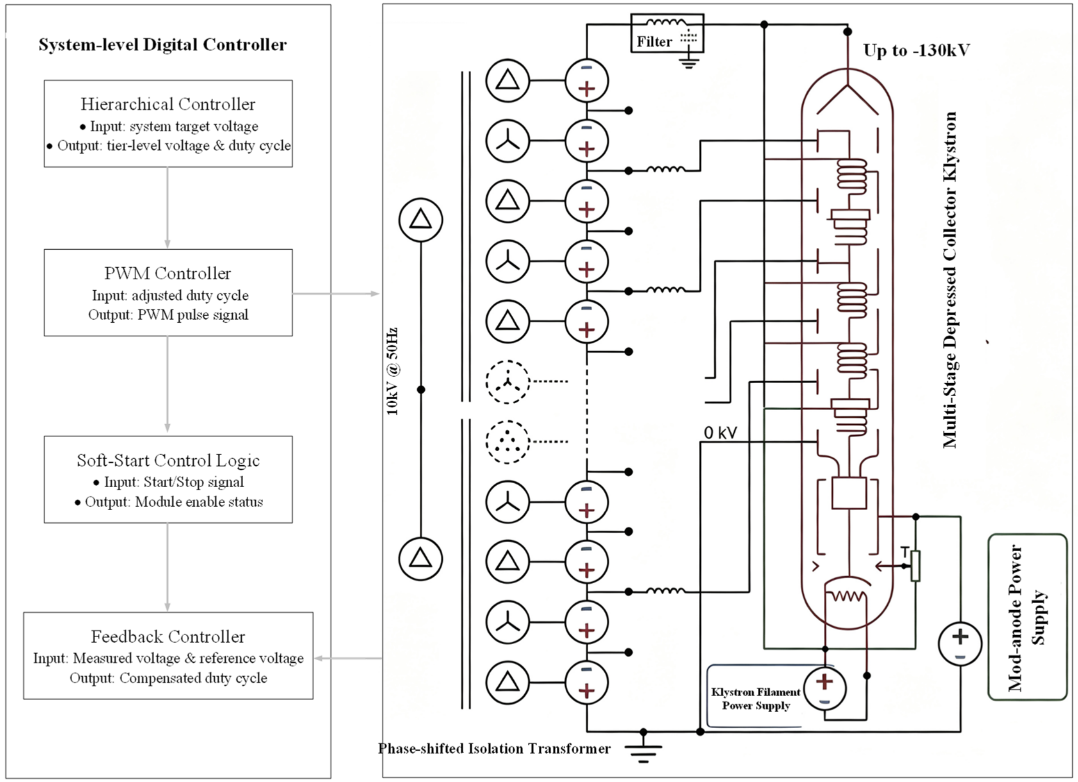
Energy recovery klystron with 1 stage DC

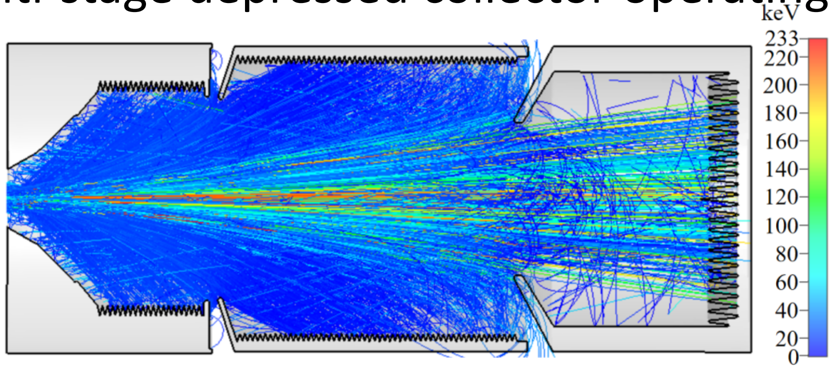
ZushengZhou. High-Efficiency RF Power Sources for Future Large-Scale Facilities. FCC Week 2026, Helsinki, Finland, Jun.8-12 2026

