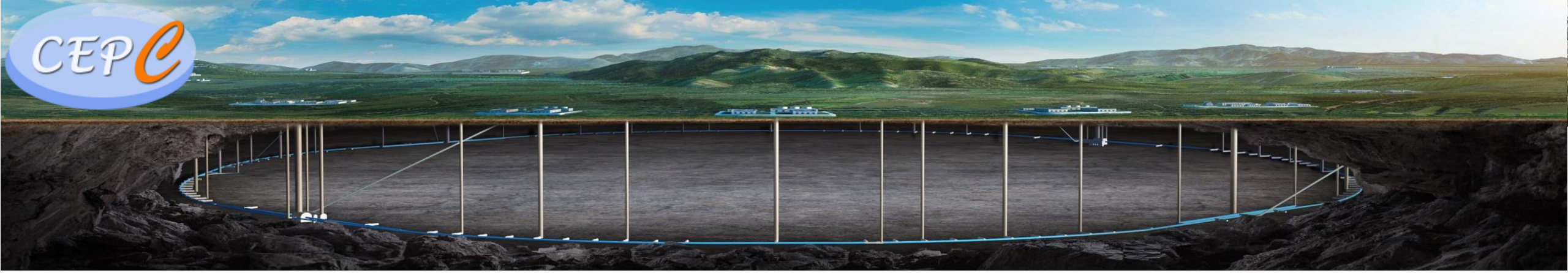

RF power sources for CEPC

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On behalf of CEPC klystron R&D team

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    - Resonant ring
- RF power source for SC cavity horizontal test

Design consideration for Collider RF sources

- Considering klystron lifetime, power redundancy and cost, the 2 cavities will be powered with one CW klystron capable to deliver more than 800 kW.
- High voltage DC power supply for high power and high efficiency klystron.
- Distributions of RF power to the cavities, including waveguide, power divider, phase shifter, circulator and load.
- Other Auxiliary PS, interlock and controls, LLRF, pre-amplifier are also included in RF power source system.

Design consideration for Collider RF sources

- Requirement list:

Klystron	96	650MHz/800kW
PSM Power Supply	96	130kV/16A and 60kV/22A
Circulator	96	650MHz/800kW
Load	96	650MHz/800kW
Phase shift	96	650MHz/800kW
Waveguide	96	Power divider/directional coupler
LLRF	96	Phase stabilization <0.1 degree, Amplitude stabilization <0.1%
Pre-amplifier	96	650MHz/100W

Design consideration for Collider RF sources

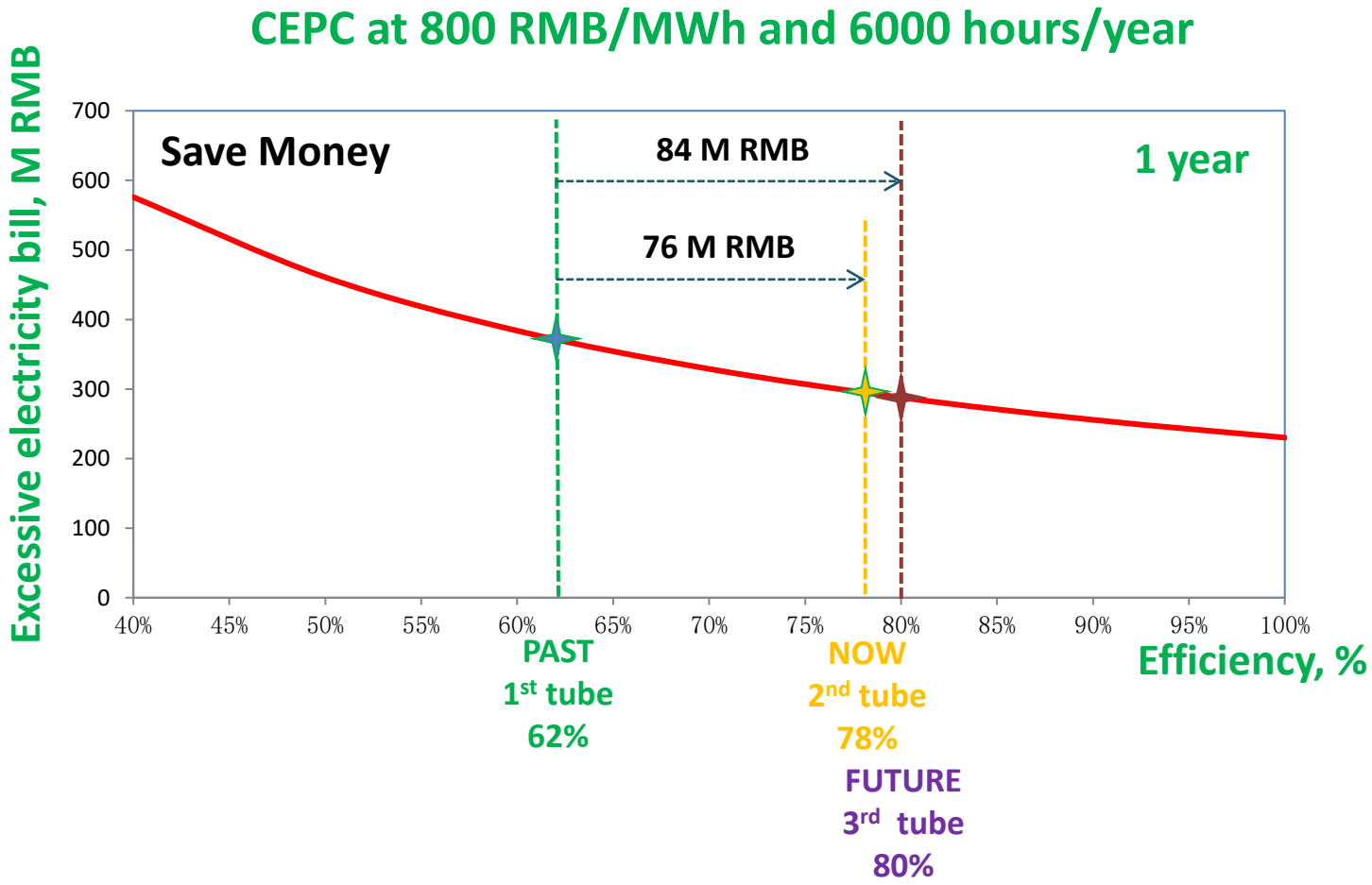
- Requirement list:

Klystron	96	650MHz/800kW	Higher efficiency
PSM Power Supply	96	130kV/16A and 60kV/22A	Mature product
Circulator	96	650MHz/800kW	Mature product
Load	96	650MHz/800kW	Mature product
Phase shift	96	650MHz/800kW	Mature product
Waveguide	96	Power divider/directional coupler	Mature product
LLRF	96	Phase stabilization <0.1 degree, Amplitude stabilization <0.1%	Mature product
Pre-amplifier	96	650MHz/100W	Mature product

Design consideration for Collider RF sources

- Cost consumption

Efficiency impact on operation cost (Only considering operation efficiency of klystrons)



Design consideration for Booster RF sources

- Design consideration

The Booster RF system consists of 1.3 GHz superconducting RF cavities. There are 12 cryo-modules for Higgs operation, each containing eight 9-cell superconducting cavities. These cavities need 96 set 1.3 GHz/25kW power sources.

