Development of MW-Level Compact P-Band Metamaterial Klystrons in CSNS

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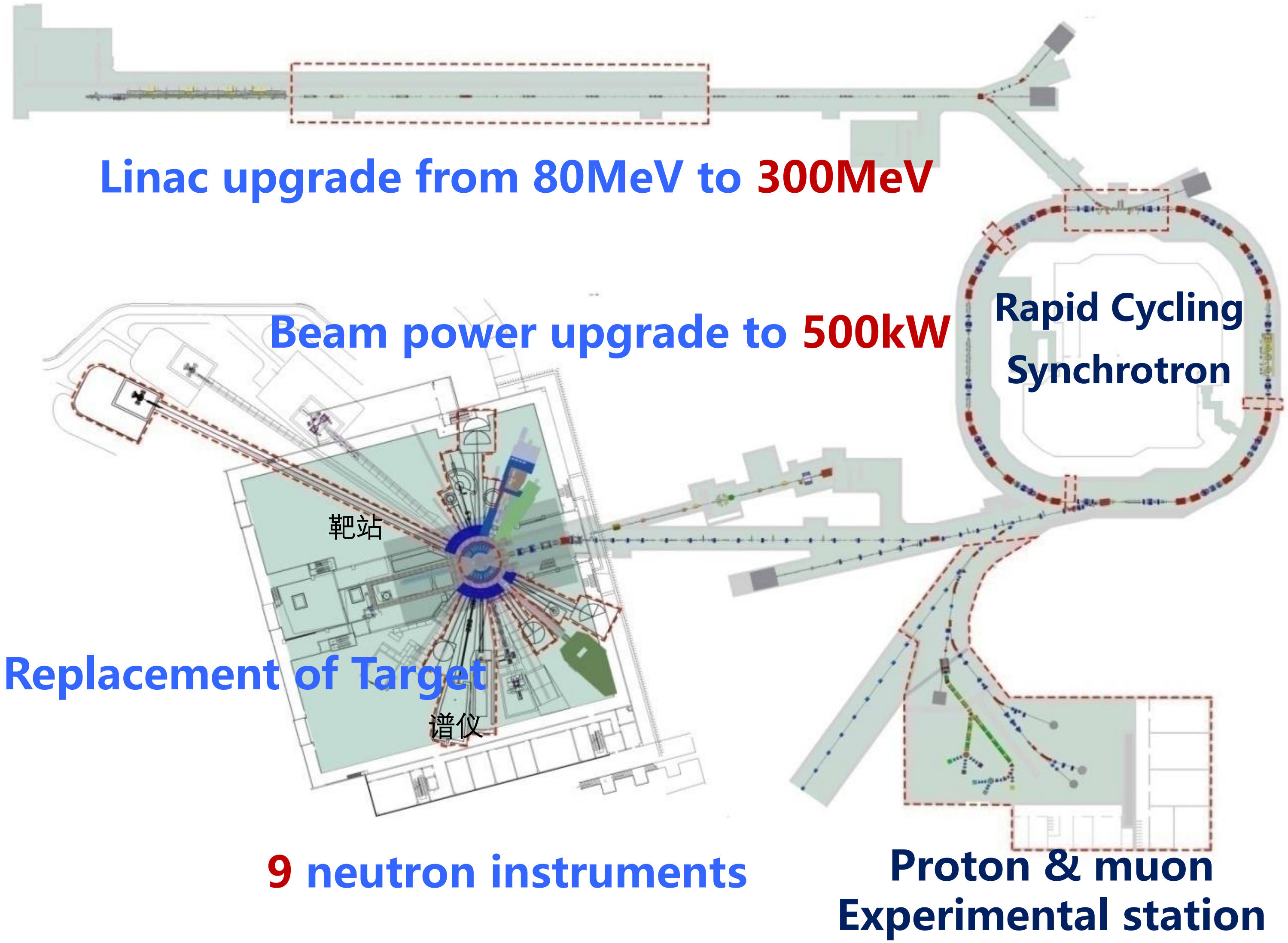
CSNS Linac RF Group

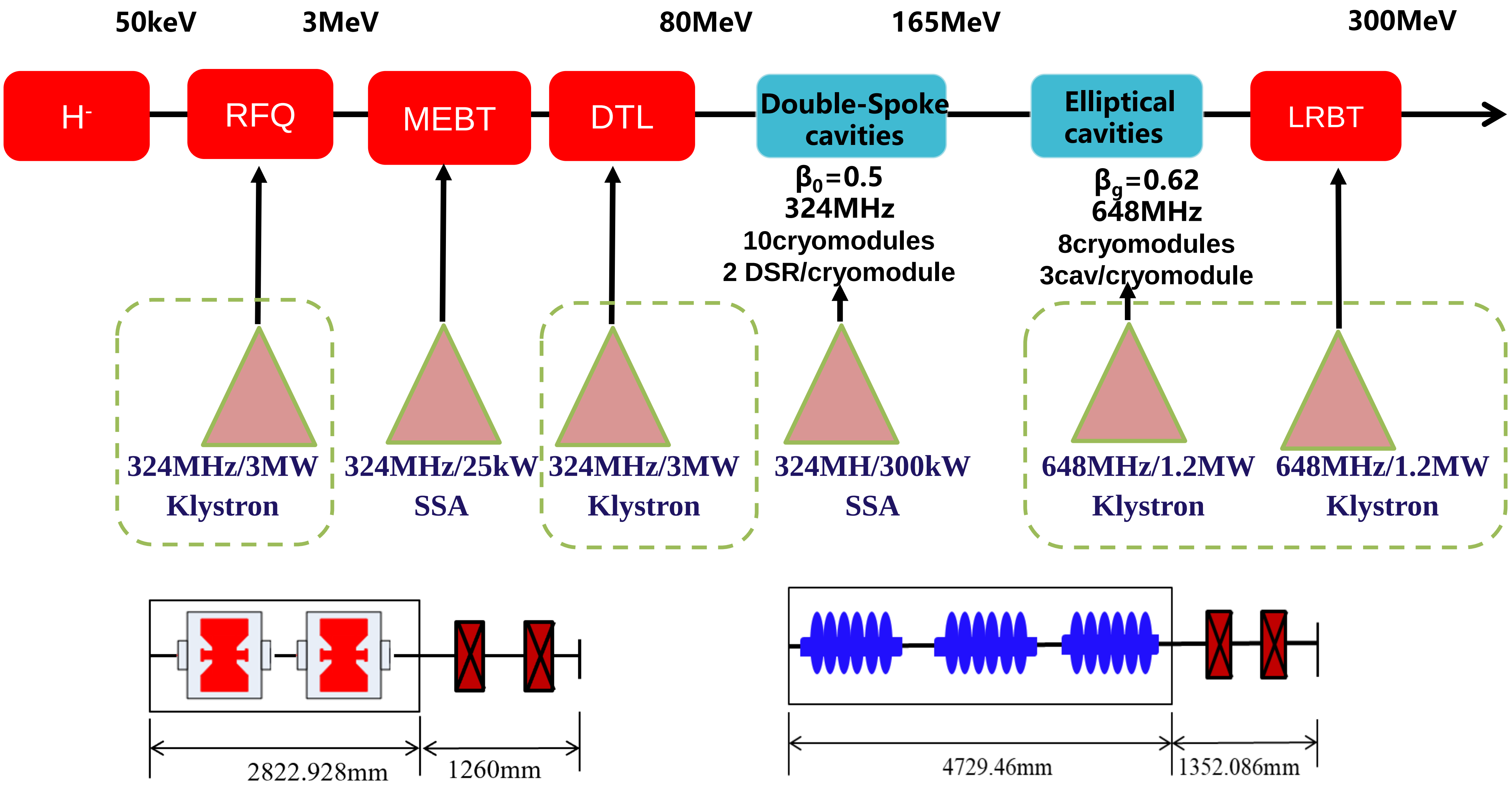
Outline

Introduction of CSNS-II



Parameters	CSNS	CSNS-II
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [uA]	62.5	312
Linac energy [MeV]	80	300
Linac type	RT	RT+SC
Linac RF frequency [MHz]	324	324/648
Linac RF pulse width[us]	650	1200
Pulse repetition rate [Hz]	25	50
Spectrometers	3	11+8

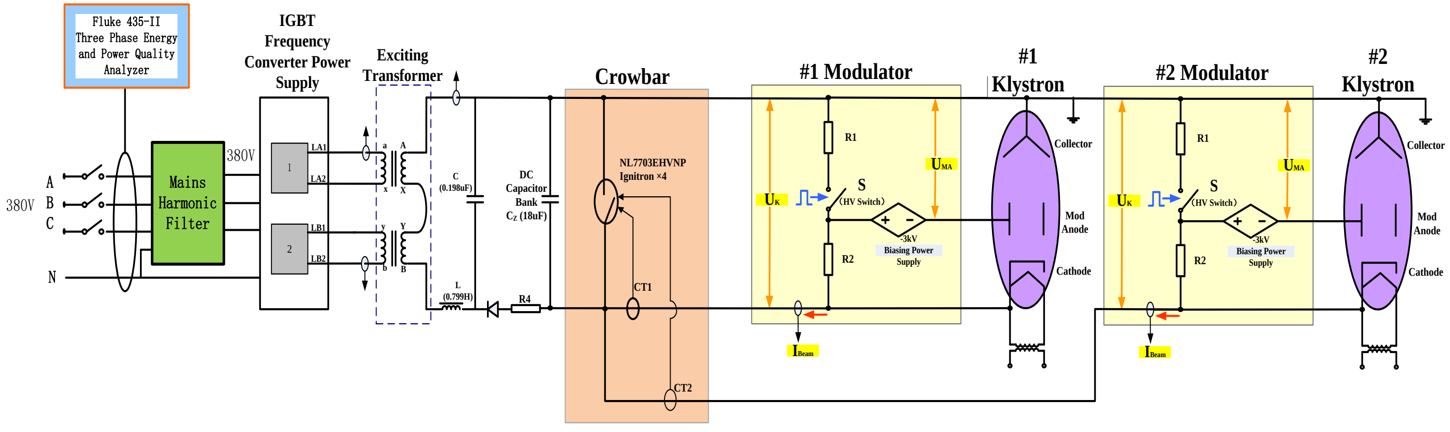
CSNS-II LINAC RF System



324MHz klystron in CSNS Linac

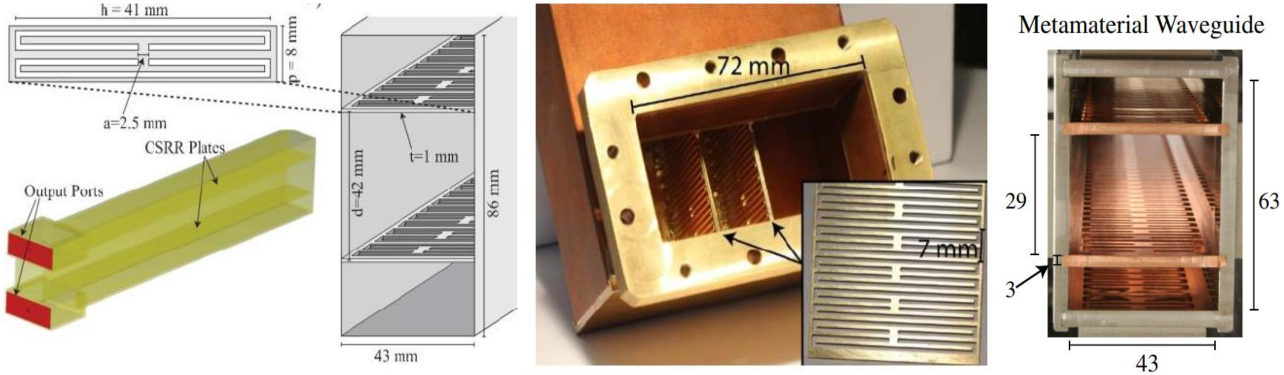
Table: Parameters of the 324MHz/3MW Klystron of CSNS Linac

