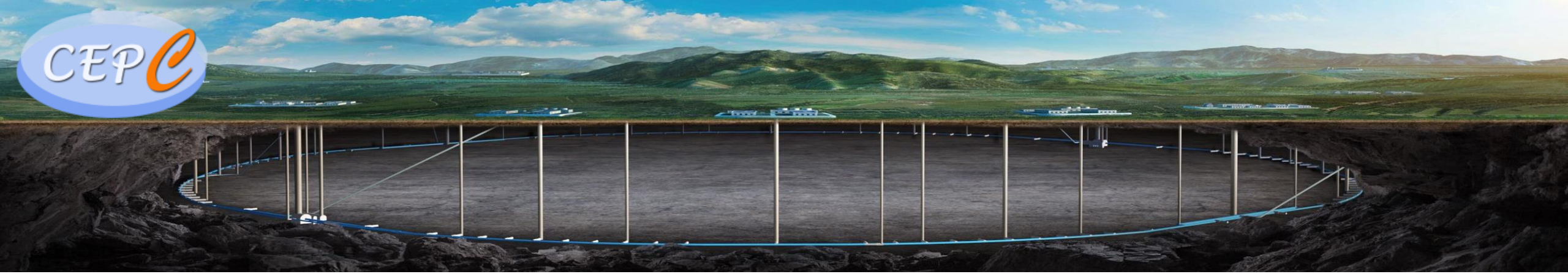

CEPC RF power sources and power distribution EDR plan and status

ZHOU Zusheng

On behalf of High power & high efficiency klystron team

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Institute of High Energy Physics
Chinese Academy of Sciences

Outline

- Introduction
- EDR goal, scope and plan
- EDR progress
- Industrialization preparation progress and status
- Key milestones from 2024-2027
- Conclusion
- Acknowledgement

Introduction

- This talk is about RF power sources and power distribution for CEPC collider ring, booster ring, damping ring and linac injector.
- This talk relates to the EDR goal, scope and plan and also includes recent progress of EDR.
- The content relates to the item “key technology research and development”.

EDR goal, scope and plan

- Accomplishment of high-power test for high efficiency klystron prototype (single beam klystron and multi-beam klystron)
- R&D
  - C band 80MW klystron(80MW/100Hz/3us)
  - S band 80MW high efficiency klystron(80MW/55%)
  - S band high efficiency PPM klystron
  - P band resonant ring(1.2MW CW power)
  - Energy recovery klystron
  - LLRF system
  - Klystron energy dissipation protection

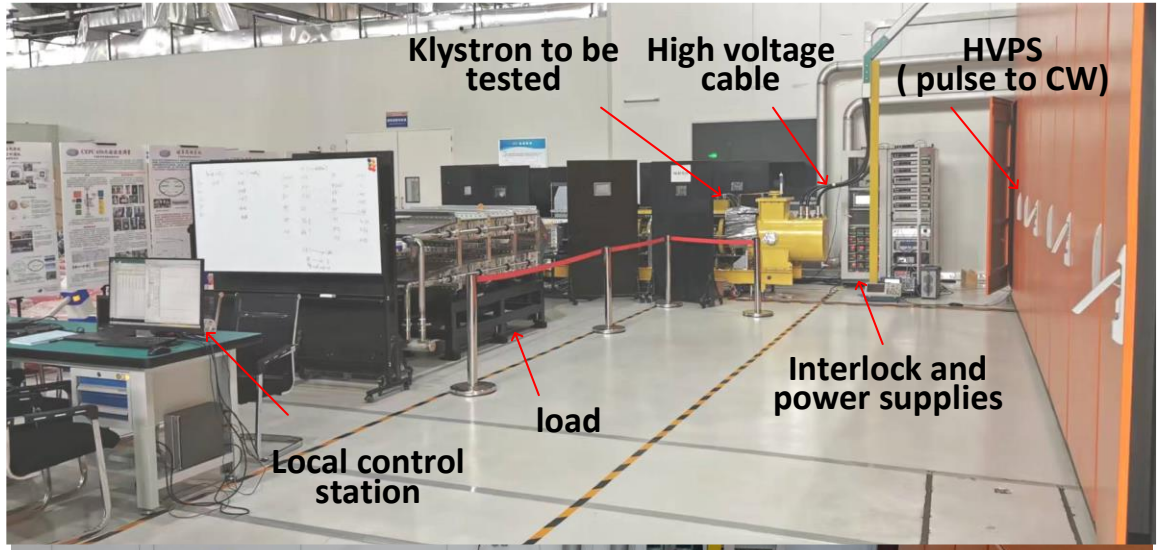
EDR progress

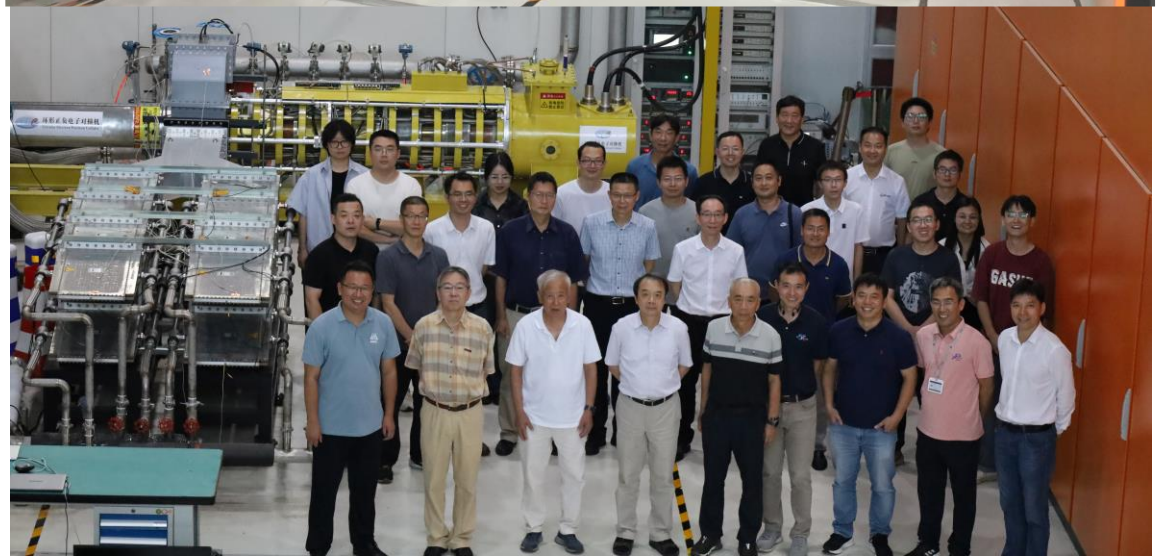
- High efficiency single beam klystron high power test
- Multi-beam klystron fabrication
- C band 80MW klystron(80MW/100Hz/3us)
- S band 80MW high efficiency klystron(80MW/55%)
- S band high efficiency PPM klystron
- P band resonant ring(1.2MW CW power)
- Energy recovery klystron
- LLRF system
- Klystron energy dissipation protection

