

## Development of ECRH Antenna System for HL-3 Device

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**Date:** 2024-05-12T00:00:00+00:00

### Abstract

Based on the requirements of the Electron Cyclotron Resonance Heating (ECRH) system for the HL-3 device, the antenna system has been designed, developed, tested, and installed. The HL-3 ECRH antenna system comprises three antennas—one mid-plane antenna and two upper oblique antennas—located in the same sector on the low-field side of the device, capable of collaboratively performing heating and Neoclassical Tearing Mode (NTM) control functions. To date, the design, manufacturing, and testing of two antennas have been completed, while the transmission optical path design for the third antenna has been finalized. Test results demonstrate that the mid-plane antenna and the first upper oblique antenna exhibit precise and rapid control, meeting the requirements for experimental use on the device.

### Full Text

## Design and Development of the ECRH Launcher System on the HL-3 Tokamak

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### Abstract

[Background]: Electron cyclotron resonance heating (ECRH) is an important method for plasma heating and current control in the HL-3 tokamak. Microwaves are injected into the plasma through launchers, which constitute a critical component of the ECRH system. [Purpose]: This work aims to design and test the ECRH launcher system for the HL-3 tokamak. [Methods]: Overall planning was conducted for the launcher system, including the design of transmission paths and launcher structures. The effects of microwave injection were simulated and calculated. The transmission angles and rotation speeds of the

launchers were tested, and the rotation angles were calibrated. [Results]: The optical path design for the No. 2 upper launcher has been completed. The full-range response time of the equatorial launcher is less than 90 ms, while that of the No. 1 upper launcher is less than 190 ms. [Conclusions]: The optical path design of the No. 2 upper launcher meets the system requirements. Both the equatorial launcher and the No. 1 upper launcher demonstrate precise and fast control, satisfying the requirements for experimental operation on the tokamak.

**Keywords:** HL-3 tokamak; Launcher; ECRH

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## 1. HL-3 ECRH System

The ECRH system consists of radio frequency (RF) and auxiliary subsystems. The RF system primarily includes gyrotrons, transmission lines, and launchers, while the auxiliary system comprises control systems, microwave parameter diagnostics, power supplies, and cooling systems. Based on the HL-3 tokamak operating parameters and experimental research requirements, the ECRH system is planned to have a total power of 9.5 MW, including three launchers and related auxiliary systems. Currently, 7.5 MW has been developed, consisting of one 68 GHz/500 kW/1s system, five 105 GHz/1 MW/3s systems, and two 140 GHz/1 MW/3s systems. The frequencies of the remaining two systems will be determined later according to device operational requirements.

The wave source system of the ECRH is located in a wave heating hall adjacent to the HL-3 tokamak hall. Transmission lines connected to the wave sources pass through wall penetrations between the two halls to interface with three integrated launchers mounted on the device. The cathode high-voltage power supplies are installed in a rectifier hall, with high-voltage cables laid through underground pipelines to the wave heating hall. The supervisory computer of the control system is placed in the heating control room, communicating with local devices via Ethernet and uniformly controlling the ECRH/ECCD system operation and monitoring system status under the management of the main control system.

[Figure 1: see original paper]

## 2. Overall Planning of the Launcher System

The HL-3 ECRH system employs three gyrotron frequencies—68 GHz, 105 GHz, and 140 GHz—to expand the operational range through coordinated injection under different parameters. Figure 2 shows the deposition locations for microwaves of different frequencies under various parameters, where the dash-dotted line represents 68 GHz, the solid line represents 105 GHz, and the dashed line represents 140 GHz. The system can achieve injection across a toroidal field range of 1.0–3.0 T.

To meet the functional requirements for heating, current drive, auxiliary startup, and NTM suppression, the system includes three launchers: an equatorial launcher, Upper Launcher No. 1, and Upper Launcher No. 2. All three launchers are located in the same sector on the low-field side of the device. Their window positions on the device are shown in Figure 3, and their parameters and functions are listed in Table 1.

[Figure 2: see original paper]

[Figure 3: see original paper]

### 3.1 Equatorial Launcher Design

The equatorial launcher is positioned at the mid-plane port, enabling vertical injection into the plasma with high heating efficiency. Its relatively large space allows simultaneous injection of multiple microwave beams. Consequently, it serves as the primary heating component of the launcher system, with four beams planned for injection. The final layout is a  $2 \times 2$  configuration with four focusing mirrors and two plane mirrors for controlling injection direction. Each pair of microwave beams on the left and right sides shares one plane mirror. The optical path schematic is shown in Figure 4 (side view).

Sharing one plane mirror and its drive mechanism between two beams significantly saves limited space. However, this results in a non-zero actual emission angle when the mirror is at the poloidal zero position, as shown in Figure 4. Calculations indicate that to deposit the microwave at the plasma center from this position, the mirror must be precisely aligned to compensate for the geometric offset.

[Figure 4: see original paper]

### 3.2 Upper Launcher No. 1 Design

Upper Launcher No. 1 is installed in a  $\text{Ø}300$  mm port with limited space. This port is relatively far from the plasma, making it minimally affected by plasma interactions. By extending the final rotatable mirror out of the window to face the plasma, the launcher can cover a wide injection range. Upper Launcher No. 1 is primarily designed for real-time NTM control, requiring high response speed and rotation accuracy. The final design features a poloidal-only rotation structure using a push-rod mechanism to achieve high precision. NTMs typically occur during high-parameter operation, so the launcher is configured for dual-frequency injection at 105 GHz and 140 GHz to expand the operational parameter range.