Parameters	**Values**
Frequency	1.3 GHz
Power	25 kW
Gain	≥65 dB
Bandwidth (1dB)	≥ 1 MHz
Amplitude stability	≤0.1% RMS
Phase stability	≤0.1° RMS
Phase Variation	≤10°
Harmonic	< -30 dBc
Spurious	< -60 dBc
Efficiency at 25kW	≥45%
MTBF	≥30000 h
Redundancy	1 power module failure

Design consideration for Booster RF sources

- Requirement list:

SSA	96	1300MHz/25kW
Circulator	96	1300MHz/25kW
Load	96	1300MHz/25kW
Waveguide	96	Directional coupler
LLRF	96	Phase stabilization <0.1 degree, Amplitude stabilization <0.1%

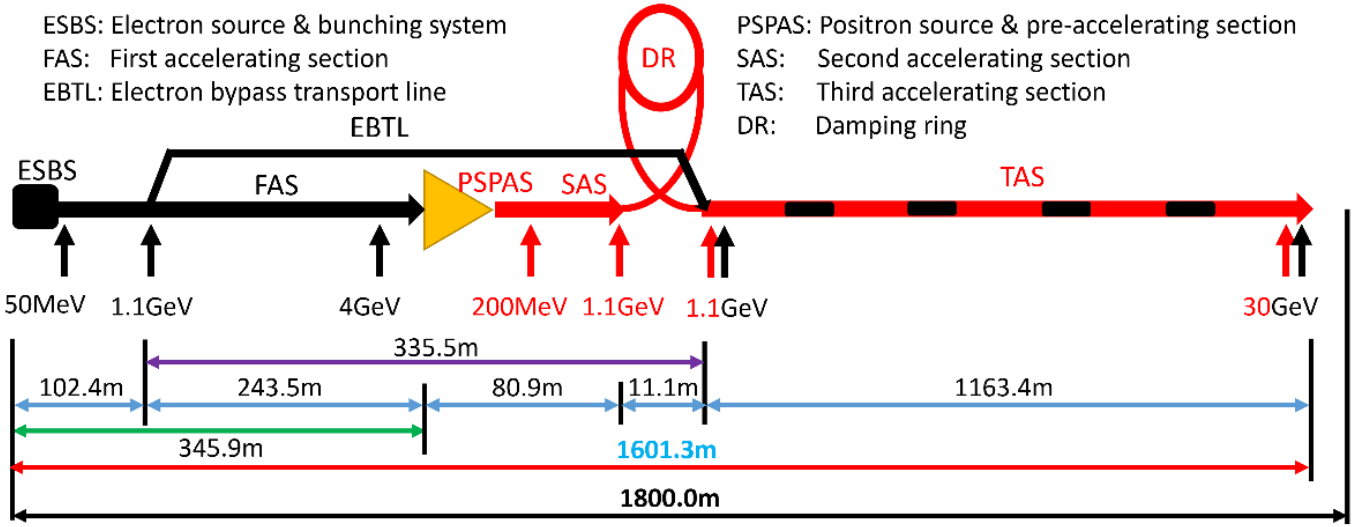
Design consideration for Booster RF sources

- Requirement list:

SSA	96	1300MHz/25kW	Mature product
Circulator	96	1300MHz/25kW	Mature product
Load	96	1300MHz/25kW	Mature product
Waveguide	96	Directional coupler	Mature product
LLRF	96	Phase stabilization <0.1 degree, Amplitude stabilization <0.1%	Mature product

Design consideration for Linac RF sources

- The main high power RF sources components are 33 units of 80MW S-band klystron, 236 units of 50MW C-band klystron and related modulators.



Type	QTY	Freq.(MHz)	Structure type
S-band klystron	33	2860	1 1-to-1, standard-bunch 3 1-to-2, standard acc. structure. 8 1-to-2, large aperture acc. structure 21 1-to-4, standard acc. structure.
C-band klystron	236	5720	1-to-2, standard acc. structure.

Design consideration for Linac RF sources

- Requirement list:

S band klystron	33	2860MHz/80MW
Modulator of S band klystron	33	400kV/500A
C band klystron	236	5720MHz/50MW
Modulator of C band klystron	236	350kV/400A

Design consideration for Linac RF sources

- Requirement list:

S band klystron	33	2860MHz/80MW	Mature product
Modulator of S band klystron	33	400kV/500A	Mature product
C band klystron	236	5720MHz/50MW	Mature product
Modulator of C band klystron	236	350kV/400A	Mature product

Design consideration for Linac RF sources

- Why we develop C band 80MW klystron?
  - Only C band of **50MW** klystron is mature product in the world.
  - 1 klystron only power to 2 accelerator structures (CEPC Linac baseline).
  - QTY of C band klystron is very large (**236 set**).

Type	QTY	Freq.(MHz)	Structure type
S-band klystron	33	2860	1 1-to-1，standard-bunch 3 1-to-2，standard acc. structure. 8 1-to-2，large aperture acc. structure 21 1-to-4，standard acc. structure
C-band klystron	236	5720	1-to-2，standard acc. structure.

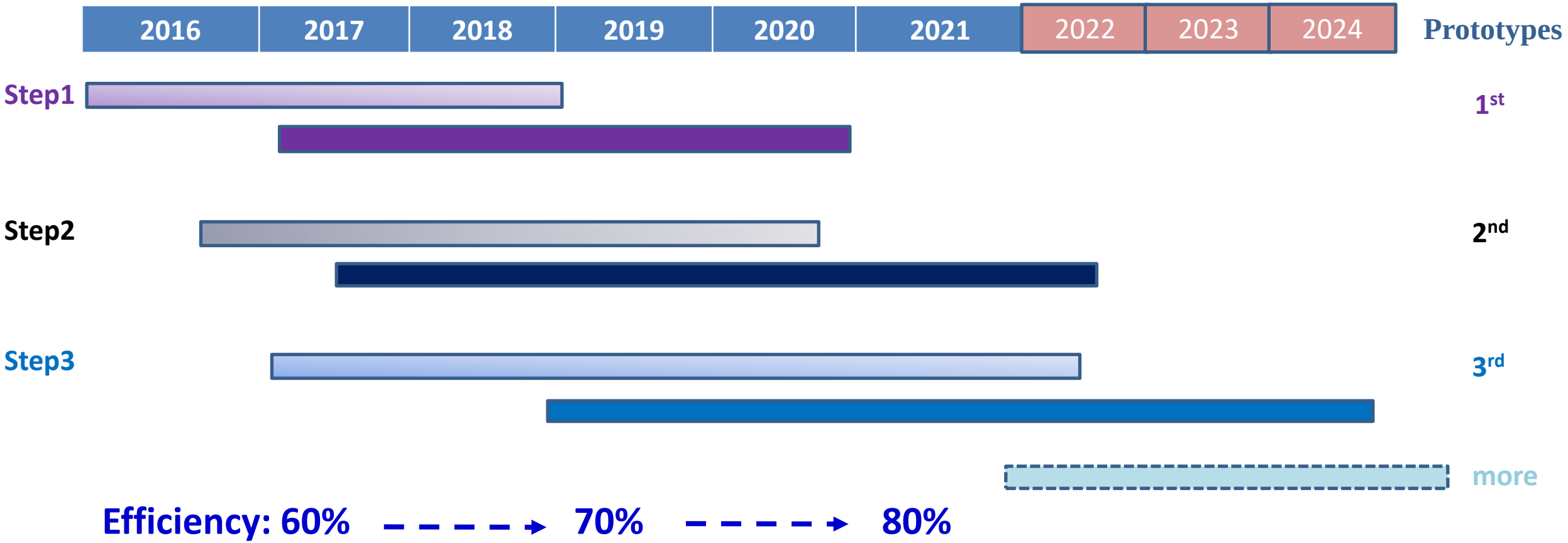
CEPC Linac baseline

- IF output power of C band klystron is up to 80MW, the quantity of klystron will be reduced by half. (1 klystron power to 4 accelerator structures).