1. High power test of high efficiency klystron

Milestone(2024)

- Jan.11 Klystron shipped to PAPS site；
- Feb.2, 1‰ duty factor, 800kW
- Jun.18, 10% duty factor, 800kW
- Jul.10, 50% duty factor, 800kW
- Jul.15, CW 600kW
- Jul.16, CW 700kW
- Jul.23, CW 800kW （max. 809kW）
- Aug.18, CW 803kW, Eff. 78.5%

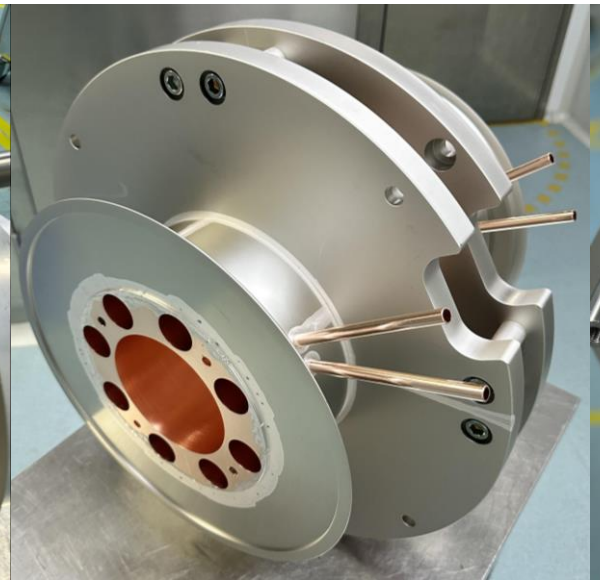




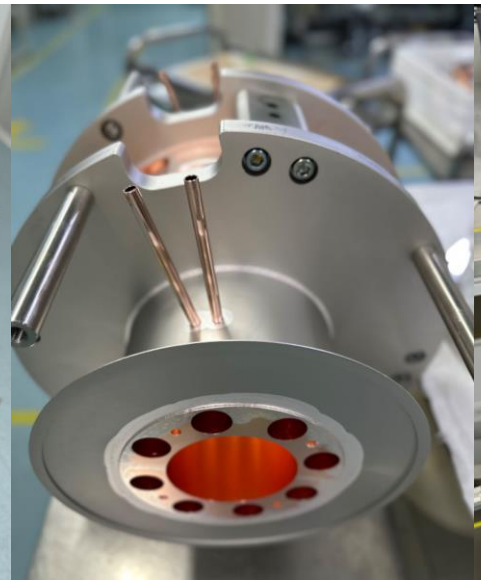
2. Multi-beam klystron Fabrication

- MBK’s cavity1, 2, 3, 4, 5 and 6 have completed brazing, leak detection and tuning, while the parts of cavity 7 are still being processed and are expected to be completed in this month.

CAV 3



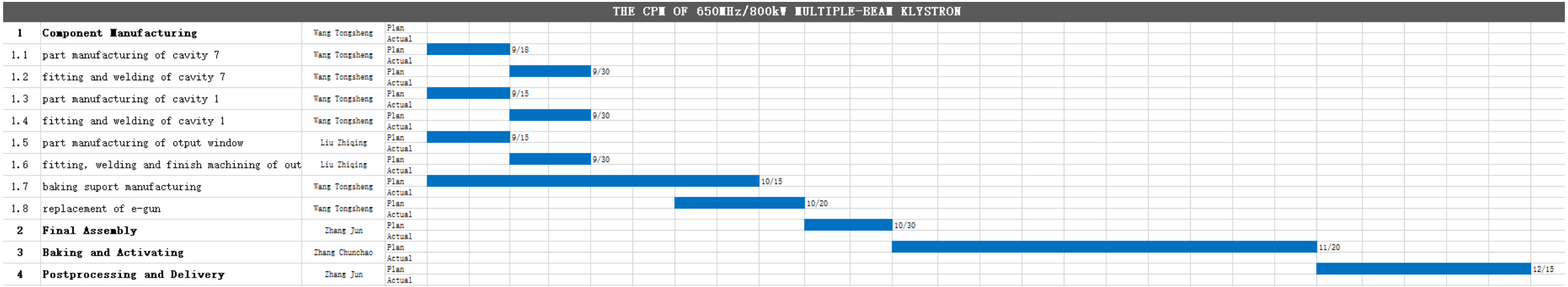
CAV 4



CAV 5

CAV 6

MBK fabrication schedule



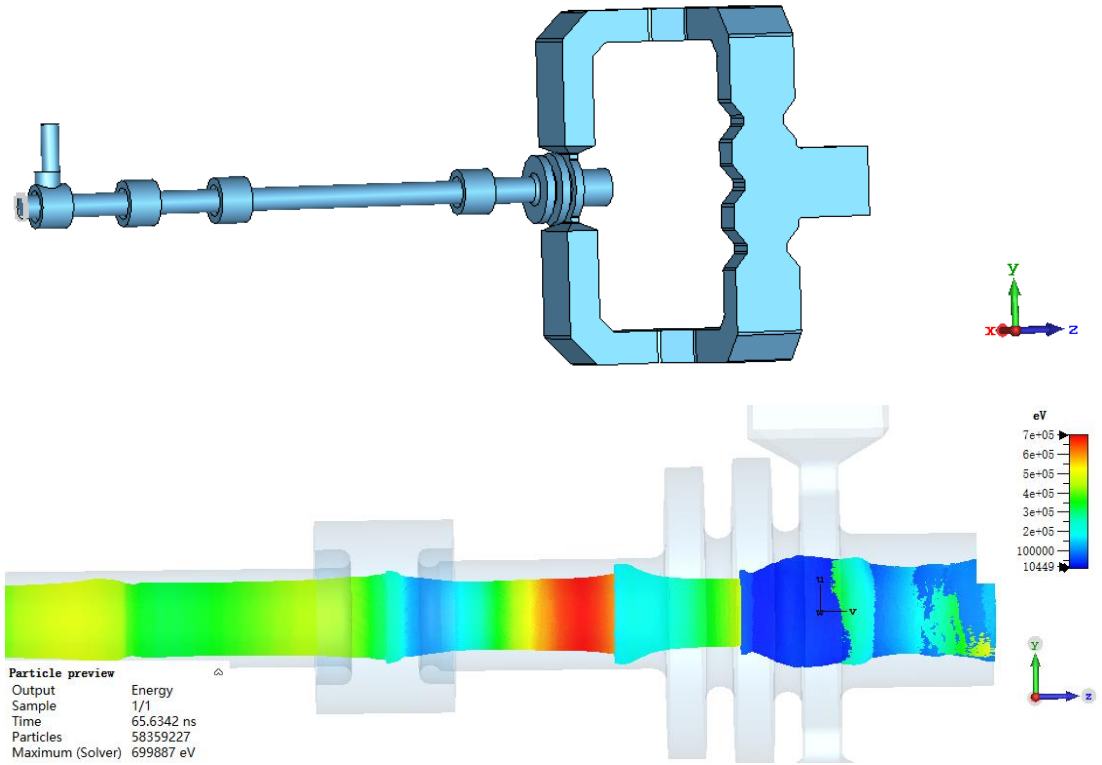
	THE CP▮ OF 650▮Hz/800k▼ ▮ULTIPLE-BEA▮ KLYSTRON			
1	**Component ▮anufacturing**	Wang Tongsheng	Plan	
			Actual	
1.1	part manufacturing of cavity 7	Wang Tongsheng	Plan	9/18
			Actual	
1.2	fitting and welding of cavity 7	Wang Tongsheng	Plan	9/30
			Actual	
1.3	part manufacturing of cavity 1	Wang Tongsheng	Plan	9/15
			Actual	
1.4	fitting and welding of cavity 1	Wang Tongsheng	Plan	9/30
			Actual	
1.5	part manufacturing of otput window	Liu Zhiqing	Plan	9/15
			Actual	
1.6	fitting, welding and finish machining of out	Liu Zhiqing	Plan	9/30
			Actual	
1.7	baking suport manufacturing	Wang Tongsheng	Plan	10/15
			Actual	
1.8	replacement of e-gun	Wang Tongsheng	Plan	10/20
			Actual	
2	**Final Assembly**	Zhang Jun	Plan	10/30
			Actual	
3	**Baking and Activating**	Zhang Chunchao	Plan	11/20
			Actual	
4	**Postprocessing and Delivery**	Zhang Jun	Plan	12/15
			Actual	

