

CEPC high efficiency and high power klystron development

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Motivation and power demand

RF Power Dominates CEPC Energy Consumption

30 MW per beam → 60 MW total RF power demand

Klystron efficiency directly drives operational electricity costs

Improving efficiency is essential for long-term sustainable operation

Objective

Maximize klystron efficiency → minimize grid power

R&D requirement

CEPC Klystron R&D Targets

Efficiency:

60% \rightarrow \geq 80% (P band Klystron, CW Klystron)

42% \rightarrow \geq 55% (S-band, pulsed klystron)

Output power: 50 MW \rightarrow 80 MW (C-band upgrade)

Mature engineering solutions required

Efficiency improvement = major reduction in operation cost

Progress overview

Achieved: 60% → 78.5% Efficiency @ 650 MHz / 800 kW

23 MW reduction in CEPC power consumption

High-efficiency klystron validated in CW operation

MBK development underway → 80% efficiency expected soon

These achievements lay a solid foundation for future:

Energy recovery technology (ERK)

R&D Stratage

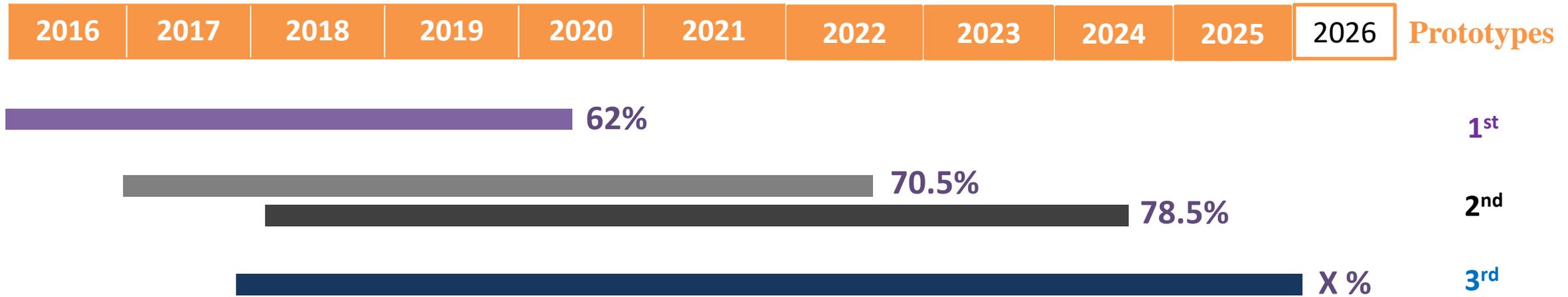
- **Continuous improvement in efficiency**
- **Fully established R&D chain:**
Design → fabrication → testing → industrialization
- **Transition from conventional to next-generation klystron systems**

P band klystron

(650MHz/800kW/CW)

650 MHz high-efficiency klystron timeline

■ Efficiency-oriented prototype iteration

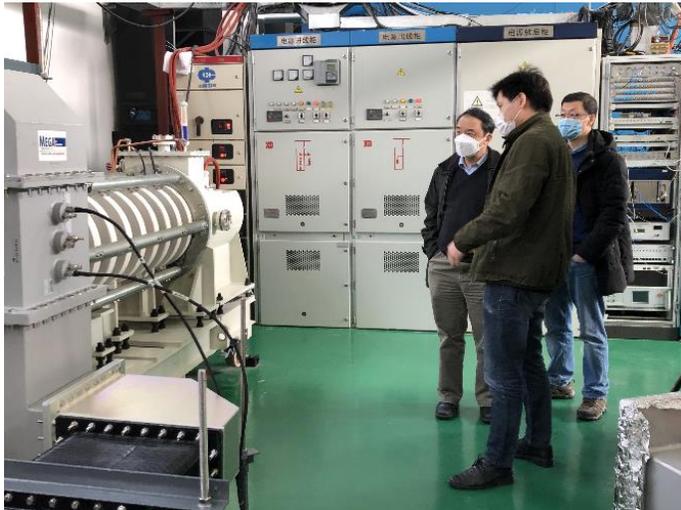


- Multiple prototypes developed and tested to ensure robust performance validation.
- Continuous optimization in gun, cavities, magnetic system, and collector.
- Engineering improvements guided by high-power experimental data.

R&D progress and achievements

■ 650MHz klystron-development roadmap

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

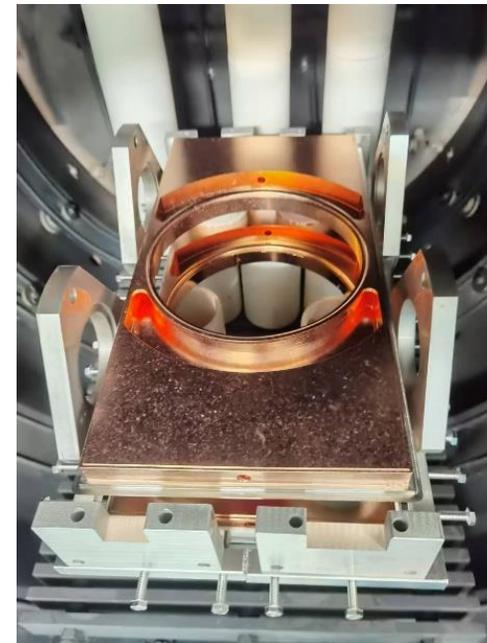


MBK Window Manufacturing and Testing

- Improved ceramic window sealing and reliability achieved.
- Window re-fabrication completed with enhanced brazing technology.
- High-power vacuum baking scheduled to resume this year.



