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

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Date: 2024-05-10T00:00:00+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 and developed, with antennas subsequently tested and installed. The HL-3 ECRH antenna system comprises three antennas—one mid-plane antenna and two upper oblique antennas—situated in the same sector on the weak-field side of the device, capable of collaboratively performing heating, neoclassical tearing mode (NTM) control, and other functions. To date, the design, manufacturing, and testing of two antennas have been completed, while the launcher optical path design has been finalized for the third antenna. Test results demonstrate that the mid-plane antenna and Upper Oblique Antenna #1 exhibit precise, rapid control, satisfying the requirements for experimental operation on the device.

Full Text

Preamble

Vol. XX, No. X, XXX 20XX, Nuclear Techniques, ChinaXiv

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 the launcher, which constitutes 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. Microwave injection effects were simulated and calculated. The transmission angle and rotation speed 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 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

In magnetic confinement fusion research, electron cyclotron resonance heating is widely employed for plasma heating, current profile control, neoclassical tearing mode (NTM) suppression, and auxiliary startup due to its high wave absorption efficiency, excellent deposition locality, efficient plasma coupling, and the ability to position the launcher far from the plasma [1-7]. The HL-3 tokamak is currently planning to construct an ECRH system with a total power of 9.5 MW, consisting of three launcher sets and associated auxiliary systems [8]. This paper provides a detailed description of the design and development of the launcher system.

Funding: National Key R&D Program of China (Grant No. 2022YFE03020002); National Natural Science Foundation of China (Grant No. U2267209)

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Received: 20XX-00-00; **Revised**: 20XX-00-00

1 HL-3 Tokamak ECRH System

The ECRH system comprises a radio frequency system and auxiliary systems. The RF system primarily includes gyrotrons, transmission lines, and launchers, while the auxiliary systems consist of control systems, microwave parameter measurement systems, power supplies, and cooling systems [9]. Based on the HL-3 tokamak operating parameters [10] and experimental research requirements [11], the ECRH system is planned to have a total power of 9.5 MW. The overall system layout is shown in Figure 1 [Figure 1: see original paper]. Currently, 7.5 MW has been developed, including one 68 GHz/500 kW/1 s system, five 105 GHz/1 MW/3 s systems, and two 140 GHz/1 MW/3 s systems. The frequencies of the remaining two systems will be determined later according to operational requirements.

The wave source system of the ECRH is located in the wave heating hall adjacent to the HL-3 tokamak hall. Transmission lines connected to the wave sources pass through penetrations in the wall between the two halls to interface with three integrated launcher sets on the tokamak. The cathode high-voltage power supplies are installed in the rectifier hall, with high-voltage cables laid through underground piping networks to the wave heating hall. The upper-level computers of the control system are placed in the heating control room, communicating with local devices via Ethernet and operating under the management of the main control system to uniformly control the ECRH/ECCD system and monitor its operational status [12].

2 Overall Launcher System Planning

The HL-3 tokamak ECRH system employs three gyrotron frequencies: 68 GHz, 105 GHz, and 140 GHz. Synergistic injection through the launcher system under various parameters can enhance the operational range of the ECRH system. Figure 2 [Figure 2: see original paper] shows the deposition positions of microwaves at different frequencies under various parameters, where the dot-dash 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 T to 3.0 T.

To satisfy functional requirements for heating, current drive, auxiliary startup, and NTM suppression, the system plans 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 tokamak are shown in Figure 3 [Figure 3: see original paper], and the launcher parameters and functions are listed in Table 1 .

3.1 Equatorial Launcher Design

The equatorial launcher is positioned at the tokamak's equatorial port, enabling vertical injection into the plasma with high heating efficiency. The ample space allows simultaneous injection of multiple microwave beams, making it responsible for the primary heating function of the launcher system. The equatorial launcher is planned to inject four microwave beams, with a final 2$×$2 layout installing four focusing mirrors and two steerable plane mirrors. Two microwave beams on each side share one mirror, with the optical path schematic shown in Figure 4 [Figure 4: see original paper] (side view).

Sharing one mirror and its corresponding drive mechanism between two microwave beams significantly saves limited space. However, this results in the actual emission angle not being zero when the mirror's poloidal position is at 0°, as shown in Figure 4. Calculations indicate that to deposit the microwave at the plasma center from this position, the mirror must be precisely oriented to achieve the required injection angle.