R&D Status

650MHz klystron R&D strategy and plan

- 3 or more klystron prototypes for klystron efficiency improvement



Design scheme

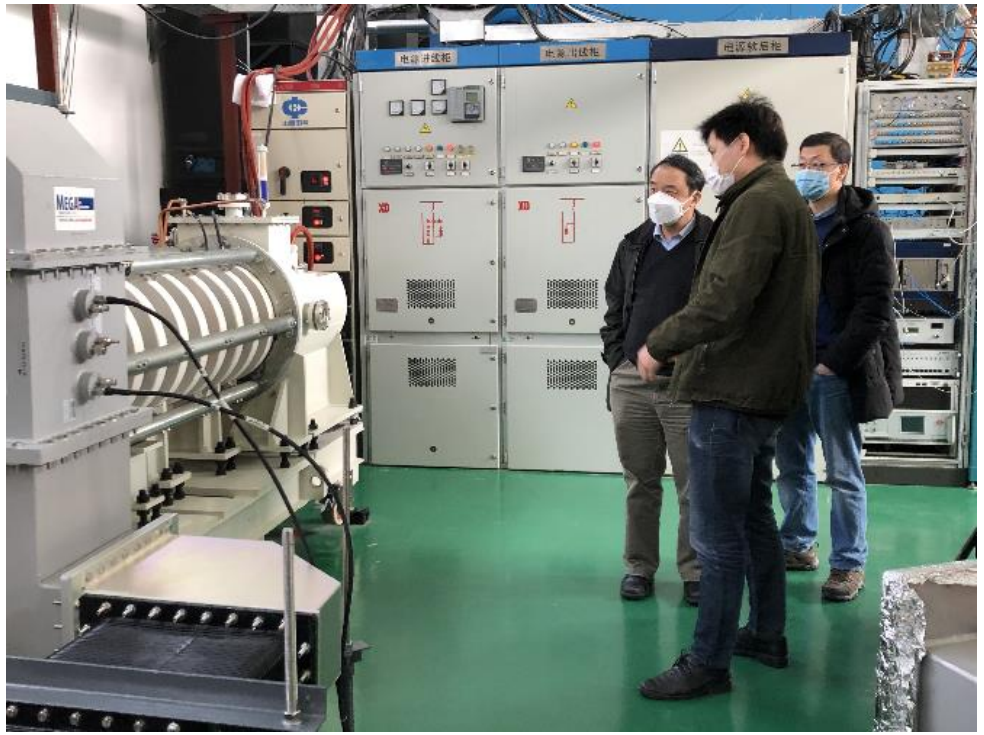
- Scheme 1: Traditional way for >60% efficiency
- Scheme 2: With high voltage gun (110 kV/9.1 A), low perveance (HE, >75%)
- Scheme 3: MBK, 54 kV/20A electron gun (8 beams) (HE, >80%)

Parameter	Scheme1(1st prototype)	Scheme2(2nd)	Scheme3(3rd)
Freq. (MHz)	650	650	650
Voltage (kV)	82	110	54
Current (A)	16	9.1	20(2.5×8)
Beam No.	1	1	8
Perveance (μP)	0.65	0.25	1.6(0.2×8)
Efficiency (%)	65	~80	>80
Power(kW)	800	800	800(100×8)

1st prototype milestone

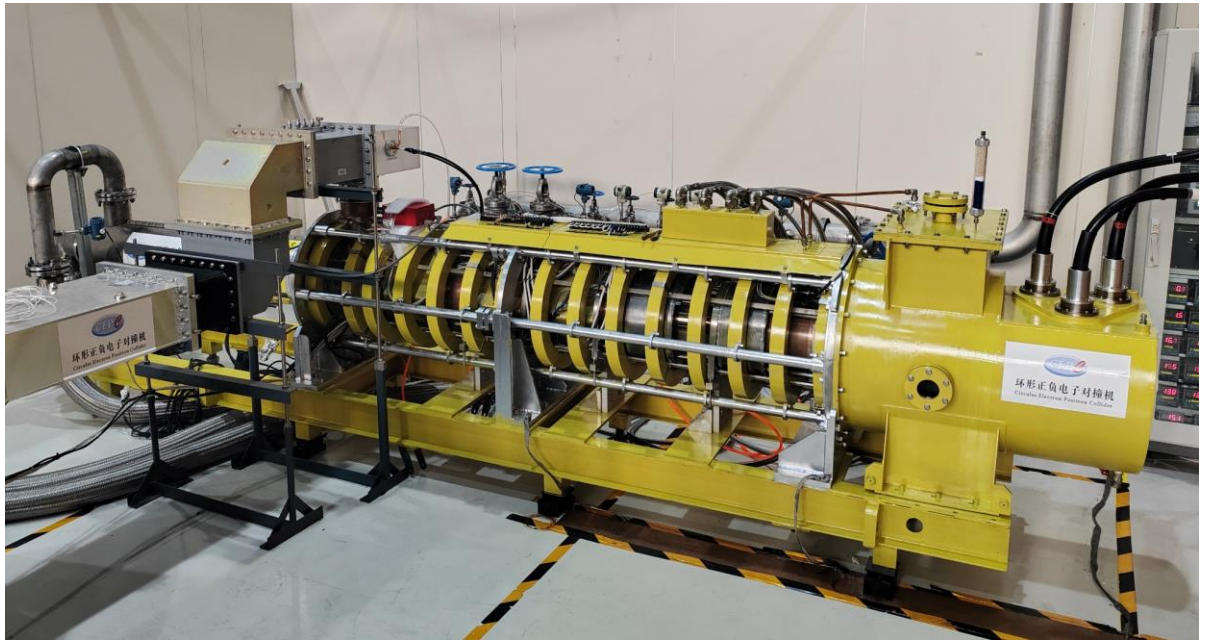
- Oct. 2017 Design report
- Mar. 2020 High power test at IHEP

Parameters	Design	Test
Operating frequency (MHz)	650	650
Beam Voltage (kV)	81.5	80
Beam Perveance (μA/$V^{3/2}$)	0.65	0.7
Efficiency(%)	65	62
Saturation Gain(dB)	≥45	47
Output power(kW)	800	800
1 dB Bandwidth(MHz)	≥1	1.8



2nd prototype (HE design) milestone

- Jan., 2021: Klystron manufacture started
- Jul., 2022: CW 630kW with Eff. 70.5% (1st stage high power test)
- Aug., 2024: CW 803kW with Eff. 78.5% (2nd stage high power test)



3rd prototype (Multi-beam design) milestone

- Dec., 2021: Klystron beam tester manufacture started
- Oct., 2023: Accomplishment of klystron beam tester high voltage conditioning and beam emission.
- Sep. 2024: Klystron manufacture is in progress.
- Dec. 2024: Klystron will be delivered to IHEP and started to high power test.

CAV. No.	2	3	4	5	6
Design Freq. (MHz)	651.2	1296	1942.5	670	671
Cold test before brazing (MHz)	651.237	1303.99	1936.875	666.9375	670.3125
Cold test after brazing (MHz)	649.375	1290.5	1937.4719	667.21875	669.7356
Cold test after tuning (MHz)	651.1625	1295.75	1942.3249	669.8125	670.7325
Cold test after temperature and humidity correction (MHz)	651.108	1295.624	1941.983	669.819	670.844
	18℃ RH% 45%	22℃ RH% 56%	21℃ RH% 52%	21.5℃ RH% 47%	20℃ RH% 38%
	2023/2/17	2024/5/30	2024/7/23	2024/6/21	2024/5/6