Frequency	324	MHz
Bandwidth (1dB):	±0.1	MHz
Peak Power	≥3	MW
Rep. Rate	25	Hz
RF Pulse Width	650	μs
Beam Current Pulse Width	750	μs
Efficiency	≥55	%
Gain	≥45	dB
Cathode High Voltage(max)	-110	kV
Back Bias Voltage	-3	kV

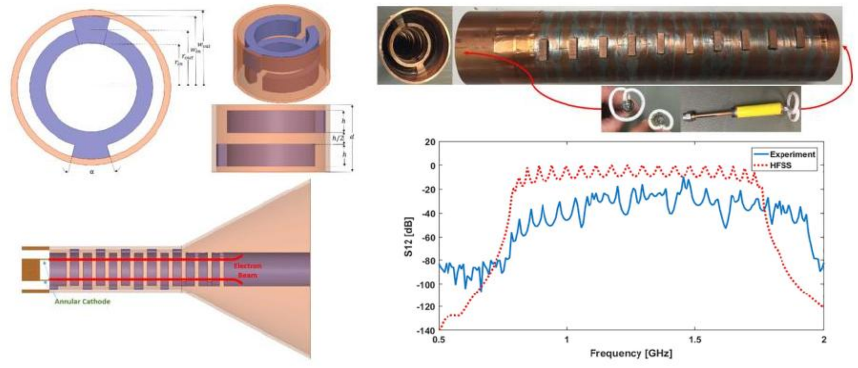


- RFQ, four DTLs are powered by 324MHz/3MW Klystron;
- One klystron feeds the two couplers of the RFQ via a Magic-T;
- 3 CPI VKP-8324a and 2 Canon E3740A inline operation;
- Beam macropulse.ave current 15mA and the Rep. rate 25Hz;
- Klystron HV power supply: DC HV power supply, crowbar, modulator;
- CSNS-II: Beam macropulse.ave current 40mA and the Rep. rate 50Hz;
- Development of Metamaterial klystron and new modulator.

Survey of Mega-material



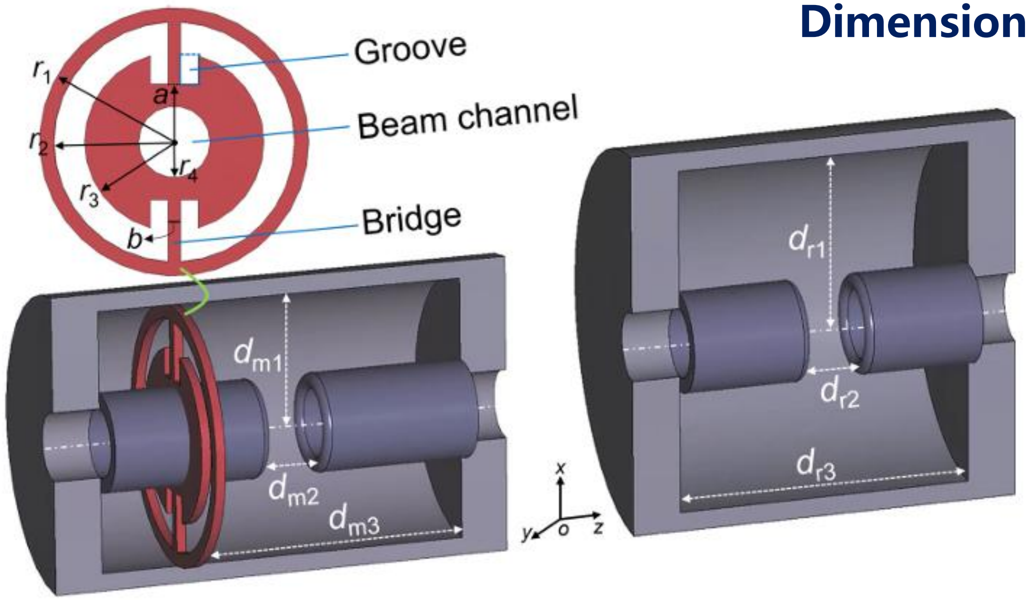
MIT Periodic Planar Meta-material BWO



UNM Meta-material CSRR Backward Wave Oscillator

- The resonant effect of meta-materials enhances electromagnetic coupling efficiency between high-energy beams and waves. Their subwavelength nature reduces volume and increases power-energy density.
- Lancaster University (UK), NASA, AFRL, MIT, and UW-Madison have conducted extensive theoretical and experimental research on meta-material-based microwave vacuum electronic devices.
- MIT designed a planar-meta-material vacuum HPM source: interaction length reduced to 40% of conventional structure, generating 5MW pulse power at 2.6GHz.
- University of New Mexico developed a SRR-meta-material relativistic BWO. Hot test yielded 100MW pulse power (~20% improvement); transverse dimensions reduced by more than half.

Metamaterial Cavity



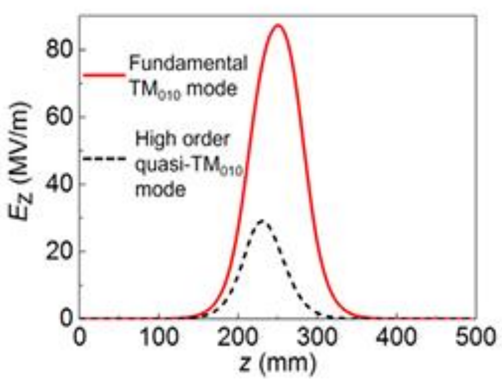
324 MHz cavity loaded with a single CeSRR unit (left); conventional reentrant cavity (right)

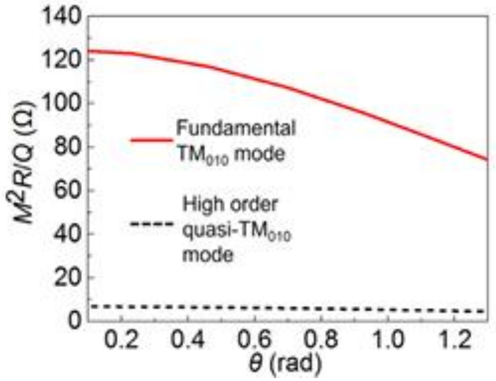
Dimensions of 324 MHz metamaterial and reentrant cavities (unit: mm)

r_1	r_2	r_3	r_4
136.9	122.3	91.1	36.5
a	b	d_{m1}	d_{m2}
59.2	13	136.9	58
d_{m3}	d_{r1}	d_{r2}	d_{r3}
304.9	182.2	58	304.9

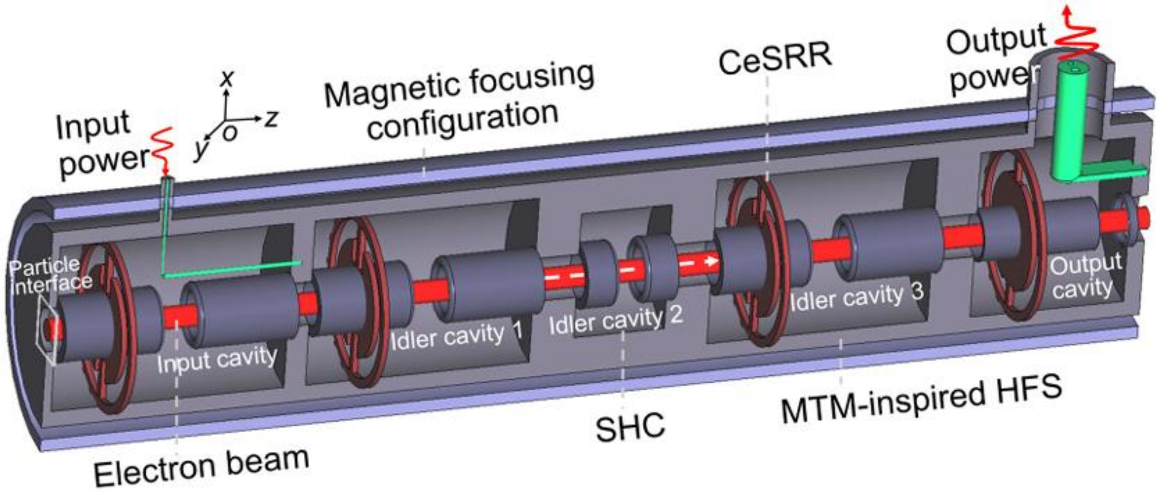
- **Radial size reduced jointly by CeSRR loading and lowered gap transit angle**
- **25% shorter than reentrant cavity, corresponding to 44% smaller base area**

- **Fundamental TM010 resonant frequency: 324 MHz Higher-order quasi-TM010 resonant frequency: 433.5 MHz**
- **Effective R/Q of TM010 far exceeds that of quasi-TM010, indicating higher-order modes barely interact with the electron beam**

