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Report

Experimental Progress of High Frequency Terahertz Gyrotrons in Peking University

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2026/8/27

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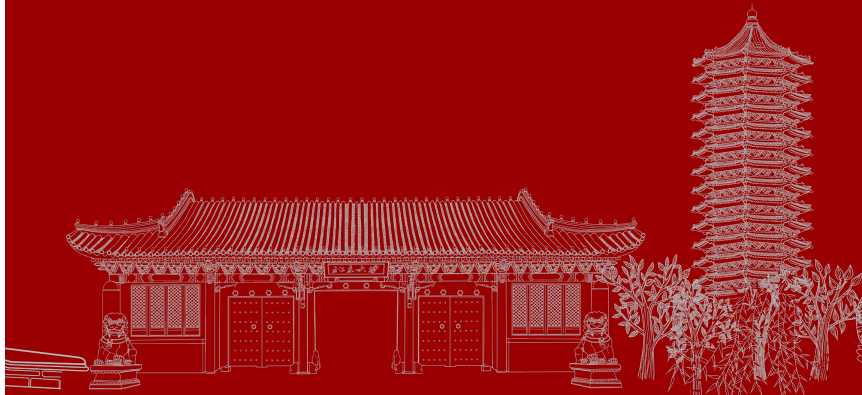

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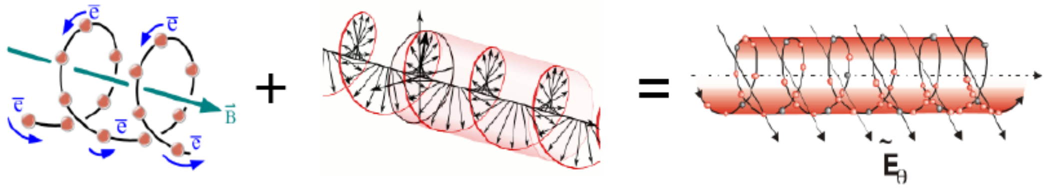
Research Background

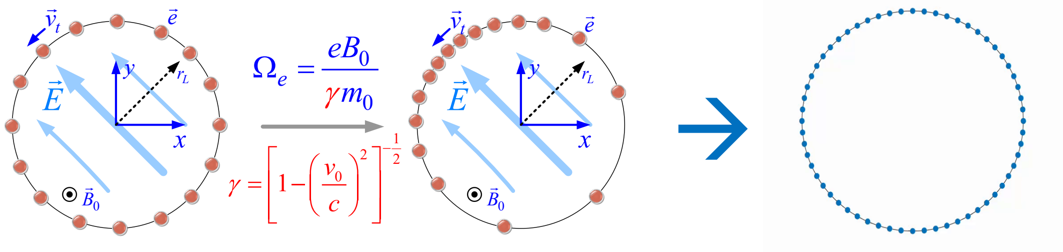
Terahertz Gyrotron

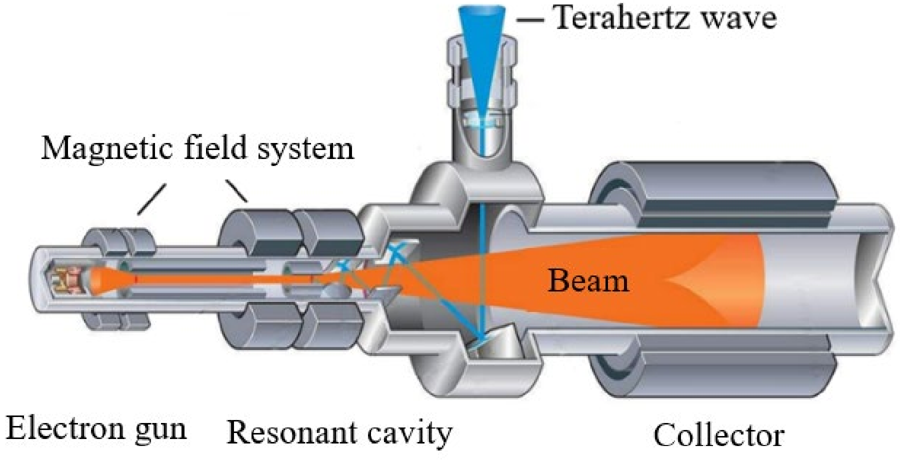
Electron Cyclotron Maser (ECM)-based energy conversion mechanism



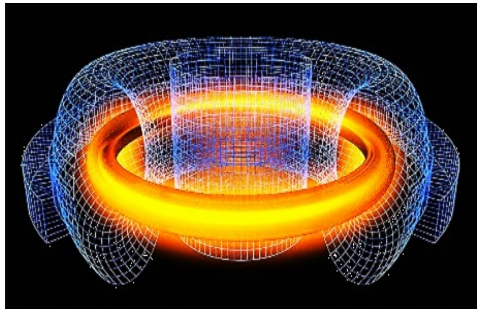
Cyclotron electron beam　　Polarized EM wave　　ECM radiation

Azimuthal electron bunching mechanism based on relativistic effects





- Kilowatt- to megawatt-level high power capability
- High energy conversion efficiency of 30%–70%
- Long-term, highly stable, and reliable operation without special environmental requirements



Controlled fusion heating

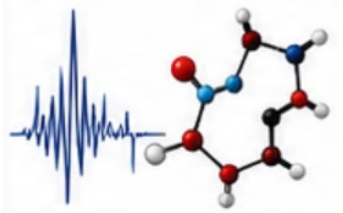
High power weapons

Military radar

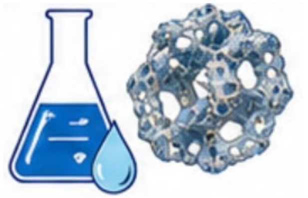
Special material processing

Research Background

Expanded Applications



DNP-NMR & spectroscopy



Materials analysis (zeolites, MOFs, APIs)

Biomedical imaging & theranostics

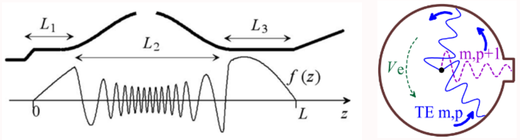
THz irradiation for cancer & sterilization

- The applications of gyrotrons have expanded into fields such as biological science, medical treatment, spectroscopy and so on.
- Require gyrotrons to operate at **higher frequencies** and under **more flexible conditions.**

High Harmonic Gyrotron

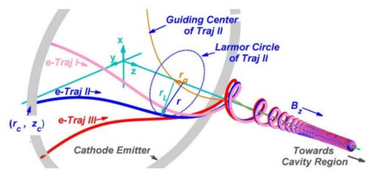
Access higher THz frequencies → Severe mode competition

Mode Selective Circuit



- Scatter undesired modes while having small impact on the operating mode
- **High fabrication precision in terahertz frequency range**
- **Low Robustness to Parameter Variations**

Axis-Encircling Beam

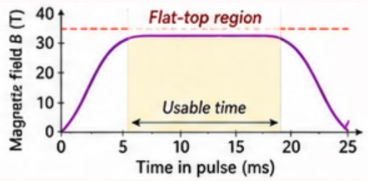


- Fundamentally suppress parasitic modes whose azimuthal index is unequal to harmonic orders.

High-Field Pulsed Gyrotron

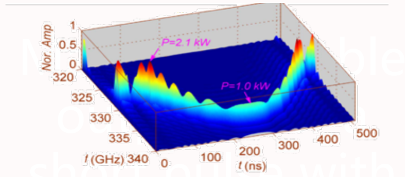
Pulsed magnet provides ultrahigh magnetic field → Short available time / varying field

Flat-Top Magnetic Field



- Provide a stable operating window which support stable output
- **Generating an ultrahigh magnetic field with a sufficient long and stable flat-top duration is technically challenging.**

Conventional Pulsed Field



- Broadband Tuning through Mode Cluster Operation
- The **time-varying magnetic field** naturally provides a pathway to hard excitation.