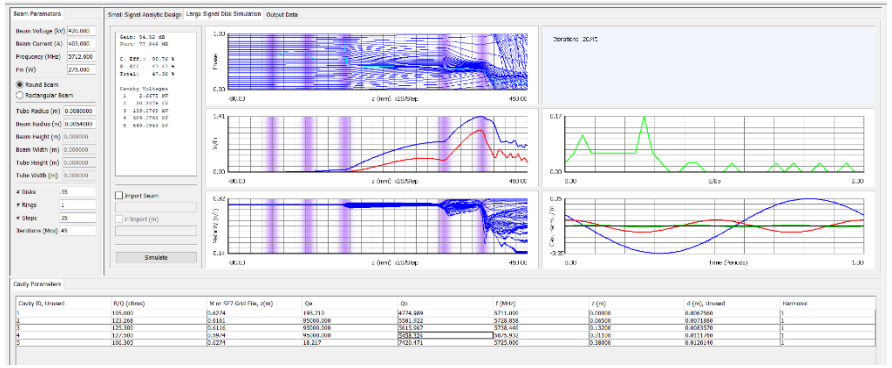
5720MHz klystron design

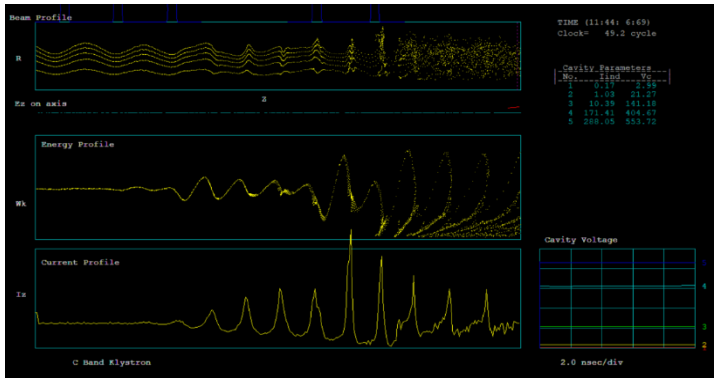
Design progress

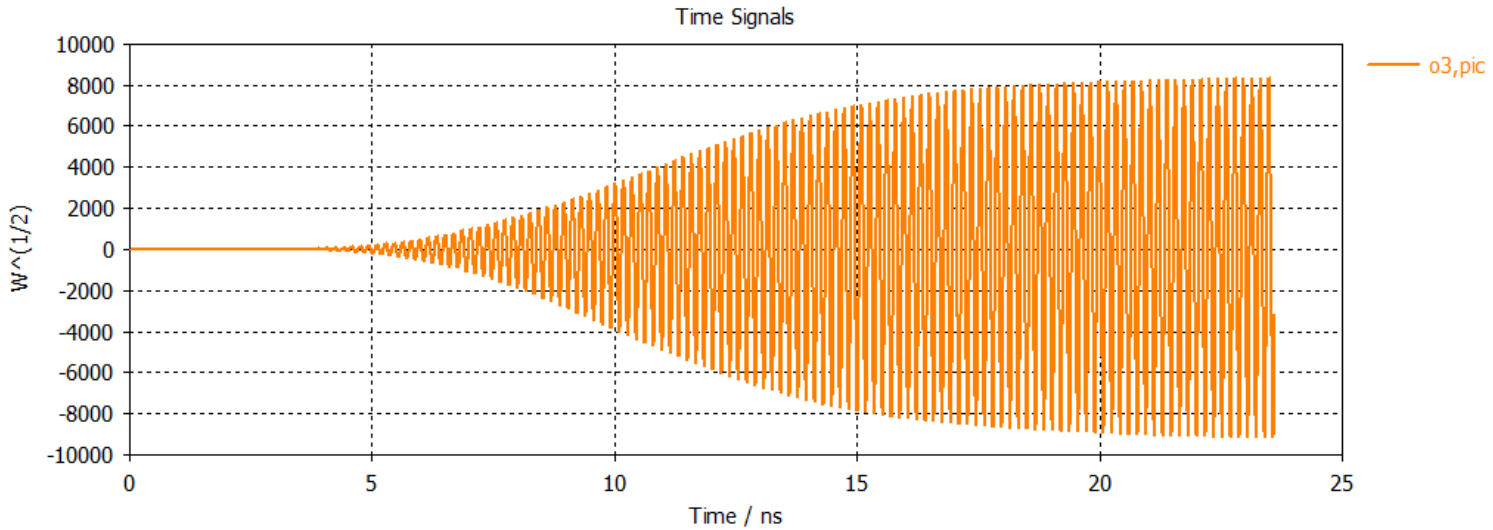
Main parameters

Parameters	Value
Frequency	5720 MHz
Output Power	**80MW**
Pulsed width	**3us**
Repetition rate	**100Hz**
Gain	54 dB
Efficiency	47%
Beam voltage	420 kV
Beam current	403 A

Beam dynamics

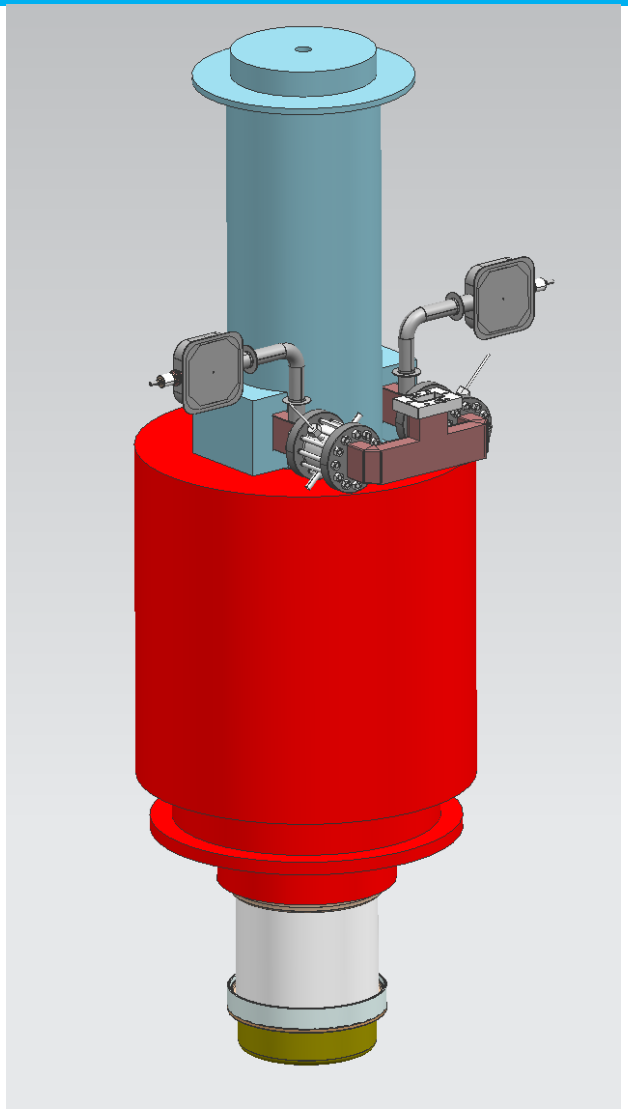






Fabrication progress

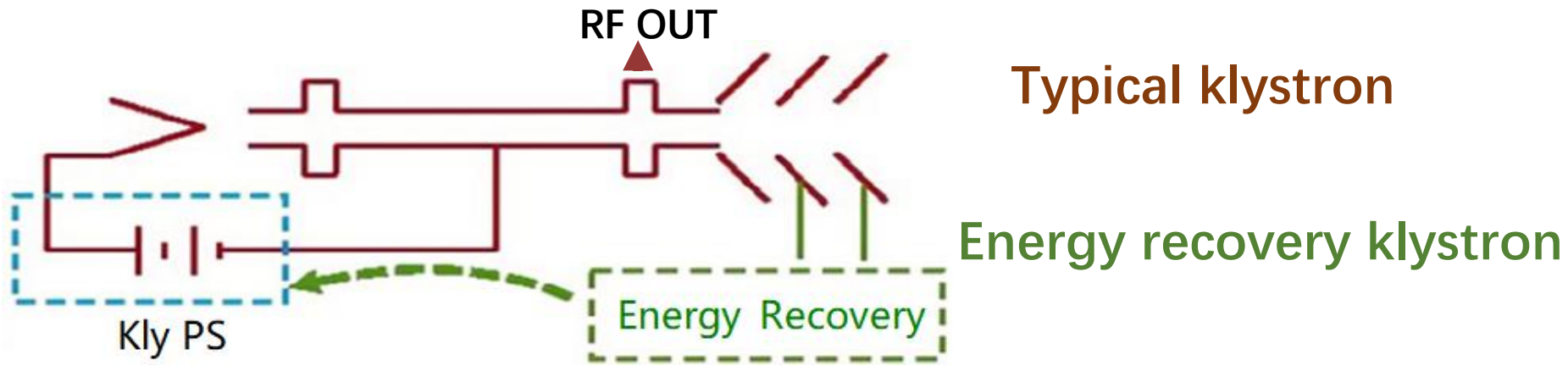
- Mechanical and process design review @Aug.12
  - The design scheme is feasible, meet the technical, and has the conditions for production implementation.
  - C-band 80MW klystron **enter the production stage**.



