Tsinghua University

ACCELERATOR LABORATORY of TSINGHUA UNIVERSITY

Power Combination of Magnetrons as compact X-band RF source

Jiayang Liu on behalf of VED team in THU

May 19, 2022

Outline

- Background
- Power combination of conventional magnetrons
- Power combination of magnetrons with dual ports
- Power combination of magnetrons with parallel cathodes
- Summary

Outline

- Background
  - Motivations
  - Locking technologies
- Power combination of conventional magnetrons
- Power combination of magnetrons with dual ports
- Power combination of magnetrons with parallel cathodes
- Conclusions

Motivations

- **Advantages of X-band structures:**
  - Compact size, light weight, high shunt impedance…
- **Advantages of magnetrons:**
  - Compact size, low cost, high efficiency…

} Preferred for industrial and medical applications

- **Bottleneck of miniaturization:**
  - Peak power of magnetrons (2MW)

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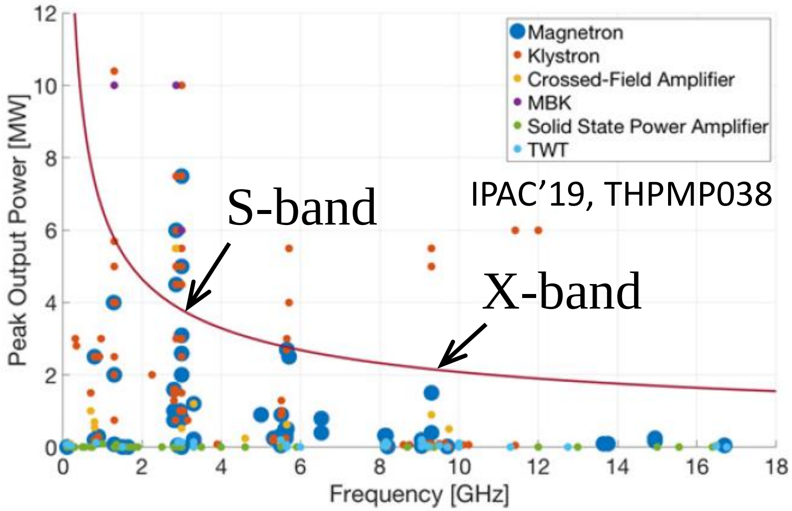
  - Longer structures
  - Lower dose rate

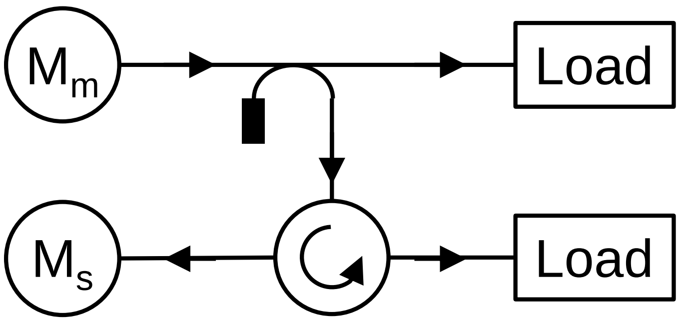


- Power combination of the magnetrons seems to be a cost-effective solution

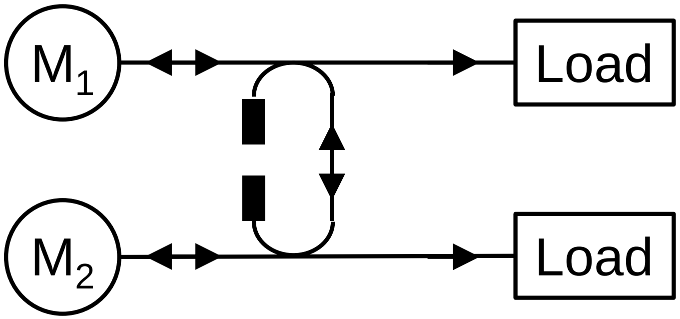
Locking Technologies

- The frequency- and phase-locking of the magnetrons is critical for the power combination of magnetrons.

Master-to-slave locking



Peer-to-peer locking

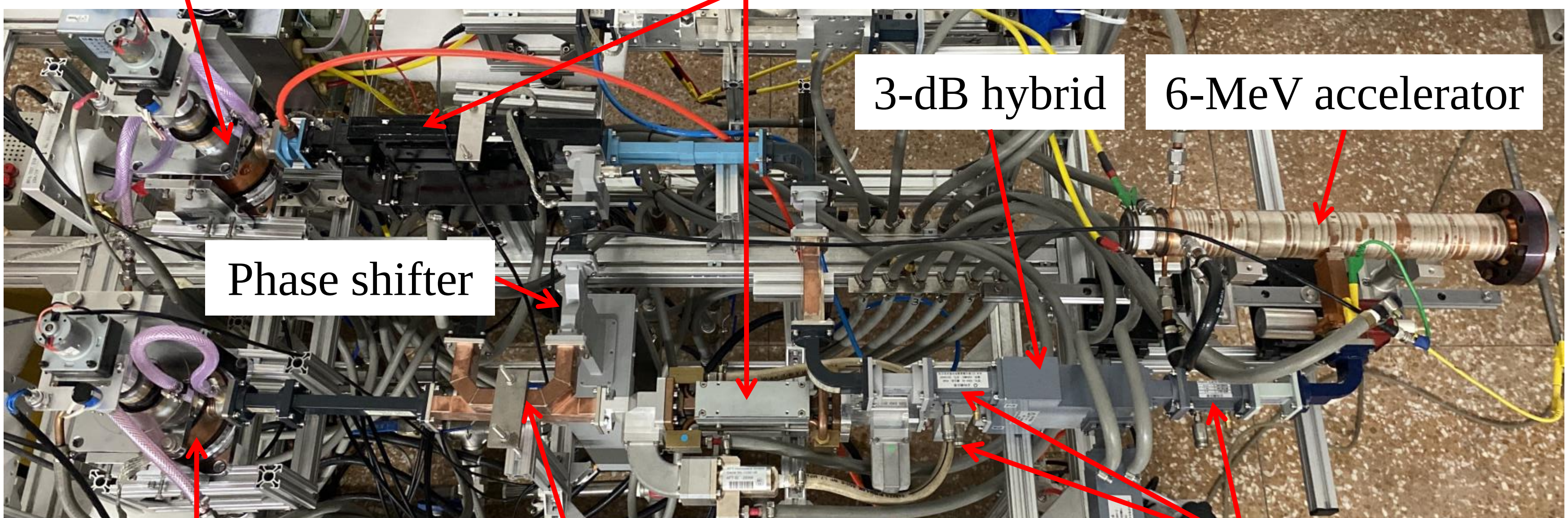


Outline

- Background
- Power combination of conventional magnetrons
  - Based on master-to-slave locking
  - Based on peer-to-peer locking
- Power combination of magnetrons with dual ports
- Power combination of magnetrons with parallel cathodes
- Conclusion

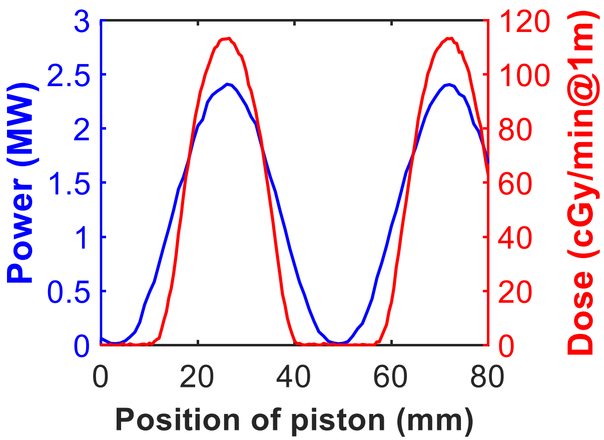
Master-to-Slave Locking

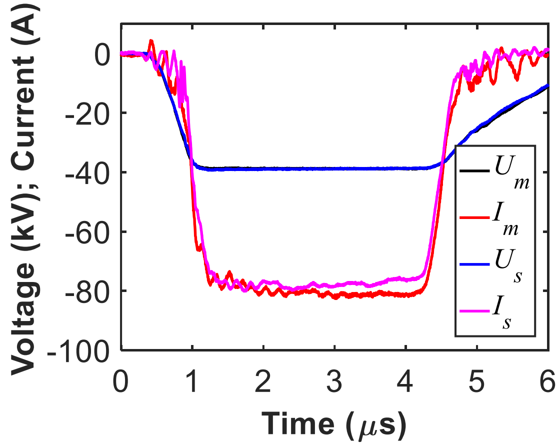
- The power for phase locking was extracted from the master magnetron by utilizing a 15-dB coupler, and then fed into the slave magnetron through a 4-port circulator.
- A phase shifter was employed in the locking circuit to adjust the phase difference between two magnetrons.