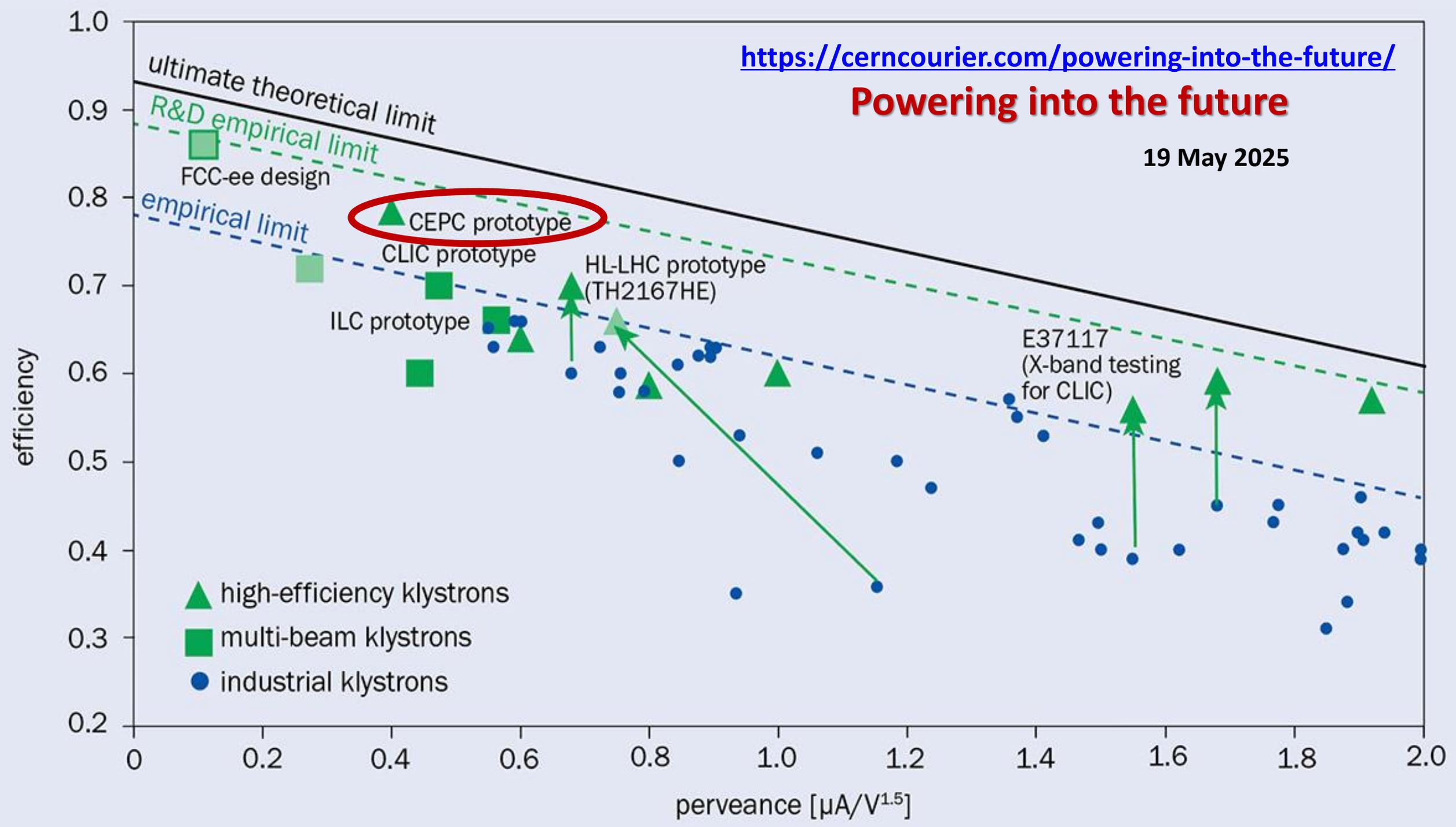
Final assembly



Window re-fabrication

Powering into the future

19 May 2025



C band klystron

(5720MHz/80MW/100Hz/3us/47%)

C-band 80 MW high-power klystron

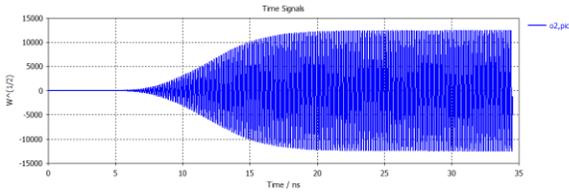
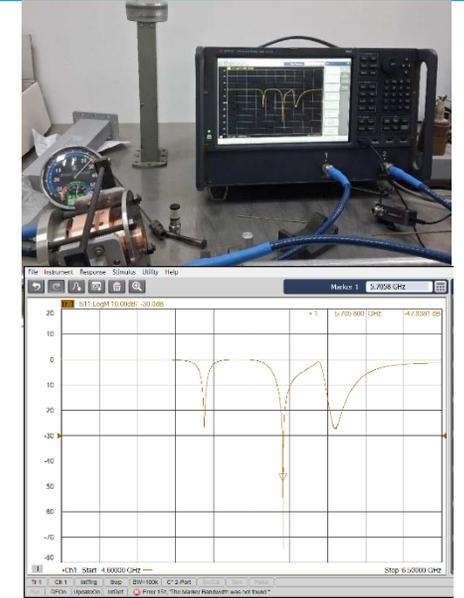
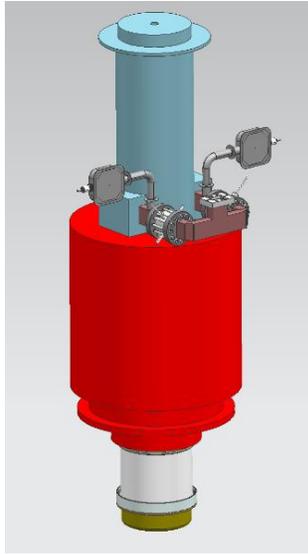
■ Baseline upgrade for CEPC Linac

- Output power: 50 → 80 MW (+60%)
- One klystron → 4 structures
- Device count reduced by >30%
- Fabrication ongoing / high-power test: this year

■ Major cost & complexity reduction in Linac RF system

R&D progress and achievements

Parameters	Value
Frequency	5712 MHz
Output Power	80MW
Drive power	350W
Gain	54 dB
Efficiency	47%
3dB bandwidth	± 10 MHz
Beam voltage	420 kV
Beam current	403 A
Focusing field	~ 0.27 T maximum



Physics design review
May.12 2024

Mechanical design review
Aug. 12 2024

Part manufacturing
Oct. 15 2024

Gun and cavity manufacturing
Feb. 28 2025

Cavity cold test
Apr. 14 2025

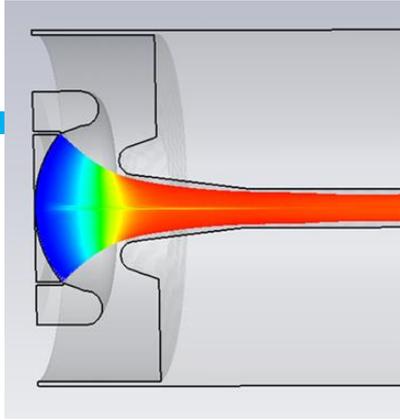
- Mechanical processing and manufacturing are in progress.
- **High-power test** is expected to be carried out **this year**.

S band high efficiency klystron

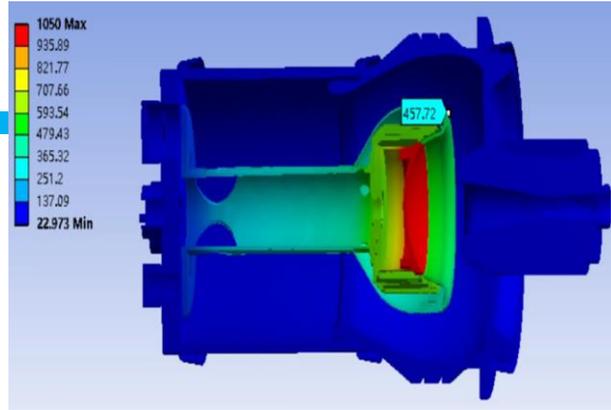
(2860MHz/80MW/100Hz/4us/55%)

S-band high-efficiency klystron

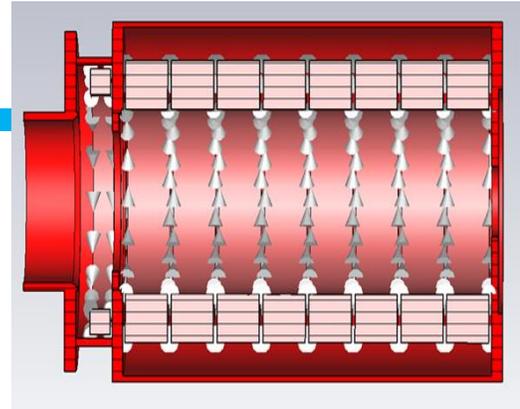
- **Supports CEPC Linac, BEPCII upgrades and domestic accelerator demand.**
- **Target: 80 MW, 55% efficiency.**
- **Beam optics and thermal design optimized for reliability.**