Energy recovery klystron

Energy recovery klystron(ERK)

- If 60MW SR power (e+&e-) of CEPC, RF power demands 109.5MW, waster power is still about 49.5MW. (Klystron efficiency~65% @linear region and ~80%@saturate region).
- The energy recovery klystron recovers energy from the spent electron beam by multi-depressed collector, thereby reducing the power demand from the grid and significantly lowering operation.



Roughly theoretical analysis

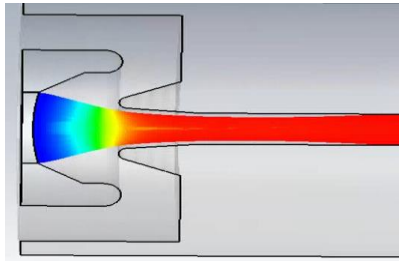
Based on klystron efficiency at linear region-----**65%**
Final efficiency is the whole efficiency of RF power source system

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**

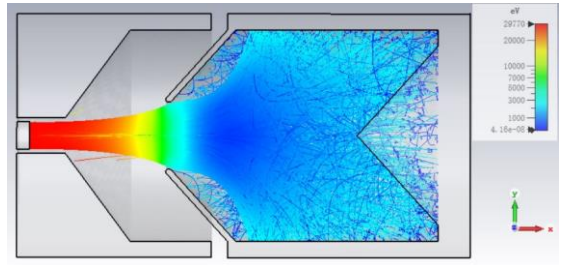
ERK with MBK		
Stage No.	Final Eff.	Stage Voltage
Single stage	75.16%	29.5kV
Two stages	81.46%	17.7kV **54kV**
Three stages	86.10%	6.8kV 24.2kV **54kV**

Depressed collector prototype

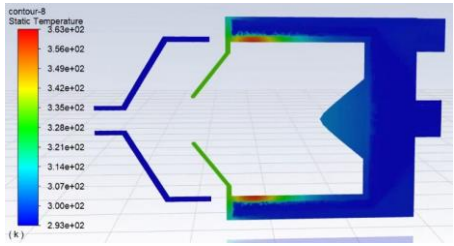
- **Milestone:**
  - Electronic gun design completed in June 2023
  - Collector design completed in September 2023
  - Cooling system design completed in October 2023
  - Prototype ceramic insulation structure design completed in December 2023
  - Mechanical mechanism design completed in December 2023
  - Machining started in March 2024
  - Overall assembly and exhaust completed in June 2024
  - Arrived at IHEP on July 3, 2024



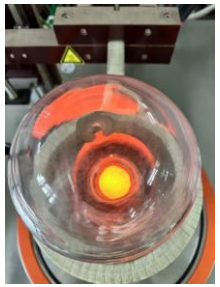
Verify the prototype electron gun



Collector beam optics



Thermal analysis of the water cooling system



Cathode activation

Welding of the cathode and focusing electrode of the electron gun

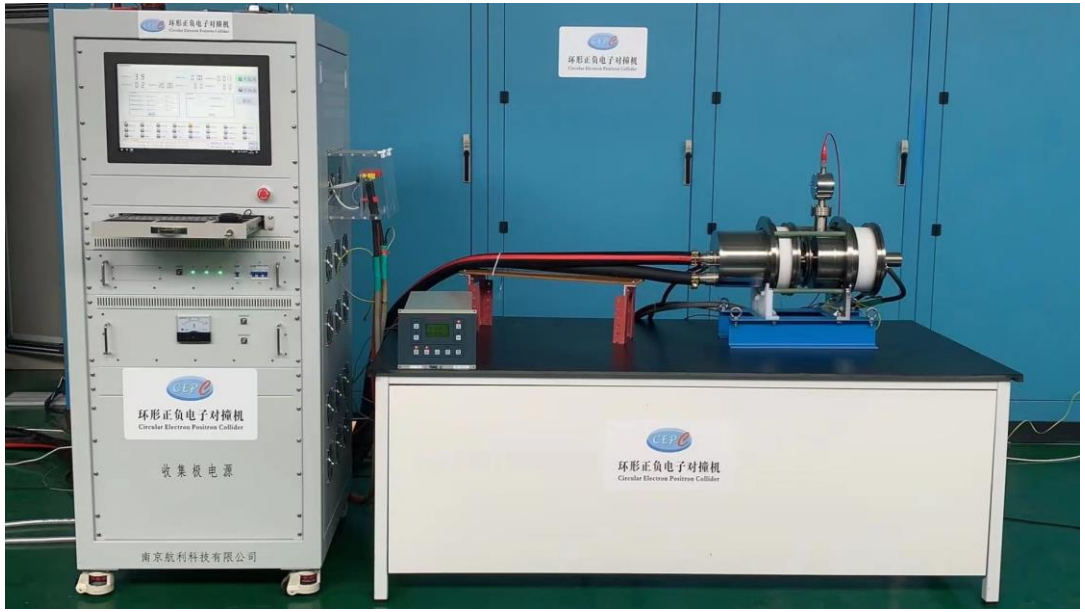
Degassing furnace evacuation

Unboxing inspection upon arrival of the prototype

Vacuum condition of the prototype upon arrival

Depressed collector prototype

- **Test stand preparation:**
  - 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 testing in progress



PPM klystron

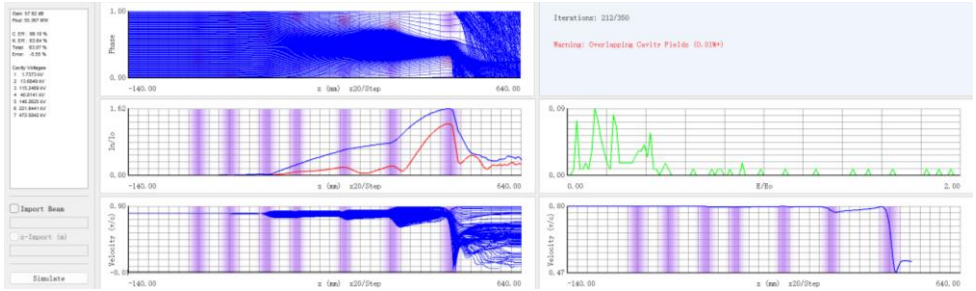
PPM advantage

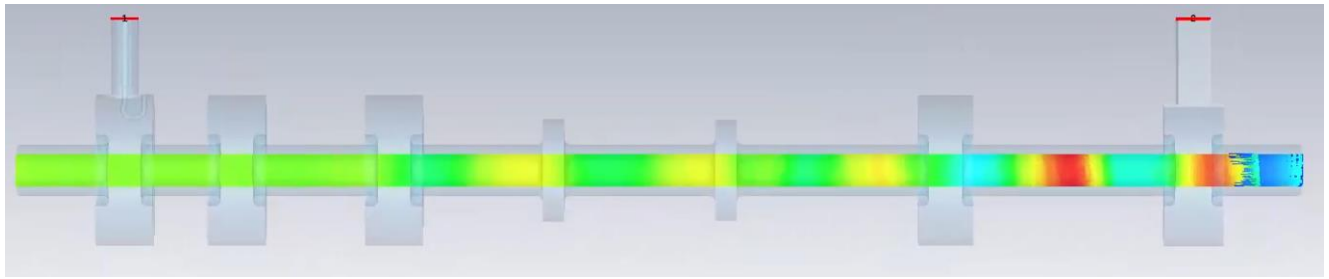
- Small volume, light weight, and does not require water cooling and power supply.
- It saves the power consumption and cost of power supply, and on the other hand, it avoids the risk of power supply failure and water leakage.