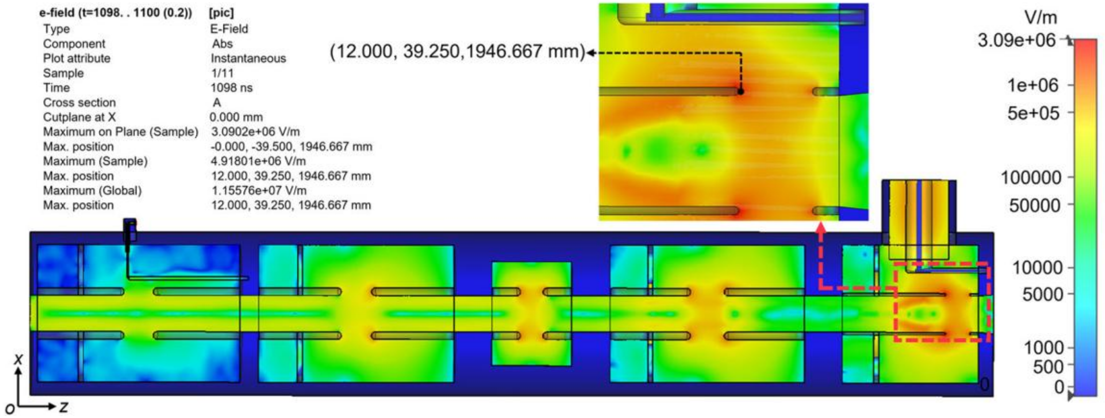




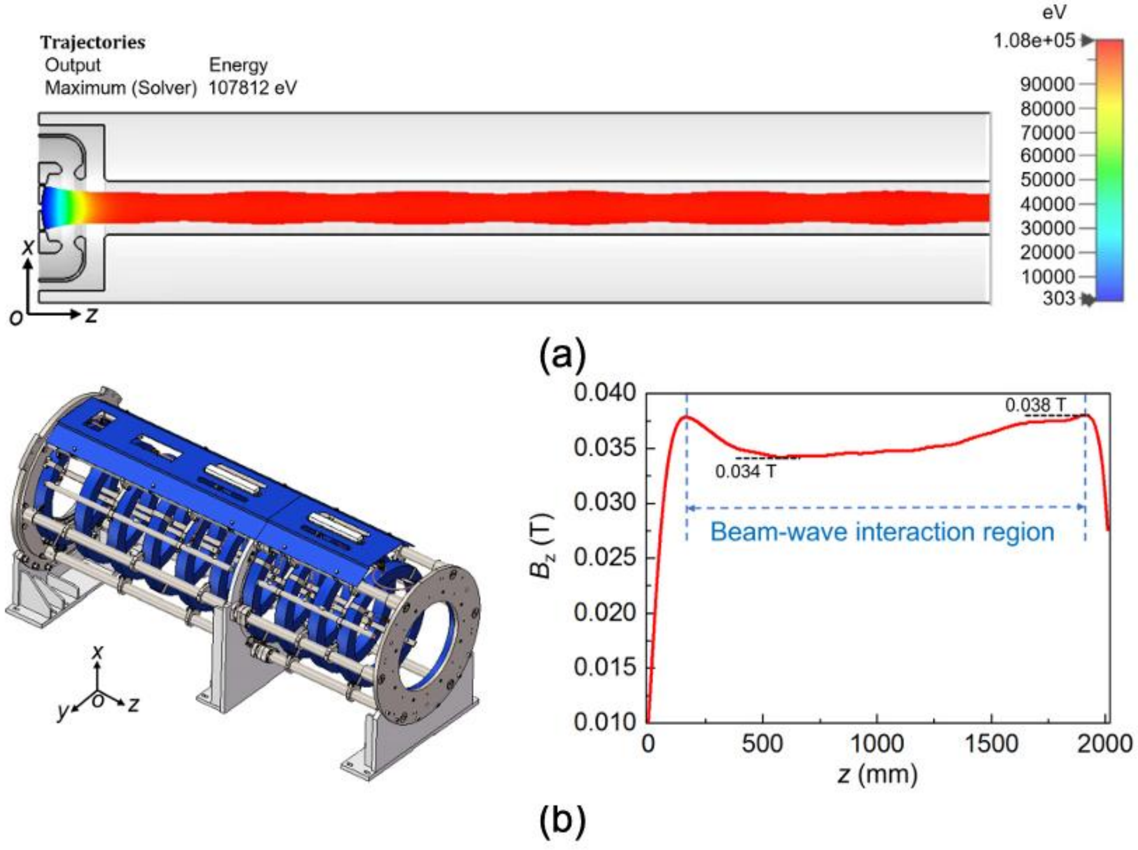
M-Klystron design



Based on the study of the CeSRR-loaded resonant cavity, the amplification mechanism of a five-cavity MTM-inspired HFS with CeSRRs is investigated



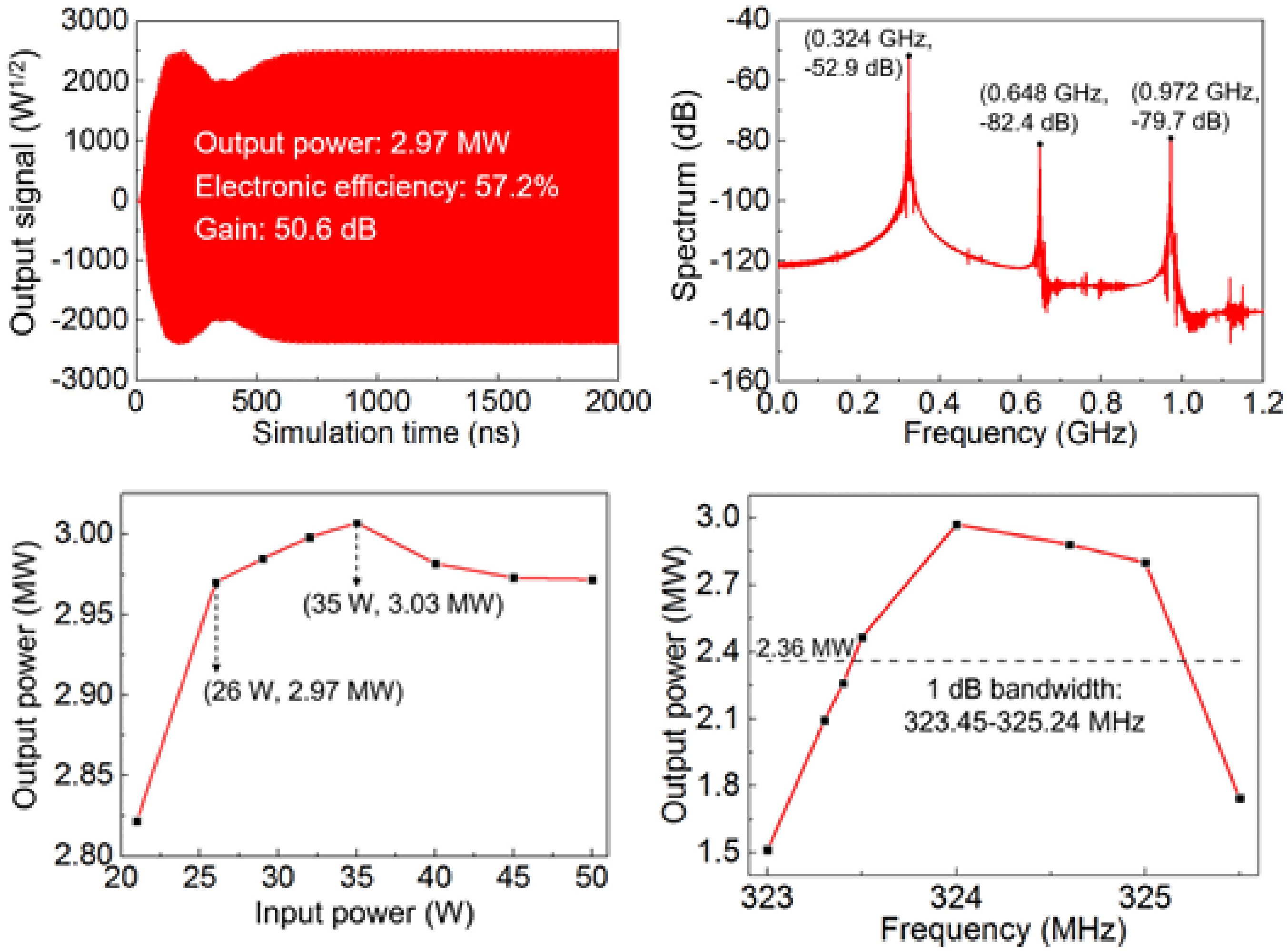
Electric field distributions



Electron-optical system.

(a) Electron beam trajectory from the electron gun.
(b) Model of the solenoidal magnetic focusing configuration and the corresponding Bz.

M-Klystron3-D Particle Simulation

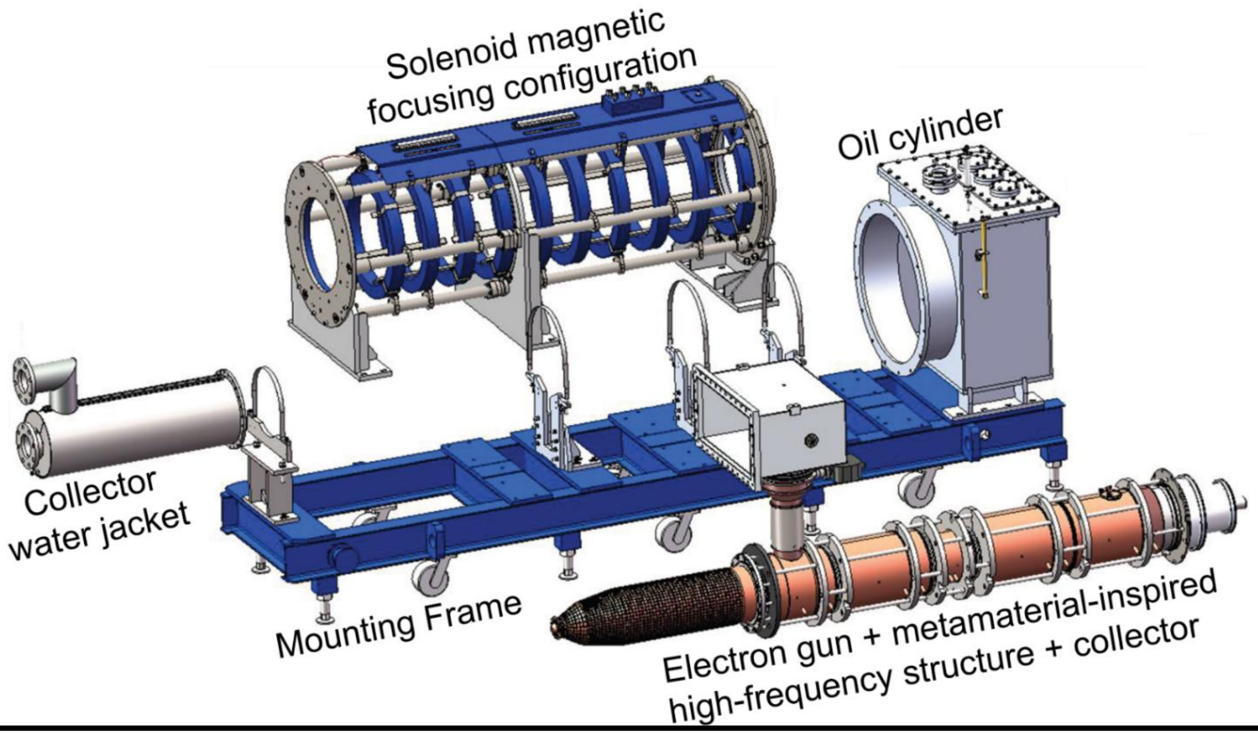


- Output power amplitude stabilizes at steady state
- Output signal spectrum is clean