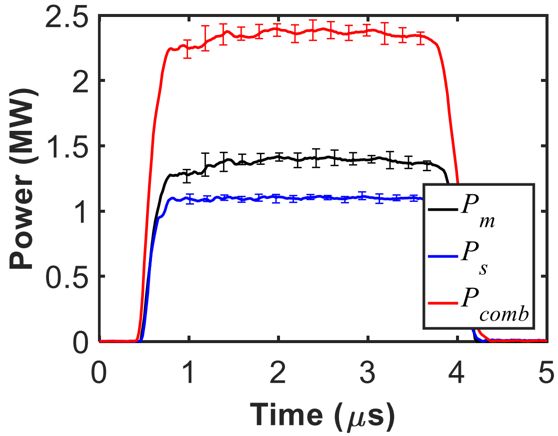


Master-to-Slave Locking

f (MHz)	U_m (kV)	I_m (A)	P_m (MW)	U_s (kV)	I_s (A)	P_s (MW)	P_{comb} (MW)	η_{comb} (%)	η_{total} (%)
9304.3	38.8	80.3	1.39	38.9	77.8	1.10	2.37	95	39



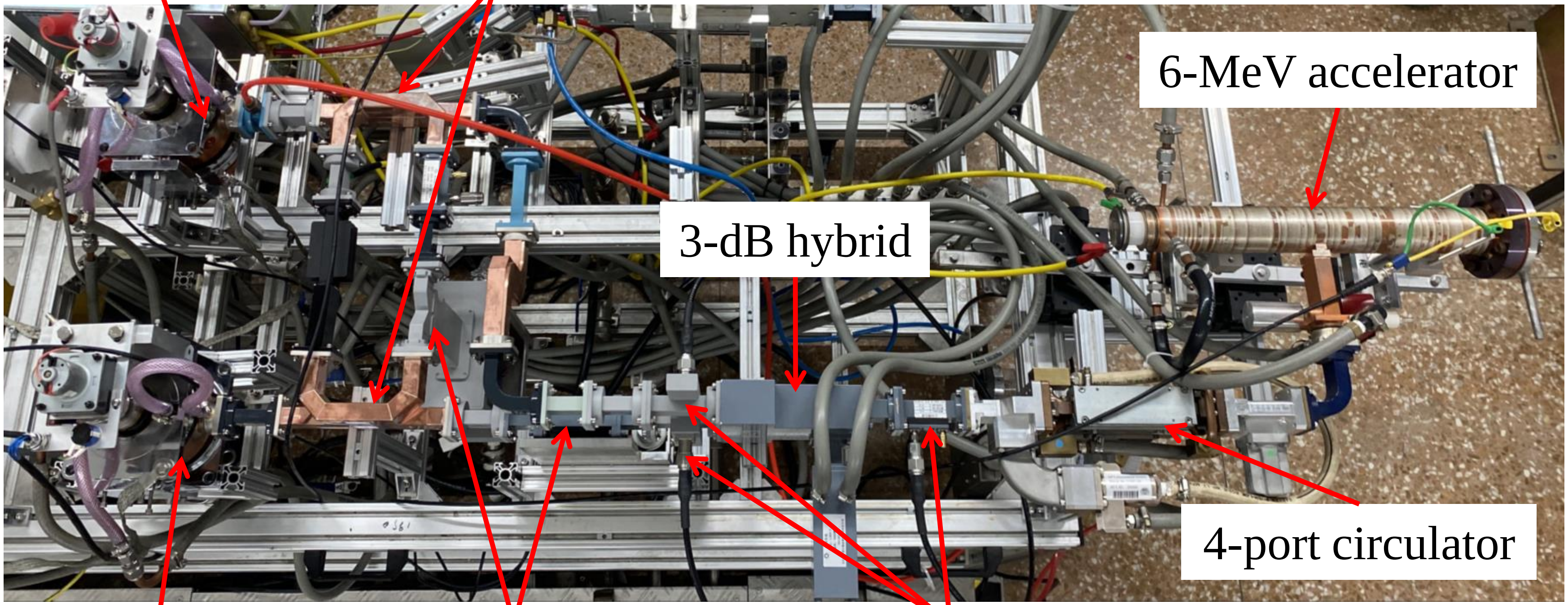




RF power source	Peak power (MW)	Pulse width (us)	Duty cycle (‰)	Dose rate (cGy/min)	Dose rate@1‰ (cGy/min)
Power combination	2.37	3.5	0.070	113.3@1m	1619@1m
2-MW magnetron	2.0	3.8	0.076	88.8@1m	1168@1m

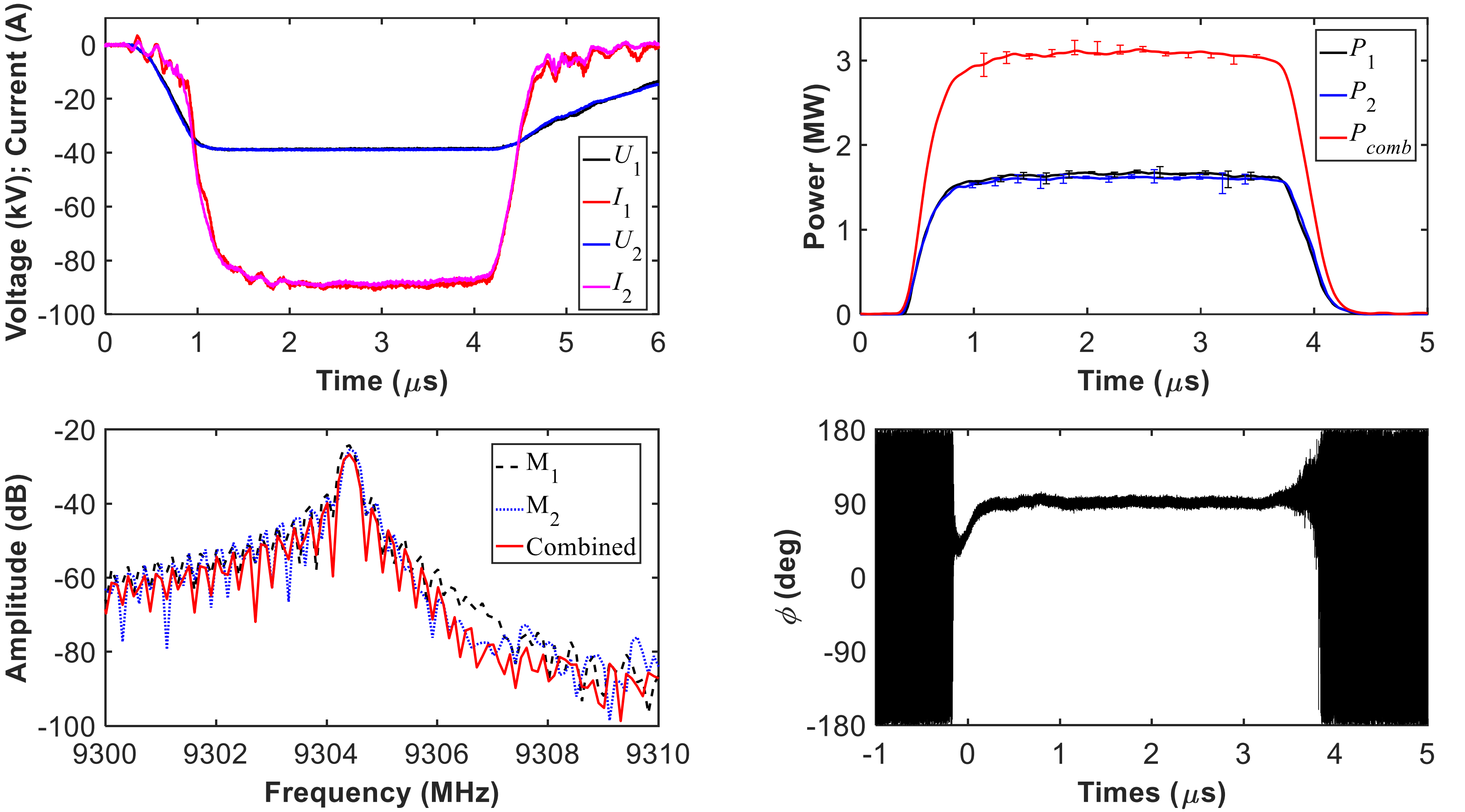
Peer-to-Peer Locking

- The power for peer-to-peer locking circuit was picked up by two 10-dB couplers adjacent to the magnetrons.