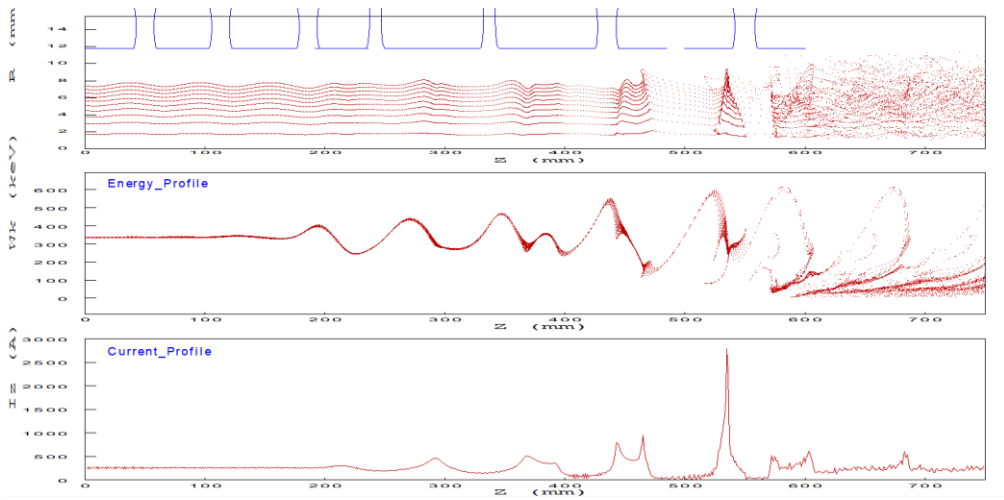
	E37212	E37302A
Frequency(MHz)	5712	2998
Output Power (MW)	51	47
Beam Power (MW)	118.3	123.5
Average Power (kW)	35.5	24.7
Solenoid Power (kW)	8.4	3.4
RF efficiency (%)	**43.1**	**38**
Overall efficiency(%)	**34.9**	**33.5**

PPM klystron

- On the basis of the S band klystron with high efficiency design, the electromagnetic focusing is being changed to PPM focusing structure.

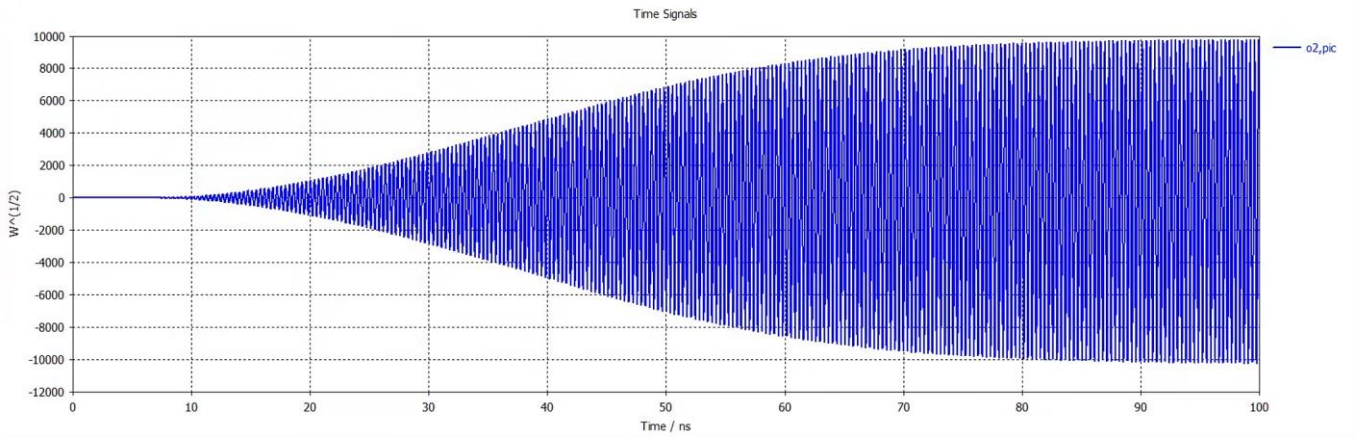


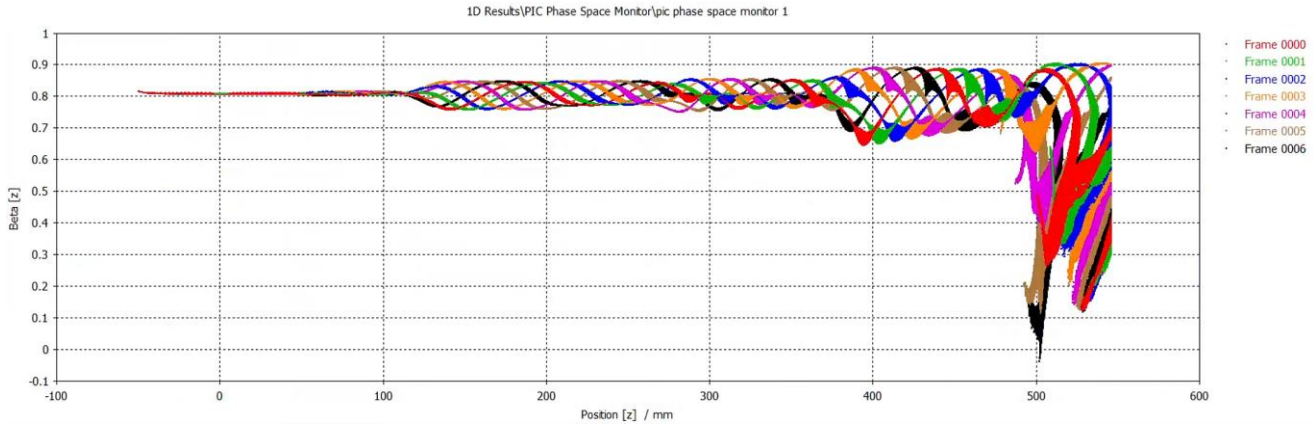




Parameters	Value
Freq. (MHz)	2856
Output power (MW)	≥50
Eff. (%)	≥55
Focusing structure	PPM

Design status





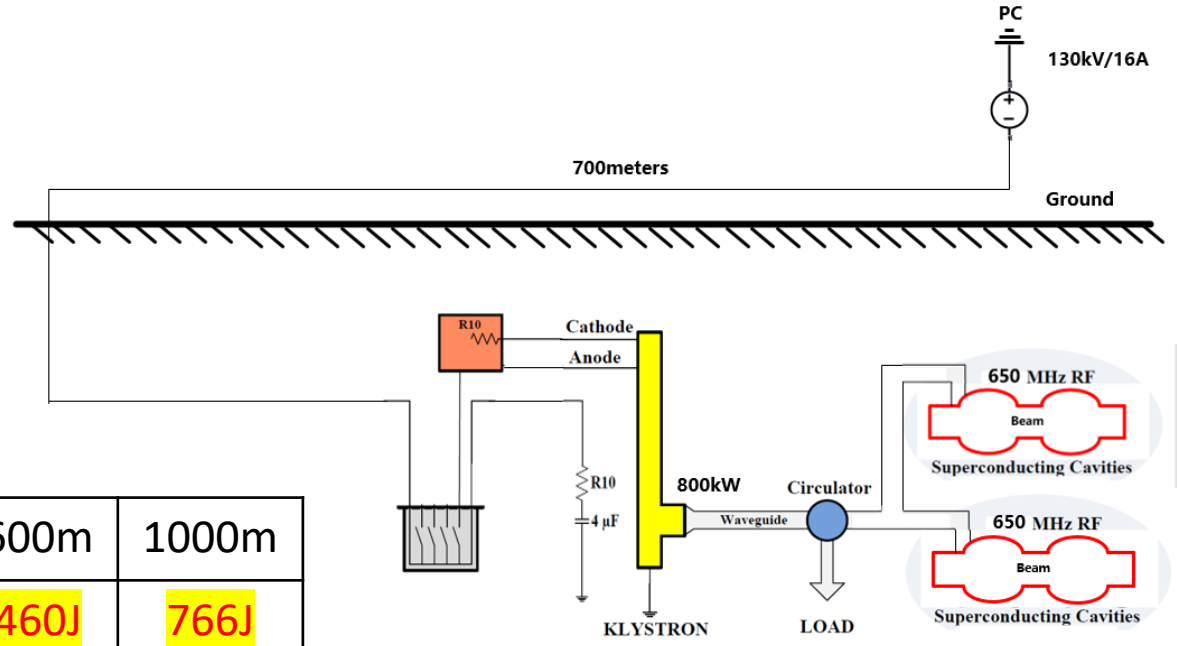
Simulation results

	Output Power (MW)	Eff. (%)
Ajdisk	55.4	63
EMSYS	51.4	59
CST	50.1	55

Klystron energy dissipation protection

Klystron energy dissipation protection

- CEPC Klystron is on the auxiliary tunnel and high voltage power supply is on the ground. The distance is about 700m.
- Klystron energy dissipation protection
  - Voltage level: 130kV
  - Protection time: ≦5us