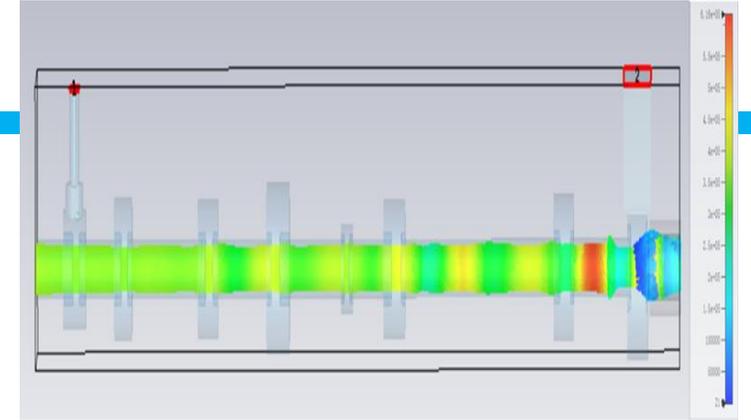
Beam optics
H. V.: 350kV
Current: 415A



Gun thermal analysis

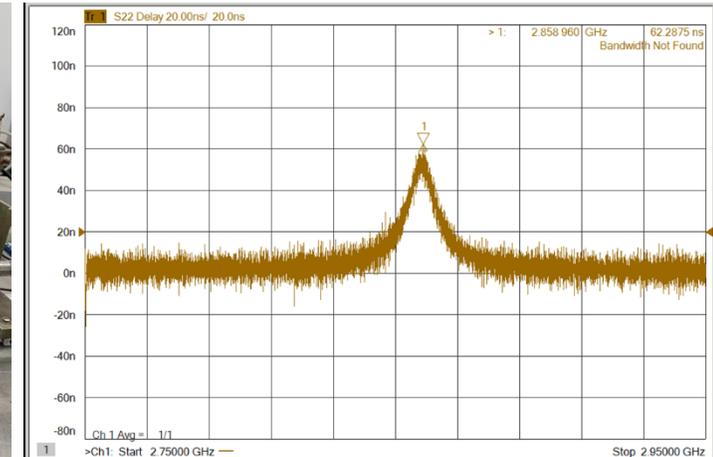
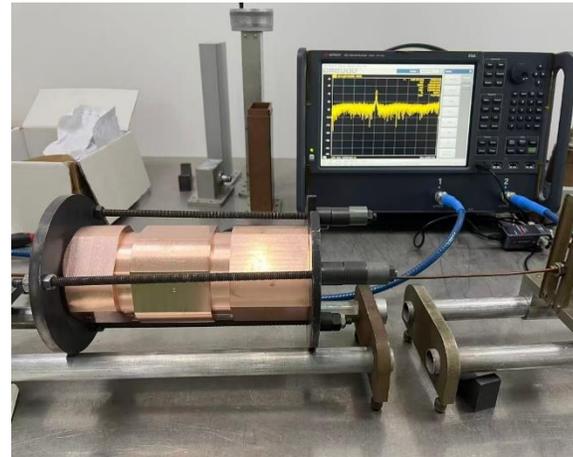


Magnet coil design



Beam dynamics
Efficiency: 55%
Output power: 80MW

- Mechanical processing and manufacturing are in progress.
- Cavity parts processing and cold test have been completed.
- **High-power test** is expected to be carried out **this year**.



Cold test

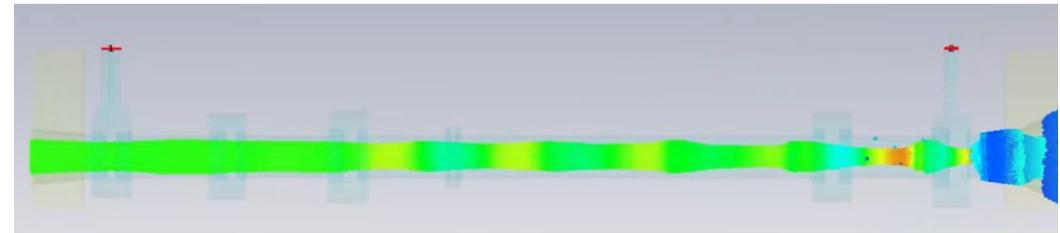
S band PPM klystron

(2856MHz/50MW/53%)

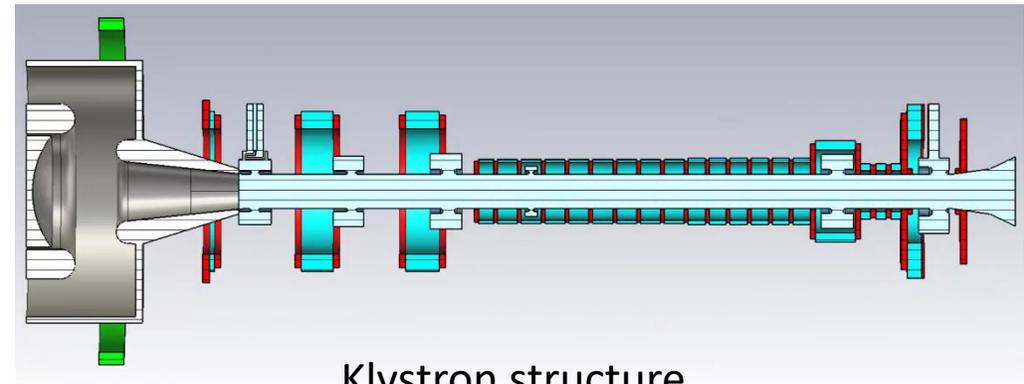
Design status

- Compact design with permanent magnet focusing.
- Higher efficiency and simplified system compared with solenoid types.
- CST simulation results: 51.2 MW, 53.8% efficiency.
- Fabrication to begin this year.

S-band 50MW PPM Klystron	Design Specifications
Beam Voltage	350kV
Beam Current	272A
Frequency	2856MHz
Tube Radius	13.8mm
Beam Radius	9mm
Output Power	50MW
Efficiency	53%



Beam dynamic



Klystron structure

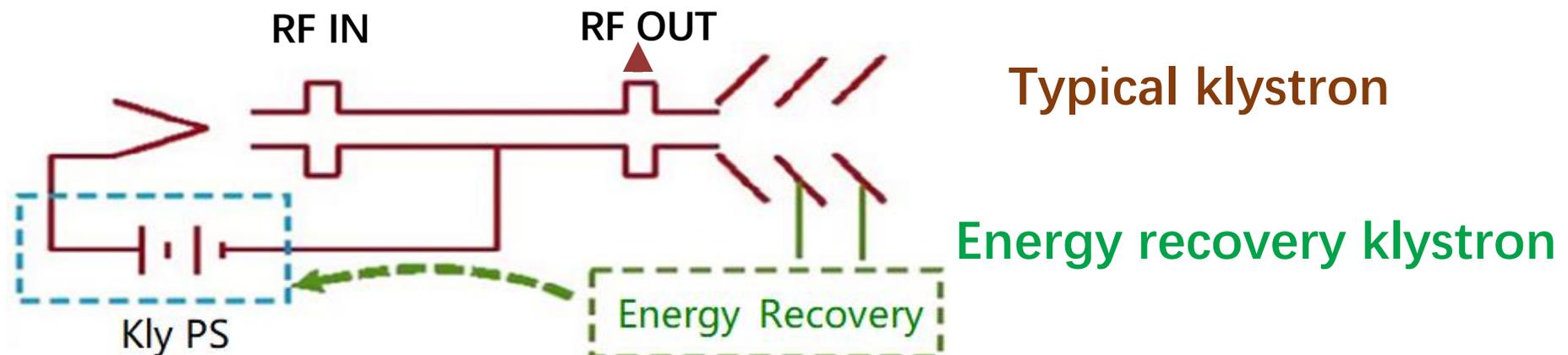
Energy recovery klystron

(650MHz/800kW/CW/85%)