December 15, 2024, it will be delivered to IHEP and started to high power test

3. C band 80MW klystron

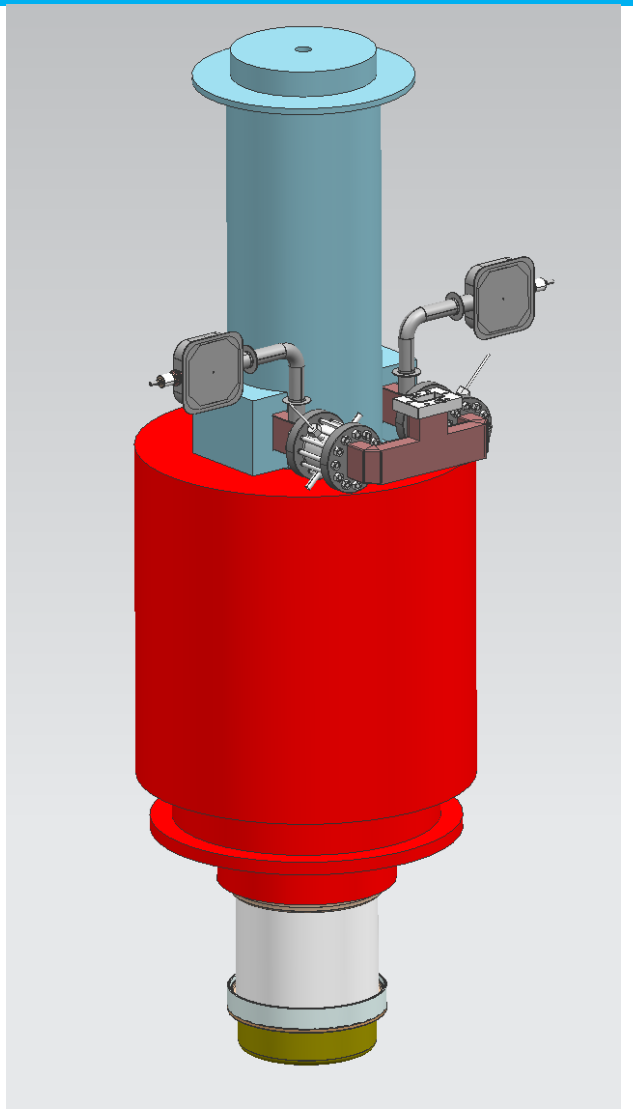
- Physical design @May.12, 2024
  - The design scheme is reasonable and feasible, and the design results have achieved the expected goals.

Parameters	Value	Cannon
Frequency	5720 MHz	5712MHz
Output Power	**80MW**	**50MW**
Repetition rate	**100Hz**	**50Hz**
Pulsed width	3us	3us
Efficiency	47%	42%
Beam voltage	420 kV	360kV
Beam current	403 A	320A



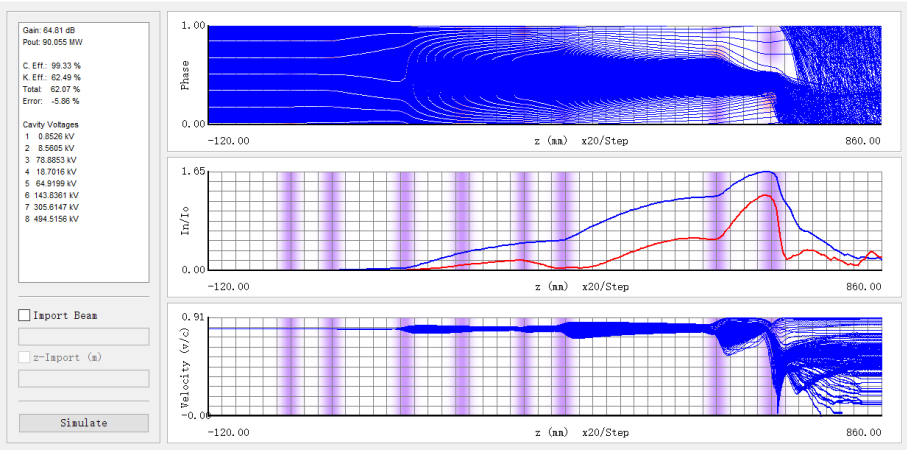
3. C band 80MW klystron

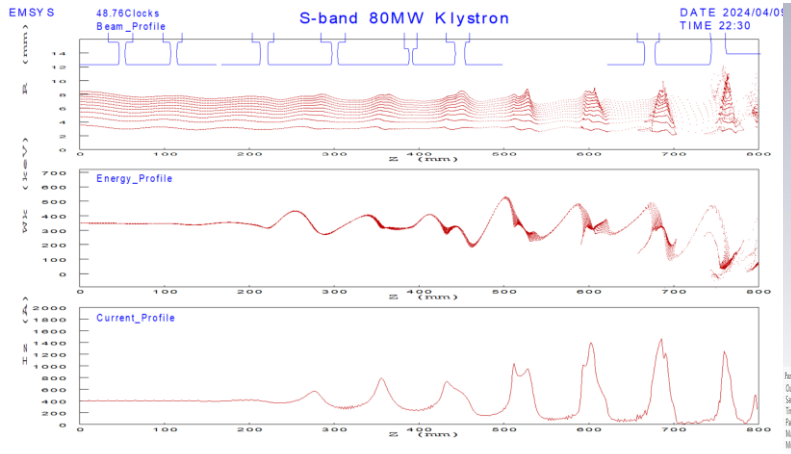
- Mechanical and process design review @Aug.12
  - The design scheme is feasible, meet the technical, and has the conditions for production implementation.
  - C-band 80MW klystron **enter the production stage**.