- Operating voltage: 110 kV
- Beam current: 48 A
- Output power: 2.97 MW
- Electronic efficiency: 57.2%
- Gain: 50.6 dB
- 1 dB bandwidth: 1.8 MHz

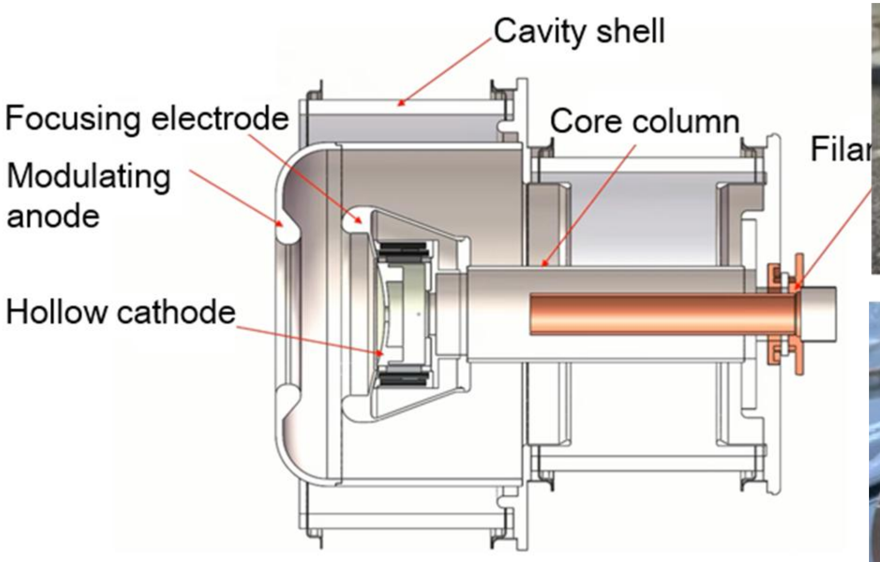
Joint simulation results: output power & spectrum; output power & efficiency vs. input power and frequency

Klystron Design and Fabrication

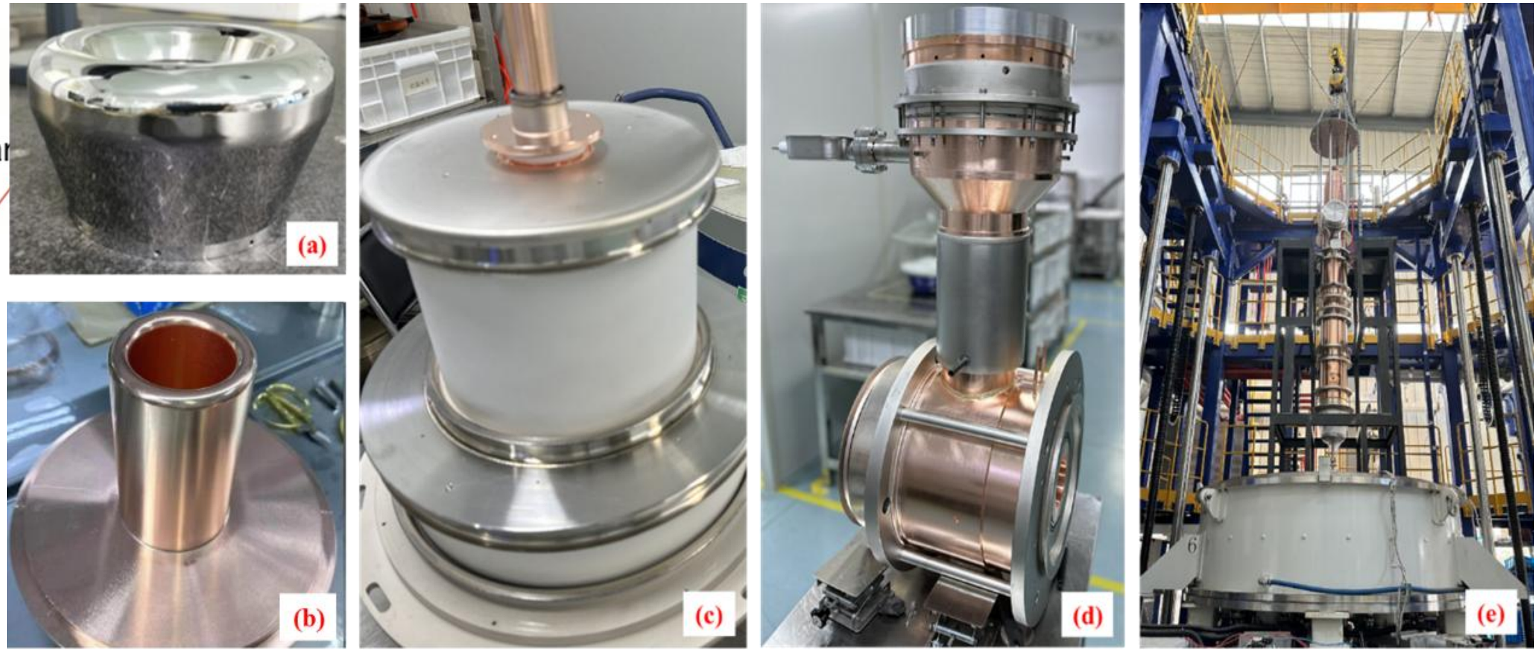


- **The layout diagram of the metamaterial-inspired klystron**
- **The main subsystems of the device are as follows:**
  - ➢the core assembly (electron gun, metamaterial-inspired high-frequency structure, and collector)
  - ➢the solenoid magnetic focusing configuration
  - ➢the auxiliary systems (oil cylinder, collector water jacket, and mounting frame)
- **The high-voltage insulation is provided by the oil cylinder, and the collector is cooled by water jacket.**

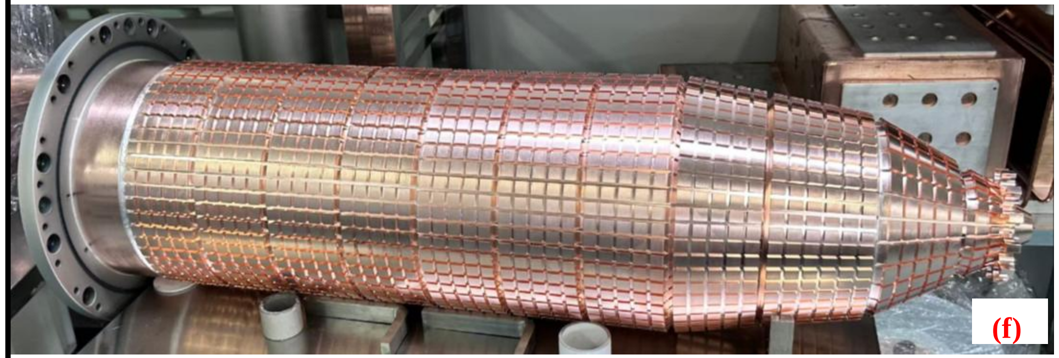
Key parts and fabrication



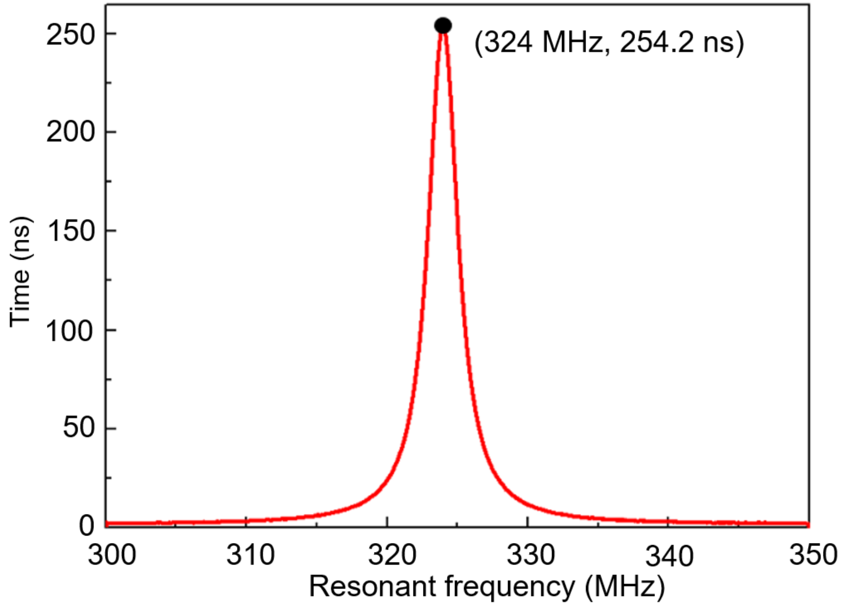
Electron gun



- **The key components during fabrication process:**
  - (a) the electron gun focus electrode;
  - (b) the drift tube;
  - (c) the assembled electron gun;
  - (d) output cavity with coupler;
  - (e) the cavity chain on the degas station;
  - (f) The collector