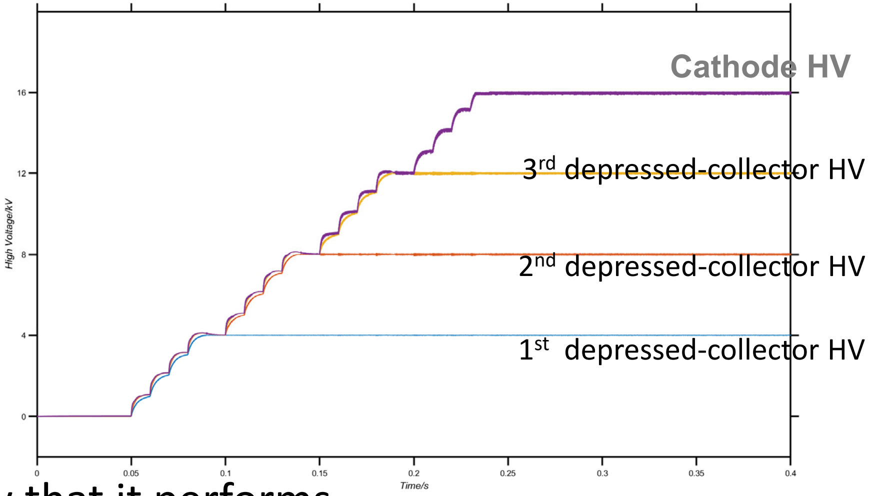
R&D Progress overview

Mode1: High-Voltage DC Power Supply Configuration for Multi-Stage Depressed Collector (MSDC) Klystrons

- with Cascaded HVDC Power Supplies topology & Hybrid Modulation-Control Strategy
- the power supply can adapt for 1st 2nd 3rd 4th and multi-stage depressed collector operating requirements