Peer-to-Peer Locking

f (MHz)	U_1 (kV)	I_1 (A)	P_1 (MW)	U_2 (kV)	I_2 (A)	P_2 (MW)	P_{comb} (MW)	η_{comb} (%)	η_{total} (%)
9304.4	38.6	89.0	1.66	38.9	88.1	1.61	3.09	94	45



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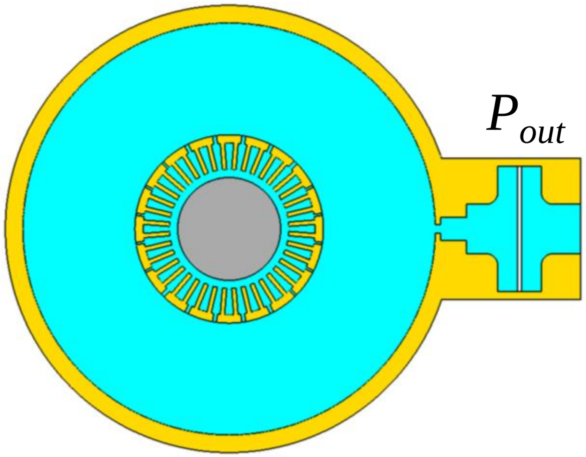
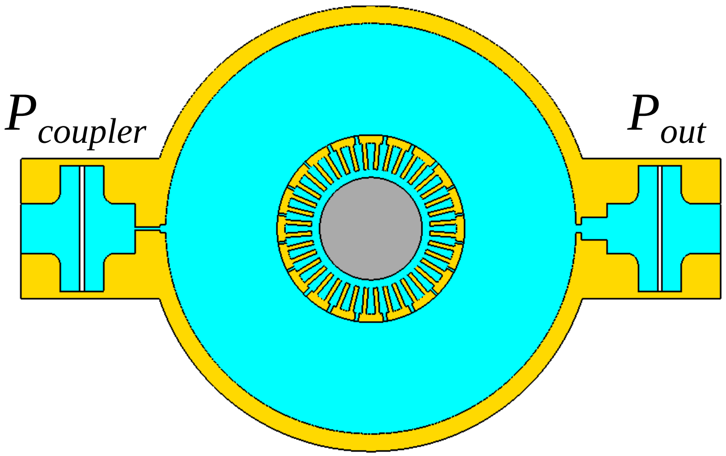
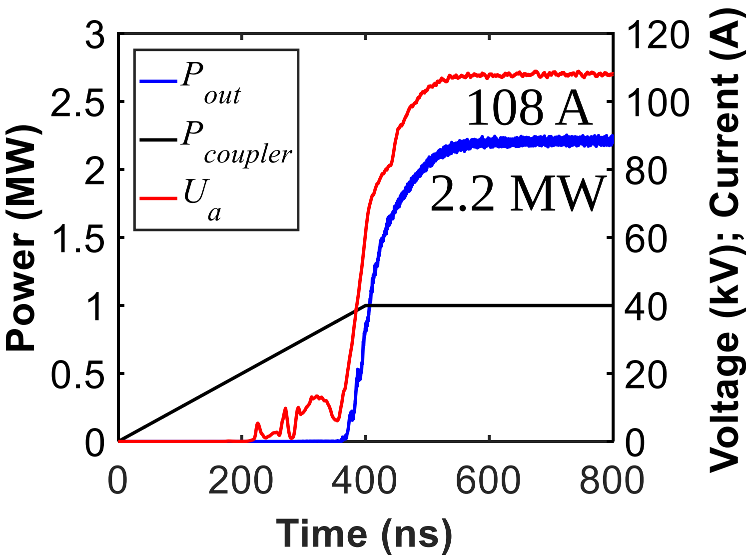
- Power combination of magnetrons with dual ports
  - Design and assembly
  - High-power experiments
- Power combination of magnetrons with parallel cathodes
- Summary

