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# Progress of the electron cyclotron resonance heating system and the related experiments on J-TEXT

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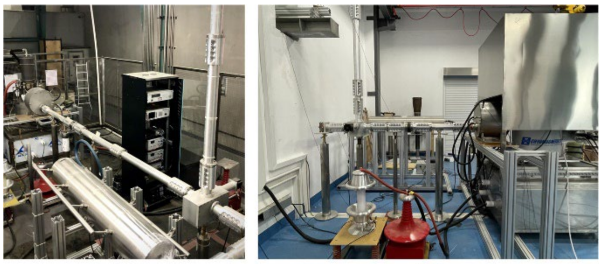
**Abstract.** To augment the capabilities of the J-TEXT tokamak, efforts were undertaken in 2017 to commence the construction of an electron cyclotron resonance heating (ECRH) system. A significant milestone was achieved in 2019 when the successful operation took place using this 105 GHz ECRH system. The system consists of components including the gyrotron from GYCOM, a transmission line spanning approximately 30 meters, and a quasi-optical launcher equipped with an elliptical mirror and movable flat mirror. Another identical system was deployed in 2023 for experimental purposes. Notably, modifications were made to the launcher to support the injection of two beams. Various experiments have been conducted utilizing this system including assisted plasma start-up, control methods for tearing mode, and observations involving toroidal injection of electron cyclotron wave (ECW), etc.

## 1 Introduction

The ECRH system has been utilized to research some experiments of plasma such as MHD control in recent magnetic confinement devices [1-5]. Some significant advancements have been made on Joint-TEXT (J-TEXT) since 2017 with a X2 electron cyclotron resonance heating (ECRH) system [6-8]. This endeavour seeks to augment the capability of the J-TEXT tokamak for experimental investigations in plasma physics. J-TEXT has been equipped with some specialized auxiliary systems, alongside an extensive array of diagnostic tools. The integrated system provides a robust framework for conducting advanced experiments that research deeper into the mechanics of plasma heating, current drive, and the dynamics of fast electrons, etc. Further exploration into the control and mitigation of magnetic islands, sawteeth, and plasma disruptions, as well as investigations into boundary physics are facilitated by this system.

## 2 ECRH system of the J-TEXT

Given that J-TEXT predominantly operates within a toroidal field range from 1.4 to 2.2 T, the ECRH system is engineered to function optimally at the second harmonic electron cyclotron resonance (X2 mode) with a frequency of 105 GHz. The arrangement is strategically chosen for efficient heating in the resonant layers. A photograph of the J-TEXT ECRH system can be observed in Figure 1, while Figure 2 provides a schematic representation of the ECRH system.



(a) (b)

**Fig. 1.** The image depicting the first ECRH system (a) and the second ECRH system (b) of J-TEXT

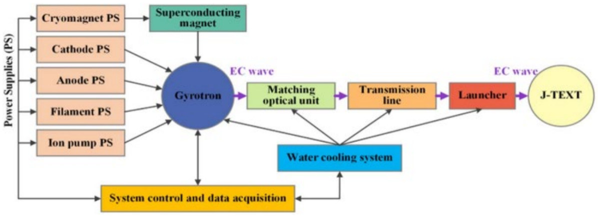


**Fig. 2.** Diagram illustrating the composition of the J-TEXT ECRH system. Reproduced from [10].

The system has been equipped with two GYCOM gyrotrons shown in Figure 3. Each gyrotron is specifically designed to generate an output power of 500 kW. As a result, the combined output power capability reaches up to 1 MW. The key parameters that define the main characteristics of the gyrotrons are presented in Table 1.

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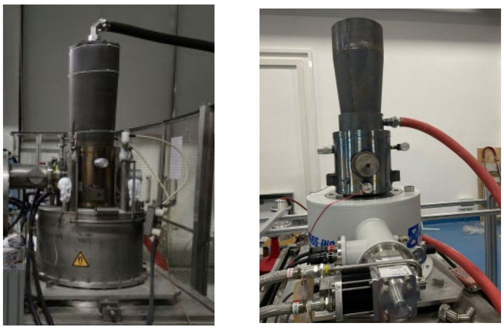
(a) (b)

**Fig. 3.** The 105 GHz ECRH system consists of gyrotron #1 (a) and gyrotron #2 (b). Reproduced from [10].

**Table 1.** Key parameters that define the main characteristics of the gyrotrons

| **Parameters** | **Value (gyrotron #1)** | **Value (gyrotron #2)** |
|---|---|---|
| Frequency | 105 GHz | 105 GHz |
| Output power | ⩽500 kW | ⩽500 kW |
| Output pulse duration | ⩽1 s | ⩽1 s |
| Mode purity | ~97% | ~98% |
| Efficiency | ~45% | ~45% |

Different subsystems and devices are essential for ensuring the effective operation of the systems. The electric field for accelerating electrons is facilitated by two high-voltage power supplies [11, 12]. Besides, there are three auxiliary power supplies. The responsibility of the magnet power supply is to provide energy to the magnet in order to produce a consistent magnetic field. The filament power supply provides the necessary current to heat the filament of the gyrotron, thereby producing the electron beam. The ion pump power is responsible for maintaining the vacuum inside the gyrotron. Table 2 shows the details of the supplies mentioned above.