High-harmonic operation and high-field pulsed operation provide two important routes toward high frequency and application-oriented THz gyrotron

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High-Harmonic LOG Gyrotron

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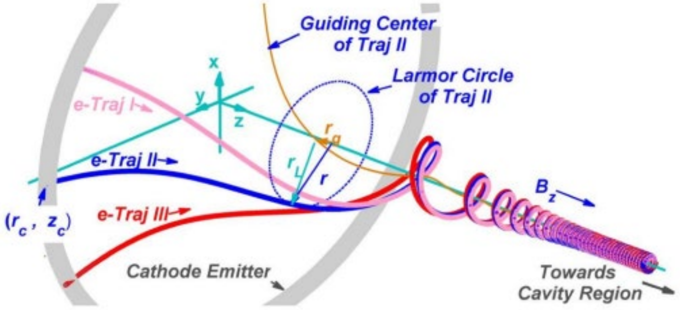
Large-orbit electron beam



The initial generalized angular momentum of electrons on the cathode surface:

$$P_{\theta c} = -e r_c^2 B_{zc} / 2 \qquad (1)$$

The generalized angular momentum of electrons before entering the interaction cavity:

$$P_{\theta i} = -e B_{zi} \left(r_g^2 - r_L^2 \right) / 2 \qquad (2)$$

Conservation of generalized angular momentum： Busch's theorem

$$B_{zc} r_c^2 = B_{zi} \left(r_g^2 - r_L^2 \right) \qquad (3)$$

Under the strong magnetic field, MCG has a particularly high magnetic compression ratio——high velocity spread

Velocity spread compensation principle

Velocity spread $$\boxed{\frac{\Delta v_t}{v_t}} = \boxed{\frac{\Delta P_{\phi c}}{2P_{\phi c}}} + \boxed{\frac{r_g^2}{r_L^2} \cdot \frac{\Delta r_g}{r_g}} \qquad (4)$$

Initial generalized angular momentum spread at cathode surface

- The morphology of cathode surface
- The magnetic field in cathode region

Guiding radius spread in cavity region

- The radial or axial magnetic field
- The tilted electrode
- space Coulomb forces

coordinated optimization of multiple parameters.

Gradient Descent Optimization Algorithm Based on Theoretically Predicted Initial Values

Theoretically Predicted Initial Value
Based on the near-zero velocity-spread condition and electron-gun theory, analytically calculate the initial value x_0 of key parameters (B_{cg}, r_c, θ_c, etc.)

➡

Construct Objective Function
Use the velocity spread δv as the objective function
$f(x)$

➡

Evaluate Objective Function
Calculate the velocity spread under the current optimization variables and conditions, and evaluate the objective function $f(x_k)$

➡

Parameter Update
$x_{k+1} = x_k - \alpha_k \nabla f(x_k)$
(adaptive step size α_k)

➡

Convergence Criterion
If $|\nabla f(x_k)| < \varepsilon$
Stop iteration

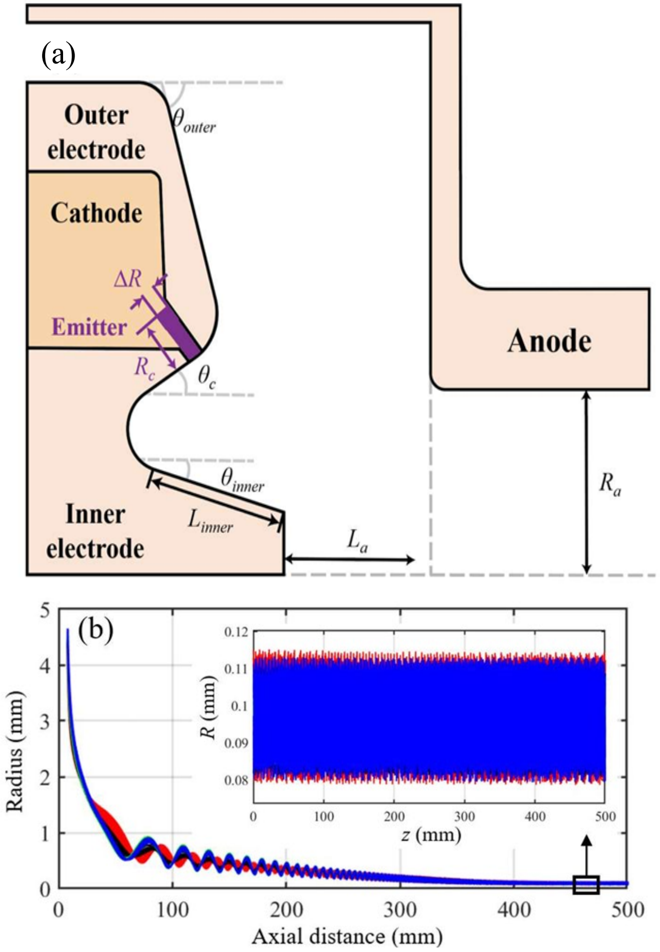
★ *The final optimization goal of the above compensation principle :*

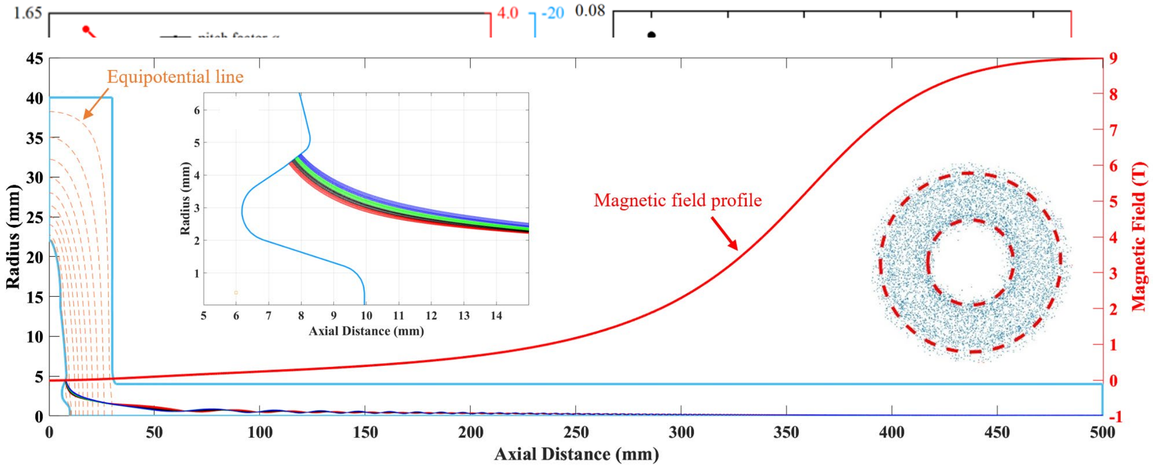
Make the velocity spread close to 0

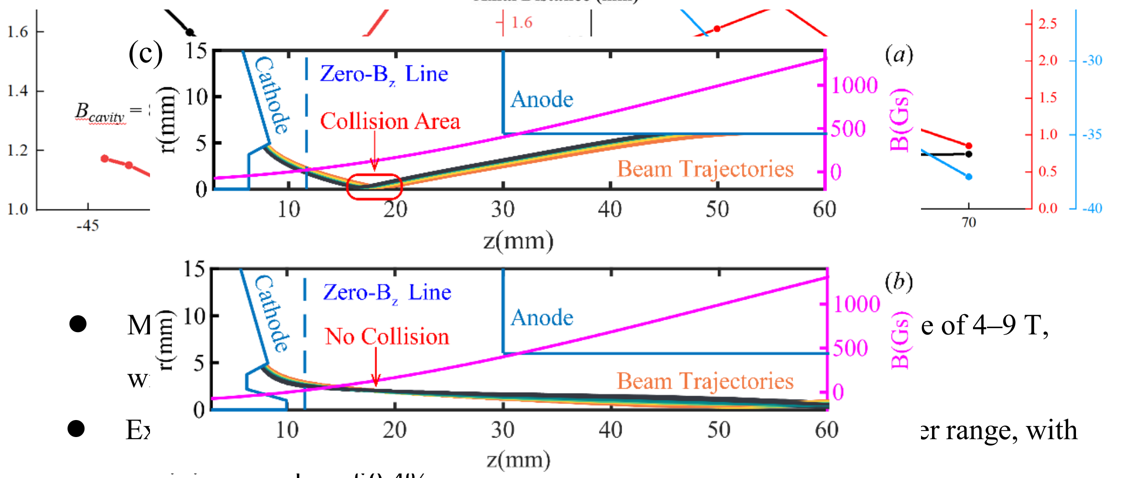
High-Harmonic LOG Gyrotron

Structure and performance of the MCG

	Parameter	Value
R_c	emitter depth	4.7 mm
ΔR	emitter thickness	0.5 mm
R_a	radius of anode channel	4 mm
L_a	cathode–anode spacing	25 mm
L_{inner}	length of inner electrode	3.9 mm
θ_c	tilt angle of emitting surface	38°
θ_{inner}	tilt angle of inner electrode	17°
θ_{outer}	tilt angle of outer electrode	75°
V_b	accelerating voltage	60 kV
I	beam current	1 A
α	emitter depth	1.5
Δv	emitter thickness	0.4%