Energy recovery klystron(ERK)

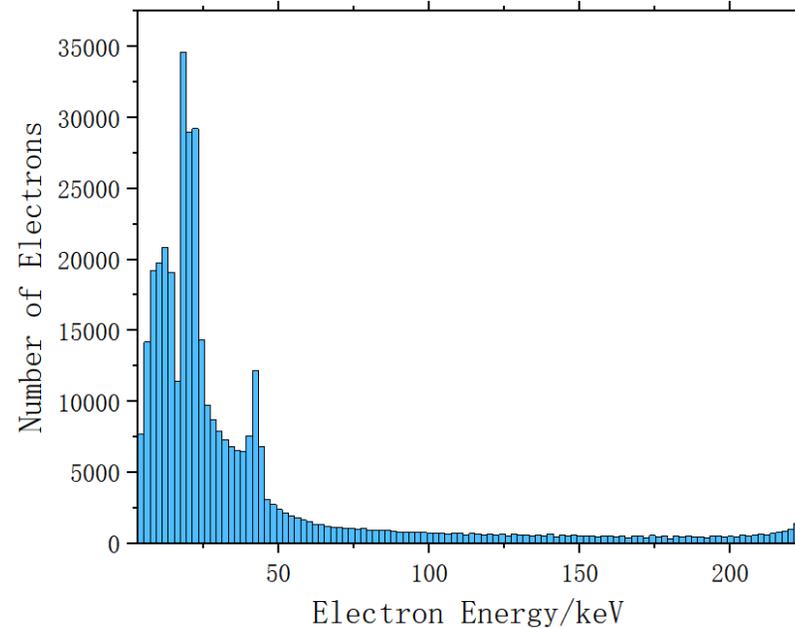
■ ERK Concept

- Energy recovery via multi-stage depressed collector (MDC)
- Recovers spent-beam energy rather than dumping as heat
- Substantial reduction in grid power demand

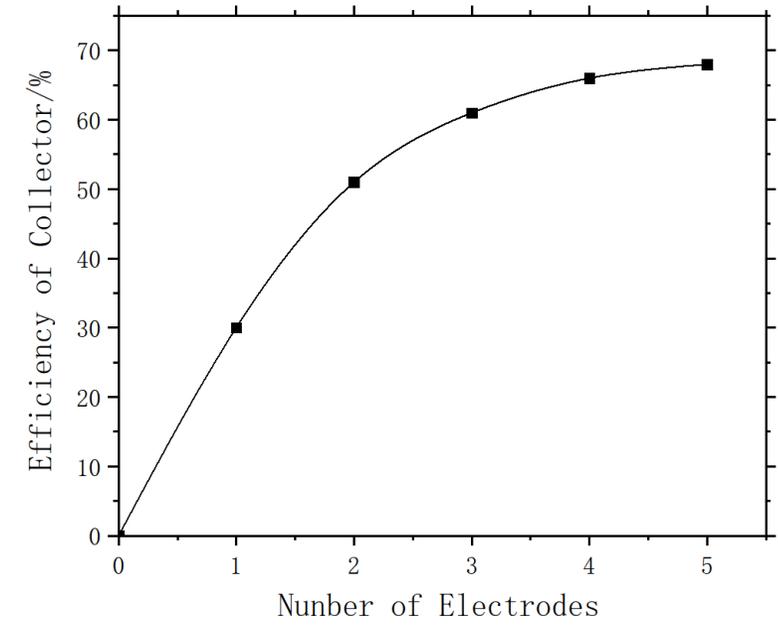


ERK beam dynamics

Parameter	Value
Frequency	650 MHz
Beam Voltage	113 kV
Output power	800 kW
Beam perveance	0.25 μ P
Beam current	9.5A
Efficiency(1 stage DC)	$\geq 85\%$



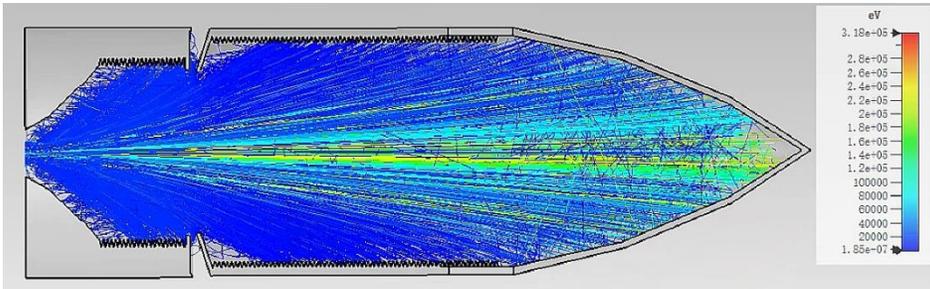
Energy distribution of spent electron beams



Collector recovery efficiency

- Optimized beam-wave interaction for high efficiency
- Reduced energy spread of the spent beam
- Enables effective collector potential staging

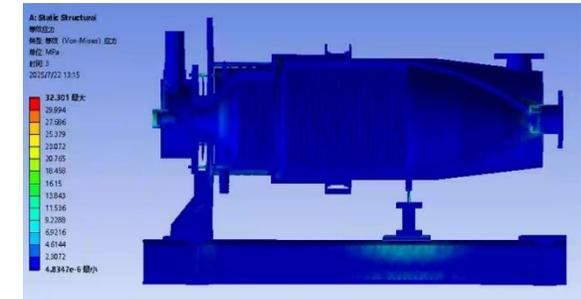
Collector design and thermal analysis



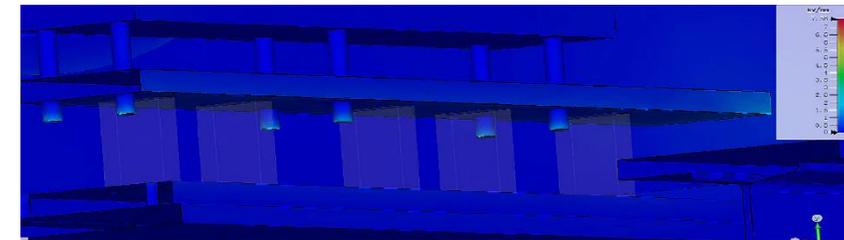
Beam Trajectory



Temp. distribution at full power



Mechanics analysis



Electrostatic field analysis

- Improved cooling design
- Reduced hot spots
- Electrostatic optimized to minimize beam backstreaming
- Supports $\geq 85\%$ total efficiency target (RF + recovery)