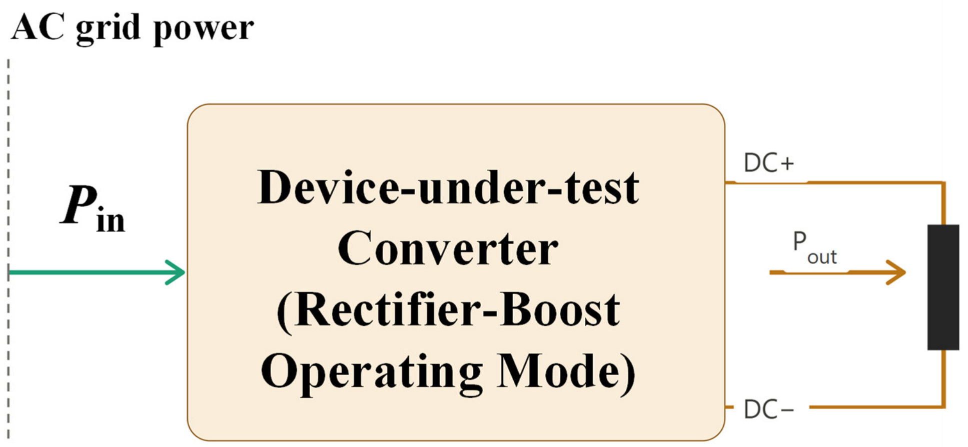




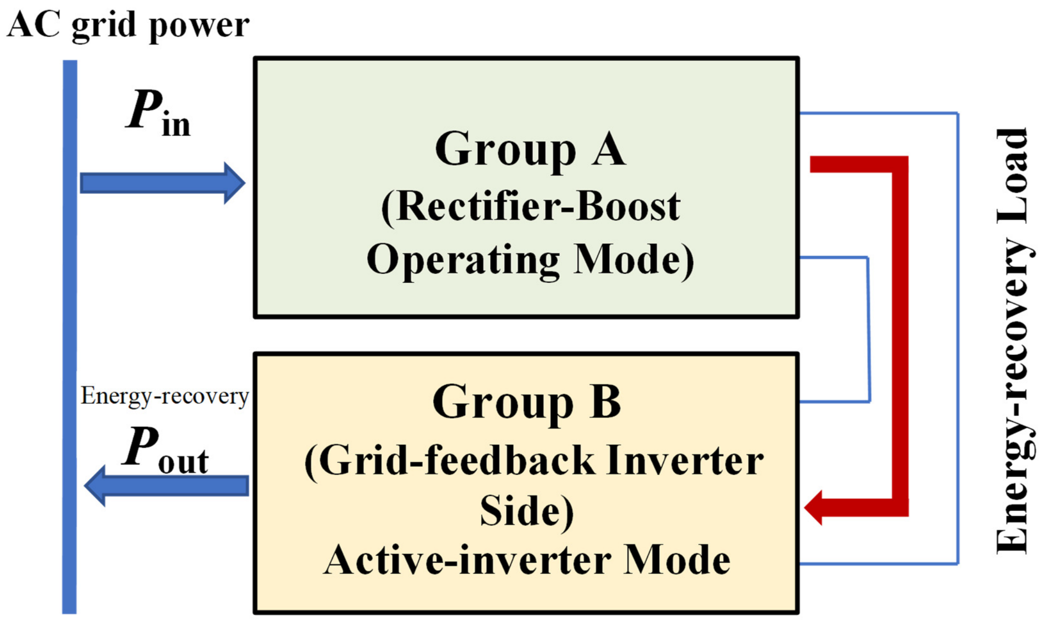


Preliminary experimental results of the three-stage configuration show that it performs flexibly and can adapt well, providing a solid foundation for future engineering applications.

Mode 2: Reliability-test for Megawatt-level High-voltage Power Supply



Conventional Reliability Test
(Resistive-Load Type)