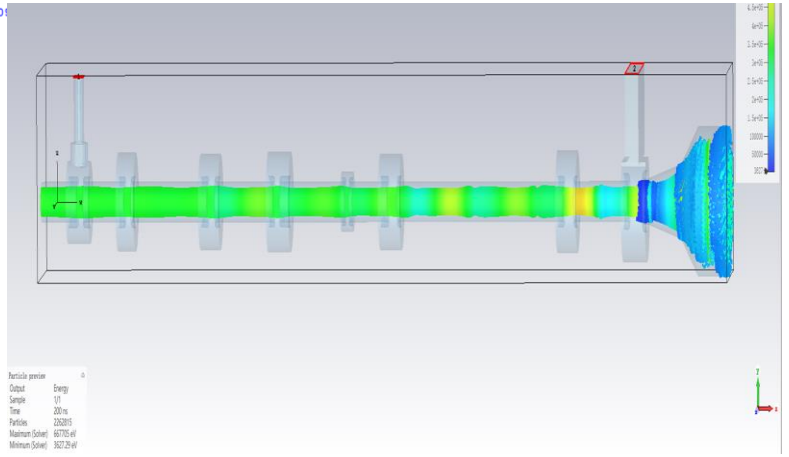


4. S band 80MW high efficiency klystron

- It is planned to apply the high efficiency method of klystron to the S-band to achieve a peak power output of 80 MW and an RF conversion efficiency of 55%.
- Currently using 8 resonant cavities, the RF conversion efficiency is 62% in 1D and 58% in 2D, and 3D simulation is underway.



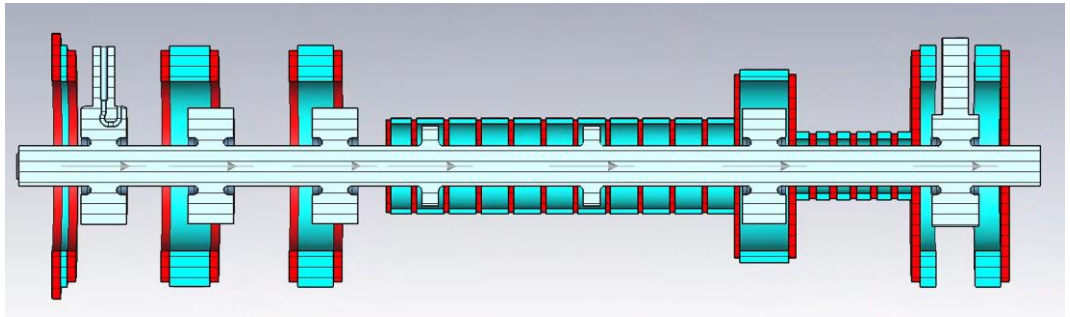




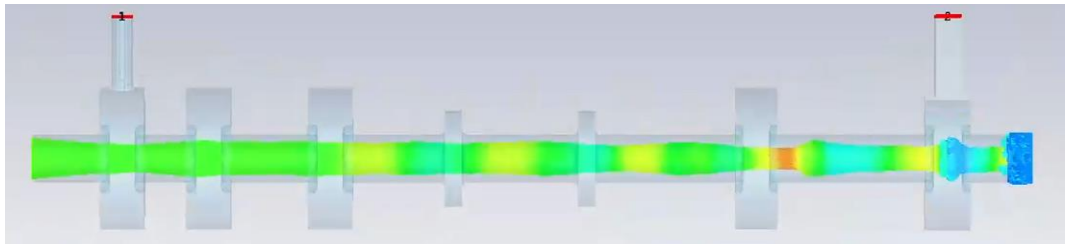
5. S band PPM klystron

- In order to improve the efficiency of the klystron and miniaturize the system, S-band 50MW periodic permanent magnet klystron was be proposed. At present, a output power of 50MW with an efficiency of 55% have been achieved and will be expected to 57%.

Frequency （Mhz）	2856
Efficiency （%）	55
Output power （MW）	50
Voltage(kV)	373
Current （A）	245
Perveance （μP）	1.08
Beam radius （mm）	7.1
Tube radius （mm）	11.8