3.2 Upper Launcher No. 1 Design

Upper Launcher No. 1 is located at a Ø300 mm port with limited space. This port is relatively far from the plasma, making it minimally affected by plasma interactions. If the final rotatable mirror extends outward from the port facing the plasma, the launcher can cover a wide injection angle range. Upper Launcher No. 1 is primarily designed for real-time NTM control, requiring extremely high response speed and rotation accuracy [13,14]. The final design features a poloidal-only rotation structure using a push-rod mechanism to achieve high rotational precision. Since NTMs typically occur during high-parameter operation, two microwave beams at 105 GHz/140 GHz dual frequency are selected to broaden the operational parameter range.

The main structure of Upper Launcher No. 1 includes a vacuum-sealed box, focusing and plane mirrors, and mechanical rotation and transmission systems. The launcher has two reflection paths, each with one focusing mirror and three plane mirrors. The conceptual design of each mirror and its rotation mechanism is shown in Figure 5 [Figure 5: see original paper]: microwaves initially incident from the sealed window connecting the waveguide to the plane mirror M1, reflect to focusing mirror A1, are focused and then emitted to plane mirror B, and finally reflected to plane mirror C1. Poloidal rotation of plane mirror C1 via push-rod actuation enables microwave injection into the plasma at different poloidal emission angles.

The fundamental principle of focusing mirror design is to position the microwave beam waist as close as possible to the plasma center region. However, this may create excessively large spots on plane mirrors, 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.

3.3 Upper Launcher No. 2 Design

The port for Upper Launcher No. 2 has a diameter of only 200 mm. Additionally, the toroidal field coils, poloidal field coils, water cooling systems, and cable routing around the HL-3 tokamak's upper port create a complex environment, limiting the size of the vacuum-sealed box. Currently, only the internal optical path design has been completed for this launcher.

Given the limited space and the fact that the Upper Launcher No. 2 port is far from the plasma with minimal plasma interaction, extending the final rotatable mirror outward makes the transmission mechanism difficult to design. Therefore, only poloidal rotation is considered for now, with possible future addition of toroidal rotation or redesign of the reflection path based on requirements.

The poloidal injection range of Upper Launcher No. 1 covers nearly the entire plasma. Due to space limitations, Upper Launcher No. 2 is primarily intended for NTM control, so its design focuses on covering the main region where magnetic islands occur [15]. The final optical path design is shown in Figure 6 [Figure 6: see original paper], meeting the poloidal emission range requirements. The theoretical emission range of Upper Launcher No. 2 and the corresponding angle of the final mirror are shown in Table 2 , demonstrating that the final mirror angle changes only slightly. This presents a significant challenge for precise emission angle control, requiring increased motor lead screw travel for the same angular change in subsequent transmission system design.

4.1 Equatorial Launcher Testing

The equatorial launcher testing primarily included emission angle range testing and poloidal rotation speed testing. Toroidal rotation uses a lead screw mechanism with a slow motor, so its speed was not tested.

In actual testing, shielding baffles, device wall thickness, and first-wall installation around the port limited the final poloidal emission angle range to -18° to 18° and the toroidal emission angle range to -18.5° to 18.5°. The poloidal test results are shown in Figure 7 [Figure 7: see original paper]. Figure 7(a) shows the position and velocity versus time for the left plane mirror drive motor moving 13.02 mm full scale from -18° to 18° injection angle at 50 ms intervals, while Figure 7(b) shows the same for the right plane mirror drive motor moving 12.96 mm full scale. The figures demonstrate that the position commands from the servo driver and the actual motor feedback positions nearly coincide. Motor response times were less than 1 ms (microsecond level), and at any given time, the difference between commanded and actual positions was less than 0.07 mm. The measured fastest full-scale travel time was 79 ms for the left mirror and 87.75 ms for the right mirror.

4.2 Upper Launcher No. 1 Testing

Upper Launcher No. 1 testing included emission angle range testing, poloidal rotation speed testing, and calibration of the relationship between launcher rotation angle and motor absolute position. The designed emission angle range was -15° to -80°. Table 3 shows the measured effective poloidal emission angle range, confirming that the actual injection angles meet the theoretical design maximum range and fully satisfy experimental requirements, enabling heating from the plasma edge to the center.

The motor testing aimed to verify response time, operational precision, and full-scale travel time against system requirements. Figure 8 [Figure 8: see original paper] shows the test results: Figure 8(a) displays position and velocity versus time for the left plane mirror drive motor moving 60.14 mm full scale from -15° to -80° injection angle at 50 ms intervals, while Figure 8(b) shows the same for the right plane mirror drive motor moving 60.275 mm full scale. The results show that servo driver commands and actual motor feedback positions nearly coincide. Motor response times were less than 1 ms (microsecond level), with differences between commanded and actual positions less than 0.045 mm at any time. The measured fastest full-scale travel time was 189.875 ms for the left mirror and 189.5 ms for the right mirror.