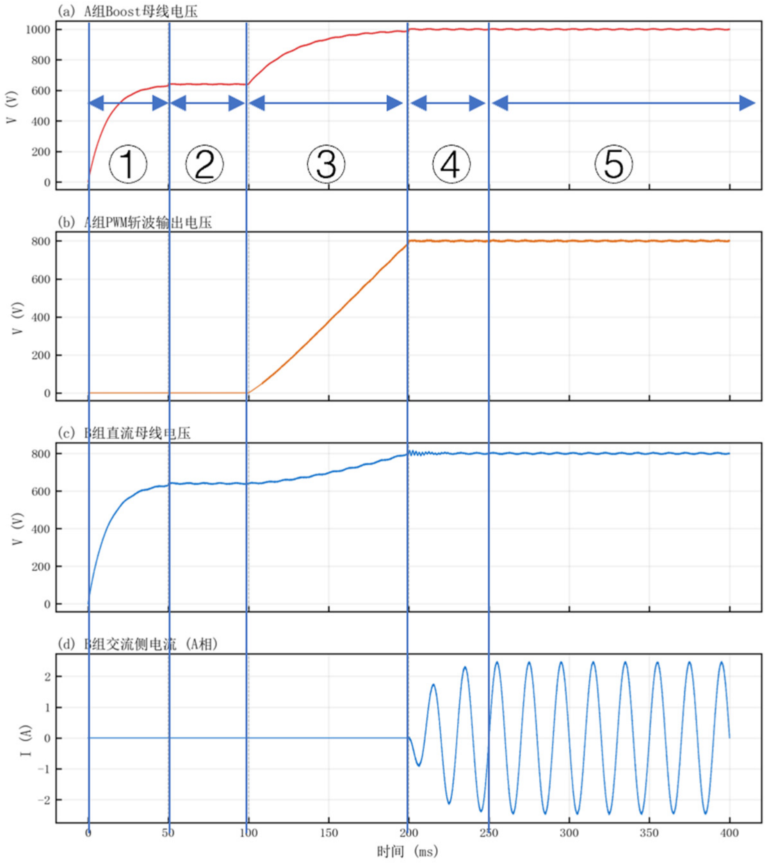


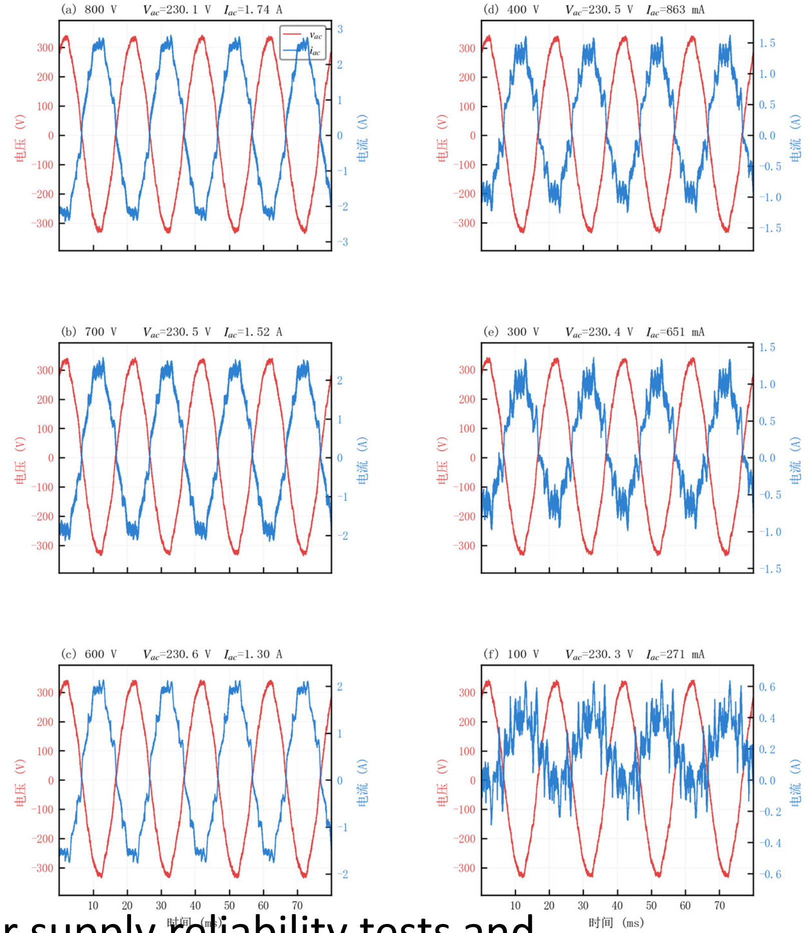
Reliability Test (Energy-recovery Load)

- adopt an energy-recovery load to replace traditional resistive loads.
- conventional resistive loads are usually only capable of hundreds-of-kilowatt-level power tests.
- The energy-recovery load enables megawatt-level power cycle testing; only system losses need to be supplemented by the grid, thus overcoming the power limit of traditional loads.

R&D Progress overview

Preliminary experimental results at module level show that the full-load efficiency reaches 90.0 % at 800 V, and the grid-side THD is 6.66 %.

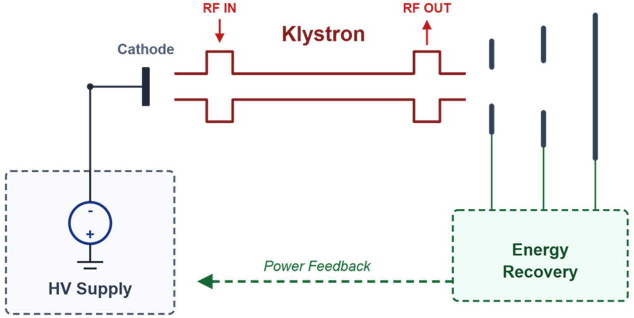




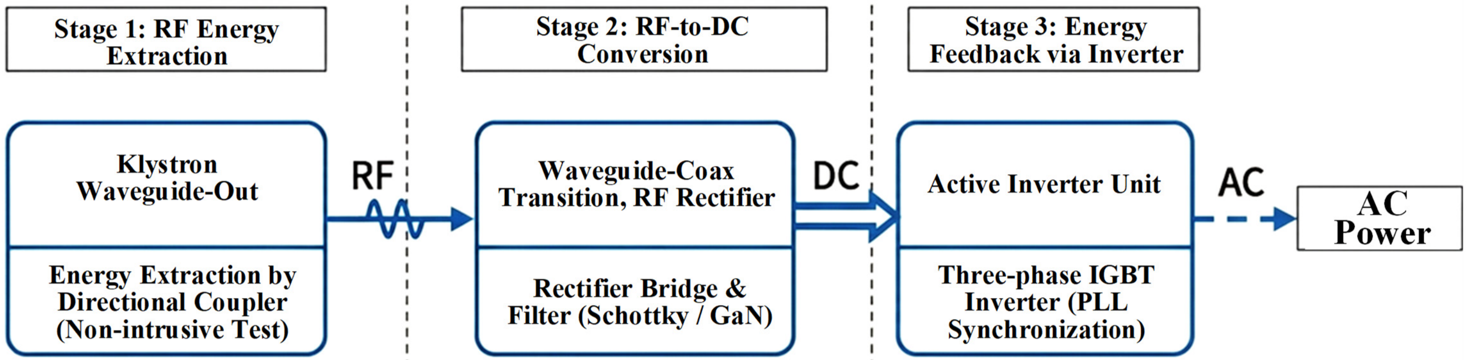
This technology provides strong support for high power supply reliability tests and possesses important engineering application value.