Internal vacuum and magnetic structure

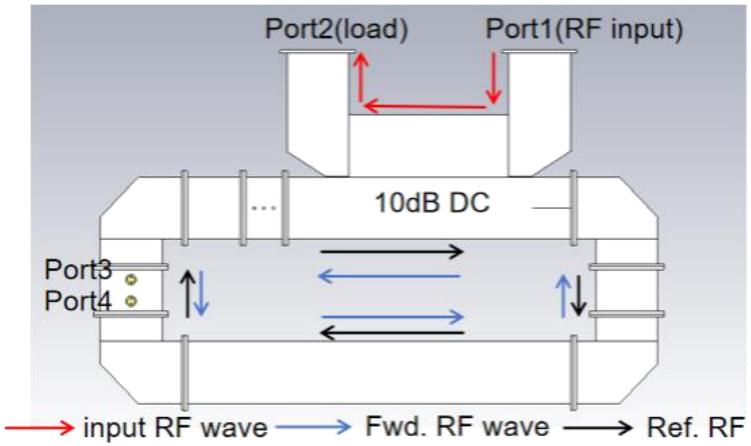


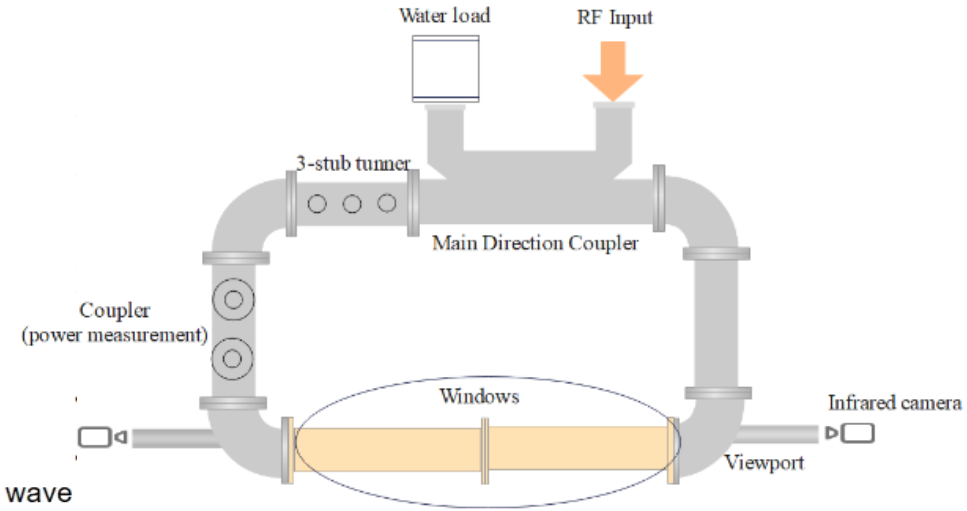
Beam simulation

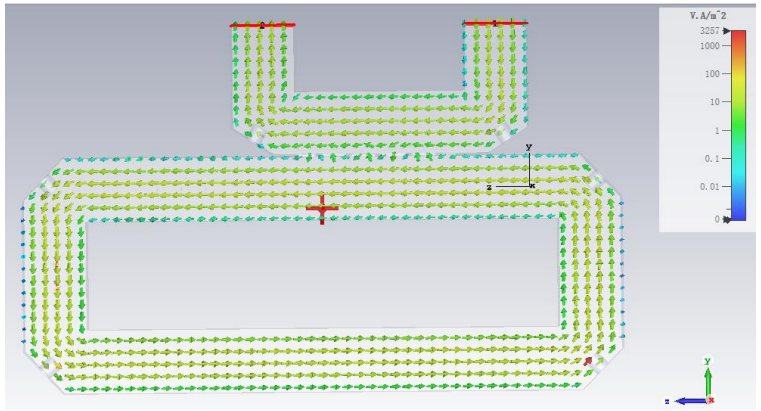
6. P band resonant ring

- 1.2 MW P-band Travelling Wave Resonant Ring (TWRR),
- 1.5 times (800-kW klystron) for conditioning of klystron window, cavity coupler and waveguide…

Coupling coefficient: 10dB
Max. power gain: 24
Length: 9.8m



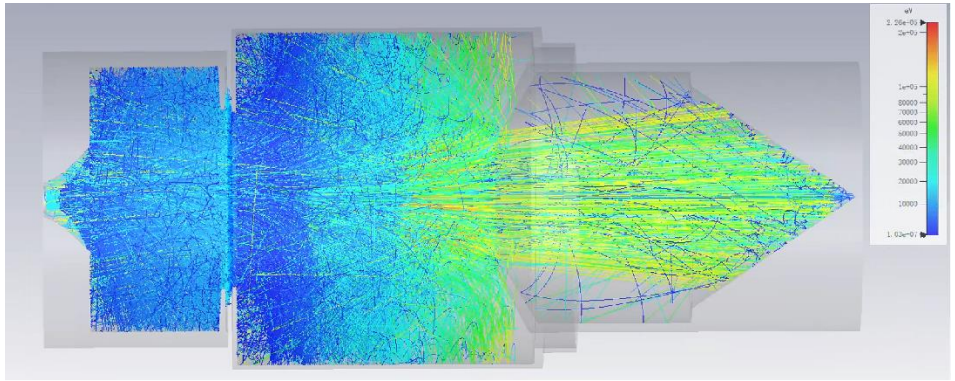




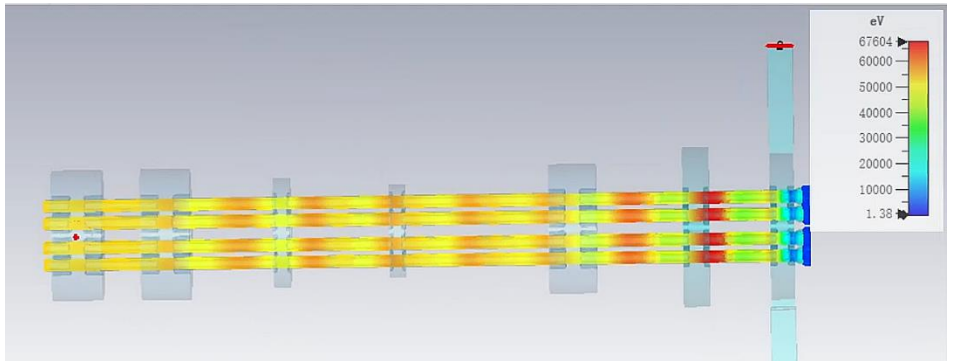
TWRR layout

7. Energy recovery klystron (ERK)

- Design of ERK with single beam klystron
  - Complete theoretical analysis and obtain preliminary design parameters
  - Complete 3D simulation and obtain preliminary structural parameters
  - Structural optimization, cooling and insulation design are in progress
- Design of ERK with Multi-beam klystron
  - Through data analysis, preliminary design parameters are obtained.
  - Beam dynamics simulation is being carried out.



ERK simulation with single beam klystron



ERK simulation with MBK

Design comparison

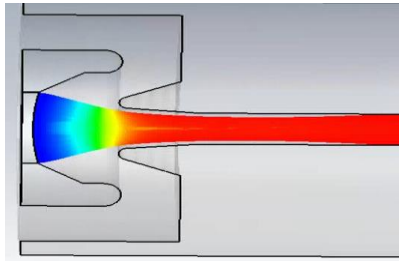
Based on klystron efficiency at linear region-----**65%**
Final efficiency is the whole efficiency of RF power source system

ERK with single beam klystron		
Stage No.	Final Eff.	Stage Voltage
Single stage	72.92%	17.3kV
Two stages	79.38%	17.2kV **113kV**
Three stages	82.95%	16.7kV 33.9kV **113kV**

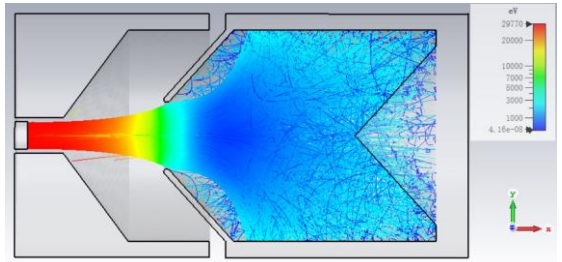
ERK with MBK		
Stage No.	Final Eff.	Stage Voltage
Single stage	75.16%	29.5kV
Two stages	81.46%	17.7kV **54kV**
Three stages	86.10%	6.8kV 24.2kV **54kV**