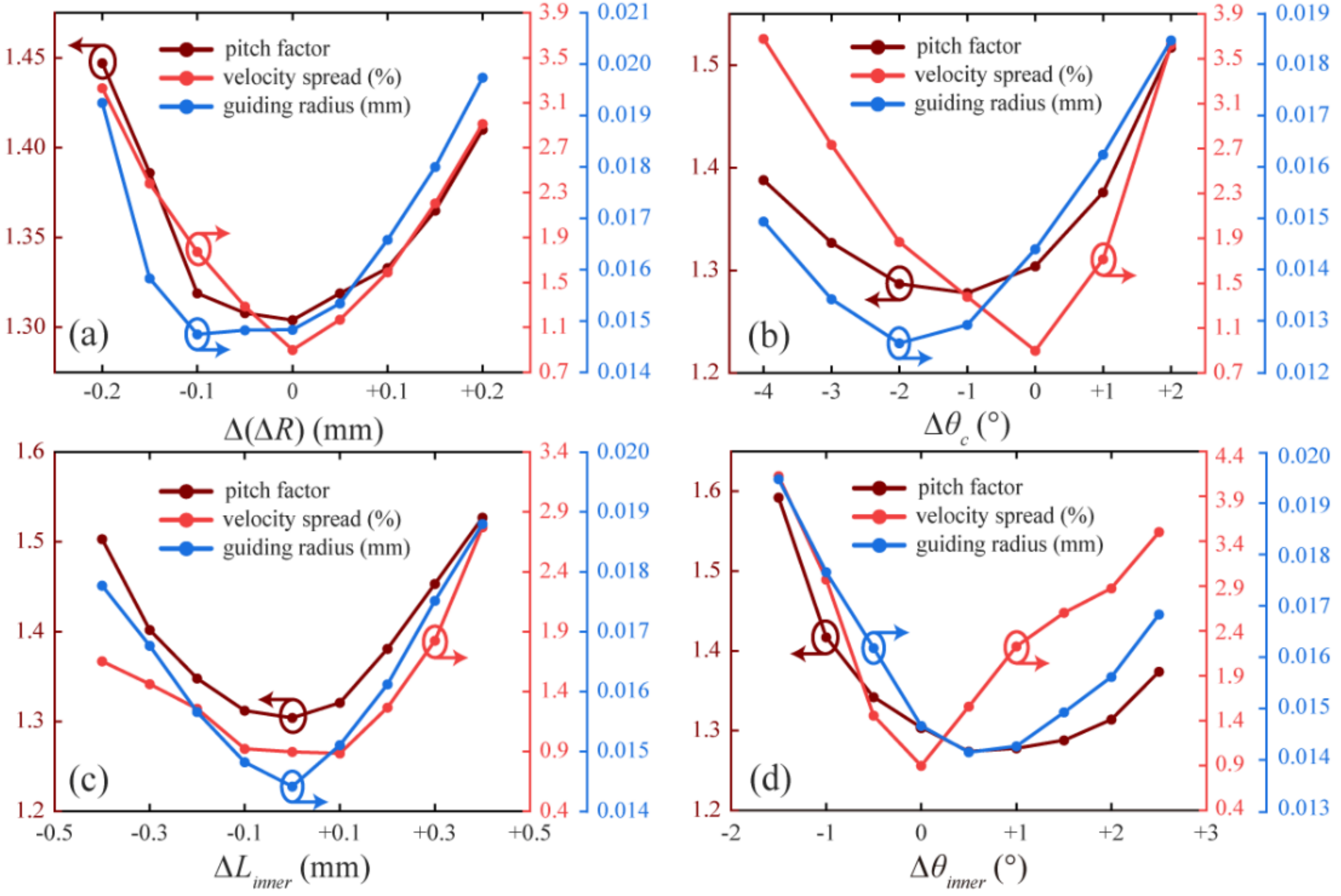


- M... e of 4–9 T, w...
- Ex... er range, with a minimum value of 0.4%.

The influence of inner focusing electrode on beam trajectory

Highly robust, high-quality axis-encircling electron beam, lays a solid foundation for multi-harmonic radiation over a wide range of magnetic fields.

Manufacturing Tolerance of MCG



The influence of deviations in four key parameters on the beam quality at a magnetic field of 8.6 T:

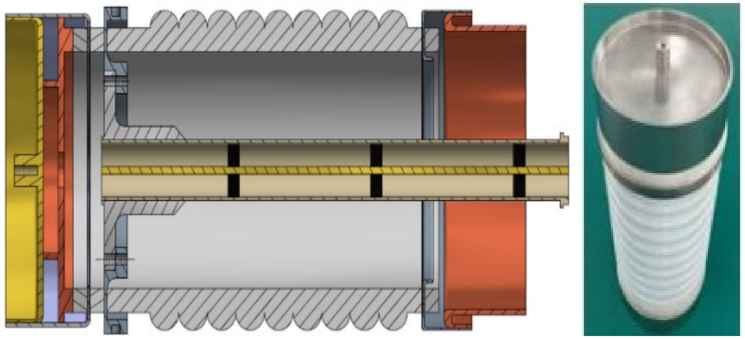
emitter thickness ΔR, tilt angle of emitting surface θ_c, length of inner electrode L_{inner} and tilt angle of inner electrode θ_{inner}.

- Within the deviation range of ±0.2 mm and ±2°, the velocity spread increases to over 3%. Further deviations will cause a more rapid degradation of beam quality.
- it can be inferred that the MCG is tolerant of machining errors exceeding hundred micrometers, which is completely acceptable for practical fabrication and assembly.