M-Klystron Cold Testing



The measured electromagnetic properties of the metamaterial-cavities

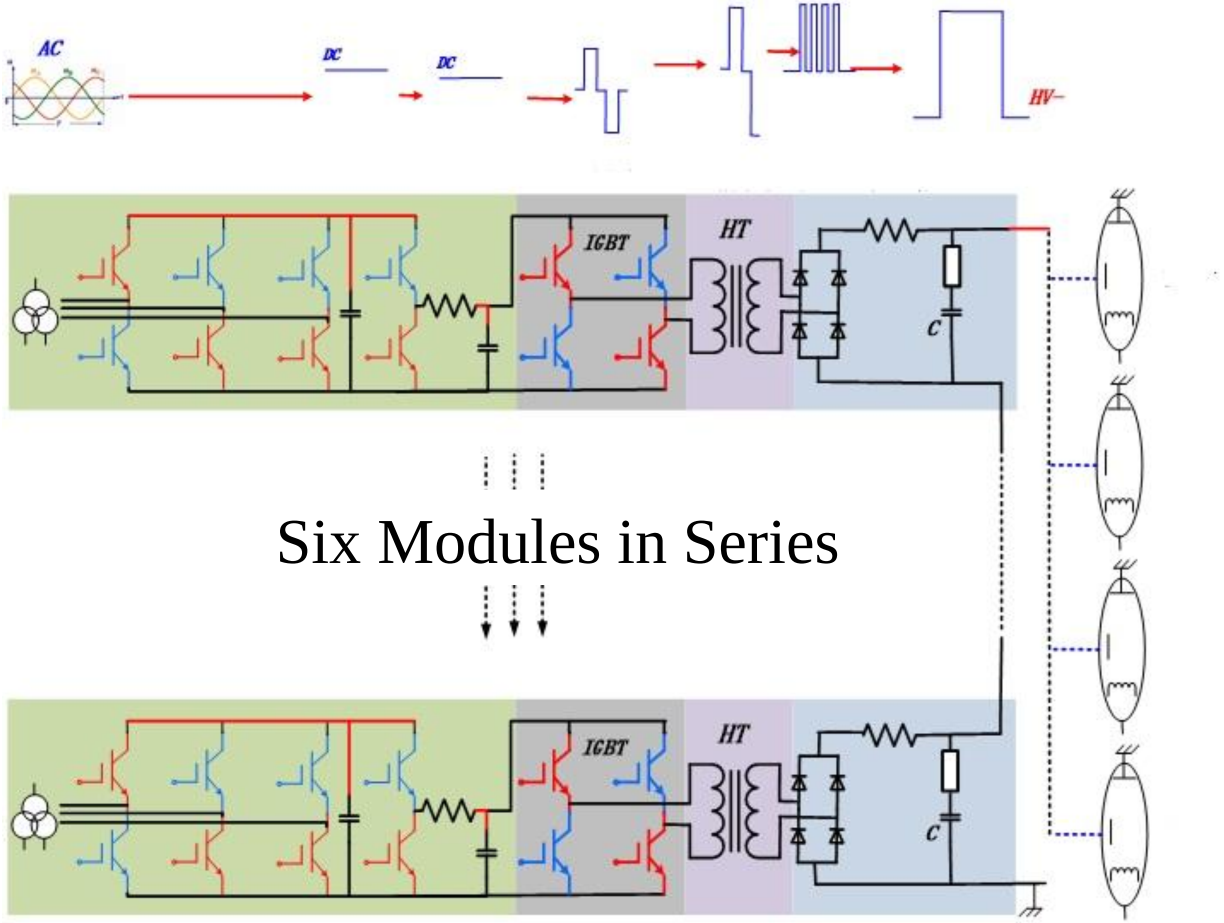
Parameter / Cavity	f (MHz)		Q_e	
	Measured	Simulated	Measured	Simulated
Input cavity	324.00	324.00	129.4	121.2
Idler cavity 1	325.33	325.35	-	-
Idler cavity 2	641.56	641.84	-	-
Idler cavity 3	337.04	337.08	-	-
Output cavity	324.00	324.00	17.1	18.6

- **The CeSRR-loaded input cavity was cold-tested by the vector network analyzer.**
- **The test platform and the measured results are shown in left.**
- **The measured resonant frequency and group delay are 324 MHz and 254.2 ns, respectively, from which the external quality factor Q_e of 129.4 is obtained.**

Long Pulse Solid-State Modulator

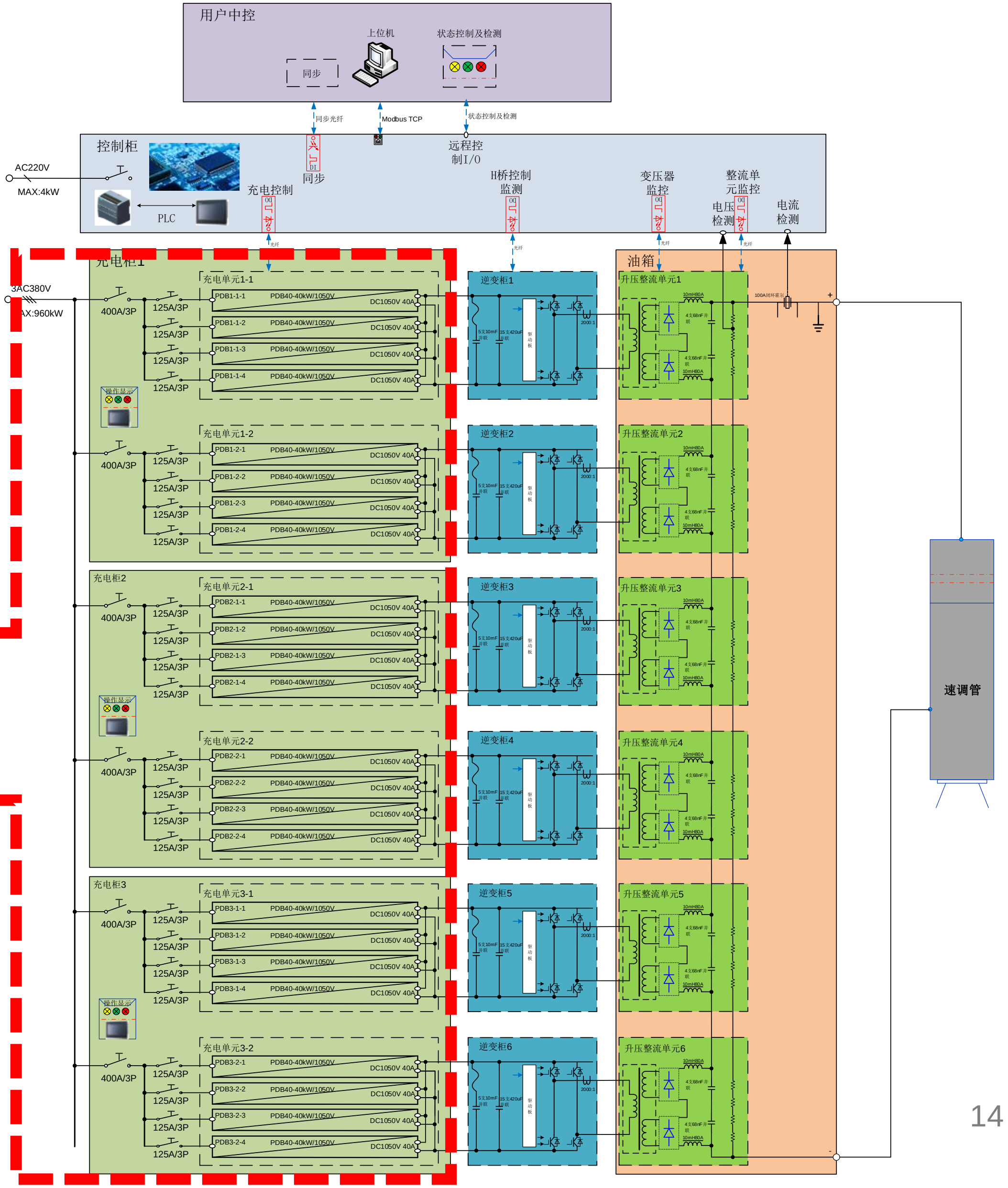
- The topology of the modulator is refer to ESS modulator design;
- The power conversion: AC/DC, 1kV capacitor energy storage, H-bridge high-frequency inversion, high-frequency transformer voltage step-up, rectification and filtering.
- Six modules in series output 120kV/80A;

Parameters	Value
Pulse High Voltage	120 kV
Pulse Current	80A
Pulse Length [flat-top]	1500 uS
Pulse Drop	<1%
Rising time	<150 uS
Repetition Rate	50 Hz
Ripple	<0.3%
Efficiency	>90%
THD	<5%



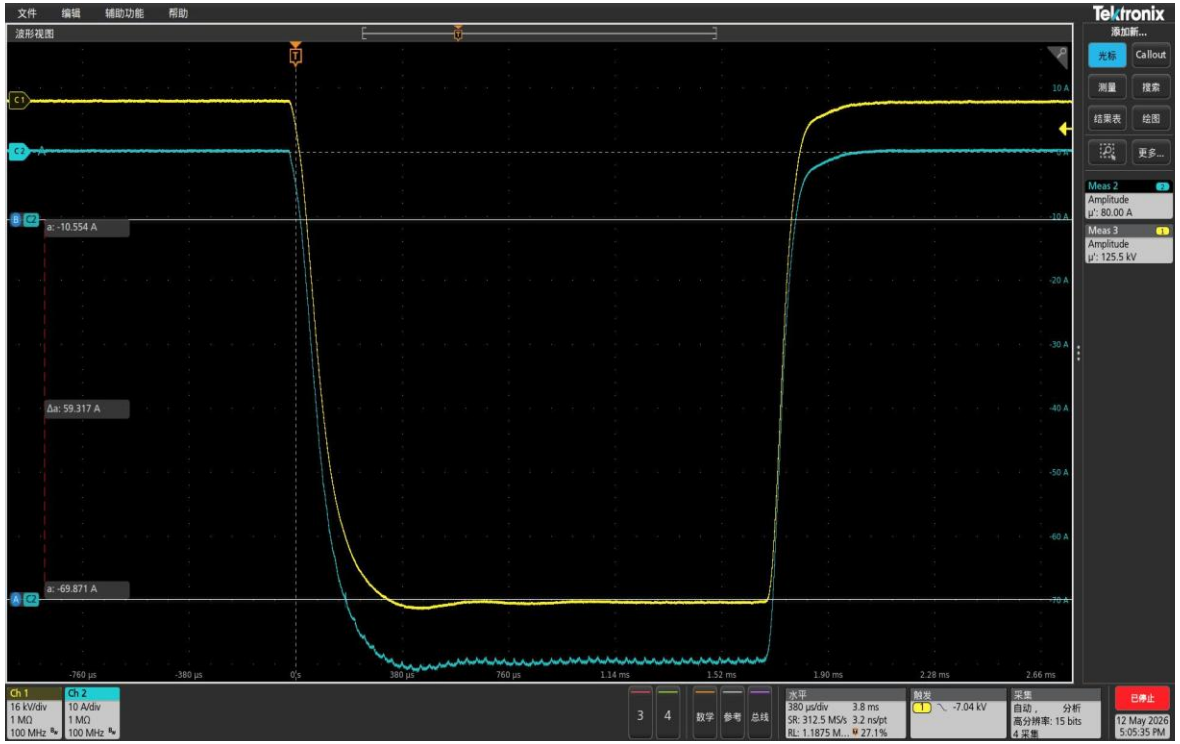
Long Pulse Solid-State Modulator

- The AC/DC charging section employs of high-frequency power supply modules, featuring parallel current-sharing and redundant design with high stability;