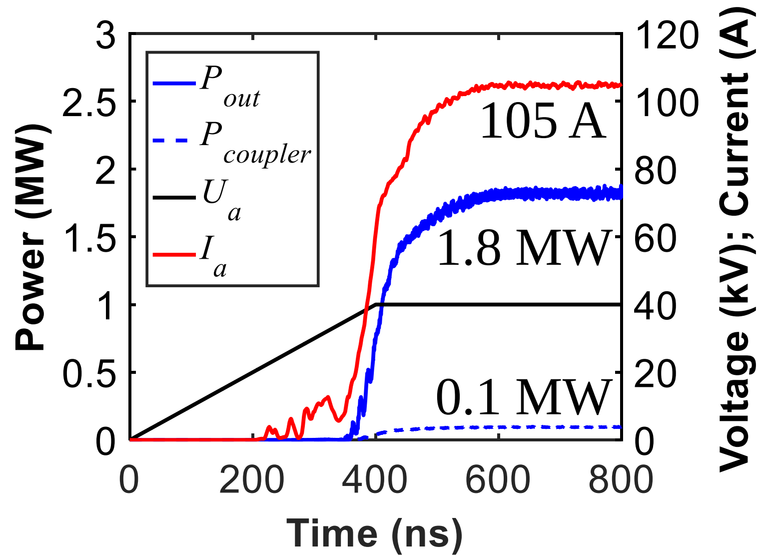
Magnetron with Dual Ports

➢ Design



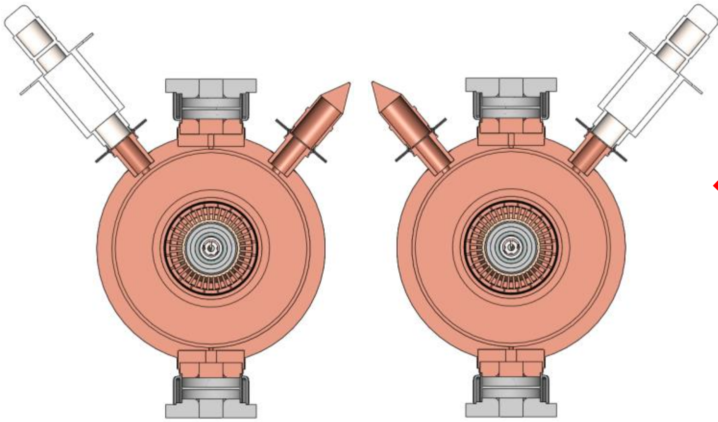




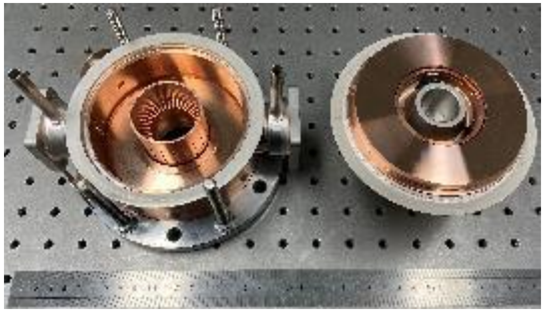


Magnetron with Dual Ports

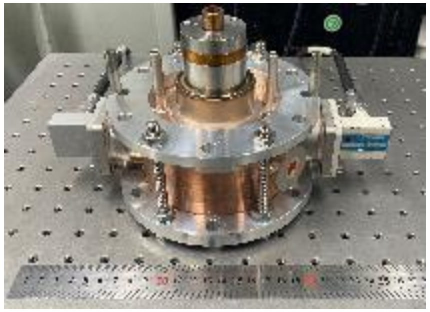
- Assembly



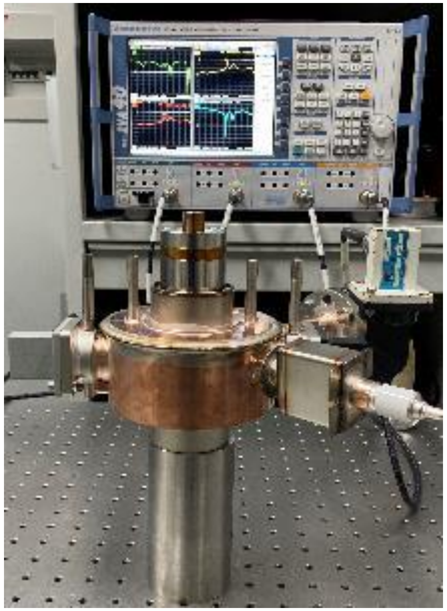
Mechanical design



Fabrication



Cold test
before welding



Cold test
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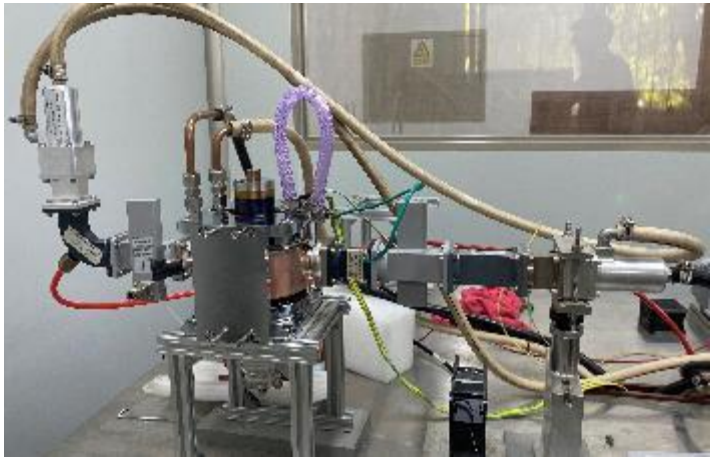
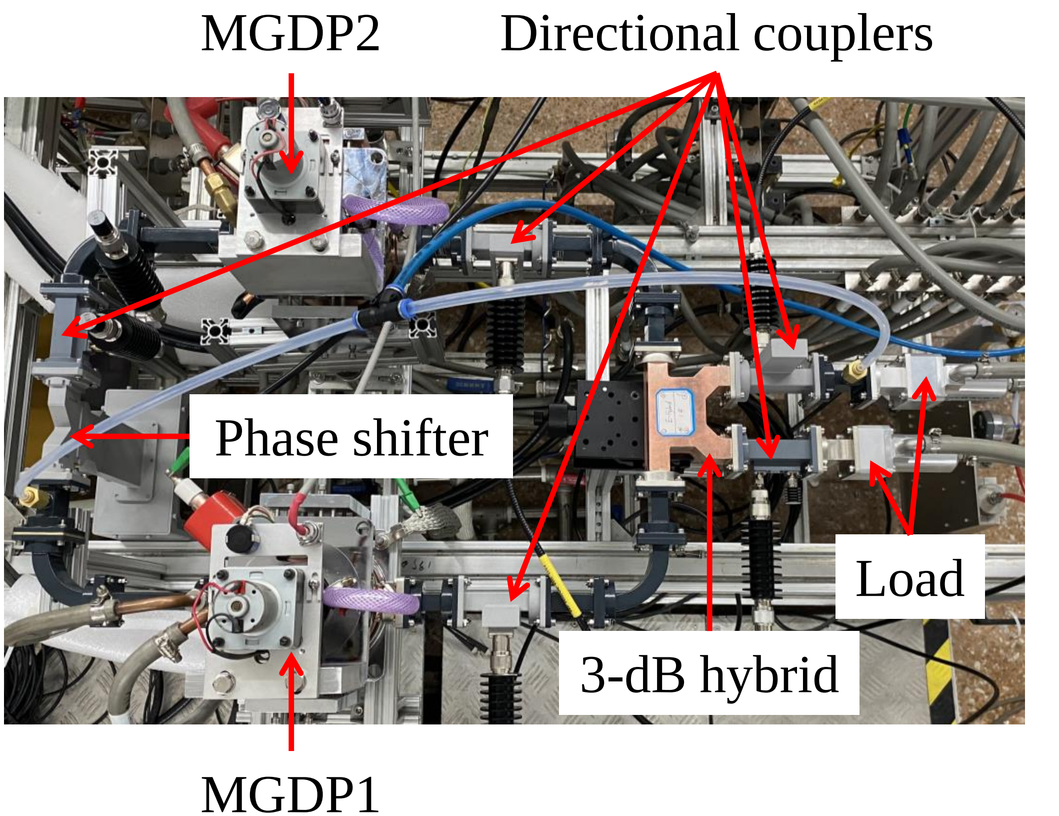
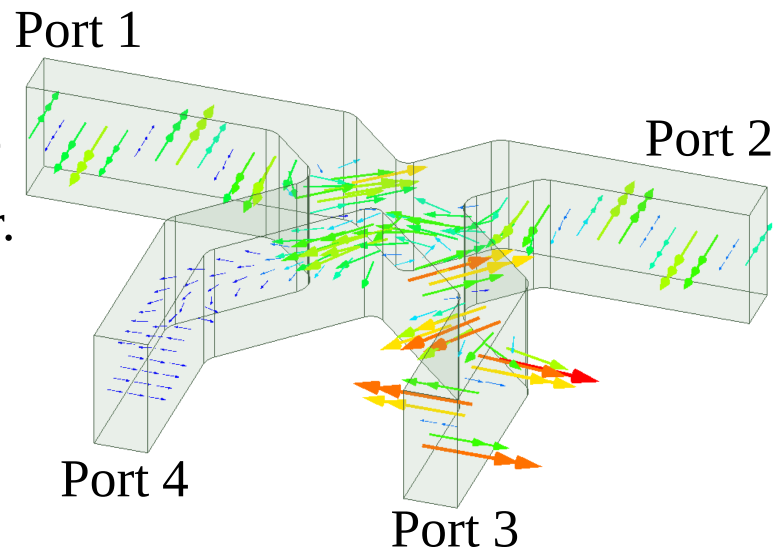


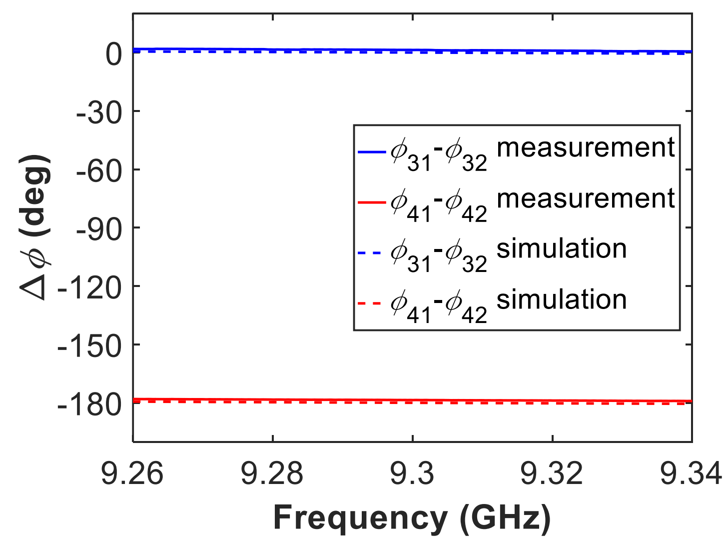
Conditioning

Magnetron with Dual Ports

- High-power experiments
- Asymmetric 3-dB hybrid with 0 and π phase characteristic was used to combine the power.