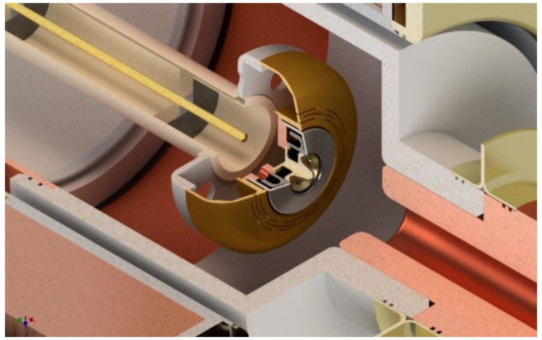
High-Harmonic LOG Gyrotron

Fabrication and assembly of some key components

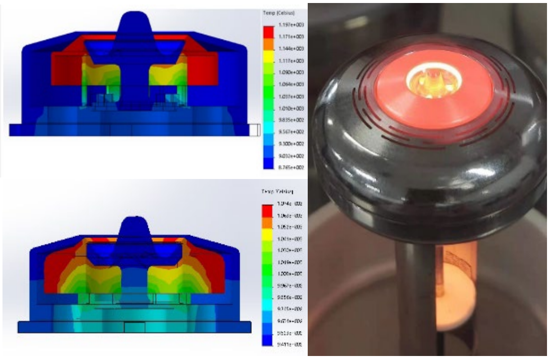
Insulating ceramics for electron guns

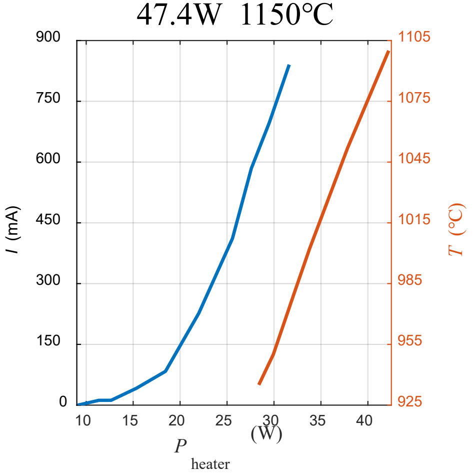


Optimized thermal structure of cathode

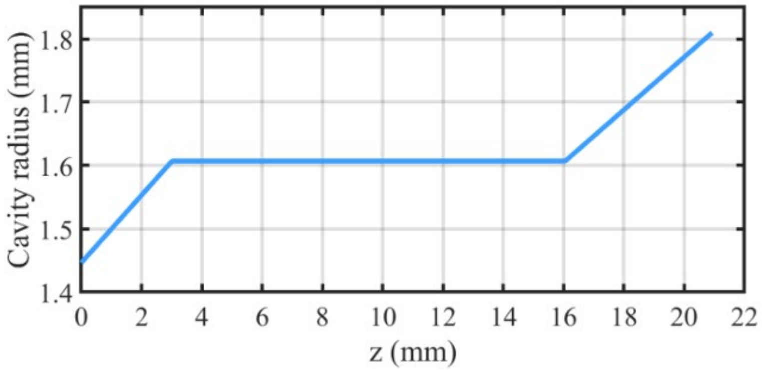


Thermal testing of cathode emitter

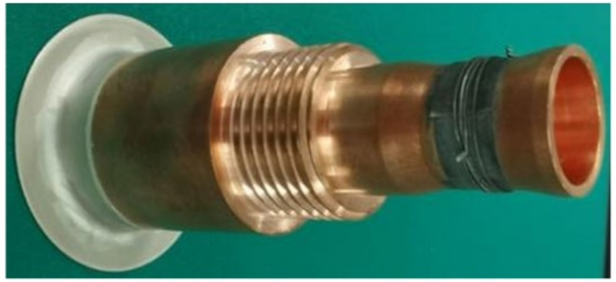


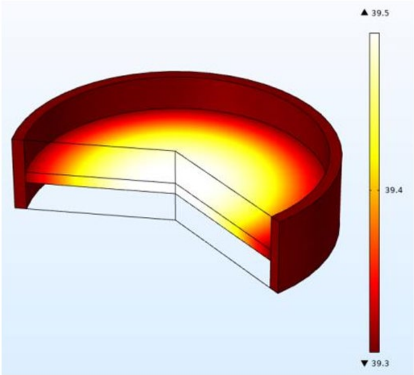


Structure of interaction cavity



Single-Crystal Sapphire Output Window

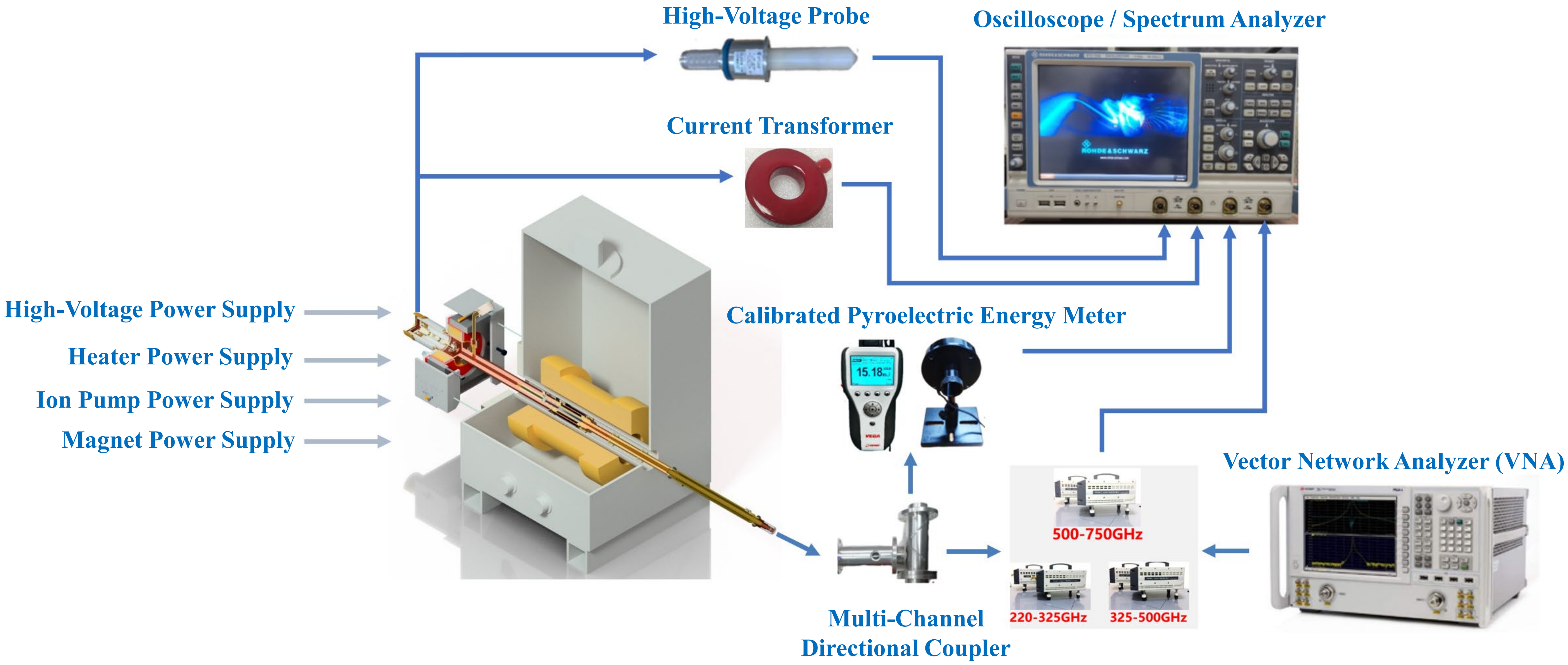




- The highest temperature at the center of the window reaches about 39.5 degrees.
- The maximum temperature difference between the copper and the sapphire window is only about 0.2 degrees. Therefore, the differential thermal expansion between them is also very small.