Depressed collector prototype

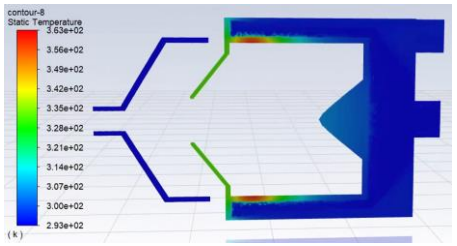
- **Milestones:**
  - Electron gun design completed in June 2023
  - Collector design completed in September 2023
  - Cooling system design completed in October 2023
  - Machining started in March 2024
  - Overall assembly and exhaust completed in June 2024
  - Arrived at IHEP on July 3, 2024



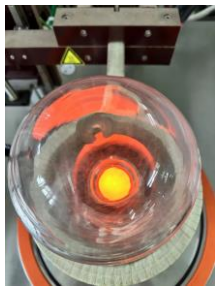
Gun simulation



Collector beam optics



Thermal analysis



Cathode activation

Welding of the cathode and focusing electrode of the electron gun

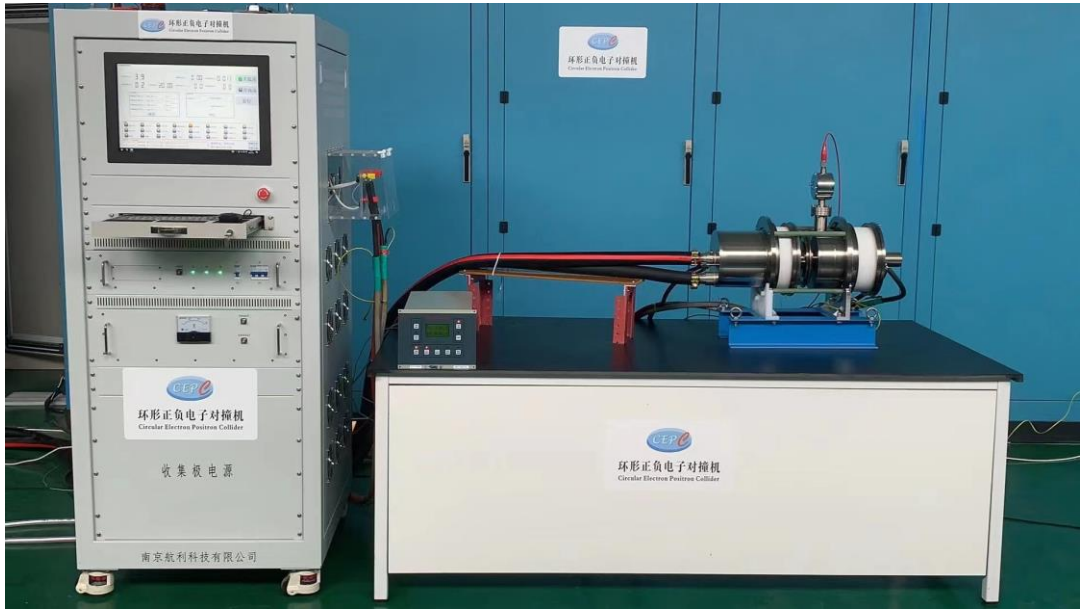
Degassing furnace evacuation

Unboxing inspection upon arrival of the prototype

Vacuum condition of the prototype upon arrival

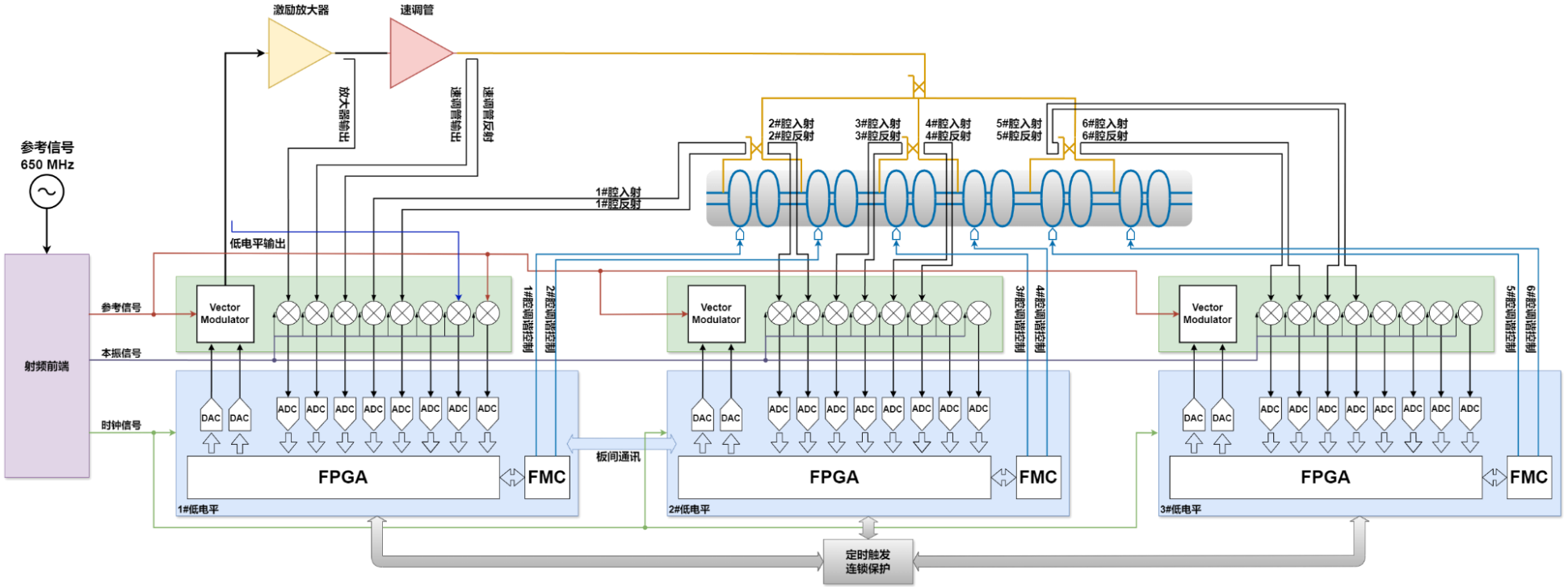
Depressed collector prototype

- **High power test:**
  - Completed cold high-pressure conditioning, vacuum normal
  - Test platform setup completed (interlocking control for water, electricity, flow, temperature, ion current, etc.)
  - Cathode filament power supply completed
  - High-voltage conditioning
  - Oct 22, 2024. **87.2% recovery efficiency**



8. LLRF system

- Design consideration：
  - The system is based on a **domestic MicroTCA** platform and includes three control boards.
  - A vector-sum-based multi-cavity control algorithm is used to achieve synchronous control of the amplitude, phase, and frequency of the six cavities.