**Table 2.** Characteristics of electrical power supplies

| **Parameters** | **Value (gyrotron #1)** | **Value (gyrotron #2)** |
|---|---|---|
| Cathode voltage ($V_c$) | -44 kV | -45 kV |
| Cathode current ($I_c$) | 25 A | 24.5 A |
| Anode voltage ($V_a$) | 30 kV | 32 kV |
| Anode current ($I_a$) | 150 mA | 200 mA |
| Magnet field ($B_{mag}$) | 4.1 T | 4.1 T |
| Filament power ($P_f$) | 780 W | 770 W |
| Ion pump voltage ($V_{ion}$) | 5 kV | 5 kV |
| Ion pump current ($I_{ion}$) | 10mA | 10 mA |

A control system specifically developed for the ECRH system is utilized, which encompasses various functionalities such as timed activation, signal monitoring, protection, communication interface, and data acquisition [13]. To ensure efficient protection of the gyrotron, it is crucial to restrict the response time to 2 μs. The control system has consistently maintained a high level of stability thus far. Figure 4 illustrates the structure of the control system.

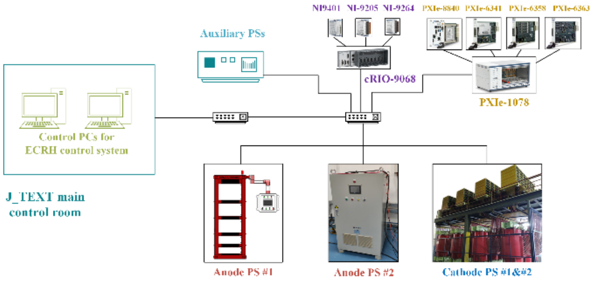

**Fig. 4.** Diagram of ECRH control system structure.

To ensure efficient delivery of high-power electron cyclotron waves to the plasma, both the transmission line and the launcher play crucial roles. The transmission line employs corrugated waveguides (diameter: 63.5 mm) and includes various components such as a switch, multiple miter bends, polarizers, directional coupler, a DC break, and two bellows. Power loss from these elements is expected to remain below 15%.

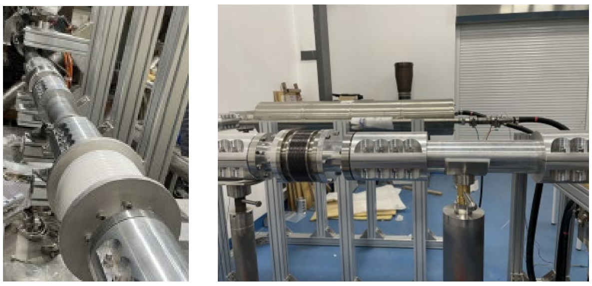
(a) (b)

**Fig. 5.** Photo of the transmission line

In 2022, significant progress has been achieved in enhancing the ECRH system through the integration of a dual-launcher [14], as depicted in Figure 6. This dual-launcher is designed on the foundational principles of Gaussian optics and the quasi-optical approximation, tailored to achieve a focused and localized EC wave power deposition at the plasma core for enhanced heating efficiency. The restricted port size on the J-TEXT tokamak allows for variable toroidal and poloidal injection angles ranging from -10° to +15° and -15° to +15°.

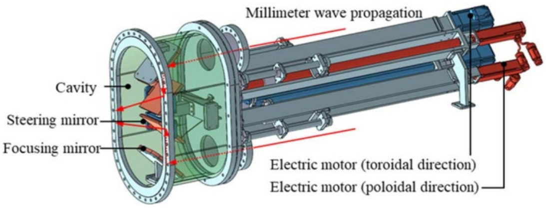

**Fig. 6.** Drawing of the dual-launcher for the J-TEXT ECRH system. Reproduced from [10].

## 3 Commissioning tests of the gyrotron

A series of commissioning tests need to be systematically performed to verify the performance, which is prior to the experiments on the ECRH system. The commissioning tests of the gyrotrons usually contains several stages. The initial step is of utmost importance in achieving the alignment of the magnetic field. The subsequent step involves operating the gyrotron to determine its optimal operating conditions. The Matching Optics Unit (MOU) is essential for the ECRH system and is designed to optimize the coupling efficiency between microwave power and plasma by transforming the output wave from the gyrotron into a distribution that resembles Gaussian shape.