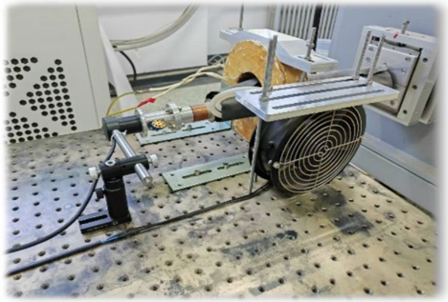
High-Harmonic LOG Gyrotron

Measurement and Diagnostic System of Terahertz Harmonic Gyrotron



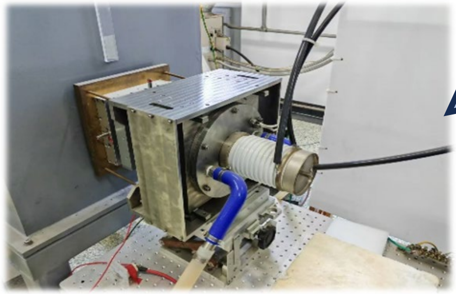
High-Harmonic LOG Gyrotron

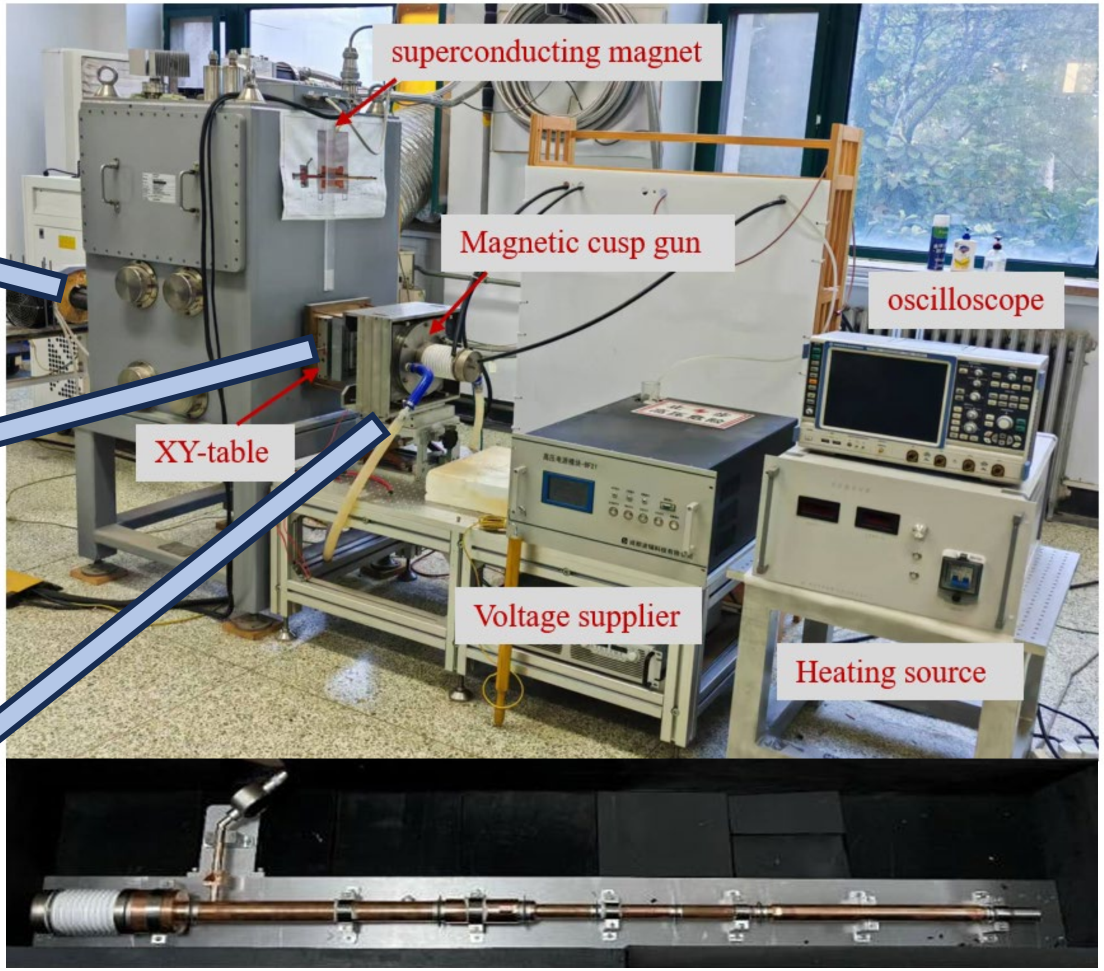
Collector Side



Precision Alignment Table

MCG



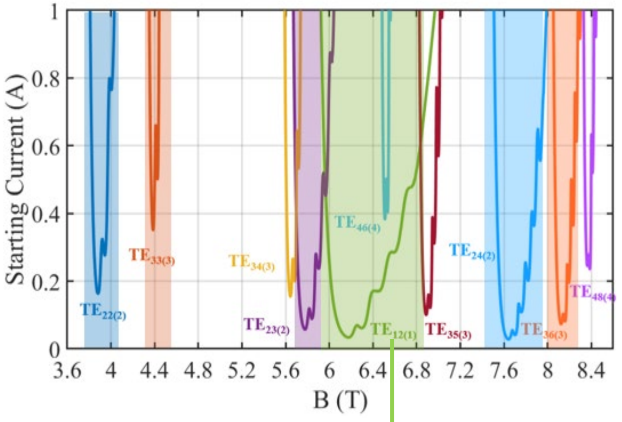


Terahertz Harmonic Gyrotron System Based on Axis-encircling Electron Beam and Superconducting Magnet

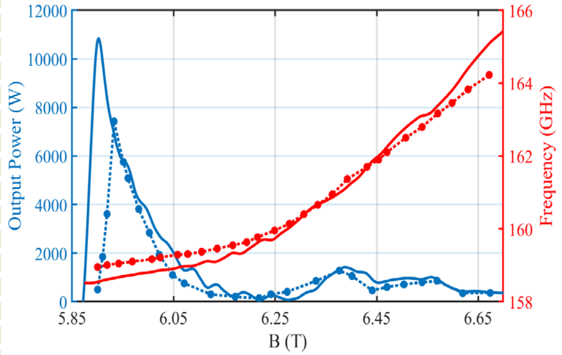
High-Harmonic LOG Gyrotron

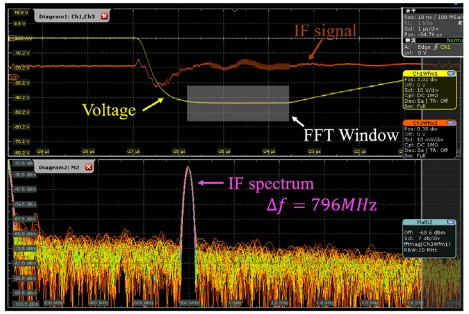
Experimental Results of Terahertz Harmonic Gyrotron

Starting Current Distribution of different Modes



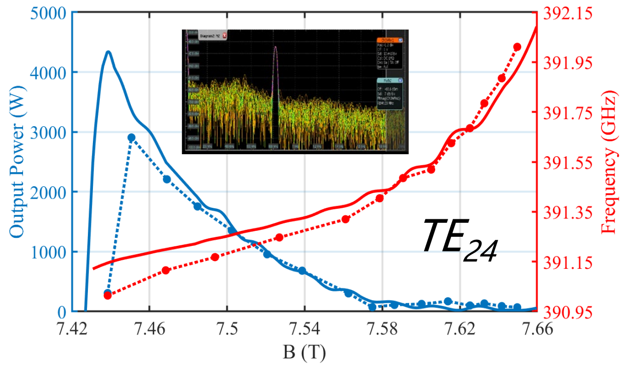
- The use of LOB reduces the mode density in the gyrotron cavity and suppresses mode competition.
- Multiple high harmonics have a stable space for single-mode operation.





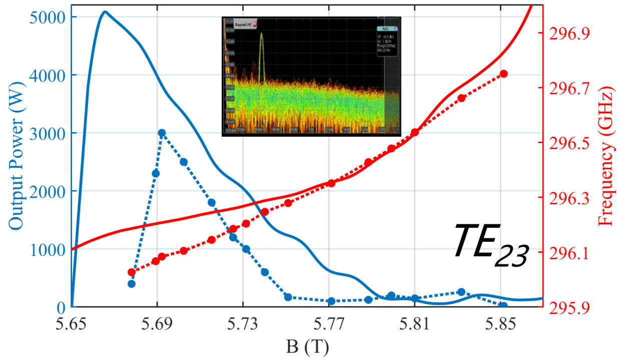
~45kV/0.7A/3us

- The TE_{12} mode features a tuning bandwidth of 5.27 GHz (158.95–164.27 GHz).
- Peak power of 7.45 kW (23.65% operating efficiency).
- Good agreement between experimental and simulation results.



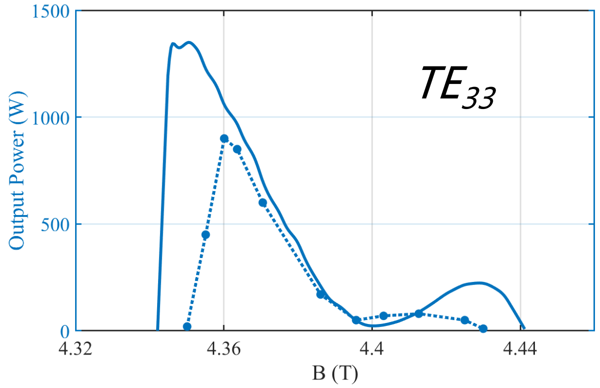
Peak power: 2.91kW (9.2% efficiency)

Tuning bandwidth: 1 GHz (391.0-392.0 GHz)



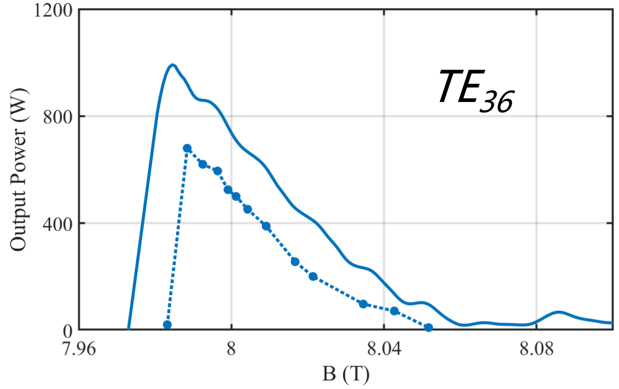
Peak power: 3kW (9.5% efficiency)

Tuning bandwidth: 0.75 GHz (296.0-296.75 GHz)



Peak power: 0.9 kW (2.86% efficiency)

Operating frequency: **338GHz**



Peak power: 0.68 kW (2.16% efficiency)

Operating frequency: **628GHz**

- Mode Switching between multiple harmonic modes is achieved by adjusting the magnetic field
- The gyrotron achieves high-power output at **5 discrete frequencies** with certain frequency-tuning capability.

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High-Field Pulsed-Magnet Gyrotron

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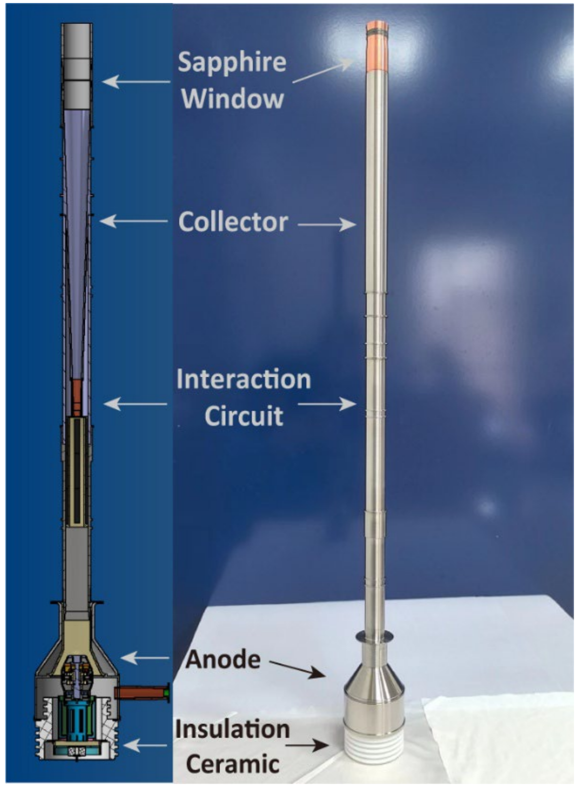
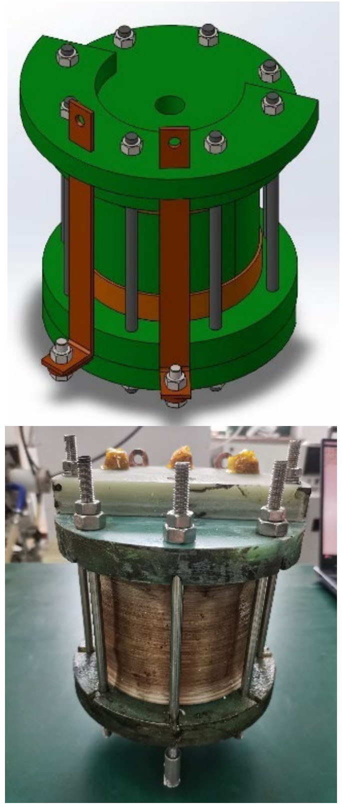
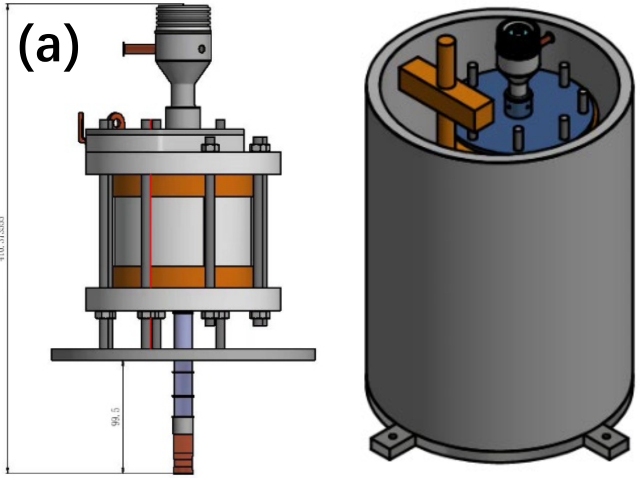
System Composition