LLRF progress

- Software
  - Completed the development of the domestic low-level control board's firmware
  - Ongoing work includes porting LLRF algorithms, developing multi-cavity control algorithms, and EPICS upper-layer application development.
- Hardware
  - Completed the development of the domestic low-level control board's firmware
  - Ongoing work includes porting LLRF algorithms, developing multi-cavity control algorithms, and EPICS upper-layer application development.

LLRF progress

- Some of the system hardware

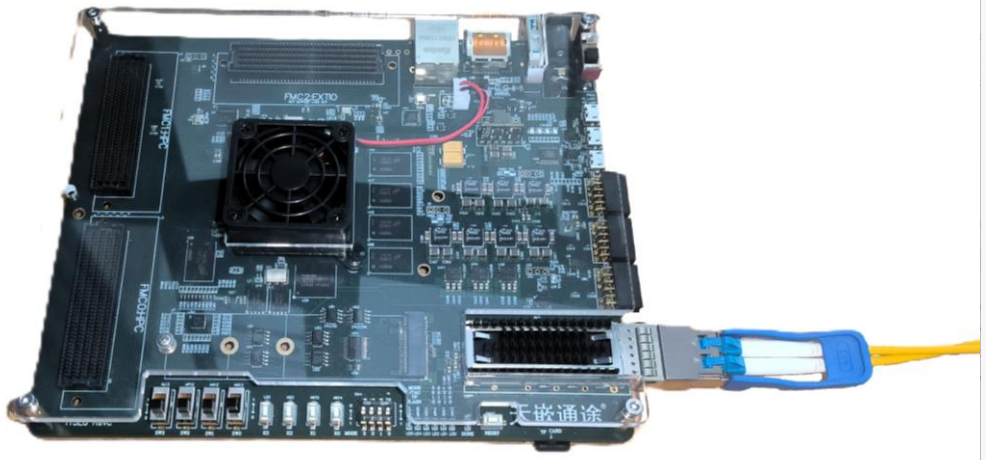
SC cavity tuning control board

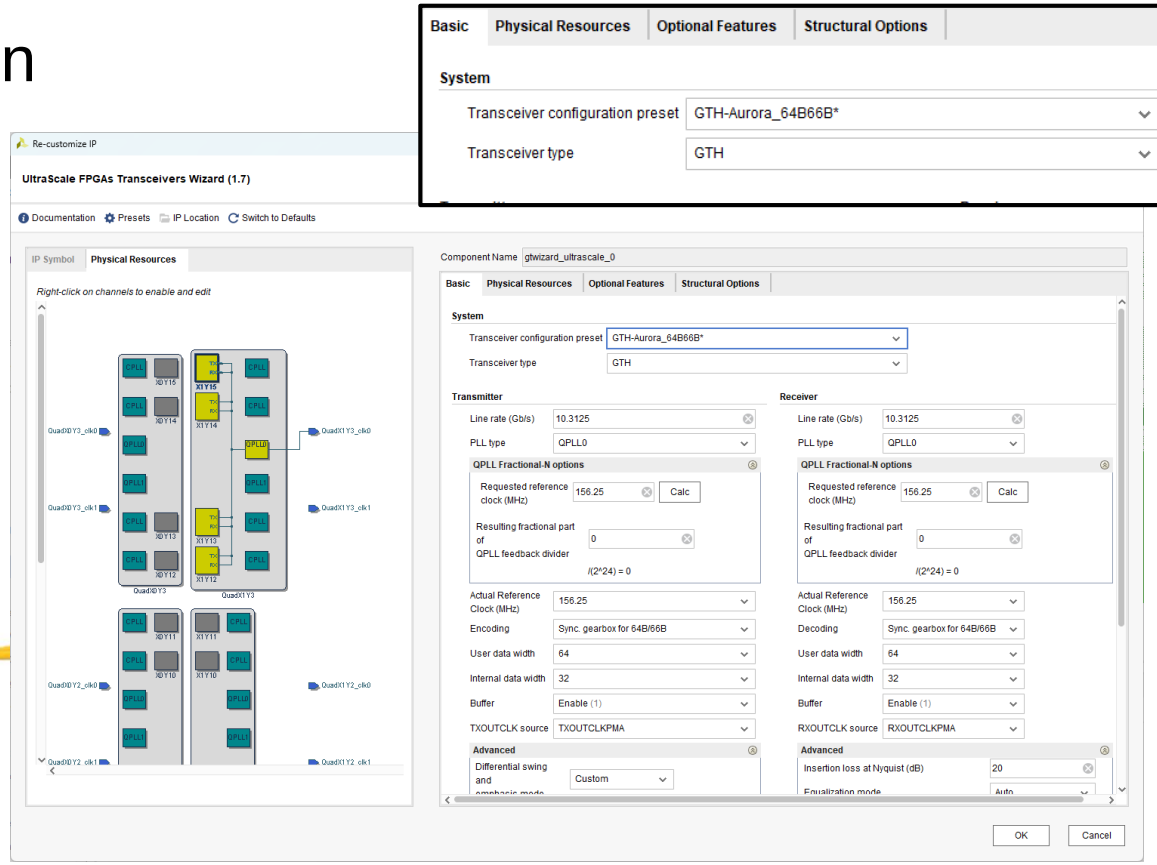
FMC daughter cards used for tuner control