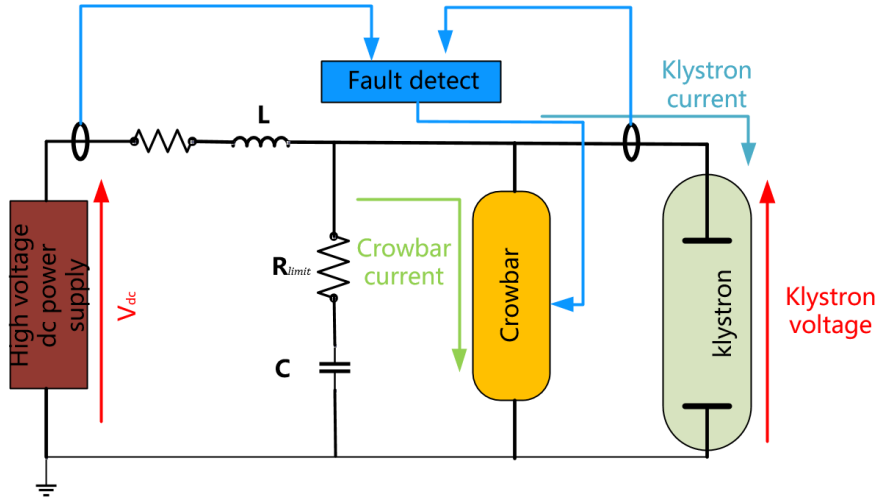


Klystron layout at TDR

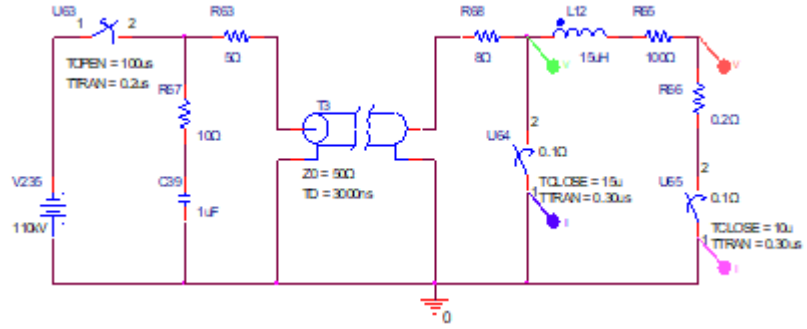
Cable length	12.5m	50m	80m	100m	200m	300m	600m	1000m
Storage energy	9.6J	38J	61J	76J	153J	230J	460J	766J

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

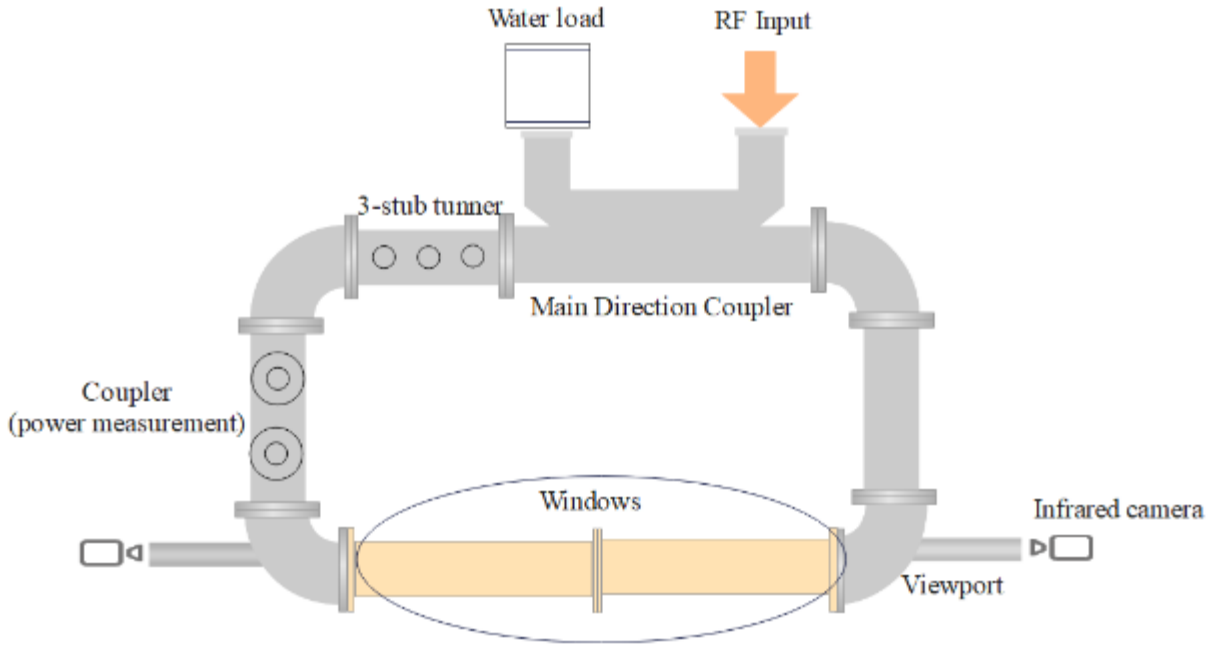


System modeling and simulation

Resonant ring

P band resonant ring

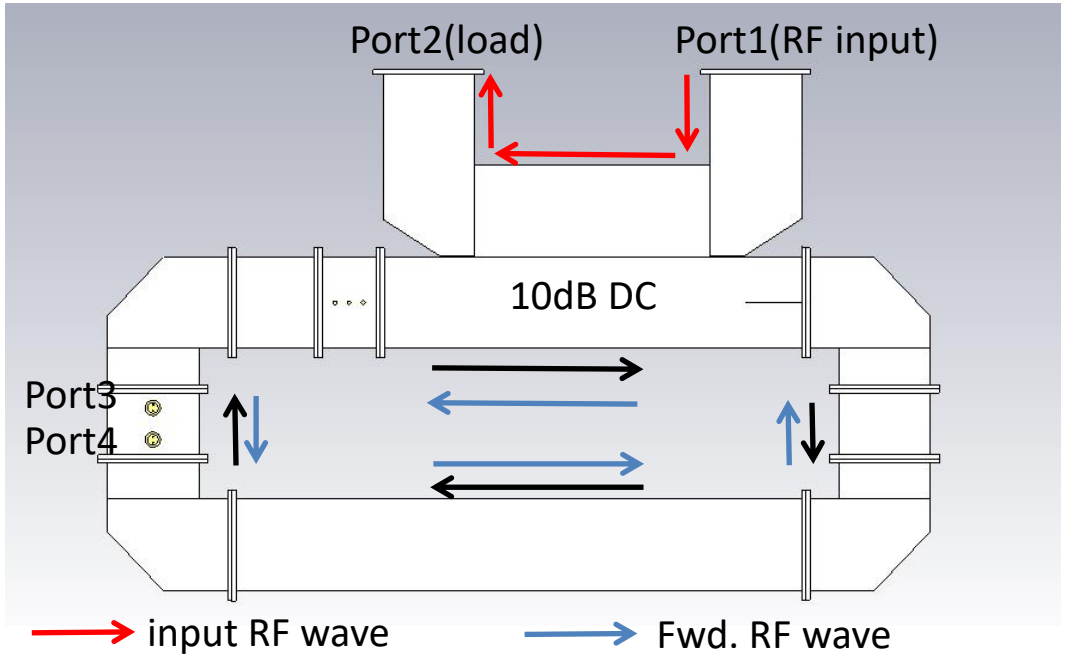
- Development of 1.2 MW P-band Travelling Wave Resonant Ring (TWRR), This TWRR is capable of testing at 1.5 times the rated power of an 800kW klystron, significantly reducing the risk of the window broken during operation and also for cavities coupler.