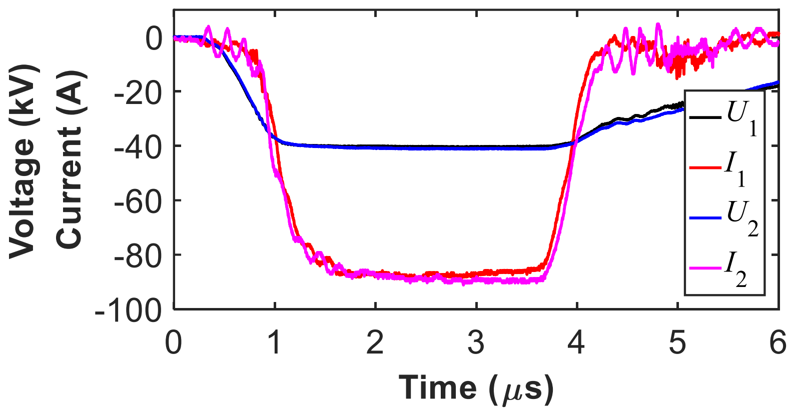


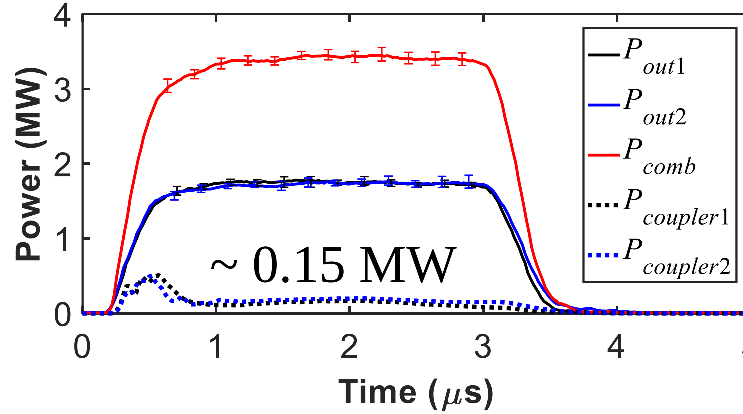


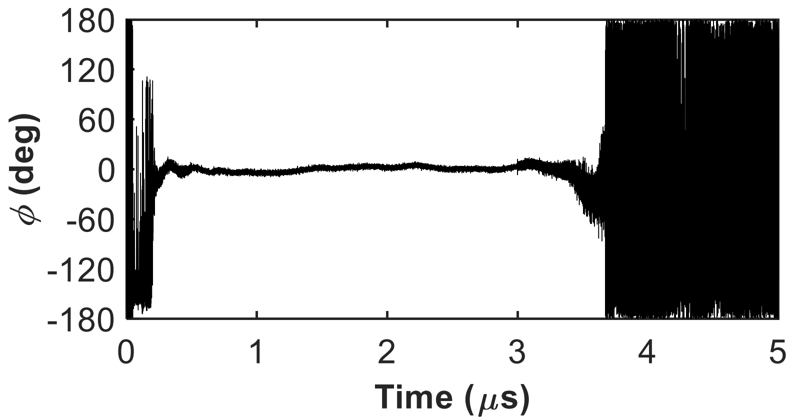


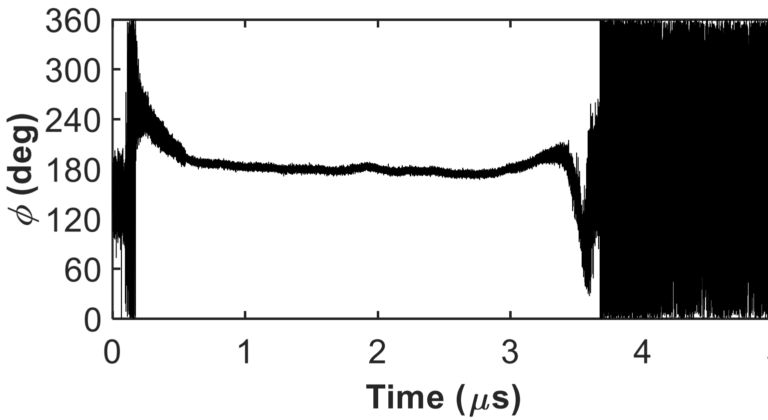
Magnetron with Dual Ports

Phase	f (MHz)	U_1 (kV)	I_1 (A)	P_1 (MW)	U_2 (kV)	I_2 (A)	P_2 (MW)	P_{comb} (MW)	η_{comb} (%)	η_{total} (%)
0	9303.4	40.3	87.2	1.75	41.0	88.7	1.73	3.39	97	47
π	9303.5	40.3	86.0	1.74	41.0	87.5	1.70	3.27	95	46









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  - Design and simulations
  - Fabrication and assembly
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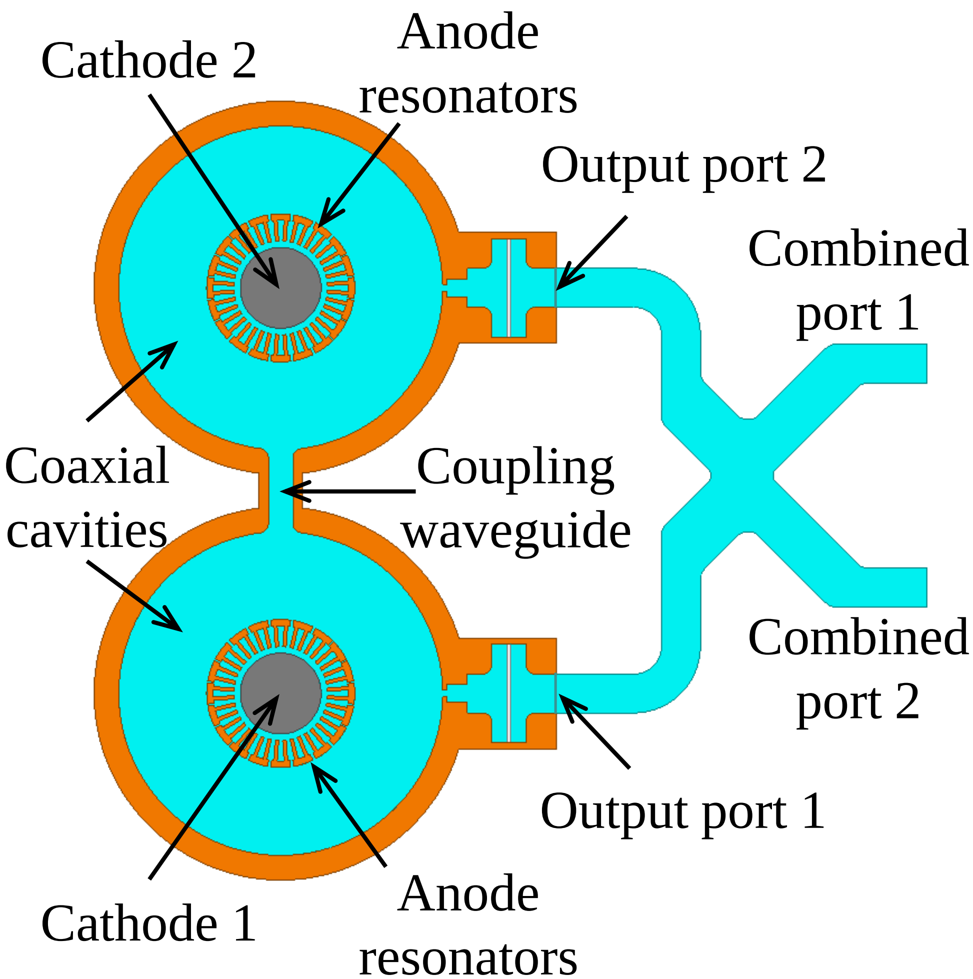
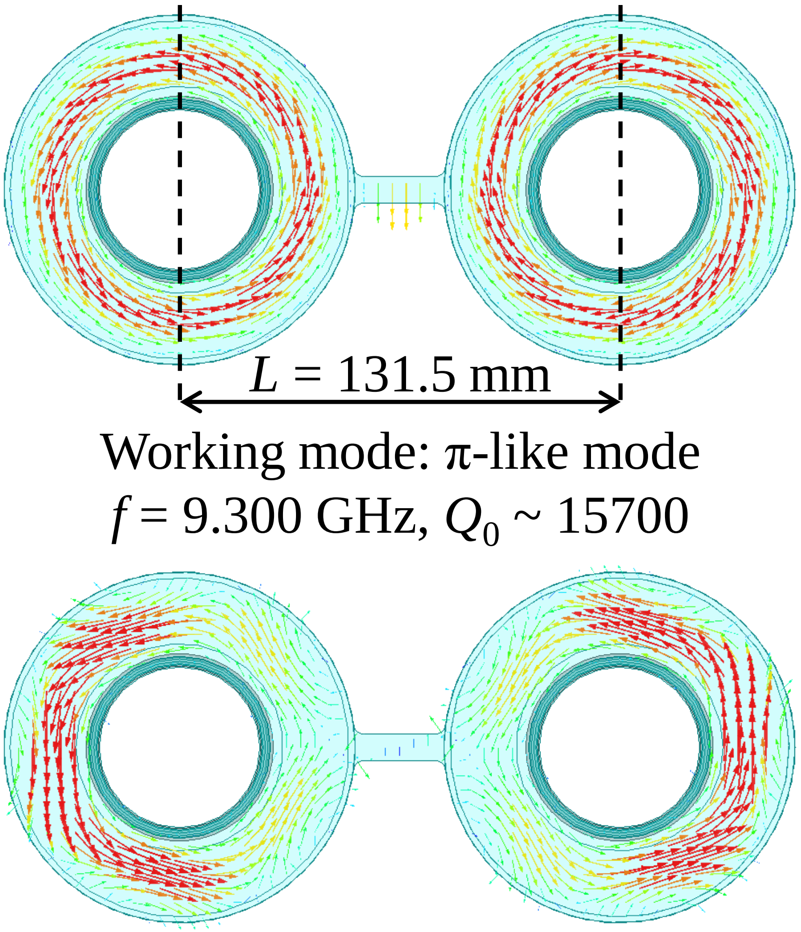
Magnetron with Parallel Cathodes