The main structure of Upper Launcher No. 1 includes a vacuum sealing box, focusing and plane mirrors, and a mechanical rotation and transmission system. The launcher has two reflection paths, each with one focusing mirror and three plane mirrors. The conceptual design of the mirrors and rotation mechanisms is shown in Figure 5: microwaves initially incident from the sealing window

connected to the waveguide reflect onto plane mirror M1, then to focusing mirror A1. After focusing, the beam is directed to plane mirror B and finally reflected onto plane mirror C1. Poloidal rotation of plane mirror C1, driven by the push rod, enables microwave injection at different poloidal angles.

The fundamental principle of focusing mirror design is to place the microwave beam waist as close as possible to the plasma center. However, this may enlarge the spot size on plane mirrors, potentially reducing their effective rotation range. Due to space constraints, the final plane mirror of Upper Launcher No. 1 has a small area, so the beam waist is positioned on this mirror surface to minimize diffraction losses.

[Figure 5: see original paper]

### 3.3 Upper Launcher No. 2 Design

The port for Upper Launcher No. 2 has a diameter of only 200 mm, and the surrounding environment on the HL-3 tokamak—including toroidal and poloidal field coils, water cooling, and cable routing—is complex. Therefore, the design must carefully consider surrounding conditions, limiting the size of the vacuum sealing box.

Currently, only the internal optical path has been designed. Given the space constraints and the port's distance from the plasma (which minimizes plasma effects), extending the final rotatable mirror out of the window would complicate the transmission mechanism design. Thus, only poloidal rotation is considered for now, with possible future additions of toroidal rotation or redesigned reflection paths based on requirements.

The poloidal injection range of Upper Launcher No. 1 covers nearly the entire plasma. Due to its limited space, Upper Launcher No. 2 is primarily intended for NTM control, focusing on covering the main region where magnetic islands appear. The final optical path design is shown in Figure 6, meeting the required poloidal emission range. Table 2 shows the theoretical emission range of Upper Launcher No. 2 and the corresponding angles of the final mirror. The mirror angle changes only slightly across the range, posing a significant challenge for precise emission angle control. Future design of the control transmission system must increase the motor lead screw travel distance corresponding to the same angular change.

[Figure 6: see original paper]

### 4.1 Equatorial Launcher Testing

Testing of the equatorial launcher focused on emission angle range and poloidal rotation speed. Toroidal rotation uses a lead screw with a slow motor, so speed testing was unnecessary.

In actual testing, shielding baffles, device wall thickness, and first-wall installation around the port limited the final poloidal emission angle range to  $-18^\circ$  to  $18^\circ$  and the toroidal range to  $-18.5^\circ$  to  $18.5^\circ$ . Poloidal test results are shown in Figure 7. Figure 7(a) shows the position and velocity over time for the left plane mirror drive motor moving 13.02 mm full scale from  $-18^\circ$  to  $18^\circ$  in 50 ms intervals, while Figure 7(b) shows the same for the right plane mirror moving 12.96 mm full scale. The commanded and actual motor positions nearly coincide, with response times under 1 ms (microsecond scale). At any given time, the deviation between commanded and actual positions is less than 0.07 mm. The measured minimum full-scale travel time is 79 ms for the left mirror and 87.75 ms for the right mirror.

[Figure 7: see original paper]

#### 4.2 Upper Launcher No. 1 Testing

Testing of Upper Launcher No. 1 included emission angle range, poloidal rotation speed, and calibration of the relationship between mirror angle and motor absolute position. The designed emission angle range was  $-15^\circ$  to  $-80^\circ$ . Table 3 lists the measured effective poloidal emission angles, showing that the actual injection range meets the theoretical design and fully satisfies experimental requirements, enabling heating from the plasma edge to the core.

Motor testing aimed to verify response time, positioning accuracy, and full-scale travel time. Figure 8 shows the results: Figure 8(a) displays position and velocity for the left plane mirror drive motor moving 60.14 mm full scale from  $-15^\circ$  to  $-80^\circ$ , while Figure 8(b) shows the right mirror moving 60.275 mm full scale. Commanded and actual positions nearly coincide, with response times under 1 ms and deviations less than 0.045 mm. The minimum full-scale travel times are 189.875 ms (left) and 189.5 ms (right).

Calibration of the relationship between launcher angle and motor position provides essential control data for experiments. The test setup involved an optical platform with a fixed launcher and laser source. A servo driver controlled motor speed and lead screw position, using a laser to simulate microwave injection. The laser spot position on a target board after passing through the launcher determined the relationship between emission angle and motor travel.

Final calibration results are shown in Figure 9, with Figure 9(a) for the left path and Figure 9(b) for the right path. The excellent linear relationship between emission angle and motor position facilitates launcher control during experiments.

[Figure 8: see original paper]

[Figure 9: see original paper]

## Conclusion

Based on the requirements of the HL-3 tokamak ECRH system, the launcher system has been designed, developed, tested, and installed. Two launchers have completed design, manufacturing, and testing, while the optical path design for the third launcher has been finished. The results demonstrate that the optical path design of Upper Launcher No. 2 meets system requirements, and both the equatorial launcher and Upper Launcher No. 1 exhibit precise and fast control, satisfying the requirements for experimental operation on the device.

## Acknowledgments

We thank the HL-3 ECRH team members for their assistance and the technical staff of Room 103 for their support with leak detection and installation.

## Author Contributions

Zheng Wanxin completed the theoretical design of the launchers, participated in testing and installation, processed data, and wrote the paper. Ye Jiruo participated in launcher testing and installation. Chen Gangyu completed the mechanical design and drafting. Huang Mei participated in system design and revised the paper.

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