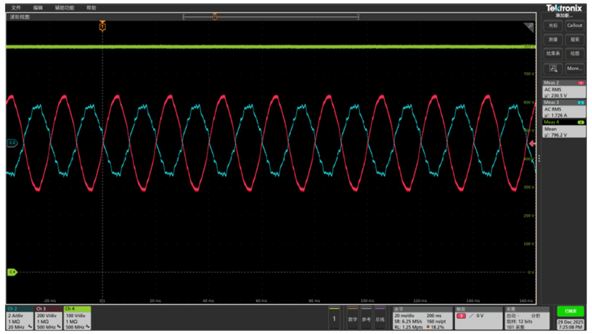
Mode 3: RF-to-DC RF Energy-Recovery Mode

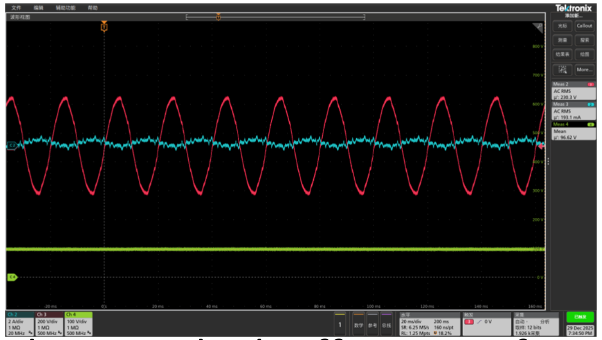
- To achieve efficient recovery of the radio-frequency energy output by the klystron.
- To convert the originally dissipated microwave energy into reusable electric energy.
- To reduce the overall system energy consumption and improve energy-utilization efficiency.



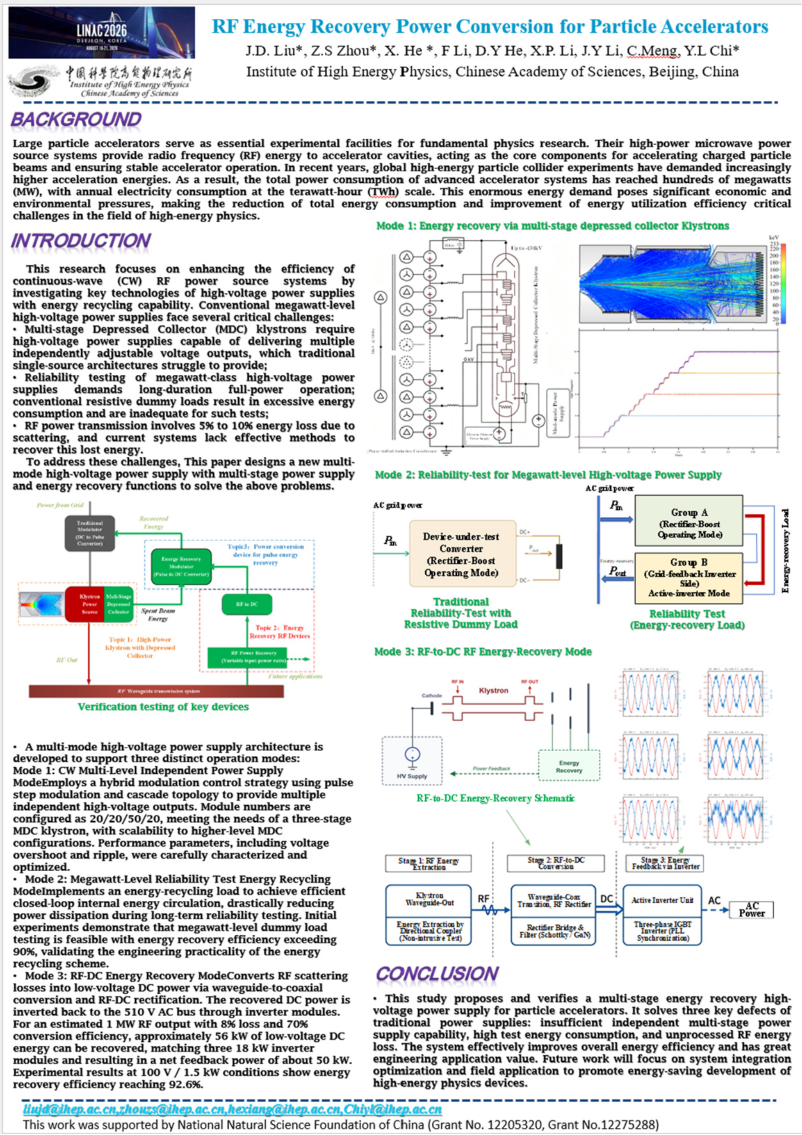
RF-to-DC Energy-Recovery Schematic







This report focuses on the DC-side energy recovery power conversion module, which achieves a high efficiency of over 95% under the 1.5 kW operating condition.