- Design



Eigenmode simulation

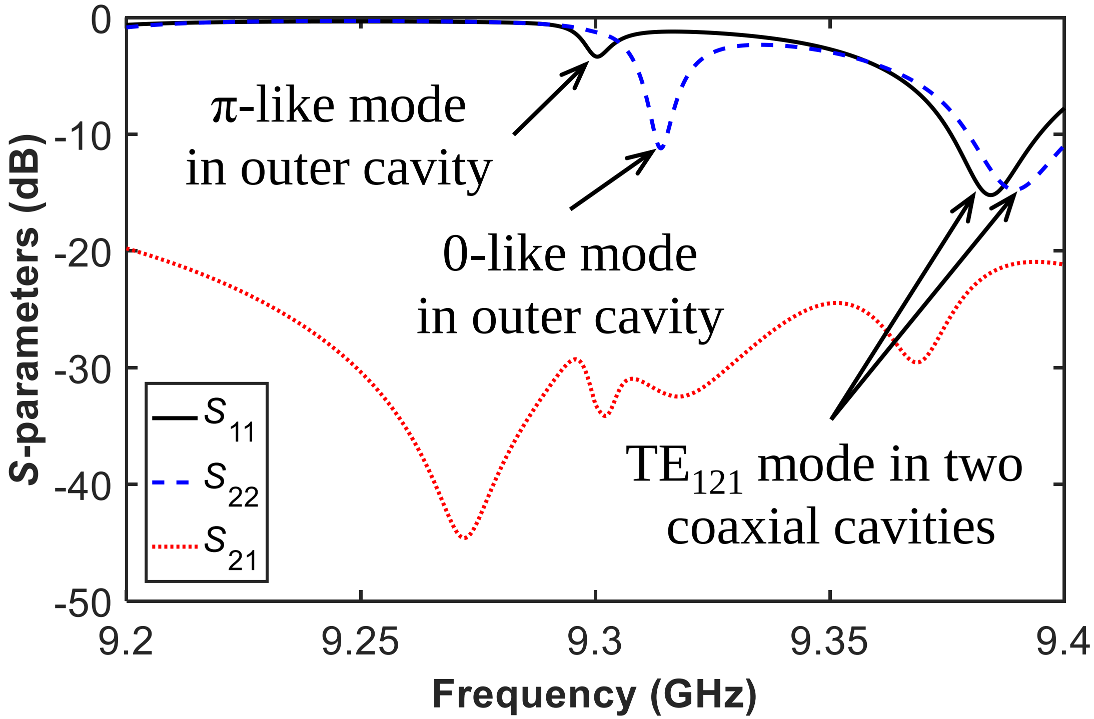


Working mode: π-like mode
f = 9.300 GHz, Q_0 ~ 15700

Parasitic mode: 0-like mode
f = 9.313 GHz, Q_0 ~ 5600

Magnetron with Parallel Cathodes

- Frequency-domain simulation
  - π-like mode in outer cavity: 9.300 GHz
  - 0-like mode in outer cavity: 9.314 GHz
  - TE_{121} mode in two coaxial cavities: 9.387 GHz



Magnetron with Parallel Cathodes

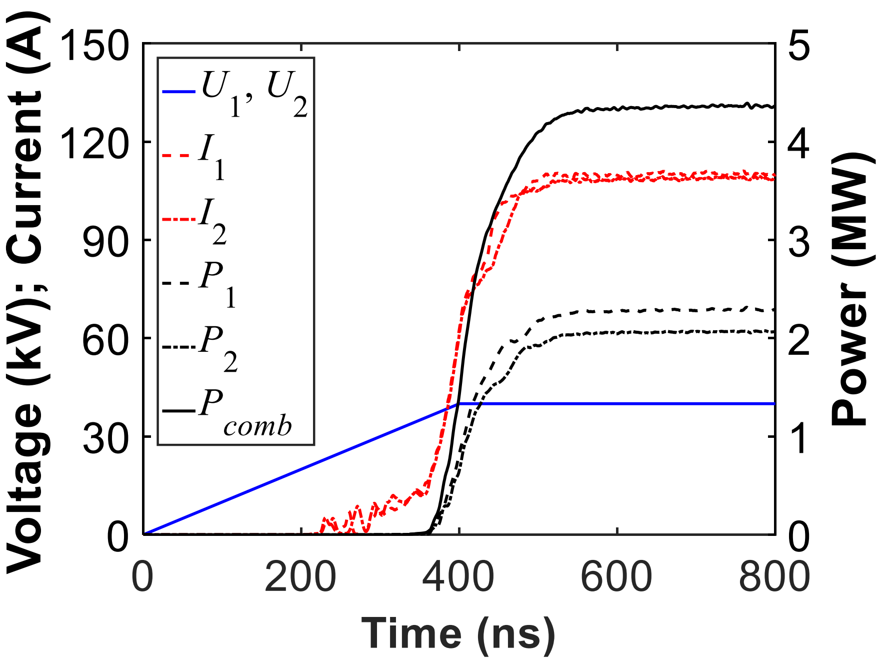
- Particle-in-cell simulation

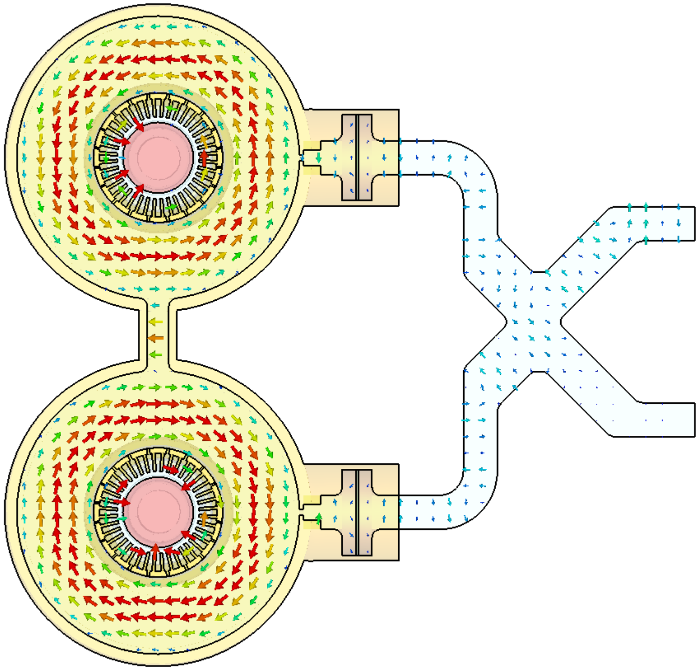
- f = 9296.25 MHz, $U_1 = U_2$ = 40 kV, I_1 = 110 A, I_2 = 109 A