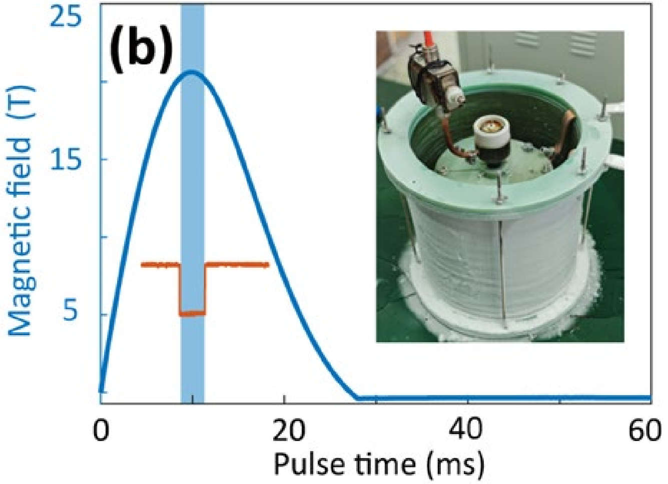
Terahertz Gyrotron (<40 cm)



Pulsed Magnet (40T)



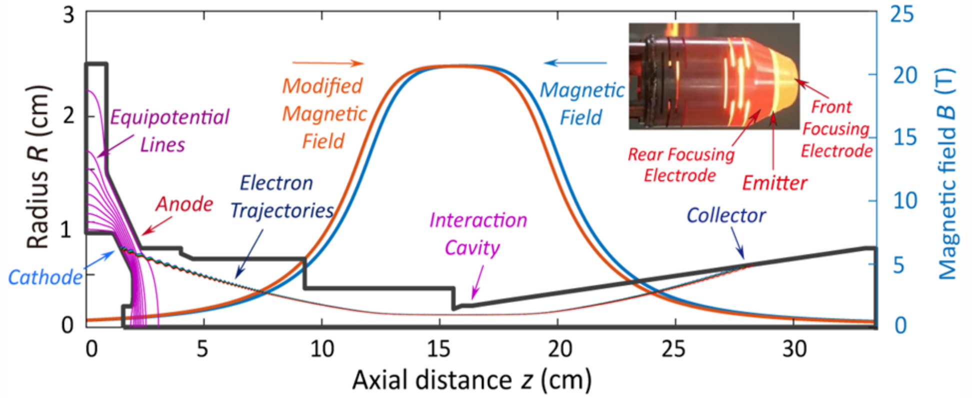




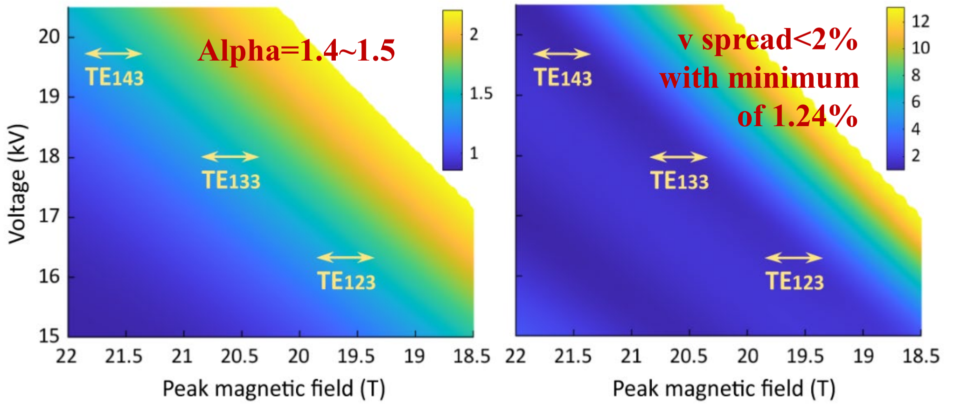
This configuration provides a compact platform for investigating high-frequency terahertz radiation under a time-varying magnetic field, including mode evolution and hard-excitation phenomena.

High-Field Pulsed-Magnet Gyrotron

Basic Design of the Electron Gun



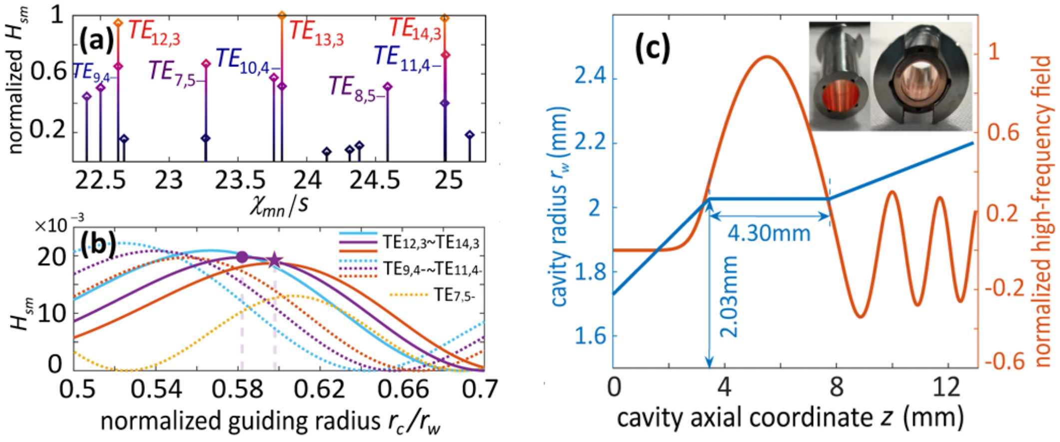
Profile of the Electron Optic System

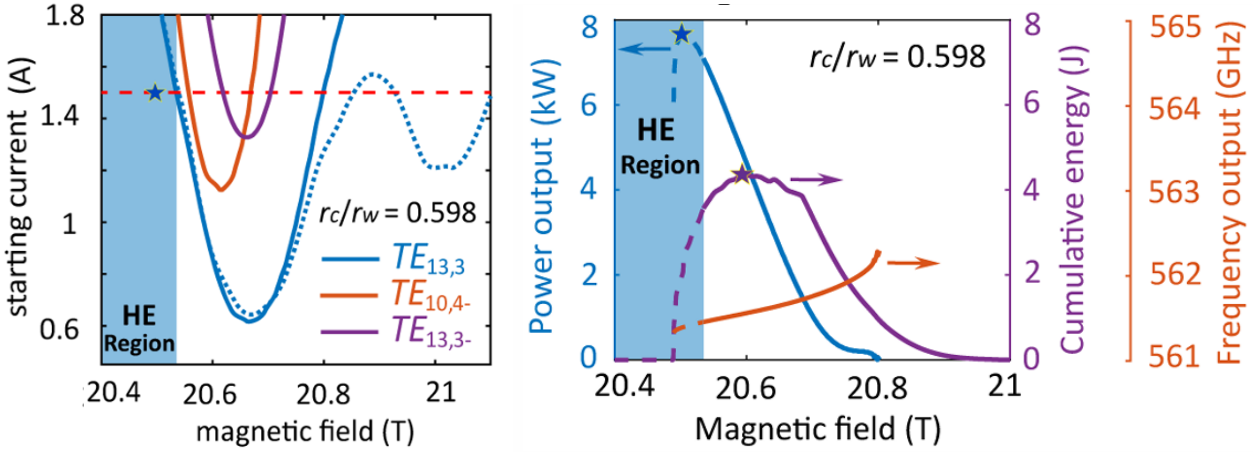


2D Dependence of the beam parameters on the voltage and magnetic field

- The α is around 1.4 to 1.5, while the velocity spread remains below 2%, with a minimum value of about 1.24%.
- When α becomes too large, the electrons may not propagate through to the interaction region.