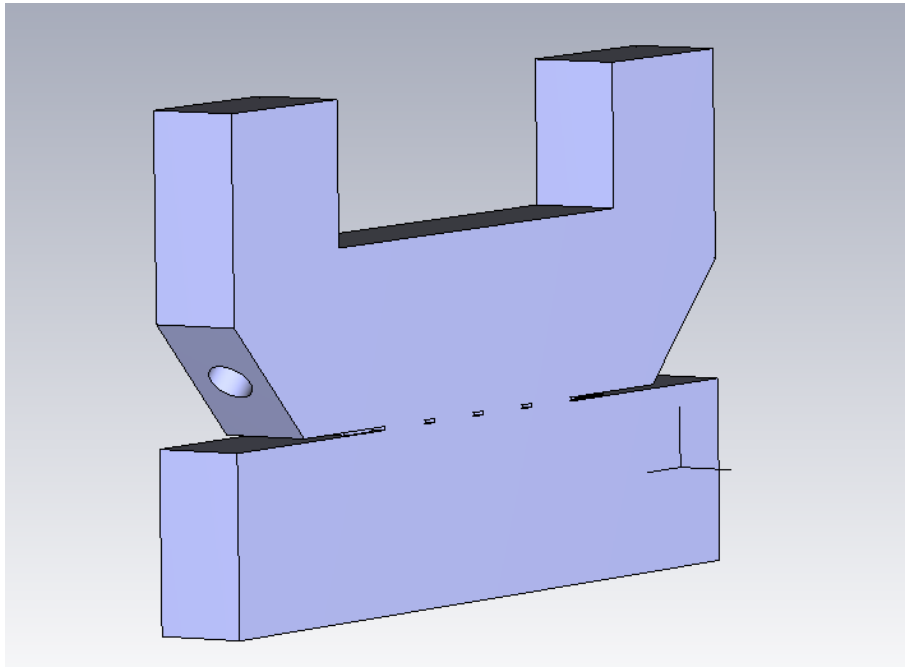
TWRR layout

Design progress of TWRR

- The length of TWRR is 9.8m with an available design of 10dB directional coupler. Power gain is about 25 times.



Model of P-band Travelling Wave Resonant Ring

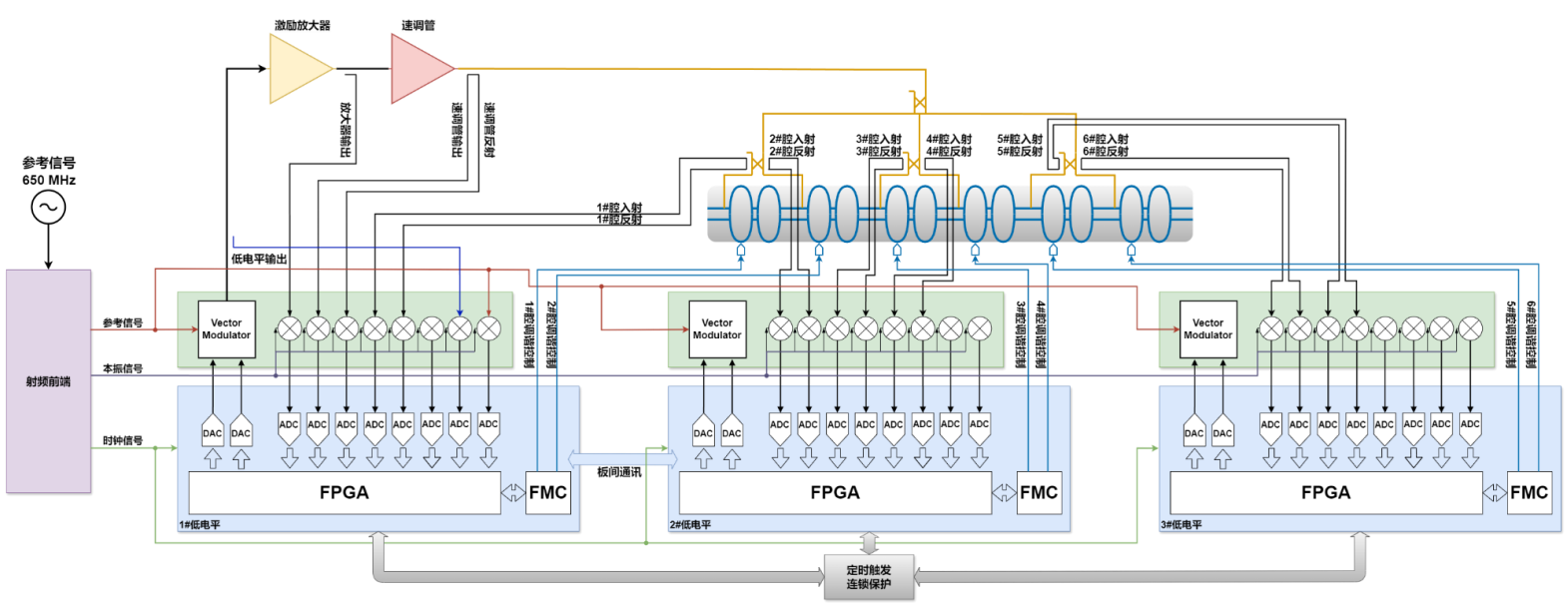


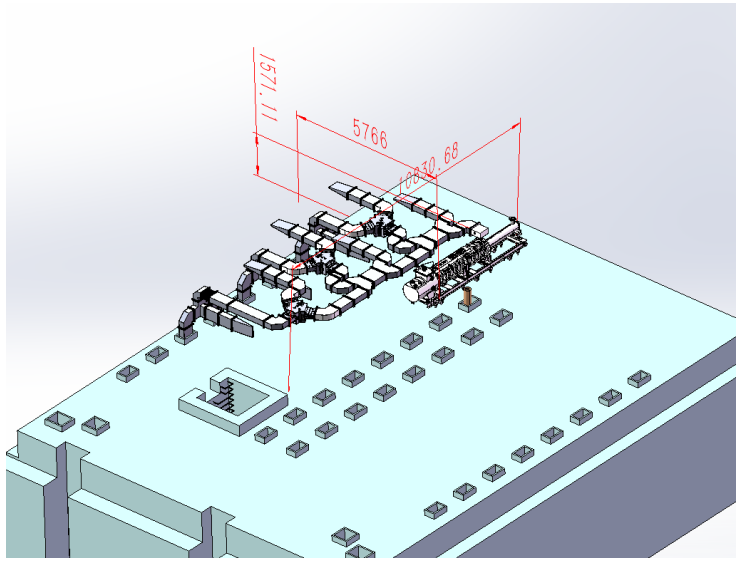
Model of Main direction coupler

RF power source for SC cavity horizontal test

LLRF system and power distribution

- Design consideration：
  - The LLRF system is designed for a 650 MHz 2-cell superconducting cavity with 6 cavities driven by a single klystron power source.
  - The system is based on a **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.





Key milestones from 2024-2027

- Proposal preparation of RF power source for China's 15th five year plan.(**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 and PPM 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.

Thanks for your attention!