Design review

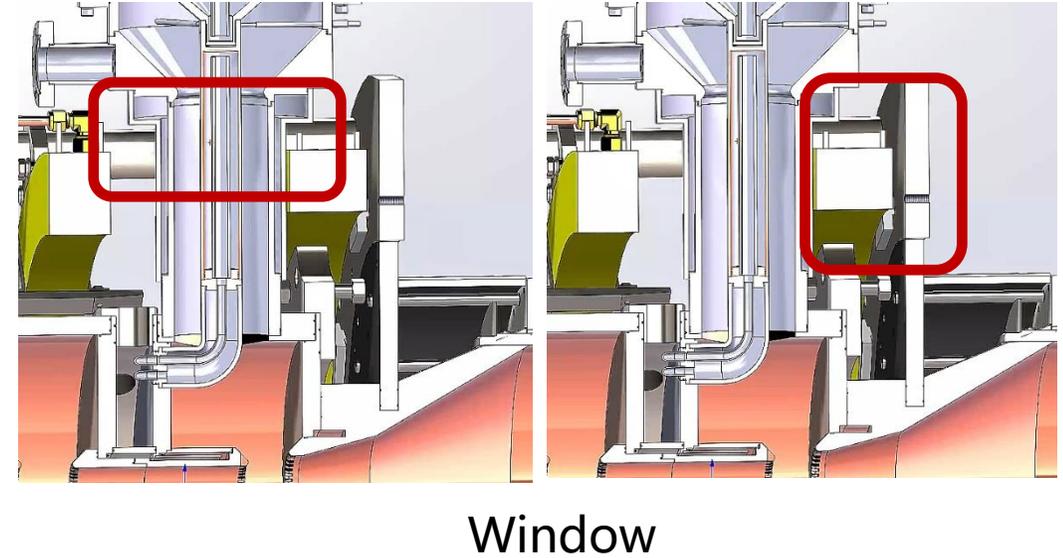
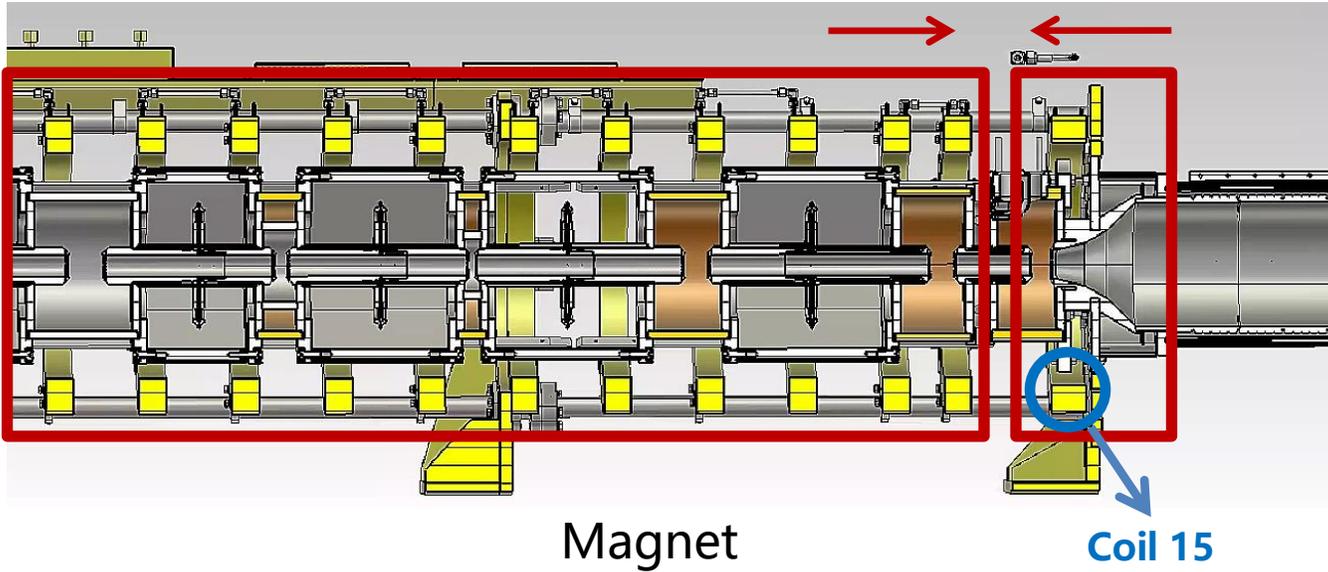