Basic Design of the Cavity

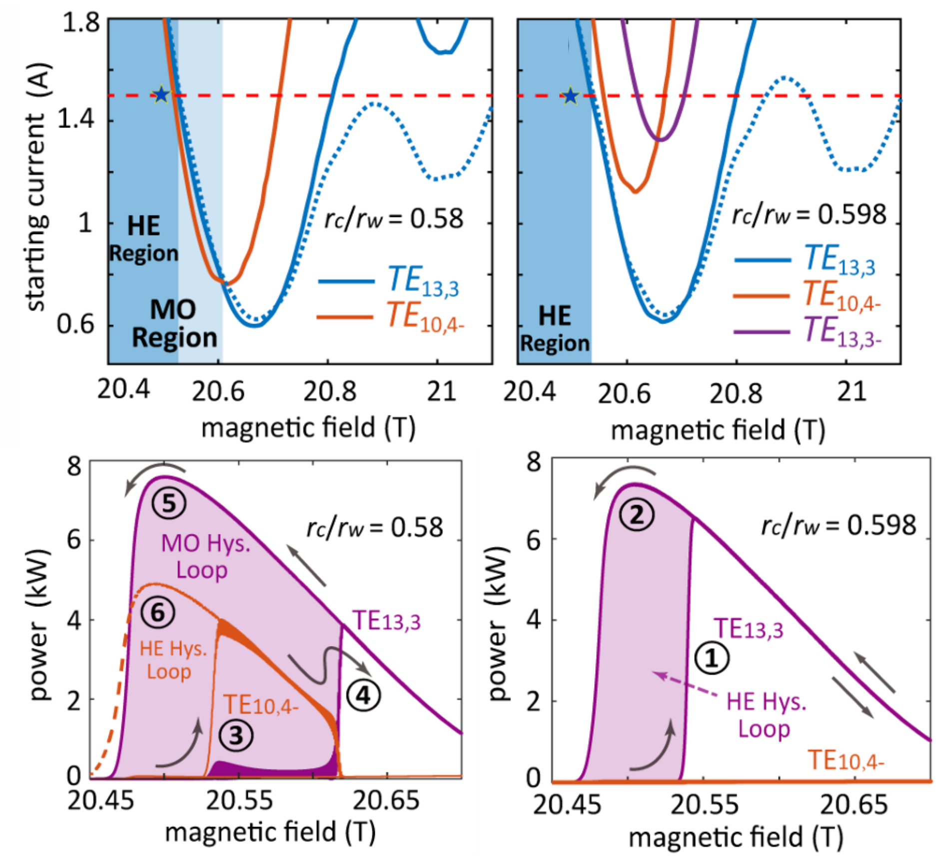


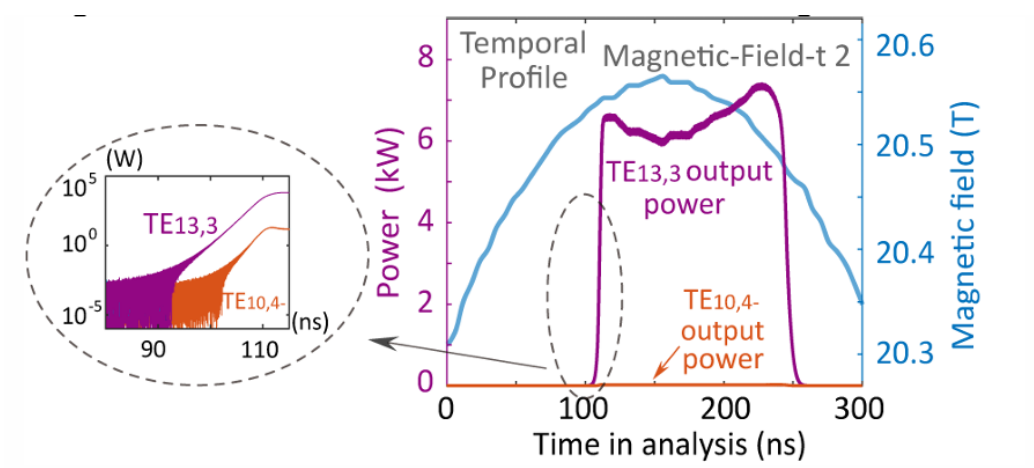


- The maximum power is achieved in the **hard excitation (HE) region**

High-Field Pulsed-Magnet Gyrotron

Hysteresis Induced by the Hard-Excitation Effect

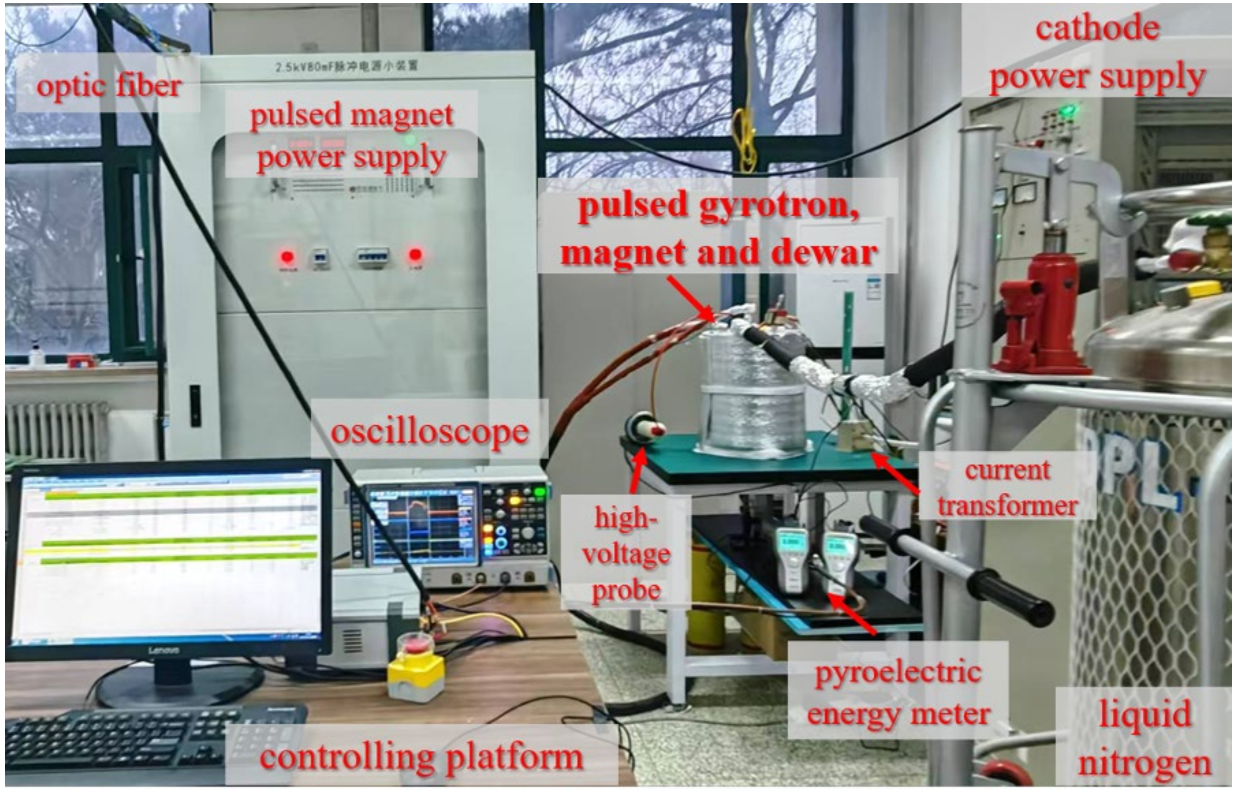




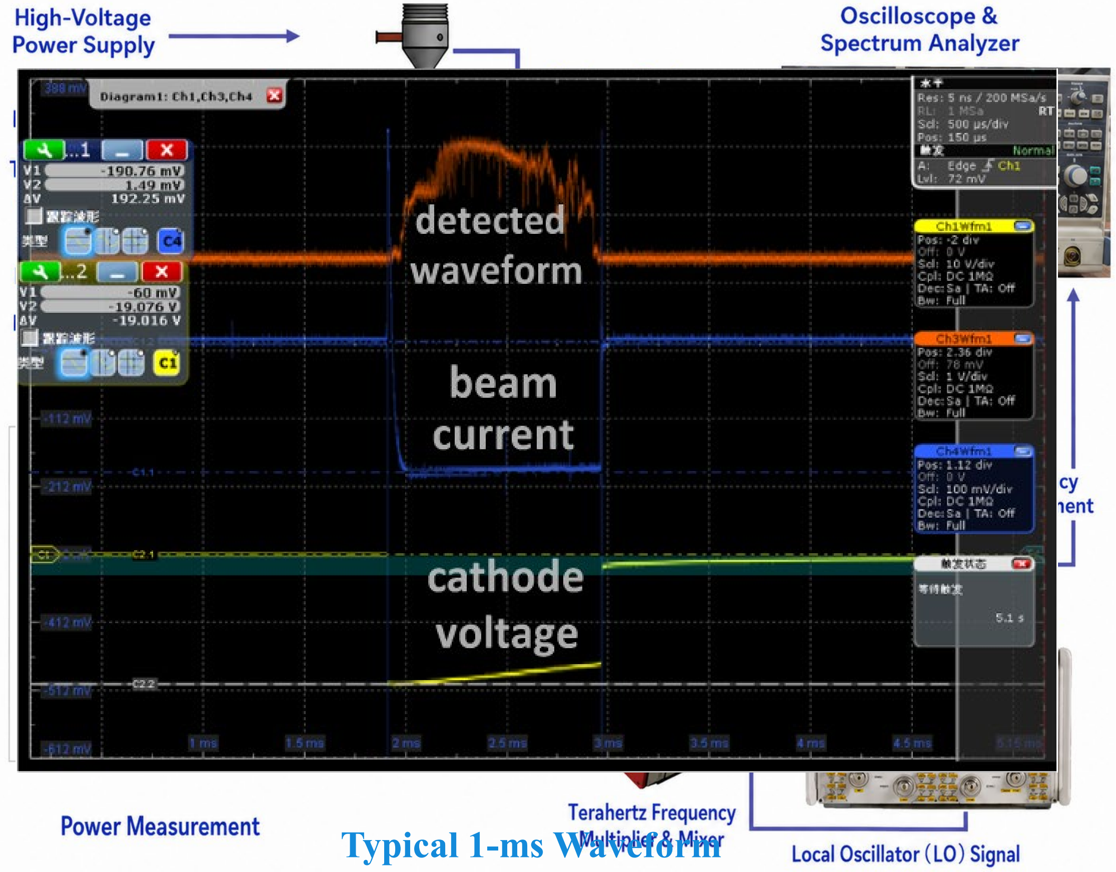
- The starting current of competing mode $TE_{10,4-}$ is lifted by enlarging the normalized guiding radius from 0.58 to 0.598.
- The up-tuning and down-tuning processes follow different trajectories and form a clear hysteresis loop——provides a pathway to hard excitation.
- The rising and falling parts of the magnetic pulse produce asymmetric operating boundaries.
- This hysteresis is mainly caused by the hard-excitation itself, rather than by conventional multimode competition.

High-Field Pulsed-Magnet Gyrotron

Experimental Platform and Typical 1-ms Waveform



Terahertz Pulsed Gyrotron Testing Platform



Typical 1-ms Waveform

Terahertz Pulsed Gyrotron Measurement and Diagnostic System

18GW/15A/1ms

High-Field Pulsed-Magnet Gyrotron

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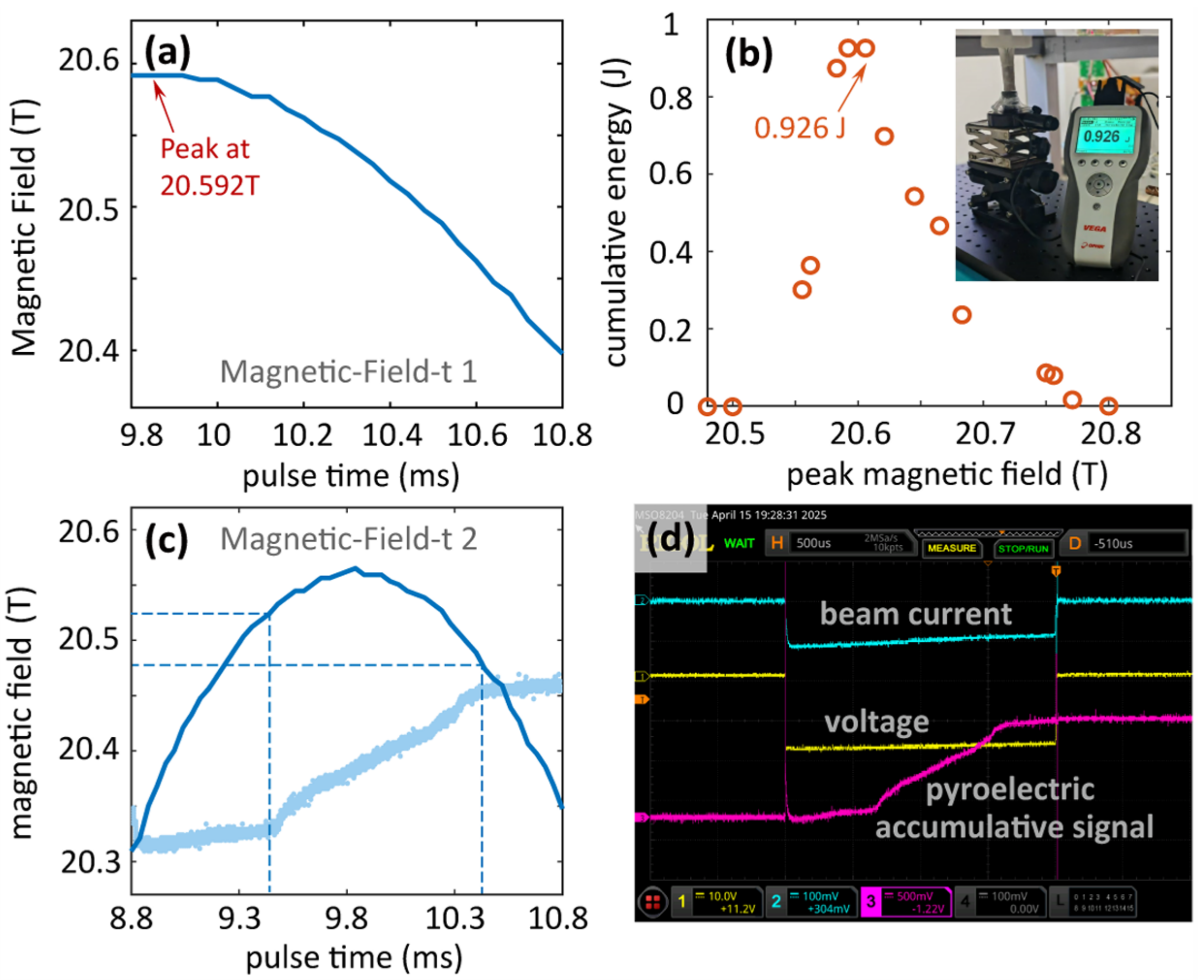
Key Experimental Results under descending magnetic field



- **Ms-level pulse width**
- **Joule-level-energy**
- Descending magnetic field provides a natural trace into the hard-excitation region