### 3.1 Magnet alignment

Figure 7 shows contrasts examples of suboptimal and optimal magnet alignments. A dummy tube, is employed as a substitute for the gyrotron in this stage. This surrogate, being dimensionally identical to the gyrotron, aids in accurate alignment. A fluorescent ring resembling orbit 1 denotes successful alignment. In contrast, orbit 2 necessitates further adjustment to ensure the magnetic field is suitably aligned for effective gyrotron performance.

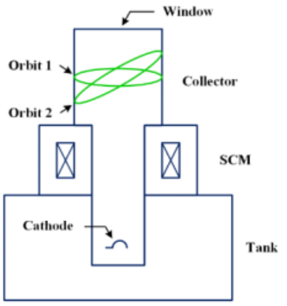

**Fig. 7.** Diagram of the magnet alignment

### 3.2 Gyrotron operation

The primary objective of the commissioning tests is to identify the optimal operational parameters for the gyrotron. The magnetic field, filament power, cathode voltage, and anode voltage are the most significant factors. In addition to comprehending how these parameters impact gyrotron operation, it is crucial to evaluate its performance. Three approaches are employed to achieve this goal. Firstly, a platform is established for measuring the microwave signal. Secondly, a frequency meter is utilized to measure the output microwave frequency. Lastly, a dummy load is employed to measure its power output. The satisfactory operational status of the gyrotron can be inferred if both the microwave signal and frequency are accurately measured, and the output power reaches its maximum value. Figure 8 illustrates the measured microwave signal while Figure 9 presents a temperature rise curve that can be used for calculating microwave power.

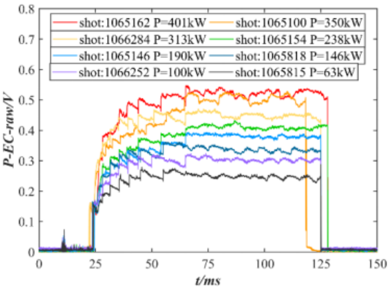

**Fig. 8.** Measured RF signal during gyrotron operation

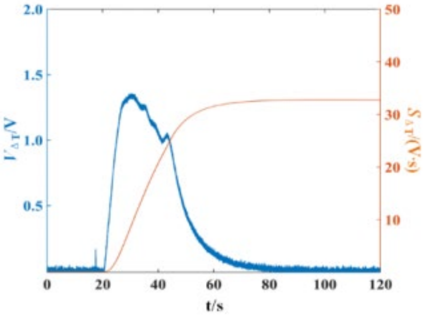

**Fig. 9.** Temperature rise curve during gyrotron operation

## 4 Experiments with the ECRH system

The first ECRH system was successfully used to heat plasma on J-TEXT for the first time in 2019. By 2023, the heating capacity was further enhanced with the addition of a second gyrotron. With the injection of the EC waves, a noticeable enhancement in electron temperature was observed using the curved crystal spectrometer, with measurements indicating an increase from 1 keV to 2.5 keV [18].

The effectiveness of ECW in assisting plasma startup with a low toroidal electric field ($E_\varphi$) has been demonstrated. Experiments conducted on J-TEXT using the X2 mode ECW aimed to determine the minimum power requirement and gain a deeper understanding of the underlying physics [17]. By introducing ECW into the vacuum vessel prior to applying $E_\varphi$, it was possible to reduce the minimum $E_\varphi$ needed for successful startup from 2.5 V/m (ohmic) to 0.56 V/m (ECRH) [17].

By injecting electron cyclotron waves (ECW) perpendicular to the magnetic surface and directing the power towards the rational magnetic surface, it is feasible to achieve complete suppression of 2/1 classical tearing modes (TMs) [18]. The TM remains absent even after discontinuing ECW injection. However, a lower power level of ECW can only partially suppress the TM, and its amplitude recovers once the ECW is deactivated. It is likely that the dominant factor in suppressing TMs is attributed to heating effects [18].

The efficiency of ECCD has been examined on J-TEXT, where the estimation of current drive efficiency can be achieved through the assessment of loop voltage alterations resulting from toroidal injection of ECW [19]. By analyzing the ECW power using a static $I_p$ and $n_e$, it is possible to express the decrease in loop voltage ($\Delta V/V_{OH}$) as a function of the normalized ECW power, $P_{norm} = P_{ECCD}/n_e I_p R$. This holds significant scientific and engineering implications for optimizing tokamak operations in future fusion reactors and stabilizing neoclassical tearing modes (NTM).

Further researches with the injection of ECW become more important. The related physics problems are investigated more thoroughly in [20].

## 5 Summary

The J-TEXT 1 MW ECRH system has been established and developed over the past five years. Following the completion of commissioning, the system successfully achieved high-power and long-pulse operations, meeting the design specifications.

Numerous experiments have been carried out on J-TEXT with the assistance of the ECRH system, focusing on ECRH and ECCD. More related experiments are about to be conducted in the future.

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