Physical design review
May.23 2025



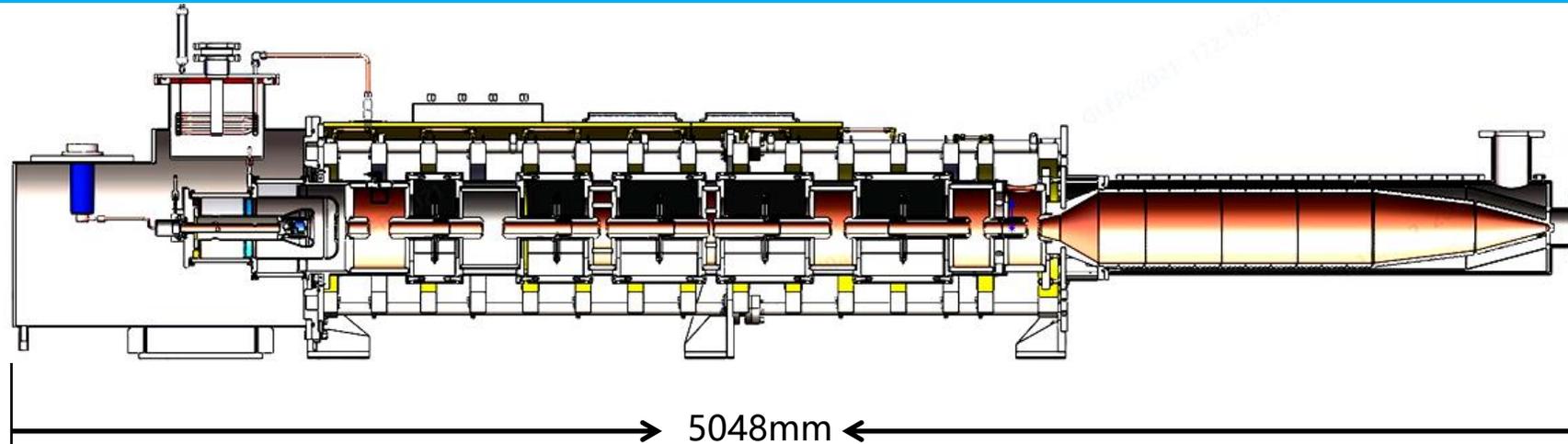
Mechanical design review
Jul. 6 2025

Klystron body redesign

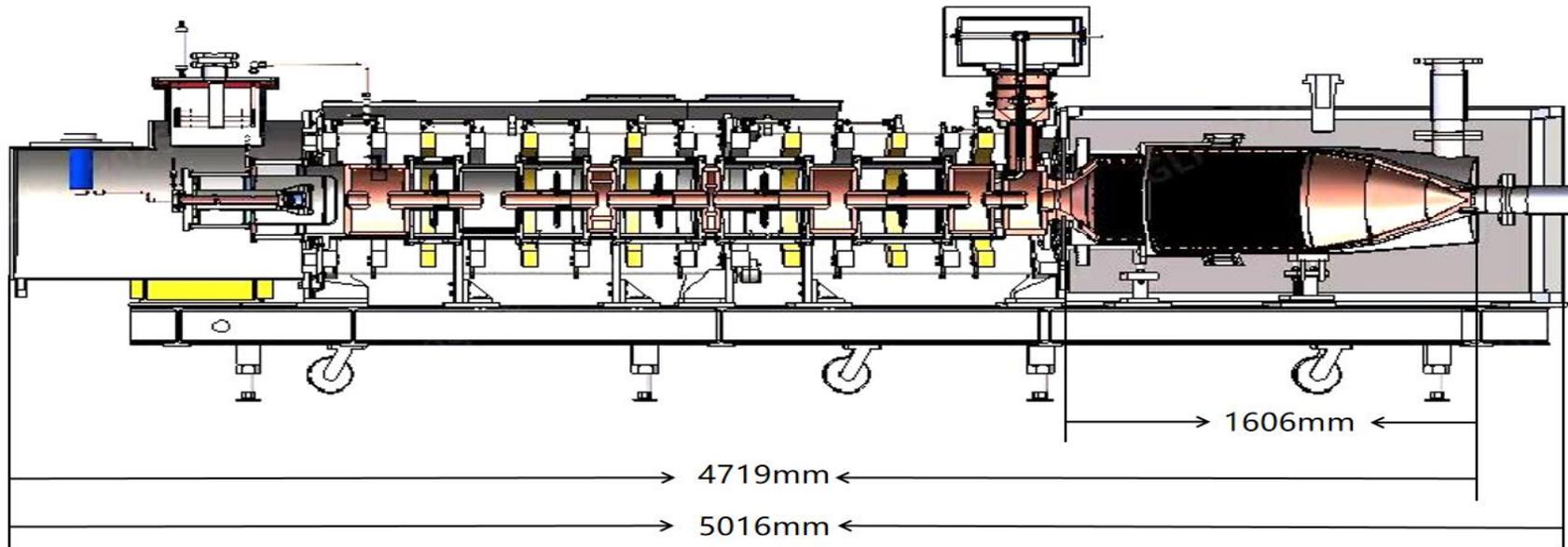


- Increased size of Coil 15
- Extended window coupler
- Enlarged support flange

Mechanical design



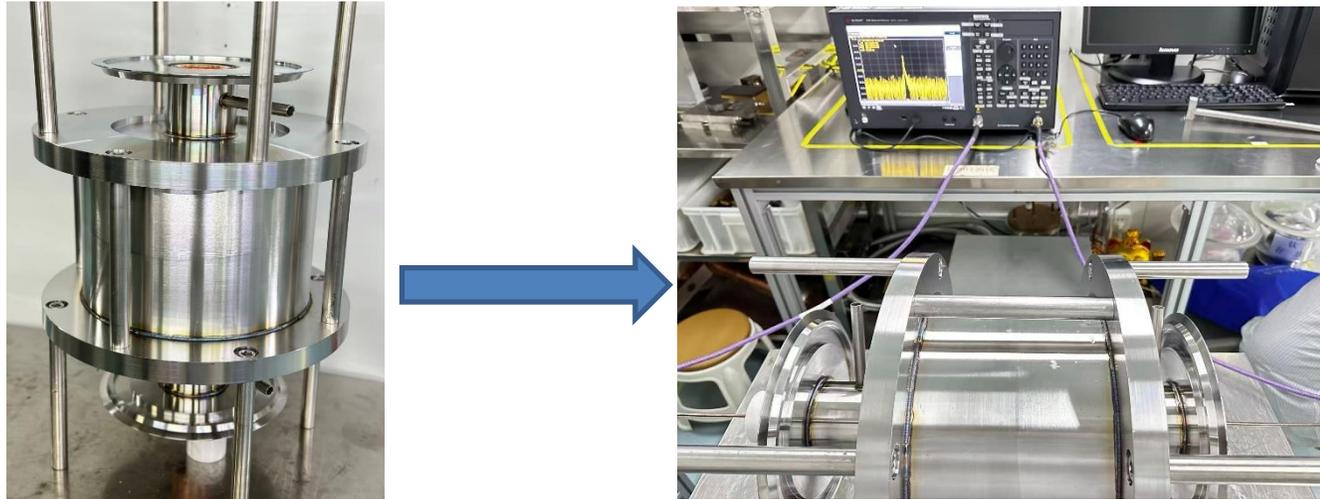
High efficiency
klystron prototype



Energy recovery
klystron with 1
stage DC

Fabrication status

- Mechanical processing and manufacturing are in progress.
- **High-power test** is expected to be carried out **in Sep. 2026**.



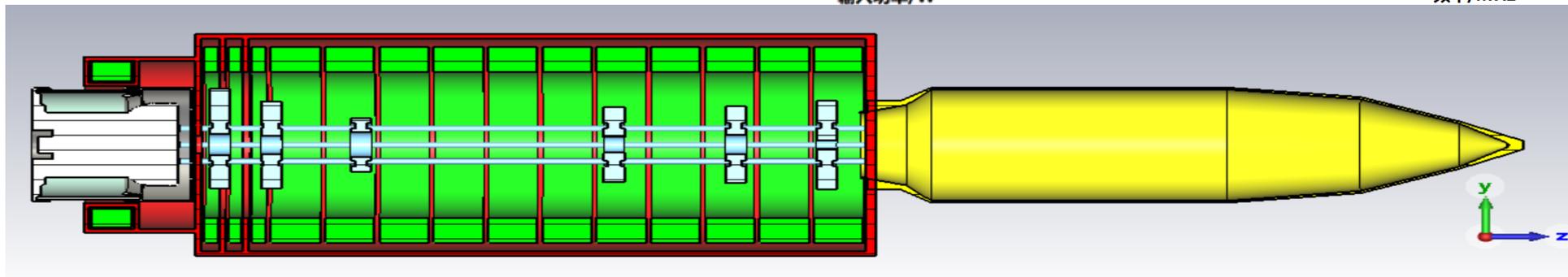
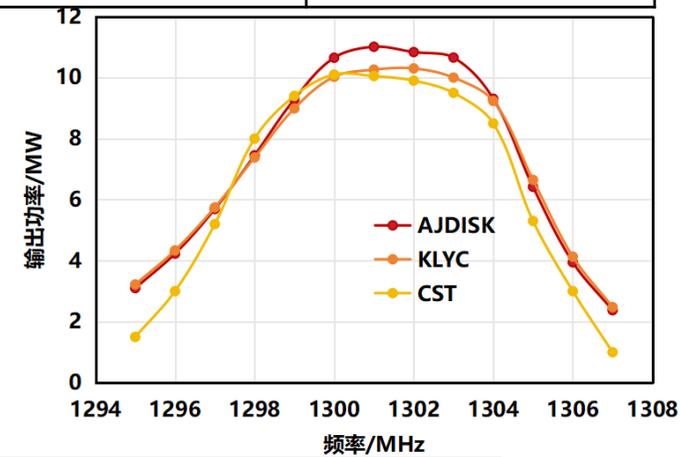
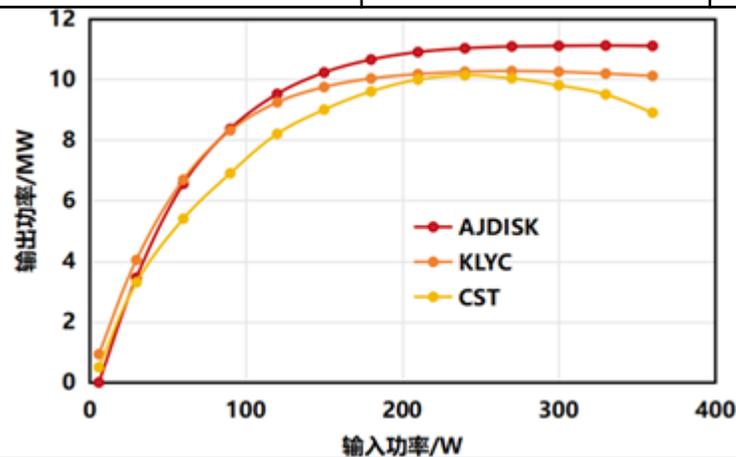
Long pulsed klystron

(1.3GHz/10MW/1.5ms/10Hz)