  P_1 = 2.29 MW, P_2 = 2.07 MW, P_{comb} = 4.36 MW, η_{comb} > 99%, η_{total} = 50%

- Conventional coaxial magnetron:

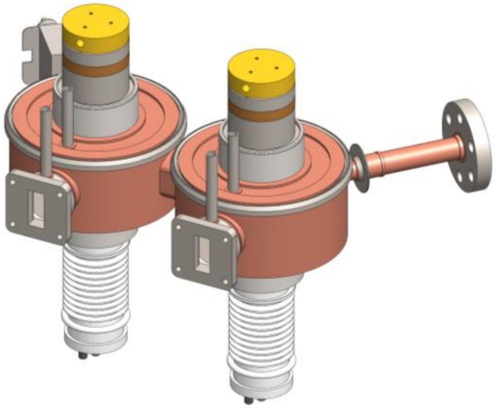
  f = 9295.00 MHz, U = 40 kV, I = 112 A, P = 2.27 MW, η_{total} = 51%

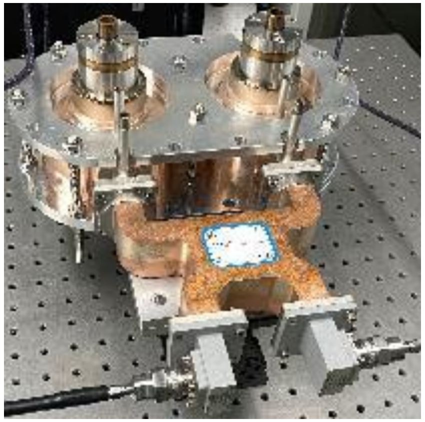
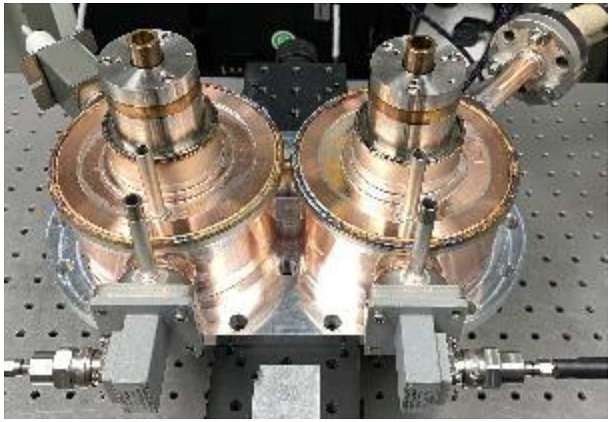


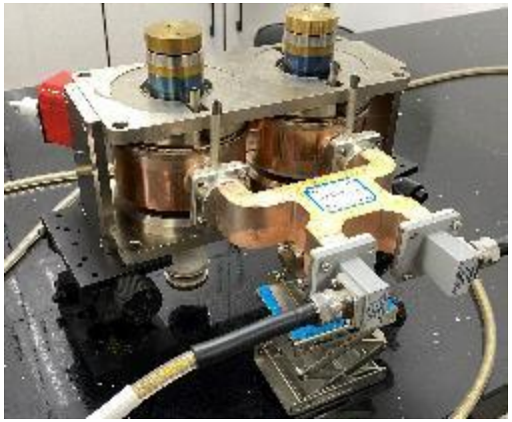


Magnetron with Parallel Cathodes

- Fabrication and assembly
- Magnetron prototype(12.9 kg) + permanent magnet(12.2 kg) + asymmetric 3-dB hybrid(1.8 kg) ≈ 27 kg