domestically produced MicroTCA hardware

LLRF progress

- Inter-board communication solution



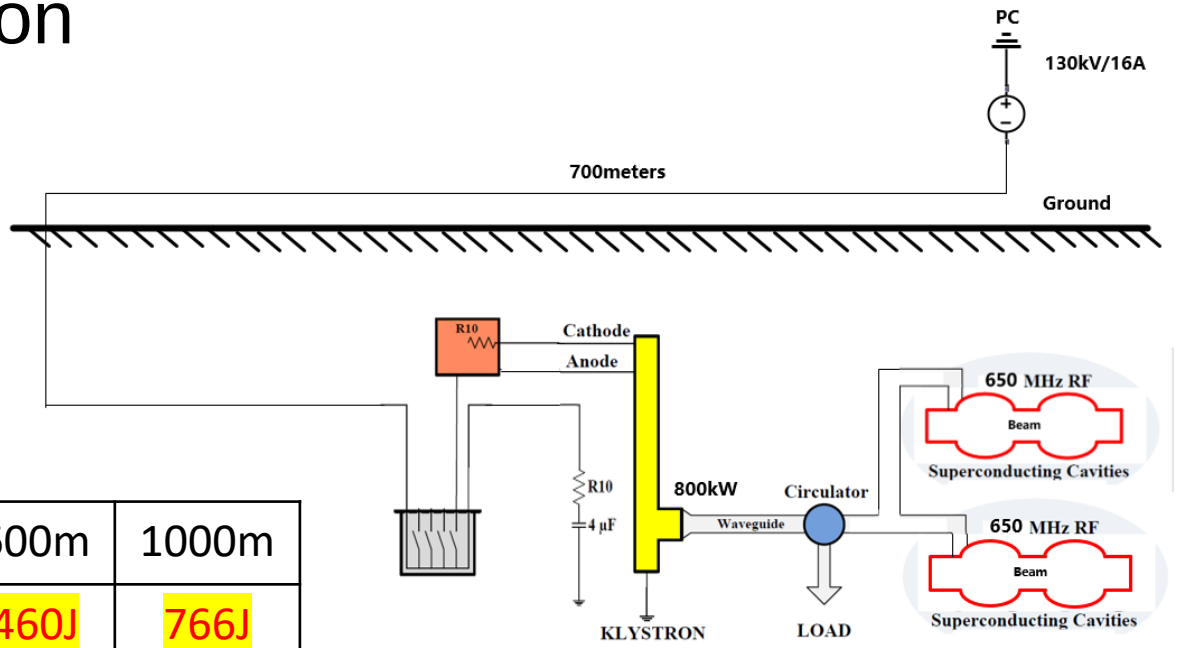


The hardware uses QSPF+ optical module communication, and the communication rate can theoretically reach 40Gbps

Inter-board communication is based on ZYNQ Ultrascale+ GTH transceiver and Aurora 64b66b communication protocol, which is currently under development and debugging.

9. Klystron energy dissipation protection

- Based on CEPC operation mode
  - Klystron is on the auxiliary tunnel and high voltage power supply is on the ground. The distance is about 500~700m.
- Klystron energy dissipation protection
  - Voltage level: 120kV
  - Protection time: ≦5us

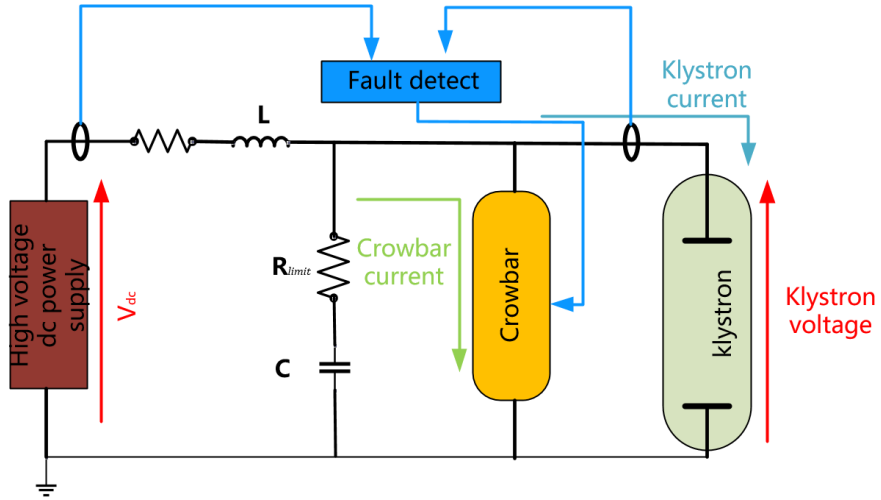


Klystron layout at TDR

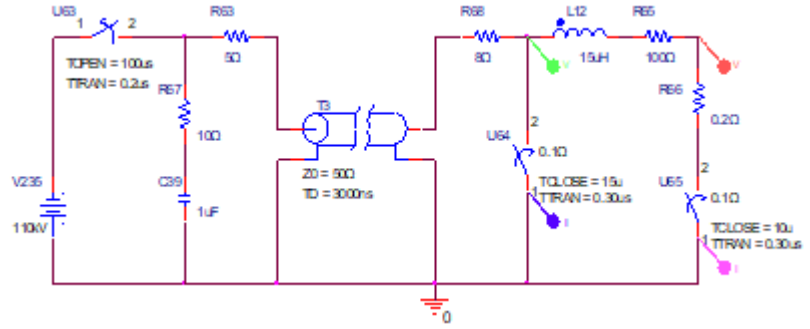
Cable length	12.5m	50m	80m	100m	200m	300m	600m	1000m
Storage energy	9.6J	38J	61J	76J	153J	230J	460J	766J

Design consideration

- Connect crowbar in parallel at one end of the klystron to bypass and discharge the energy
- Complete the energy analysis of the distributed capacitance discharge of long-distance cables
- Complete system modeling and system simulation, energy calculation and verification method design
- Complete the design review and conduct experimental verification



Schematic diagram of protection system



System modeling and simulation

Industrialization preparation progress and status

- 650MHz/800kW high efficiency klystron R&D
  - Close collaboration with partner for mass production of high efficiency klystron （GUOLI @Jiangsu province）
  - A new 800kW klystron will be completely manufactured in the middle of 2025.
- 5720MHz/80MW high power klystron R&D
  - Close collaboration with HANGUANG company at Hubei province
  - A new 80MW klystron will be completely manufactured in the beginning of 2025.
- 2860MHz, 5720MHz and 1.3GHz solid state amplifier
  - Close collaboration with HUAKANG company at Jiangsu province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HSPA-2000 2kW-S波段固态放大器
S波段固态放大器
无锡市华康广播电视设备厂
电源
风机
衰减
输出
输入

Key milestones from 2024-2027

- Proposal preparation of RF power source.(**2025**)
- Mass production preparation for high efficiency klystron.(**2024-2025**)
  - P band klystron and C band klystron
- LLRF, klystron protection system and power distribution system will be implemented for horizontal test of superconducting cavity.(**2024-2025**)
- Development of energy recovery klystron is for exploration of a much higher efficiency klystron.(**2024-2027**)

Conclusion

- The high power test of high-efficiency klystron prototype has been successfully completed, achieving a continuous wave (CW) output of 803 kW and an efficiency of 78.5%.
- Mass production preparations are underway for high efficiency klystron and high power klystron.
- Processing and high-power test of the MBK will be conducted this year.
- Development of an energy recovery klystron based on both MBK and single-beam klystron technologies is progressing.
- Efforts are also being made in the development of P-band and C-band resonant rings.
- An auxiliary system for the horizontal test of superconducting cavities will encompass LLRF, klystron energy dissipation protection, power distribution and transmission systems.

Acknowledgement

- We would like to express our sincere gratitude to Yifang Wang for his leadership and support through the **Ten Thousand Talents Program**, which has been instrumental in the success of this work.
- We also acknowledge the CEPC study group, GuoLi, Hanguang and Huakang company for their excellent cooperation.
- Additionally, we extend our appreciation to all colleagues and collaborators who contributed their time, expertise, and resources to this work.

Thanks for your attention