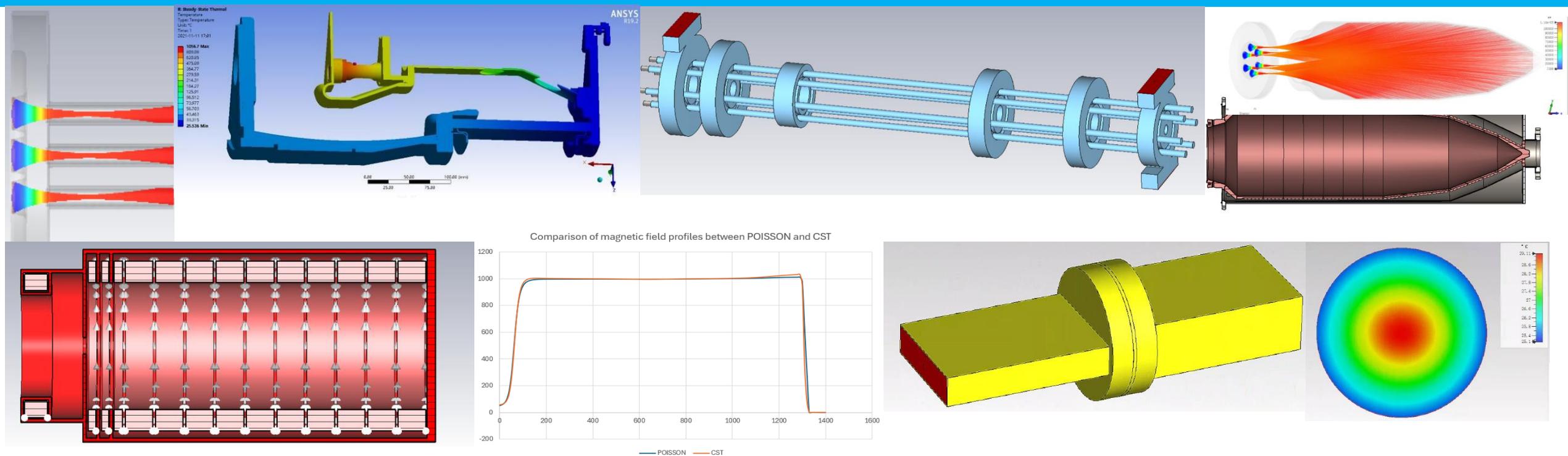
Beam dynamics

Parameters	Value
Freq.(GHz)	1.3
H.V.(kV)	115
Current(A)	21×6
Beam No.	6
Rep. Rate(Hz)	10
Pulse Width(ms)	1.5
Power(MW)	≥10
Eff.	≥65%

Parameters	AJDISK	KLYC	CST
Power(MW)	10.7MW	10.3MW	10.1MW
Eff.	74.8%	71.1%	69.9%
Gain	47.7dB	48.6dB	48.0dB



Component design



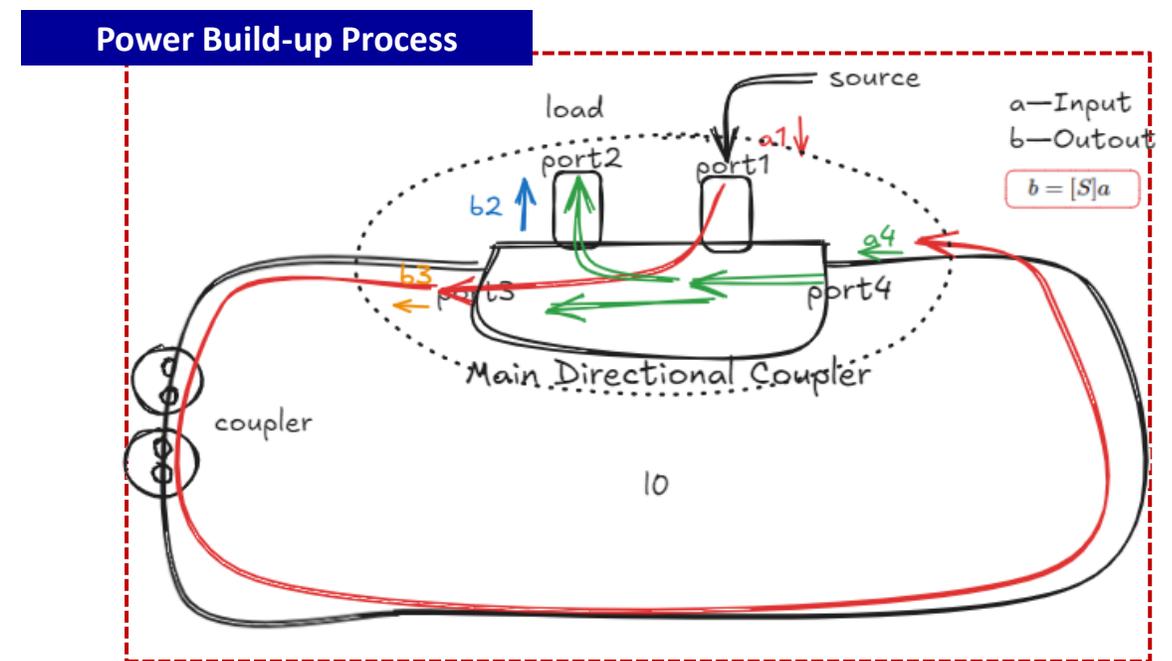
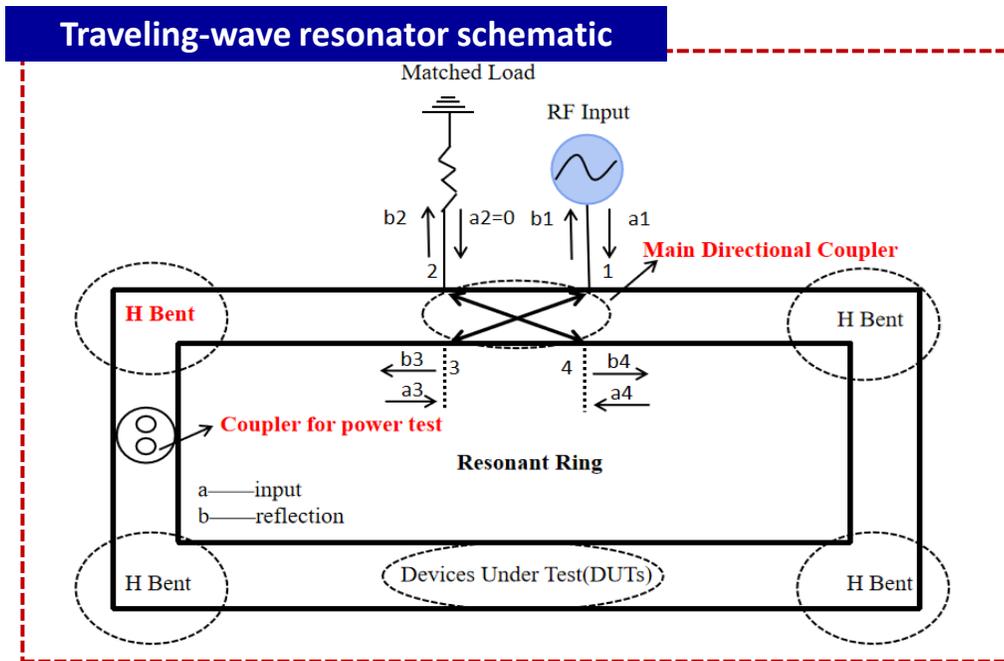
Physical and mechanical design reviews of the klystron have been completed. Fabrication and high-power testing are planned to be completed **by the end of 2026.**

Resonant ring

(650MHz/1.2MW/CW)