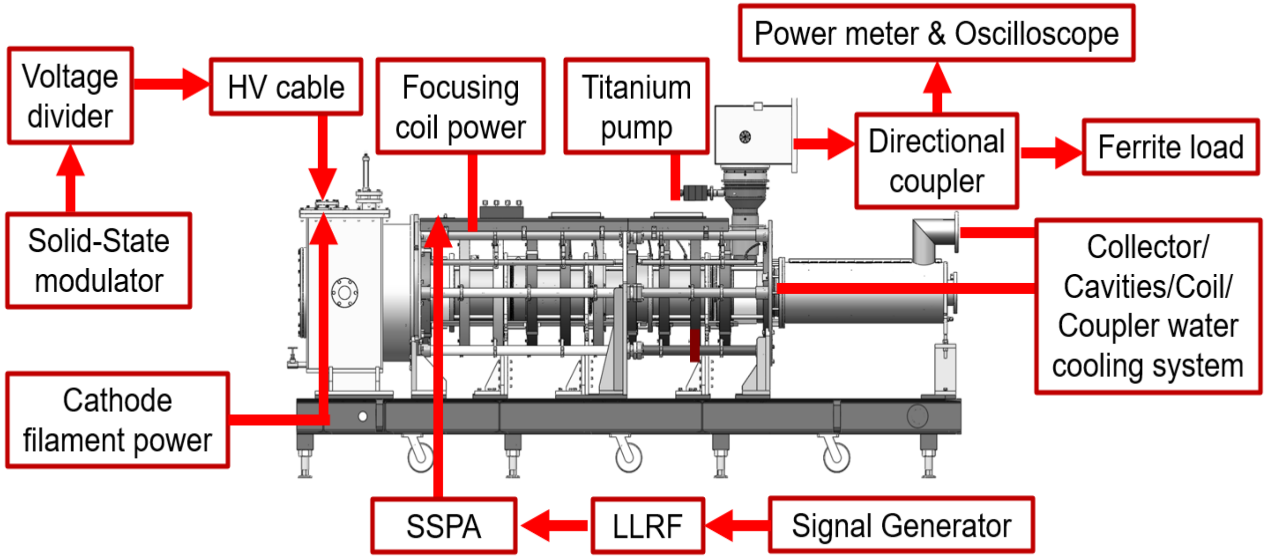


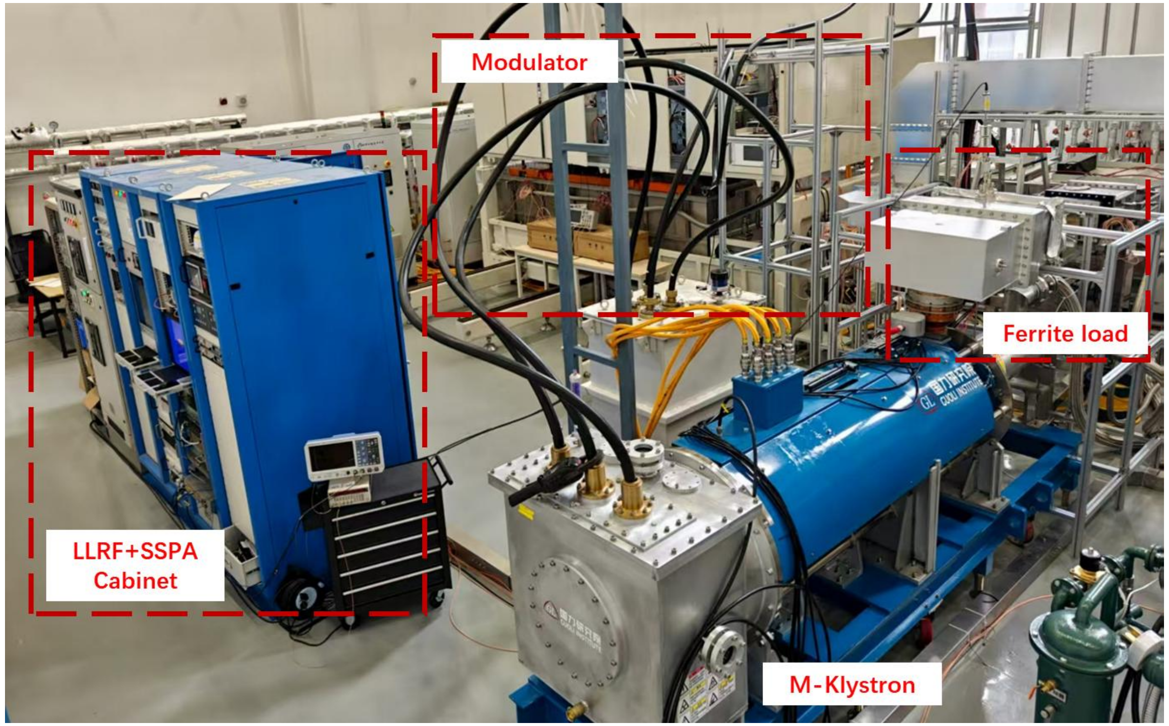
Long Pulse Solid-State Modulator

- Tests of the Modulator Prototype on dummy load
  - The test results are shown below: pulse high voltage 120kV, pulse current 80A, repetitive rate 50Hz, pulse width 1.5ms (90%~90%), rising time 150μs (10%~90%), Pulse Drop <0.3%, ripple<0.3%;
  - Applied to the commissioning of the 324MHz metamaterial klystron.



M-Klystron RF Testing

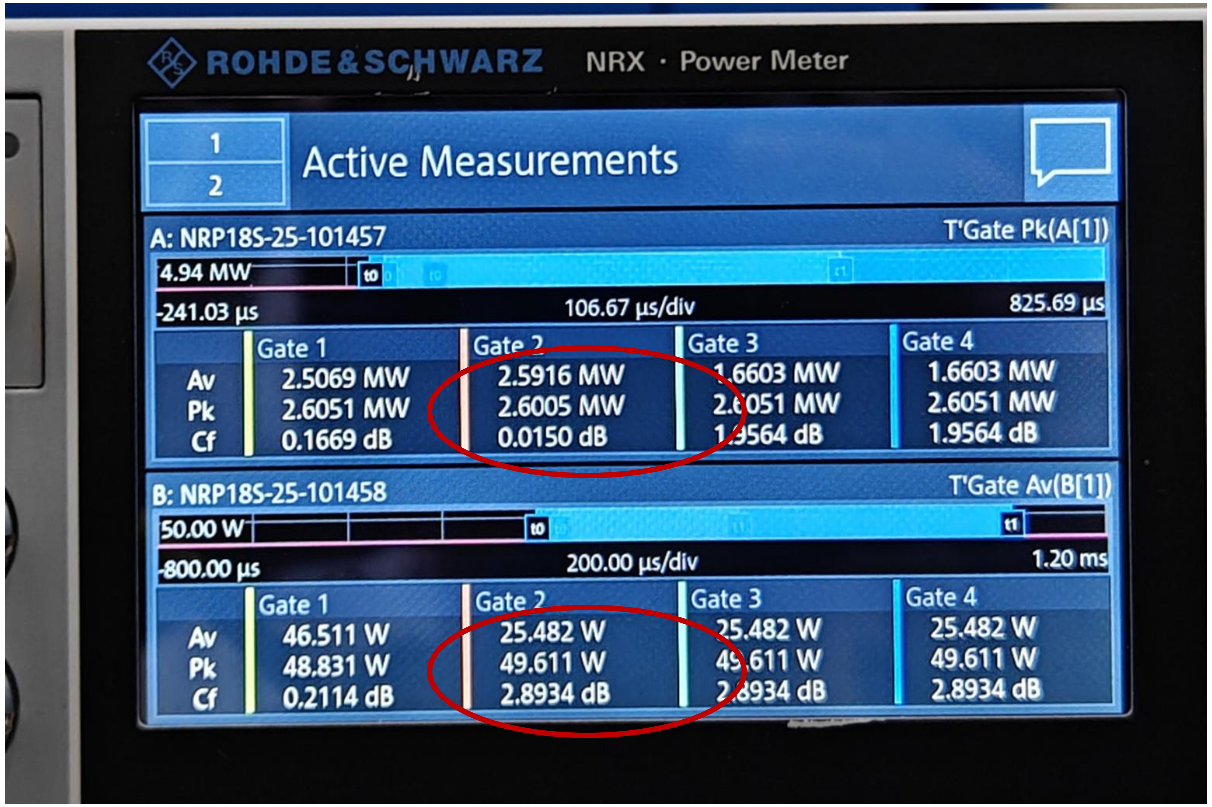


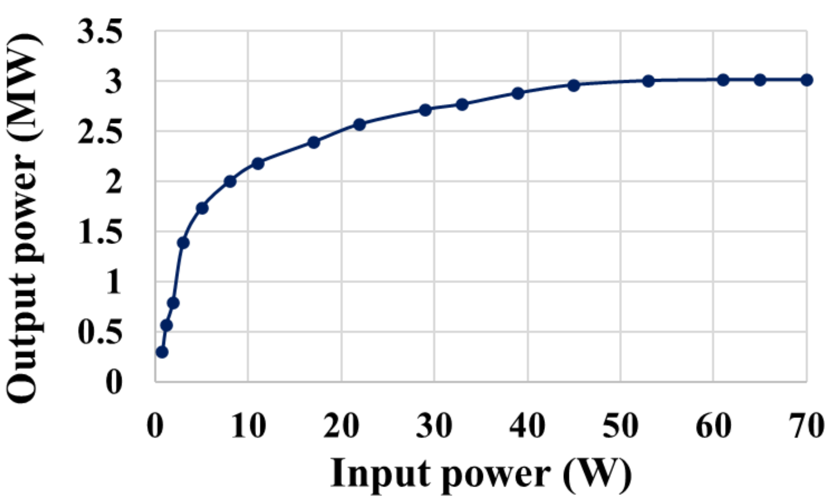


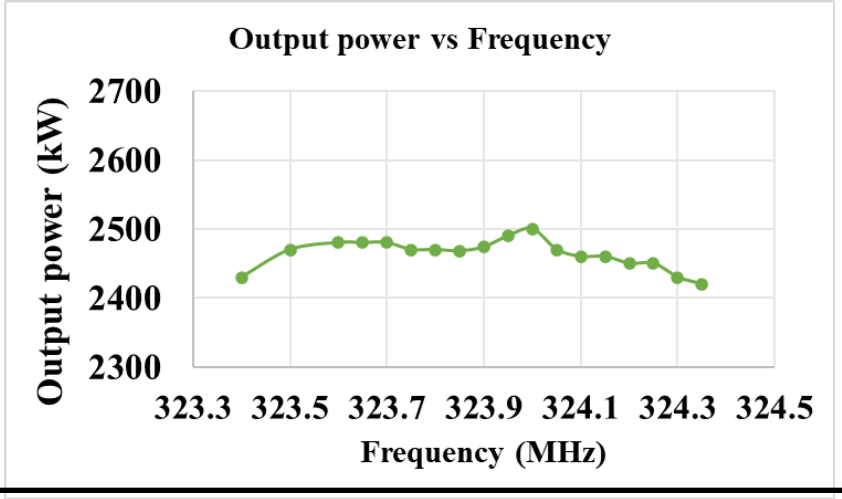
- The klystron's high voltage is derived from a long-pulse solid-state modulator, which delivers stable **–110 kV pulses at 25 Hz with a 950-μs flat-top duration.**
- A solid-state amplifier provides the RF drive.
- The klystron then feeds the RF power into a high-power ferrite dummy load.