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BACKGROUND

Large particle accelerators serve as essential experimental facilities for fundamental physics research. Their high-power microwave power source systems provide radio frequency (RF) energy to accelerator cavities, acting as the core components for accelerating charged particle beams and ensuring stable accelerator operation. In recent years, global high-energy particle collider experiments have demanded increasingly higher acceleration energies. As a result, the total power consumption of advanced accelerator systems has reached hundreds of megawatts (MW), with annual electricity consumption at the terawatt-hour (TWh) scale. This enormous energy demand poses significant economic and environmental pressures, making the reduction of total energy consumption and improvement of energy utilization efficiency critical challenges in the field of high-energy physics.

INTRODUCTION

This research focuses on enhancing the efficiency of continuous-wave (CW) RF power source systems by investigating key technologies of high-voltage power supplies with energy recycling capability. Conventional megawatt-level high-voltage power supplies face several critical challenges:

- Multi-stage Depressed Collector (MDC) klystrons require high-voltage power supplies capable of delivering multiple independently adjustable voltage outputs, which traditional single-source architectures struggle to provide;
- Reliability testing of megawatt-class high-voltage power supplies demands long-duration full-power operation; conventional resistive dummy loads result in excessive energy consumption and are inadequate for such tests;
- RF power transmission involves 5% to 10% energy loss due to scattering, and current systems lack effective methods to recover this lost energy.

To address these challenges, This paper designs a new multi-mode high-voltage power supply with multi-stage power supply and energy recovery functions to solve the above problems.

Verification testing of key devices

- A multi-mode high-voltage power supply architecture is developed to support three distinct operation modes:

Mode 1: CW Multi-Level Independent Power Supply ModeEmploys a hybrid modulation control strategy using pulse step modulation and cascade topology to provide multiple independent high-voltage outputs. Module numbers are configured as 20/20/50/20, meeting the needs of a three-stage MDC klystron, with scalability to higher-level MDC configurations. Performance parameters, including voltage overshoot and ripple, were carefully characterized and optimized.

- Mode 2: Megawatt-Level Reliability Test Energy Recycling ModeImplements an energy-recycling load to achieve efficient closed-loop internal energy circulation, drastically reducing power dissipation during long-term reliability testing. Initial experiments demonstrate that megawatt-level dummy load testing is feasible with energy recovery efficiency exceeding 90%, validating the engineering practicality of the energy recycling scheme.
- Mode 3: RF-DC Energy Recovery ModeConverts RF scattering losses into low-voltage DC power via waveguide-to-coaxial conversion and RF-DC rectification. The recovered DC power is inverted back to the 510 V AC bus through inverter modules. For an estimated 1 MW RF output with 8% loss and 70% conversion efficiency, approximately 56 kW of low-voltage DC energy can be recovered, matching three 18 kW inverter modules and resulting in a net feedback power of about 50 kW. Experimental results at 100 V / 1.5 kW conditions show energy recovery efficiency reaching 92.6%.

Mode 1: Energy recovery via multi-stage depressed collector Klystrons

Mode 2: Reliability-test for Megawatt-level High-voltage Power Supply

Traditional Reliability-Test with Resistive Dummy Load

Reliability Test (Energy-recovery Load)

Mode 3: RF-to-DC RF Energy-Recovery Mode

RF-to-DC Energy-Recovery Schematic

CONCLUSION

- This study proposes and verifies a multi-stage energy recovery high-voltage power supply for particle accelerators. It solves three key defects of traditional power supplies: insufficient independent multi-stage power supply capability, high test energy consumption, and unprocessed RF energy loss. The system effectively improves overall energy efficiency and has great engineering application value. Future work will focus on system integration optimization and field application to promote energy-saving development of high-energy physics devices.

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