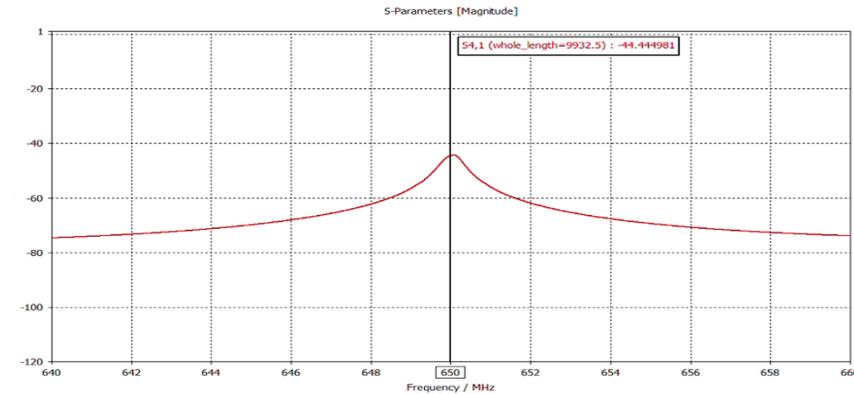
Design progress

- Dedicated for high-power component validation:
 - Windows, couplers, transmission elements
- Supports 1.2 MW CW testing ($1.5 \times$ klystron output)

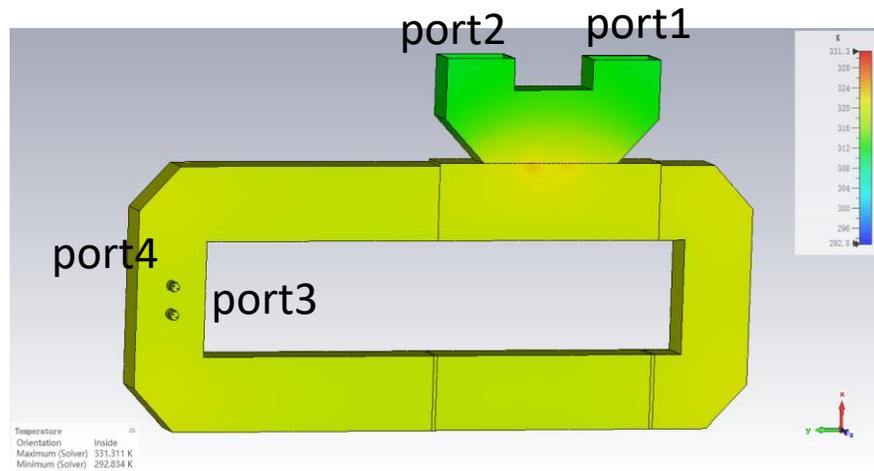


Design status

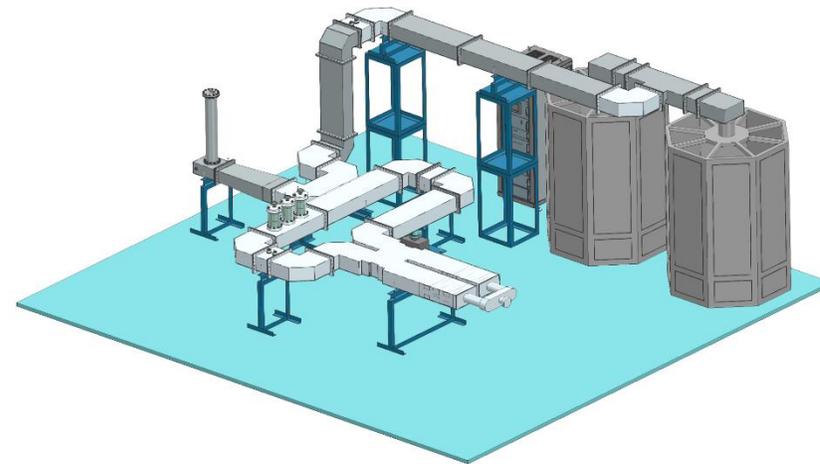
Waveguide	WR1500
Length of the ring	9.28m
Coupling coefficient	-10dB
Power Gain _{theoretical}	36.7
Max. power gain	15.56 dB
Max.temperature rise	38°C



P-band TWRR power gain is 15.56dB@650MHz (35.9)



Temperature rise of P-band TWRR



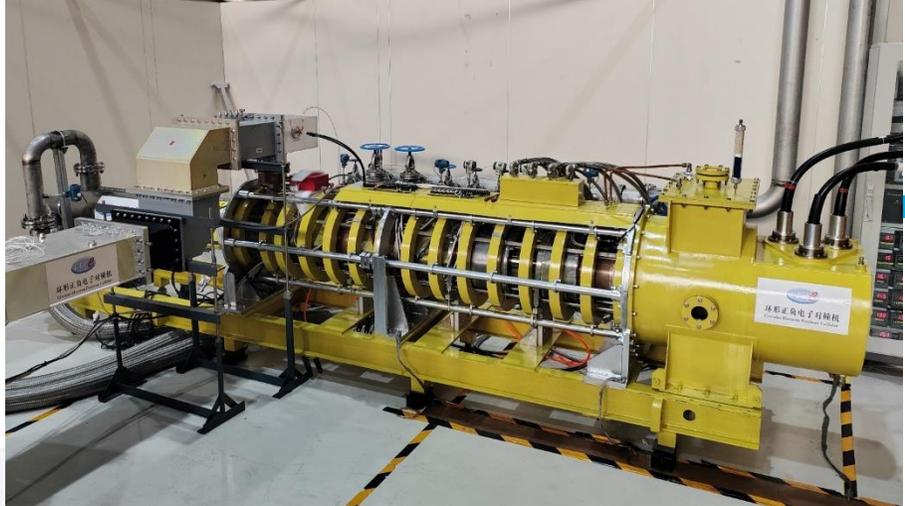
P-band TWRR fabrication planned this year.

R&D Summary

Type	Goal	Status	Completion time
650MHz multi-beam klystron	800kW CW, 80% eff.	Processing	Apr. 2026
5720MHz high power klystron	80MW/100Hz	Processing	Mar. 2026
2860MHz high efficiency klystron	80MW, 55% eff.	Processing	Feb. 2026
650MHz energy recovery klystron	800kW CW, 85% eff.	Processing	Sep. 2026
2860MHz PPM klystron	50MW, PPM	Physical design	Dec. 2026
1300MHz long pulse klystron	10MW, 1.5ms	Processing	Dec. 2026
650MHz resonant ring	1.2MW, CW	Mechanical design	Sep. 2026

Industrialization preparation

- P-band and L-band high-efficiency klystron R&D
 - Close collaboration with **Guoli** company
 - Development of 26 sets P-band klystron for the CSNS-II project
- S-band and C-band 80 MW high-power klystron R&D
 - Close collaboration with **Hanguang** company
 - S-band and C-band klystrons for BEPCII, BEPCII-U, and other domestic accelerator facilities



Conclusion

- Successfully completed high-power testing of the high-efficiency klystron prototype.
- MBK, S band and C band klystron fabrication and high-power testing scheduled for this year.
- Continued R&D on S-band PPM klystrons and energy-recovery klystrons.
- Advancing the development of a P-band resonant ring for high-power testing.
- Establishing an auxiliary system for horizontal superconducting cavity tests, including:
 - LLRF system
 - Klystron energy dissipation protection
 - Power distribution and transmission systems

Acknowledgement

- We sincerely thank to **Prof. Yifang Wang** for his leadership and support through the ***Ten Thousand Talents Program***, which has been critical to this progress.
- We also acknowledge the CEPC study group and our industrial partners for their excellent collaboration.
- Finally, we appreciate the dedication and contributions from all colleagues and students involved in this effort.



电子对撞机(CEPC)高效率速调管”
科技成果鉴定会