M-Klystron RF Testing

Output Power and Bandwidth

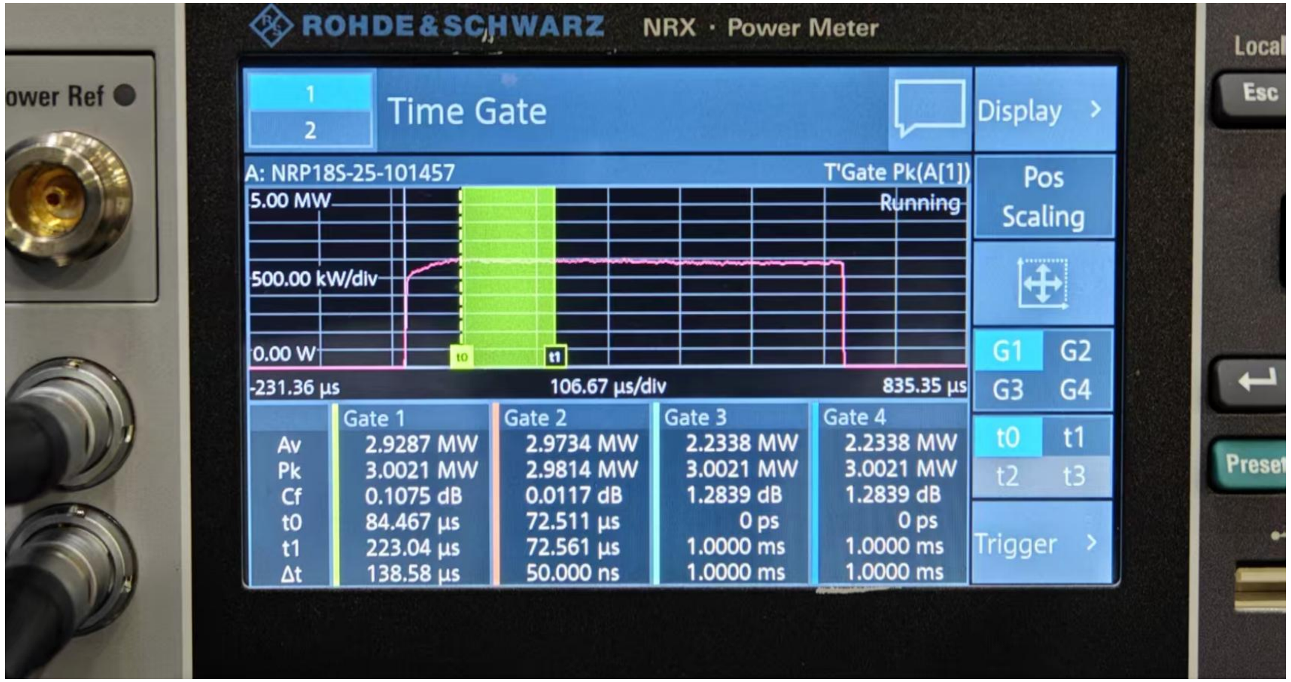






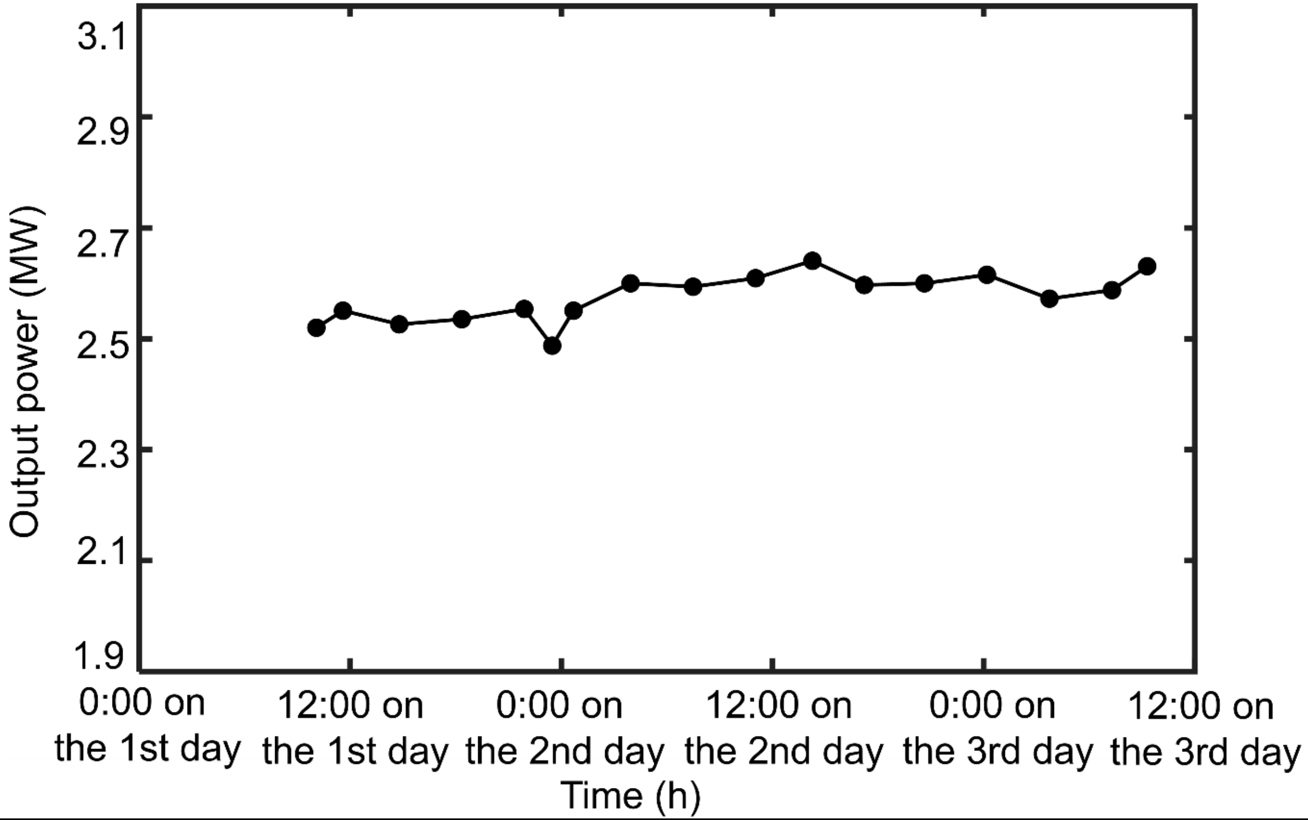
- At 2.5 MW saturated output, solid-state amplifier RF pulse power measured at 46.5 W
- Output power > 2 MW (1 dB compression) from 323.4–324.3 MHz; 1 dB bandwidth > ±0.3 MHz

M-Klystron RF Testing



- **Simulation: at 110 kV / 47.2 A, klystron outputs 2.93 MW;**
- **Cathode HV raised to 110 kV: beam current 51.5 A, HV pulse 950 µs, 25 Hz — RF peak saturated output 3 MW / 650 µs / 25 Hz;**
- **Electronic efficiency: 3 MW / (110 kV × 51.5 A = 5.66 MW) = 53.1%.**

M-Klystron RF Testing

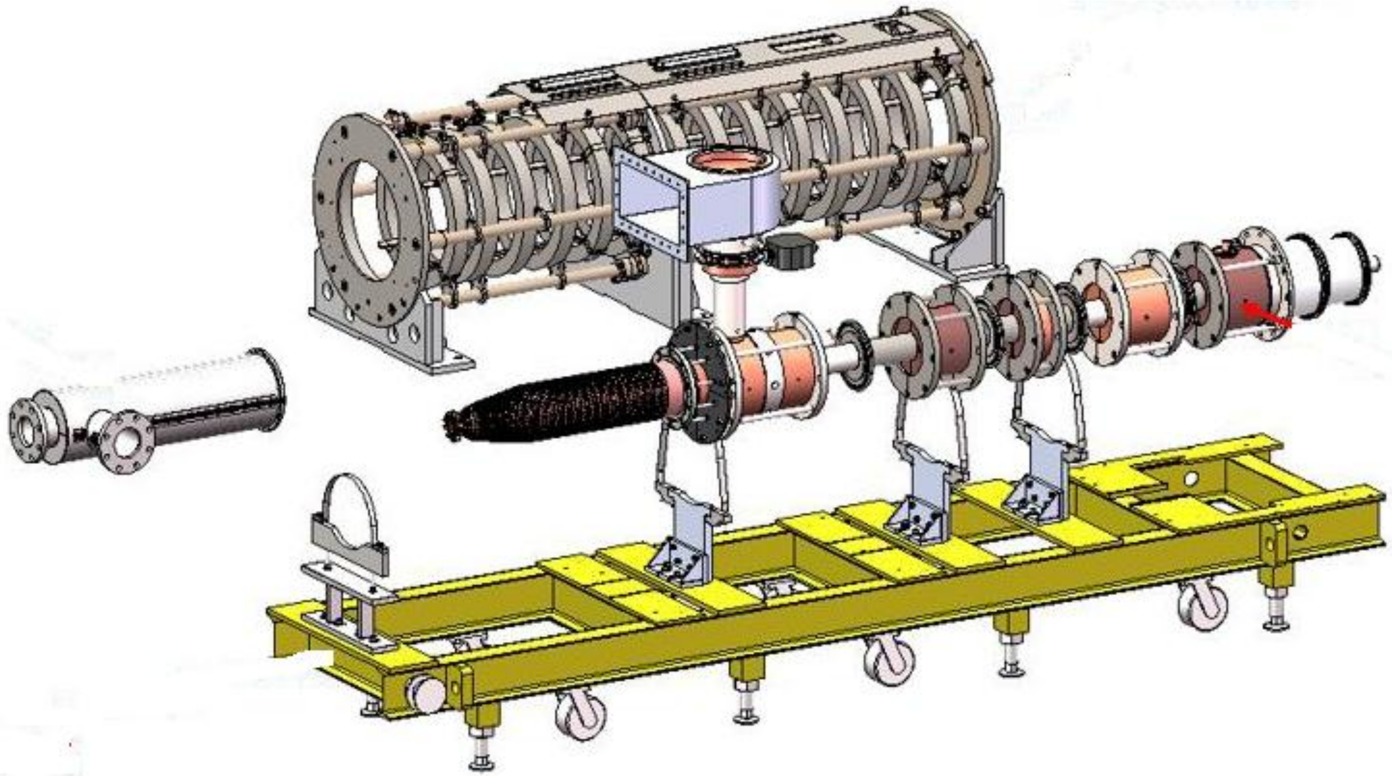


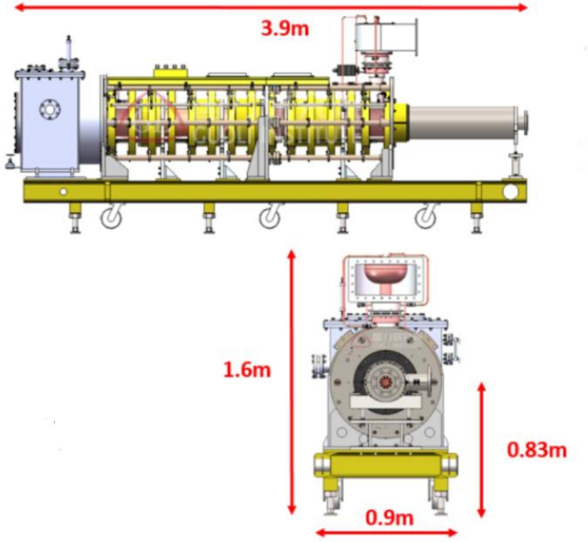
- After commissioning: 48-hour full-power full-duty stability test at 2.5 MW / 25 Hz / 650 μs, zero failures, meeting design requirements;
- Nearly one month of 24/7 testing indirectly verified long-pulse solid-state modulator stability, largely meeting expectations