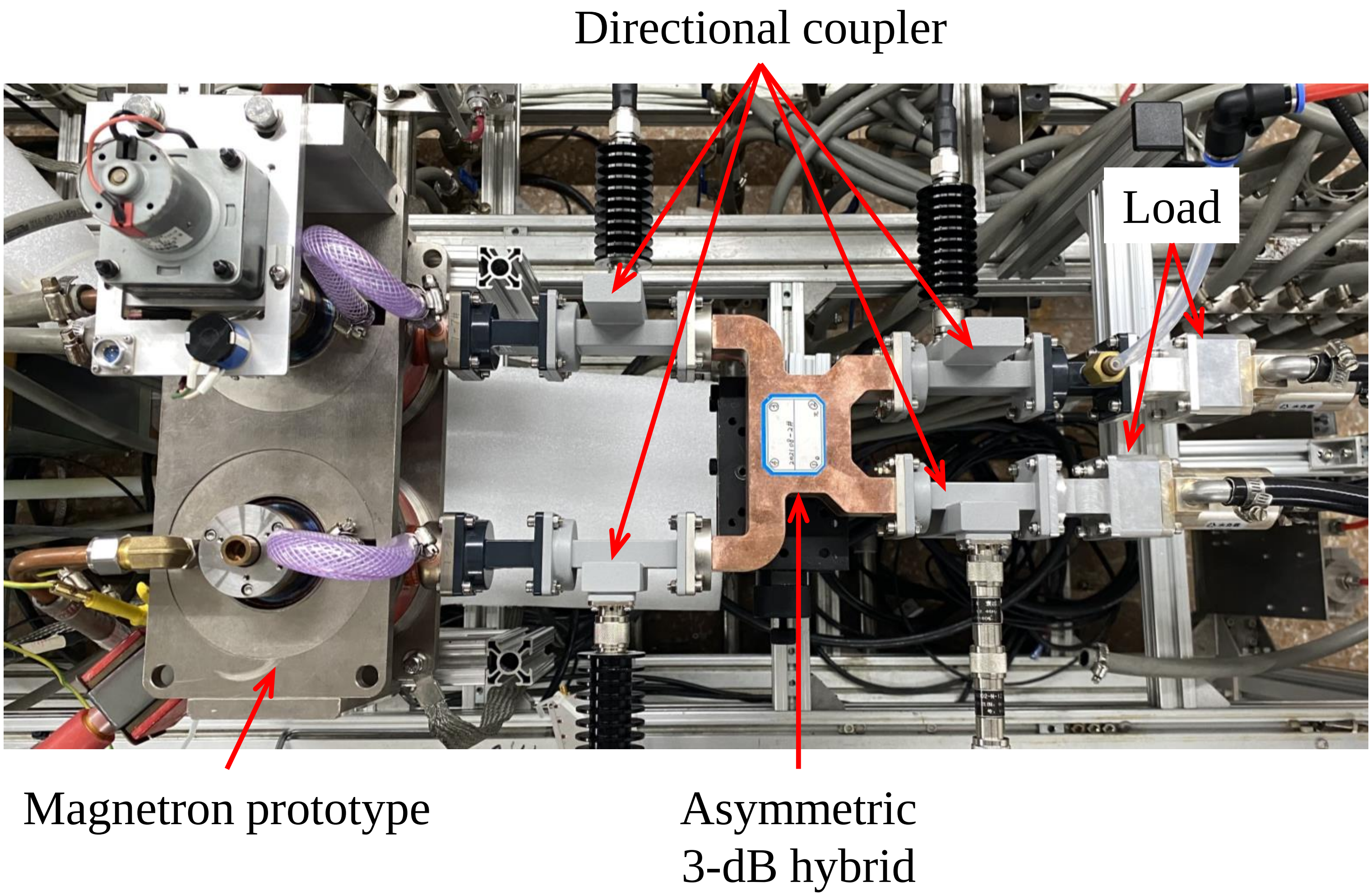




Magnetron with Parallel Cathodes

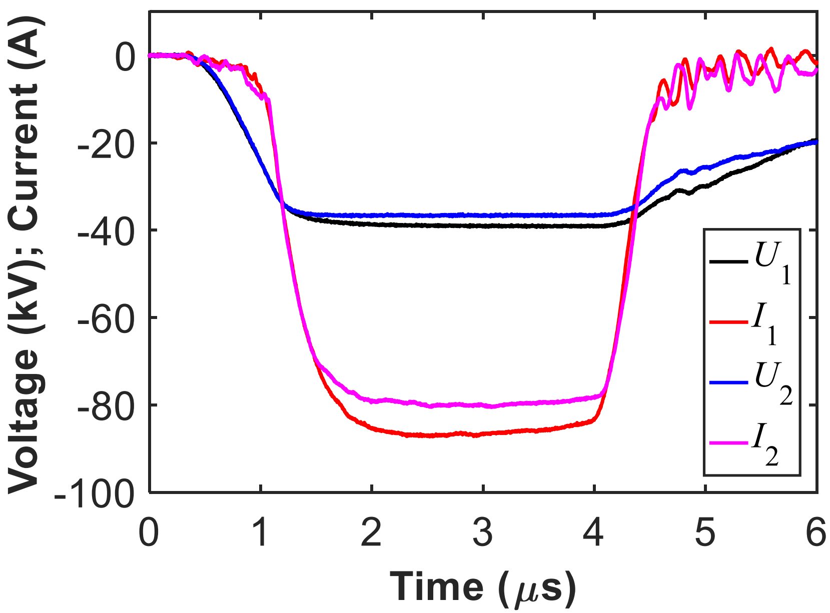
➢ High-power experiments

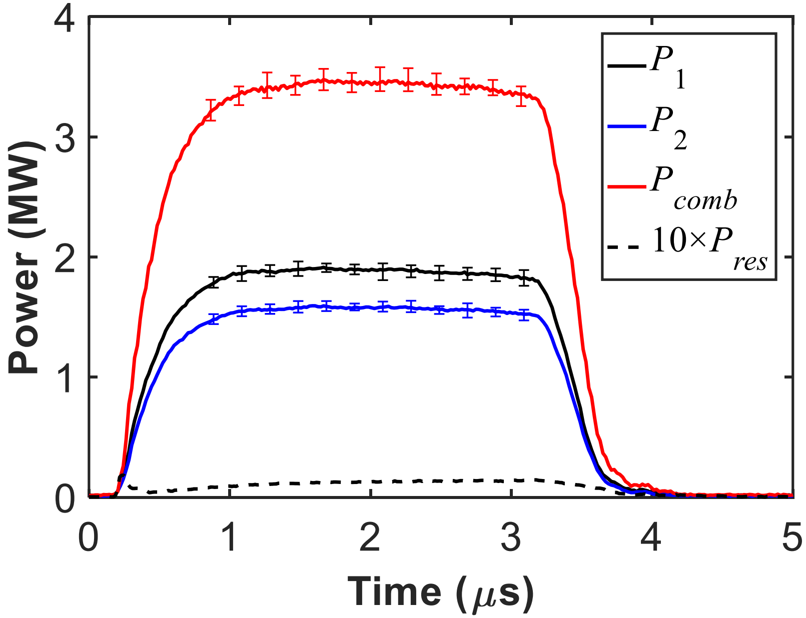


Magnetron with Parallel Cathodes

- High-power experiments

f (MHz)	U_1 (kV)	I_1 (A)	P_1 (MW)	U_2 (kV)	I_2 (A)	P_2 (MW)	P_{comb} (MW)	η_{comb} (%)	η_{total} (%)
9284.0	38.8	86.7	1.84	36.7	79.0	1.57	3.38	99	54
9286.3	38.9	85.0	1.80	36.7	79.8	1.57	3.34	99	54
9289.2	39.0	86.1	1.88	36.6	79.6	1.57	3.43	99	54





Magnetron with Parallel Cathodes

➢ High-power experiments

f (MHz)	U_1 (kV)	I_1 (A)	P_1 (MW)	U_2 (kV)	I_2 (A)	P_2 (MW)	P_{comb} (MW)	η_{comb} (%)	η_{total} (%)
9284.0	38.8	86.7	1.84	36.7	79.0	1.57	3.38	99	54
9286.3	38.9	85.0	1.80	36.7	79.8	1.57	3.34	99	54
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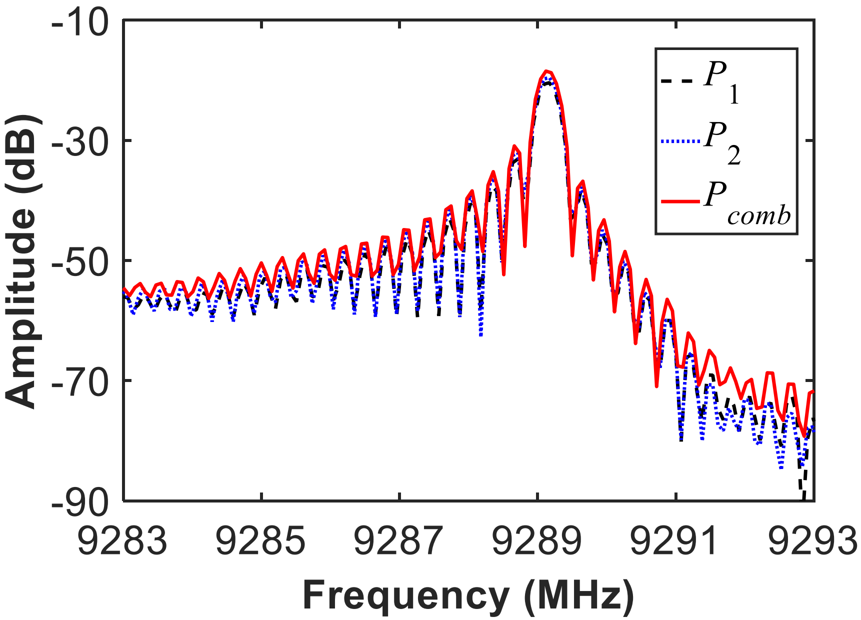

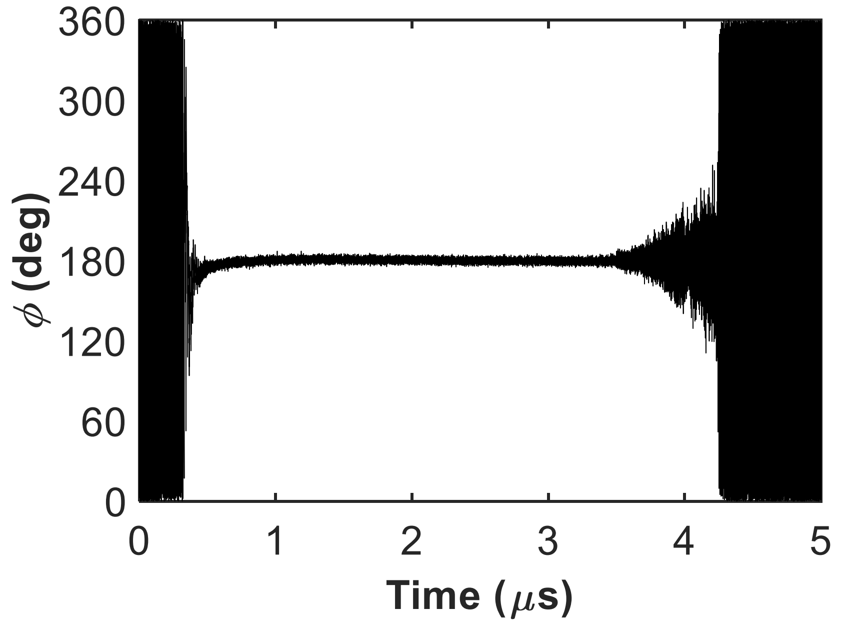

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Summary

- The power combination of magnetrons based on conventional coaxial magnetron has been proven effective.
- A peak output power greater than 3 MW has been achieved by the power combination of magnetrons.
- Magnetron with parallel cathodes is compact and has prominent performance, which can be a possible candidate as the RF power source for the X-band linacs.

Thanks for your attention!

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