Calibration of the relationship between launcher rotation angle and motor absolute position provides the control data needed for actual experiments—specifically, the motor positions corresponding to different emission angles. The test setup involved building an optical experiment platform with fixed launcher and laser source, using a servo driver to control motor speed and lead screw position. A laser simulated the incident microwave, and the position where the laser hit a target plate after passing through the launcher was measured to determine the relationship between emission angle and motor travel distance.

The final calibration results are shown in Figure 9 [Figure 9: see original paper]. Figure 9(a) shows the test and fitting results for the left optical path, and Figure 9(b) shows those for the right optical path. The excellent linear relationship between emission angle and motor position facilitates launcher manipulation during actual experiments.

Conclusion

Based on the requirements of the HL-3 tokamak electron cyclotron resonance heating (ECRH) system, the design and development of the launcher system have been completed, along with testing and installation. The design, manufacturing, and testing of two launchers have been completed, and the emission 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, while the equatorial launcher and Upper Launcher No. 1 exhibit precise and fast control, satisfying the requirements for experimental operation on the tokamak.

Acknowledgments

We thank the members of the HL-3 tokamak ECRH team for their assistance, and we thank the technical staff of Room 103 for their help with launcher 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.

References

1. Erckmann V, Gasparino U. Electron cyclotron resonance heating and current drive in toroidal fusion plasmas[J]. Plasma Physics & Controlled Fusion, 1994, 36(12):1869. DOI:10.1088/0741-3335/36/12/001.
2. Prater R. Heating and current drive by electron cyclotron waves[J]. Physics of Plasmas, 2004, 11(5):2349-2376. DOI:10.1063/1.1690762.
3. Maraschek M. Control of neoclassical tearing modes[J]. Nuclear Fusion, 2012, 52(7):p.074007.1-074007.17. DOI:10.1088/0029-5515/52/7/074007.
4. Chapman I T, Haye R J L, Buttery R J, et al. Sawtooth control using electron cyclotron current drive in ITER demonstration plasmas in DIII-D[J]. Nuclear Fusion, 2012, 52(6):063006. DOI:10.1088/0029-5515/52/6/063006.
5. Kobayashi T, Kajiwara K, Oda Y, et al. Development of two directional beam steering ECH/CD launcher for JT-60SA[J]. Fusion Engineering and Design, 2019, 146(Sep.):1647-1651. DOI:10.1016/j.fusengdes.2019.03.008.
6. Avelino Mas Sánchez, René Chavan, Gagliardi M, et al. Design status of the double Closure Plate Sub-Plate concept for the Electron Cyclotron Upper Launcher[J]. Fusion Engineering & Design, 2018, 136(PT.A):503-508. DOI:10.1016/j.fusengdes.2018.03.006.
7. HUANG Mei, RAO Jun, SONG Shaodong, et al. Design and Research of Electron Cyclotron Resonance Heating and Current System on HL-2M Tokamak[J]. European Physical Journal Conferences, 2017, 147:04006. DOI:10.1051/epjconf/201714704006.
8. YUAN Baoshan, JIANG Shaofeng, LU Zhihong. Fundamentals of Tokamak Device Engineering[M]. Atomic Energy Press, 2011.
9. Li Qiang. The component development status of HL-2M tokamak[J]. Fusion Engineering and Design, 2015, 96-97: 338-342. DOI: 10.1016/j.fusengdes.2015.06.106.
10. XUE L, Garcia J, ZHENG G, et al. Integrated plasma scenario analysis for HL-2M tokamak[J]. Nuclear Fusion, 2019, 60(1). DOI:10.1088/1741-4326/ab4c65.
11. HUANG Mei, WANG He, ZHANG Feng, et al. Design and development of ECRH/ECCD system on HL-2M tokamak[J]. Nuclear Fusion and Plasma Physics, 2021, 41(S02): 5. DOI: 10.16568/j.0254-6086.2021s2012.
12. Takahashi K, Kobayashi N, Abe G, et al. Development of a direct mirror angle detector for ITER EC launchers[J]. Fusion Engineering and Design, 2017, 123. DOI: 10.1016/j.fusengdes.2017.04.114.
13. YAN Longwen, JI Xiaoquan, SONG Shaodong, et al. Experimental study on real-time control of tearing mode in HL-2A tokamak[C]. National Conference on Plasma Science and Technology, 2017.
14. Bardoczi L, Choi M J, Navarro A B, et al. Controlled neoclassical tearing mode (NTM) healing by fueling pellets and its impact on electron cyclotron current drive requirements for complete NTM stabilization[J]. Nuclear Fusion, 2019, 59(12):126047.1-126047.14. DOI:10.1088/1741-4326/ab472d.