648MHz/1.2MW klystron

◆ **648 MHz/1.2 MW klystron**

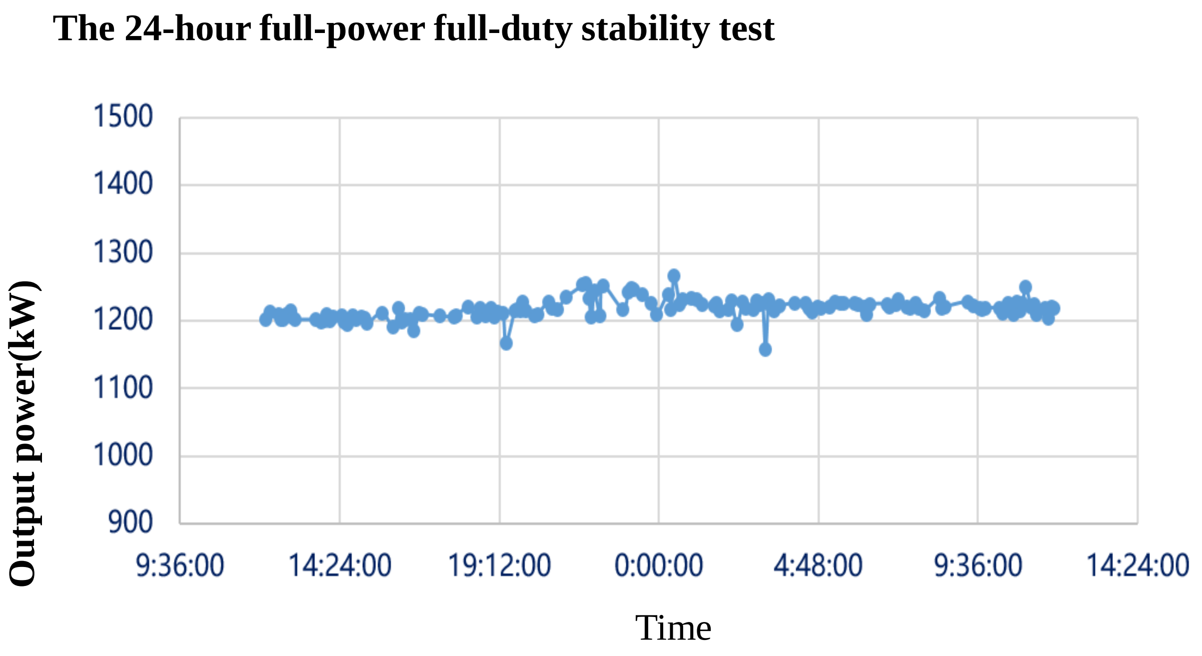
- Conventional structure with 6 resonant cavities;
- 26 klystrons for the Ellip. cavities of CSNS-II Linac;
- In 2020, the R&D of the 648MHz/1.2MW klystron prototype was initiated.



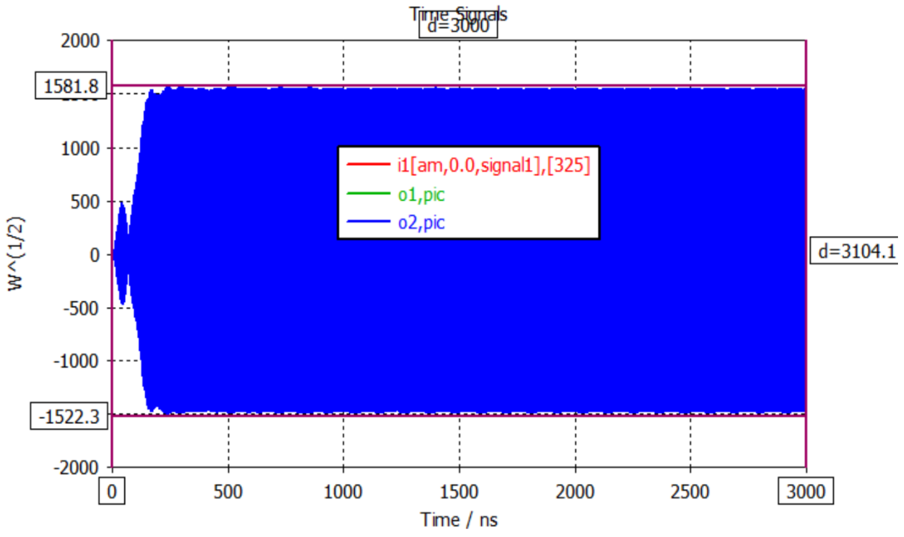


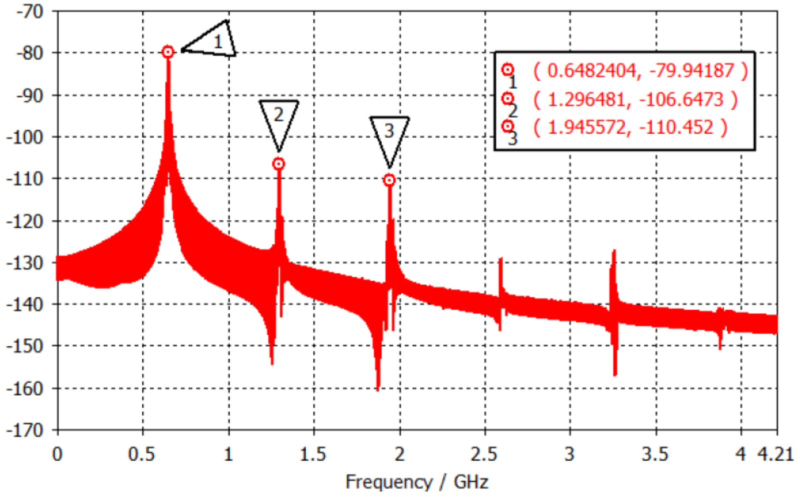
648MHz/1.2MW klystron

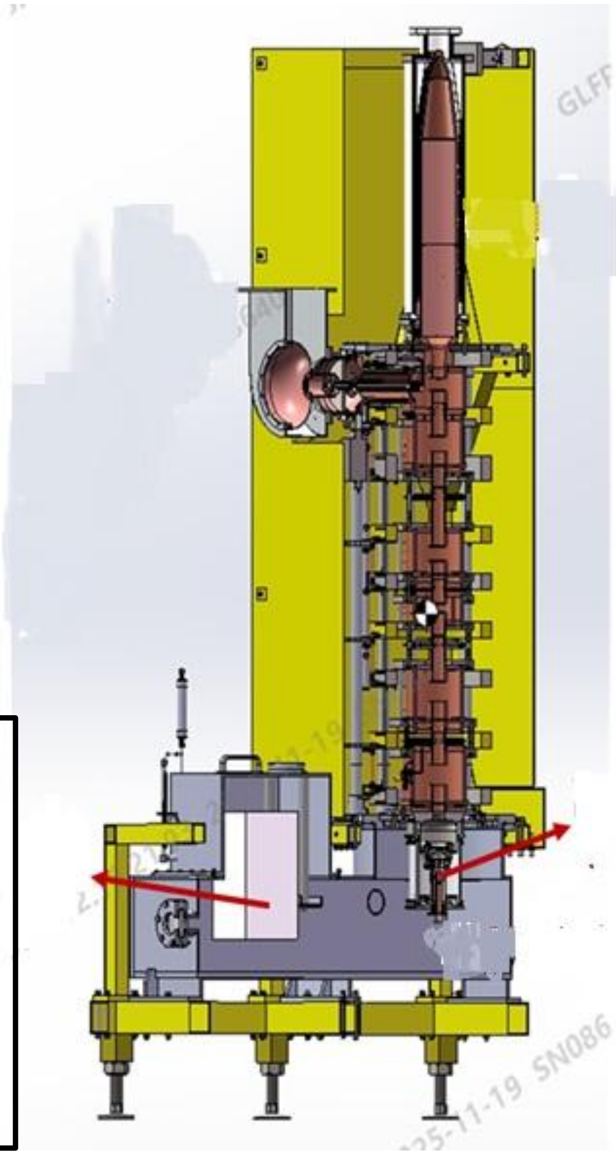
- **Test results of the 648MHz klystron prototype.**
  - **High Voltage -104kV, Beam Current 22.3A, Peak Power>1.2MW, Efficiency 52.47%;**
  - **The driving power 36.5W，RF Peak Power 1.217MW，Gain 45.2dB**.
  - After the klystron testing was completed, a 24-hour full-power, full-duty cycle stability test was carried out. No failures occurred during this period;
  - The Rep. rate is up to 50Hz in the Batch Production.



Design of 648MHz M-klystron







Time-domain analysis: approximately 1.2 MW is reached after 300 ns, with no oscillation observed within 3000 ns.

Frequency-domain analysis: the second harmonic component is approximately 27 dB lower than the fundamental.

- Base on the successful development of the 324MHz M-klystron, the team has initiated the design of 648MHz M-klystron.
- RF peak power 1.2MW output with 100kV/20A.
- Compared with the conventional design, cavity-string length is reduced from 2.1 m to 1.3 m, roughly 40% reduction.
- Vertical layout, and high-power testing by the end of 2026

Summary and Outlook

- The beam commissioning of CSNS-II Linac is scheduled in May 2028;
- The mass production of 648MHz/1.2MW conventional klystrons for CSNS-II Linac Elliptical cavities is underway, the heavy installation and commissioning will begin in March 2027.
- To meet CSNS-II and other project needs: a 324MHz/3MW/50Hz metamaterial klystron is designed, output cavity, collector, and other components are upgraded for higher power capacity and thermal dissipation, high power testing is scheduled to begin at the end of this year.
- The development of a compact, vertically oriented 648MHz metamaterial klystron is currently underway, and high power testing is also scheduled to begin at the end of this year.

Thank you for your attention!