- The operating magnetic-field range shows a clear **asymmetry boundaries**, which is consistent with the hard-excitation-induced hysteresis predicted in our previous analysis.
- The experiment not only demonstrates Ms-level, joule-level terahertz radiation, but also provides experimental evidence of hard excitation under a time-varying pulsed magnetic field.

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Summary and Outlook

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Summary

- Developed an MCG capable of generating a high-quality large-orbit electron beam with a magnetic compression ratio above **3000**. The MCG exhibits excellent robustness, maintaining **low velocity spread below 3.8% (minimum 0.6%) across a broad magnetic field range of 4-9 T while preserving constant pitch factor.**
- A harmonic gyrotron system based on LOB has been developed, enabling **multiple harmonic radiation** through magnetic field tuning (benefit from designed MCG).
- Experimental study of a pulsed gyrotron driven by a 20-T high-field pulsed magnet, demonstrating **ms-scale pulses**, **joule-level radiation**, hard excitation, and asymmetric boundaries associated with magnetic-field hysteresis.

Outlook

- Measurement of forth harmonic modes and more other modes, enable the gyrotron to support as many modes as possible and extend the available operating frequency range.
- A 1-THz pulsed gyrotron operating at a magnetic field of 40 T is currently under development.

Thanks for Your Attention！

Reported by Feng Zhang

2026/8/27